Searches for Vector-Like Quarks

Seminar in Physics

March 20, 2018

Outline

- Elementary Particle Physics
- A Brief History
- The Standard Model
- Gauge Theories
- Higgs Mechanism
- Naturalness Problem
- Planck Scale
- Vector-Like Quarks
- LHC and CMS
- Current VLQ Analysis Status
- LHC Timeline
- Future

Elementary Particle Physics

Study of the small scale structure of the universe

- What are the basic building blocks?
- How do they interact with one another?
- Is there a smallest amount of space and time?
- Is there a theory of everything?

Elementary Particle Physics circa 1932

muon 1936

neutrino ν

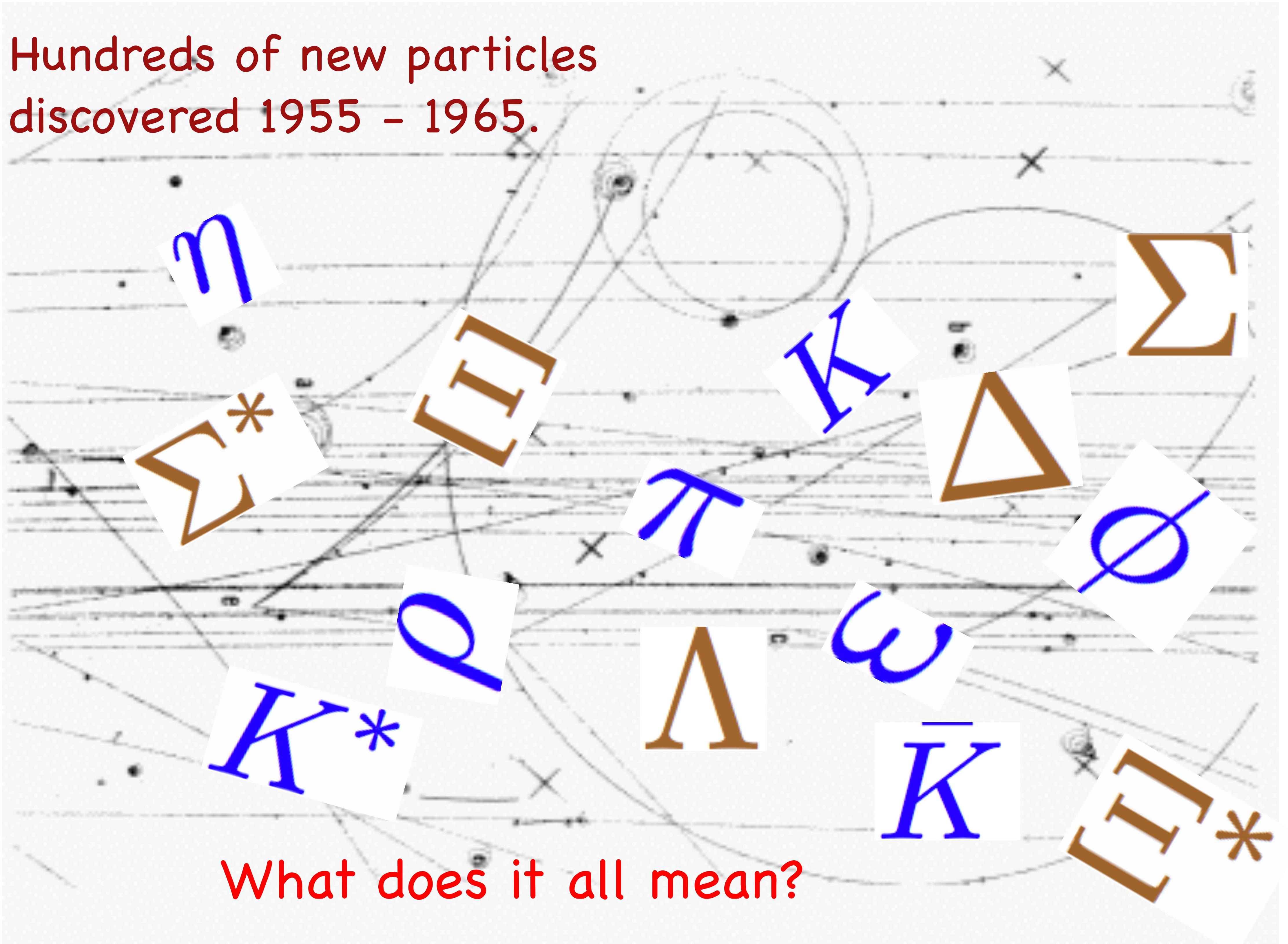
electron e^- μ^- Who ordered that?

proton p

photon γ

neutron n

Confusion in the 1960's



Elementary Particle Physics circa 1970

muon neutrino 1962

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

$$\gamma$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad \begin{pmatrix} \\ s \end{pmatrix}$$

quarks 1968

The 1970's Revolution

1974 to 1983

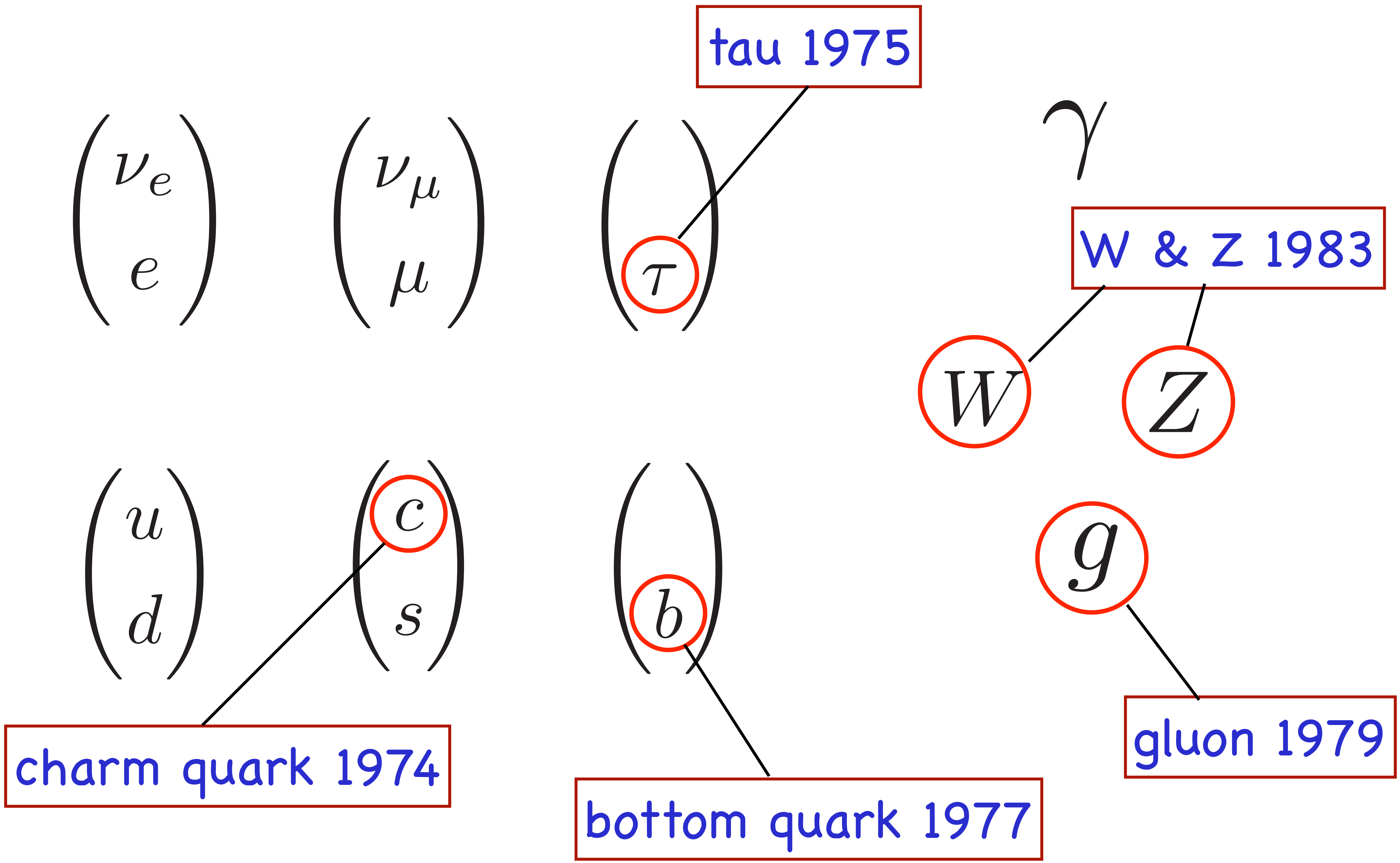
Experimental Revolution

Particle discoveries

Theoretical Revolution

The Standard Model

Particle Discoveries



Particle Discoveries post 1970's

tau neutrino 2000

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \qquad \gamma$$

$$W \qquad Z$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \qquad g$$

top quark 1995

Standard Model of Particle Physics

Ingredients

Matter Particles

Gauge Particles

Fundamental Interactions

Higgs Boson

Standard Model Particles

Matter particles

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Gauge particles

$$\gamma$$

$$W \quad Z$$

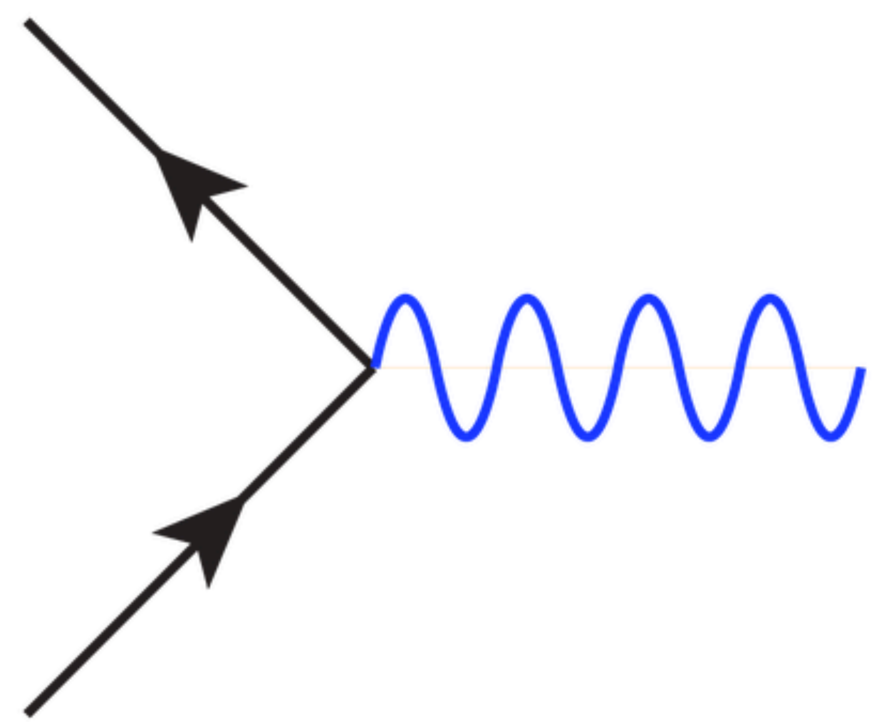
$$g$$

Gauge Interactions

Special Relativity + Quantum Mechanics

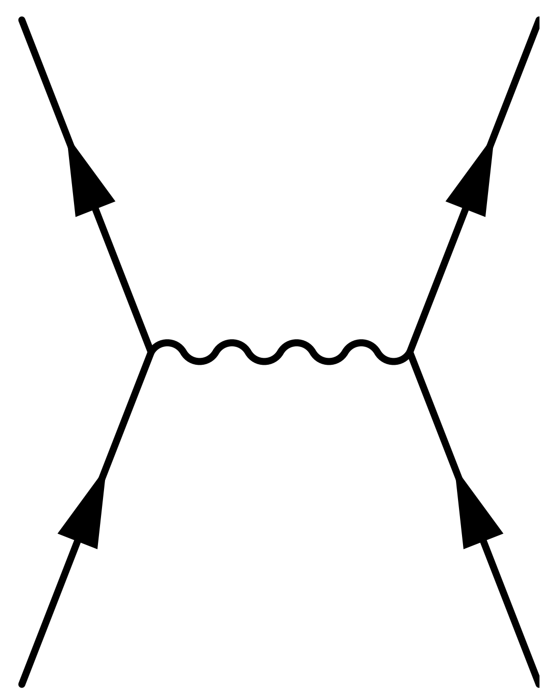
→ Gauge Quantum Field Theory

Only way for a matter particle to interact



Standard Model Interactions

Gauge Interactions



$$m_\gamma = 0$$

$$m_g = 0$$

$$m_W = 80 \text{ GeV/c}^2$$

$$m_Z = 91 \text{ GeV/c}^2$$

QED: photon coupled to electric charge

QCD: gluons coupled to color charge

Weak: W^+, W^-, Z^0 coupled to weak isocharge

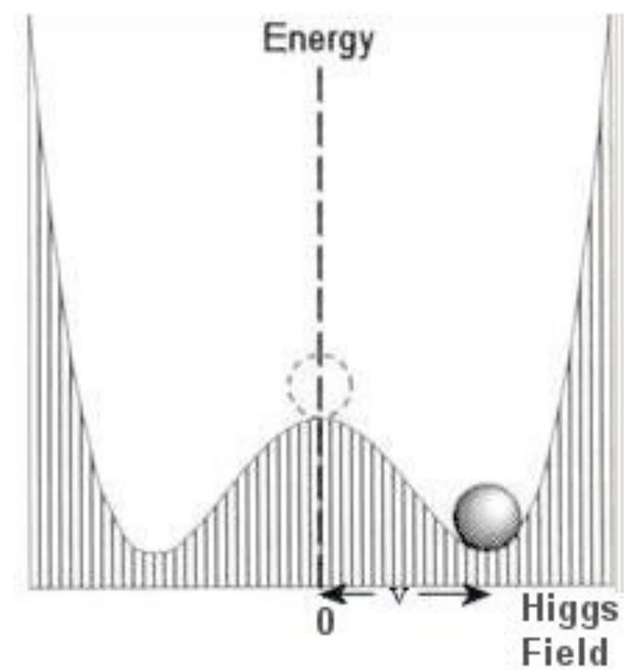
Higgs Mechanism

Spontaneous Symmetry Breaking

Higgs field potential

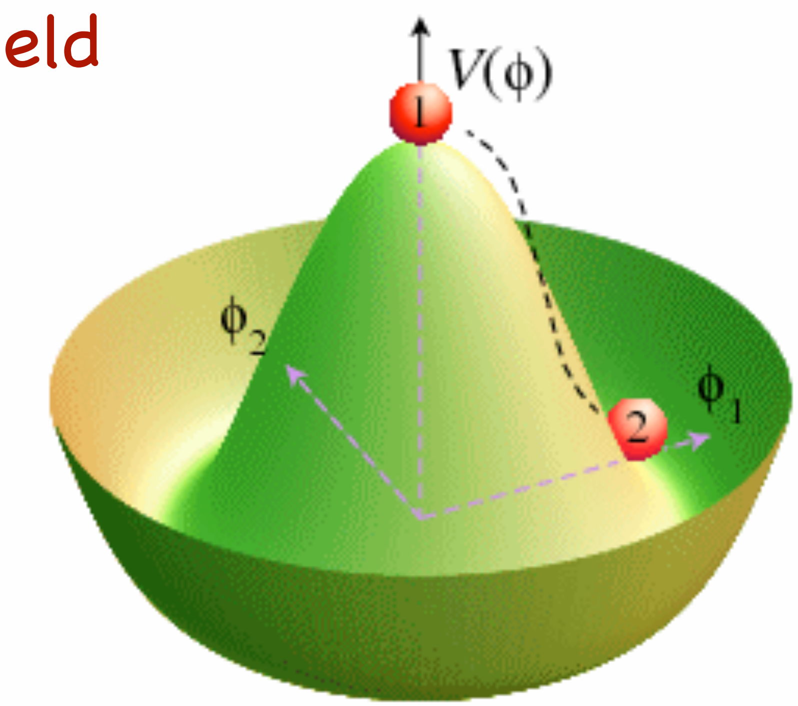
$$V = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

If $\mu^2 < 0$ ground state of the universe has non-zero expectation value of ϕ



The solution (the universe) breaks the symmetry by choosing one of the (many) solutions

complex scalar field



$$m_W \sim v$$

$$m_H \sim \lambda^{1/2} v$$

Standard Model Particles

Matter particles

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Gauge particles

$$\gamma$$

$$W \quad Z$$

$$g$$

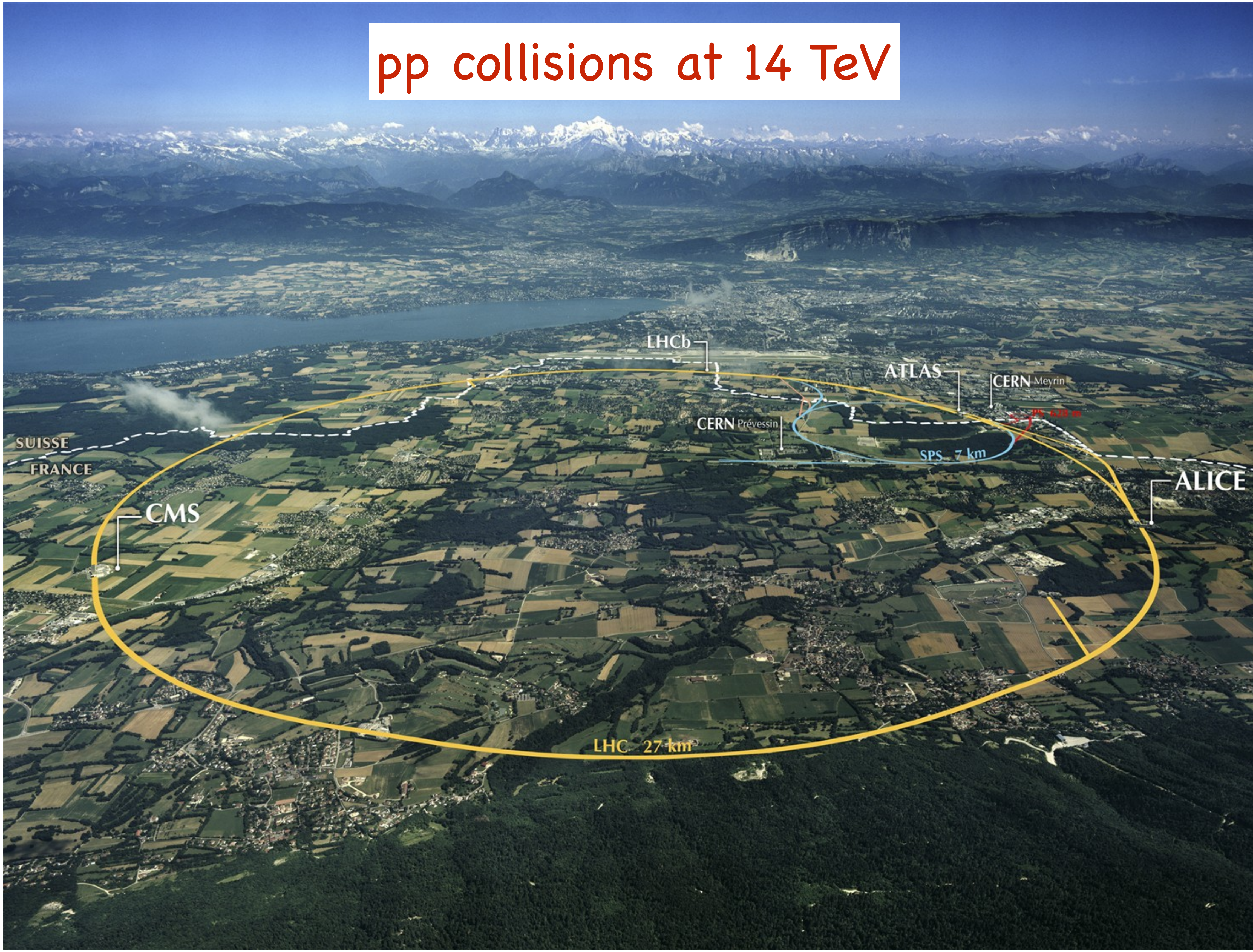
Higg Boson

$$H$$

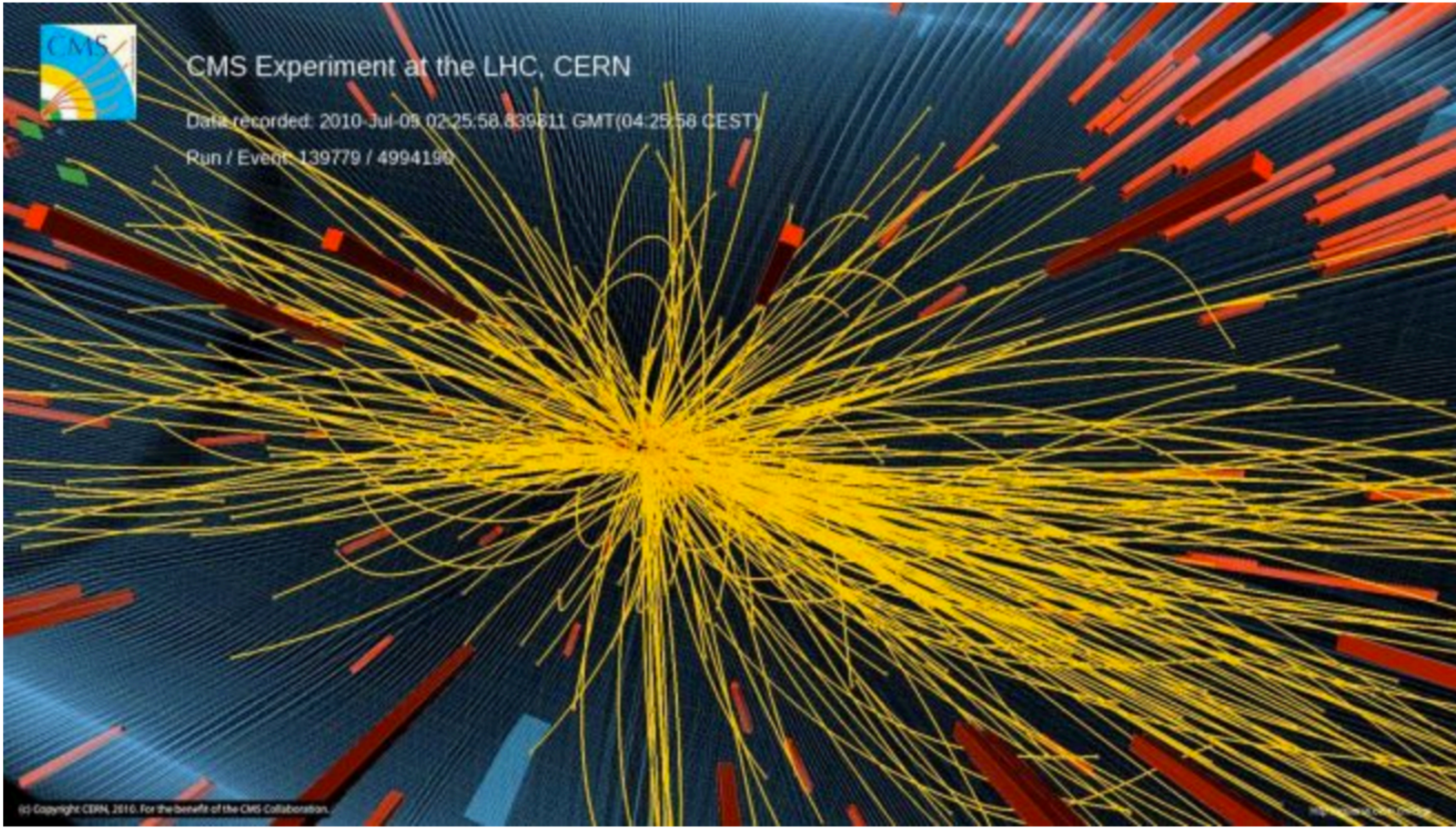
Collision

Particle physicists attempt
to find out how a car works

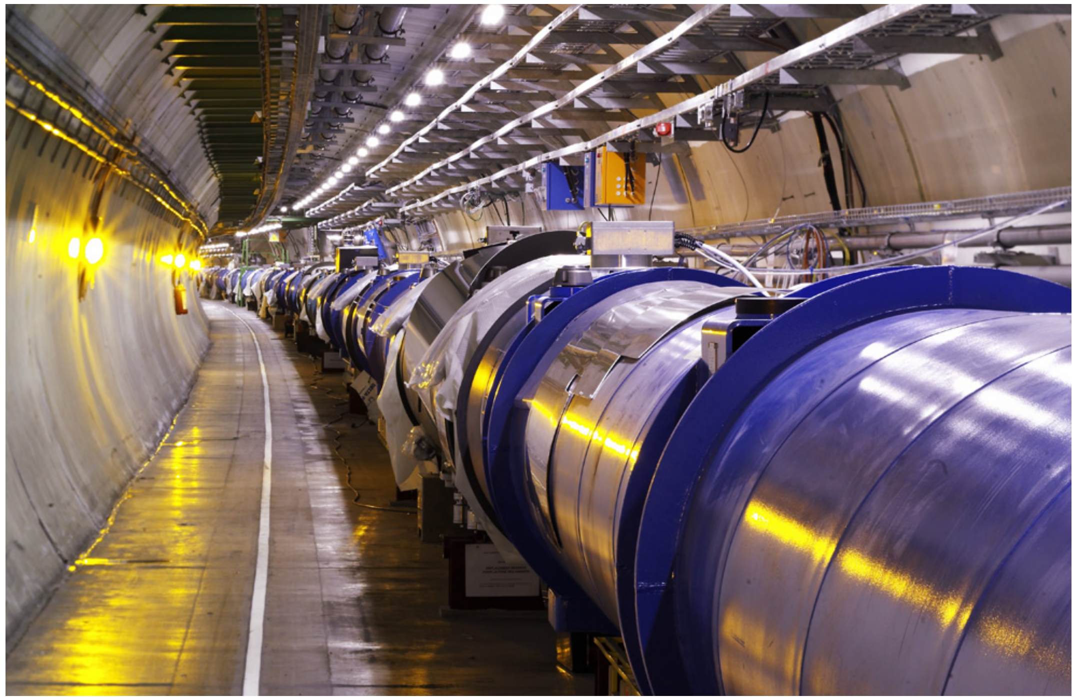
The Large Hadron Collider

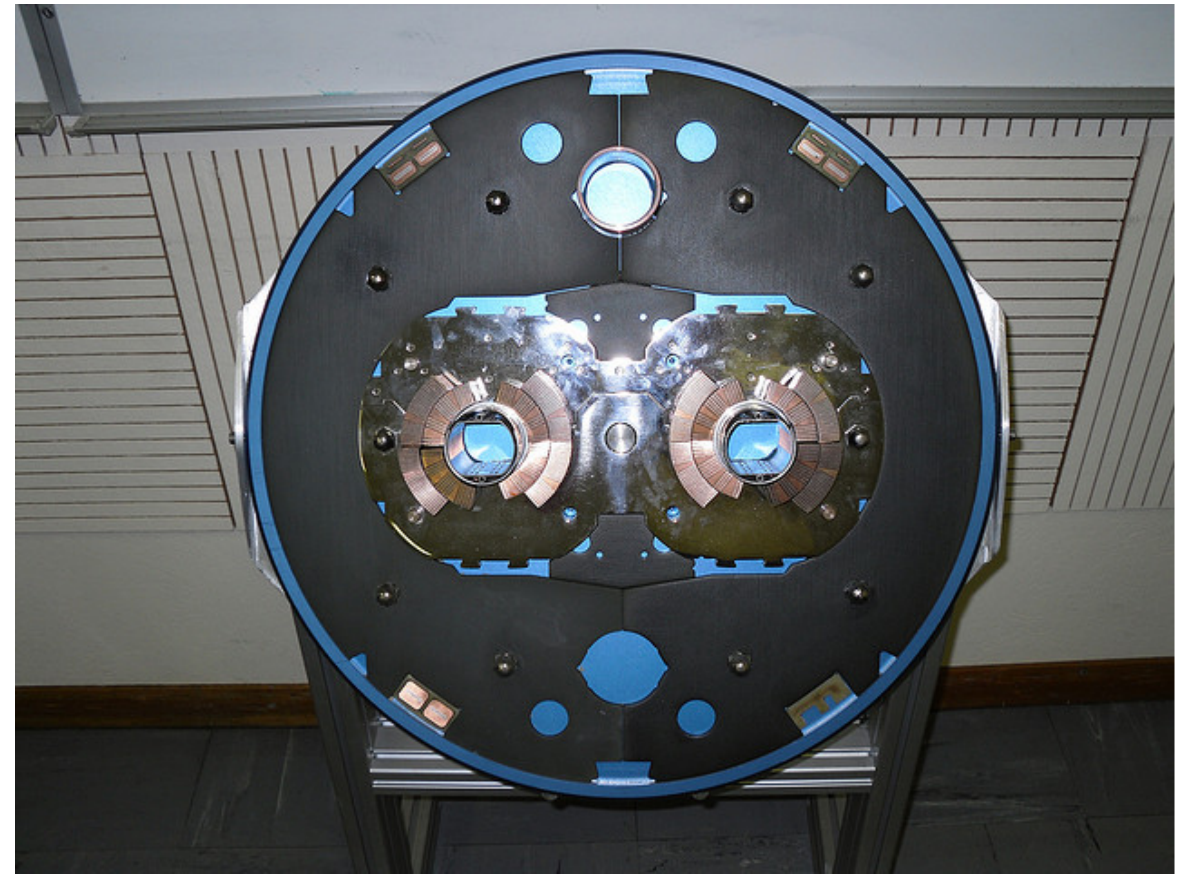


LHC Event

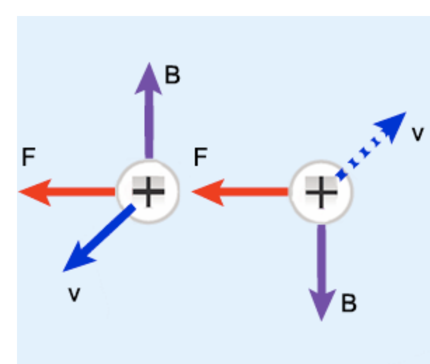

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2010-Jul-09 02:25:58.839811 GMT(04:25:58 CEST)
Run / Event: 139779 / 4994190
(c) Copyright CERN, 2010. For the benefit of the CMS Collaboration.

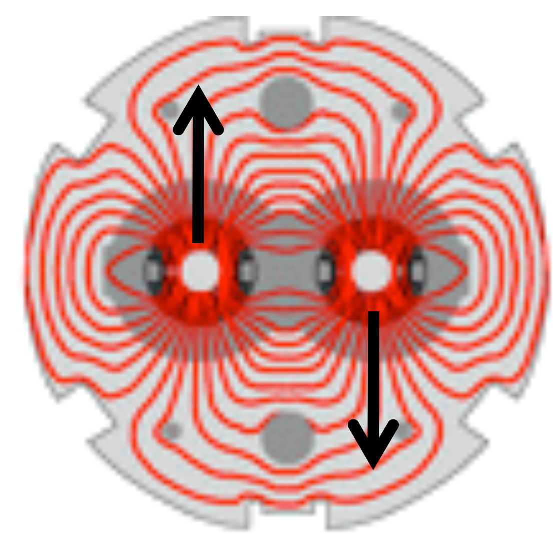
LHC Magnets



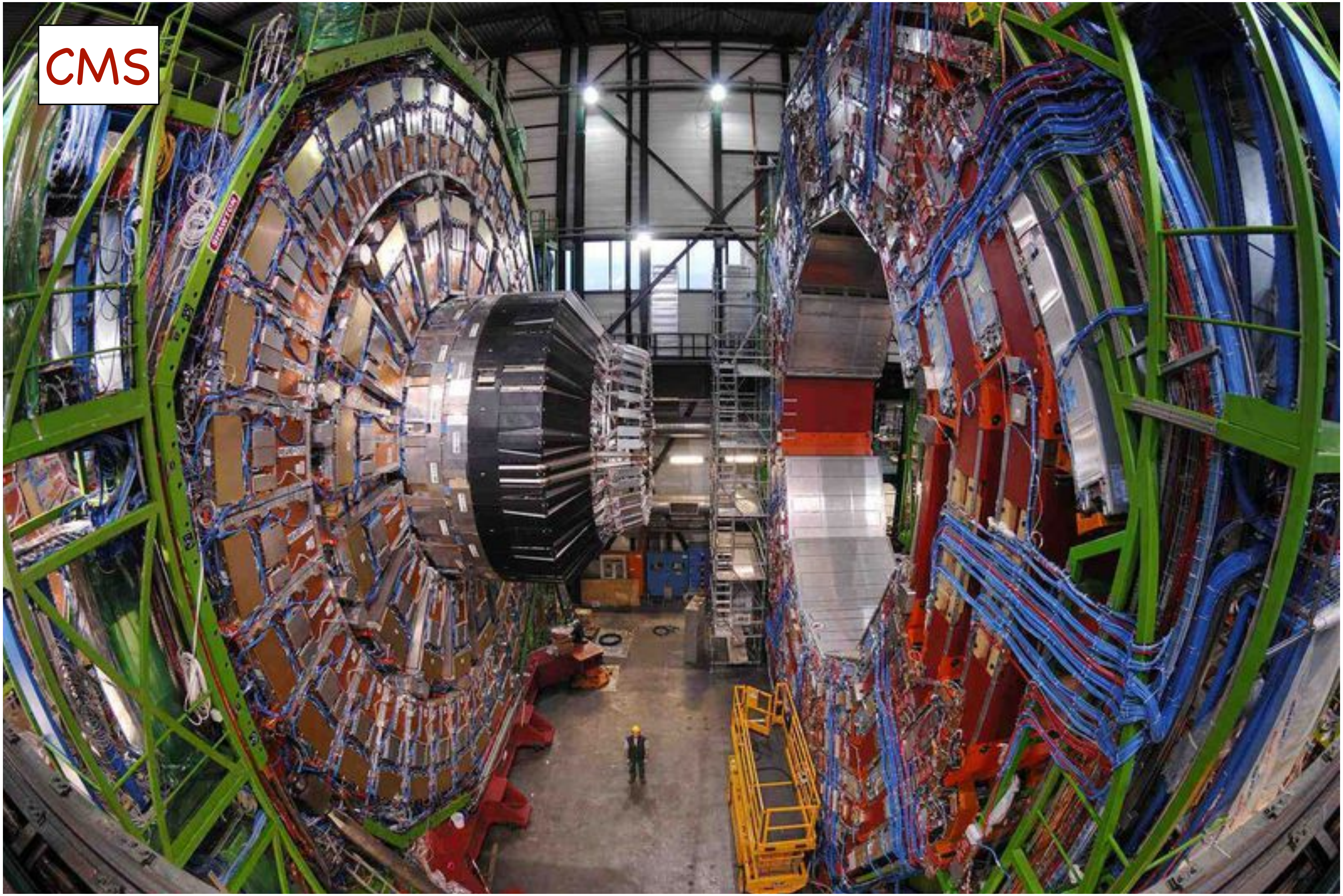


- 1232, 15-m long, 35 tons
- 8.4 T (for 7 TeV beam)
- 11,700 Amps
- 1.9° K



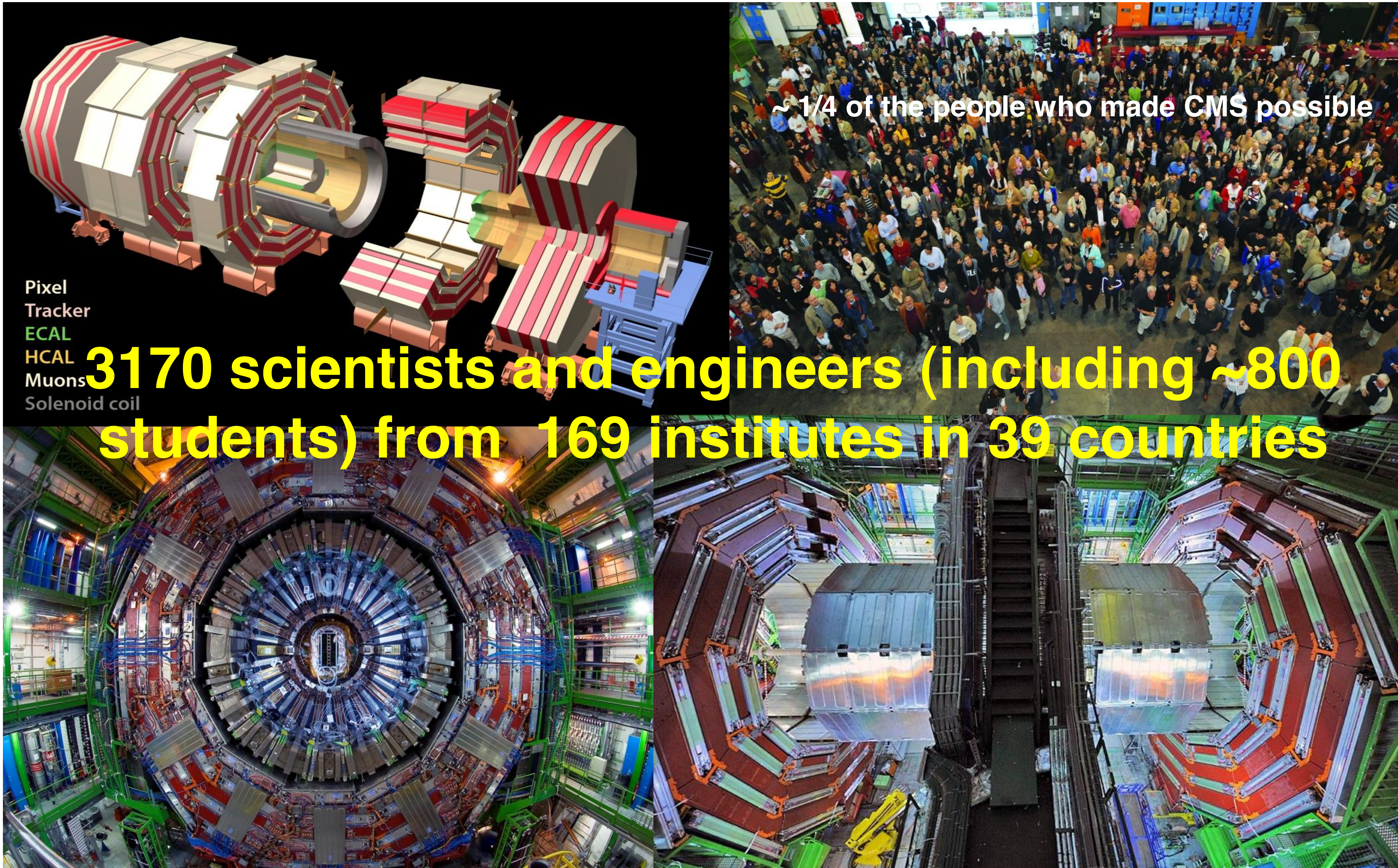


The Experiments are Big



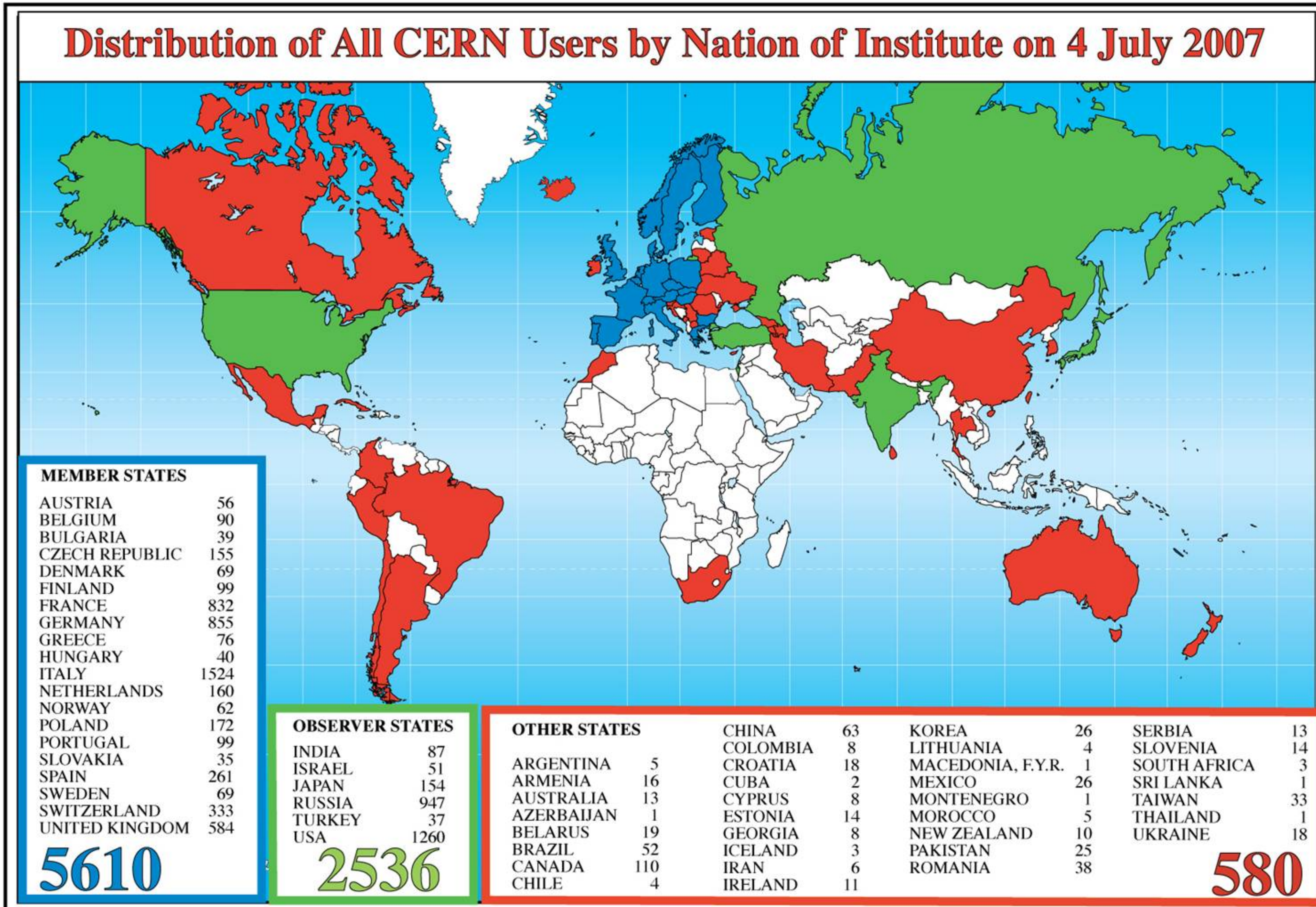
The CMS Collaboration

The CMS Collaboration



3170 scientists and engineers (including ~800 students) from 169 institutes in 39 countries

Global Effort



LHC Physics

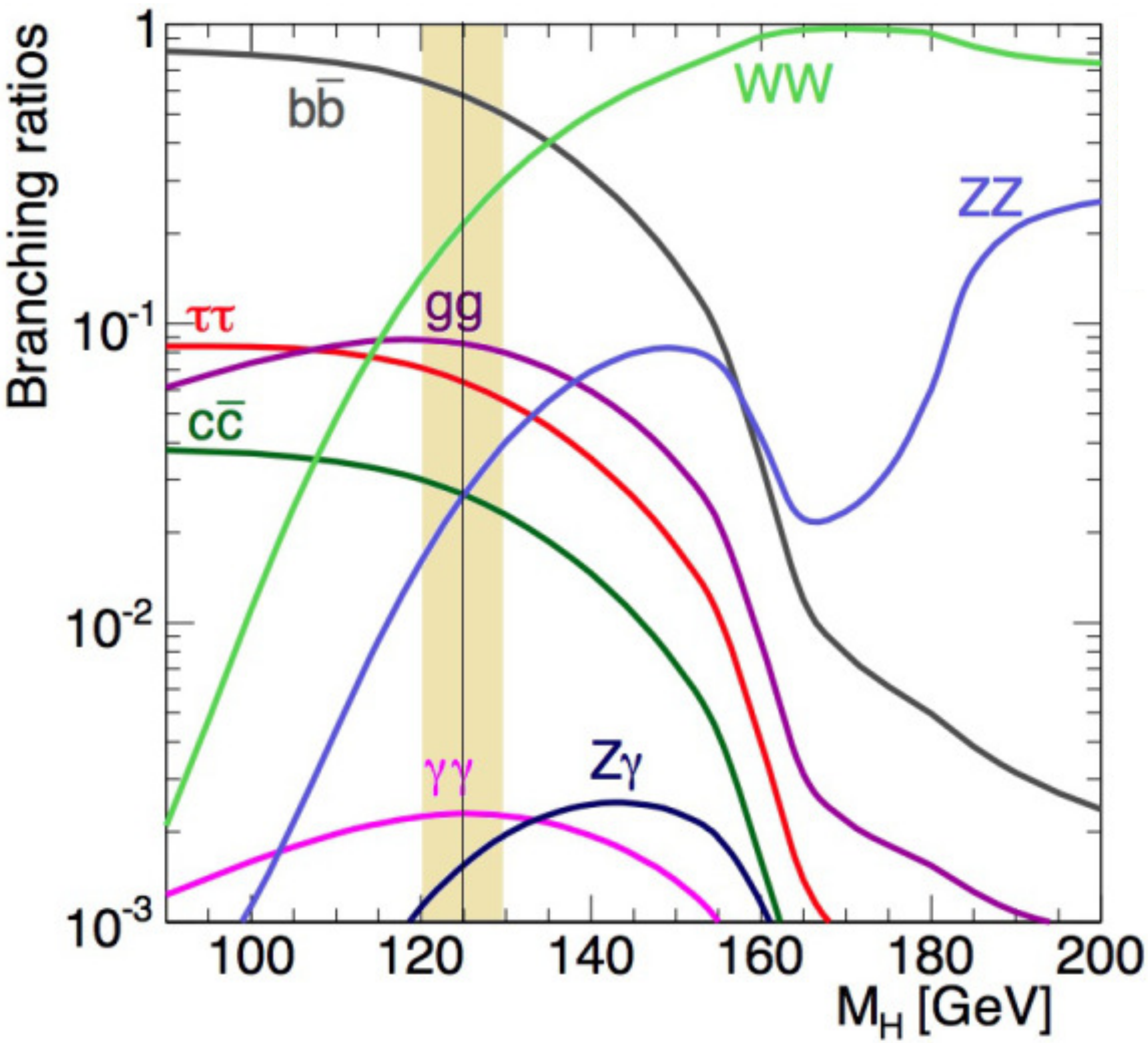
Discovery of the Higgs Boson

- Missing ingredient of the Standard Model (SM)
- Now have complete mathematically consistent theory
- Agrees with all experiments down to 10^{-19} m scale

What lies beyond the SM at smaller distance (higher energy) scales?

- Measure decay fractions of Higgs to 1% precision
- Search for Supersymmetry (SUSY)
  - Might explain why Higgs is unnaturally light
  - Lightest SUSY particle provides Dark Matter candidate
- Search for other exotics
  - Vector - Like quarks, . . .
- Find the unexpected

Higgs Decay Fractions



$H \to b\bar{b}$ 58%

$H \to W^+W^-$ 22%

$H \to gg$ 8.6%

$H \to \tau^+\tau^-$ 6.3%

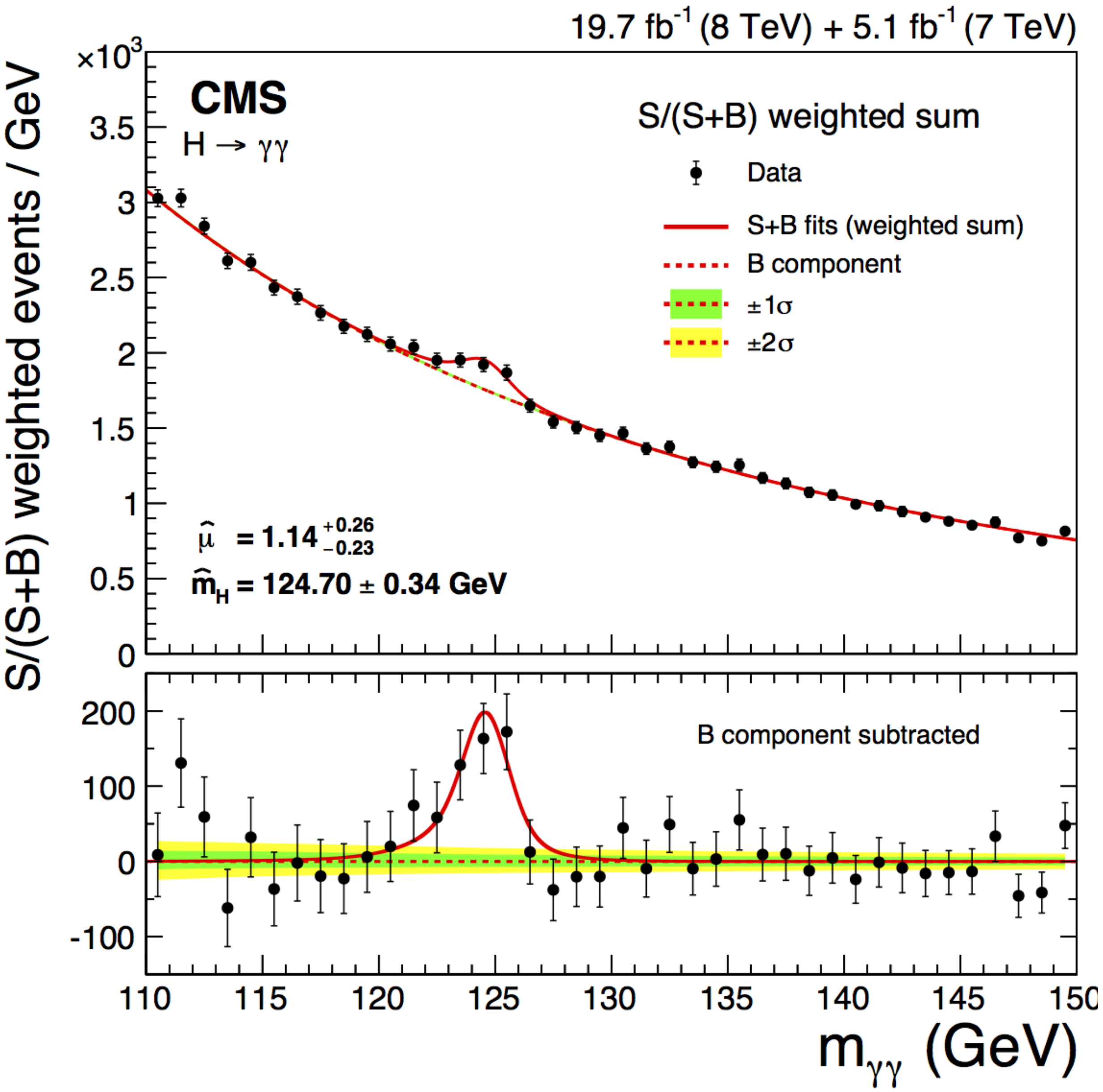
$H \to c\bar{c}$ 2.9%

$H \to ZZ$ 2.6%

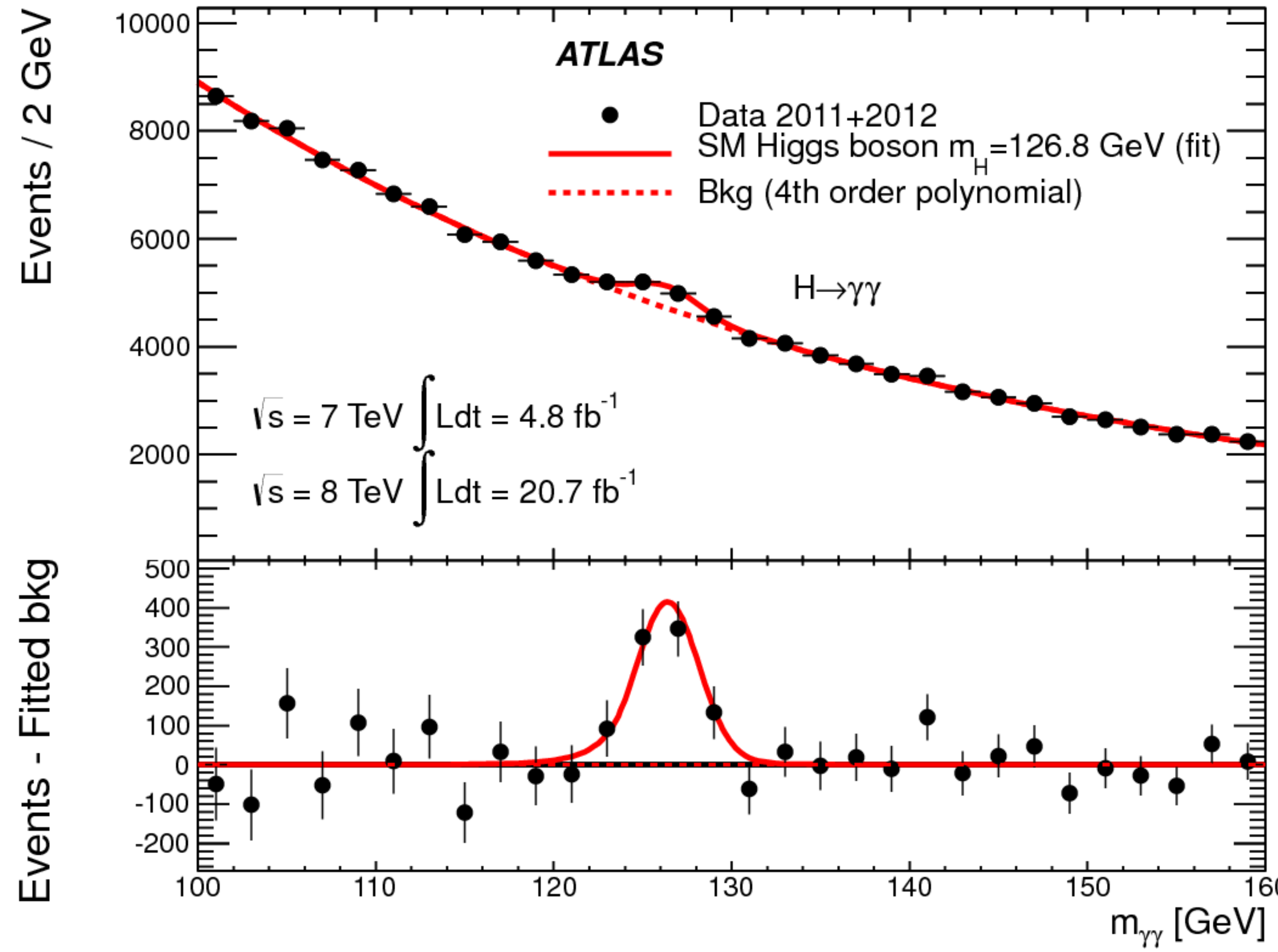
$H \to \gamma\gamma$ 0.2%

The Higgs Discovery

CMS



ATLAS



Standard Model Particles

Matter particles

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Gauge particles

$$\gamma$$

$$W \quad Z$$

$$g$$

$$H$$

Higgs Boson 2012

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Study of Small Distance Requires High Energy

Large Hadron Collider

Energy scale

10^3 GeV

Distance scale

10^{-19} m

Temperature

10^{16} K

Naturalness Problem

Why is the Higgs mass so light?

Measured Higgs mass: 10^2 GeV

Natural Higgs mass:

without gravity: ∞

with gravity: 10^{19} GeV

Biggest problem in particle physics today

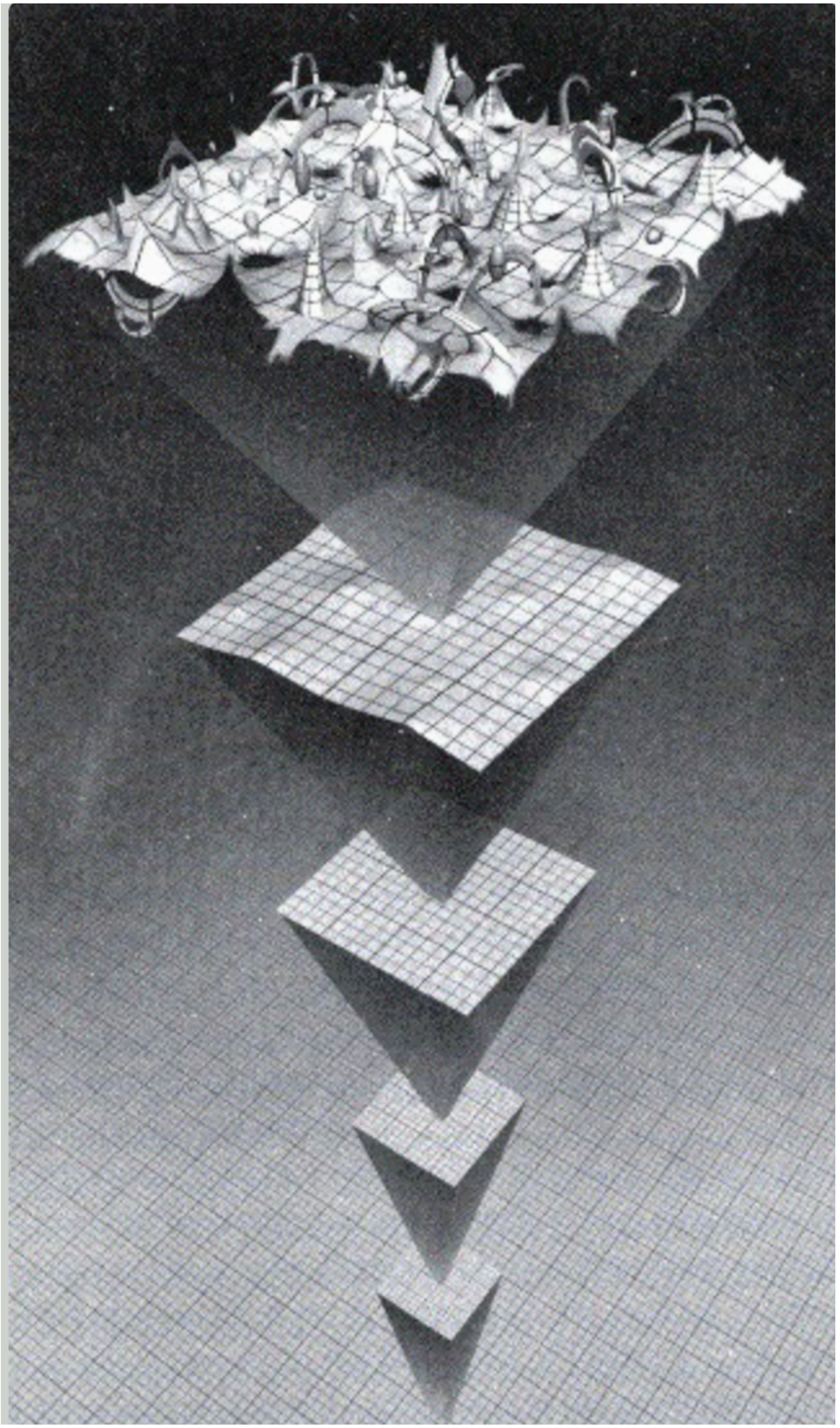
Quantum Fluctuations

Vacuum energy fluctuations inversely proportional to distance probed

$$E \propto \frac{1}{\lambda}$$

Is there a limit?

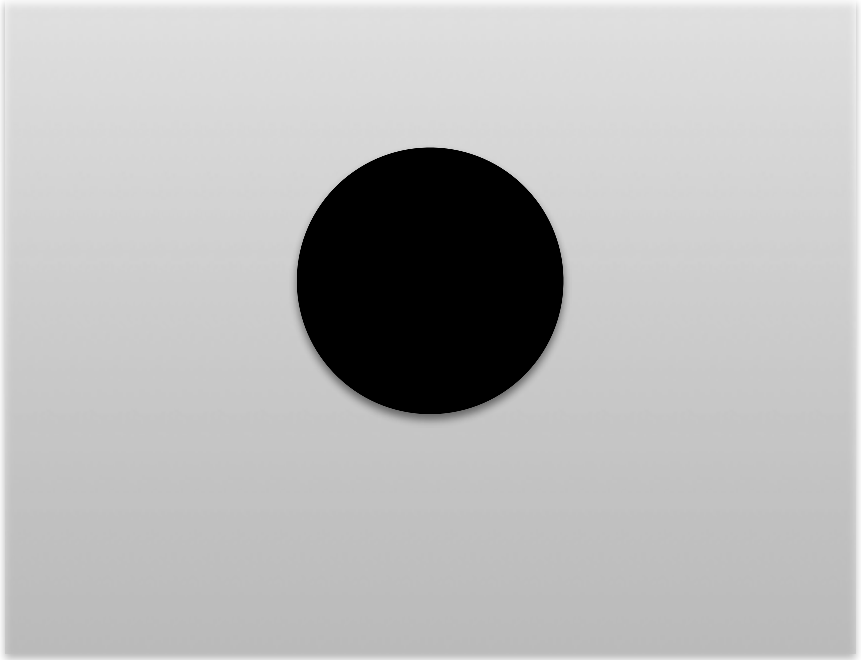
Yes



Planck Scale

What happens when you put more and more energy (mass) into a smaller and smaller volume?

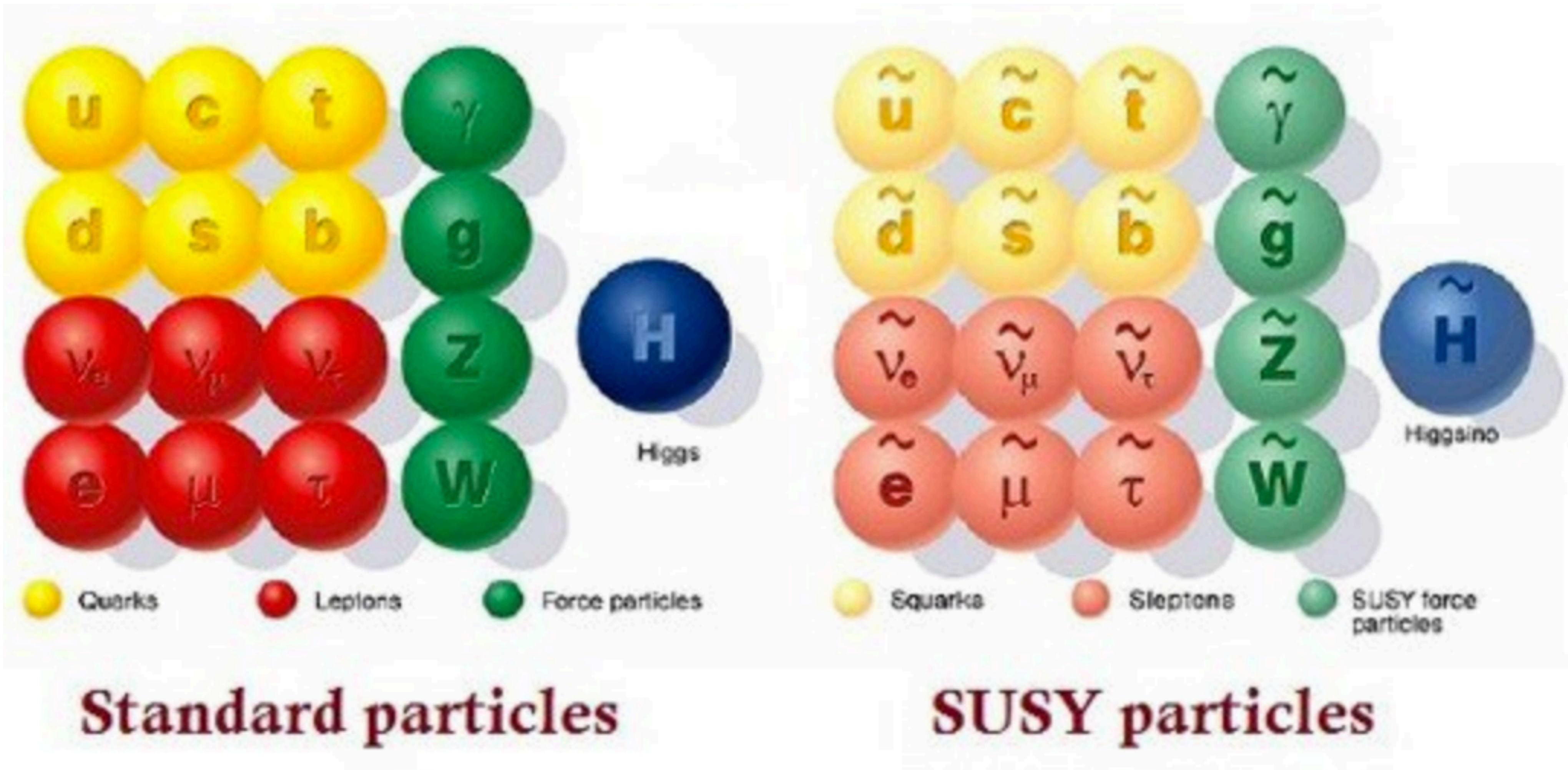
Black Hole



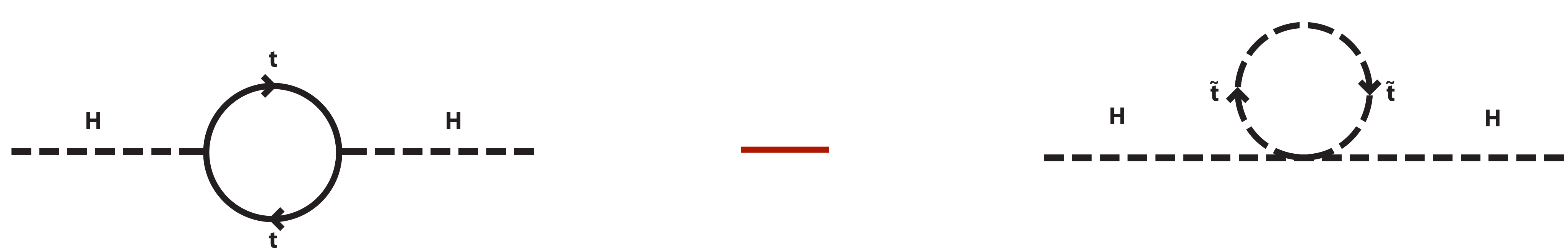
10^{19} GeV in cube

10^{-35} m on a side

Supersymmetery



Higgs mass corrections



SUSY Lagrangian

Complications because SUSY is broken

Minimal SUSY

$$
\begin{aligned}
-\mathcal{L}_{soft}^{MSSM} &= \frac{1}{2}\left[M_3\lambda_{\widetilde{g}}\lambda_{\widetilde{g}} + M_2\widetilde{W}^a\widetilde{W}^a + M_1\widetilde{B}\widetilde{B} + \text{h.c.}\right] \\
&+ \epsilon_{\alpha\beta}[B\mu H_d^\alpha H_u^\beta - a_{u_{ij}} H_u^\alpha \widetilde{\overline{u}}_i \widetilde{Q}_j^\beta + a_{d_{ij}} H_d^\alpha \widetilde{\overline{d}}_i \widetilde{Q}_j^\beta + a_{e_{ij}} H_d^\alpha \widetilde{\overline{e}}_i \widetilde{L}_j^\beta + \text{h.c.}] \\
&+ m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + \widetilde{Q}_i^\alpha m_{Q\,ij}^2 \widetilde{Q}_j^{\alpha *} \\
&+ \widetilde{L}_i^\alpha m_{L\,ij}^2 \widetilde{L}_j^{\alpha *} + \widetilde{\overline{u}}_{Ri}^{*} m_{u\,ij}^2 \widetilde{\overline{u}}_j + \widetilde{\overline{d}}_i^{*} m_{d\,ij}^2 \widetilde{\overline{d}}_j + \widetilde{\overline{e}}_i^{*} m_{e\,ij}^2 \widetilde{\overline{e}}_j .
\end{aligned}
$$

120 pramters

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Composite Higgs

Naturalness resolved if Higgs
is not a fundamental scalar

→ Composite fermions
coupled to SM fermions

$M \sim 1$ TeV

Vector-Like Quarks

top and bottom partners

$$B \to bZ$$

$$B \to bH$$

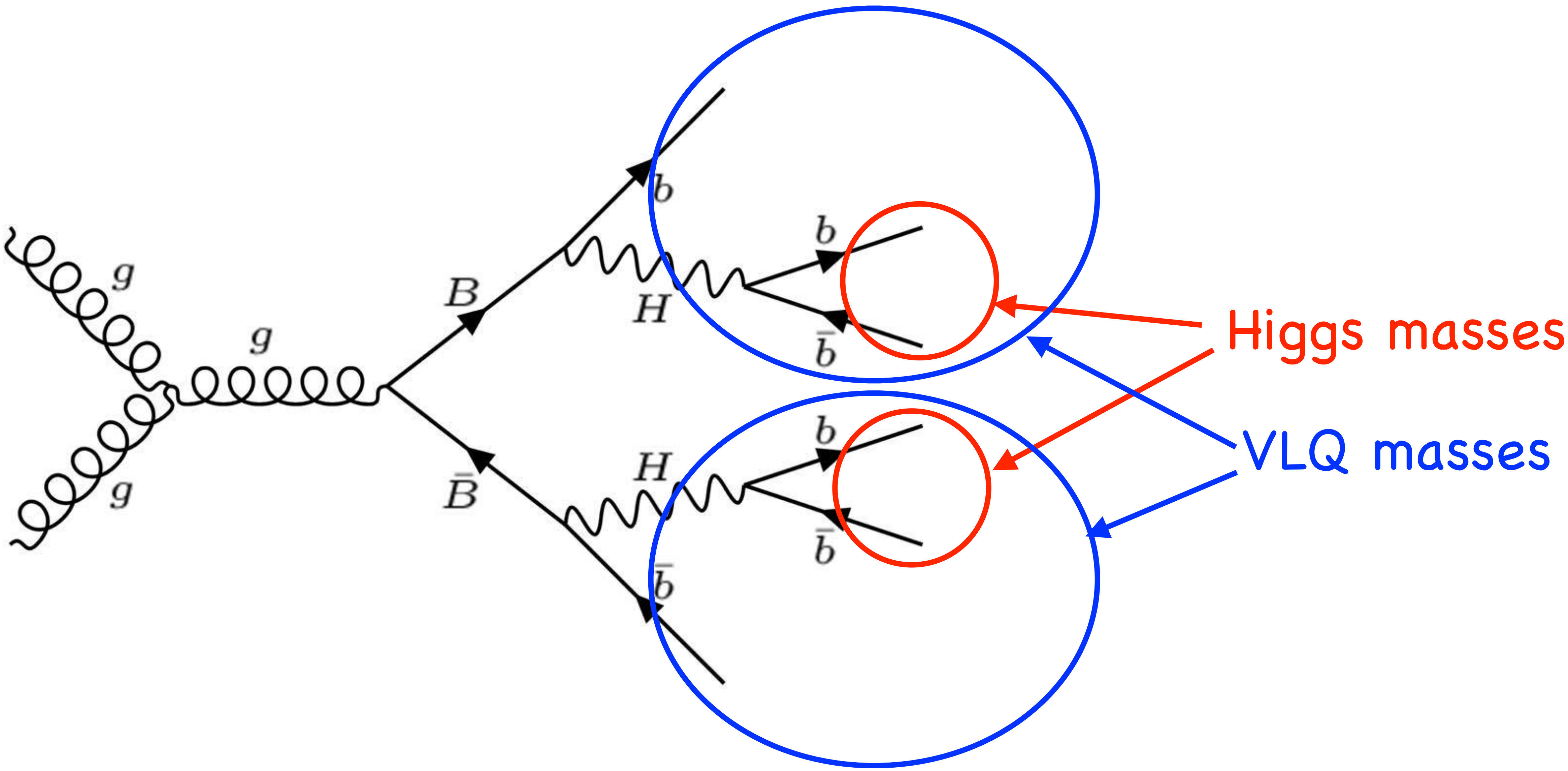
$$B \to tW$$

branching ratios highly model dependent

Assume 100% $B \to bH$

Event Signature

6 b quarks (jets) in final state



Analysis Techniques

- Select 6 jet events
- Find best combination by χ^2

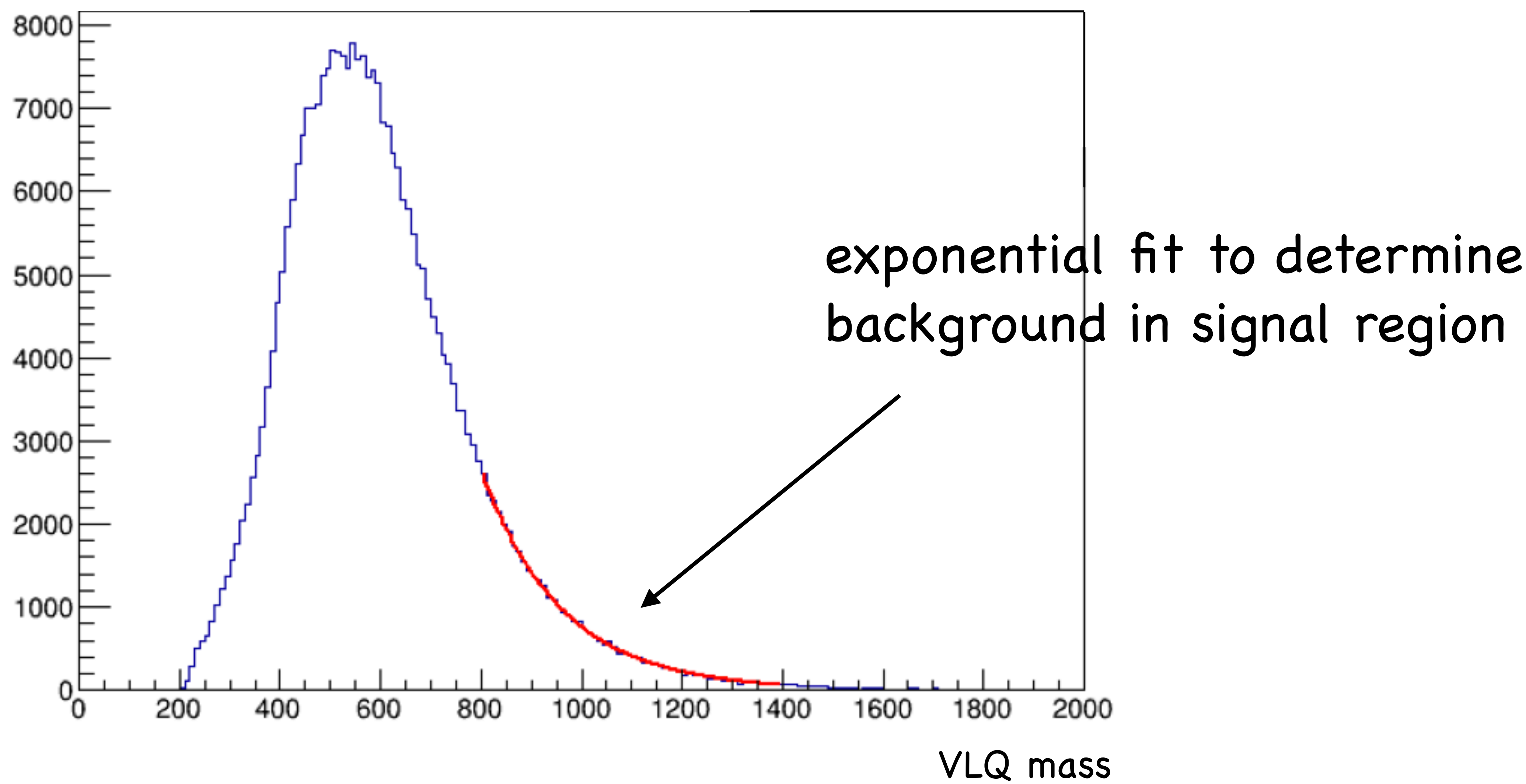
$$\chi^2 = \frac{(m_{j_1 j_2} - m_H)^2}{\sigma_H^2} + \frac{(m_{j_3 j_4} - m_H)^2}{\sigma_H^2}$$

$$+ \frac{[2(m_{3j_1} - m_{3j_2})/(m_{3j_1} + m_{3j_2})]^2}{\sigma_{\text{diff}}^2}$$

- Cut on χ^2
- b-jet requirement
- Plot average VLQ mass
- Fit low mass region to determine background

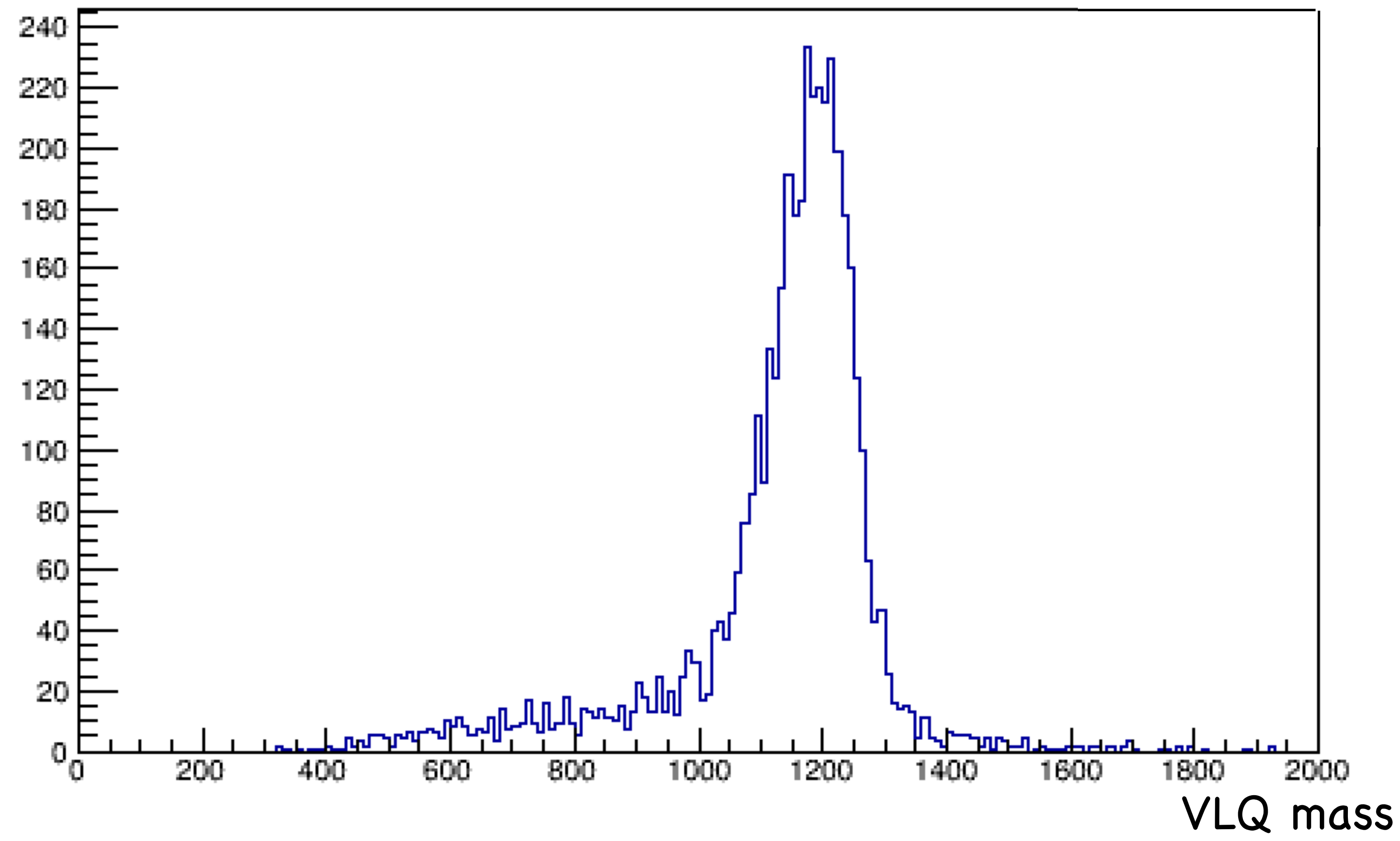
Background

Determined from data



Signal

1200 GeV VLQ



Merged Jets

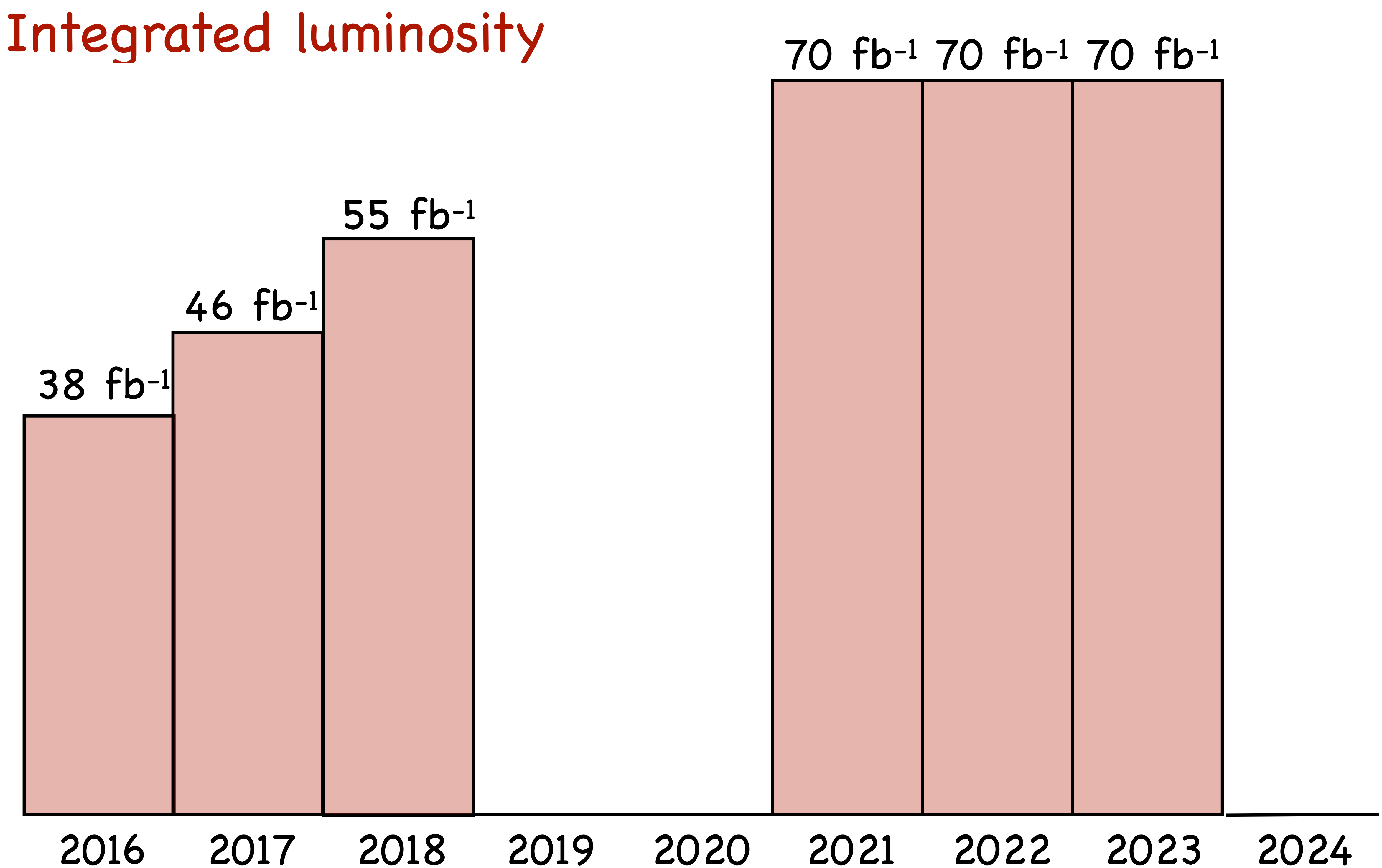
Higgs are boosted so sometimes only a single "merged" jet rather than two distinct jets

Select 5 and 4 jet events with 1 and 2 jets with invariant mass of Higgs

Future Plans

- Remove extra jet in 6jet and 5 jet events
  - investigate machine learning techniques
- Apply jet analysis to bHbZ events
- Dilpeton analysis of bHbZ events
- Apply jet analysis to qHqH events
- Apply dilepton analysis to bZbZ events
  - golden events very little background
  - will require lots of data

LHC Schedule



Expected Sensitivity

Current lower mass limit is 1000 GeV

$$\sigma \sim m^{-7}$$

Expect to reach 1600 GeV with 2018 data

Expect to reach 2000 GeV with 2023 data

Doubling energy equivalent
to factor of 100 in luminosity

Standard Model

Interactions

Quantum Electrodynamics (electromagnetism)

Quantum Chromodynamics (strong)

Weak

~~Gravity~~

Gravity

Extremely weak

Only attractive

Dual role of mass

$$F = G\,\frac{m_1 m_2}{r^2}$$

$$F = ma$$

Planck Scale

Scale of quantum gravity

Energy = 10^{19} GeV

Distance = 10^{-35} m

Scale of the LHC

Energy = 10^{3} GeV

Distance = 10^{-19} m

Size of Planck scale LHC

Diameter = 10^{4} m X 10^{16} = 10^{20} m

= 10,000 light years

LHC at the Planck Scale