The future of particle physics

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Universität Hamburg

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Particle physics (I)

Fundamental questions

- What are we maid of ?
- What are fundamental building bloks of matter and how they interact ?
- What is the origin and evolution of the Universe ?

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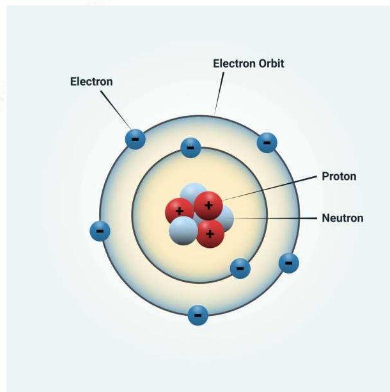
Small scales

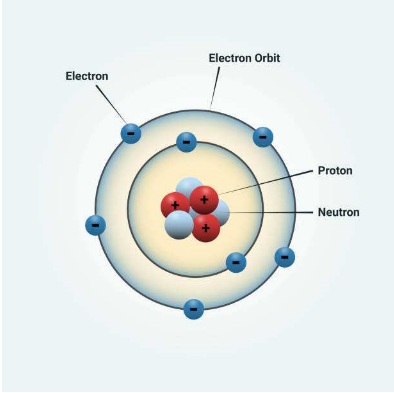
- Typical human hair has thickness of about 50 to 100 μm ($5 \cdot 10^{-5}$m to 10^{-4}m)

- Size of an atom 10^{-10}m
  $\rightarrow$ one million times smaller



Particle physics

- Comparison: size of an atom 10^{-10}m
  size of its core 10^{-15}m
- Universe its mostly empty



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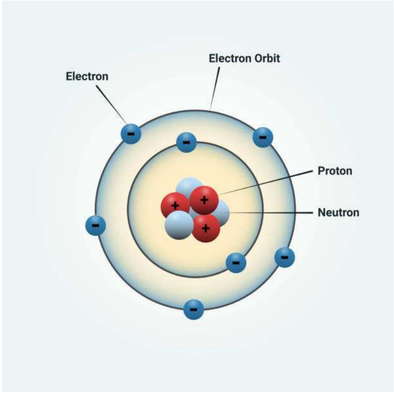
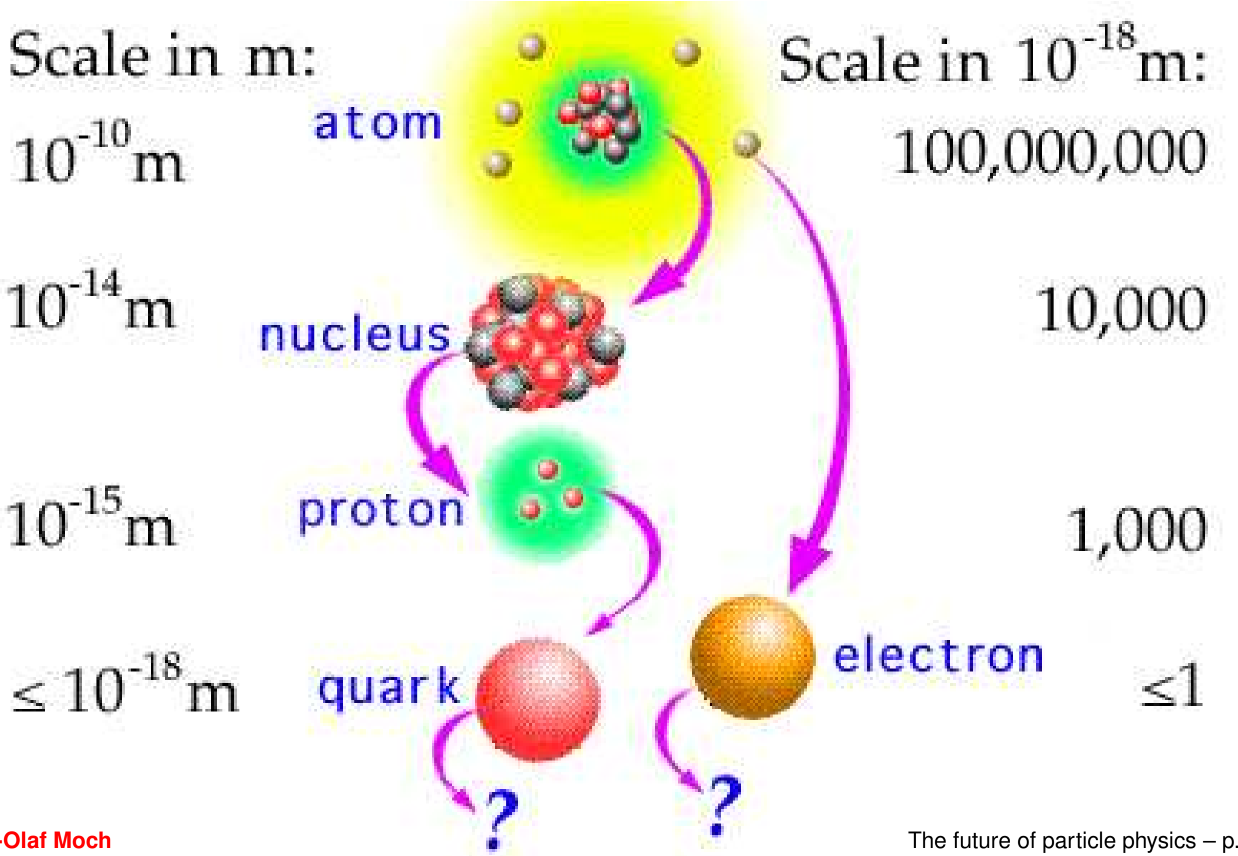


- Comparison: size of an atom 10^{-10}m
  size of its core 10^{-15}m
- Universe its mostly empty
- Subatomic distances at 10^{-15}m and less



Standard Model of elementary particles

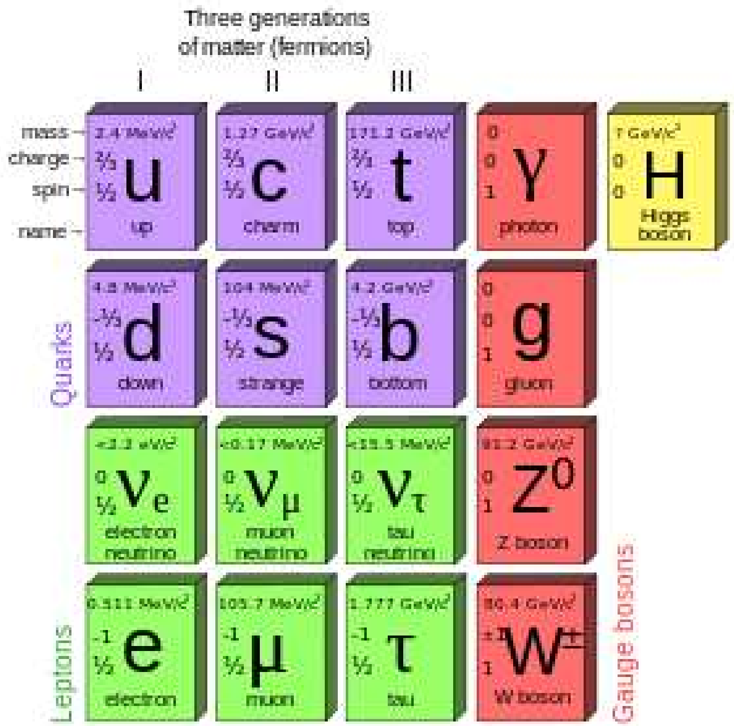
“Periodic table” of elementary particles

– **Quarks**
  (constituents of matter)

– **Leptons**
  (constituents of matter)

– **Gauge bosons**
  (carriers of exchange forces)

– **Higgs boson**
  (responsible for mass of elementary particles)



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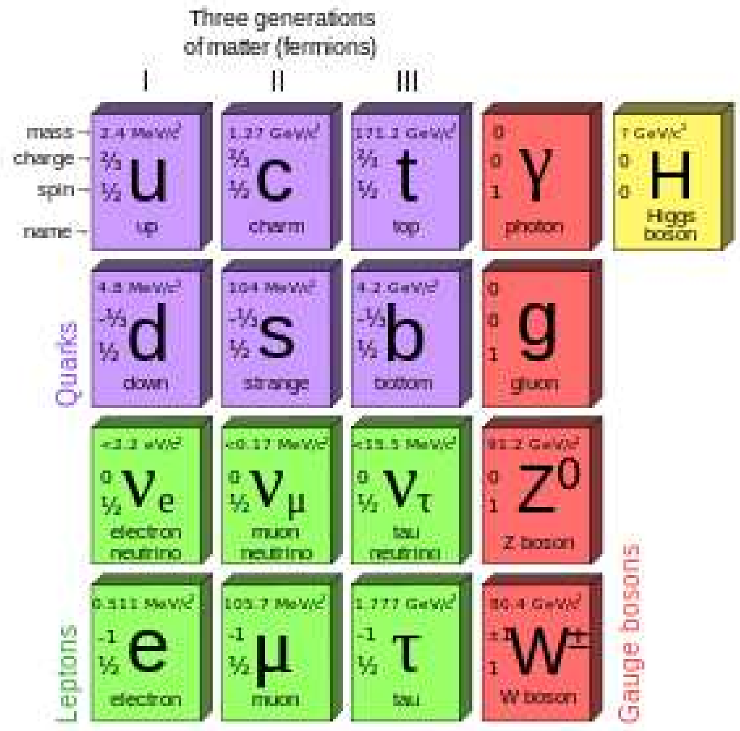

Is this table complete?

Nobel prizes for particle dicoveries

Particle	Discovery	Discoverer(s)	Nobel Prize(s)	Year
Electron (e^-)	1897	J.J. Thomson	J.J. Thomson	1906
Positron (e^+)	1932	C.D. Anderson	C.D. Anderson	1936
Neutron (n)	1932	J. Chadwick	J. Chadwick	1935
e-Neutrino (ν_e)	1956	C. Cowan, F. Reines	F. Reines	1995
Muon (μ^-)	1936	Anderson, Neddermeyer	–	–
Pion (π)	1947	C.F. Powell et al.	C.F. Powell	1950
Antiproton ($\overline{p}$)	1955	Segrè, Chamberlain	Segrè, Chamberlain	1959
μ-Neutrino (ν_μ)	1956	Schwartz & Steinberger	Schwartz & Steinberger	1988
Quark Structure	1968+	Friedman, Kendall, Taylor (SLAC)	Friedman, Kendall, Taylor	1990
Charm Quark (J/ψ)	1974	Ting, Richter	Ting, Richter	1976
Gluon (indirect)	1979	DESY (PETRA Experiment)	–	–
Tau Lepton (τ)	1975	M. Perl	Perl, Reines (shared)	1995
Bottom Quark (b)	1977	Lederman & collaborators	Lederman	1988
W and Z Bosons	1983	CERN (UA1, UA2)	Rubbia, van der Meer	1984
Top Quark (t)	1995	CDF, D0 (Fermilab)	–	–
Higgs Boson (H)	2012	CMS, ATLAS (CERN)	Englert, Higgs (theory)	2013

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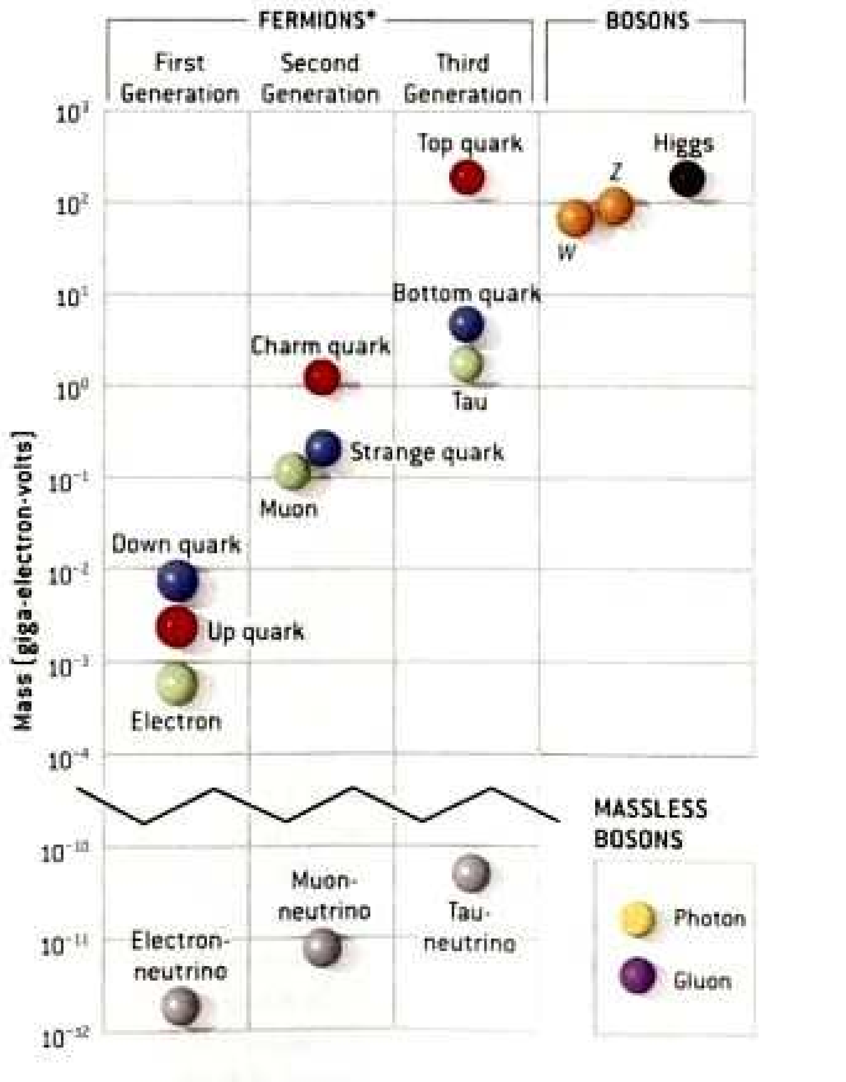
Nobel prize in physics 2013

... for the theoretical discovery of **a mechanism that contributes to our understanding of the origin of mass of subatomic particles***, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider***.**

Masses of elementary particles

- Mass of a gold atom (Au)
  $m_{\mathrm{Au}} \approx 10^{-25}$ kg

Particle	Mass (kg)	Ratio to Au
Top quark (t)	10^{-25}	1
Higgs boson (H)	10^{-25}	10^{-1}
Z boson (Z)	10^{-25}	10^{-1}
W boson (W)	10^{-25}	10^{-1}
Bottom quark (b)	10^{-26}	10^{-1}
Charm quark (c)	10^{-27}	10^{-2}
Tau lepton (τ^-)	10^{-27}	10^{-2}
Muon (μ^-)	10^{-28}	10^{-3}
Electron (e^-)	10^{-30}	10^{-5}
Up/Down quark (u, d)	10^{-30}	10^{-5}
Neutrinos (ν)	$< 10^{-36}$	$< 10^{-11}$



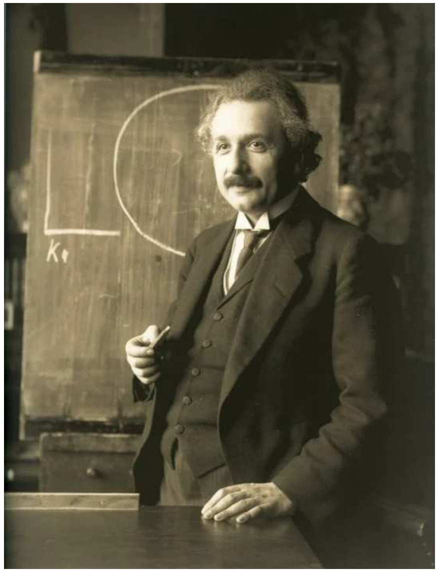
Classical scattering experiment

- In classical physics, no new particles are produced

High-energy colliders

Einstein relation

- $E = mc^2$



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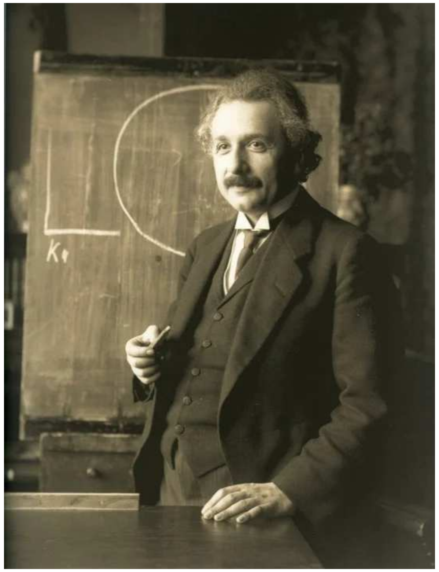


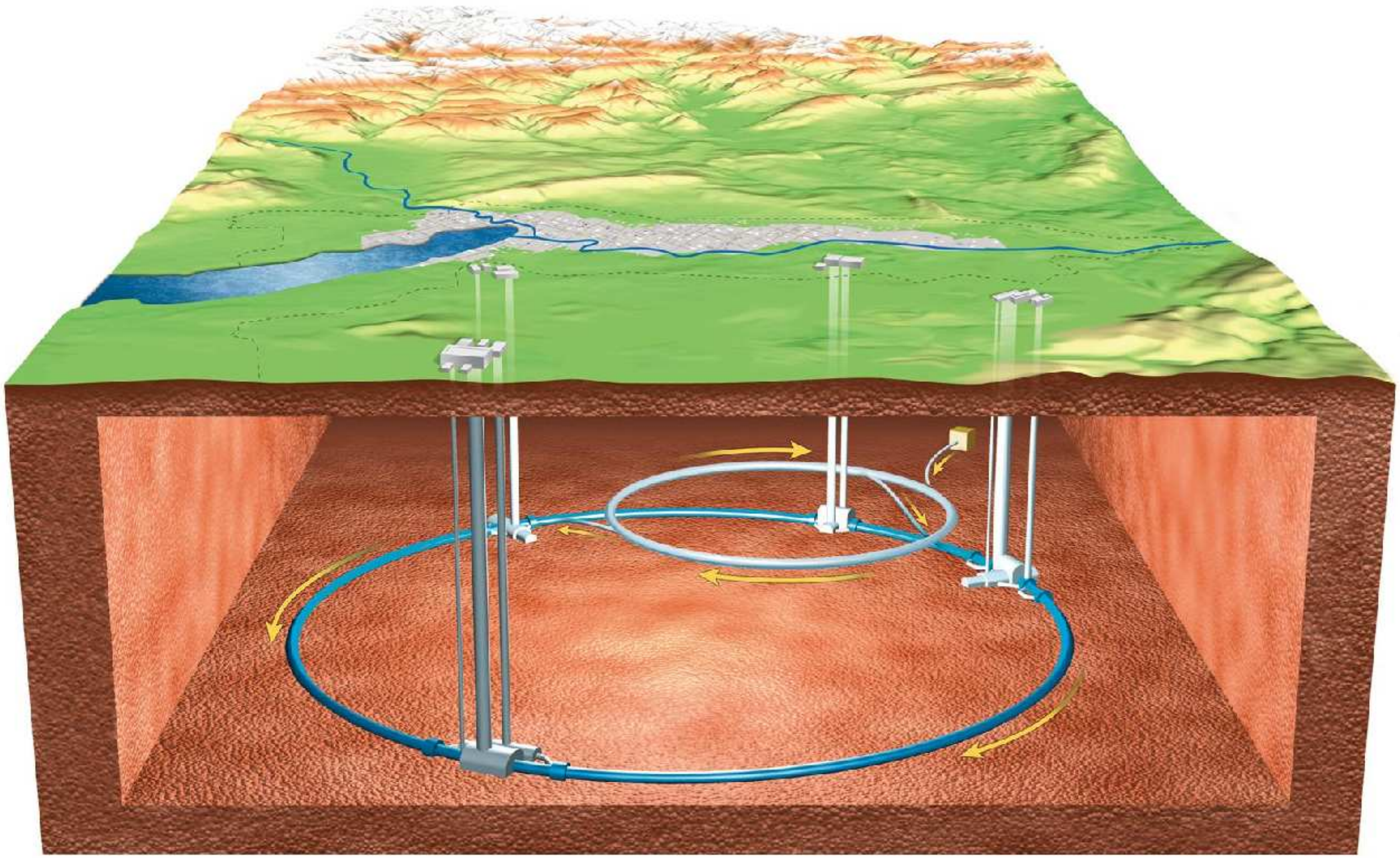
It is a quantum world

- $E > mc^2$:
  Anything that is allowed will happen
- $E < mc^2$: Anything that is forbidden can happen for a short period of time according to Heisenberg's Uncertainty Principle $\Delta E\, \Delta t \gtrsim \hbar$

The Large Hadron Collider

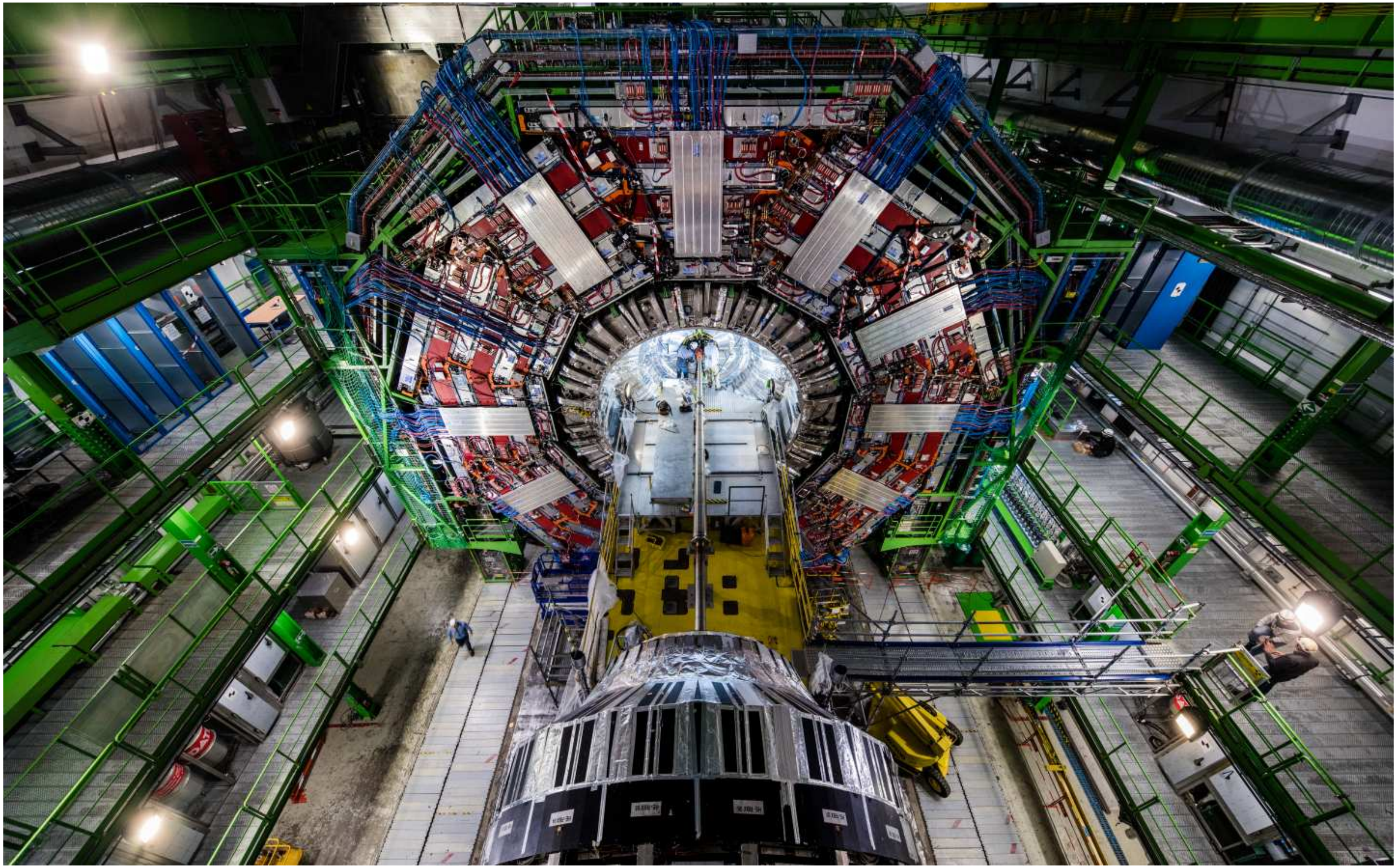
- Highest energies at colliders until 203x

Model of LHC

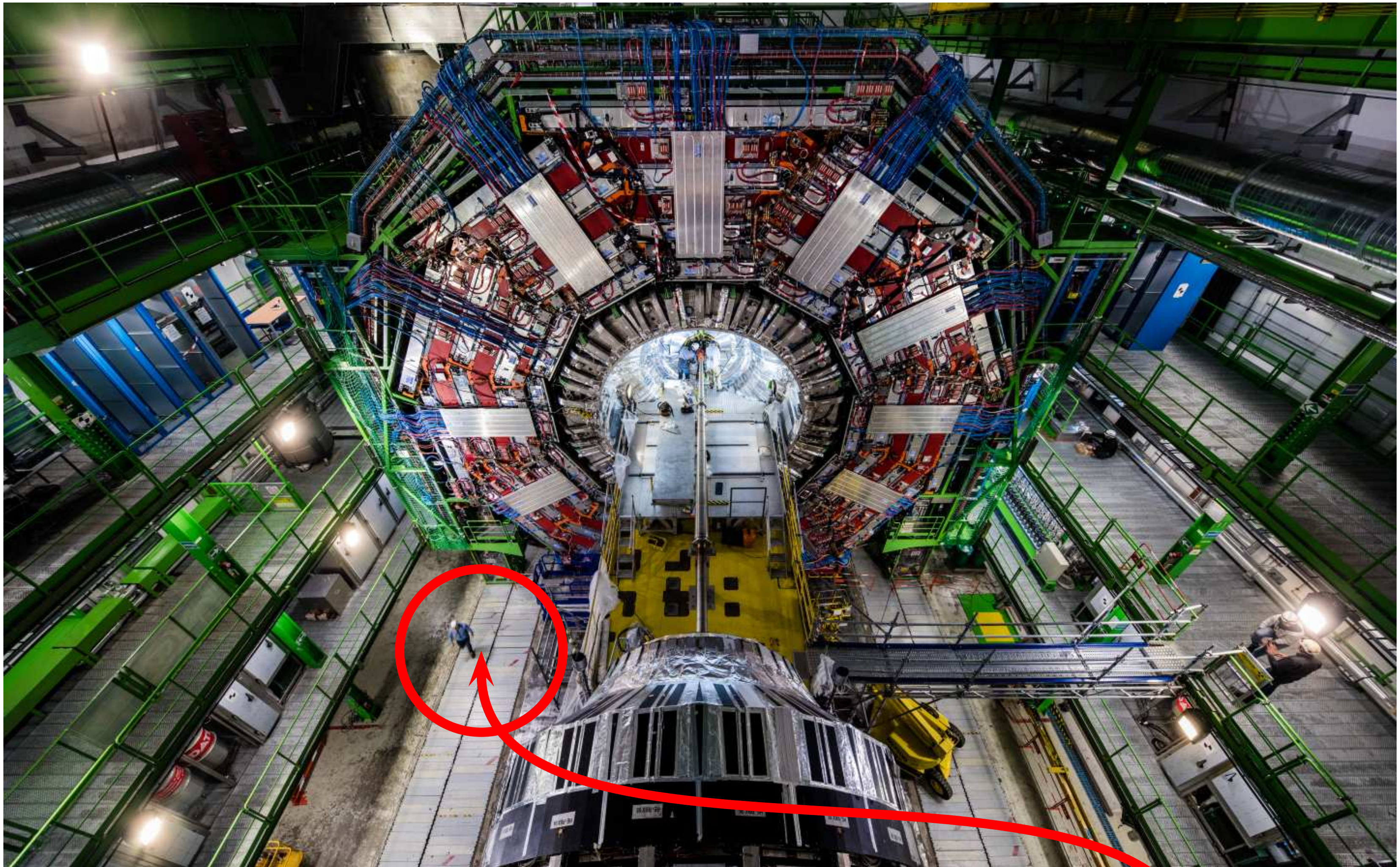


- Ring and experiments approximately 100m underground
  - ATLAS, CMS, Alice, LHCb

CMS experiment

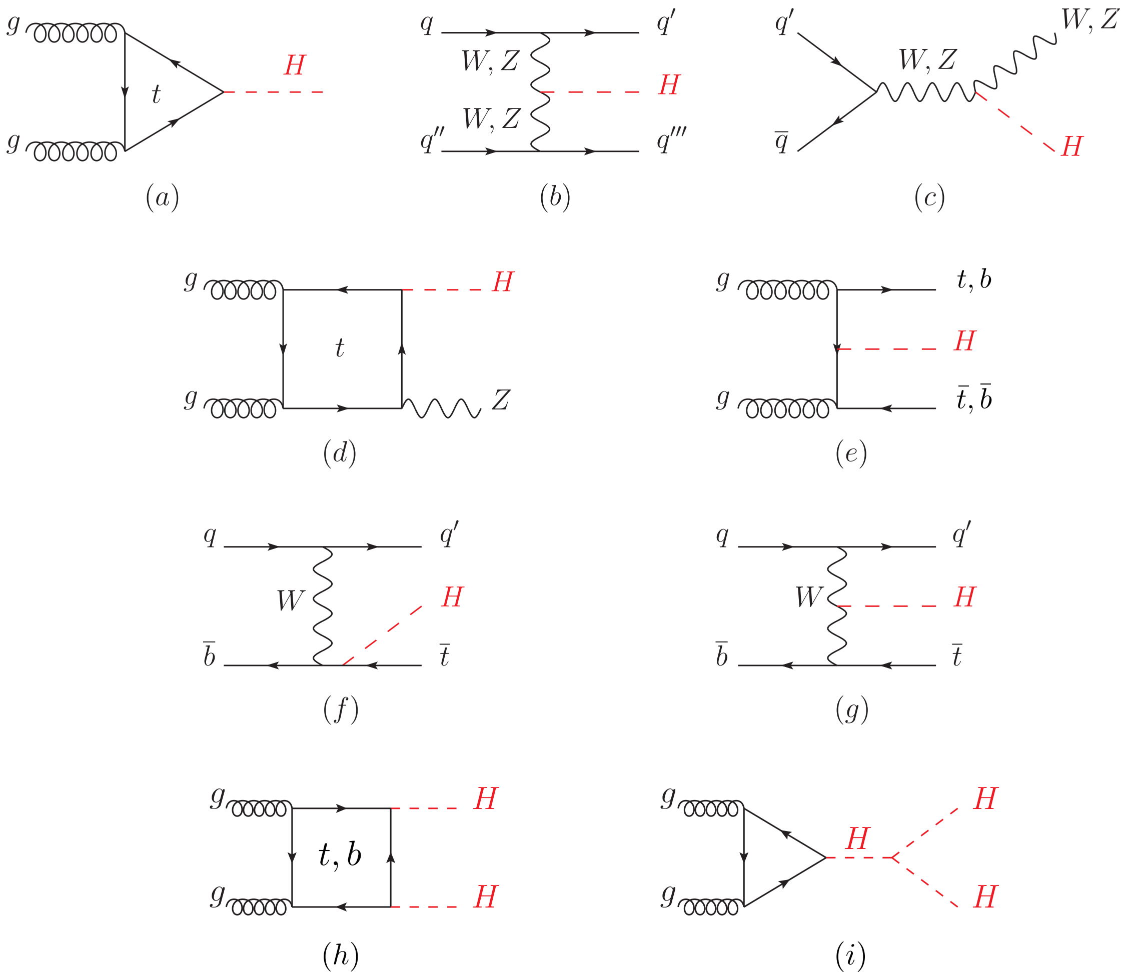


CMS experiment



person

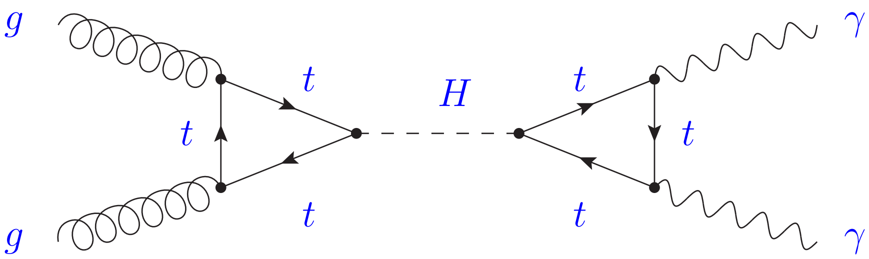
Particle interactions



- Production of Higgs bosons from other Standard Model particles according to $E = mc^2$

Higgs boson discovery

- Higgs boson H production at the LHC
  - fusion of two gluons (via top-quark loop) to Higgs boson
  - Higgs decay (via top-quark loop) to two photons



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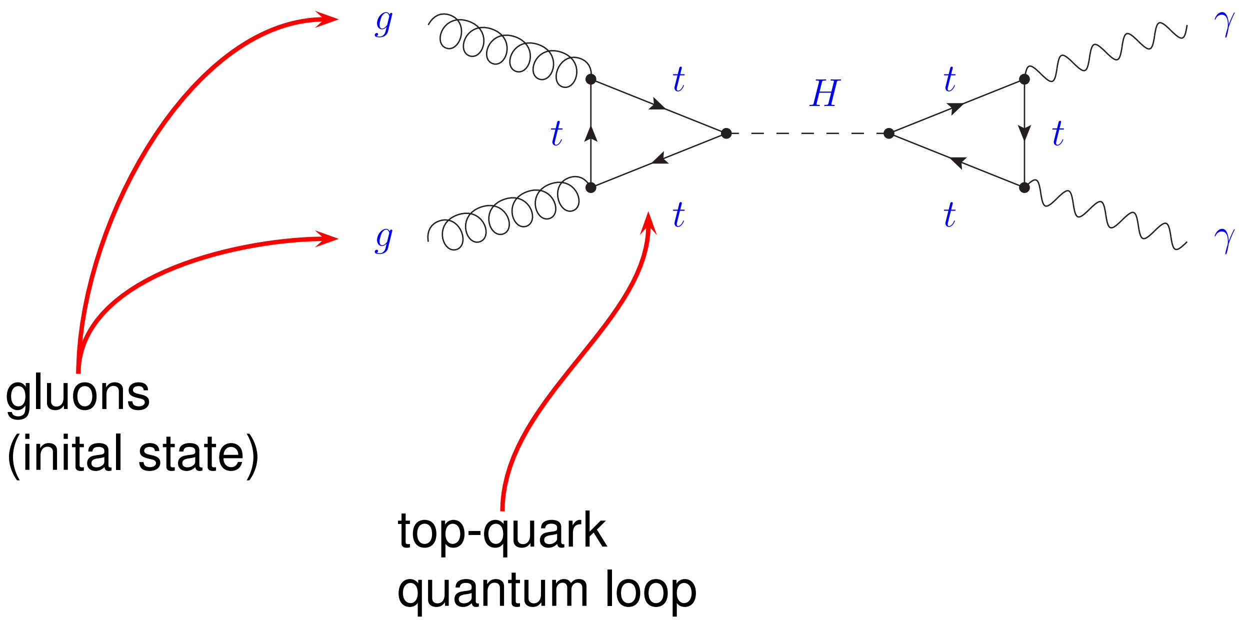

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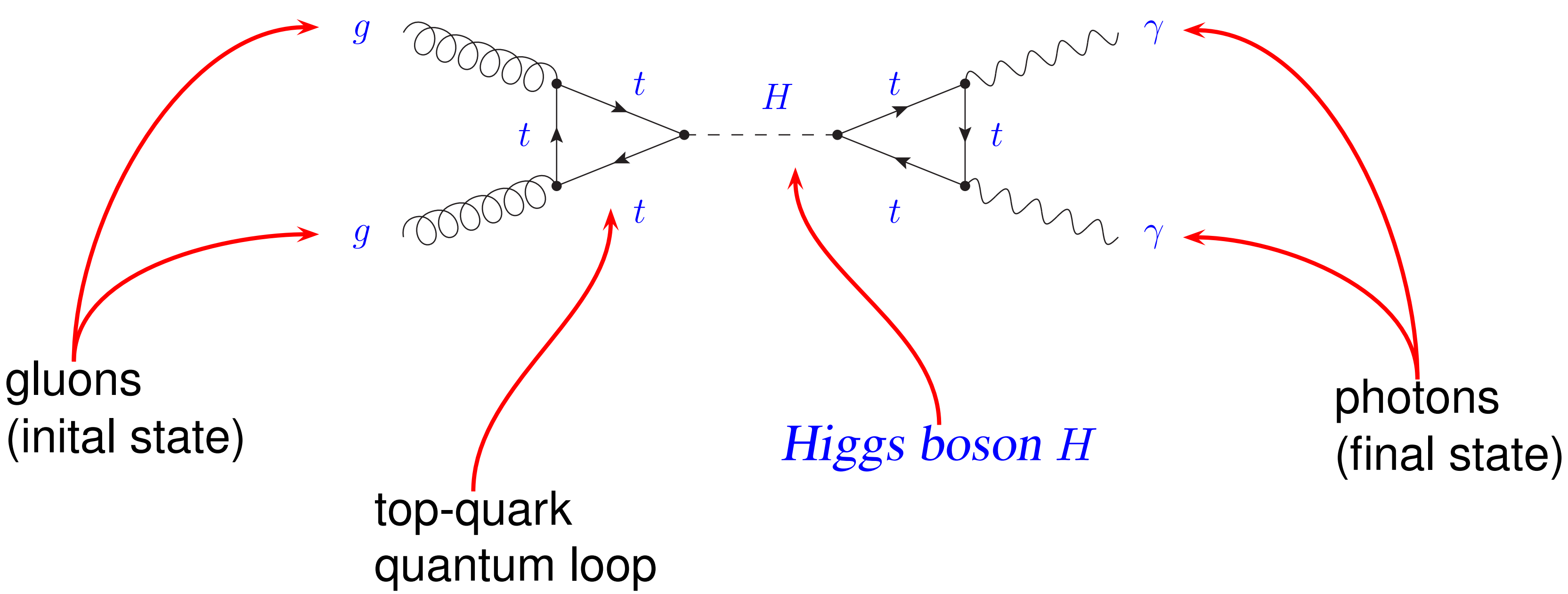

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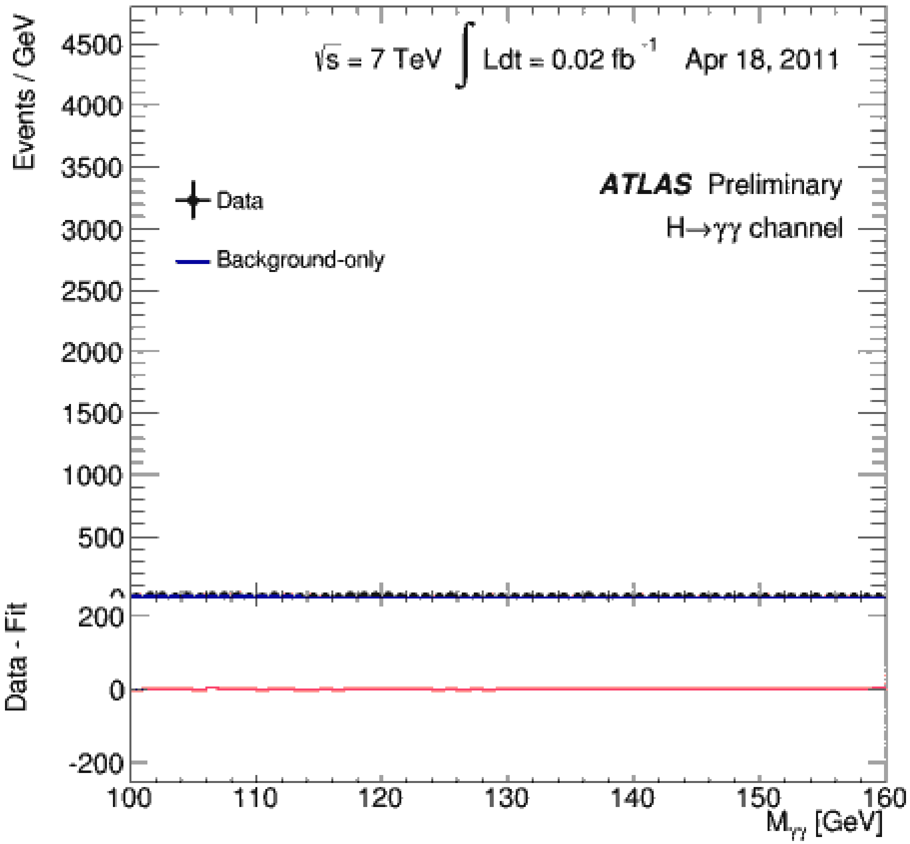

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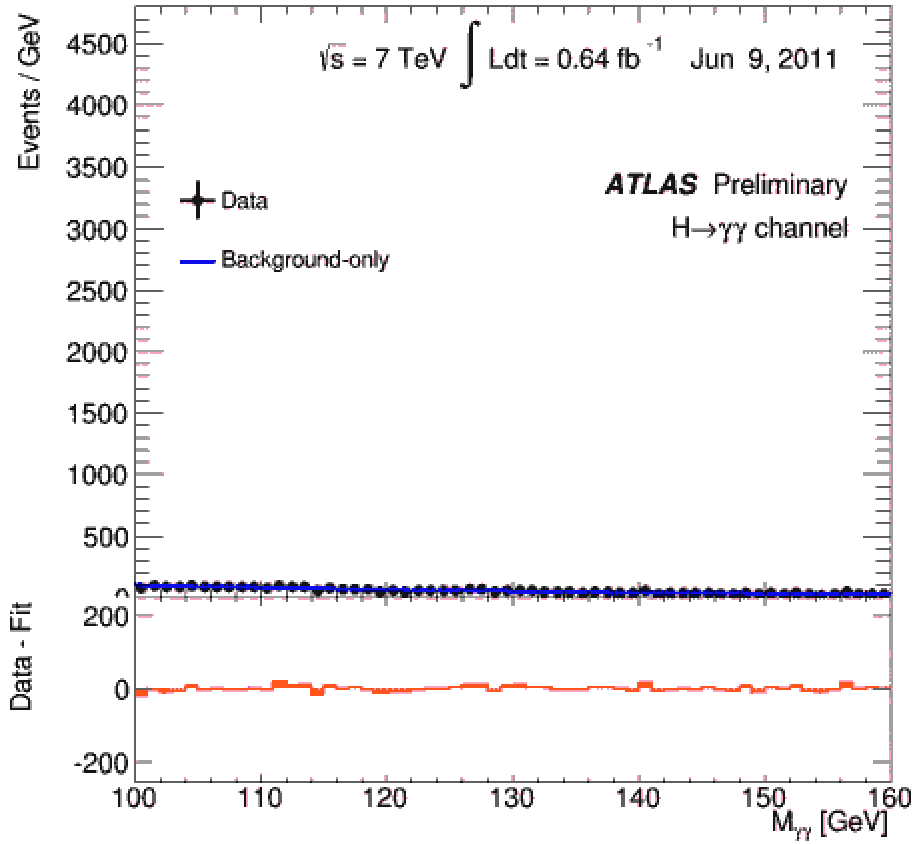

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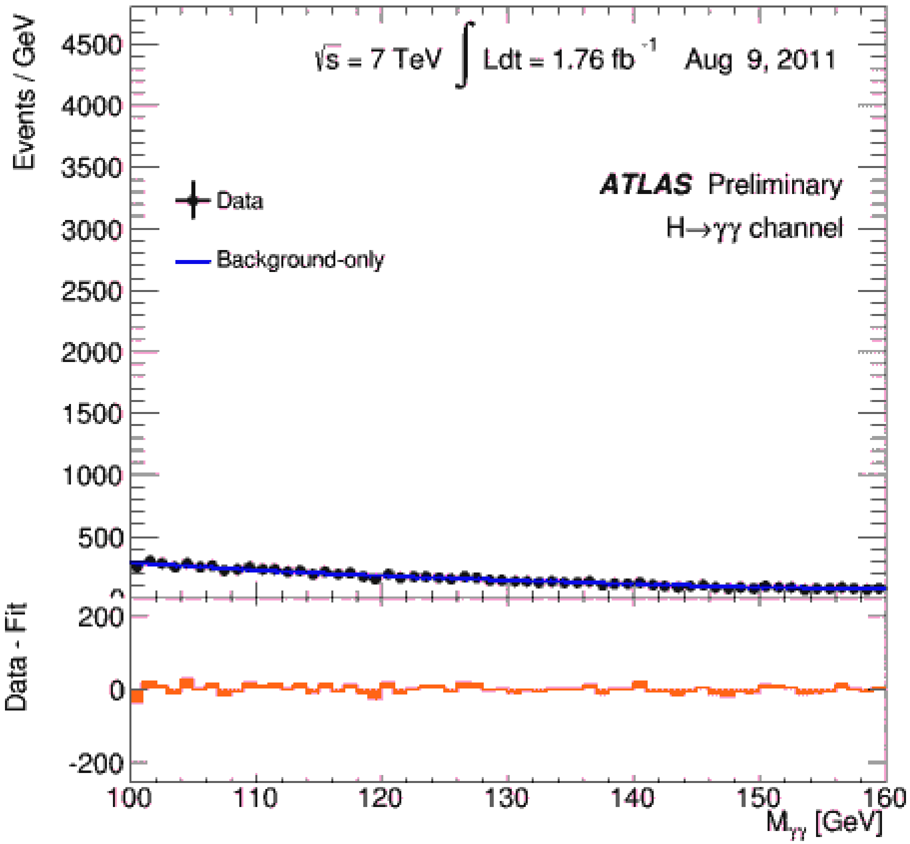

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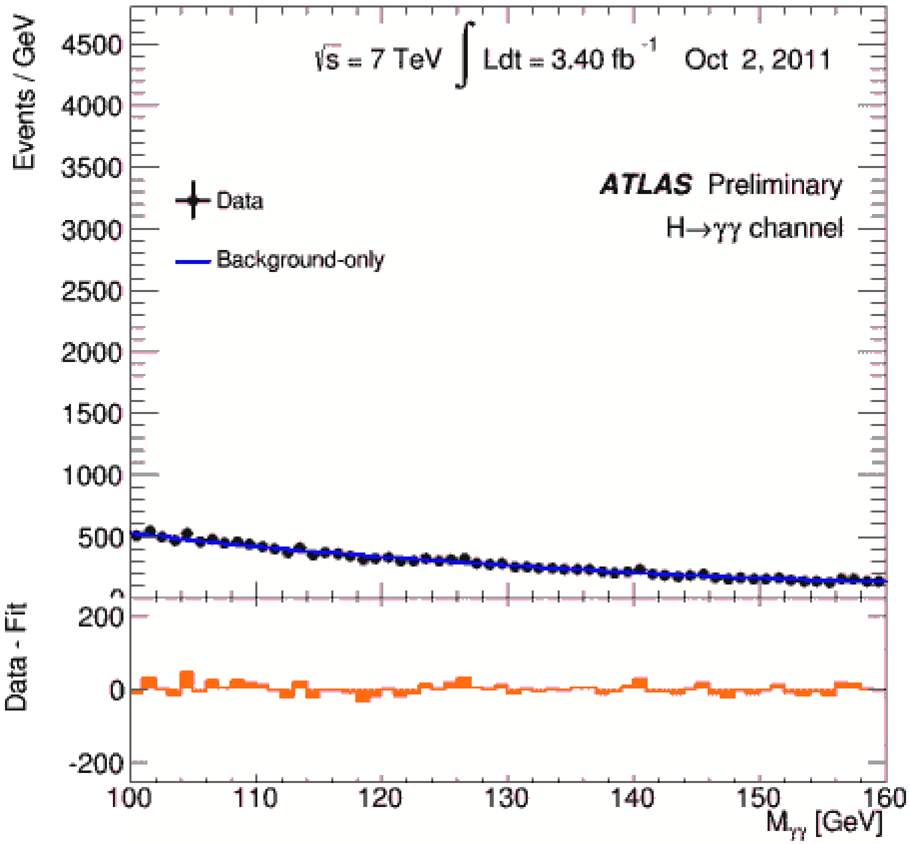

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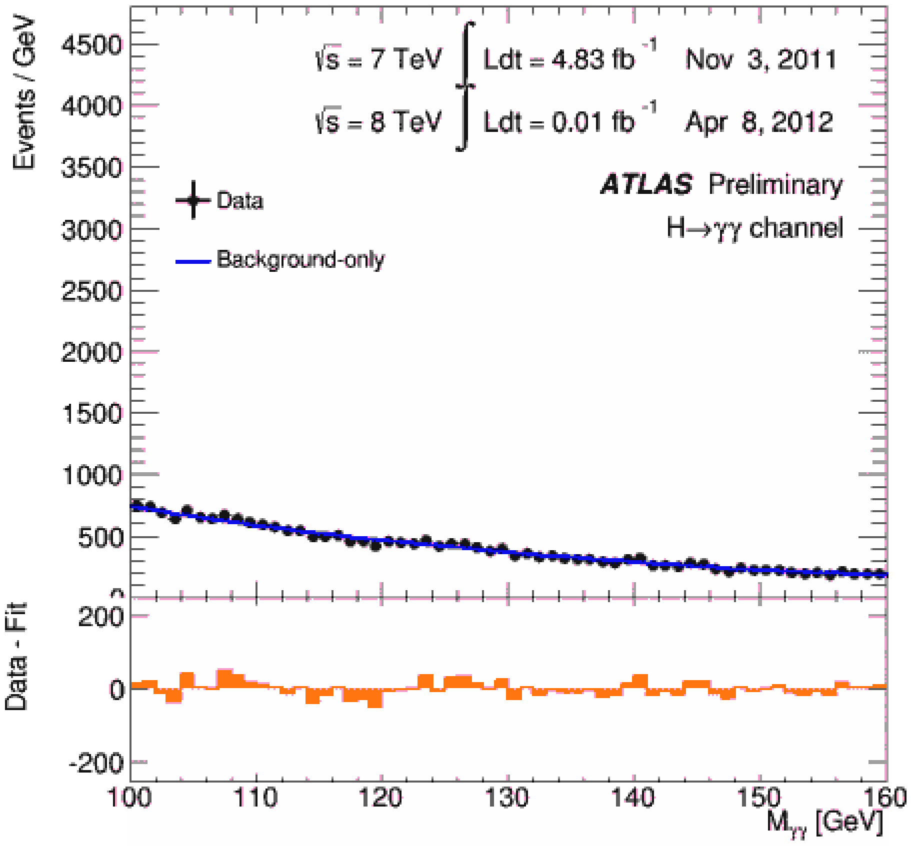

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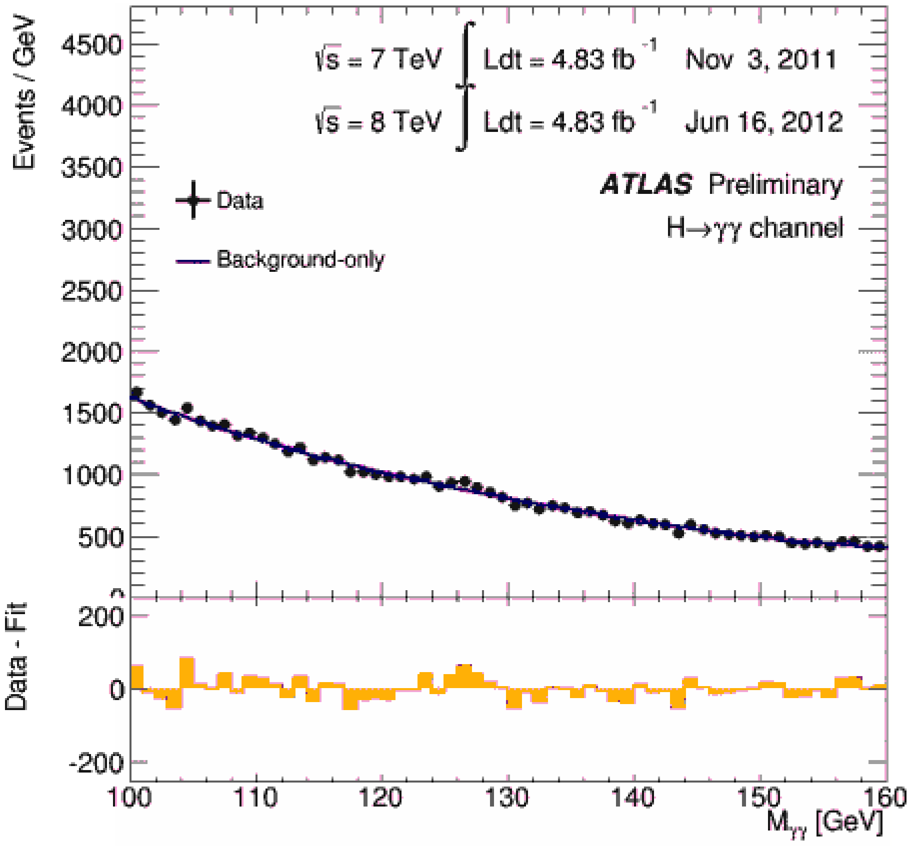

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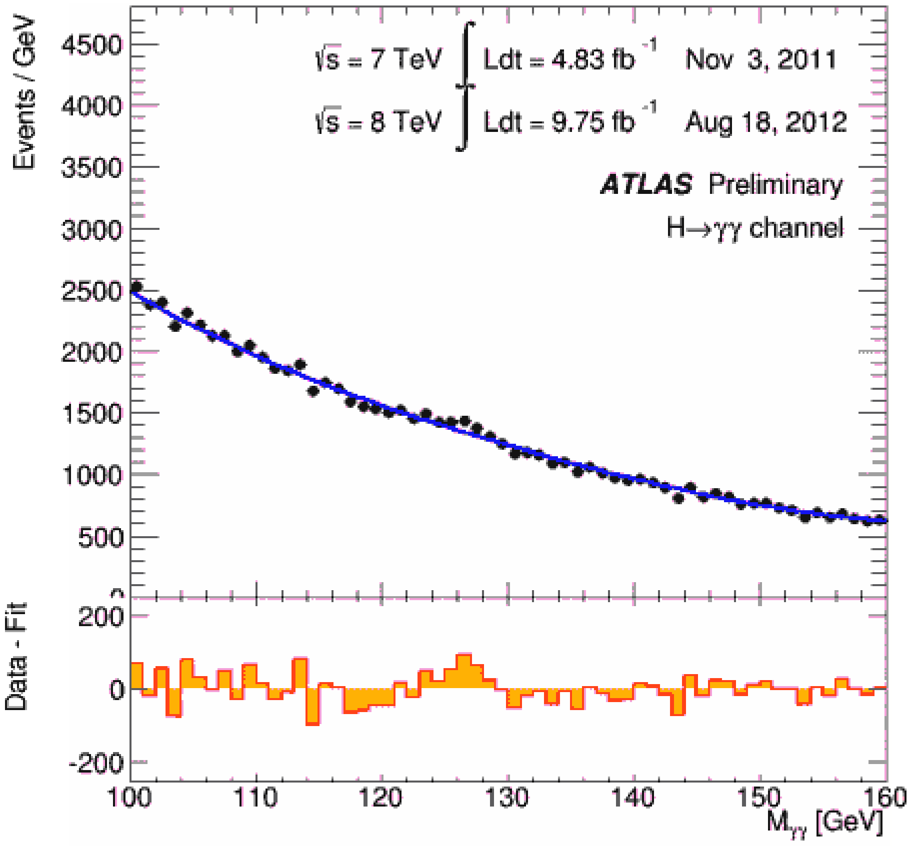

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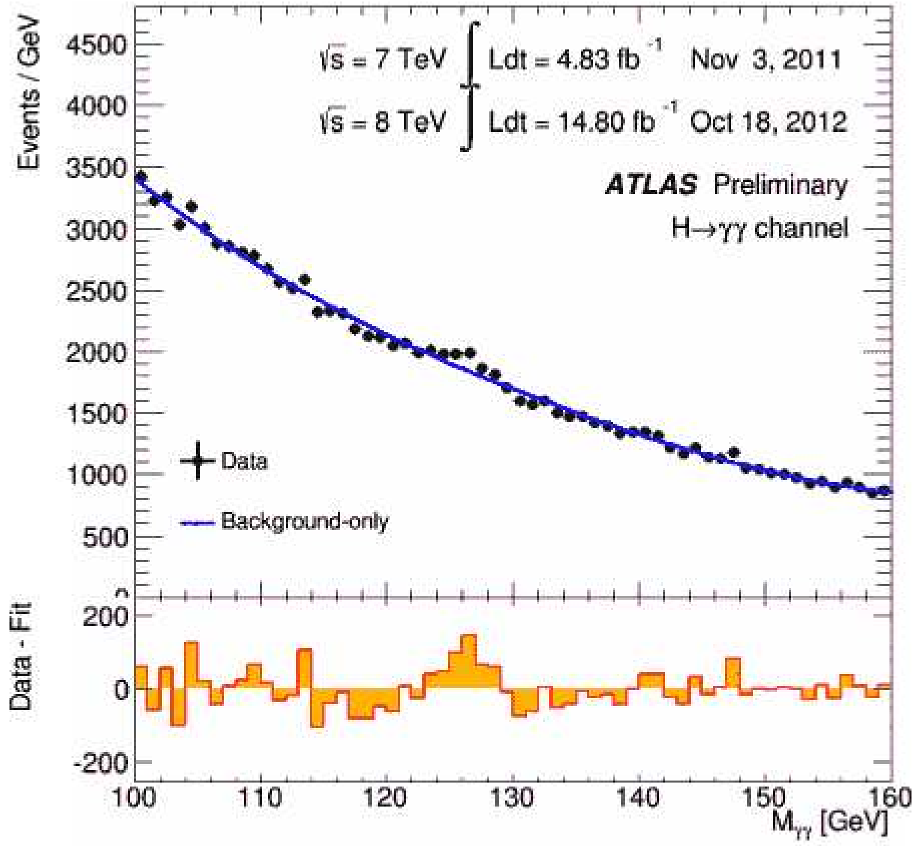

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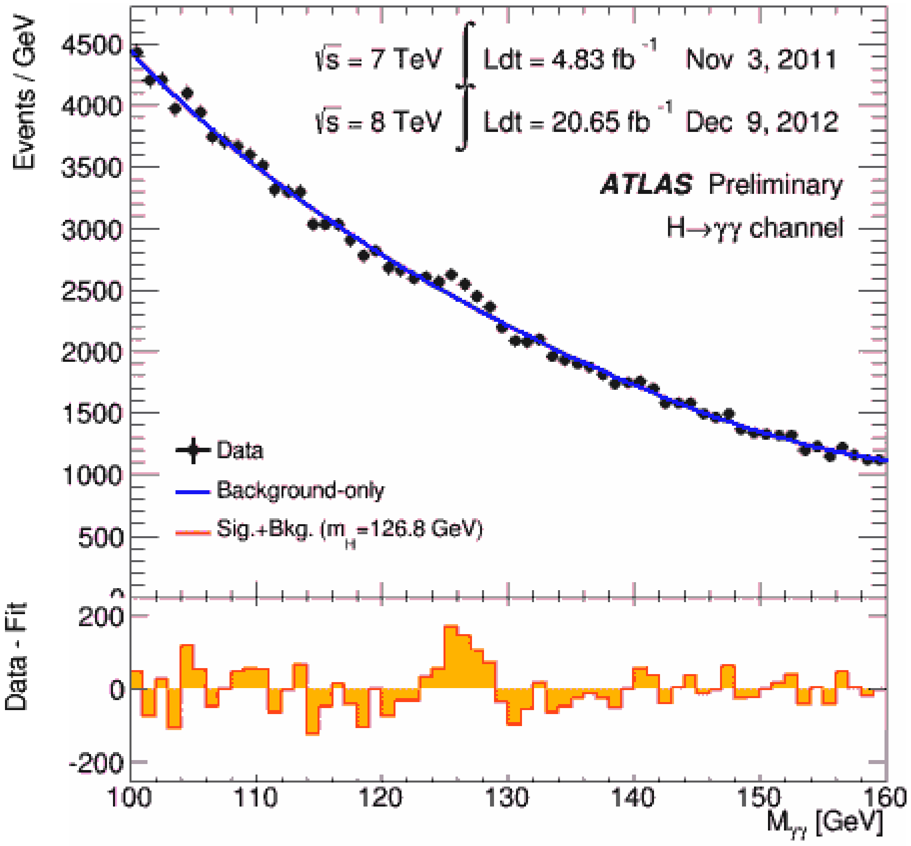

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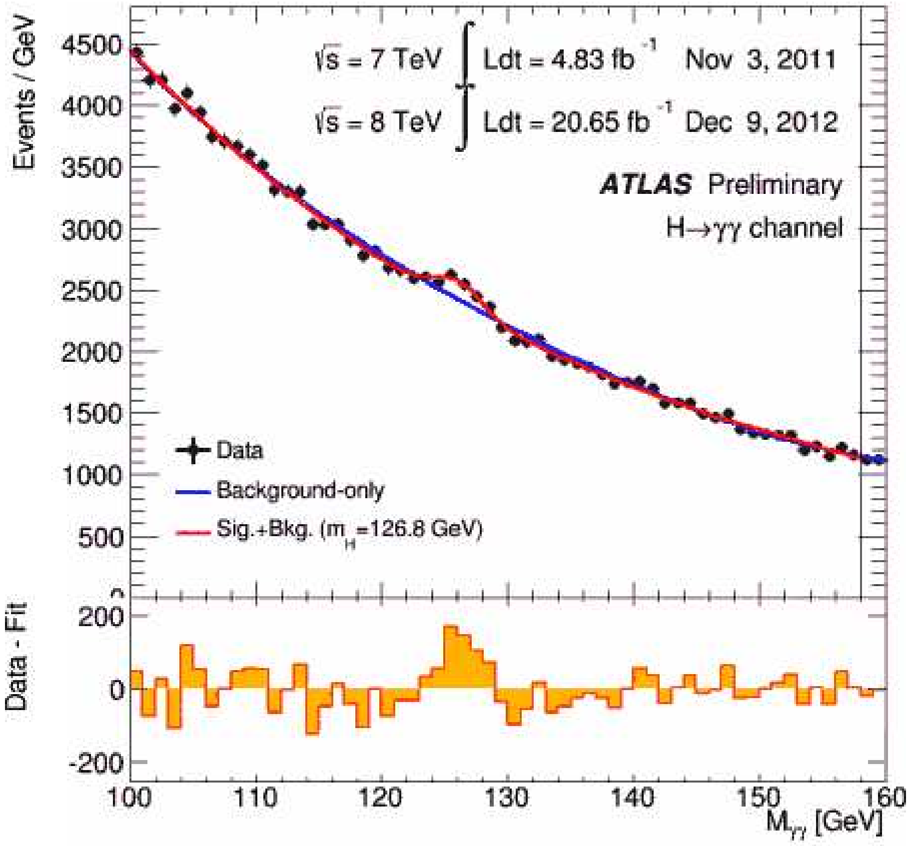
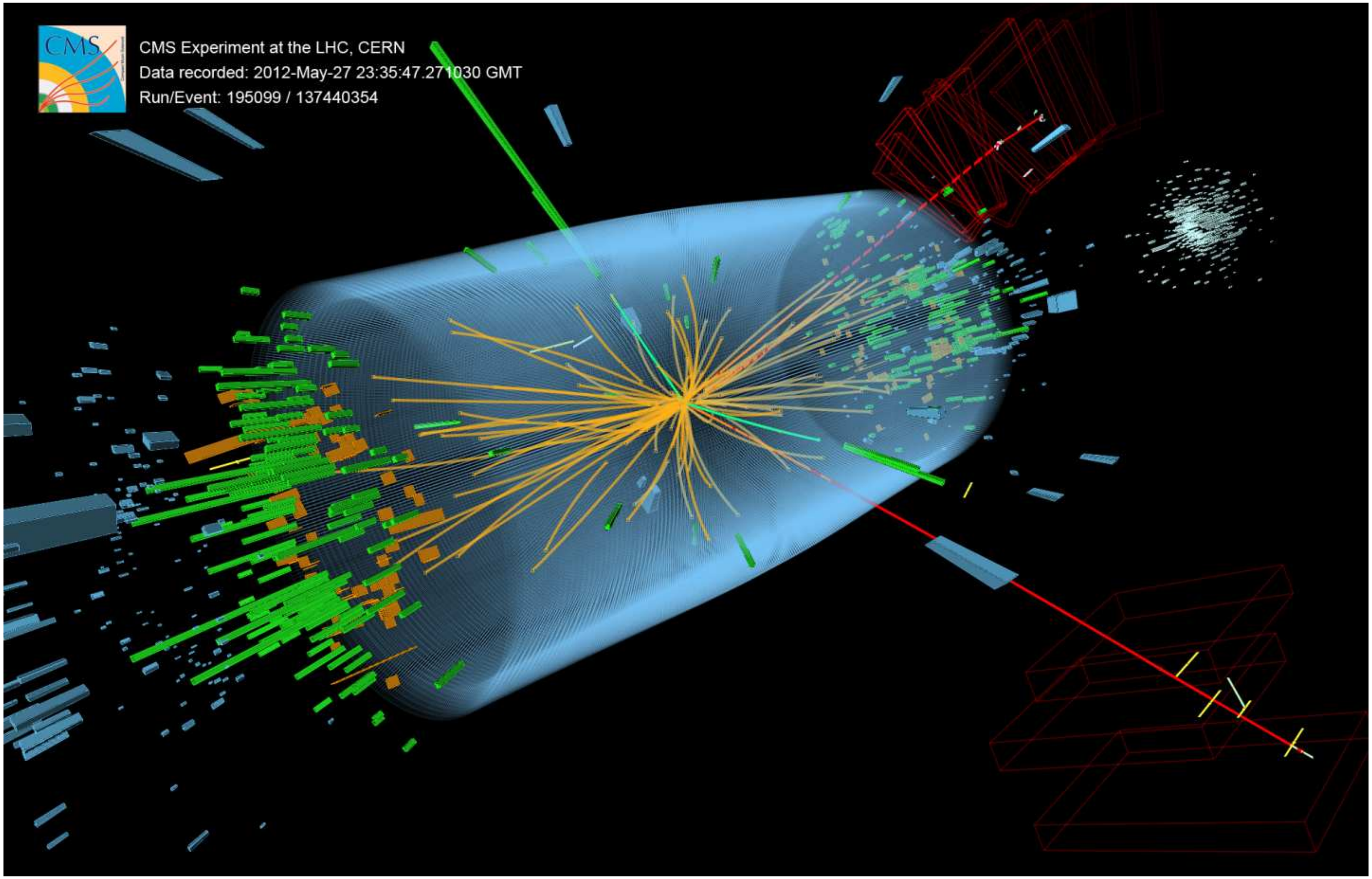
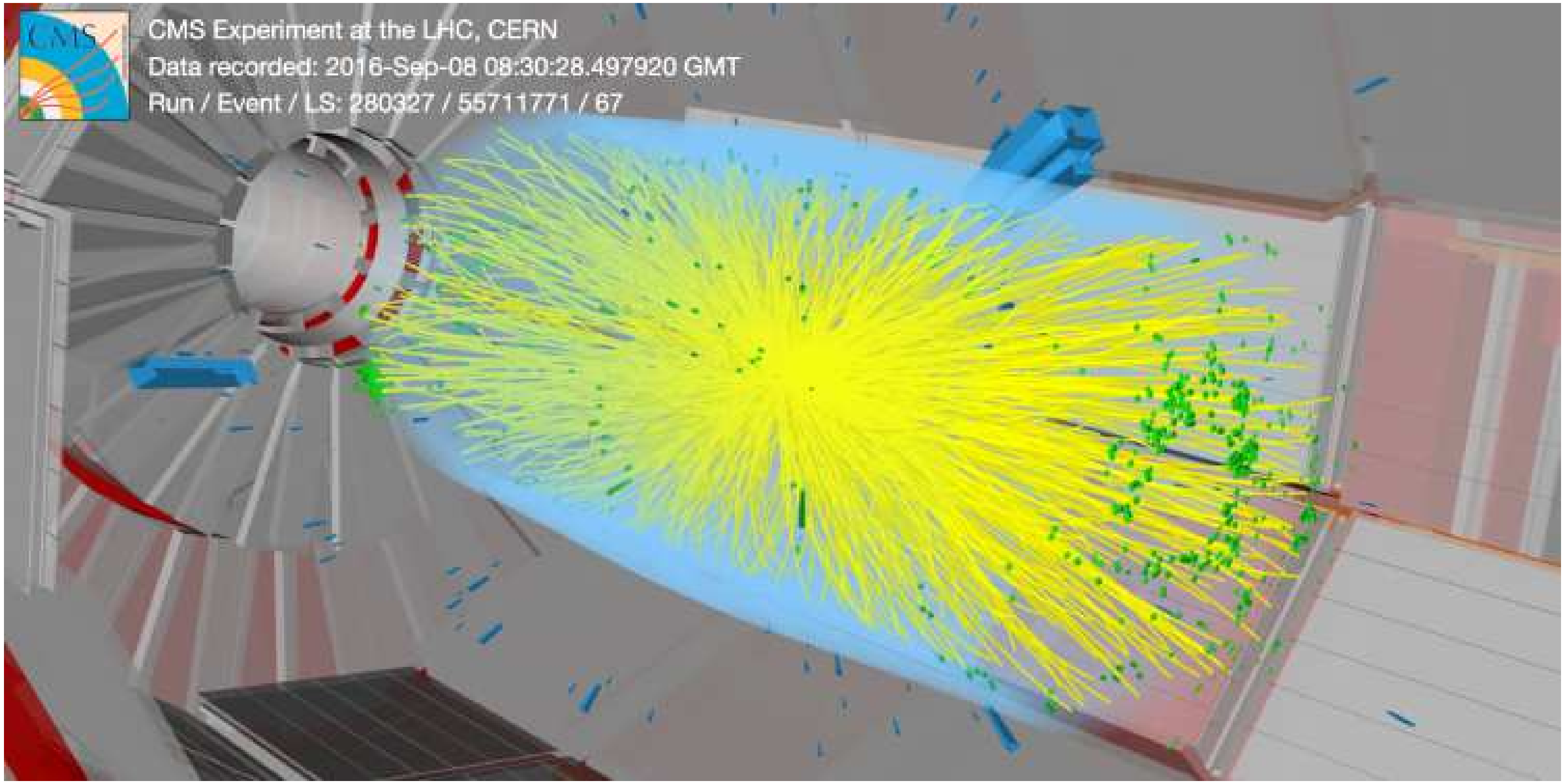


Higgs event



- Candidate event $H \to ZZ \to e^+e^- \, \mu^+\mu^-$

Real event



- Real event in a collision (pile-up , minimum bias, background, . . .)
  - fast triggers (hardware) for removal of pile-up, minimum bias etc.
  - deep neural networks (software) for signal and backround separation
- Machine learning and artificial intelligence heavily used in physics analyses

Costs of a Higgs boson

Category	Estimated Cost (up to 2024)
Construction	EUR 4.6 billion
Operation	EUR 5.25 billion
Total	**EUR10 billion**

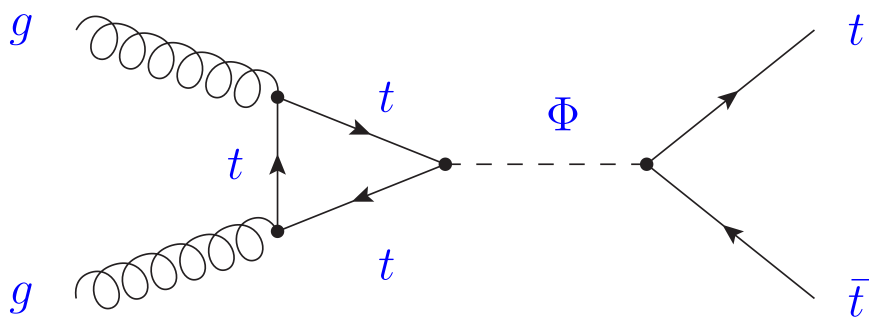
- Summary of LHC costs up to 2024 (approximate values)

LHC Run	Years	Higgs Bosons Produced (est.)
Run 1	2010–2012	0.2 million
Run 2	2015–2018	7 million
Run 3	2022–mid 2024	3.7 million
Total	**2010–mid 2024**	**11 million**

- Estimated Higgs boson production at the LHC up to mid-2024
- Each Higgs boson produced (2010–2024) now costs less then EUR 1000

Search for new heavy scalar bosons

- Heavy scalar boson Φ decaying to top quark pairs



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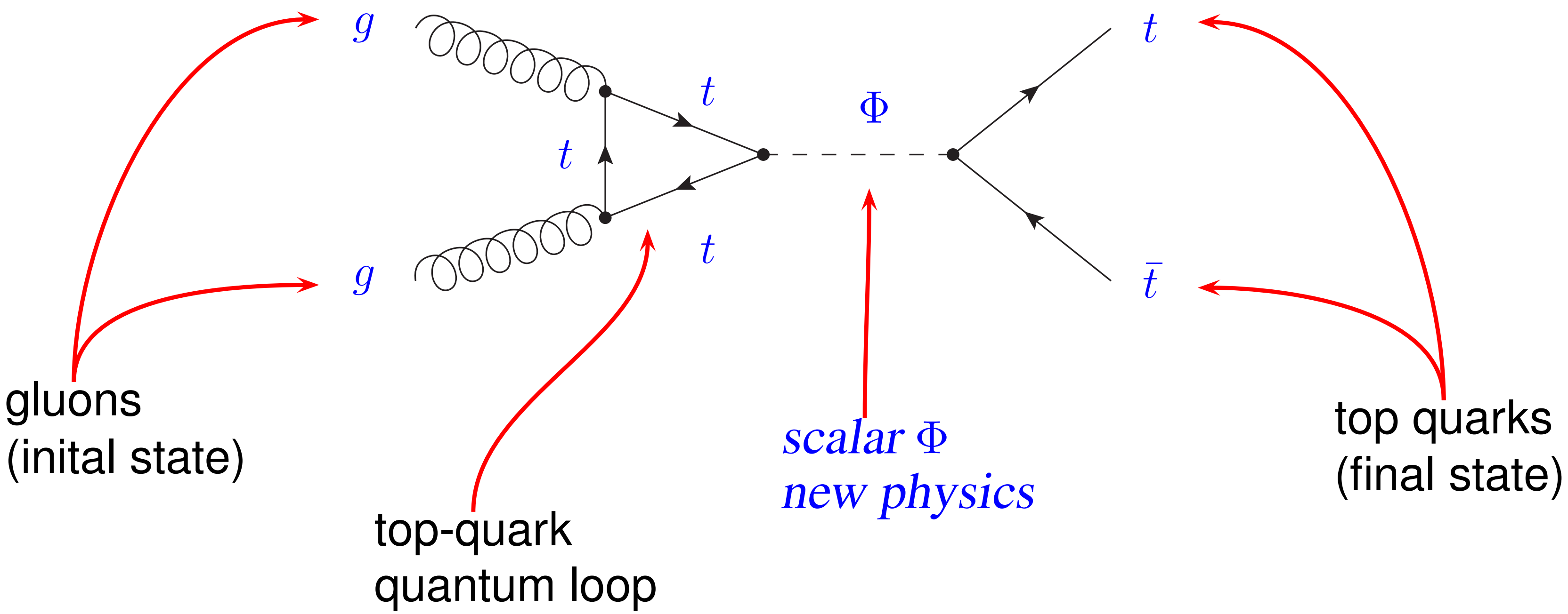

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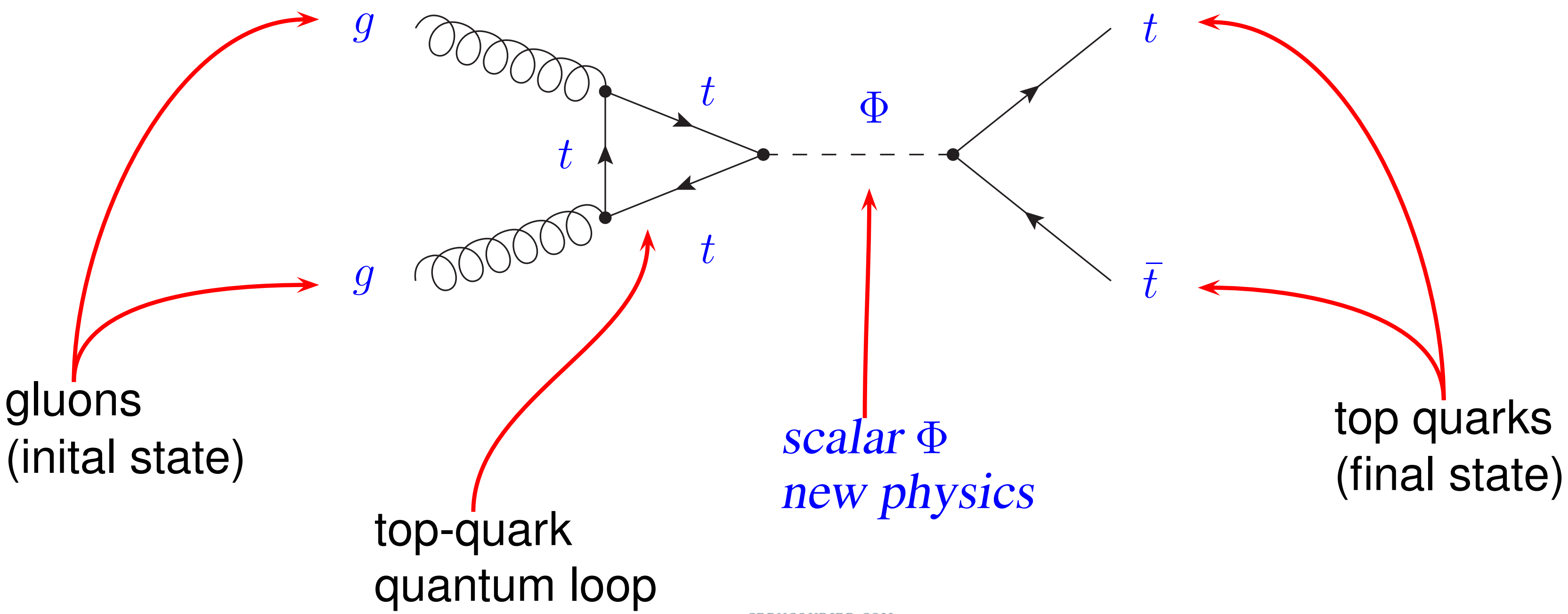


Excitement in the community

- CERN courier
  edition May 2025

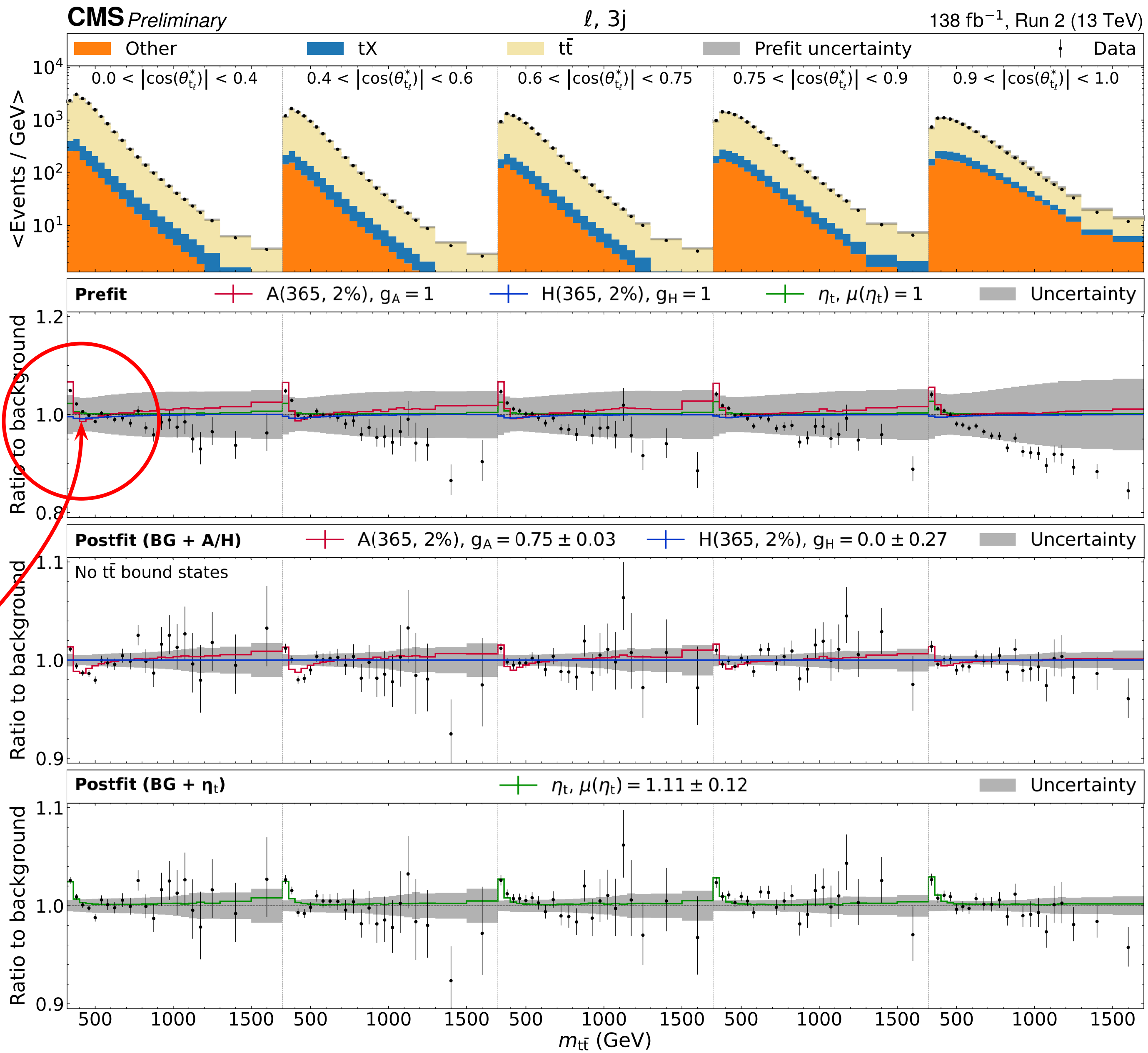
CERNCOURIER.COM

NEWS ANALYSIS

STRONG INTERACTIONS

CMS observes top–antitop excess

Experimental data

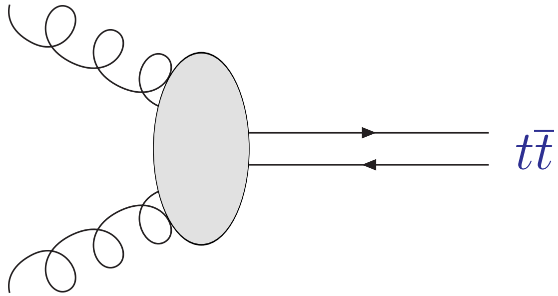


excess of data

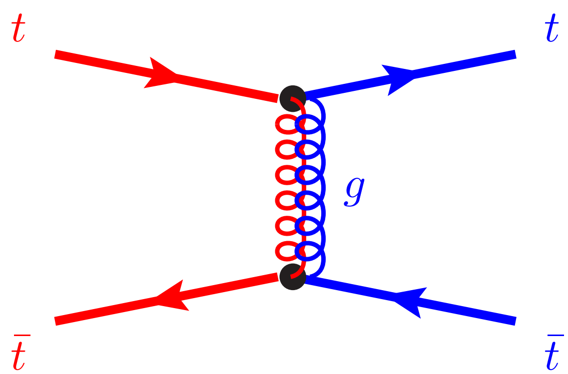
- Invariant mass distribution of top-quark pairs

Top-quark production

- Top-quarks produced close to threshold $E \gtrsim mc^2$
- Slowly moving color charges r, g, b



- Exchange of (many) gluons between quark and anti-quark



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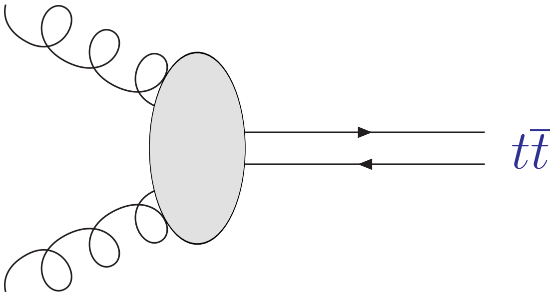

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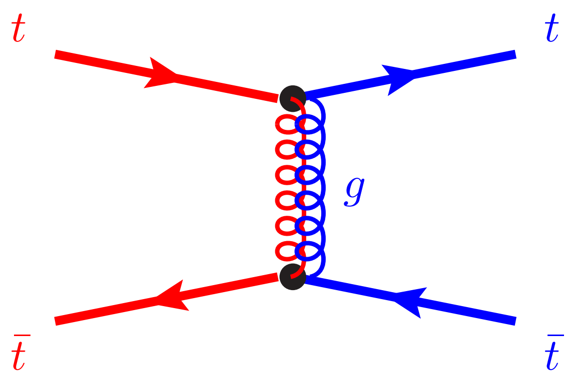

Electromagnetism

- Coloumb interaction of static charges

Top-quark bound state

Schrödinger equation

- Coulomb interaction from solution of Schrödinger equation

$$\left\{ -\frac{\vec{\nabla}^2}{m_t} + V_{\mathsf{QCD}}(\vec{x}) - (E + \mathrm{i}\Gamma_t) \right\} G(E, \vec{x}) \quad = \quad \delta^{(3)}(\vec{x})$$

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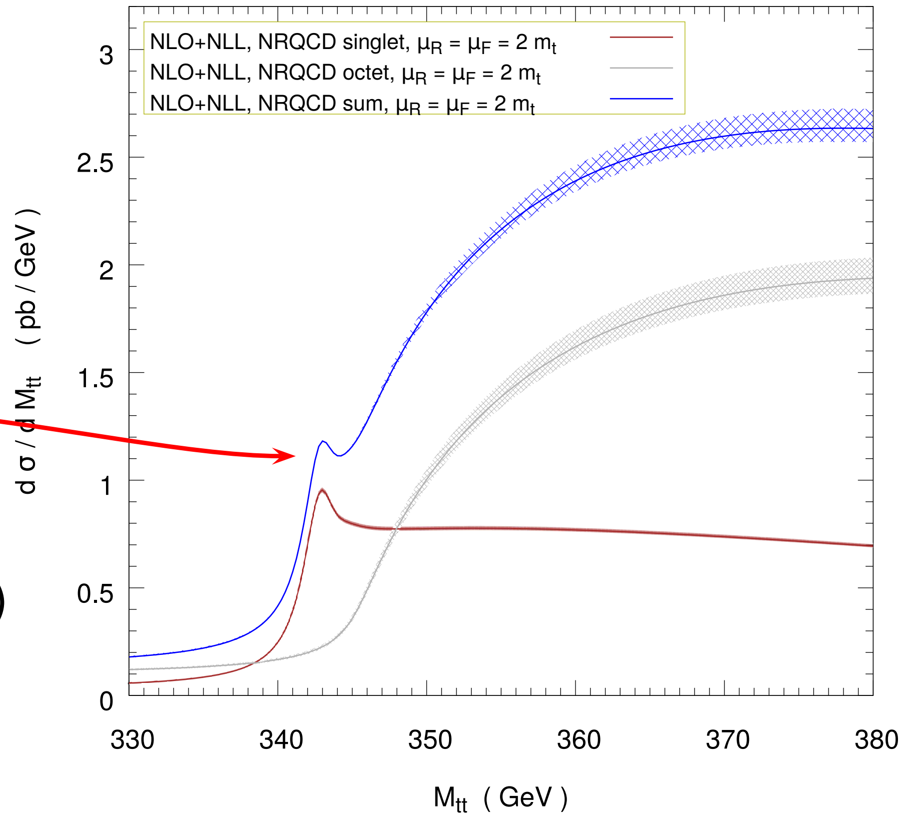
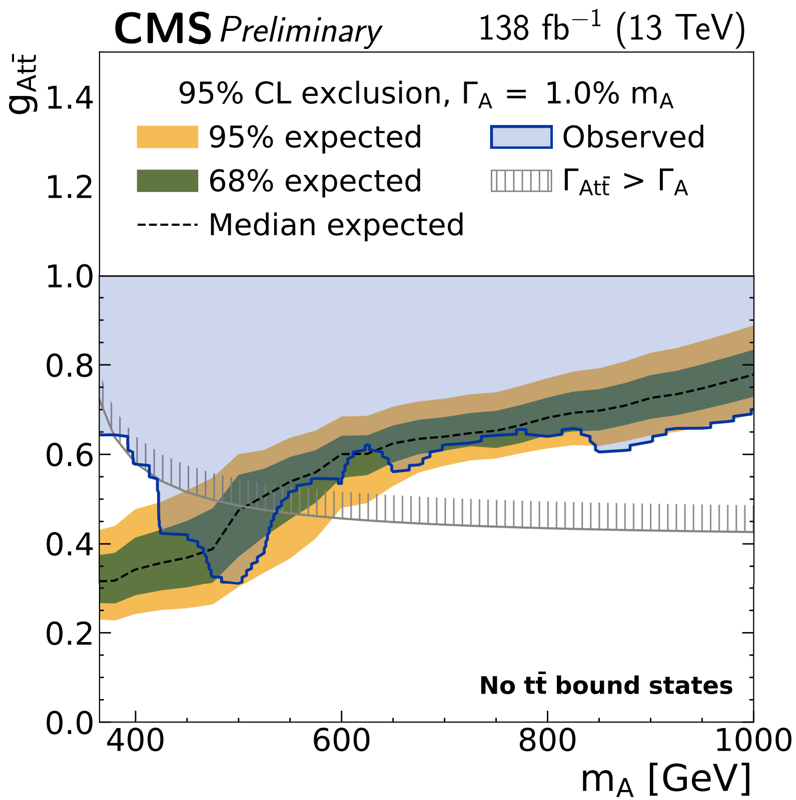
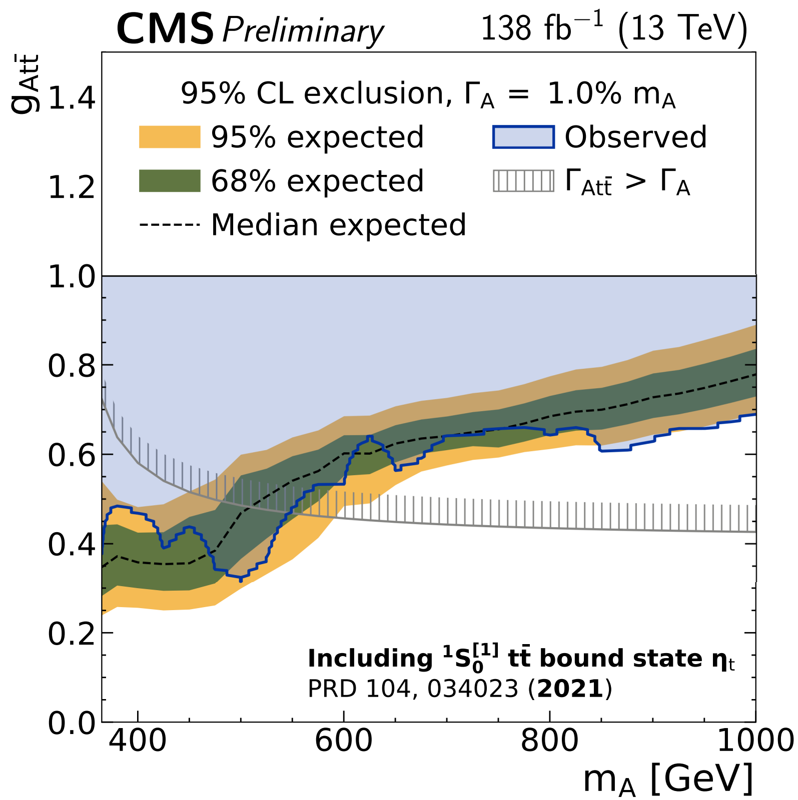


attractive interaction
(resonant enhancement)

Analysis of experimental data

- Left: background-only hypothesis
- Right: including top-quark bound state





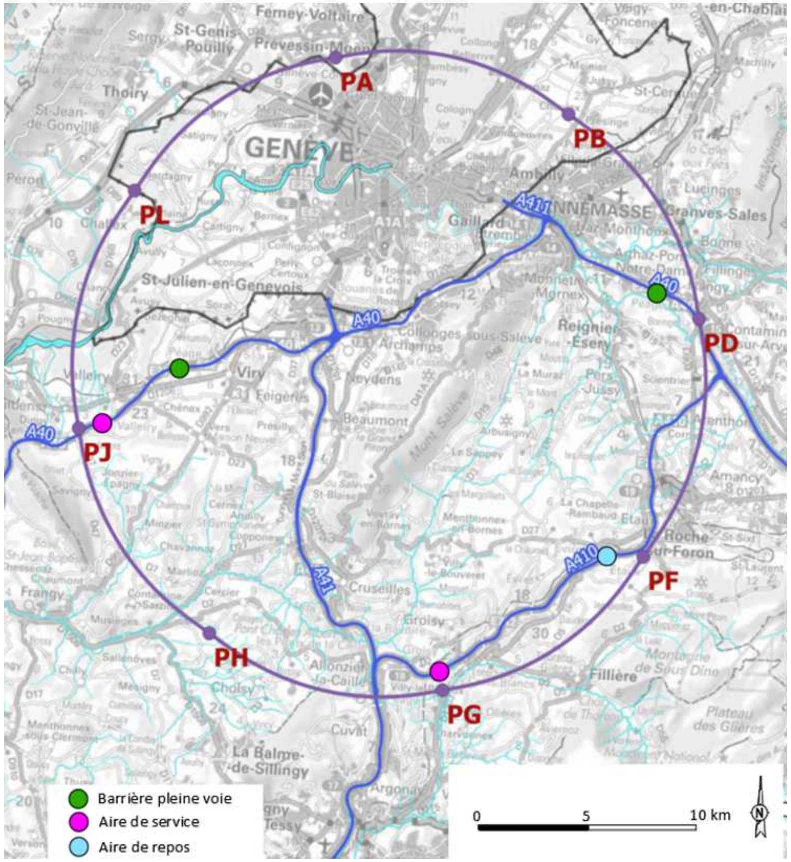
Upshot

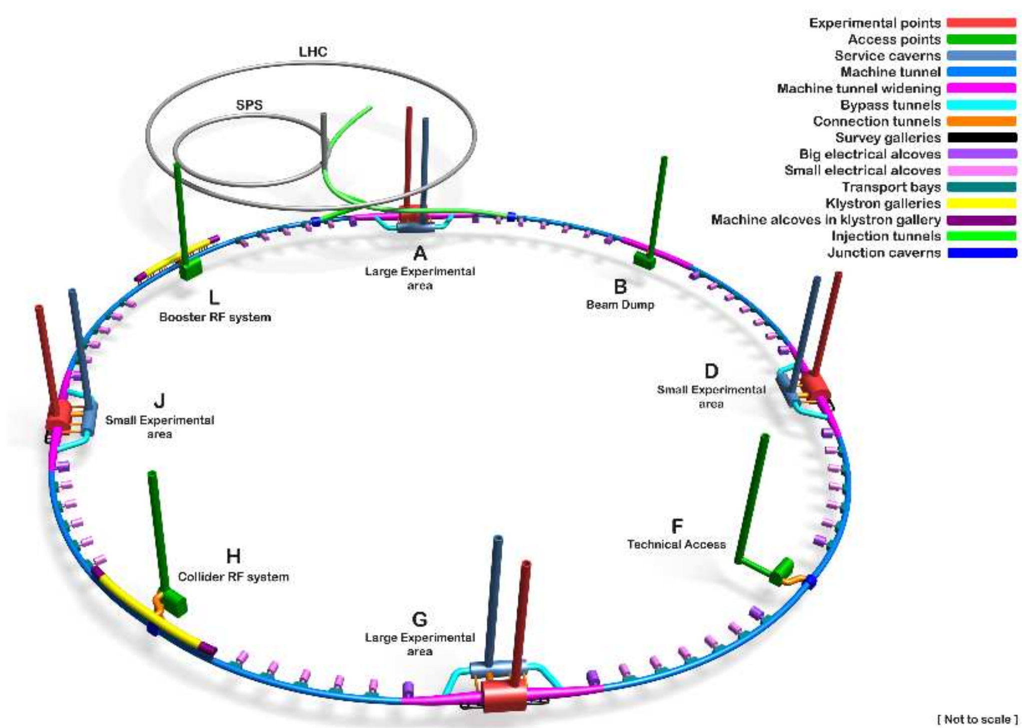
- No more deviations for low values of m_A mass

The future

Prediction is very difficult, especially if it is about the future

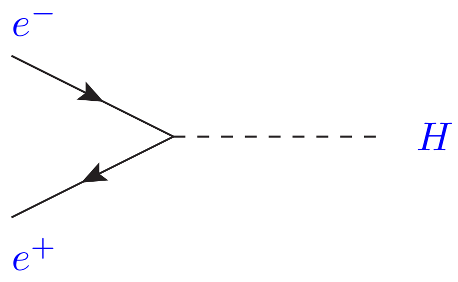
Future colliders





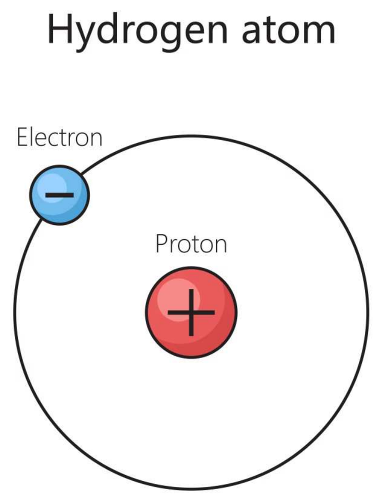
- FCC - Future Circular Collider
  - a new collider ring with 91 km circumference (in operation after 2045)
- Precision measurements of Higgs bosons, top-quarks, . . .

Mass of the electron



- FCC-ee can check if electron mass m_e is indeed due to Higgs mechanism $e^+e^- \to H$
- Run a number of years at energy of Higgs boson mass
- Caveats
  - serious background $e^+e^- \to q\bar{q}$
  - experimentally very difficult

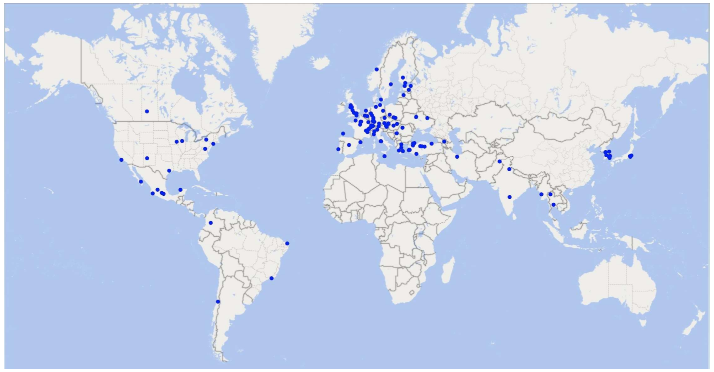
Atomic size



- We would understand the size of atoms!
  - Bohr radius (size of hydrogen atom) $a_0 = \dfrac{\hbar}{m_e\, c\, \alpha}$
  - Planck's constant $\hbar$
  - speed of light c
  - Fine structure constant (electron charge) α

FCC scope

- Scientific discovery: address fundamental questions in particle physics
- Technological innovation: advance cutting-edge technologies (e.g., superconductors, computing)
- Training and education: top-tier training of international talent
- Economic benefits: investment in high-tech industries (proven spin-offs into industry and society)
- International collaboration: reinforcement of Europe's leadership in global science

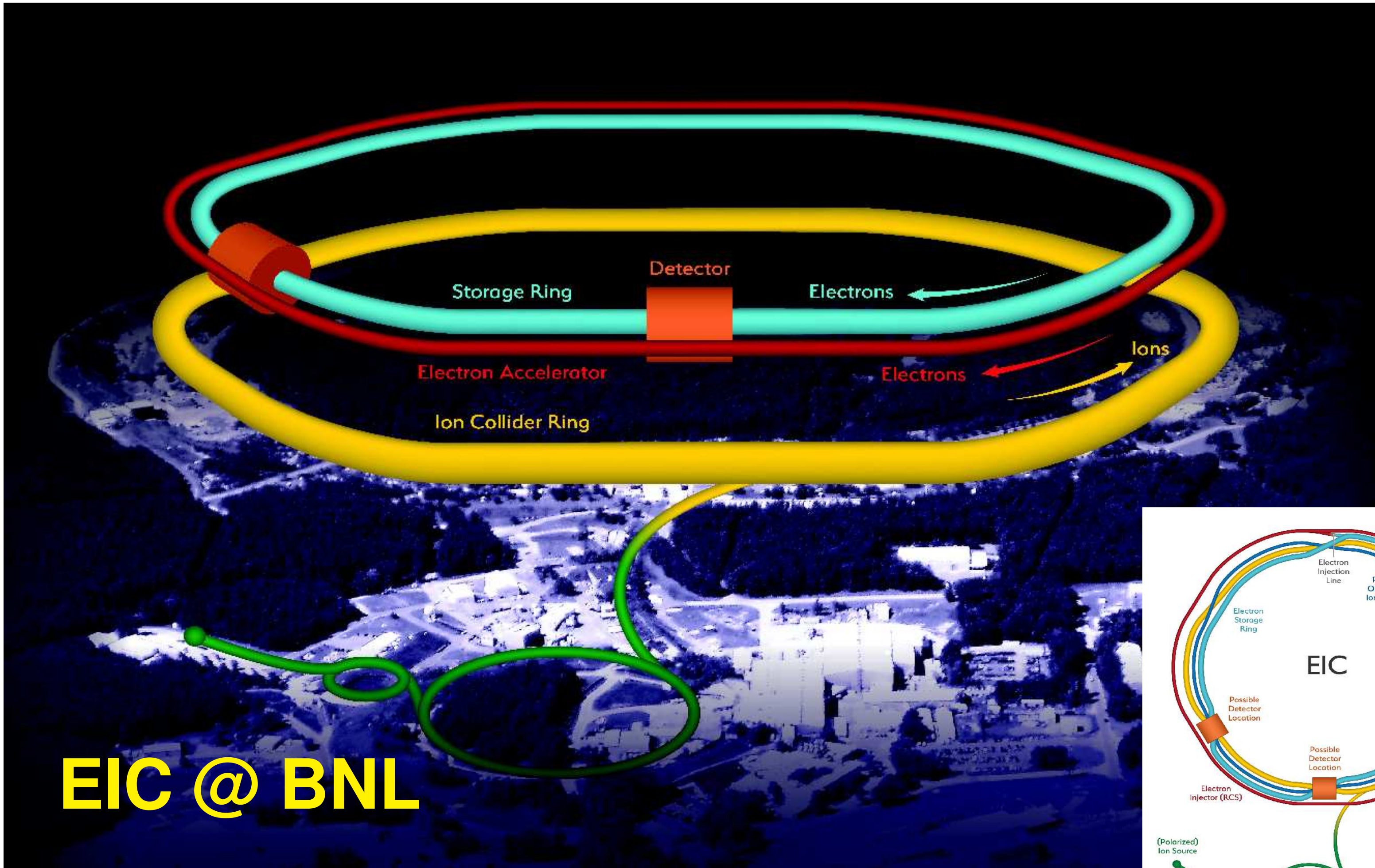


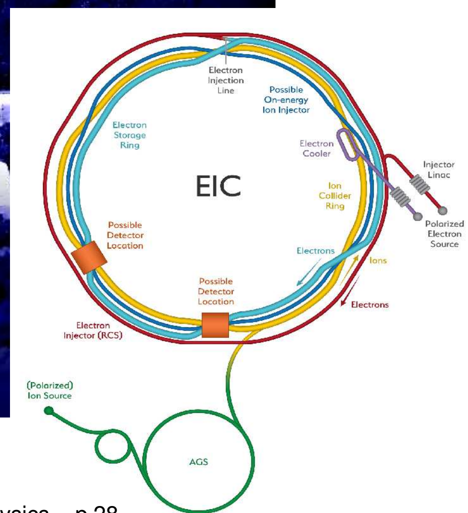
Parameters

- Total construction costs 15.320 MCHF (incl. four experiments 1.300 MCHF)
- Planned construction period 2033 - 2046
- Peak power during beam operations $\approx$ 300 MW
- Total energy consumption $\approx$ 1.4 TWh/year

Near future (I)

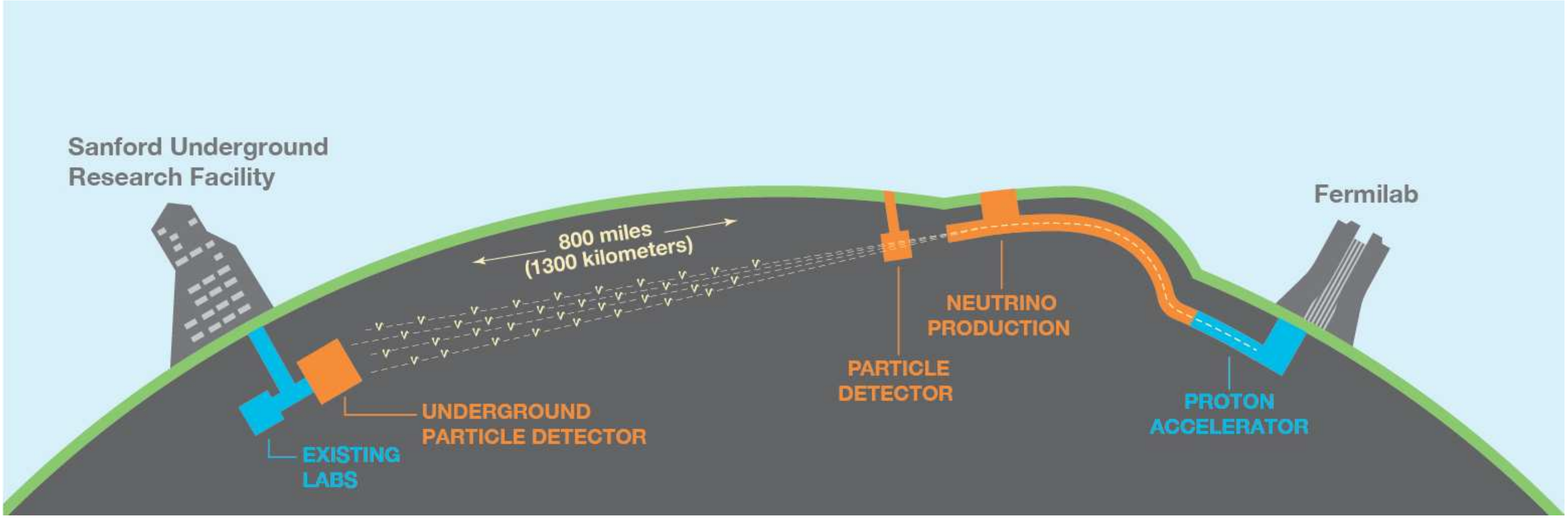
- Electron-Ion Collider
  A machine that will unlock the secrets of the strongest force in Nature





Near future (II)

- Deep Underground Neutrino Experiment
  An international flagship experiment to unlock the mysteries of neutrinos



DUNE @ LBNF

Near future (III)

- Vera C. Rubin Observatory
  will bring the night sky to life and revolutionize the way we explore the cosmos

Rubin Observatory in Chile

Summary

State-of-the-art

- Particle physics revealed matter’s fundamental components via Standard Model
- Notable successes include discovering the Higgs boson and precise measurements

Open questions

- Higgs boson interactions and potential
- Neutrino masses
- Imbalance between matter and antimatter
- Nature of dark matter

Future

- Future experiments and new technologies will address open questions
- Potential for groundbreaking discoveries that could fundamentally deepen understanding of Universe