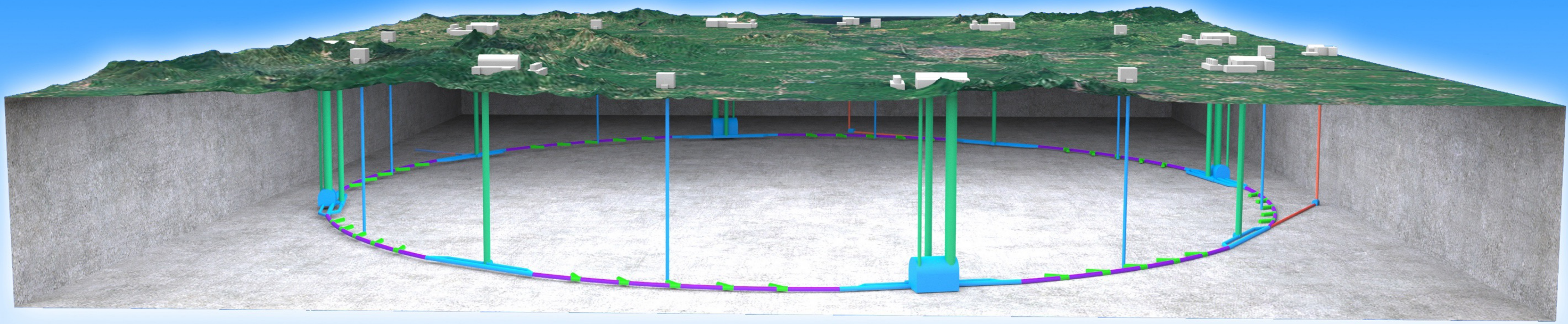
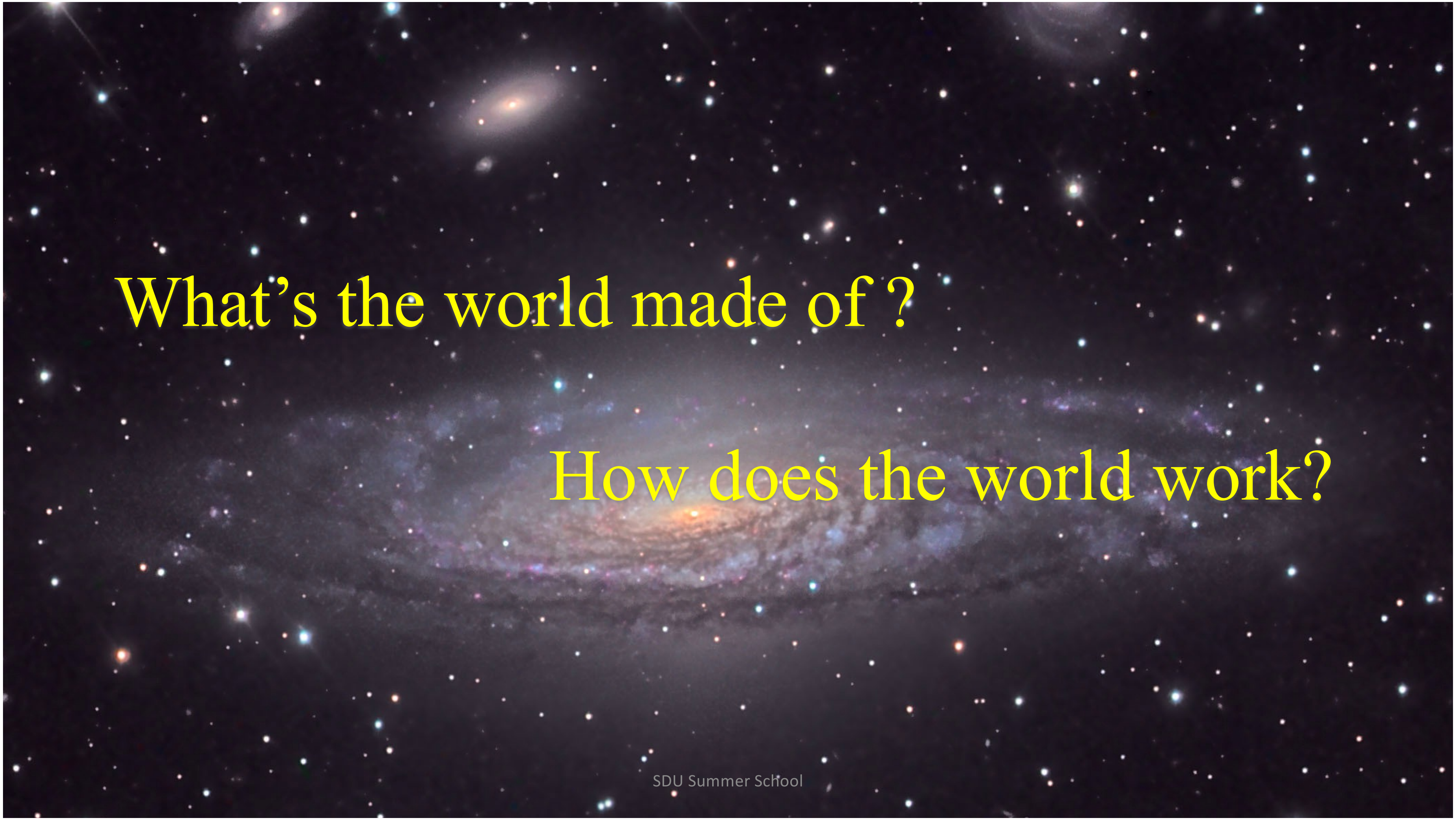
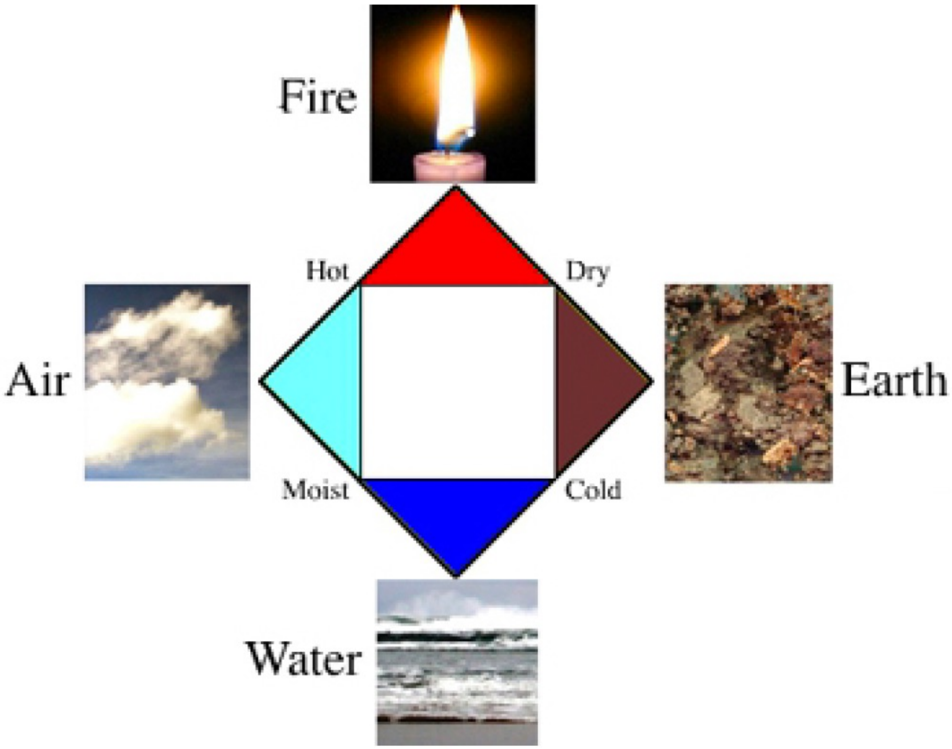
Circular Electron Positron Collider: Science & Status

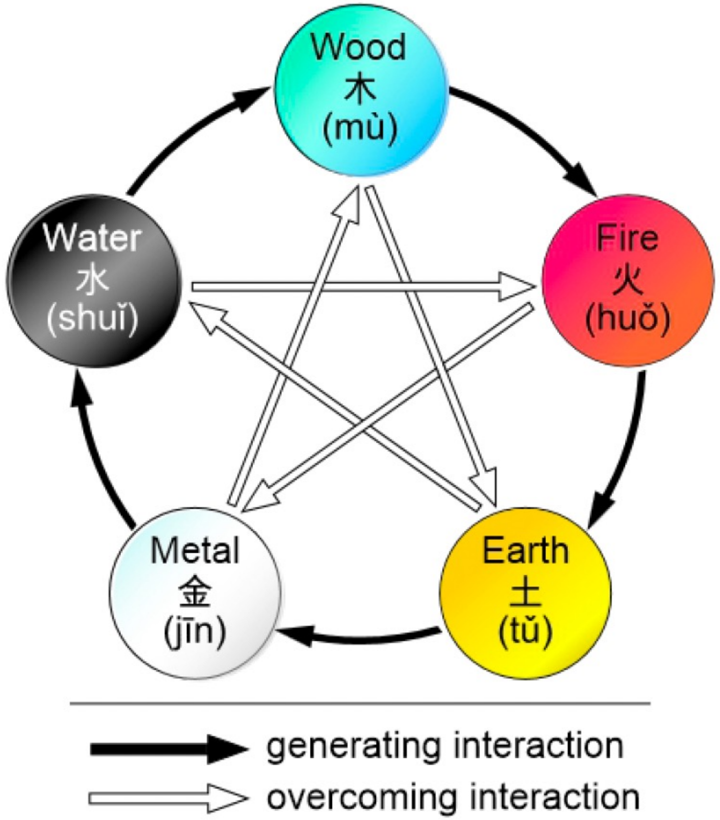


Manqi RUAN(IHEP, Beijing)

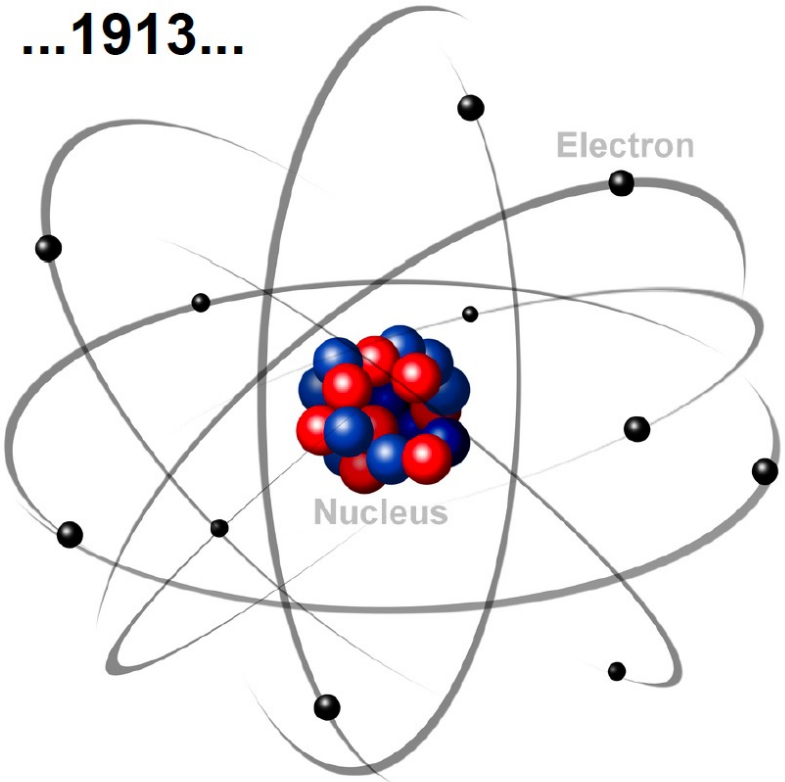

What’s the world made of ?
How does the world work?

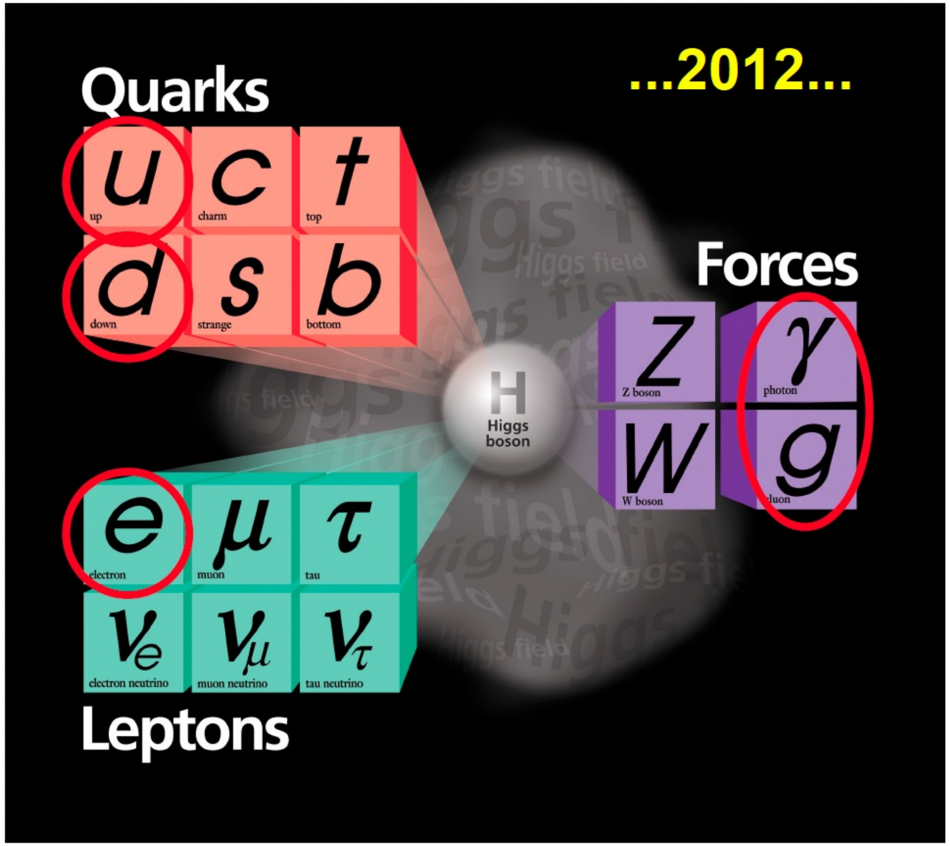
~ 3000 years ago



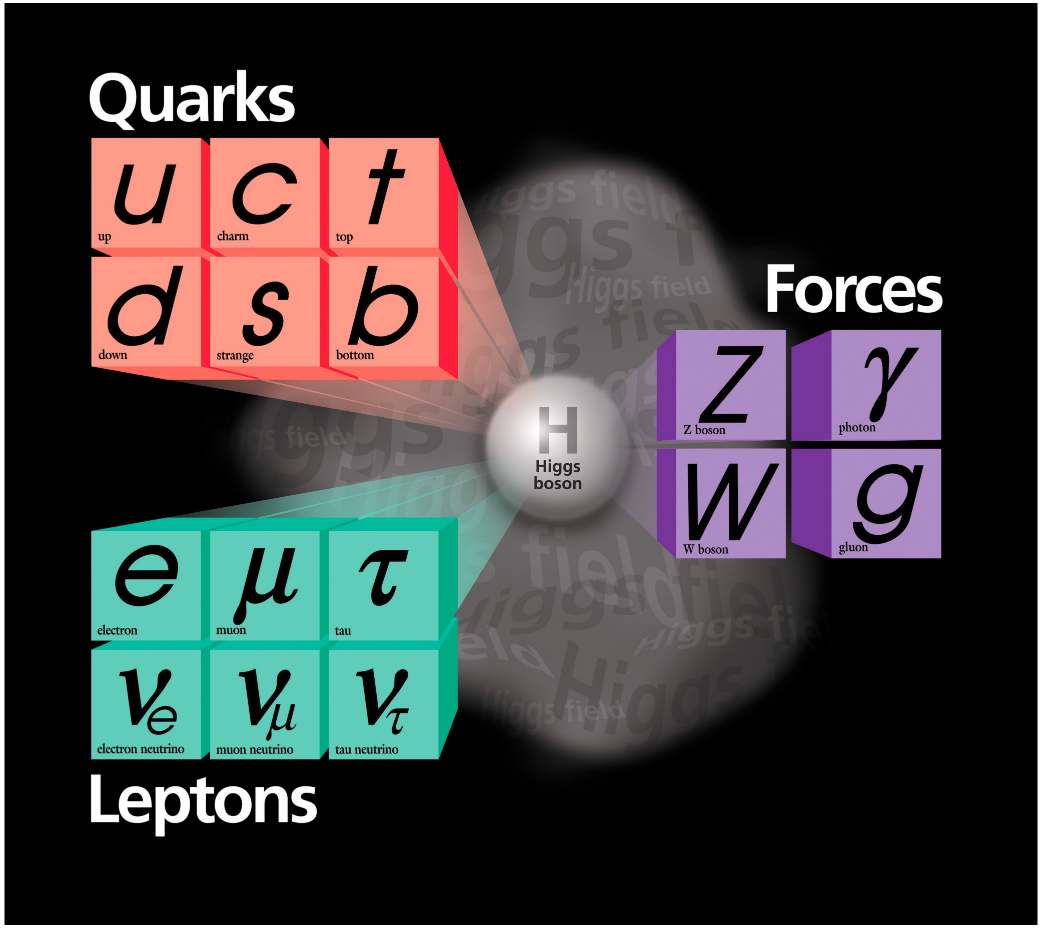


…20th to 21st century

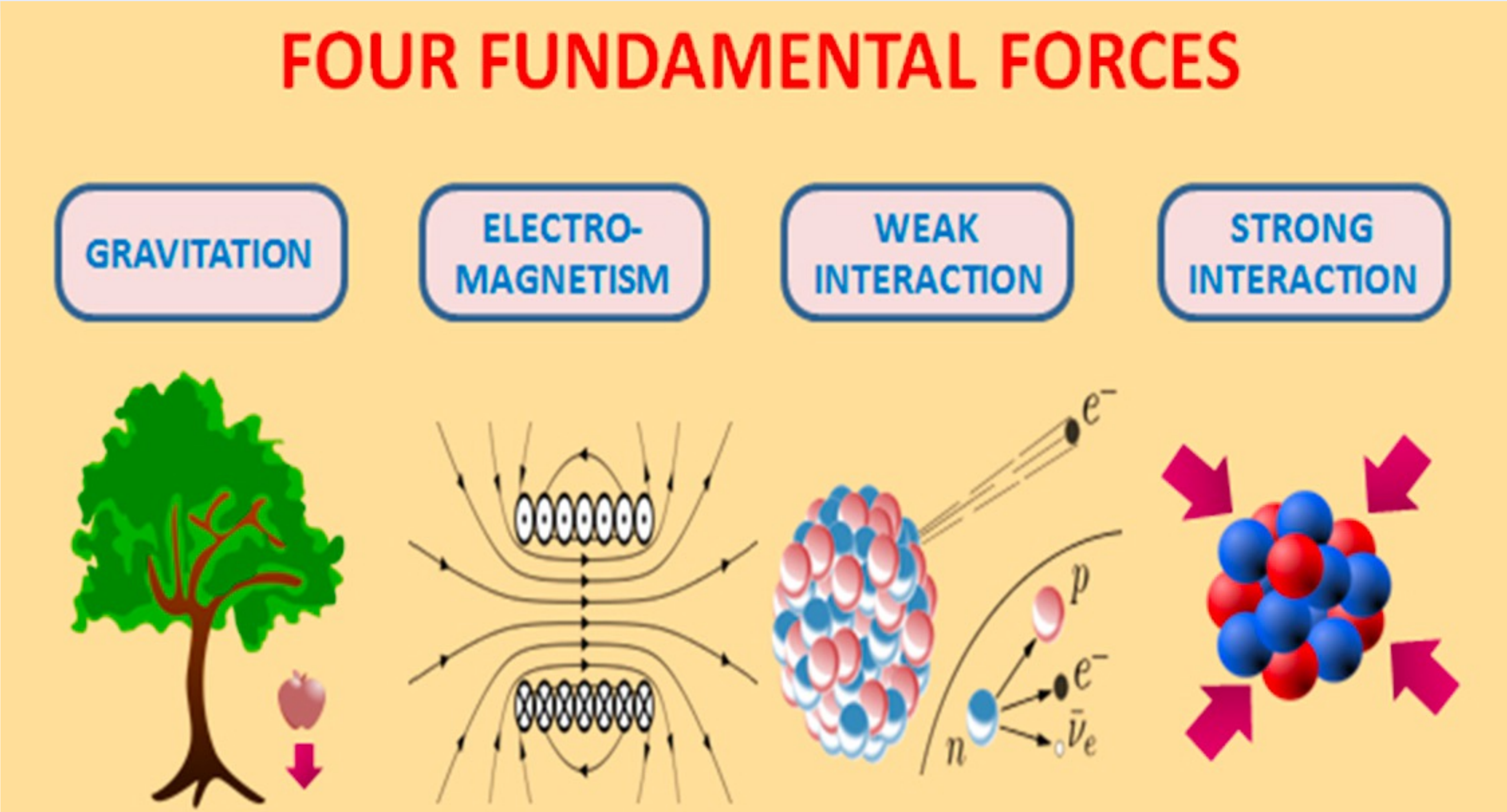




The SM of particle physics: predicts lots of new particles, and found them in the experiments

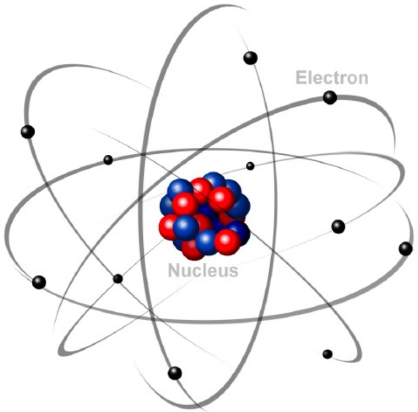


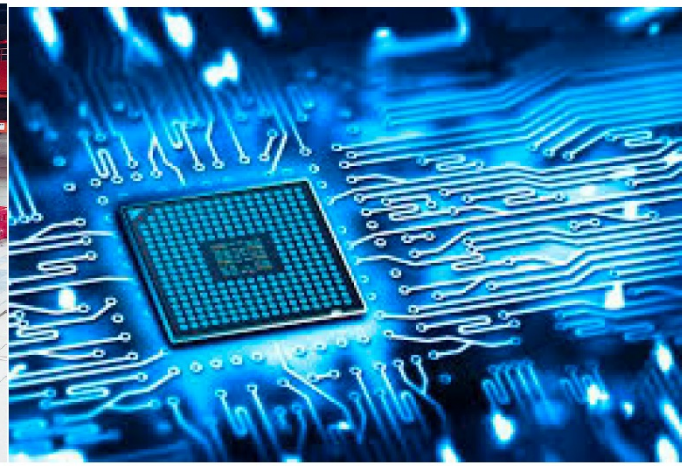
- Discoveries (Nobel Price in Physics)
  - 2015, 2013
  - 2002
  - 1995, 1990
  - 1988, 1984, 1980
  - 1976
  - 1969
  - 1959, 1951, 1950
- Instrumentations
  - 1992
  - 1968, 1960
  - 1958
  - 1948

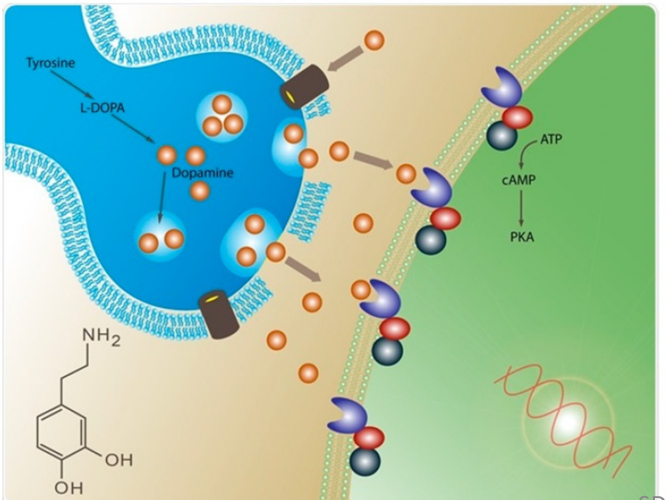


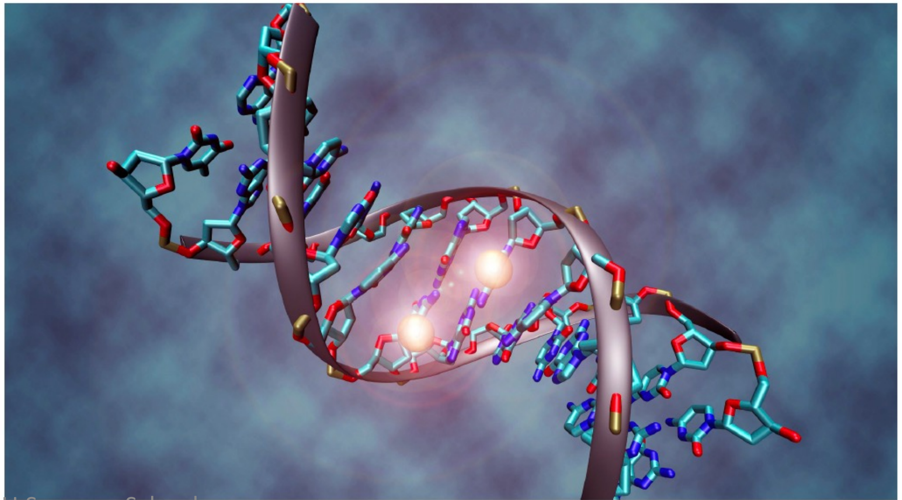
How does the world work

The electromagnetic interaction

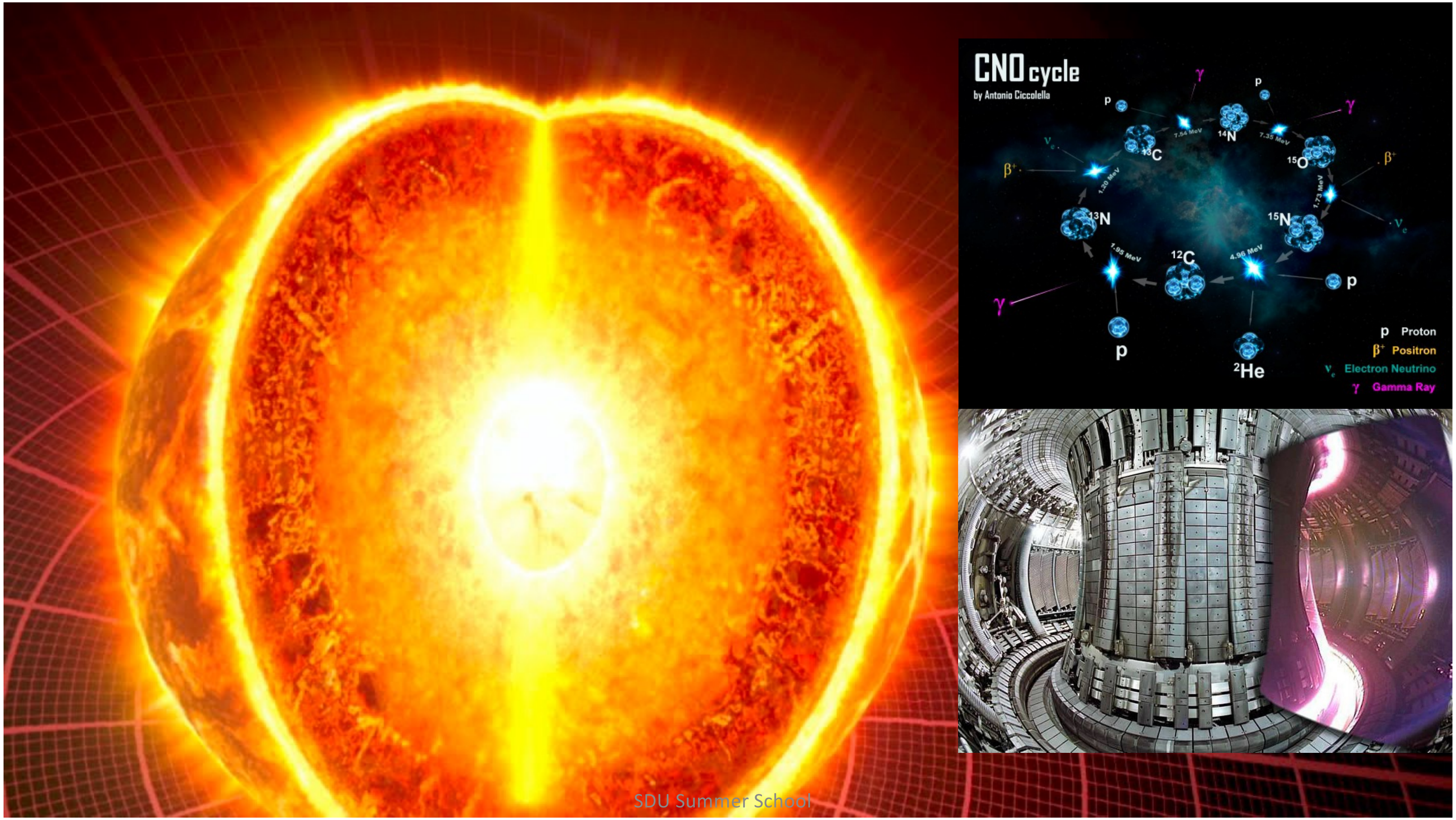




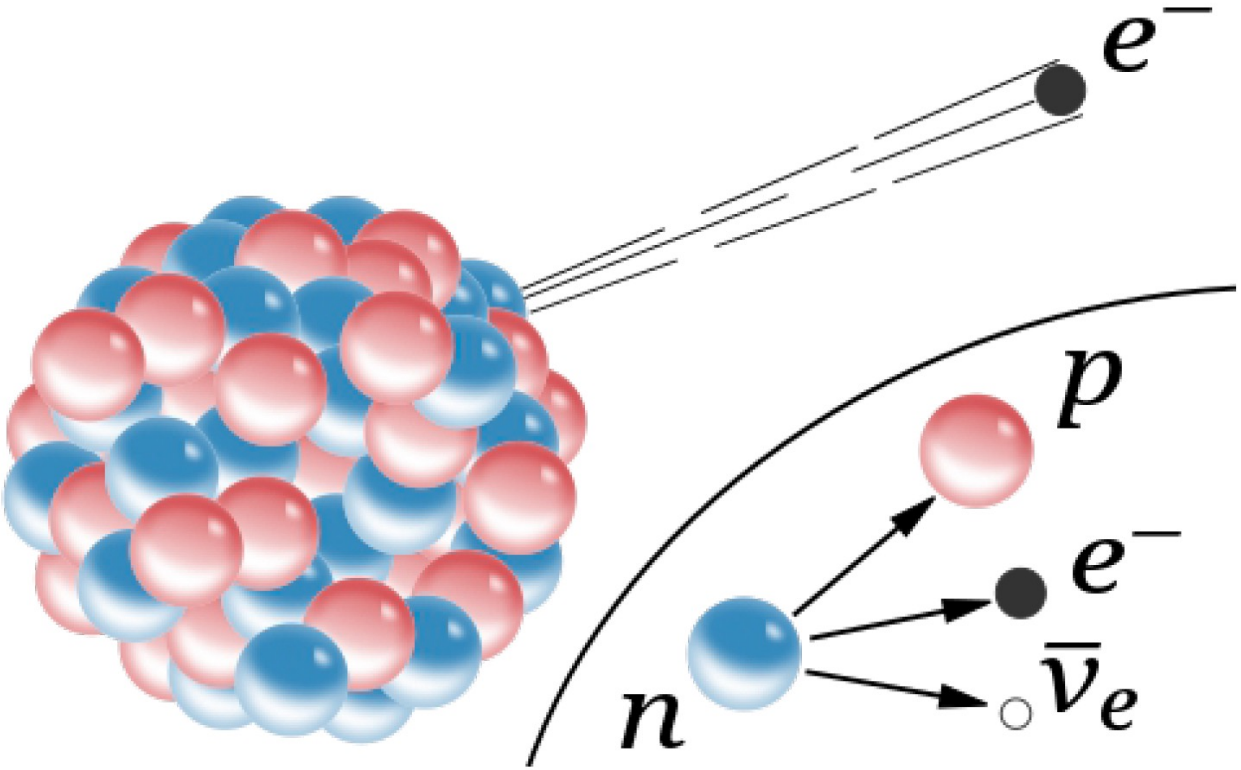


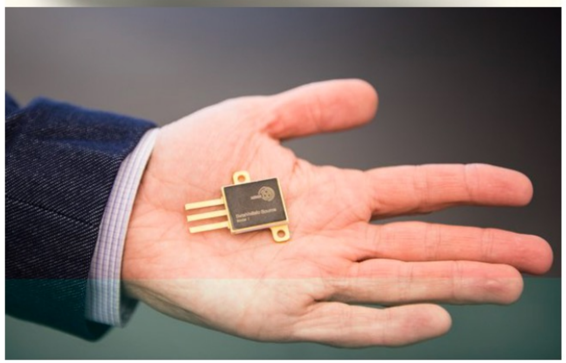


The strong interaction

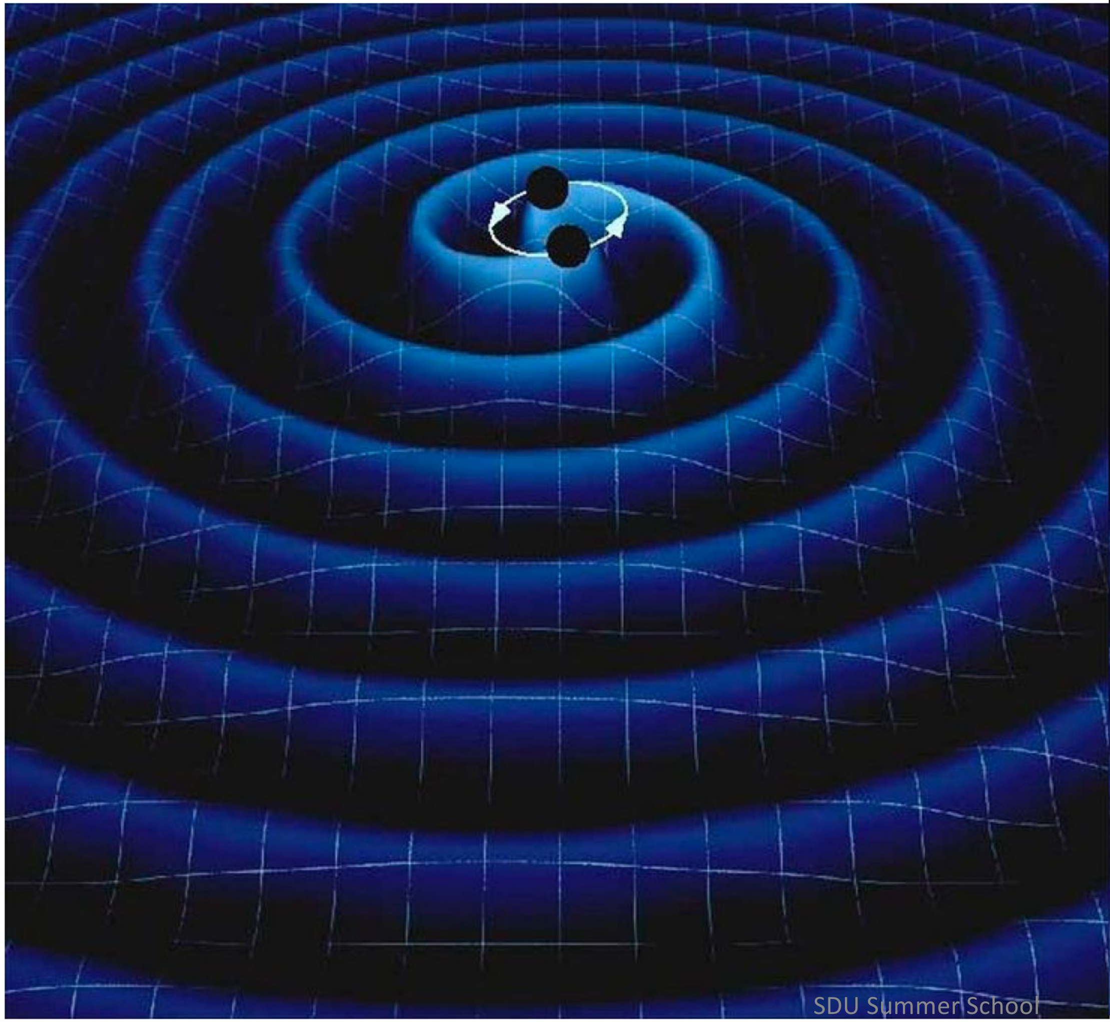


The weak interaction

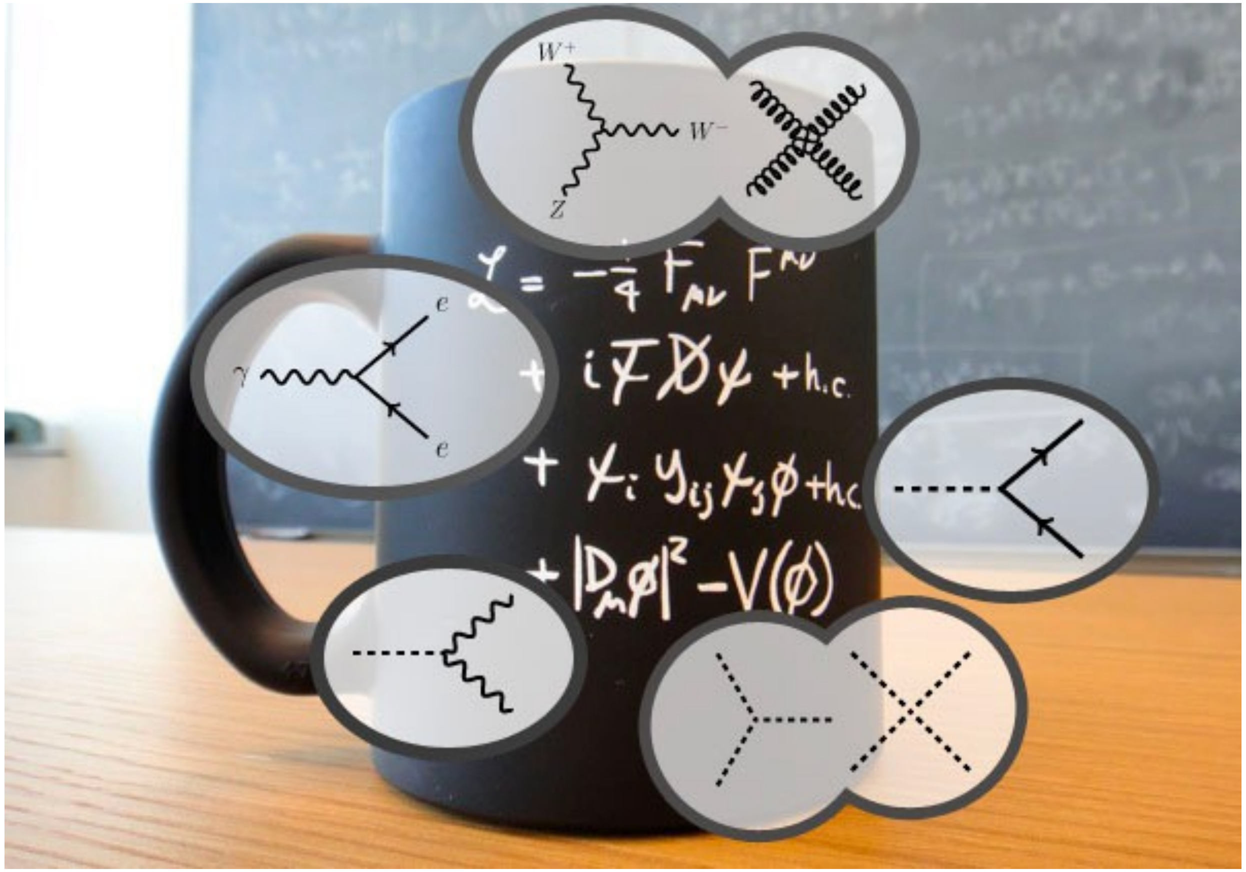




The gravitational interaction

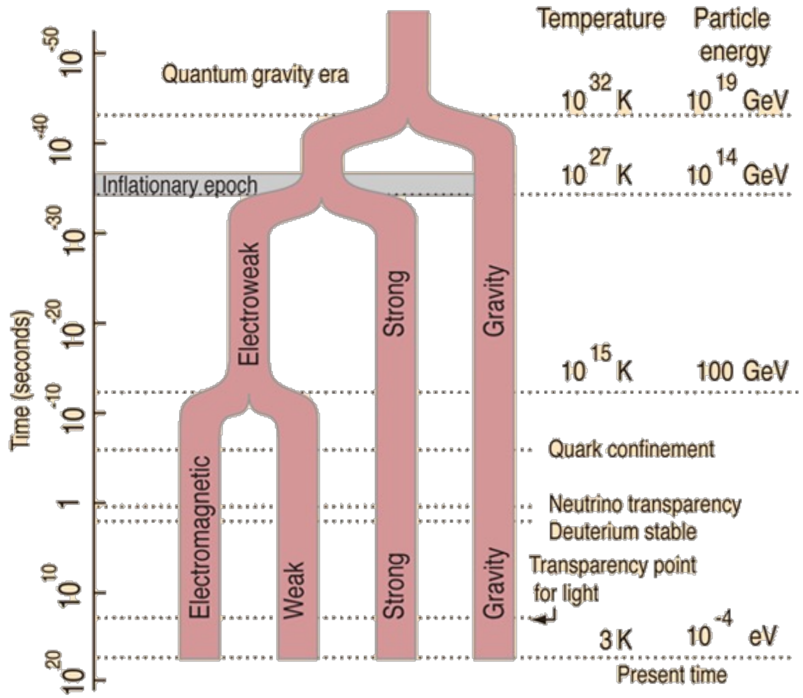


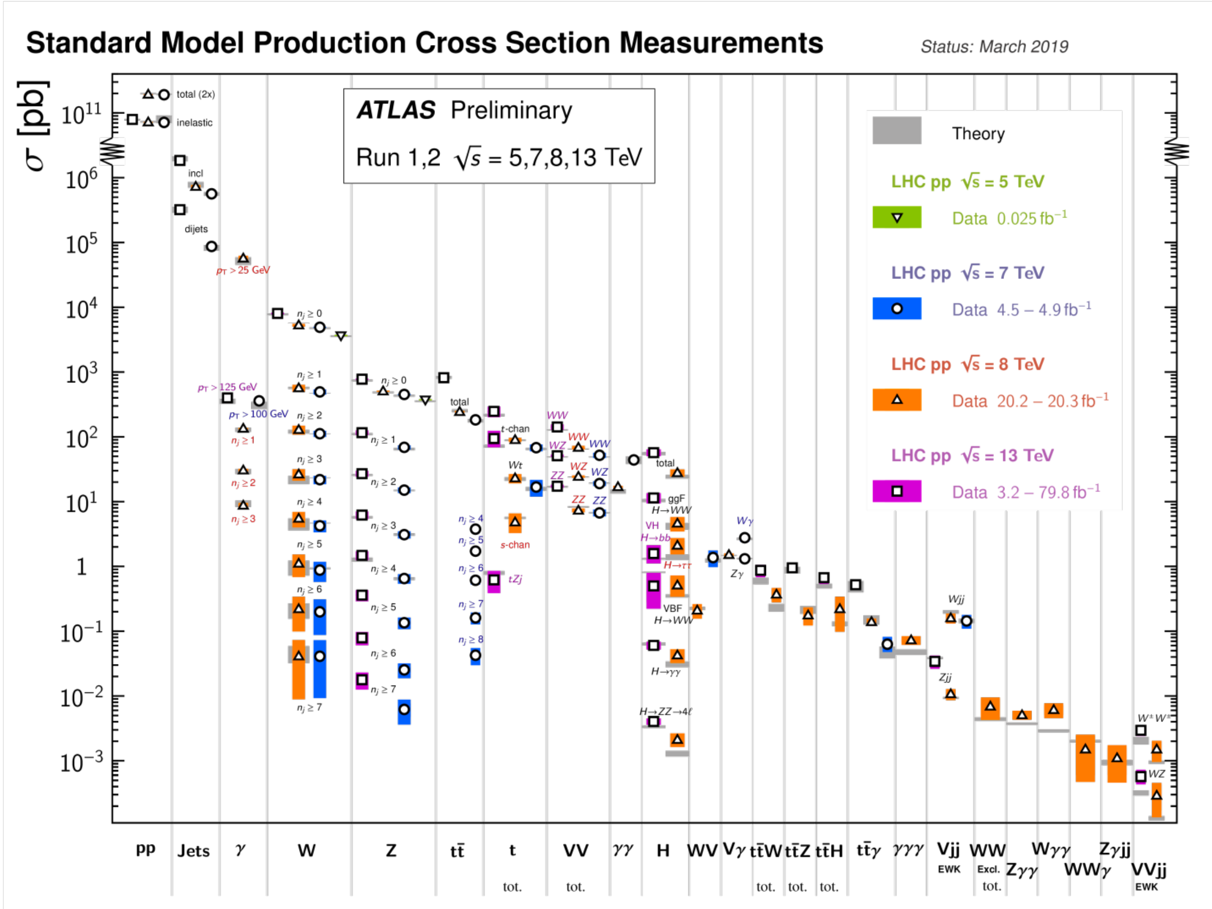
The SM of particle physics: unifies the strong, the weak, and the electromagnetic interactions



- Relevant Nobel prices (theoretical)
  - 2008
  - 2004
  - 1999
  - 1979
  - 1965
  - 1957
  - 1949

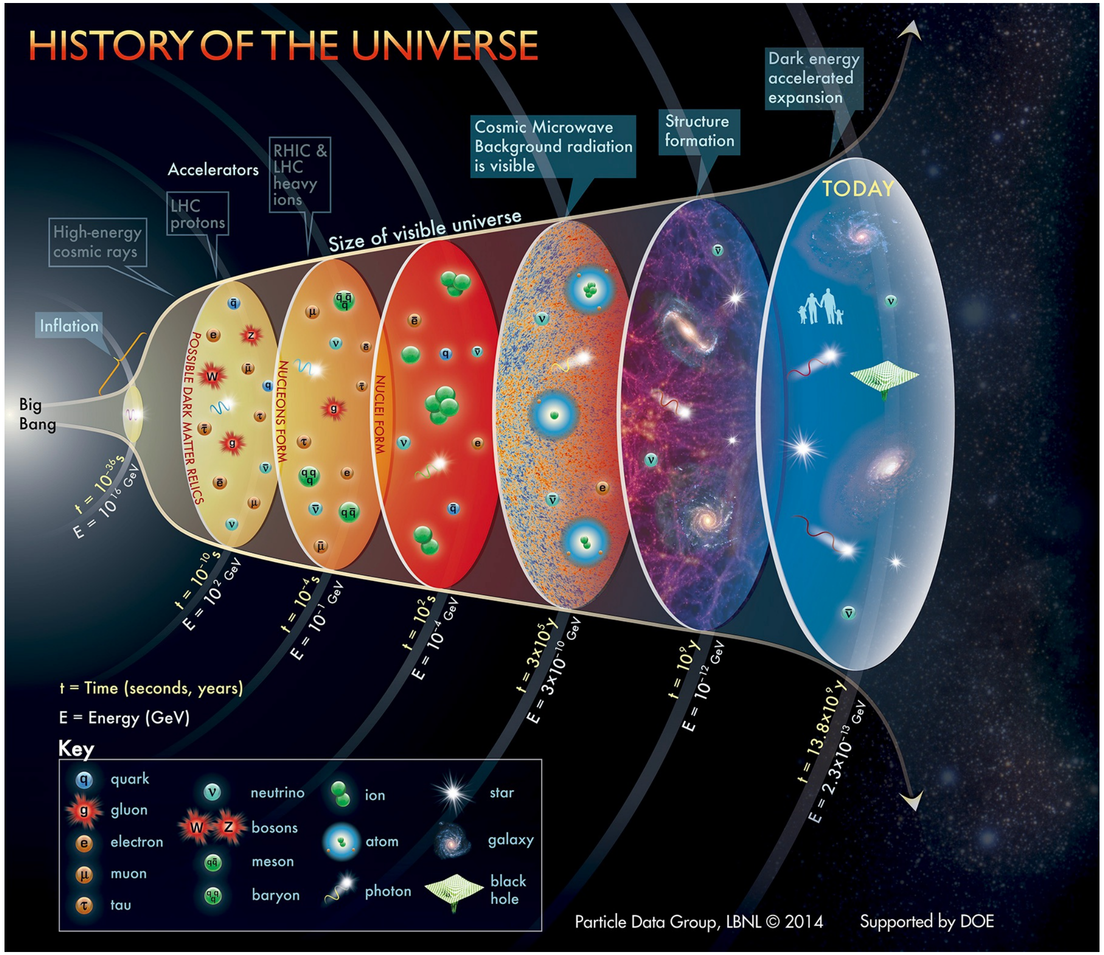
The SM: predicts and interprets almost all the experimental data at accelerator experiments





The SM: describes the fundamental interactions that governs the evolution of universe: from 0.1 ns after Big Bang until now

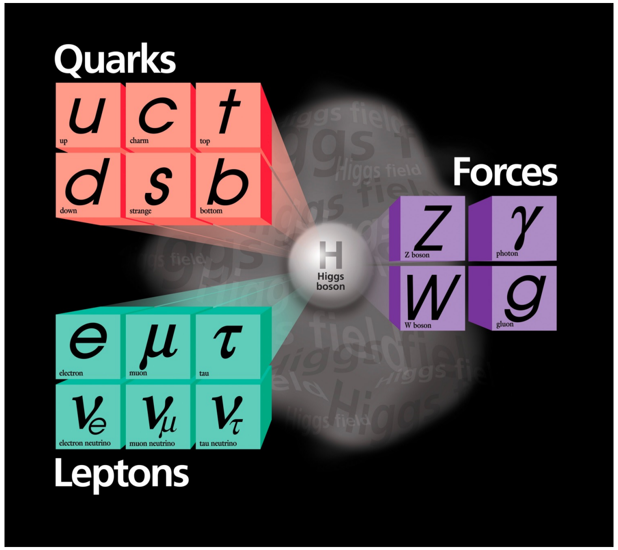
Wikipedia, Pablo

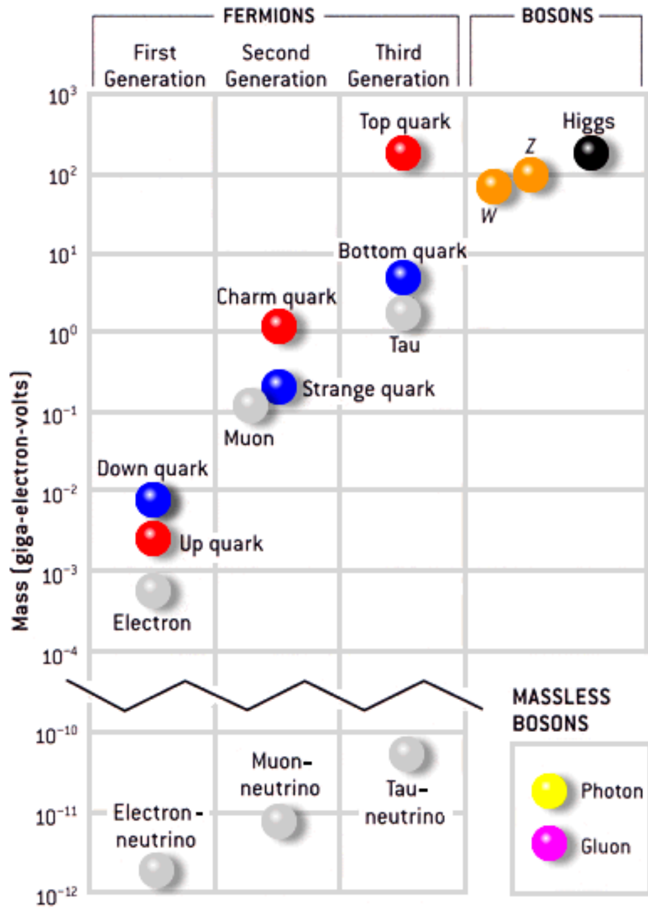


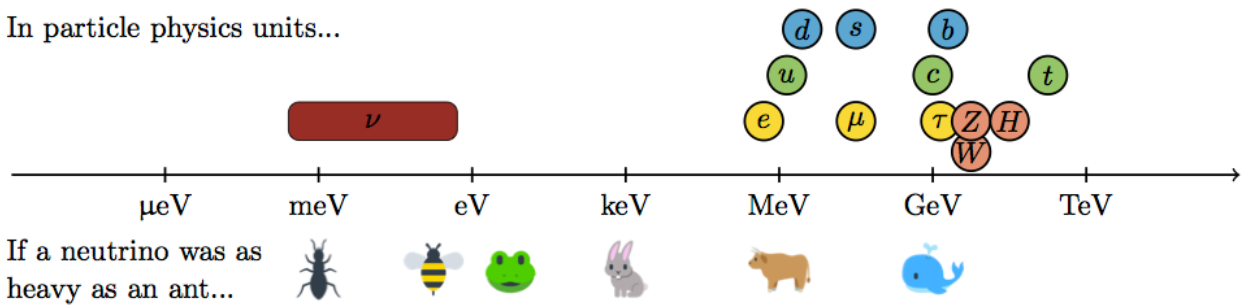
The challenges to the SM: Neutrino mass & Oscillation

The challenges to the SM: mass hierachy

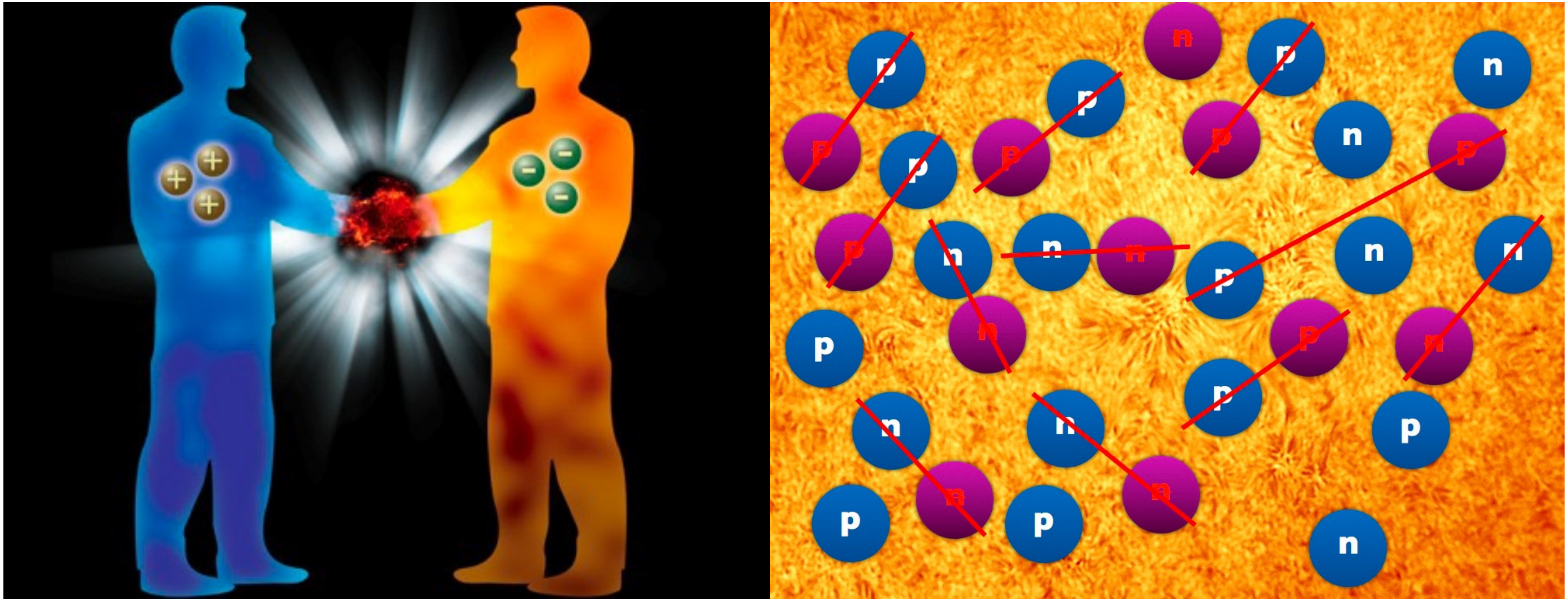
- Electrons mass ~ 1E-5 * Top quark mass
- Neutrino mass ~ 1E-15 * top quark mass!
- Are their mass generated with the same mechanics?



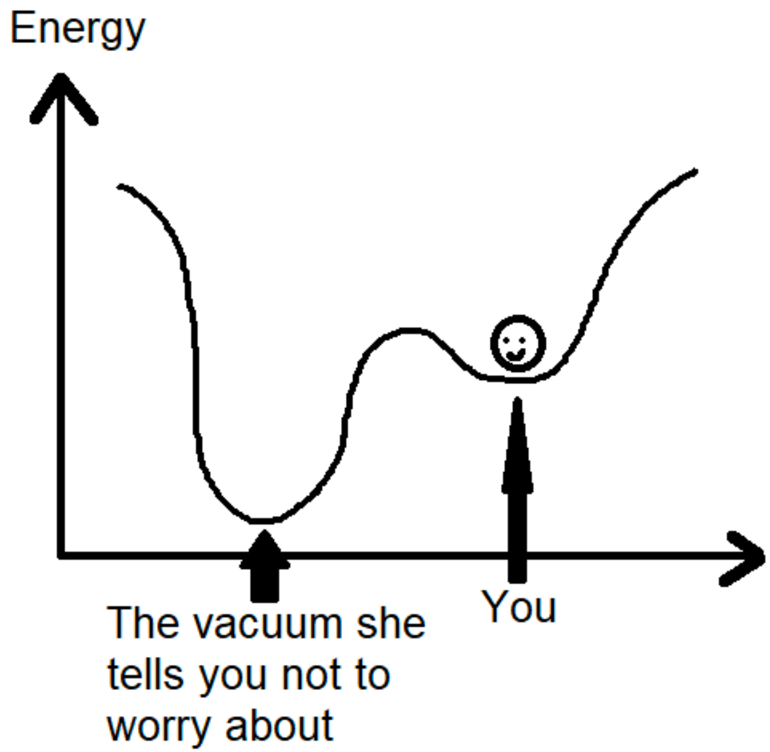




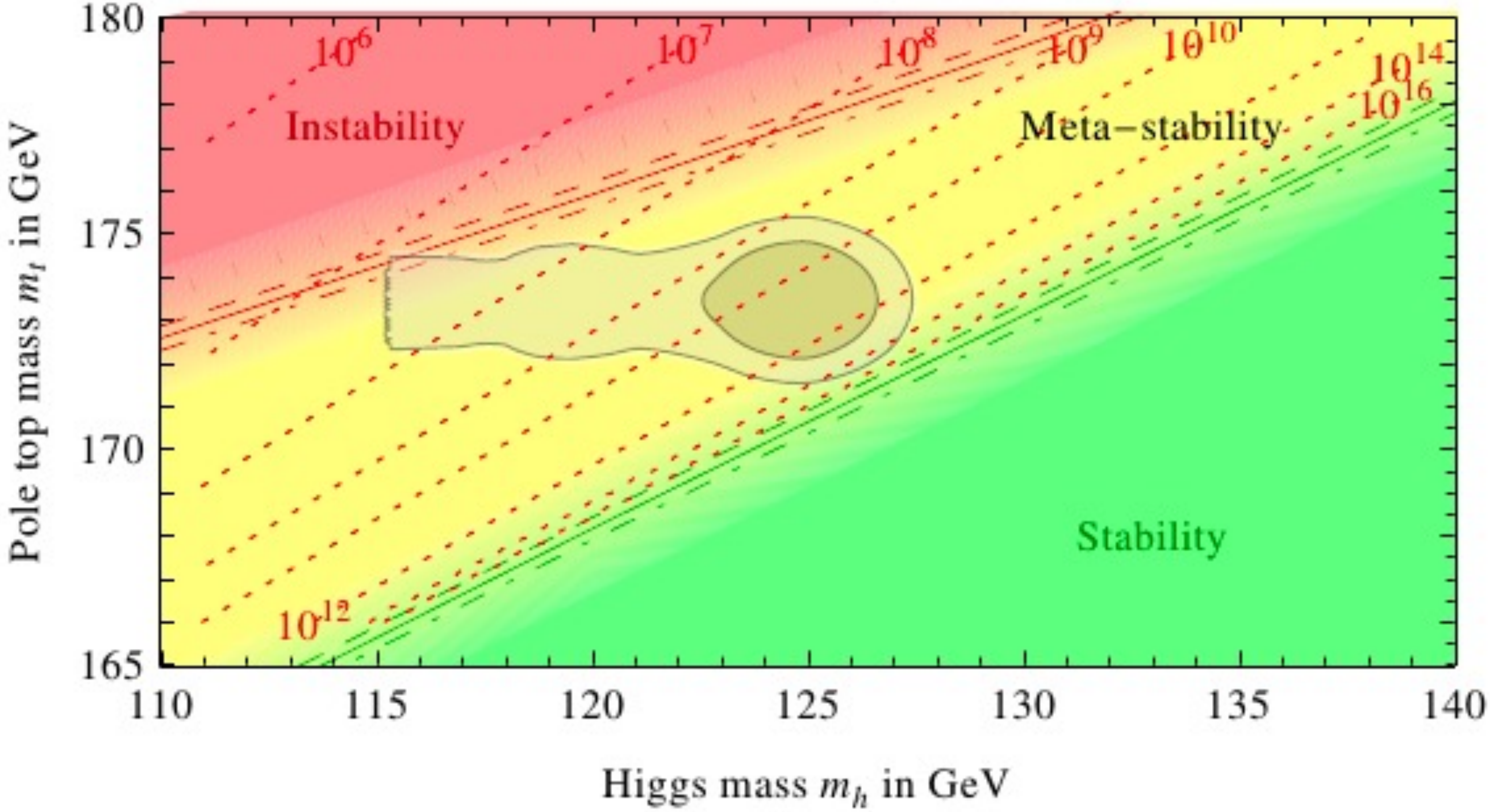
The challenges to the SM: what’s the origin of matter?



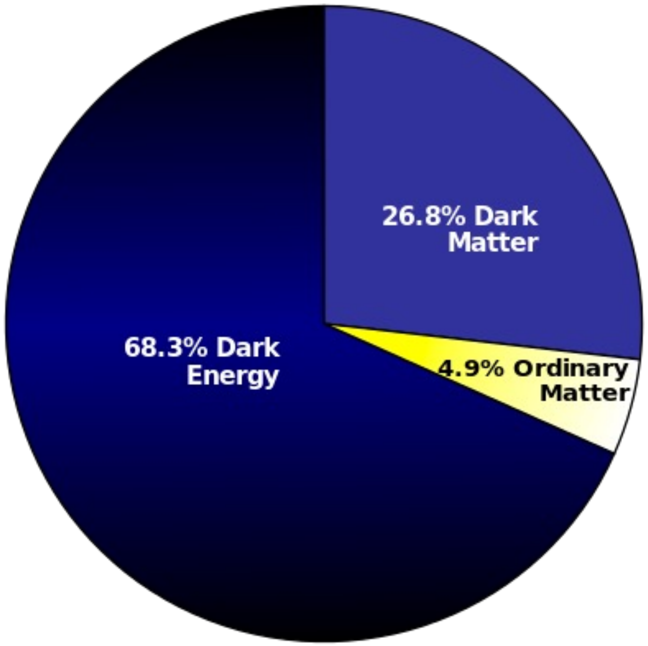
The challenges to the SM: the stability of universe

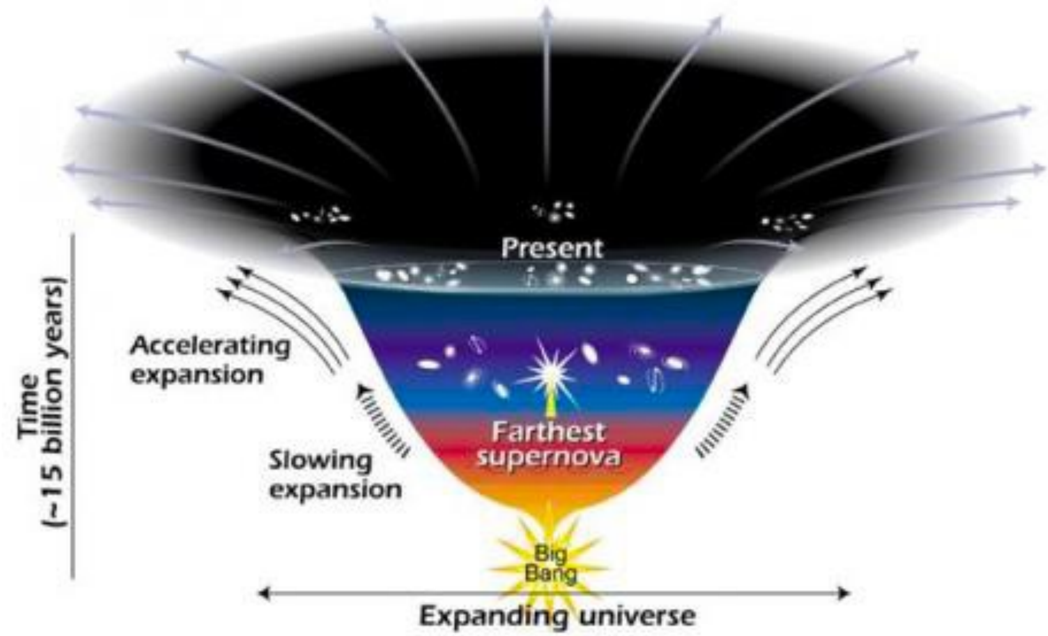


The challenges to the SM: the stability of universe

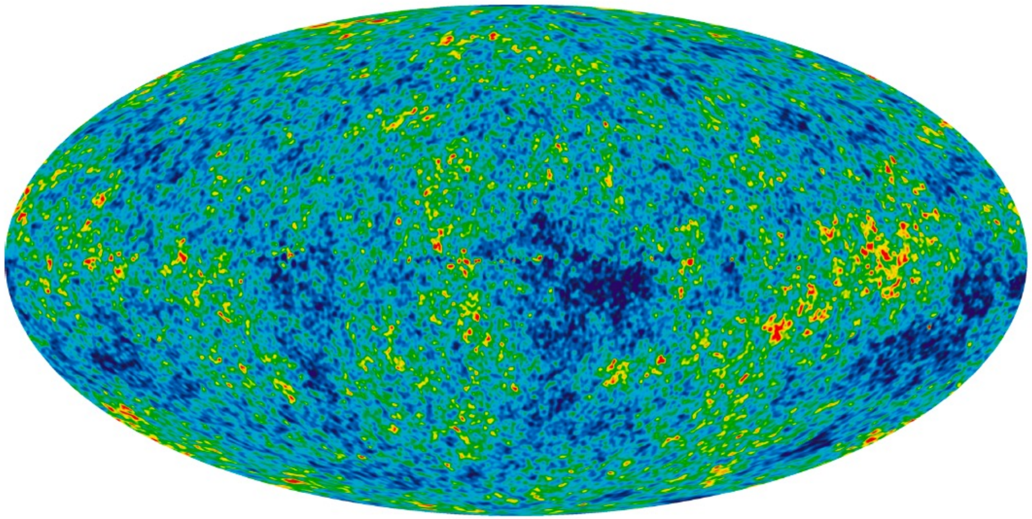


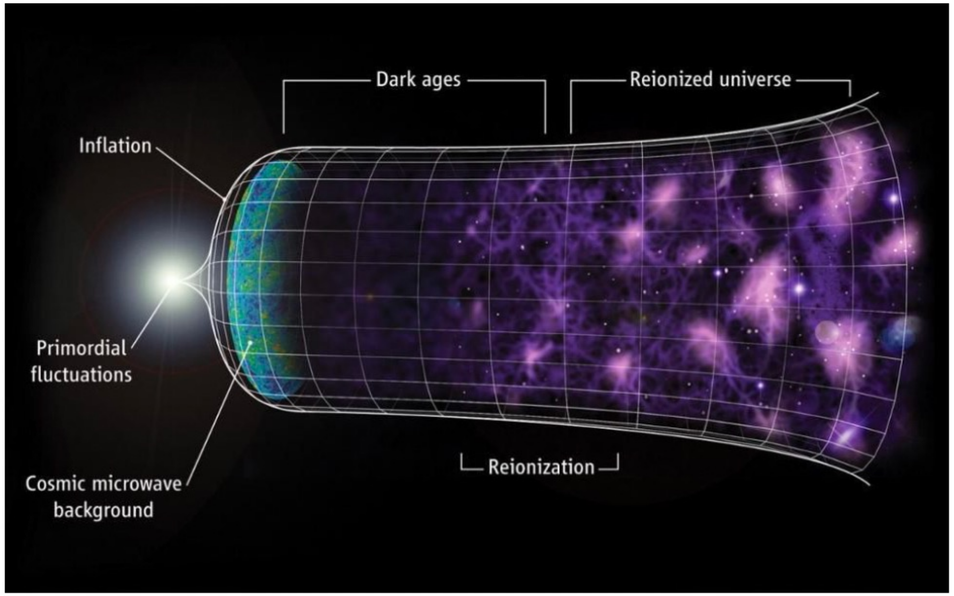
The challenges to the SM: dark matter, dark energy





The challenges to the SM: Inflation in the early universe





The challenges to the SM

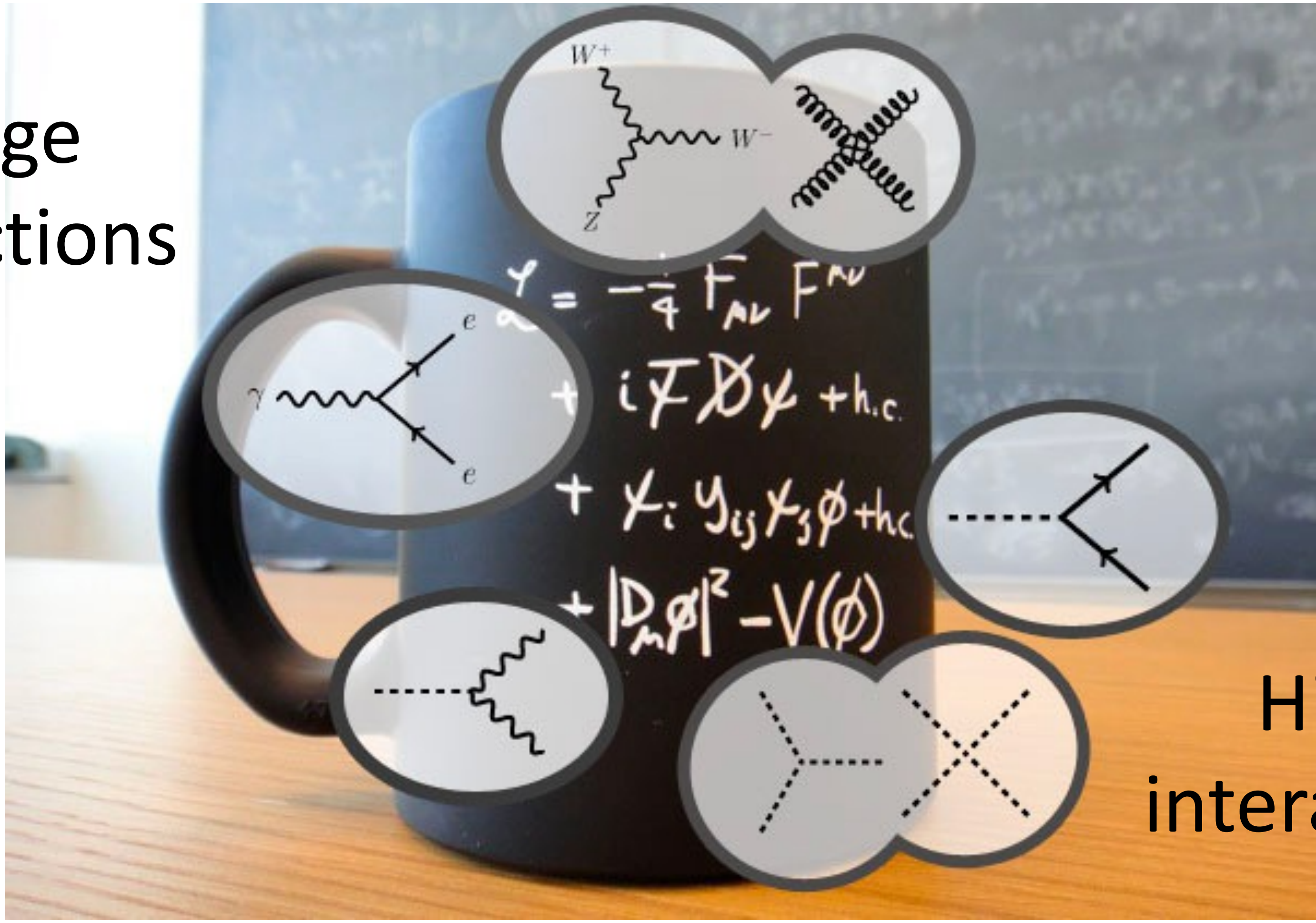
- Inflation
- Mass hierarchy
- Neutrino Mass
- Matter-Anti matter asymmetry
- Stability of the Universe: depends on the Particle Mass
- Dark Matter: nature & origin of mass…
- Dark Energy, Inflation: nature…

The challenges to the SM

- Inflation
- Mass hierarchy
- Neutrino Mass
- Matter-Anti matter asymmetry
- Stability of the Universe: depends on the Particle Mass
- Dark Matter: nature & origin of mass…
- Dark Energy, Inflation: nature…

The Higgs field, heart of the SM

Gauge interactions



Higgs interactions

The Higgs field, origin of mass – associated with most of the Challenges to the SM

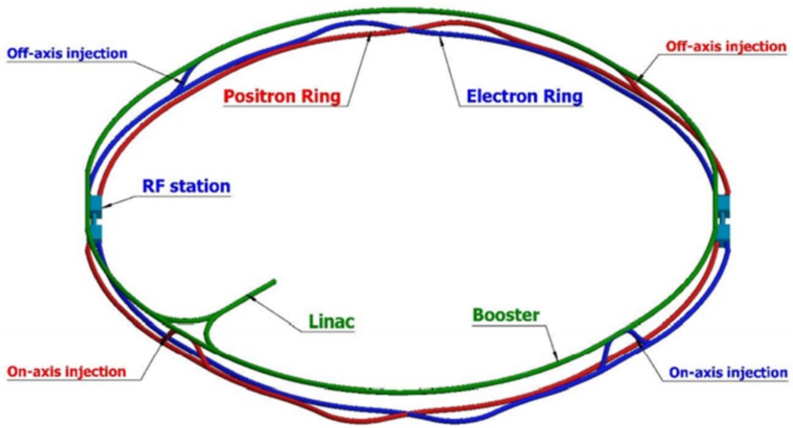
- Higgs interactions: beyond the gauge interactions
- Determines the mass of the SM particles,
  - The mass of electron – size of the atom
  - The mass of W & Z boson – strength of the weak interaction
  - The mass of up & down quark – stability of the proton
  - The mass of top & Higgs – stability of the universe
- Couples to the matter & anti-matter in a slightly different manner -> origin of matter

- *Could well be the origin of dark matter mass, and could be also highly relevant to the dark energy & inflations*

A brief introduction to CEPC

- CEPC: an e^+e^- Higgs factory producing H and W/ Z bosons and top quarks
  aims at discovering new physics beyond the Standard Model
  - CEPC + SppC complex proposed in 2012 right after the Higgs discovery
  - Conceptual Design Report delivered in Nov. 2018, 1st for circular ee Higgs factory
  - R&D reaching maturity, accelerator TDR planned for 2023, high-impact innovations

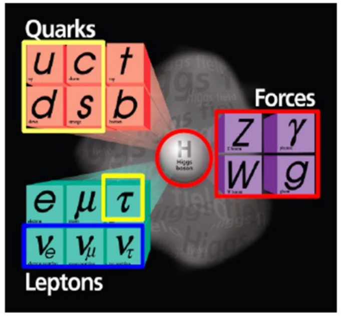
- Proposed to commence the construction in ~2026
  to deliver Higgs data in 2030s

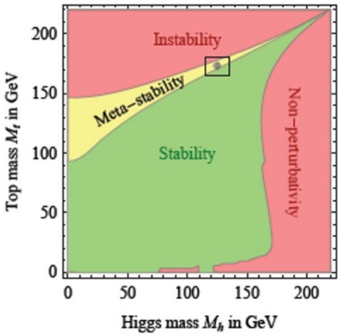


CEPC circumference ~ 100km

Scientific objectives, significance, and strategic value

- We have a very successful Standard Model
- But we still have a lot of issues and questions:
  - Anything fundamentals behind the flavor symmetry ?
  - Mass hierarchy of elementary particles normal ?
  - Fine tuning of Higgs mass natural ?
  - Why a meta-stable vacuum ?
  - What are dark matter particles ?
  - No CP in the SM to explain Matter-antimatter asymmetry
  - Dirac or Majorana Neutrino mass ?
  - Unification of interactions at a high energy ?
- We are at a turning point:
  - a new, much deeper theory ?
  - Choices of experimental approaches ?
    - e^+e^-, pp, ep, $\mu^+\mu^-$ or no machine ?





- "Small cost" to look for hints. If yes, go for direct searches

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2}\mathcal{O}_{6,i} \qquad \delta \sim c_i \frac{v^2}{M^2}$$

No signal at LHC:

Direct searches: M ~ 1 TeV

10% precision: M ~ 1 TeV

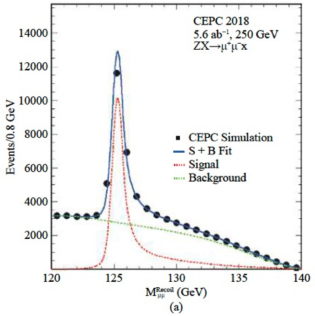
Look for signals at CEPC/FCC-ee:

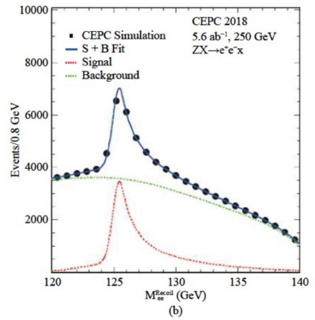
Precisions exceed HL-LHC ~ 1 order of magnitude (1% precision) ➔ M ~10 TeV

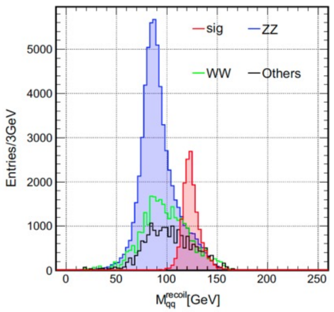
Naturalness will be at ~10^{-4} up to 10 TeV
If no New Physics up to 10 TeV, there will be no naturalness ➔ even bigger discovery ?

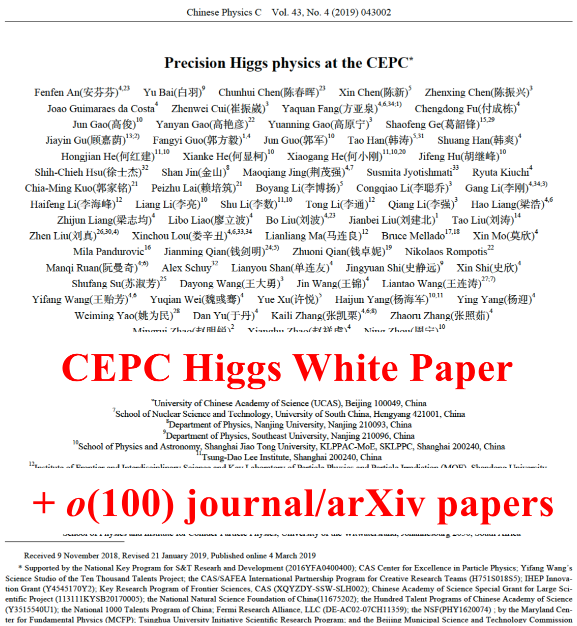
Pressing science questions, best addressed by an e^+e^- Higgs factory (~1% precision)

Scientific objectives, significance, and strategic value





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Precision Higgs physics at the CEPC*

Received 9 November 2018, Revised 21 January 2019, Published online 4 March 2019

CEPC Higgs White Paper

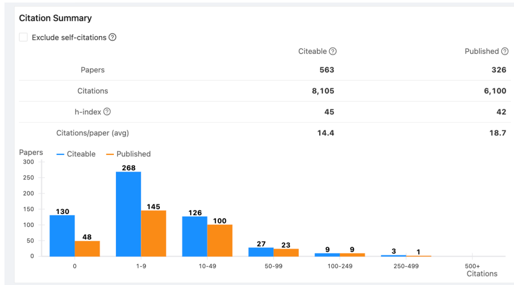
+ $o(100)$ journal/arXiv papers

Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data are used for comparison. [2]

Higgs			W, Z and top		
Observable	HL-LHC projections	CEPC precision	Observable	Current precision	CEPC precision
M_H	20 MeV	3 MeV	M_W	9 MeV	0.5 MeV
Γ_H	20%	1.7%	Γ_W	49 MeV	2 MeV
$\sigma(ZH)$	4.2%	0.26%	M_{top}	760 MeV	$\mathcal{O}(10)$ MeV
$B(H \to bb)$	4.4%	0.14%	M_Z	2.1 MeV	0.1 MeV
$B(H \to cc)$	-	2.0%	Γ_Z	2.3 MeV	0.025 MeV
$B(H \to gg)$	-	0.81%	R_b	3×10^{-3}	2×10^{-4}
$B(H \to WW^*)$	2.8%	0.53%	R_c	1.7×10^{-2}	1×10^{-3}
$B(H \to ZZ^*)$	2.9%	4.2%	R_μ	2×10^{-3}	1×10^{-4}
$B(H \to \tau^+\tau^-)$	2.9%	0.42%	R_τ	1.7×10^{-2}	1×10^{-4}
$B(H \to \gamma\gamma)$	2.6%	3.0%	A_μ	1.5×10^{-2}	3.5×10^{-5}
$B(H \to \mu^+\mu^-)$	8.2%	6.4%	A_τ	4.3×10^{-3}	7×10^{-5}
$B(H \to Z\gamma)$	20%	8.5%	A_b	2×10^{-2}	2×10^{-4}
$Bupper(H \to inv.)$	2.5%	0.07%	N_ν	2.5×10^{-3}	2×10^{-4}

Scientific Significance quantified by **CEPC physics** studies, via full simulation/phenomenology studies:

- Higgs: Precisions exceed HL-LHC ~ 1 order of magnitude.
- EW: Precision improved from current limit by 1-2 orders.
- Flavor Physics, sensitive to NP of 10 TeV or even higher.
- Sensitive to varies of NP signal.
- …



Scientific objectives, significance, and strategic value

Energy Scale
to be explored

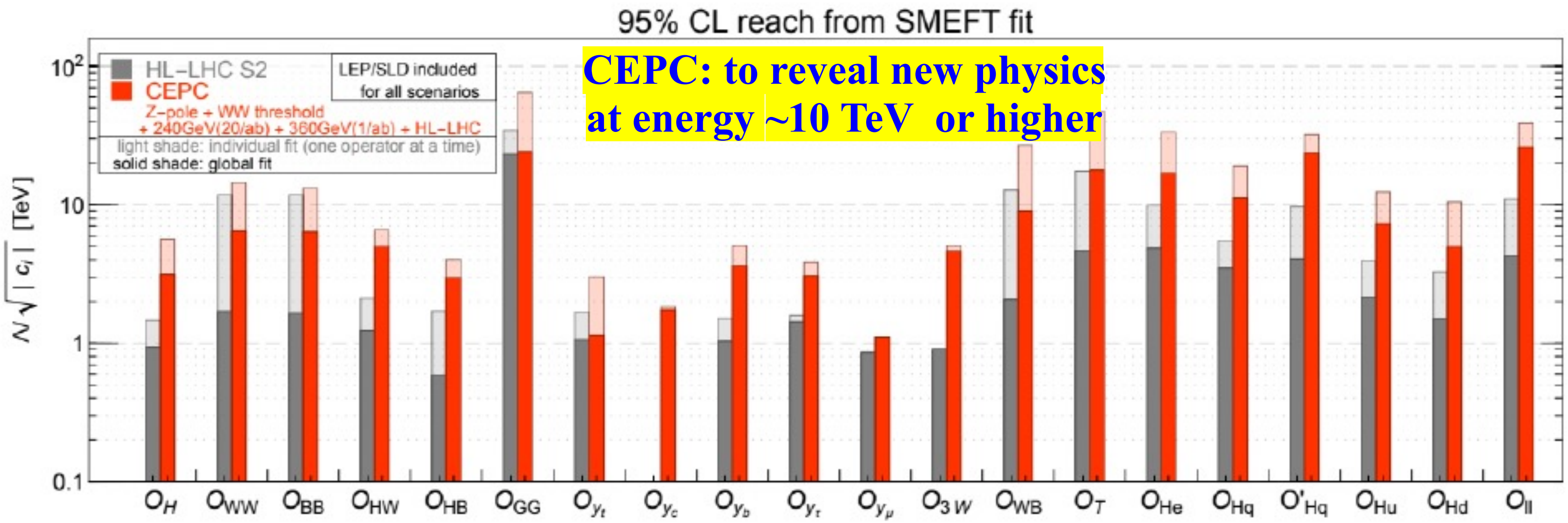


Figure 2.1: Covered energy scales of new physics from CPEC and HL-LHC, based on measurements of operators in the framework of the Standard Model Effective Field Theory (SMEFT). [1]

CEPC targets a major breakthrough in basic research, will greatly expand our understanding of the world.

Scientific objectives, significance, and strategic value

The scientific importance and strategical value of an electron positron Higgs factory is clearly identified.

XIANGSHAN SCIENCE CONFERENCES

clear consensus in HEP community

*2013, 2016: **the CEPC is the best approach** and a major historical opportunity for the national development of accelerator-based high-energy physics program.*

2020 European Strategy Update

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

Conclusion from Executive Summary

Given the **strong motivation** and existence of proven technology to build an **e^+e^- Higgs Factory in the next decade**, the **US should participate** in the construction of **any facility that has firm commitment** to go forward.

Sridhara Dasu (Wisconsin)

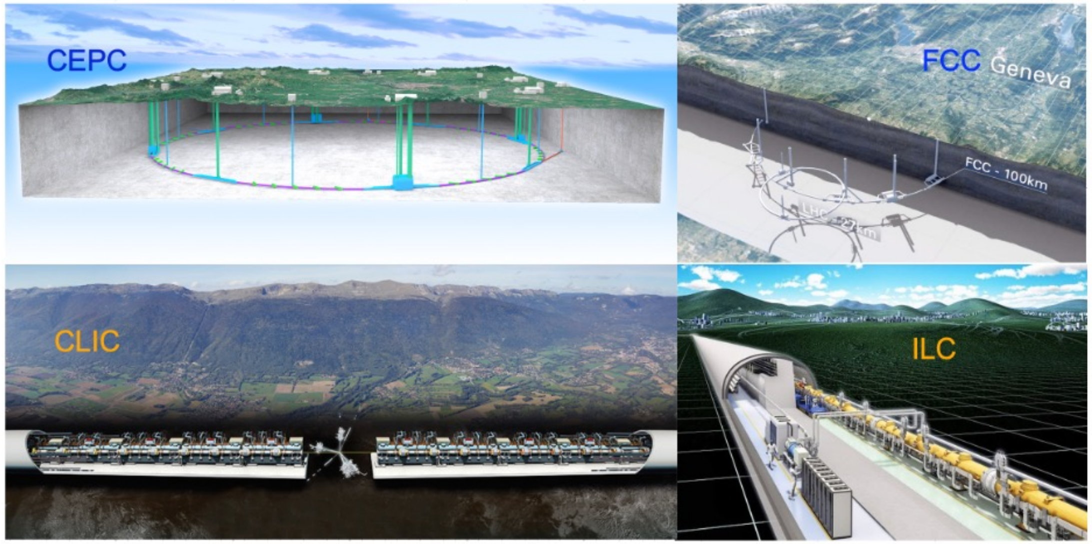
ICFA

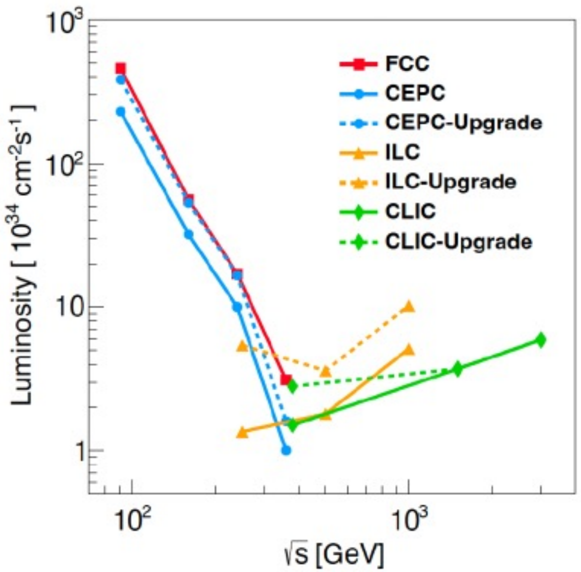
*In April 2022, the International Committee for Future Accelerators (ICFA) "reconfirmed the international consensus on the importance of **a Higgs factory as the highest priority for realizing the scientific goals of particle physics**", and expressed support for the above-mentioned Higgs factory proposals. Recently, the United States also proposed a new linear collider concept based on the cool copper collider (C3) technology [31].*

Scientific objectives, significance, and strategic value

- CEPC, as a global high energy physics facility, will not only be a flagship of particle physics, but also of the global science. **It can promote China to a leading position in the international community of particle physics**.
  - Science: a major player in fundamental science & innovation, with significant contributions to the mankind
  - Technology: promote the technology not only for China, but also for the world
  - International Cooperation: host thousands of world-class talents for cooperative innovation, enhance the international cooperation, and may contribute to the World Peace.
  - Education & Training: train talents with international experience
  - Economics: cultivate high-tech enterprises; boost local economy with a science center

International competition & Comparative advantages





- Electron-positron Higgs factories identified as top priority for future collider (ESPPU).
- CEPC has strong advantages among mature electron-positron Higgs factories (design report delivered),
  - **Earlier data**: collision expected in 2030s (vs. FCC-ee ~ 2040s), **larger tunnel cross section** （ee, pp coexistence)
  - **Higher precision** vs. linear colliders with more Higgs & Z; potential for **proton collider upgrade**.
  - **Lower cost** vs. FCC-ee, ~1/2 the construction cost with similar luminosity up to 240 GeV.
- CEPC is well recognized in particle physics world, as a major choice for the future flagship facility.

Key scientific and technological issues (route)

New Physics ~10 TeV
- ✓ Dark Matter
- ✓ Extended Higgs
- ✓ Composite Higgs
- ✓ Supersymmetry
- ……

High Precision ~1%
- ✓ Higgs: 1%-0.1%
- ✓ EW : $O(10^2\text{-}10^3)$ vs current
- ✓ Flavor
- ……

Detector — Particle Flow
- ✓ High Granularity
- ✓ Good Resolution
- ✓ Reliable PID
- ……

Design & Implementation — Detector & Accelerator
- ✓ Multi-purposed Acc.
- ✓ New concept Detector
- ✓ Cost, added values
- ✓ Spill-over
- ……

- ✓ Management
- ✓ Collaboration
- ……

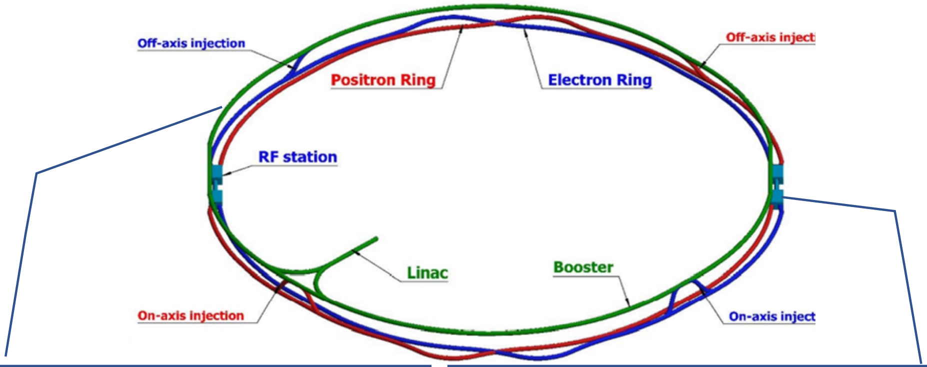
High Lumi. $\sim 10^{34\text{-}36}\,cm^{-2}s^{-1}$
- ✓ Higgs: 20 ab^{-1}
- ✓ Z: 100 ab^{-1}
- ✓ W: 6 ab^{-1}
- ✓ Top: 1 ab^{-1}

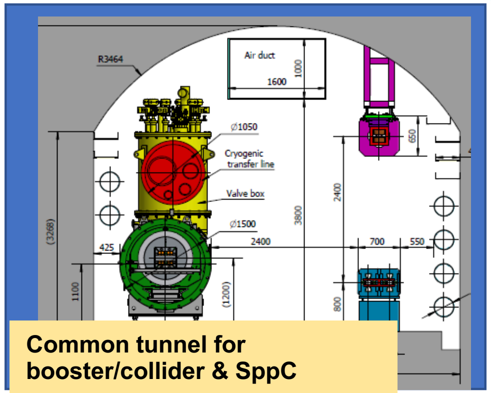
Accelerator — 2 IPs/100 km
- ✓ Switchable Operations
- ✓ Upgradability
- ✓ Large Piwinski angle with Crab-waist
- ……

Operation mode	Z	W	Higgs
Center-of-mass energy (GeV)	91	160	240
Operation time (year)	2	1	10
Instantaneous luminosity/IP ($10^{34}cm^{-2}s^{-1}$)	115	16.0	5.0
Integrated luminosity (ab^{-1}, 2 IPs)	60	3.6	12
Event yield (30 MW)	2.5×10^{12}	1.0×10^{8}	2.5×10^{6}
Event yield (50 MW)	4.0×10^{12}	1.6×10^{8}	4.0×10^{6}

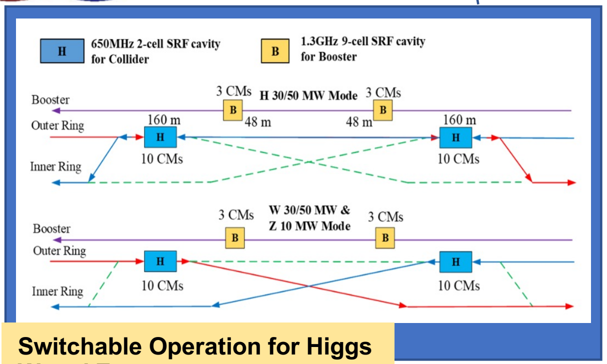
Design of experimental facility and technical requirements

- **Circular collider**: **Higher luminosity** than a linear collider
- **100km circumference**: Optimum **total cost**, good also for **SppC**
- **Shared tunnel**: Accommodate **CEPC** booster &collider and **SppC**
- **Switchable operation**: Higgs, W/Z, top



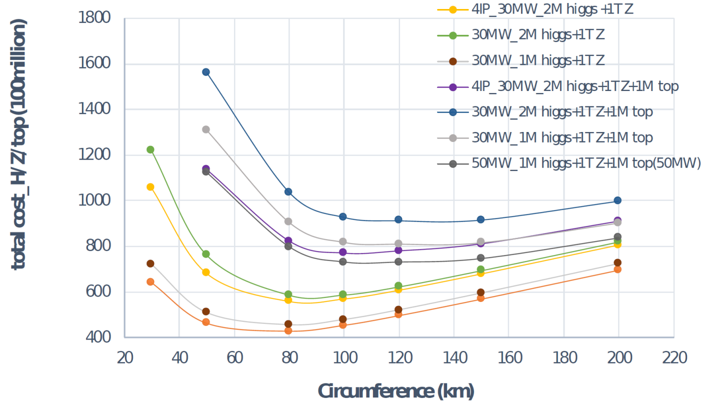


Common tunnel for booster/collider & SppC



Switchable Operation for Higgs W and Z

Cost optimization vs.. circumference



D. Wang *et al* 2022 *JINST* **17** P10018

Main Parameters: High luminosity as a Higgs Factory

	Higgs	W	Z	ttbar
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	**50**			
Energy [GeV]	**120**	**80**	**45.5**	**180**
Bunch number	415	2161	19918	59
Emittance (εx/εy) [nm/pm]	0.64/1.3	0.87/1.7	0.27/1.4	1.4/4.7
Beam size at IP (σx/σy) [um/nm]	15/36	13/42	6/35	39/113
Bunch length (SR/total) [mm]	2.3/3.9	2.5/4.9	2.5/8.7	2.2/2.9
Beam-beam parameters (ξx/ξy)	0.015/0.11	0.012/0.113	0.004/0.127	0.071/0.1
RF frequency [MHz]	650			
Luminosity per IP[10^{34}/cm^2/s]	**8.3**	**27**	**192**	**0.83**

Design of experimental facility and technical requirements

Innovative Design	➢ 100km Full/Partial Double Rings ➢ Switchable operation for Higgs, W and Z ➢ Flexible injection modes to satisfy different energies ➢ World's 1st design of a high energy/flux gamma-ray synchrotron light
Technical Performance	➢ High efficiency Klystron (aim at highest transfer efficiency) ➢ High performance SRF cavities (state-of-the-art Q and gradient) ➢ Novel magnets: Weak field dipole, dual aperture magnets (First Qualified Prototype)
Major Technology Breakthrough	➢ Plasma wakefield acceleration for Injector(New Acceleration Principle) ➢ High field superconducting magnet (Iron based HTS proposal)

Innovative designs and key technology R&D fulfill the challenging requirement.

Design of experimental facility and technical requirements

GOAL

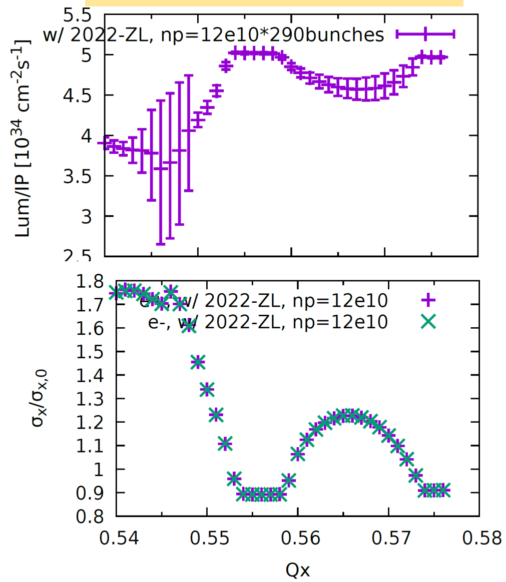
- e+e- circular collider as a high lumi. Higgs factory
- Switchable operation for Higgs, W, Z and Top runs
- A green machine with a maximum Luminosity

Design

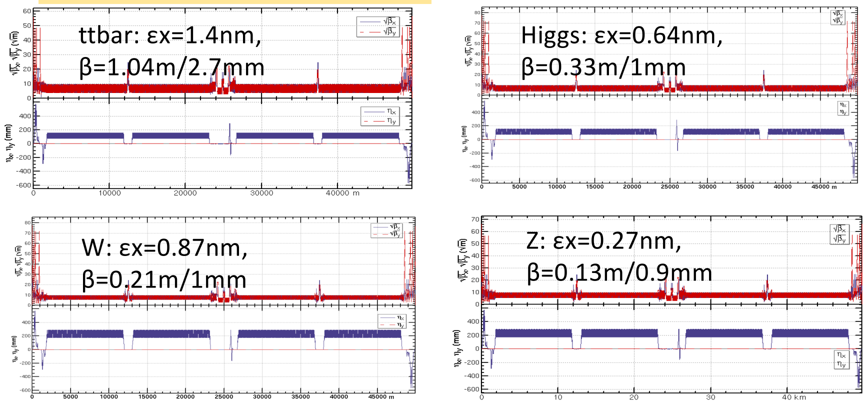
- Complete acc. design w. latest ideas
- Lattice optimization for all energies
- Sufficient DA for all energies
- Beam-beam & collective instability

workable 100km accelerator design for all operation modes – completed

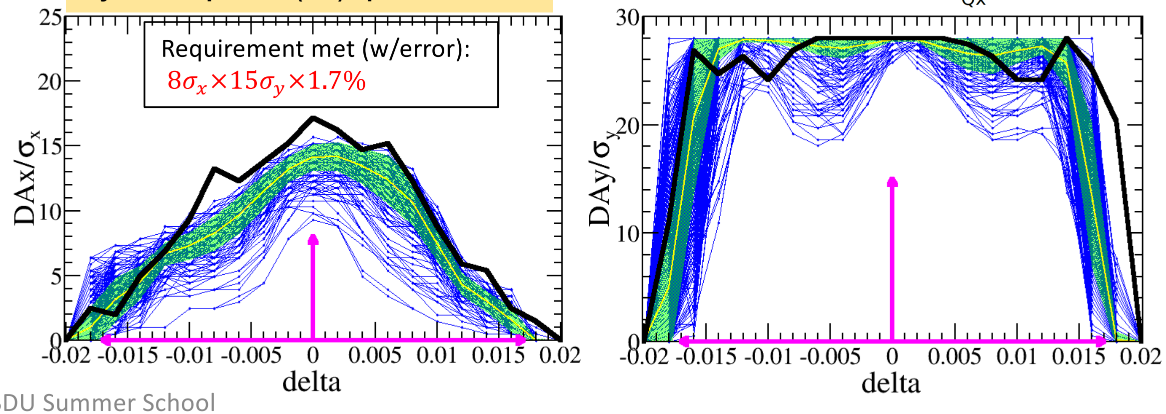
Beam-beam effect study



Lattice for all energies



Dynamic Aperture (DA) optimization



Design of experimental facility and technical requirements

Key Technology	Status
High efficiency klystron	Current eff.>70%, aim at 80%
High Q SRF cavity	Exceeds CEPC requirement
Novel magnet	CEPC requirement met
PWFA injector	Design positron acceleration scheme, >10GeV beam
HTS high field magnet	HTS with IBS

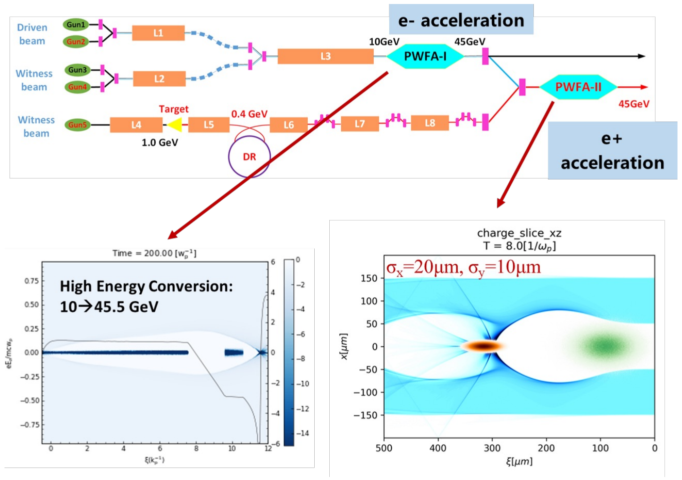
world leading technical performance

Selected Leading Technologies

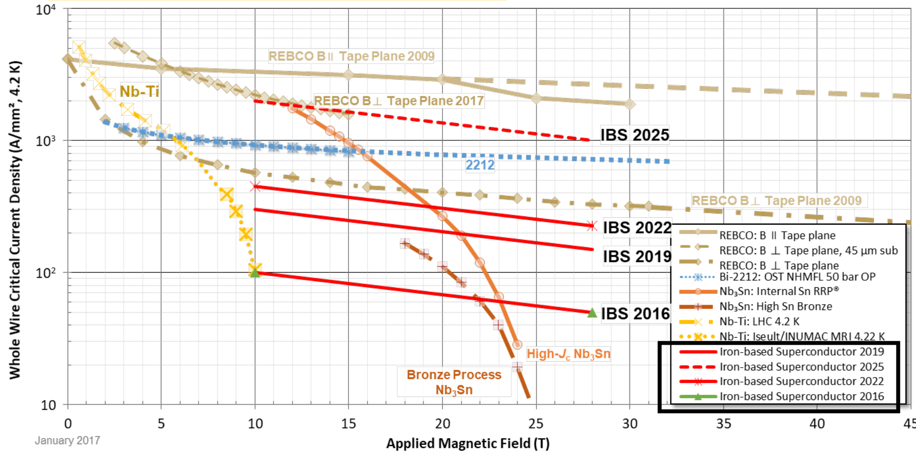
Table 5.3: Status of key technology R&D for CEPC, in comparison with the status quo of world leading accelerator laboratories

Device	Requirement	IHEP status	CERN status	FNAL status	KEK status	LBNL status
1.3 GHz SRF cavity	Q=3×10^{10} @24 MV/m	Q=4.3×10^{10} @31 MV/m	Preliminary progress	Comparable to IHEP	Comparable to IHEP	N/A
650 MHz 2-cell SRF cavity	Q=4×10^{10} @22 MV/m	Q=6×10^{10} @22 MV/m	N/A	Comparable to IHEP	N/A	N/A
High-efficiency klystron	Efficiency $\geq 80\%$	Efficiency $\approx 70\%$	R&D on Efficiency $\approx 80\%$	N/A	Efficiency $\approx 60\%$	N/A
High-field superconducting magnet	20-24 T	12.5 T achieved next goal is 16 T	14-16 T	14.5 T	10 T	14-16 T

PWFA as an alternative Linac injection



Fast development of IBS material



Upgrade capability and added values

SR power per beam upgrade to **50 MW**: High Luminosity (8E34 @ 240 GeV)

The **center-of-mass energy** can increase to **360 GeV**: top quark data

Add a **super proton-proton collider** (SppC) with c.m.s >**100 TeV**

Expandability: High energy & high flux synchrotron light source provides gamma-ray energy up to 300 MeV, critical for multi-disciplinary science

Boost the developments of multiple technologies:
Fast electronics, mechanics, vacuum, beam diagnostics, RF acceleration, cryogenic system, novel magnets, high-accuracy power supplies, control systems, big data, automation and intelligence, etc

- Upgradable scenarios: compatibilities included in design and construction
- Upgrades in several highly valuable ways, bring up discovery power, lifetime spans > 5 decades
- **Significant spillover effects on multidisciplinary sciences and applications**

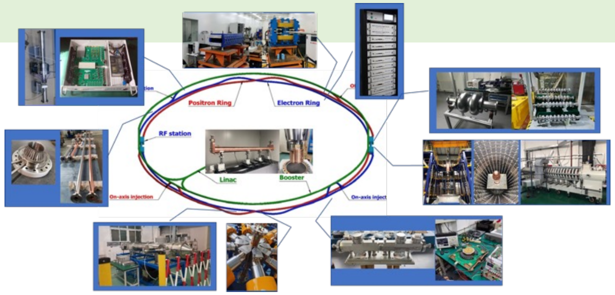
Status and maturities of the CEPC technologies

- CEPC received ~ 260 Million CNY from MOST, CAS, NSFC, etc for R&D
- Large amount of key technologies validated in other projects by IHEP: BEPCII, HEPS, …

CEPC R&D ~ 50% cost of acc. components	➢ **High efficiency klystron** ➢ **650MHz SRF cavities** ➢ **Key components to e+ source** ➢ **High performance Linac** ➢ **Electrostatic Deflector** ➢ **Cryogenic system**	➢ **Novel magnets: Weak field dipole, dual aperture magnets** ➢ **Extremely fast injection/extraction** ➢ **Vacuum chamber tech.** ➢ **Survey & Alignment for ultra large Acc.** ➢ **MDI**
BEPCII / HEPS ~ 40% cost of acc. components	➢ **High precision magnet** ➢ **Stable magnet power source** ➢ **Vacuum chamber with NEG coating** ➢ **Instrumentation, Feedback system** ➢ **Traditional RF power source** ➢ **SRF cavities**	➢ **Electron Source, traditional Linac** ➢ **Survey & Alignment** ➢ **Ultra stable mechanics** ➢ **Radiation protection** ➢ **Cryogenic system** ➢ **MDI**

~10% missing items consist of anticipated challenges in the machine integration, commissioning etc. and the corresponding international contribution

Status and maturities of the CEPC technologies



✔ **Specification Met**

☑ **Prototype Manufactured**

	Accelerator	Cost (billion CNY)	Ratio
✔	Magnets	4.47	27.3%
✔	Vacuum	3.00	18.3%
☑	RF power source	1.50	9.1%
✔	Mechanics	1.24	7.6%
✔	Magnet power supplies	1.14	7.0%
✔	SCRF	1.16	7.1%
✔	Cryogenics	1.06	6.5%
✔	Linac and sources	0.91	5.5%
✔	Instrumentation	0.87	5.3%
☑	Control	0.39	2.4%
☑	Survey and alignment	0.40	2.4%
✔	Radiation protection	0.17	1.0%
☑	SC magnets	0.07	0.4%
✔	Damping ring	0.04	0.2%

Table 5.1: Summary of key technologies under R&D essential for CEPC

Device	Accelerator	Quantity	CEPC specification	R&D status
1.3 GHz SRF cavity (9-cell)	Booster	96	Q=3×10^{10} @ 24 MV/m	Specification met
650 MHz SRF cavity (2-cell)	Collider	240	$Q = 4 \times 10^{10}$@22 MV/m	Specification met
650 MHz klystron	Collider	120	Efficiency: 80% Power: 800 kW	Prototype manufactured
C-band NC accelerating tube	Linac	292	Gradient: 45 MV/m	Prototype manufactured
S-band bunch compressor	Linac	35	Peak power gain: 7 dB	Prototype manufactured
Positron source flux concentrator	Linac	1	Central peak magnetic field >6 T	Specification met
Dual-aperture dipole magnet	Collider	2384	Field: 140 Gs-560 Gs aperture: 70 mm length: 28.7 m; harmonic$< 5 \times 10^{-4}$ relative field difference<0.5%	Specification met
Dual-aperture quadrupole magnet	Collider	2392	Gradient: 3.2-12.8 T/m length: 2 m; harmonic$< 5 \times 10^{-4}$ aperture: 76 mm relative field difference<0.5%	Specification met
Weak field dipole	Booster	16320	Field error $\leq 10^{-3}$@60 Gs	Specification met
Electrostatic separator	Collider	32	Electric field: 2.0 MV/m field uniformity: 5×10^{-4} good field region: 46 mm*11 mm	Specification met by prototype
Cryogenic refrigerator	Collider/ Booster	4	18 kW @ 4.5 K	Collaboration with IPC CAS, a refrigerator system of 2.5 kW @ 4.5 K has been developed
Ceramic vacuum chamber and coating	Transport lines	~ 20	$75 \times 56 \times 5 \times 1200$mm	Prototype in production
MDI SCQ	Collider	8	Gradient: 136T/m; length: 2m Aperture: 40mm; included angle: 33mrad	Prototype in manufacture
Visual instrument	All	11	Image accuracy: 5 μm+(5 μm/m) horizontal angle: 1.8 arc·second vertical angle: 2.2 arc·second	Prototype completed

Table 5.2: Summary of key technologies in engineering applications essential for CEPC

Device type	Accelerator	Quantity	CEPC specifications
S-band copper accelerating tube	Linac	111	$\sim$30 MV/m
vacuum chamber and coating	Collider/ Booster	Total length 200 km	Length: 6 m aperture: 56 mm vacuum: 3×10^{-10} Torr NEG coating pump speed for H_2: 0.5 L/s· cm^2
BPM and electronics	All	$\sim$5000	Closed orbit resolution: 0.6 μm
kicker & fast pulser	Transport line	$\sim$25	Pulse width <10 ns (strip-line) trapezoidal pulse width <250 ns (slotted-pipe)
Lambertson septum	Transport line	$\sim$20	Septum thickness $\leq$3.5 mm (in-air) thickness $\leq$2 mm (in-vacuum)
Power supply	All	9294	Stability 100-1000 ppm
RF-shielded bellows	Collider Booster	24000 /12000	Contact force 125$\pm$25 g/finger

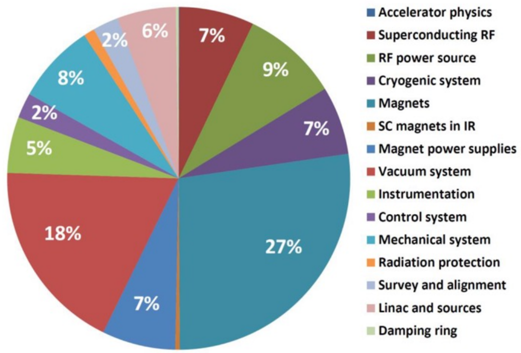
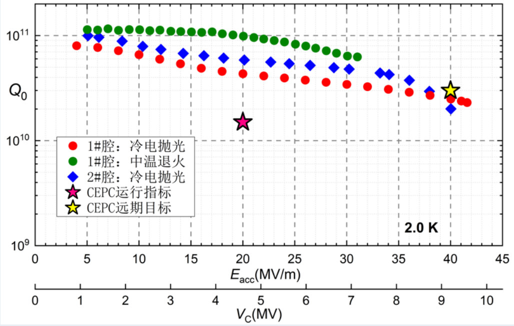


Figure 12.3: Cost breakdown of the CEPC accelerator technical systems.

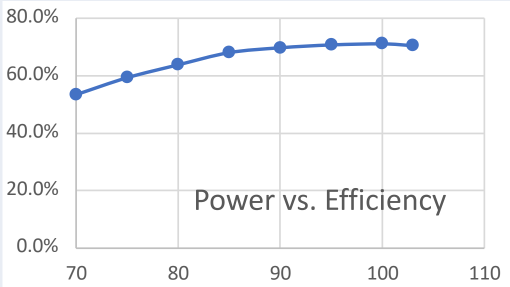
Status and maturities of the CEPC technologies

State-of-the-art: Key Components

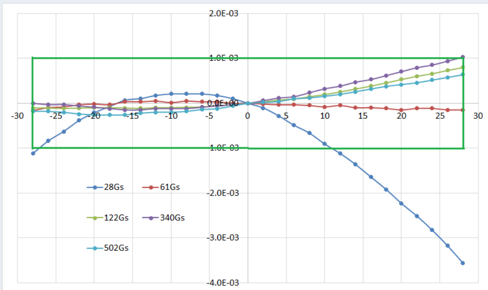
650MHz SRF cavity



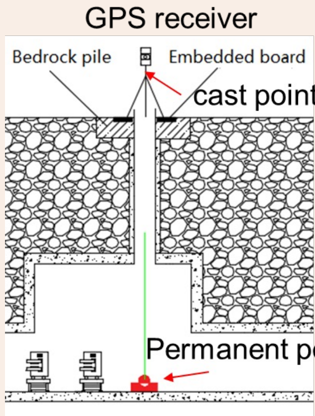
High efficiency klystron



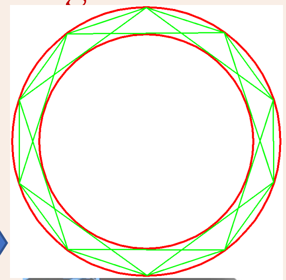
Weak field dipole

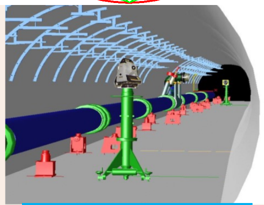


100km Acc. Alignment & Installation R&D

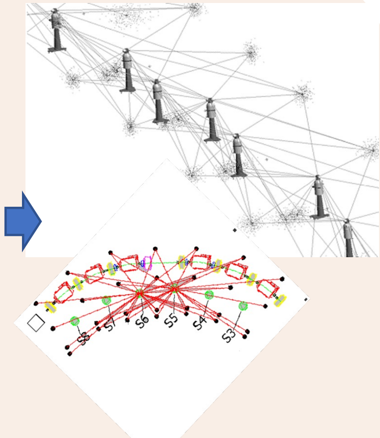


Control Point

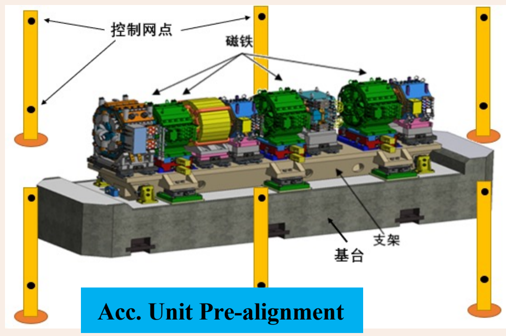




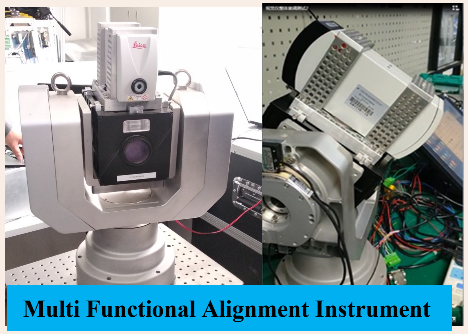
Backbone Network



Tunnel Control Network



Acc. Unit Pre-alignment



Multi Functional Alignment Instrument

Efficient alignment scheme + instrumentation R&D to guarantee the installation within 4 years

Status and maturities of the CEPC technologies

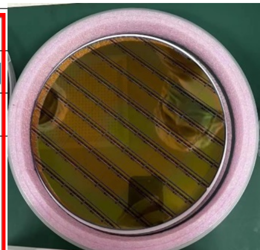
- **Extensive detector R&D benefitted from experience**
  - Silicon strip : Experience from ATLAS upgrade
  - MDI, Drift chamber & SC magnet : Experience from BESIII
- **CEPC R&D on key technologies**
  - Silicon pixel, silicon tracker and TPC
  - PFA calorimeter

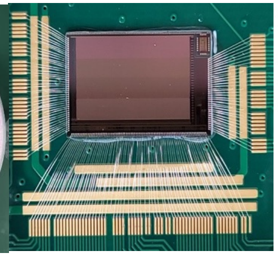
- **With international partners, all sub-detector covered**
  - PFA calorimeter: with CALICE Collaboration
  - TPC: with LCTPC Collaboration
  - Drift cham: with Italian colleague
  - Silicon tracker: with UK/Germany/Italian colleague
  - Silicon vertex: with French/Spain colleague

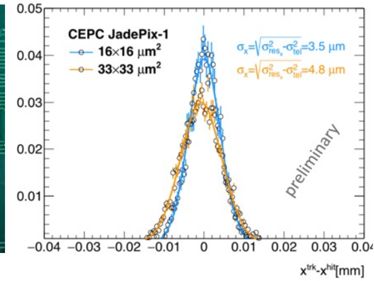
Prototypes under evaluation

	Sub-detector	Specification	Requirement	World-class level	CEPC prototype
	Pixel detector	Spatial resolution	$\sim 3\ \mu m$	$3-5\ \mu m$ [12, 13]	$3-5\ \mu m$ [14–16]
	TPC/drift chamber	dE/dx (dN/dx) resolution	$\sim 2\%$	$\sim 4\%$ [17, 18]	$\sim 4\%$ [19–21]
PFA calorimeter	Scintillator-W ECal	Energy resolution Granularity	$< 15\%/\sqrt{E(\mathrm{GeV})}$ $\sim 2\times 2\ \mathrm{cm}^2$	12.5% [22]	Prototype built to be measured $0.5\times 0.5\ \mathrm{cm}^2$
PFA calorimeter	4D crystal ECal	EM energy resolution 3D Granularity	$\sim 3\%/\sqrt{E(\mathrm{GeV})}$ $\sim 2\times 2\times 2\ \mathrm{cm}^3$	$2\%/\sqrt{E(\mathrm{GeV})}$ [23, 24] N/A	Prototyping [25] $\sim 3\%/\sqrt{E(\mathrm{GeV})}$ $\sim 2\times 2\times 2\ \mathrm{cm}^3$
PFA calorimeter	Scintillator-Steel HCal	Support PFA, Single hadron σ_E^{had}	$< 60\%/\sqrt{E(\mathrm{GeV})}$	$57.6/\sqrt{E(\mathrm{GeV})}\%$ [26]	Prototyping
PFA calorimeter	Scintillating glass HCal	Support PFA Single hadron σ_E^{had}	$\sim 40\%/\sqrt{E(\mathrm{GeV})}$	N/A	Prototyping $\sim 40\%/\sqrt{E(\mathrm{GeV})}$
	Low-mass Solenoid magnet	Magnet field strength Thickness	$2\ \mathrm{T}-3\ \mathrm{T}$ < 150 mm	$1\ \mathrm{T}-4\ \mathrm{T}$ [27–29] > 270 mm	Prototyping

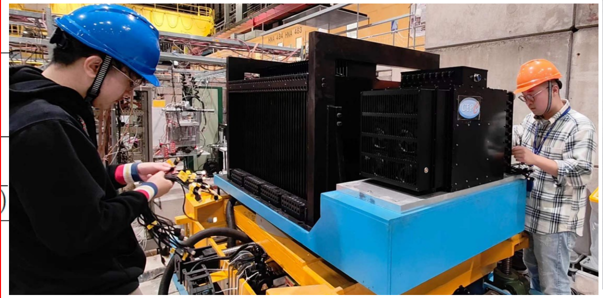
Vertex detector R & D (3- 5 μm reso.)



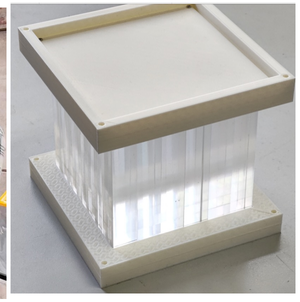




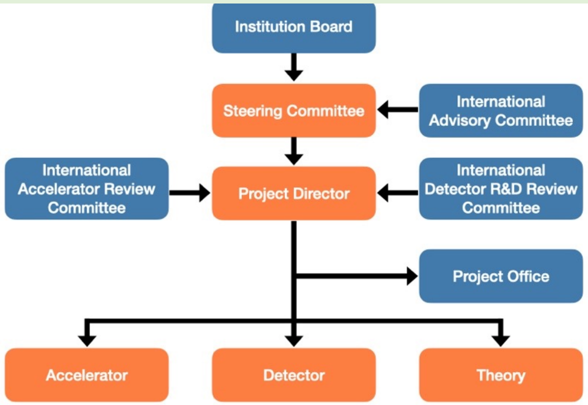
PFA scintillator-W ECAL



4D crystal ECAL



Core team, the host institution and the existing support



- Institution Board: 32 institutes, top universities/institutes in China
- Management team: comprehensive management experience at construction projects of BEPCII/CSNS/HEPS, and international projects of BESIII/Daya Bay/JUNO/…
- Accelerator team: fully over all disciplines with rich experiences at BEPCII, HEPS…
- Physics and Detector team: fully over all disciplines with rich experiences at BESIII, Daya Bay, JUNO, ATLAS, CMS, …

Table 7.2: Team of Leading and core scientists of the CEPC

Name	Brief introduction	Role in the CEPC team
Yifang Wang	Academician of the CAS, director of IHEP	The leader of CEPC, chair of the SC
Xinchou Lou	Professor of IHEP	Project manager, member of the SC
Yuanning Gao	Academician of the CAS, head of physics school of PKU	Chair of the IB, member of the SC
Jie Gao	Professor of IHEP	Convener of accelerator group, vice chair of the IB, member of the SC
Haijun Yang	Professor of SJTU	Deputy project manager, member of the SC
Jianbei Liu	Professor of USTC	Convener of detector group, member of the SC
Hongjian He	Professor of USTC	Convener of theory group, member of the SC
Shan Jin	Professor of NJU	Member of the SC
Nu Xu	Professor of IMP	Member of the SC
Meng Wang	Professor of SDU	Member of the SC
Qinghong Cao	Professor of PKU	Member of the SC
Wei Lu	Professor of THU	Member of the SC
Joao Guimaraes da Costa	Professor of IHEP	Convener of detector group
Jianchun Wang	Professor of IHEP	Convener of detector group
Yuhui Li	Professor of IHEP	Convener of accelerator group
Chenghui Yu	Professor of IHEP	Convener of accelerator group
Jingyu Tang	Professor of IHEP	Convener of accelerator group
Xiaogang He	Professor of SJTU	Convener of theory group
Jianping Ma	Professor of ITP	Convener of theory group

Table 7.3: Team of the CEPC accelerator system

Number	Sub-system	Convener	Team (senior staff)
1	Accelerator physics	Chenghui Yu, Yuan Zhang	18
2	Magnets	Wen Kang, Fusan Chen	12
3	Cryogenic system	Rui Ge, Ruixiong Han	11
4	SC RF system	Jiyuan Zhai, Peng Sha	12
5	Beam Instrumentation	Yanfeng Sui, Junhui Yue	7
6	SC magnets	Qingjin Xu	10
7	Power supply	Bin Chen, Fengli Long	9
8	Injection & extraction	Jinhui Chen	7
9	Mechanical system	Jianli Wang, Lan Dong	4
10	Vacuum system	Haiyi Dong, Yongsheng Ma	5
11	Control system	Ge lei, Gang Li	6
12	Linac injector	Jingyi Li, Jingru Zhang	13
13	Radiation protection	Zhongjian Ma	3
	Sum		117

Table 7.4: Team of the CEPC detector system

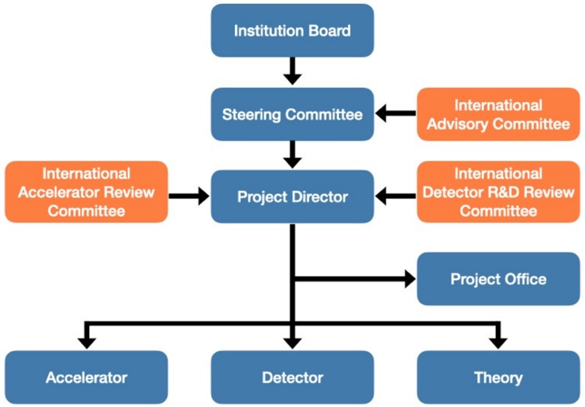
Number	Sub-system	Conveners	Institutions	Team (senior staff)
1	Pixel Vertex Detector	Zhijun Liang, Qun Ouyang, Xiangming Sun , Wei Wei	CCNU, IFAE, IHEP, NJU, NWPU, SDU, Strasbourg, ...	~ 40
2	Silicon Tracker	Harald Fox, Meng Wang, Hongbo Zhu	IHEP, INFN, KIT, Lancaster, Oxford, Queen Mary, RAL, SDU, Tsinghua, Bristol, Edinburgh, Livepool, USTC, Warwick, Sheffield, ZJU, ...	~ 60
3	Gaseous detector	Franco Bedeschi, Zhi Deng, Mingyi Dong, Huirong Qi	CEA-Saclay, DESY, LCTPC Collab., IHEP, INFN, NIKHEF, THU, ...	~ 30
4	Magnet	Feipeng Ning	IHEP	~ 10
5	Calorimetry	Roberto Ferrari, Jianbei Liu, Haijun Yang, Yong Liu	CALICE Collab., IHEP, INFN, SJTU, USTC	~ 40
6	Muon	Paolo Giacomelli, Liang Li, Xiaolong Wang	FDU, IHEP, INFN, SJTU, ...	~ 20
7	Physics	Manqi Ruan, Yaquan Fang, Liantao Wang, Mingshui Chen	IHEP, FDU, SJTU, ...	~ 80
8	Software	Shengseng Sun, Weidong Li, Xingtao Huang	IHEP, SDU, FDU, ...	~ 20
	Sum			~ 300

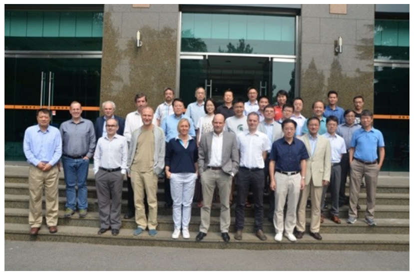
Management team, world-class leading scientists

117 accelerator + ~300 detector staffs currently, + ~ 400 from BEPC/BESIII/JUNO/HEPS…once CEPC approved

Core team, the host institution and the existing support

International Committees





Name	Affiliation	Country
Tatsuya Nakada	EPFL	Japan
Steinar Stapnes	CERN	Norway
Rohini Godbole	CHEP, Bangalore	India
Michelangelo Mangano	CERN	Switzerland
Michael Davier	LAL	France
Lucie Linssen	CERN	Holland
Luciano Maiani	U. Rome	San Marino
Joe Lykken	Fermilab	U.S.
Ian Shipsey	Oxford/DESY	U.K.
Hitoshi Murayama	IPMU/UC Berkeley	Japan
Geoffrey Taylor	U. Melbourne	Australia
Eugene Levichev	BINP	Russia
David Gross	UC Santa Barbara	U.S.
Brian Foster	Oxford	U.K
Marcel Demarteau	ORNL	USA
Barry Barish	Caltech	USA
Maria Enrica Biagini	INFN Frascati	Italy
Yuan-Hann Chang	IPAS	Taiwan, China
Akira Yamamoto	KEK	Japan
Hongwei Zhao	Institute of Modern Physics, CAS	China
Andrew Cohen	University of Science and Techbnology	Hong Kong, China
Karl Jakobs	University of Freiburg/CERN	Germany
Beate Heinemann	DESY	Germany

International Accelerator Review Committee

- Phillip Bambade, LAL
- Marica Enrica Biagini (Chair), INFN
- Brian Foster, DESY/University of Hamburg & Oxford University
- In-Soo Ko, POSTECH
- Eugene Levichev, BINP
- Katsunobu Oide, CERN & KEK
- Anatolii Sidorin, JINR
- Steinar Stapnes, CERN
- Makoto Tobiyama, KEK
- Zhentang Zhao, SINAP
- Norihito Ohuchi, KEK
- Carlo Pagani, INFN-Milano

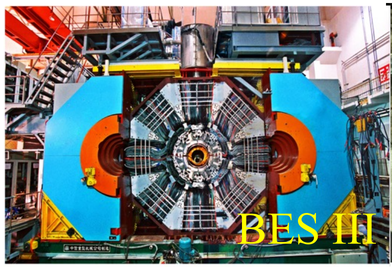
International Detector R&D Review Committee

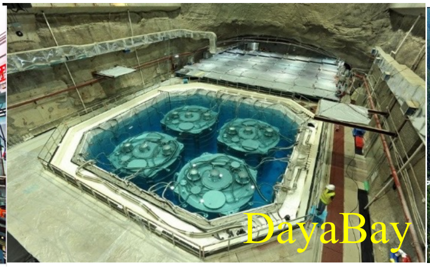
- Jim Brau, USA, Oregon
- Valter Bonvicini, Italy, Trieste
- Ariella Cattai, CERN, CERN
- Cristinel Diaconu, France, Marseille
- Brian Foster, UK, Oxford
- Liang Han, China, USTC
- Dave Newbold, UK, RAL (chair)
- Andreas Schopper, CERN, CERN
- Abe Seiden, USA, UCSC
- Laurent Serin, France, LAL
- Steinar Stapnes, CERN, CERN
- Roberto Tenchini, Italy, INFN
- Ivan Villa Alvarez, Spain, Santader
- Hitoshi Yamamoto, Japan, Tohoku

IAC: global renowned scientists and top laboratory or project leaders who have ample experience in project management, planning, and execution of strategies, **operating since 2015**

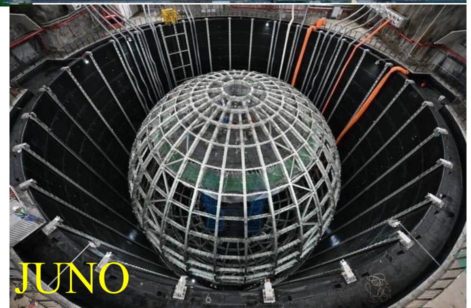
IARC & IDRC: leading experts of this field, provide guide to the project director

Core team, the host institution and the existing support





- IHEP is one of the few institution in the world that
  - has rich management experience and successful constructed many large scientific facilities
  - has a full coverage of all technical disciplines for accelerators and detectors, in particular for the design and construction of circular e+e- collider(BEPCII) and the detector(BESIII)
  - has all needed infrastructure for the construction of large facilities
  - has successfully hosted international projects such as BESIII, Daya Bay, JUNO, LHAASO, etc.
- **CEPC is committed by IHEP and workplan endorsed by CAS**



Core team, the host institution and the existing support

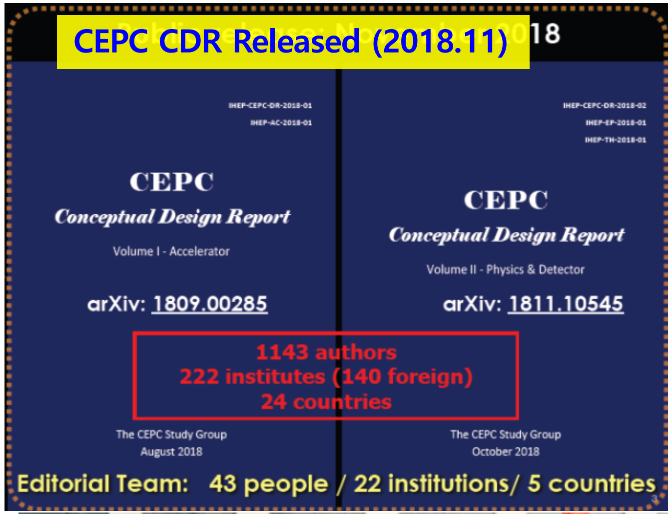
International collaboration

CEPC attracts significant International participation

- Conceptual design report: 1143 authors from 221 institutes (including 140 International Institutes)
- More than 20 MoUs signed and executed

- Intensive collaboration on Physics studies
- Oversea scientists made substantial contributions to the R&D, especially the detector system

- CEPC International Workshop since 2014
- EU-US versions of CEPC WS: Next one at Marseille
- Annual working month at HKIAS (since 2015)



Core team, the host institution and the existing support

International influence

CEPC Input to the ESPP 2018
- Physics and Detector

CEPC Physics-Detector Study Group

Abstract

The Higgs boson, discovered in 2012 by the ATLAS and CMS Collaborations at the Large Hadron Collider (LHC), plays a central role in the Standard Model. Measuring its properties precisely will advance our understandings of some of the most important questions in particle physics, such as the naturalness of the electroweak scale and the nature of the electroweak phase transition. The Higgs boson could also be a window for exploring new physics, such as dark matter and its associated dark sector, heavy sterile neutrino, et al. The Circular Electron Positron Collider (CEPC), proposed by the Chinese High Energy community in 2012, is designed to run at a center-of-mass energy of 240 GeV as a Higgs factory. With about one million Higgs bosons produced, many of the major Higgs boson couplings can be measured with precisions about one order of magnitude better than those achievable at the High Luminosity-LHC. The CEPC is also designed to run at the Z-pole and the W pair production threshold, creating close to one trillion Z bosons and 100 million W bosons. It is ... electroweak observables ... urements are complementa... C also offers excellent op... s, W, and Z bosons. The ... tau leptons produced from the decays of the Z bosons are interesting for flavor physics. The clean collision environment also makes the CEPC an ideal facility to perform precision QCD measurements. Several detector concepts have been proposed for the C... epts can fulfill ... potential and t... il in the Conc... outline futur... ribe the plann... p for the CEPC ... national collaboration would be crucial at this stage. This submission for consideration by the ESPP is part of our dedicated effort in seeking international collaboration and support. Given the importance of the precision Higgs boson measurements, the ongoing CEPC activities do not diminish our interests in participating in the international collaborations of other future electron-positron collider based Higgs factories.

ESPPU input

arXiv: 1901.03170
1901.03169

Snowmass2021 White Paper AF3- CEPC

CEPC Accelerator Study Group[1]

1. Design Overview

1.1 Introduction and status

The discovery of the Higgs boson at CERN's Large Hadron Collider (LHC) in July 2012 raised new opportunities for large-scale accelerators. The Higgs boson is the heart of the Standard Model (SM), and is at the center of many biggest mysteries, such as the large hierarchy between the weak scale and the Planck scale, the nature of the electroweak phase transition, the original of mass, the nature of dark matter, the stability of vacuum, etc. and many other related questions. Precise measurements of the properties of the Higgs boson serve as probes of the underlying fundamental physics principles of the SM and beyond. Due to the modest Higgs boson mass of 125 GeV, it is possible to produce it in the relatively clean environment of a circular electron–positron collider with high luminosity, new technologies, low cost, and reduced power consumption. In September 2012, Chinese scientists proposed a 240 GeV *Circular Electron Positron Collider* (CEPC), serving two large detectors for Higgs studies and other topics as shown in Fig. 1. The ~100 km tunnel for such a machine ... energies well beyo...

The ... hosted by China. It ... the ICFA Workshop *"Accelerators for a Higgs Factory: Linear vs. Circular"* (HF2012) in November 2012 at Fermilab. A Preliminary Conceptual Design Report (Pre-CDR, the White R... (the Yellow ... was made. T... [3] has been ... r an internati... 2018. In May ... ergy Physics ... CDR, CEPC a... d by CEPC International Advisory Committee (IAC). In TDR phase, CEPC optimization design with higher performance compared with CDR and the key technologies such as 650MHz high power and high efficiency klystron, high quality SRF accelerator technology, high precision magnets for booster and collider rings, vacuum system, MDI, etc. have been carried out, and the CEPC accelerator TDR will be completed at

[1] Correspondance: J. Gao, Institute of High Energy Physics, CAS, China
Email: gaoj@ihep.ac.cn

Snowmass input

arXiv: 2203.09451
2205.08553

- CEPC provides critical input to ESPPU & Snowmass as a **major player**
- Team member actively participated International study(ESPPU and Snowmass committees) and Panel discussions

CEPC attracts intensive international collaboration, ensuring that the CEPC design and technology are among the most advanced in the world. once approved, CEPC is expected to be substantially supported by international community.

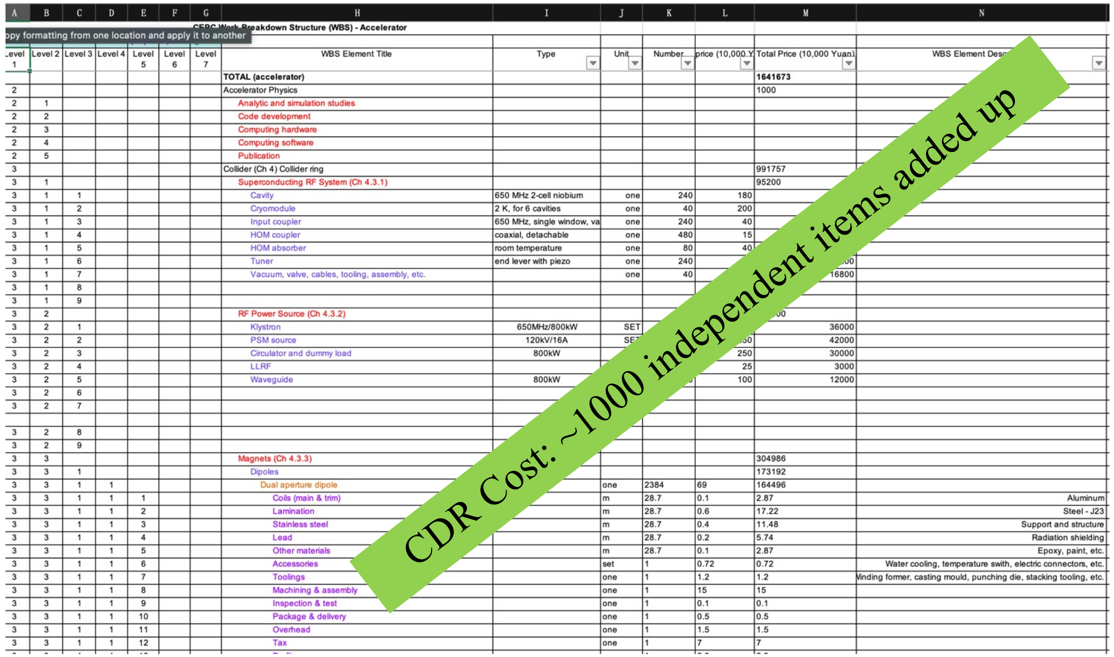
Core team, the host institution and the existing support

Industrial engagement

- CIPC, established in 2017, composed of ~ 70 high tech. enterprises, covers Superconducting materials, Superconducting cavities, cryomodules, cryogenics, Klystrons, electronics, power source, vacuum, civil engineering, etc. CIPC actively joins the Key technology R&D and **prepares for the mass production** for the CEPC construction.
- CEPC study group is **surveying main international suppliers.**
- CEPC strongly promote these relevant technology development (cost-benefit).

Budgets for R&D and construction, and the timeline

Cost estimation of the CEPC (CDR)		
Tier I	Tier II	Amount (100 M CNY)
Accelerator	Collider	99.2
	Booster	39.2
	Linac and sources	9.1
	Damping ring	0.44
	Common: Cryogenics	10.6
	Survey & alignment	4
	Radiation protection	1.7
Conventional facilities	-	102
Detectors	-	40
γ-ray beam lines	-	3
Project management (1%)	-	3
Contingency (15%)	-	46
Total	-	358

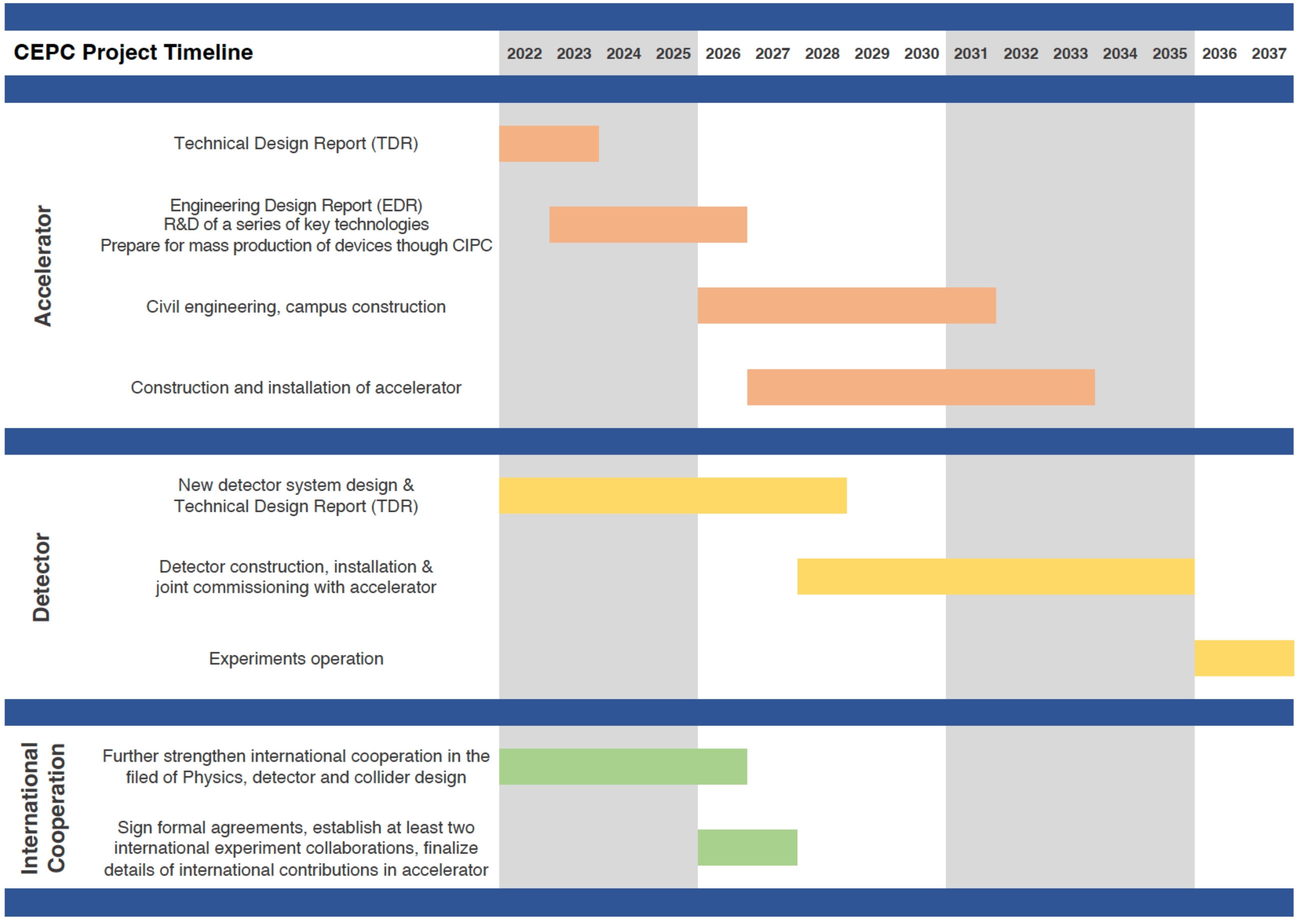


CEPC Work Breakdown Structure (WBS) - Accelerator

Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	WBS Element Title	Type	Unit	Number	price (10,000 Y	Total Price (10,000 Yuan)	WBS Element Desc
							TOTAL (accelerator)					1641673	
2							Accelerator Physics					1000	
2	1						Analytic and simulation studies						
2	2						Code development						
2	3						Computing hardware						
2	4						Computing software						
2	5						Publication						
3							Collider (Ch 4) Collider ring					991757	
3	1						Superconducting RF System (Ch 4.3.1)					95200	
3	1	1					Cavity	650 MHz 2-cell niobium	one	240	180	[illegible]	
3	1	2					Cryomodule	2 K, for 6 cavities	one	40	200	[illegible]	
3	1	3					Input coupler	650 MHz, single window, va	one	240	40	[illegible]	
3	1	4					HOM coupler	coaxial, detachable	one	480	15	[illegible]	
3	1	5					HOM absorber	room temperature	one	80	40	[illegible]	
3	1	6					Tuner	end lever with piezo	one	240	[illegible]	[illegible]	
3	1	7					Vacuum, valve, cables, tooling, assembly, etc.		one	40	[illegible]	16800	
3	1	8											
3	1	9											
3	2						RF Power Source (Ch 4.3.2)					[illegible]	
3	2	1					Klystron	650MHz/800kW	SET	[illegible]	[illegible]	36000	
3	2	2					PSM source	120kV/16A	[illegible]	[illegible]	[illegible]	42000	
3	2	3					Circulator and dummy load	800kW	[illegible]	[illegible]	250	30000	
3	2	4					LLRF		[illegible]	[illegible]	25	3000	
3	2	5					Waveguide	800kW	[illegible]	[illegible]	100	12000	
3	2	6											
3	2	7											
3	2	8											
3	2	9											
3	3						Magnets (Ch 4.3.3)					304986	
3	3	1					Dipoles					173192	
3	3	1	1				Dual aperture dipole		one	2384	69	164496	
3	3	1	1	1			Coils (main & trim)		m	28.7	0.1	2.87	Aluminum
3	3	1	1	2			Lamination		m	28.7	0.6	17.22	Steel - J23
3	3	1	1	3			Stainless steel		m	28.7	0.4	11.48	Support and structure
3	3	1	1	4			Lead		m	28.7	0.2	5.74	Radiation shielding
3	3	1	1	5			Other materials		m	28.7	0.1	2.87	Epoxy, paint, etc.
3	3	1	1	6			Accessories		set	1	0.72	0.72	Water cooling, temperature swith, electric connectors, etc.
3	3	1	1	7			Toolings		one	1	1.2	1.2	Winding former, casting mould, punching die, stacking tooling, etc.
3	3	1	1	8			Machining & assembly		one	1	15	15	
3	3	1	1	9			Inspection & test		one	1	0.1	0.1	
3	3	1	1	10			Package & delivery		one	1	0.5	0.5	
3	3	1	1	11			Overhead		one	1	1.5	1.5	
3	3	1	1	12			Tax		one	1	7	7	

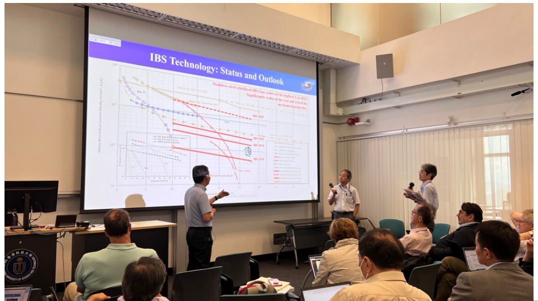
- Cost estimated with two indpendent methods, agrees at 10% level
- CEPC design relies on well studied, or mature tech. reducing uncertainties on Cost estimation
- Cost estimation for TDR phase is progress: no major change

Budgets for R&D and construction, and the timeline



CEPC Accelerator TDR International Review

- An international review meeting was hosted at Hongkong University of Science and Technology during 12-16.June.2023
- The physics design and key technology R&D status were reviewed.



Summary

CEPC

- **will address most pressing & critical science problems**
- **adds enormous strategic values; has many advantages; will be in a leading position if realized.**
- **design-technologies reaching maturity; offers great upgrade options and many added values and benefits**
- **has a strong-experienced team, IHEP support and international cooperation, which are keys to bring CEPC to fruition**
- **schedule follows China's 5-year planning; expects to complete R&D and preparation to build the facility and carry out the science program**
- **will position China to be a leading position in particle physics and contribute to the world in a major way.**

Back up

Outline

- Brief introduction to CEPC
- Scientific objectives, significance, and strategic value
- Key scientific and technological issues
- Design of experimental facility and technical requirements
- Upgrade capability and added values
- Status and maturities of the CEPC technologies
- Core team, the host institution and the existing support
- Budgets for R&D and construction, and the timeline
- Summary

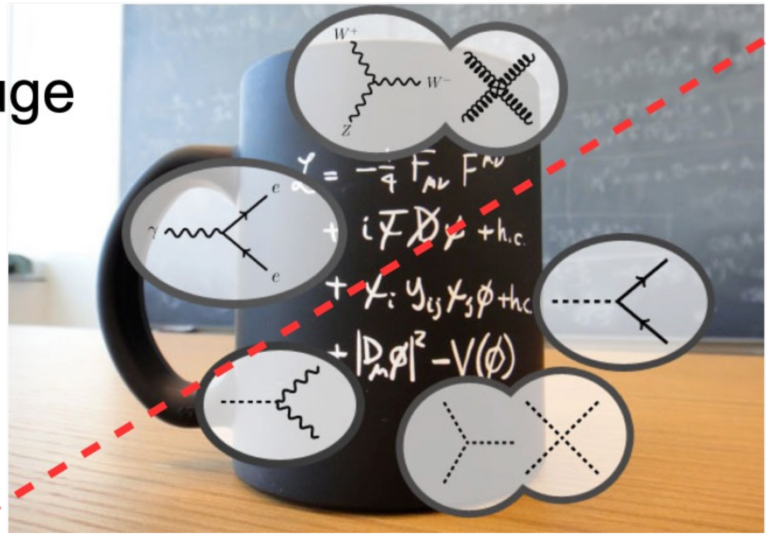
Budgets for R&D and construction

Cost and benefit analysis

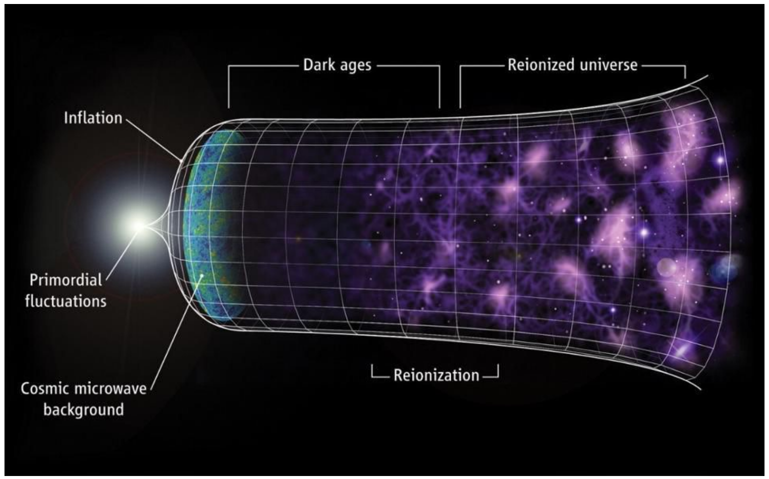
- *CEPC **is priceless** in revealing potential discoveries & knowledge. CEPC may provide the **Higgs data** in 2030s, thus brings upon mankind a new era in the science exploration.*
- *The **current CEPC design is optimized**. The cost is reduced through innovative design & new tech. development.*
- *CEPC will host **thousands of users and operates for decades**. The investment per researcher per year is comparable, or even smaller than that of other facilities & other disciplines.*
- *CEPC has the upgradable capability and provides **strong boost to the technologies**, is a highland for global talent training & **cooperative innovations**. It could revolutionize multiple key-tech. that has huge potential for application.*
- *CEPC attracts significant **International collaboration,** enhance the international communication, contribute to the World Peace.*
- *The science city of CEPC could strongly **promote** local **economic**.*

Scientific objective: Higgs field & Challenges to the SM

Gauge



Higgs



- Hierarchy: From neutrinos to the top mass, masses differs by 13 orders of magnitude
- Naturalness: Fine tuning of the Higgs mass
- Masses of Higgs and top quark: meta-stable of the vacuum
- Unification?
- Dark matter candidate?
- Not sufficient CP Violation for Matter & Antimatter asymmetry

- **Most issues related to Higgs**

CEPC Measurement Precision

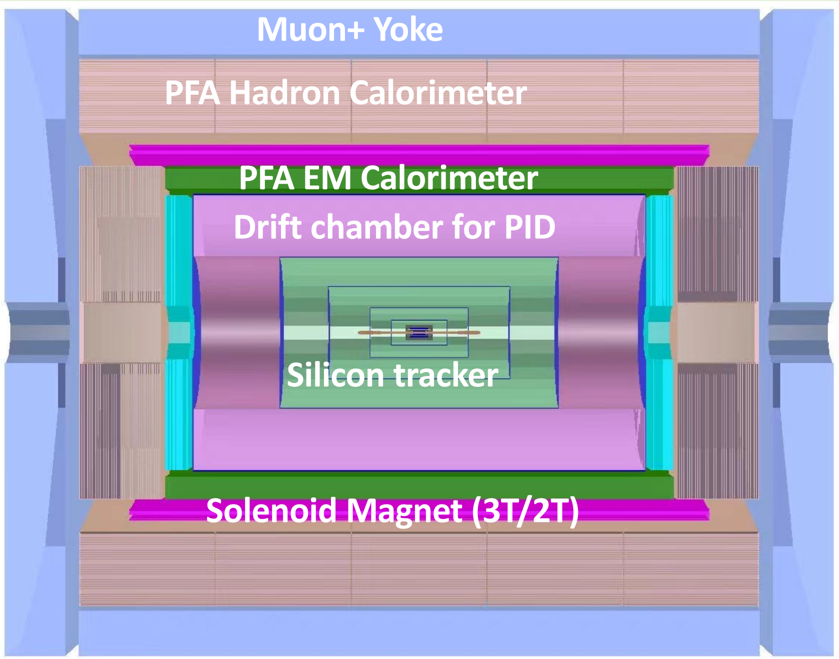
Table 2.1: Precision of the main parameters of interests and observables at CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data [2] are used for comparison

Higgs			W, Z, and top		
Observable	HL-LHC projections	CEPC precision	Observable	Current precision	CEPC precision
M_H	20 MeV	3 MeV	M_W	9 MeV	0.5 MeV
Γ_H	20%	1.7%	Γ_W	49 MeV	2 MeV
$\sigma(ZH)$	4.2%	0.26%	M_{top}	760 MeV	$\mathcal{O}(10)$ MeV
$B(H \to bb)$	4.4%	0.14%	M_Z	2.1 MeV	0.1 MeV
$B(H \to cc)$	-	2.0%	Γ_Z	2.3 MeV	0.025 MeV
$B(H \to gg)$	-	0.81%	R_b	3×10^{-3}	2×10^{-4}
$B(H \to WW^*)$	2.8%	0.53%	R_c	1.7×10^{-2}	1×10^{-3}
$B(H \to ZZ^*)$	2.9%	4.2%	R_μ	2×10^{-3}	1×10^{-4}
$B(H \to \tau^+\tau^-)$	2.9%	0.42%	R_τ	1.7×10^{-2}	1×10^{-4}
$B(H \to \gamma\gamma)$	2.6%	3.0%	A_μ	1.5×10^{-2}	3.5×10^{-5}
$B(H \to \mu^+\mu^-)$	8.2%	6.4%	A_τ	4.3×10^{-3}	7×10^{-5}
$B(H \to Z\gamma)$	20%	8.5%	A_b	2×10^{-2}	2×10^{-4}
Bupper$(H \to \text{inv.})$	2.5%	0.07%	N_ν	2.5×10^{-3}	2×10^{-4}

Accelerator	Cost (billion CNY)	Ratio	CEPC R&D	BEPCII /HEPS
Magnets	4.47	27.3%	20.0%	7.0%
Vacuum	3.00	18.3%	10.0%	8.0%
RF power source	1.50	9.1%	5.0%	2.0%
Mechanics	1.24	7.6%	N.A	6.6%
Magnet power supplies	1.14	7.0%	0.5%	6.5%
SCRF	1.16	7.1%	5.1%	2.0%
Cryogenics	1.06	6.5%	3.0%	2.5%
Linac and sources	0.91	5.5%	2.0%	2.5%
Instrumentation	0.87	5.3%	2.3%	3.0%
Control	0.39	2.4%	0.1%	0.5%
Survey and alignment	0.40	2.4%	1.4%	1.0%
Radiation protection	0.17	1.0%	0.1%	0.2%
SC magnets	0.07	0.4%	0.2%	0.1%
Damping ring	0.04	0.2%	N.A.	N.A.
Total			**49.7%**	**41.9%**

Design of experimental facility and technical requirements

Detector

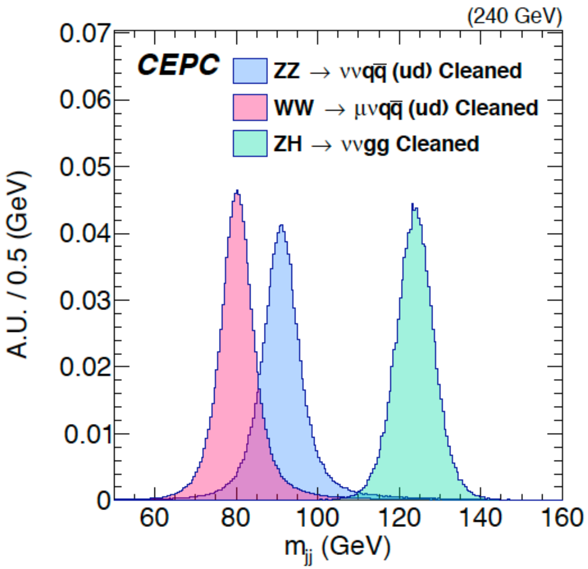


Requirements
boson mass resolution (BMR ~3%)

→

Challenges

- Support Particle flow with
  - High granularity
  - High precision



Novel detector design based on PFA calorimeter. Aim at improving BMR from 4% to 3%

Detector	Key parameter	World-class level	CEPC design
PFA based EM calorimeter	EM shower E resolution	~20%/√E	<3%/√E
PFA based Hadron calorimeter	Single hadron E resolution	~50%/√E	~40%/√E

Design of experimental facility and technical requirements

CEPC: innovative design & key technologies R&D at the leading position of international future colliders.

Conceptual Innovation	Upgradable Capability	State-of-the-art Tech.	Green & Cost Saving	Revolutionary Principle	Spillover
★ (grey)	★ (blue)	★ (red)	★ (green)	★ (cyan)	★ (yellow)

	Conceptual Innovation	Upgradable Capability	State-of-the-art Tech.	Green & Cost Saving	Revolutionary Principle	Spillover
100km circular collider	★	★				
Partial/Full double ring	★	★		★		
Switchable energies H/W/Z	★			★		
One tunnel for booster/collider and SppC	★	★		★		
High efficiency Klystron			★	★		★
SRF cavities			★	★		★
Weak field dipole			★			
Dual aperture magnets			★	★		
PWFA Injector	★	★		★	★	★
Iron based HTS Mag	★		★	★	★	★
Innovative PFA Detector	★		★		★	★