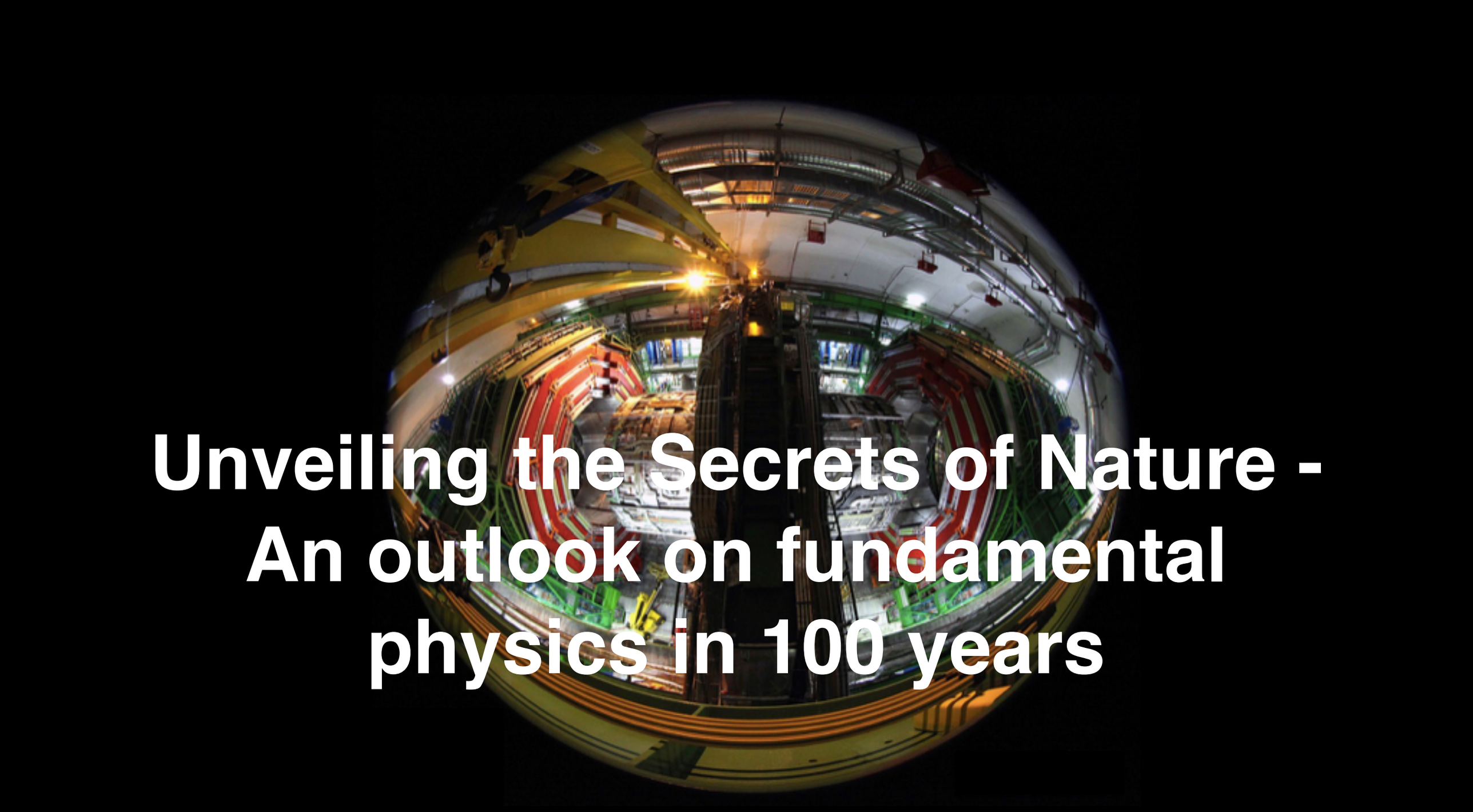
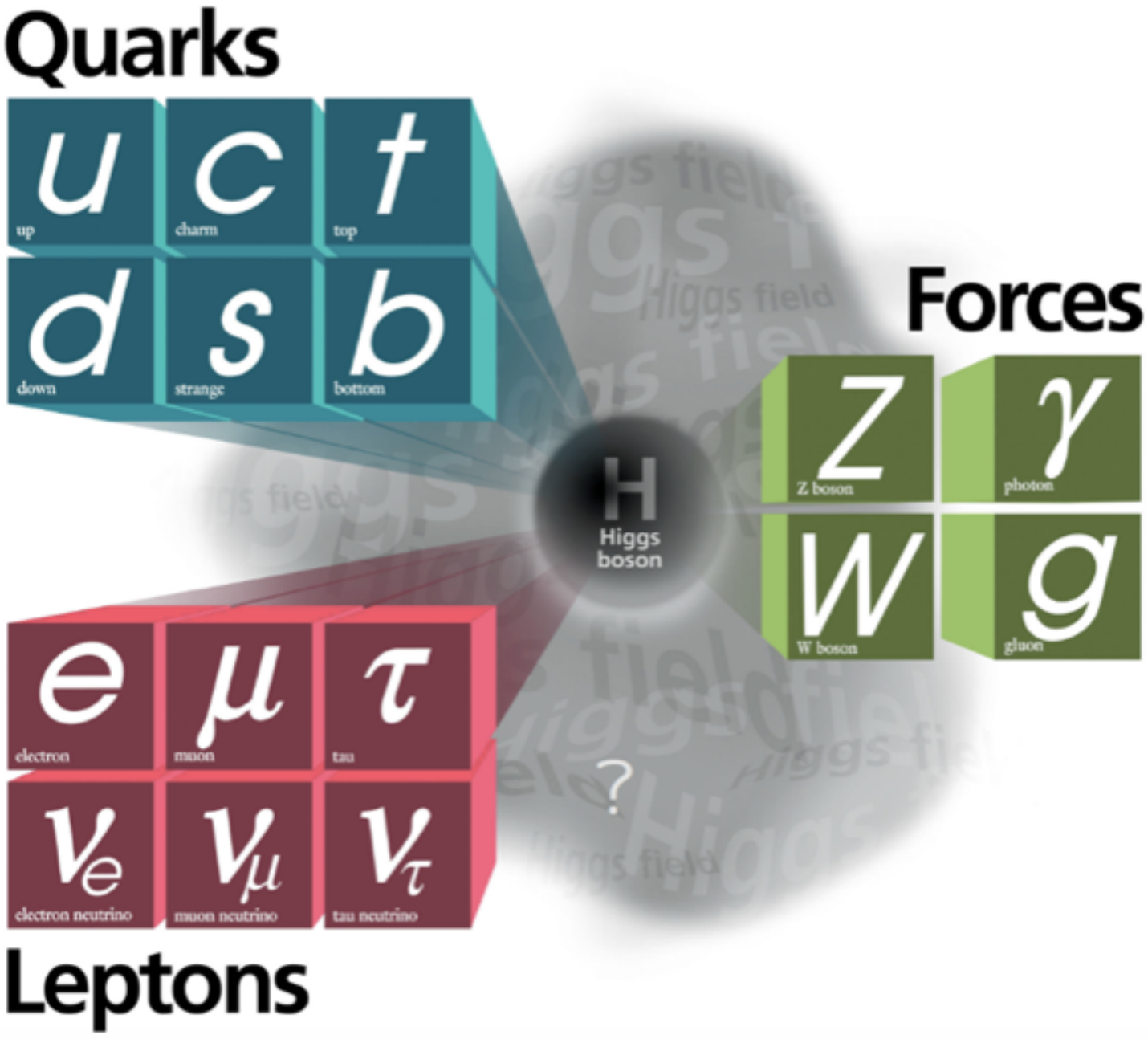


Unveiling the Secrets of Nature - An outlook on fundamental physics in 100 years

Planck 2017 - Warsaw
May 23rd, 2017
Markus Klute (MIT)

Fundamental Physics Today

Complete theory valid to very high energies



Fundamental Physics Today

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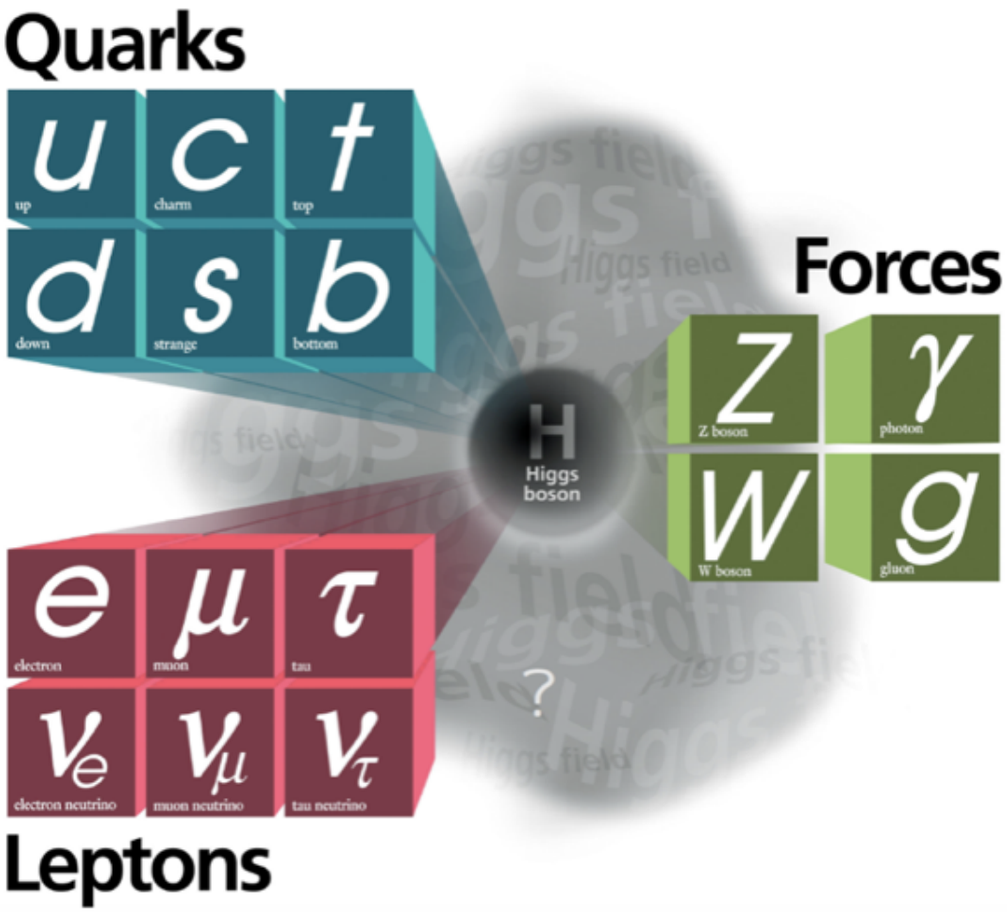
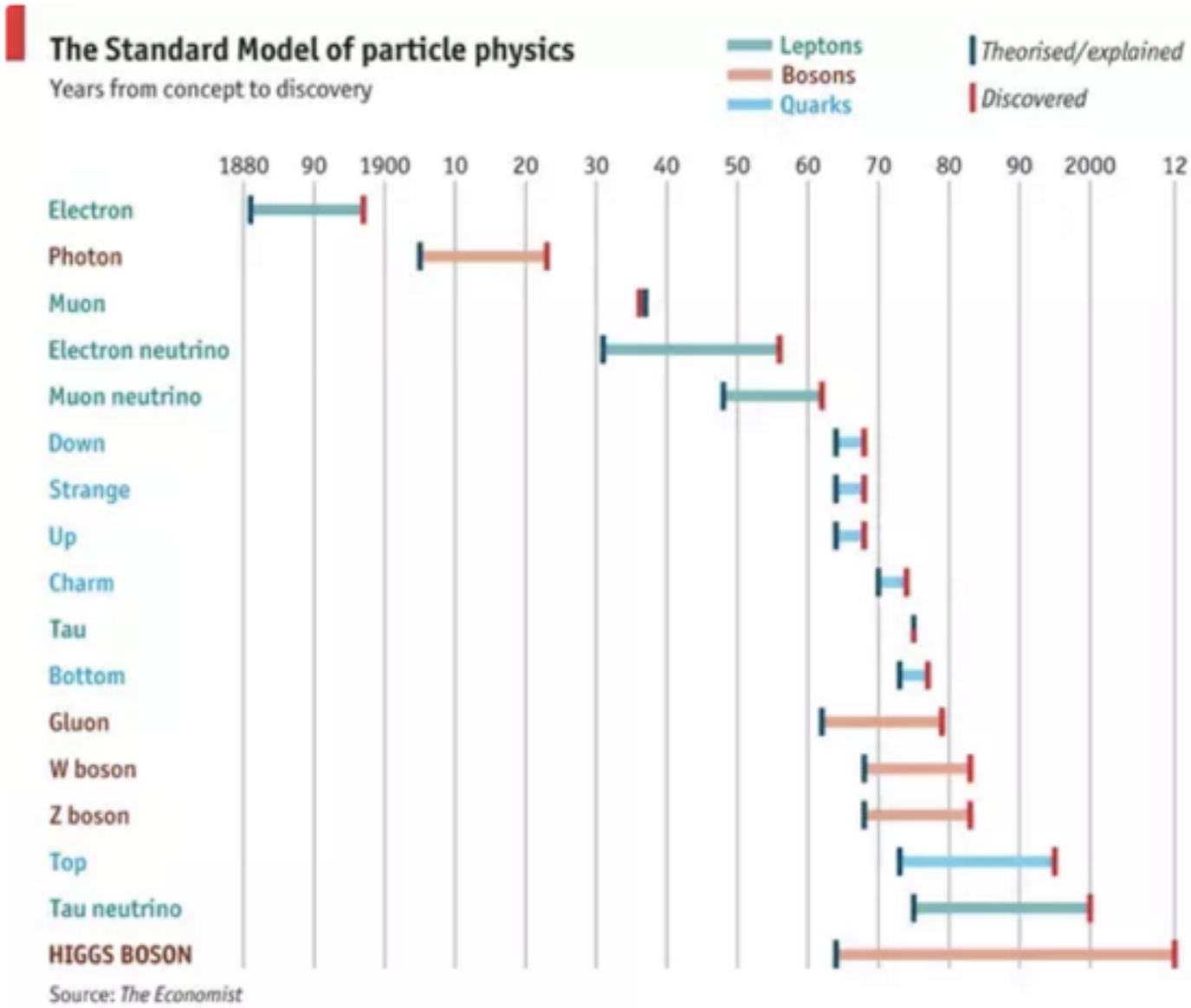
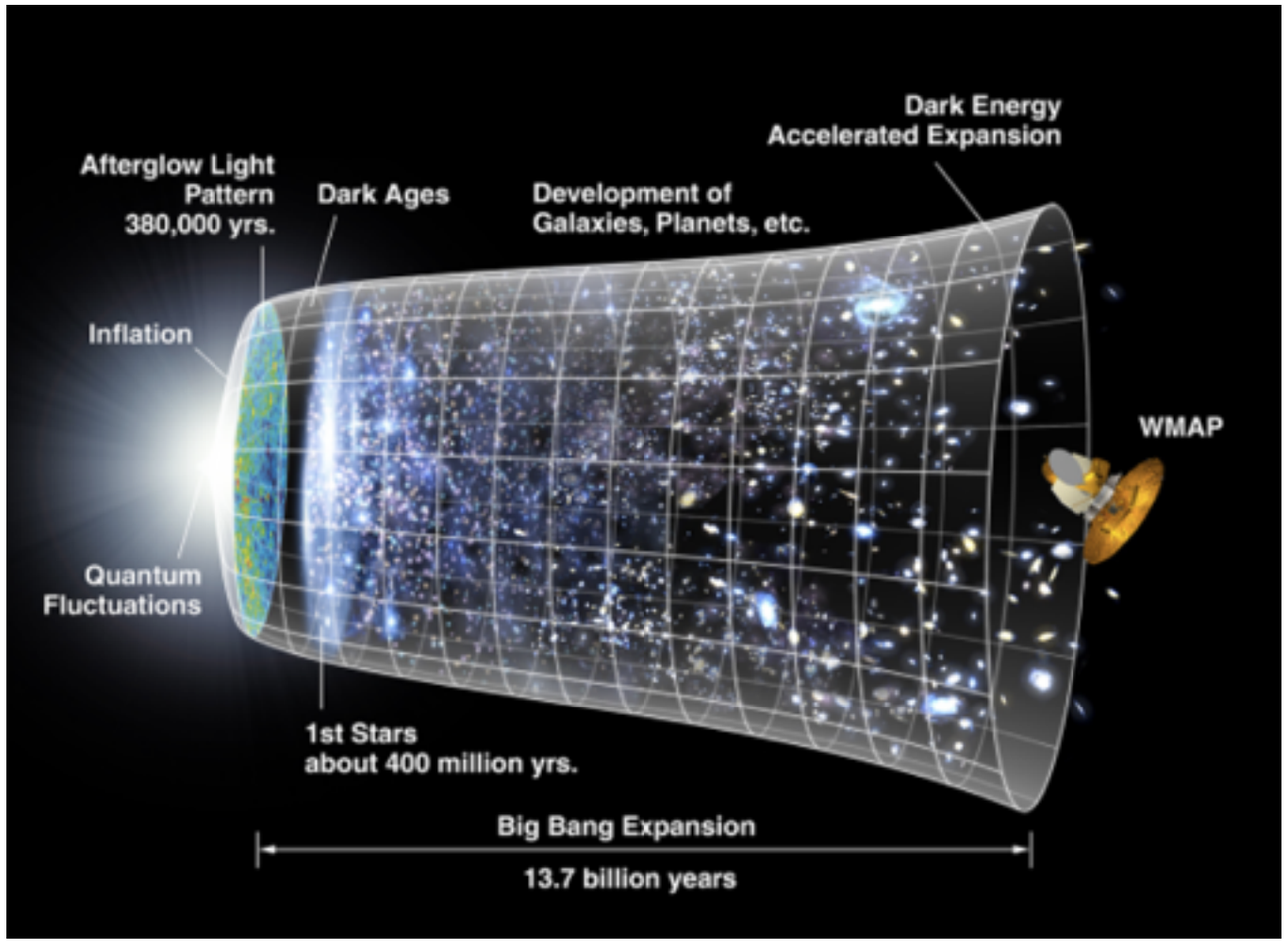
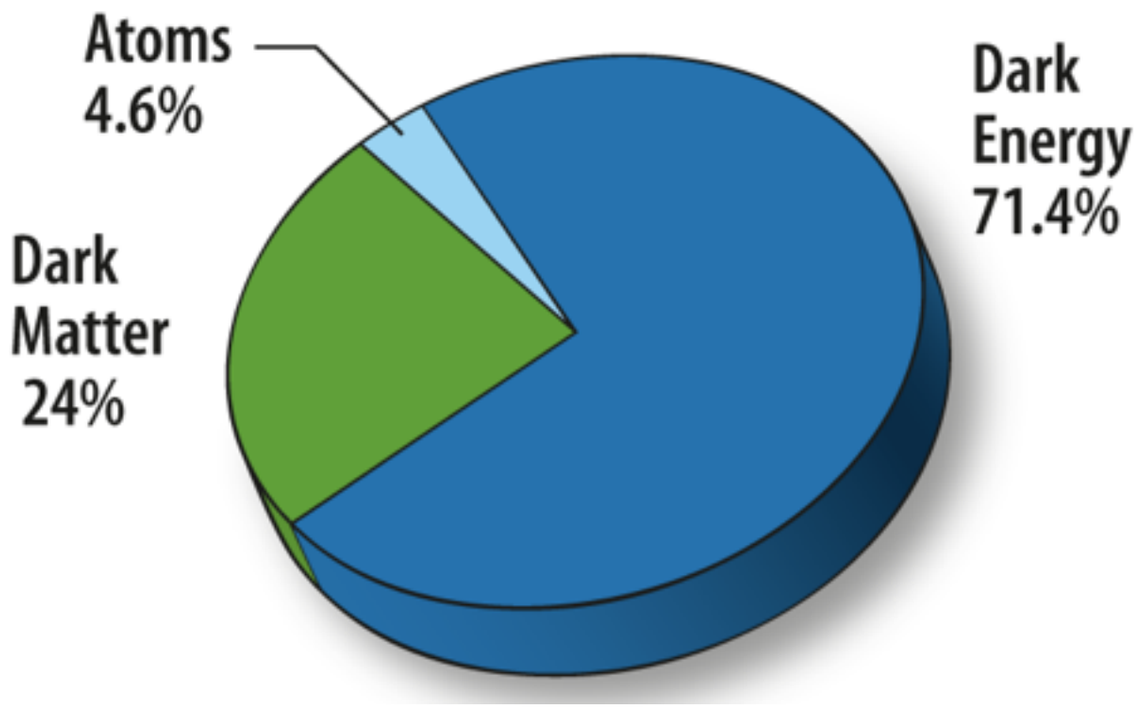




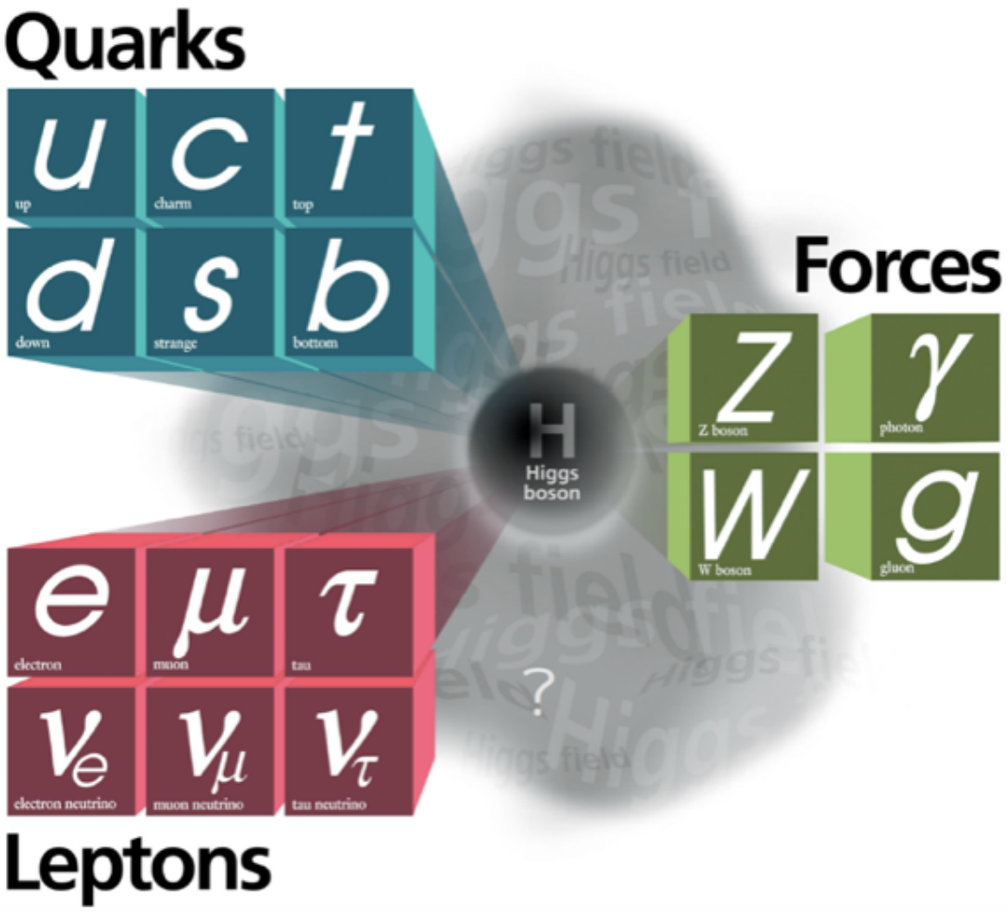
Fundamental Physics Today

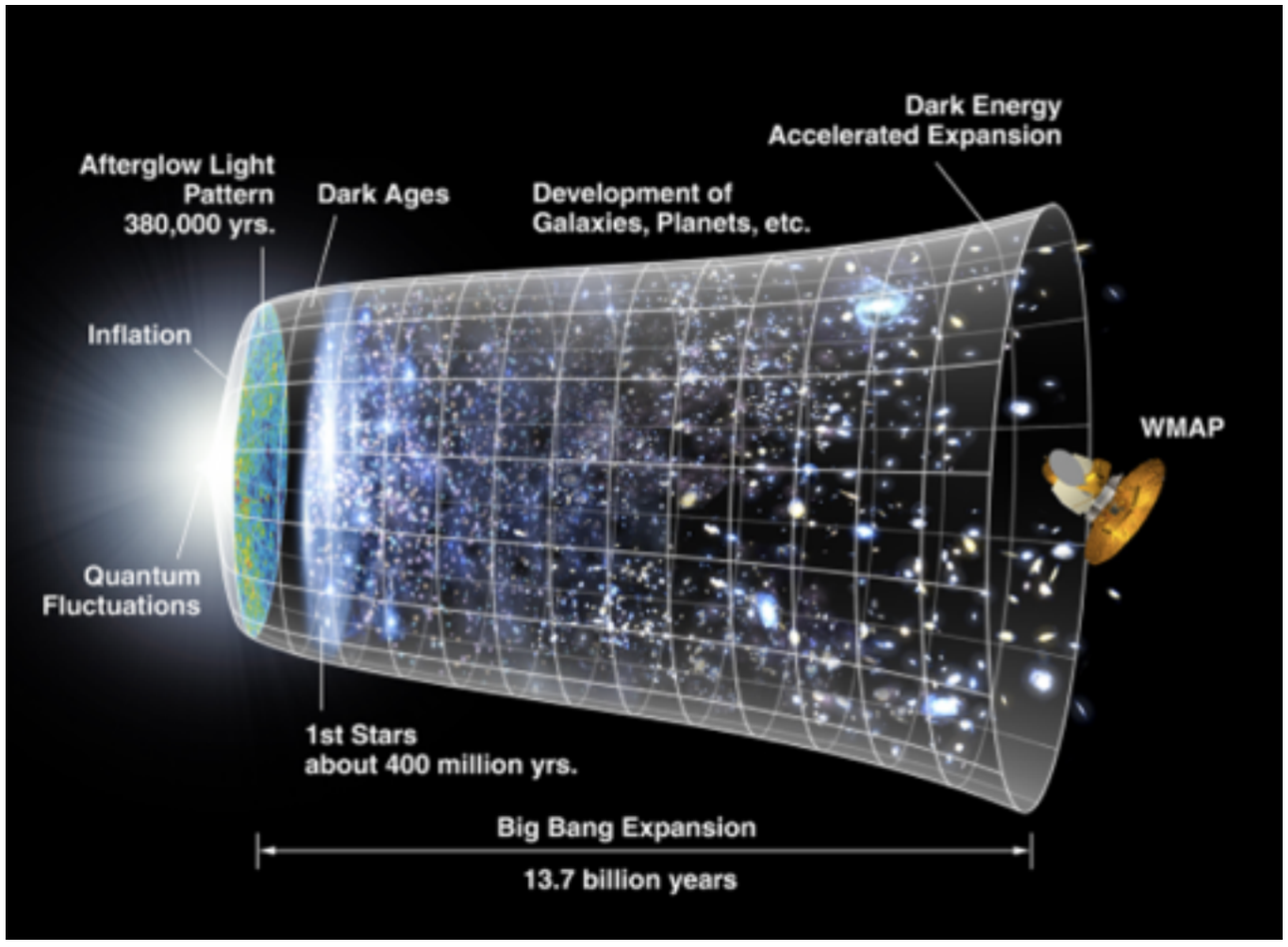




Fundamental Physics Today

Complete theory valid to very high energies





Fundamental Physics Today

Is this the end? **Of course not!**

Is there anything new to be discovered? **Of course!**

➡ **The SM fails to explain important observations**

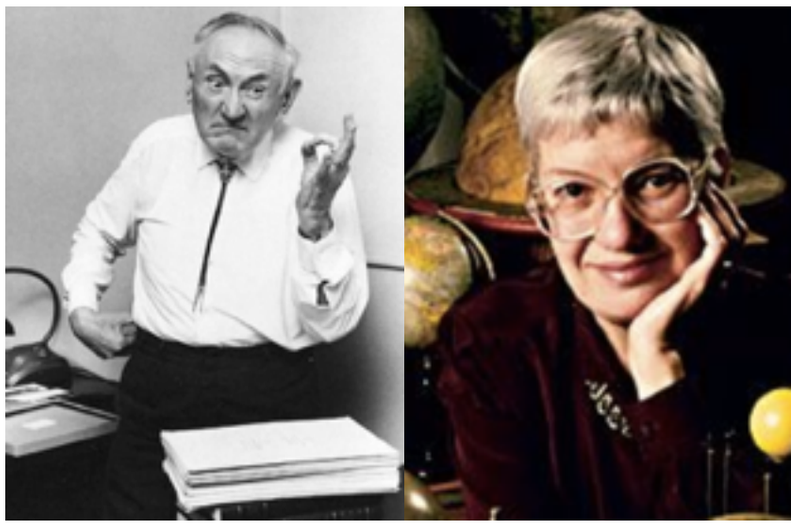
➡ **Experimental proof for physics beyond the SM**

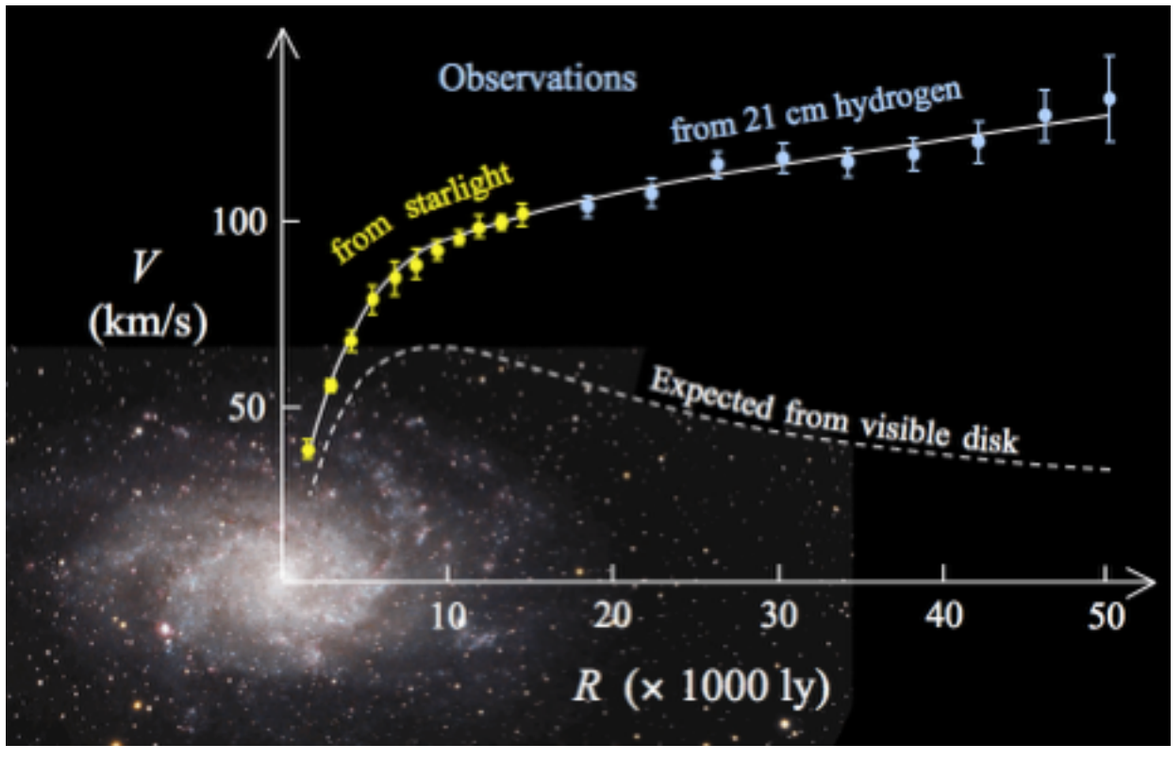
- Cosmological dark matter (DM)
- Baryon asymmetry
- Non-zero, but very small neutrino mass
- A hint: the small Higgs boson mass is rather unnatural

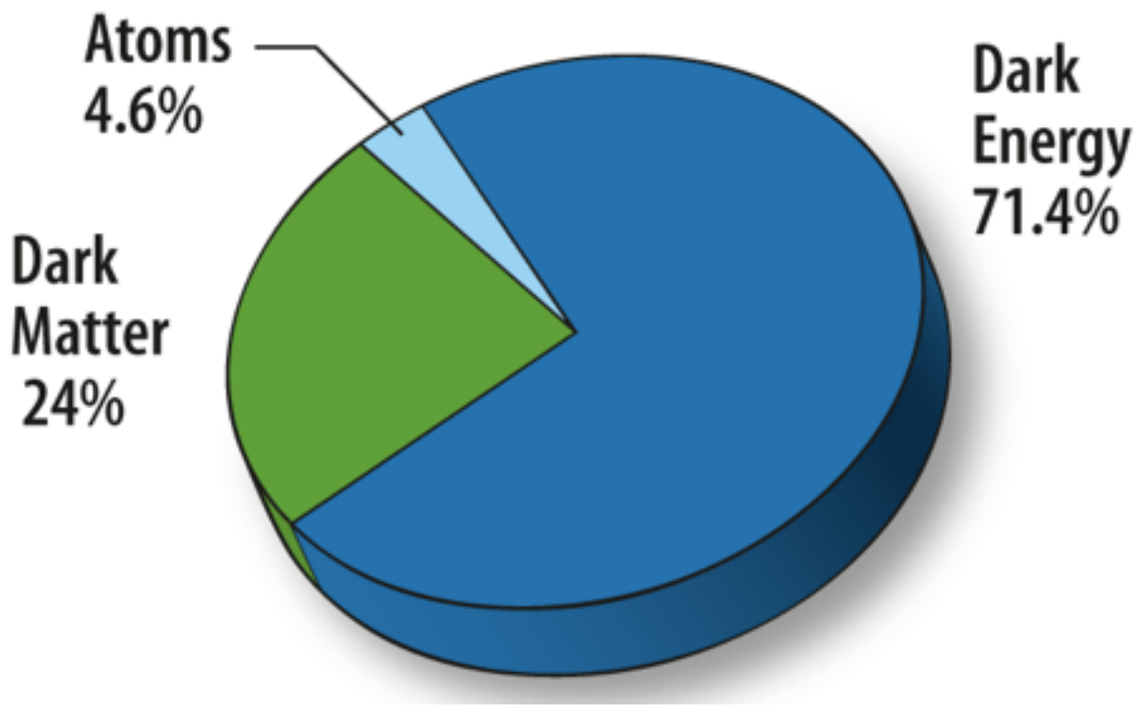
Fundamental Physics Today

➡ **Dark Matter: the matter we can not see**

- first proposed as a concept by Oort and Zwicky in the ~1930th
- confirmed by Rubin and Ford in galaxy rotation curves ~1960-70th
- evidence through gravitational effects only
- leading candidate: weakly interacting massive particle





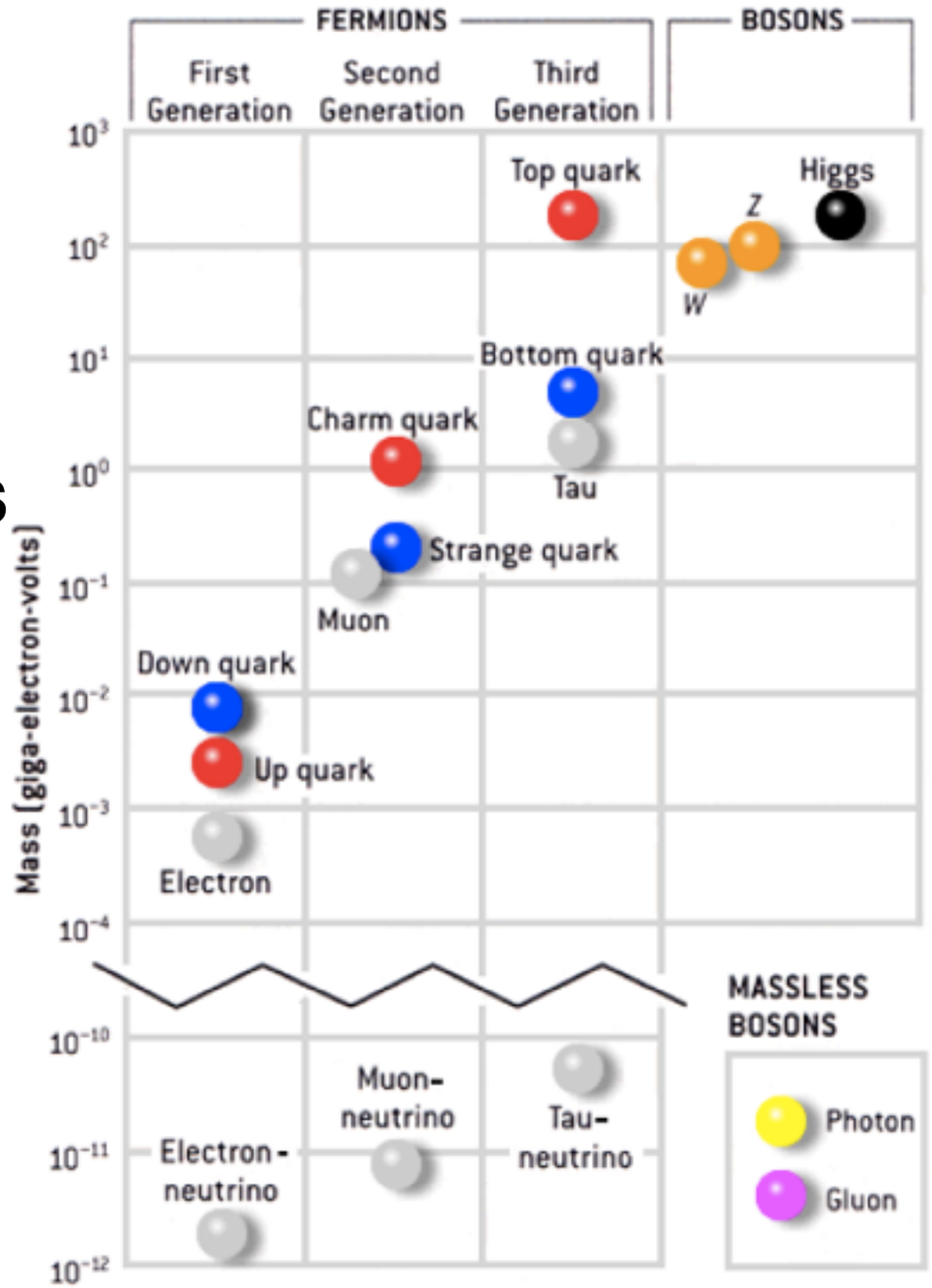


Fundamental Physics Today

➡ **Baryon matter asymmetry**

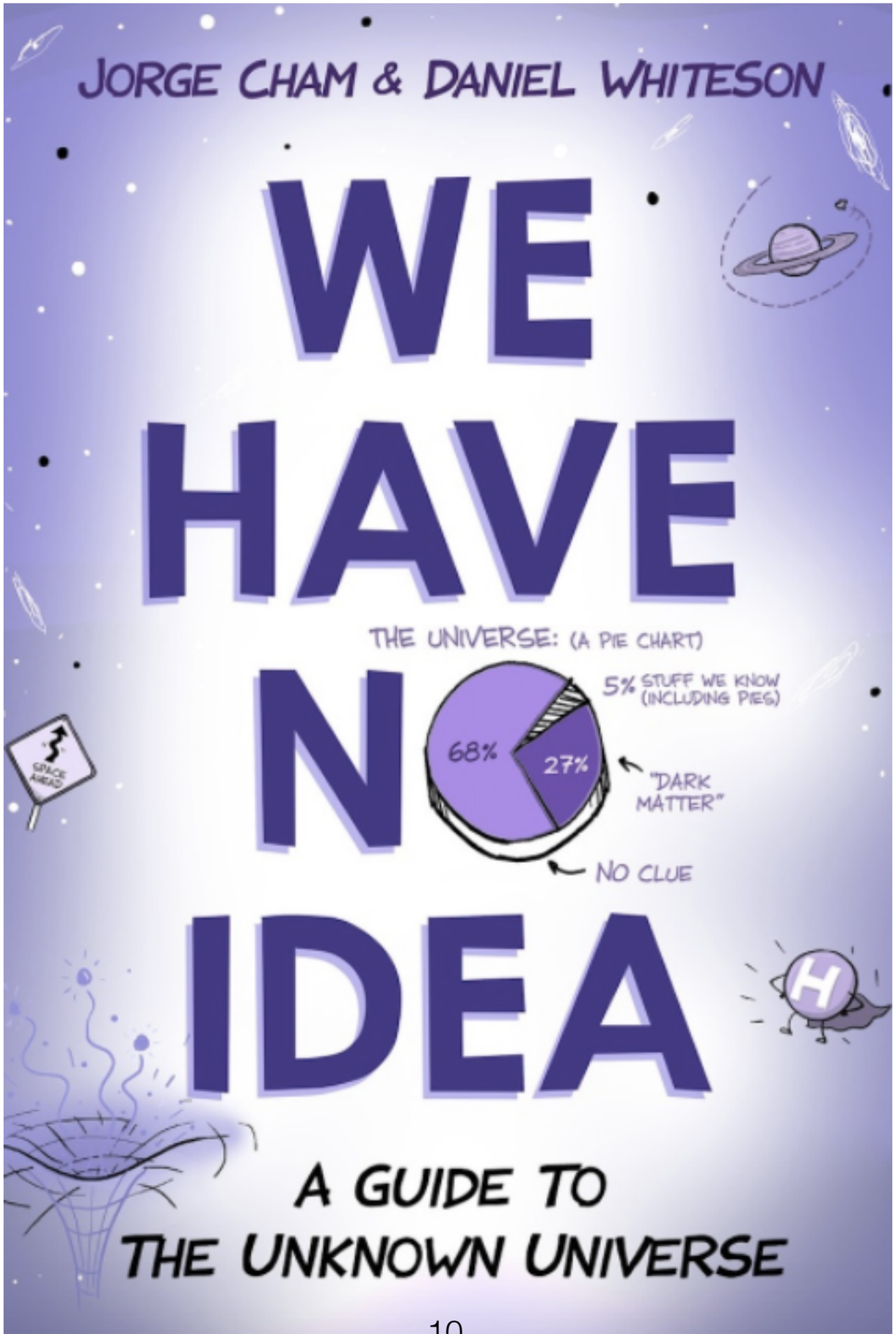
Fundamental Physics Today

How do particles acquire mass?



Why do they have these masses?

Why are neutrino masses tiny?

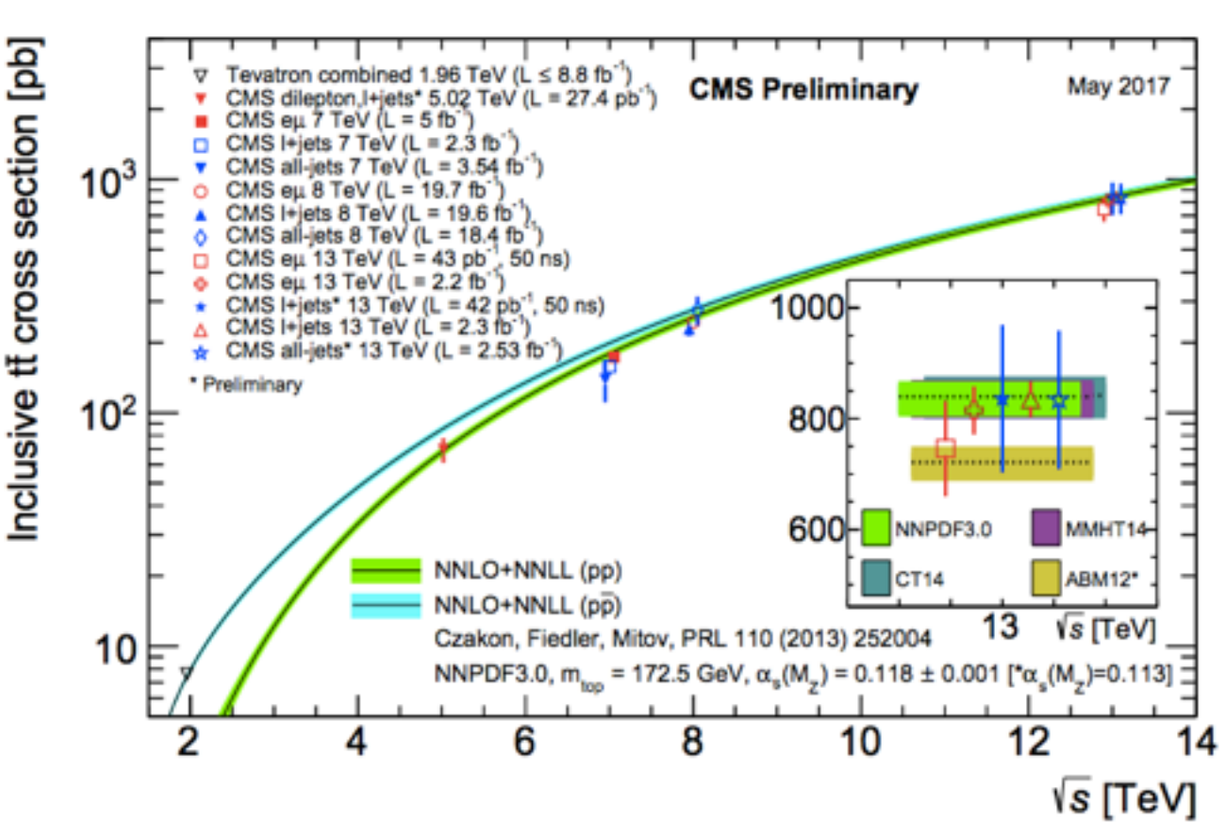

JORGE CHAM & DANIEL WHITESON
WE HAVE NO IDEA
A GUIDE TO THE UNKNOWN UNIVERSE
THE UNIVERSE: (A PIE CHART)
5% STUFF WE KNOW (INCLUDING PIES)
68%
27%
"DARK MATTER"
NO CLUE
SPACE AHEAD
H

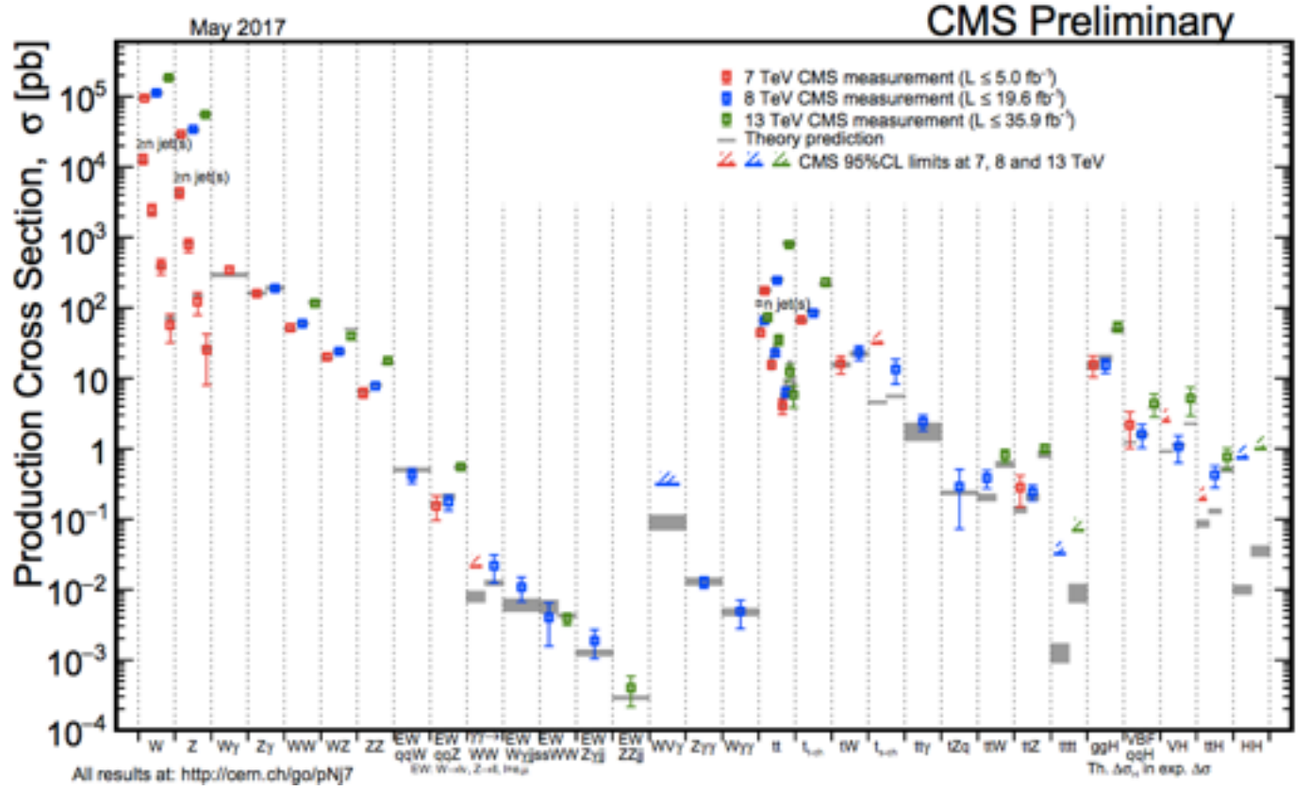
Fundamental Physics Today

➡ **… wait a minute**

➡ Standard Model of Particle Physics is very predictive

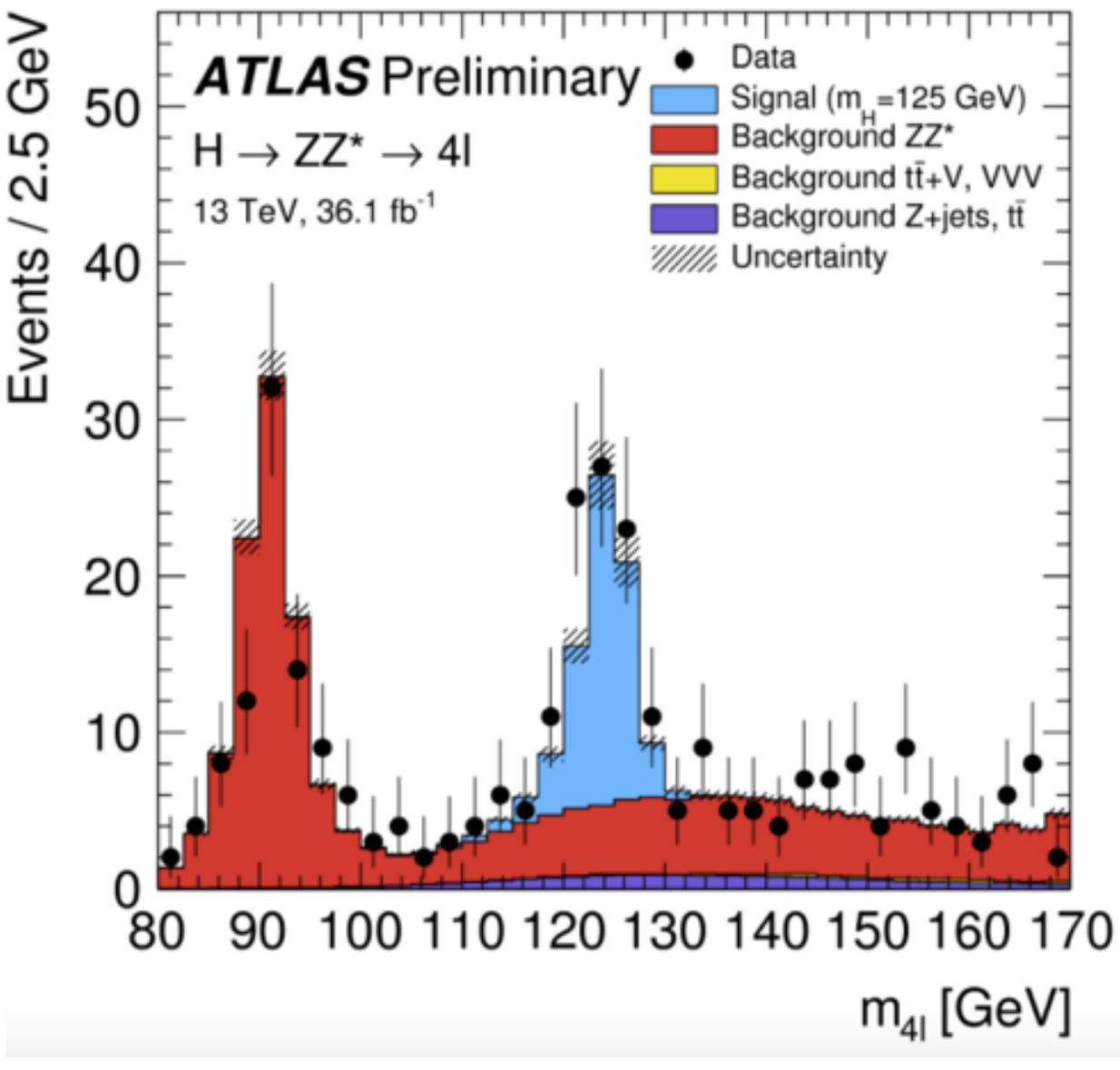
- there are a finite number of free parameter
- “infinite” number of measurements are in excellent agreement

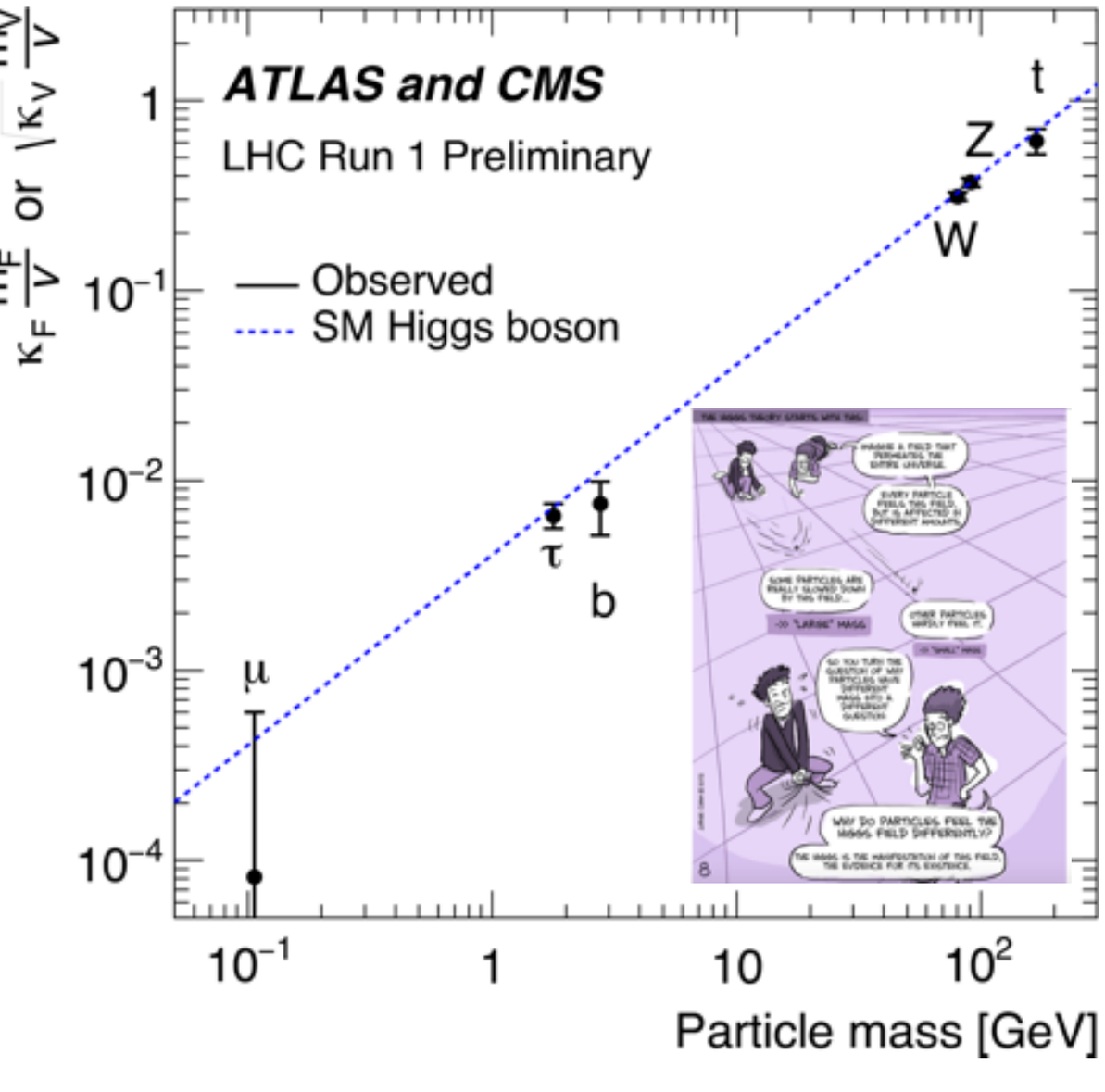




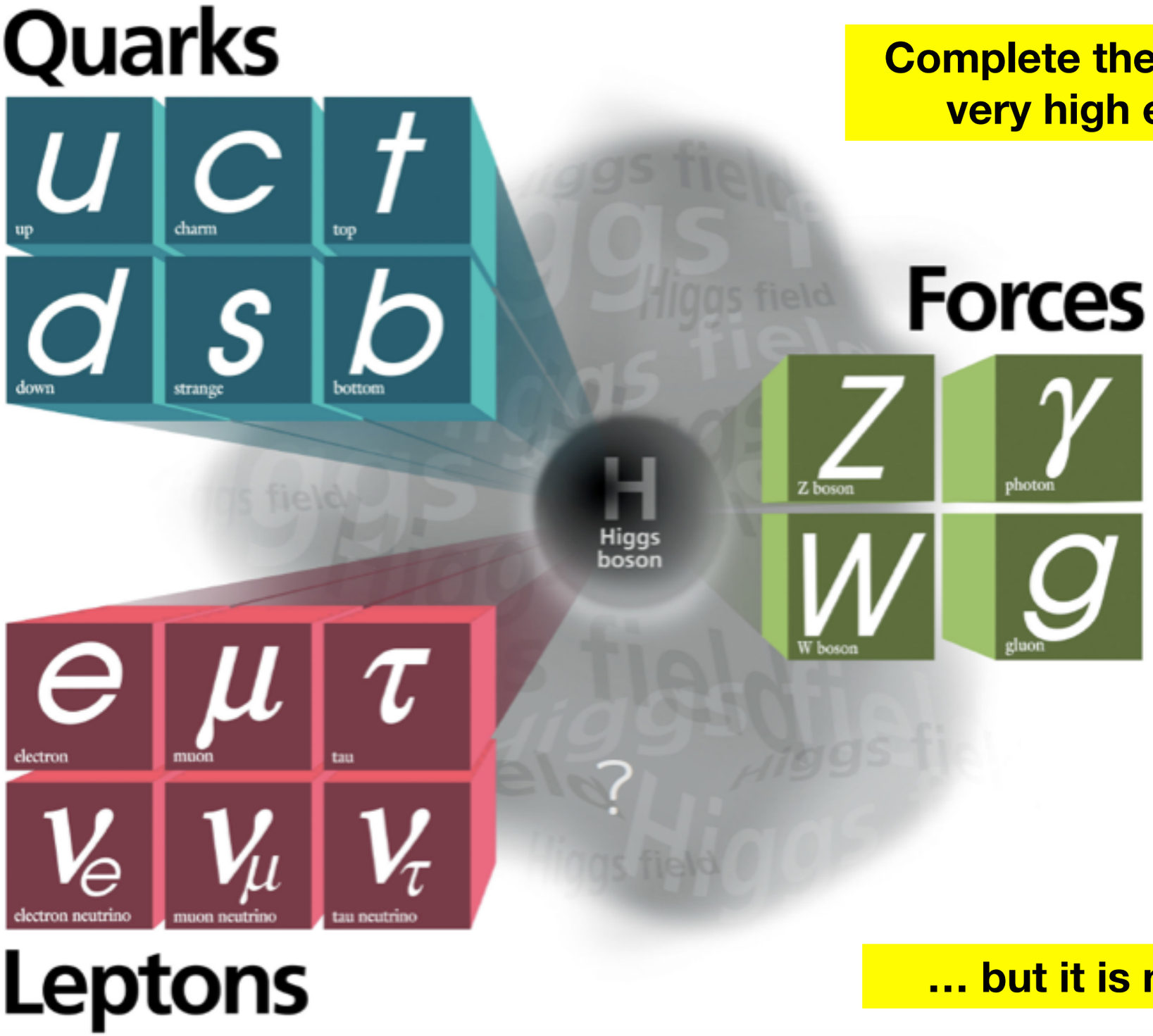
Fundamental Physics Today

- Standard model did not only predict the outcome of scattering experiments, but also the existence of a new particle and it's properties - **the Higgs boson**





Fundamental Physics Today



Complete theory valid to very high energies

… but it is not enough

Experimental Approach

Study particle interaction, resulting reaction products and features
Measure energy, direction and identity of collision products

➡ **The highest energies allows us to**

- look deep into matter “powerful microscope”: E ~ 1/size

de Broglie

Experimental Approach

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Measure energy, direction and identity of collision products

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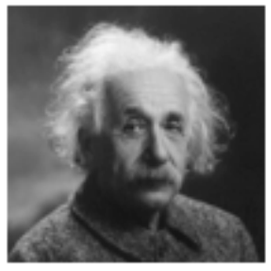
de Broglie

- produce heavy particles: $E = mc^2$


Einstein

Experimental Approach

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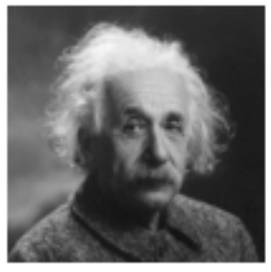

Einstein

- probe conditions of the early universe: $E = kT$


Boltzmann

Experimental Approach

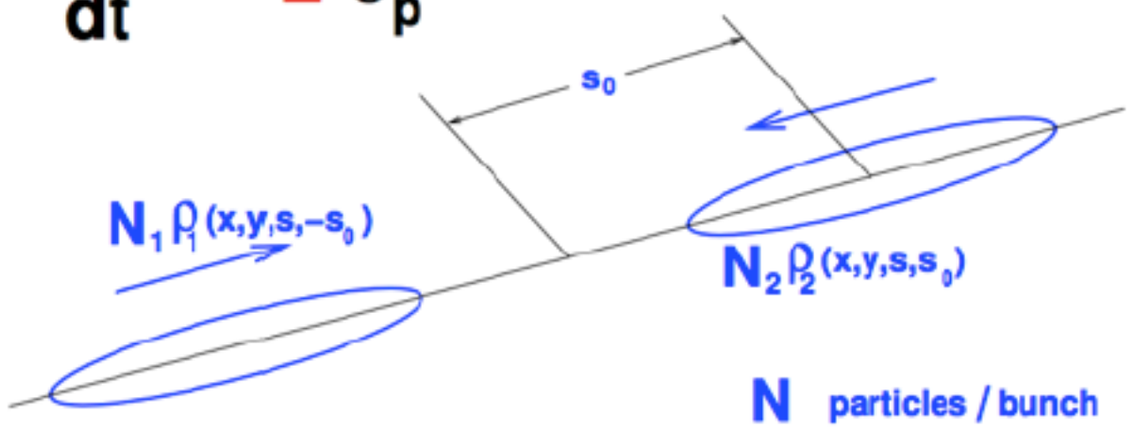
➡ Elements of collider

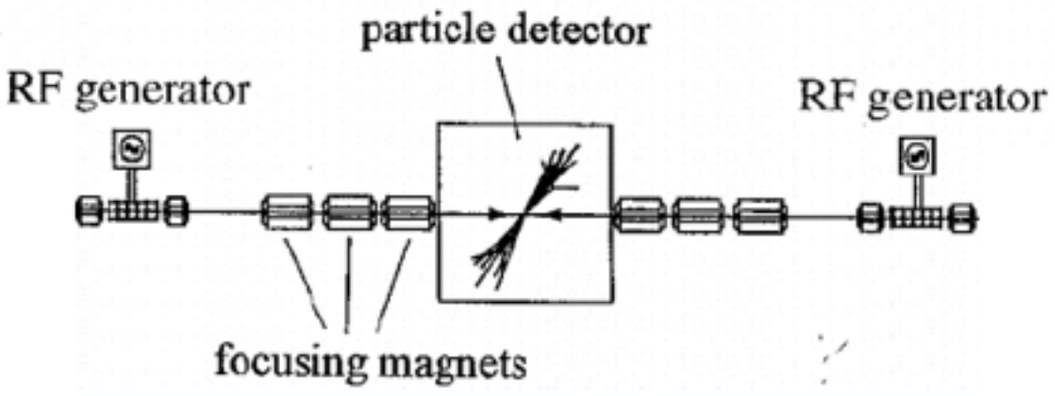
Key collider parameter

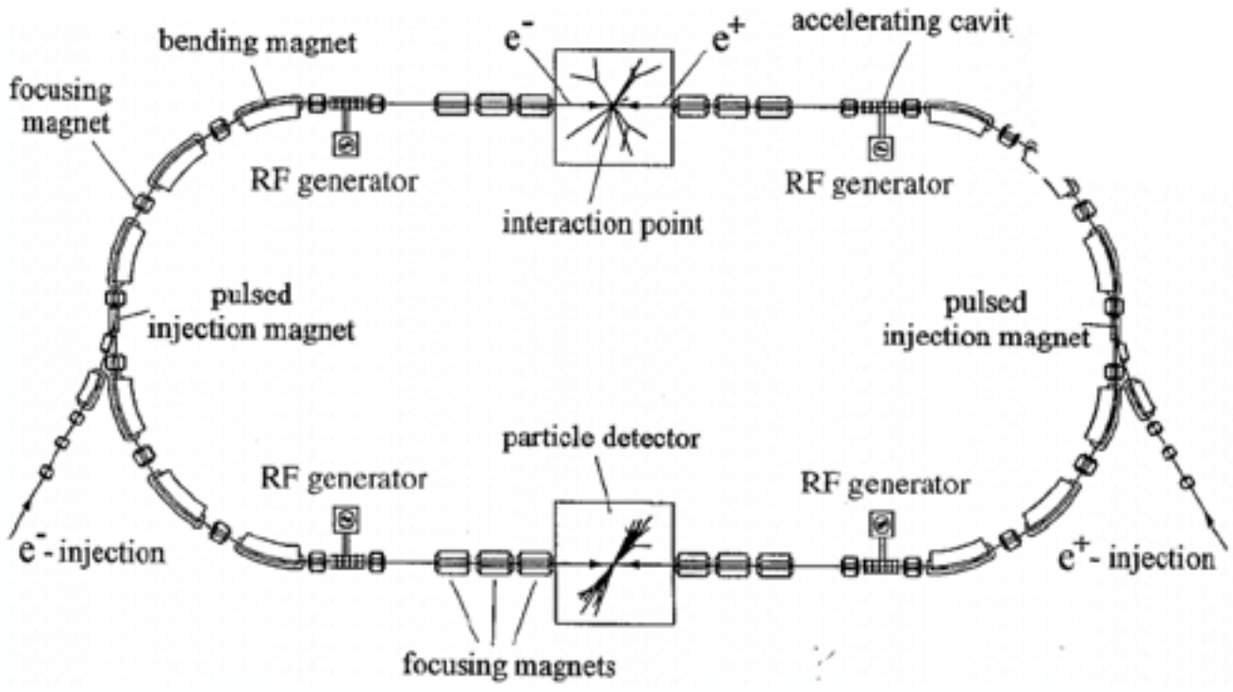
$$E_{\mathrm{cm}}^2 = (E_1 + E_2)^2$$

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$

$$\frac{dR}{dt} = L\,\sigma_p$$







Experimental Approach

➡ **Linear** **vs** **Circular**

- no synchrotron radiation
- no bending magnets
- currents and focusing are limiting L
- gradients are limiting E
- limited to one experiment

- accelerate over long distance by repetition
- recycle particles not used in collisions
- in principle, this leads to larger L and E

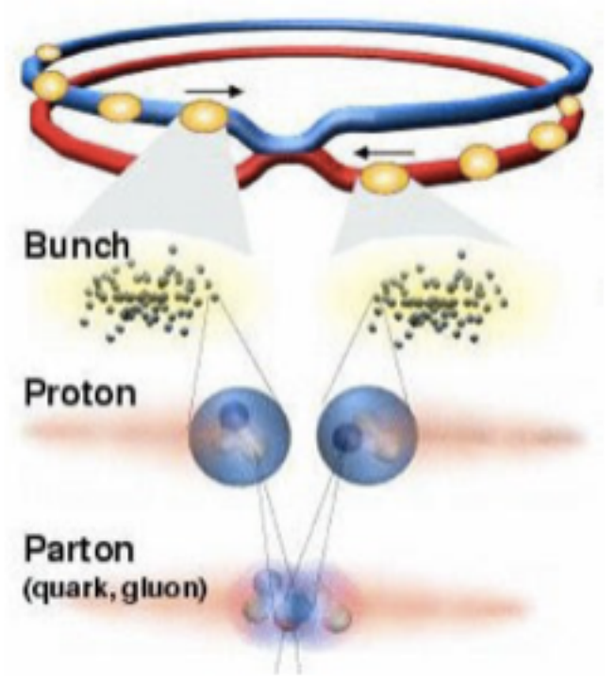
$$P_{\text{radiation}} = \frac{c}{6\pi\varepsilon_0} N \frac{q^2}{\rho^2} \gamma^4 \quad \Downarrow$$

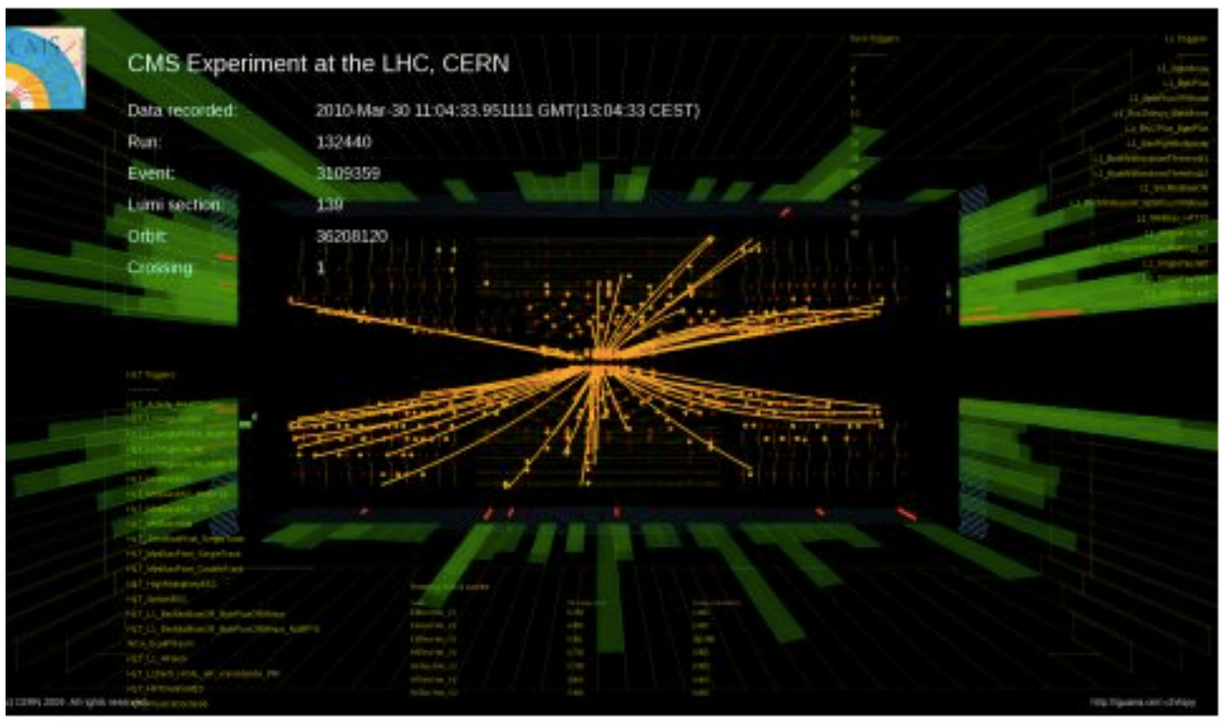
Energy needed to compensate

Radiation becomes too large

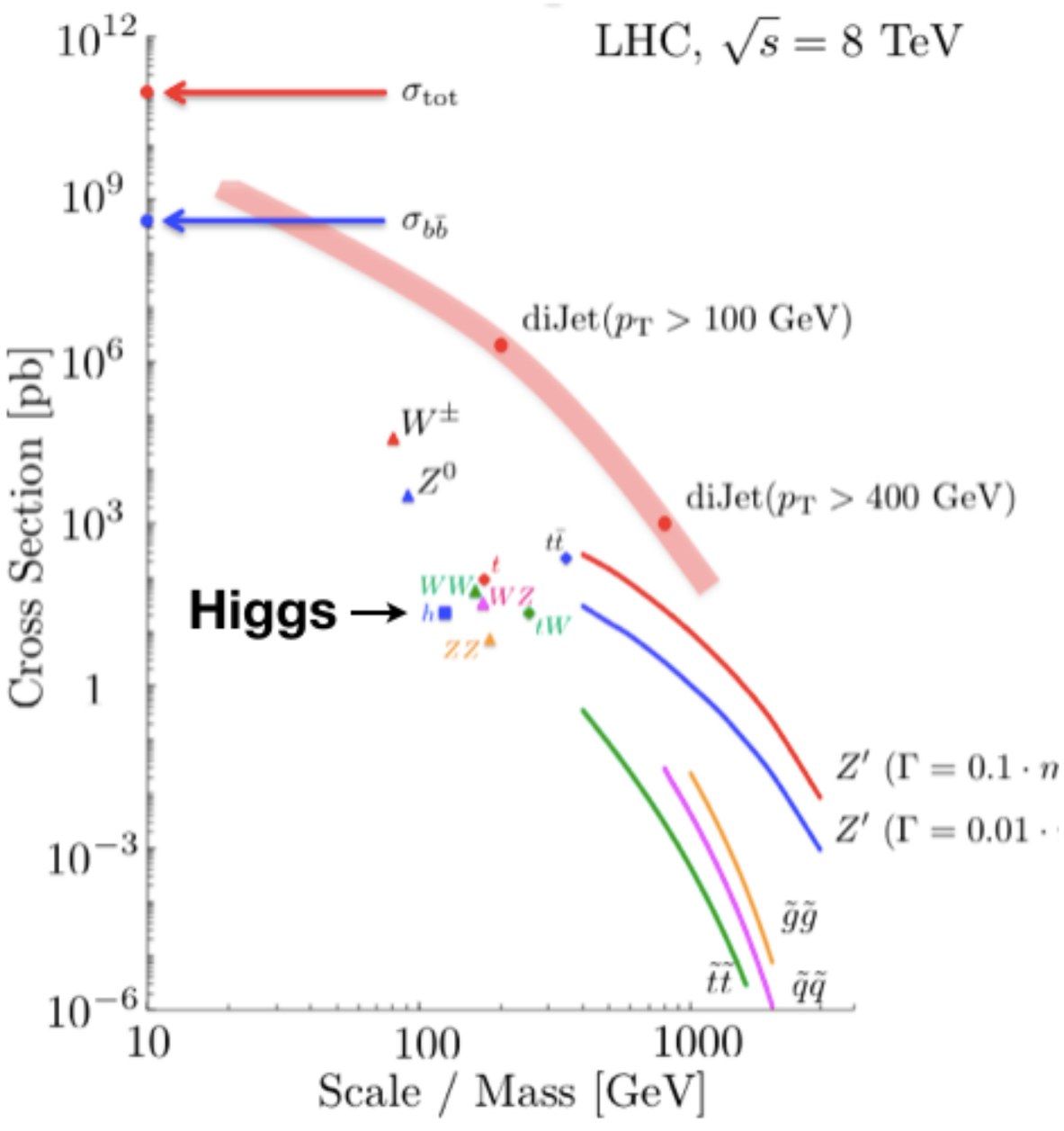
$$\rho = \frac{p}{qB} \quad \Rightarrow \quad \text{The rings become too long}$$

Experimental Approach

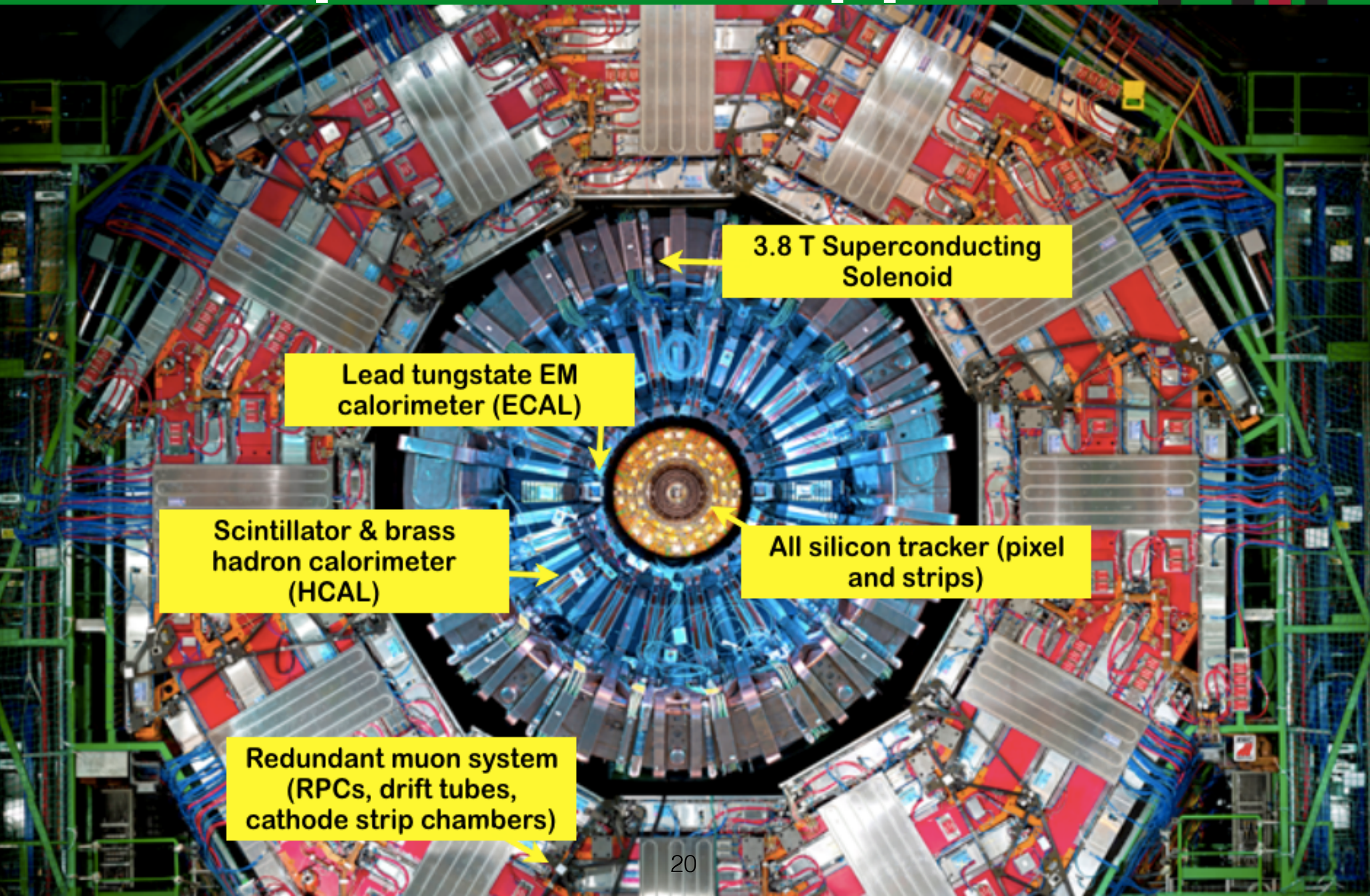




1 barn = 10^{-24} cm^2



Experimental Approach



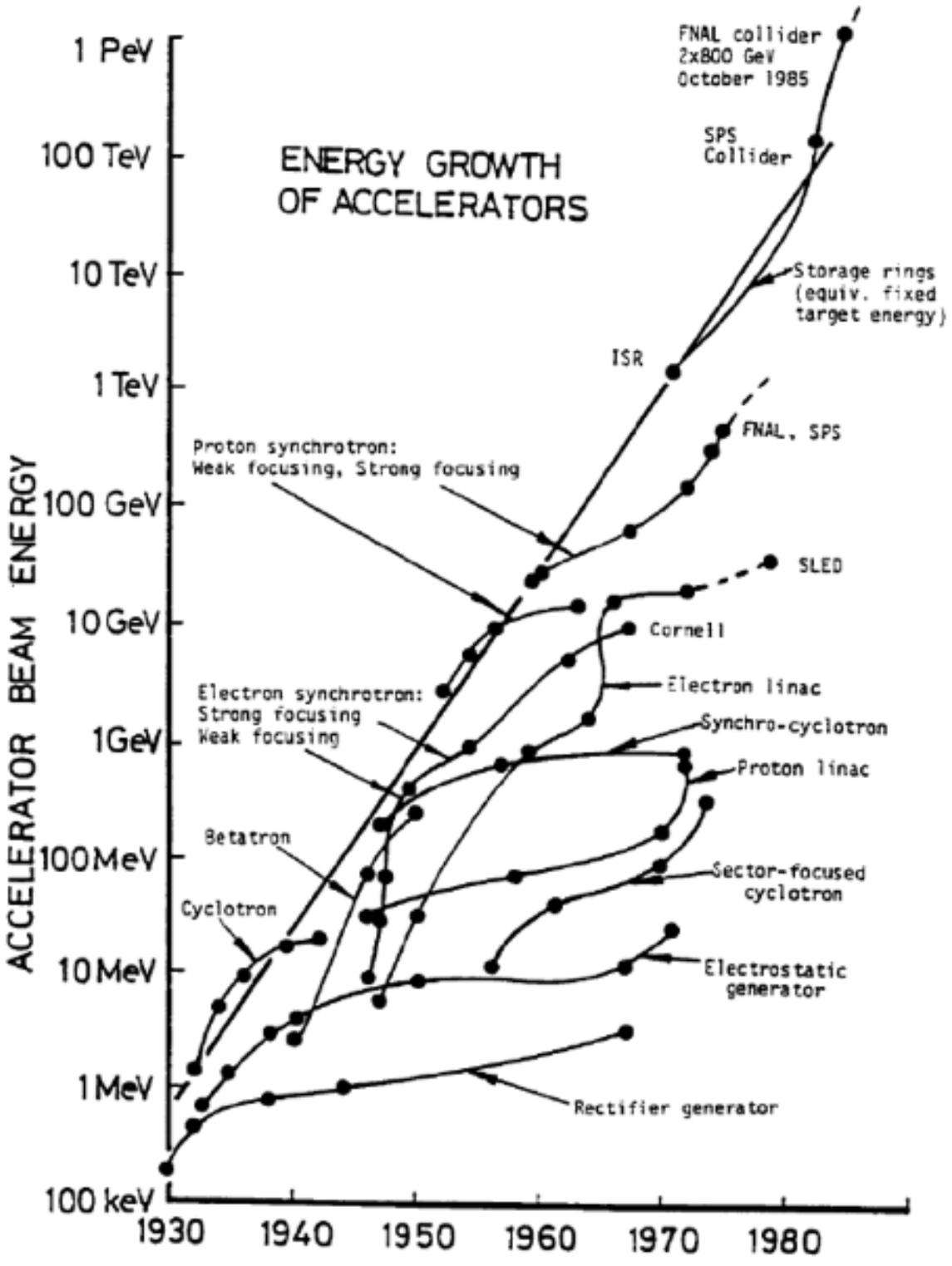
Experimental Approach

- **Hadron vs Lepton Collider**

"Every event at a lepton collider
is physics, every event at a
hadron collider is background."
- Sam Ting.

"All events (background)
are equal but some events
are more equal than others."
- George Orwell (Klute-fied)

Roadmap for Particle Physics



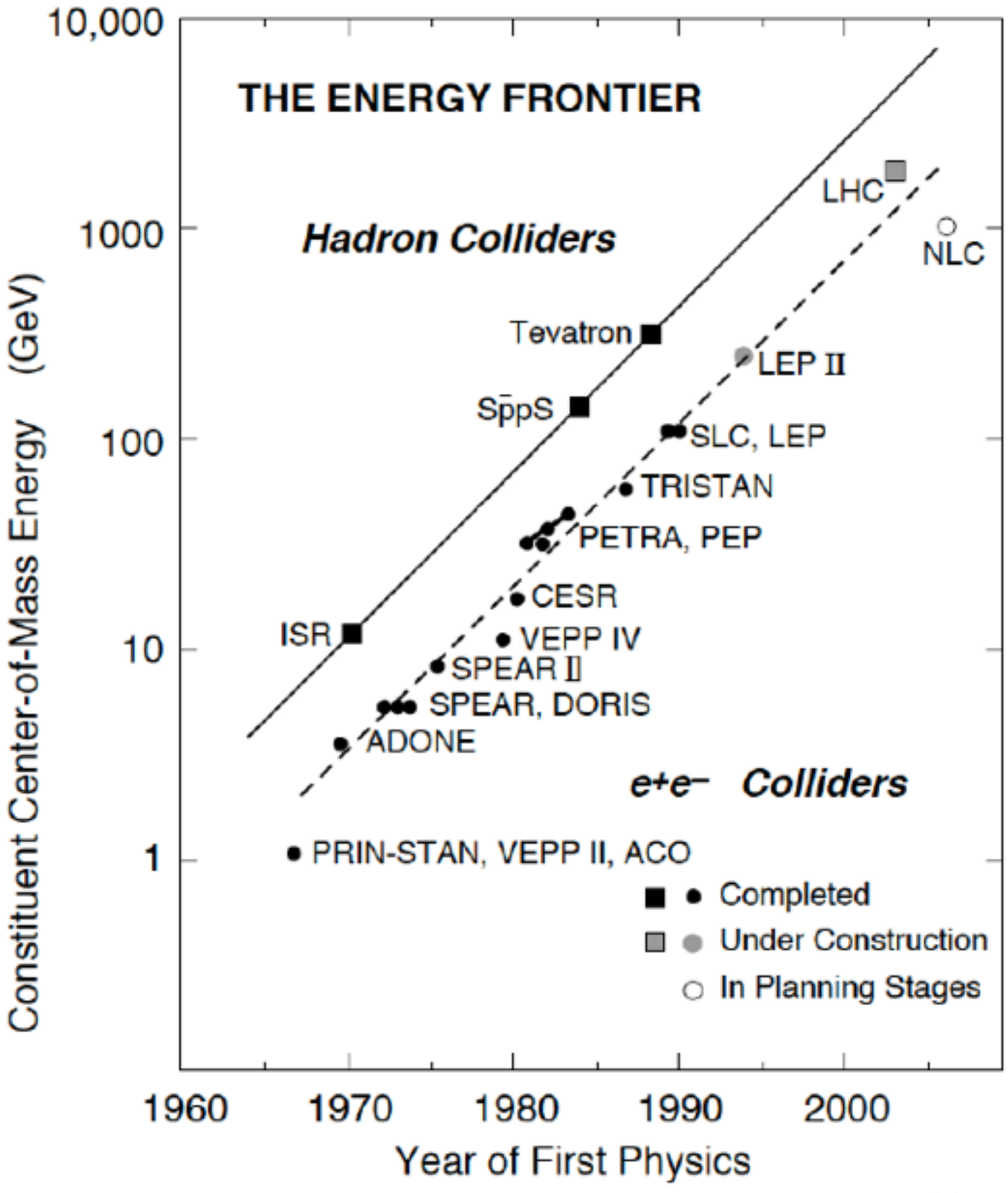
➡ Using history as a guide for the future

- The last ~100 year in particle physics with collider

➡ Livingston Plot ~1985

- nearly 6 decades of growth
- driven by continuous innovation
- pushing energy (discovery) frontier

Roadmap for Particle Physics



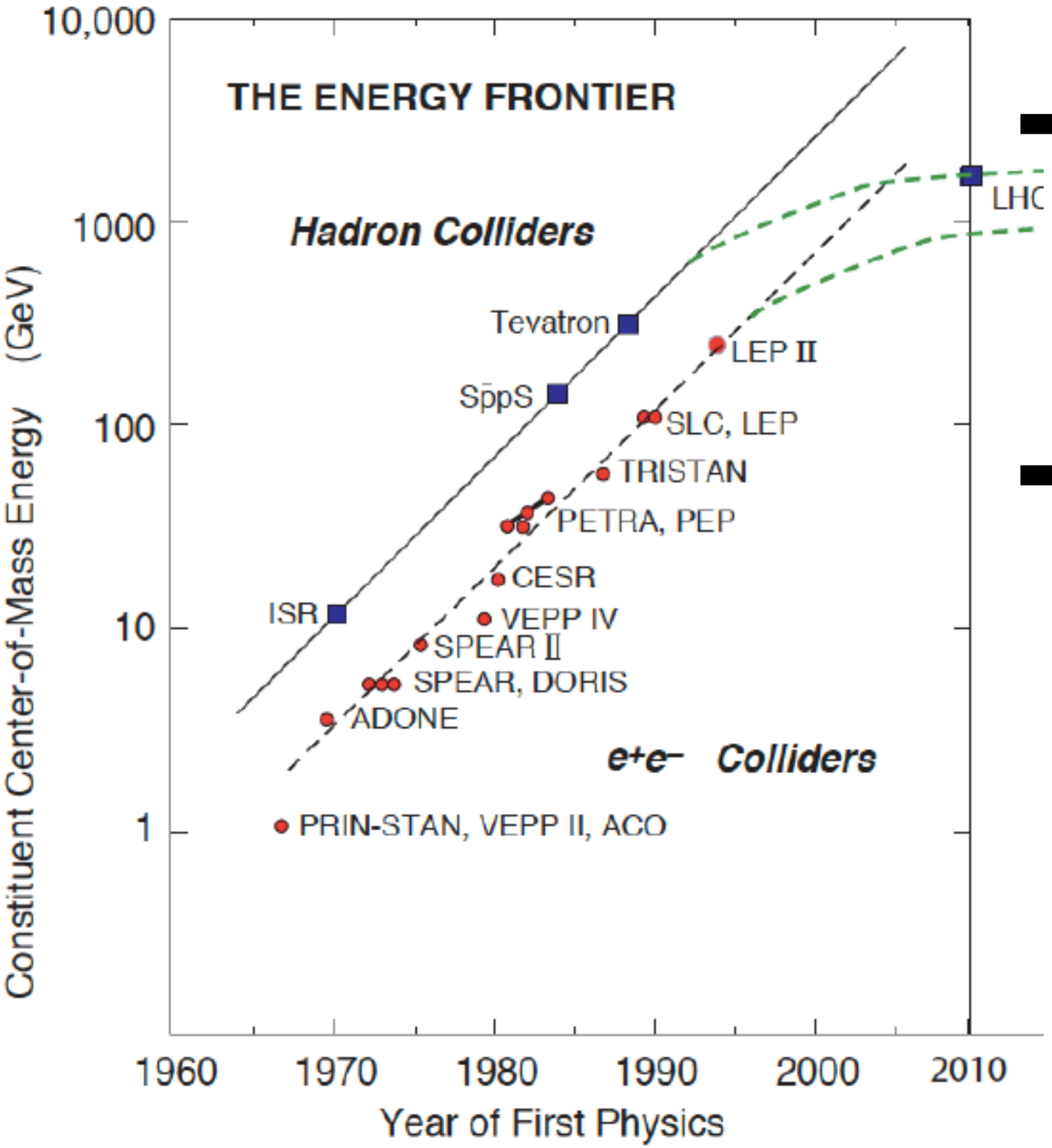
➡ Using history as a guide for the future

- The last ~100 year in particle physics with collider

➡ Livingston Plot ~1996

- It was clear that trend can not be continued into the 21st century
- SSC was meant to fall on the line!
- Two directions
  - electron-positron collider for precision measurements
  - energy frontier hadron collider

Roadmap for Particle Physics



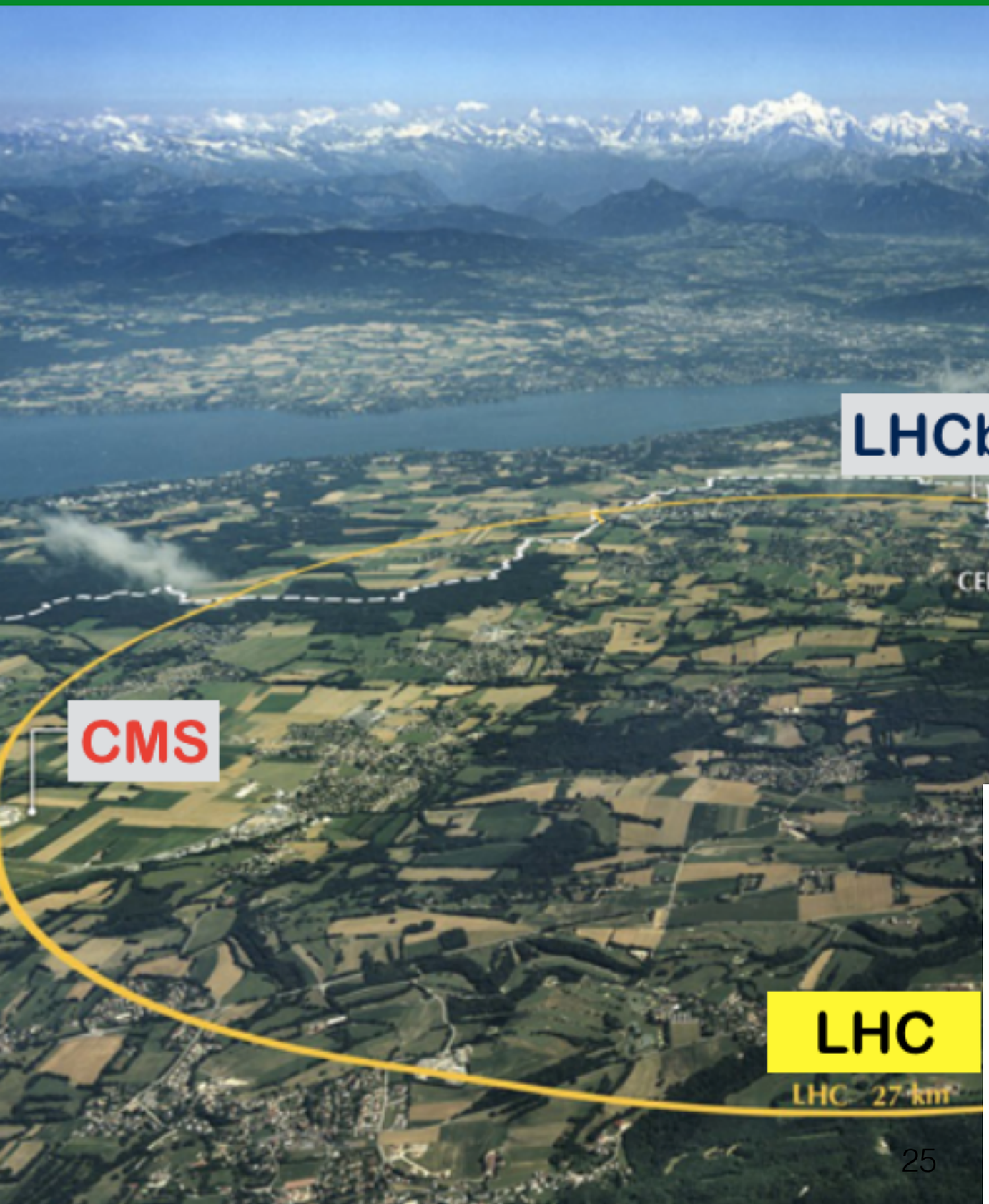
➡ Using history as a guide for the future

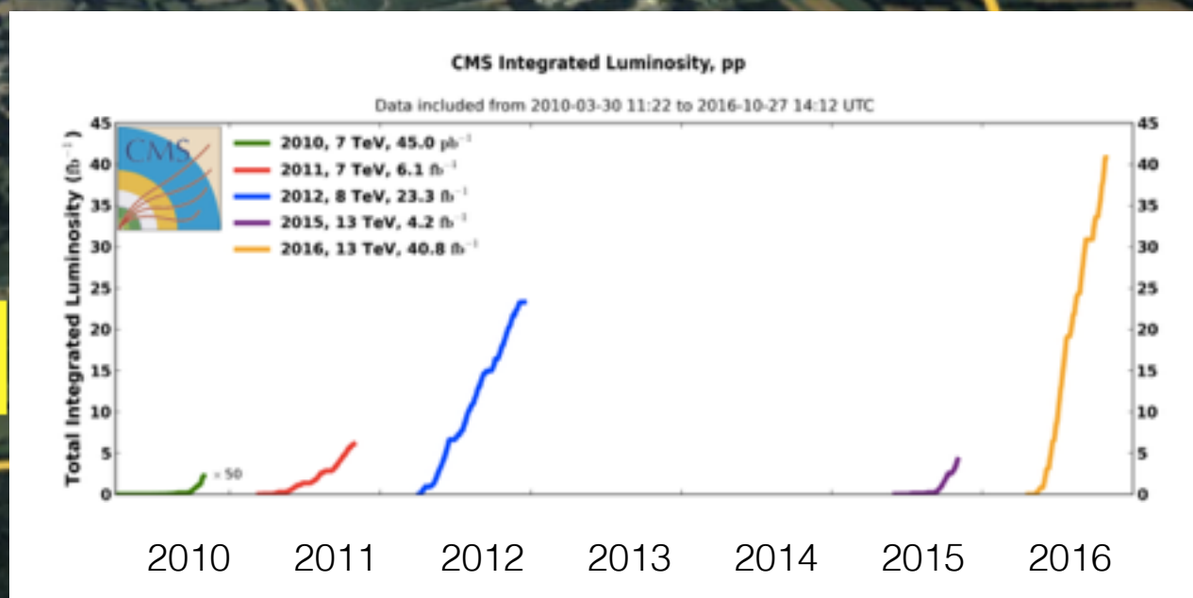
- The last ~100 year in particle physics with collider

➡ Livingston Plot ~2010

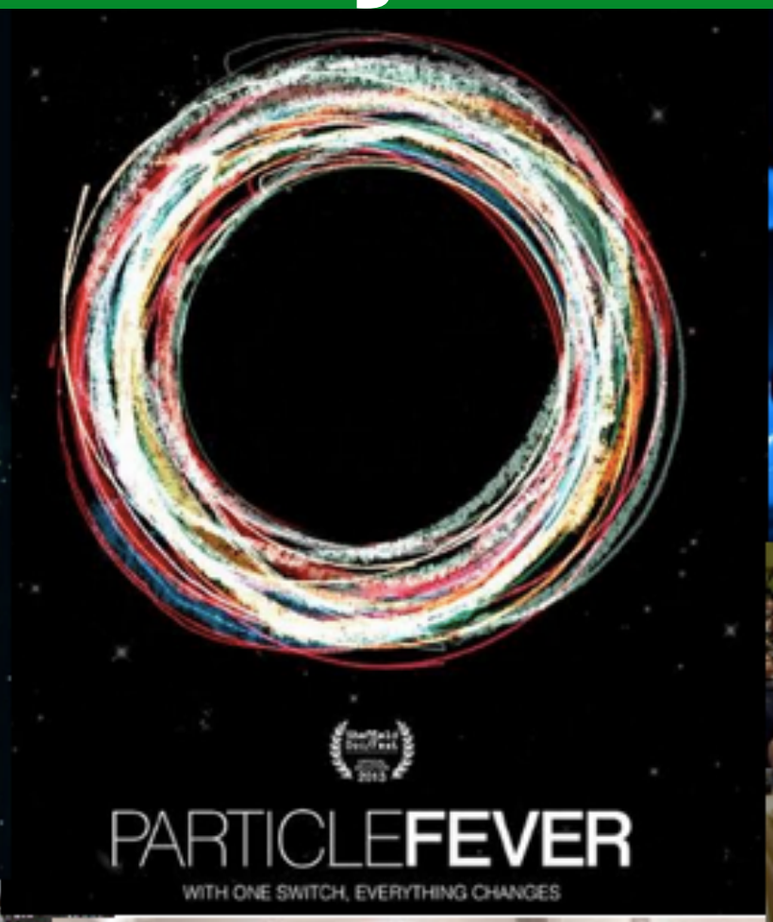
- Progress slowed down considerably
- Investment in accelerator technology is still large, but directed towards tools like light sources
- Limiting factor → cost (size)!

Roadmap for Particle Physics

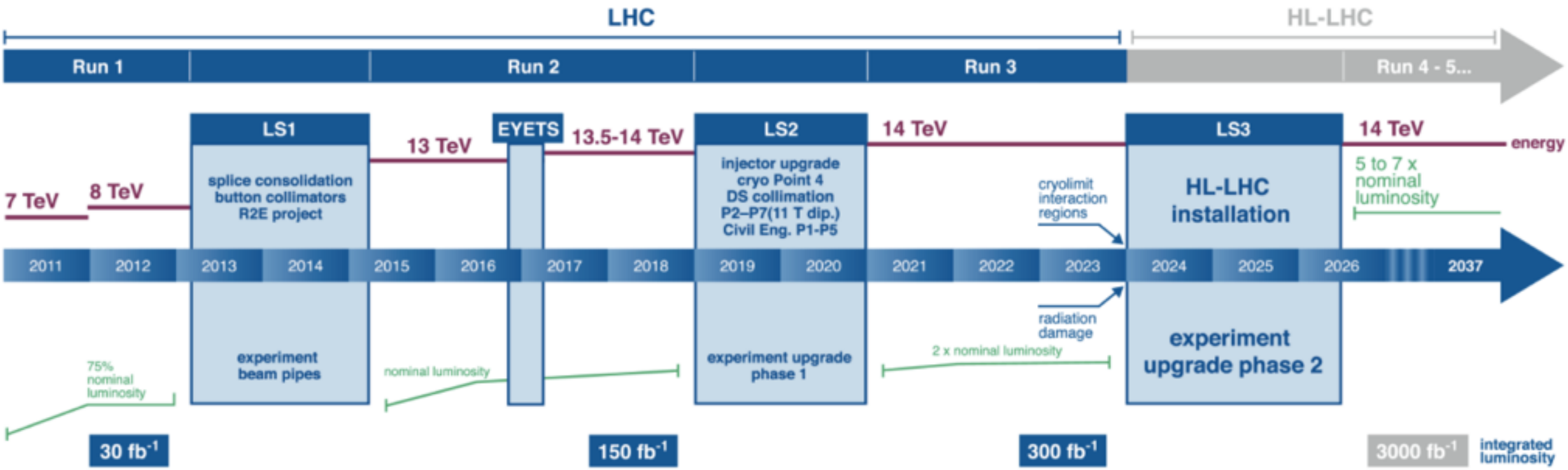


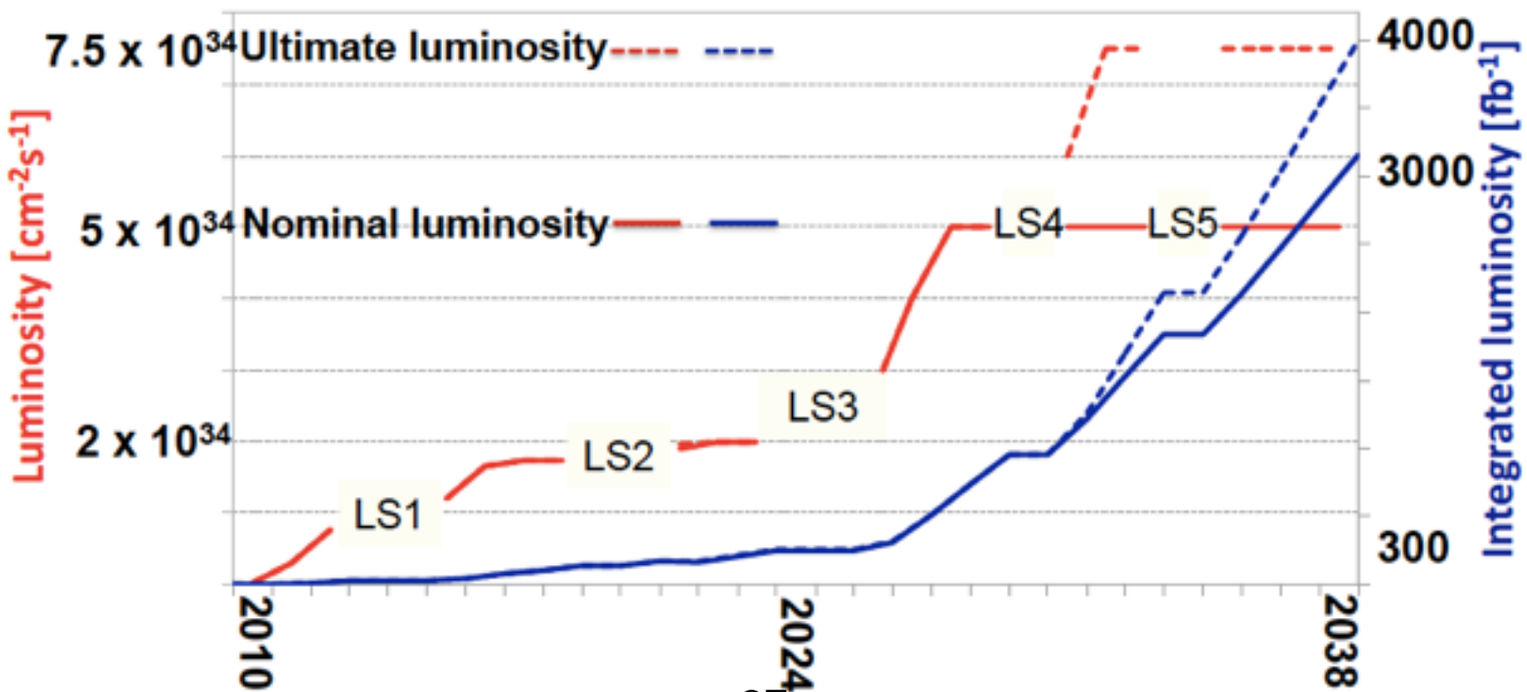


Higgs Discovery 2012

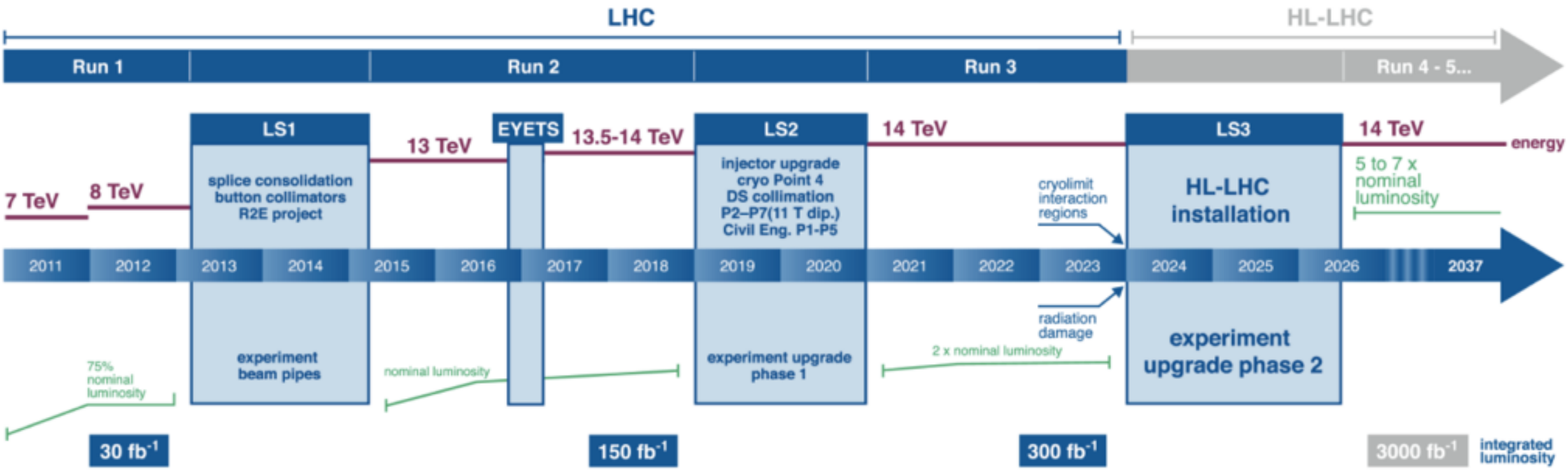


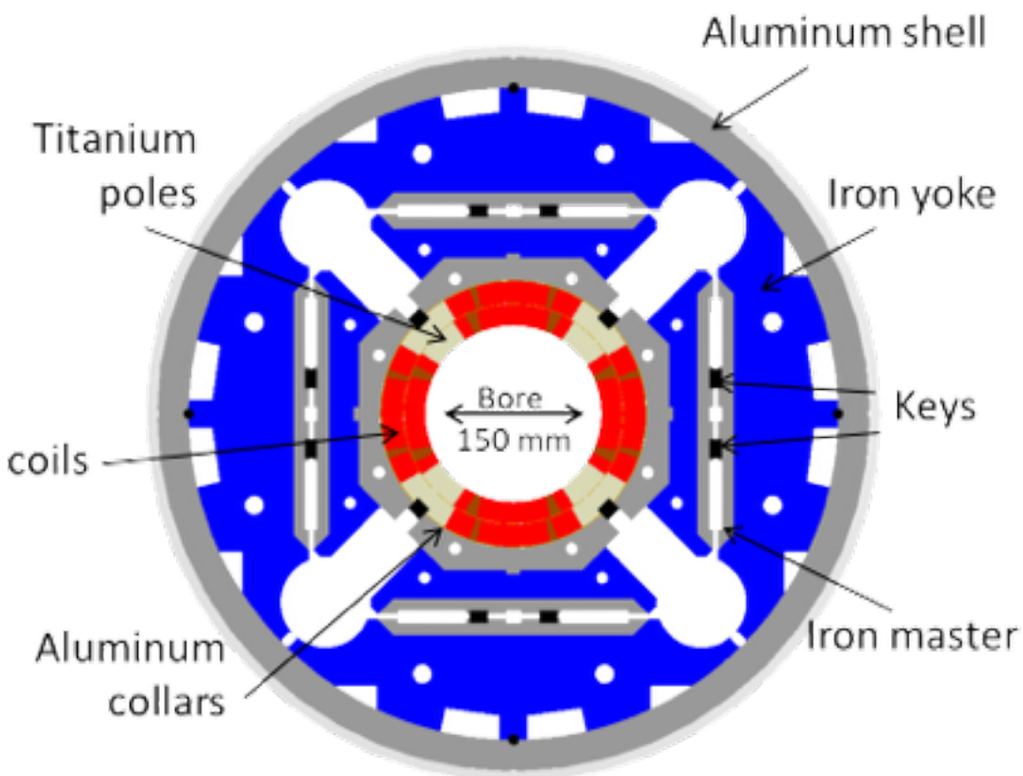
Roadmap for Collider Experiments





Roadmap for Collider Experiments





- **LHC dipoles stretched NbTi technology to its limit**
  - 8.3T in central region via operation at 1.8k
- **HL-LHC needs new technology in iteration region: Nb_3SN**
  - 12T quadrupoles with 150mm aperture to shrink β*
- **Operating and upgrading the LHC is a very significant investment**

HL-LHC Physics Case

➡ **Higgs case at the start of the LHC was exceptional**

- something to built on, not the reference

➡ **Goal for the future LHC and HL-LHC program**

- **Explore the energy frontier**

➡ **Precision measurements of SM parameters (including the Higgs boson)**

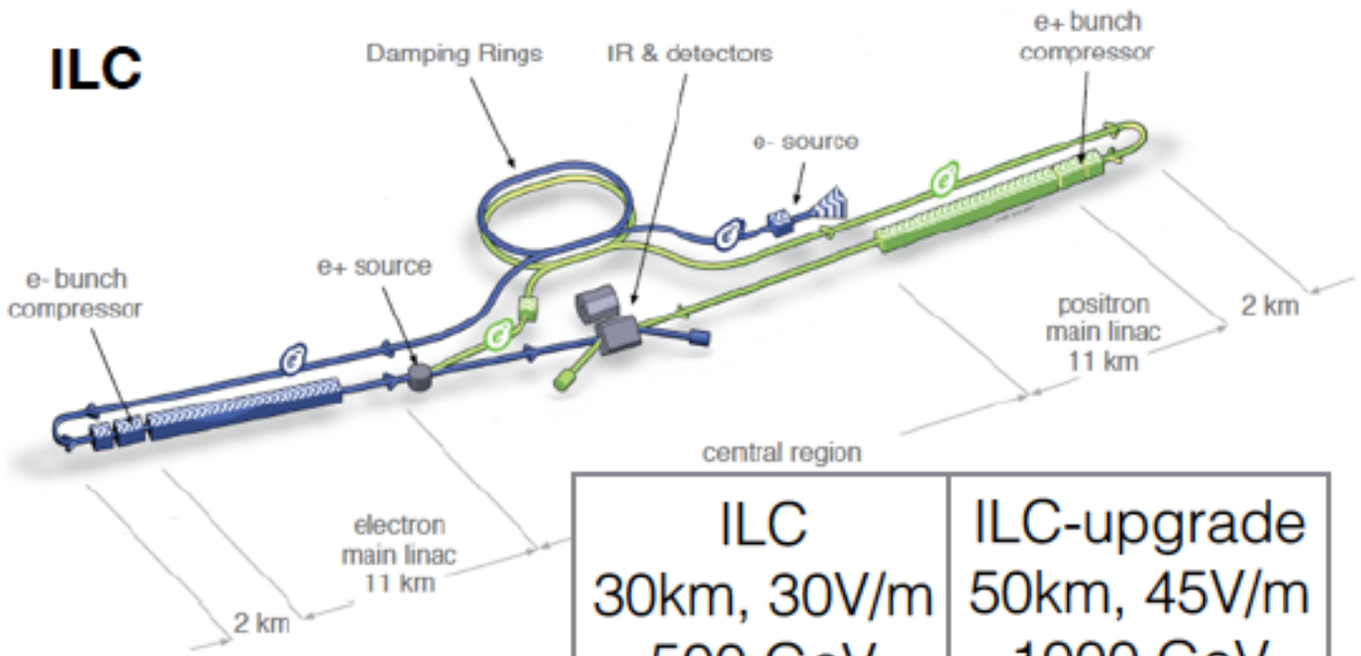
➡ **Sensitivity to rare SM & rare BSM processes**

➡ **Extension of discovery reach in high-mass region**

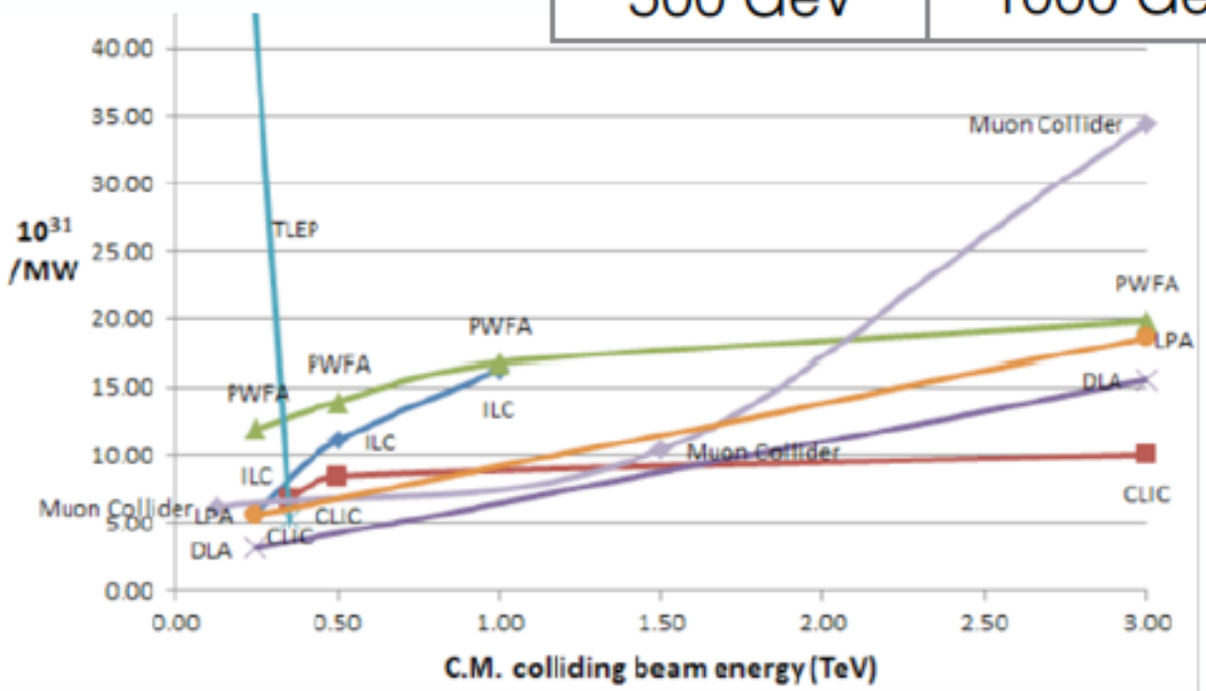
➡ **Determination of BSM parameter**

Roadmap for Particle Physics

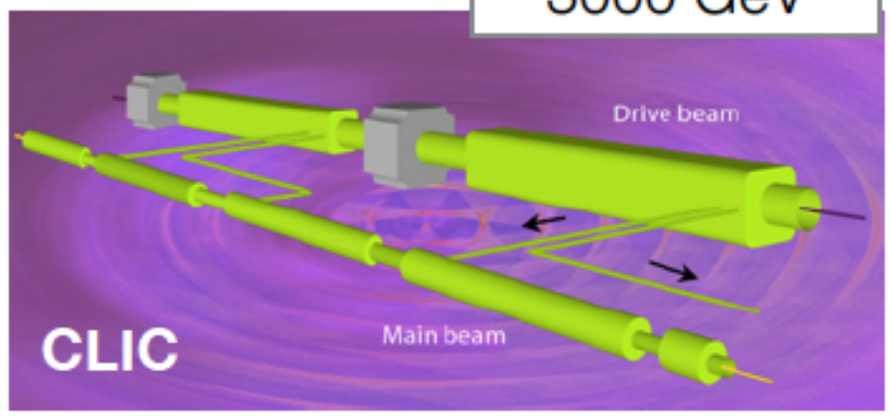
➡ Future Lepton Collider



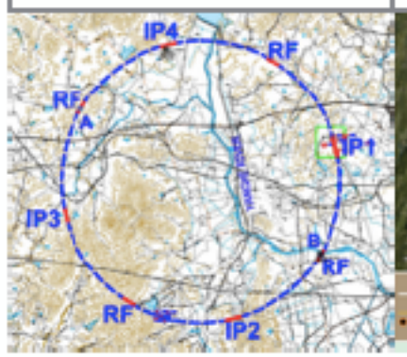
ILC	ILC-upgrade
30km, 30V/m	50km, 45V/m
500 GeV	1000 GeV



CLIC
50km, 100V/m
3000 GeV



CEPC	FCC-ee
50km	100km, 200MV
240 GeV	350 GeV

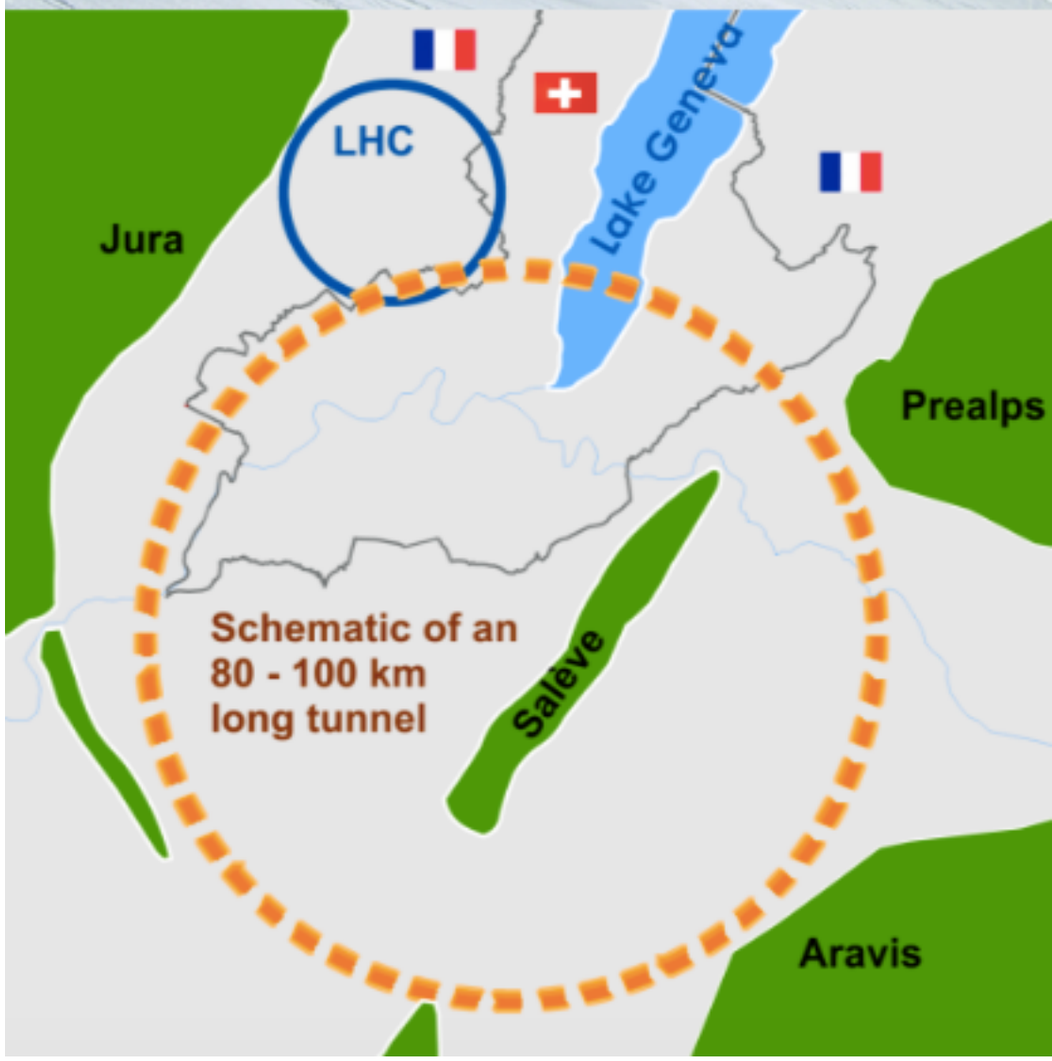


Future Circular Collider (FCC-ee)

Circular Electron Position Collider (CEPC)

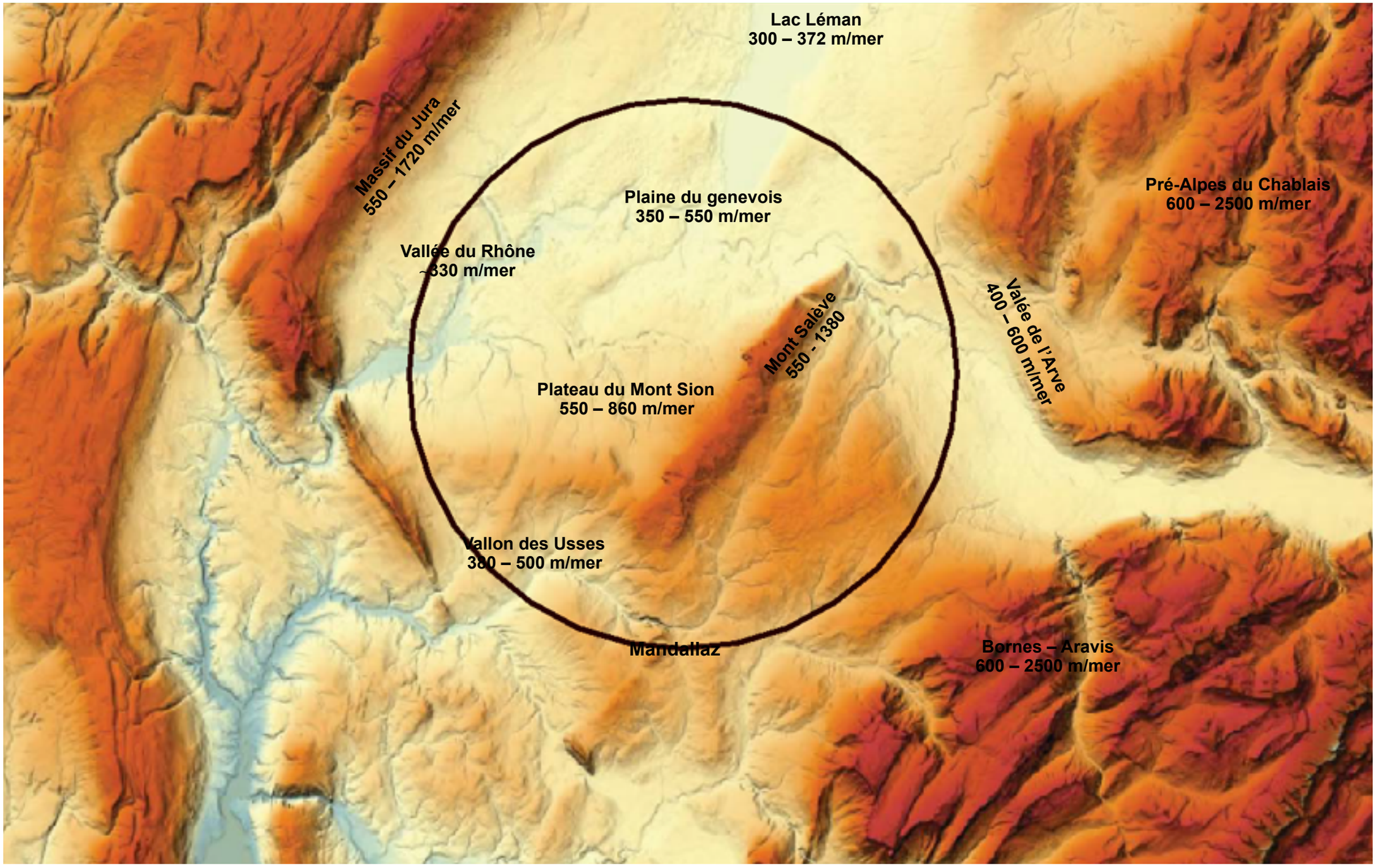
Roadmap for Particle Physics

- **International FCC collaboration to study**
  - pp collider (FCC-hh)
  - e^+e^- collider (FCC-ee)
  - p-e (FCC-he)
- 80-100 km infrastructure in Geneva area
- **Goal:** CDR and cost review by 2018
- Similar studies in China (50-70 km infrastructure)
  - pp collider (SppS)
  - e^+e^- collider (CepC)



Roadmap for Particle Physics

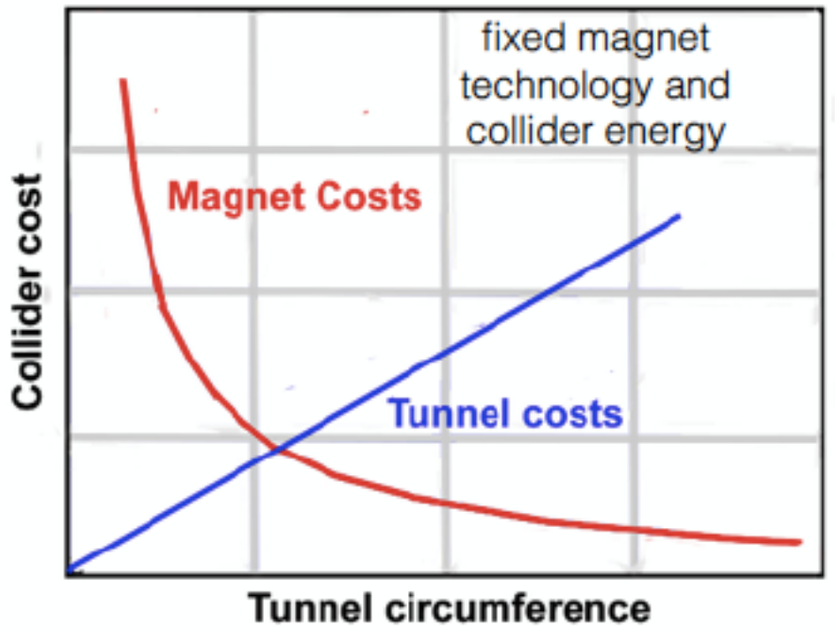
➡ Future Hadron Collider

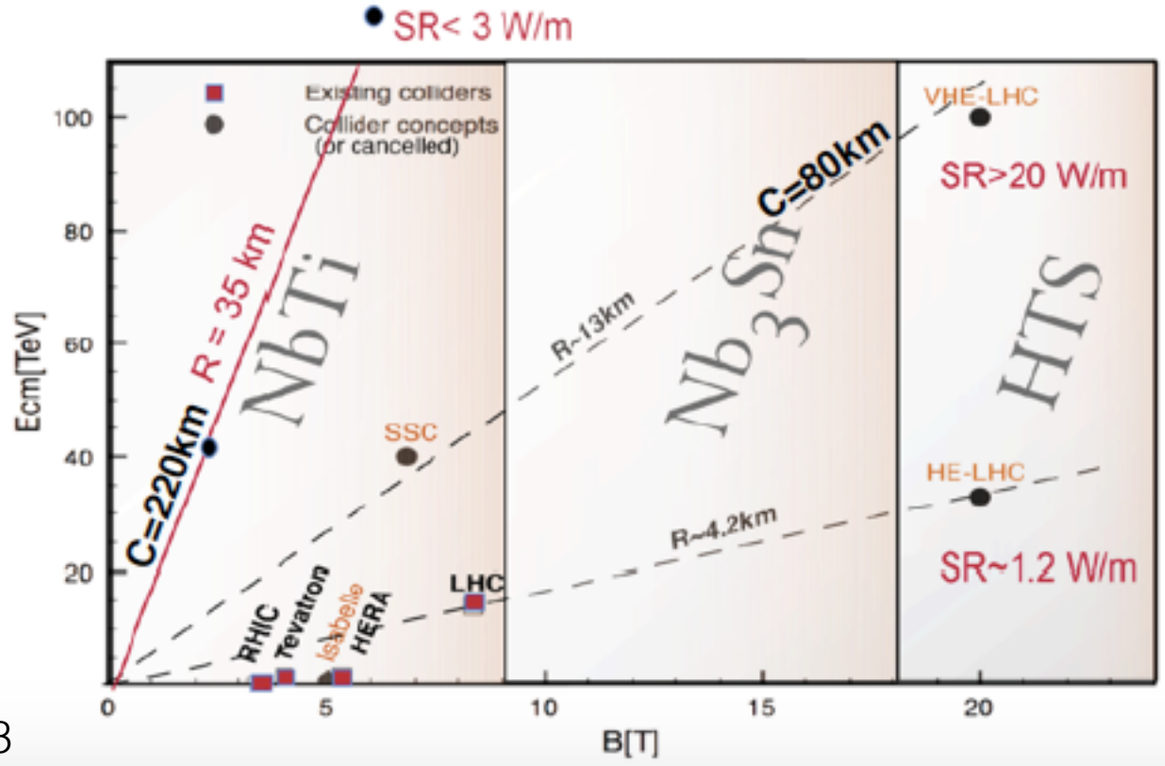


Roadmap for Particle Physics

➡ Future Hadron Collider Challenges

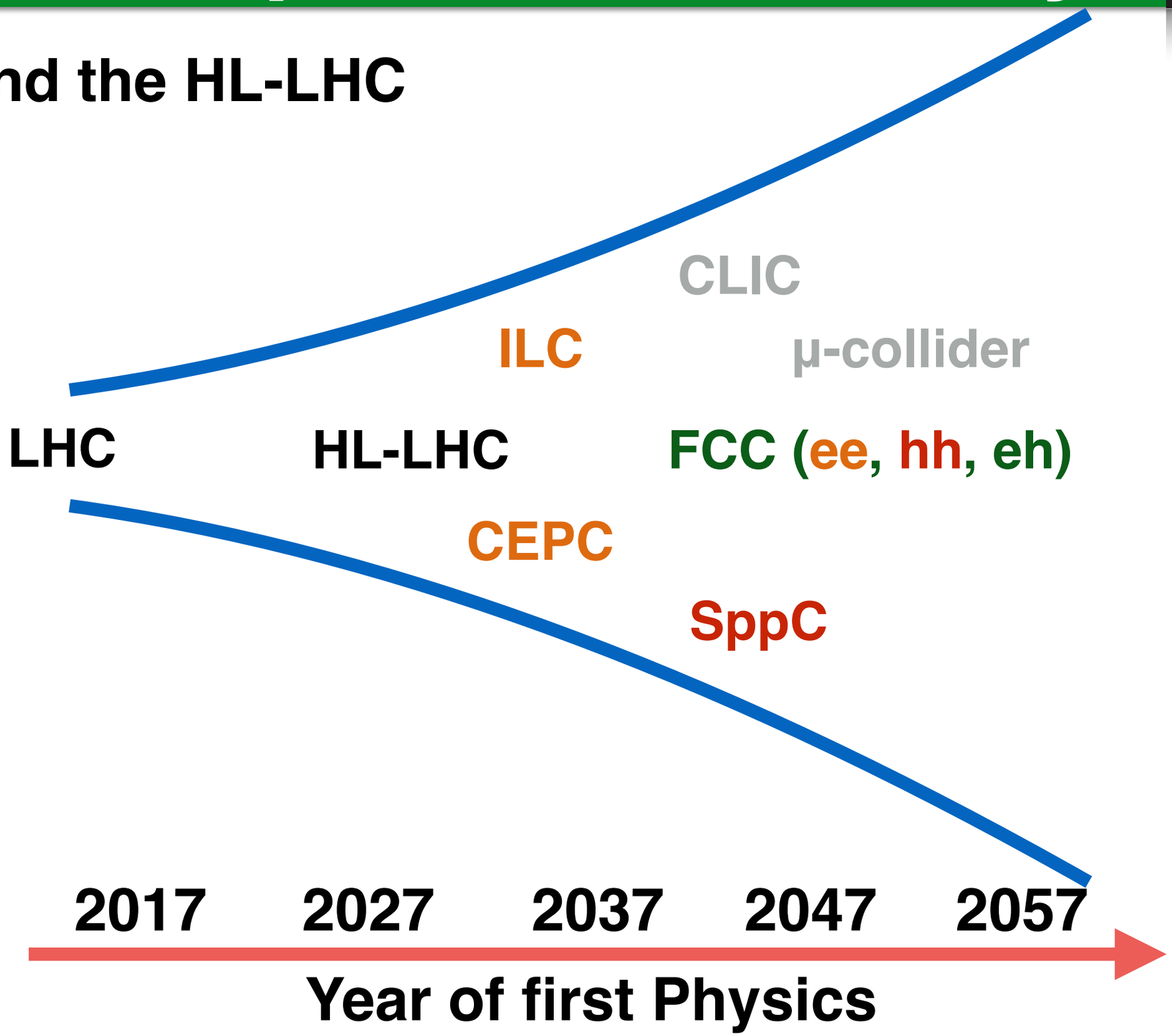
- **Overall construction cost**
  - cost driver are magnets and the tunnel
  - depend on magnet technology
  - tunnel cost highly geology dependent
- **Magnet technology**
  - Nb_3SN foreseen for HL-LHC
- **Total energy stored**
  - for 100km, 20T machine
    - ~200 GJ in magnet
    - ~10 GJ in beam,
  - both are very challenging (~20*LHC)
- **Proton synchrotron radiation**





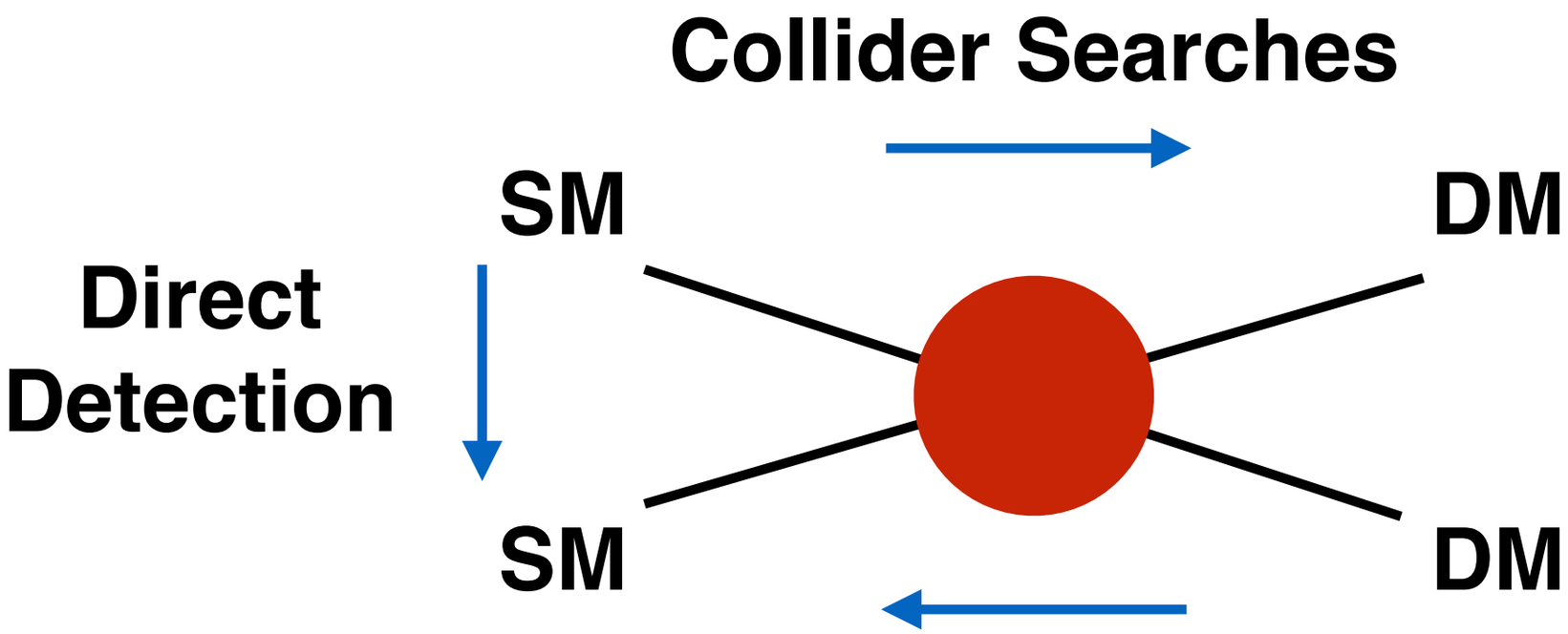
Roadmap for Particle Physics

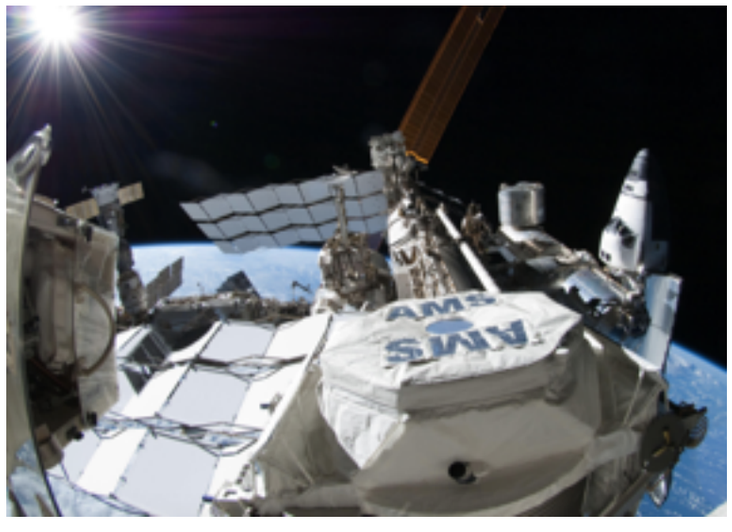
➡ **Beyond the HL-LHC**



Roadmap for Particle Physics

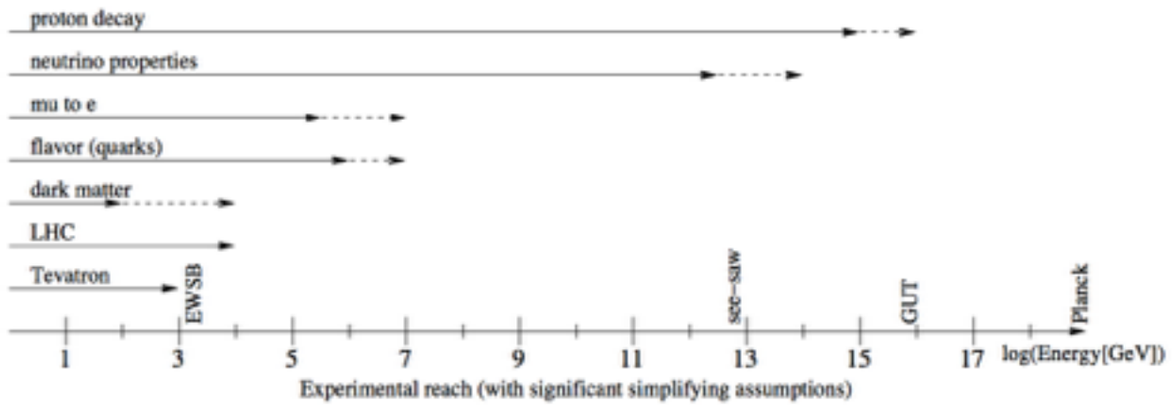
➡ **Beyond the energy frontier**

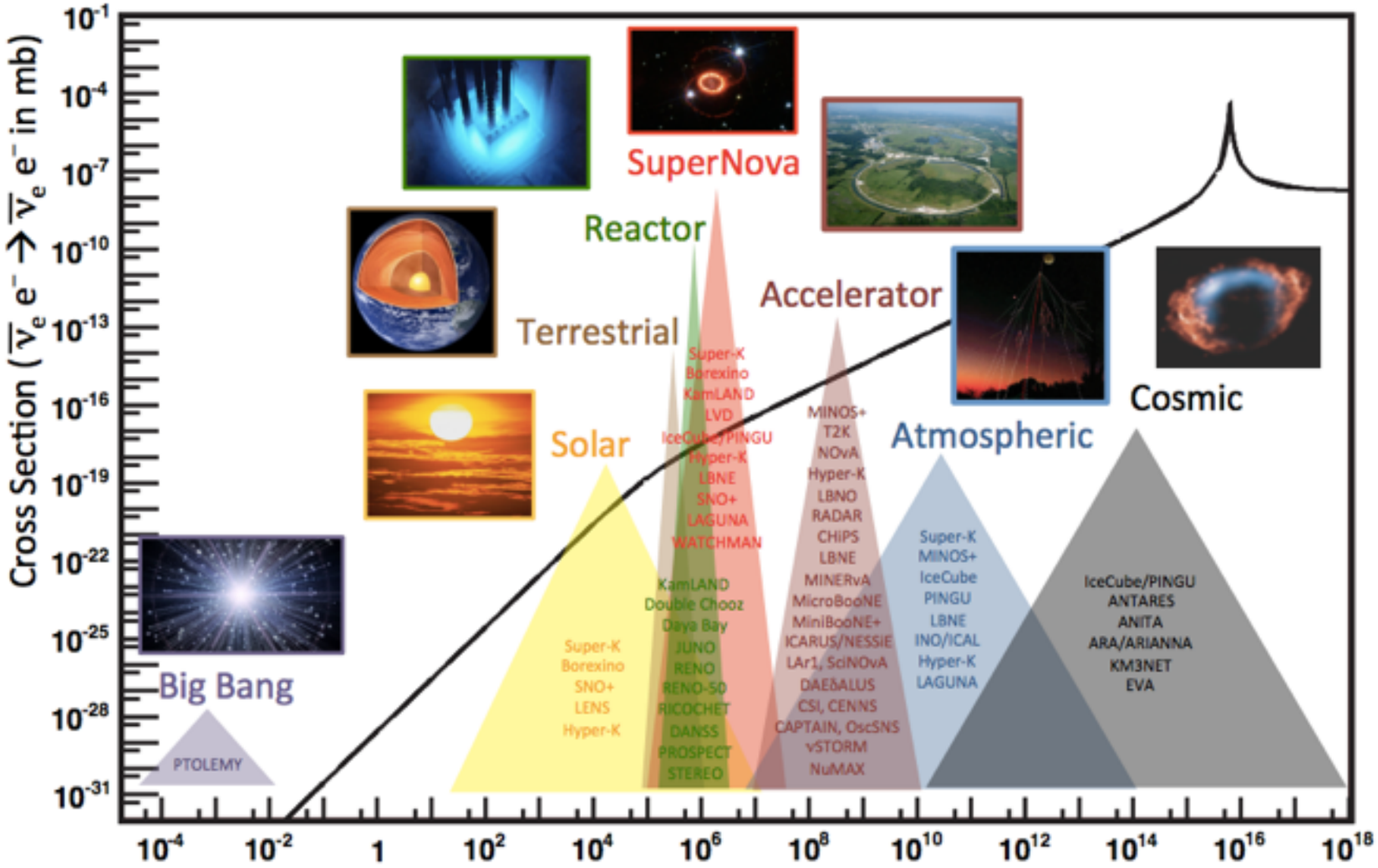




Roadmap for Particle Physics

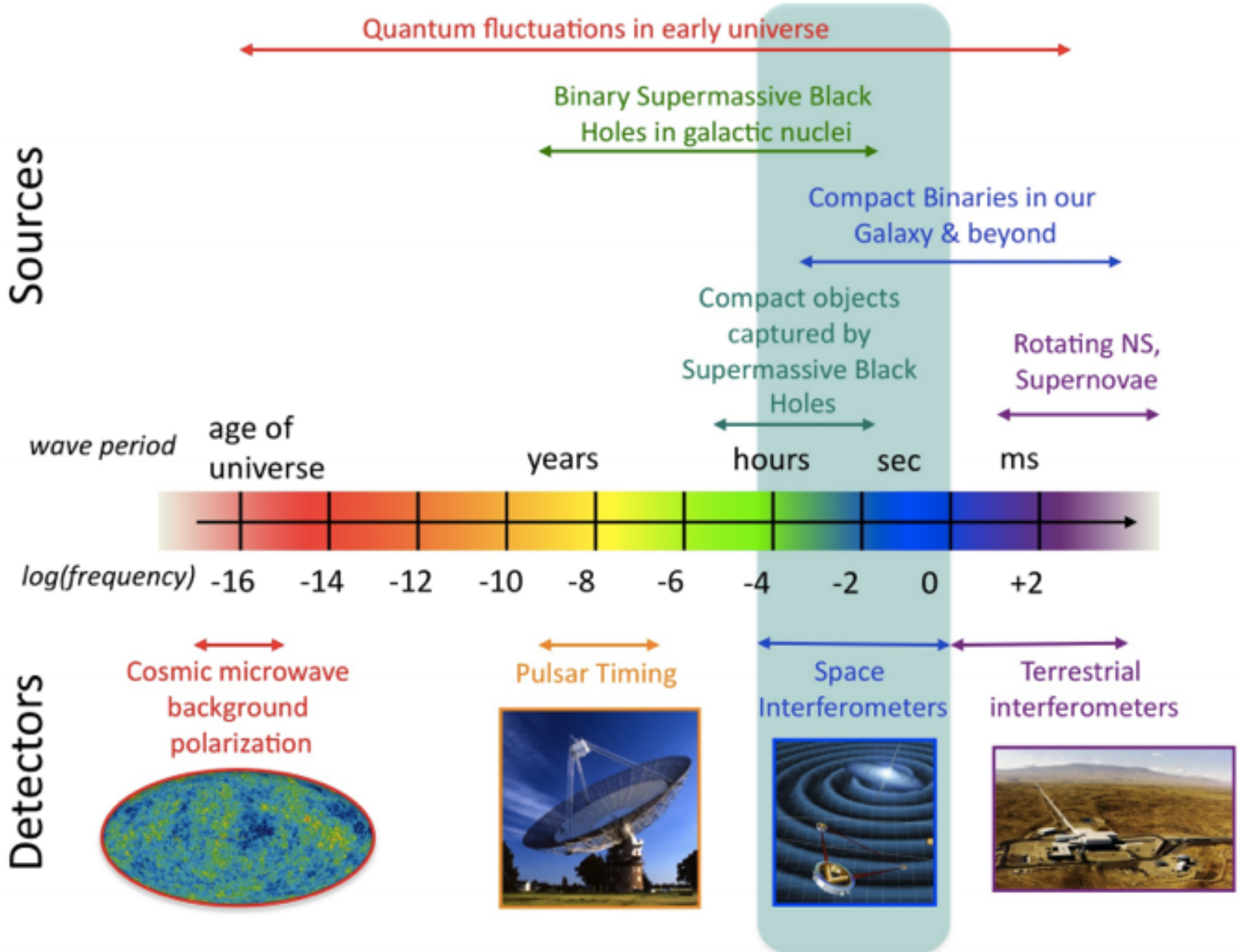
➡ **Beyond the energy frontier**





Roadmap for Particle Physics

➡ **Beyond the energy frontier**

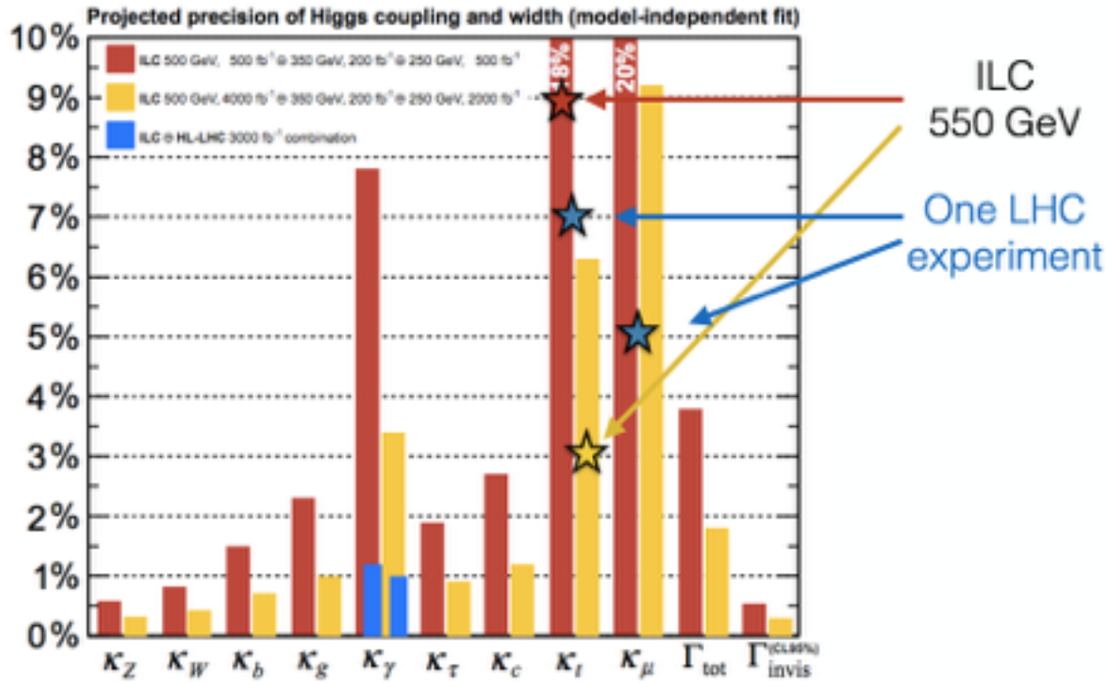


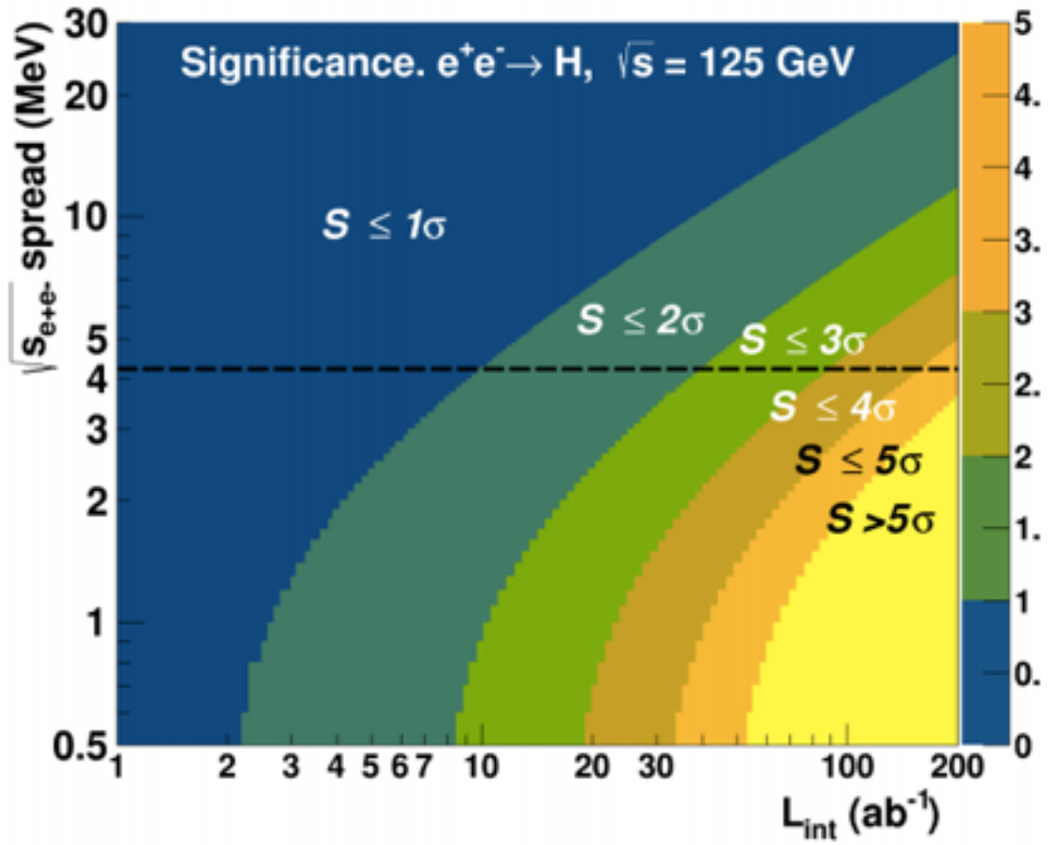
Prospects

➡ **Example: the Higgs boson (mechanism)**

- predicted in 1964
- discovered in 2012
- today's knowledge
  - ✤ consistent with SM prediction ~20% level
  - ✤ Spin-0
  - ✤ gives mass to W and Z bosons
  - ✤ gives mass to 3 generation fermions

- **in 100 years we will know**
  - ✤ consistent (or not) with SM prediction ~0.1% level
  - ✤ gives mass to 2 and 1 generation fermions
  - ✤ whether there is more than one Higgs boson

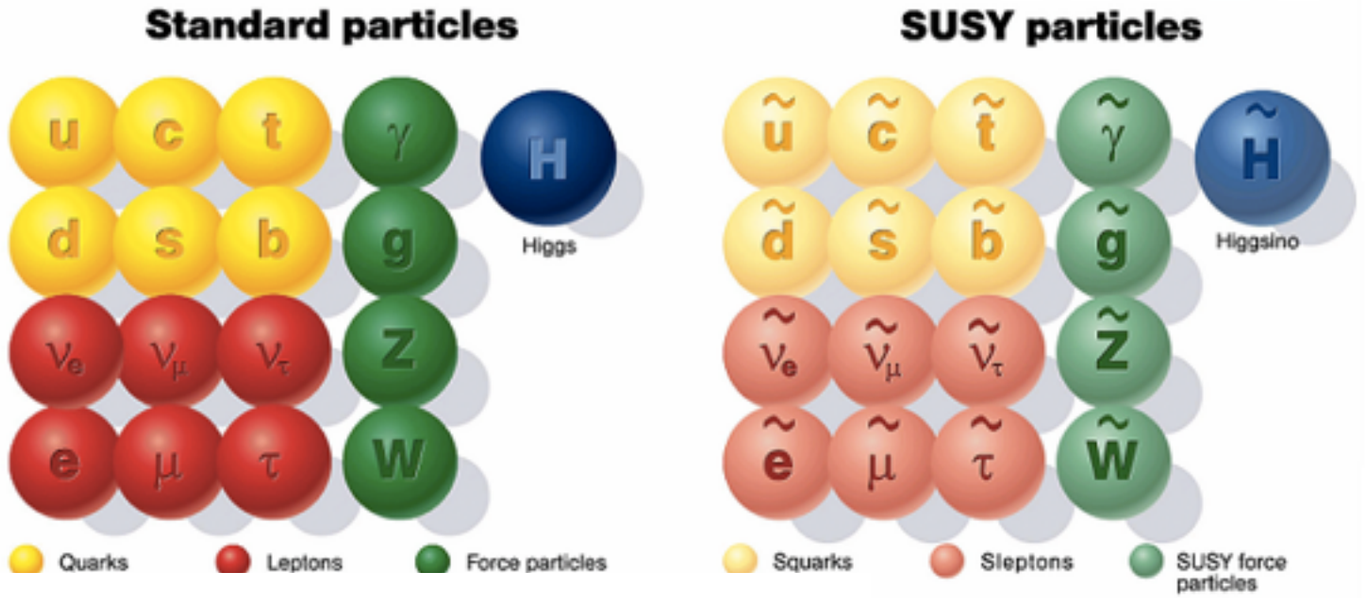


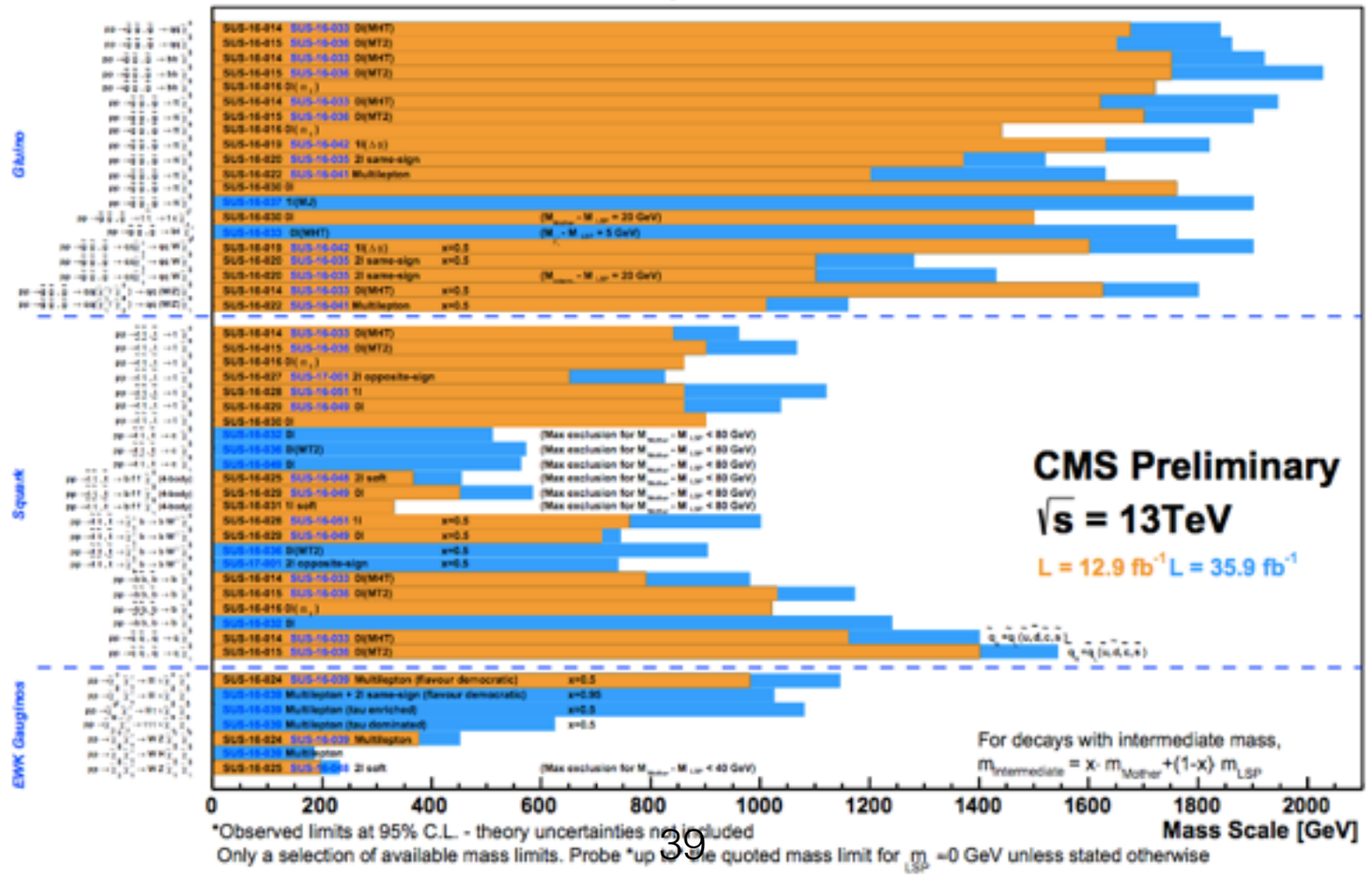


Prospects

➡ **Example: Supersymmetry**

- proposed in ~1974 (by Wess & Zumino)
- **today's knowledge**
  - **Supersymmetry must be broken**
- discovery in …
- in 100 years we will know





Prospects

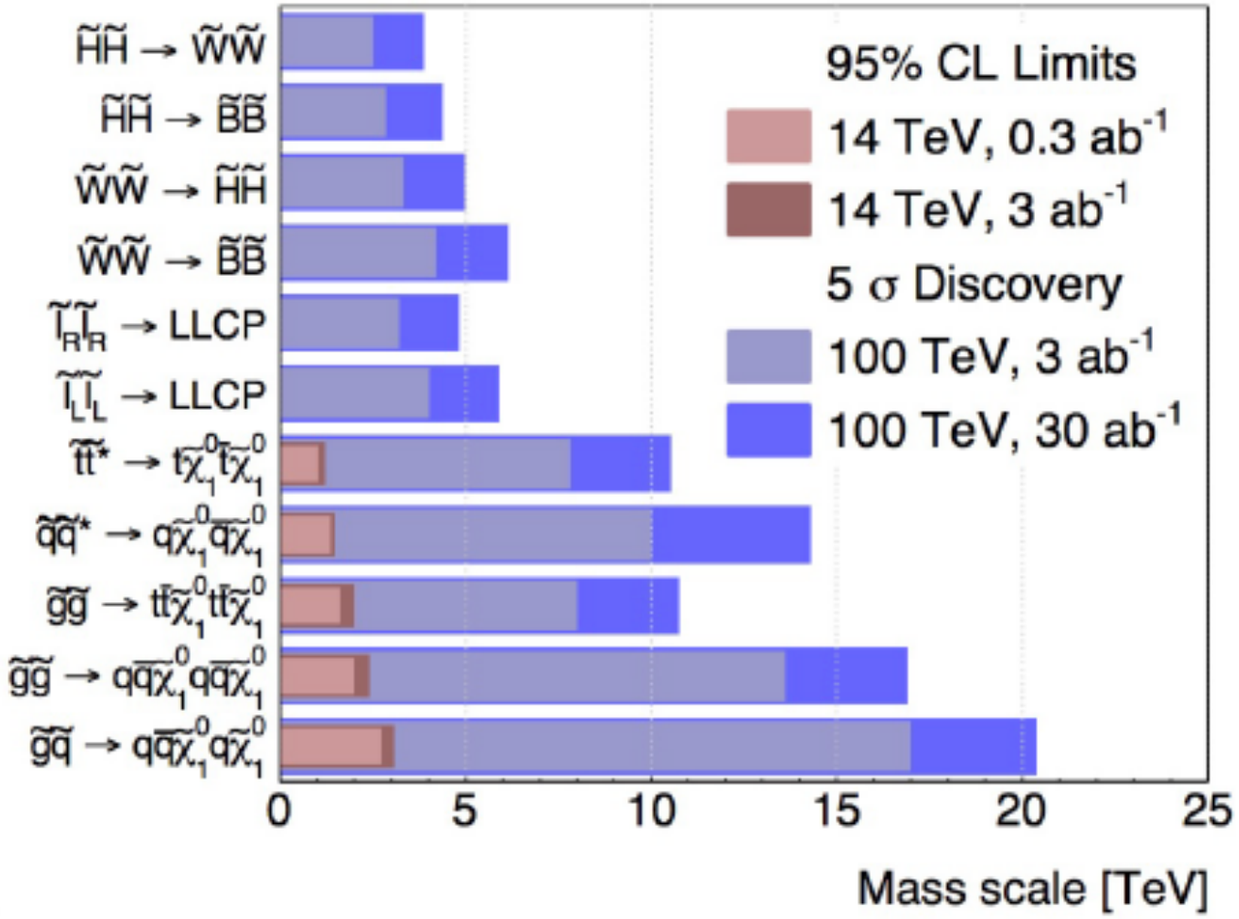
➡ **Example: Supersymmetry**

- proposed in ~1974 (by Wess & Zumino)
- today's knowledge
- **discovery in …**
- in 100 years we will know

HL-LHC

Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (HT-MHT) search	300					
	3000					
all-hadronic (MT2) search	300					
	3000					
all-hadronic $\tilde{b}_1$ search	300					
	3000					
1-lepton $\tilde{t}_1$ search	300					
	3000					
monojet $\tilde{t}_1$ search	300					
	3000					
$m_{\ell^+\ell^-}$ kinematic edge	300					
	3000					
multilepton + b-tag search	300					
	3000					
multilepton search	300					
	3000					
ewkino WH search	300					
	3000					

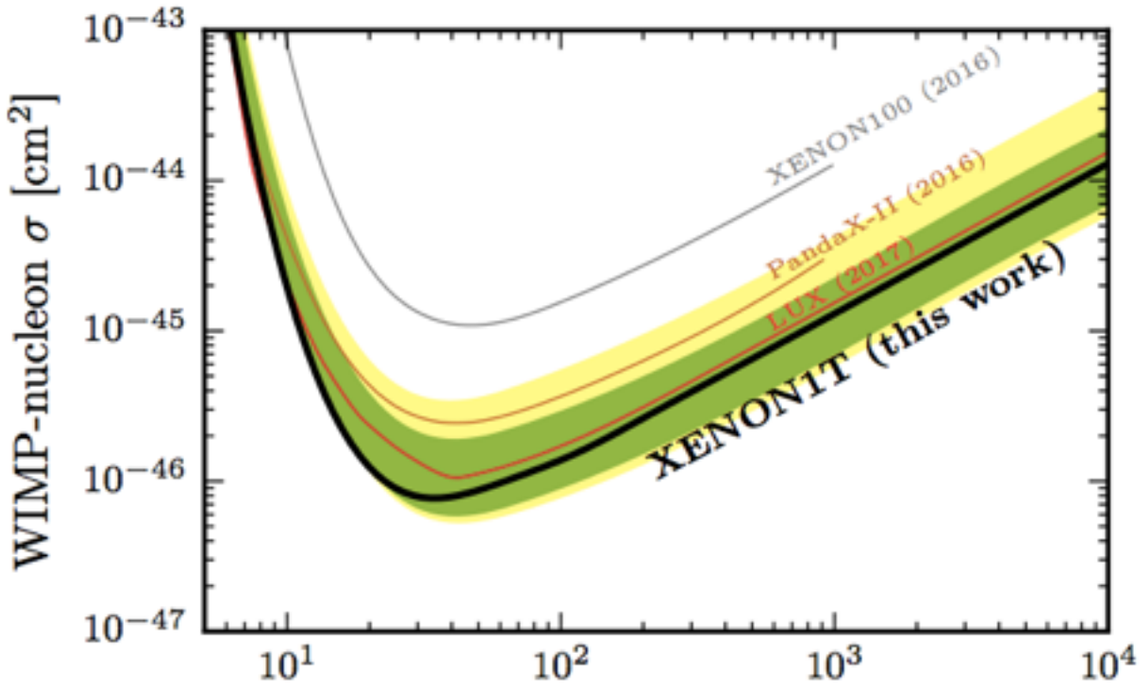
$< 3\sigma$ | $3 - 5\sigma$ | $> 5\sigma$

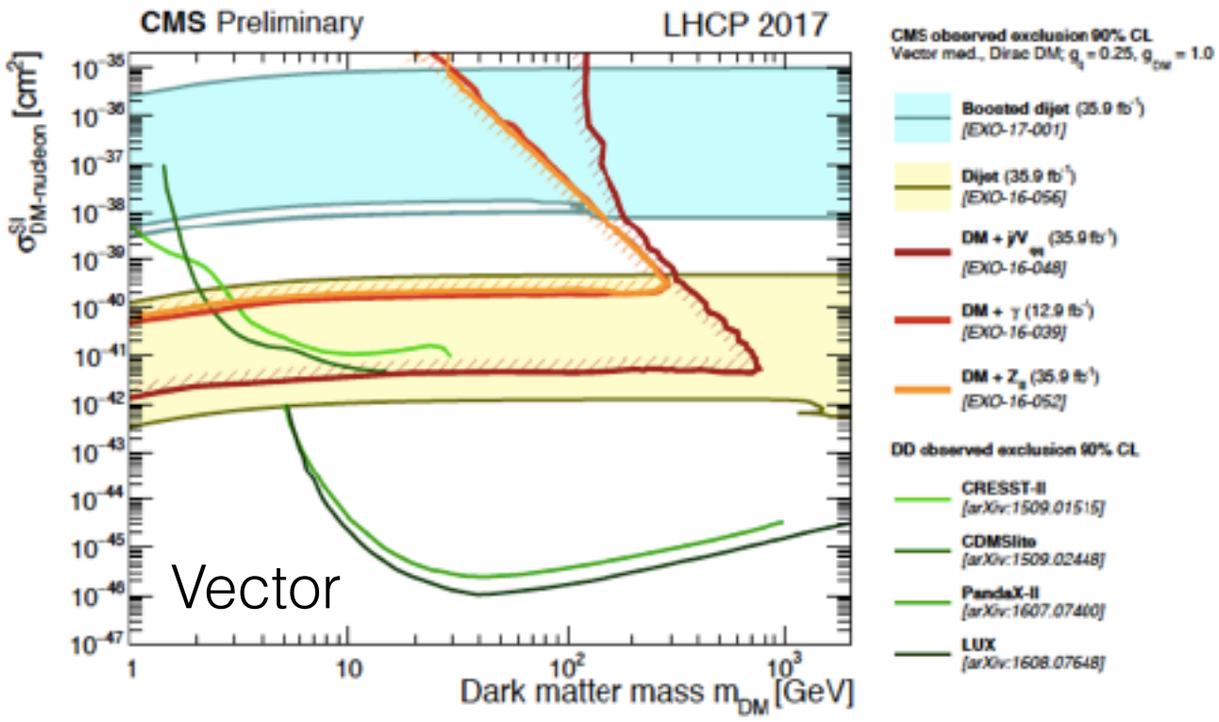


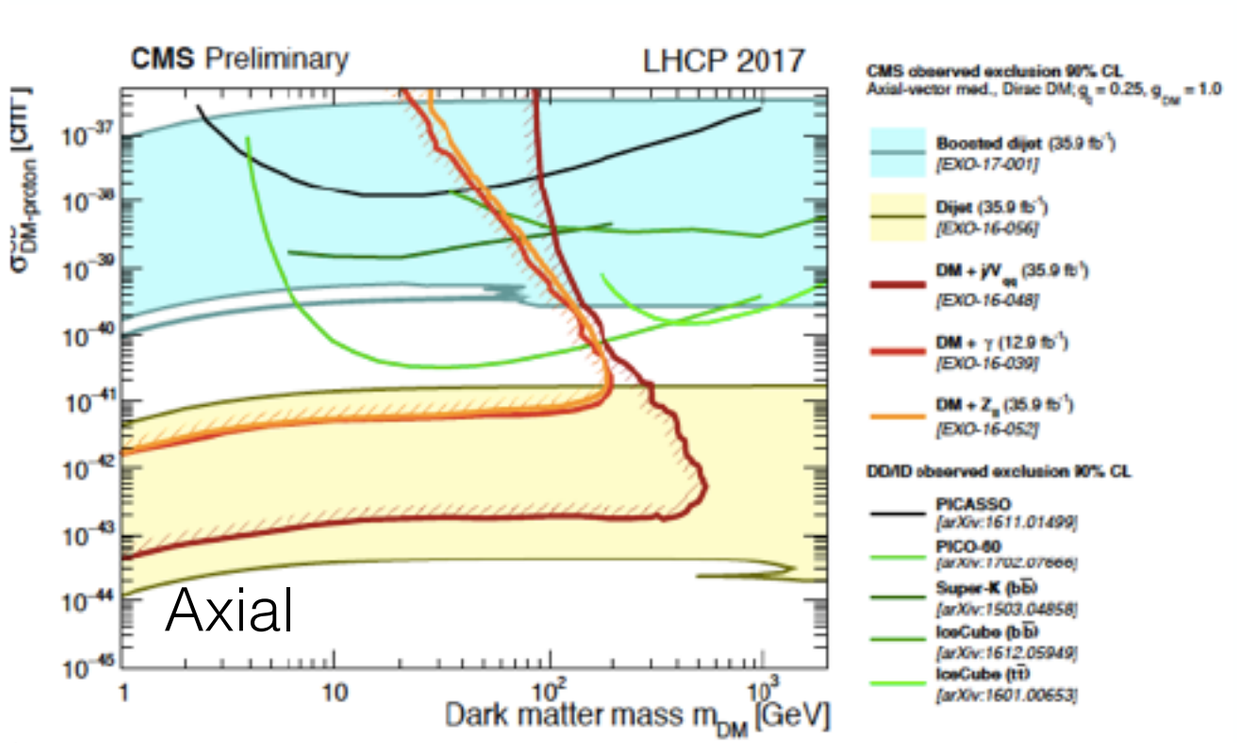
Prospects

➡ **Example: dark matter**

- proposed in ~1930
- confirmed in ~1970
- **today's knowledge**
  - **dark matter is very very weakly interacting**
- discovery in …



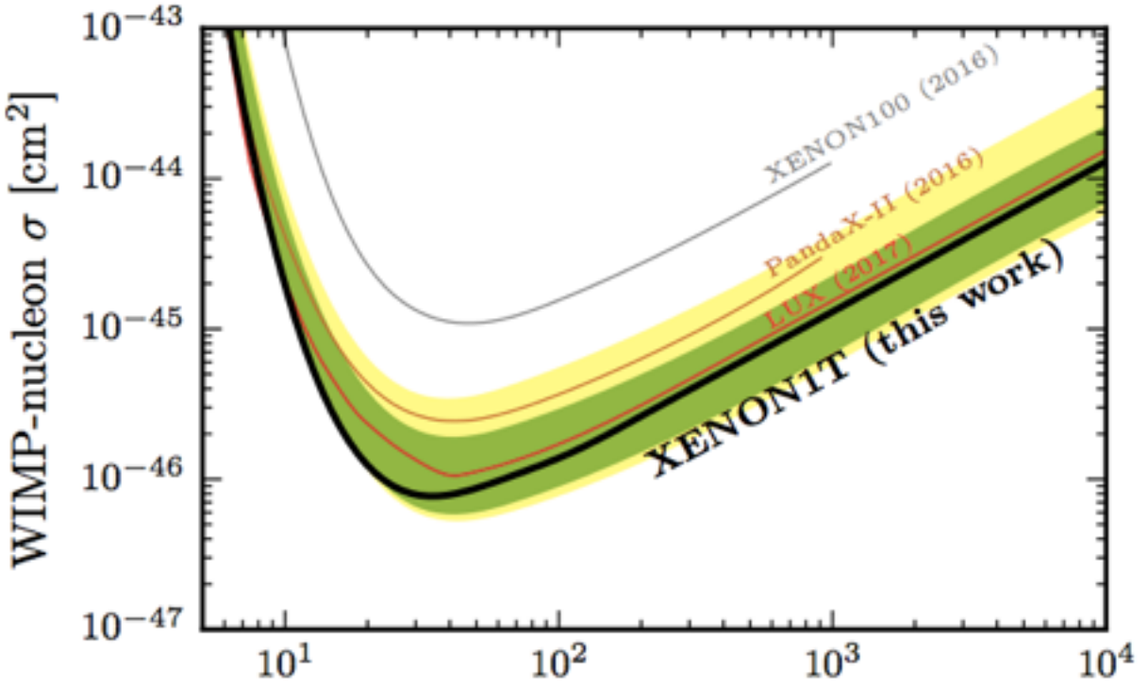


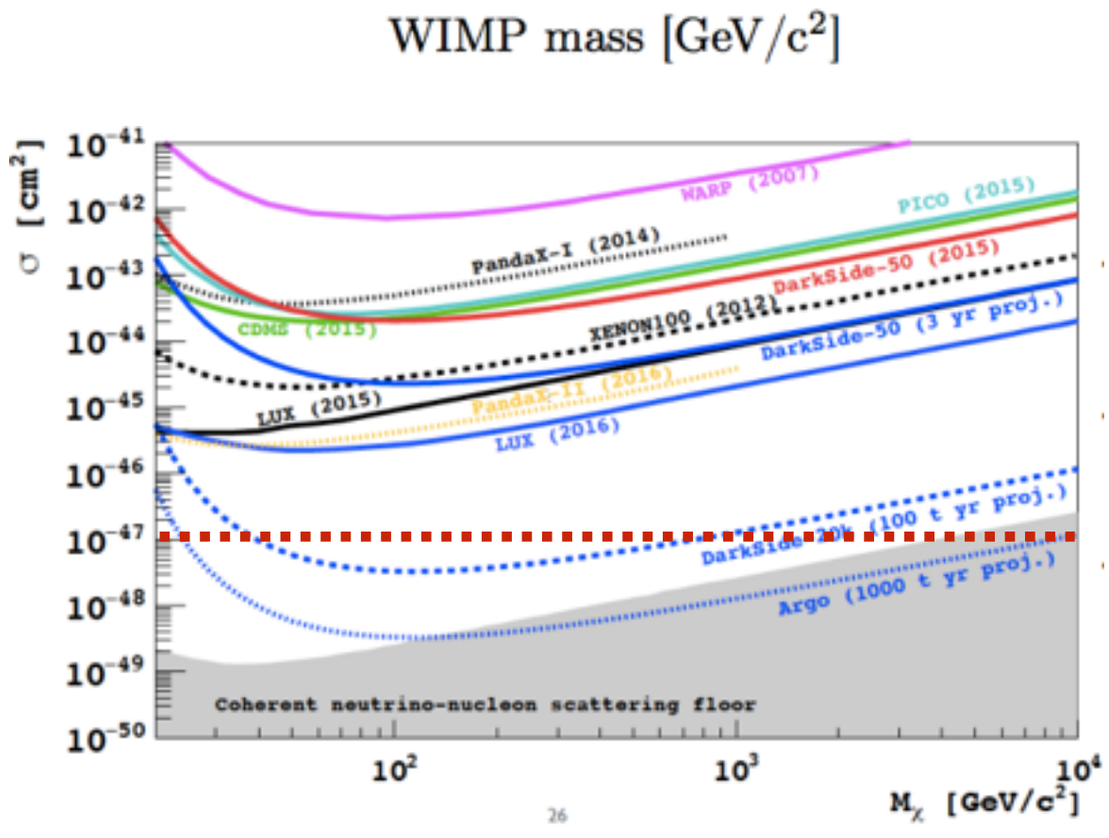


Prospects

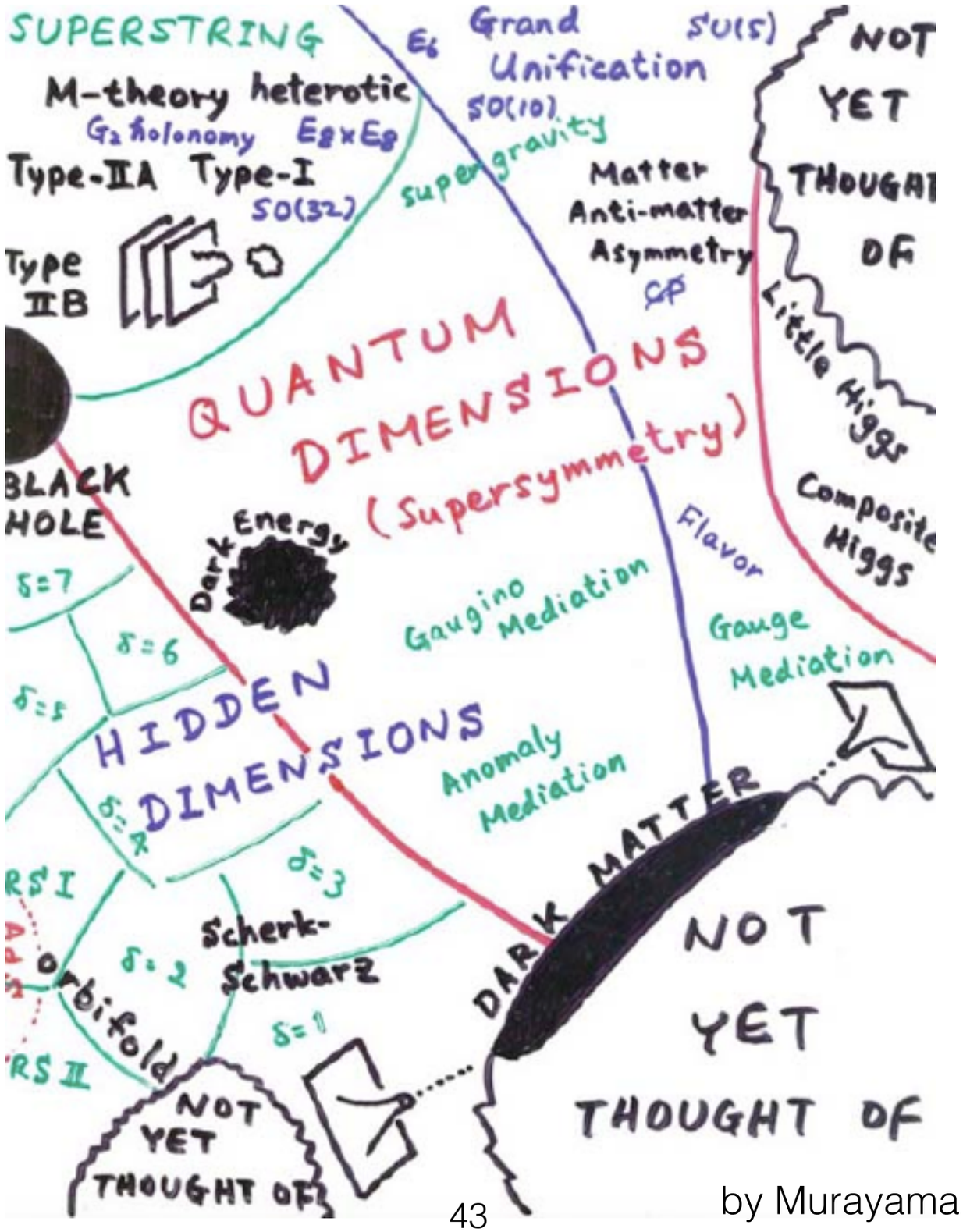
➡ **Example: dark matter**

- proposed in ~1930
- confirmed in ~1970
- today's knowledge
- discovery in …
- **in 100 years we will know**
- **whether (or not) WIMPs exist**
- **and have answers for alternative ideas**





Landscape



Large space of "Not Yet Thought Of"

by Murayama

Exploration

Christopher Columbus Discovers America, 1492. Columbus led his three ships - the Nina, the Pinta and the Santa Maria - out of the Spanish port of Palos on August 3, 1492. His objective was to sail west until he reached Asia (the Indies) where the riches of gold, pearls and spice awaited.

Conclusion

Unveiling the Secrets of Nature - An outlook on fundamental physics in 100 years

Concluding Remarks

➡ **Prediction**

- Niels Bohr: “it is very difficult to predict - especially the future”

➡ **Progress through technology and new ideas**

- Continuous innovation (investment) is crucial

➡ **Spirit of exploration**

- It is in the nature of fundamental research that we do not know what’s beyond our current knowledge