Status of LHC and the Higgs Search

Andrei Gritsan

Johns Hopkins University

August, 2011

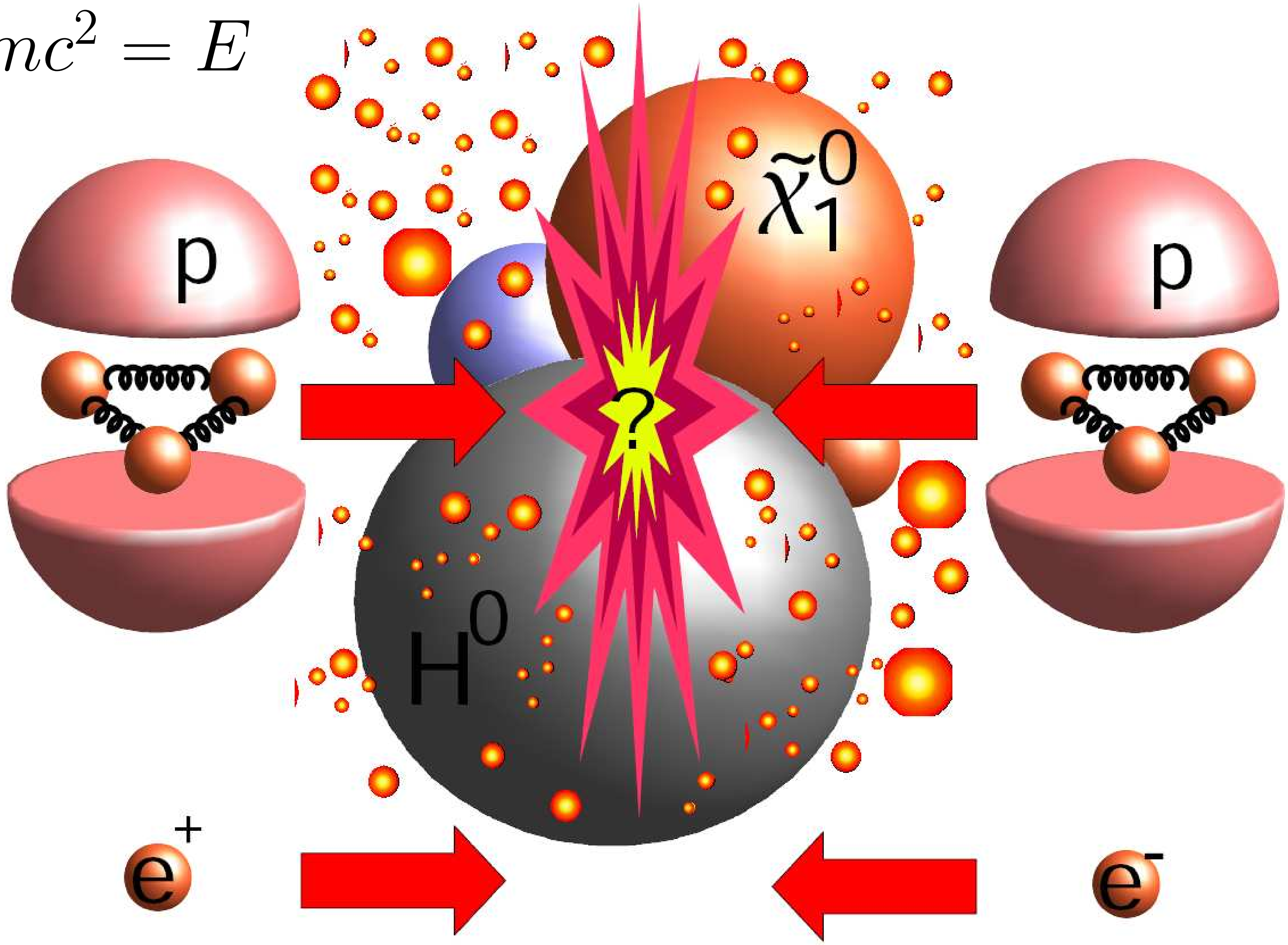
JHU Quarknet Meeting

Finding the Higgs

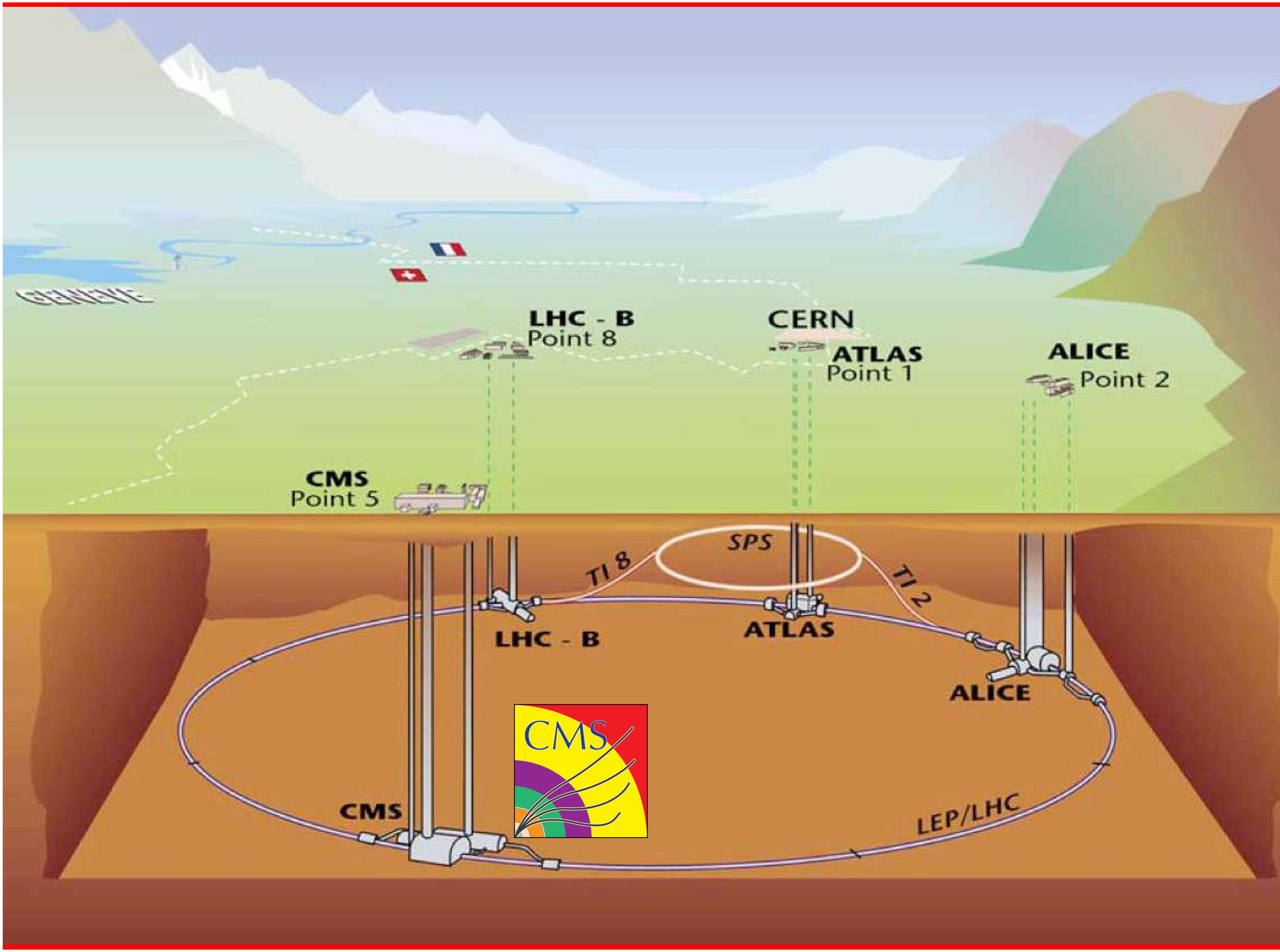
- Higgs mechanism is responsible for
  generating mass of fundamental particles
  (discuss later how)
- Is it responsible for our mass?
  (discuss later why)
- Why have not we seen the Higgs ?
  (A) it is too heavy for past experiments
  (B) it does not exist
- If Higgs is so important:
  – how do we find the Higgs ?
  – or prove that it does not exist...

Produce the Higgs: Reaching Highest Energy

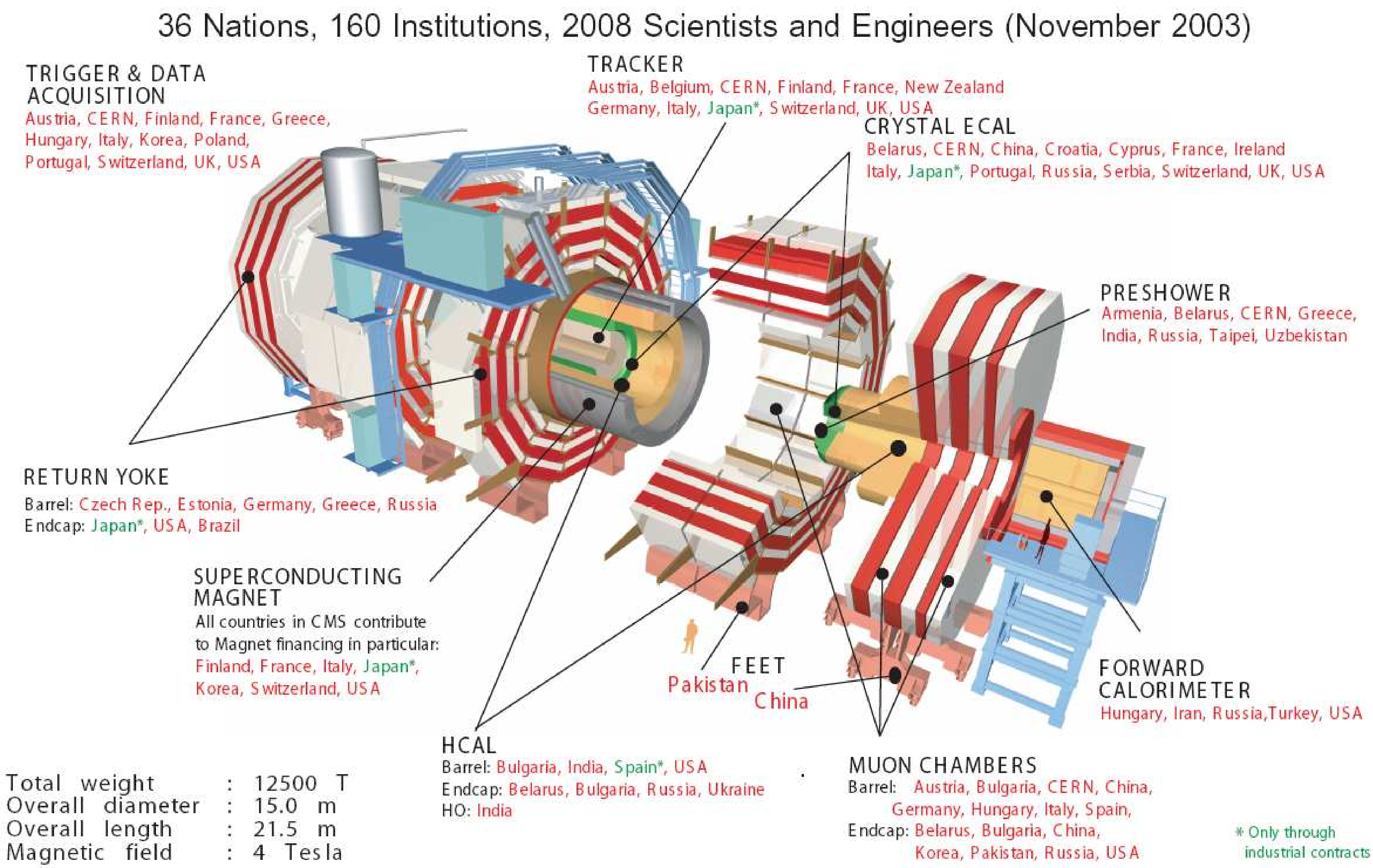
- $mc^2 = E$



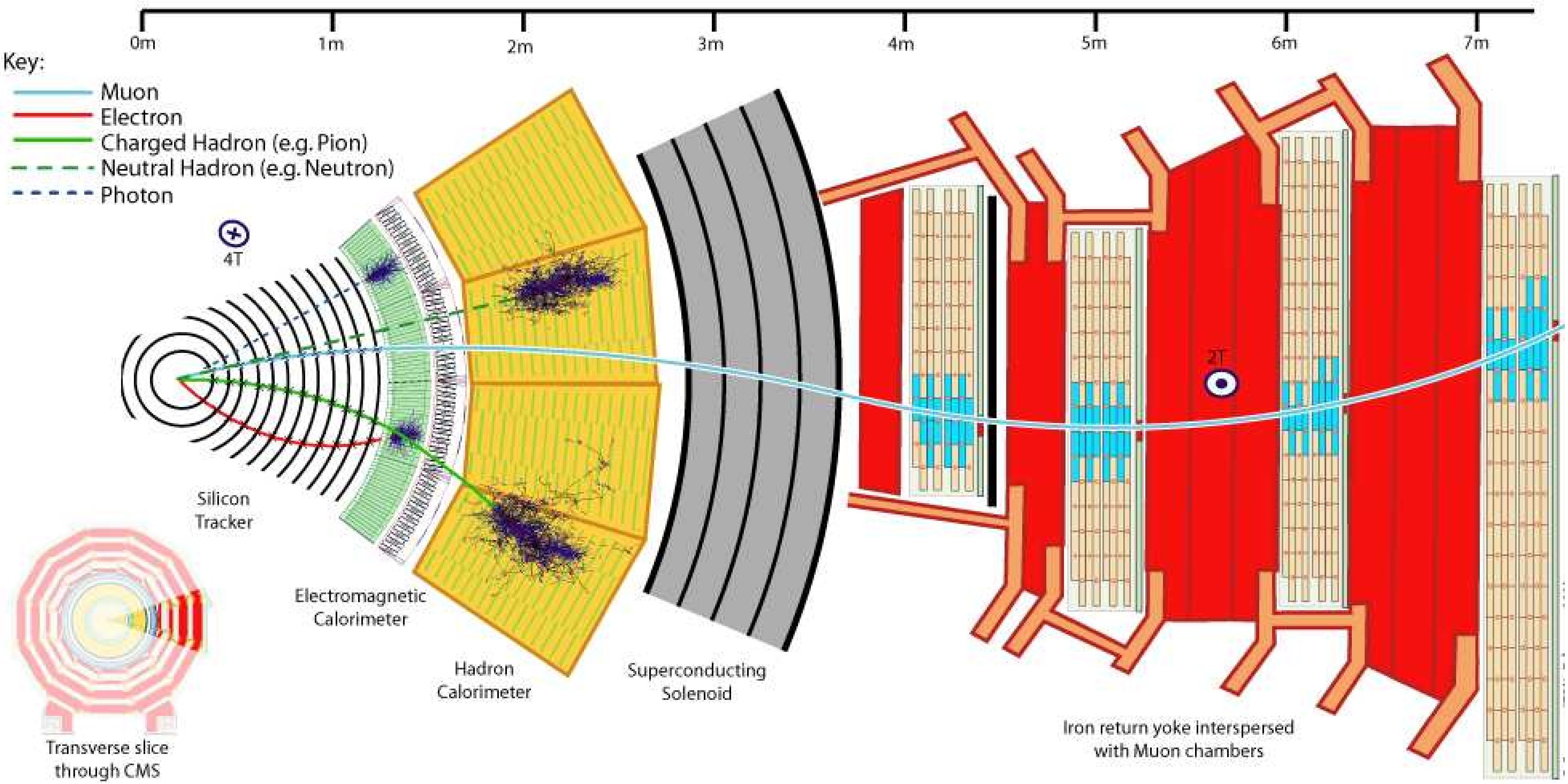
Large Hadron Collider: Running at Full Speed



CMS Experiment



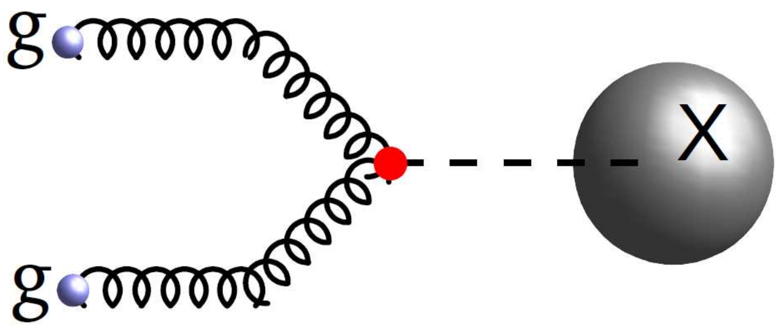
Detecting Particles at CMS

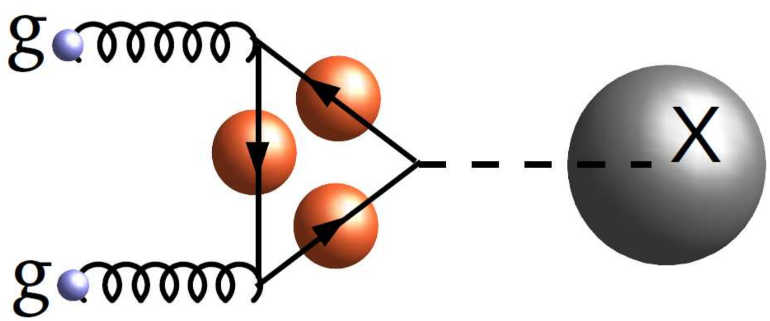


Production of the Higgs

- Higgs interaction strength $\propto$ mass of particles

  of color-neutral
  & charge-neutral Higgs



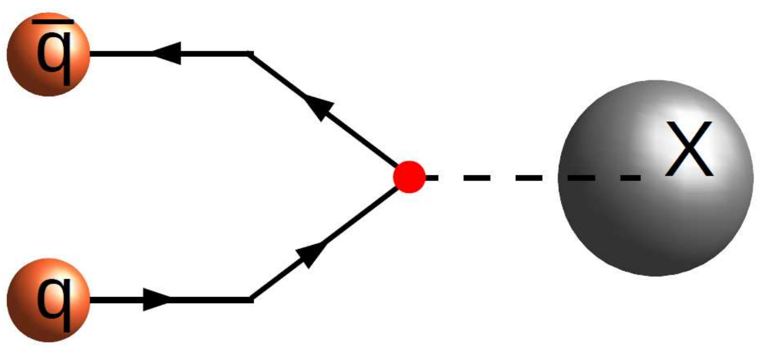


- Does not interact with

  massless gluons directly

  gg$\longrightarrow X$

  only through a "loop"



- Very unlikely to interact with

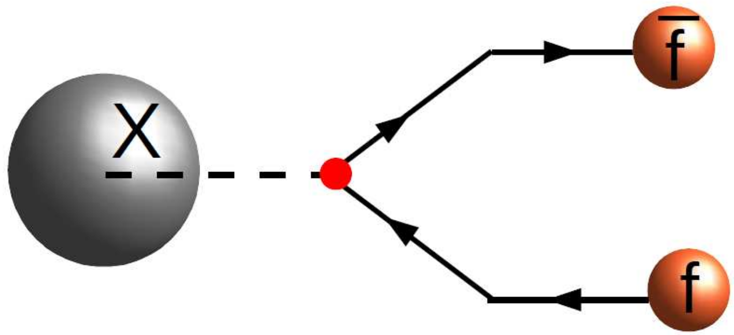
  light quarks in proton

  $q\bar{q} \longrightarrow X$

  negligible

Decay of the Higgs

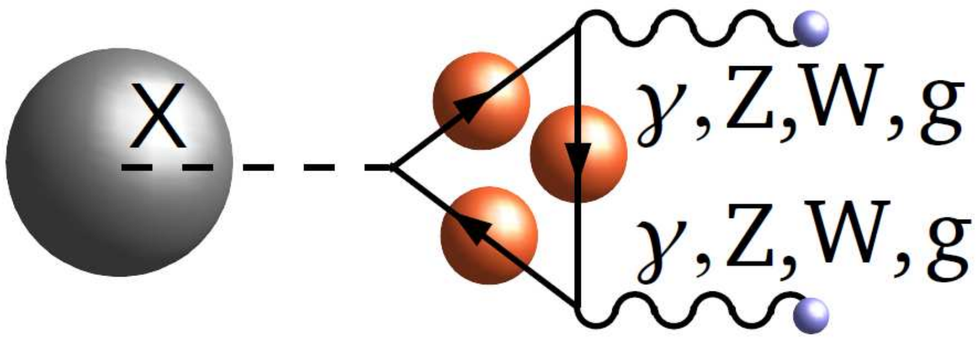
- Consider decay back to Standard Model particles



- Decay to fermions

$X \to l^+l^-,\ q\bar{q}$

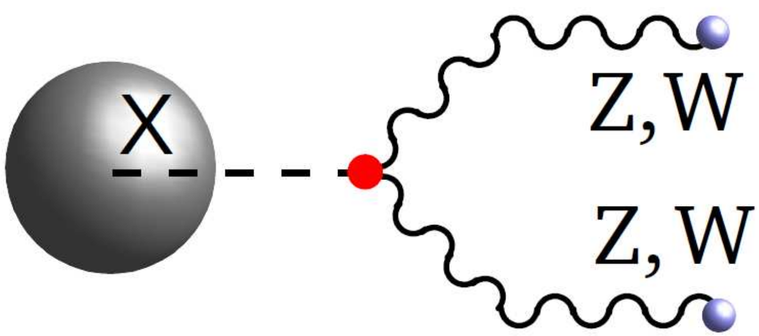
again very unlikely (light)



- Decay to gauge bosons

$X \to \gamma\gamma,\ W^+W^-,\ ZZ,\ \mathrm{gg}$

$\gamma\gamma$ trough a loop

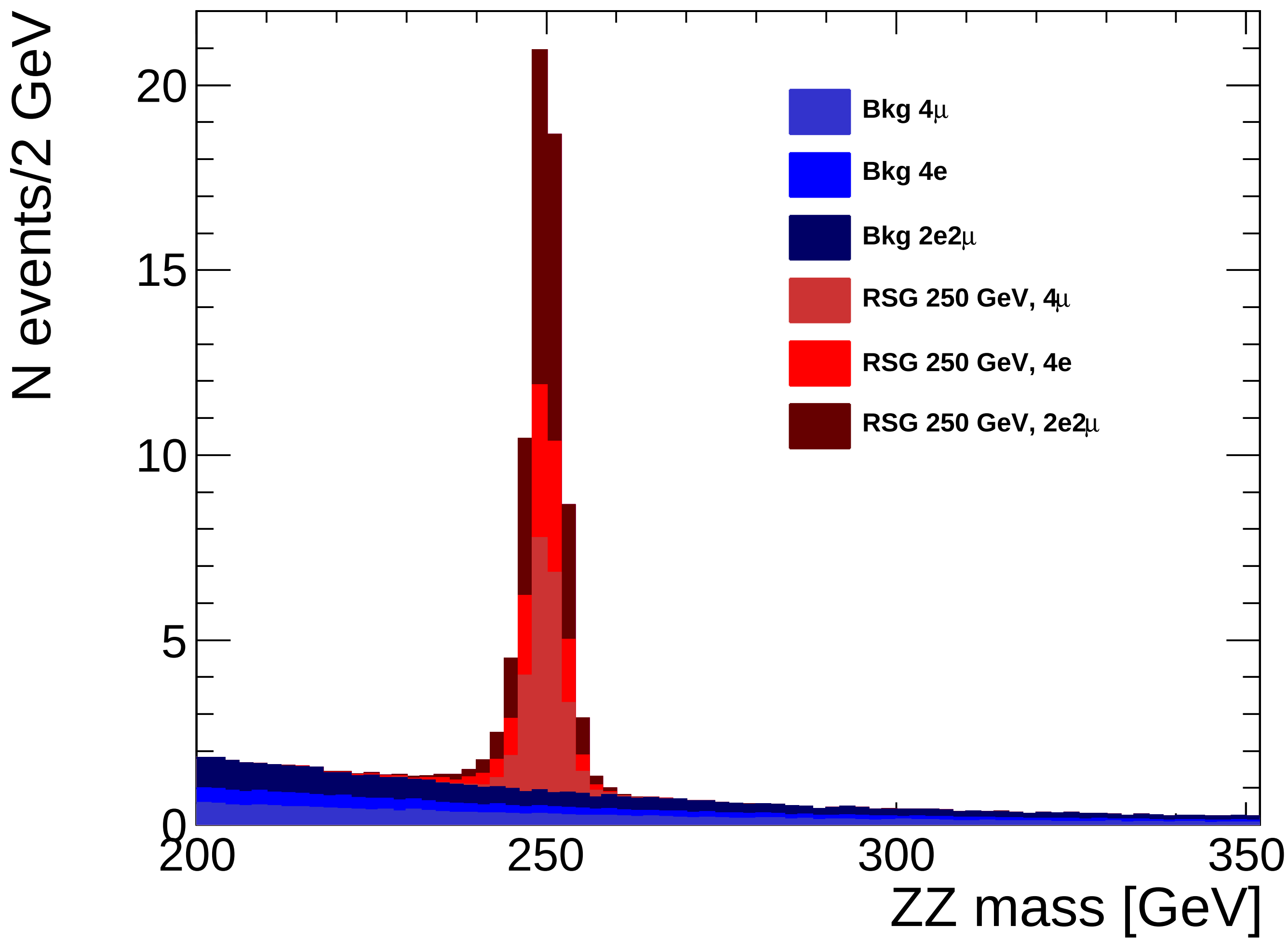


two likely channels WW, ZZ

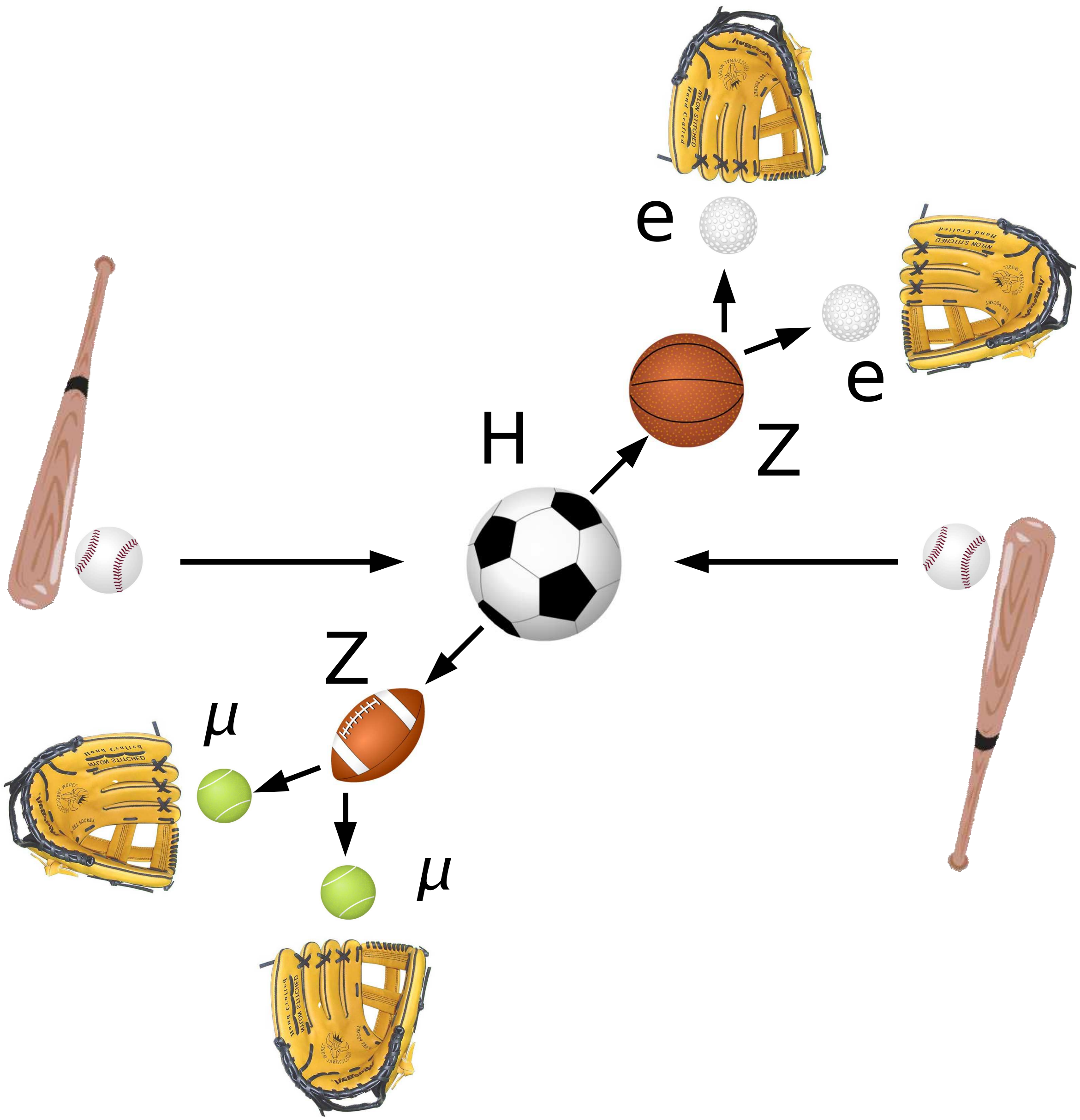
but Higgs mass $>\sim 2m_W$

Next Steps

- If there is a Higgs
  - likely to appear as a "resonance" on top of "background"
  - "background" = random combination of particles

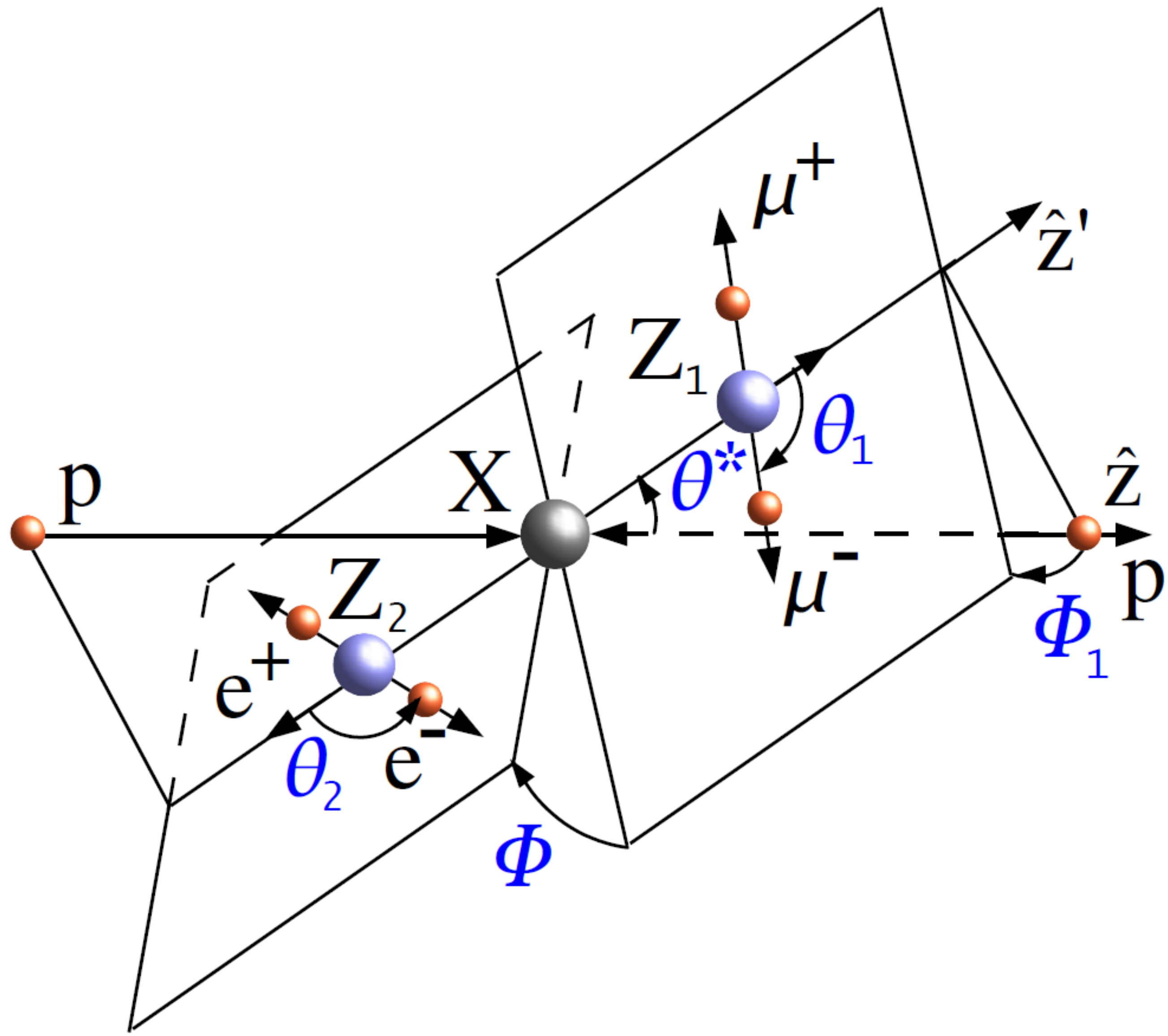


Cartoon of an Experiment



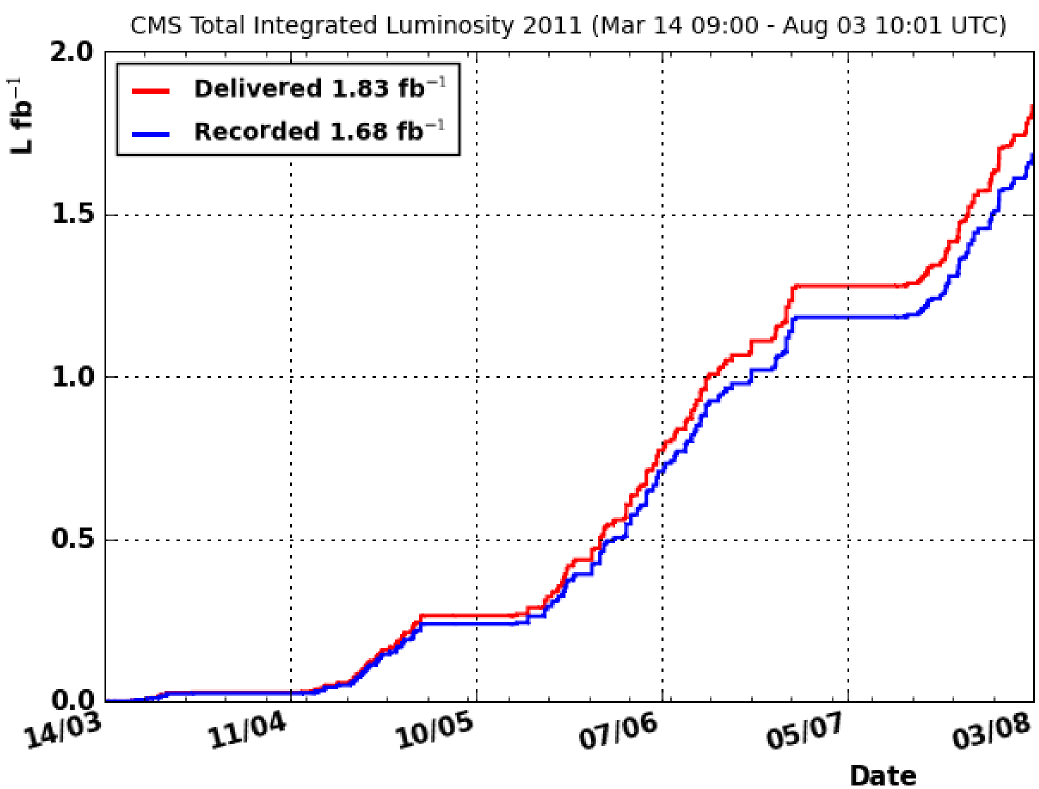
Kinematics of $X \rightarrow ZZ$ and WW

- We can describe kinematics of decay and distinguish from others

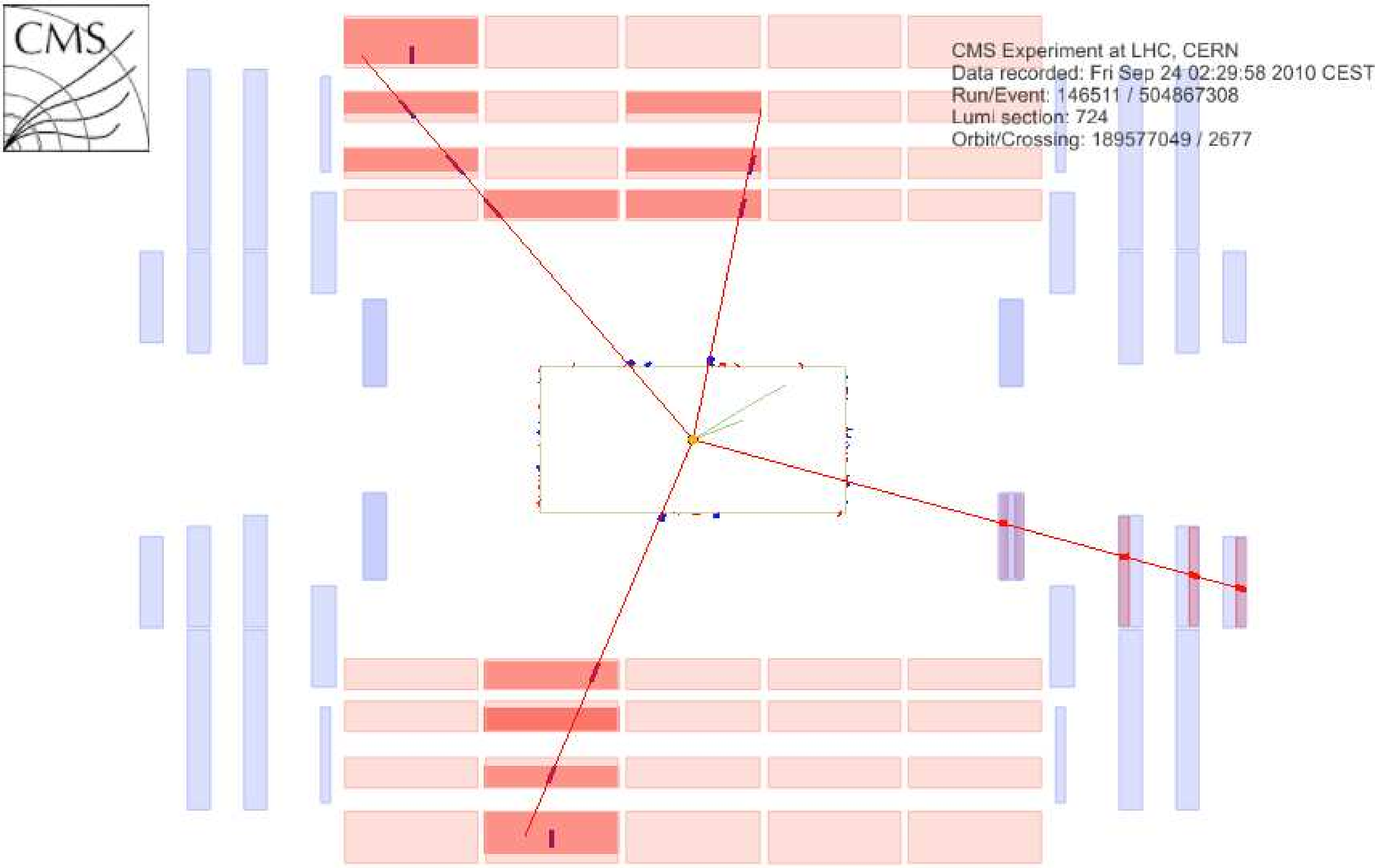


Higgs at LHC

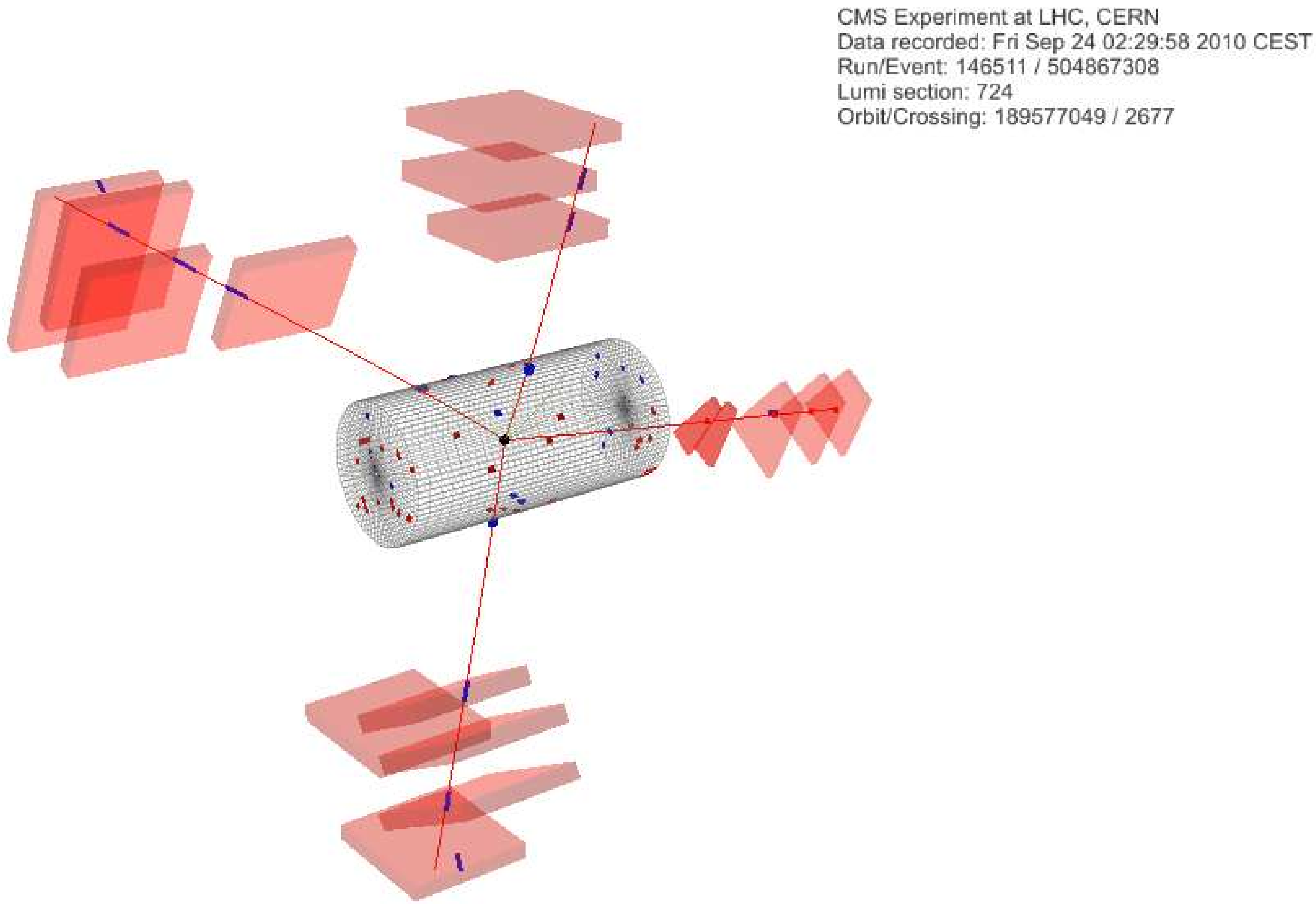
- By the end of June 2011 collected $\sim$1 fb^{-1} of data
  $\sim$ 100 trillion proton-proton collisions
  for comparison, in 2010 we had $\sim$0.04 fb^{-1}



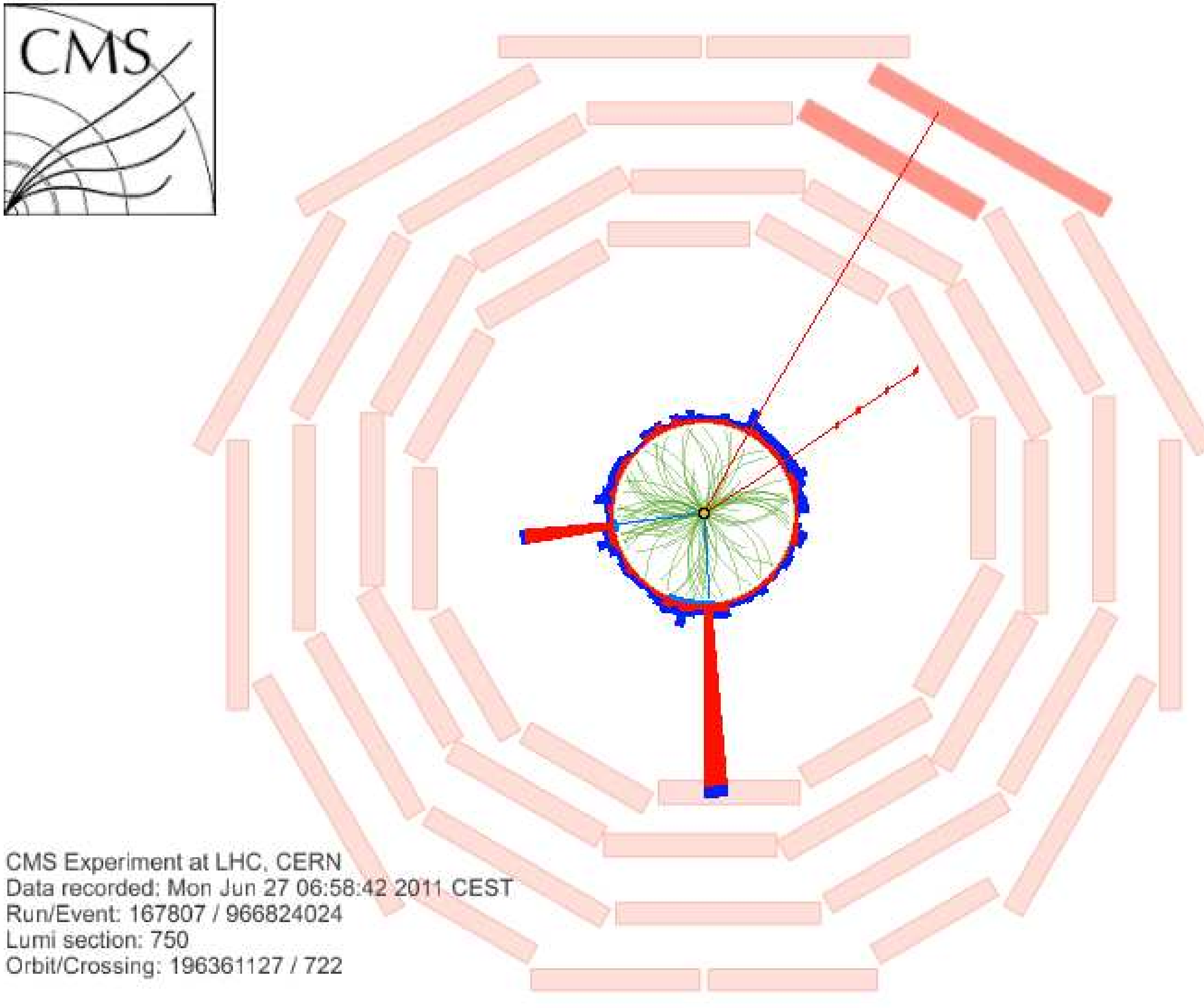
Higgs at LHC: Candidate Events $H \to ZZ$



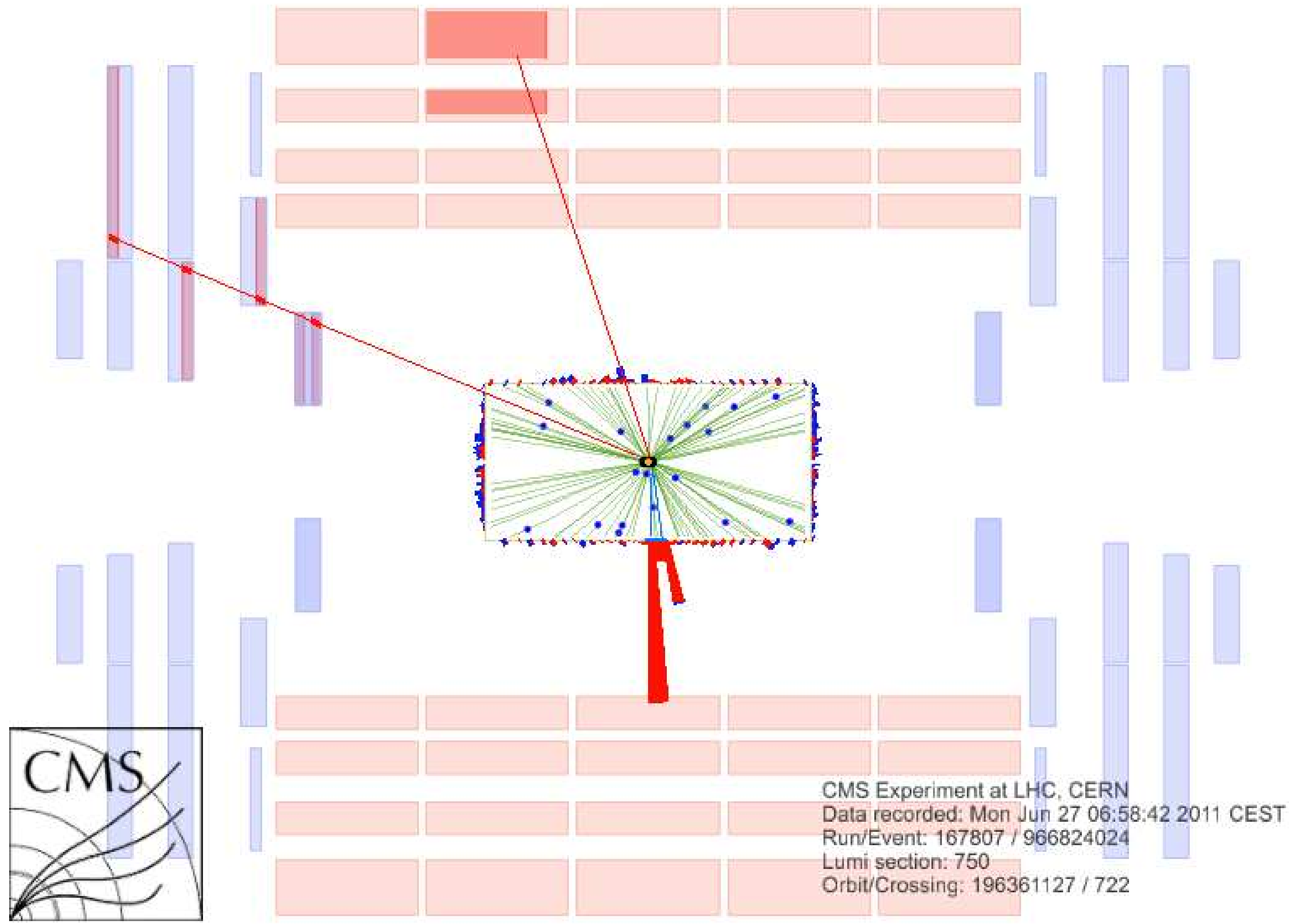
Higgs at LHC: Candidate Events $H \to ZZ$



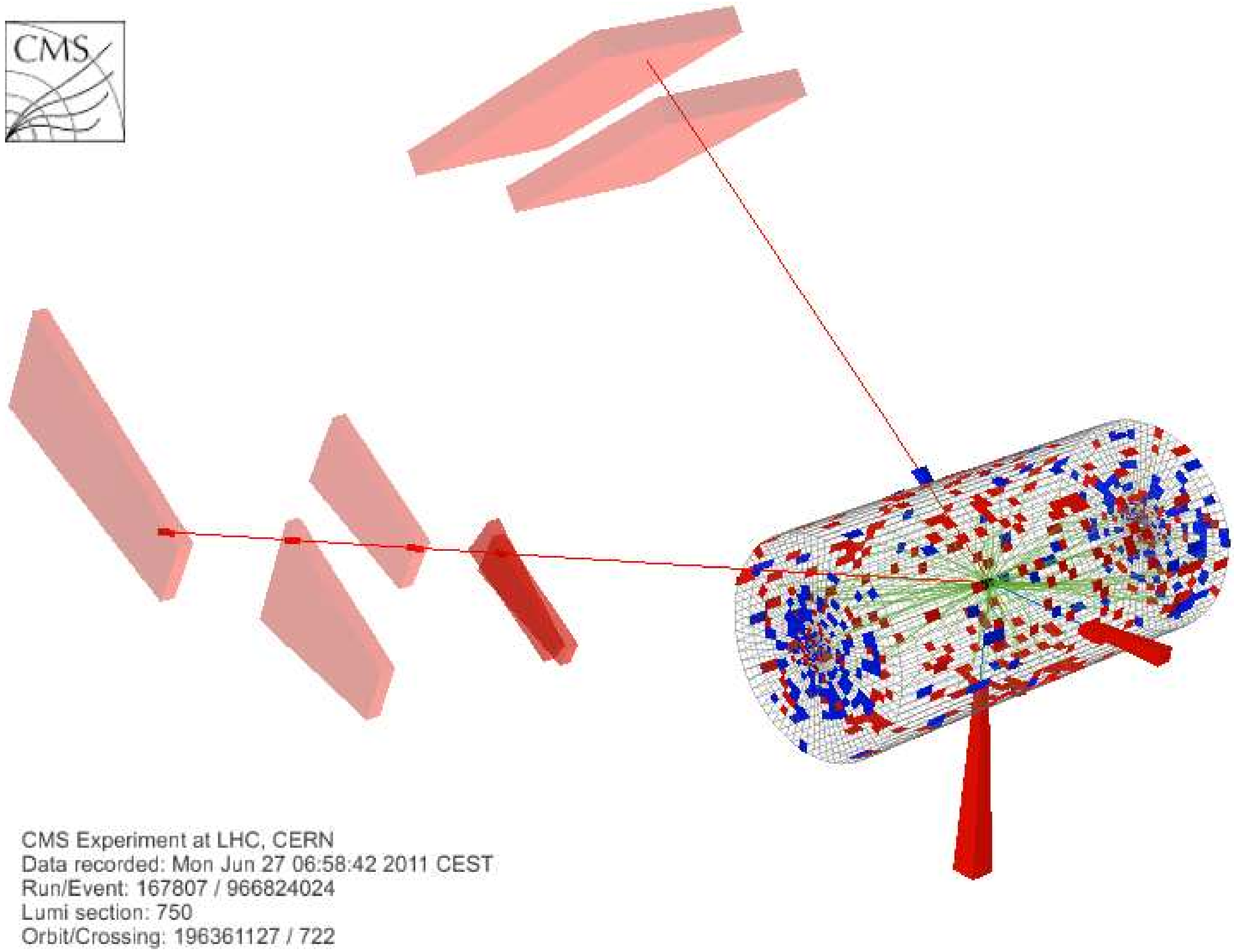
Higgs at LHC: Candidate Events $H \to ZZ$



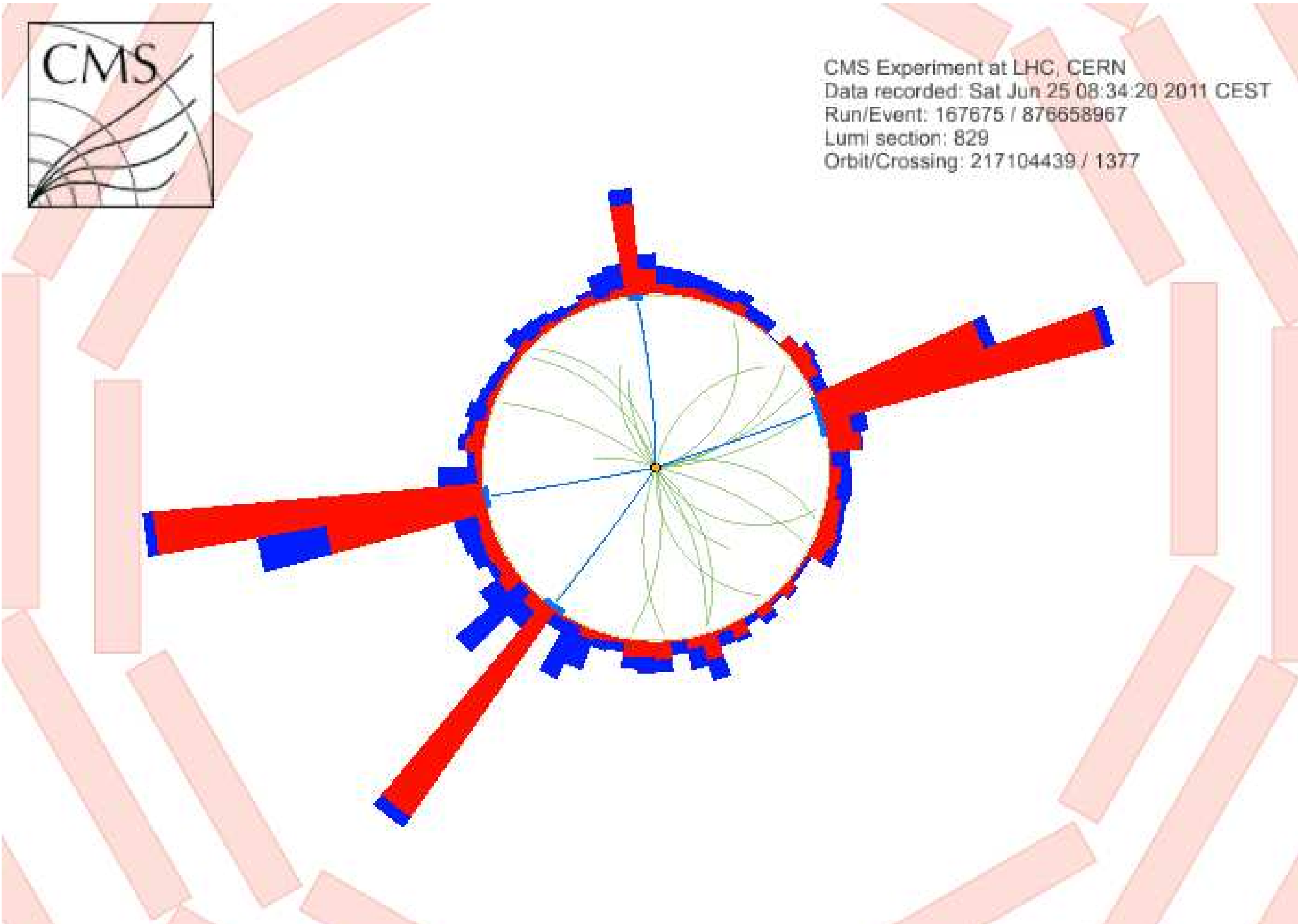
Higgs at LHC: Candidate Events $H \to ZZ$



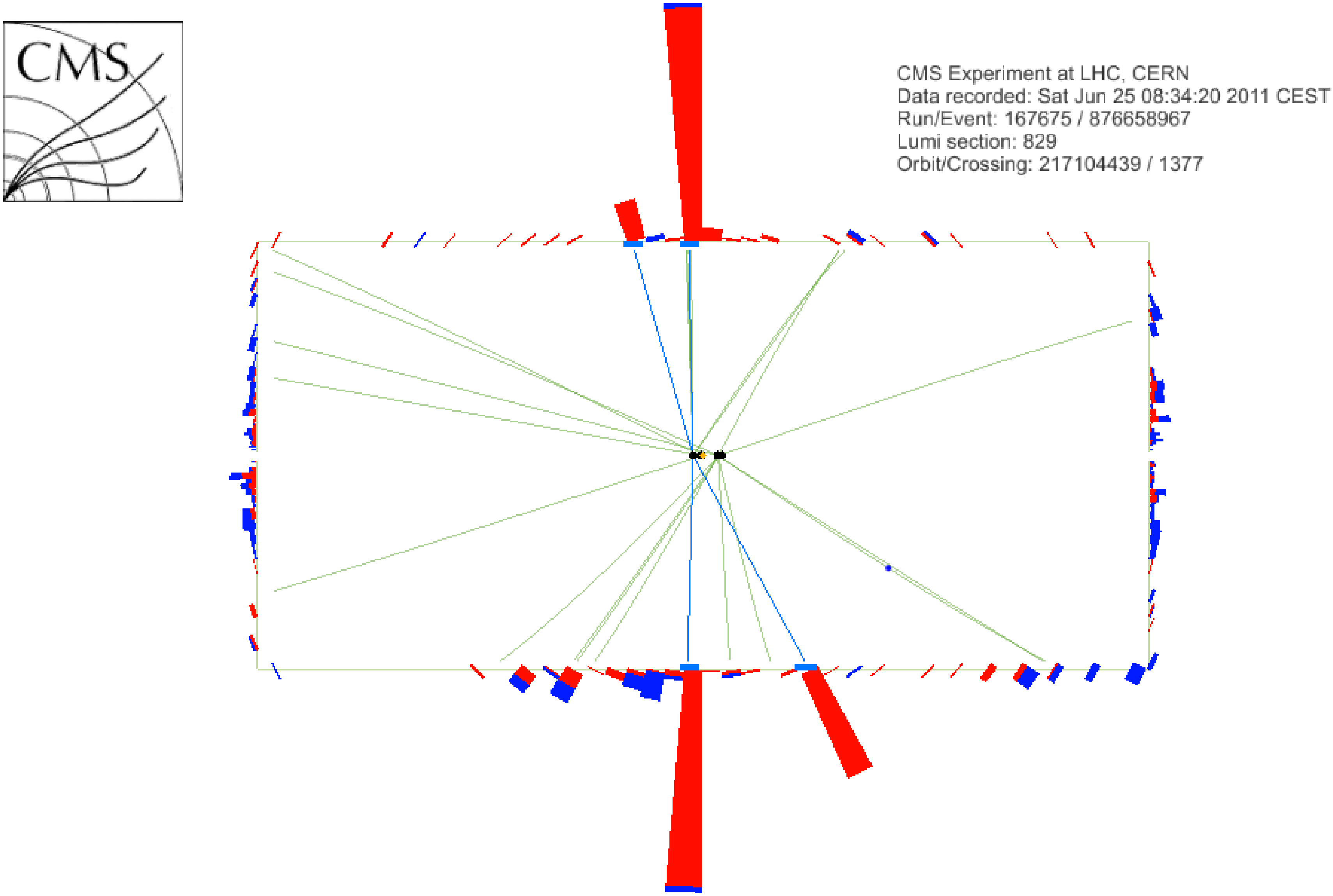
Higgs at LHC: Candidate Events $H \rightarrow ZZ$



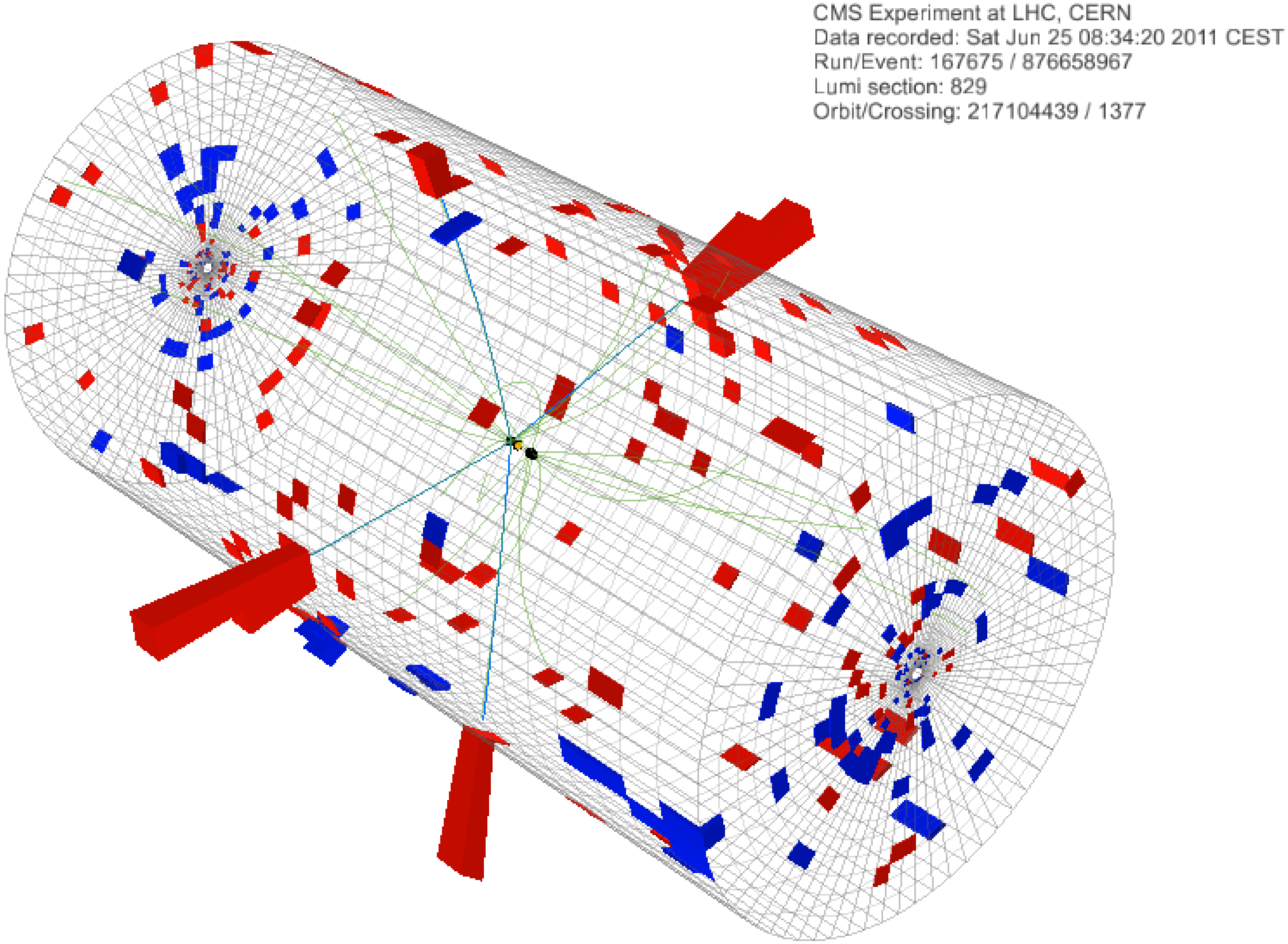
Higgs at LHC: Candidate Events $H \to ZZ$



Higgs at LHC: Candidate Events $H \to ZZ$

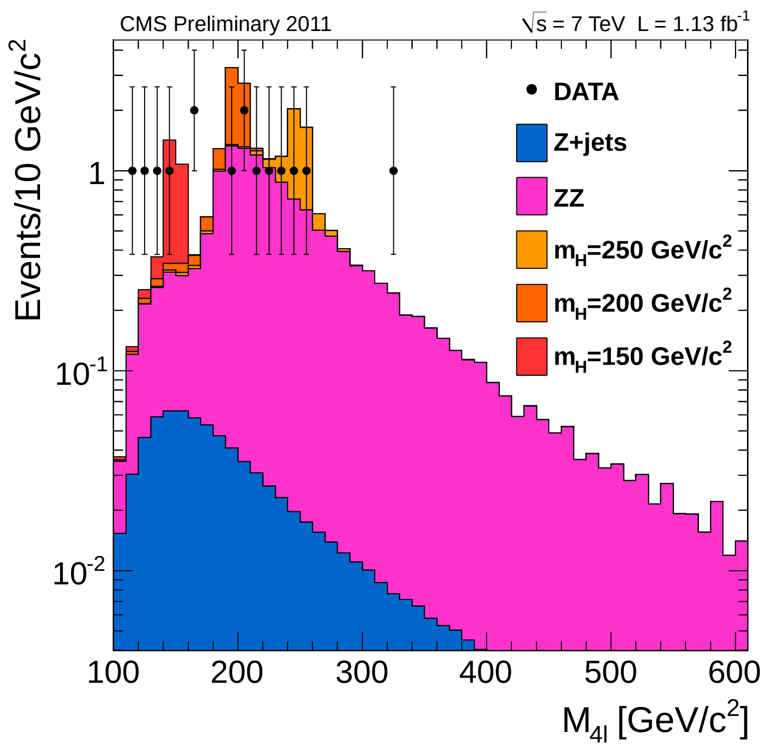


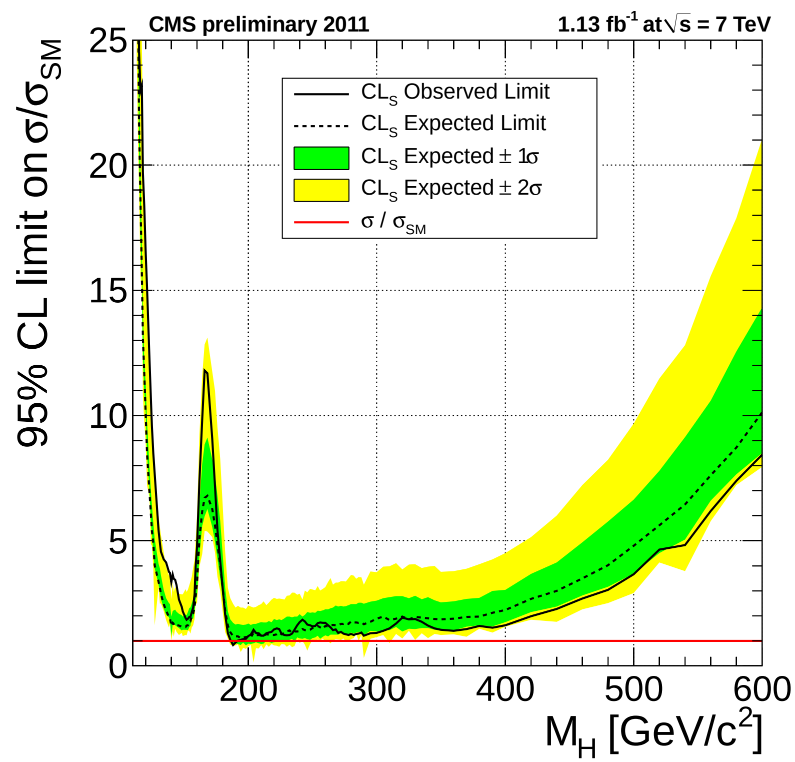
Higgs at LHC: Candidate Events $H \to ZZ$



Higgs at LHC: $H \rightarrow ZZ \rightarrow 4l$

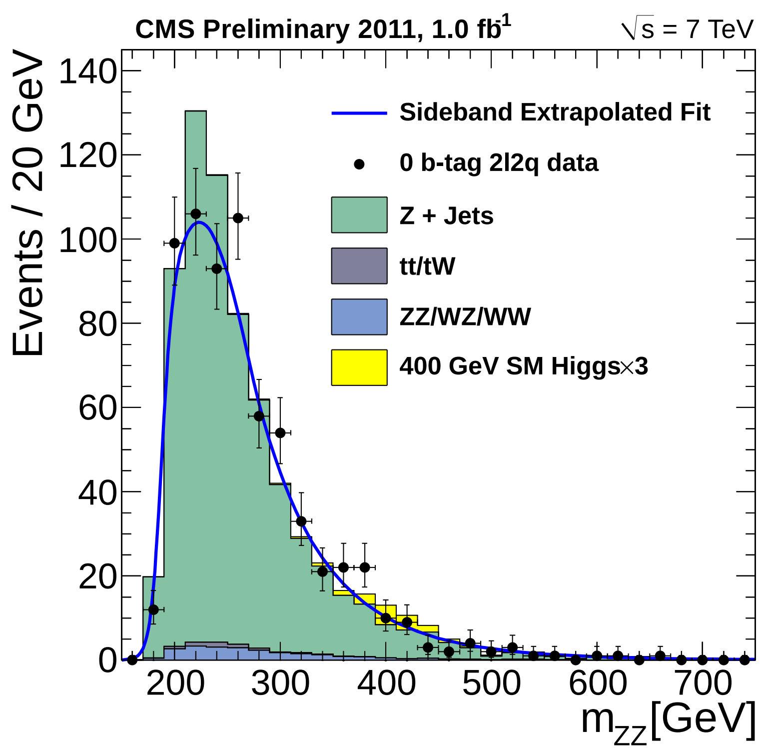
- Perform statistical analysis of observed events
  - data are consistent with background only
  - can try to reject Higgs at 95% confidence

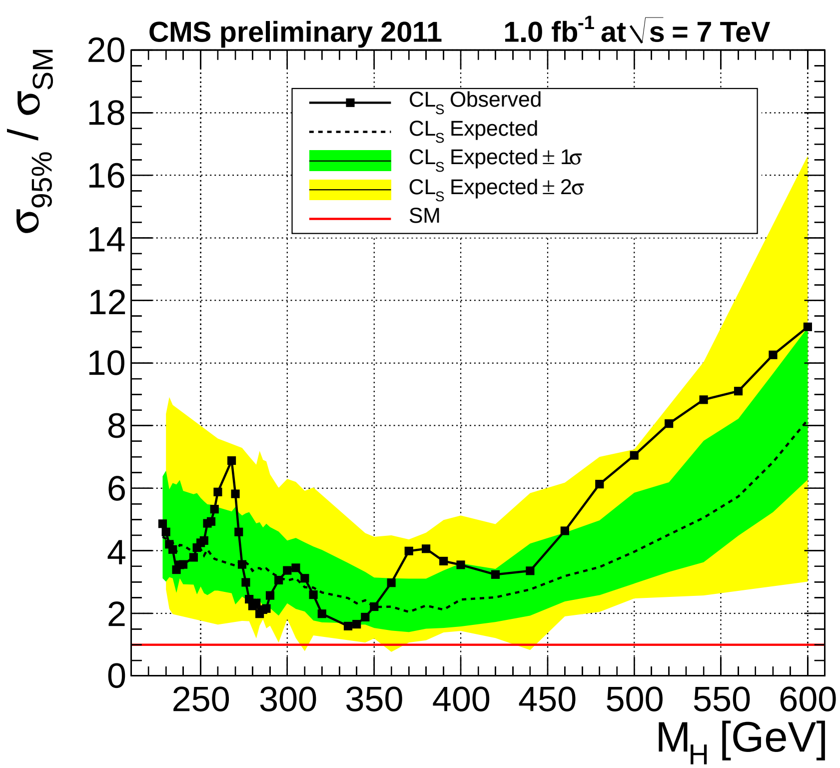




Higgs at LHC: $H \to ZZ \to 2l2q$

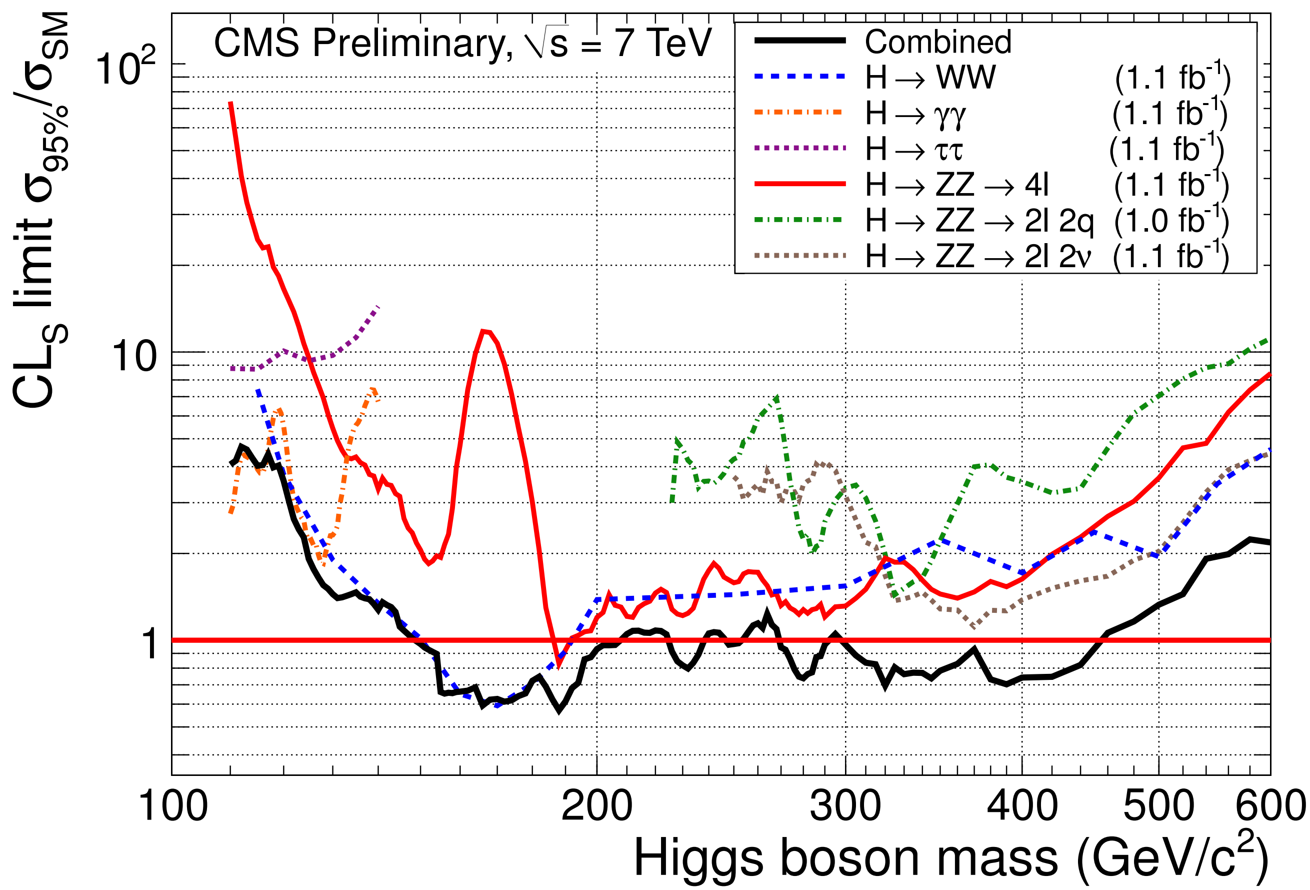
- Perform statistical analysis of observed events
  - data are consistent with background only
  - can try to reject Higgs at 95% confidence





Higgs at LHC: Combine All Channels

- Combine all Higgs channels
  - Higgs$\rightarrow \gamma\gamma, \tau\tau, WW, ZZ$, with $ZZ \rightarrow 4l, 2l2q, 2l2\nu$
  - reject Higgs at 95% confidence in large range of masses



Closing on the Higgs

- We are excluding large range of masses now
- Preparing new results by mid-August, LHC performs well
- Even better by the end of 2011, and in 2012
- We will either FIND or REJECT the SM Higgs hypothesis
  - both options are exciting
  - both will be only the first step to explain puzzles

(1) if Higgs found, still new discoveries expected to explain incosistencies of the model

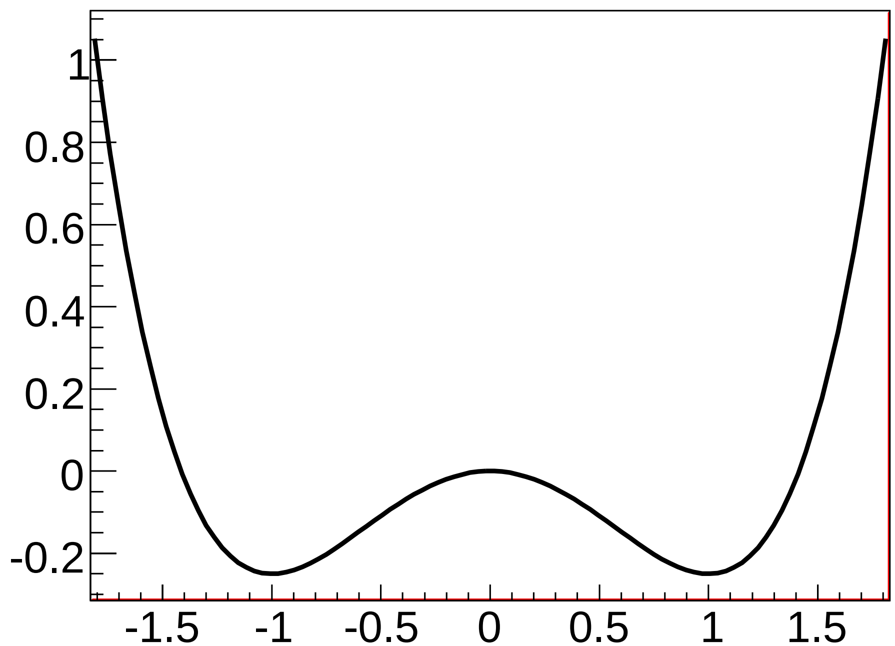
(2) if Higgs not found, even more expected to explain the mechanism of mass

What is the Higgs Particle?

- This answer is probably not very satisfying to see first:

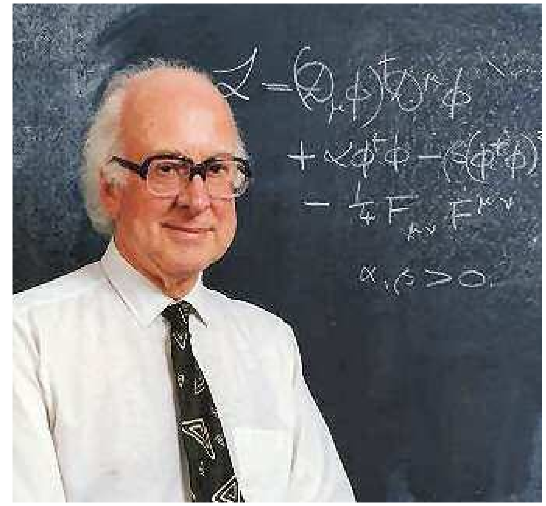
Higgs appears from introduction of this Lagrangian in the quantum field theory of particles

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \left[\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4\right]$$



What is Higgs?

- There are several phenomena:
  - Peter Higgs
  - Higgs mechanism
  - Higgs field
  - Higgs particle (still elusive particle)



- People sometimes confuse these phenomena
  - especially the last two
- So far there is hard evidence only for the first:
  - 1964 article by Peter Higgs in *Physics Review Letters*

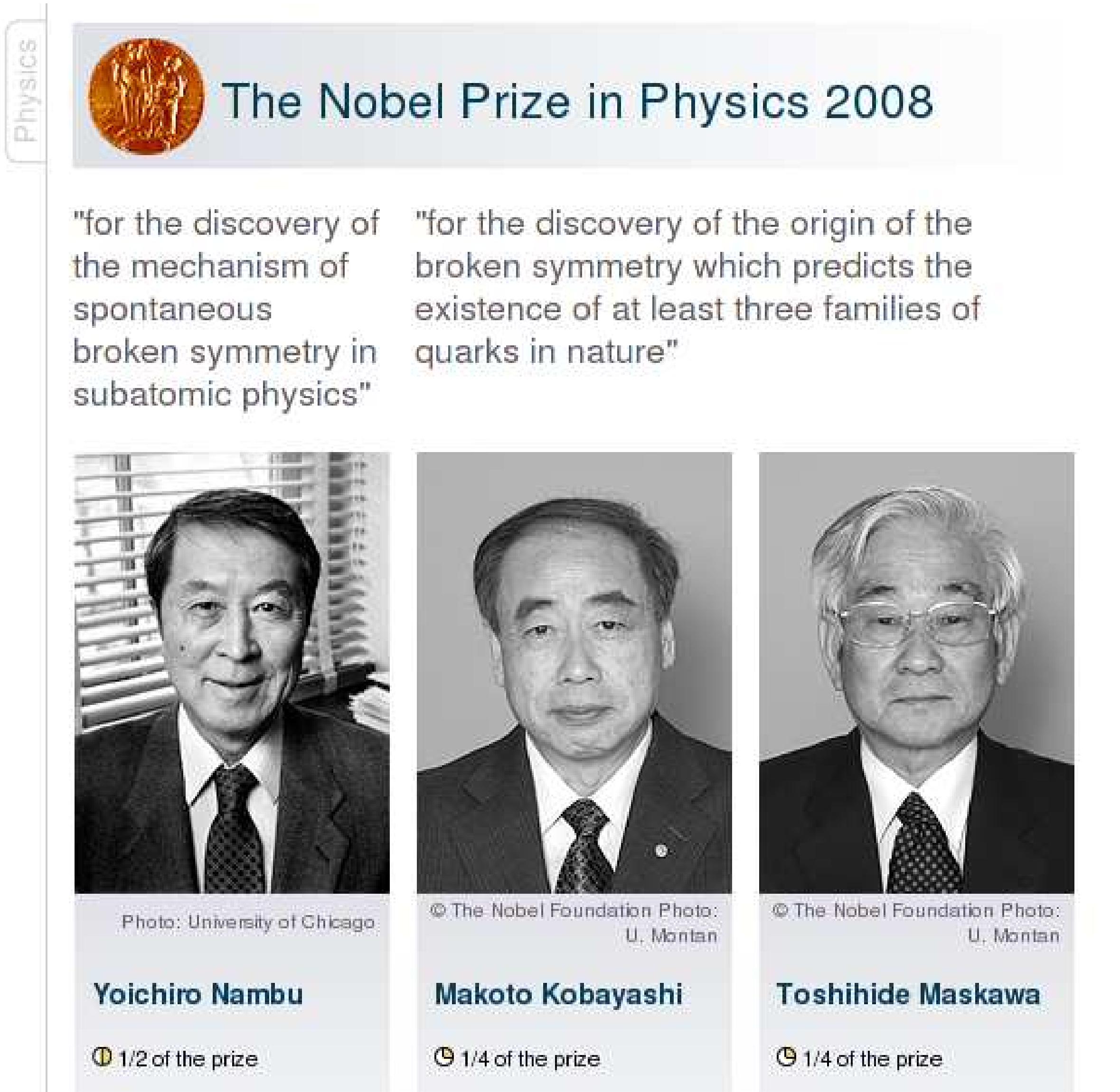
Why is it Higgs Mechanism ?

- In fact, there are several names of the Higgs mechanism:
  - Brout-Englert-Higgs mechanism
  - Higgs-Brout-Englert-Guralnik-Hagen-Kibble mechanism
  - Anderson-Higgs mechanism
  - Higgs mechanism is just simpler
  - all for authors of independent papers on the topic

- Partly due to ironic history with the paper by Higgs:
  - rejected from European *Physics Letters*
    "of no obvious relevance to physics"
  - added a paragraph predicting a new particle

Spontaneous Symmetry Breaking

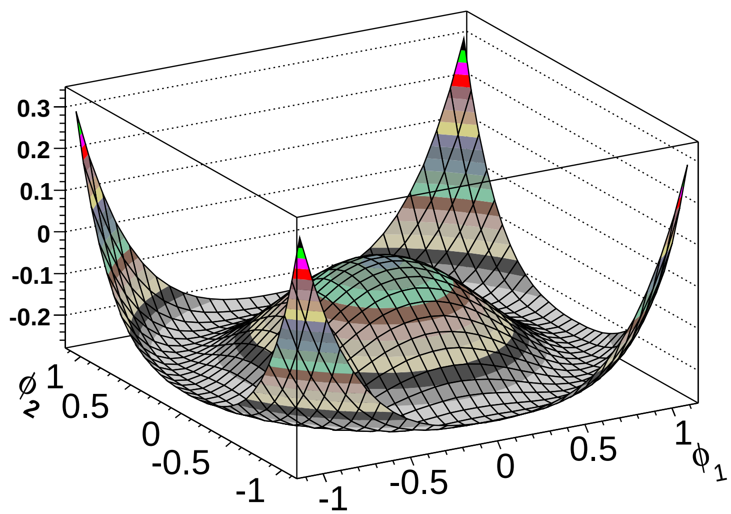
- Spontaneous symmetry breaking $\longrightarrow$ Higgs mechanism
- 3 quark families $\longrightarrow$ matter over antimatter asymmetry

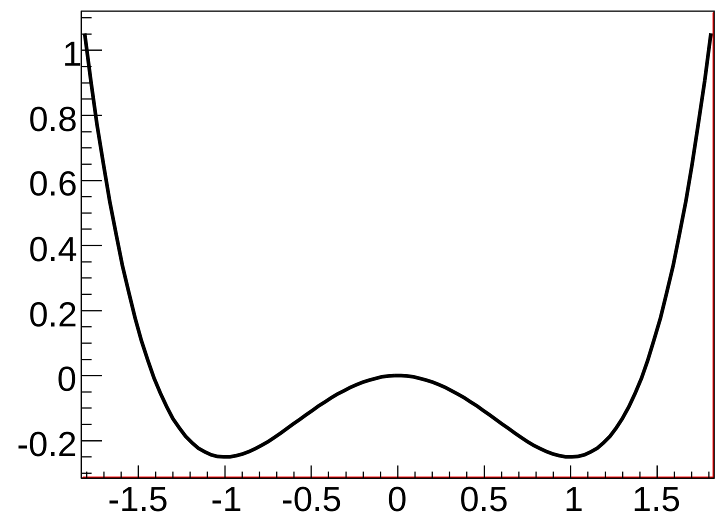


Spontaneous Symmetry Breaking

- Symmetry spontaneously broken: pick $\phi = v$ at minimum of potential energy of Higgs field ($\mu^2 < 0$)

$$V(\phi_1, \phi_2, \phi_3, \phi_4) = \frac{1}{2}\mu^2 \left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right] + \frac{1}{4}\lambda \left[\ldots\right]^2$$



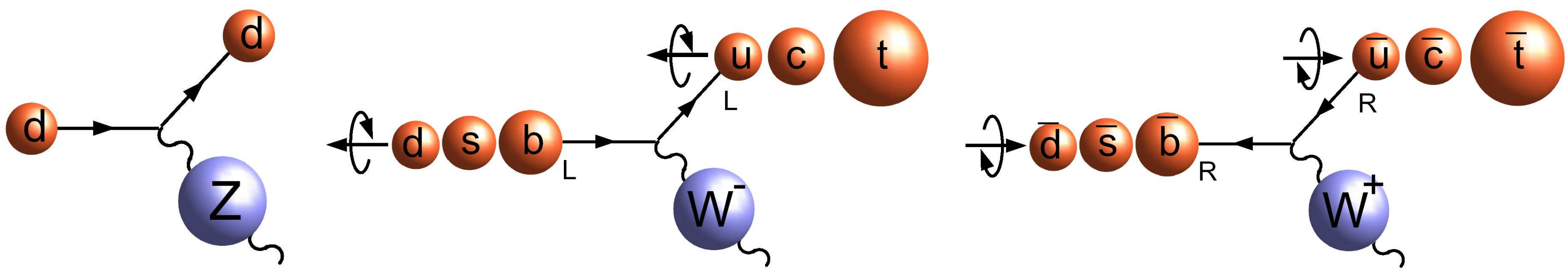


- Higgs particle described by one field component

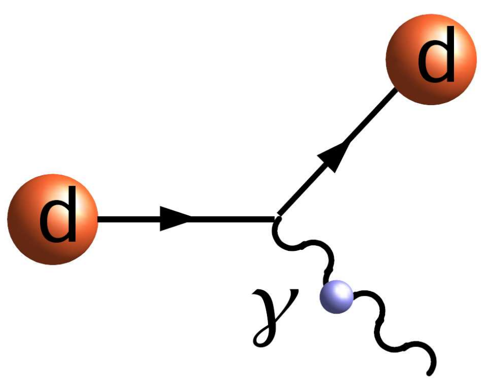
$$\eta = \phi_1 - v$$

What about other Higgs field components?

- The other field components ϕ_2, ϕ_3, ϕ_4 "couple"
  to Weak Interaction bosons $\boldsymbol{Z}$, $\boldsymbol{W}^-$, $\boldsymbol{W}^+$
  and give them mass



- Photon γ is the same Weak Interaction boson
  but remains massless (does not couple to Higgs field)



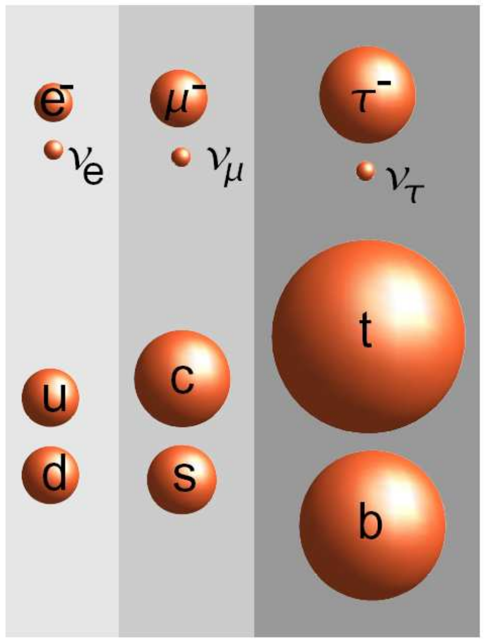
All Elementary Particles get Mass from Higgs Field

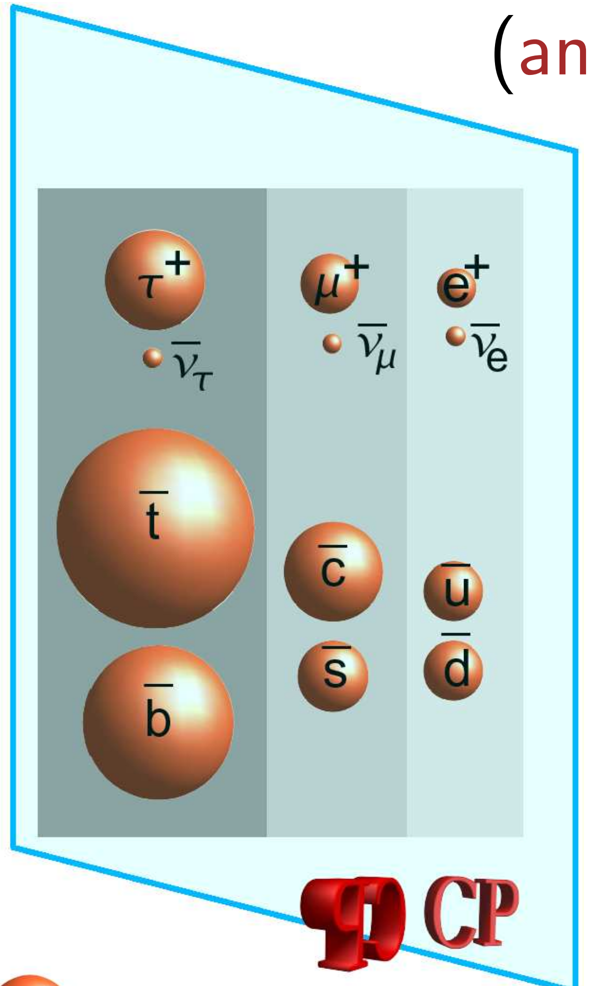
(anti-matter)

- Fermions $S = \frac{\hbar}{2}$ (matter)

leptons

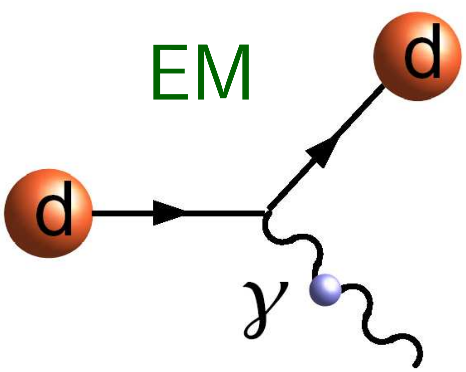
quarks



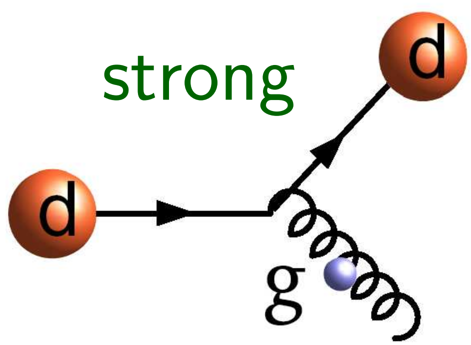


- Bosons $S = \hbar$ (force carries):

EM



strong

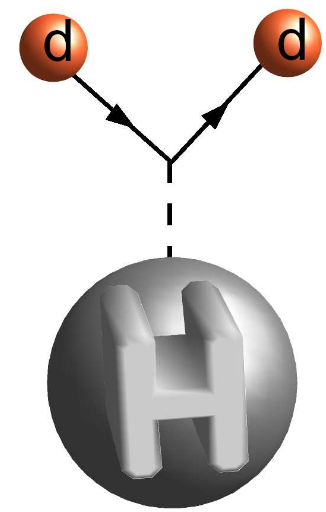


$\leftarrow$ massless

(weak force bosons mass)

What is Higgs?

- Higgs mechanism
  - existence of Higgs field
  - spontaneous symmetry breaking and "gauge" invariance (interaction with $Z, W^{\pm}$)
  - gives mass to all <u>elementary</u> particles
  - predicts existence of Higgs particle

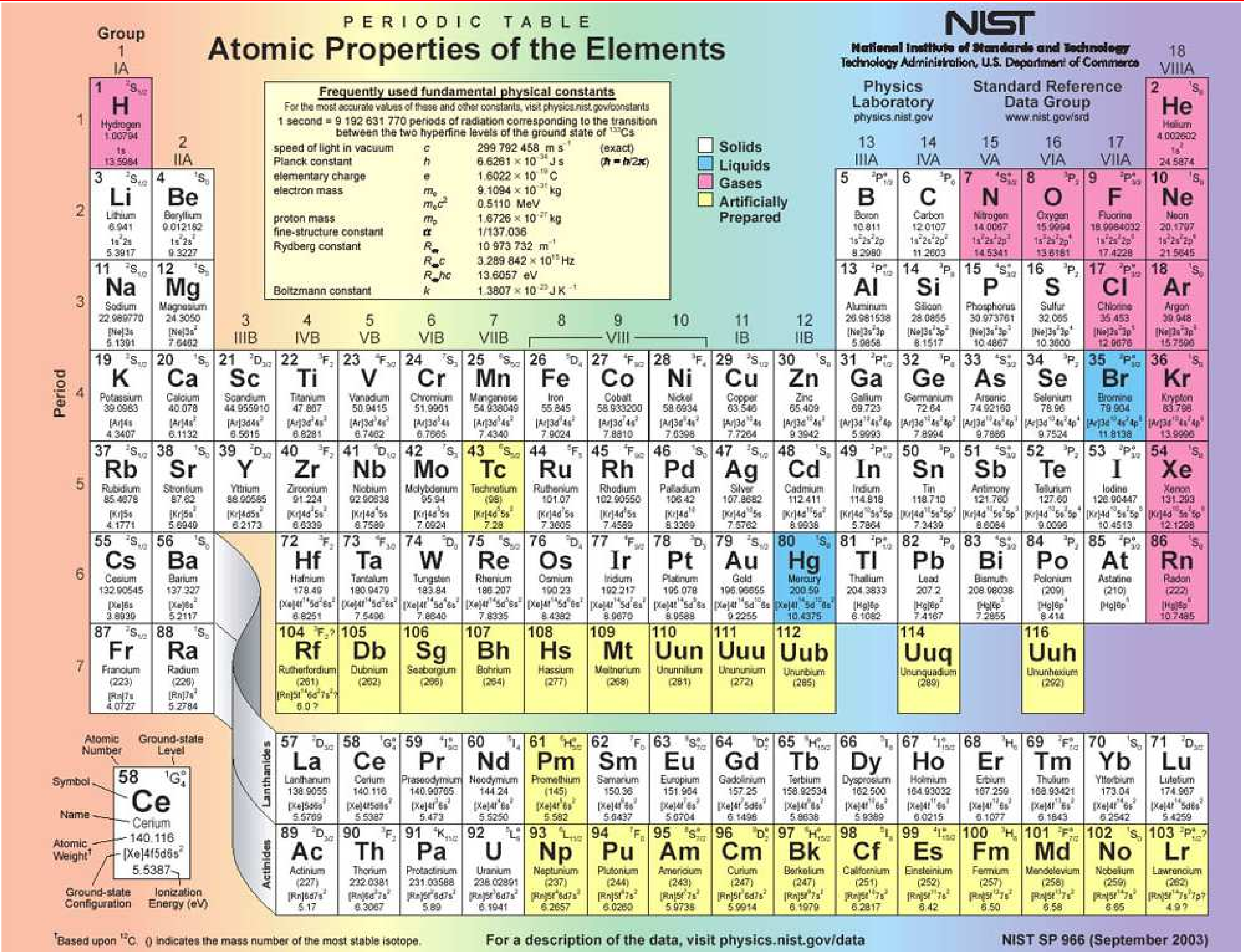


- Everything works perfectly, except:
  - we have not observed the Higgs particle yet
- Why: – Higgs particle is too heavy to produce (if it exists) (more than $100\times$ proton mass)
  - hope to produce or exclude at Large Hadron Collider
  - still possible that Higgs mechanism is not correct

Do we have mass due to Higgs mechanism?

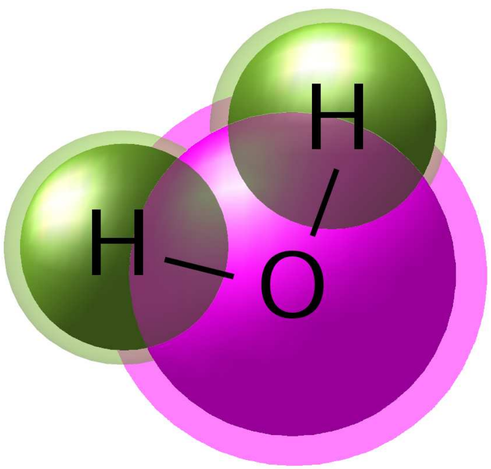
- Yes and no
  – we are not elementary particles...

What does give us mass? Molecules? Atoms?

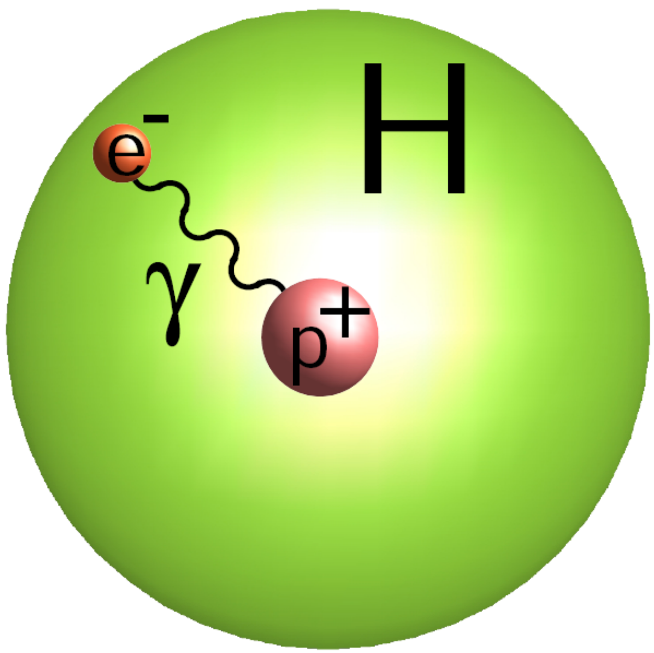


What does make mass?

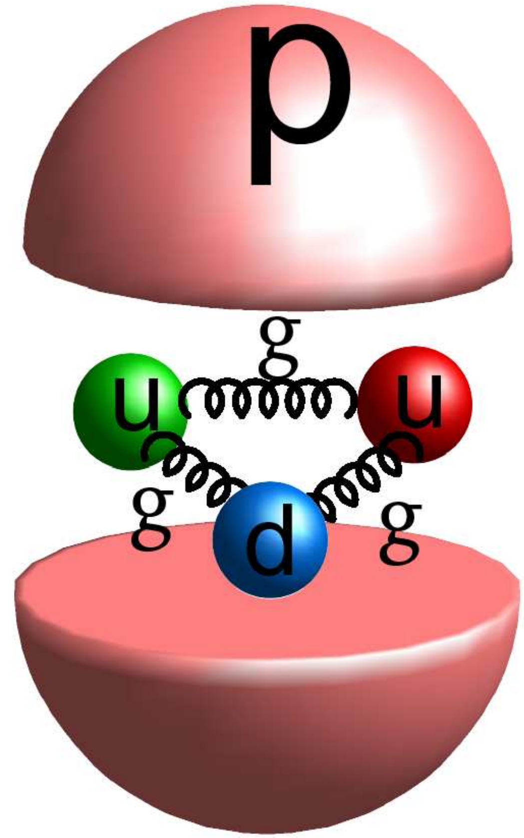
- What gives us mass?



Molecules



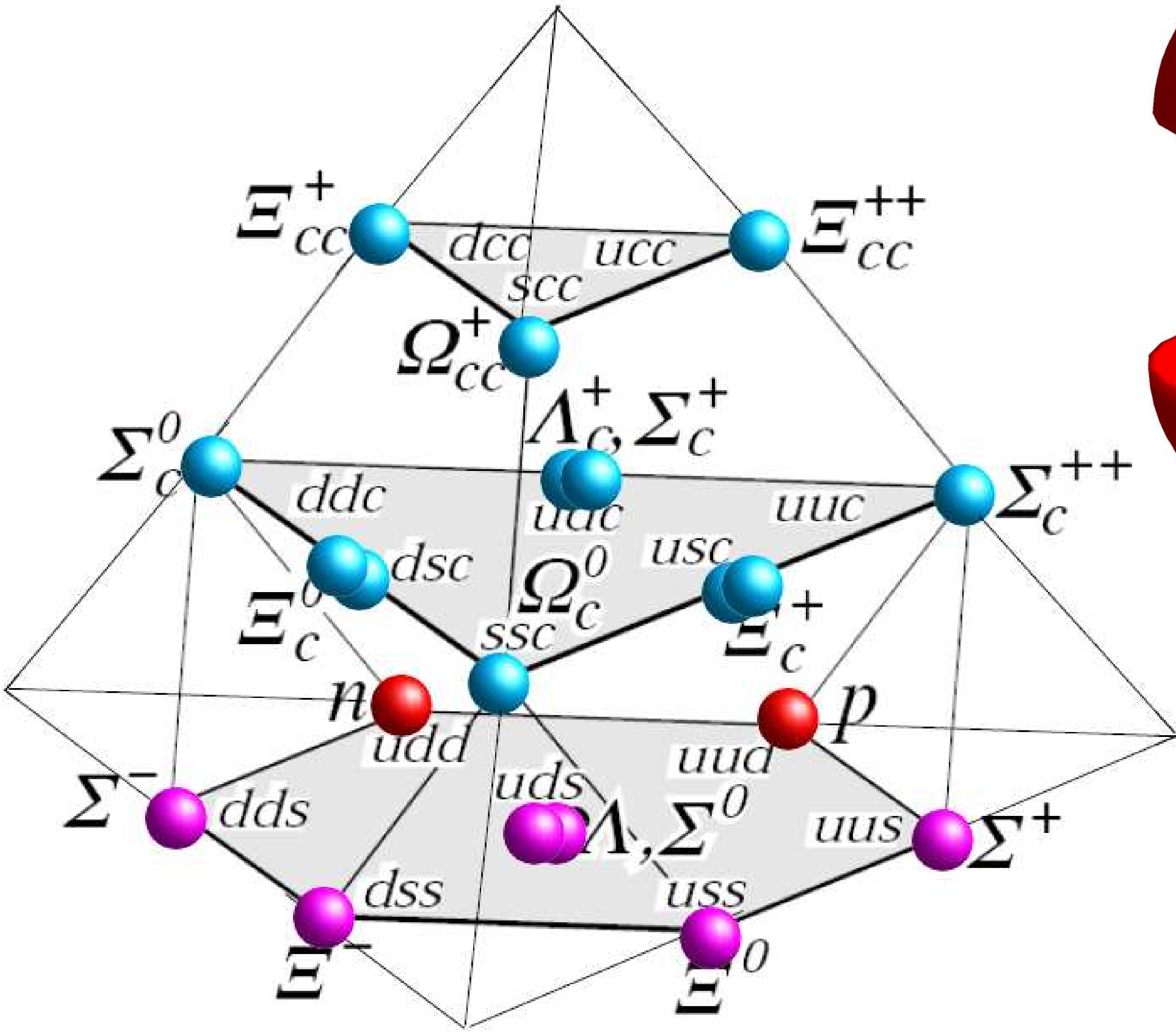
Atoms

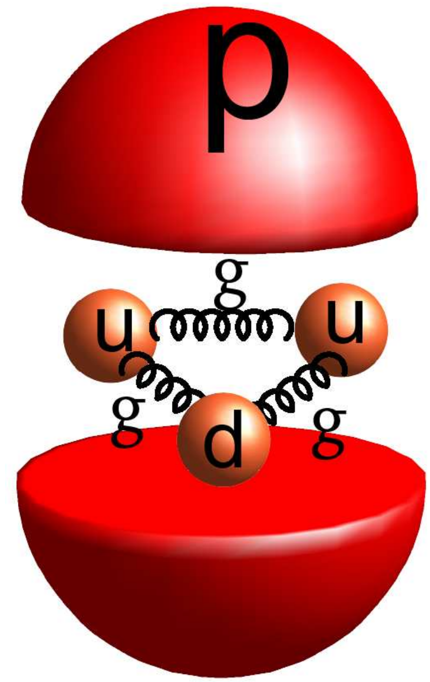


Nucleus

"Periodic Table" of Baryons: Proton, Neutron,...

- Three quarks make up a Baryon:





What Gives Mass to Baryons: Proton, Neutron,...

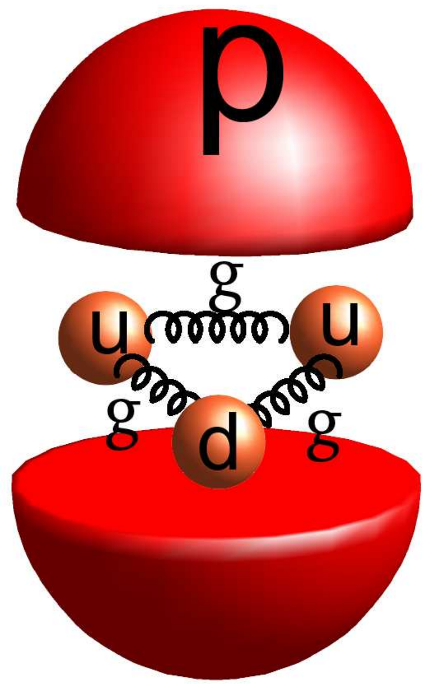
- Remember Einstein's formula

$$E = mc^2$$

m(u or d) $< 1\%$ m(proton)

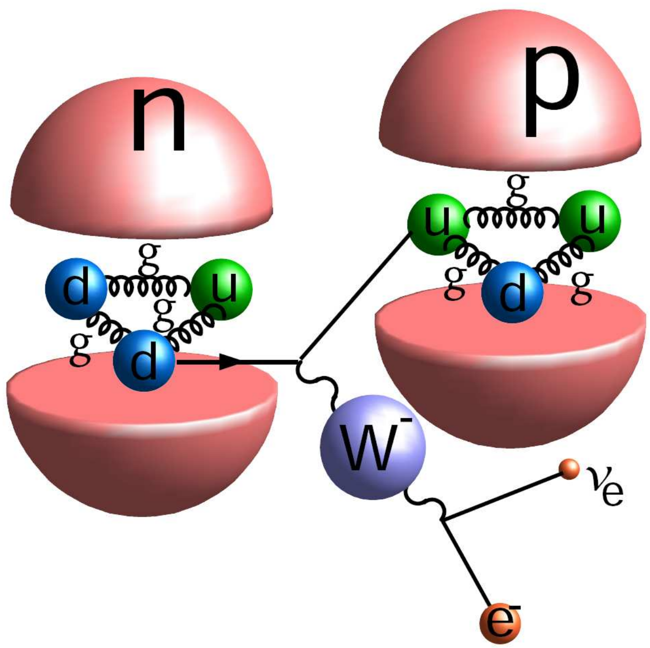
Mostly energy of gluons and quarks inside gives proton mass

not really the Higgs mechanism



But Higgs Mechanism is Very Important

- Makes Weak Interactions weak: mass of Z, W^-, W^+



similarly first step in sun fusion

$$p + p \rightarrow d + e^+ + \nu_e$$

- Makes certain hierarchy of masses

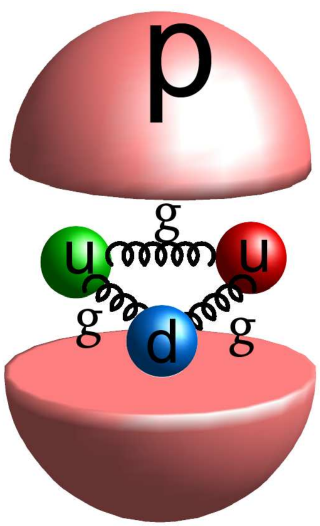
  essential for our existence

Hypothetical Scenario: Different Quark Mass

- Again, normally proton is stable and neutron decays:

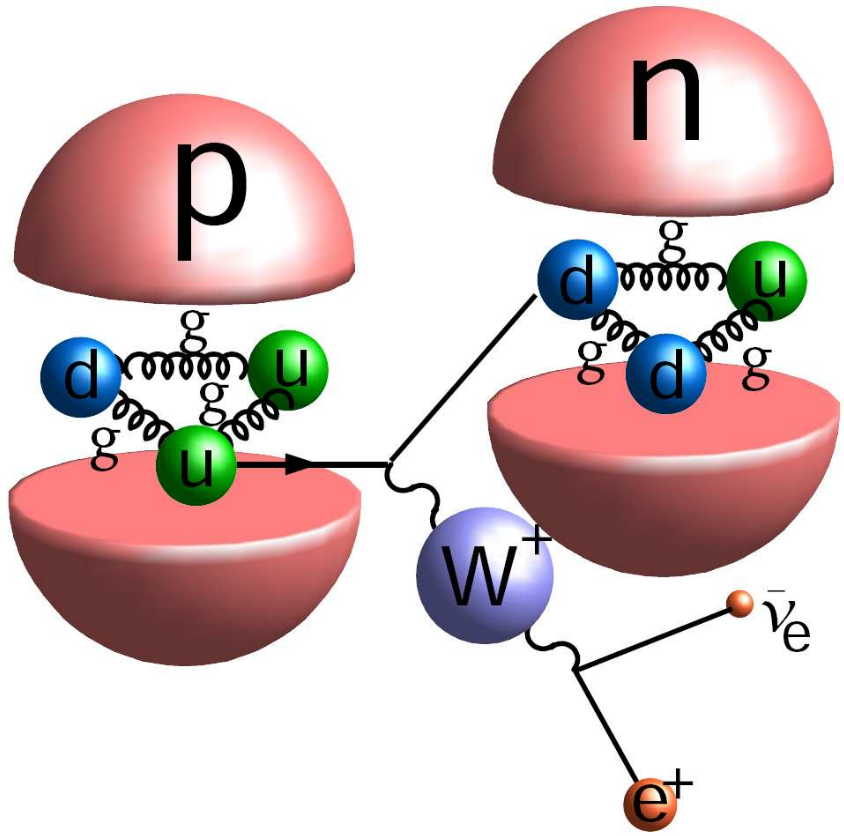
  $$\mathrm{m}(n) > \mathrm{m}(p) + \mathrm{m}(e) + \mathrm{m}(\nu_e)$$

- Why is $\mathrm{m}(n) > \mathrm{m}(p)$
  - $\mathrm{m}(p) = 938$ MeV, $\mathrm{m}(n)$ – $\mathrm{m}(p) = 1.3$ MeV
  - tiny difference makes a big difference!
  - naively expect $\mathrm{m}(p) > \mathrm{m}(n)$ if u and d were the same
  - but $\mathrm{m}(d) > \mathrm{m}(u)$
- New scenario:
  - what if $\mathrm{m}(d) < \mathrm{m}(u)$



Hypothetical Scenario: Different Quark Mass

- If m(d) $<$ m(u), proton decays:



- Consequence: no Hydrogen, no $H_2 0$, no life
  - still have He^4, rapid nn fusion, instead of slower pp

We are likely to find more than just Higgs

- New (super)symmetry:

$Q|\text{fermion}\rangle = |\text{boson}\rangle$

$Q|\text{boson}\rangle = |\text{fermion}\rangle$

- Solve:

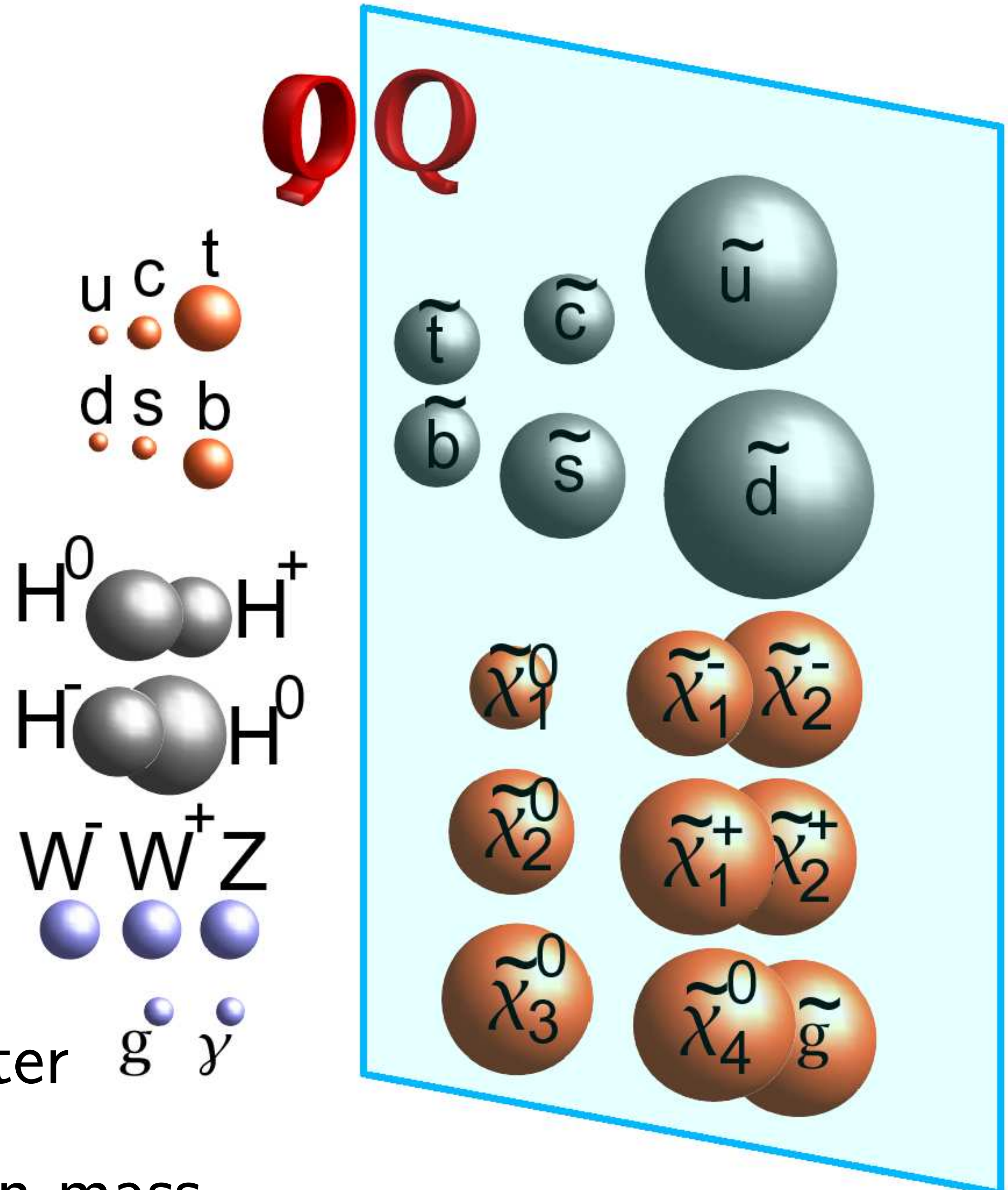
(1) natural light

Higgs

(2) dark matter

lightest $\tilde{\chi}_1^0$

(3) large matter/antimatter

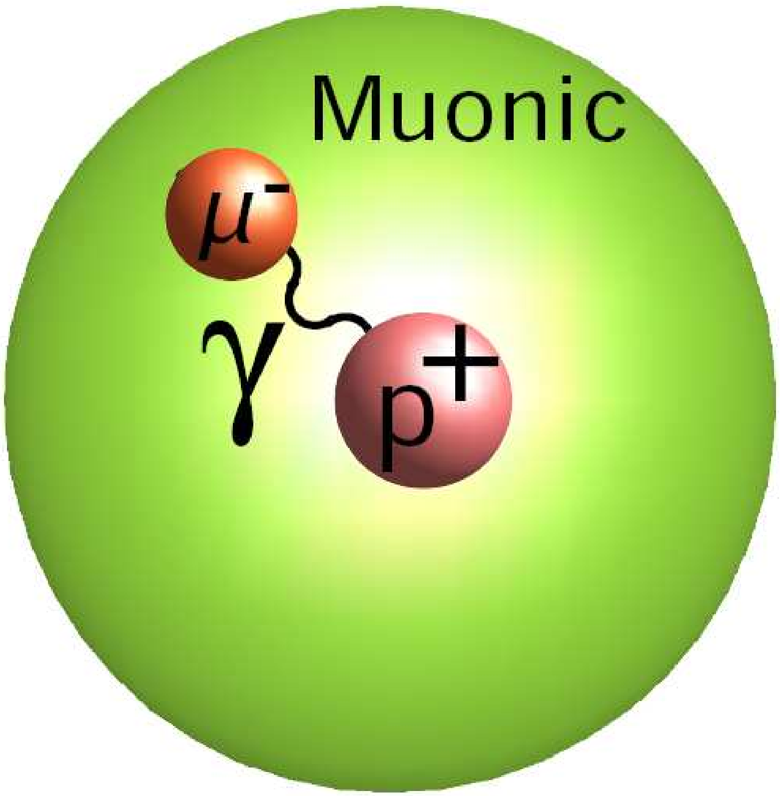


- Just around the corner in mass...

BACKUP SLIDES

(1) Another Scenario: Muonic World

- We would get a muonic atom:



- Size changes:

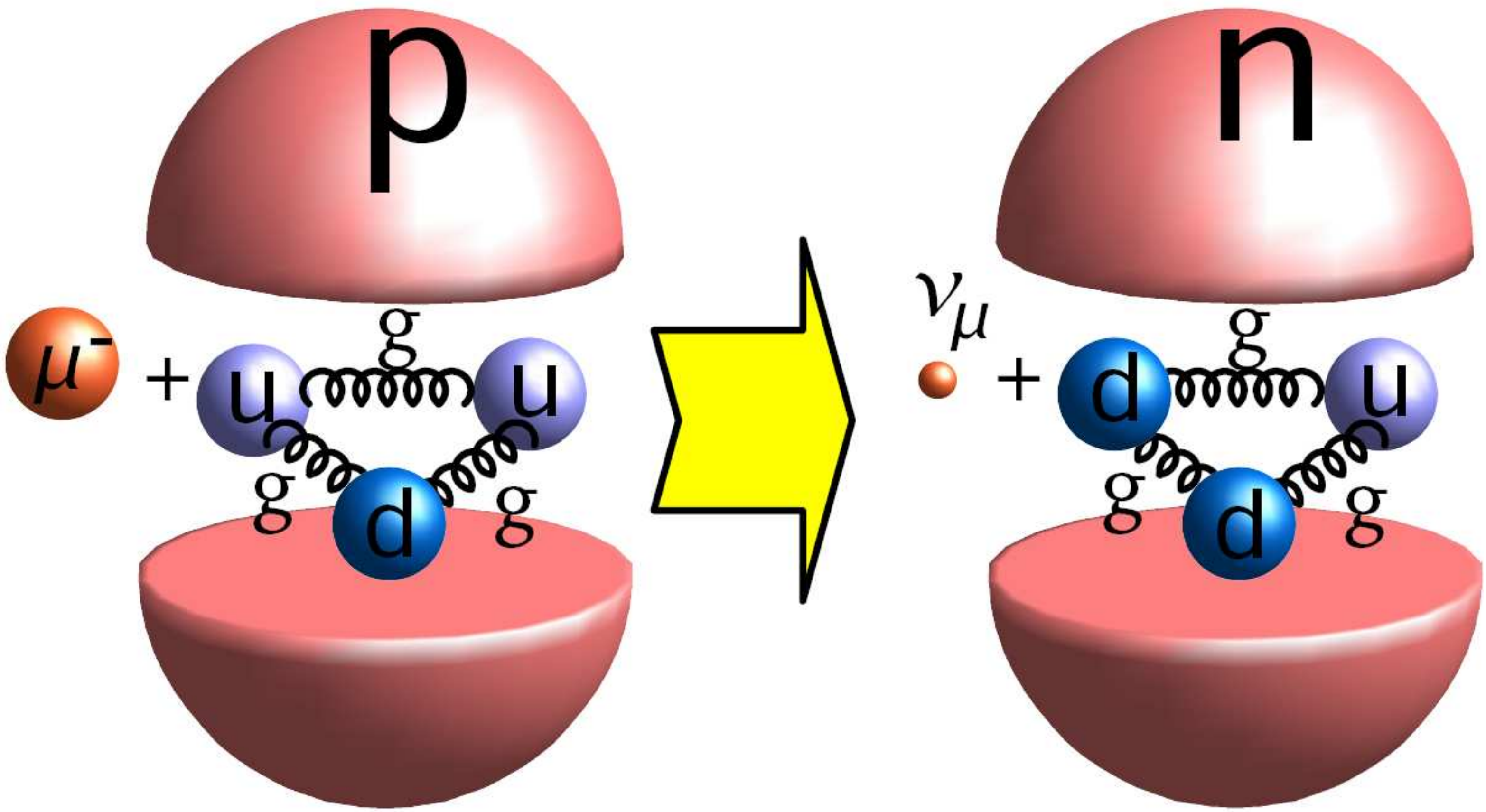
radius $r = \frac{4\pi\epsilon_0\hbar^2}{m_\mu e^2}$, 200 smaller !

Hydrogen radius

$r = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = 5 \times 10^{-11}$ m

(1) Scenario: Muonic World

- However muonic hydrogen would decay:

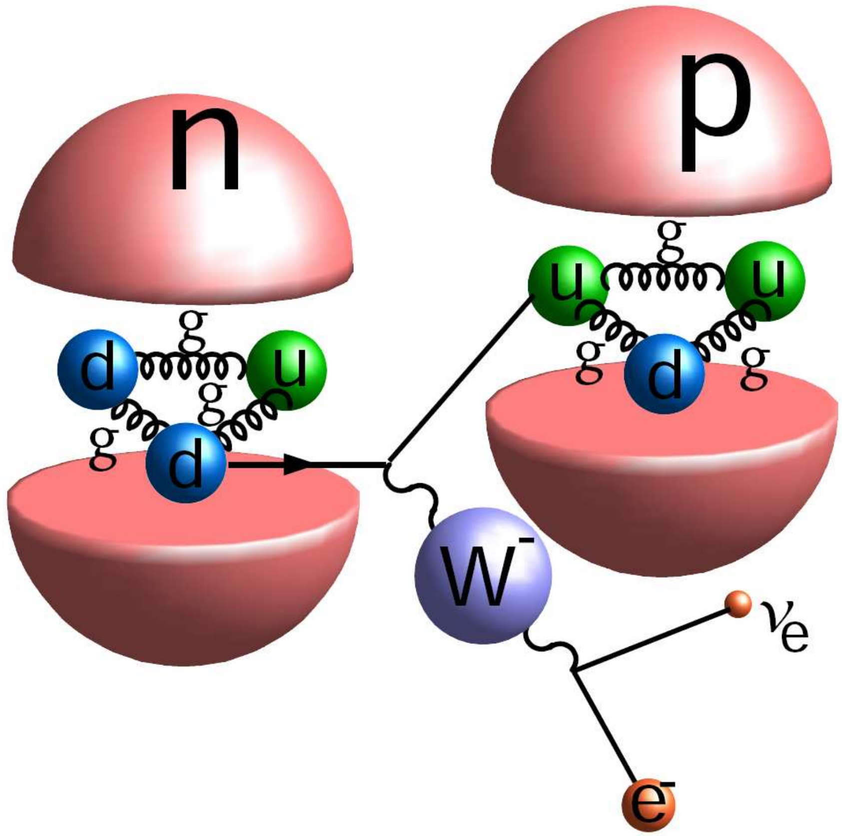


- Not very interesting universe
  – filled with neutral "balls" of neutrons and neutrinos

(1) Scenario: Muonic World

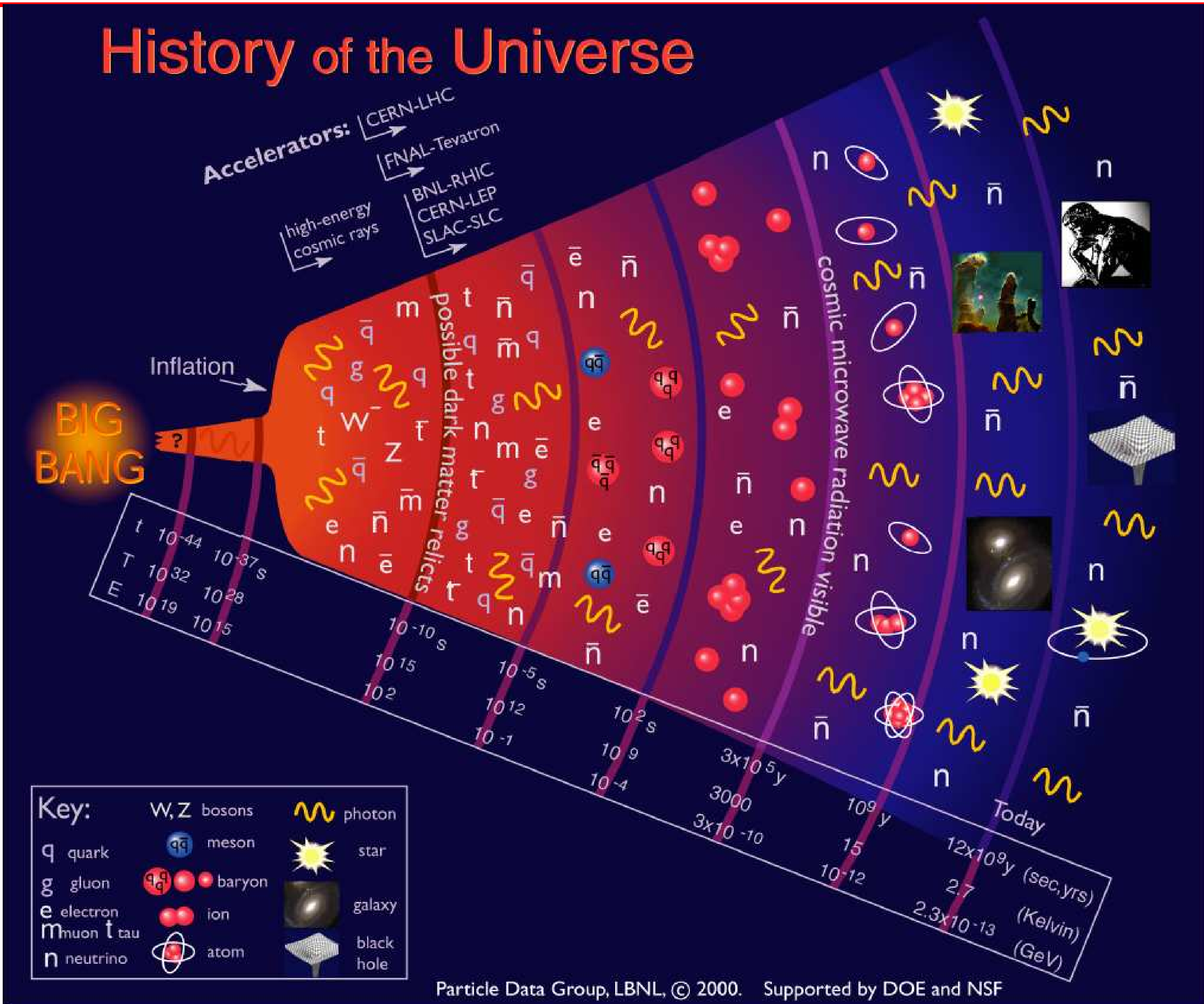
- Normally neutron is not stable (life $\tau \sim 886$ seconds)

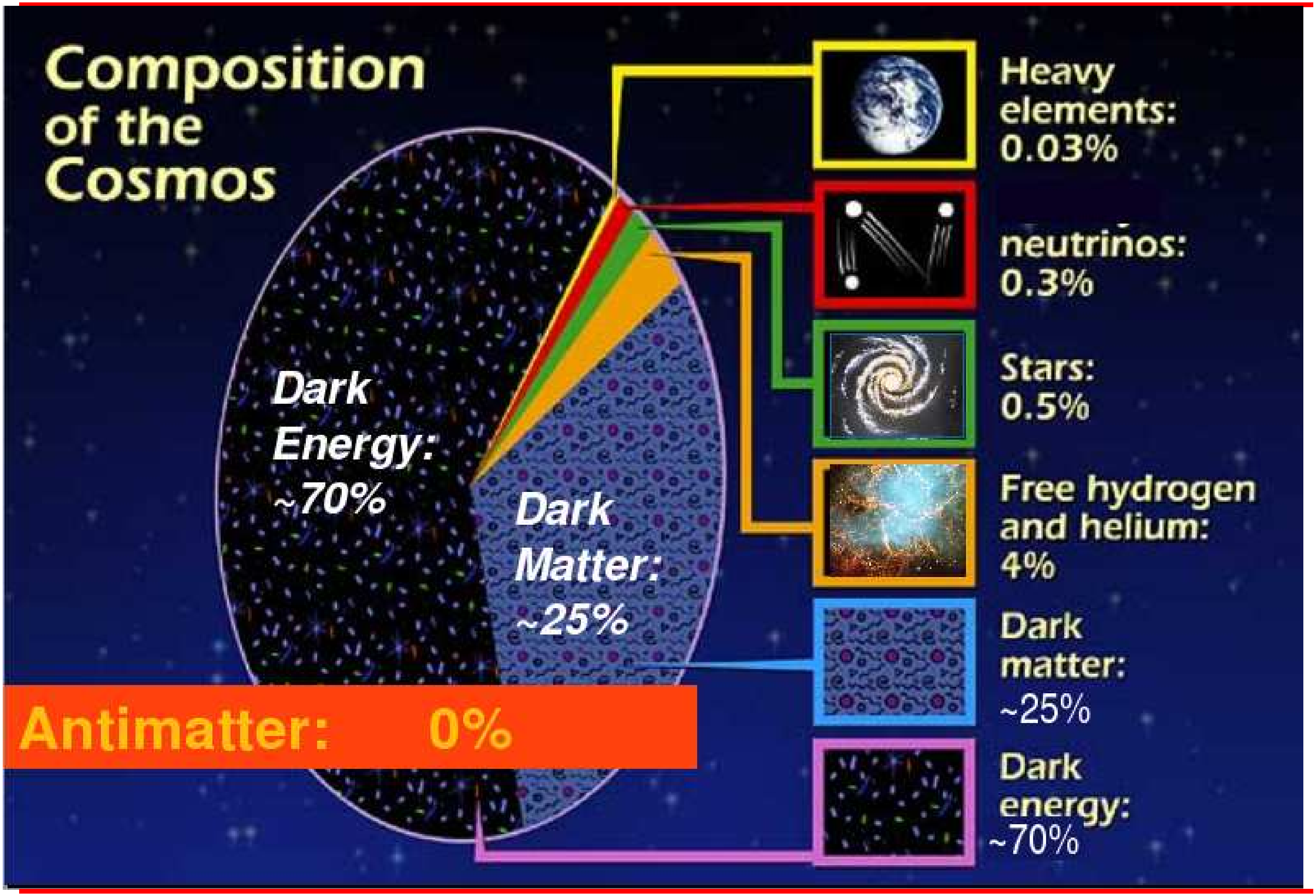
$$\mathrm{m}(n) > \mathrm{m}(p) + \mathrm{m}(e) + \mathrm{m}(\nu_e)$$



- But stable in the muonic world:

$$\mathrm{m}(n) < \mathrm{m}(p) + \mathrm{m}(\mu) + \mathrm{m}(\nu_\mu)$$


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


Composition of the Cosmos
Dark Energy: ~70%
Dark Matter: ~25%
Heavy elements: 0.03%
neutrinos: 0.3%
Stars: 0.5%
Free hydrogen and helium: 4%
Dark matter: ~25%
Dark energy: ~70%
Antimatter: 0%

Look Beyond the Standard Model

- Why does matter dominate (Sakharov):
  - CP-asymmetry
  - baryon non-conservation
  - non-equilibrium
- Mysterious Higgs field
  - gives mass to particles
- Need something beyond the SM
  - large CP-asymmetry
  - dark matter
  - light Higgs