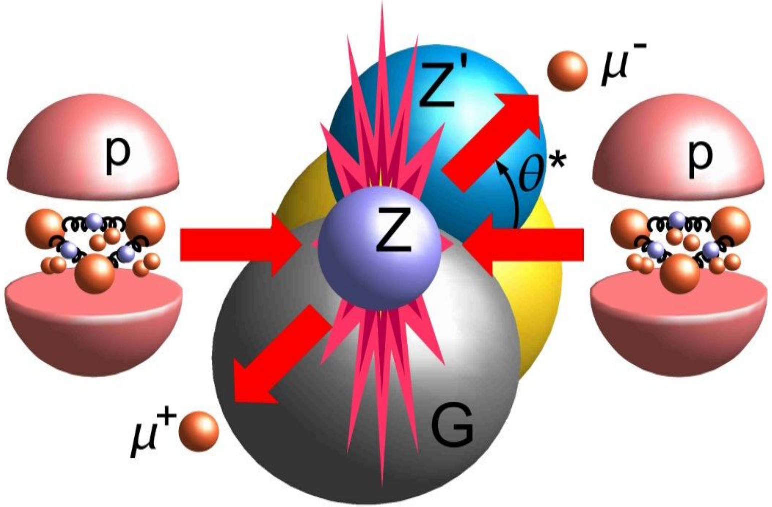
对撞机物理



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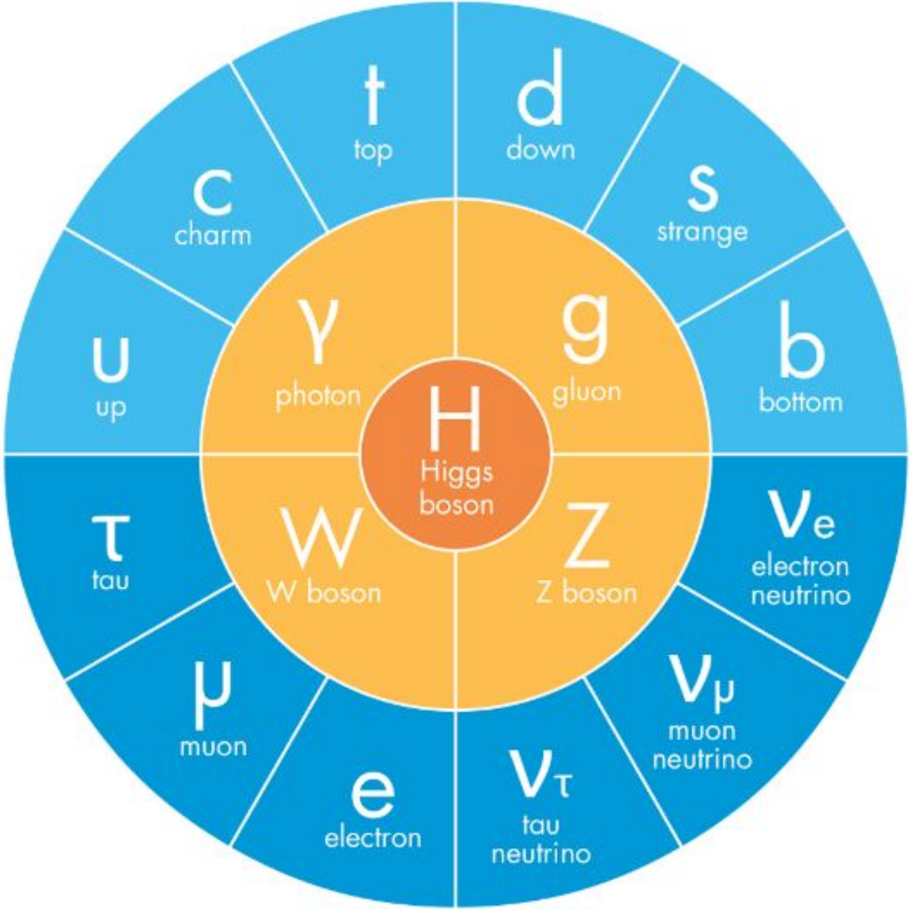
qliphy0@pku.edu.cn，15210033542

1. 前言
2. 高能物理简介
3. 大型强子对撞机(LHC)
4. Higgs的发现
5. 中国未来对撞机(CEPC)
6. 其他对撞机
7. 高能物理中的机器学习
8. 总结与展望



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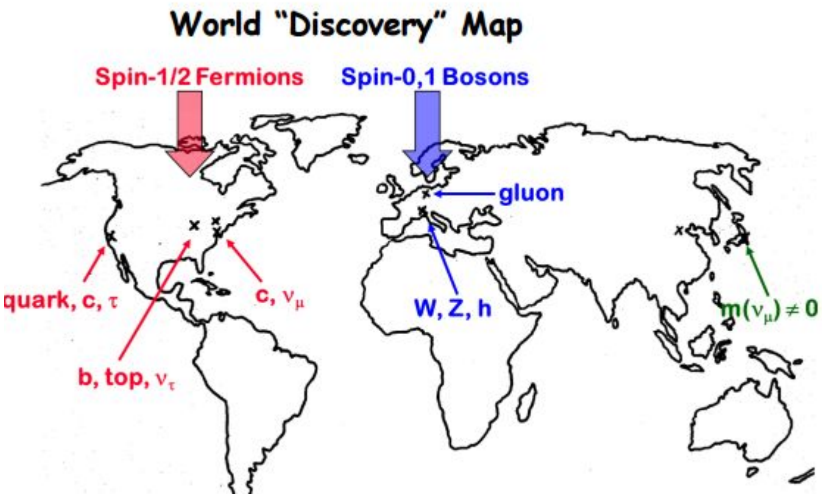
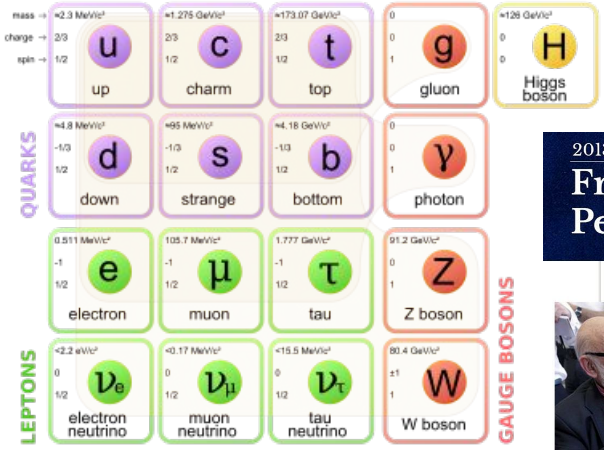
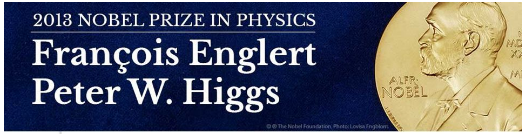
高能物理简介







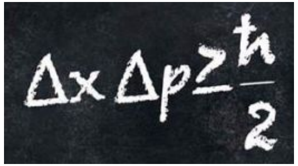
8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

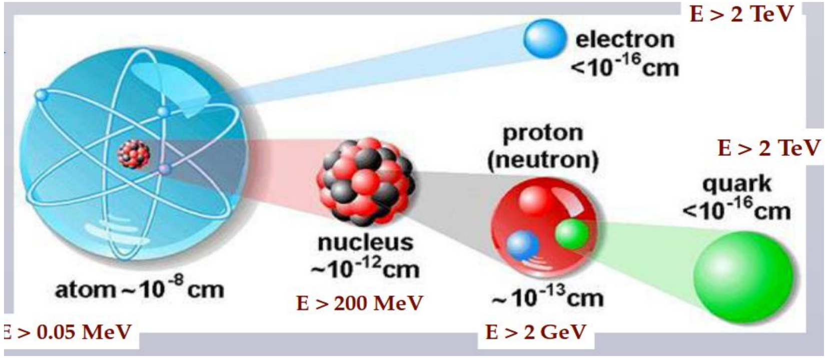
François Englert and Peter Higgs

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

小尺度,
大能量



$$(1\ \mathrm{GeV})^{-1} = 0.2\ \mathrm{fm} = 0.2\ 10^{-15}\ \mathrm{m}$$



More or Less

More Is Different

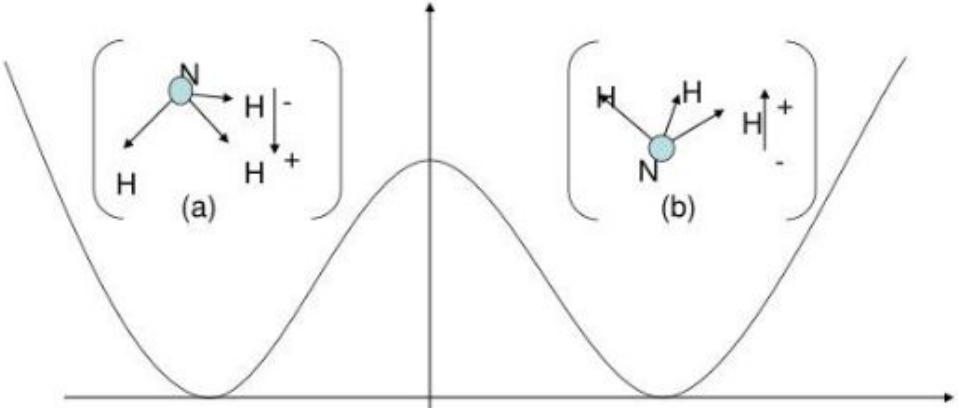
Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

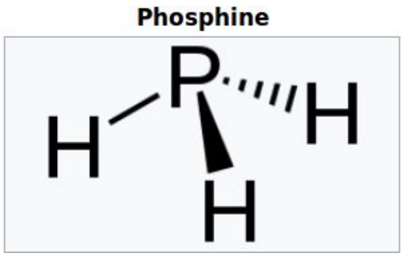
In closing, I offer two examples from economics of what I hope to have said. Marx said that quantitative differences become qualitative ones, but a dialogue in Paris in the 1920's sums it up even more clearly:

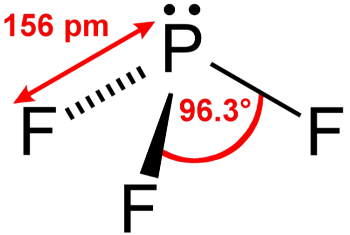
FITZGERALD: The rich are different from us.

HEMINGWAY: Yes, they have more money.



每秒300亿次穿越





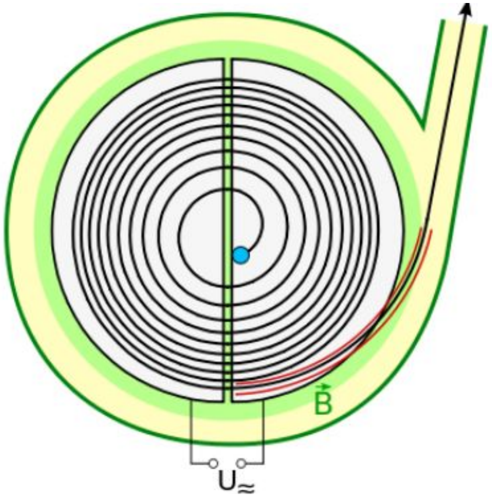
However, there are always people get attracted in the direction towards less/simple world!

电磁学内容

The Nobel Prize in Physics 1939

Photo from the Nobel Foundation archive.
Ernest Orlando Lawrence
Prize share: 1/1

"for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements."



回旋加速器(cyclotron):获得高速粒子的一种装置，其基本原理就是利用回旋频率与粒子速率无关的性质.

在能量达到10MeV以上的回旋加速器中，B的数量级为1T，D形盒的直径在1m以上.

$$v_{\max} = \frac{qBR}{m}$$

考虑相对论效应，粒子质量及回旋周期都会随速度增大而增大

同步加速器：变化磁场

同步回旋加速器：改变交变电压频率

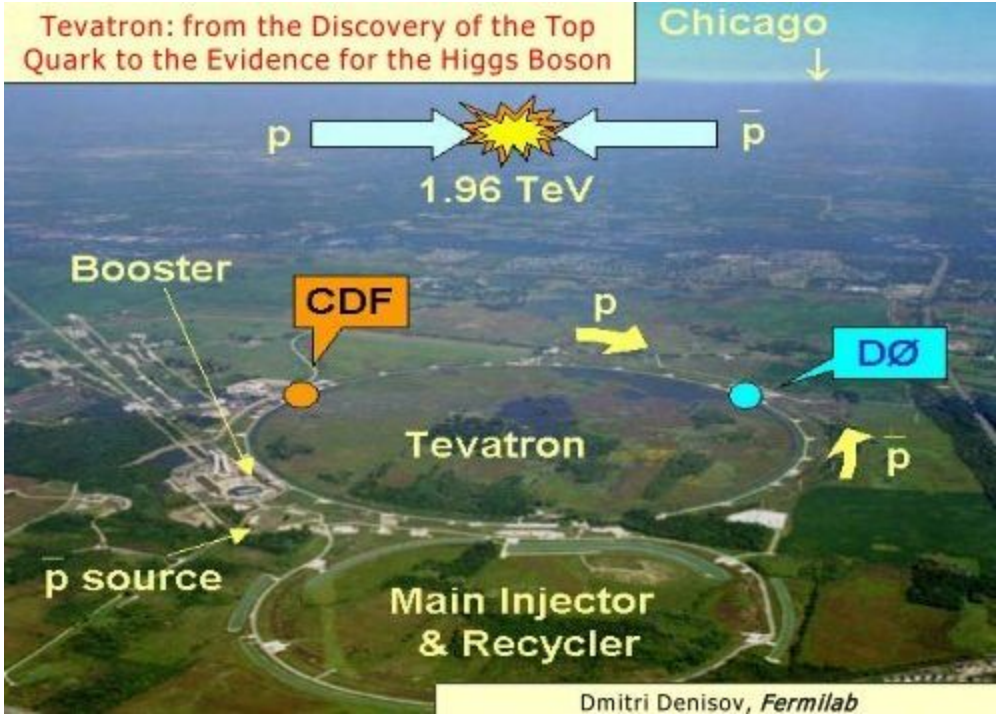
$$E = \gamma M c^2$$

$$B r = \frac{\gamma M v}{q}$$

Synchrotron

对撞机:过去、现在及未来

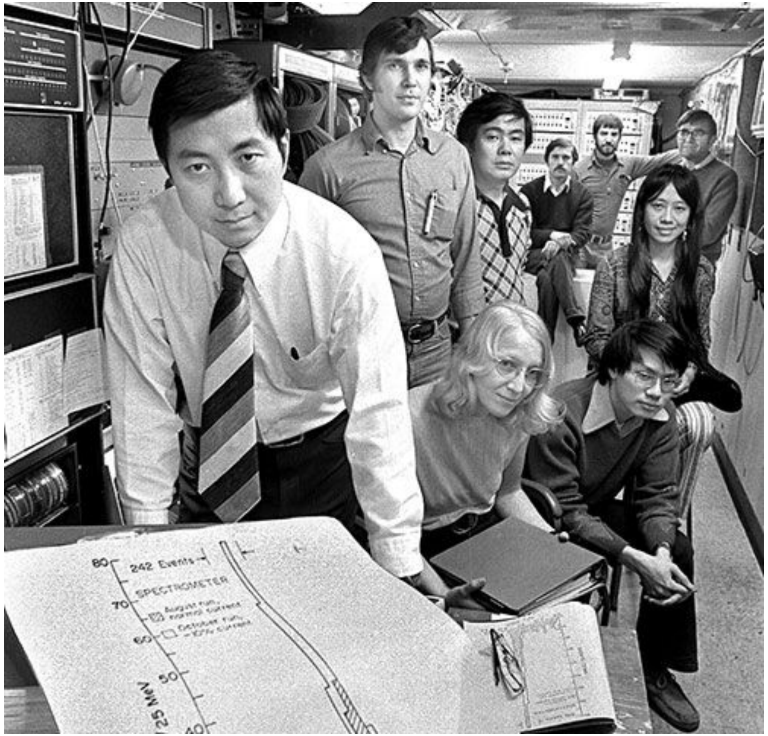
CERN Super Proton Synchrotron
正负质子对撞
1983年1月25日 宣布发现W玻色子

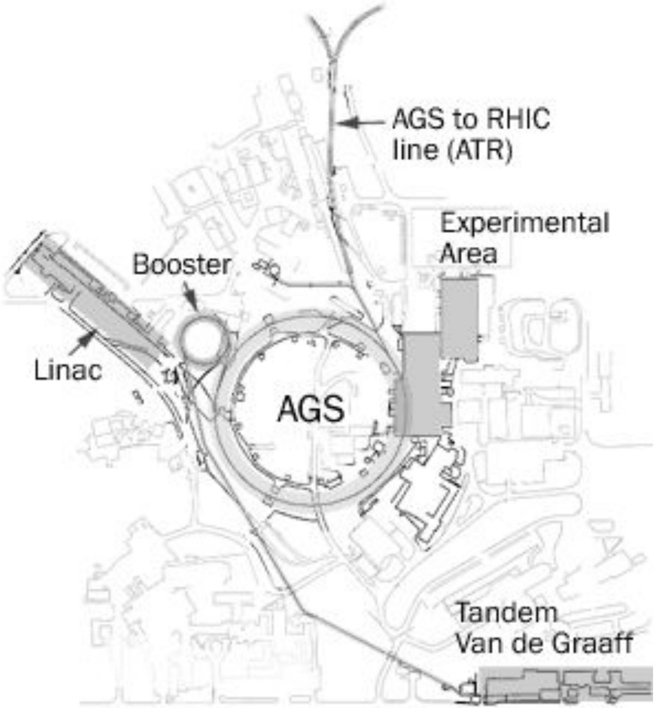


美国Tevatron 1992-2011 正负质子对撞
1995年发现Top夸克

https://en.wikipedia.org/wiki/List_of_accelerators_in_particle_physics#Colliders 对撞机列表

对撞机:过去、现在及未来





1976年美国BNL Alternating Gradient Synchrotron以及美国SLAC SPEAR正负电子对撞机发现J/ψ粒子即Charm quark的发现。

对撞机:过去、现在及未来

现役对撞机

Belle2: (7+4)^2-(7-4)^2=112
Belle: (8+3.5)^2-(8-3.5)^2=112

sqrt(112)~=10.58GeV

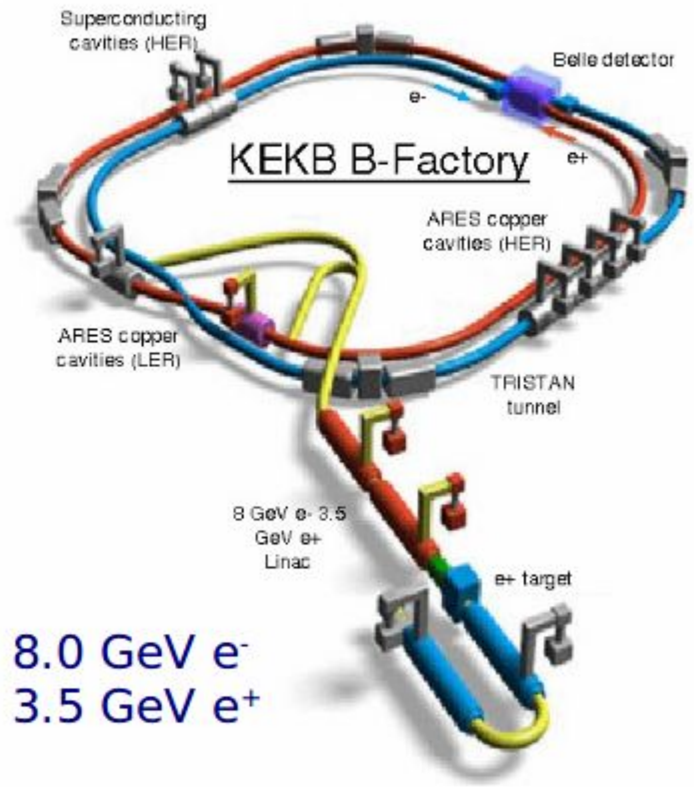
Operating colliders [edit]

Sources: Information was taken from the website Particle Data Group[11] and *Handbook of accelerator physics and engineering*.[12]

Accelerator	Centre, city, country	First operation	accelerated particles	max energy per beam, GeV	Luminosity, 10^{30} cm^{-2} s^{-1}	Perimeter (length), km
VEPP-2000	INP, Novosibirsk, Russia	2006	e^+e^-	1.0	100	0.024
VEPP-4M	INP, Novosibirsk, Russia	1994	e^+e^-	6	20	0.366
BEPC II	IHEP, Beijing, China	2008	e^+e^-	3.7	700	0.240
DAFNE	Frascati, Italy	1999	e^+e^-	0.7	436[13]	0.098
KEKB/SuperKEKB	KEK, Tsukuba, Japan	1999	e^+e^-	8.5 (e-), 4 (e+)	21100	3.016
RHIC	BNL, United States	2000	pp, Au-Au, Cu-Cu, d-Au	100/n	10, 0.005, 0.02, 0.07	3.834
LHC	CERN	2008	pp, Pb-Pb, p-Pb, Xe-Xe	6500 (planned 7000), 2560/n (planned 2760/n)	20000,[14] 0.003, 0.9, ≈0.0002	26.659

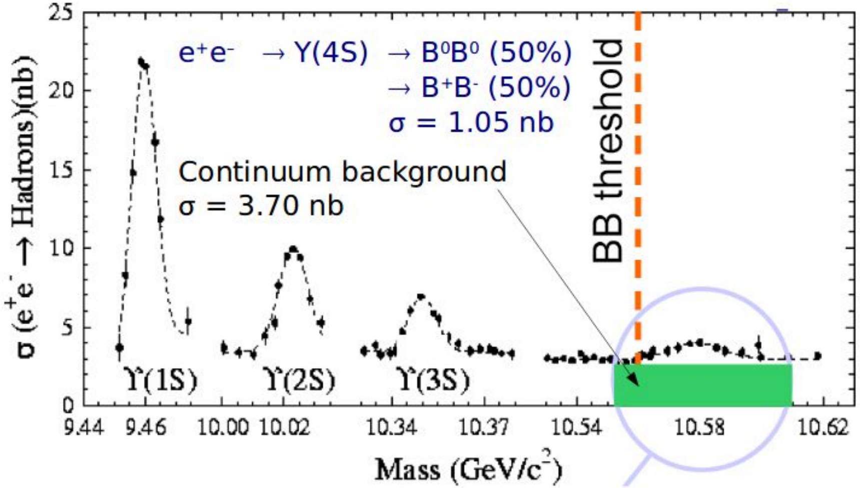
https://en.wikipedia.org/wiki/List_of_accelerators_in_particle_physics#Colliders

对撞机:过去、现在及未来



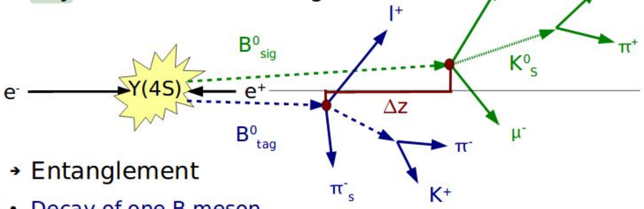
8.0 GeV e^-
3.5 GeV e^+

日本 筑波



Measurement of time-dep. CP Violation

- Asymmetric beam energies



- Entanglement
  - Decay of one B meson at time t_{tag} in flavor eigenstate Q → tagging
  - Other B meson is at time t_{tag} in flavor eigenstate $\bar{Q}$
  - Time measurement: $\Delta t = t_{sig} - t_{tag} = \Delta z / c\beta\gamma$

对撞机:过去、现在及未来

北京正负电子对撞机(BEPC)于1988年10月在中国科学院高能物理所建成,在Charm夸克物理领域取得了一批世界领先结果。

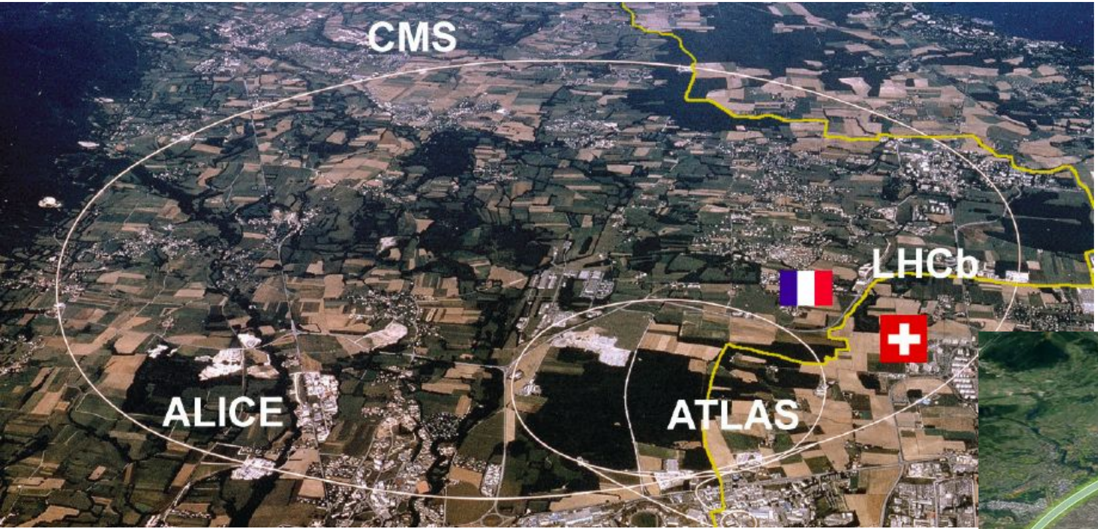
北京谱仪国际合作组发现四夸克物质Zc(3900)入选2013年物理学重要成果

Four-Quark Matter

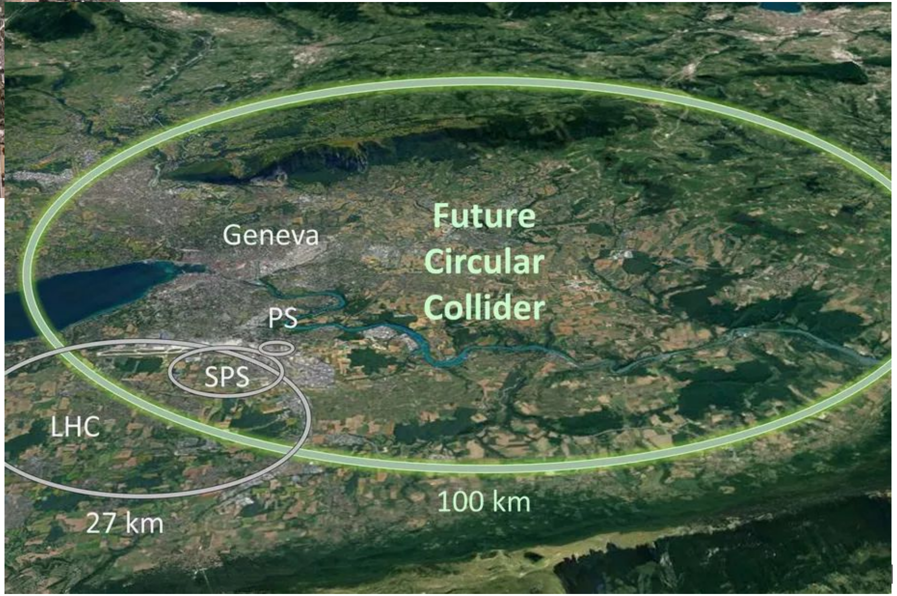
Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a **mysterious particle** that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since **seen** a series of other particles that appear to contain four quarks.

https://physics.aps.org/articles/v6/139

对撞机:过去、现在及未来



Large Hadron Collider:
欧洲核子中心；环长27公里，地下100米；质子-质子 13TeV对撞；其上有4个大型实验：
ALICE、ATLAS、CMS、LHCb



2013年Higgs发现之后，国际高能物理学界提出了**下一代对撞机方案**，包括：
欧洲的FCC-ee, FCC-hh；
中国的CEPC，SPPC。
以及国际直线加速器ILC等等。

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以下列出1957年以来与基本粒子物理相关的部分诺贝尔奖

宇称破坏：弱作用

The Nobel Prize in Physics 1957

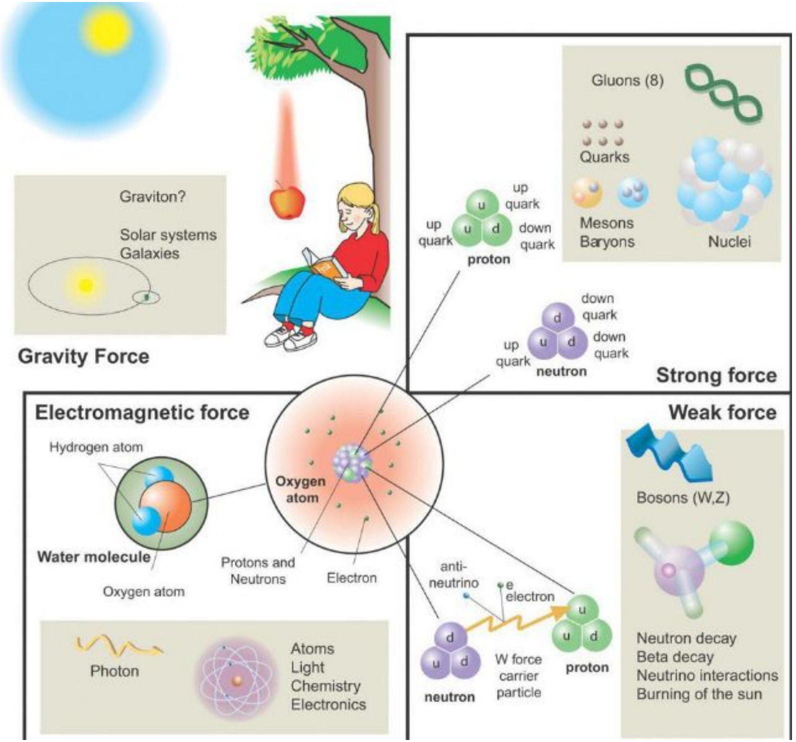
Chen Ning Yang

Prize share: 1/2

Tsung-Dao (T.D.) Lee

Prize share: 1/2

The Nobel Prize in Physics 1957 was awarded jointly to Chen Ning Yang and Tsung-Dao (T.D.) Lee *"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"*



四大相互作用

The Nobel Prize in Physics 1958

切伦科夫辐射、探测器

Pavel Alekseyevich Cherenkov

Prize share: 1/3

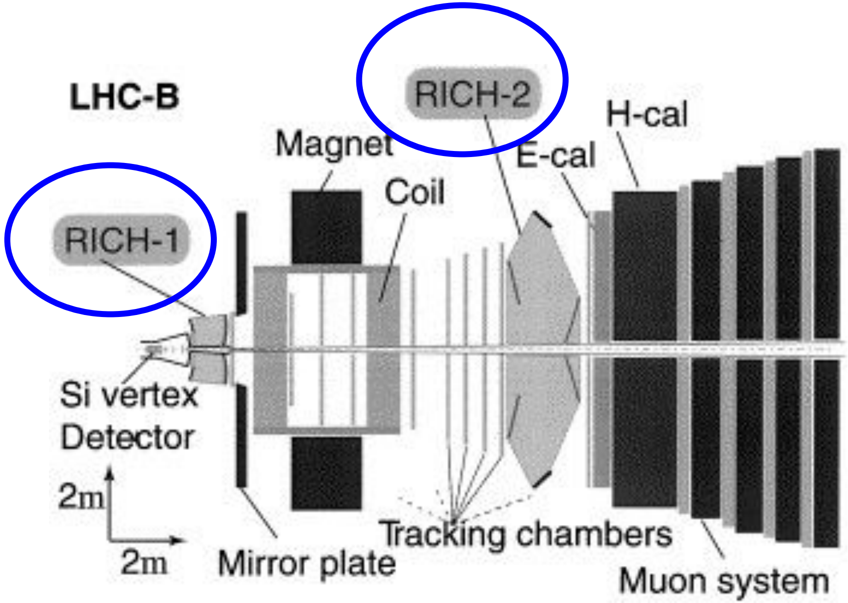
Il´ja Mikhailovich Frank

Prize share: 1/3

Igor Yevgenyevich Tamm

Prize share: 1/3

The Nobel Prize in Physics 1958 was awarded jointly to Pavel Alekseyevich Cherenkov, Il´ja Mikhailovich Frank and Igor Yevgenyevich Tamm *"for the discovery and the interpretation of the Cherenkov effect"*.



When a charged particle travels faster than light does through a given medium, it emits Cherenkov radiation at an angle that depends on its velocity. The particle's velocity can be calculated from this angle. Velocity can then be combined with a measure of the particle's momentum to determine its mass, and therefore its identity.

The Nobel Prize in Physics 1959

反质子

Emilio Gino Segrè

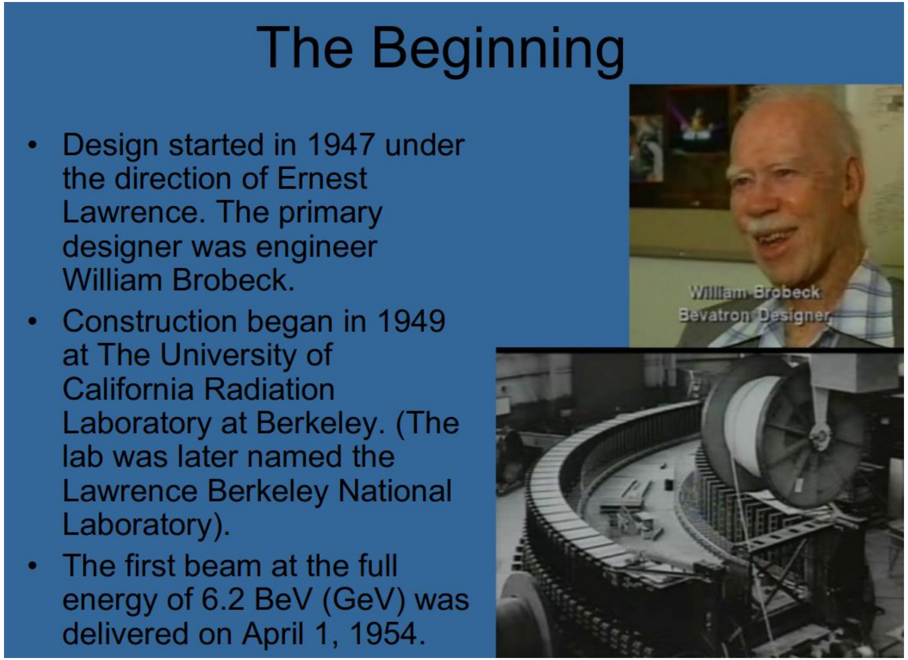
Prize share: 1/2

Owen Chamberlain

Prize share: 1/2

The Nobel Prize in Physics 1959 was awarded jointly to Emilio Gino Segrè and Owen Chamberlain *"for their discovery of the antiproton"*

- 1928年Dirac方程负能量解，预言了antimatter。
- 1932年，宇宙线中发现正电子。
- 1955年，Lawrence Berkeley National Laboratory 的Bevatron发现反质子。



Observation of Antiprotons

Owen Chamberlain, Emilio Segrè, Clyde Wiegand, and Thomas Ypsilantis
Phys. Rev. **100**, 947 – Published 1 November 1955

质子打靶

气泡室：<u>弱中性流</u>

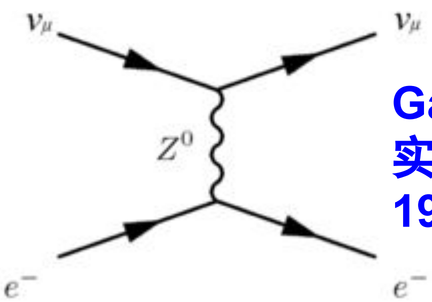
The Nobel Prize in Physics 1960

Donald Arthur Glaser

Prize share: 1/1

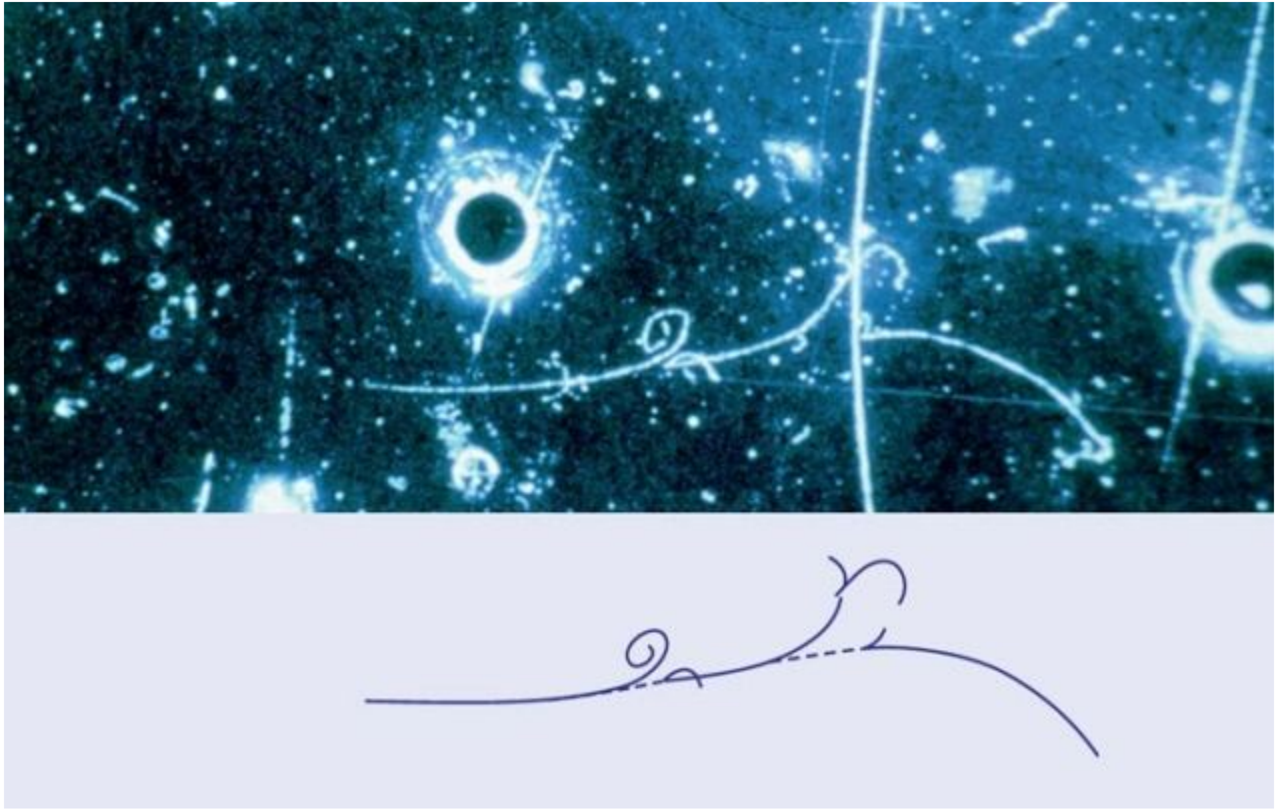
The Nobel Prize in Physics 1960 was awarded to Donald A. Glaser *"for the invention of the bubble chamber"*.

- A bubble chamber is a vessel filled with a superheated transparent liquid used to detect electrically charged particles moving through it.
- It was invented in 1952 by Donald A. Glaser, may be after looking at the bubbles in a glass of beer.



Gargamelle 实验 1973

https://cerncourier.com/a/neutral-currents-a-perfect-experimental-discovery/



https://cerncourier.com/a/neutral-currents-a-perfect-experimental-discovery/

The Nobel Prize in Physics 1965

Sin-Itiro Tomonaga

Prize share: 1/3

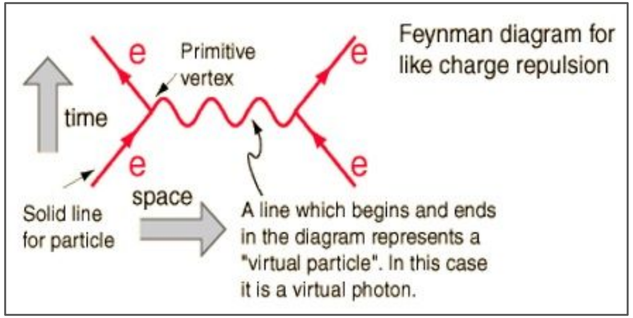
Julian Schwinger

Prize share: 1/3

Richard P. Feynman

Prize share: 1/3

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman *"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"*.



量子电动力学

relativistic quantum field theory of electrodynamics describes how light and matter interact and is the first theory where full agreement between quantum mechanics and special relativity is achieved.

电子磁矩

PRL 100, 120801 (2008) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2008

New Measurement of the Electron Magnetic Moment and the Fine Structure Constant

D. Hanneke, S. Fogwell, and G. Gabrielse*

Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

(Received 4 January 2008; published 26 March 2008)

A measurement using a one-electron quantum cyclotron gives the electron magnetic moment in Bohr magnetons, $g/2 = 1.001\,159\,652\,180\,73\,(28)$ [0.28 ppt], with an uncertainty 2.7 and 15 times smaller than for previous measurements in 2006 and 1987. The electron is used as a magnetometer to allow line shape statistics to accumulate, and its spontaneous emission rate determines the correction for its interaction with a cylindrical trap cavity. The new measurement and QED theory determine the fine structure constant, with $\alpha^{-1} = 137.035\,999\,084\,(51)$ [0.37 ppb], and an uncertainty 20 times smaller than for any independent determination of α.

New determination of the fine structure constant and test of the quantum electrodynamics

Phys. Rev. Lett. 106, 080801 (2011)

Rym Bouchendira,[1] Pierre Cladé,[1] Saïda Guellati-Khélifa,[2] François Nez,[1] and François Biraben[1]

[1] *Laboratoire Kastler Brossel, Ecole Normale Supérieure, Université Pierre et Marie Curie, CNRS, 4 place Jussieu, 75252 Paris Cedex 05, France*

[2] *Conservatoire National des Arts et Métiers, 292 rue Saint Martin, 75141 Paris Cedex 03, France*

We report a new measurement of the ratio h/m_{Rb} between the Planck constant and the mass of ^{87}Rb atom. A new value of the fine structure constant is deduced, $\alpha^{-1} = 137.035\,999\,037\,(91)$ with a relative uncertainty of 6.6×10^{-10}. Using this determination, we obtain a theoretical value of the electron anomaly $a_e = 0.001\,159\,652\,181\,13(84)$ which is in agreement with the experimental measurement of Gabrielse ($a_e = 0.001\,159\,652\,180\,73(28)$). The comparison of these values provides the most stringent test of the QED. Moreover, the precision is large enough to verify for the first time the muonic and hadronic contributions to this anomaly.

The Nobel Prize in Physics 1968

液氢气泡室，一批共振态

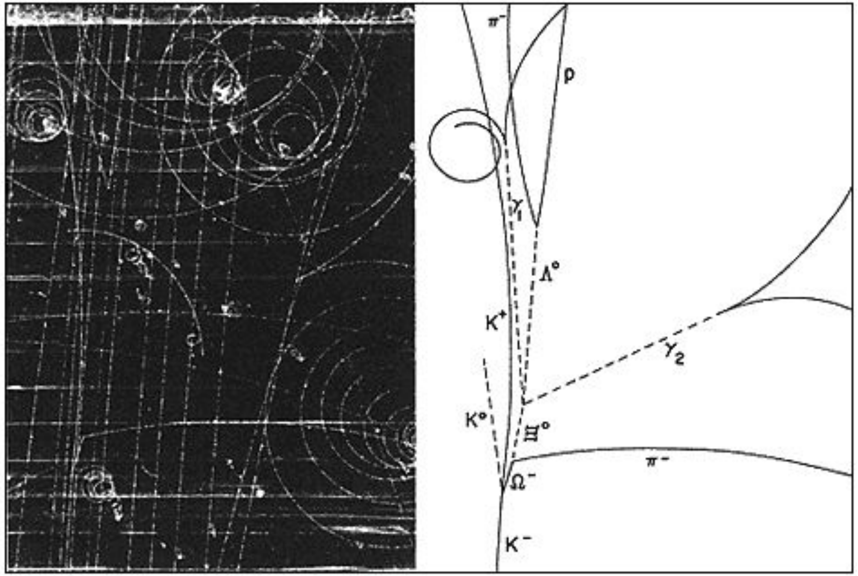
Photo from the Nobel Foundation archive.

Luis Walter Alvarez

Prize share: 1/1

The Nobel Prize in Physics 1968 was awarded to Luis Walter Alvarez "for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using hydrogen bubble chamber and data analysis."

Particle	Symbol	Makeup	Rest mass MeV/c^2	Spin	B	S	Lifetime	Decay Modes
Omega	Ω^-	sss	1672	3/2	+1	-3	0.82 x10^{-10}	$\Xi^0\pi^-$, Λ^0K^-



The bubble chamber picture of the first omega-minus. An incoming K- meson interacts with a proton in the liquid hydrogen of the bubble chamber and produces an

Brookhaven in 1964.

confirmed the validity of the SU(3) symmetry of the hadrons.

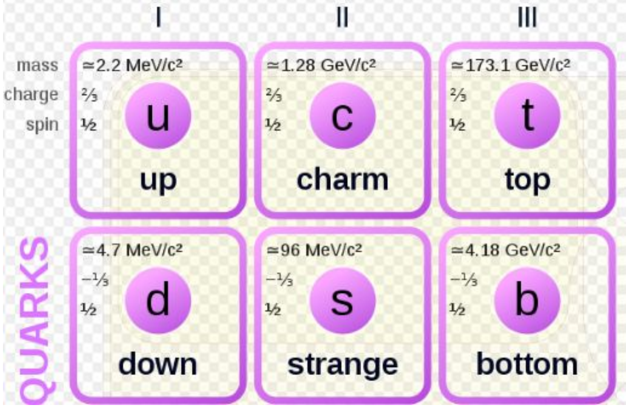
盖尔曼 八重道
(The Eightfold Way)

The Nobel Prize in Physics 1969

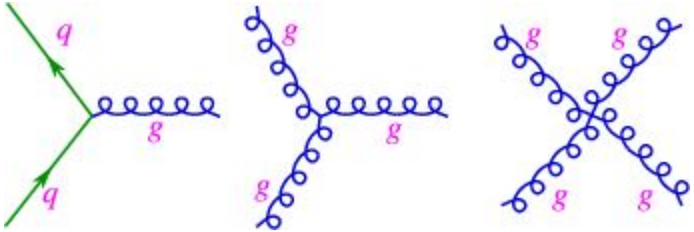
QCD，夸克

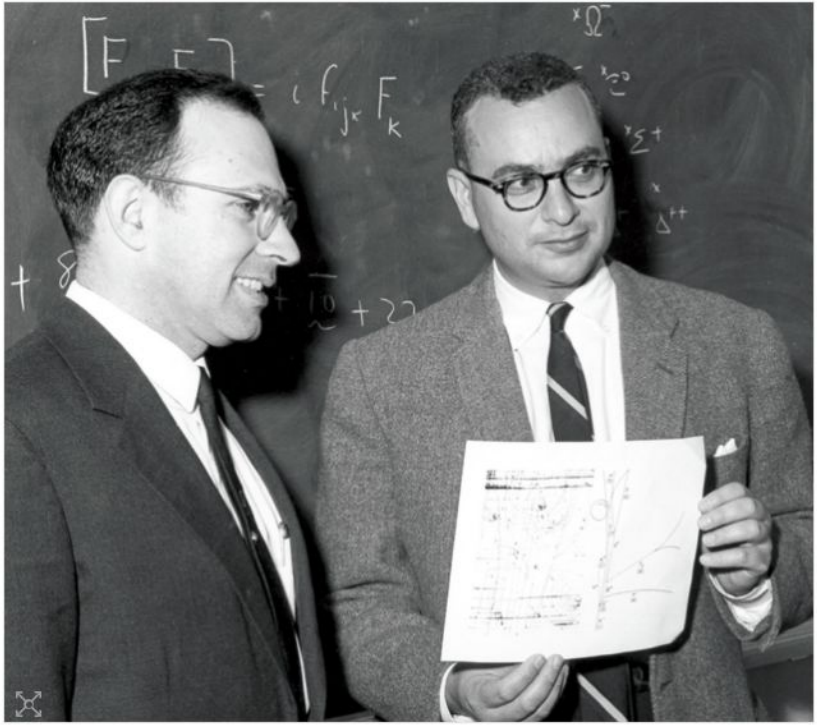
Murray Gell-Mann

Prize share: 1/1



The Nobel Prize in Physics 1969 was awarded to Murray Gell-Mann *"for his contributions and discoveries concerning the classification of elementary particles and their interactions".*





Triply strange Yuval Ne'eman (left) and Gell-Mann in March 1964, holding a copy of the event display that proved the existence of the Ω^- baryon that was predicted by Gell-Mann's "eightfold way". Credit: Courtesy of the Archives, California Institute of Technology.

The Nobel Prize in Physics 1976

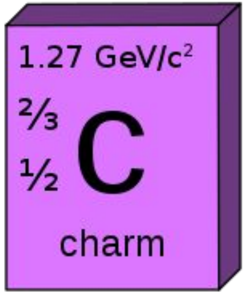
J/ψ，粲夸克

Burton Richter

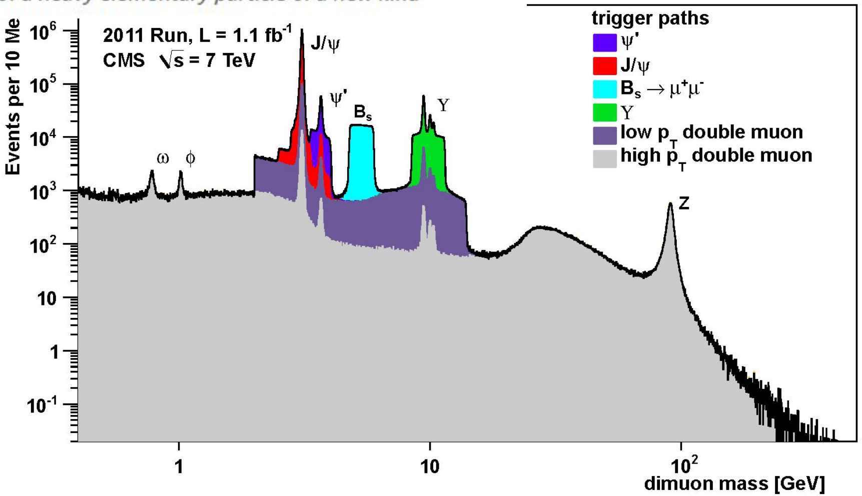
Prize share: 1/2

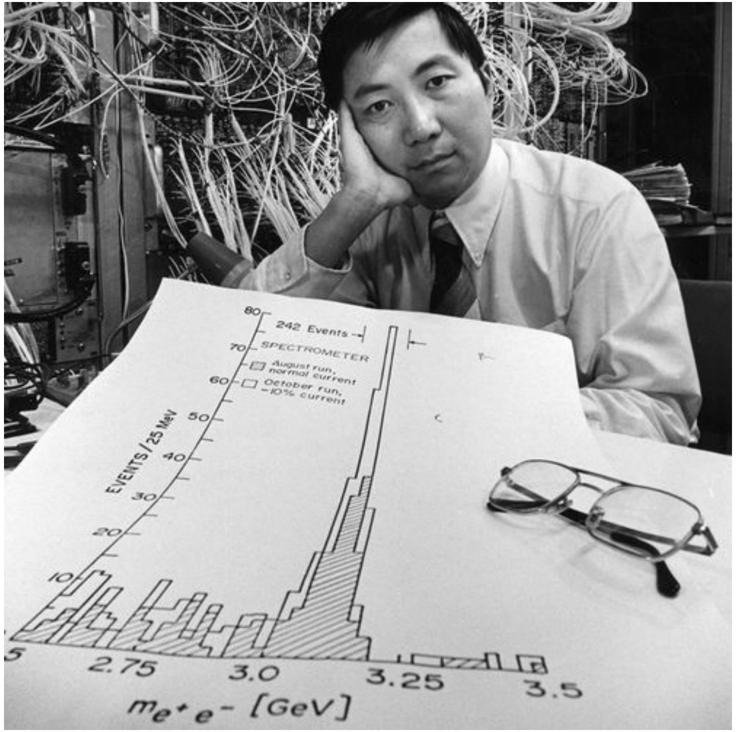
Samuel Chao Chung Ting

Prize share: 1/2



The Nobel Prize in Physics 1976 was awarded jointly to Burton Richter and Samuel Chao Chung Ting *"for their pioneering work in the discovery of a heavy elementary particle of a new kind"*





The Nobel Prize in Physics 1979

电弱理论

Sheldon Lee Glashow
Prize share: 1/3

Abdus Salam
Prize share: 1/3

Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

Start with 4 massless bosons W^+, W_3, W^- and B. The neutral bosons mix to give physical bosons (the particles we see), i.e. the $W^\pm$, Z, and γ.

$$\begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix};\ B \quad \rightarrow \quad \begin{pmatrix} W^+ \\ Z \\ W^- \end{pmatrix};\ \gamma$$

Physical fields: W^+, Z, W^- and A (photon).

$$Z = W_3 \cos\theta_W - B \sin\theta_W$$

$$A = W_3 \sin\theta_W + B \cos\theta_W$$

θ_W Weak Mixing Angle

$W^\pm$, Z "acquire" mass via the Higgs mechanism.

标准模型 Standard Model

$$\boxed{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \xrightarrow{\text{SSB}} SU(3)_C \otimes U(1)_{\text{QED}}}$$

The Nobel Prize in Physics 1984

W，Z玻色子

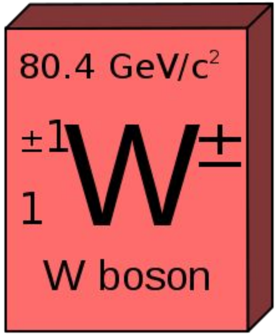
Carlo Rubbia

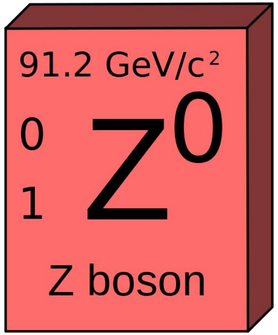
Prize share: 1/2

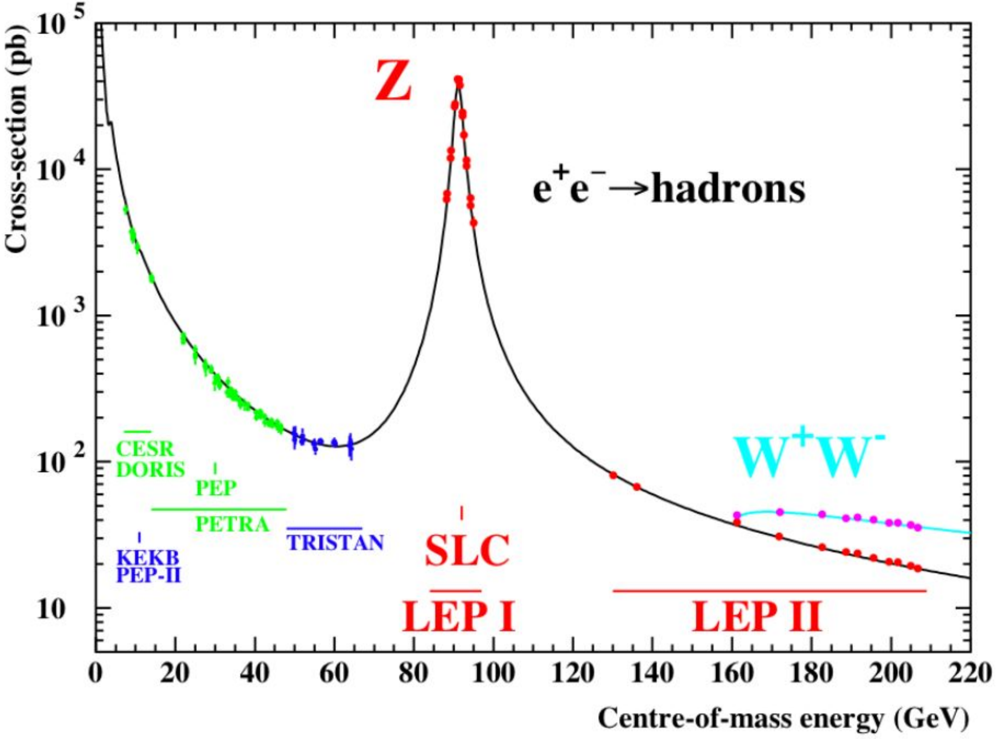
Simon van der Meer

Prize share: 1/2

The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer *"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"*







The Nobel Prize in Physics 1988

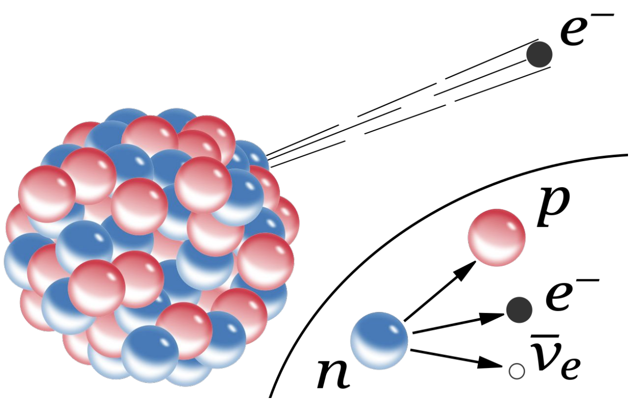
缪子中微子

Leon M. Lederman
Prize share: 1/3

Melvin Schwartz
Prize share: 1/3

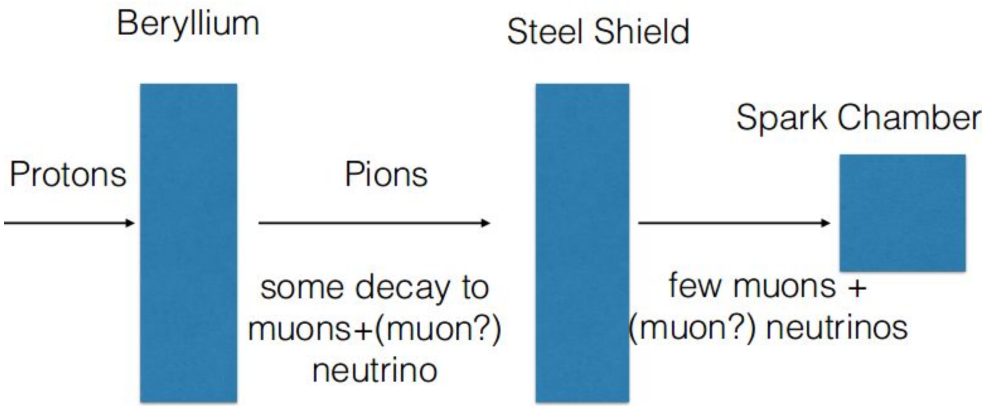
Jack Steinberger
Prize share: 1/3

The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz and Jack Steinberger *"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino".*



Pauli, Nobel Prize portrait

The AGS Neutrino Experiment at Brookhaven, 1962



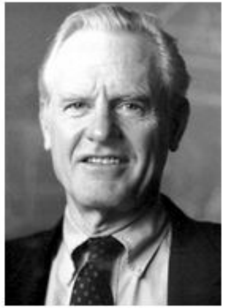
1930
Pauli
预言
中微子

The Nobel Prize in Physics 1990

深度非弹，夸克模型

Jerome I. Friedman

Prize share: 1/3



Henry W. Kendall

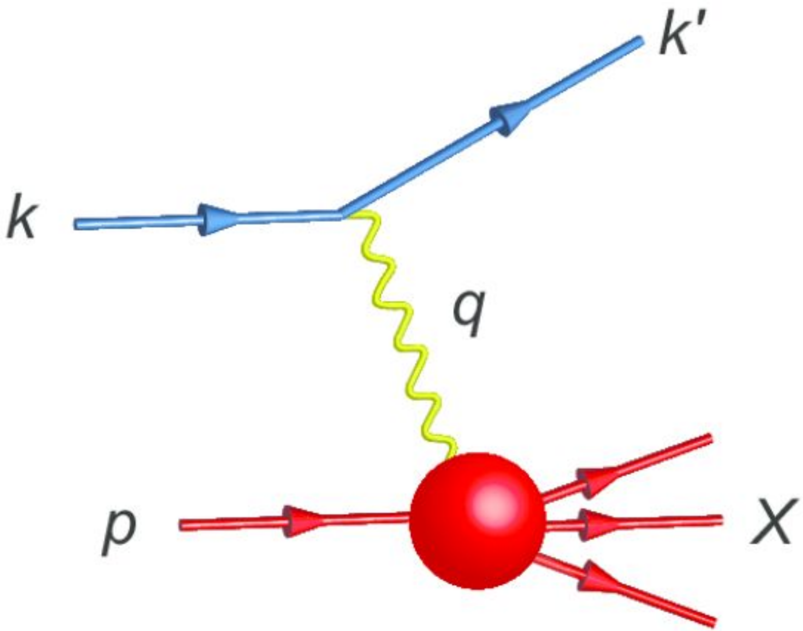
Prize share: 1/3

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"*.



电子、质子碰撞

The Nobel Prize in Physics 1992

多丝正比室

Drift Tube, Time Projection Chamber

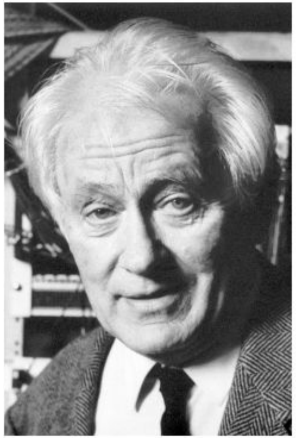
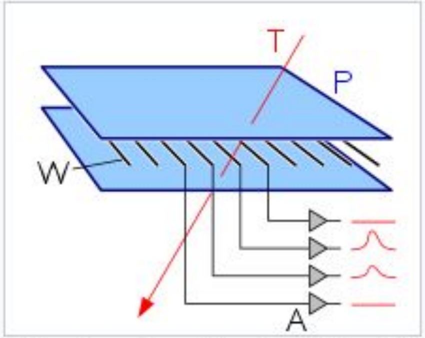


Photo from the Nobel Foundation archive.

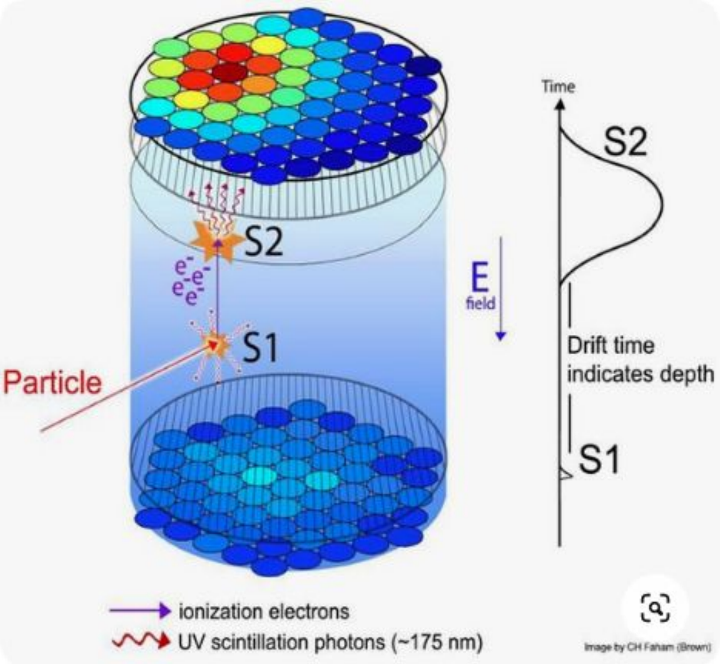
Georges Charpak

Prize share: 1/1



Wire chamber with wires (W) and cathode (−) plates (P). The particles flying through T will ionize gas atoms and set free a charge that an amplifier (A) collects (impulse at the output).

The Nobel Prize in Physics 1992 was awarded to Georges Charpak "for his invention and development of particle detectors, in particular the multiwire proportional chamber."



Dark Matter TPC detector: 3D position reconstruction: X-Y from top PMTs array and Z from drift time between S1 and S2.

The Nobel Prize in Physics 1995

Tau轻子 1977

探测中微子 电子反中微子 1956

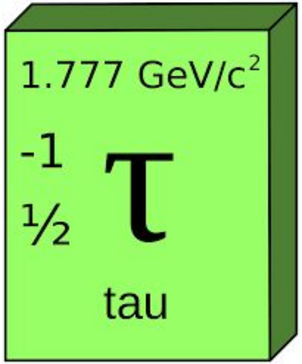
Martin L. Perl

Prize share: 1/2

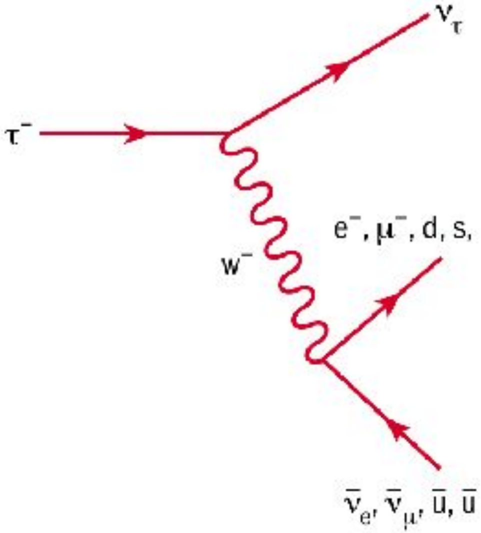
© University of California Regents

Frederick Reines

Prize share: 1/2



$$\bar{\nu}_e + p \rightarrow n + e^+$$



The Nobel Prize in Physics 1995 was awarded *"for pioneering experimental contributions to lepton physics"* jointly with one half to Martin L. Perl *"for the discovery of the tau lepton"* and with one half to Frederick Reines *"for the detection of the neutrino"*.

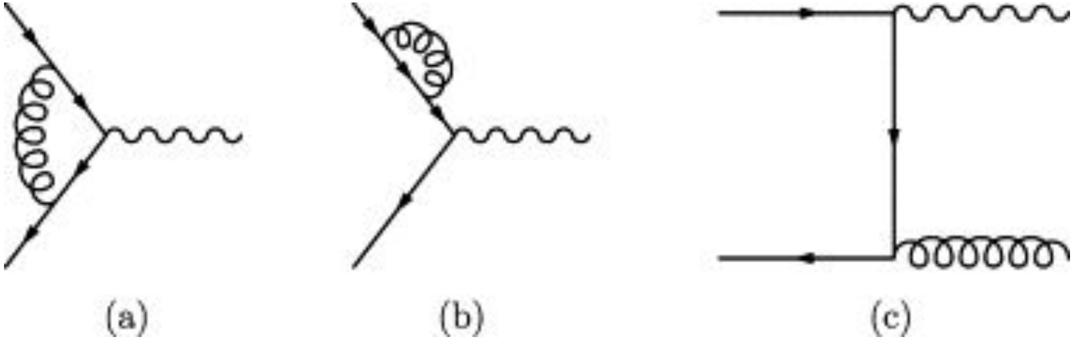
Stanford Positron Electron Asymmetric Rings, 1977.

The Nobel Prize in Physics 1999

标准模型重整化

Gerardus 't Hooft
Prize share: 1/2

Martinus J.G. Veltman
Prize share: 1/2



The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman *"for elucidating the quantum structure of electroweak interactions in physics"*

1/0-1/0: infinity cancellation, regularization
Meanifull predictions from theoretical calculations

The Nobel Prize in Physics 2004

QCD渐进自由

David J. Gross

Prize share: 1/3

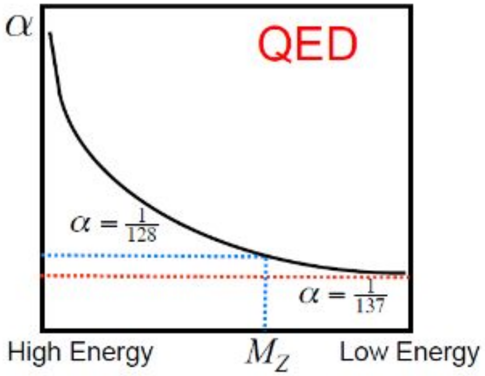
H. David Politzer

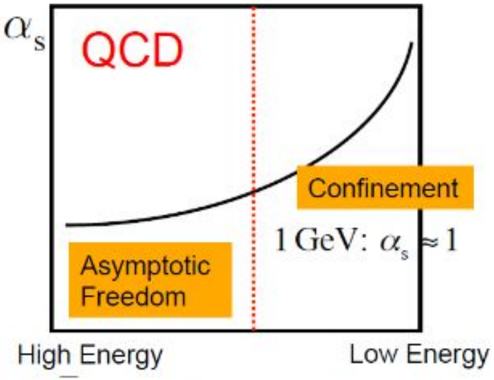
Prize share: 1/3

Frank Wilczek

Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.





$\sqrt{s} = 100\ \mathrm{GeV}, \quad \alpha_s = 0.12$

QED: U(1) 阿贝尔群

QCD: SU(3) 非阿贝尔群 -> 渐进自由，胶子自相互作用

The Nobel Prize in Physics 2008

Photo: University of Chicago

Yoichiro Nambu

Prize share: 1/2

© The Nobel Foundation Photo: U. Montan

Makoto Kobayashi

Prize share: 1/4

© The Nobel Foundation Photo: U. Montan

Toshihide Maskawa

Prize share: 1/4

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

对称性自发破缺
CKM, top夸克

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{\mathrm{CKM}}} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

质量本征态 ！= 弱相互作用本征态

The Nobel Prize in Physics 2013

Higgs Boson

Photo: A. Mahmoud

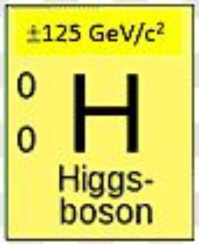
François Englert

Prize share: 1/2

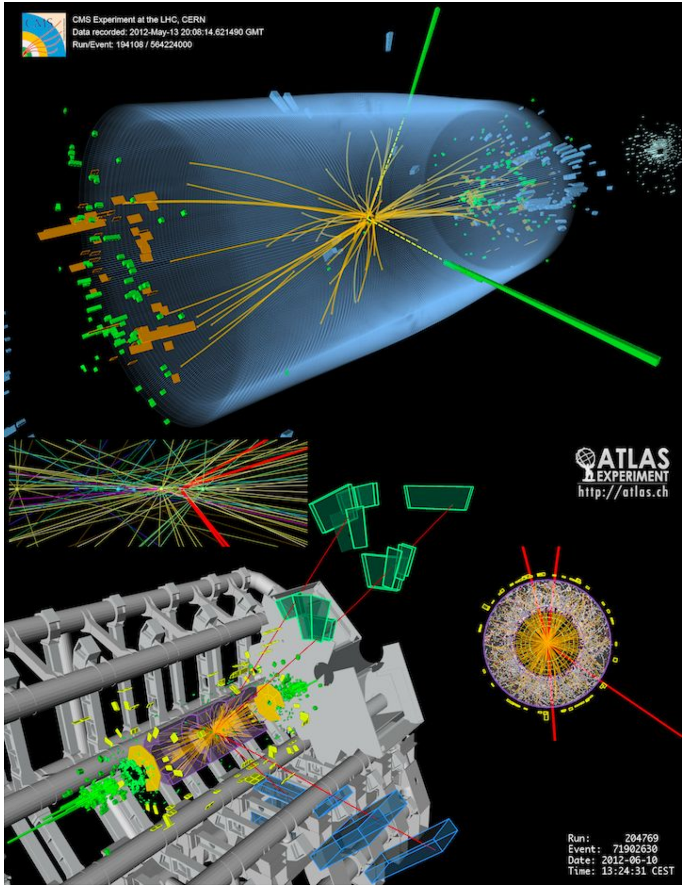
Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2



The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*



视频 2013@CERN

https://videos.cern.ch/

1. 前言
2. 高能物理简介
3. **大型强子对撞机(LHC)**
4. Higgs的发现
5. 中国未来对撞机(CEPC)
6. 其他对撞机
7. 高能物理中的机器学习
8. 总结与展望

Large Hadron Collider

世界上能量最高对撞机，2012年发现希格斯粒子。

CMS（紧致缪子螺线圈）是LHC上4个对撞点实验之一，研究物质世界最深层次的规律。包含40多国家，200多个研究单位，3000多位科学家。

北大高能组1996年加入CMS国际合作组。

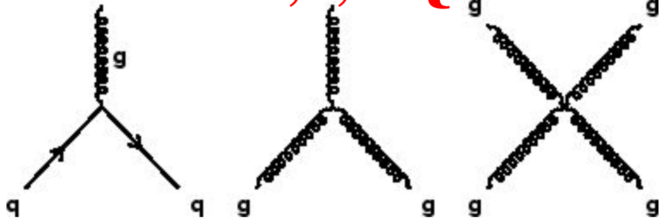
QED vs QCD

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij}\right)\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$
$$G^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g f^{abc}\mathcal{A}^b_\mu \mathcal{A}^c_\nu\,,$$

a=1…8,

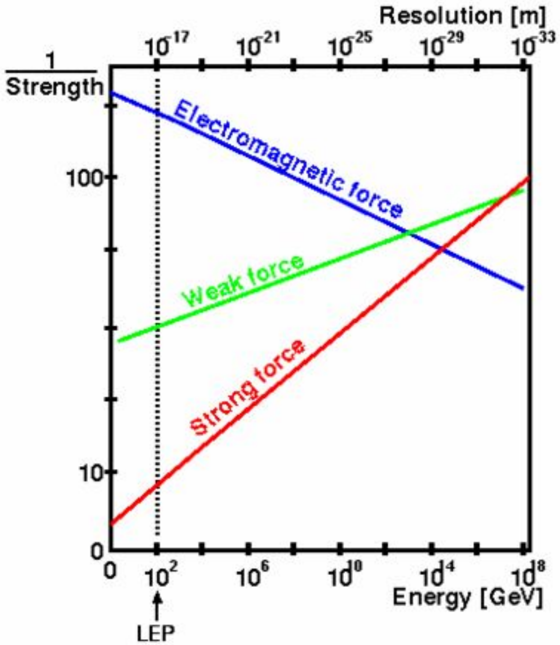
i=1,2,3 QCD colors



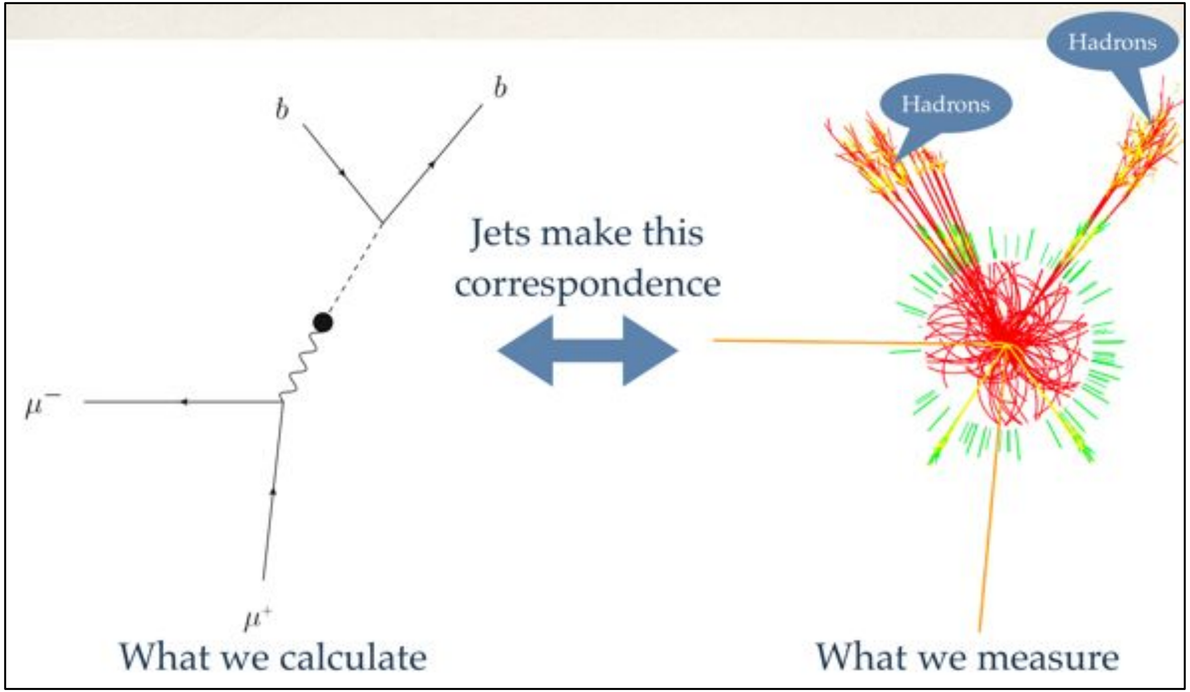
Self-interactions

$$\alpha_{em} = \frac{e^2}{4\pi} \sim \frac{1}{137}$$

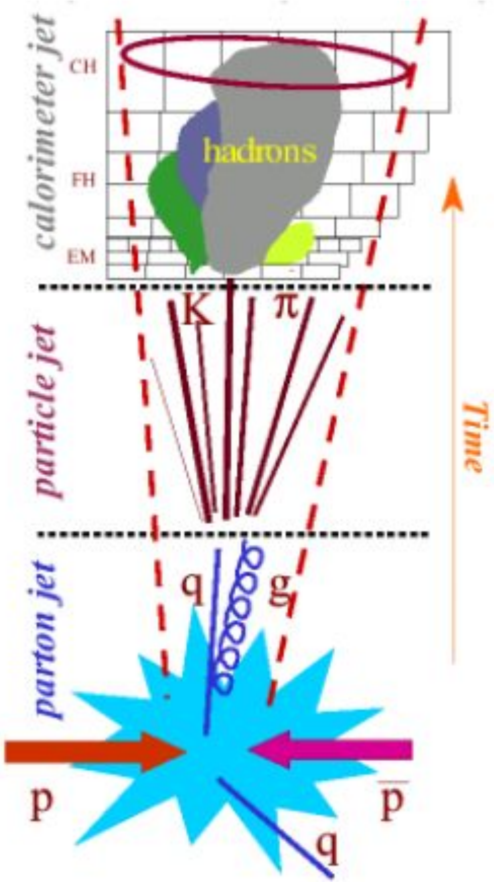
$$\alpha_{QCD}(100GeV) = \frac{g_{s^2}}{4\pi} \sim 0.13$$



Parton, Jet

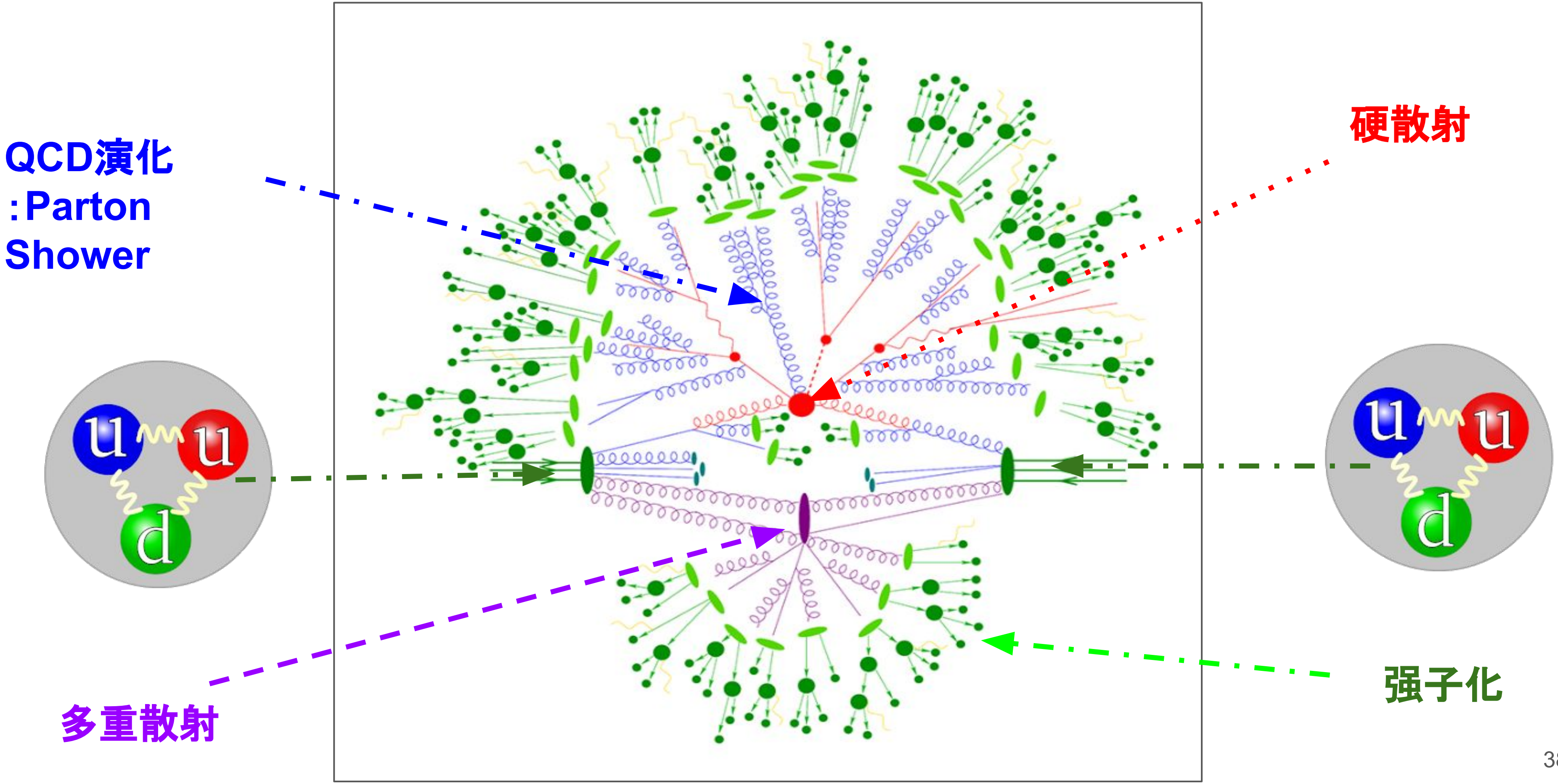


b
b
μ⁻
μ⁺
What we calculate
Jets make this correspondence
Hadrons
Hadrons
What we measure

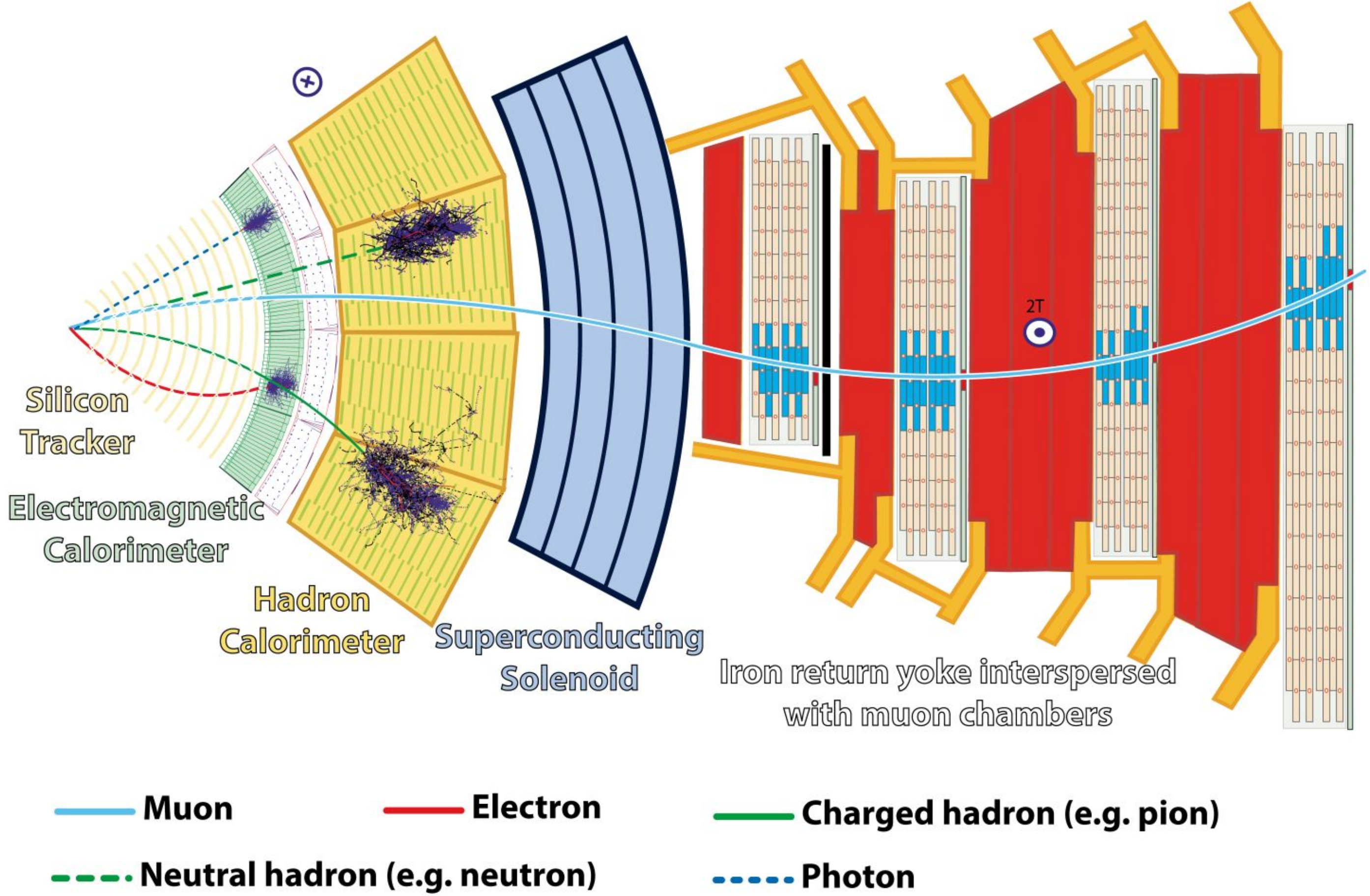


calorimeter jet
CH
FH
EM
hadrons
K
π
particle jet
parton jet
q
g
p
p̄
q
Time

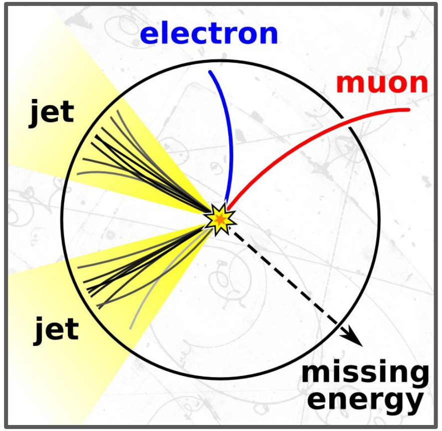
高能对撞



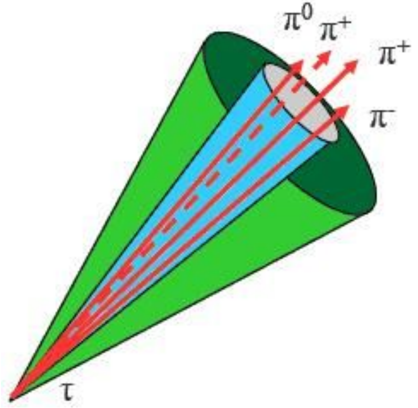
高能对撞机：探测⟶信息



2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with muon chambers
Muon
Electron
Charged hadron (e.g. pion)
Neutral hadron (e.g. neutron)
Photon

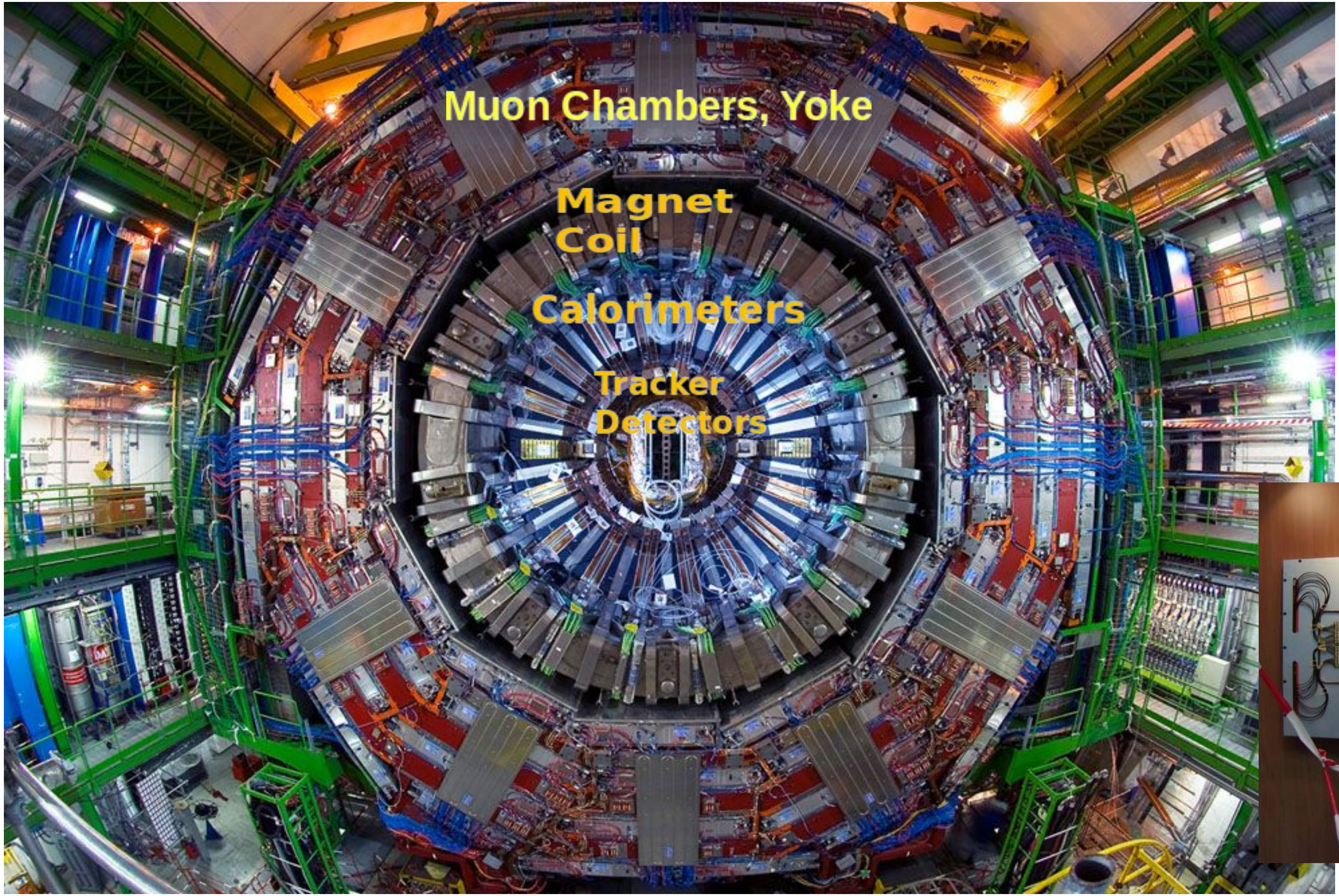


electron
muon
jet
jet
missing energy



π^0 π^+
π^+
π^-
τ

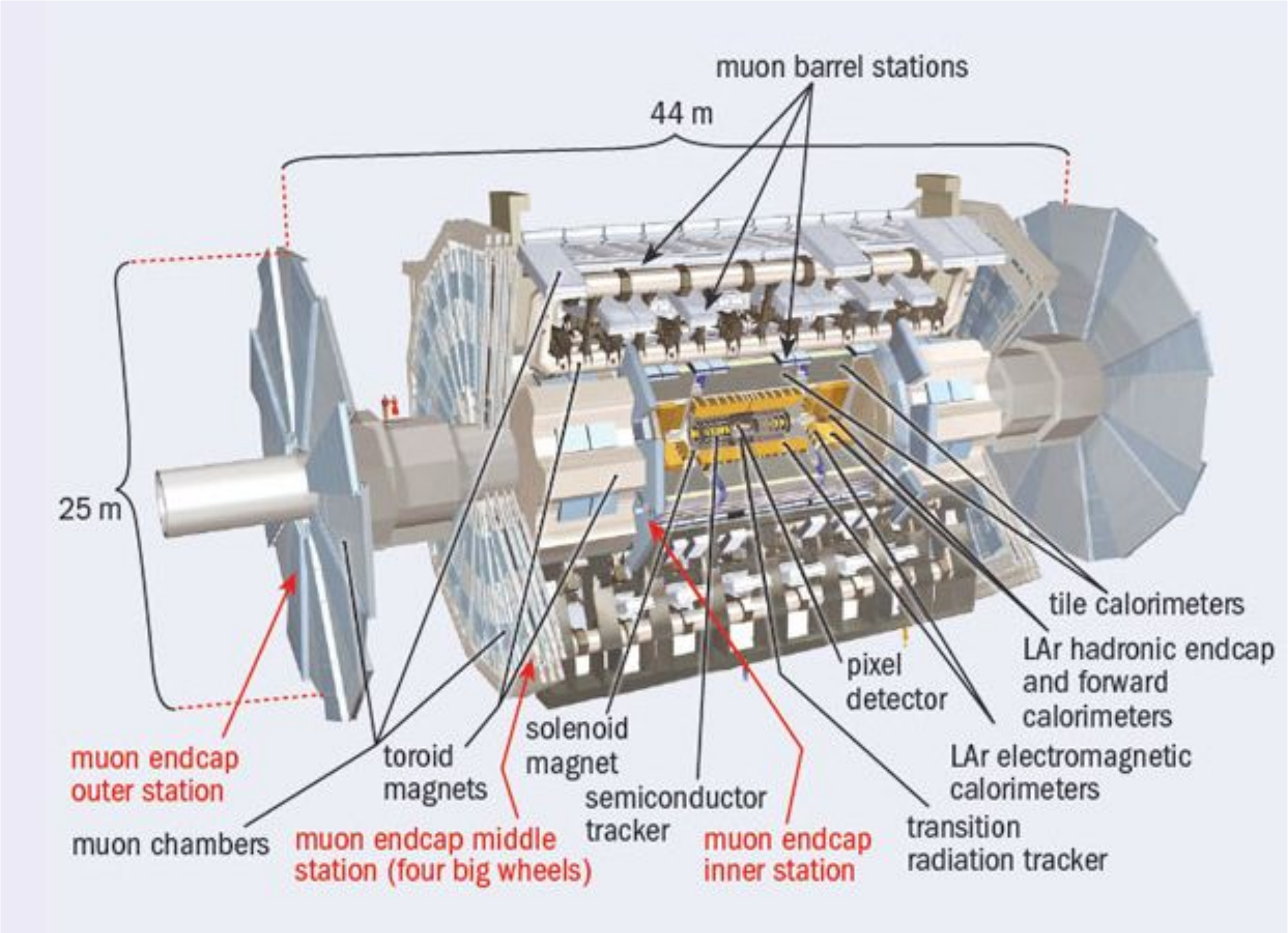
高能对撞机：CMS探测器



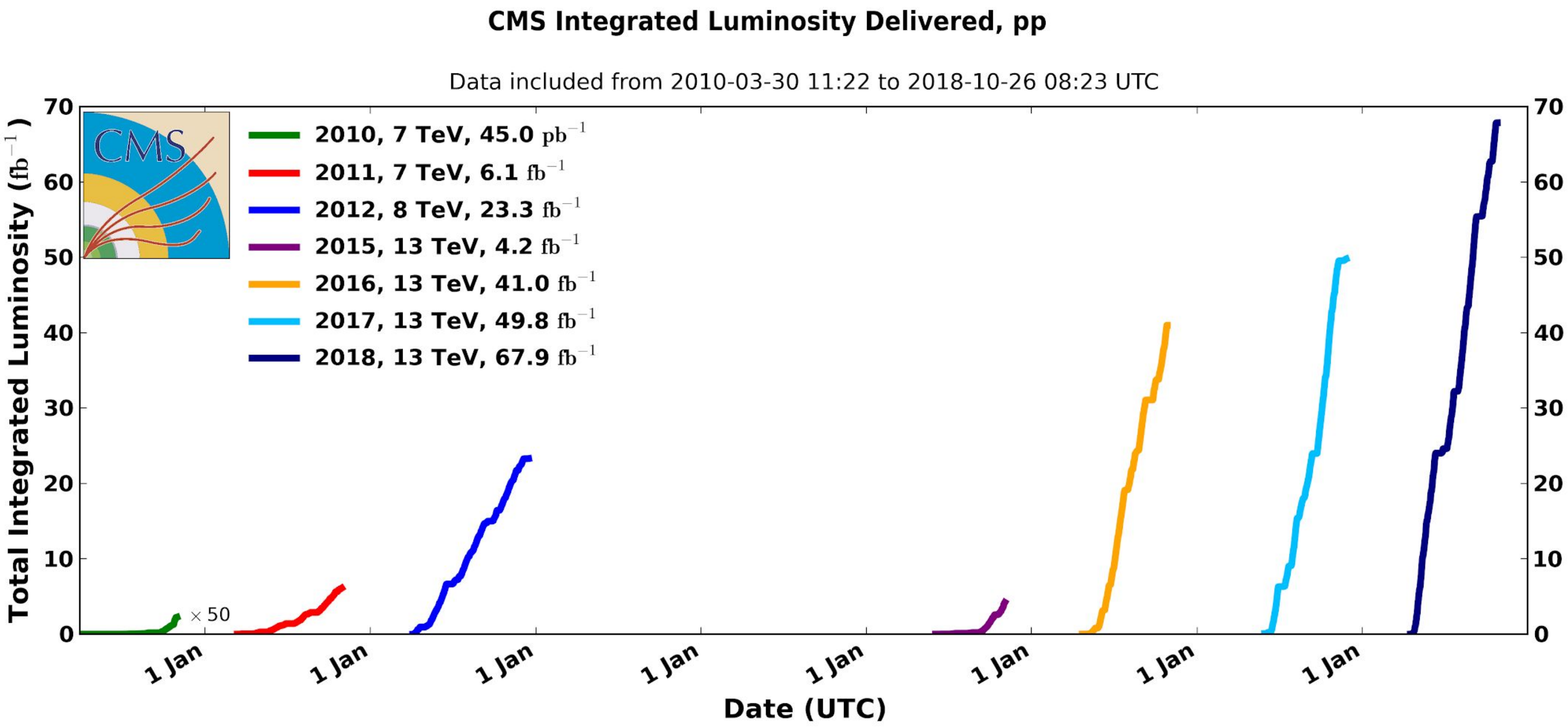
weight: 12500 t
overall diameter: 15 m
overall length: 21.6 m

照相机？
录音机？

高能对撞机：ATLAS探测器

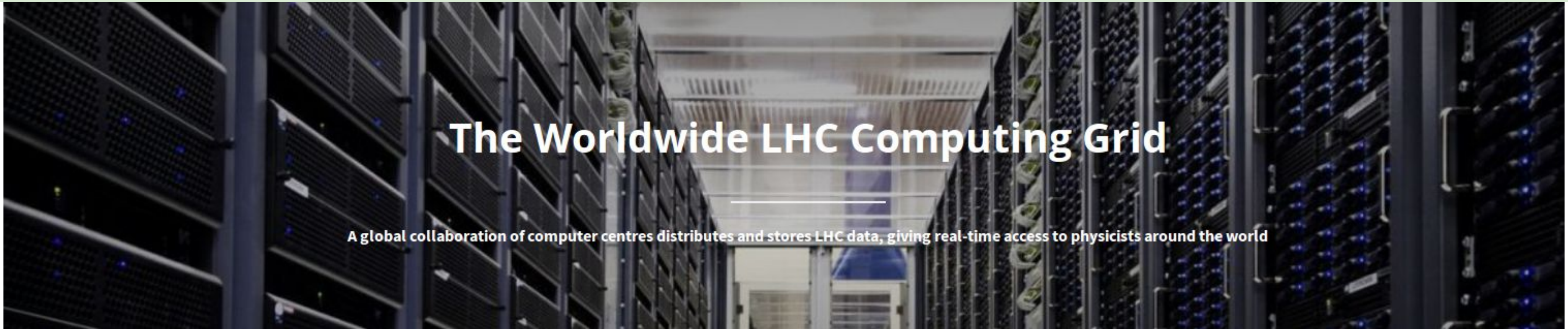


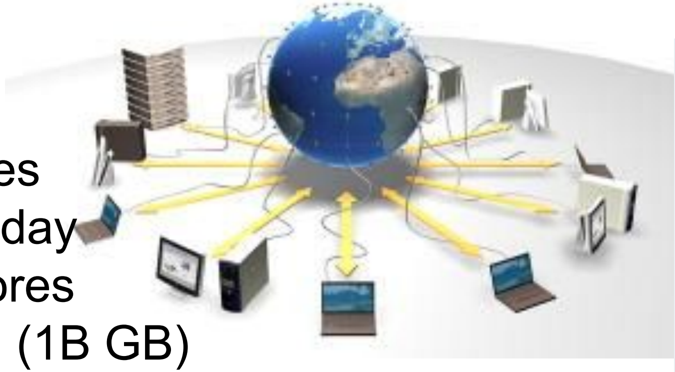
LHC数据亮度



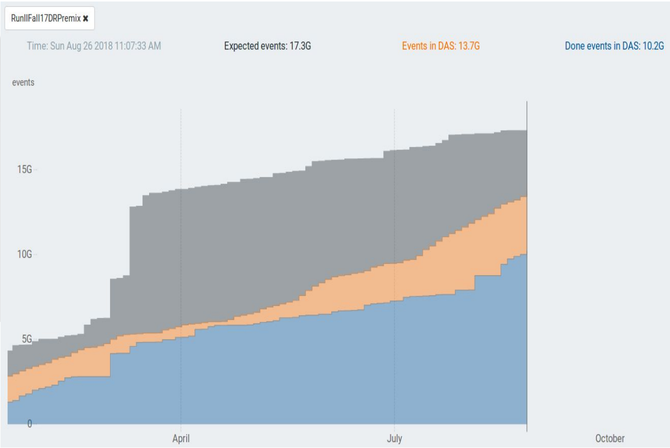
CMS Integrated Luminosity Delivered, pp
Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC
CMS
2010, 7 TeV, 45.0 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
2015, 13 TeV, 4.2 fb^{-1}
2016, 13 TeV, 41.0 fb^{-1}
2017, 13 TeV, 49.8 fb^{-1}
2018, 13 TeV, 67.9 fb^{-1}
× 50
Total Integrated Luminosity (fb^{-1})
Date (UTC)
1 Jan
0
10
20
30
40
50
60
70

高能对撞机：大数据



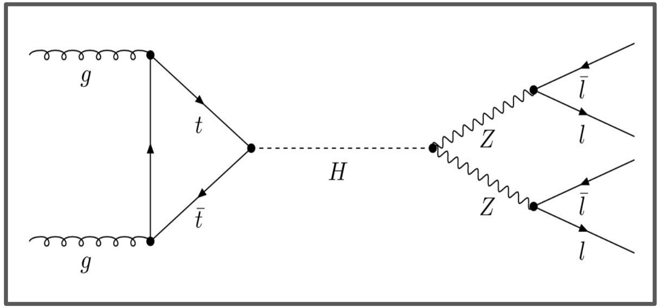


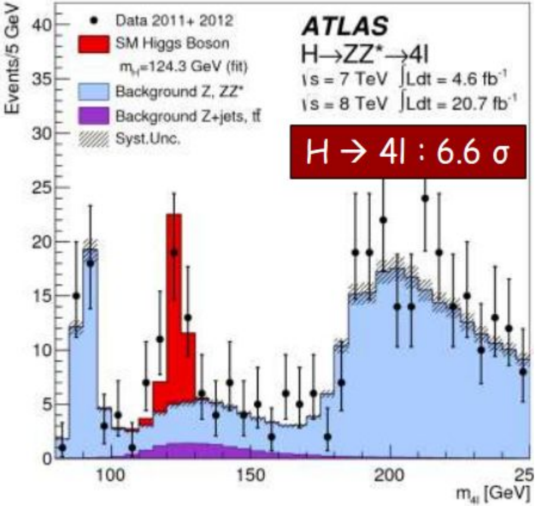
42 countries
170 computing centres
Over 2 million tasks/ day
1 million computer cores
1 exabyte of storage (1B GB)

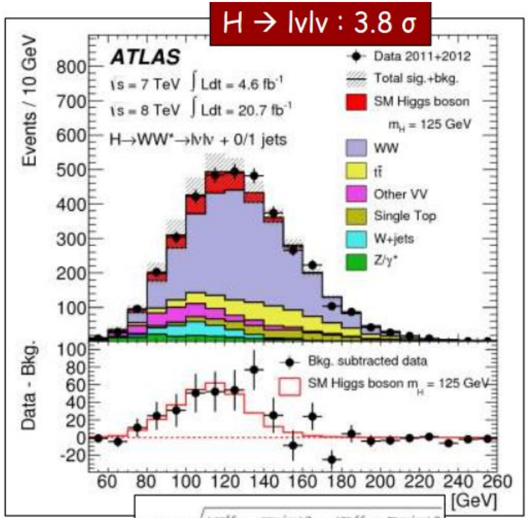


CMS： 15B events in 8 months

高能对撞机：大数据







$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\rm miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{\rm miss})^2}$$

Needles in a haystack

In ATLAS, up to July 4, 2012:

A million billion collisions

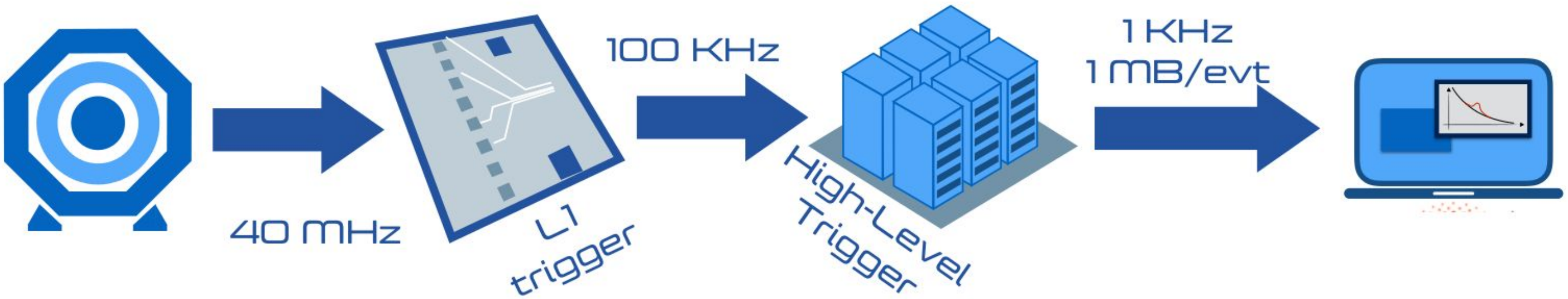
4.2 billion events analyzed

240,000 Higgs particles produced

~350 diphoton Higgs events detected

~8 four-lepton Higgs events detected

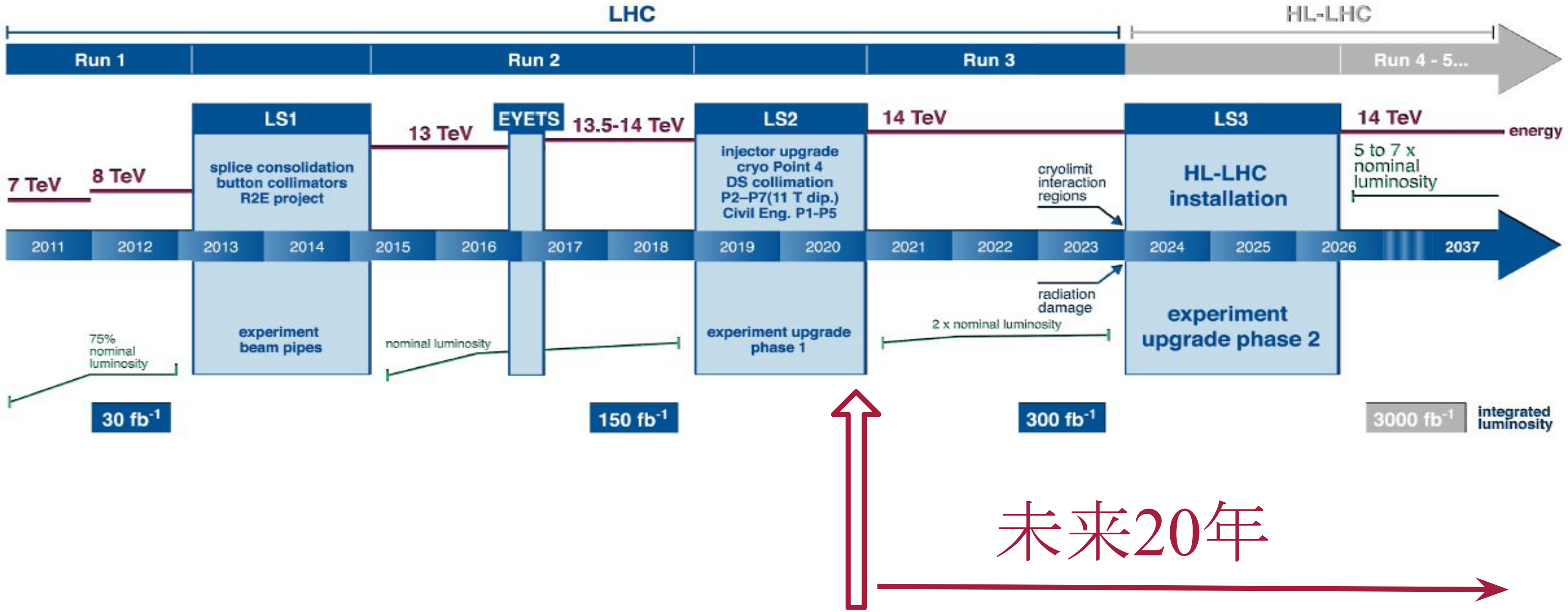
LHC数据流



- **L1 trigger:** local, hardware based, on FPGA, @experiment site
- **HLT:** local/global, software based, on CPU, @experiment site
- **Offline:** global, software based, on CPU, @CERN T0
- **Analysis:** user-specific applications running on the grid

机器学习：粒子鉴别；信号挖掘；快速判断；自主学习

LHC及HL-LHC时间线



视频 LHC

https://videos.cern.ch/

1. 前言
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6. 其他对撞机
7. 高能物理中的机器学习
8. 总结与展望

1964年

1

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

2

Volume 12, number 2 PHYSICS LETTERS 15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

3

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

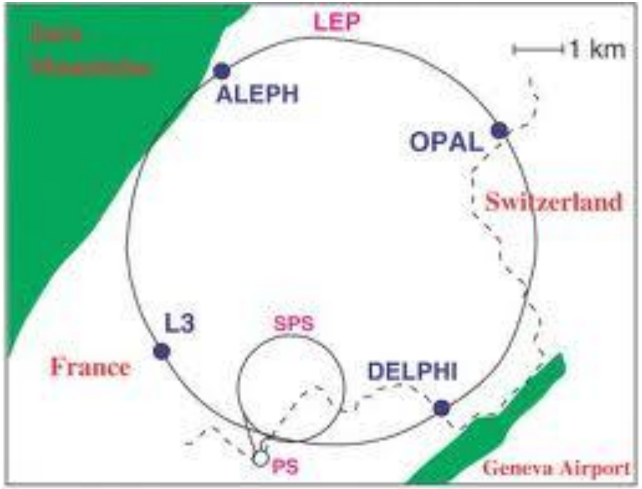
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

4

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

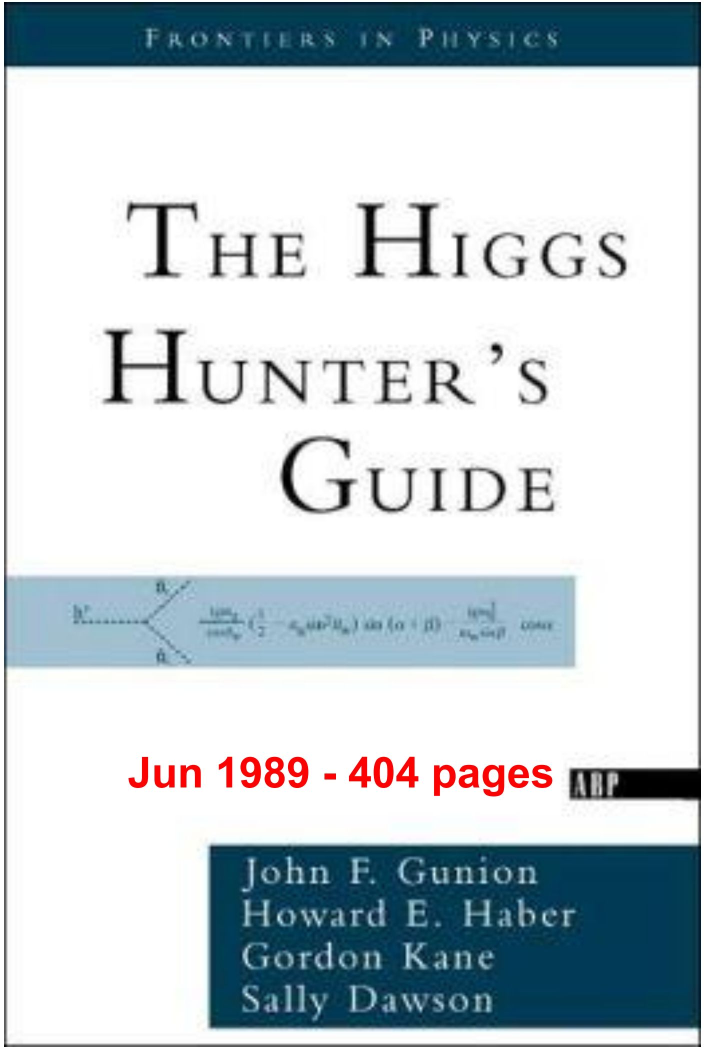
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)



CERN LEP
(The Large Electron-Positron Collider)
1989.7-2000.11: 91-209GeV
115GeV Higgs hint before shutdown?

Fermilab Tevatron, US
1983-2011
Proton-antiproton collider
1.8/1.96TeV
1995 Top quark discovery



Jun 1989 - 404 pages

A Phenomenological Profile of the Higgs Boson

John R. Ellis (CERN) , Mary K. Gaillard (CERN & Orsay, LPT) , Dimitri V. Nanopoulos (CERN)

Oct 1975 - 62 pages

Nucl.Phys. B106 (1976) 292
DOI: 10.1016/0550-3213(76)90382-5
CERN-TH-2093

So let me come finally to 1975, which was when the hunt for the Higgs boson began, and in particular to the last sentence of the paper published in 1976 by John Ellis, Mary K. Gaillard and Dimitri Nanopoulos [24]: 'We should perhaps finish with an apology and a caution. We apologize to experimentalists for not having any idea what is the mass of the Higgs boson, unlike the case with charm, and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons, we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.'

The Nobel Prize in Physics 2013

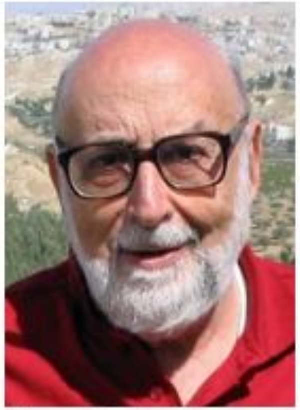


Photo: Pnicolet via Wikimedia Commons

François Englert

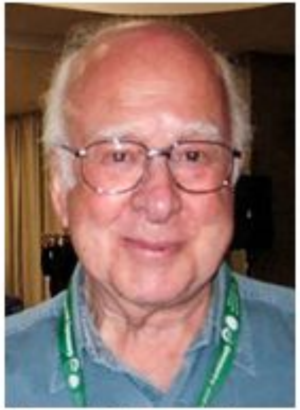
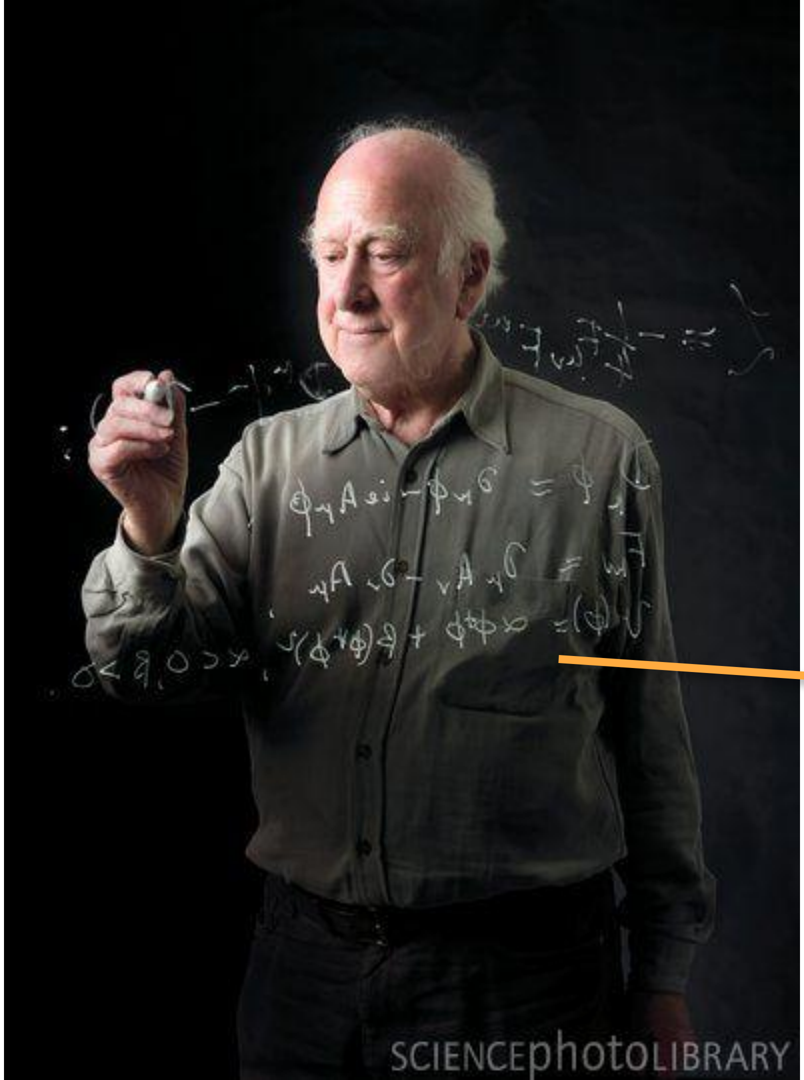


Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

An accepted definition for a "discovery": a 5-sigma level of certainty 99.99994 %.

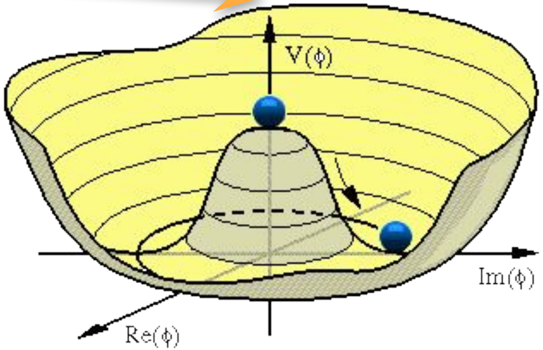


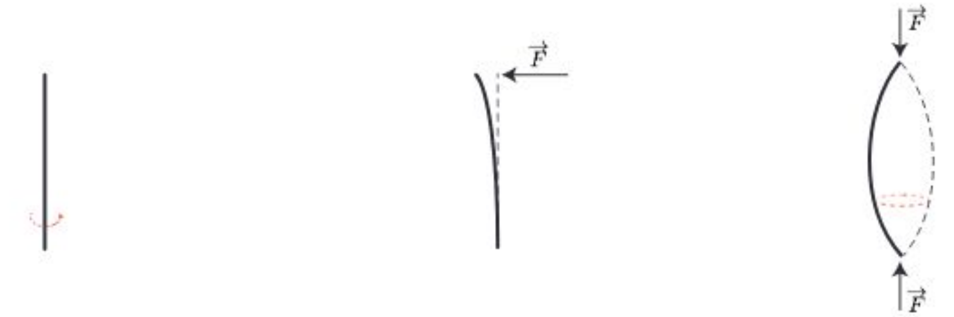
Spontaneous Symmetry Breaking
in
Quantum Gauge Field Theory

Generating V mass
while keeping Gauge Symmetry
and
avoiding massless goldstone

$$Higgs - Potential:$$

$$\alpha\phi\phi^{*} + \beta(\phi\phi^{*})^{2}, \alpha < 0, \beta > 0$$



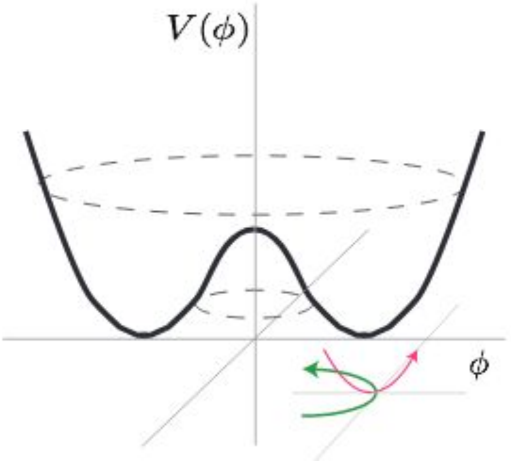


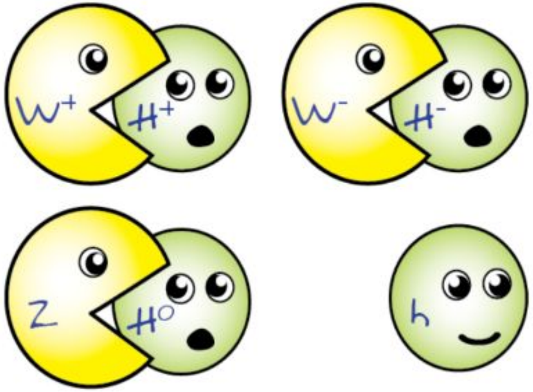
(a) Unbroken symmetry: the rod in its original state is rotationally invariant

(b) Explicitly broken symmetry: the rod bends due to an external force and loses rotational invariance

(c) Spontaneously broken symmetry: the rod bends in an arbitrary direction and loses rotational invariance

无质量
Goldstone





规范场情形，W、Z吞并了
Higgs分量

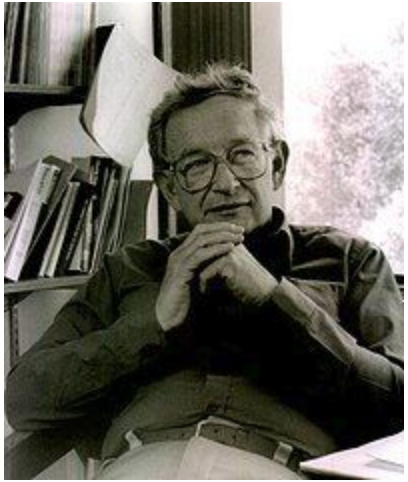
Deep root from Condensed Matter Physics

MY LIFE AS A BOSON: THE STORY OF "THE HIGGS"

My life as a boson
by Peter Higgs

PETER HIGGS
Department of Physics and Astronomy
University of Edinburgh, Scotland

The story begins in 1960, when Nambu, inspired by the BCS theory of superconductivity, formulated chirally invariant relativistic models of interacting massless fermions in which spontaneous symmetry breaking generates fermionic masses (the analogue of the BCS gap). Around the same time Jeffrey Goldstone discussed spontaneous symmetry breaking in models con-

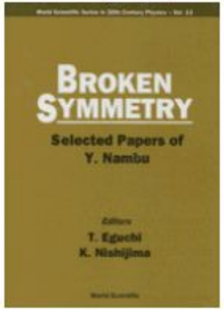


Philip W. Anderson
1977 Nobel Physics Prize

Anderson continued with this suggestion, which in the context of the paper I would describe as speculation: 'The Goldstone zero-mass difficulty is not a serious one, because we can probably cancel it off against an equal Yang-Mills zero-mass problem.' But why is that a speculation? He never discussed the theorem, he did not say what was wrong with it, and he did not discuss explicitly any relativistic model.

Deep root from Condensed Matter Physics

Autobiography in



One day before publication of the BCS paper, Bob Schrieffer, still a student, came to Chicago to give a seminar on the BCS theory in progress. . . . I was very much disturbed by the fact that their wave function did not conserve electron number. It did not make sense. . . . At the same time I was impressed by their boldness and tried to understand the problem.

Schrieffer joined Chicago faculty for a year

PHYSICAL REVIEW VOLUME 117, NUMBER 3 FEBRUARY 1, 1960

Quasi-Particles and Gauge Invariance in the Theory of Superconductivity*

YOICHIRO NAMBU
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois

(Received July 23, 1959)

it took him two years

The gauge invariance, to the first order in the external electromagnetic field, can be maintained in the quasi-particle picture by taking into account a certain class of corrections to the charge-current operator due to the phonon and Coulomb interaction. In fact, generalized forms of the Ward identity are obtained between certain vertex parts and the self-energy. The Meissner effect calculation is thus rendered strictly gauge invariant, but essentially keeping the BCS result unaltered for transverse fields.

6. THE COLLECTIVE EXCITATIONS

In order to understand the mechanism by which gauge invariance was restored in the calculation of the Meissner effect, and also to solve the integral equations

...

We interpret this as describing a pair of a particle and an antiparticle interacting with each other to form a bound state with zero energy and momentum $q=p'-p=0$.

"zero modes"

ACKNOWLEDGMENT

We wish to thank Dr. R. Schrieffer for extremely helpful discussions throughout the entire course of the

Photo: University of Chicago

Yoichiro Nambu

Prize share: 1/2

2008 Nobel Physics Prize

How to search for a Higgs particle?

Not so easy!

Needles in a haystack

In ATLAS, up to July 4, 2012:

A million billion collisions

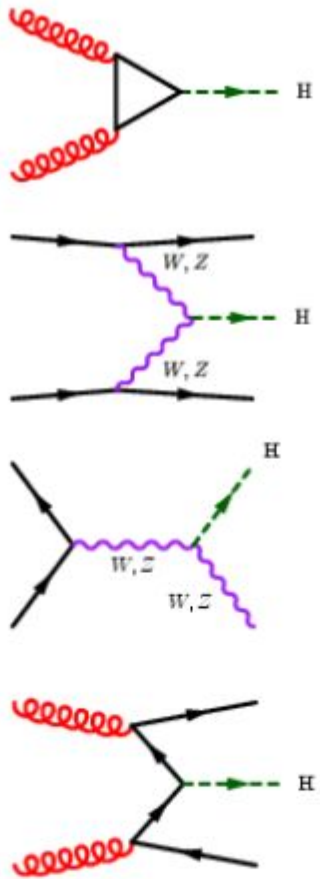
4.2 billion events analyzed

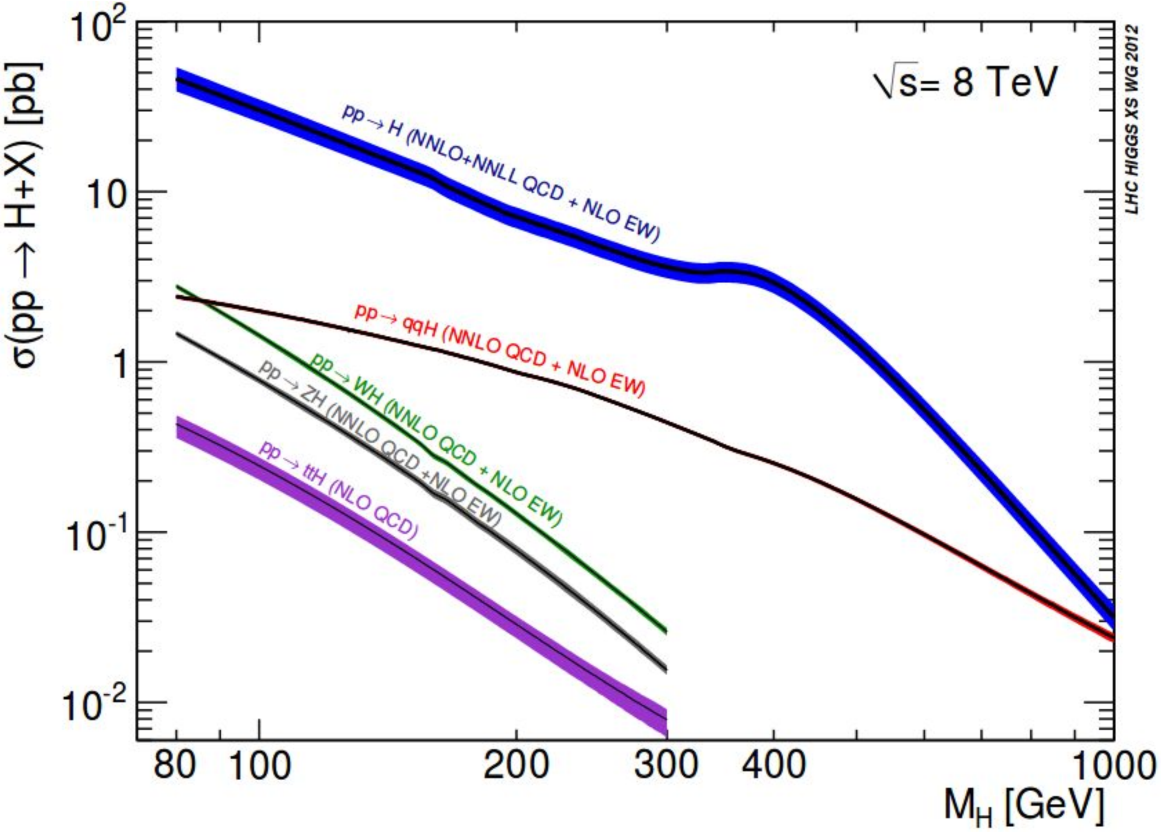
240,000 Higgs particles produced

~350 diphoton Higgs events detected

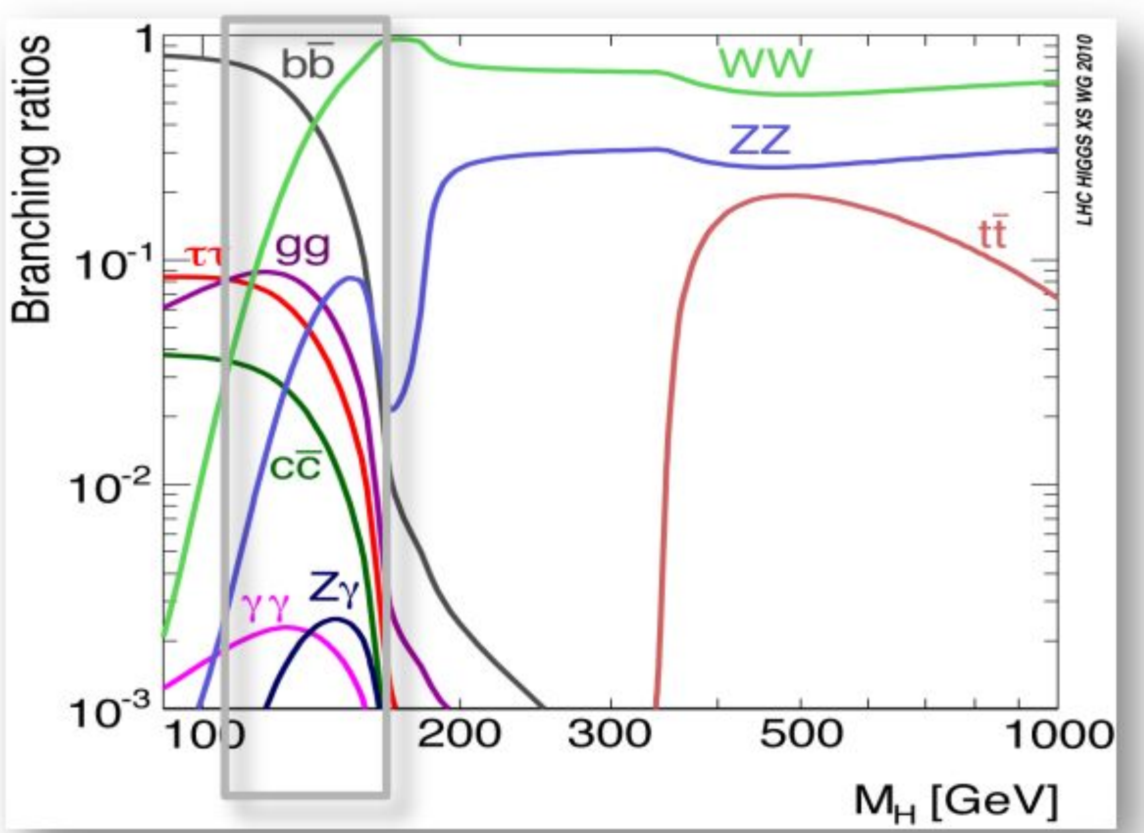
~8 four-lepton Higgs events detected

Higgs Production



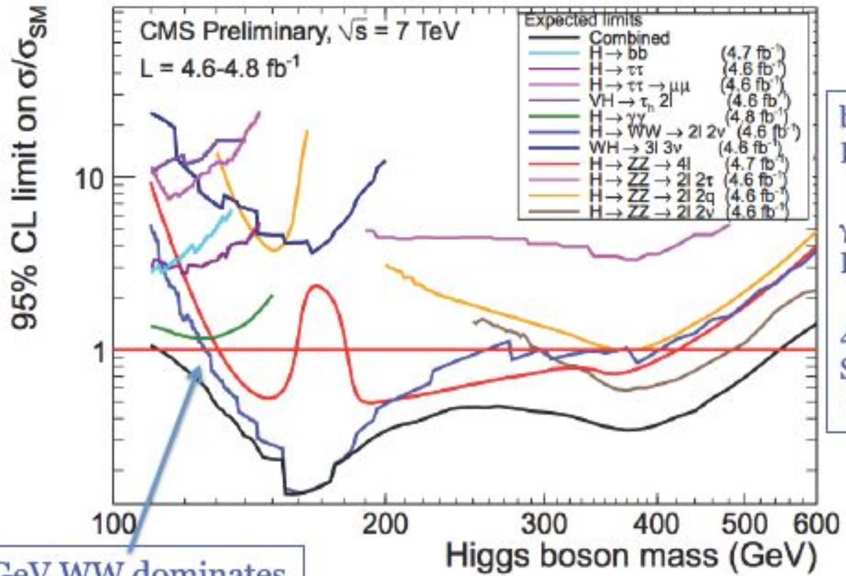


Higgs Decay



Branching ratios
1
10^{-1}
10^{-2}
10^{-3}
$b\bar{b}$
WW
ZZ
$t\bar{t}$
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
100
200
300
500
1000
M_H [GeV]
LHC HIGGS XS WG 2010

Higgs search strategy



bb/ττ/WW
Poor mass resol

γγ and 4l
Excellent mass resol

4l is ~backg free
Single event has
an impact

Above ~123 GeV WW dominates
At lower masses γγ takes over

m_H < 135 GeV
H -> γγ exclusion and discovery
H -> 4l exclusion and discovery
H -> WW/ττ/bb

140 < m_H < 180 GeV
H -> WW->2l2ν
ZZ->4l also

m_H>180 GeV
H ->ZZ channels for discovery
H->WW->lνjj

中国科学：物理学 力学 天文学 2013 年 第 43 卷 第 10 期：1216–1235
SCIENTIA SINICA Physica, Mechanica & Astronomica phys.scichina.com
《中国科学》杂志社 SCIENCE CHINA PRESS
北京大学物理百年华诞纪念专刊 · 评述

LHC 上的重大进展 —— 发现 Higgs 粒子

冒亚军 *，班勇，李强 *，王大勇，徐子骏，郭威，温一闻，张照茹，李晶
北京大学物理学院核物理与核技术国家重点实验室，北京 100871
* 联系人：冒亚军，E-mail: maoyj@pku.edu.cn; 李强，qliphy0@pku.edu.cn

表 3 CMS寻找125GeV附近的轻的SM Higgs所采用的分析道[49]。在CMS综合多个分析道测量Higgs质量、耦合等性质的最新研究 [29]中，还加入了比如VH标记的$\gamma\gamma$, WW和$\tau\tau$道，ttH标记的$b\bar{b}$道，并且$ZZ \to 4l$道被分为喷注数目大于等于2和小于2两类，等等。

H 衰变模式	H 产生类	m_H 区域 (GeV)	m_H 测量精度
$\gamma\gamma$	无标记（untagged）	110–150	1–2%
	VBF-标记	110–150	1–2%
$ZZ \to 4l$	遍举（inclusive）	110–180	1–2%
$WW \to l\nu l\nu$	0 or 1 jet	110–160	20%
	VBF-标记	110–160	20%
$\tau\tau$	0 or 1 jet	110–145	20%
	VBF-标记	110–145	20%
bb	VH-标记	110–135	10%

表 4 CMS通过玻色子衰变信号寻找质量145GeV以上的SM Higgs所采用的分析道 [50]。

H 衰变模式	H 产生类	m_H 区域 [GeV]	m_H 测量精度
$WW \to l\nu l\nu$	0/1-喷注	145–600	20%
$WW \to l\nu l\nu$	VBF标记	145–600	20%
$WW \to l\nu qq$	无标记	180–600	5–15%
$ZZ \to 4l(l = e, \mu)$	遍举	145–1000	1–2%
$ZZ \to 2l2\tau(l = e, \mu)$	遍举	200–1000	10–15%
$ZZ \to 2l2q$	遍举	200–600	3%
$ZZ \to 2l2\nu$	无标记	200–1000	7%
$ZZ \to 2l2\nu$	VBF-标记	200–1000	7%

LHC ERA The path to Higgs discovery

From C.S. Wu

- *EPS-HEP 2011 (July)*
- *Lepton-Photon 2011 (August)*
- *CERN 2011 December Council Meeting*

- *Moriond 2012 (March)*
- *ICHEP 2012 (July)*
- *Discovery publications, July 2012 (submitted)* **5 σ !** *ATLAS CMS*
- *HCP 2012 (November)*
- *CERN 2012 December Council Meeting*

- *Moriond QCD 2013 (March)* **> 10 σ!** *(ATLAS)*
- *EPS 2013 (July) Spin, parity and Couplings measured.*

LHC ERA

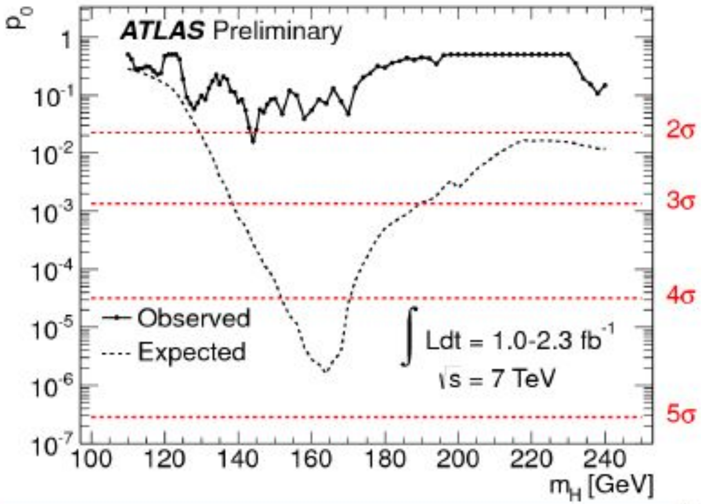
EPS-HEP 2011 (July)
Lepton-Photon 2011 (August)

At EPS both ATLAS and CMS see >2σ excess at low mass in H→WW→lνlν channel

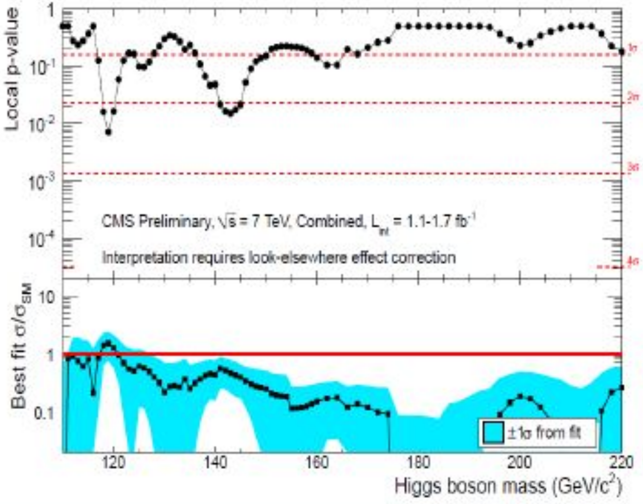
p_0: probability that the background fluctuates to the observed data (or higher)

p_0 = Local p-value

ATLAS H→γγ, ττ, WW(lνlν), ZZ(4l, llνν, llqq)



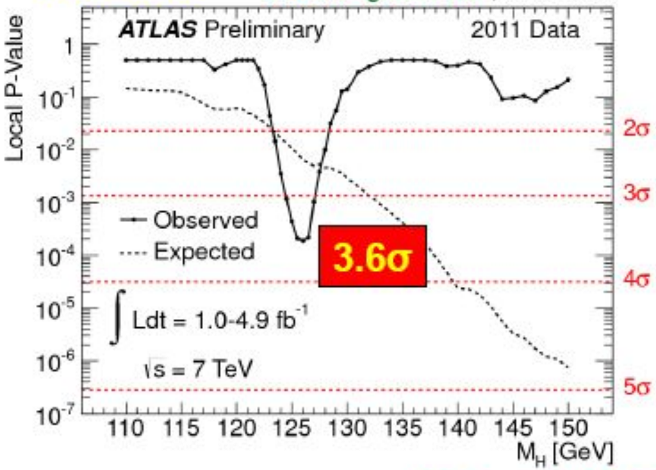
H→γγ, bb, ττ, WW(lνlν), ZZ(4l, llττ, llνν, llqq)



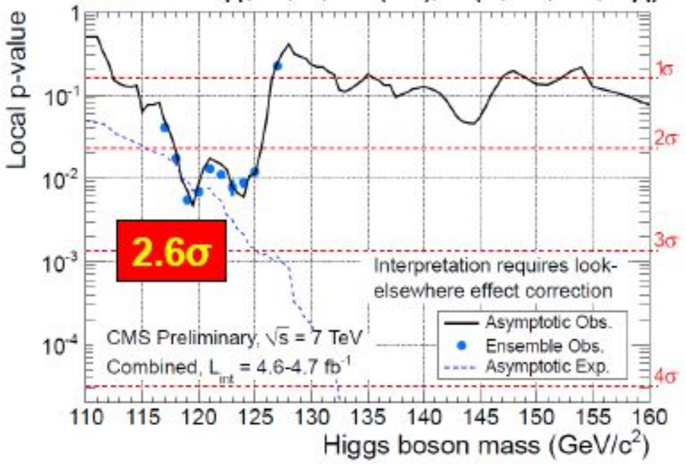
ATLAS (LP11)	**CMS (LP11)**
largest local excess: 2.1σ at 145 GeV	***largest local excess: 2.3σ at 120 GeV***

LHC ERA CERN Council (Dec 2011) Higgs combined

ATLAS H→γγ, ττ, WW(lvlv, lvqq), ZZ(4l, llvv, llqq, llbb)
red: $5\,fb^{-1}$ green: $1\,fb^{-1}$, black: $2\,fb^{-1}$



CMS H→γγ, bb, ττ, WW(lvlv), ZZ(4l, llττ, llvv, llqq)



Largest local excess: 3.6σ at 126 GeV

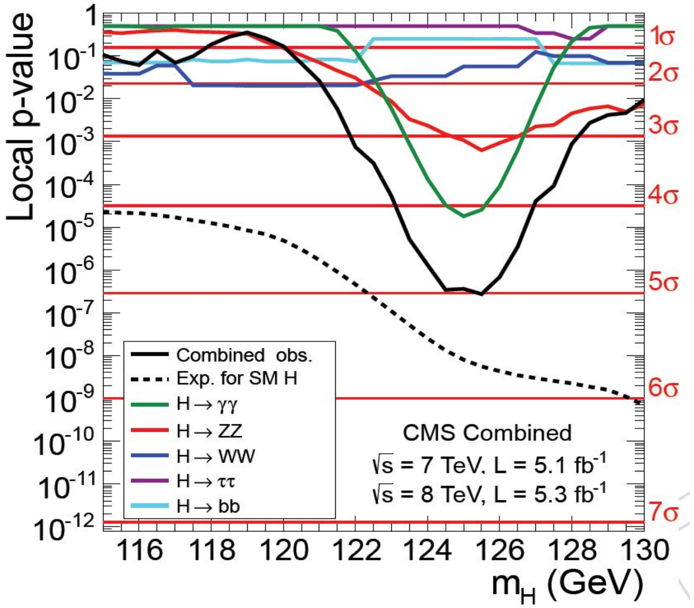
Largest local excess: 2.6σ at ~120 GeV

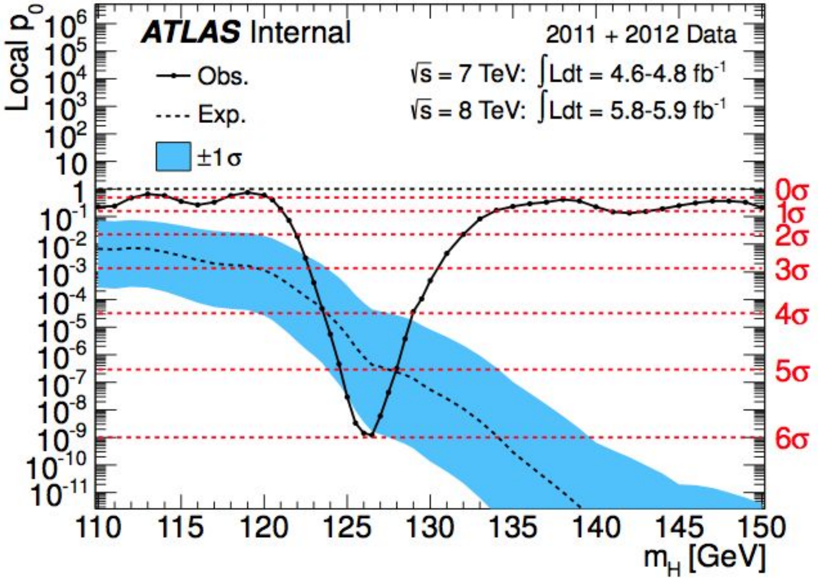
Fabiola Gianotti

"Tantalizing hints"

Guido Tonelli

July 4th, 2012: Discovery of a new boson





Combined significance 5.0σ for CMS and 5.9σ for ATLAS

125.3+-0.4+-0.5GeV

0.87+-0.23

126.0+-0.4+-0.4GeV

1.4+-0.3

2012.07 Big Discovery

arXiv.org > hep-ex > arXiv:1207.7214

Search or

High Energy Physics - Experiment

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC

The ATLAS Collaboration

(Submitted on 31 Jul 2012)

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^-1 collected at sqrt(s) = 7 TeV in 2011 and 5.8 fb^-1 at sqrt(s) = 8 TeV in 2012. Individual searches in the channels H->ZZ^(*)->llll, H->gamma gamma and H->WW->e nu mu nu in the 8 TeV data are combined with previously published results of searches for H->ZZ^(*), WW^(*), bbbar and tau^+tau^- in the 7 TeV data and results from improved analyses of the H->ZZ^(*)->llll and H->gamma gamma channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 +/- 0.4(stat) +/- 0.4(sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7x10^-9, is compatible with the production and decay of the Standard Model Higgs boson.

Comments:	24 pages plus author list (39 pages total), 12 figures, 7 tables, submitted to Physics Letters B
Subjects:	**High Energy Physics - Experiment (hep-ex)**
Report number:	CERN-PH-EP-2012-218
Cite as:	arXiv:1207.7214v1 [hep-ex]

5.9sigma

Phys.Lett. B716 (2012) 1-29

arXiv.org > hep-ex > arXiv:1207.7235

Search or Art

High Energy Physics - Experiment

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration

(Submitted on 31 Jul 2012)

Results are presented from searches for the standard model Higgs boson in proton-proton collisions at sqrt(s)=7 and 8 TeV in the CMS experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 inverse femtobarns at 7 TeV and 5.3 inverse femtobarns at 8 TeV. The search is performed in five decay modes: gamma gamma, ZZ, WW, tau tau, and b b-bar. An excess of events is observed above the expected background, a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, gamma gamma and ZZ; a fit to these signals gives a mass of 125.3 +/- 0.4 (stat.) +/- 0.5 (syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

Comments:	Submitted to Phys. Lett. B
Subjects:	**High Energy Physics - Experiment (hep-ex)**
Report number:	CMS-HIG-12-028; CERN-PH-EP-2012-220
Cite as:	arXiv:1207.7235v1 [hep-ex]

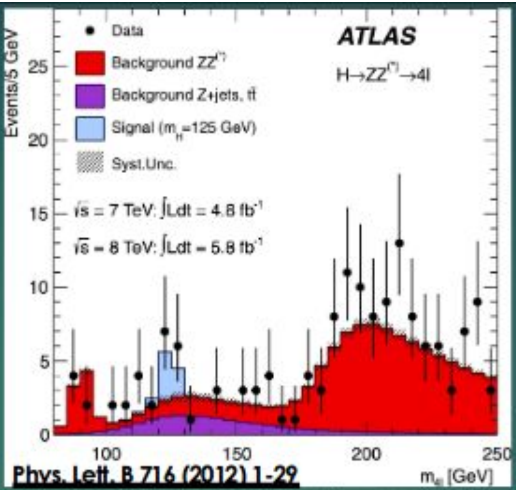
5.0sigma

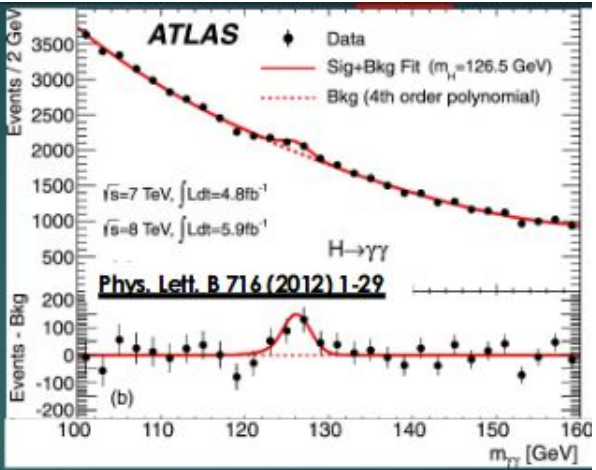
Phys. Lett. B 716 (2012) 30

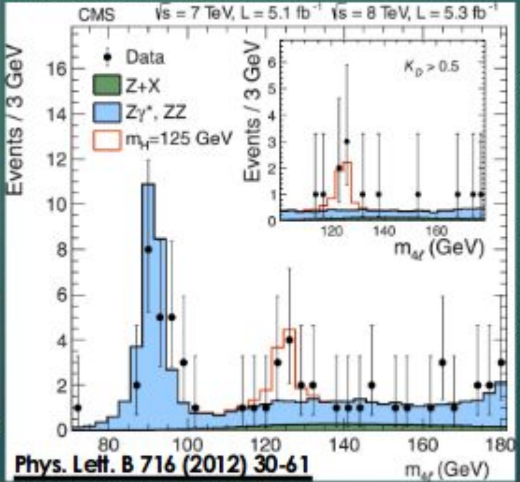
2012

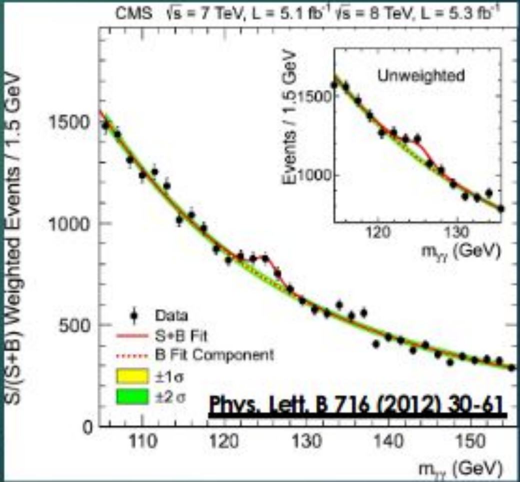
8 years ago…

- ATLAS and CMS both first observed the Higgs boson.
  - Theorized in summer of 1964
  - Francois Englert and Peter Higgs were awarded the 2013 Nobel Prize in physics for this prediction.





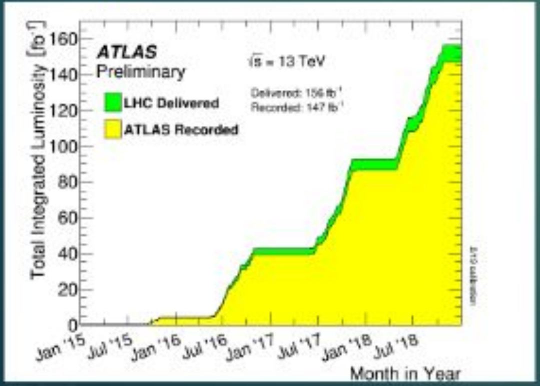


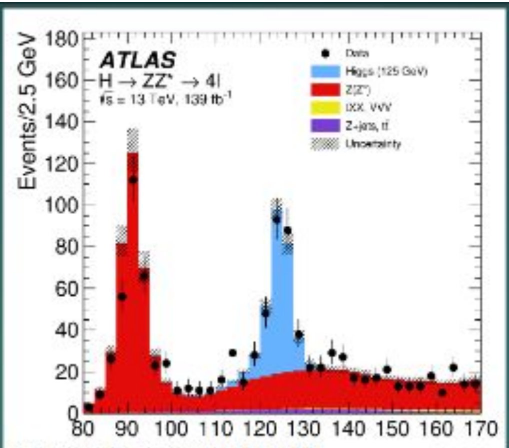


2020

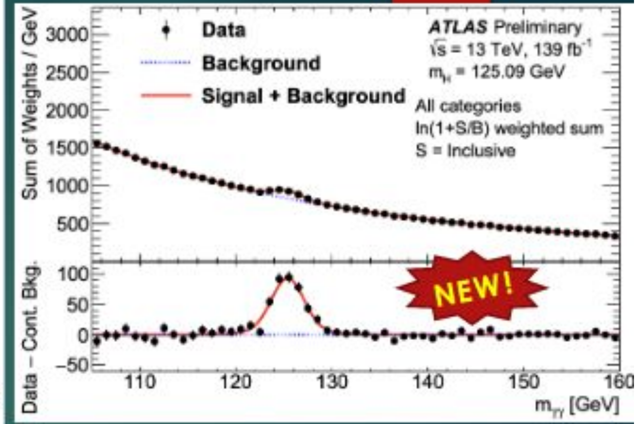
Full LHC Run 2

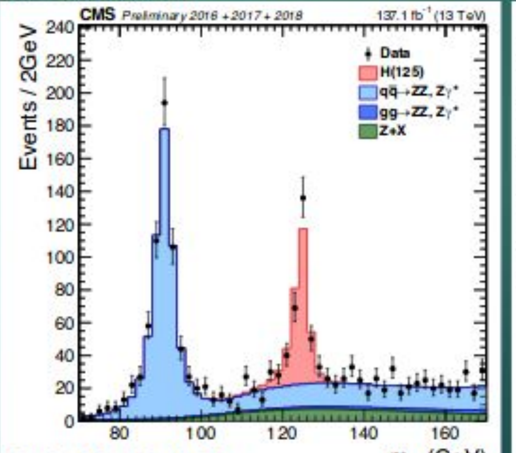
- With LHC's exceptional performance from 2015-2018 each experiment has ~140/fb of proton-proton collision data at 13 TeV, from which to harvest Higgs bosons!
  - LHC operated at twice design (!) luminosity in 2018!
  - Very impressive! Thank you LHC!



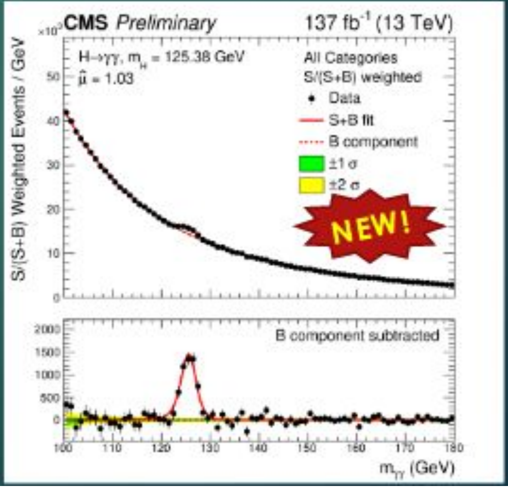


https://arxiv.org/abs/2004.03447
(Accepted in EPJC)

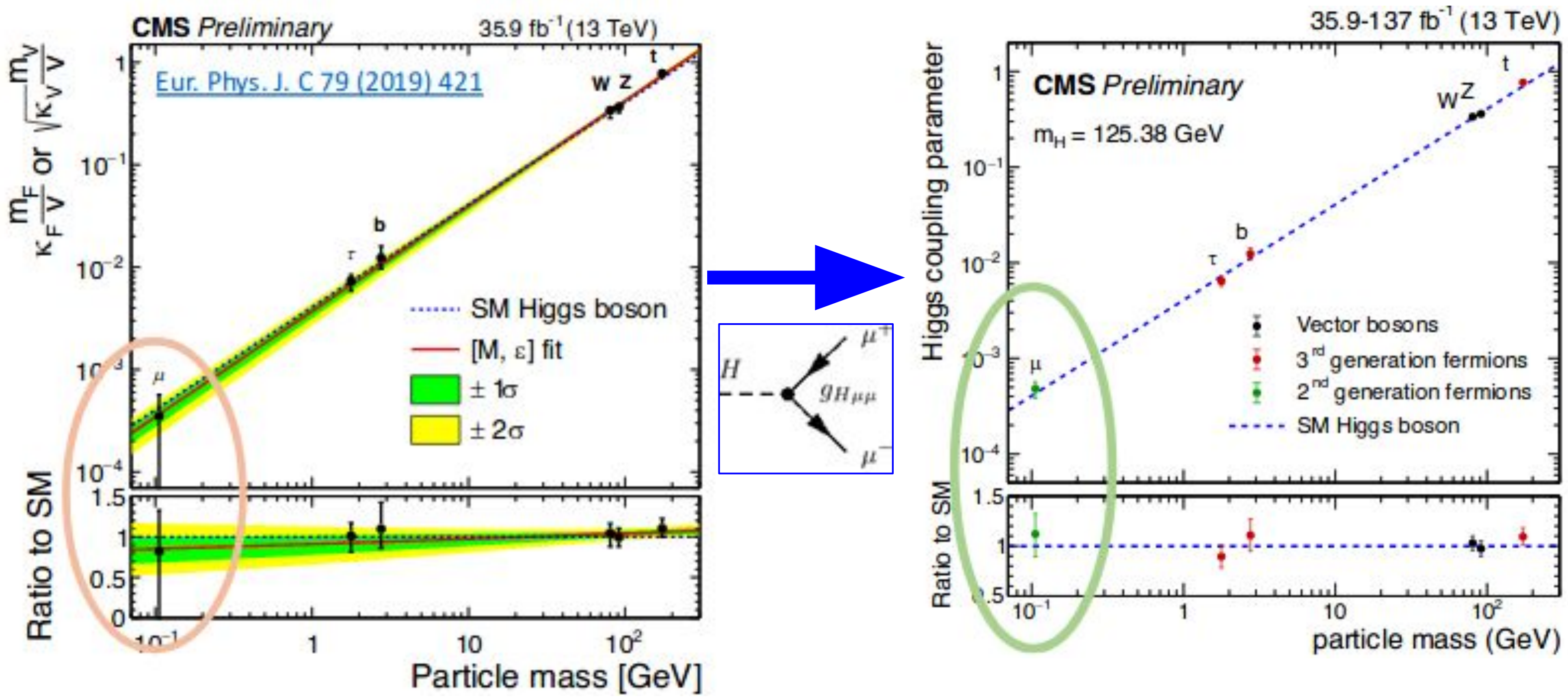




CMS-PAS-HIG-19-001



2020.8 Higgs与第二代费米子相互作用的证据！



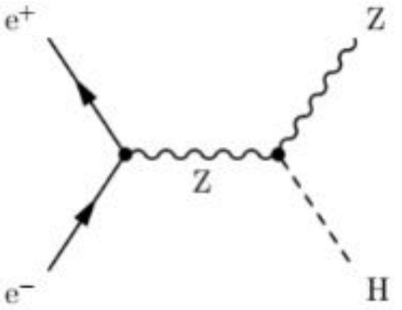
视频 two PKU Students@CERN in 2009

https://www.youtube.com/watch?v=dJEwyPO5PYE

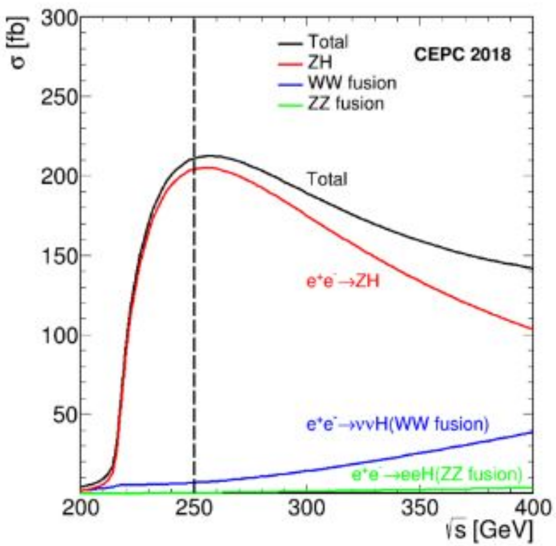
CMS TImes Interview: Bo Zhu & Haiyun Teng from Peking University

196 views • Oct 30, 2009 0 0 SHARE SAVE ...

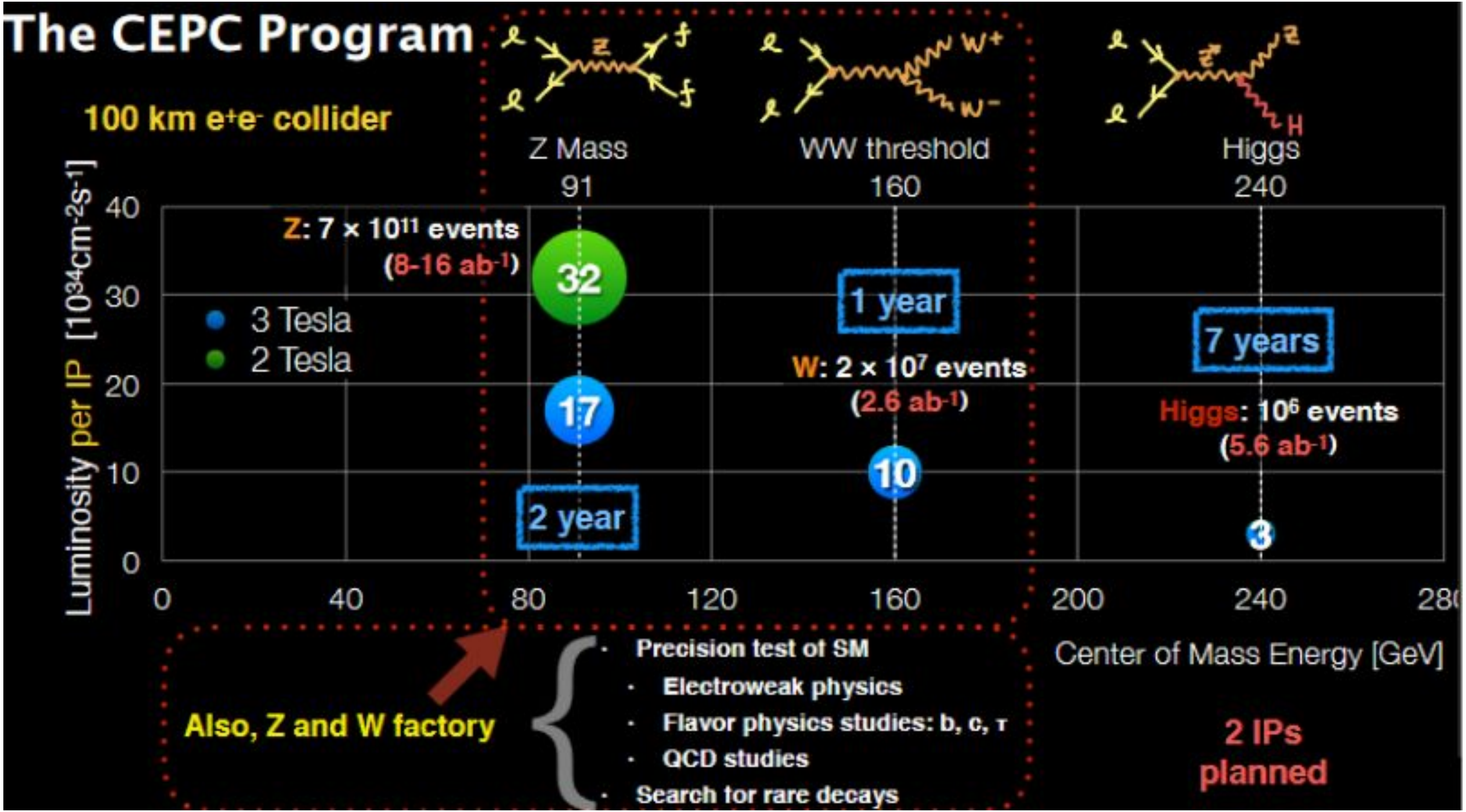
中国环形正负电子对撞机CEPC



Production cross sections



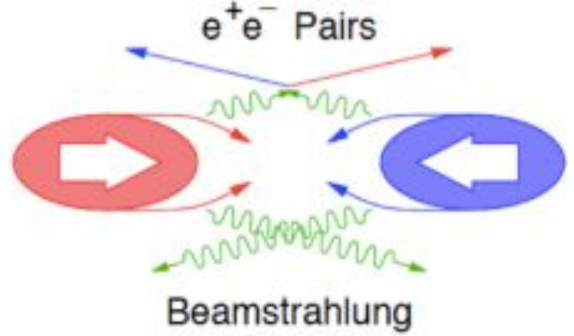
2018.11 发布概念设计报告CDR。
100公里隧道；
240-250GeV 正负电子对撞；
产生约100万Higgs；
Higgs工厂： 精确测量Higgs性质。



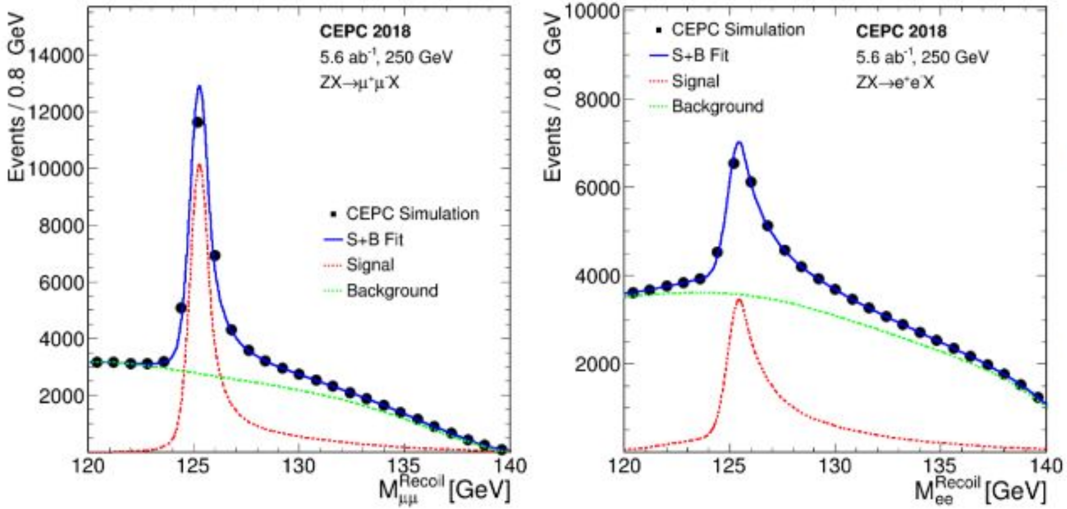
The CEPC Program
100 km e+e- collider
Z Mass
91
WW threshold
160
Higgs
240
Z: 7 × 10¹¹ events
(8-16 ab⁻¹)
32
17
2 year
1 year
W: 2 × 10⁷ events
(2.6 ab⁻¹)
10
7 years
Higgs: 10⁶ events
(5.6 ab⁻¹)
3
3 Tesla
2 Tesla
Luminosity per IP [10³⁴cm⁻²s⁻¹]
Center of Mass Energy [GeV]
Also, Z and W factory
Precision test of SM
Electroweak physics
Flavor physics studies: b, c, τ
QCD studies
Search for rare decays
2 IPs
planned

与pp对撞机相比：

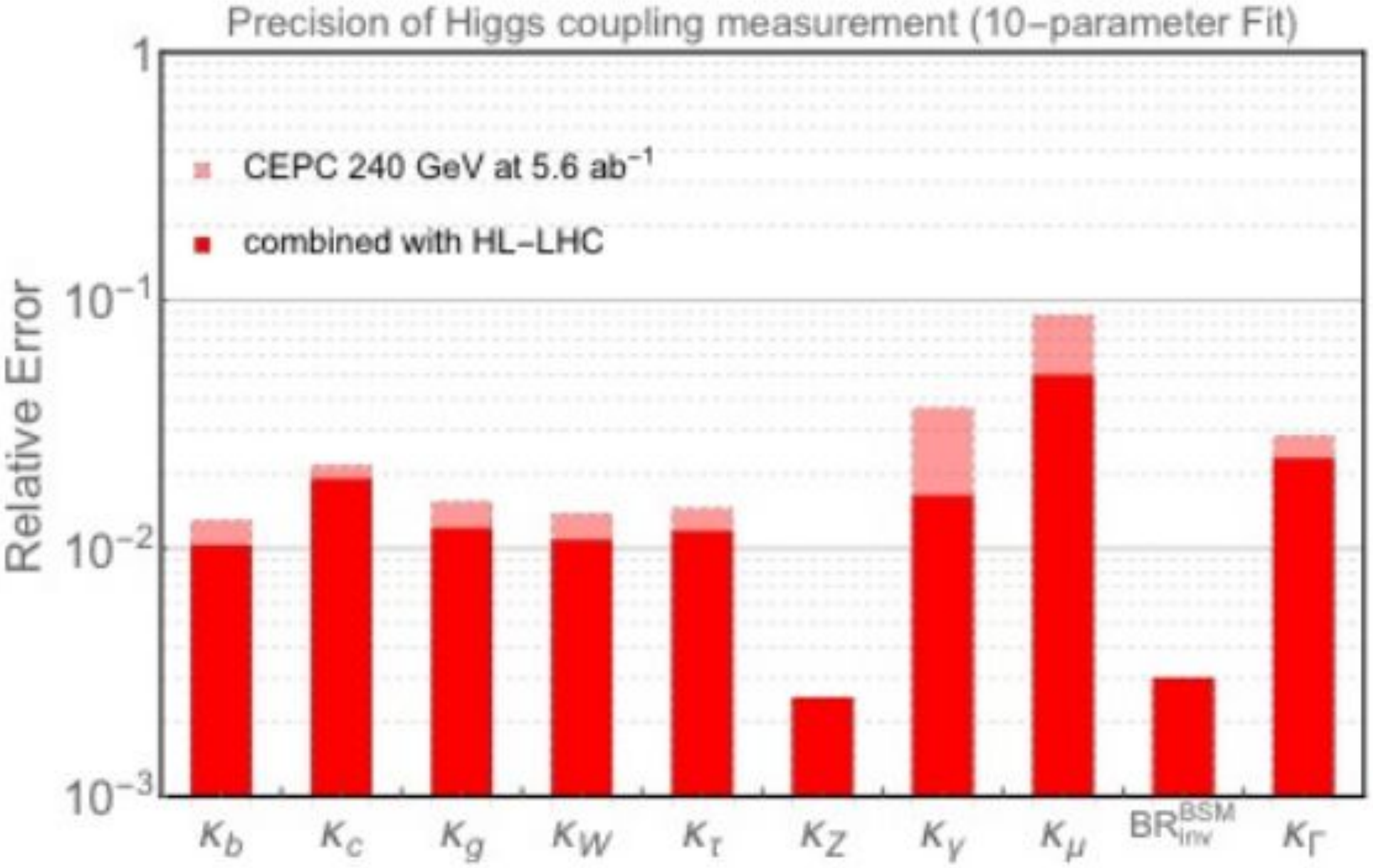
- 反冲技术，可以模型无关确定Higgs性质；
- 本底少，环境干净；
- 束流辐射会展宽对撞能量；



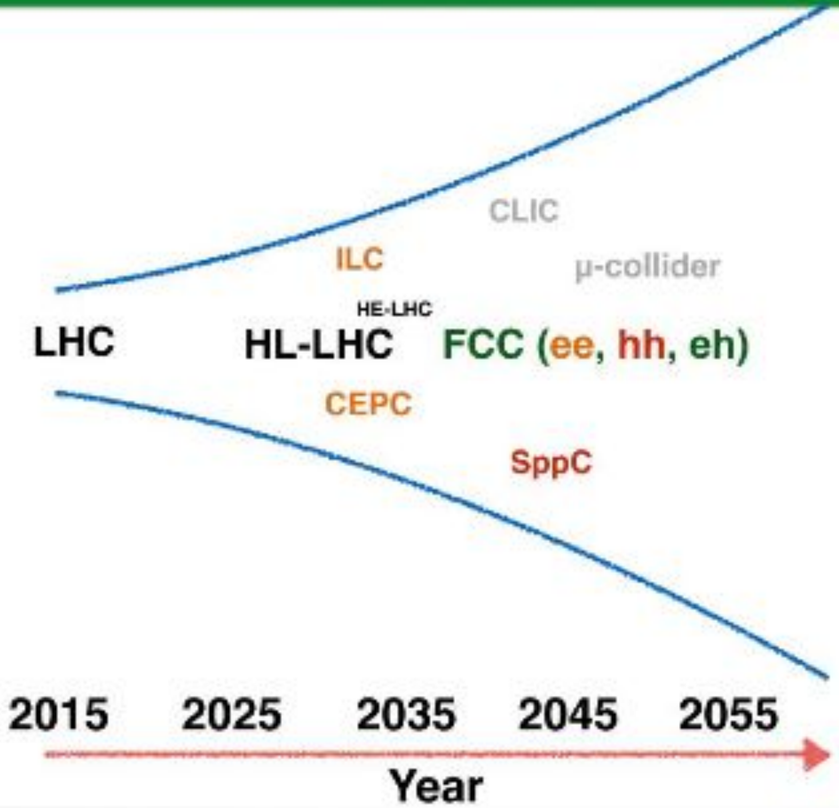
- Higgsstrahlung (ee->ZH), Z decays to a pair of visible fermions(ff), the recoil mass against the Z: $M_{\text{recoil}}^2 = (\sqrt{s} - E_{ff})^2 - p_{ff}^2 = s - 2E_{ff}\sqrt{s} + m_{ff}^2$



- Higgs boson mass can be measured from the peak of the recoil resonance
- Resonance width dominated by the beam energy spread (ISR included) and energy/momentum resolution (if Higgs width is 4.07MeV)
- σ (ZH) can be extracted by the fitting of M_{recoil}


Precision of Higgs coupling measurement (10−parameter Fit)
CEPC 240 GeV at 5.6 ab^{-1}
combined with HL−LHC
Relative Error
1
10^{-1}
10^{-2}
10^{-3}
κ_b
κ_c
κ_g
κ_W
κ_τ
κ_Z
κ_γ
κ_μ
BR_{inv}^{BSM}
κ_Γ

The Road Ahead

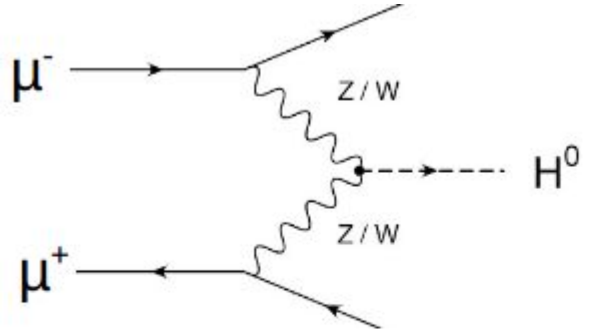


Klute, 2016

Muon colliders have suppressed synchrotron radiation.

- Clean events as in e+e- colliders
- High collision energy as in hadron colliders

But lifetime at rest only 2.2 μs.



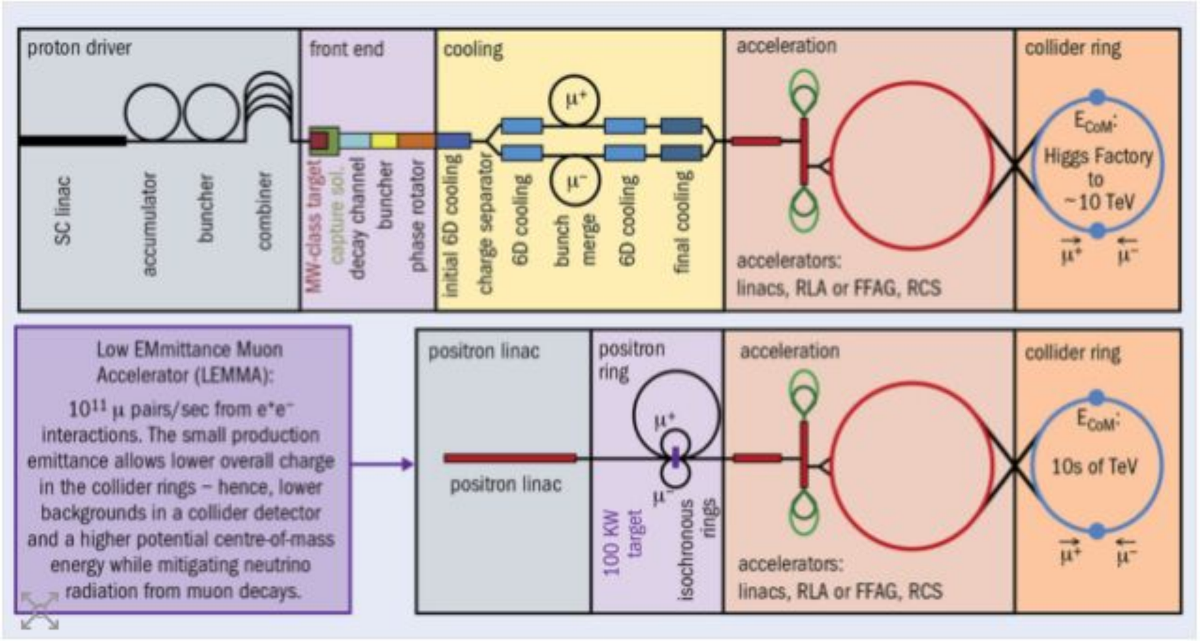
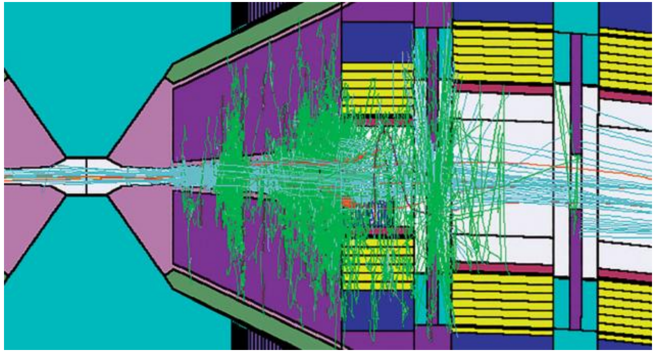


Fig. 1. Schematic layouts of the two muon-collider concepts: the proton-driven scheme explored by MAP (top) and the more recent LEMMA proposal (bottom). Source: arXiv:1901.06150



Muon Ionisation Cooling Experiment (MICE)


nature > articles > article

MENU

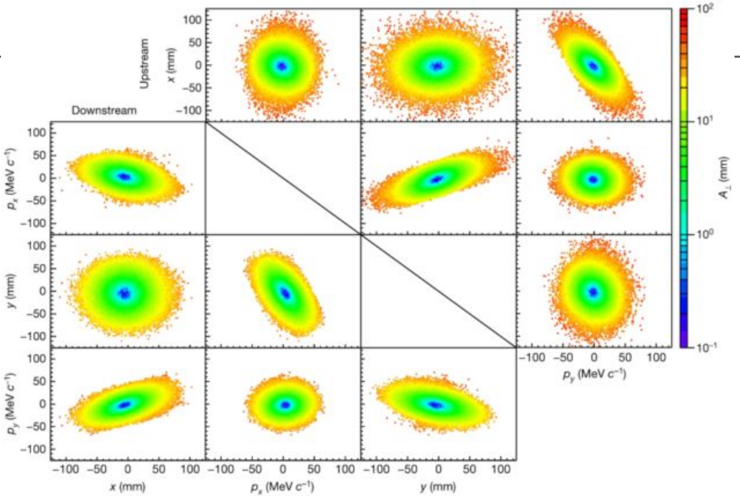
nature

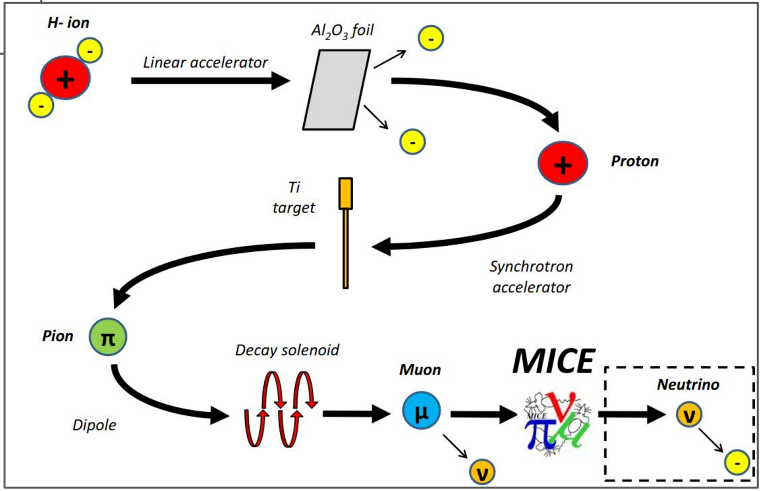
Article | Open Access | Published: 05 February 2020

Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

Nature **578**, 53–59(2020) | Cite this article





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6. 其他对撞机
7. **高能物理中的机器学习**
8. 总结与展望

高能物理及机器学习

Peter Higgs
CH FRS FRSE FInstP

Nobel laureate Peter Higgs at a press conference, Stockholm, December 2013

Born	Peter Ware Higgs 29 May 1929 (age 90) Newcastle upon Tyne, England, UK
Residence	Edinburgh, Scotland, UK
Nationality	British[1]
Alma mater	King's College London (BSc, MSc, PhD)
Known for	Higgs boson Higgs field Higgs mechanism Symmetry breaking

Institutions	University of Edinburgh Imperial College London University College London King's College London
Thesis	*Some problems in the theory of molecular vibrations* (1955)
Doctoral advisor	Charles Coulson[2][3] Christopher Longuet-Higgins[2][4]

Charles Alfred Coulson: 应用数学家，化学家
Christopher Longuet-Higgins，理论化学家，40岁（1970s），改行做人工智能

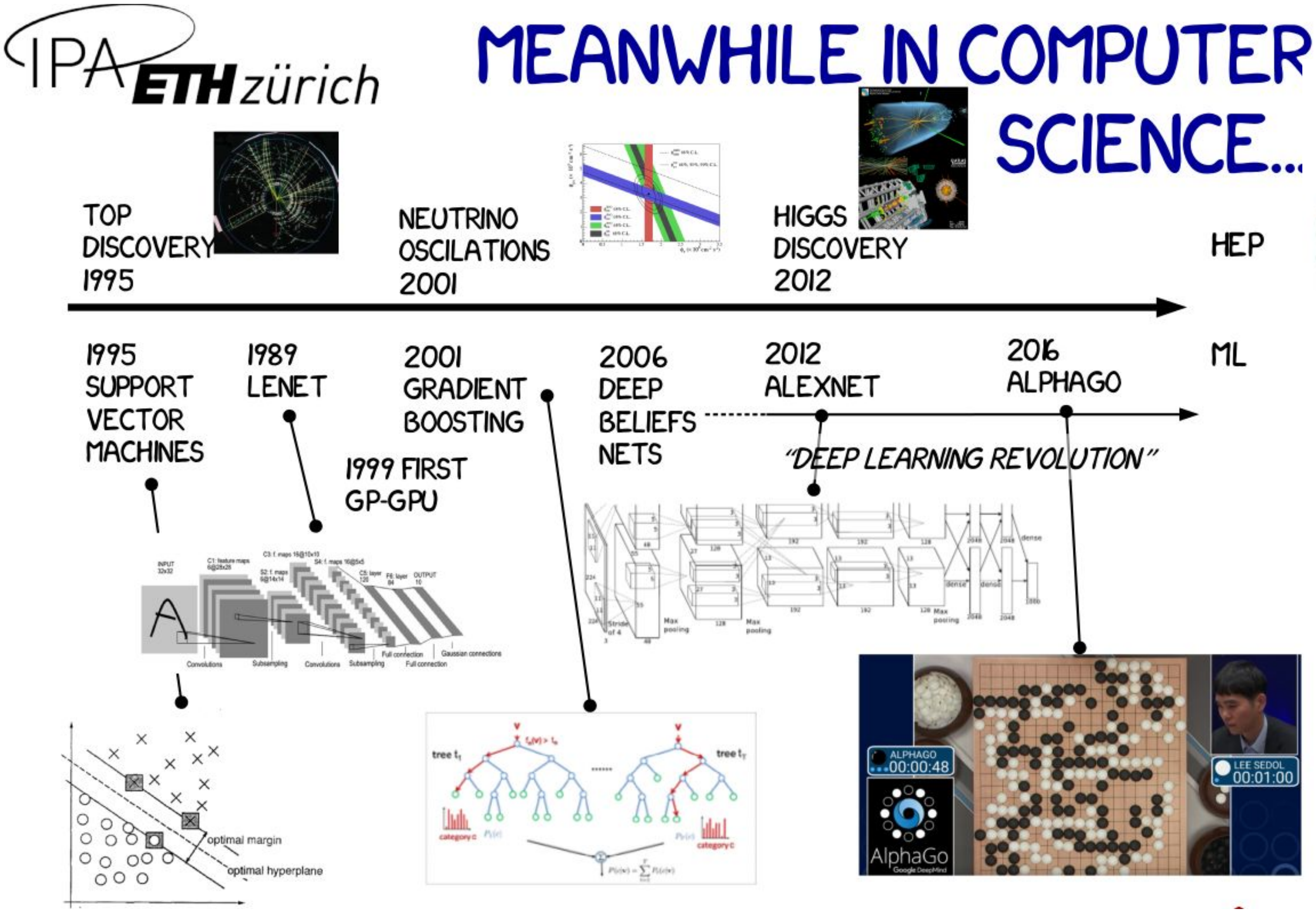
Doctoral advisor	Christopher Longuet-Higgins[3][4][5]
Doctoral students	Richard Zemel[6] Brendan Frey[7] Radford M. Neal[8] Ruslan Salakhutdinov[9] Ilya Sutskever[10]
Other notable students	Yann LeCun (postdoc) Peter Dayan (postdoc) Zoubin Ghahramani (postdoc)

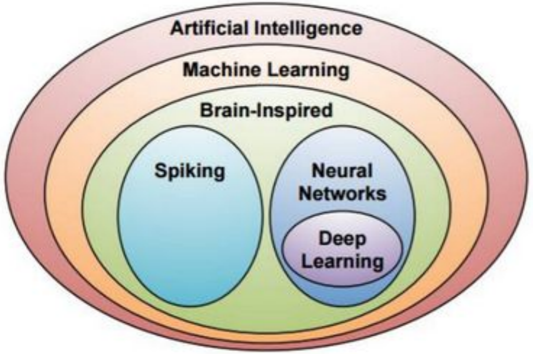
Geoffrey Hinton
FRS FRSC CC

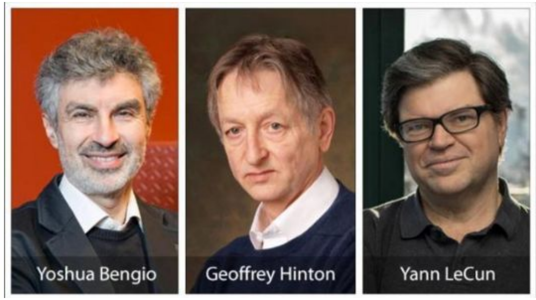
Hinton in 2013

Born	Geoffrey Everest Hinton 6 December 1947 (age 71)[1] Wimbledon, London
Residence	Canada
Alma mater	University of Cambridge (BA) University of Edinburgh (PhD)

机器学习简史

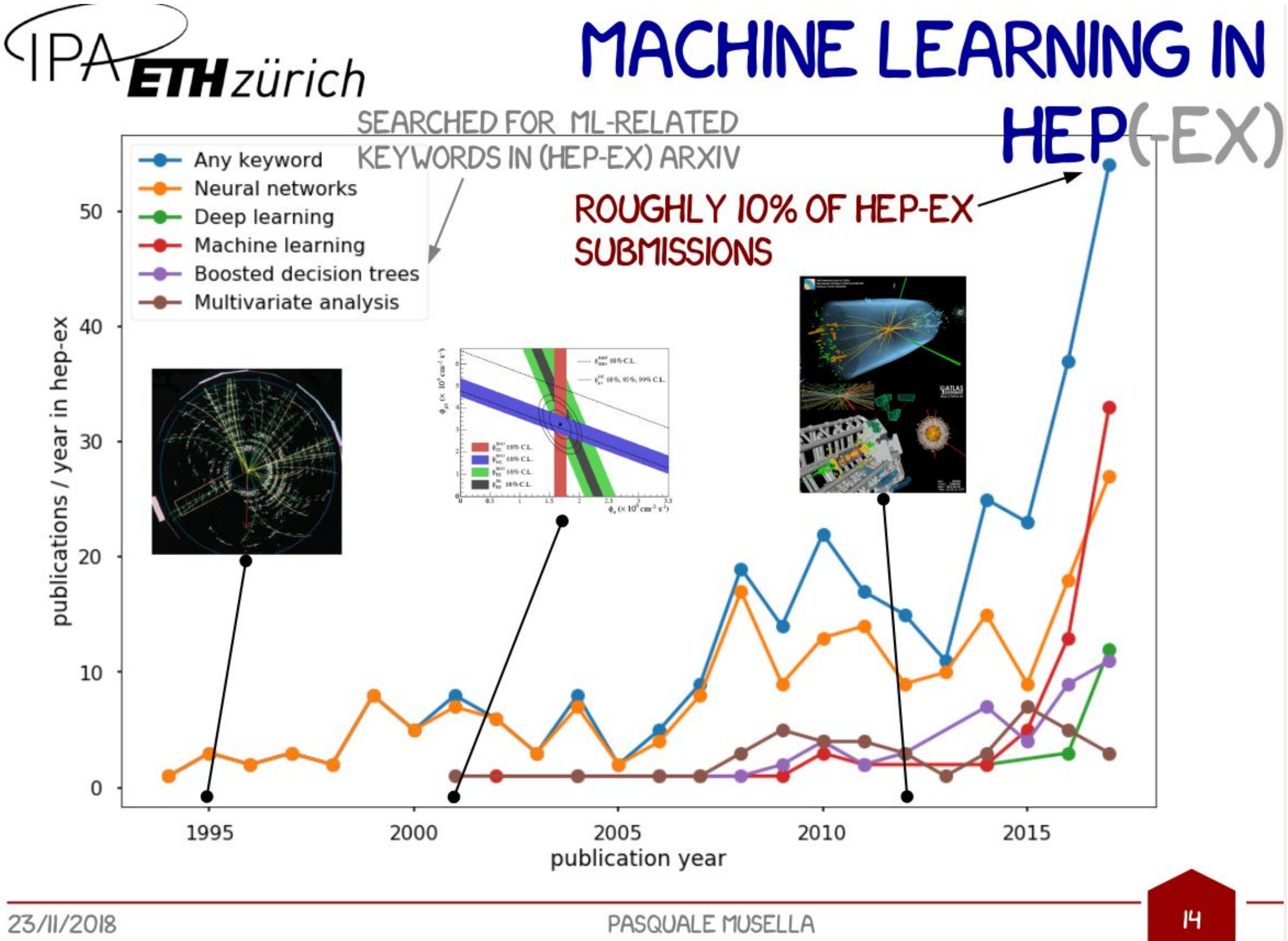


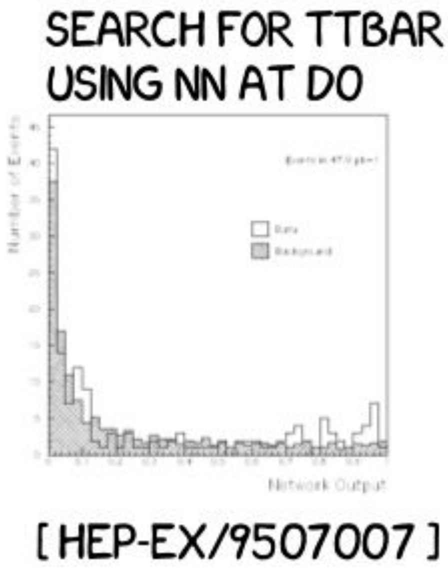




2018年图灵奖

高能物理机器学习应用简史





Tevatron：Top夸克

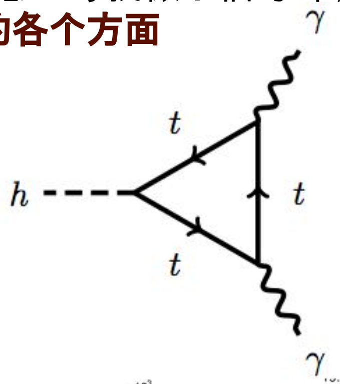
LHC: Higgs发现

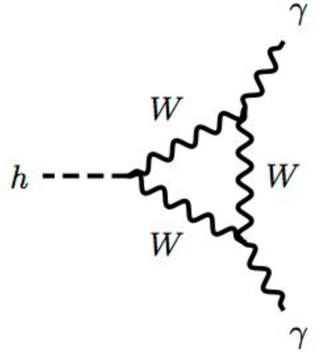
miniBOONE: 粒子鉴别

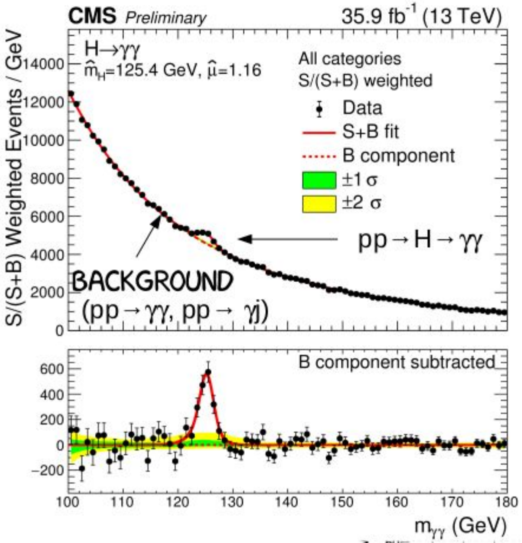
机器学习应用：Higgs粒子寻找

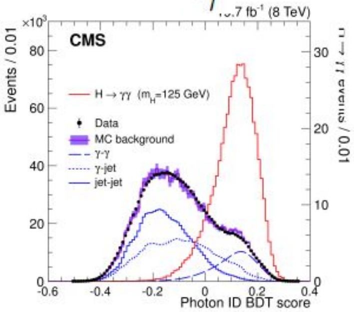
CMS实验中Higgs双光子道的寻找：

- 分支比10^{-3}: 在本底上寻找微小信号峰；
- **BDT应用于分析的各个方面**
    - 光子鉴别
    - 事例分类
    - 光子能量
    - 双光子顶点



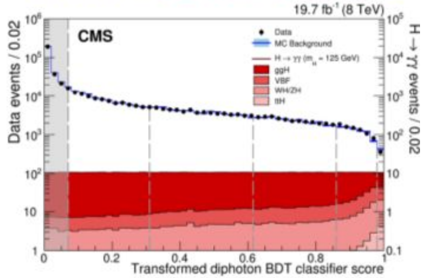




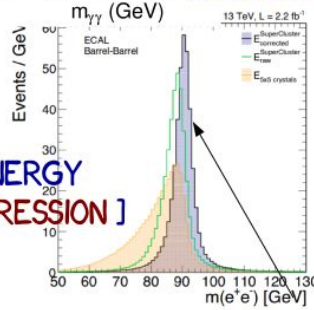


[PARTICLE-ID: SEPARATE PROMPT γ FROM HADRONIC JETS]

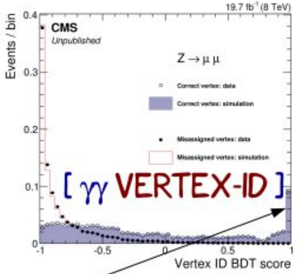
[EVENT CLASSIFICATION]



[INVARIANT MASS ESTIMATION]



[γ ENERGY REGRESSION]



[γγ VERTEX-ID]

$m^2 = E_1E_2(1-\cos\alpha)$

机器学习应用：NNPDF

ANNs provide **universal unbiased interpolants** to parametrize the non-perturbative dynamics that determines the **size and shape of the PDFs** from experimental data

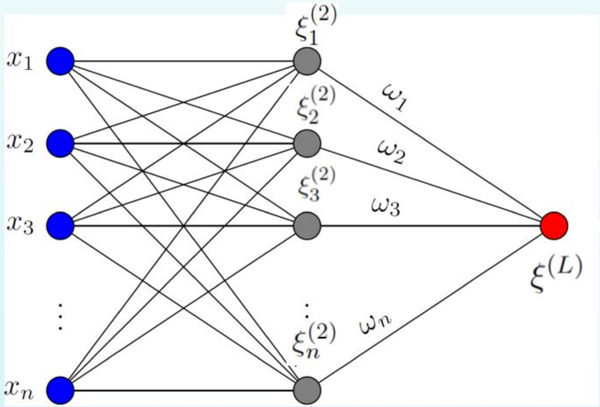
Traditional approach

$$g(x,Q_0) = A_g(1-x)^{a_g}x^{-b_g}\left(1+c_g\sqrt{s}+d_g x+\ldots\right)$$

not from QCD!

NNPDF approach

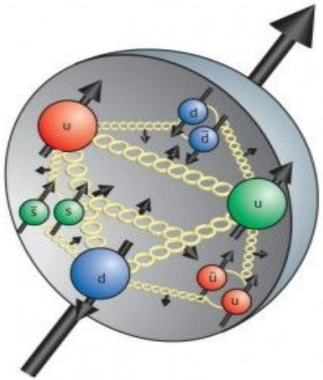
$$g(x,Q_0) = A_g \mathrm{ANN}_g(x)$$

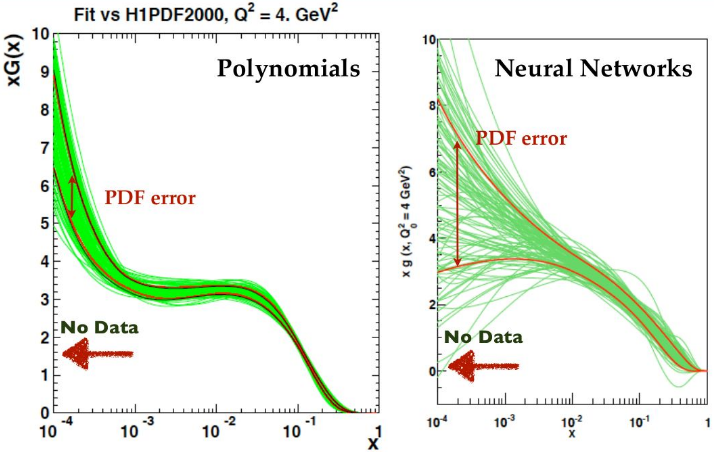


$$\mathrm{ANN}_g(x) = \xi^{(L)} = \mathcal{F}\left[\xi^{(1)}, \{\omega_{ij}^{(l)}\}, \{\theta_i^{(l)}\}\right]$$

$$\xi_i^{(l)} = g\left(\sum_{j=1}^{n_{l-1}} \omega_{ij}^{(l-1)}\xi_j^{(l-1)} - \theta_i^{(l)}\right)$$

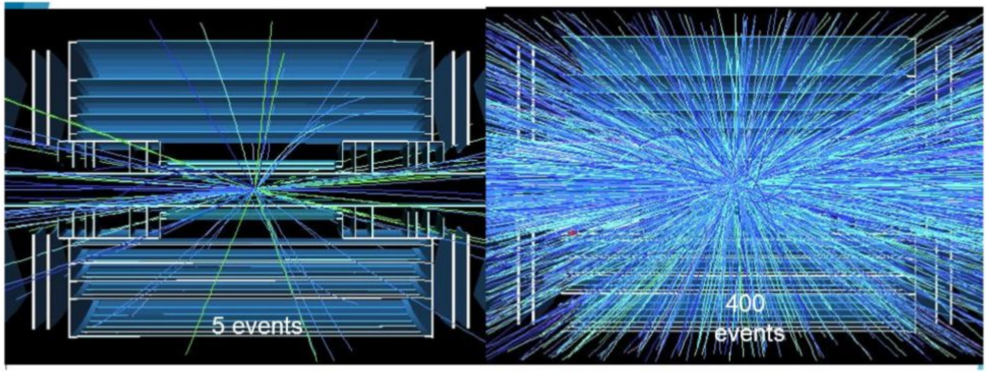
- ANNs eliminate **theory bias** introduced in PDF fits from choice of *ad-hoc* functional forms
- NNPDF fits used **O(400) free parameters**, to be compared with O(10-20) in traditional PDFs. Results stable if **O(4000) parameters used!**



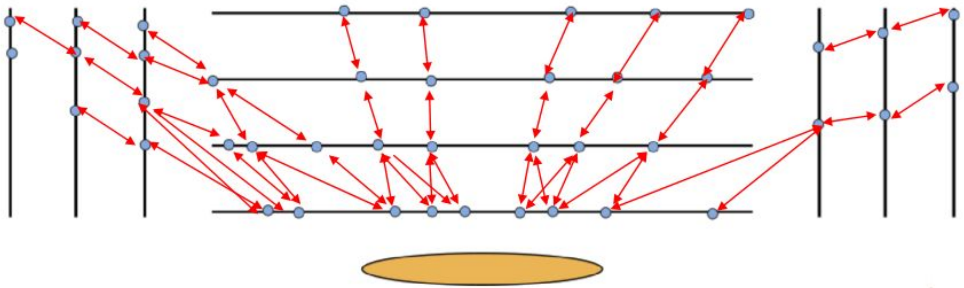


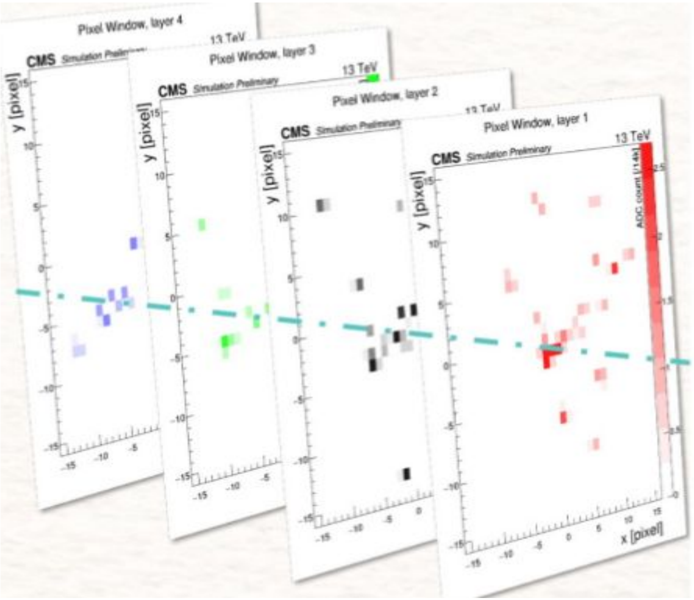
ANNs avoid biasing the PDFs, faithful extrapolation at small-x (very few data, thus error blow up)

CNN应用：径迹重建



嘈杂环境中重建带电粒子径迹，具有挑战性：
误组合，假种子

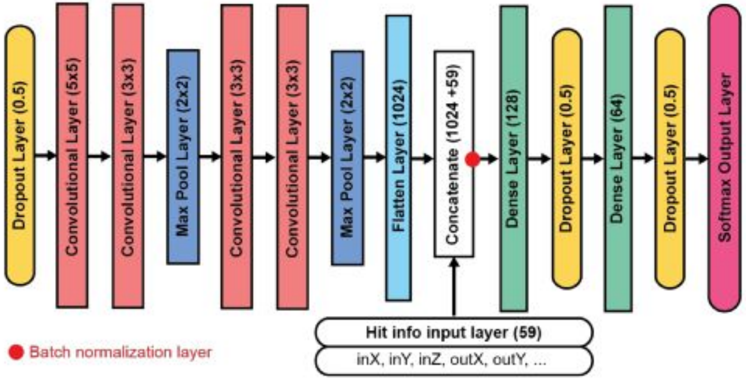




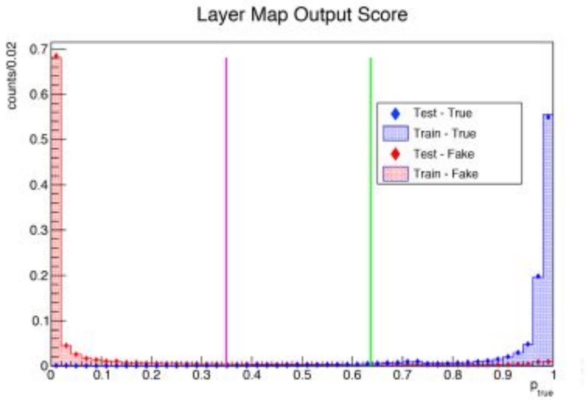
CNN应用： 径迹重建

PixelSeed ConvNN

- The final model uses two sets of inputs:
  - the hit images
  - a set of expert features (e.g., position of the hits in the detector) to help the learning process



- The trained model shows a good separation of true vs fake seeds



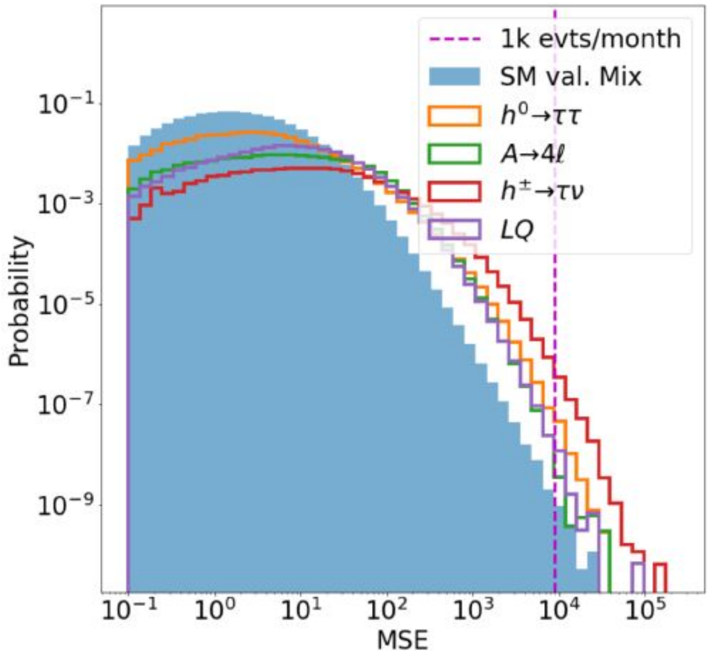
- ***One can reduce the fake rate by one order of magnitude with a few % loss in efficiency***

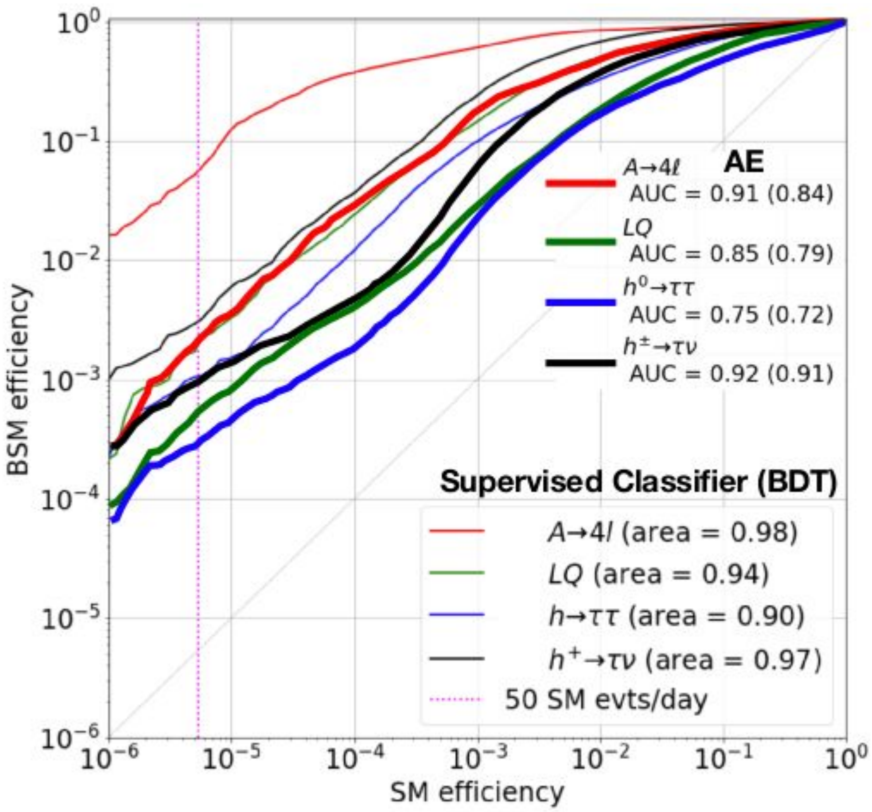
```
Efficiency (tpr) @ fake rejection
tpr @ rej 50%: 0.998996700259
tpr @ rej 75%: 0.990524391331
tpr @ rej 90%: 0.922210826719
tpr @ rej 99%: 0.338669401587
```

自编码:自动寻找新物理

- Train on standard events
- Run autoencoder on new events
- Consider as anomalous all events with loss > threshold

Worse than Supervised but results encouraging





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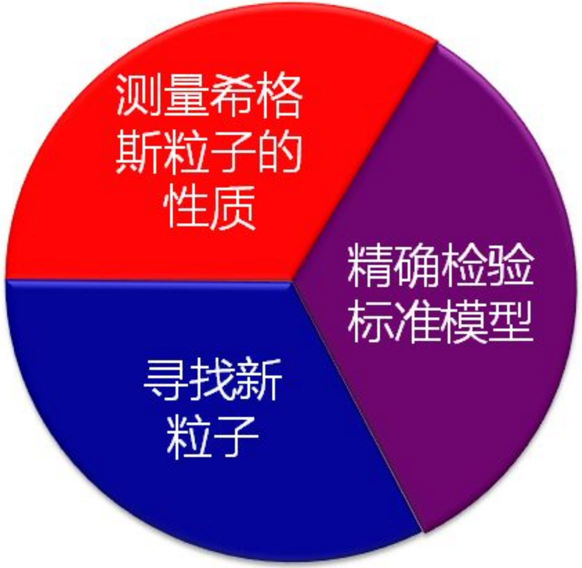
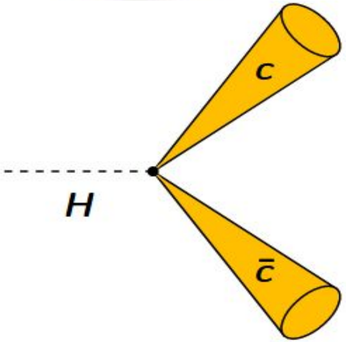
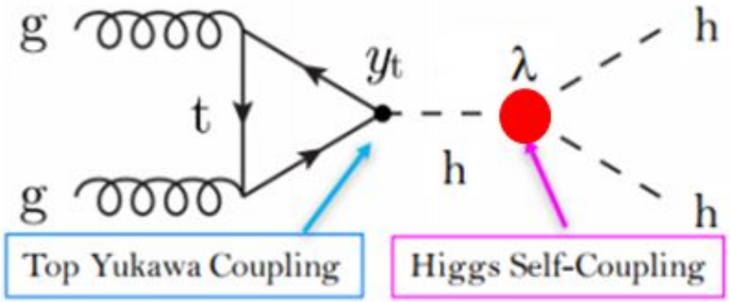
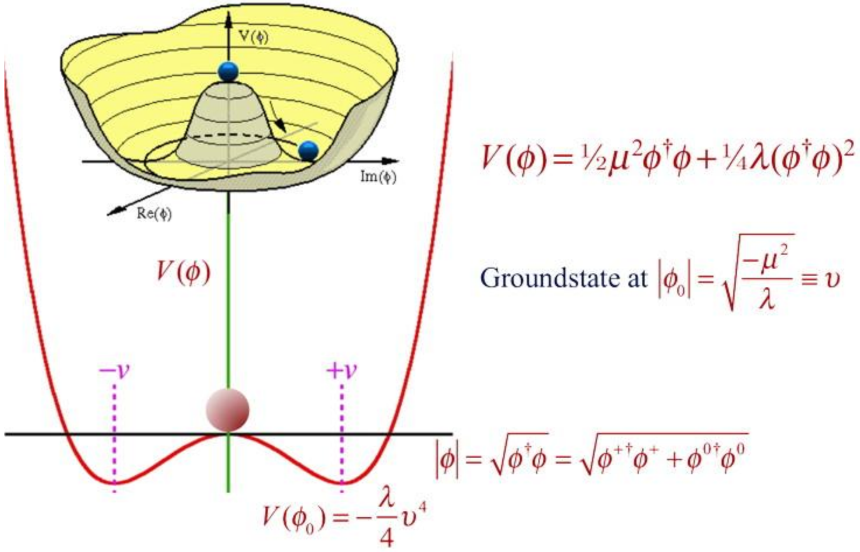
Summary

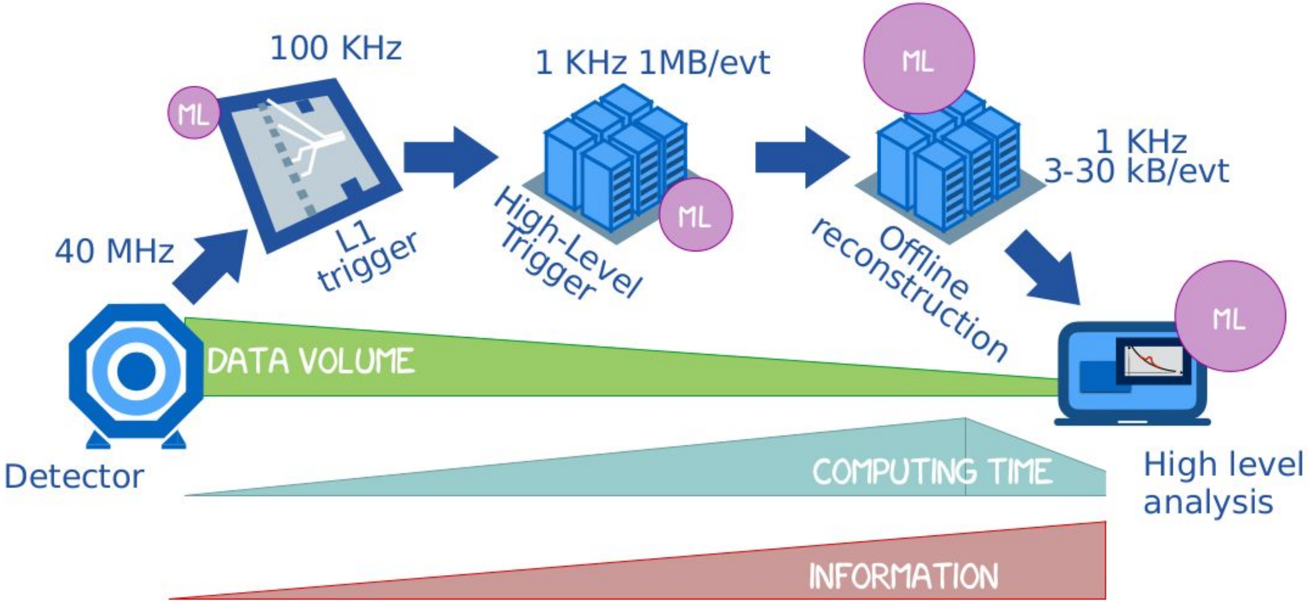

测量希格斯粒子的性质
精确检验标准模型
寻找新粒子


c
H
c̄


g
g
t
y_t
h
λ
h
h
Top Yukawa Coupling
Higgs Self-Coupling


V(ϕ)
Im(ϕ)
Re(ϕ)
$V(\phi)$
$-v$
$+v$
$V(\phi)=\frac{1}{2}\mu^2\phi^\dagger\phi+\frac{1}{4}\lambda(\phi^\dagger\phi)^2$
Groundstate at $|\phi_0|=\sqrt{\frac{-\mu^2}{\lambda}}\equiv v$
$|\phi|=\sqrt{\phi^\dagger\phi}=\sqrt{\phi^{+\dagger}\phi^+ +\phi^{0\dagger}\phi^0}$
$V(\phi_0)=-\frac{\lambda}{4}v^4$

Summary



Faster、Deeper、Stronger in HEP

附录

七律·对撞机

一声霹雳惊天地，万象森罗入眼中。
自有神通驱鬼魅，不劳巧匠运斤弓。
山河大好春如海，草木欣荣日似虹。
我欲乘风游汗漫，人间何处觅仙宫。

https://www.aichpoem.com/#/shisanbai/poem

The Nobel Prize in Physics 2002

中微子振荡

Raymond Davis Jr.

Prize share: 1/4

Masatoshi Koshiba

Prize share: 1/4

Riccardo Giacconi

Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

P_T and (pseudo-)Rapidity

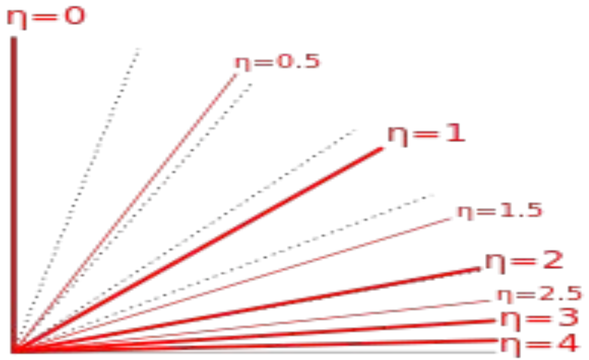
$$y \equiv \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

$$\eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}|+p_L}{|\mathbf{p}|-p_L}\right) = \quad -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$$p_T \equiv \sqrt{p_x^2+p_y^2}$$

$$(\Delta R)^2 \equiv (\Delta\eta)^2 + (\Delta\phi)^2$$

Lorentz Invariant Distance

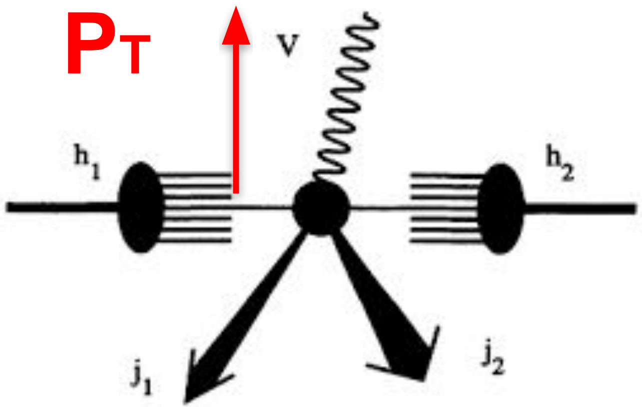


LHC typical:

PT>20-30GeV

$|\eta|$<2.5, 4.7

$\Delta R > 0.3, 0.4, 0.5, 0.7, 0.8$

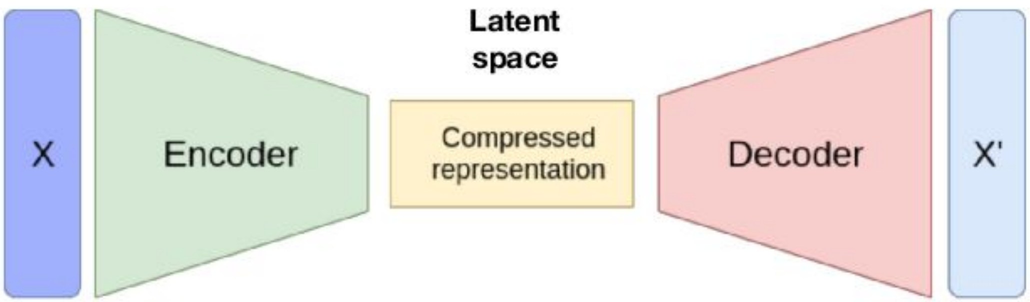


自编码Autoencoders

- *Autoencoders are networks with a typical “bottleneck” structure, with a symmetric structure around it*
  - *They go from $\mathbb{R}^n \rightarrow \mathbb{R}^n$*
  - *They are used to learn the identity function as $f^{-1}(f(x))$*

where $f: \mathbb{R}^n \rightarrow \mathbb{R}^k$ and $f^{-1}: \mathbb{R}^k \rightarrow \mathbb{R}^n$

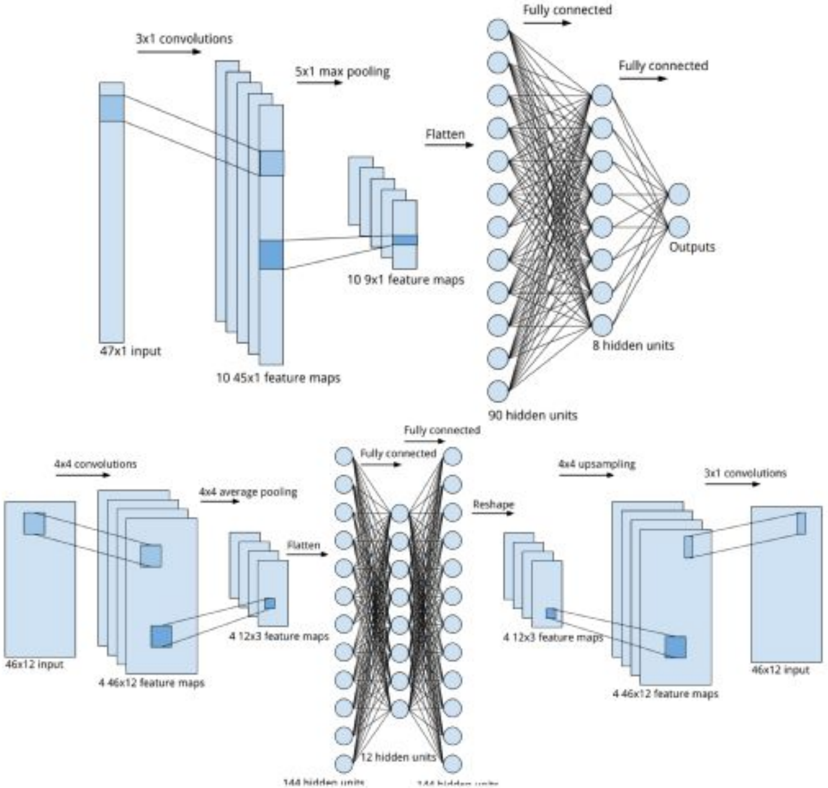
- *Autoencoders are essential tools for unsupervised studies*



自编码：数据监控

- *Given the nature of these data, ConvNN are a natural analysis tool. Two approaches pursued*
  - *Classify good vs bad data. Works if failure mode is known*
  - *Use autoencoders to assess data “typicality”. Generalises to unknown failure modes*

A. Pol et al., to appear soon



Pol, G. Cerminara, C. Germain, MP and A. Seth arXiv:1808.00911