Mass, Measurement, and Physics

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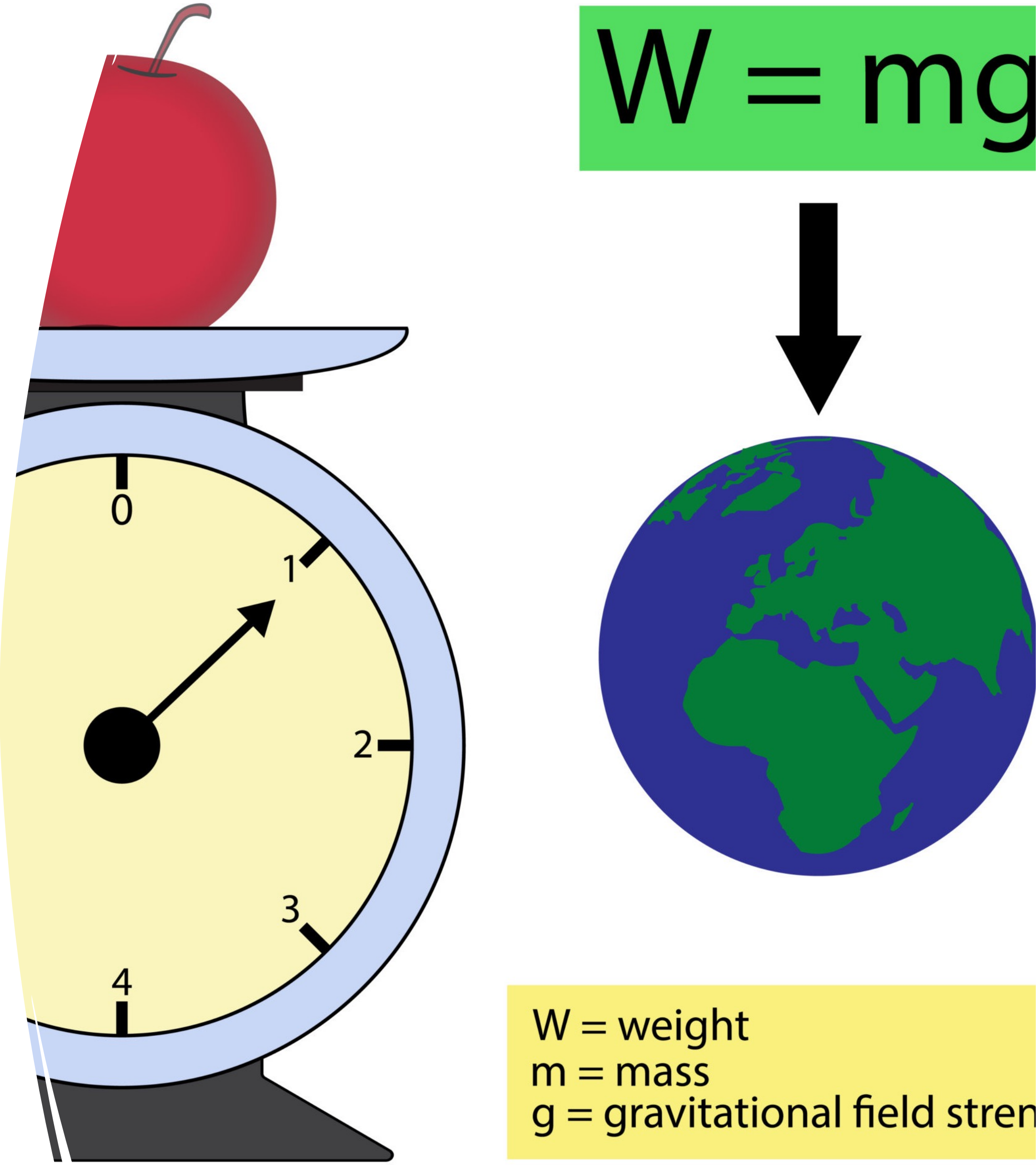
Outline

- Introduction
- The Standard Model
- Leptons, Bosons, and Hadrons: Baryons and Mesons
- Instruments for measuring particles masses
- Example one: mass measurement (BaBar/Belle experiments)
- Example two: mass measurement (ATLAS/CMS experiment)
- Summary

Mass

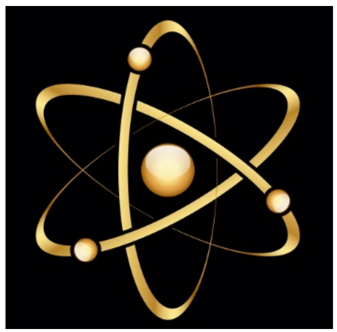
- **Amount of matter in an object!**



Where does mass come from?

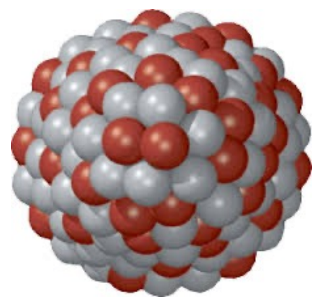
Matter (macroscopic)

Atom (10^{-10} m)



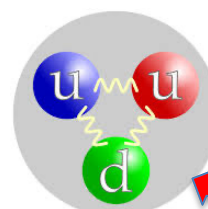
a) Democritus
b) John Dalton
c) J. J. Thompson

Nucleus (10^{-14}m)



Ernest Rutherford

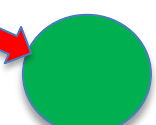
Nucleon (10^{-15}m)



Ernest Rutherford
James Chadwick

32 years
1932-1964

Quark ($\leq 10^{-18}$m)



Murray Gell-Mann

Road Map to the Quark Model

1932 -1964

a) How two or more protons exits in a nucleus?

-- Hideki Yukawa assumed that the proton and neutron are attracted to one another by some sort of field, just as the electron is attracted to the nucleus by an electric field and the moon to the earth by a gravitational field – Nobel prize in 1949

Force	Strength	Range (m)
strong	1	10^{-15}
electromagnetic	1/137	infinite
weak	10^{-6}	10^{-18}
gravity	6×10^{-39}	infinite

Road Map to the Quark Model

1932 -1964

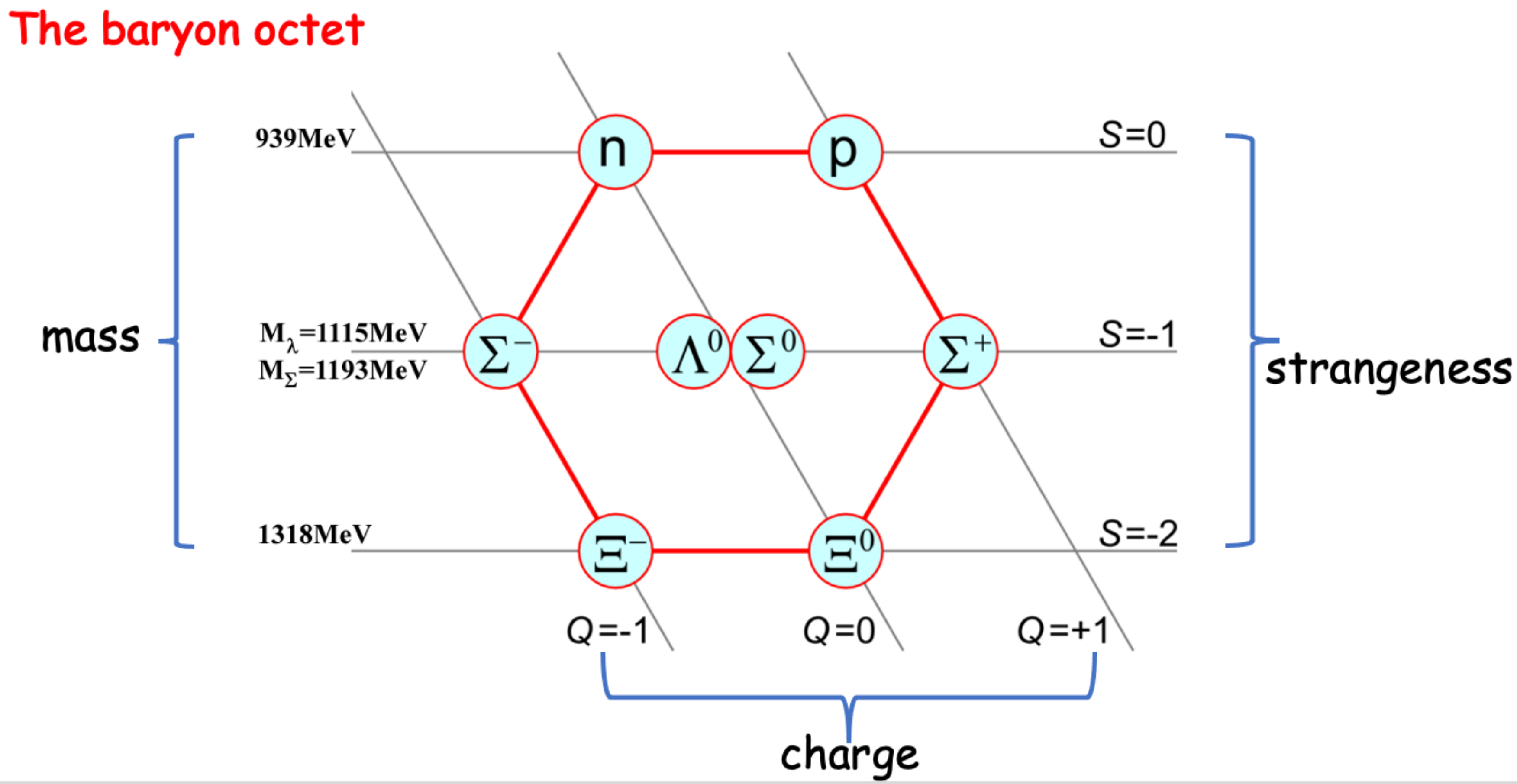
b) Cosmic Ray Particles
-- Many particles, e.g. μ, π, K, e^+, ν etc., were discovered in Cosmic rays and in the particle accelerators that can't be described by the protons, neutrons, and electrons

c) Kaons' (K) having longer life-time than expected (10^{-10} seconds instead of the expected 10^{-23} seconds) contains a strange quark

d) Why Muon? Who ordered that? (Q. by Isaac Rabi who got Nobel prize in 1944 for NMR)

Introduction to the Quark Model (1961)

Gell-Mann's Famous Eightfold Way



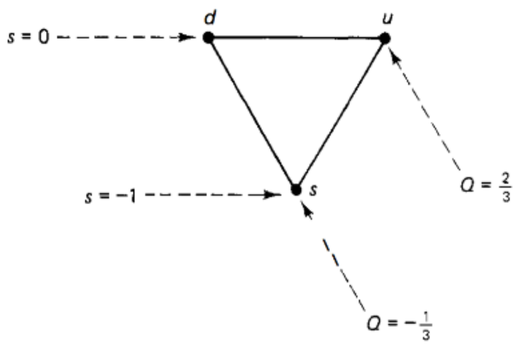
The Quark Model (1964)

Murry Gell-Mann
1929 - 2019

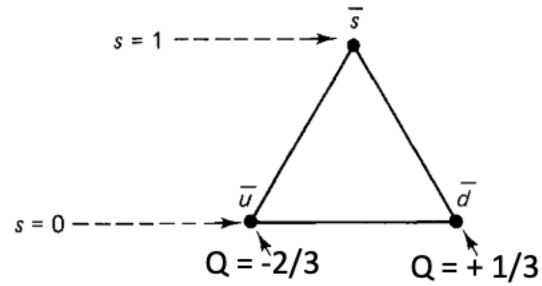
George Zweig
1937 -

- Gell-Mann and Zweig independently proposed that all hadrons are in fact composed of even more elementary constituents, which Gell-Mann called ***"quarks"***.

The Quark Model (1964)



The Quarks



The Antiquarks

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High-Energy Inelastic $e-p$ Scattering at 6° and 10°

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, G. Miller, L. W. Mo, R. E. Taylor, M. Breidenbach, J. I. Friedman, G. C. Hartmann, and H. W. Kendall

Phys. Rev. Lett. **23**, 930 – Published 20 October 1969

Physics See Focus story: *Landmarks—Discovery of Particles inside the Proton*

An article within the collection: Letters from the Past - A PRL Retrospective

Article References Citing Articles (343) PDF Export Citation

ABSTRACT

Cross sections for inelastic scattering of electrons from hydrogen were measured for incident energies from 7 to 17 GeV at scattering angles of 6° to 10° covering a range of squared four-momentum transfers up to 7.4 $(\mathrm{GeV}/c)^2$. For low center-of-mass energies of the final hadronic system the cross section shows prominent resonances at low momentum transfer and diminishes markedly at higher momentum transfer. For high excitations the cross section shows only a weak momentum-transfer dependence.

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DOI: https://doi.org/10.1103/PhysRevLett.23.930

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The Nobel Prize in Physics 1990

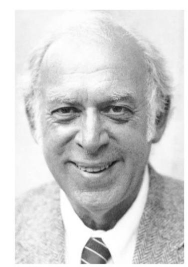


Photo from the Nobel Foundation archive.

Jerome I. Friedman

Prize share: 1/3

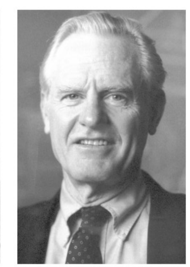


Photo from the Nobel Foundation archive.

Henry W. Kendall

Prize share: 1/3

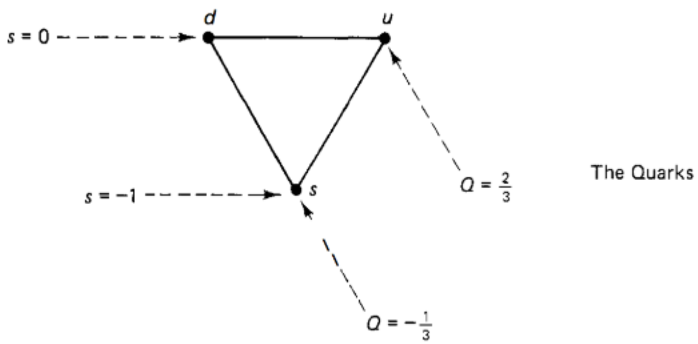
Photo: T. Nakashima

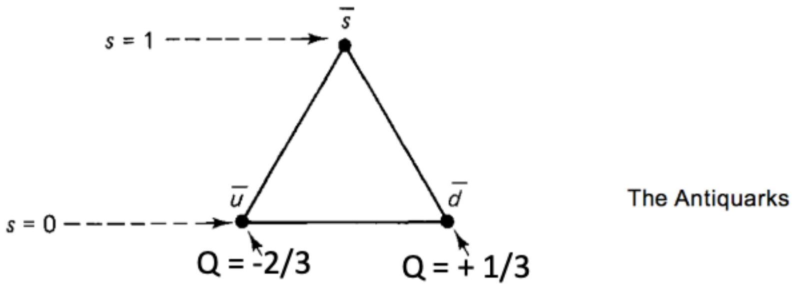
Richard E. Taylor

Prize share: 1/3

The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics."

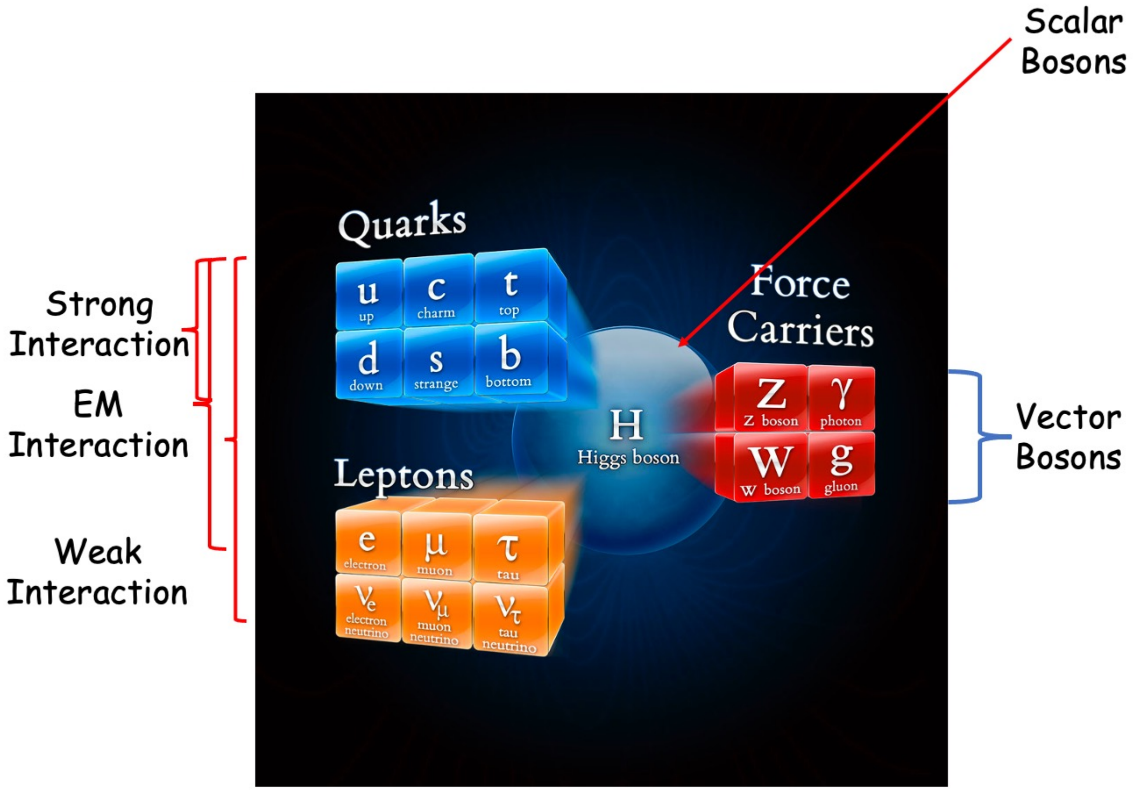
More Quarks and Leptons





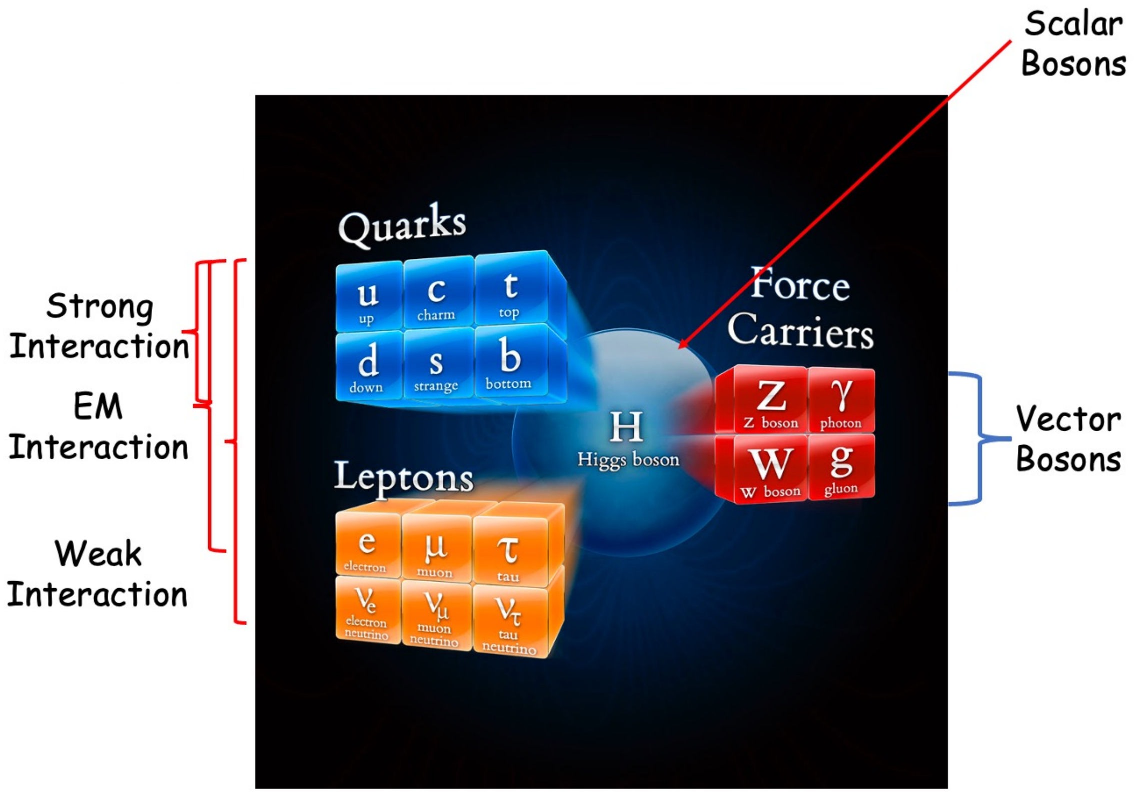
- 1974: J/ψ ($c\bar{c}$); $c \rightarrow charm\ quark$ by Burton Richter (SLAC) and Samuel Chao Chung Ting (BNL)
- 1975: $\tau\ lepton$ by Martin Lewis Perl (SLAC)
- Six leptons require more quarks!
- 1977: new resonance $\Upsilon \rightarrow b\bar{b}$ by Leon M Lederman (Fermilab)
- 1995: top quark discovered by CDF and D0 collaboration (Fermilab)

The Standard Model (SM)



The Standard Model (SM)

- Hadron: Baryon, Meson
- Every baryon is composed of three quarks (and every antibaryon is composed of three antiquarks)
- Every meson is composed of a quark and an antiquark



Where does mass come from to the SM particles?

Higgs Mechanism

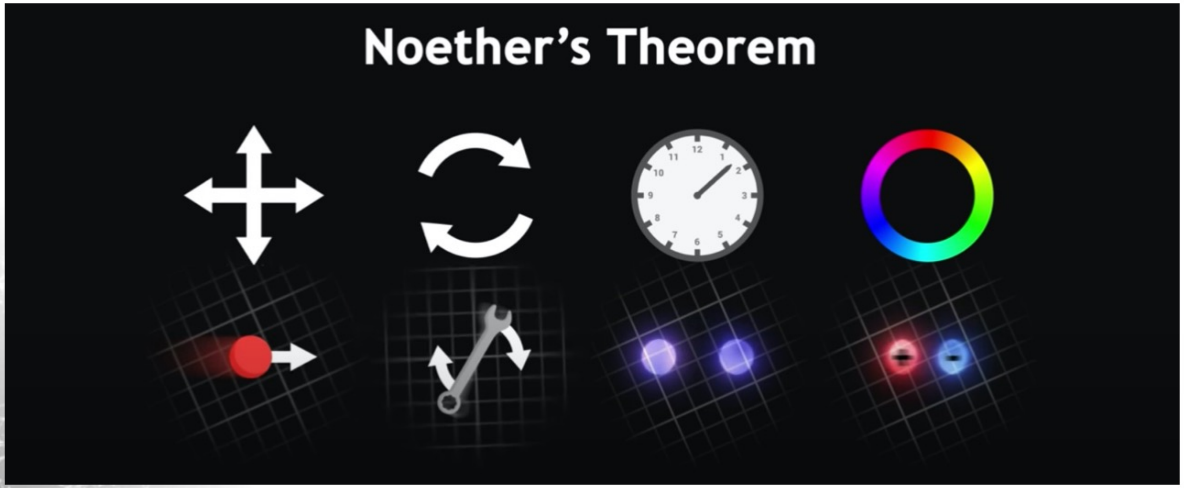
- How the elementary particles acquired masses? Why do they have different masses for different particles?
- In the 1960s, a group of physicists, including Peter Higgs, worked independently on explaining the above question.
- Peter Higgs idea: all the space in the Universe is uniformly filled with the invisible substance. The invisible substance sort of like molasses, which is also called "The Higgs Field."
- A particle interacts with these molasses and gains mass. Different particles have different resistance in molasses and acquired different masses.
- Peter Higgs's first submitted paper on this idea was rejected for publication, but he finally was able to convince the scientific community by providing his beautiful mathematical calculation.

Particle	Mass(GeV)
Photon, gluon	0
Neutrinos	~ 0
Electron	0.0005
Muon	0.105
Tau	1.77
Up quark	0.002
Down quark	0.004
Strange quark	0.100
Charm quark	1.27
Bottom quark	4.18
Top quark	172
W boson	80.3
Z boson	91.2
Higgs	125

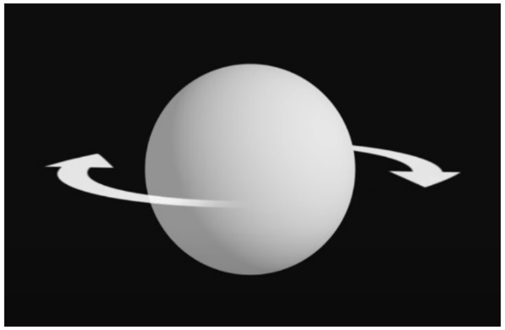
Higgs Mechanism

- The Standard Model is a paradigm of the "Quantum Field Theory (QFT)."
- QFT is the mathematical framework for the SM particles in which a Lagrangian controls the dynamics and kinematics of the theory.
- The Standard model is described using group theory SU(3)×SU(2)×U(1). SU(3) is the gauge group of the strong interaction and SU(2) x U(1) is the group of electroweak interaction

Symmetry



Example



➢ For every symmetry there is a corresponding conservation law – Emmy Noether (1882-1935)

SM Lagrangian

- $\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$

$+ i\bar{\psi}\gamma^{\mu}D_{\mu}\psi + h.c$

$+ D_{\mu}\phi^{\dagger}D^{\mu}\phi - V(\phi)$

$+ \psi_L \hat{Y} \Phi \psi_R + h.c$

$$
\begin{gathered}
\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\frac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\frac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\frac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\frac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \frac{1}{8}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \frac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\frac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\frac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\frac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\frac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \frac{g}{2}\frac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\frac{g}{2}\frac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \frac{ig}{2}\frac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \frac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\frac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\frac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \frac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\frac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\frac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right) .
\end{gathered}
$$

Higgs field and the elementary particles mass (Spontaneous symmetry breaking)

$\mathcal{L}_H = D_\mu \phi^\dagger D^\mu \phi - V(\phi);$

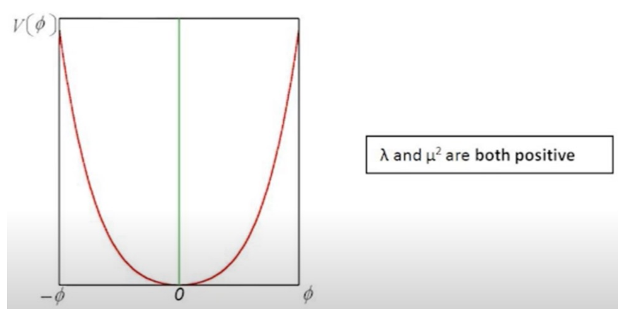
$\phi \rightarrow complex\ scaler\ field, with$

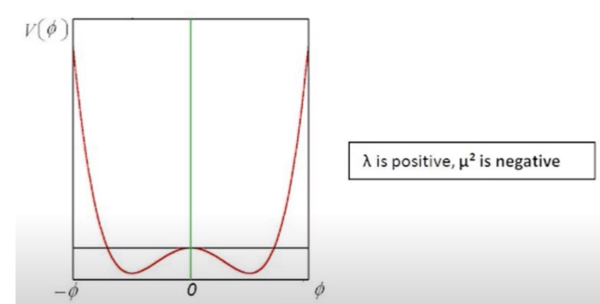
$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi 4 \end{pmatrix} \quad \text{and}$$

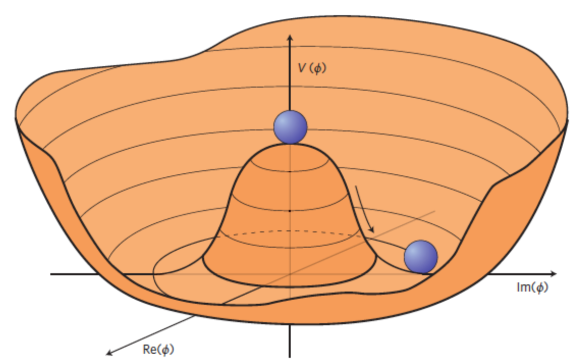
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

$\mu \rightarrow mass; \lambda \rightarrow self - interaction\ of\ field$

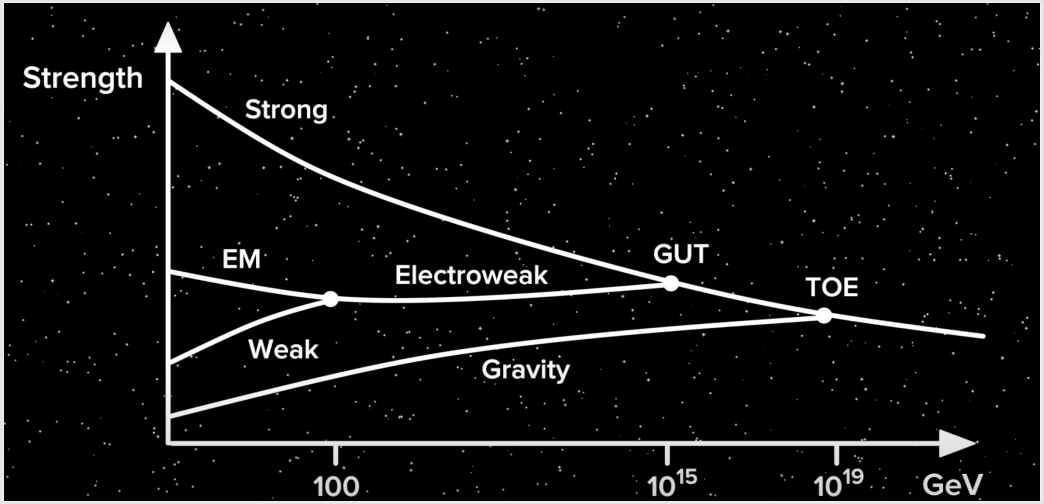
$\mathcal{L}_H$ exibits symmetry with $\phi\ and\ -\phi$







Forces and Unifications



- The unification of forces is the idea that it's possible to view all of nature's forces as manifestations of one single, all-encompassing force – Symmetry Magazine

Elementary particles in the Laboratory

Mass and Energy

- Rest energy of proton $mc^2 = 938MeV \approx 1GeV$
- Relativistic energy $E = \gamma mc^2; \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$
- $v = c\sqrt{1-\left(\frac{mc^2}{E}\right)^2}$; $E_P = 7TeV = 7000GeV$
- $v = 0.999999989c$
- $r = \frac{mv}{qB}; \lambda = \frac{h}{p}$

- Can we make a 7 TeV electron accelerator?
- Which machine is better, electron or proton? Why?

Large Hadron Collider

- When protons meet during an LHC collision, they break apart and the quarks and gluons come spilling out. They interact and pull more quarks and gluons out of space, eventually forming a shower of fast-moving hadrons.

Important figures: the energy of the LHC for Run 2

Quantity	Number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	6.5 TeV
Nominal energy, ions	2.56 TeV/u (energy per nucleon)
Nominal energy, protons collisions	13 TeV
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.2×10^{11}
Number of turns per second	11245
Number of collisions per second	1 billion

SLAC National Accelerator Laboratory

By the Numbers

slac.stanford.edu

What is SLAC National Accelerator Laboratory? The numbers tell the tale.

As one of **17** Department of Energy national labs, SLAC pushes the frontiers of human knowledge and drives discoveries that benefit humankind. We invent the tools that make those discoveries possible and share them with scientists all over the world.

Founded in **1962** with **200** employees.

Today we have **1,600** employees from **55** countries

470 postdocs and grad students

2,600 scientists from around the world use our cutting-edge facilities each year.

4 Nobel prizes awarded to **6** laureates for research at SLAC that discovered **2** fundamental particles, proved protons are made of quarks and showed how DNA directs protein manu-facturing in cells.

426-acre site near the main Stanford campus.

Our linear accelerator structure is **3,073.72** meters (**1.9** miles) long – one of the longest modern buildings on Earth.

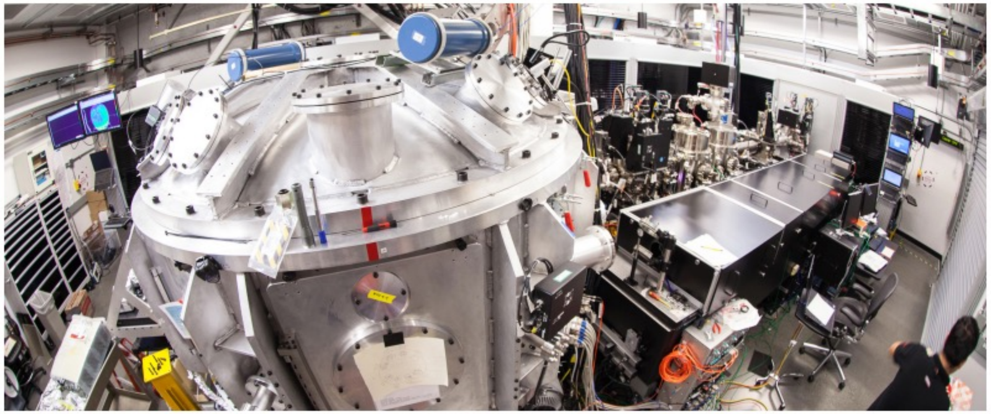
Electrons zip down the accelerator at **669,600,000** mph – **99.9999999**% of the speed of light.

The energy each electron gains is equivalent to **33 billion** AA b

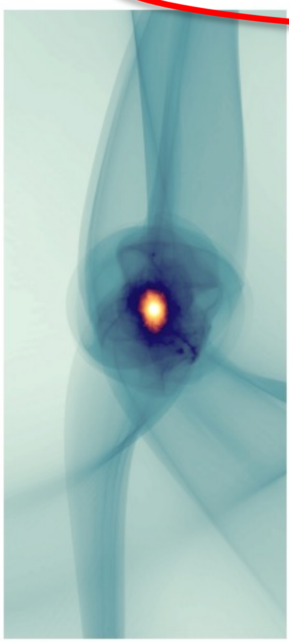
Technology we're developing could make future accelerator **1,000** times shorter.

180 universities and research institutes make use of ou
20 companies use our X-ray facilities for research aim medicines and other products.

SLAC NATIONAL ACCELERATOR LABORATORY



Above: An experimental station at SLAC's Linac Coherent Light Source X-ray laser where scientists study matter exposed to extreme heat and pressure. Below: 10 million years after the Big Bang, a halo of dark matter forms around a galaxy in this visualization from the joint SLAC/Stanford Kavli Institute for Particle Astrophysics and Cosmology.



SLAC works with Stanford in 5 joint research centers and facilities that focus on cosmology and astrophysics, materials and energy science, cryogenic electron microscopy, catalysis and ultrafast science.

Our X-ray laser zaps samples with pulses that are **millionths of a billionth** of a second long.

A **3.2 billion**-pixel camera we're building for the world's deepest sky survey will shoot the equivalent of **800,000 8**-megapixel digital camera images per night. Over a span of **10** years it will take pictures of more galaxies than there are people on Earth.

Our labs create **36-million**-degree-F matter that mimics extreme conditions in the hearts of stars and planets, and pressures equivalent to **5,200** large African elephants stacked on **1** square inch of ground.

SLAC's highest experiment orbits **300+** miles overhead at **17,400** mph and has discovered **200+** pulsars.

SLAC's deepest experiment will hunt for dark matter in a Canadian nickel mine **6,800** feet below ground.

Our telescope near the South Pole looks for patterns left by cosmic inflation in the first **trillionth of a trillionth of a trillionth** of a second after the Big Bang.

Our LCLS-II X-ray laser beam will be **10,000x** brighter and fire **8,000x** faster than the first LCLS beam, up to **1 million** pulses per second.

The new beam will operate at **2** degrees Kelvin – colder than outer space.

We hauled **699** tons of equipment out of the SLAC linac to make room for it.

In **1975** the Homebrew Computer Club began meeting in the SLAC auditorium and helped spark the personal computing revolution.

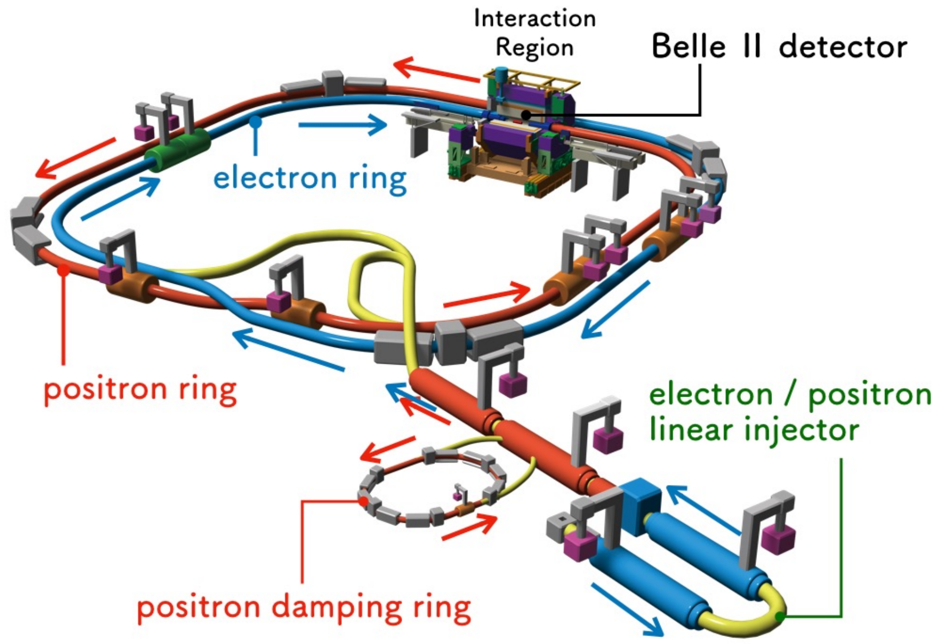
In **1991** we opened the 1st website in North America. It h physicists share their research results.

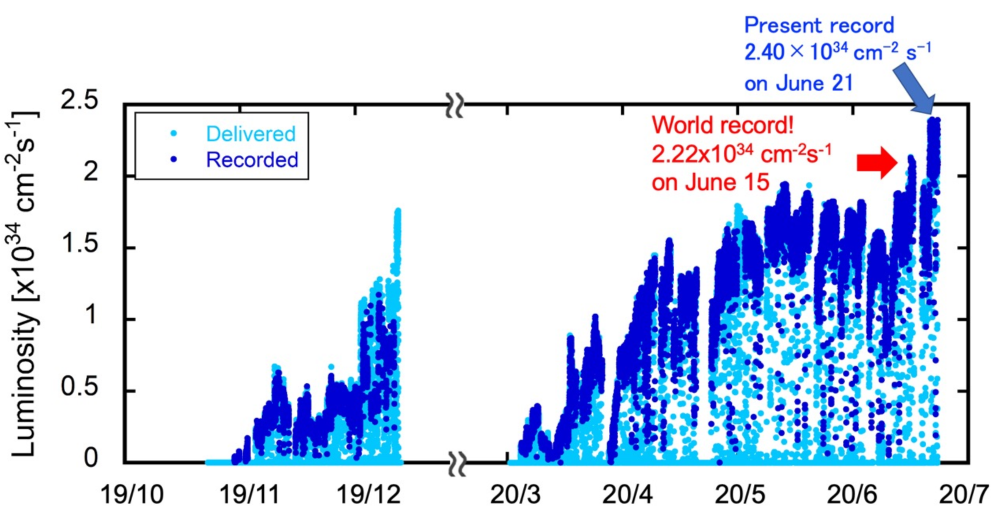
SLAC's **1st** scientific discovery was a fossil: *Neoparadc* found in **1964** during excavation for the linac. It live ago and resembled a hippo.

SLAC is operated by Stanford University for the U.S. Department of Energy Office of Science

SLAC National Accelerator Laboratory

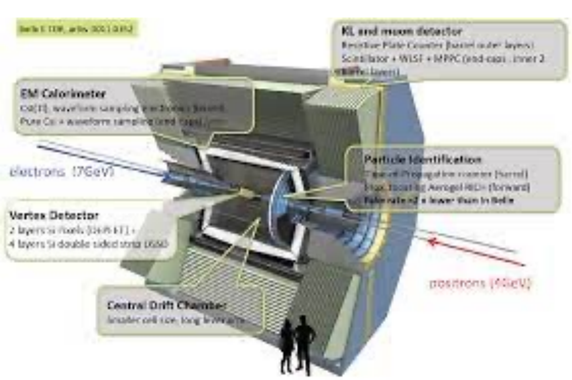
- **SuperKEKB Collider Achieves the World's Highest Luminosity**

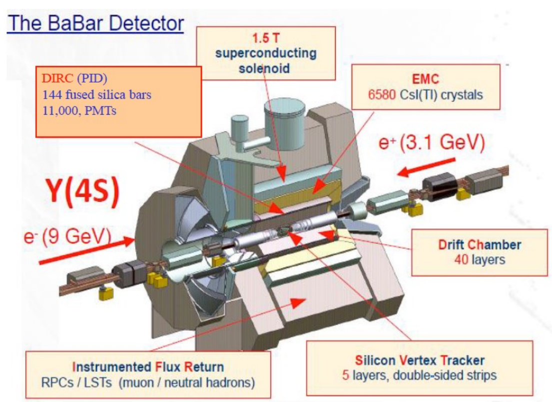




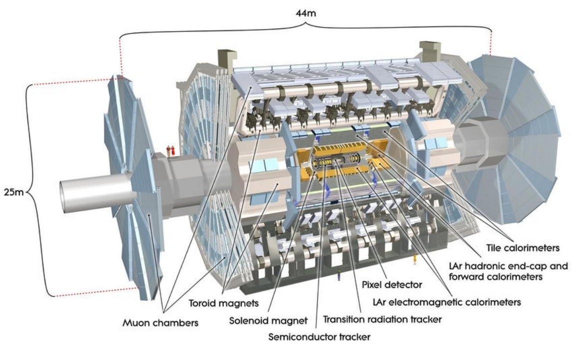
How do we see this incredible number of collisions? – particle detector

Belle II Detector

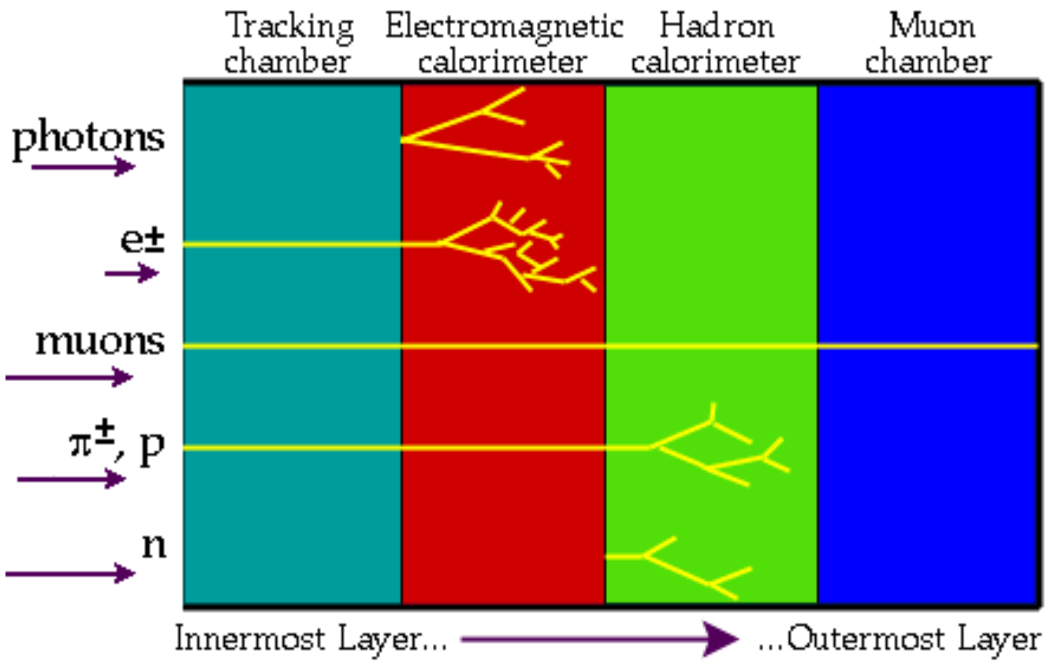




ATLAS Detector



Particles Interaction with Matter



Four Momentum and Kinematics

$$p^\mu = \left(\frac{E}{c}, p_x, p_y, p_z\right) \approx (E, \vec{p}), c = 1$$

$$p_\mu p^\mu = E^2 - \vec{p}^2 = m^2$$ ← Lorentz Invariant

$$m = \sqrt{E^2 - \vec{p}^2}$$

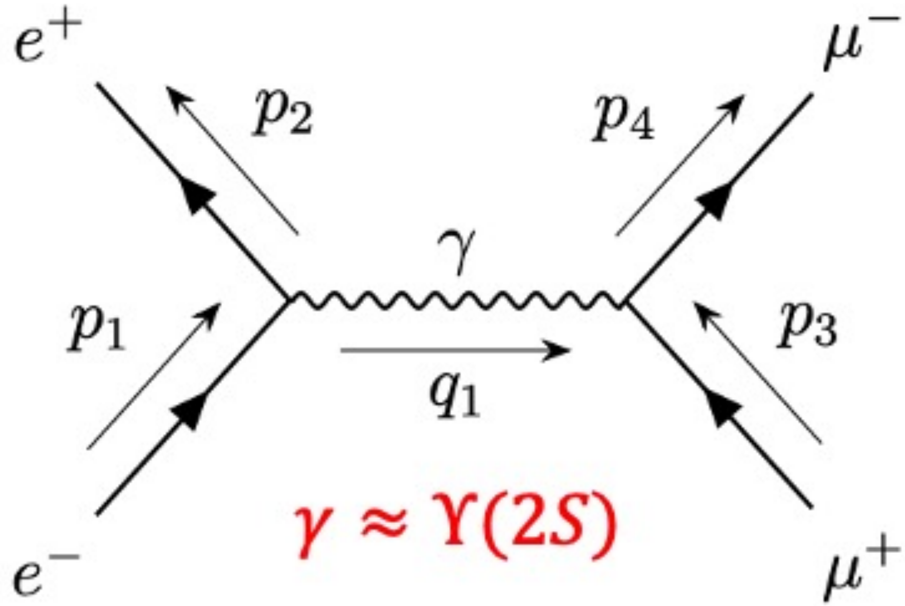
$$E = E_k + mc^2 = \gamma mc^2 = \frac{mc^2}{\sqrt{1 - u^2/c^2}}$$

$$\vec{p} = \gamma m \vec{v}$$

Mass Measurements

- Example one:
- Patrick's Honours Thesis – 2019
- BABAR experiment

$$e^+e^- \to \Upsilon(2S) \to \mu^+\mu^-$$



$$\gamma \approx \Upsilon(2S)$$

Mass Measurements

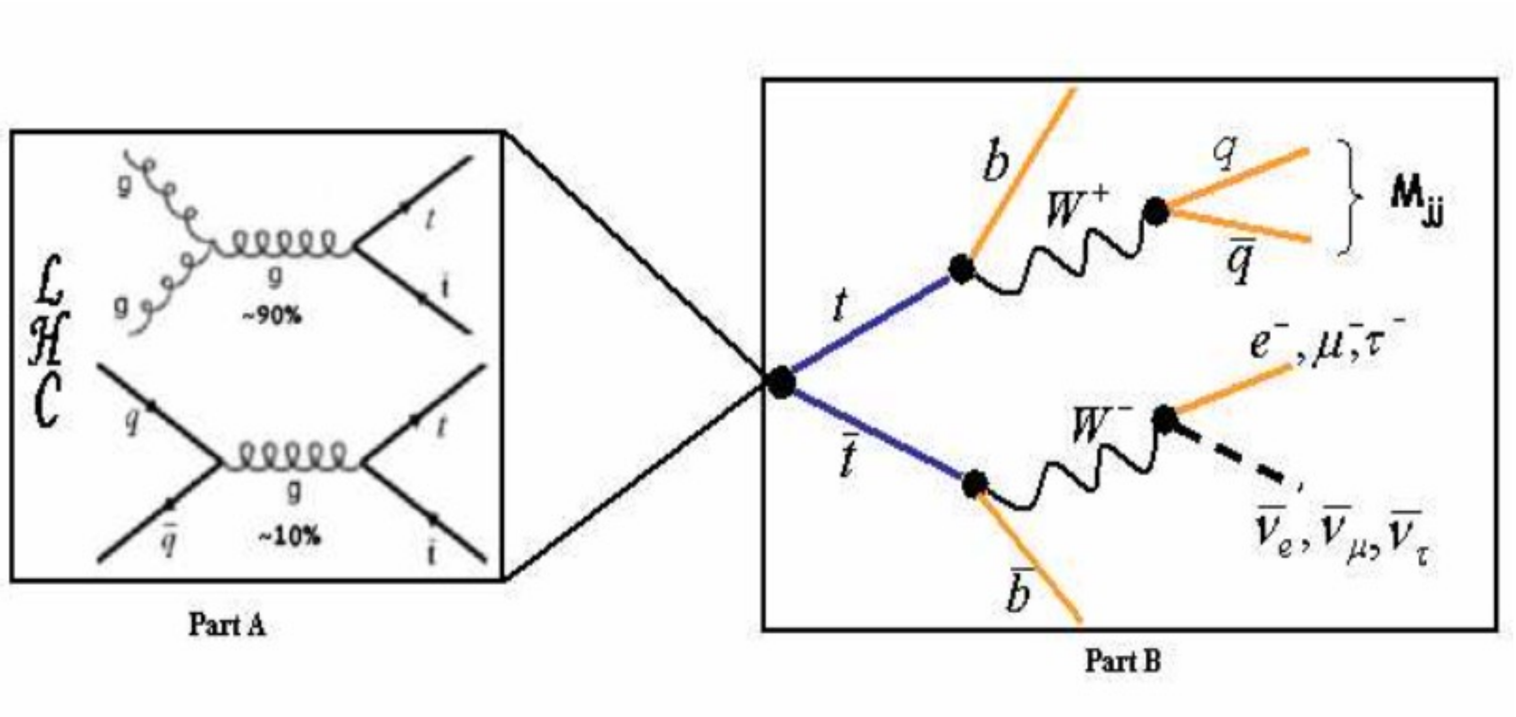
- Example two:
- A Ph.D. Thesis
- Phys. Rev. Lett. **128**, 091804
- BABAR experiment

Search for Lepton Flavor Violation in $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$

J. P. Lees *et al.* (*BABAR* Collaboration)
Phys. Rev. Lett. **128**, 091804 – Published 3 March 2022

Mass Measurements

- Example three:
- ATLAS experiment



Data Analysis

Data analysis framework

Raw data

MC samples

Event selections

Results

Analysis Strategy

- Preselection or Skim (starting sample for the analysis)
- Blind analysis
- Data:
  - Hit in the detector from collision
  - Digitized and reconstructed into tracks and clusters
  - Particle Identification (PID) algorithms identify each tracks or cluster as a candidate for a given type or particle
- Simulation Production (SP) :
  - Continuum and generic
  - Used for data/MC agreement
  - Estimate the background rate
  - Determine efficiencies

Analysis Strategy

MC signal

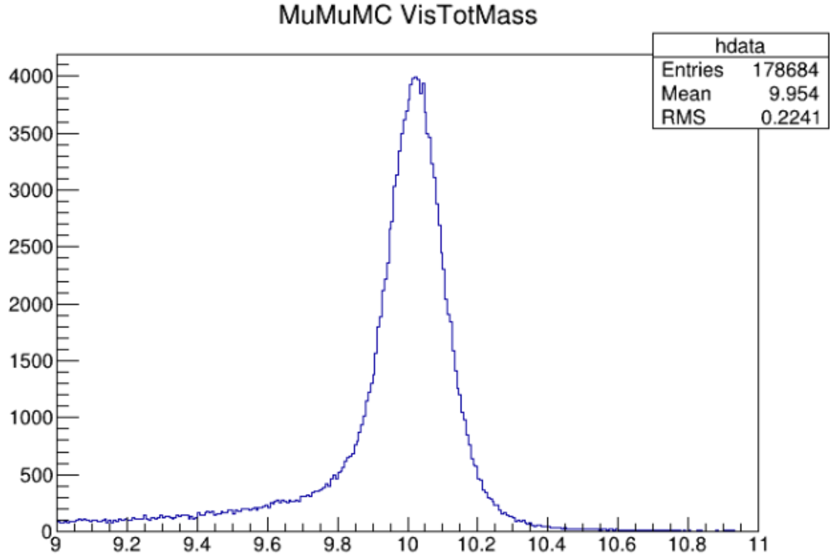
```
#####################################################################
#                                                                   #
# Upsilon(2S)->e mu                                                 #
#      (for lepton flavor violation studies)                        #
# Author:   Ben Hooberman  bhoob Mar 11 2008
# Modified: Hossain Ahmed May 2018                                  #
#                                                                   #
#####################################################################

Decay Upsilon(2S)
0.500 e- mu+       PHOTOS VLL;
0.500 e+ mu-       PHOTOS VLL;
Enddecay

End
#####################################################################
```

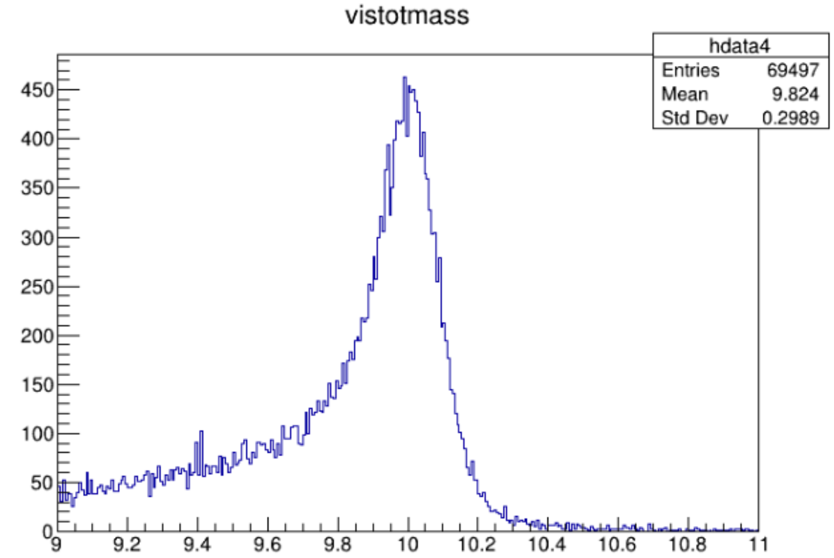
- SP-11974-Run7-Y2S_OnPeak-R24
- 145,000 events are generated!

Example one

$$e^+e^- \rightarrow \Upsilon(2S) \rightarrow \mu^+\mu^-$$

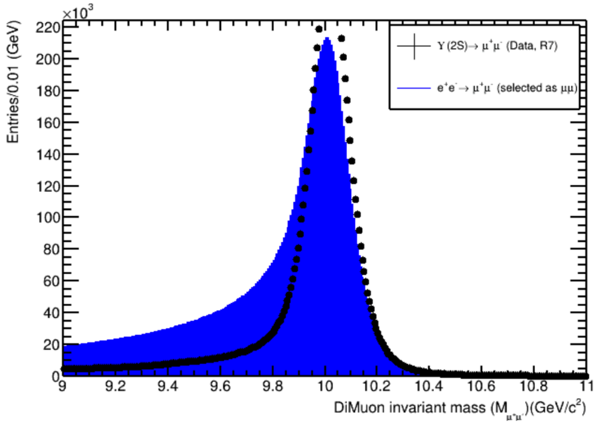
$$m_{\mu\mu} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1^{\,2} + \vec{p}_2^{\,2})^2}$$



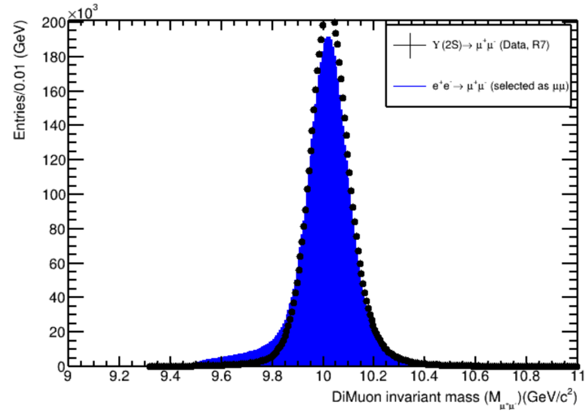


Example one

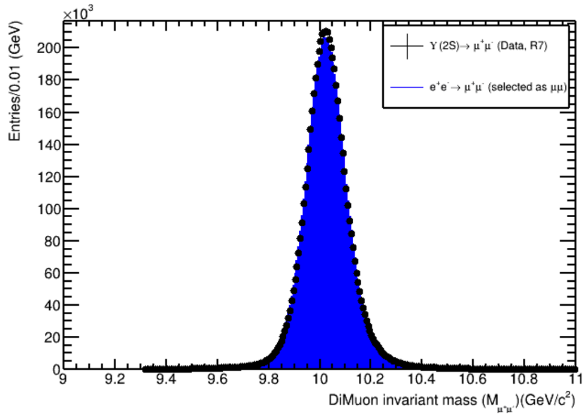
$$e^+e^- \rightarrow \Upsilon(2S) \rightarrow \mu^+\mu^-$$



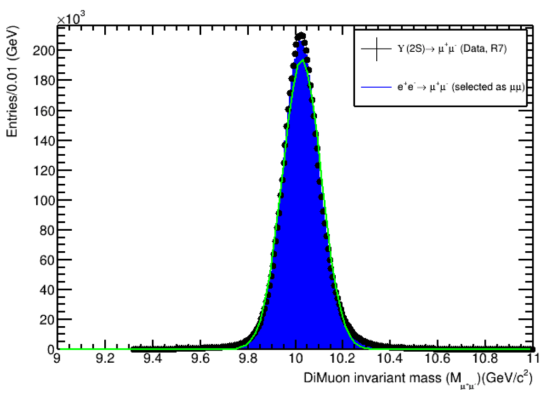
No cut applied!

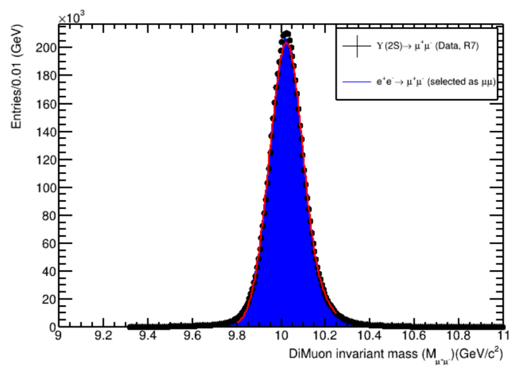


Back-to-back cut applied!



Particle Identification (charge)





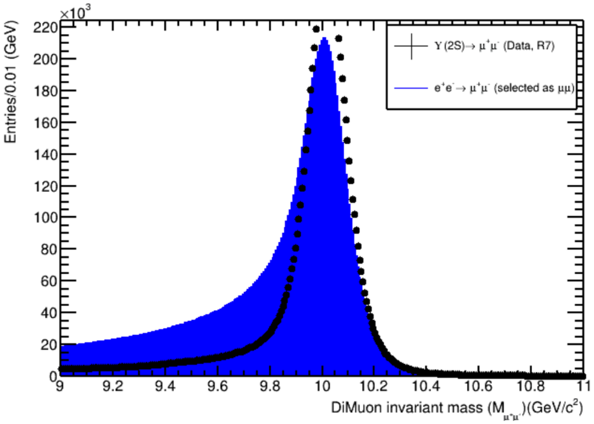
10022.50 ± 0.04 MeV/c^2 --Data
10023.26 ± 0.31 MeV/c^2 --PDG

$$f(x) = a \exp - \frac{(x-b)^2}{2c^2}$$

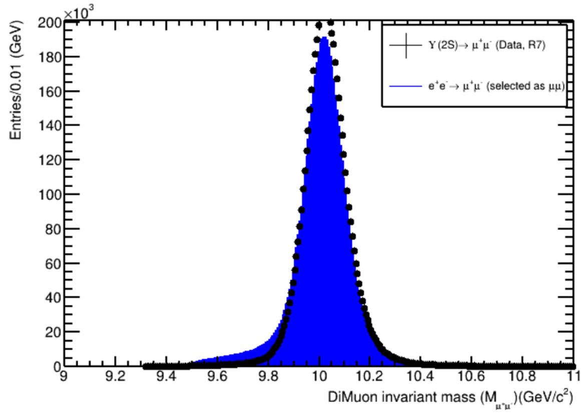
$$f(x;\alpha,n,\bar{x},\sigma) = \begin{cases} \exp - \frac{(x-\bar{x})^2}{2\sigma^2} & \text{, for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n} & \text{, for } \frac{x-\bar{x}}{\sigma} \leq \alpha \end{cases}$$

Example one

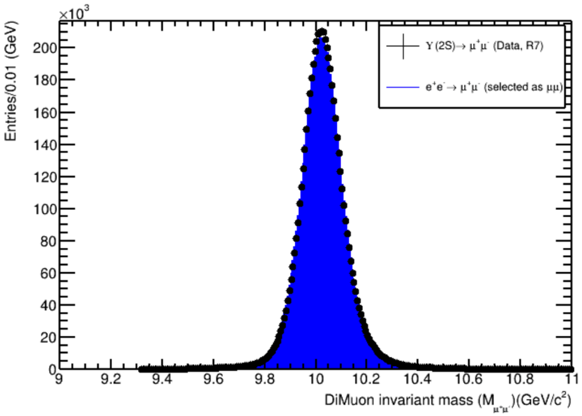
$$e^+e^- \rightarrow \Upsilon(2S) \rightarrow \mu^+\mu^-$$



No cut applied!



Back-to-back cut applied!



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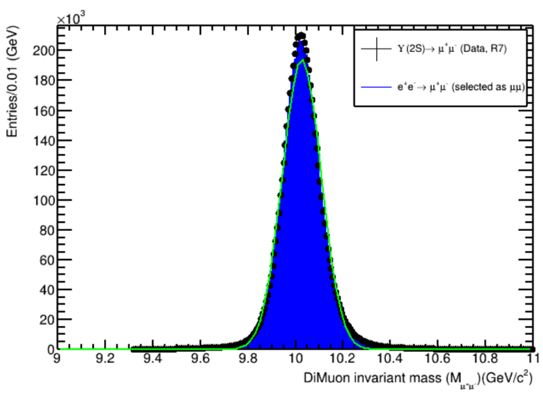
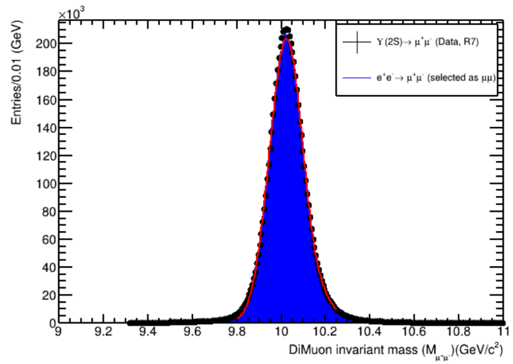




10022.50 ± 0.04 MeV/c² --Data
10023.26 ± 0.31 MeV/c² --PDG

$$f(x) = a \exp - \frac{(x-b)^2}{2c^2}$$

$$f(x;\alpha,n,\bar{x},\sigma) = \begin{cases} \exp - \frac{(x-\bar{x})^2}{2\sigma^2} & ,\text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n} & ,\text{for } \frac{x-\bar{x}}{\sigma} \leq \alpha \end{cases}$$

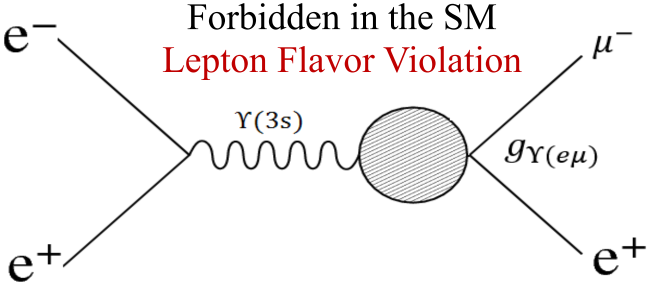
Example two: Charged Lepton Flavor Violation

- **Theory:**

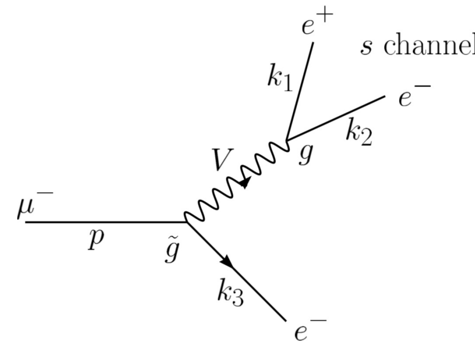
$\Upsilon(3S) \to e^{\pm}\mu^{\mp}$

S. Nussinov, et. al.
Phys.Rev. D63 (2001) 016003

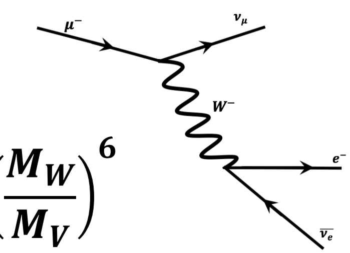
Forbidden in the SM
Lepton Flavor Violation



Re-ordering
incoming/outgoing particles



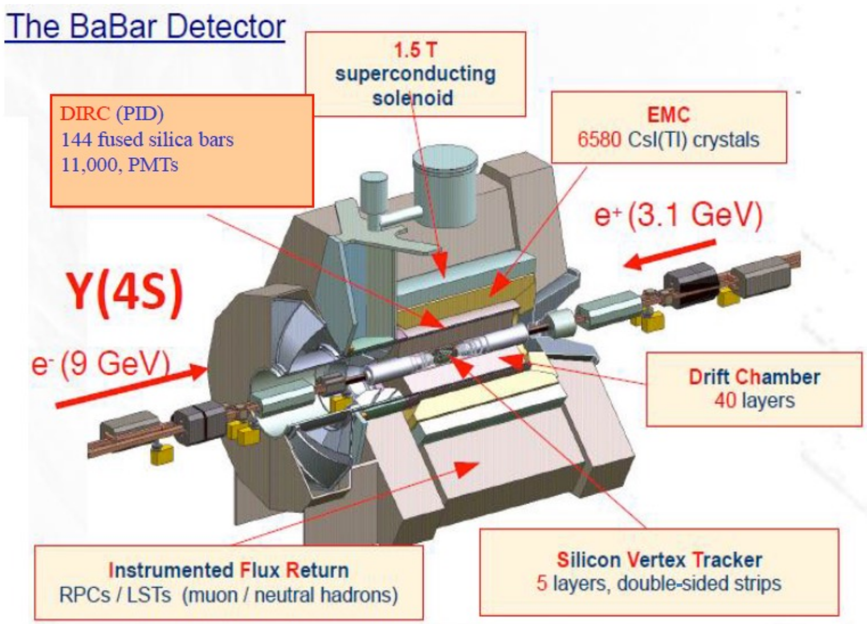
- Compare the re-ordered diagram with the ordinary Muon decay



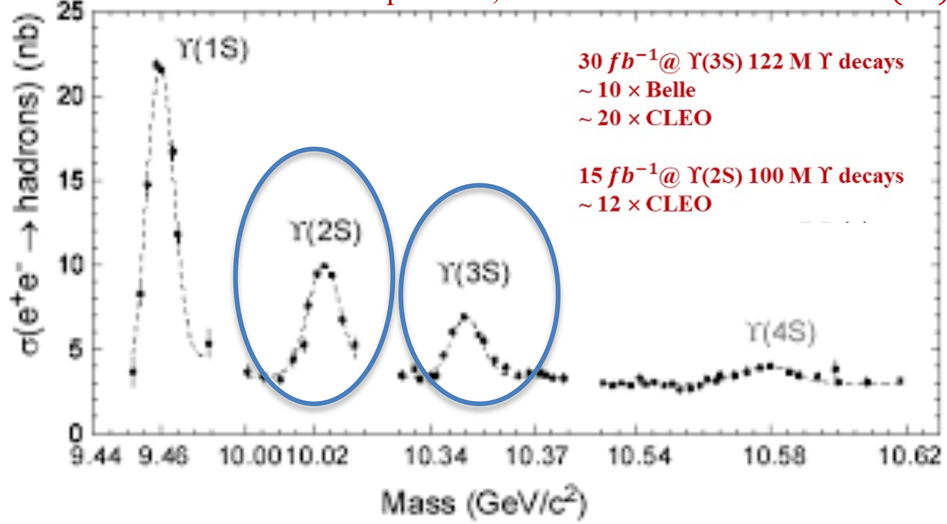
$$\frac{\boldsymbol{\Gamma(\mu \to 3e)_{V-exchange}}}{\boldsymbol{\Gamma(\mu \to e\nu\bar{\nu})}} \approx [\boldsymbol{BR(\mu \to 3e)}]_{\boldsymbol{V-exch.}} \approx \frac{\boldsymbol{\Gamma(V \to e^{+}e^{-})\Gamma(V \to e^{\pm}\mu^{\mp})}}{\boldsymbol{\Gamma^{2}(W \to e\nu)}} \left(\frac{\boldsymbol{M_W}}{\boldsymbol{M_V}}\right)^{\boldsymbol{6}}$$

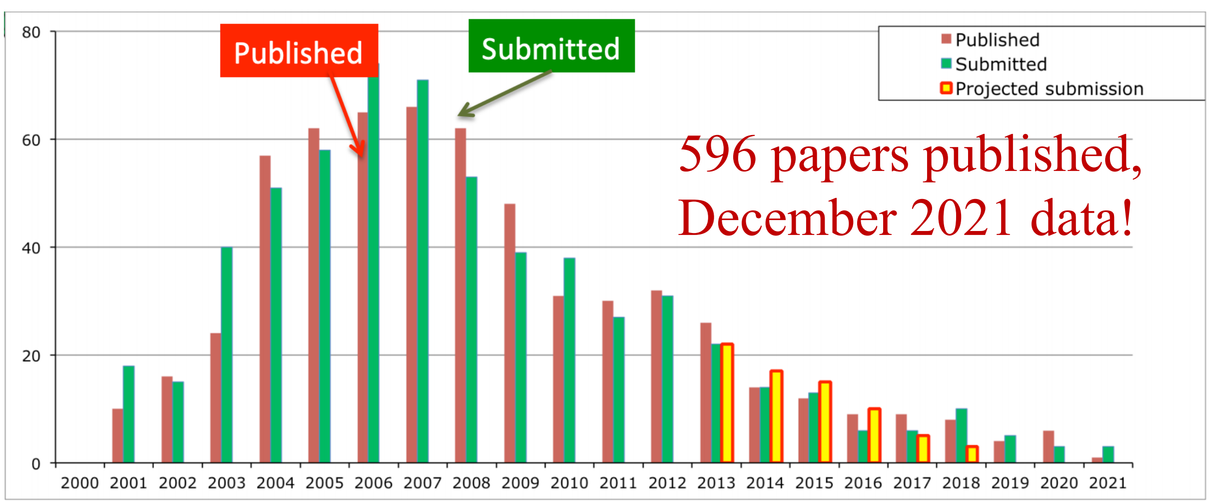
- S. Nussinov, et. al. estimated that the contribution of the virtual $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$ to the $\mu \to eee$ rate would be reduced by approximately $M^2_{\mu}/(2 M^2_{\Upsilon})$

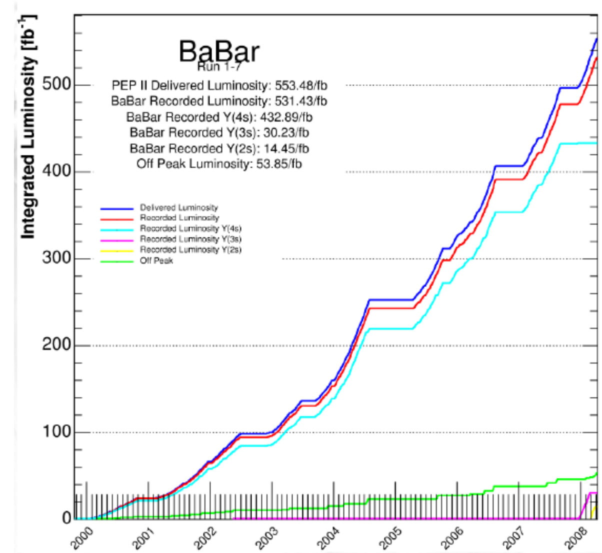
BaBar Detector



Between Dec. 2007 – Apr. 2008, BaBar collected data below $\Upsilon(4S)$







Example two

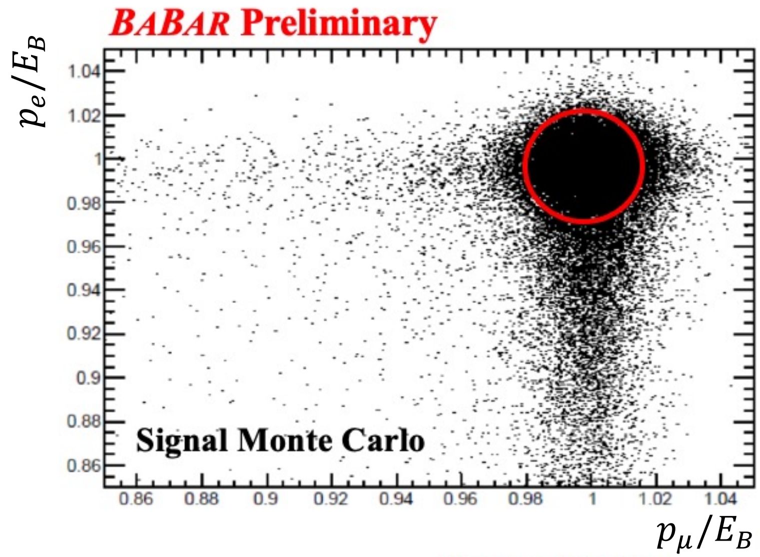
CLFV
$\Upsilon(3S) \to e^{\pm}\mu^{\mp}$

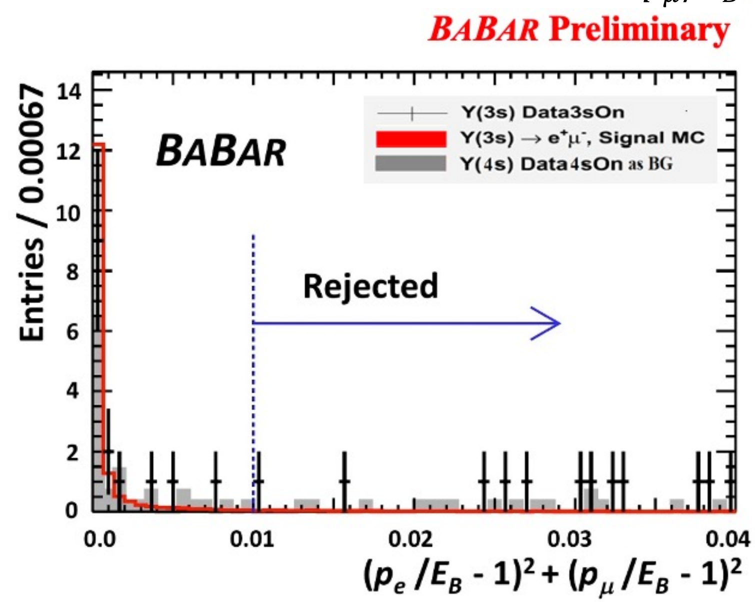
- 27.9 fb^{-1} $\Upsilon(3S)$ on-peak data (signal events)
- 78.31 fb^{-1} $\Upsilon(4S)$ on-peak data and
- 7.75 fb^{-1} $\Upsilon(4S)$ off-peak data (40 MeV below the on-peak) and
- 2.62 fb^{-1} $\Upsilon(3S)$ off-peak data (40 MeV below the on-peak) are used for sytematic studies (data driven continuum background)
- MC signal: $e^{+}e^{-} \to \Upsilon(3S) \to e^{\pm}\mu^{\mp}$: 103000 events

Charged Lepton Flavor Violation

$$\left(\frac{p_e}{\sqrt{s}*0.5}-1\right)^2+\left(\frac{p_\mu}{\sqrt{s}*0.5}-1\right)^2<0.01$$

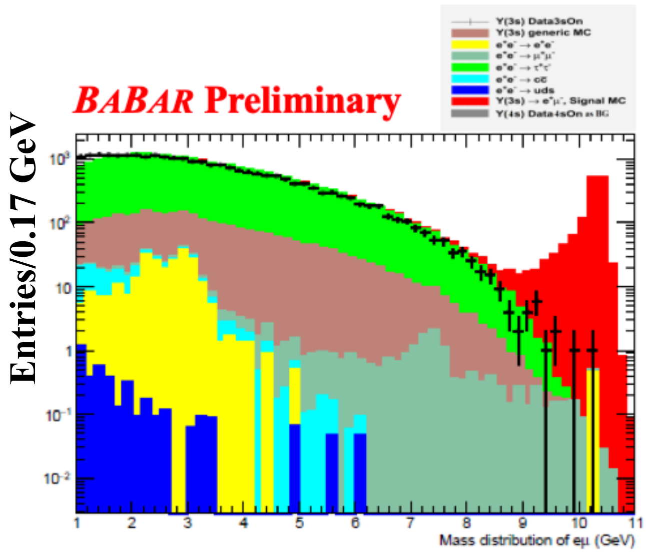
- **Data Analysis: selection and reconstruction**
  - two oppositely charged tracks (directly from $\Upsilon(3S)$ → signal candidates!)
  - momentum close to beam energy ($E_B=\frac{\sqrt{s}}{2}$)
  - angle between two tracks: $\theta_{12}^{CM}>179^o$
  - energy deposit by muons on EMC > 50 MeV
  - EMC acceptance $24^o<\theta_{Lab}<130^o$
  - main sources of backgrounds: $e^+e^-\to\tau^+\tau^-,\mu^+\mu^-(\gamma),e^+e^-(\gamma)$
  - in second stage tighter and optimized particle identification (PID) and kinematics criteria applied, i.e. lepton momentum plane



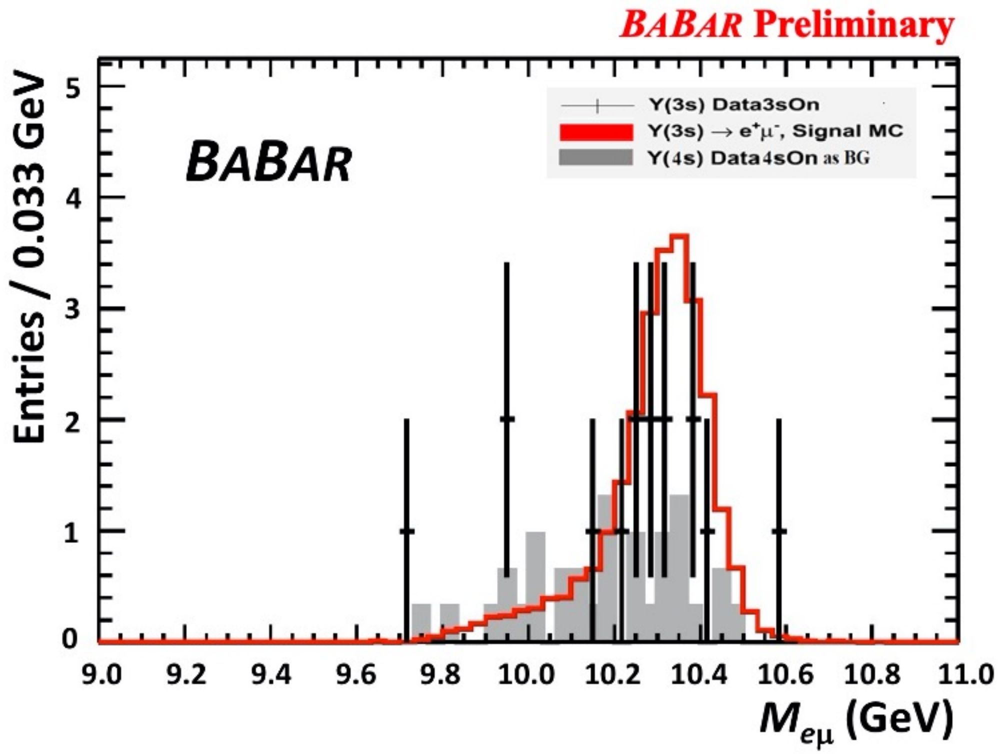


Charged Lepton Flavor Violation

❑ **Data Analysis: results**



Before final selection criteria were applied (3% unblinded preselected data)



➢ **Branching Fraction:** $\frac{N_{\text{Candidate}} - N_{BG}}{\varepsilon_{sig} \times N_{\Upsilon}} = (1.0 \pm 1.4_{stat(N_{Candidate})} \pm 0.8_{syst}) \times 10^{-7}$

➢ **Set an upper limit at 90% confidence level:** $\mathcal{B}(\Upsilon(3S) \to e^{\pm}\mu^{\mp}) < 3.6 \times 10^{-7}$ @ 90% CL

Systematics

- Systematics

TABLE II: Summary of systematic uncertainties. The values of the efficiency, background, and number of $\Upsilon(3S)$ decays are presented in the first column and their uncertainties in the second column. The different contributions to the efficiency systematic uncertainties are also presented.

Component Value	Uncertainties by Source	
	Lep. Mom. cut:	0.0068 (2.9 %)
	Back-to-back cut:	0.0026 (1.1 %)
	All other cuts:	0.0028 (1.2 %)
Signal	MC statistics:	0.0003 (0.13 %)
Efficiency: 0.2342	± 0.0078 (3.3 %)	
N_{Υ}: 117.7×10^6	$\pm 1.2 \times 10^6$ (1.0 %)	
BG: 12.2	$\pm$ 2.3 (19 %)	

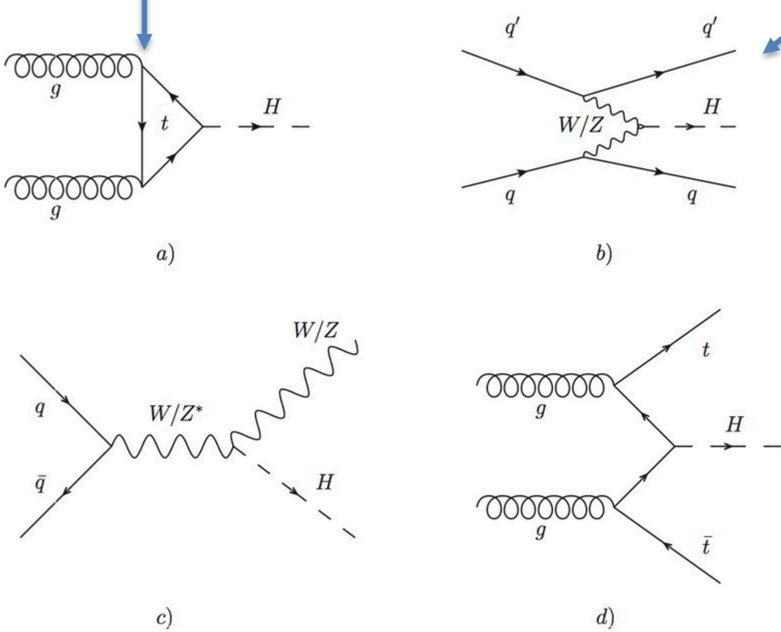
- First-ever result of this kind was published recently at Phys. Rev. Lett. **128**, 091804

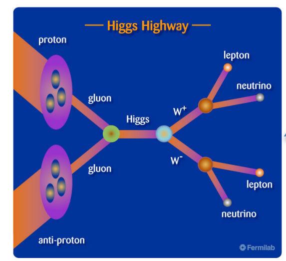
Example three
Higgs Boson (LHC)

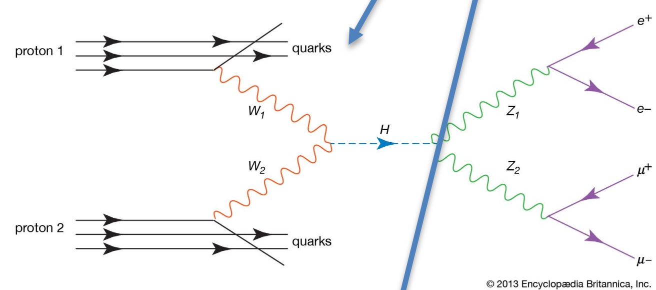
Gluon-gluon fusion ~88%

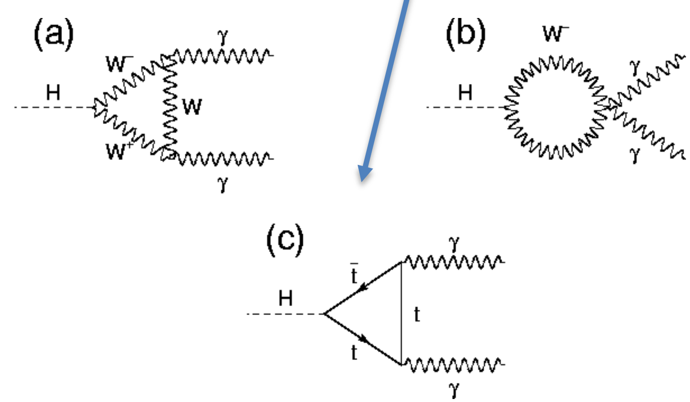
Vector bosons fusion ~07%

Higgs Decay









$Ht\bar{t}$ ~01%

Associated production
with vector bosons ~04%

Example three
Higgs Boson Mass