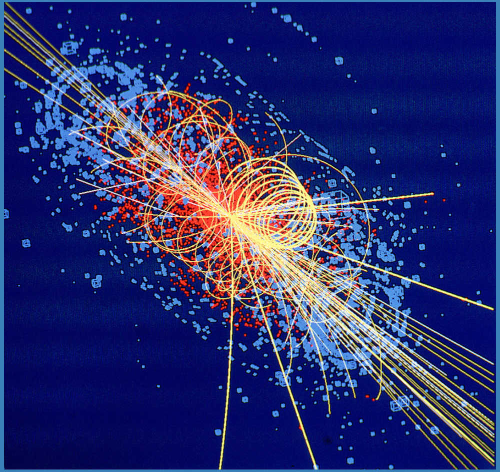
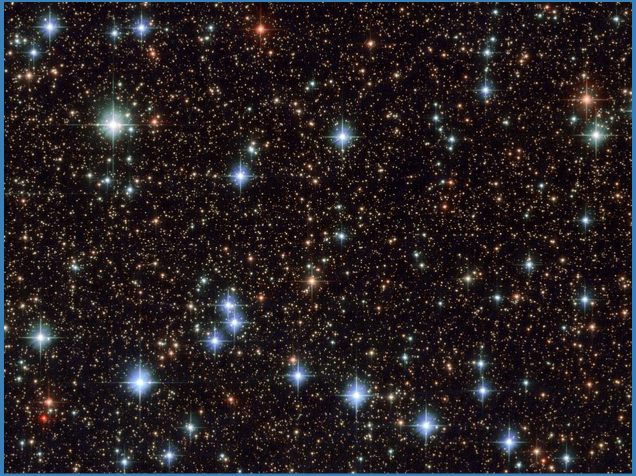
Objetivos científicos de la agrupación CPAN española de física de partículas, astropartículas y nuclear





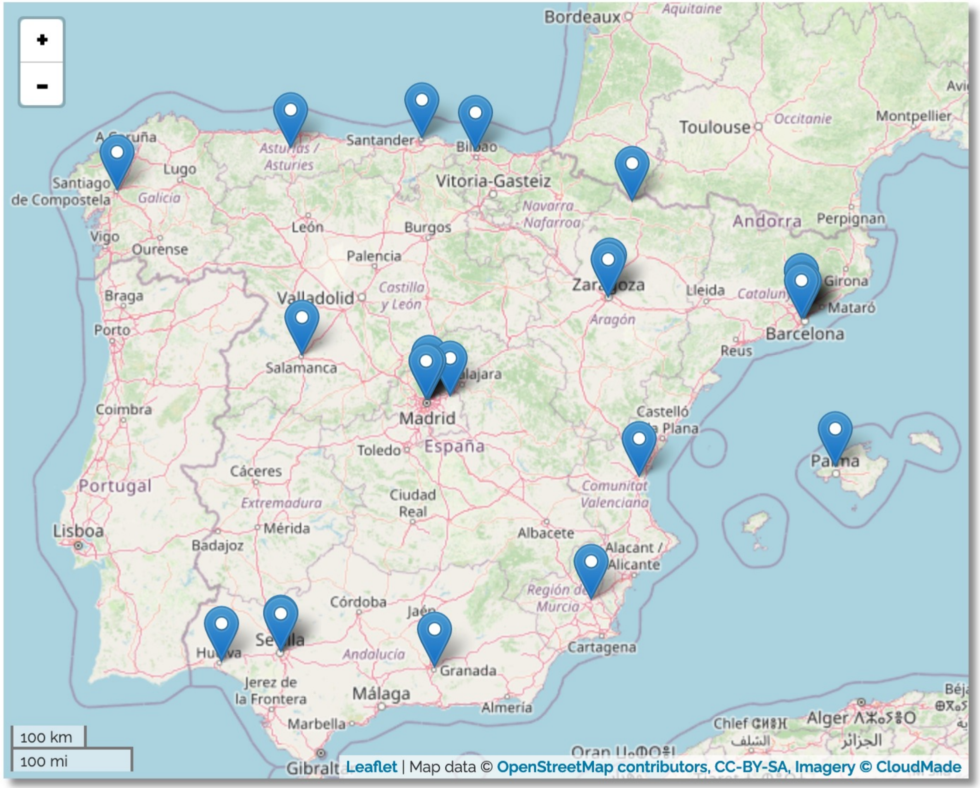
Directora: María José Costa (IFIC, CSIC-UV)
Vice-Directora: Carlos Salgado (IGFAE)

¿Qué es el CPAN?

- El CPAN es una agrupación científica cuyo objeto primordial es establecer un **marco de colaboración estable entre las instituciones en el campo** de la investigación, innovación y desarrollo tecnológico en Física de Partículas, Astropartículas y Física Nuclear.
  - Promover una **participación coordinada** para consolidar su presencia en el contexto internacional, optimizar los recursos e incrementar el peso y visibilidad de la comunidad española.
  - **Defender las prioridades e intereses científicos** en las colaboraciones y proyectos internacionales, así como delate de las agencias de financiación.
- Los representantes legales de las correspondientes instituciones firmaron un **Memorando de Entendimiento** en Madrid, a 14 de junio de 2016 [http://ific.uv.es/~cpan/MoU-CPAN-2016.pdf], que fue ampliado en 2020 [http://ific.uv.es/~cpan/Adenda-MoU-CPAN-2020.pdf], **vigente hasta el 13 de junio de 2024** (proceso de renovación en marcha como Protocolo General de Actuación).

¿Quiénes somos?

- La Agrupación está integrada por **28 Centros, Laboratorios, Departamentos o Grupos de Investigación** pertenecientes a las instituciones firmantes del Memorando/Protocolo General de Actuación.



CIEMAT
CNA
ICE (CSIC)
IEM (CSIC)
IFAE
IFCA (CSIC-UC)
IFF (CSIC)
IFIC (CSIC-UV)
IFT (CSIC-UAM)
IGFAE
IMB-CNM (CSIC)
ITAINNOVA
LSC
UAH
UAM
UB
UCM
UGR
UHU
UIB
UM
UO
UPC
UPV/EHU
URL
US
USAL
CAPA-UNIZAR

¿Cómo estamos organizados?

Directora:
María José Costa Mezquita (IFIC)

Vicedirector:
Carlos Alberto Salgado López (IGFAE)

Gerente:
María José Gracia Vidal (IFIC)

IPs de los 28 Grupos:

- Nicanor Colino Arriero (CIEMAT)
- Carlos Guerrero Sánchez (CNA)
- Emilio Elizalde Rius (ICE)
- María José García Borge (IEM)
- Aurelio Juste Rozas (IFAE)
- Iván Vila Álvarez (IFCA)
- Beatriz Gato Rivera (IFF)
- Antonio Pich Zardoya (IFIC)
- Juan Antonio Aguilar Saavedra (IFT)
- Abraham Gallas Torreira (IGFAE)
- Giulio Pellegrini (IMB)
- Fernando Arteche González (ITAINNOVA)
- Carlos Peña Garay (LSC)
- Luis del Peral Gochicoa (UAH)
- Jorge Fernández de Troconiz Acha (UAM)
- Ricardo Vázquez Gómez (UB)
- Antonio Dobado González (UCM)
- Antonio Bueno Villar (UGR)
- José Rodríguez Quintero (UHU)
- Alicia Sintes Olives (UIB)
- José Antonio Oller Berber (UM)
- Francisco Javier Cuevas Maestro (UO)
- Francisco Calviño Tavares (UPC)
- Miguel García Echevarría (UPV/EHU)
- Xavier Vilasís Cardona (URL)
- José Miguel Arias Carrasco (US)
- Begoña Eulogia Quintana Arnés (USAL)
- Theopisti Dafni (UNIZAR)

Consejo de Estrategia Científica

- Órgano de dirección
- Formado por el director, los representantes de las instituciones adscritas y los restantes miembros del Comité Ejecutivo (con voz, pero sin voto)
- Presidido por el Director
- Secretario: Gerente

Comité Ejecutivo:

- Asiste al director y supervisa el funcionamiento ordinario del CPAN.
- Constituido por la directora, el vicedirector, dos representantes por cada una de las áreas científicas.
- Secretario: Gerente

Física de Partículas Experimental:
Cibrán Santamarina Ríos (IGFAE) e Isidro González Caballero (UO)

Física de Partículas Teórica:
Germán Rodrigo García (IFIC) y Diego Blas (IFAE)

Física de Astropartículas:
María Lucía Martínez Pérez (CAPA-UNIZAR) y Mª Carmen Palomares Espiga (CIEMAT)

Física Nuclear:
José Enrique García Ramos (UHU) y Teresa Kurtukian Nieto (IEM)

Oficina de Apoyo:

- Gestora
- Comunicación & Divulgación: Núria Falcó (IFIC – UV-CSIC)

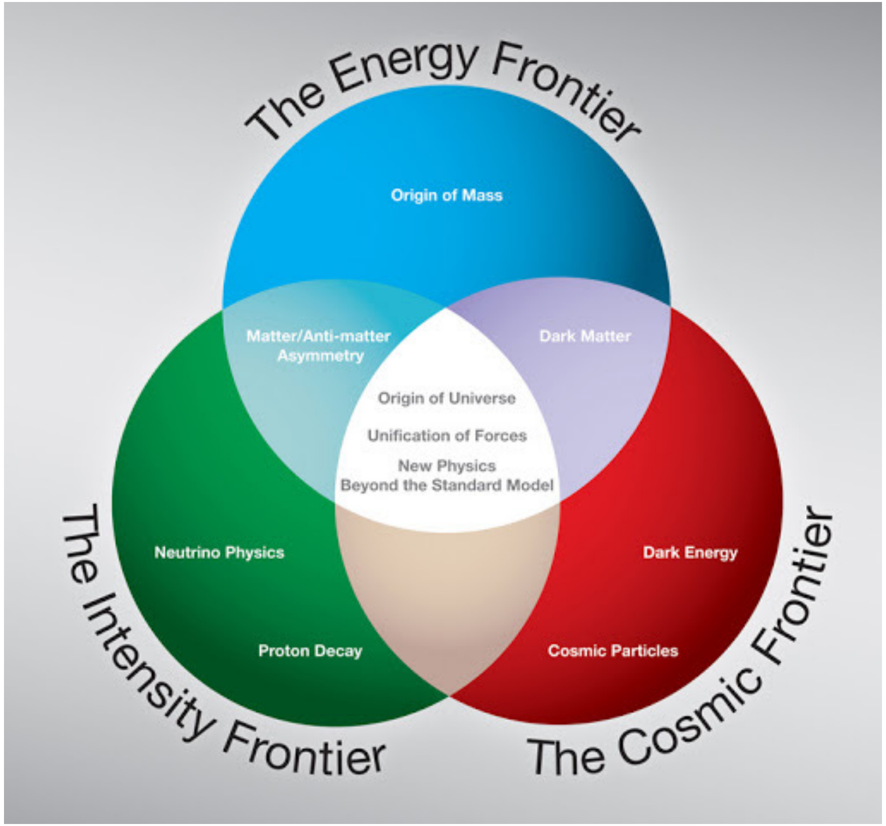
En colaboración con:

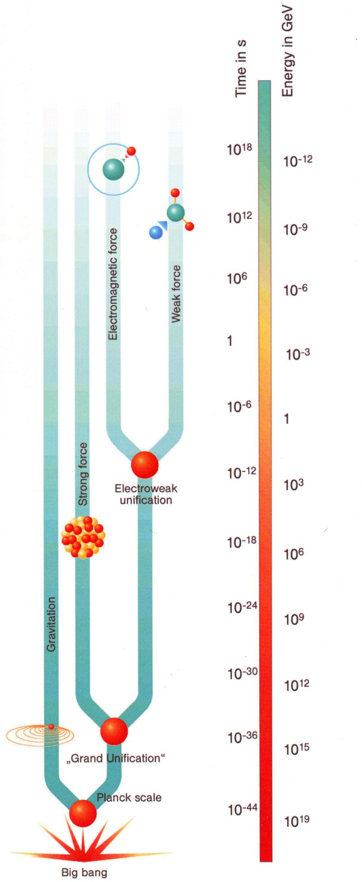
- Representantes en comités internacionales:

- RECFA (European Committee for Future Accelerators): Celso Martínez
- ApPEC (Astroparticle Physics European Consortium): Carlos Peña
- NuPPEC (Nuclear Physics European Collaboration): Joaquín Gómez
- Asesor en el Consejo del CERN Council: Nicanor Colino
- LDG (Large Particle Physics Laboratory Directors Group): Nicanor Colino (CIEMAT)

- Coordinadora de la subárea de Física de Partículas y Nuclear de la AEI: Pilar Hernández
- Coordinadores de las redes en las distintas áreas (red LHC, RENATA, COMCHA, FNUC, Futuros colisionadores, Instrumentación, etc).
- División Física Teórica y de Partículas de la RSEF: A. Dovado, M. Asorey, S. González.
- International Particle Physics Outreach Group: Jesús Puerta.

Objetivos científicos que perseguimos



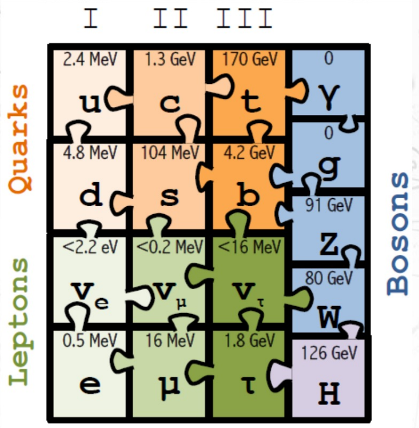


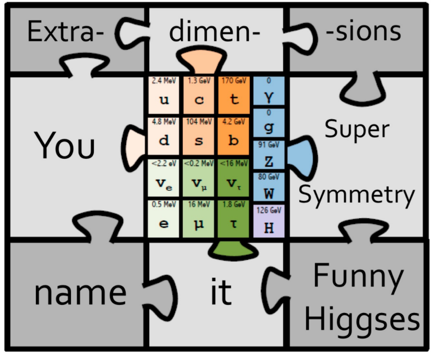
Fundamental laws of matter

- Standard Model of particle physics represents our best understanding of the fundamental components of matter and their interactions.

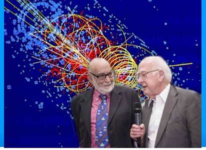
  Discovery of Higgs boson in 2012 major milestone (50 years after prediction!).
- Cannot be considered the ultimate theory.
- Cannot explain observed phenomena:
  - Dominance of matter vs antimatter in the Universe.
  - Nature of dark matter.
  - Non-zero neutrino masses.
- It does not include Gravity.

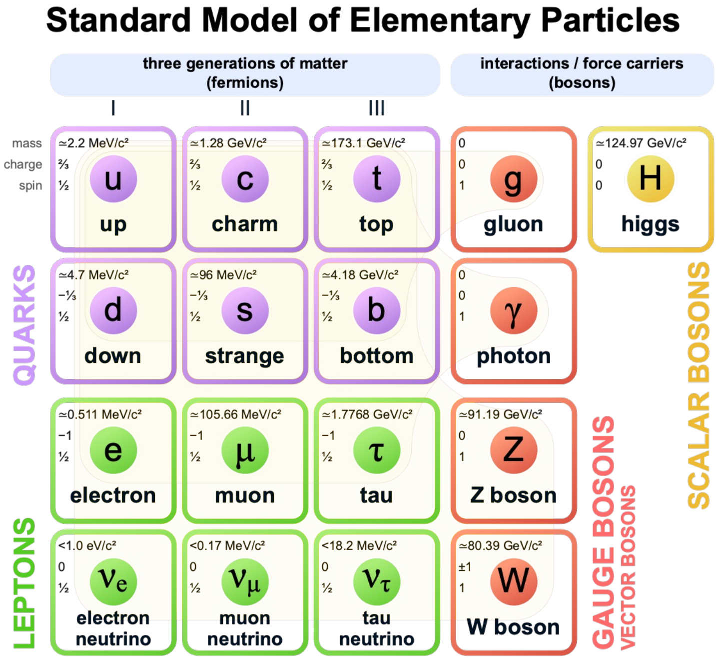
  Discovery of gravitational waves in 2016 (100 years after prediction!) opens a new observational doorway.

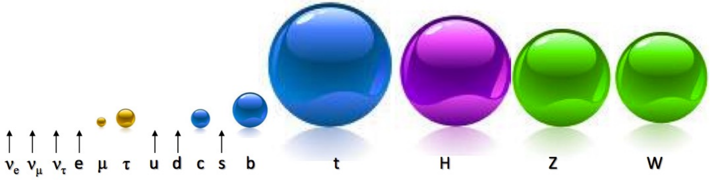




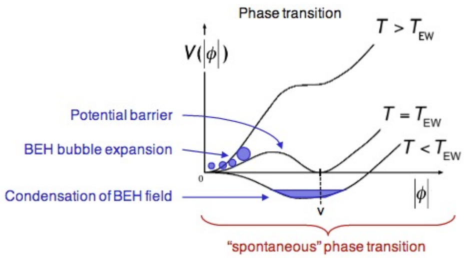
Origin of mass of elementary particles



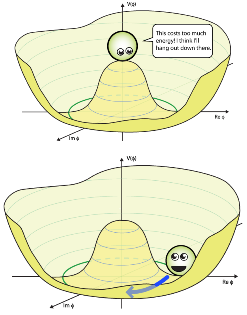


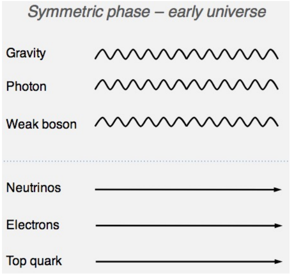


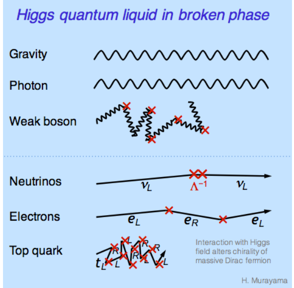
- The discovery of the Higgs boson at the LHC (no spin, no charge) represents the discovery of a **new and special interaction**.
- The Higgs mechanism provides the interaction that generates masses of elementary particles (**not clear for neutrinos**) through the spontaneous electroweak symmetry breaking (at T_{EW}, several 10^{-11} s after the big bang).



The Higgs field creates a ”vacuum viscosity”: Particles interact with the Higgs field and effectively reduce their velocity. Acquired mass proportional to interaction strength.

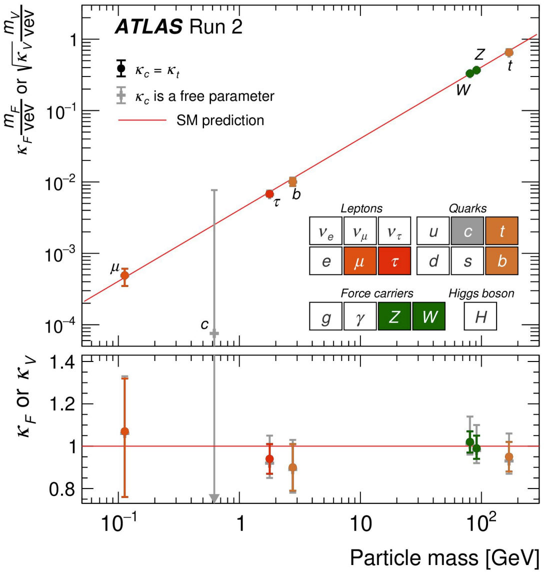


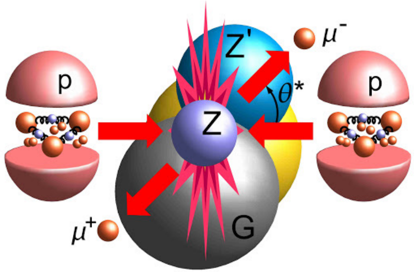


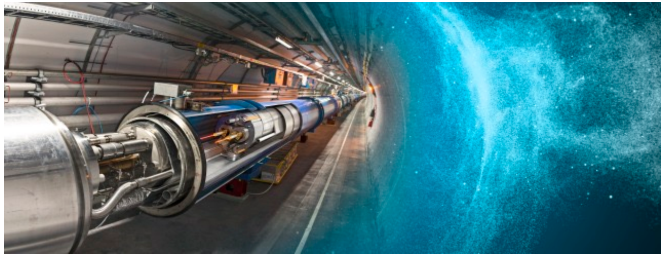


Study the new and unique Higgs force

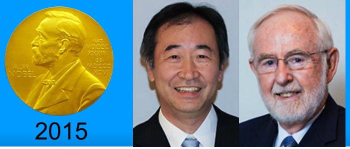
- Measurements of the Higgs boson properties confirm the picture of mass generation through spontaneous symmetry breaking.
- However, still ample room for interpretations within new theories beyond the Standard Model.
- **The Higgs sector remains a conceptual mystery**:
  - **Is it elementary or composite object?**
  - **Why is the Higgs so light?** (Higgs mass 125 GeV << Planck scale 10^{18} GeV) → Solution: alternative theories proposed (e.g. Supersymmetry) that predict the existence of new phenomena (particles, interactions, extra-dimensions) that could be produced at high energy colliders.



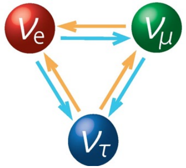




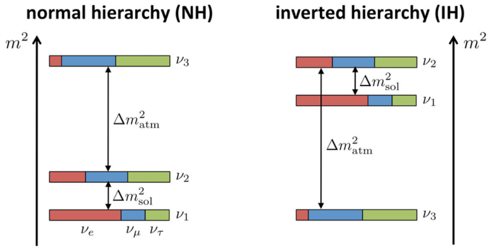
Origin of neutrino masses



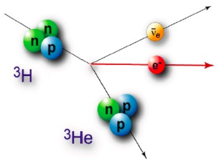
- Neutrinos are massive (confirmed by the observation of neutrino oscillations that determine Δm^2).
  - Current data prefers normal ordering (not conclusive).
- Absolute neutrino masses not yet measured.
  - Upper limits: 0.8 eV (KATRIN experiment), 0.12 eV (for the sum of neutrino masses, Cosmological observations).
- Nature of neutrinos: Are they Dirac or Majorana?
- What is the mechanism that generates neutrino masses?
  - Seesaw mechanism?
  - Are there sterile neutrinos?

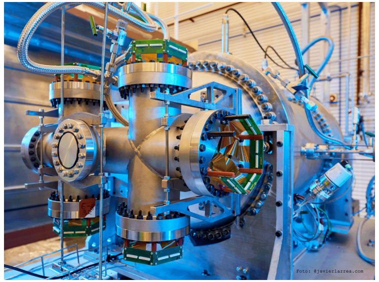


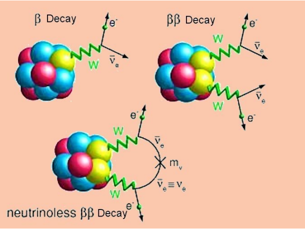
$$P_{\nu_\mu \nu_\tau} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4E_\nu}\right)$$



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





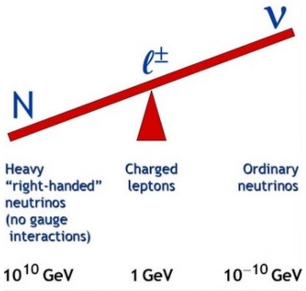


Beyond Standard Model process ($\Delta L = 2$)

$$(A, Z) \longrightarrow (A, Z+2) + 2e^-$$

Not yet observed: $T^{1/2}_{0\nu\beta\beta} > 10^{22\text{-}26}$ yr

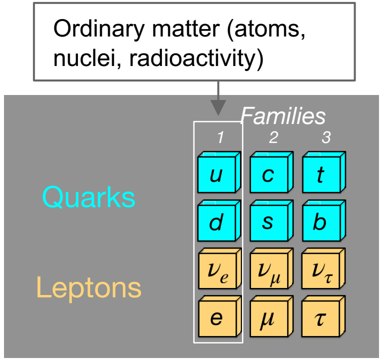
$T_{2\beta 2\nu} \sim 10^{18} - 10^{21}$ years



The flavour puzzle

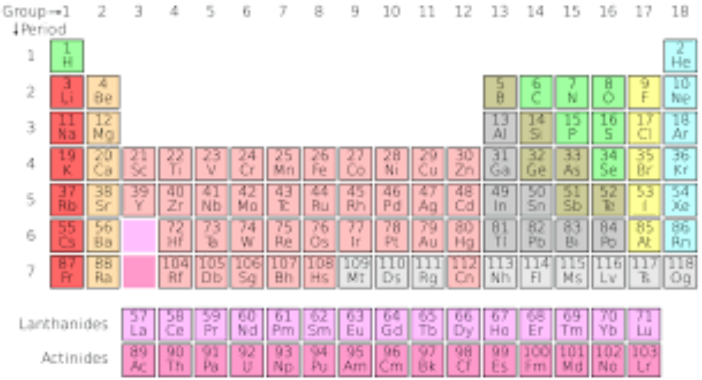
- **Symmetries are the key!** Dictate the dynamics of the system and the conserved quantities.
- The fermionic components of matter display an intriguing family structure not yet understood.
  - Why are there **3 families**?
  - What explains the **mysterious pattern of masses and mixings**?
  - Why do we observe flavour symmetries?
  - Why are they imperfect (=broken)?

Main challenge: Find the fundamental hidden symmetry behind this mysterious structure. This is known as the **flavour puzzle**



Ordinary matter (atoms, nuclei, radioactivity)

XXI century:
Discovery of the underlying structure behind the fermion families?



Group→ ↓Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Ms	116 Lv	117 Ts	118 Og
Lanthanides			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
Actinides			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

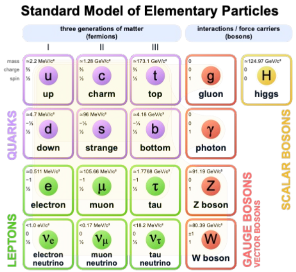
XIX century:
Discovery of the underlying structure behind the atoms

Gravity

2017

Two beautiful, extremely precise theories

but don’t work in regimes where both are important, i.e. at very small scales 10^{-35} m, 10^{18} GeV (Big bang, black hole)

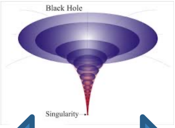


Standard Model of Elementary Particles

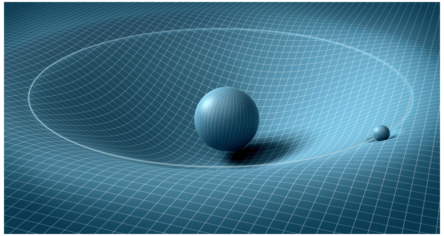
	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass charge spin	≃2.2 MeV/c^2 ⅔ ½ u up	≃1.28 GeV/c^2 ⅔ ½ c charm	≃173.1 GeV/c^2 ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c^2 0 0 H higgs
QUARKS	≃4.7 MeV/c^2 −⅓ ½ d down	≃96 MeV/c^2 −⅓ ½ s strange	≃4.18 GeV/c^2 −⅓ 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	
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	≃80.39 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS VECTOR BOSONS

The **Standard Model** of electroweak and strong interactions

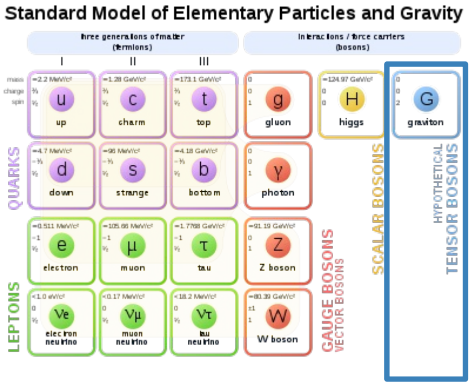
- Quantum mechanics and special relativity.



General relativity theory of gravitation

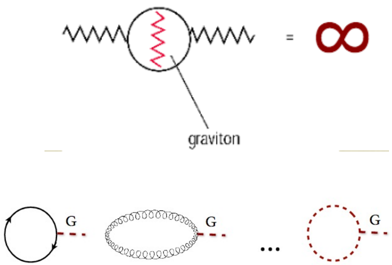


Quantum Gravity (the challenge)



Standard Model of Elementary Particles and Gravity

	three generations of matter (fermions)			interactions / force carriers (bosons)		
	I	II	III			
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	0 0 2 G graviton
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	HYPOTHETICAL TENSOR 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		
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	≃80.39 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS VECTOR BOSONS	



Issues:

- Infinities that cannot be handled via measurements.
- Large discrepancy (10^{120}) with the observed cosmological constant (vacuum energy density).

New capability to detect gravitational waves and take images of black holes opens a golden era: Theory meets observations.

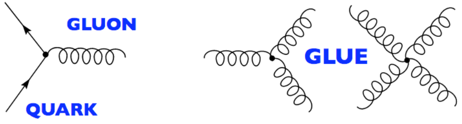
Solving Quantum Chromodynamics

- QCD: Quantum Field Theory that describes the strong force between quarks and gluons.

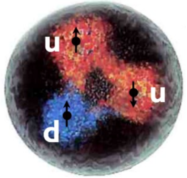
QCD

QUANTUM
CHROMO
DYNAMICS

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}\,(i\gamma_\mu \mathcal{D}^\mu - \mathbf{m})\,\psi - \frac{1}{4}\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}$$



$$\mathbf{u+u+d=proton}$$
$$\mathbf{m_u \simeq 3\,MeV}$$
$$\mathbf{m_d \simeq 5\,MeV}$$
$$\mathbf{3+3+5 \neq 938}\ \ !$$

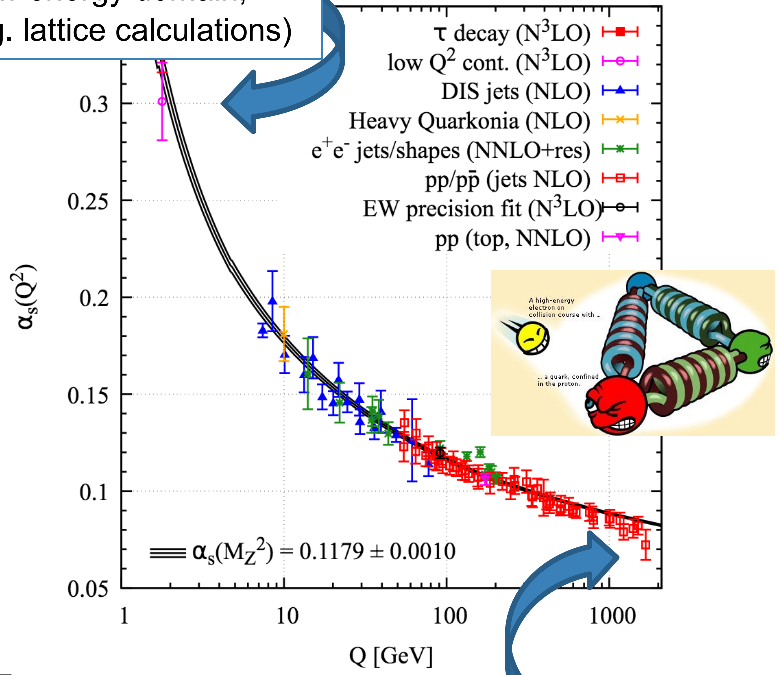


... mostly
GLUONIC
field energy
$$\mathbf{M = E/c^2}$$

A formal analytical solution of QCD is a key challenge for both physics and mathematics.

A deep understanding of the complex phenomena encompassed by the theory of the strong interactions will have a major impact on particle physics, nuclear physics, astrophysics and cosmology.

Confinement
“Hot and dense QCD”
(low energy domain,
e.g. lattice calculations)

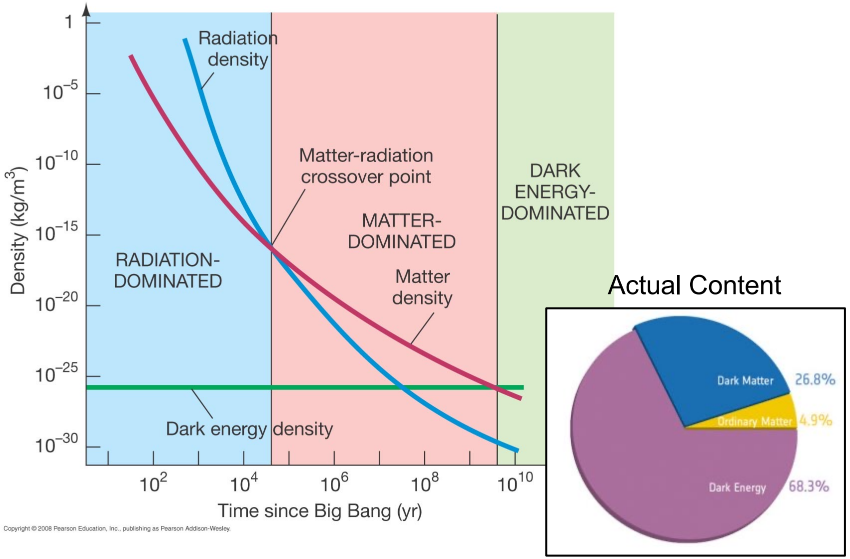


Asymptotic freedom
“Vacuum QCD”
(high energy domain, perturbative calculations)

Origin and fate of the Universe

- The Standard Model of Cosmology (ΛCDM) describes how the universe has changed over cosmic time.
- The model assumes General Relativity and can describe data well with three components:

- Cosmological constant (Λ) associated to dark energy
- Dark matter
- Ordinary matter



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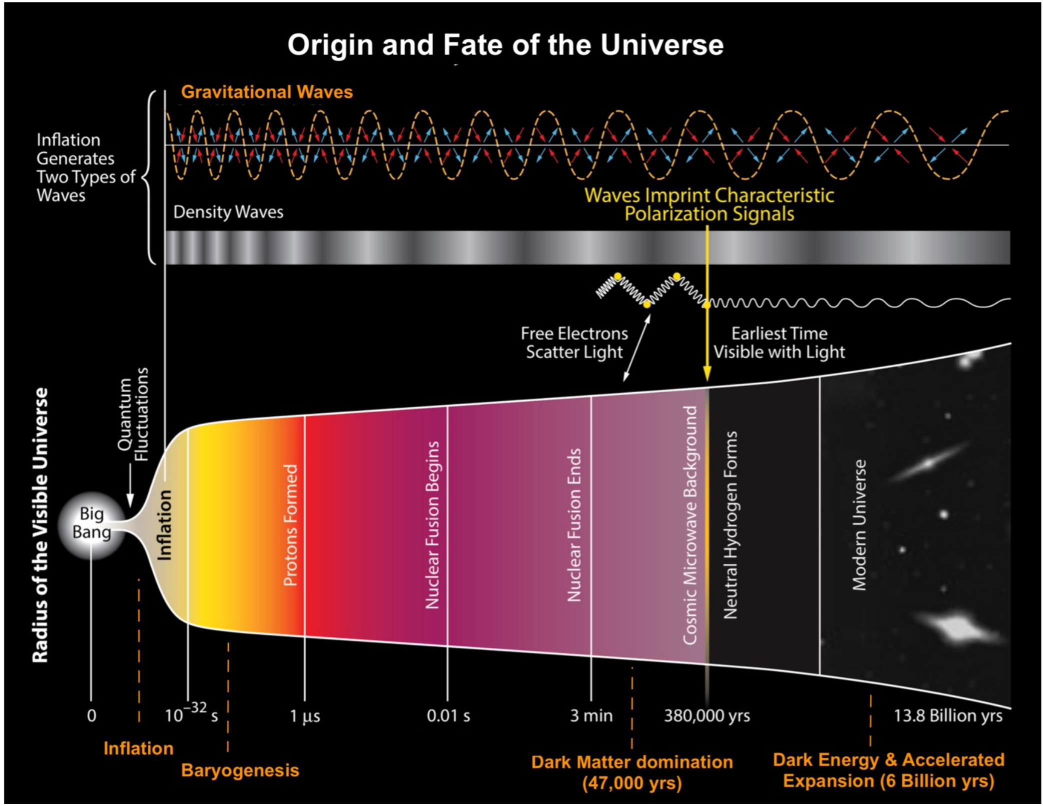
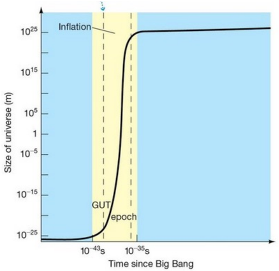


Unresolved puzzles and challenges

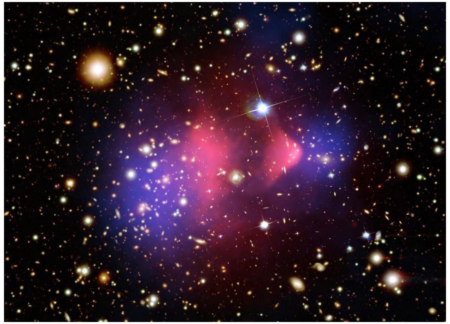
Find evidence for Cosmic Inflation

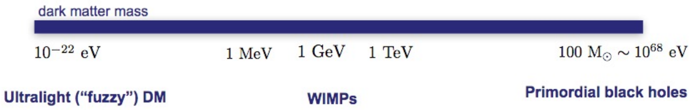
Theory of exponential expansion in early Universe. Quantum fluctuations of the inflaton field become seeds of the cosmic web.



Dark Matter

- Nature completely unknown.
- Enormous variety of candidates and experiments.

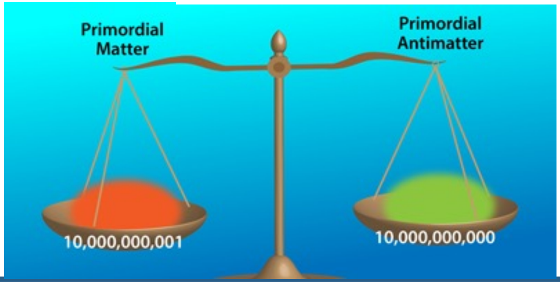




Absence of anti-matter in our Universe

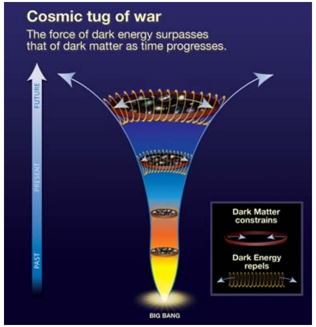
What are the processes that produced this asymmetry (after inflation and before nucleosynthesis).

After Planck: $\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.21(16) \times 10^{-10}$



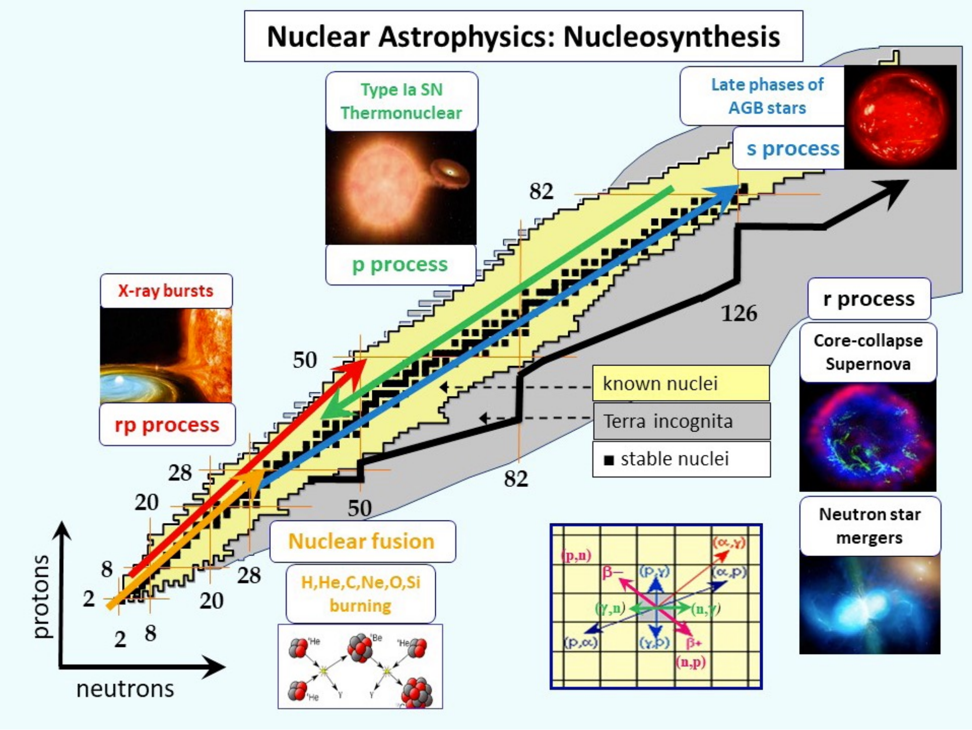
Dark Energy (Cosmic accelerated expansion)

- Nature completely unknown.
- Candidates: Cosmological constant, fields with varying energy densities, modifications of General Relativity.

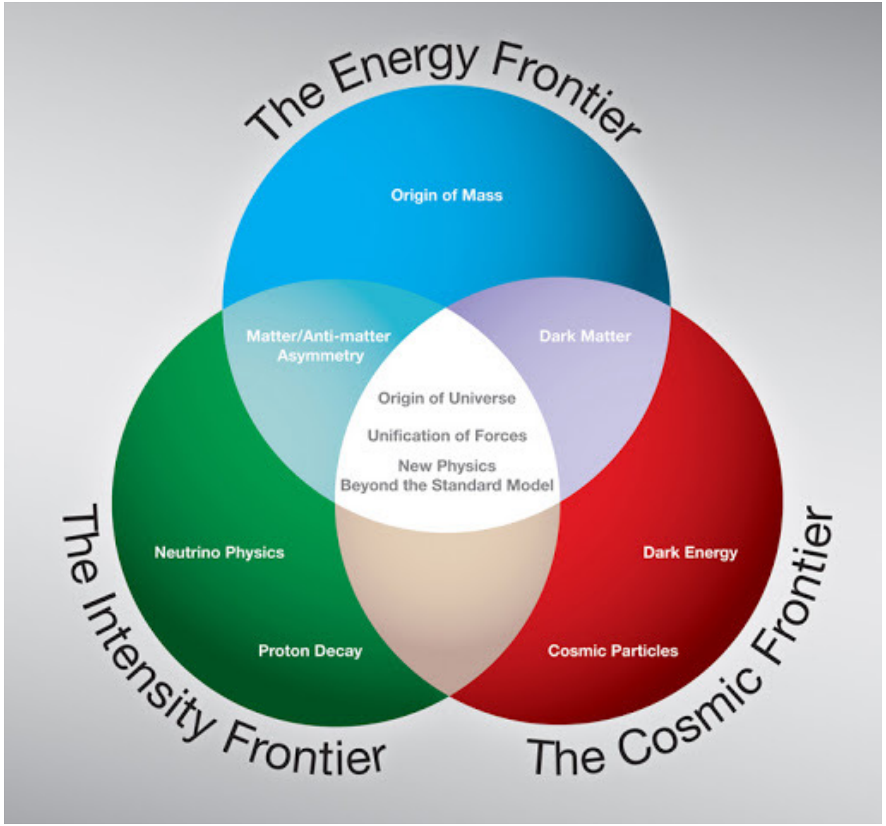


Origin of elements in the Universe

- Nuclear fusion in stars converts light elements into heavier nuclei up to the iron region.
- Nuclei beyond iron are basically produced by a variety of neutron-capture processes.
- Nuclear physics is a crucial ingredient for understanding of the evolution and explosion of stars and of the chemical evolution of the Universe.
- Many properties of the nuclei involved in nucleosynthesis processes (s, r, p, rp), such as masses, weak-interaction rates and nuclear reaction rates, have not yet been determined with enough precision.
- A significant push in this direction is expected with data from high intensity radioactive-beam and neutron-beam facilities.



How do we reach the scientific objectives?



- To address these fundamental questions, a multi-pronged approach with a variety of experiments, a world-wide effort and long time scales are needed.
  - **World-wide** large international collaborations and facilities (such as CERN), use of ICTS and ESRI infrastructures.
  - **Long time scales** to design, build and exploit telescopes, accelerator, reactor and underground experiments.
  - Fundamental physics also requires **technological revolutions and theoretical developments**.

The Spanish CPAN groups are contributing to this world-wide effort from both the theoretical as well as experimental side with physicists, engineers and technicians.

Research lines and human resources

LÍNEAS DE INVESTIGACIÓN DE LA AGRUPACIÓN CPAN

Física teórica:

- Aspectos formales de teoría cuántica de campos
- Fenomenología en física de partículas elementales
- Teoría de estructura y reacciones nucleares
- Relatividad General, Cosmología y Astropartículas

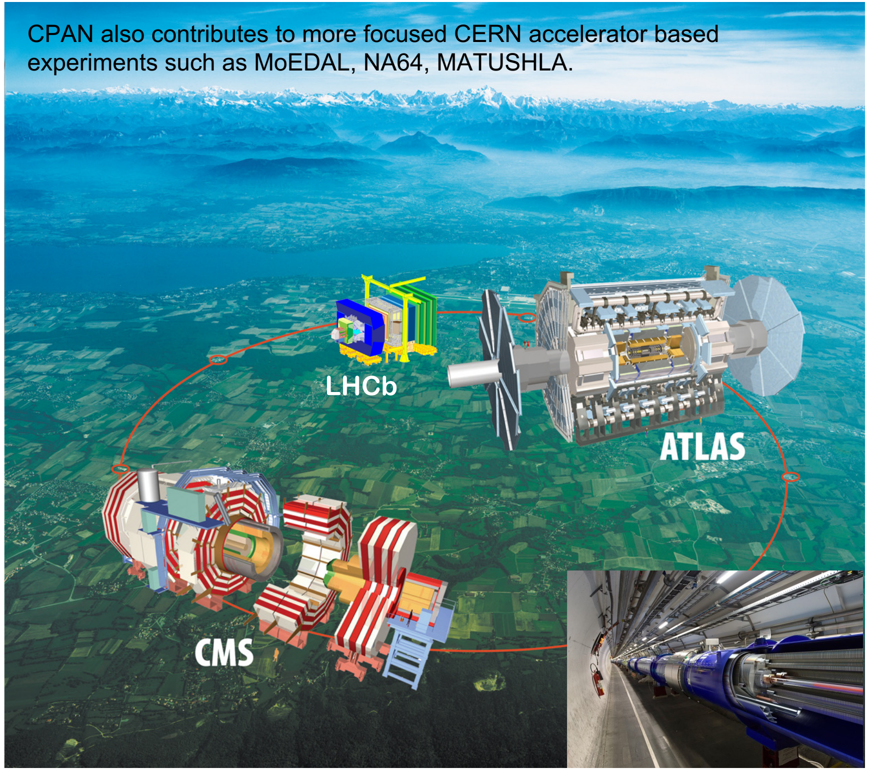
Física experimental:

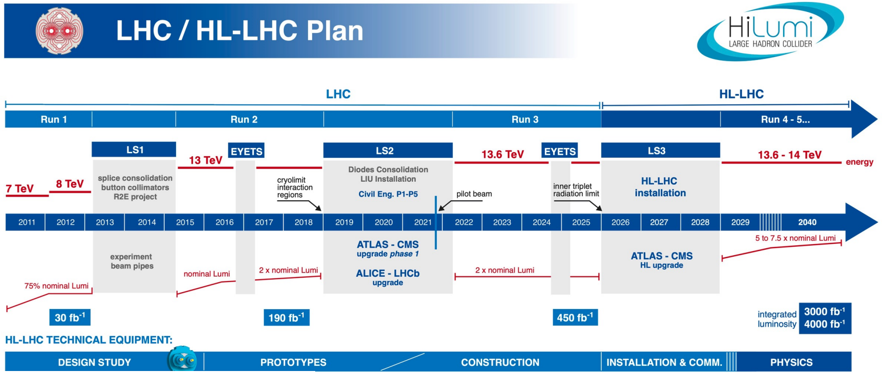
- Experimentos de física de partículas en colisionadores
- Experimentos de neutrinos
- Telescopios de neutrinos, rayos gamma y rayos cósmicos
- Cosmología Observacional
- Experimentos de ondas gravitacionales
- Física nuclear experimental
- Aplicaciones

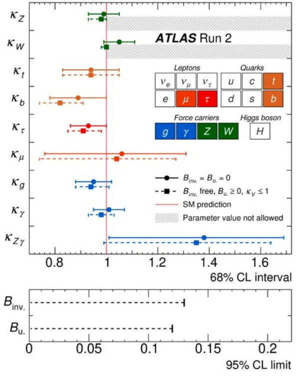
Alrededor de 1450 físicos, ingenieros y técnicos distribuidos en los 28 nodos del CPAN

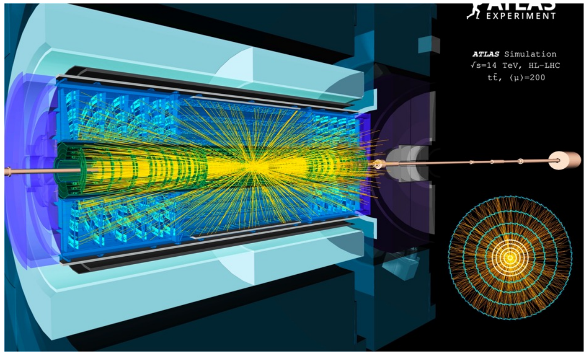
Collider based experiments: The LHC and future colliders

CPAN also contributes to more focused CERN accelerator based experiments such as MoEDAL, NA64, MATUSHLA.









- LHC has already operated for 15 years (since 2009) (produced 10M Higgs bosons so far). Only 2 more years to completion of the LHC program.
- Still, ~20 times more statistics expected at HL-LHC (2029-2041) (detector upgrades required, a reconstruction challenge).

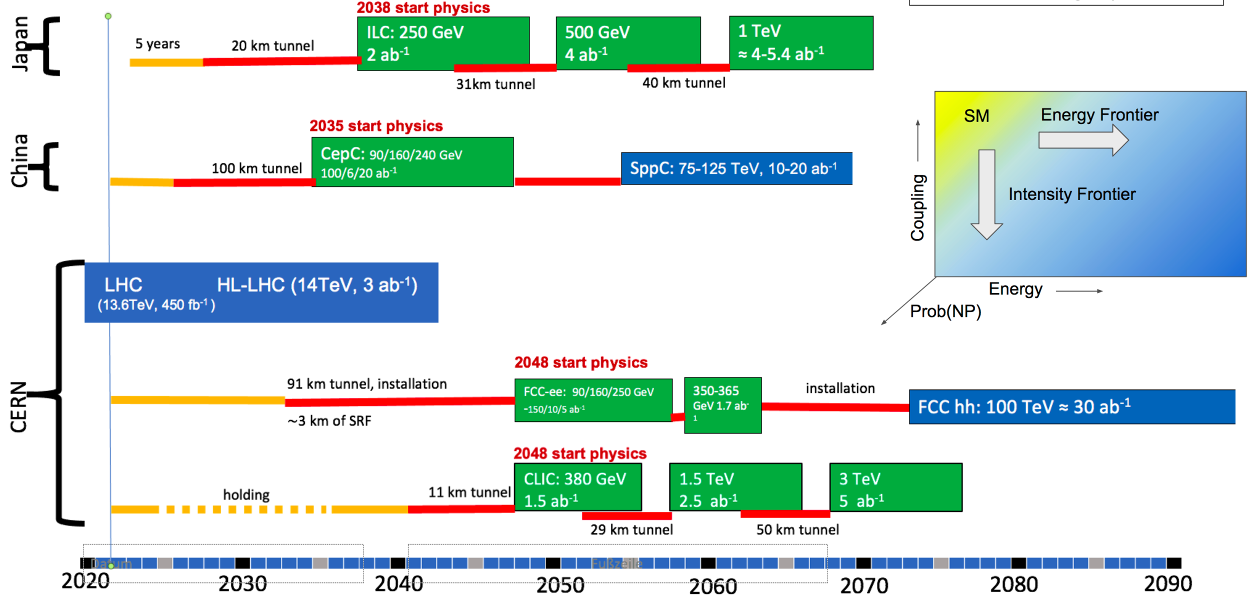
Collider based experiments: The LHC and future colliders

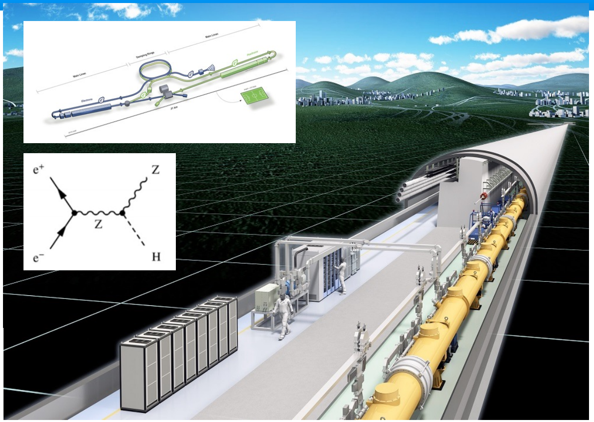
Indicative scenarios of future colliders [considered by ESG]

🟦 Proton collider
🟩 Electron collider
🟧 Muon collider

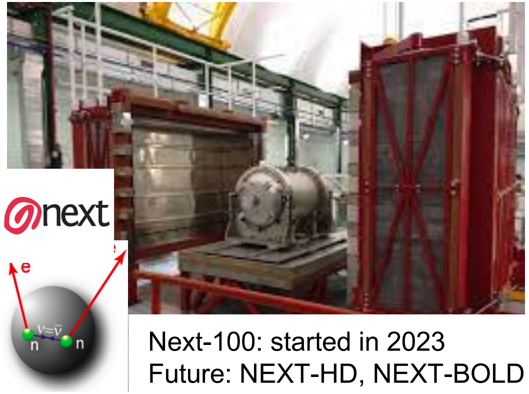
🟥 Construction/Transformation
🟨 Preparation / R&D

Original from ESG by Urusla Bassler
Updated July 25, 2022 by Meenakshi Narain
Corrected FCC tunnel length, by F.Z.





Neutrino experiments



Neutrino-less double beta decay experiment

Next-100: started in 2023
Future: NEXT-HD, NEXT-BOLD

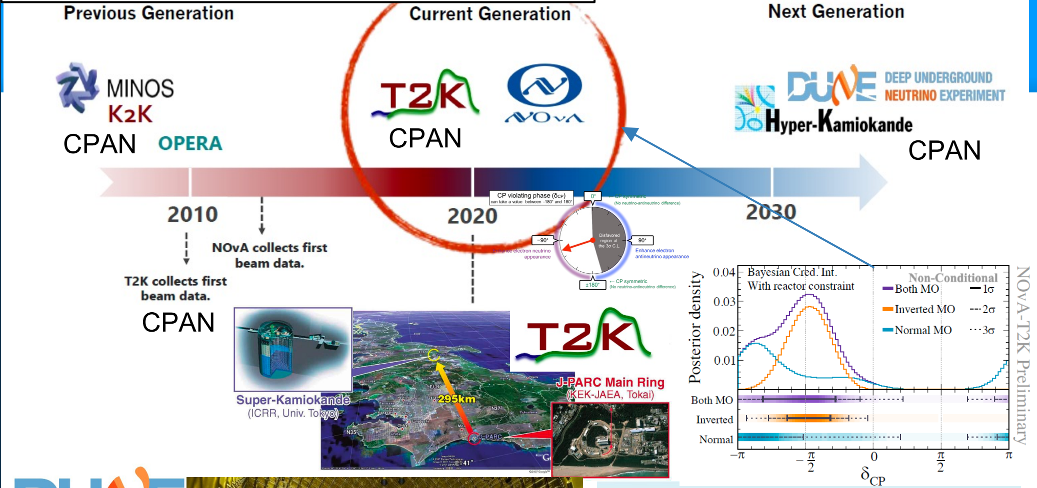
LSC
Laboratorio Subterráneo de Canfranc

(Short-baseline) reactor experiments

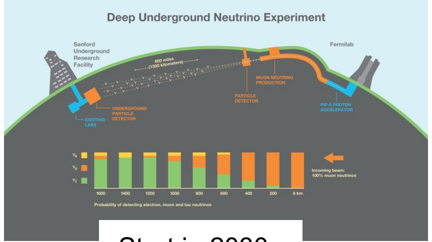
DOUBLE CHOOZ

(2011-2018)

Long-baseline accelerator experiments

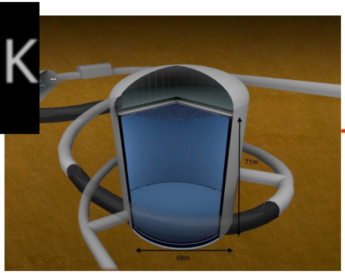


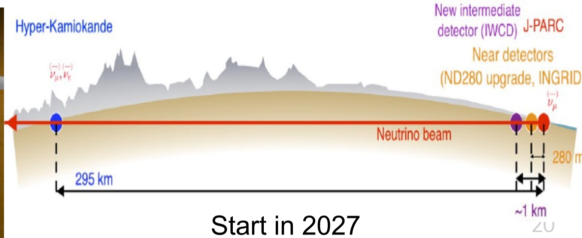
DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT



Start in 2030

T2HK

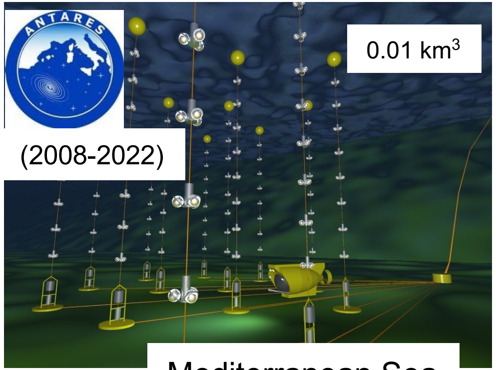




Start in 2027

Telescopes (neutrinos, gamma rays, cosmic rays)

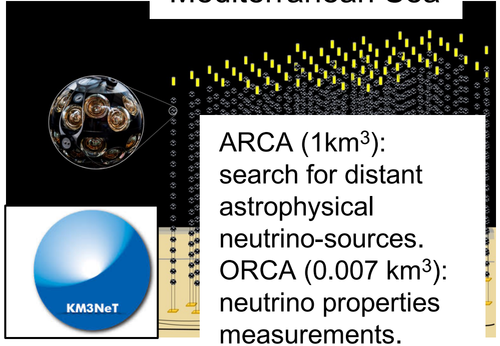
Neutrino telescopes



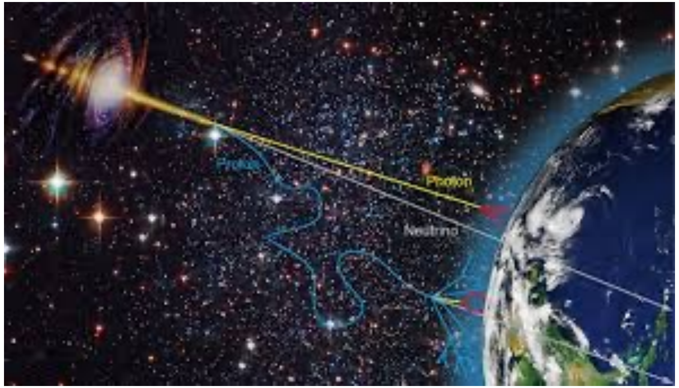
0.01 km^3

(2008-2022)

Mediterranean Sea

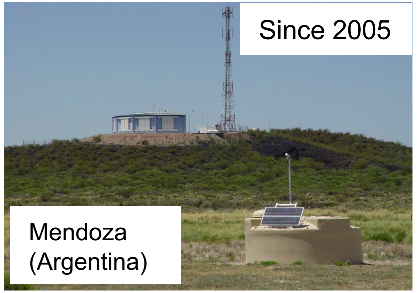


ARCA (1km^3): search for distant astrophysical neutrino-sources.
ORCA (0.007 km^3): neutrino properties measurements.



Cosmic-rays

PIERRE AUGER OBSERVATORY

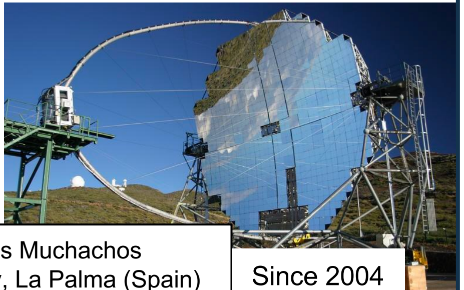


Since 2005

Mendoza (Argentina)

γ-rays

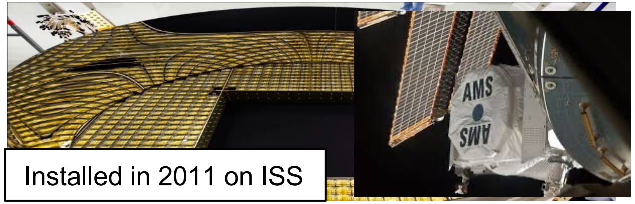
MAGIC



Roque de los Muchachos Observatory, La Palma (Spain)

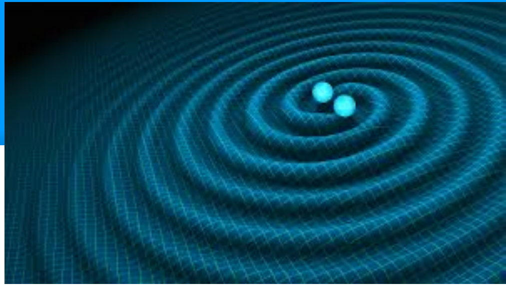
Since 2004

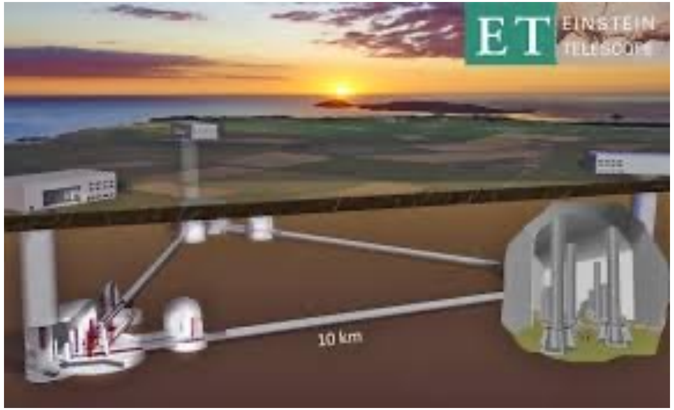
Roque de los Muchachos Observatory, La Palma (Spain)

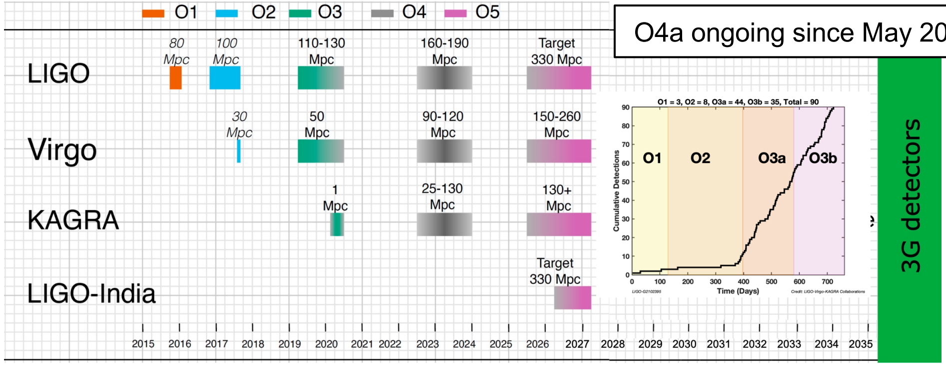


Installed in 2011 on ISS

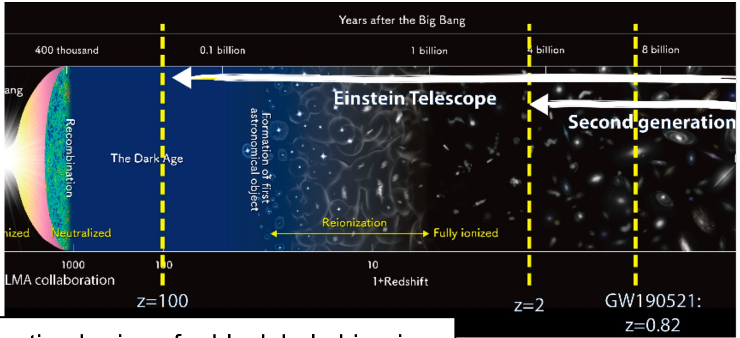
Gravitational wave experiments







O4a ongoing since May 2024



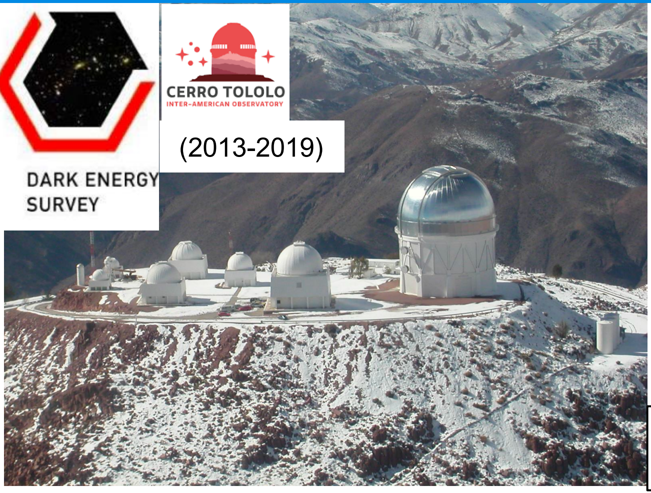
Detection horizon for black hole binaries

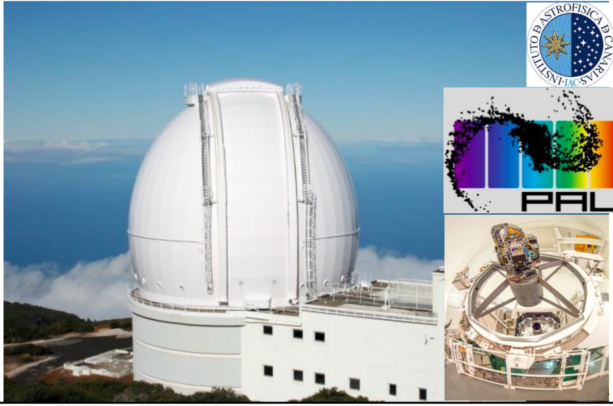
Cosmological observations: Galaxy surveys

DARK ENERGY SURVEY

CERRO TOLOLO
INTER-AMERICAN OBSERVATORY

(2013-2019)



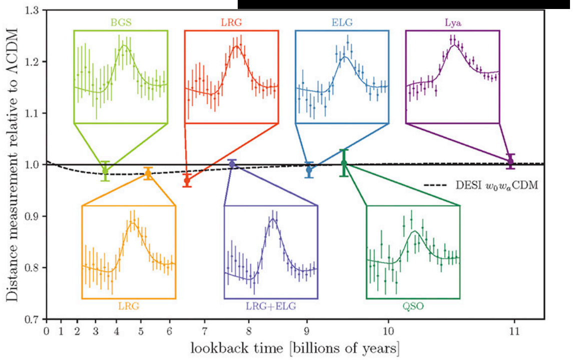


PAU

PAUCam at William Hershel Telescope, Observatorio del Roque de los Muchachos, La Palma

First results

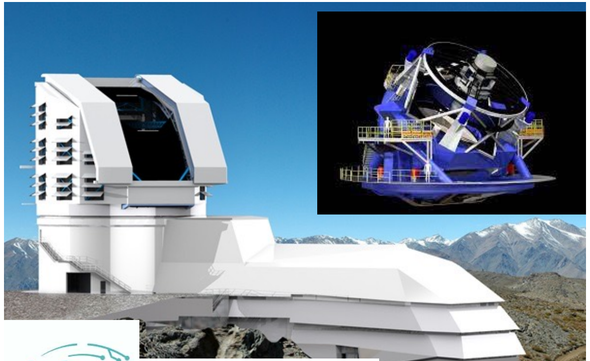
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science



DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

KITT PEAK
NATIONAL OBSERVATORY

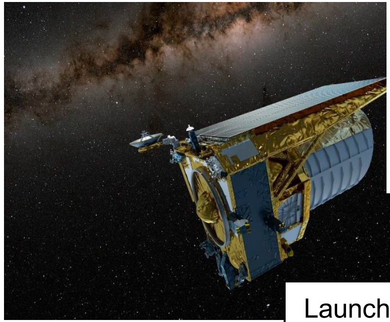
Since 2021



VERA C. RUBIN OBSERVATORY

LSST
Large Synoptic Survey Telescope

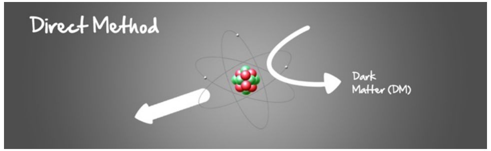
Start in 2025



esa
euclid

Launched in 2023
First cosmological results expected in 2026

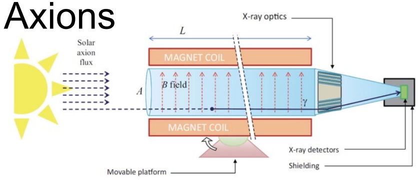
Dark matter direct detection and axion experiments



(2017-2025)

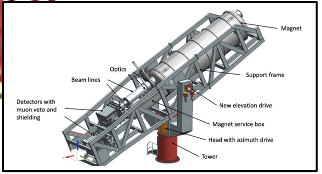
TREX-DM

Axions



RADES in CAST@CERN

BabyIAXO prototype
(Start in 2028)

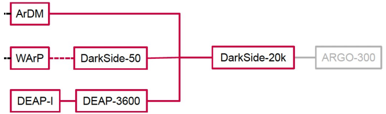


Global Argon DM Collaboration

Since 2016

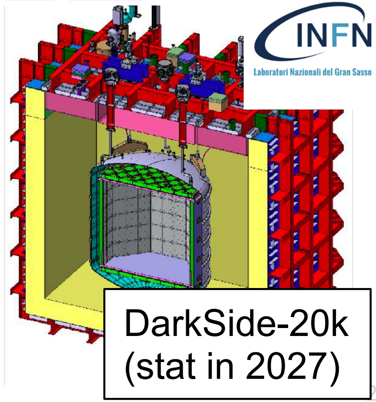
DarkSide-50

(2013-2020)



ArDM
WArP
DarkSide-50
DarkSide-20k
ARGO-300
DEAP-I
DEAP-3600

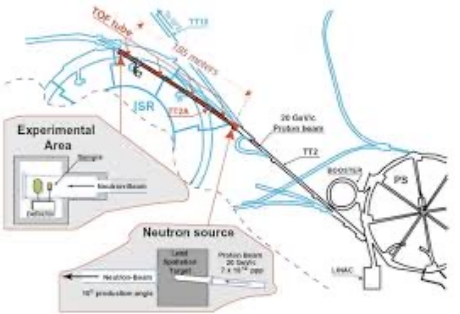
DART

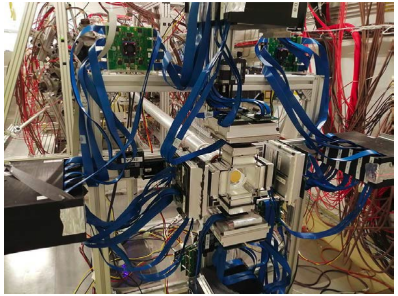


DarkSide-20k
(stat in 2027)

Nuclear physics experiments

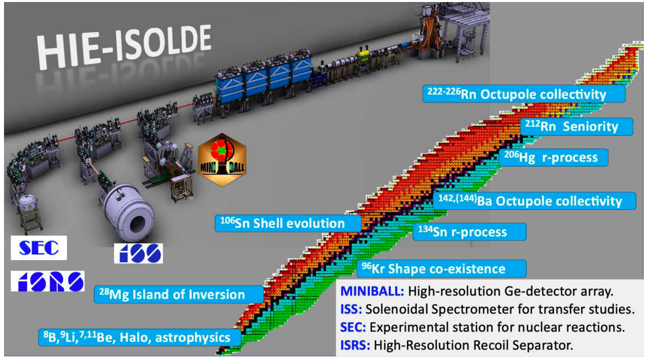
World brightest neutron source





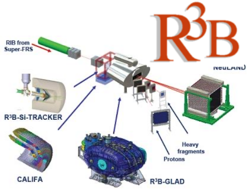
i-TED array of 4 Compton cameras installed at nTOF for the measurement of the 79Se(*n*, γ) cross section.

Source of low-energy beams of radioactive nuclides



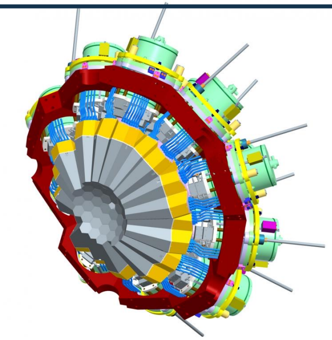
MINIBALL: High-resolution Ge-detector array.
ISS: Solenoidal Spectrometer for transfer studies.
SEC: Experimental station for nuclear reactions.
ISRS: High-Resolution Recoil Separator.

FAIR — Facility for Antiproton and Ion Research in Europe



NUSTAR Collaboration is devoted to study of NUclear STructure, Astrophysics, and Reactions using beams of radioactive species.

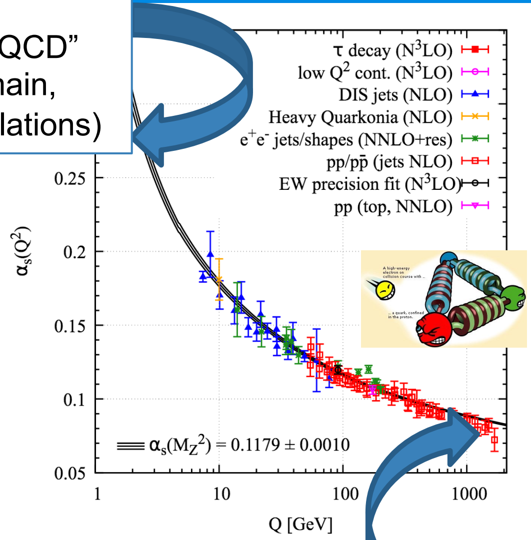
The Advanced GAmma Tracking Array (AGATA) is a European gamma-ray spectrometer

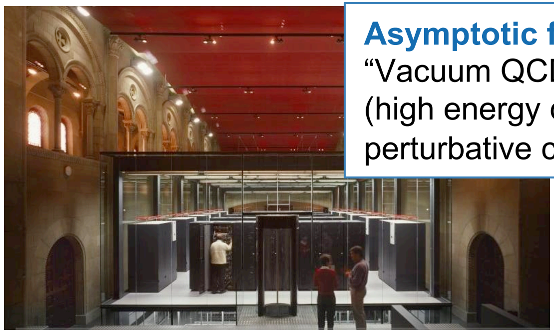


Used in experiments utilising both intense stable and radioactive ion beams, to study the structure of atomic nuclei at the limits of their stability.

Theoretical developements – Example for solving QCD

Confinement
“Hot and dense QCD”
(low energy domain,
e.g. lattice calculations)

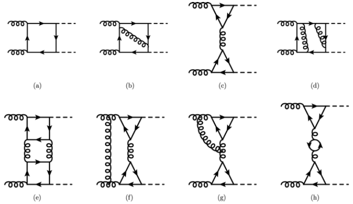




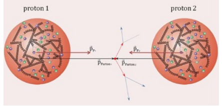
Asymptotic freedom
“Vacuum QCD”
(high energy domain,
perturbative calculations)

Ex: Perturbative theory (at high energy): Expansion in powers of $\alpha_s \ll 1$, using Feynman diagrams (many integrals to solve!)

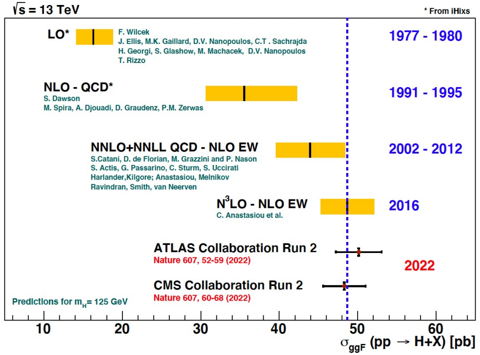
$$f = f_0 + \alpha_s f_1 + \alpha_s^2 f_2 + \alpha_s^3 f_3 + \ldots$$

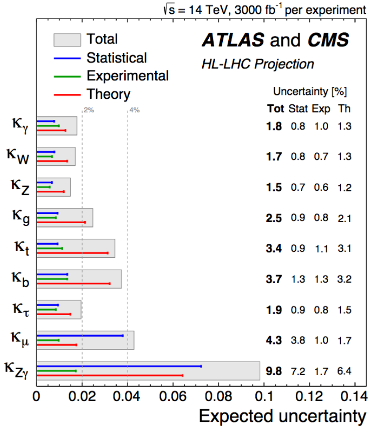


Ex: Impact on precision of Higgs properties determinations at the HL-LHC proton-proton collider



Half a century of progress in Higgs production theory predictions!





Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

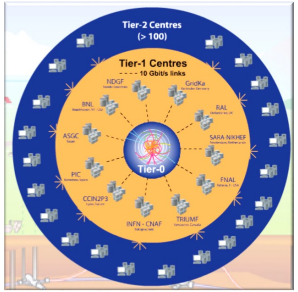
Expected measurements dominated by QCD theoretical uncertainties (even assuming a 50% improvements)

New instrumentation, techniques and computing

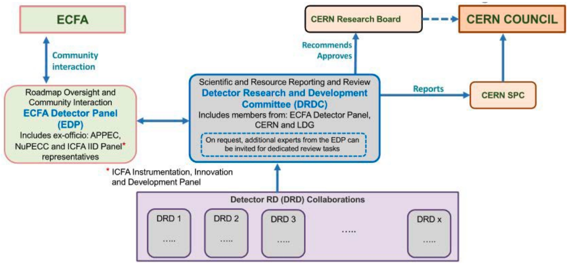
- Challenges in physics come together with challenges in the development of tools for measurement.
  - Accelerators
  - Sensors for particle detection.
  - Readout electronics & data acquisition systems
  - Intelligent filtering in real time
  - Mechanical structures
  - Computing
- New detector R&D collaborations being set-up at CERN

  Gaseous, Liquid detectors, photodetectors & particle ID, Calorimetry, Semiconductor detectors, Quantum sensors, Electronics and Integration.

World-wide LHC Computing GRID



New detector R&D Collaborations at CERN


ECFA

Community interaction

Roadmap Oversight and Community Interaction
ECFA Detector Panel (EDP)
Includes ex-officio: APPEC, NuPECC and ICFA IID Panel*
representatives

* ICFA Instrumentation, Innovation and Development Panel

CERN Research Board

CERN COUNCIL

Recommends
Approves

Scientific and Resource Reporting and Review
Detector Research and Development Committee (DRDC)
Includes members from: ECFA Detector Panel, CERN and LDG

On request, additional experts from the EDP can be invited for dedicated review tasks

Reports

CERN SPC

Detector RD (DRD) Collaborations

DRD 1 ..... DRD 2 ..... DRD 3 .... DRD x .....

Access to international and national infrastructures (e.g. CERN, national ICTS)

Centro Nacional de Aceleradores (CNA)

International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source

IFMIF DONES GRANADA

Laboratorio Subterráneo de Canfranc (LSC)

Sala Blanca Integrada de Micro y Nano Fabricación del CNM

Applications in society, industry or other fields

- Based on technologies and techniques developed for particle, astroparticle and nuclear physics, a significant effort is put on applications impacting society, industry or other fields.
- A major activity is focused on medical applications.

IV Jornadas RSEF / IFIMED de Física Médica

29 November 2023 to 1 December 2023
CNA, Sevilla
Europe/Madrid timezone

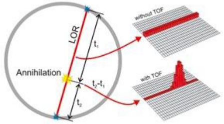
Estas jornadas de Física Médica, organizadas por la Real Sociedad Española de Física y el IFIC a través de la instalación de Física Médica IFIMED del IFIC, tienen el objetivo de favorecer el contacto entre profesionales de diversas ramas que trabajan en este campo (imagen médica, radioterapia, física de la visión, etc), tanto de la universidad y centros de investigación como hospitales, empresas, etc.

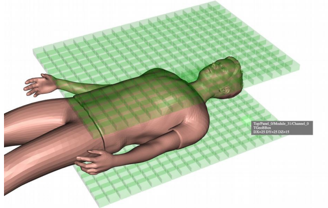
Medical Imaging

TOF-PET

PET VISION

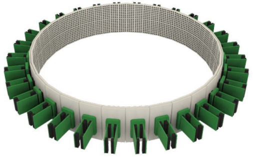
Funded by the European Union



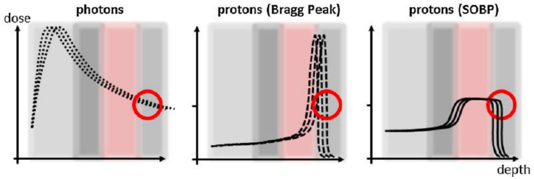


Total Body PET (affordable approaches)

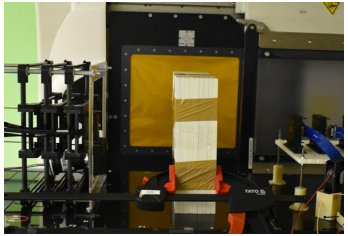
PETALO: liquid Xenon + SiPMs – continuous volume



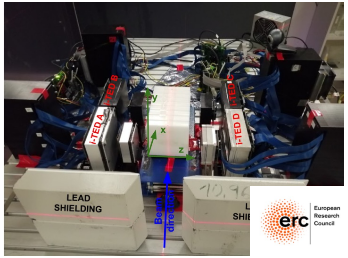
Hadron therapy monitoring



Prompt gamma imaging with Compton Camera: MACACO with LaBr3 detectors



PET-Compton combination



erc European Research Council

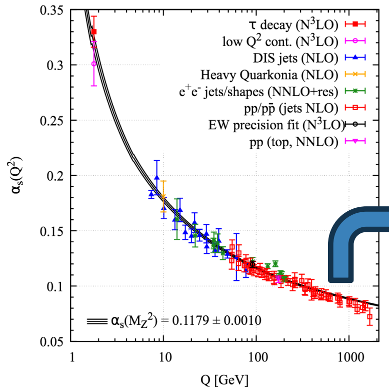
XVI Jornadas CPAN

Universidad Complutense de Madrid (UCM)
Madrid, 19-21 de noviembre.

The CPAN Days in Madrid will be the next occasion for the full community to meet and discuss about the status of our diverse and complementary research activities as well as about coordinated future strategies.

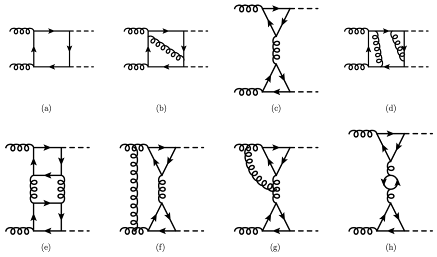
Backup

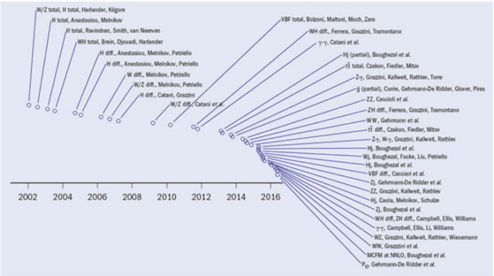
Theoretical developements – Example for solving QCD



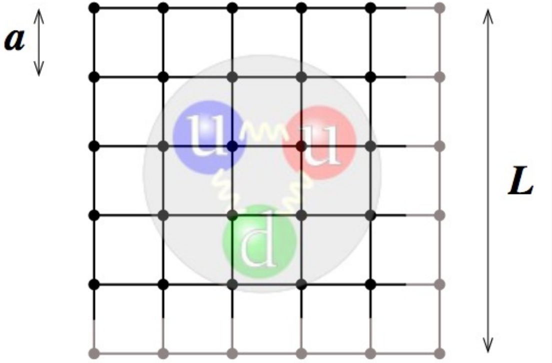
Ex: Perturbative theory (at high energy): Expansion in powers of α_s << 1, using Feynman diagrams (many integrals to solve!)

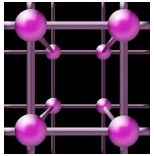
$$f = f_0 + \alpha_s f_1 + \alpha_s^2 f_2 + \alpha_s^3 f_3 + \dots$$

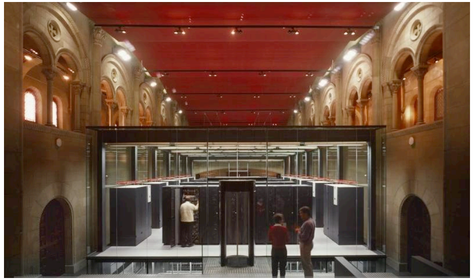




Ex: Lattice (at lower energies): discretization of QCD on a space-time lattice using numerical methods.







Flavour mixing

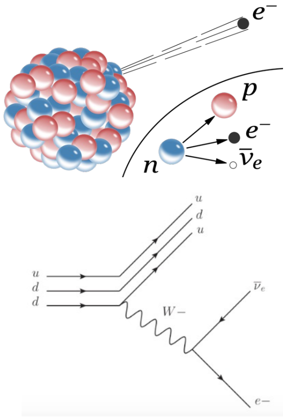

2008

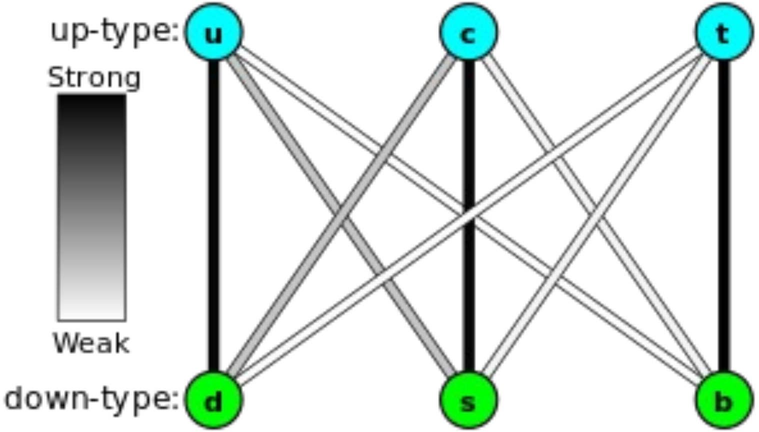
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

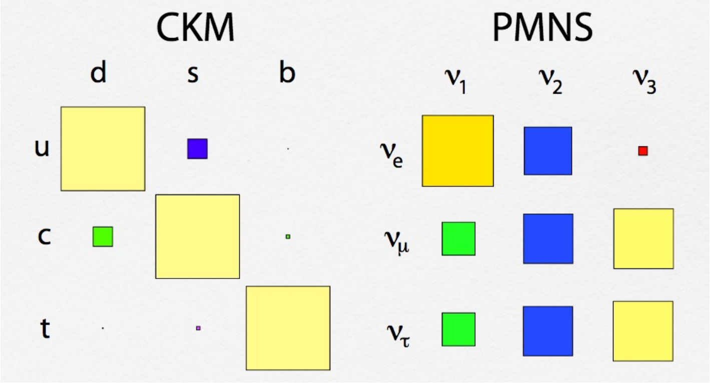
weak eigenstates

Cabibbo Kobayashi Maskawa (CKM) matrix

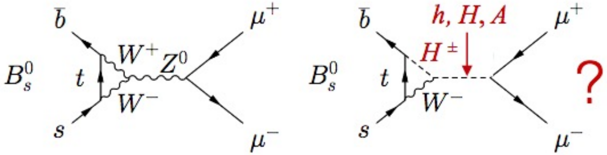
mass eigenstates







- Why is the flavour mixing so different in the quark and lepton sector?
- Rare decays are very sensitive to the presence of new physics at energies beyond the collider reach.



$B_s \to \mu\mu$ is loop process (no tree-level FCNC) that is in addition CKM & helicity suppressed

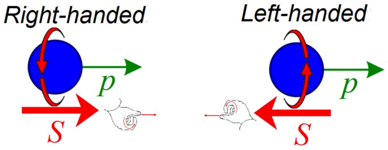
SM: $3.7 \pm 0.2 \times 10^{-9}$

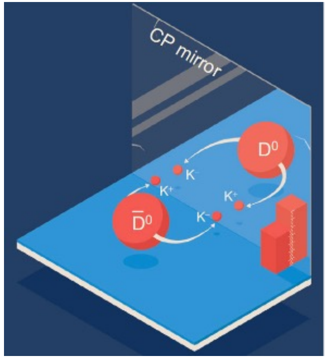
Symmetries

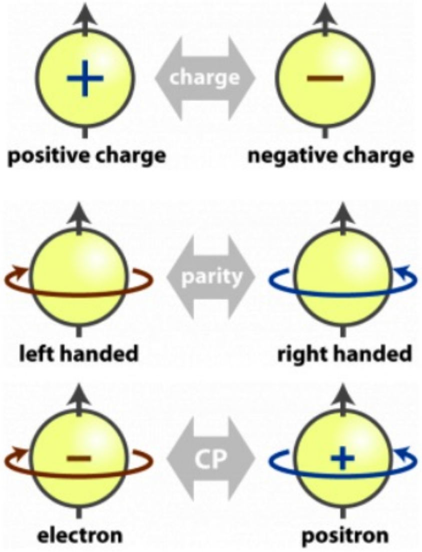
Symmetry under operator ↔ Conservation of a quantum number


2008

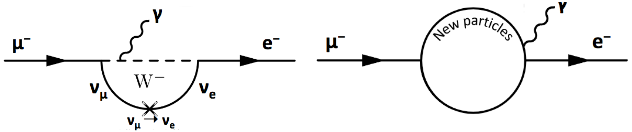
- CP is (a bit) broken in the weak interactions due to the 3-fold matter replication structure
  - Key to understand the matter-antimatter asymmetry
- Why is CP apparently conserved in the strong interactions?
  - Axions? (also a dark matter candidate)
- Are baryon and lepton number exact symmetries?
  - Unification of fundamental interactions may imply the breaking at some high-energy scale.
- Why left and right-handed particles behave differently?



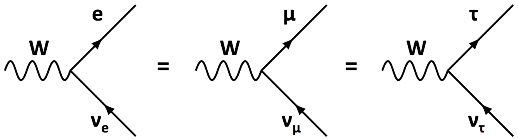




Searches for Lepton Flavour Violation:
Highly suppressed in SM: < $1/10^{50}$

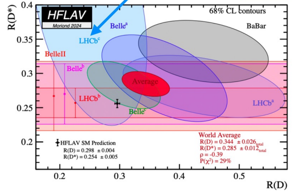


Lepton Universality probes: weak interactions act equally regardless of lepton flavour (Pillar of the Standard Model, deviations observed at LHC).



This result
[LHCb preliminary]

[NEW!]
[HFLAV]



New World Average.
Tension with SM at the level of **3.17 σ**.

Impact of solving QCD

used in experiment (applications)

“confined” hadrons & ions

Equation-of-State

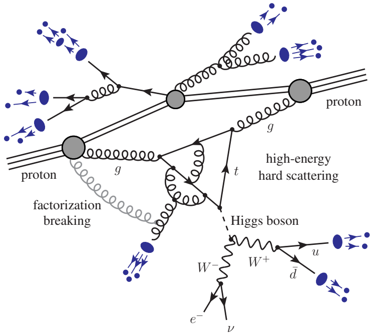
PDFs

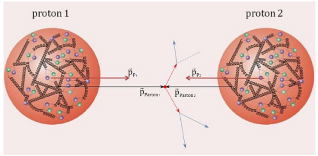
used in Lagrangian (first principles)

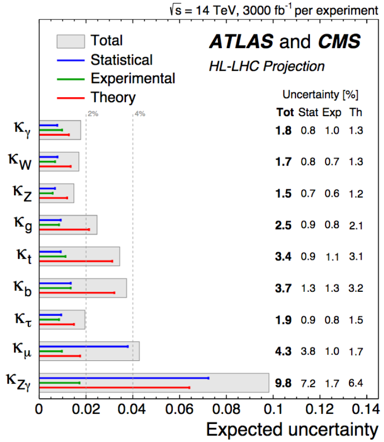
“deconfined” quarks & gluons

- **Precision tests of the Standard Model towards revealing new laws of physics**
- Extreme environments: heavy ion collisions, neutron stars and early Universe.

Ex: Higgs properties expected predictions at HL-LHC





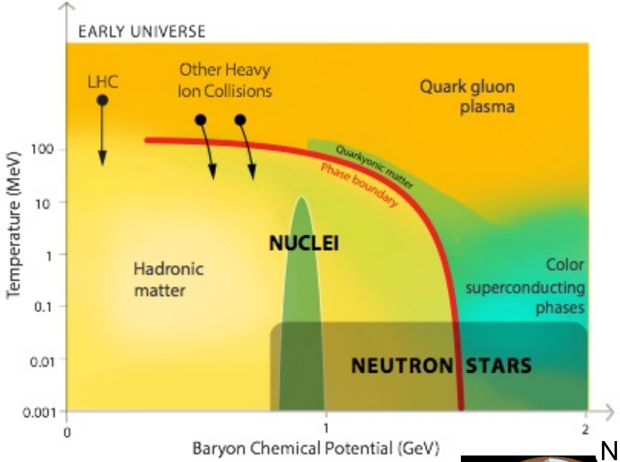


Expected measurements dominated by QCD theoretical uncertainties (even assuming a 50% improvements)

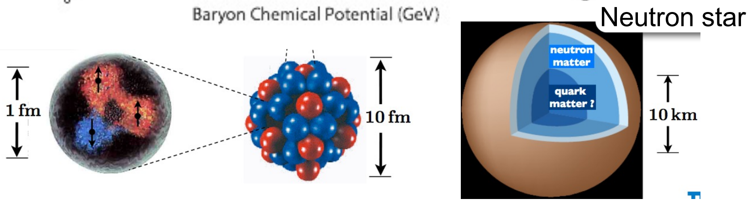
A deep understanding of the complex phenomena encompassed by the theory of the strong interactions will have a major impact on particle physics, nuclear physics, astrophysics and cosmology.

Impact of solving QCD

- Precision tests of the Standard Model towards revealing new laws of physics
- **Extreme environments: heavy ion collisions, neutron stars and early Universe.**



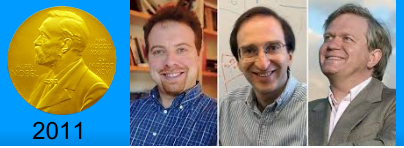
- Heavy ion collisions (LHC or RHIC) recreate conditions shortly after Big Bang (hot quark gluon plasma).
- Understanding astrophysical objects (e.g. neutron stars) involve matter at high densities.



Solving QCD will bring a quantitative understanding of the QCD phase diagram, by determining the equation of state and transport properties of extreme matter.

A deep understanding of the complex phenomena encompassed by the theory of the strong interactions will have a major impact on particle physics, nuclear physics, astrophysics and cosmology.

The Standard Model of Cosmology

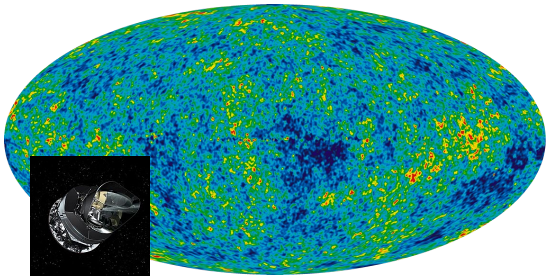


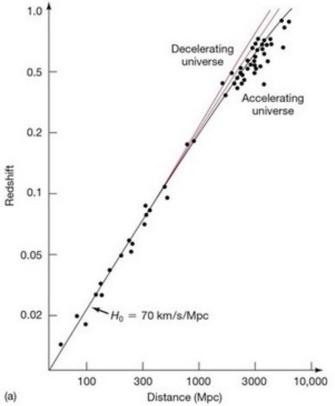
- The Standard Model of Cosmology (LambdaCDM) can fit data extremely well.
- Assumes General Relativity as the theory of gravity on cosmological scales.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = T_{\mu\nu} + g_{\mu\nu} \Lambda$$

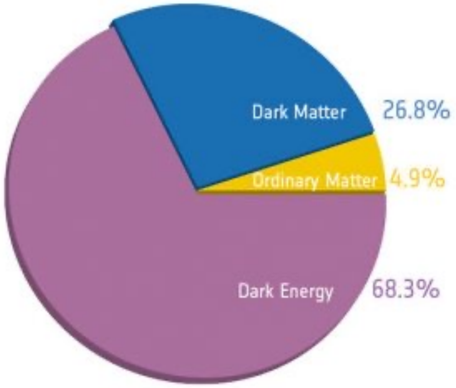
Curvature and **metric** of space-time (not rigid, can be deformed)
Energy-momentum Tensor (represents energy and matter content)

- Parametric model with **three major components**:
  - Cosmological constant (Λ) associated to dark energy.
  - Dark matter.
  - Ordinary matter.



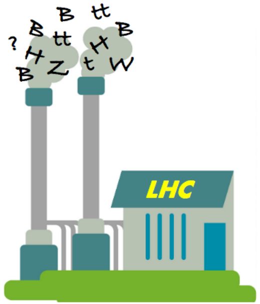


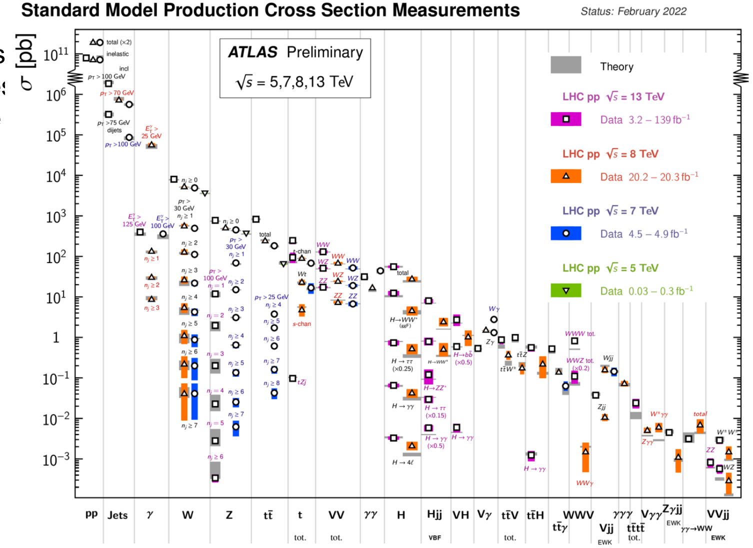
Actual Content of the Universe

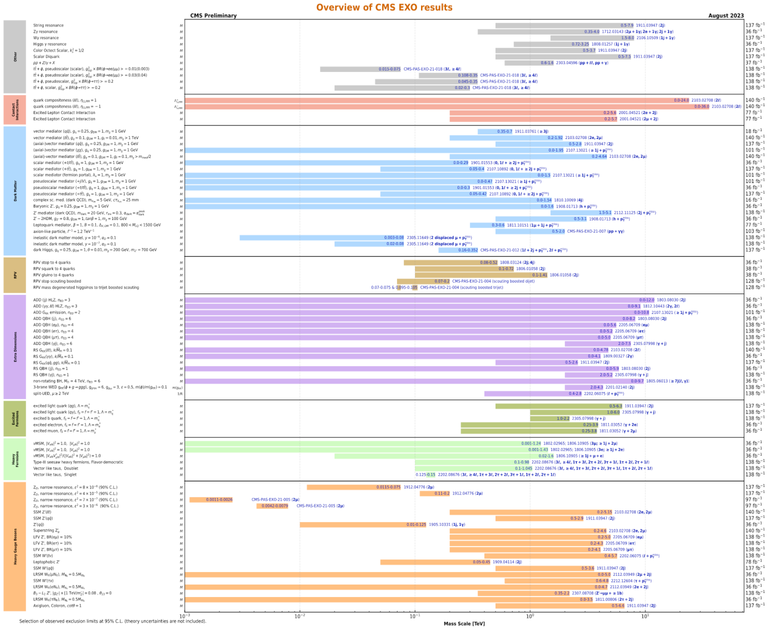


Resumen de resultados del LHC

Producción de partículas en LHC hasta ahora:
Bosón Higgs: 10 millones
Quark Top: 400 millones
Bosón Z: 10.000 millones
Bosón W: 40.000 millones
Quark b: 200 millones de millones

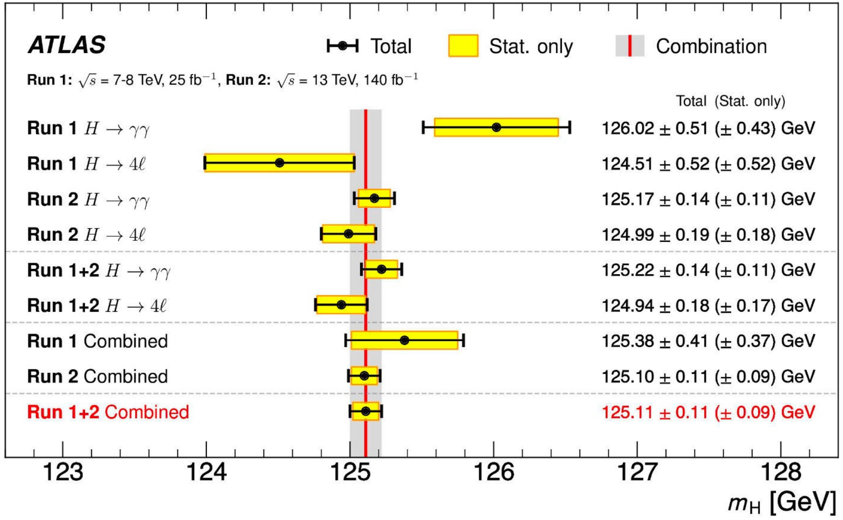


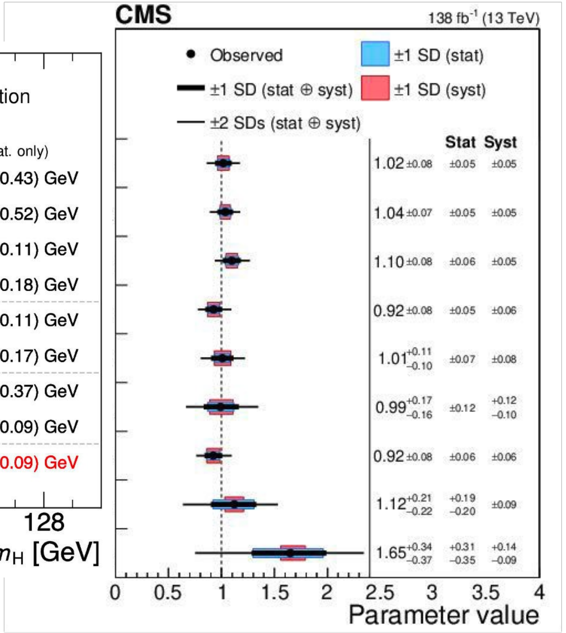




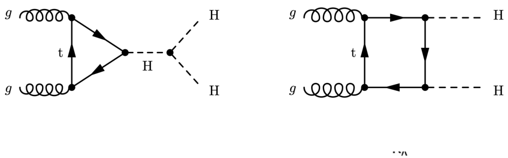
Todos los resultados están de momento en buen acuerdo con las predicciones del Modelo Estándar (midiendo procesos que cubren 9 órdenes de magnitud en secciones eficaces!).
No hay señales claras de nuevas partículas o fuerzas.

Resumen de resultados del LHC





Higgs self-coupling
Di-Higgs: 100 k events produced @LHC



Observed $-0.4 < \kappa_\lambda < 6.3$

Expected $-1.9 < \kappa_\lambda < 7.5$

HL-LHC observation of an HH signal at 5σ

50% level constraints on the Higgs boson self coupling!

At HL-LHC

κ_λ **~50%**

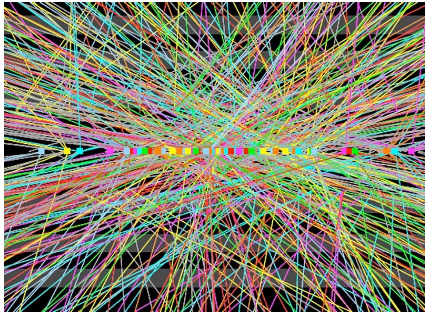
- Masa del Higgs: 0.1% de precisión en ATLAS o CMS, por separado (HL-LHC se podría alcanzar una precisión de 20 MeV)
- El acoplamiento a las partículas más pesadas está bien establecido.

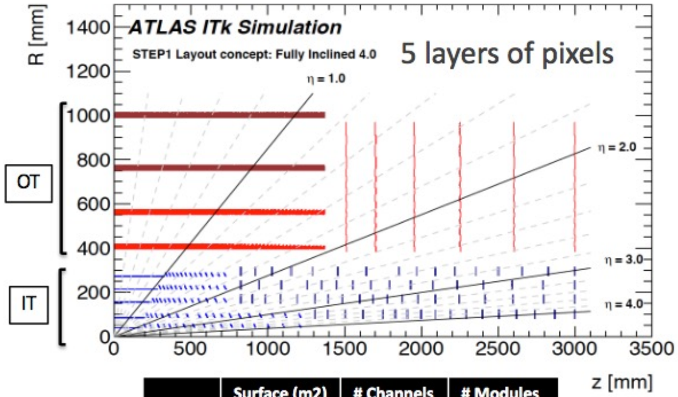
Mejoras para el HL-LHC

A luminosity **levelled @ 5×10^{34} cm^{-2}s^{-1}** , an integrated luminosity of **250 fb^{-1}/year** that will yield the expected **3000 fb^{-1}** 12 years after the upgrade.

Very high pile up: ~140

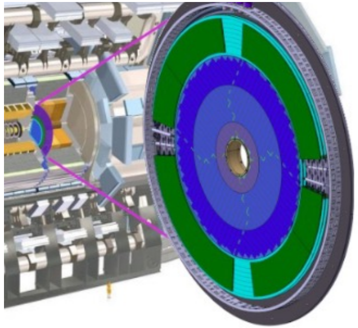
- **Detector nuevo de trazas** para aumentar granularidad (x5), cobertura y resistencia a la radiación.
- **Nueva electrónica de lectura y de adquisición** de casi todos los sistemas para lidiar con ritmos de trigger y de adquisición mucho mayores (L0 rate 100 kHz → 1-4 MHz), algoritmos más sofisticados (FPGAs, transmisiones ópticas) → output rate: 10KHz, 50 GB/s.
- **Nuevo de detector de tiempo en los endcaps** (basado LGADs) → identificar partículas de diferentes colisiones en un cruce de haces basándose en su tiempo de vuelo



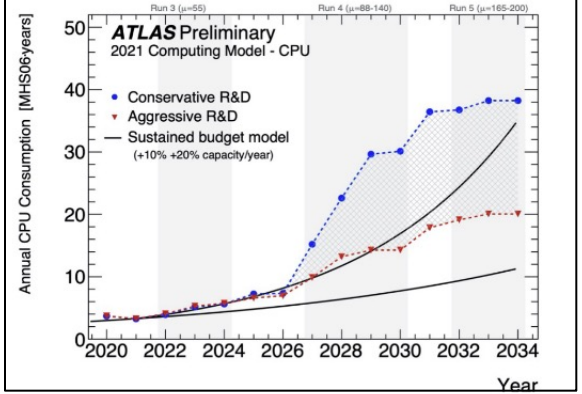


	Surface (m2)	# Channels	# Modules
Pixel	13	5.1 G	9.2 k
Strip	165	60 M	18 k

HGTD: High Granularity Timing Detector.
ATLAS implements only in the Endcap region.
4 layers each with 35-70 ps.
At least 2 hits per track.



Computing

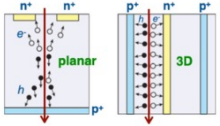


Granularity (x5 higher) to keep low occupancy.

- pixels: ~ 50x50 with first layer replaceable.
- Strips: short (2.5-5 cm) 75-90 μm pitch

Light (1/2 current weight))

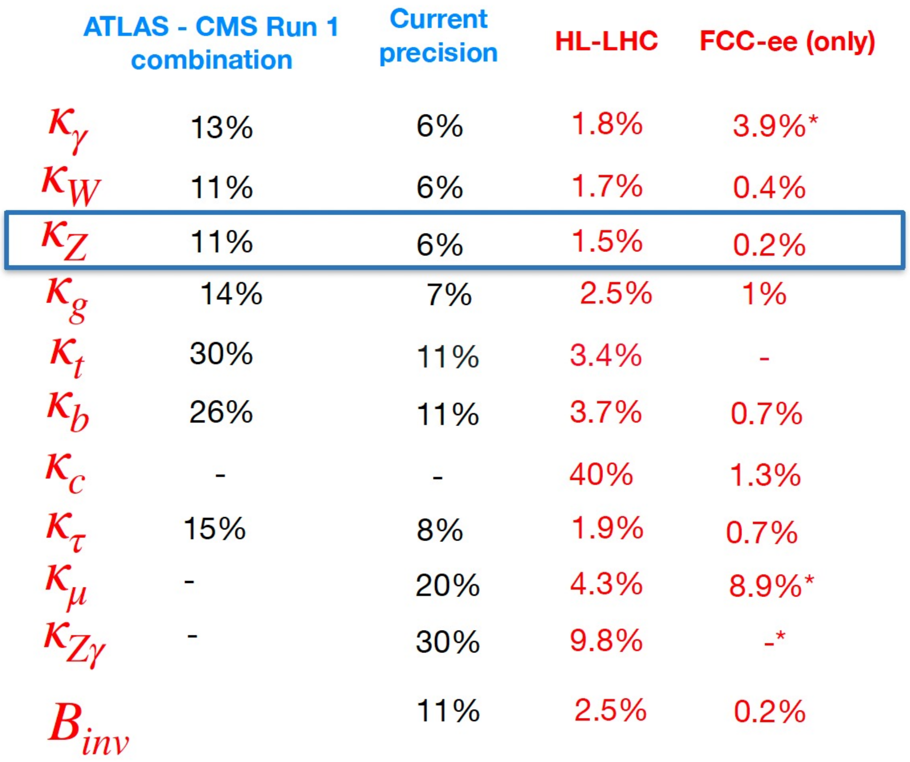
- Design, new materials
- new cooling (CO2)
- DC/DC, serial powering



Radiation tolerance

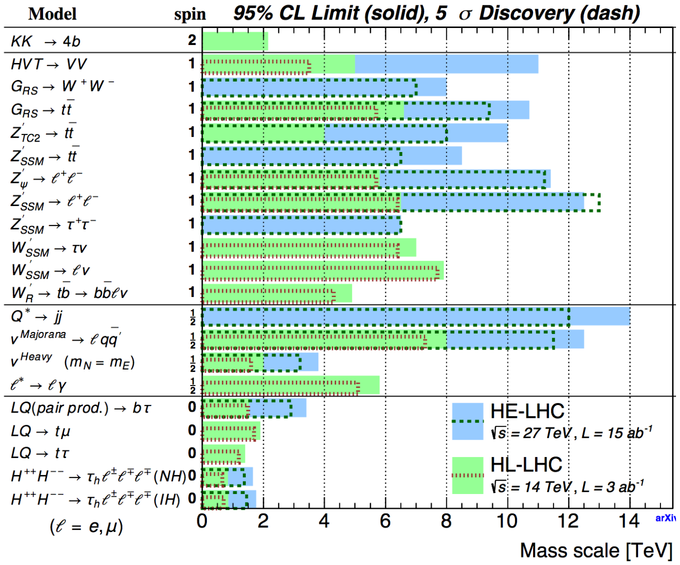
n-in-p planar and 3D sensors,
up to NIEL ≃ 2 x 10^{16} 1 MeV n$_{eq}$/cm^2 and TID of 1 GRad

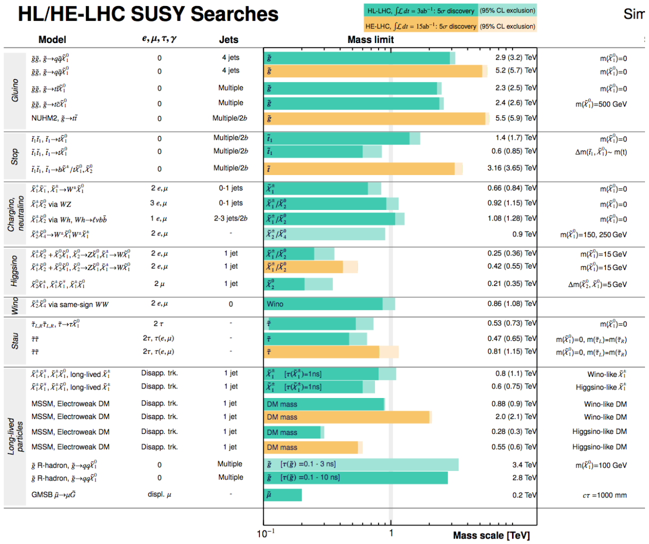
Potencial en medidas de precisión del Higgs



	ATLAS - CMS Run 1 combination	Current precision	HL-LHC	FCC-ee (only)
κ_γ	13%	6%	1.8%	3.9%*
κ_W	11%	6%	1.7%	0.4%
κ_Z	11%	6%	1.5%	0.2%
κ_g	14%	7%	2.5%	1%
κ_t	30%	11%	3.4%	-
κ_b	26%	11%	3.7%	0.7%
κ_c	-	-	40%	1.3%
κ_τ	15%	8%	1.9%	0.7%
κ_μ	-	20%	4.3%	8.9%*
$\kappa_{Z\gamma}$	-	30%	9.8%	-*
B_{inv}		11%	2.5%	0.2%

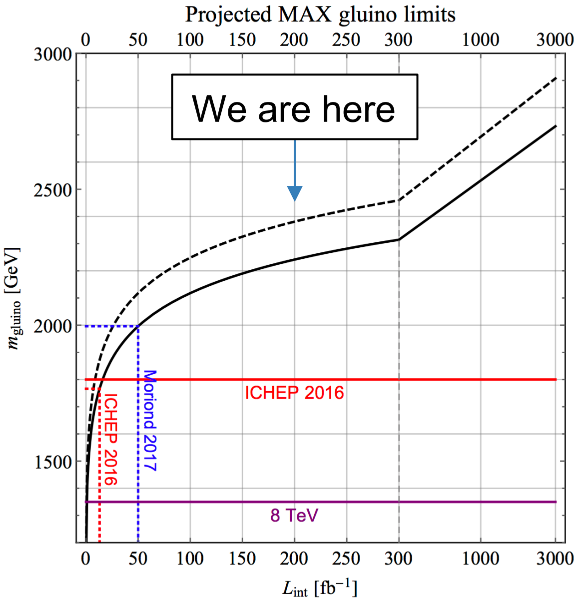
Potencial de HL-LHC en búsquedas directas





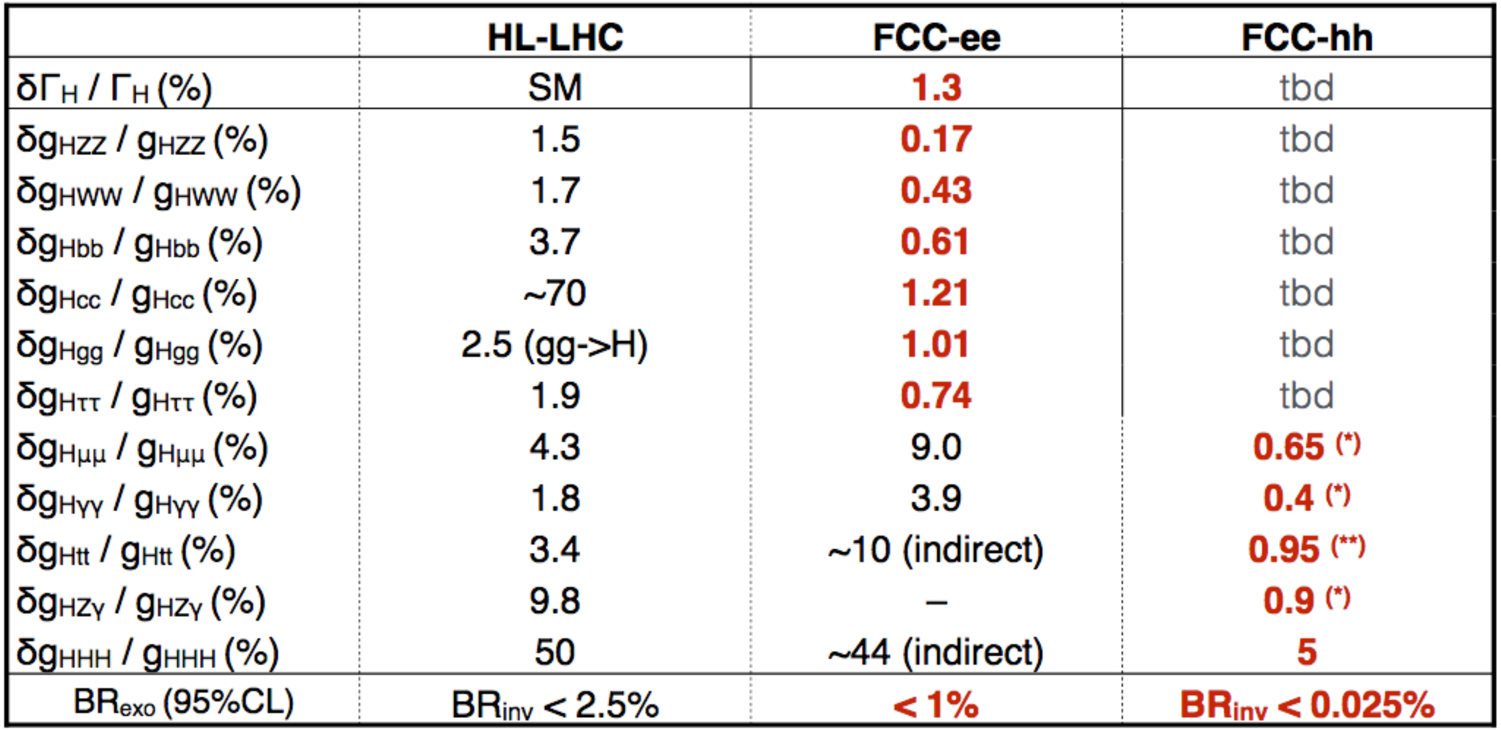
En la mayoría de los escenarios BSM, HL-LHC aumenta el alcance de masa en 20-50% (mejora sobretodo en producción EW con bajos ritmos de producción).
Materia Oscura: Mejorará la sensibilidad a masas de los mediadores en un factor 3-8.

Potencial de HL-LHC en búsquedas directas



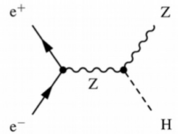
- HL-LHC: Un factor 16 en luminosidad respecto a hoy.
- Doblar la luminosidad ahora es cuestión de años (no de días como al inicio) → Descubrimientos llevarán tiempo.
- Nuevas ideas y desarrollos pueden suponer mejoras importantes.
- Mejorar la precisión (experimental y teórica) será la clave.

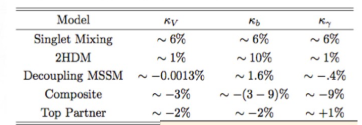
Potencial de futuros colisionadores en precisión del Higgs



	HL-LHC	**FCC-ee**	**FCC-hh**
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65** $^{(*)}$
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4** $^{(*)}$
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	**0.95** $^{(**)}$
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9** $^{(*)}$
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	**5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

Física Futuros Colisionadores

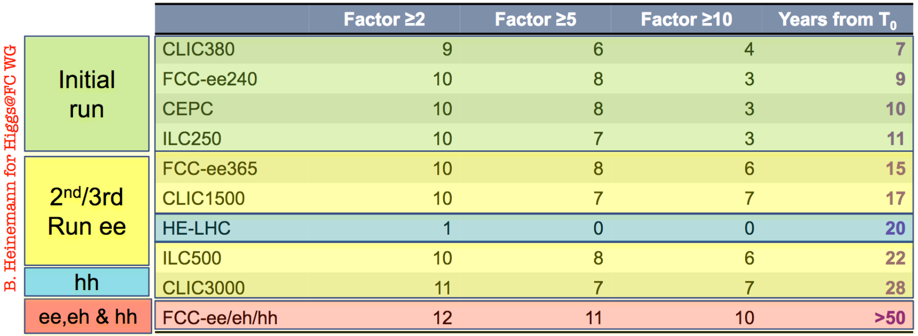




Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

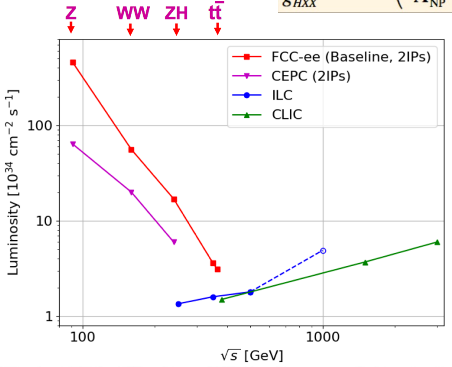
$$\frac{g_{HXX}}{g_{HXX}^{SM}} \approx 1 + \delta \times \left(\frac{1\,\text{TeV}}{\Lambda_{NP}}\right)^2$$

Higgscouplings whose sensitivity improves by 2/5/10 compared to HL-LHC



B. Heinemann for Higgs@FC WG

		Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
Initial run	CLIC380	9	6	4	7
	FCC-ee240	10	8	3	9
	CEPC	10	8	3	10
	ILC250	10	7	3	11
2^{nd}/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
hh	HE-LHC	1	0	0	20
2^{nd}/3rd Run ee	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

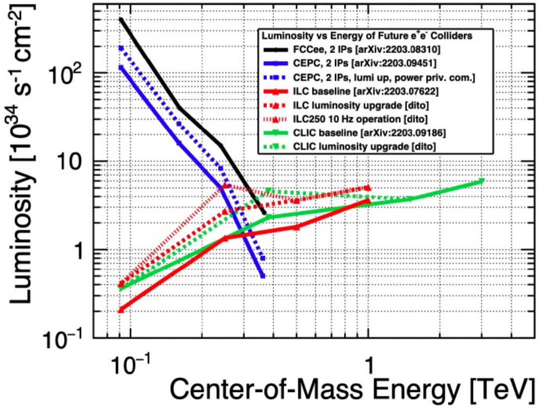


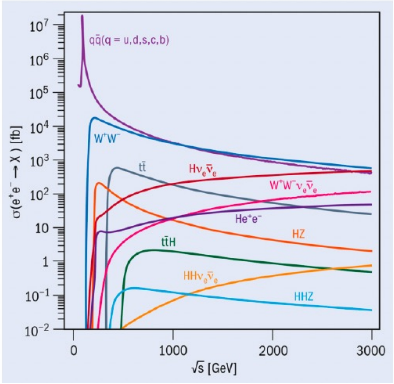
- Acoplamientos de Higgs: Aumento importante de precisión respecto a HL-LHC → Motivación para una factoría de Higgs durante 2040-2060 con colisionadores de leptones (junto a producción Z, WW, ttbar).
- Búsqueda de nueva física: Colisionadores hadrónicos más potencial para descubrimientos directos (protones 100 TeV ~ leptones de 14 TeV), mientras que los leptónicos tienden a ser mejor en búsquedas indirectas (complicado identificar la fuente de nueva física):
  - FCC-hh 100 TeV: masas de gluinos hasta 17 TeV, masas de s-tops hasta 10 TeV, masas de partículas escalares de un segundo doblete de Higgs hasta 5-20 TeV.
  - CLIC 3 TeV: puede buscar partículas con interacción EW hasta el límite cinemático (1.5 TeV para producción de pares).

Circular or linear e^+e^- colliders?

Circular e^+e^- colliders

- FCC-ee, CEPC
- Circumference: 90 - 100 km
- High luminosity & power efficiency at **low energies;** → huge rates at Z pole (table below)
- Less luminosity at higher E_{CM} (synchrotron radiation)
- Multiple interaction regions
- Very clean: little beamstrahlung





per detector in e^+e^-	# Z	# B	# τ	# charm	# WW
LEP	4×10^6	1×10^6	3×10^5	1×10^6	2×10^4
SuperKEKB	-	10^{11}	10^{11}	10^{11}	-
FCC-ee	2.5×10^{12}	7.5×10^{11}	2×10^{11}	6×10^{11}	1.5×10^8

Linear e^+e^- colliders

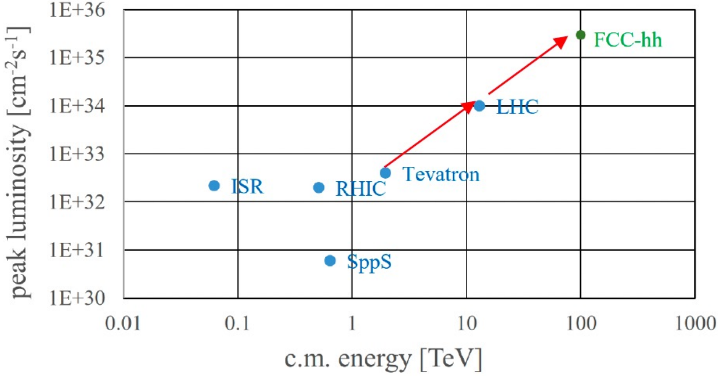
- ILC, CLIC, C^3 (new idea)
- Length
  ILC: 250 GeV – 1 TeV: 20.5 → 40 km
  CLIC: 380 GeV – 3 TeV: 11.4 → 50 km
- High luminosity & power efficiency at **high energies;**
- **Longitudinally spin-polarised beams**
- Long-term energy upgrades possible

  - longer tunnel, same technology and/or
  - replacing accelerating structure with advanced technologies (RF cavities with higher gradients, plasma acceleration?)

Slide from Karl Jakobs

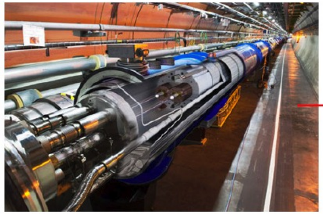
Stage 2: FCC-hh

- High energy frontier exploration machine, reaching **100 TeV pp collisions**
- Performance increase by an order of magnitude in energy and luminosity w.r.t. LHC
- Planned to accumulate ~20 ab^{-1} per experiment, over 25 years



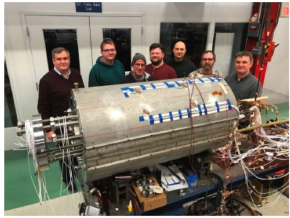
- Large challenges: - High bending power → high-field magnets with field strength of 16 – 20 T;
  - Costs (linked to magnets)

From LHC technology
8.3 T NbTi dipole



via HL-LHC technology
12 T Nb_3Sn quadrupole

via large R&D programme
(e.g. FNAL 14.5 T Nb_3Sn dipole demonstrator, 2019)



.. to high-field, high performance, industrially mass-produced FCC-hh dipole magnets

?

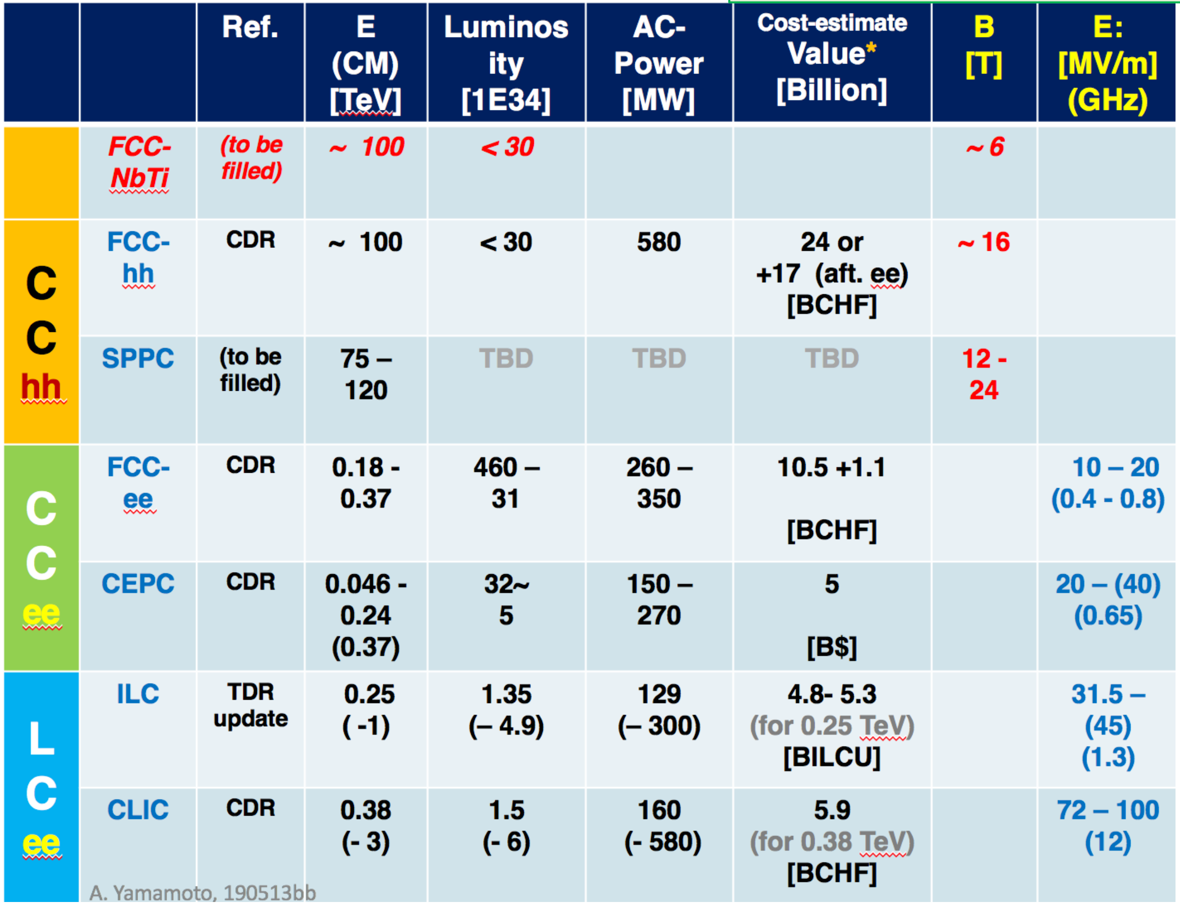
16 – 20 T
High-field magnets, HTS technology?
(High Temperature Superconductors)

→ accelerator R&D roadmap

Slide from Karl Jakobs

Coste Futuros Colisionadores

*Cost estimates are commonly for "**Value**" (material) only.

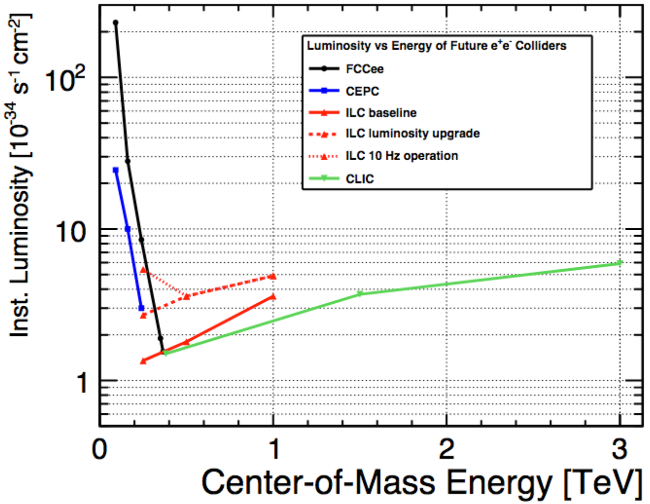


		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Cost-estimate Value* [Billion]	B [T]	E: [MV/m] (GHz)
C C hh	*FCC-NbTi*	*(to be filled)*	*~ 100*	*< 30*			*~ 6*	
	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16	
	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24	
C C ee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10 – 20 (0.4 - 0.8)
	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 – (40) (0.65)
L C ee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	4.8- 5.3 (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)
	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)

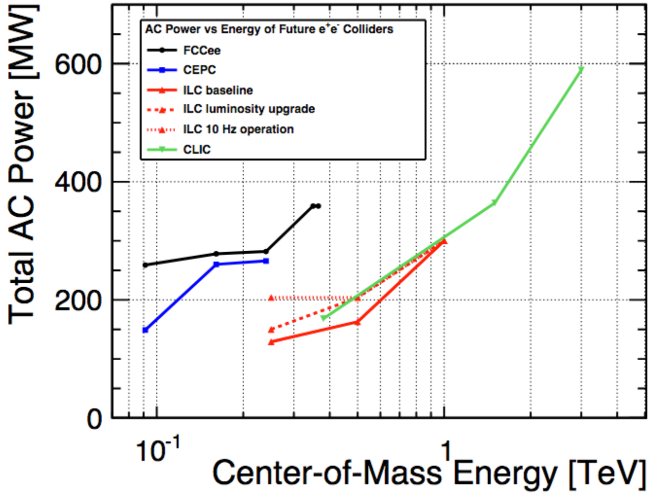
A. Yamamoto, 190513bb

Futuros Colisionadores

Luminosity



Consumption

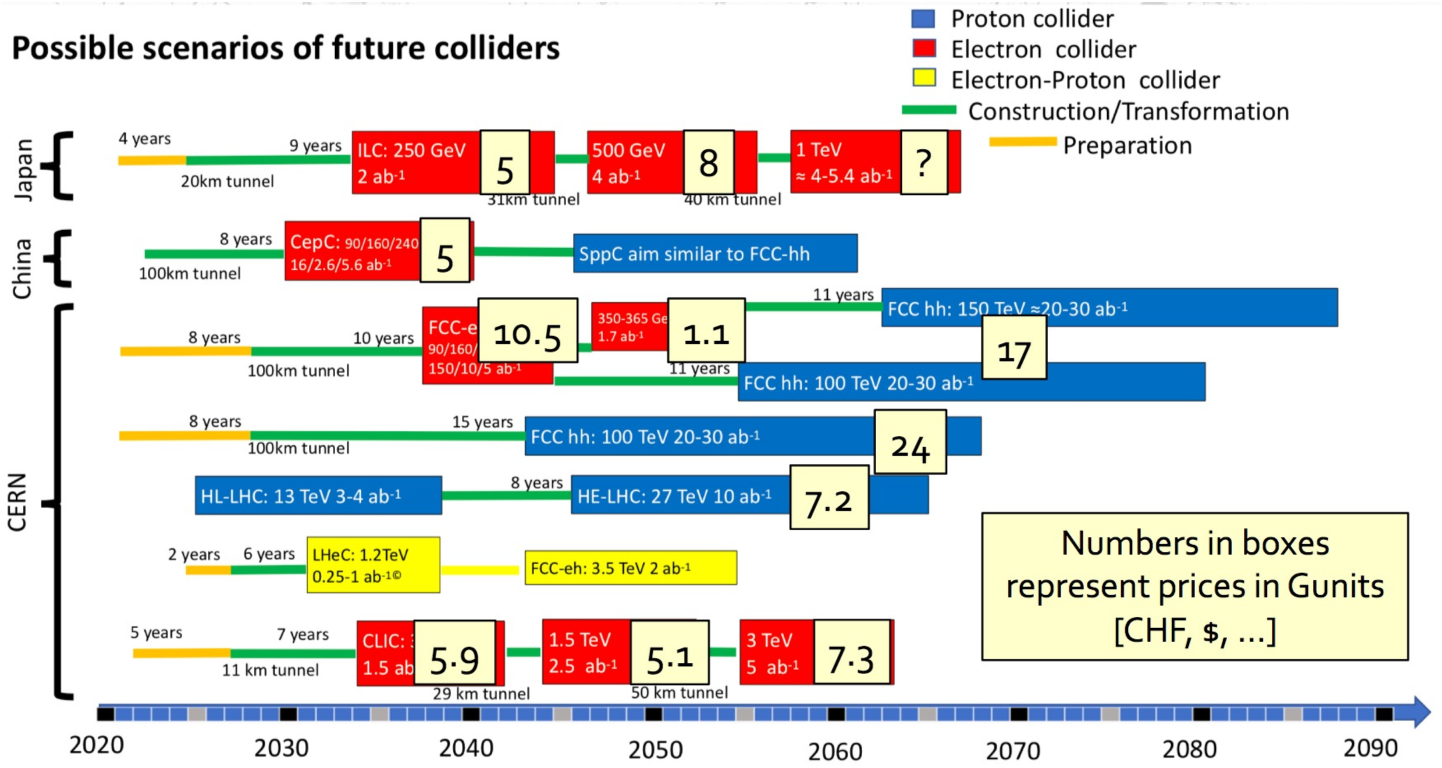


Linear Colliders ILC/CLIC: 250/380 GeV CM (Higgs Factory) extendable to ~ 1/3 TeV CM

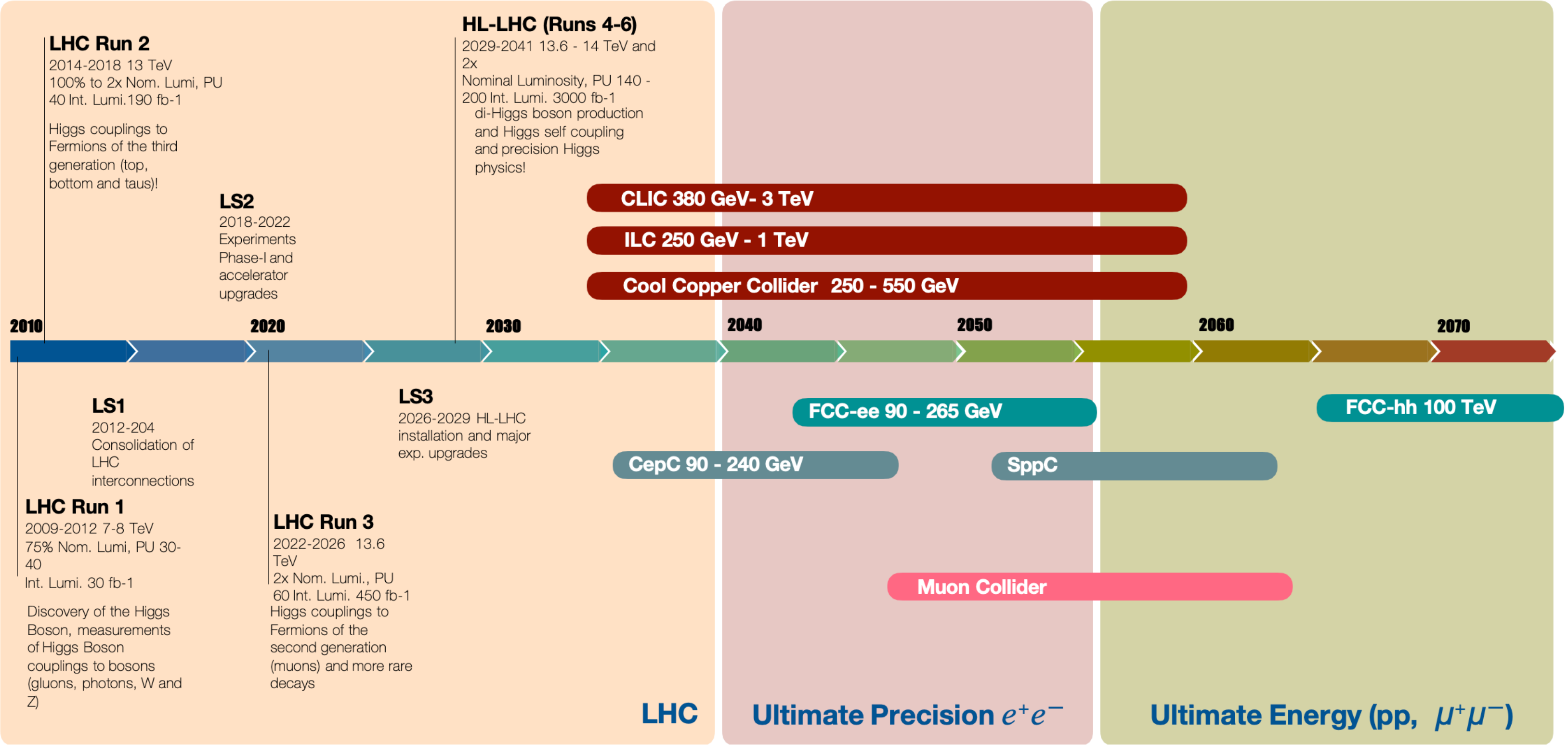
Circular Colliders: Higher Luminosities < 250 GeV

Polarisation (ILC) >80% e⁻, 30-40% e⁺ (effective factor 2.5 in Luminosity)

Coste Futuros Colisionadores



A Scientific Mission for the 21st Century



LHC Run 2
2014-2018 13 TeV
100% to 2x Nom. Lumi, PU
40 Int. Lumi.190 fb-1

Higgs couplings to
Fermions of the third
generation (top,
bottom and taus)!

LS2
2018-2022
Experiments
Phase-I and
accelerator
upgrades

HL-LHC (Runs 4-6)
2029-2041 13.6 - 14 TeV and
2x
Nominal Luminosity, PU 140 -
200 Int. Lumi. 3000 fb-1
di-Higgs boson production
and Higgs self coupling
and precision Higgs
physics!

CLIC 380 GeV- 3 TeV

ILC 250 GeV - 1 TeV

Cool Copper Collider 250 - 550 GeV

LS1
2012-204
Consolidation of
LHC
interconnections

LHC Run 1
2009-2012 7-8 TeV
75% Nom. Lumi, PU 30-
40
Int. Lumi. 30 fb-1

Discovery of the Higgs
Boson, measurements
of Higgs Boson
couplings to bosons
(gluons, photons, W and
Z)

LS3
2026-2029 HL-LHC
installation and major
exp. upgrades

LHC Run 3
2022-2026 13.6
TeV
2x Nom. Lumi., PU
60 Int. Lumi. 450 fb-1
Higgs couplings to
Fermions of the
second generation
(muons) and more rare
decays

FCC-ee 90 - 265 GeV

CepC 90 - 240 GeV

SppC

FCC-hh 100 TeV

Muon Collider

LHC

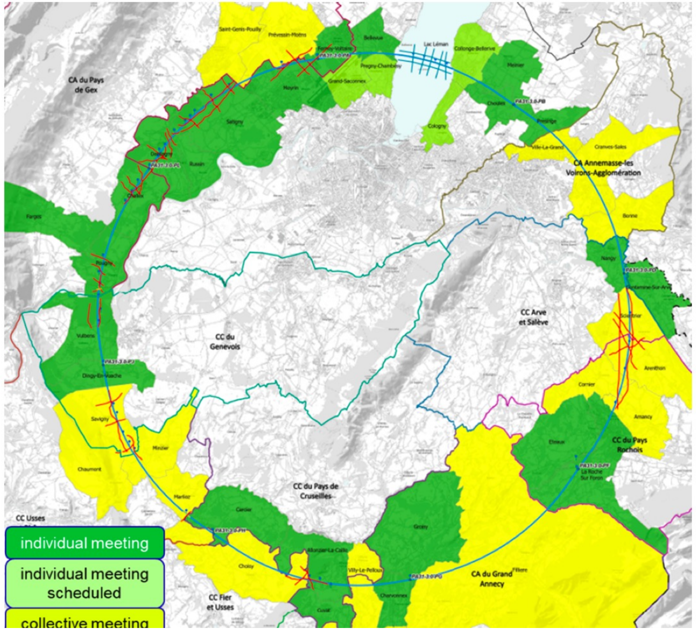
Ultimate Precision e^+e^-

Ultimate Energy (pp, $\mu^+\mu^-$)

Slide from Marumi Kado

FCC-ee feasibility study

Slides from Marumi Kado



Feasibility study to be completed by March 2025. Choice of baseline layout (90.7 km) - discussions with local authorities, environmental investigations and civil engineering designs well under way.

Power consumption

- 240 GeV the instantaneous power is 291 MW (compared to 140 MW for ILC and 110 MW for CLIC for less luminosity)
- Replace 5800 quadrupole and 4672 sextuple normal conducting magnets by Hight Temperature Superconductive CCT magnets

EW Precision

Key measurements:

- $m_Z \sim 10^{-6}$, $m_W \sim 10^{-5}$, $m_{top} \sim 10^{-4}$
- $sin^2_{\theta_W} \sim 3.10^{-6}$,$\alpha_{QED}(m_Z^2) \sim 10^{-5}$, $\alpha_S \sim 10^{-4}$

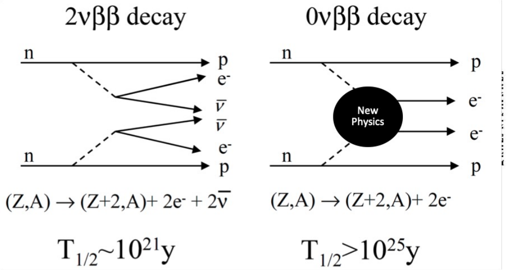
FCC-ee is much, much more than a Higgs factory!

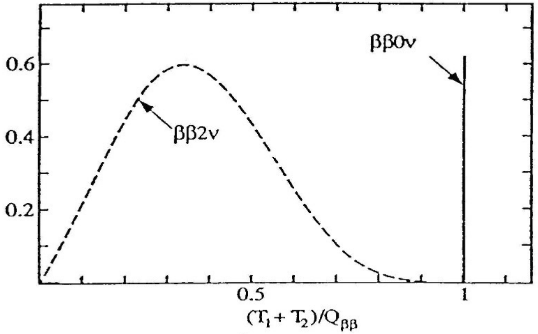
Superb precision achieved and uncertainties are dominated by systematic uncertainties!

- x10-50 Improvement on all EW observables
- Up to x10 improvement on Higgs observables
- Indirect discovery **potential up to 70 TeV**
- **x10 improvement on Belle II stats for b, c and τ**
- Huge direct discovery potential for feebly interacting particles in the 5-100 GeV range

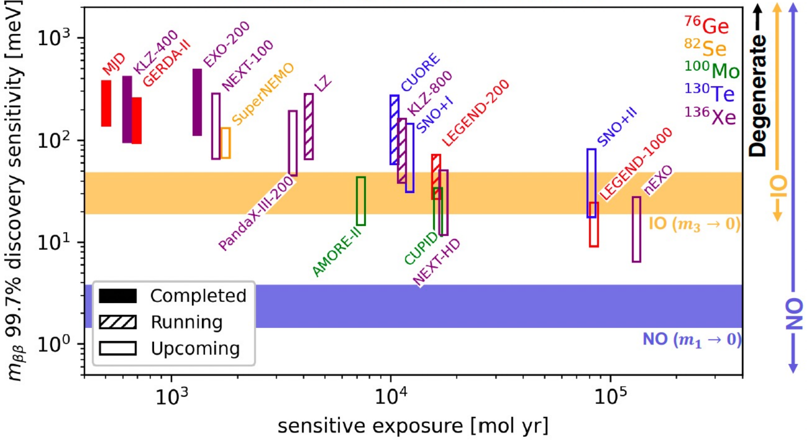
Neutrino physics

Search for neutrino-less double beta decays

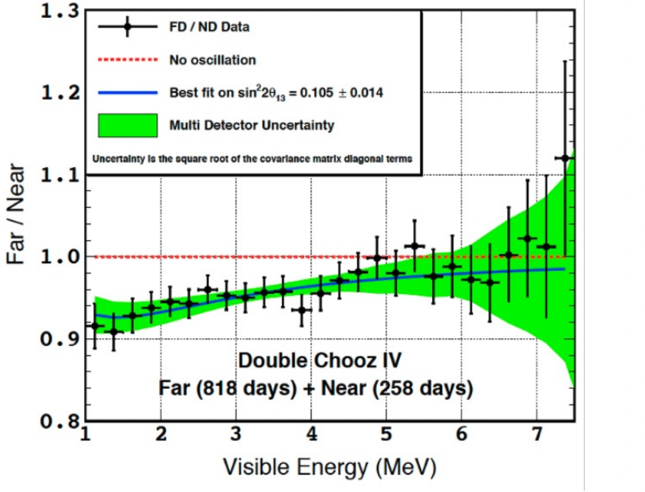




Sensitivity of upcoming experiments:



Double Chooz *Nature Physics 16 (2020) 558-564*



$\sin^2(2\theta_{13}) = 0.105 \pm 0.014$ (stat + sys)

$\chi^2/\text{dof} = 182/112$ (D2MC result)

Neutrino physics

(slides from Ines Gil)

Neutrino oscillations

3 neutrino mixing: $|\nu_\alpha >= \sum_{i=1}^{3} U_{\alpha i}\,|\nu_i>$

Pontecorvo, Maki, Nakagawa, Sakata (PMNS) 3x3 mixing matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

θ23 → Atmospheric + LBL acc.

θ13, δCP → SBL reactors + LBL acc.

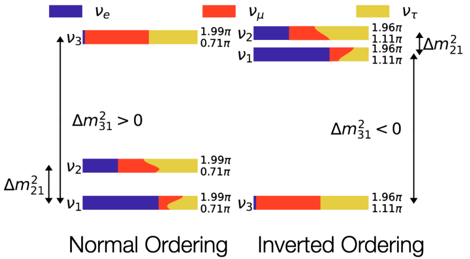
θ12 → Solar + KamLAND

Oscillation probability

$$P_{\nu_\alpha\to\nu_\beta}(L,E) = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right]\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) - 2\sum_{i>j} Im\left[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right]\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

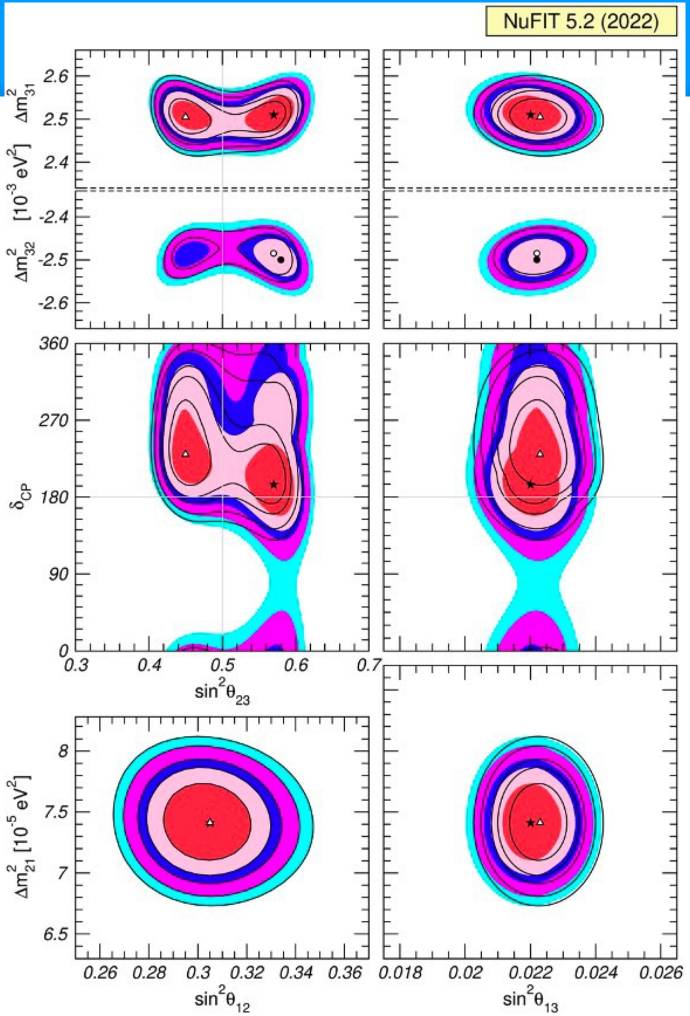
$\Delta m^2_{ij} = m^2_i - m^2_j$

Neutrino mass spectrum



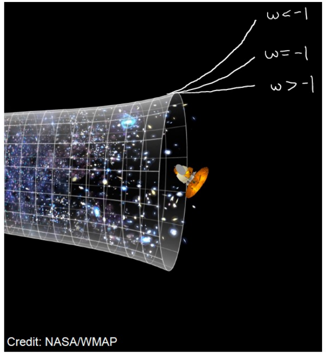
Unknown parameters: mass ordering (sign of Δm^2_{31}), δ_{CP}, octant of θ_{23}

- **θ_{23} octant** is **not resolved** yet (slight preference for the second octant)
- The sign of **Δm^2_{32}** is **unknown** (Normal Ordering preferred at ~2.5σ)
- **δ_{CP} unknown**: Some tension between current LBL and atm experiments in NO. CP-violation for IO at ~3σ



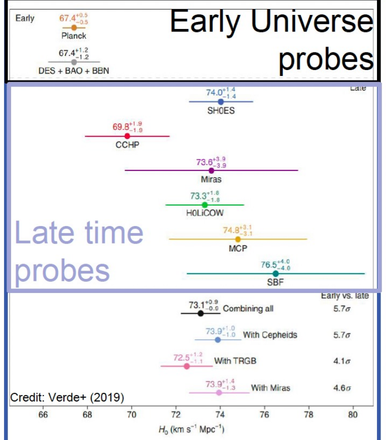
Cosmology

Evolution of Dark Energy



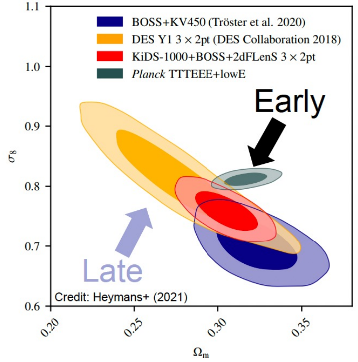
Credit: NASA/WMAP

H_0-Tension



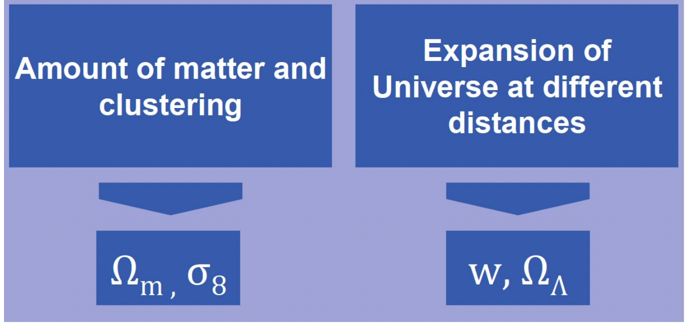
Credit: Verde+ (2019)

S_8-Tension



Credit: Heymans+ (2021)

Size and distribution of structures depends on:



Amount of matter and clustering

Ω_m, σ_8

Expansion of Universe at different distances

w, Ω_Λ

H_0
Current expansion rate

Ω_m
Matter density

Ω_b
Baryon density

Ω_Λ
Dark Energy density

σ_8
„Clumpiness“

n_s
Scale index of initial density fluctuations

Direct dark matter searches