Introduction to Particle Physics

Seyong Kim

Sejong University

Outline

Higgs has been found! (Aug. 12, 2012)

July 4th, 2012

[神의 입자 '힉스' 존재 확인] "힉스 없다"에 100달러 건 호킹(英 천재 물리학자)이 틀렸다 - 1등 인터넷뉴스 조선닷컴

http://news.chosun.com/site/data/html_dir/2012/07/05/2012070500082.html

chosun.com 사회

뜨거운 열정과 함성! 세계인의 스포츠 축제! 2012 LONDON

한국 금메달 검색

뉴스 오피니언 경제 스포츠 연예 라이프

사회 종합

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이영완 기자

전원주택의 꿈 '나는 이렇게 이루었다'

기사 100자평(11) 인포그래픽스

입력 : 2012.07.05 03:09

故이휘소 박사가 40년 전 첫 명명… 힉스 교수, 노벨상 유력
우주생성 비밀 밝혀 줄 새로운 입자 17년만에 발견… 일부선 "힉스입자 단정 일러"

우주 만물을 탄생시킨 '신(神)의 입자(粒子)' 힉스(Higgs)가 발견됐다. 유럽입자물리연구소(CERN)는 4일 스위스 제네바에서 "물질을 이루는 기본 입자 중 가장 핵심적인 힉스와 일치하는 입자를 발견했다"고 발표했다. 인류가 새로운 입자를 발견한 것은 1995년 이후 처음이다. CERN 연구에 참여한 박인규 서울시립대 교수는 "전자가 발견되면서 오늘날의 IT(정보통신) 시대가 가능해진 것처럼 새로운 입자 발견은 늘 새로운 문명을 가져왔다"며 "힉스 발견이 앞으로 어떤 결과를 가져올지 기대된다"고 말했다.

힉스는 우주탄생을 설명하는 입자물리학 '표준모형(standard model)'의 모순을 해결하기 위해 추가된 입자다. 표준모형에 따르면 우주에는 12개 기본 입자와, 이들 사이에 힘을 전달하는 4개 매개입자가 있다. 137억년 전 우주 대폭발(빅뱅) 직후 탄생한 기본 입자에는 질량이 없었다. 하지만 기본 입자들로 구성된 물질에는 질량이 존재한다.

CERN 거대강입자가속기(LHC)의 힉스 검출 개념도
LHC-스위스와 프랑스 국경 지대 지하 100m에 둘레 27㎞ 규모.
검출기-아틀라스, CMS 등 4개
CMS

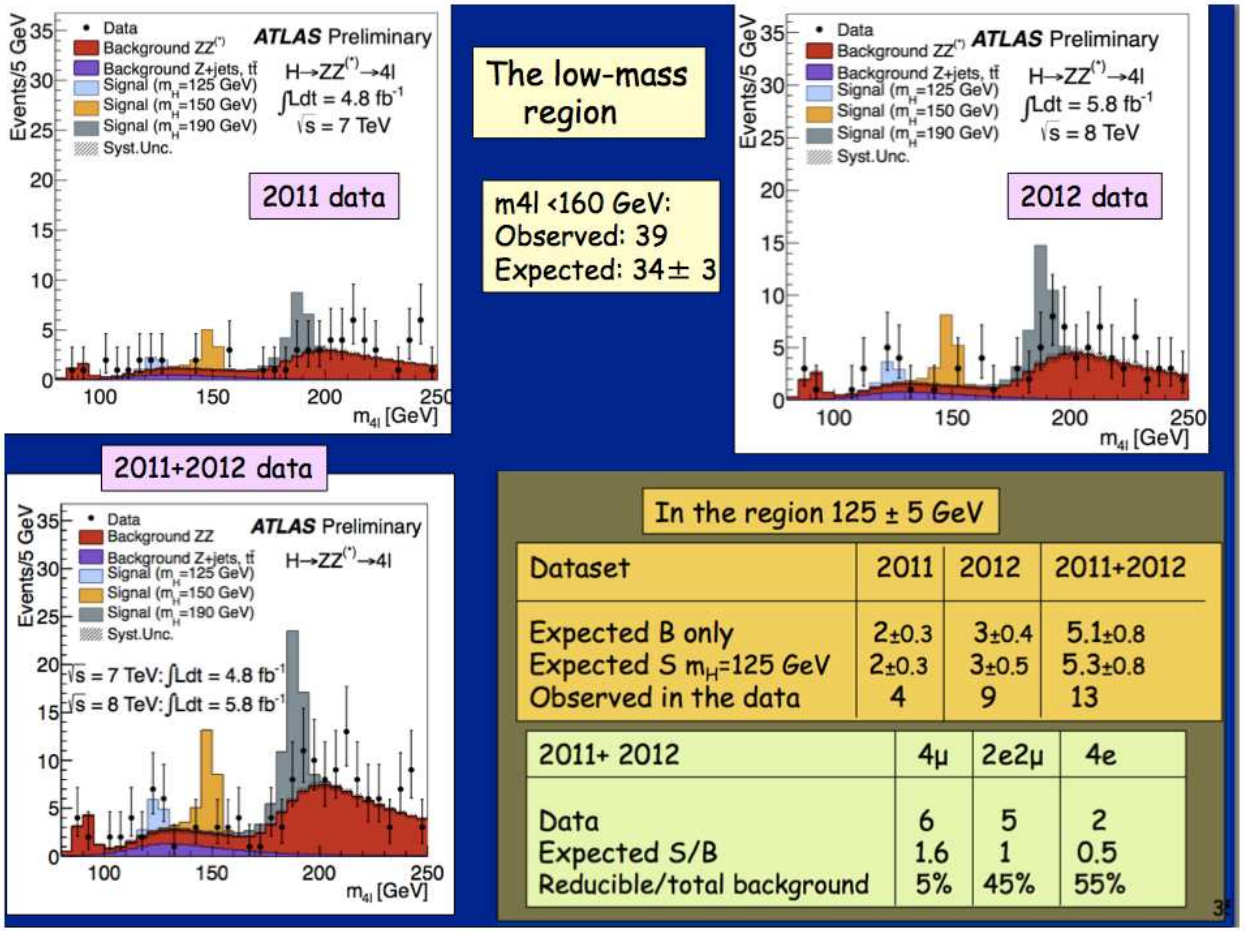
스페셜링크

화제집중
계그맨 김원효 970만원으로 바닷가 별장을!
동해바다 호텔식 별장 더 블루힐 보증금 970만원으로 마련

'뉴스ON' 앱을 만나보세요.
친구들과 기사를 쉽게 공유하고 스크랩 할 수는 없을까? '조선닷컴 뉴스ON' 지금 만나보세요!

July 4th, 2012

ATLAS collaboration presentation



Dataset	2011	2012	2011+2012
Expected B only	2±0.3	3±0.4	5.1±0.8
Expected S m_H=125 GeV	2±0.3	3±0.5	5.3±0.8
Observed in the data	4	9	13

2011+ 2012	4μ	2e2μ	4e
Data	6	5	2
Expected S/B	1.6	1	0.5
Reducible/total background	5%	45%	55%

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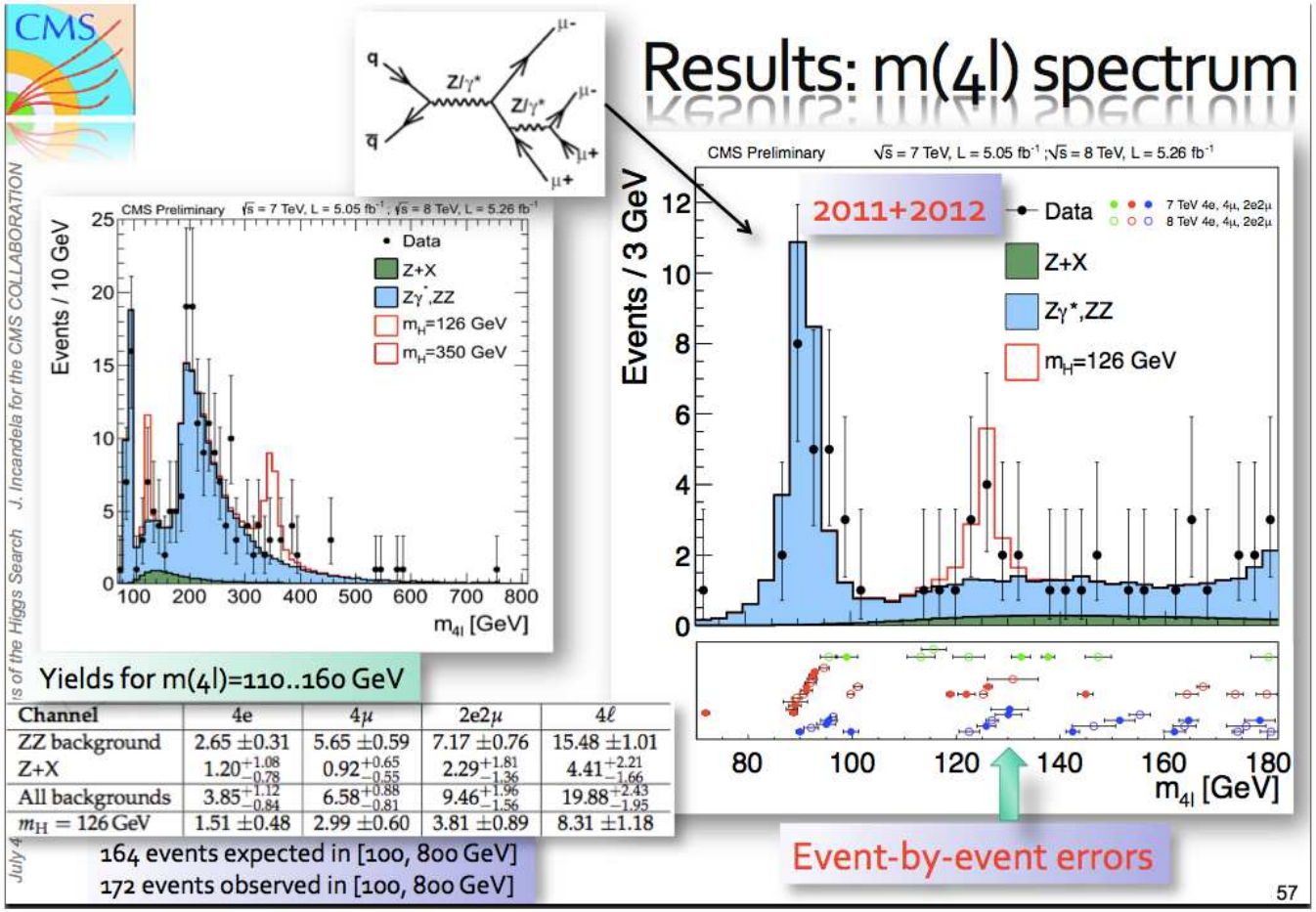

Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ± 0.31	5.65 ± 0.59	7.17 ± 0.76	15.48 ± 1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV	1.51 ± 0.48	2.99 ± 0.60	3.81 ± 0.89	8.31 ± 1.18

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Particle physics is a branch of physics that studies the existence and interactions of particles that are the constituents of what is usually referred to as matter or radiation.

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Particle physics is a branch of physics that studies the existence and interactions of particles that are the constituents of what is usually referred to as matter or radiation.

In current understanding, particles are excitations of quantum fields and interact following their dynamics.

Most of the interest in this area is in fundamental fields, each of which cannot be described as a bound state of other fields. The current set of fundamental fields and their dynamics are summarized in a theory called the Standard Model, therefore particle physics is largely the study of the Standard Model's particle content and its possible extensions.

What is particle physics?

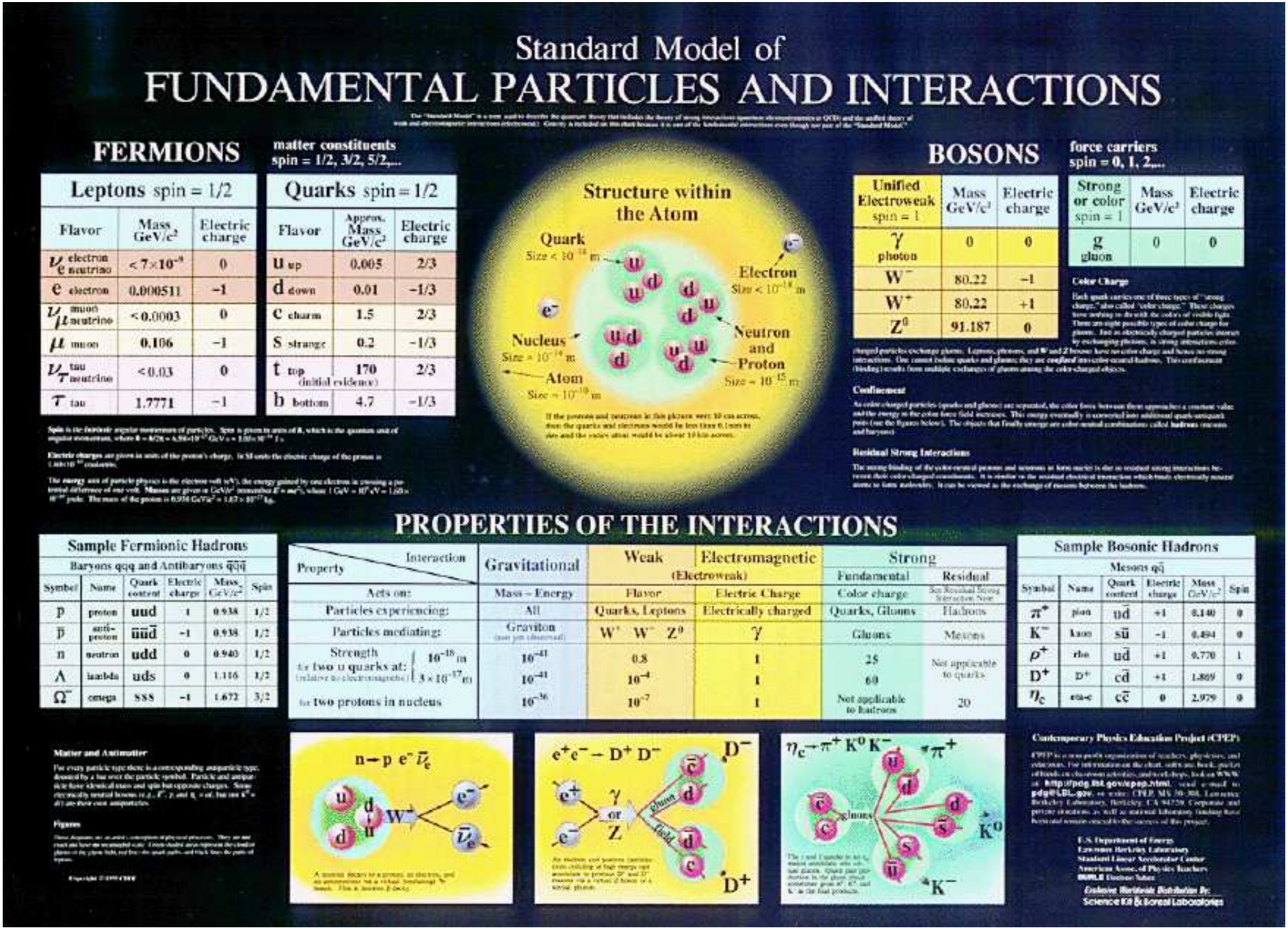
- small distance $\rightarrow$ quantum physics
- uncertainty principle

$$\Delta x \, \Delta p \geq \hbar \tag{1}$$

- special relativity $\rightarrow$ pair creation is possible

$$\Delta E \, \Delta t \geq \hbar \tag{2}$$

- based on quantum field theory
- we only “know” probabilities and probability amplitudes


Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2,...
Leptons spin = 1/2
Flavor | Mass GeV/c² | Electric charge
ν_e electron neutrino | < 7×10⁻⁹ | 0
e electron | 0.000511 | −1
ν_μ muon neutrino | < 0.0003 | 0
μ muon | 0.106 | −1
ν_τ tau neutrino | < 0.03 | 0
τ tau | 1.7771 | −1
Quarks spin = 1/2
Flavor | Approx. Mass GeV/c² | Electric charge
u up | 0.005 | 2/3
d down | 0.01 | −1/3
c charm | 1.5 | 2/3
s strange | 0.2 | −1/3
t top (initial evidence) | 170 | 2/3
b bottom | 4.7 | −1/3
Structure within the Atom
Quark
Size < 10⁻¹⁸ m
Electron
Size < 10⁻¹⁸ m
Nucleus
Size ≈ 10⁻¹⁴ m
Neutron and Proton
Size ≈ 10⁻¹⁵ m
Atom
Size ≈ 10⁻¹⁰ m
BOSONS
force carriers
spin = 0, 1, 2,...
Unified Electroweak spin = 1 | Mass GeV/c² | Electric charge
γ photon | 0 | 0
W⁻ | 80.22 | −1
W⁺ | 80.22 | +1
Z⁰ | 91.187 | 0
Strong or color spin = 1 | Mass GeV/c² | Electric charge
g gluon | 0 | 0
Color Charge
Confinement
Residual Strong Interactions
PROPERTIES OF THE INTERACTIONS
Sample Fermionic Hadrons
Baryons qqq and Antibaryons q̄q̄q̄
Symbol | Name | Quark content | Electric charge | Mass GeV/c² | Spin
p | proton | uud | 1 | 0.938 | 1/2
p̄ | anti-proton | ūūd̄ | −1 | 0.938 | 1/2
n | neutron | udd | 0 | 0.940 | 1/2
Λ | lambda | uds | 0 | 1.116 | 1/2
Ω⁻ | omega | sss | −1 | 1.672 | 3/2
Property | Interaction | Gravitational | Weak (Electroweak) | Electromagnetic (Electroweak) | Strong: Fundamental | Strong: Residual
Acts on: | Mass – Energy | Flavor | Electric Charge | Color charge | See Residual Strong Interaction Note
Particles experiencing: | All | Quarks, Leptons | Electrically charged | Quarks, Gluons | Hadrons
Particles mediating: | Graviton (not yet observed) | W⁺ W⁻ Z⁰ | γ | Gluons | Mesons
Strength for two u quarks at: (relative to electromagnetic) 10⁻¹⁸ m | 10⁻⁴¹ | 0.8 | 1 | 25 | Not applicable to quarks
3×10⁻¹⁷ m | 10⁻⁴¹ | 10⁻⁴ | 1 | 60
for two protons in nucleus | 10⁻³⁶ | 10⁻⁷ | 1 | Not applicable to hadrons | 20
Sample Bosonic Hadrons
Mesons qq̄
Symbol | Name | Quark content | Electric charge | Mass GeV/c² | Spin
π⁺ | pion | ud̄ | +1 | 0.140 | 0
K⁻ | kaon | sū | −1 | 0.494 | 0
ρ⁺ | rho | ud̄ | +1 | 0.770 | 1
D⁺ | D⁺ | cd̄ | +1 | 1.869 | 0
η_c | eta-c | cc̄ | 0 | 2.979 | 0
Matter and Antimatter
Figures
n → p e⁻ ν̄_e
e⁺e⁻ → D⁺ D⁻
η_c → π⁺ K⁰ K⁻
Contemporary Physics Education Project (CPEP)
U.S. Department of Energy
Lawrence Berkeley Laboratory
Stanford Linear Accelerator Center
American Assoc. of Physics Teachers
BUBLE Design Team
Exclusive Worldwide Distribution By:
Science Kit & Boreal Laboratories

probabilities and probability amplitudes

experimental particle physicists measure probabilities

theoretical particle physicists calculate probabilities (when they can)

probabilities and probability amplitudes

So, how do you “measure” probabilities?

probabilities and probability amplitudes

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an example of dice:
instead of an actual dice, imagine a blackbox which announces a number

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(2) write down the number each time the box announces a number

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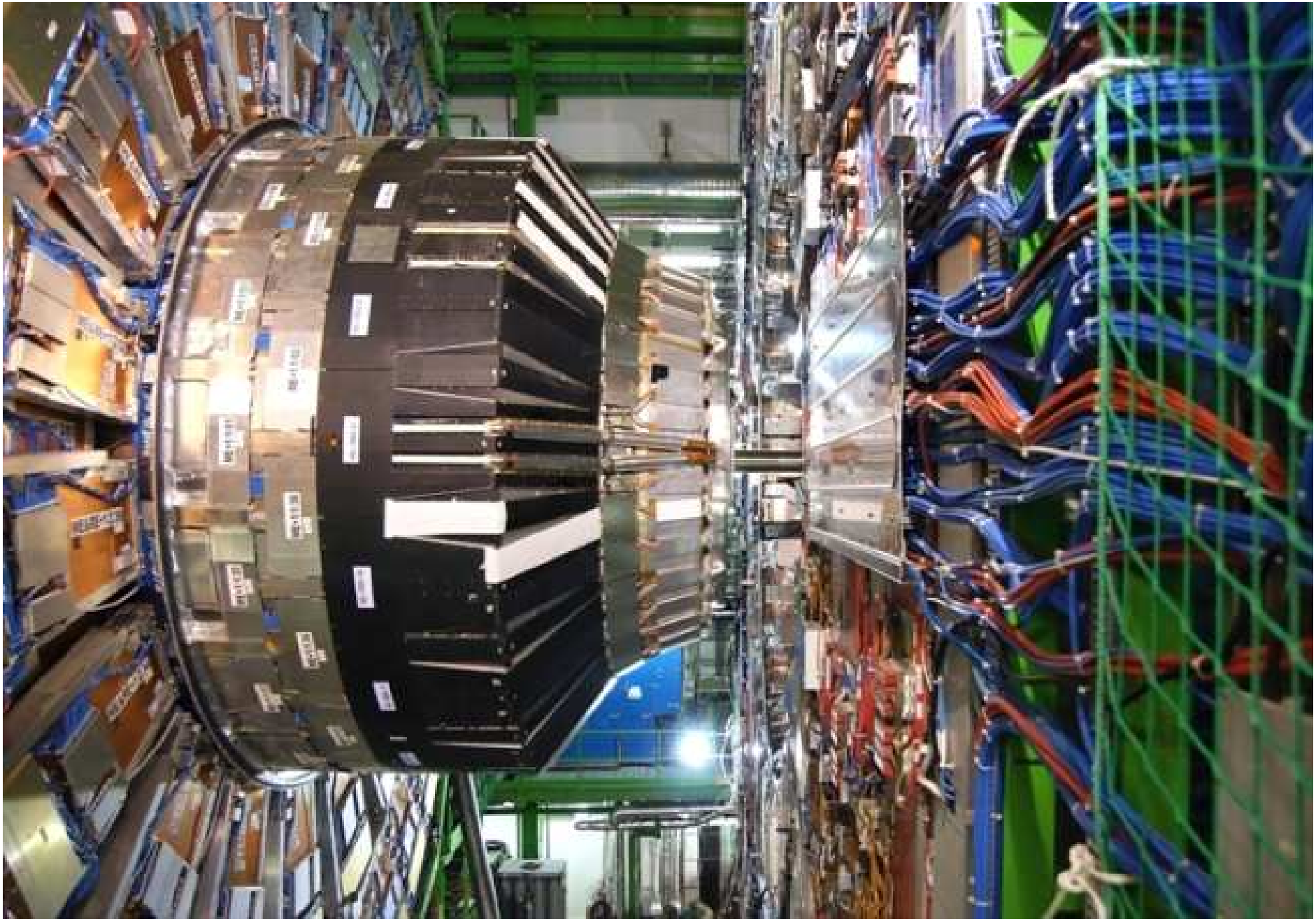
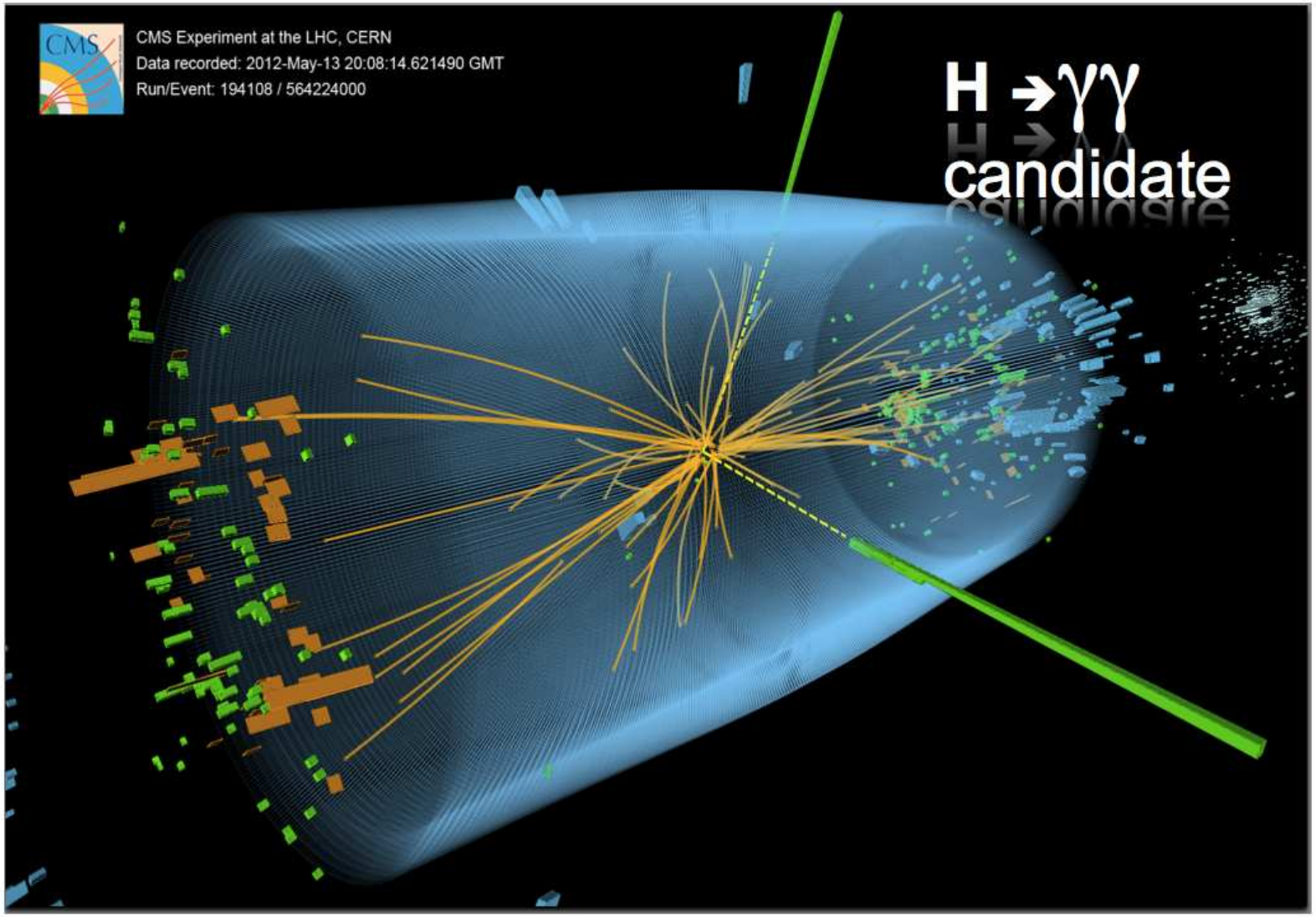
(1) prepare a notebook
(2) write down the number each time the box announces a number
(3) after n-th try, count how many times each number occurred

- rare events

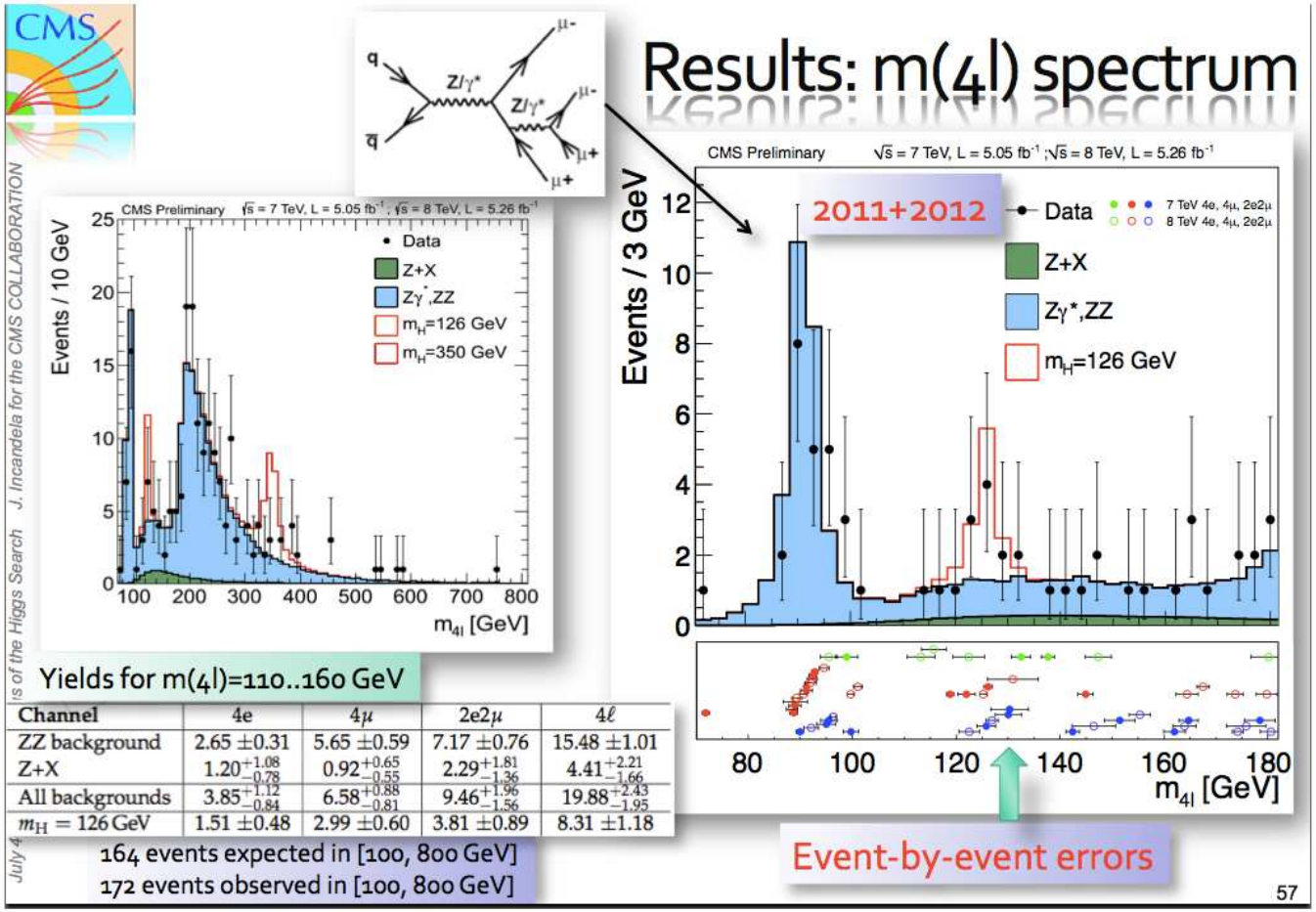
  $\rightarrow$ small probabilities

  $\rightarrow$ need to try more




CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → γγ
candidate

CMS collaboration presentation



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Not so easy!

- missing
- mis-identification
- background
- systematic errors and statistical errors
- $\cdots$ many more worries

probabilities and probability amplitudes

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probabilities and probability amplitudes

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(1) construct a lagrangian

probabilities and probability amplitudes

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(4) sum the probability amplitudes and calculate the probability

when they can

- So, lagrangian is important
- “when they can” means when they know what the lagrangian is.
- Most of time, lagrangian is not known or there are rival theories

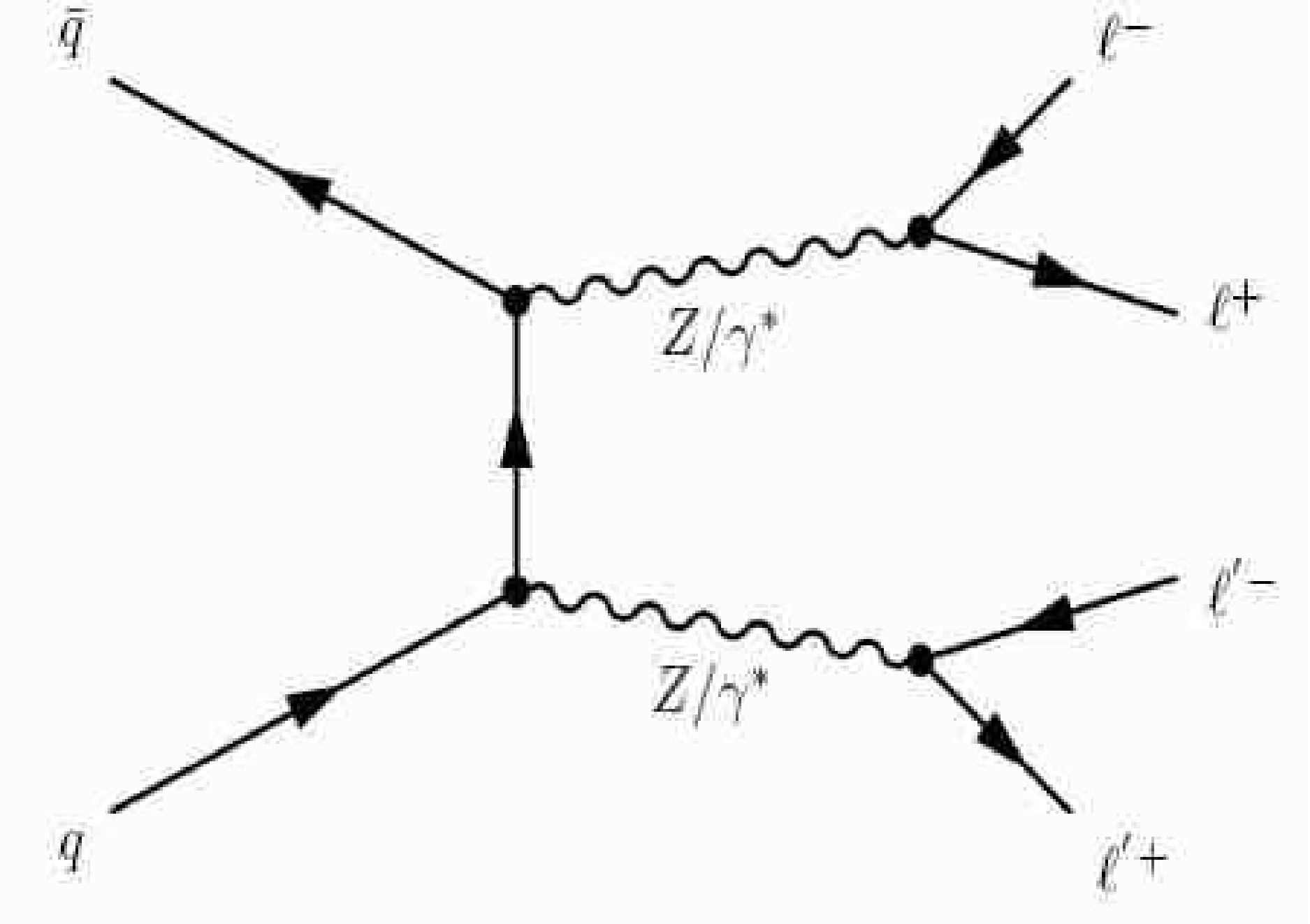
$$\mathcal{L}_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_f \overline{\psi}_f(i\not{D} - m_f)\psi_f \tag{3}$$

where

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \tag{4}$$

and

$$\not{D} = \gamma_\mu(\partial_\mu - iQ_f A_\mu) \tag{5}$$


$\bar{q}$
ℓ^-
Z/γ^*
ℓ^+
ℓ'^-
Z/γ^*
q
ℓ'^+

lagrangian and symmetry

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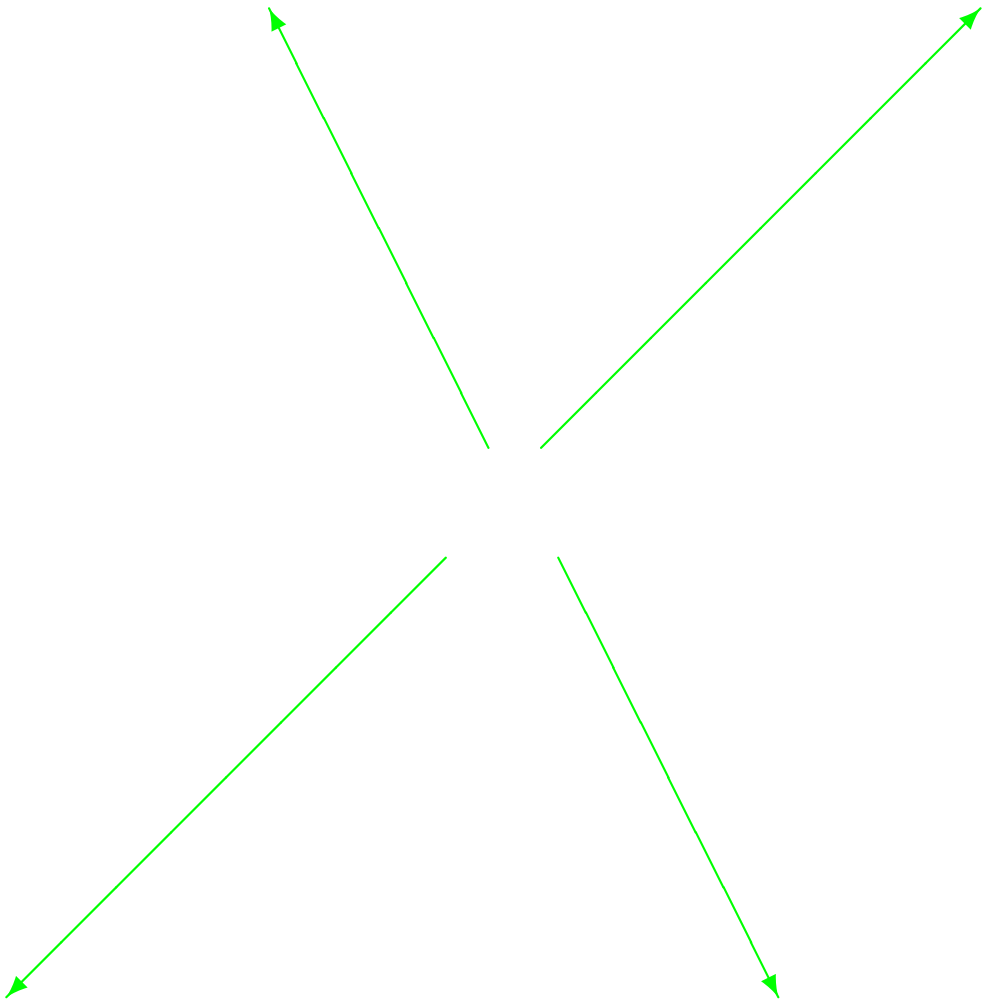

lagrangian and symmetry

Newton's law:

$$\vec{F} = m\frac{d^2\vec{x}}{dt^2} \tag{3}$$

Hamilton's principle: dynamics of a physical system is determined by variational problem for a functional based on a single function, lagrangian.

$$S = \int_{t_i}^{t_f} dt\ \mathcal{L}(q, \dot{q} = \frac{dq}{dt}) \tag{4}$$

$\rightarrow$ Euler-Lagrange equation:

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{q}}\right) - \frac{\partial \mathcal{L}}{\partial q} = 0 \tag{5}$$

lagrangian and symmetry

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{q}}\right) - \frac{\partial \mathcal{L}}{\partial q} = 0 \tag{3}$$

- a given system is symmetric

  $\rightarrow$ $\mathcal{L}$ is independent of symmetry transform

  $\rightarrow$ $\frac{\partial \mathcal{L}}{\partial q} = 0$

  $\rightarrow$ $\frac{\partial \mathcal{L}}{\partial \dot{q}}$ is independent of time.

continuous symmetry and Noether theorem

If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.

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$\rightarrow$ angular momentum is converved

4-dimensional space-time symmetry (Poincare symmetry) is underlying symmetry

time-translation, space-rotation, Lorentz boost

gauge symmetry

In electromagnetism, electric charge is conserved

Maxwell's equations

$$\vec{\nabla}\cdot\vec{E} = \frac{1}{\varepsilon_0}\rho, \quad \vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t} \tag{4}$$

$$\vec{\nabla}\cdot\vec{B} = 0, \quad \vec{\nabla}\cdot\vec{B} = \mu_0\vec{J} + \mu_0\varepsilon_0\frac{\partial\vec{E}}{\partial t} \tag{5}$$

$$\tag{6}$$

can be formulated in terms of electric potential Φ and vector potential $\vec{A}$

$$\begin{aligned} \vec{E} &= -\vec{\nabla}\Phi - \frac{\partial\vec{A}}{\partial t} \\ \vec{B} &= \vec{\nabla}\times\vec{A} \end{aligned} \tag{7}$$

gauge symmetry

Maxwell's equation is invariant under

$$\begin{aligned} \vec{A} &\rightarrow \vec{A} + Q_f \vec{\nabla}\Lambda \\ \Phi &\rightarrow \Phi - Q_f \frac{\partial \Lambda}{\partial t} \end{aligned} \tag{4}$$

QED (Quantum ElectroDynamics) has electrons (Dirac equation)

$$\mathcal{L}_f = \overline{\psi}_f (i\gamma_\mu \partial_\mu - m_f)\psi_f \tag{5}$$

With

$$\partial_\mu \rightarrow D_\mu = \partial_\mu - iQ_f A_\mu, \tag{6}$$

E & M system has a global $U(1)$ gauge symmetry

$$\psi \rightarrow e^{iQ_f \Lambda}\psi, \quad A_\mu \rightarrow A_\mu + Q_f \partial_\mu \Lambda \tag{7}$$

gauge symmetry

QED lagrangian becomes

$$\mathcal{L}_{QED} = \sum_f \overline{\psi}_f (i\not{D} - m_f)\psi_f - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \tag{4}$$

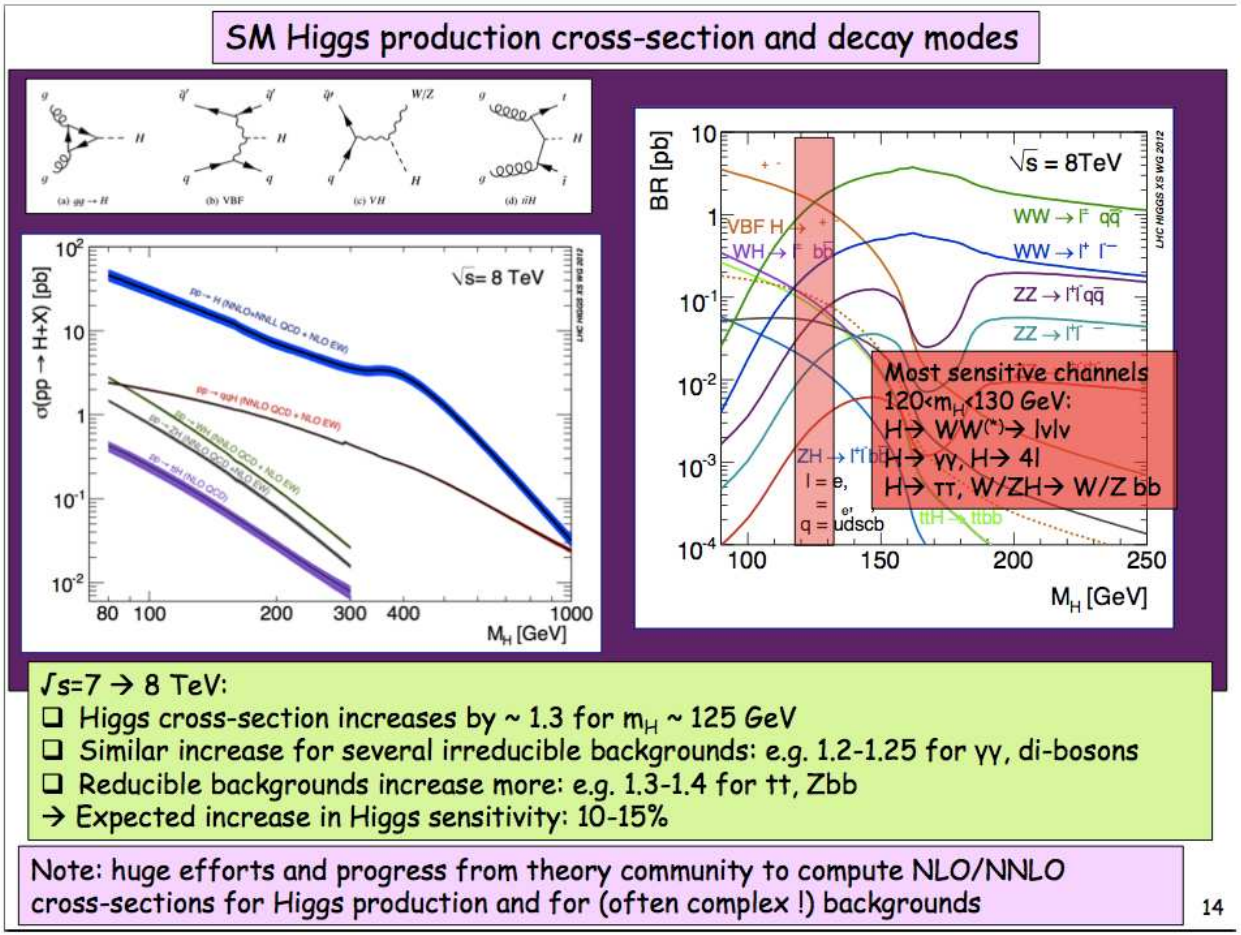
Standard model lagrangian is a generalization of gauge theory based on $SU(3)_c \times SU(2)_{EW} \times U(1)_Y$

$SU(3)$ is for the strong interaction, $SU(2)_{EW} \times U(1)_Y$ is for the electroweak interaction (the electromagnetic interaction + the weak interaction)

In Summary

- fundamental particles consist of fermions (half integer spin particles) and bosons (integer spin particles)
- 6 quarks (up, down), (charm, strange), (top, bottom)
- 6 leptons (e-neutrino, electron),(μ-neutrino, muon), (τ-neutrino, tau)
- photon, gluon, $W^{\pm}$,Z^0 boson
- interactions are based on gauge symmetries (i.e., massless bosons)
- $SU(3)_c \times SU(2)_{EW} \times U(1)_Y$ gauge interaction
- Higgs boson

ATLAS collaboration presentation



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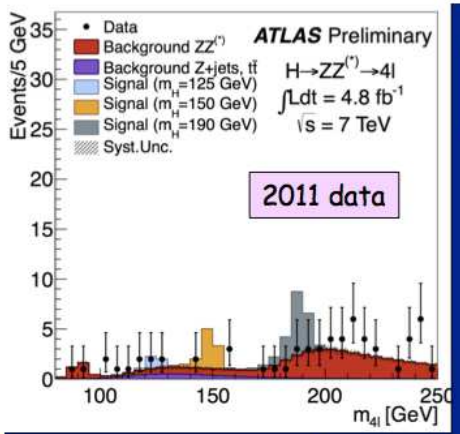
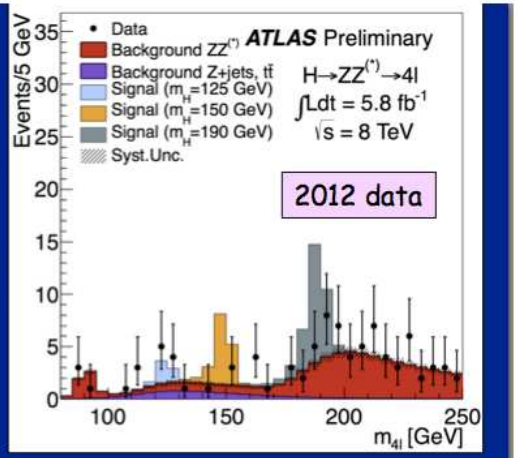
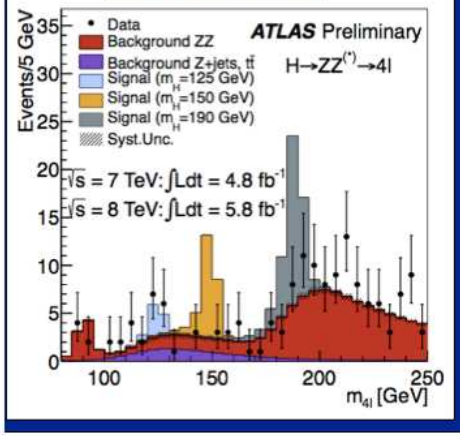


The low-mass region

m4l <160 GeV:
Observed: 39
Expected: 34± 3



2011+2012 data



In the region 125 ± 5 GeV

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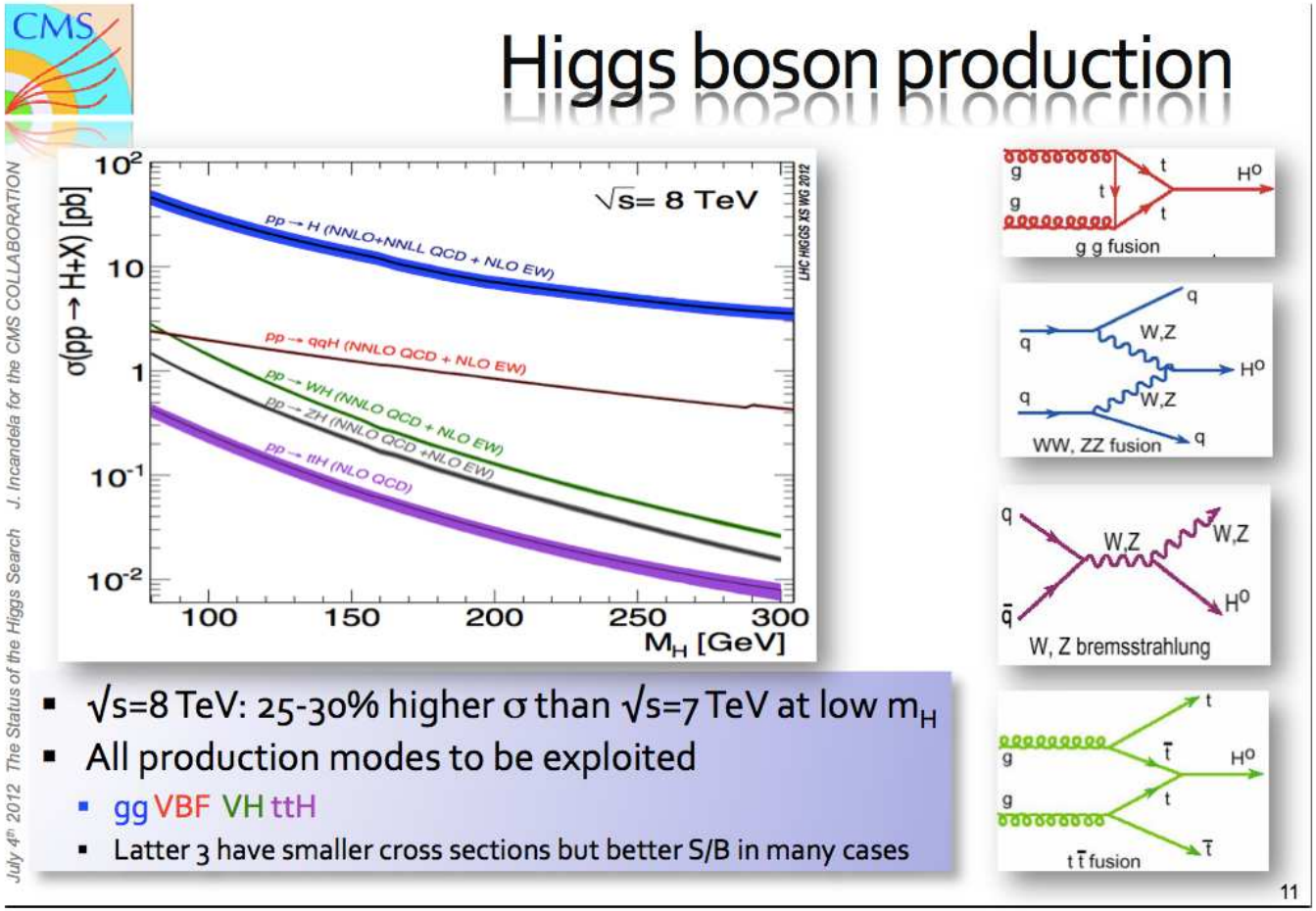
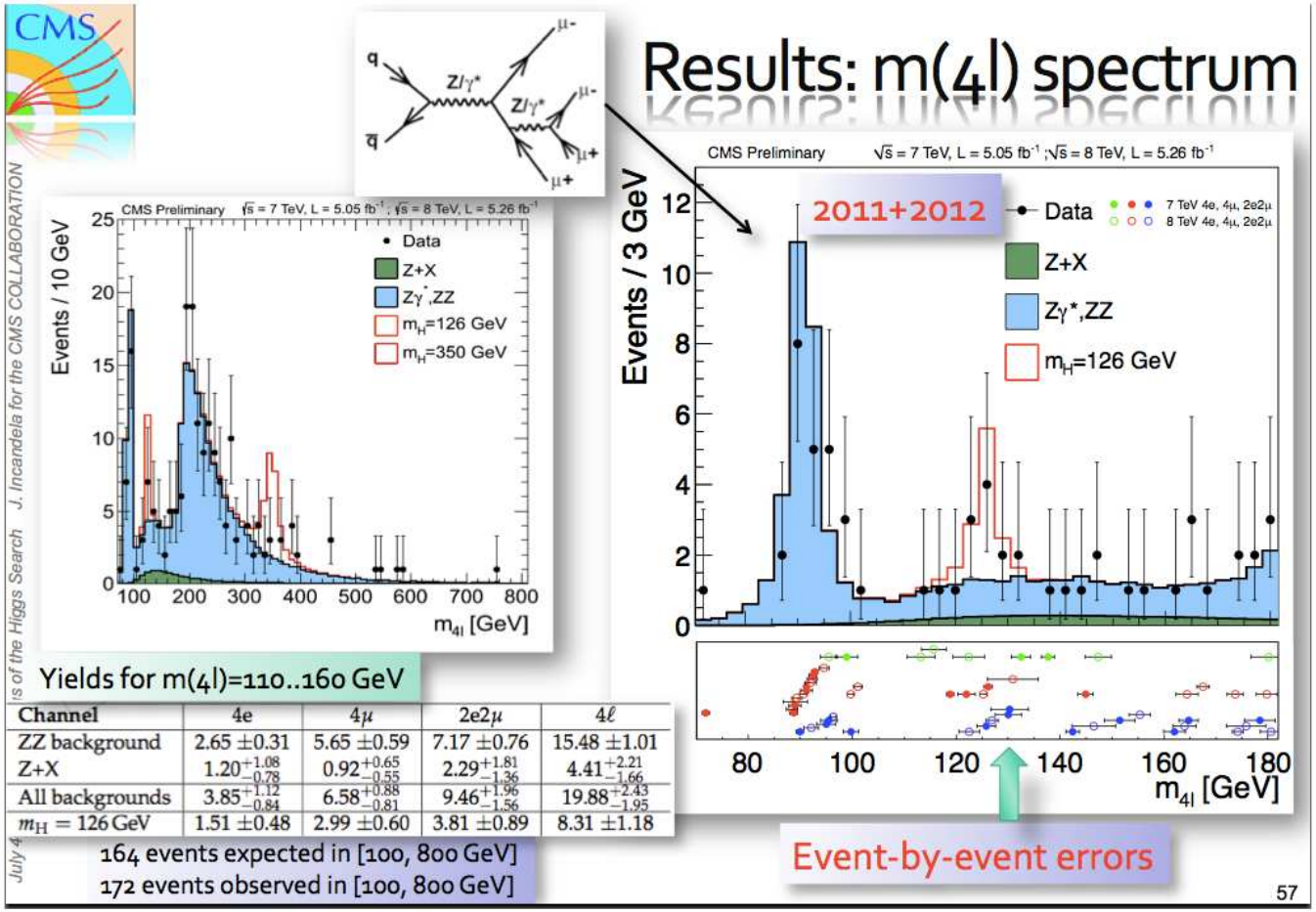
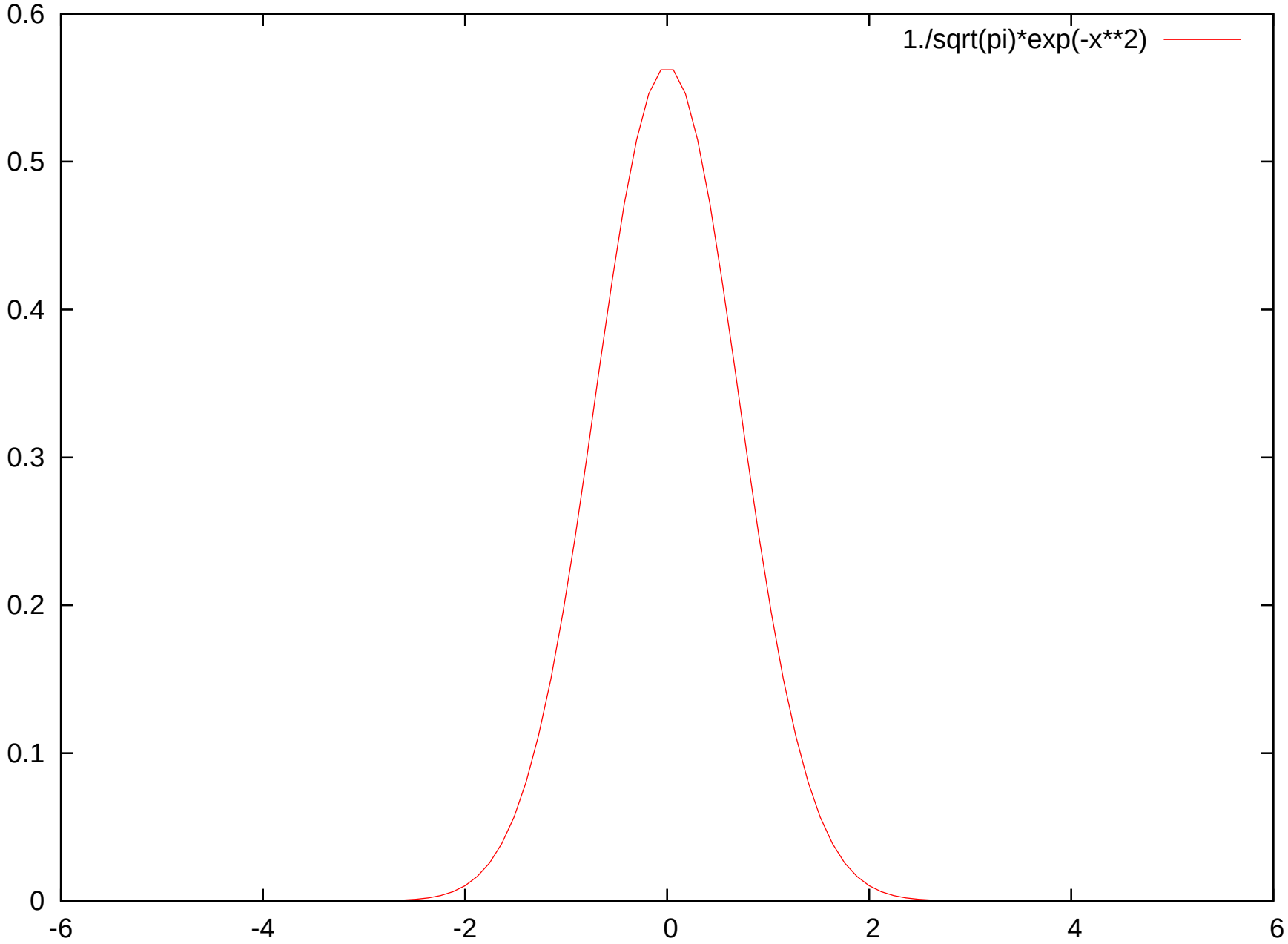


CMS collaboration presentation



Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ±0.31	5.65 ±0.59	7.17 ±0.76	15.48 ±1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV	1.51 ±0.48	2.99 ±0.60	3.81 ±0.89	8.31 ±1.18

meaning of $5-\sigma$ event



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spontaneous symmetry breaking and Goldstone's theorem

When there is a gauge symmetry, the gauge boson is massless (photon is massless). In this case, the interaction range is infinite.

Among four fundamental interactions, the gravity and the electromagnetism are long range interaction. The strong interaction and the weak interaction is short-ranged.

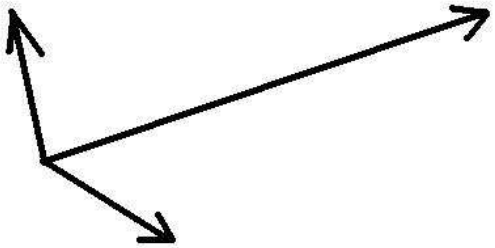
The strong interaction is short-ranged due to "color confinement".

(1) how can the weak interaction be described in terms of a gauge theory?

(2) why is the weak interaction short-ranged?

photon has the right-handed circular polarization and the left-handed circular polarization because it is massless (two components)

a $\vec{V}$ has three components. Massive particle has three. components



spontaneous symmetry breaking and Goldstone's theorem

$$\mathcal{L}_{\text{int}} = \frac{G_F}{\sqrt{2}} \overline{\psi}_p \gamma_\mu (1-\gamma_5) \psi_n \overline{e} \gamma^\mu (1-\gamma_5) \nu_e \tag{5}$$

Maybe, the lagrangian has the gauge symmetry but the ground state doesn't have the symmetry $\rightarrow$ spontaneous symmetry breaking

spontaneous symmetry breaking and Goldstone's theorem

an example of spontaneous breaking: permanent magnet

Ising model

$$H = -\kappa \vec{\sigma}_i \cdot \vec{\sigma}_{i+1} \tag{6}$$

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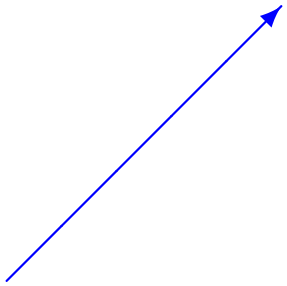

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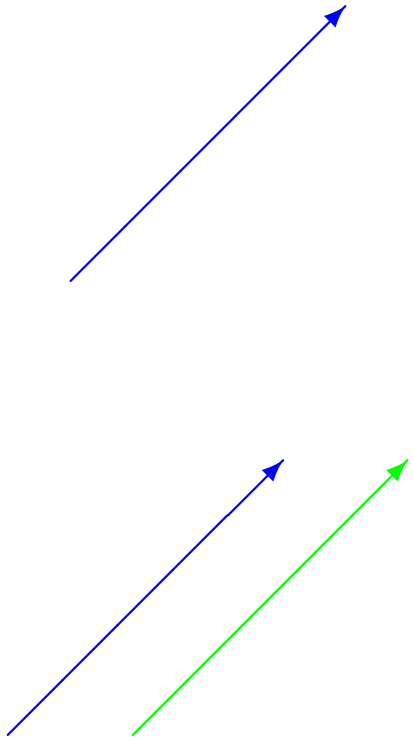
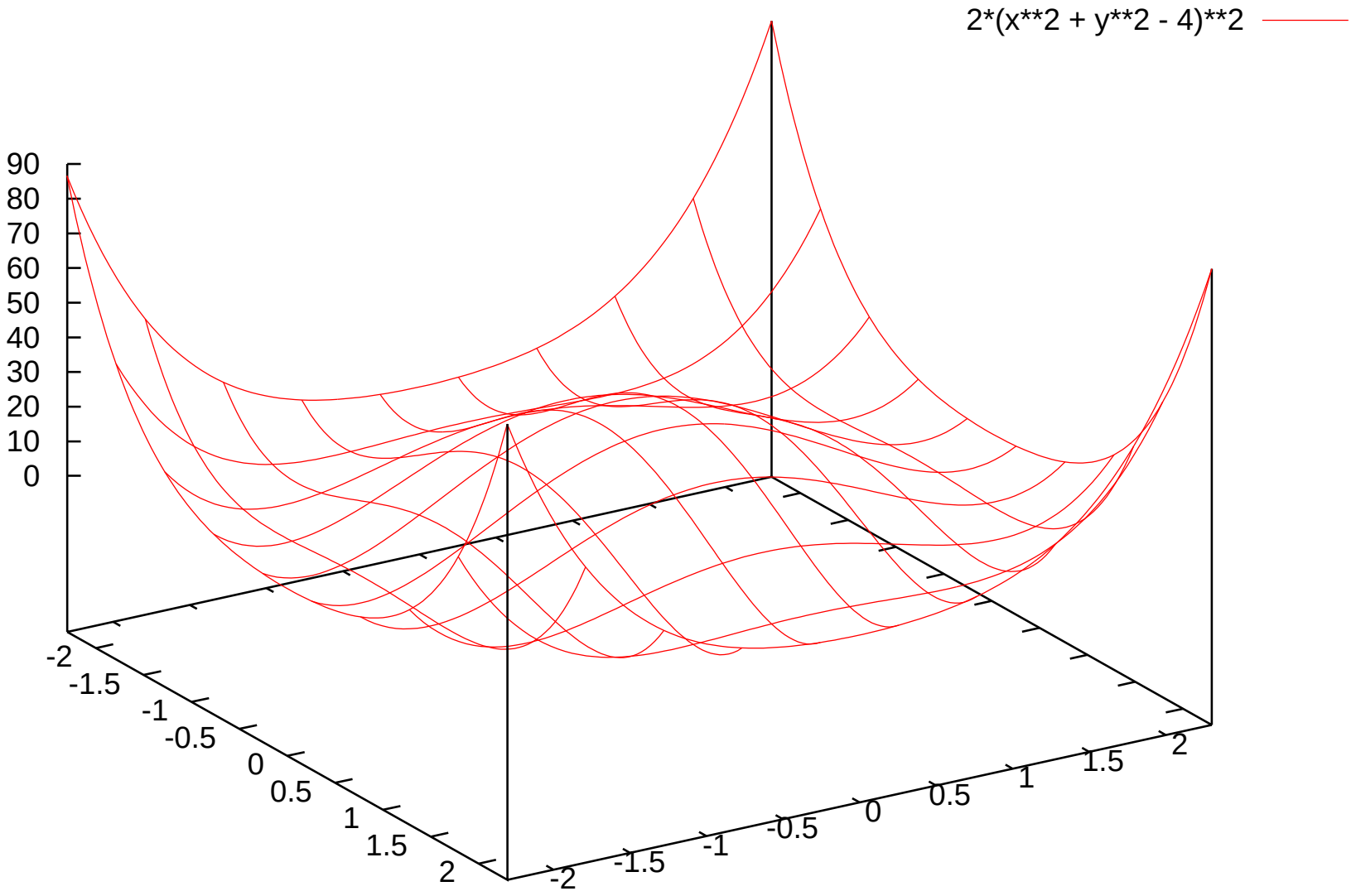


spontaneous symmetry breaking and Goldstone's theorem

Trouble !

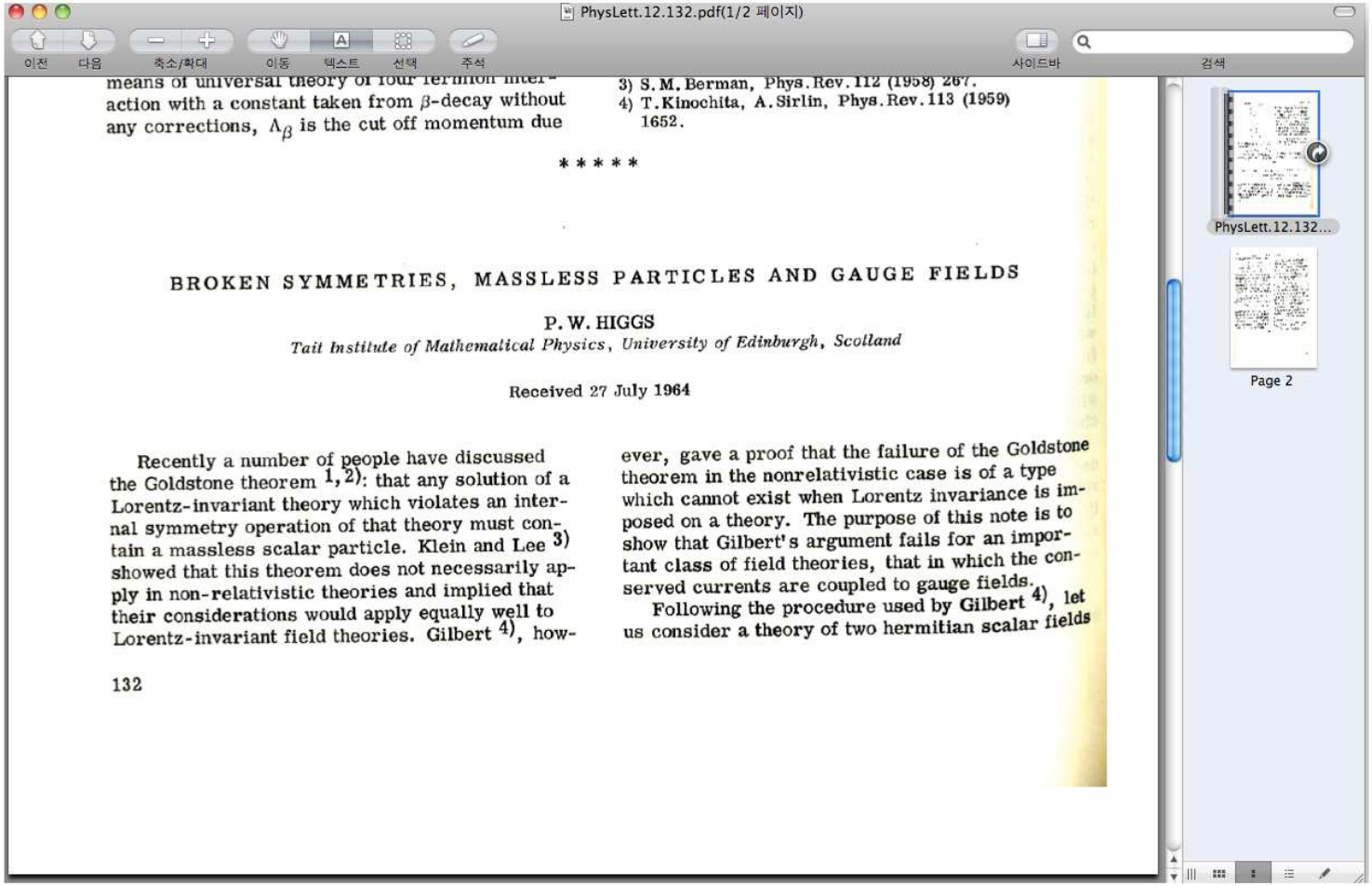
Goldstone's theorem states that if a continous symmetry is spontaneously broken (i.e., the current is conserved but the ground state is not invariant under the action of the corresponding charge), then there should be a massless scalar particle in the spectrum of possible excitations

spontaneous symmetry breaking and Goldstone's theorem



Higgs mechanism

P. Higgs, Physics Letters B12 (1964), 132



means of universal theory of four fermion interaction with a constant taken from β-decay without any corrections, Λ_β is the cut off momentum due

3) S.M. Berman, Phys. Rev. 112 (1958) 267.
4) T. Kinochita, A. Sirlin, Phys. Rev. 113 (1959) 1652.

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BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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Received 27 July 1964

Recently a number of people have discussed the Goldstone theorem [1,2]: that any solution of a Lorentz-invariant theory which violates an internal symmetry operation of that theory must contain a massless scalar particle. Klein and Lee [3] showed that this theorem does not necessarily apply in non-relativistic theories and implied that their considerations would apply equally well to Lorentz-invariant field theories. Gilbert [4], however, gave a proof that the failure of the Goldstone theorem in the nonrelativistic case is of a type which cannot exist when Lorentz invariance is imposed on a theory. The purpose of this note is to show that Gilbert's argument fails for an important class of field theories, that in which the conserved currents are coupled to gauge fields.

Following the procedure used by Gilbert [4], let us consider a theory of two hermitian scalar fields

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Higgs mechanism

Higgs mechanism introduces a scalar field (elementary or composite) which is self-interacting to a gauge theory. Spontaneous symmetry breaking of gauge symmetry makes the gauge field massive and there is no massless scalar particle left behind.

$$\mathcal{L}_H = D_\mu \phi D^\mu \phi^* - V(\phi^* \phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \tag{7}$$

where $D_\mu \phi = (\partial_\mu + ieA_\mu)\phi$.

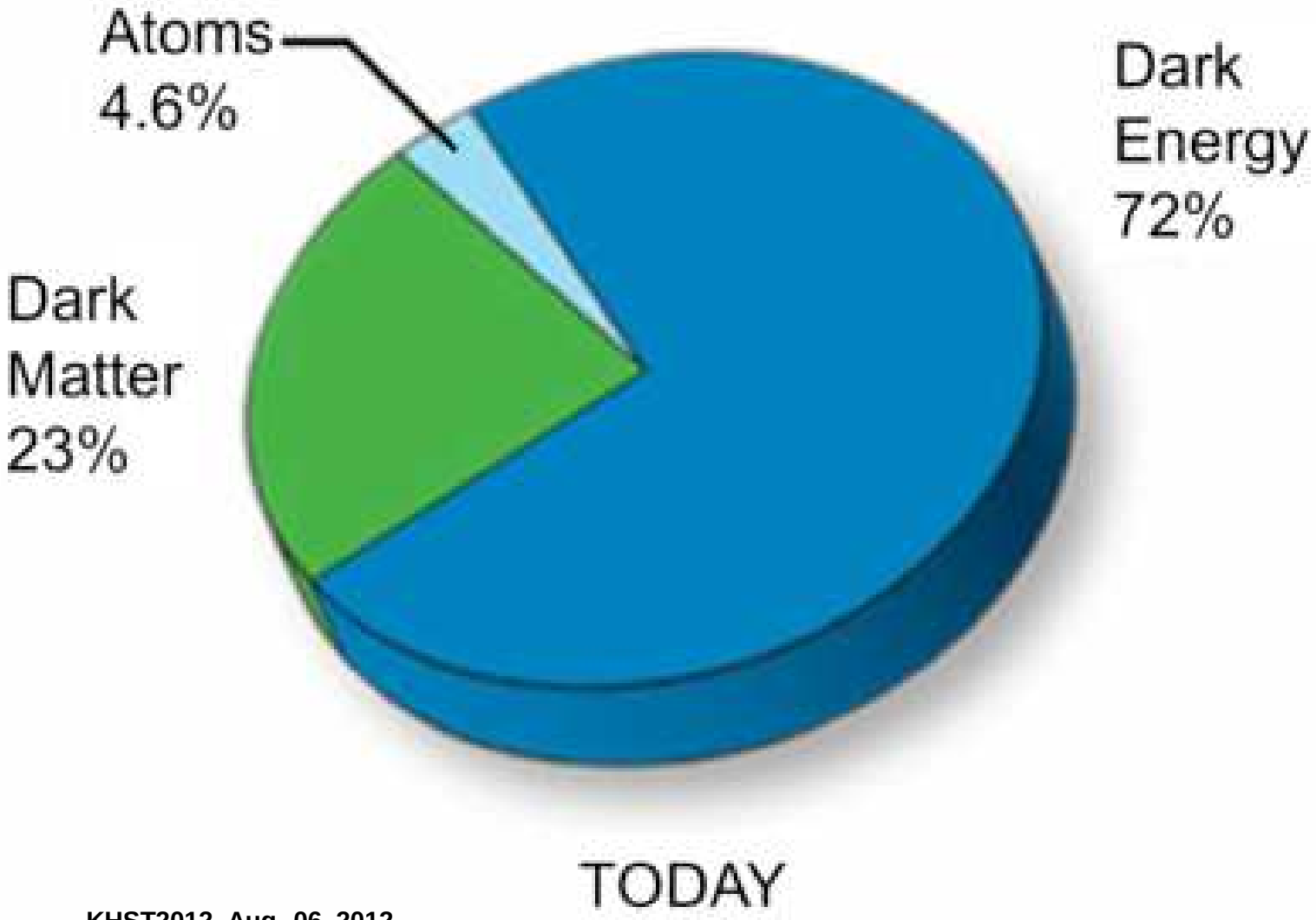
For $\phi \to \eta + iv$, $D_\mu \phi D^\mu \phi^* \to (\partial_\mu \eta)^2 + e^2 v^2 A_\mu^2$

$e^2 v^2 A_\mu^2$ is the mass term for the gauge field.

Are we there yet? (random order and personnel view)

There are many unsolved fundamental problems

(1) We only know 5% of energy density in the universe



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(2) Why is there more matter than anti-matter in the universe?

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many more important problems $\cdots$