LHC and Hadron Collider Physics

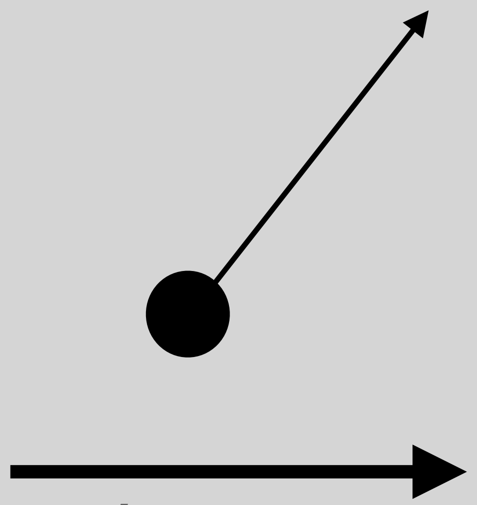
CSU-NUPAX/CERN IRES Program

Johan S Bonilla

Feb 15th and 17th, 2022

What is a Particle?

Classical



Quantum Mechanics

$$\psi_n(x) = \sqrt{\frac{1}{2^n\, n!}} \cdot \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} \cdot e^{-\frac{m\omega x^2}{2\hbar}} \cdot H_n\left(\sqrt{\frac{m\omega}{\hbar}}x\right),$$

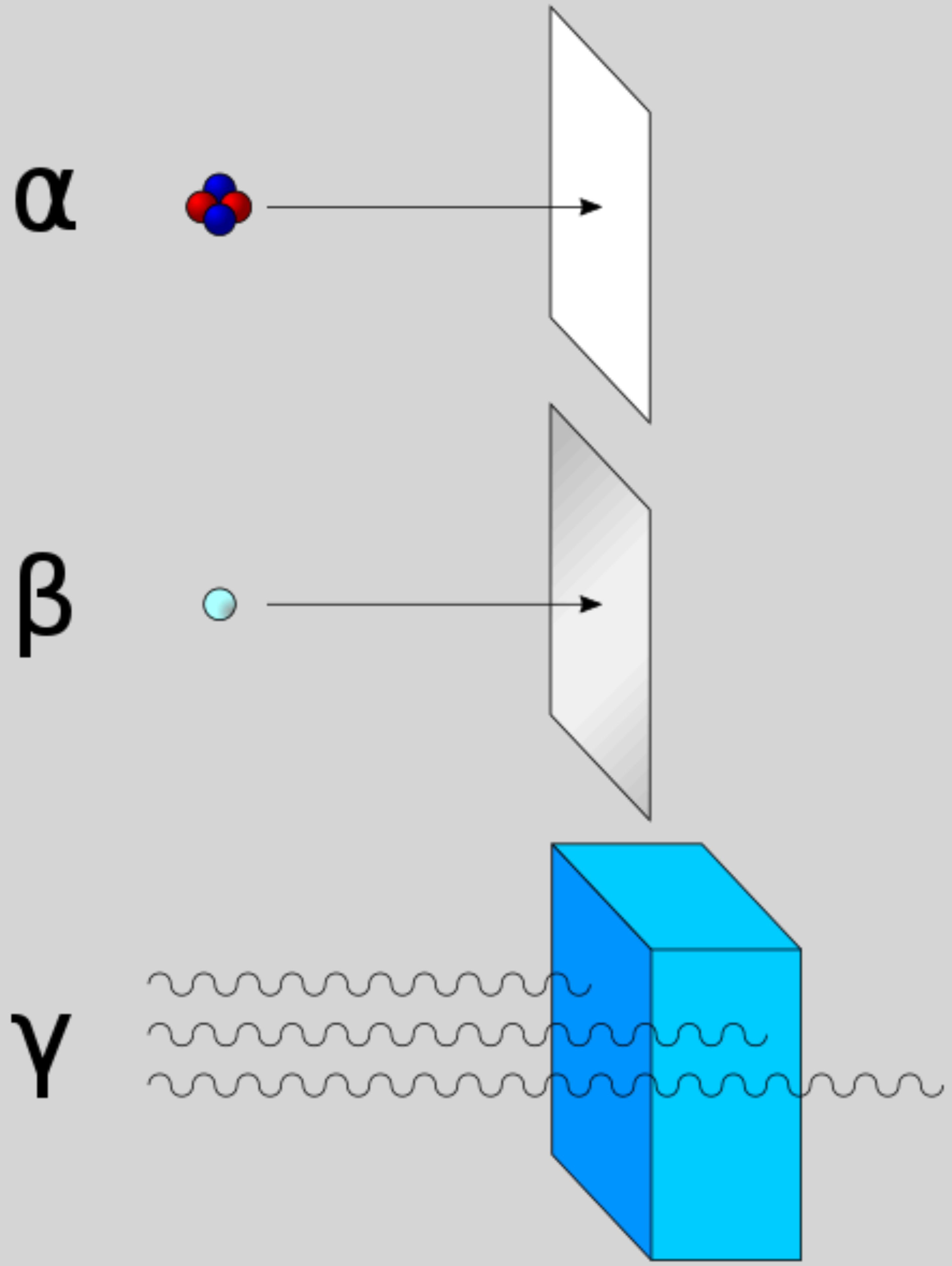
Does NOT play nice
with special relativity

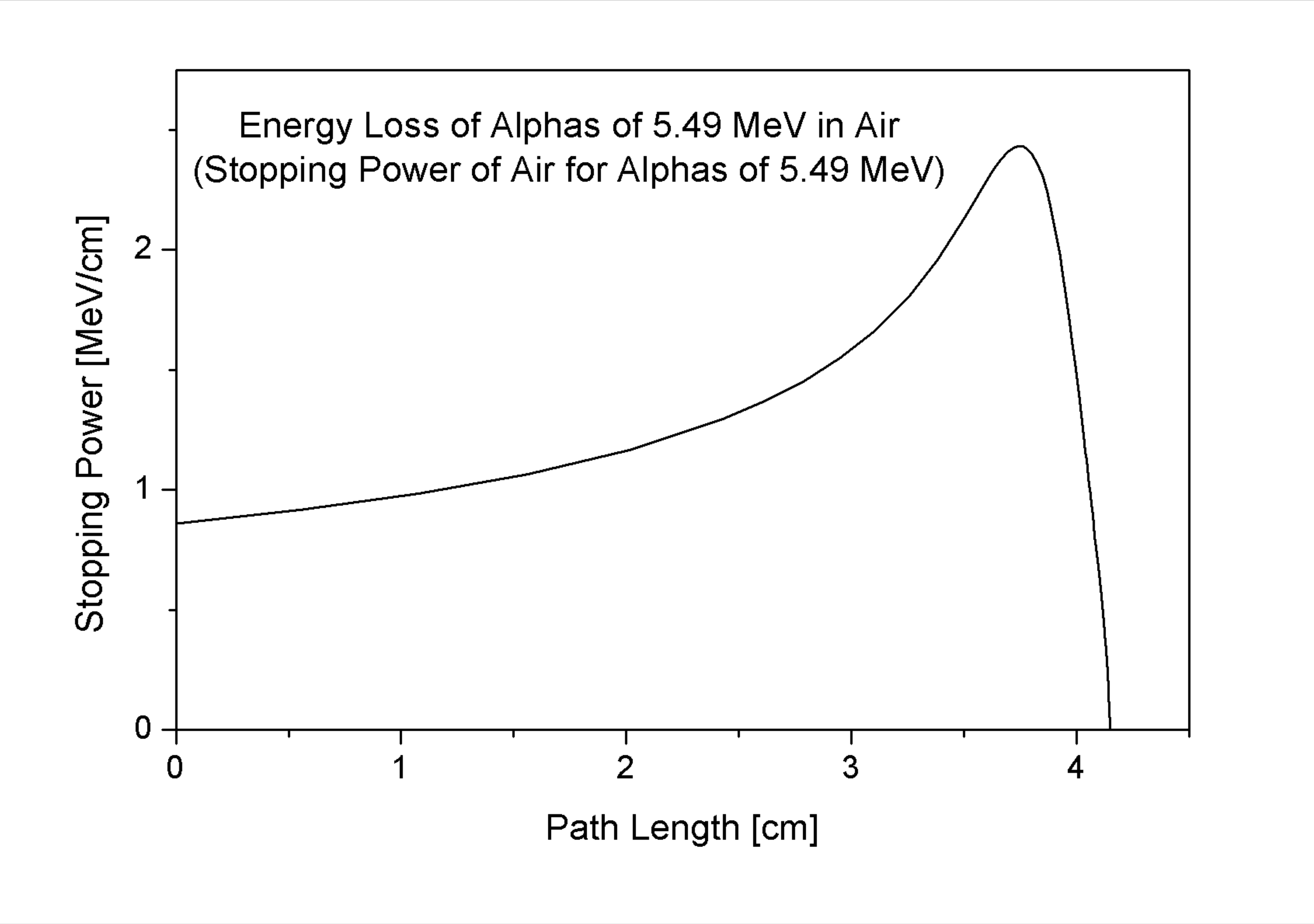
Quantum Field Theory

$$\hat{\phi}(\mathbf{x},t) = \int \frac{d^3p}{(2\pi)^3}\frac{1}{\sqrt{2\omega_{\mathbf{p}}}}\left(\hat{a}_{\mathbf{p}}e^{-i\omega_{\mathbf{p}}t+i\mathbf{p}\cdot\mathbf{x}} + \hat{a}^\dagger_{\mathbf{p}}e^{i\omega_{\mathbf{p}}t-i\mathbf{p}\cdot\mathbf{x}}\right).$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4,$$

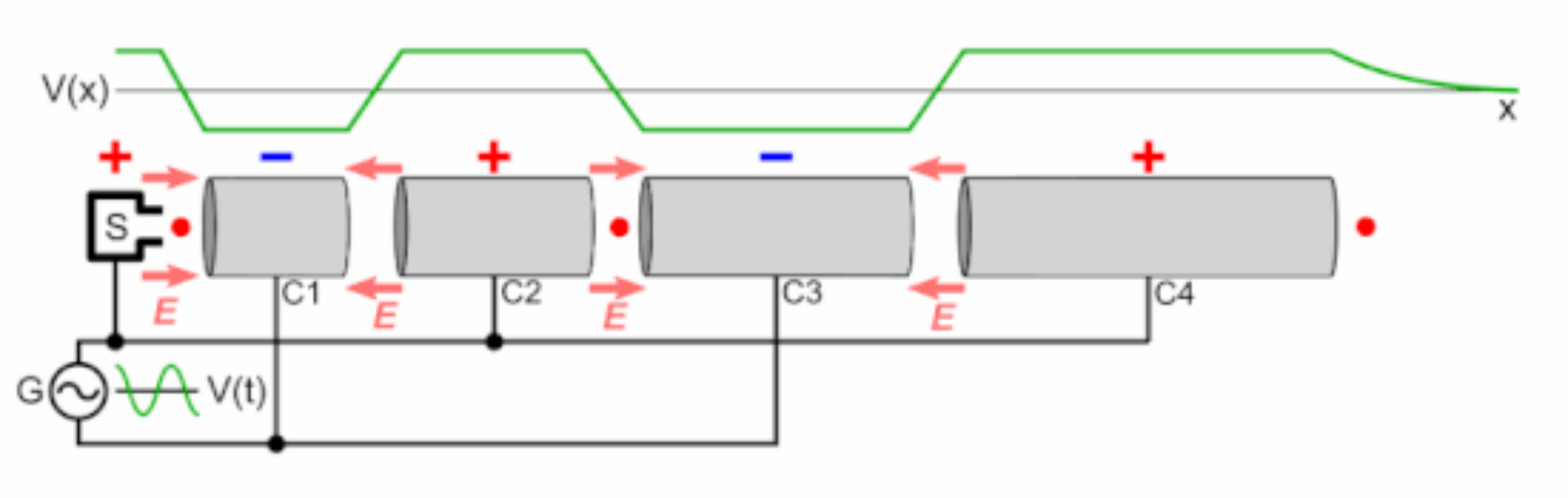
Rutherford+Villard (1899)



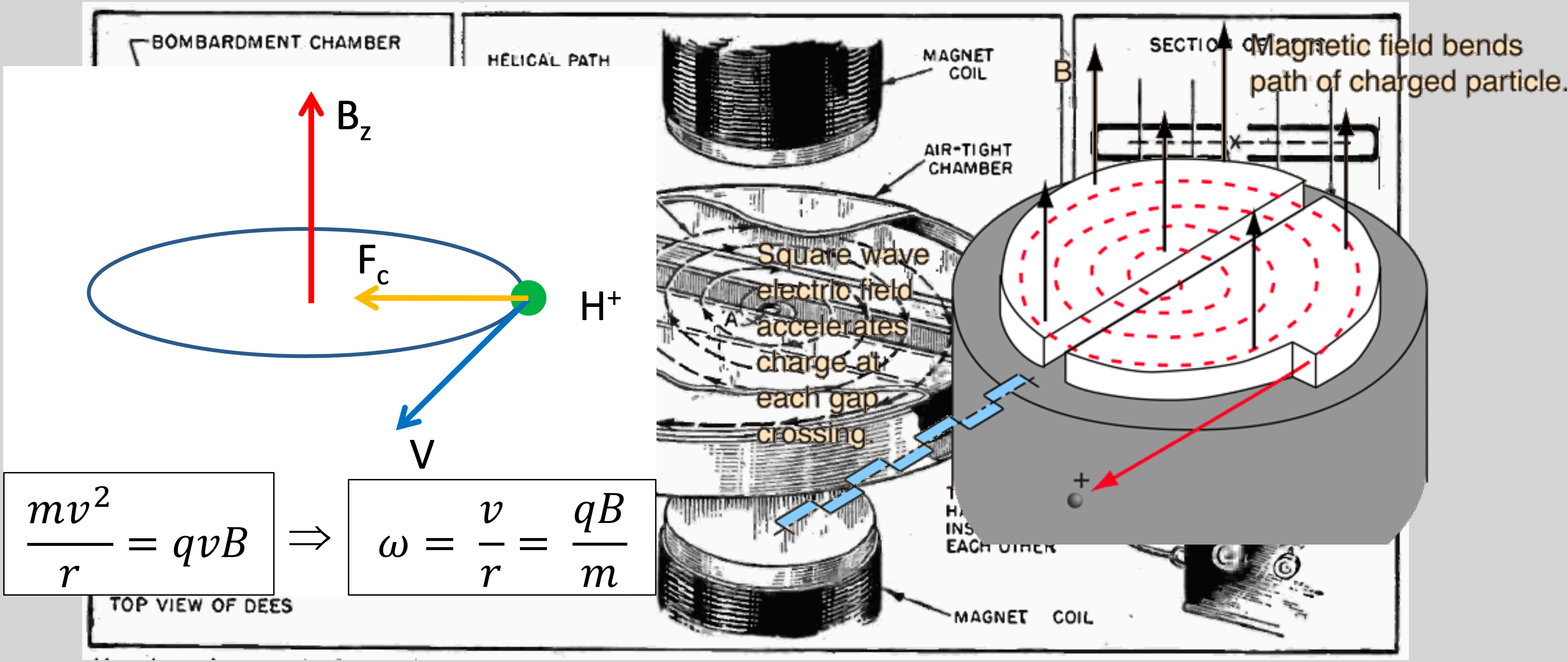


Accelerators

Linear Accelerators (1924)



Cyclotron (1930)

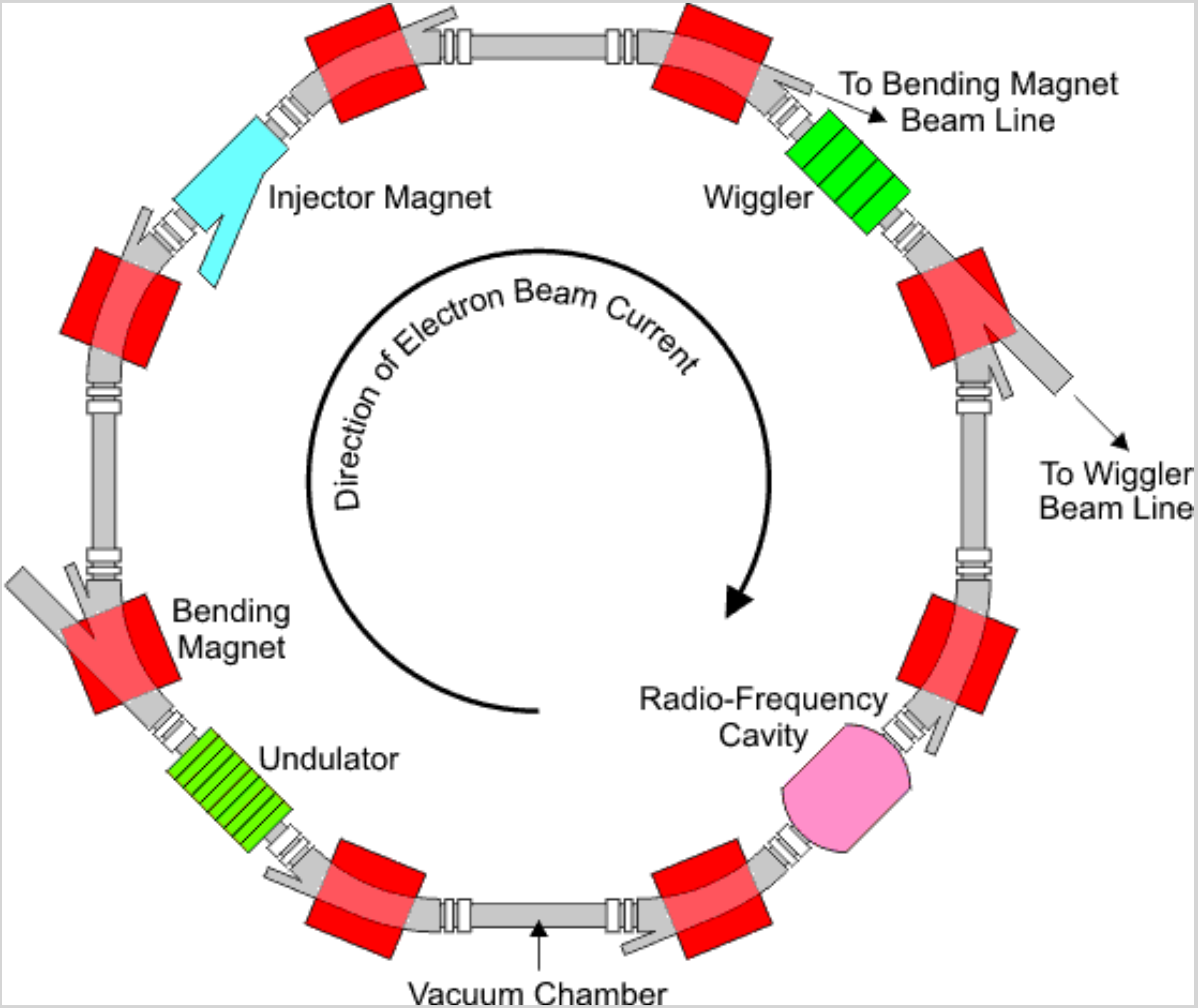


$$\frac{mv^2}{r} = qvB \Rightarrow \omega = \frac{v}{r} = \frac{qB}{m}$$

Synchrotron (1945)

Power Carried by
Synchrotron Radiation

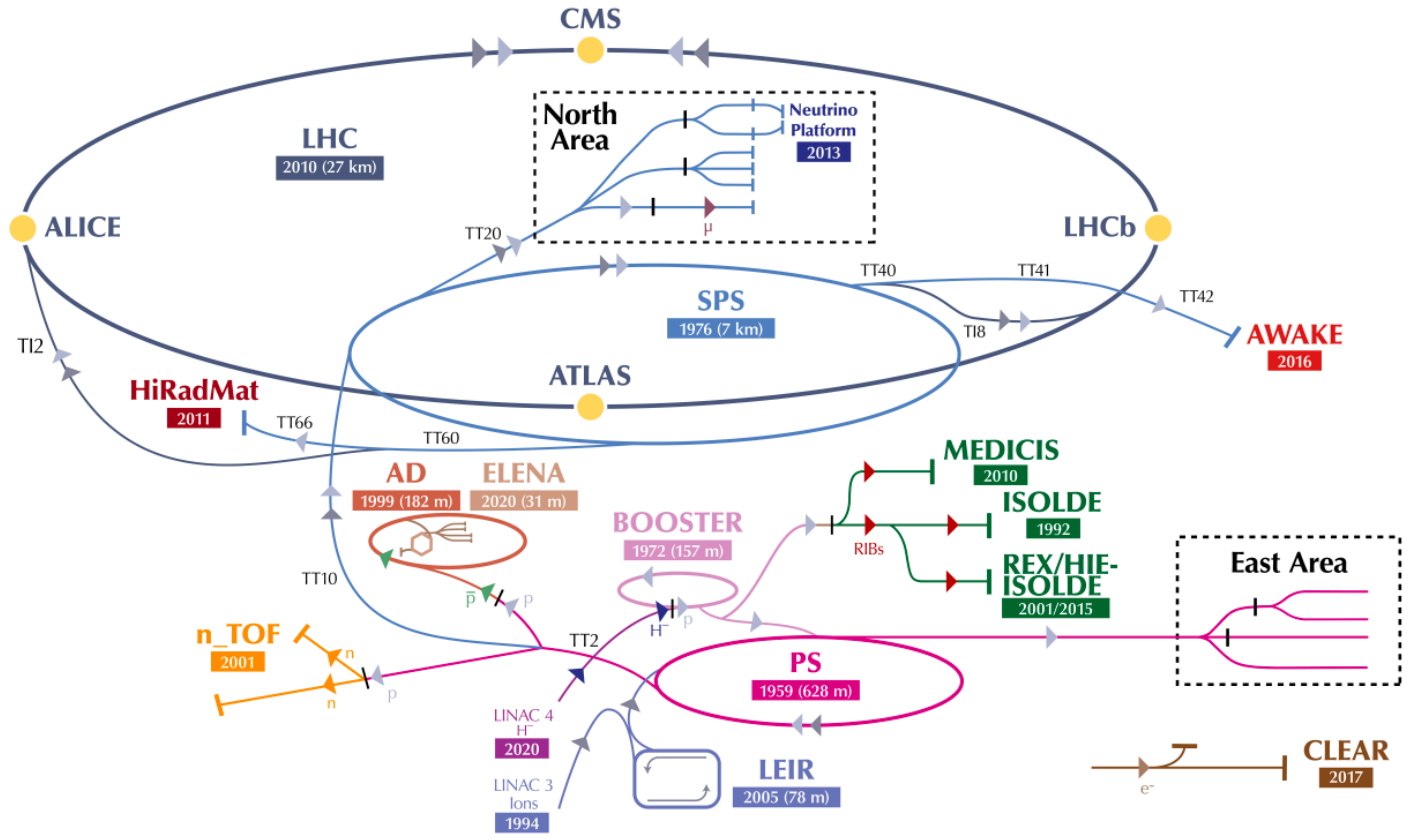
$$P_\gamma = \frac{1}{6\pi\epsilon_o}\frac{q^2 a^2}{c^3}\gamma^4$$



For equal energy electrons and protons, which radiates more power?

What does this mean for accelerator design?

The CERN accelerator complex
Complexe des accélérateurs du CERN

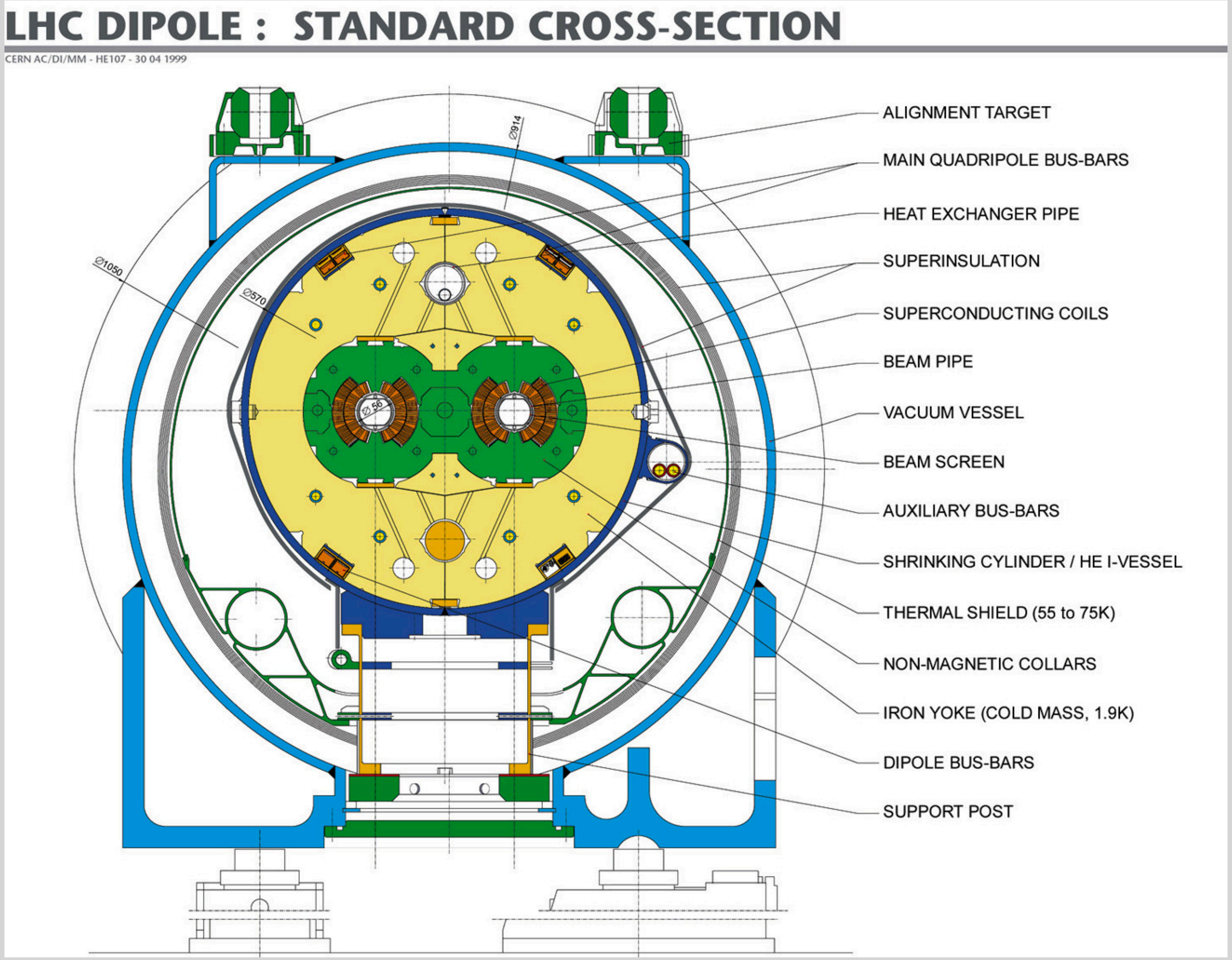


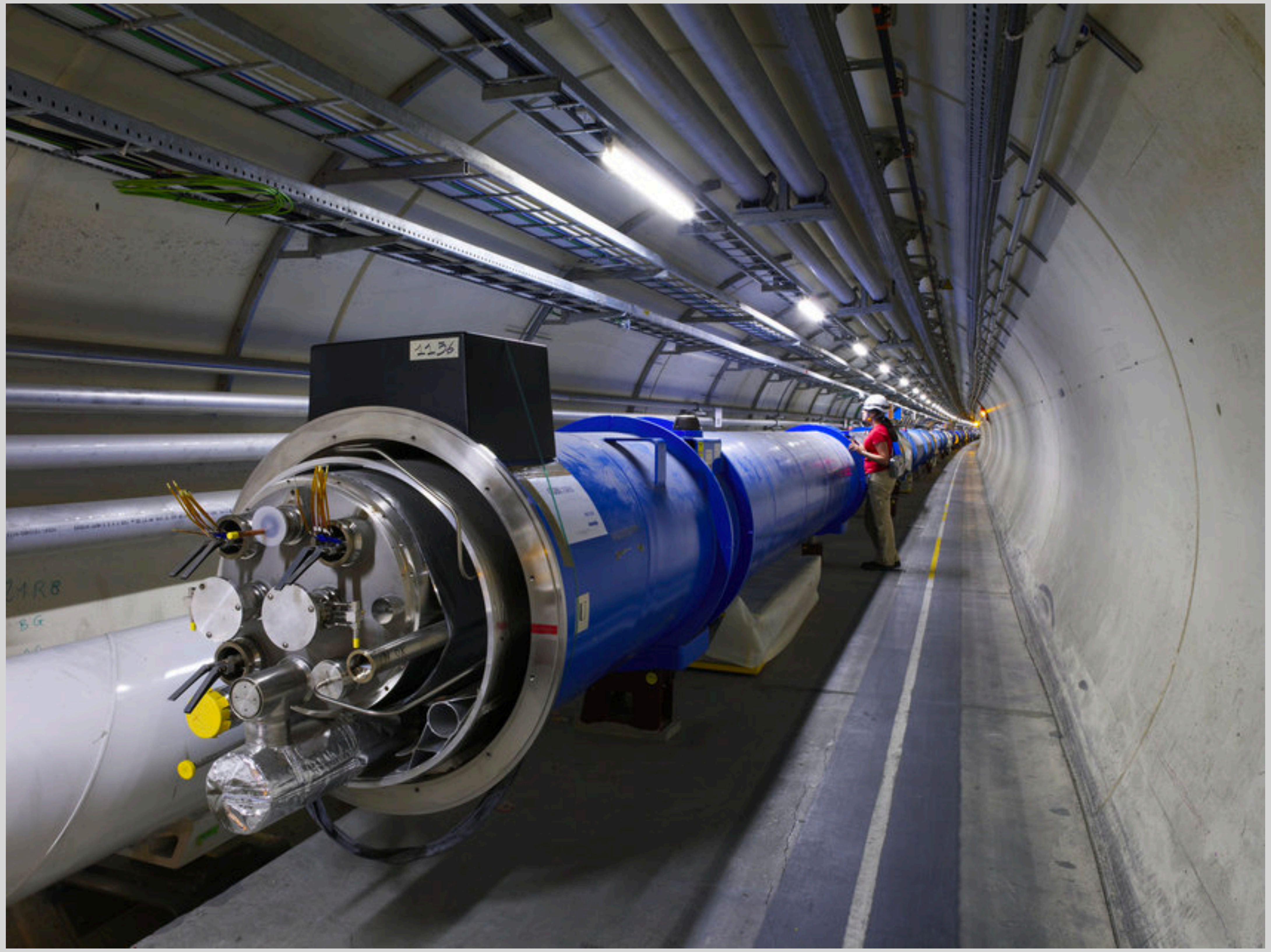
H⁻ (hydrogen anions) p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons) μ (muons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

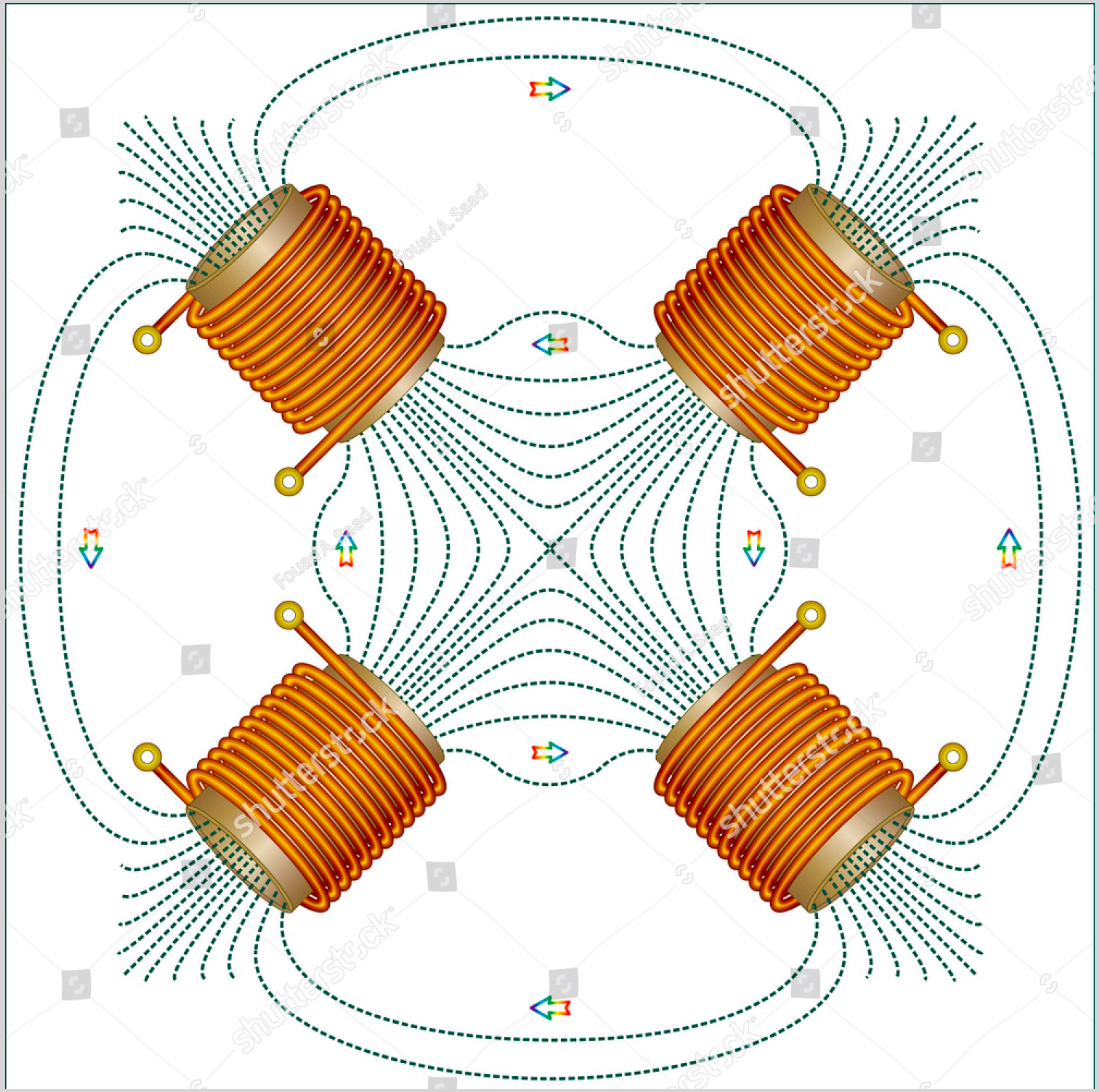
Magnets

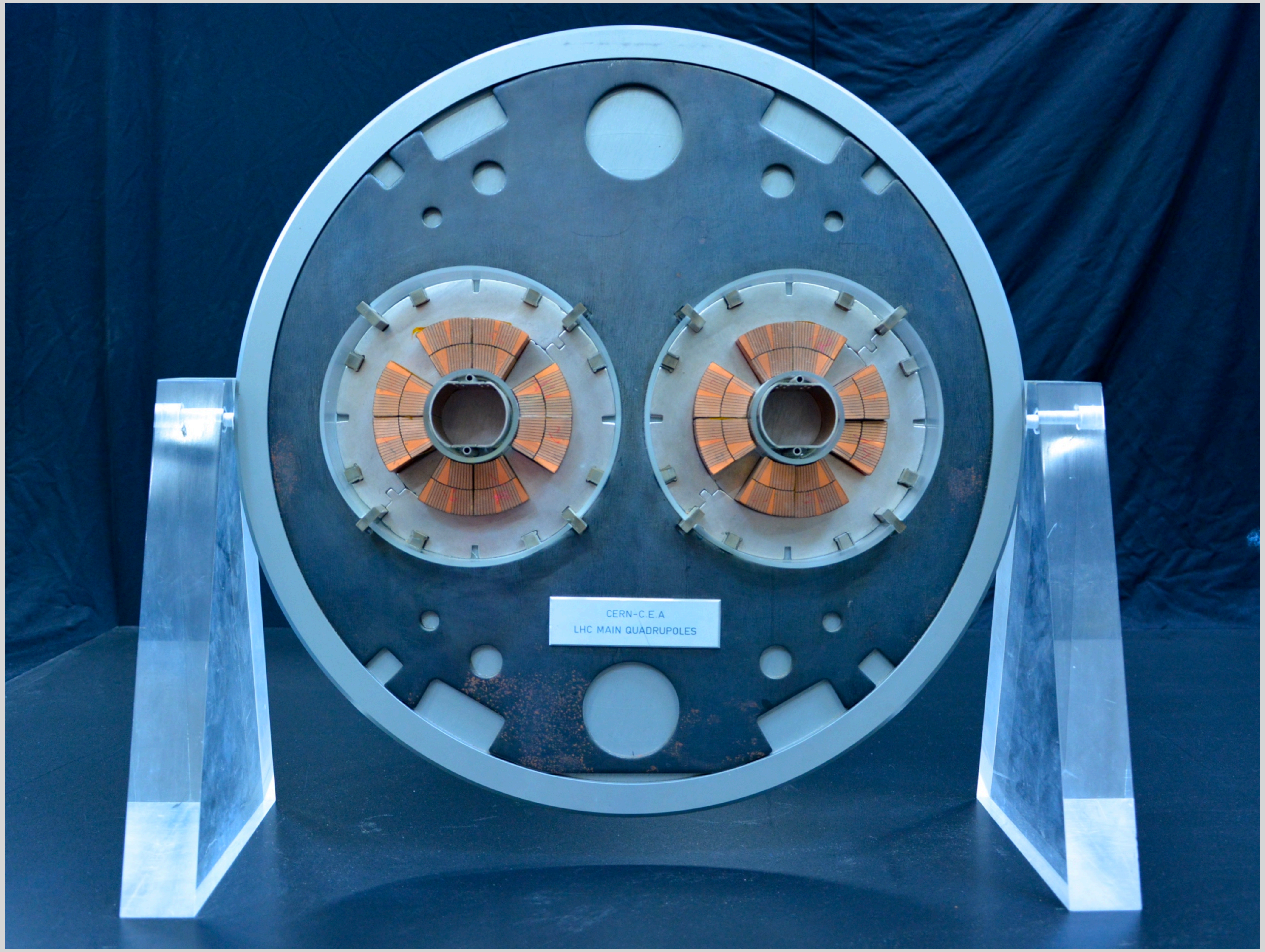
Dipoles


LHC DIPOLE : STANDARD CROSS-SECTION
CERN AC/DI/MM - HE107 - 30 04 1999
ALIGNMENT TARGET
MAIN QUADRIPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 75K)
NON-MAGNETIC COLLARS
IRON YOKE (COLD MASS, 1.9K)
DIPOLE BUS-BARS
SUPPORT POST
Ø1050
Ø570
Ø914
Ø56



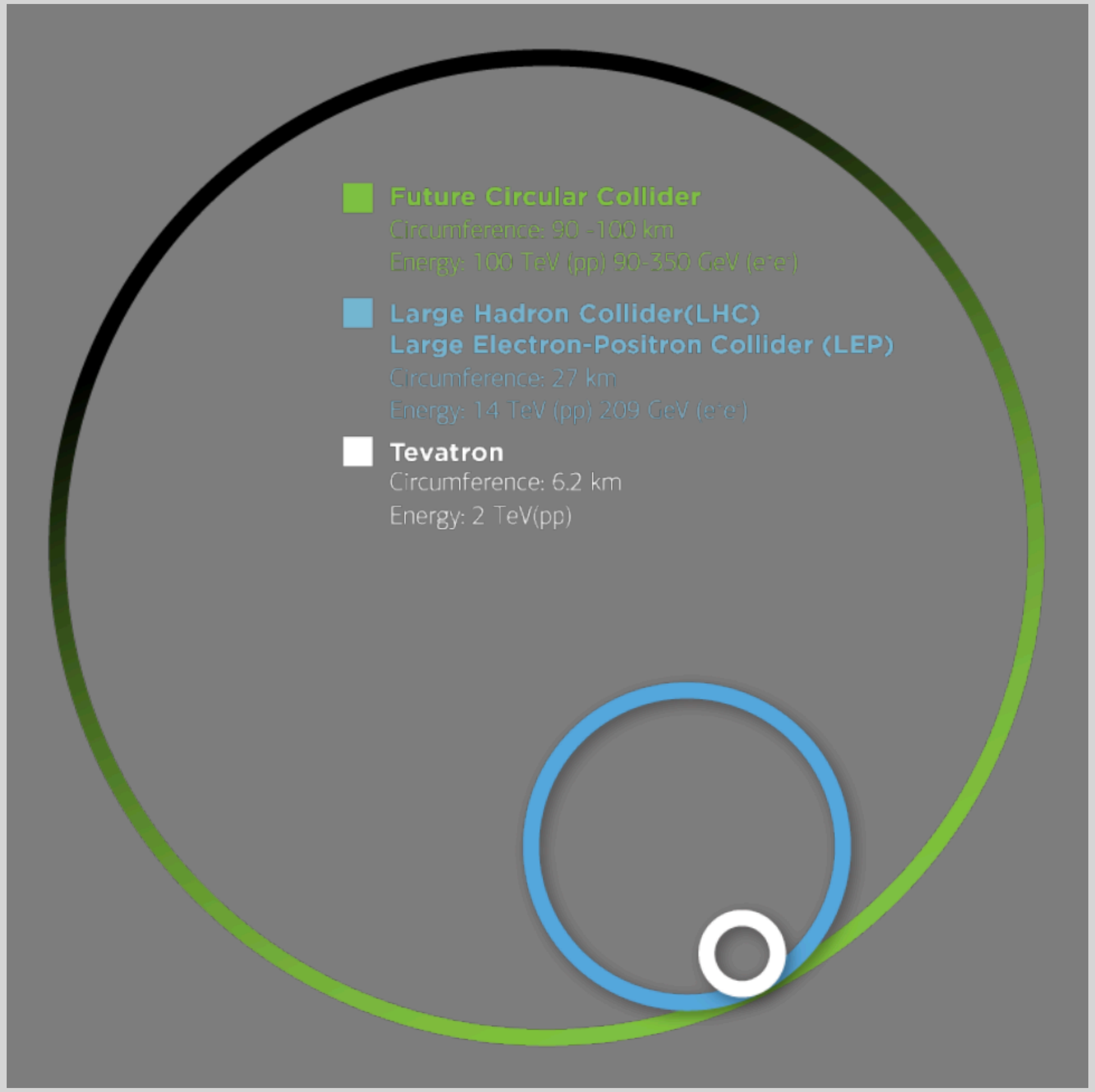
Quadrupoles





Long-Term CERN Plans


LHC / HL-LHC Plan
HiLumi
LARGE HADRON COLLIDER
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
EYETS
LS3
7 TeV
8 TeV
13 TeV
13 - 14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
Civil Eng. P1-P5
inner triplet
radiation limit
HL-LHC
installation
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2040
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
ATLAS - CMS
HL upgrade
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
5 to 7.5 x nominal Lumi
30 fb-1
190 fb-1
350 fb-1
integrated
luminosity
3000 fb-1
4000 fb-1
HL-LHC TECHNICAL EQUIPMENT:
DESIGN STUDY
PROTOTYPES
CONSTRUCTION
INSTALLATION & COMM.
PHYSICS
HL-LHC CIVIL ENGINEERING:
DEFINITION
EXCAVATION
BUILDINGS



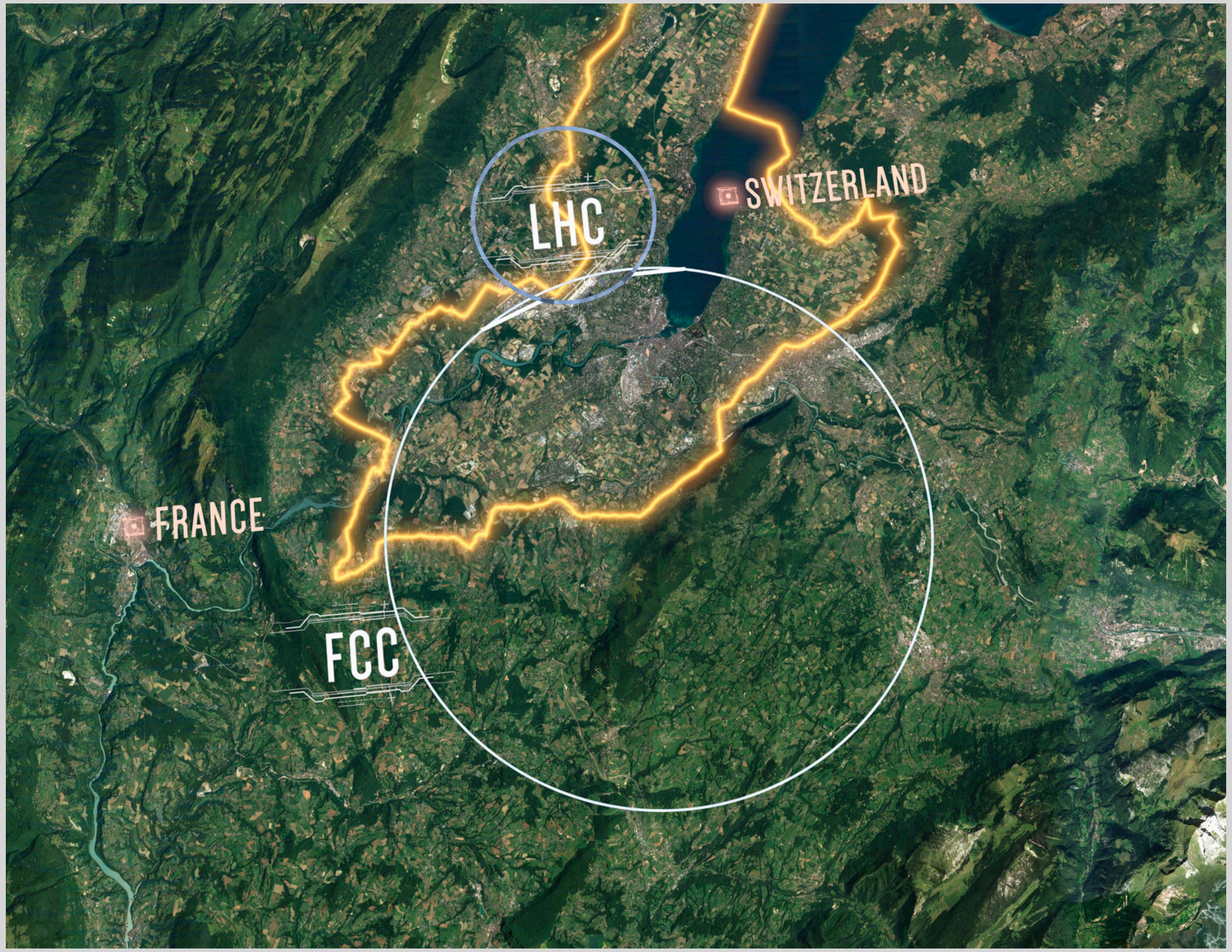


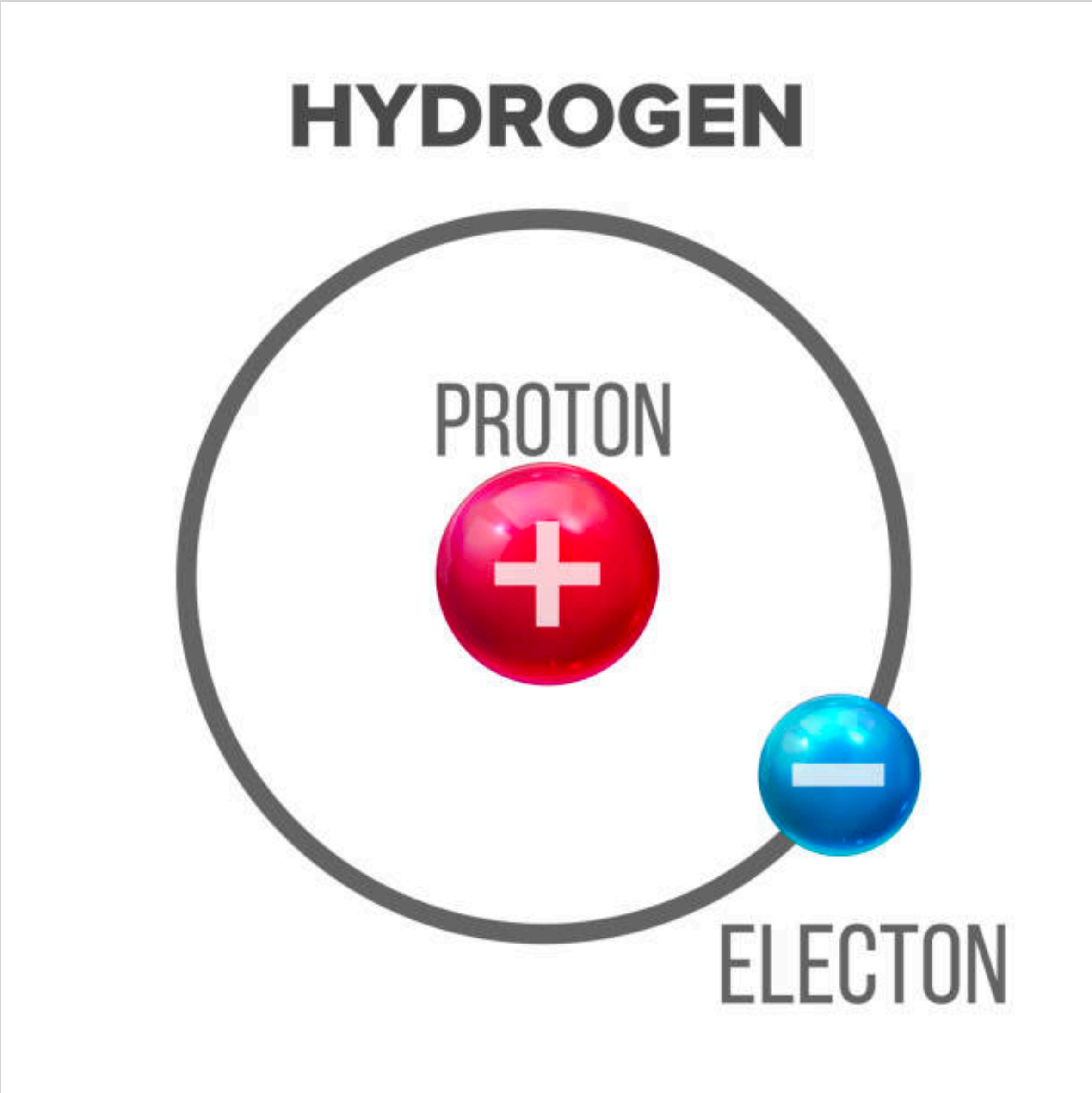
Table 1. FCC programme: schedule, construction and operating costs.

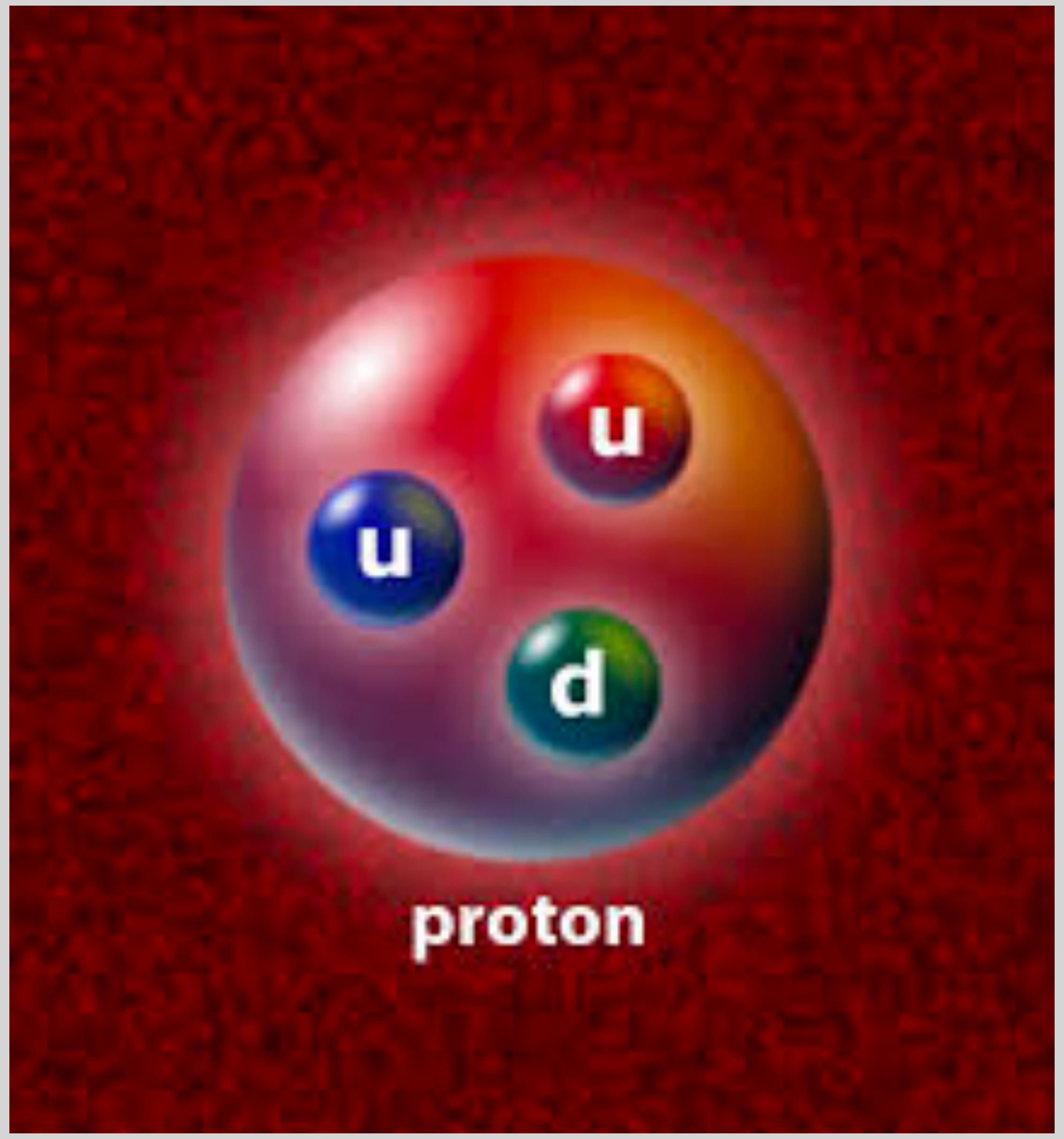
(a) Schedule of different scenarios within the FCC programme

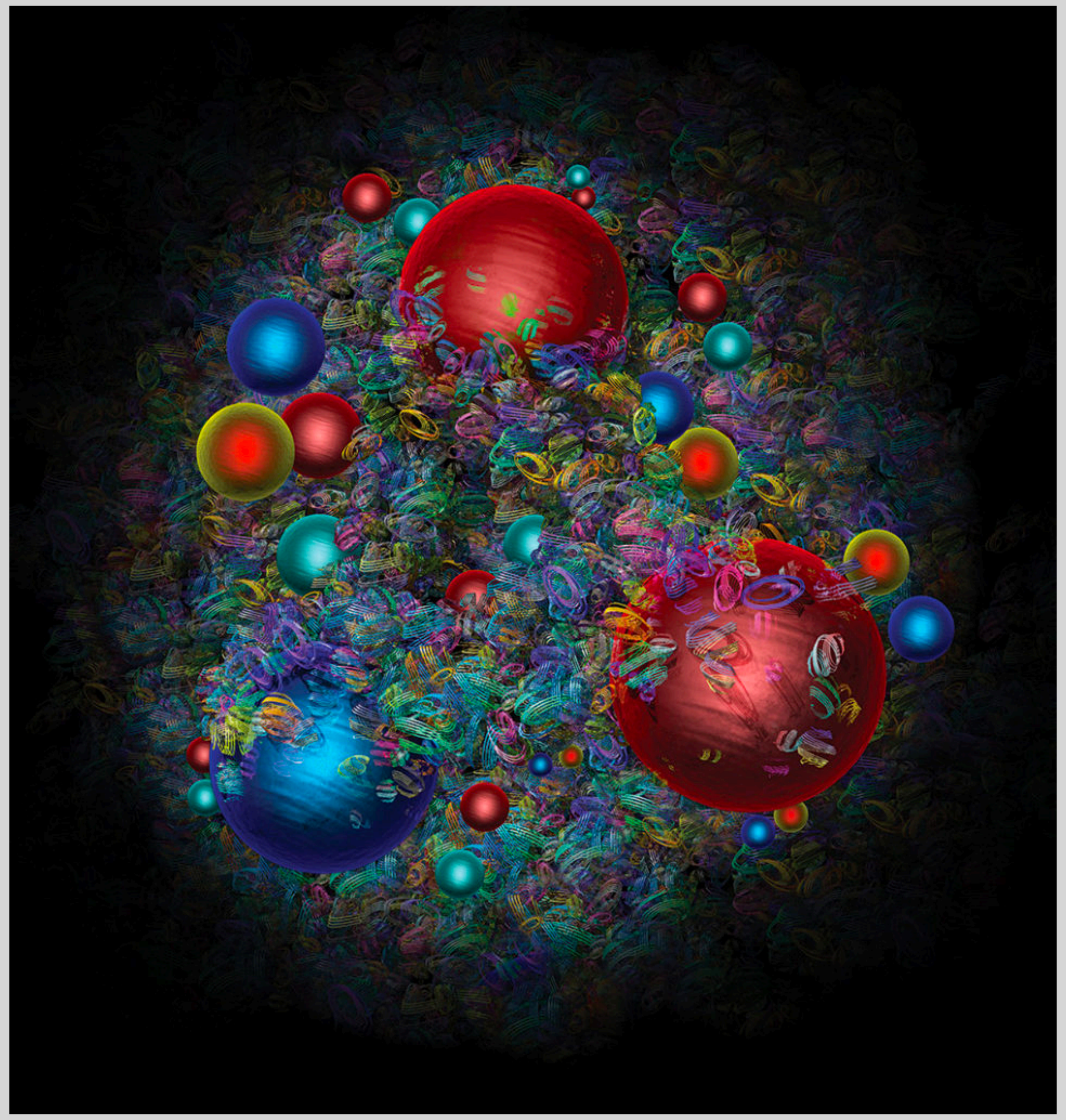
		Start		Duration		
				Implementation		
		Project	*Physics*	Preparation	Construction	*Operation*
FCC-ee		2020	2039	8	10	15
FCC-hh	*with prior implementation of FCC-ee*	2020	2039, mid 2060's	9 (8+1)	20 (10+10)	40 (15+25)
	standalone	2020	mid 2040's	8	15	25
HE-LHC		2020	mid 2040's	8	8	20

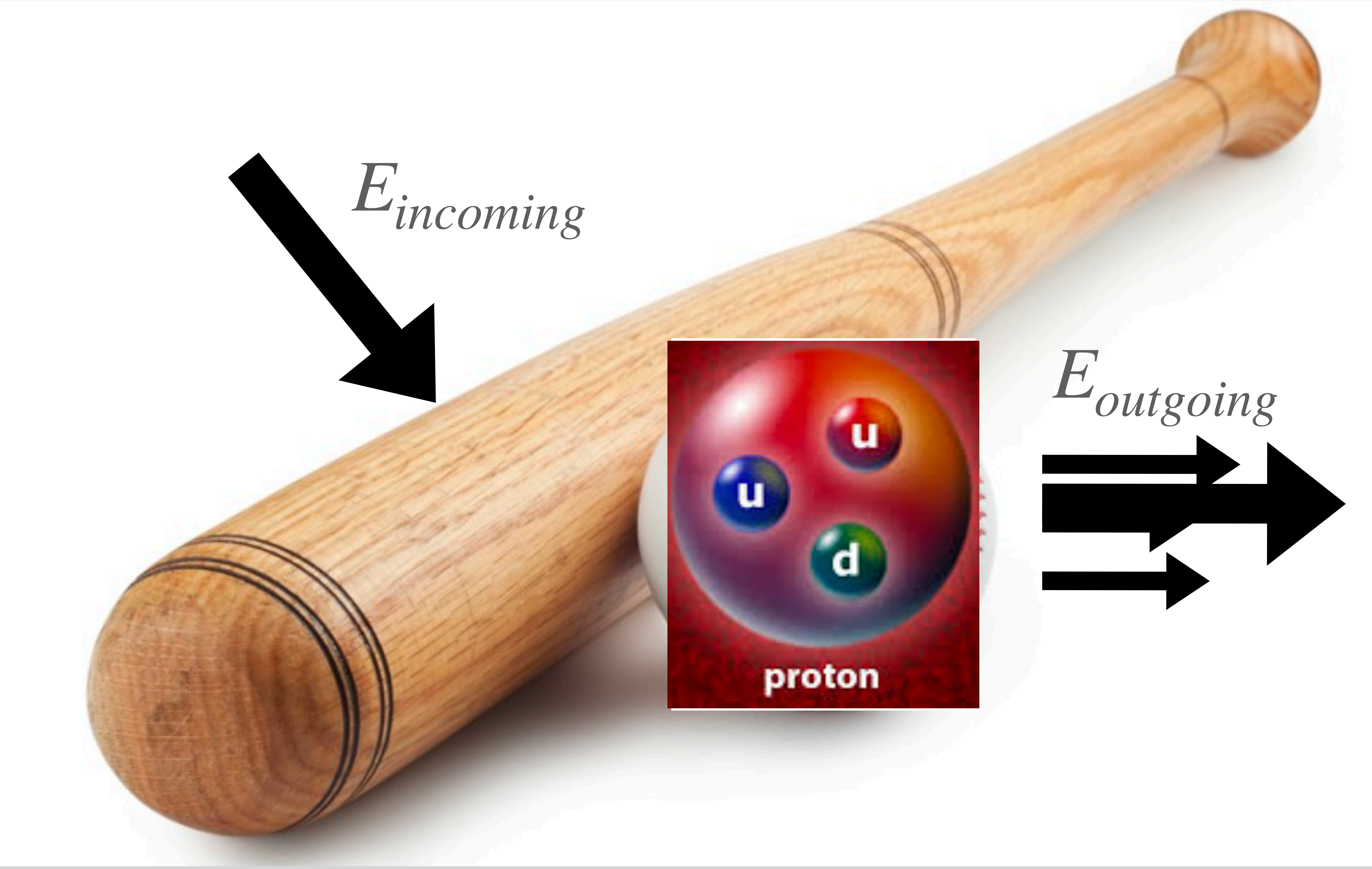
Physics of Protons

What is a Proton?

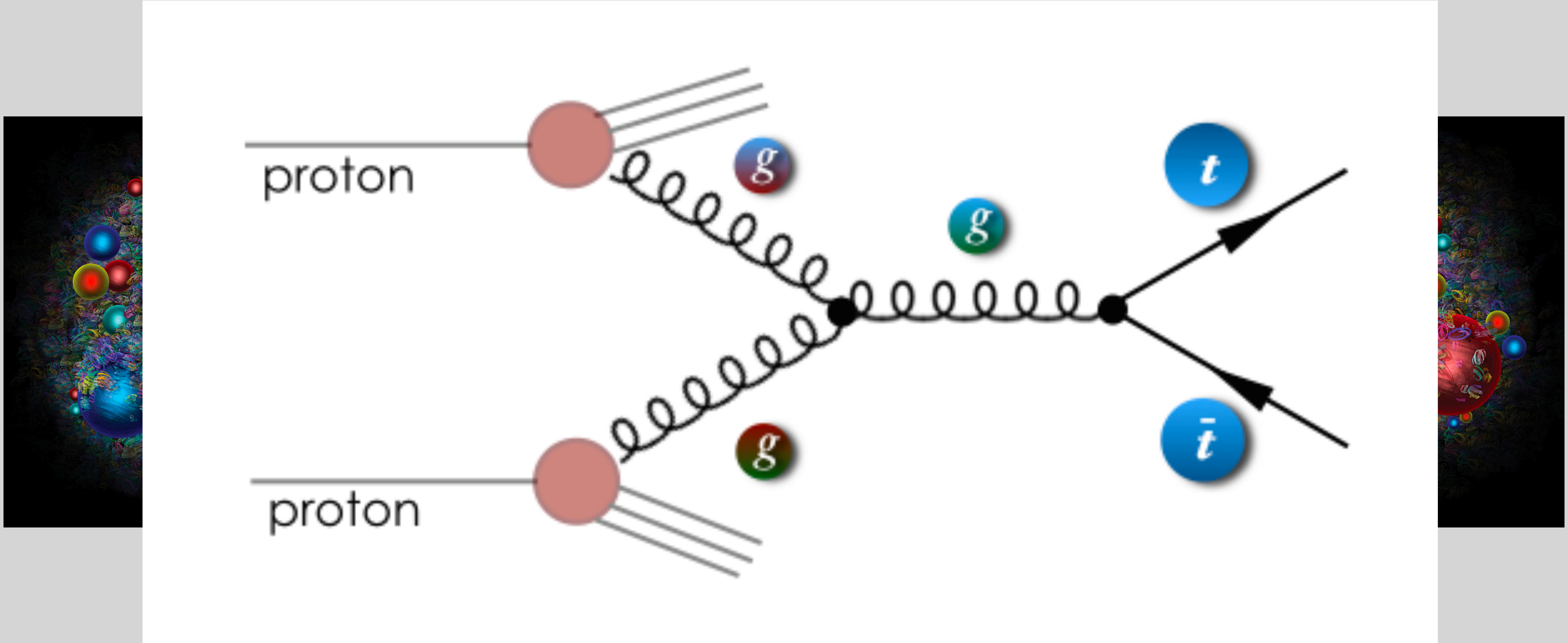




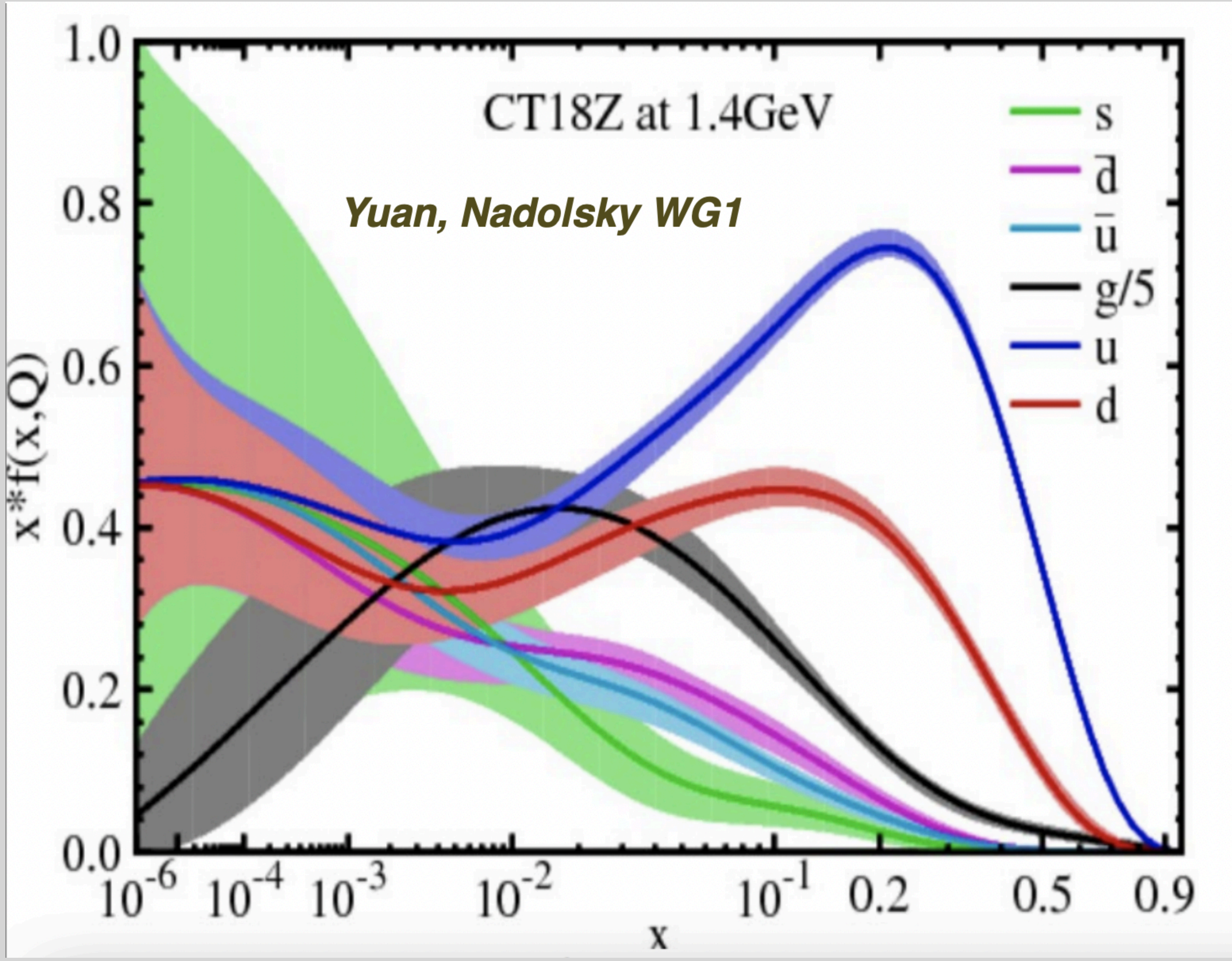


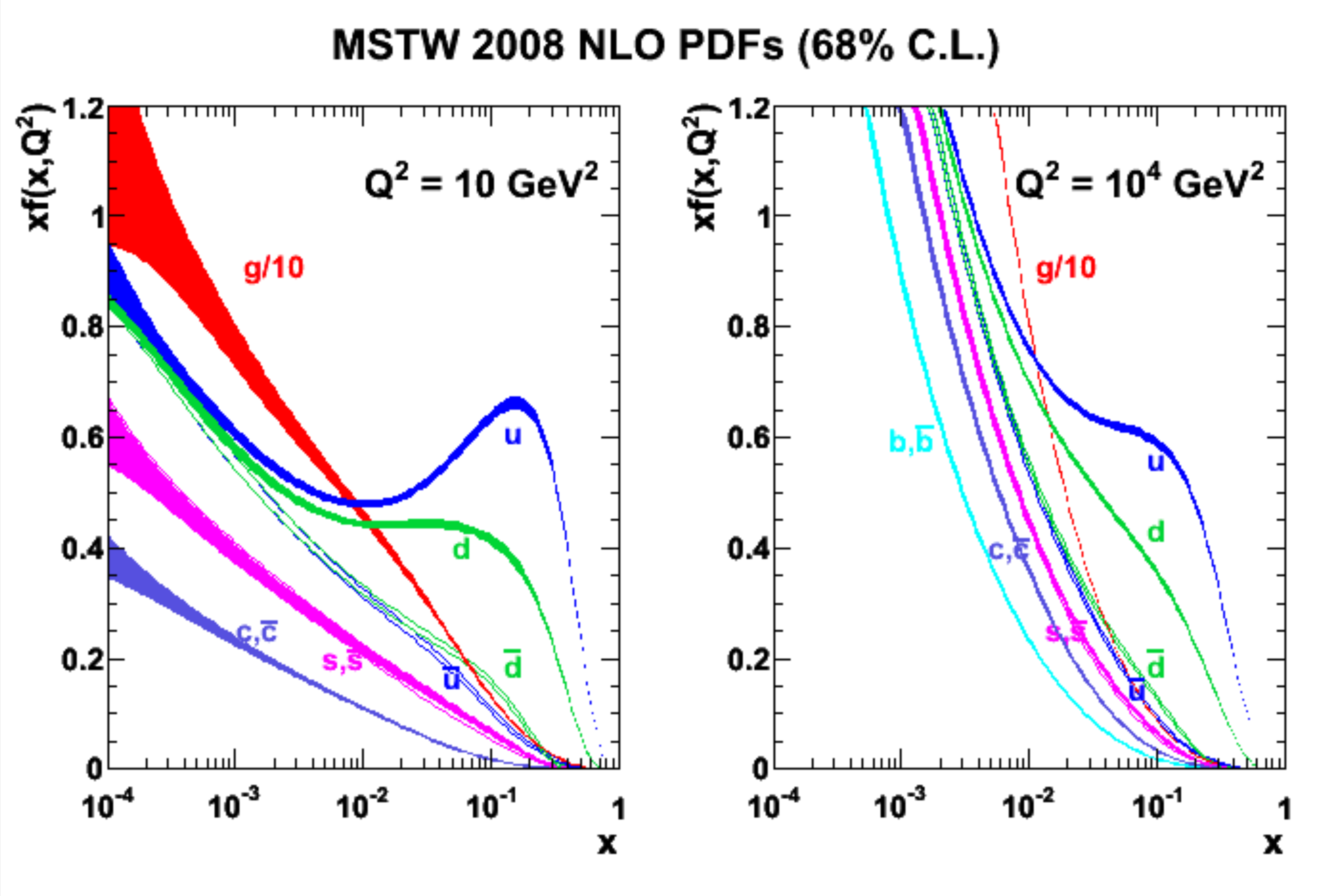

$E_{incoming}$
$E_{outgoing}$
u
u
d
proton

Proton Collisions



Parton Distribution Functions





x = momentum fraction, Q^2 momentum transfer
f(x,Q)= probability density function


Single proton-proton collision
Not pictured: ~40-60 proton-proton collisions per bunch-crossing
New Particles Produced
gluon (coil)
photon (wave)
quarks (line)
W/Z bosons (dash)
Final State EM Radiation
Electron (line)
Photon (wave)
Hadronization
Quarks+Gluons combine to form
Meson (2-quark)
Hadron (3-quark)
Initial proton with 3 valence quarks
Original Proton Constituents
Primary Vertex
Hard Interaction
Underlying event from proton by-products

HW

Due Tuesday Feb 22 by Start of Class

Use Table 2 from the LHC beam parameters here

— What are the center of mass collision energies for Lead and Xenon?
— How much energy is carried by Lead/Xenon ions in the LHC?
— Calculate the Lorentz factor of the Lead/Xenon ions
— What is the ratio of the power dissipated through synchrotron radiation by protons:LeadIon:XenonIon at standard collision energies ?
— By what factor (ratio) does the power dissipated by synchrotron radiation increase from standard collision conditions to 100 TeV Center of Mass Energy?