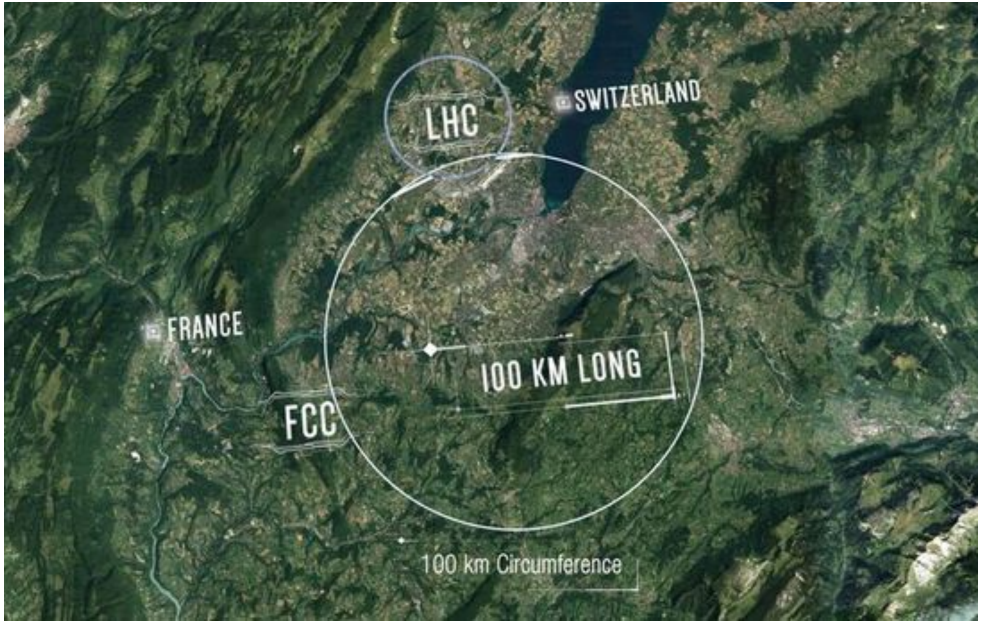
对撞机物理实验



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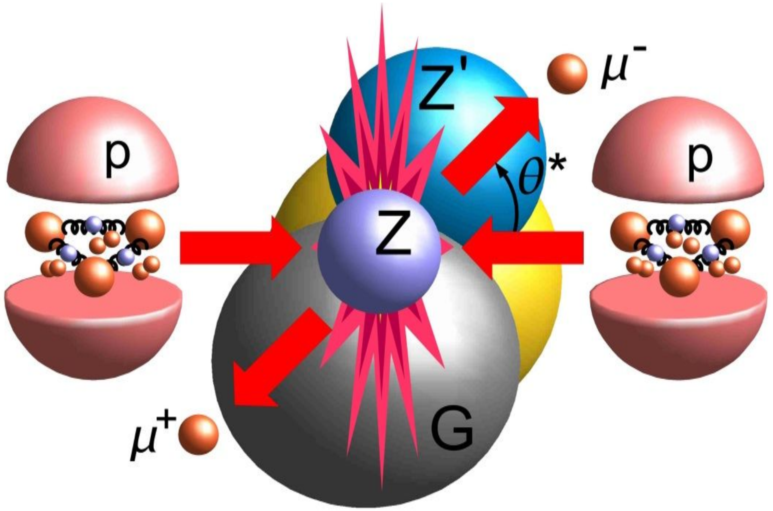
1. 前言
2. 高能物理简介
3. 大型强子对撞机(LHC)
4. Higgs的发现
5. 中国未来对撞机(CEPC)
6. 其他对撞机
7. 机器学习、量子纠缠
8. 总结与展望



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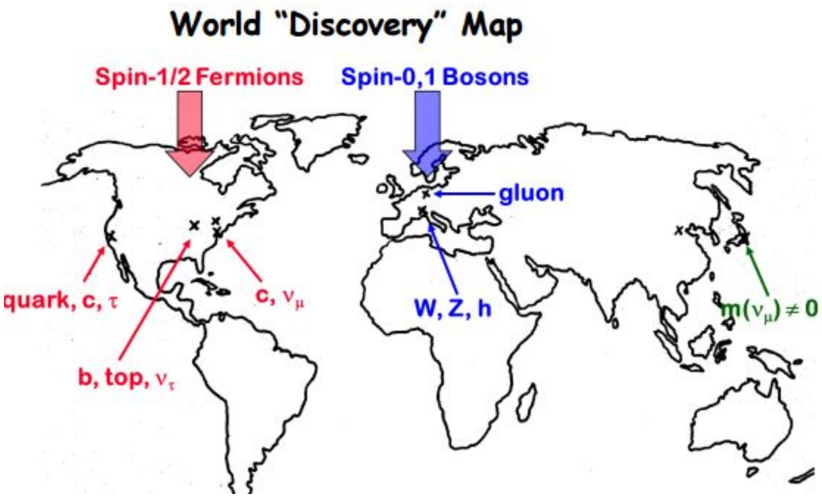
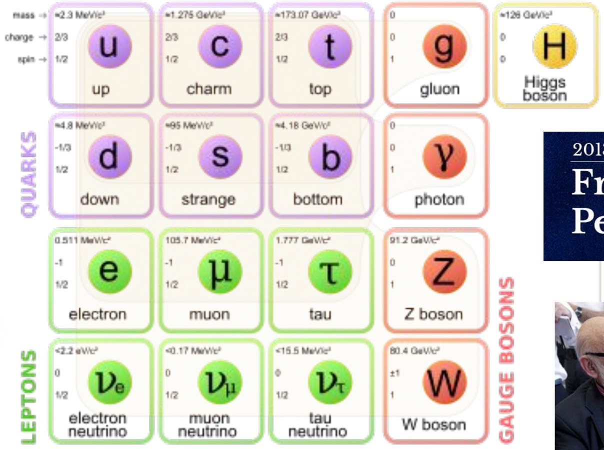
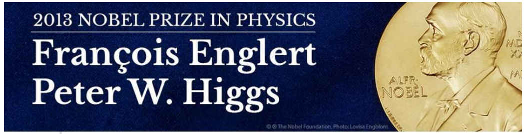
高能物理简介







8 October 2013

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

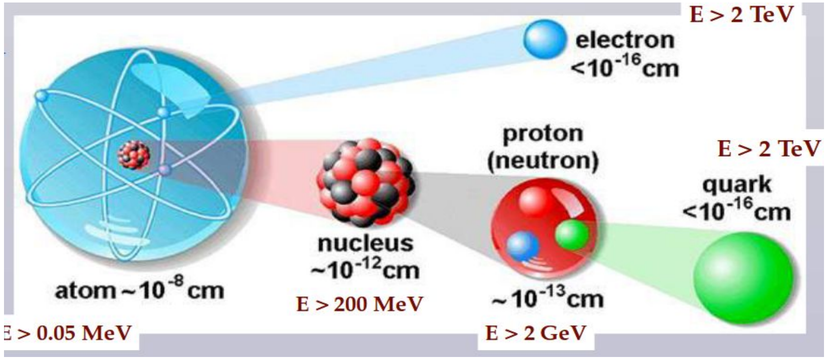
François Englert and Peter Higgs

"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

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

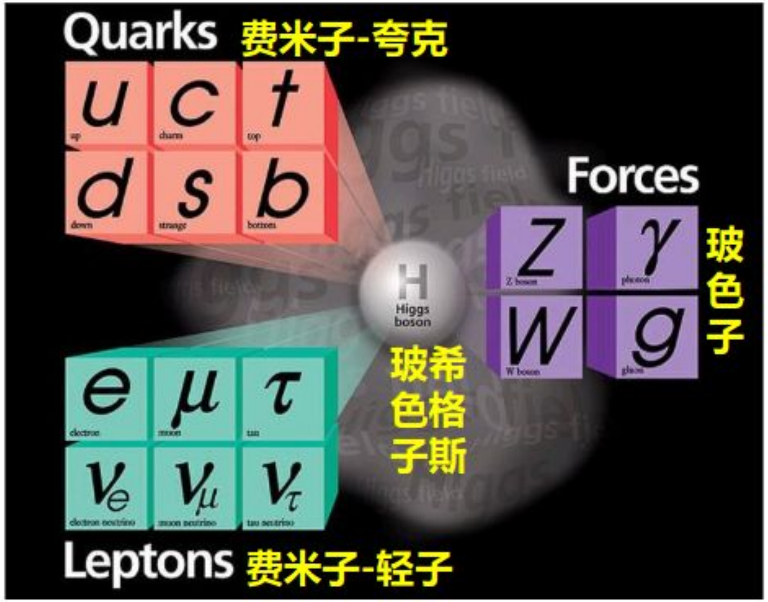
$$(1\,\text{GeV})^{-1} = 0.2\ \text{fm} = 0.2\ 10^{-15}\ \text{m}$$



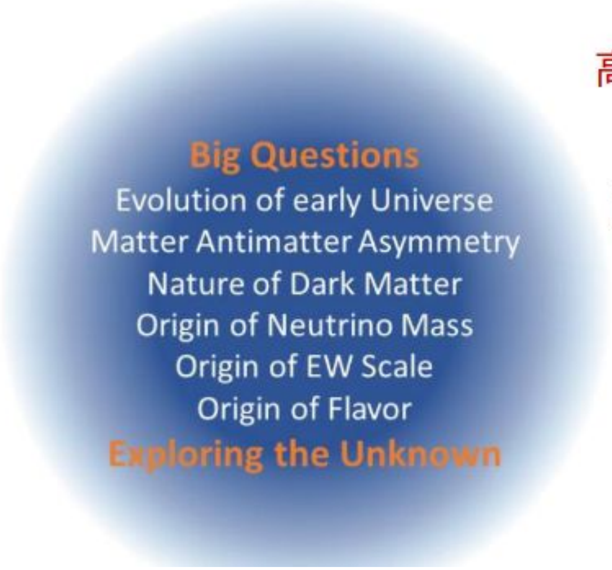
探索深层次物质规律

研究基本粒子(玻色子、费米子)的性质及相互作用。

检验粒子物理的标准模型、寻找超出标准模型的新物理。



<u>2022美国粒子物理Snowmass战略规划总结</u>



高能量前沿重大问题：

早期宇宙演化、

正反物质不对称性、

暗物质性质、

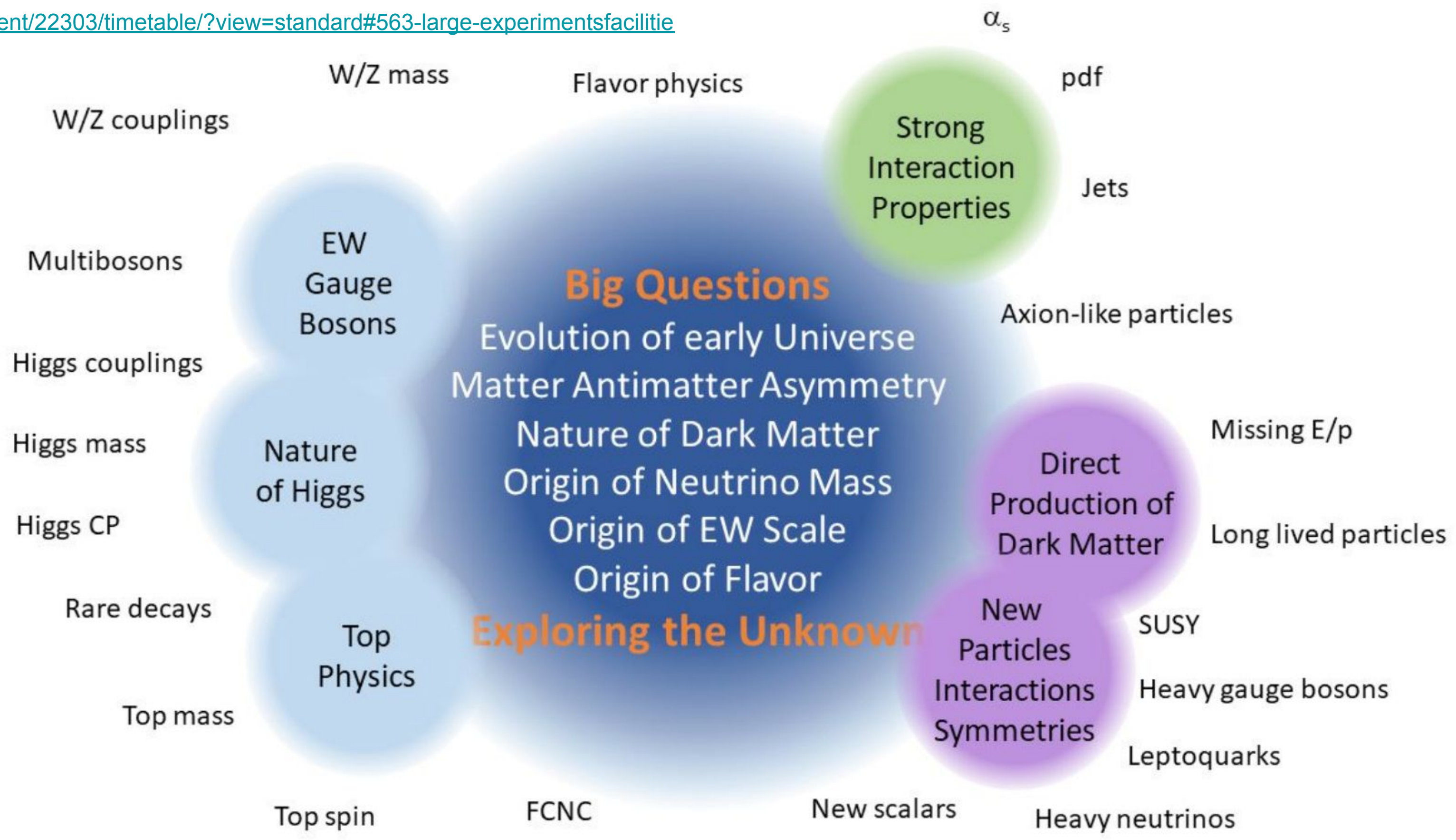
中微子质量起源、

电弱标度起源、

味道起源 等

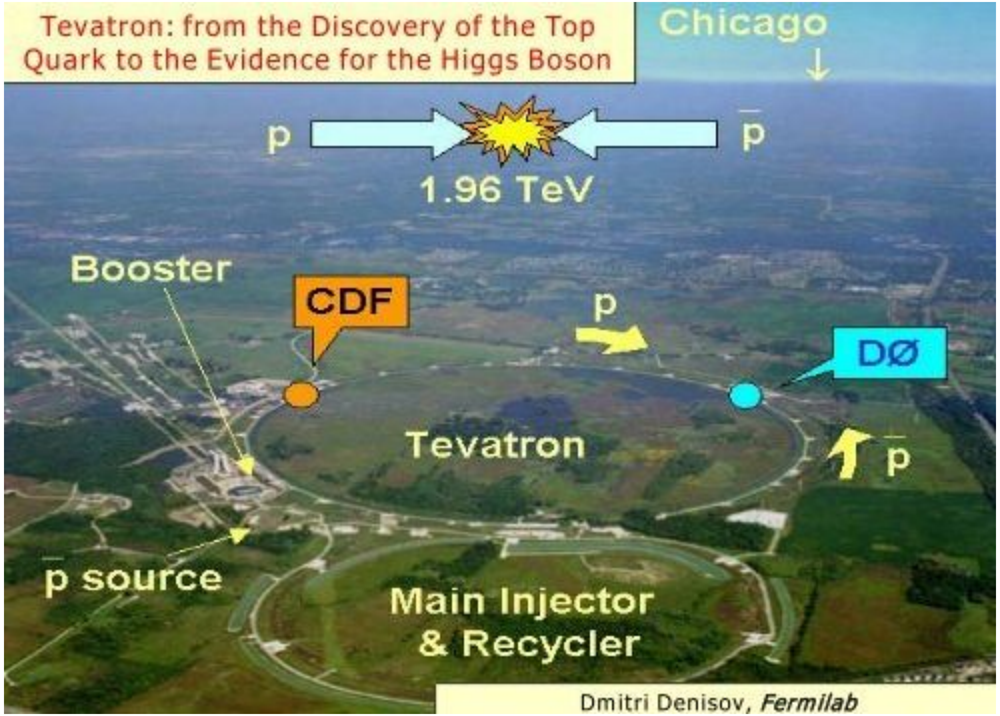
探索深层次物质规律

https://indico.fnal.gov/event/22303/timetable/?view=standard#563-large-experimentsfacilitie



对撞机:过去、现在及未来

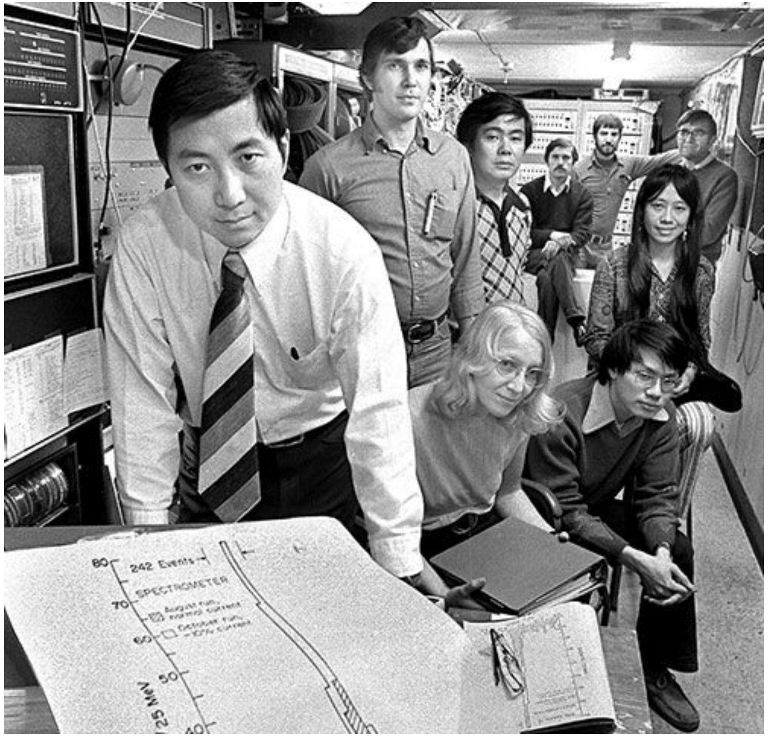
CERN Super Proton Synchrotron
正负质子对撞
1983年1月25日 宣布发现W玻色子

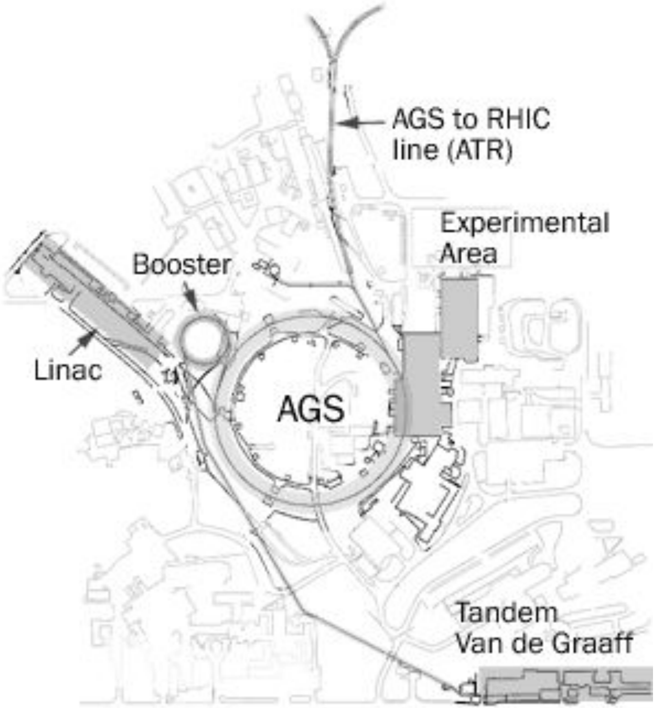


美国Tevatron 1992-2011 正负质子对撞
1995年发现Top夸克

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

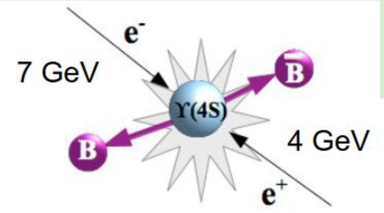
对撞机:过去、现在及未来





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



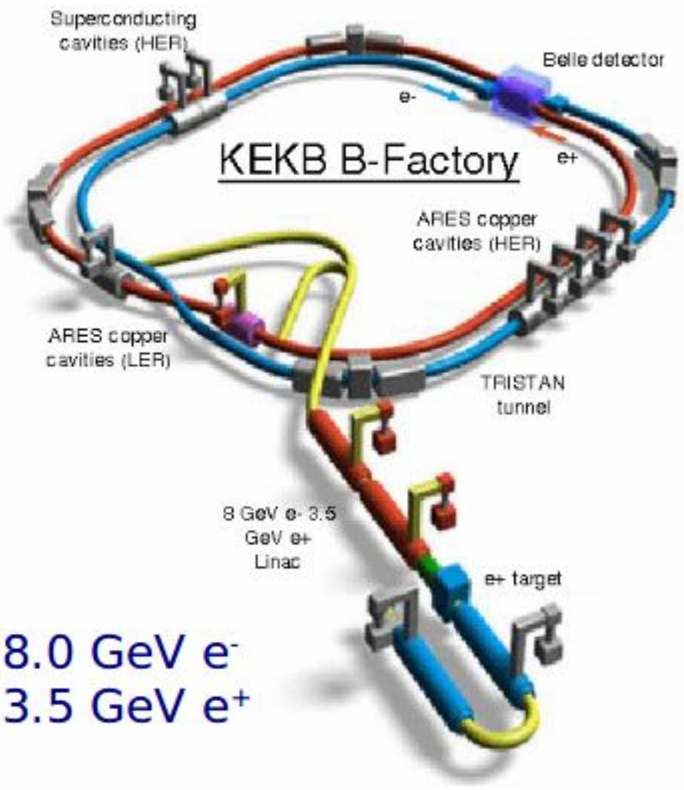
现役对撞机

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

sqrt(112)~=10.58GeV

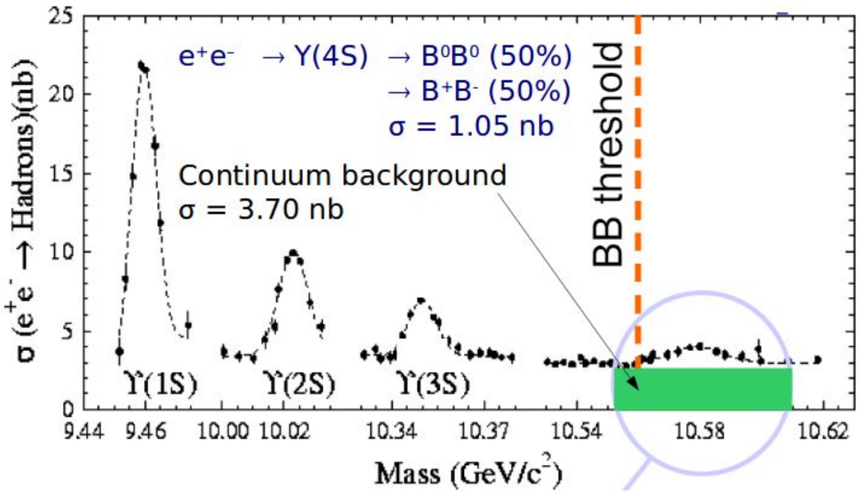
Accelerator	Centre, city, country	First operation	accelerated particles	max energy per beam, GeV	Luminosity, 10^{30} cm^{-2} s^{-1}	Perimeter (length), km
VEPP-2000	INP, Novosibirsk, Russia	2006	e^+e^-	1.0	100	0.024
VEPP-4M	INP, Novosibirsk, Russia	1994	e^+e^-	6	20	0.366
BEPC II	IHEP, Beijing, China	2008	e^+e^-	2.45[12]	1000	0.240
DAFNE	LNF, Frascati, Italy	1999	e^+e^-	0.510	453[13]	0.098
SuperKEKB	KEK, Tsukuba, Japan	2018	e^+e^-	7 (e^-), 4 (e^+)	24000[14]	3.016
RHIC	BNL, New York, United States	2000	pp, Au-Au, Cu-Cu, d-Au	255, 100/n	245, 0.0155, 0.17, 0.85	3.834
LHC	CERN	2008	pp, Pb-Pb, p-Pb, Xe-Xe	6500 (planned 7000), 2560/n (planned 2760/n)	21000,[15] 0.0061, 0.9, 0.0004	26.659

对撞机:过去、现在及未来

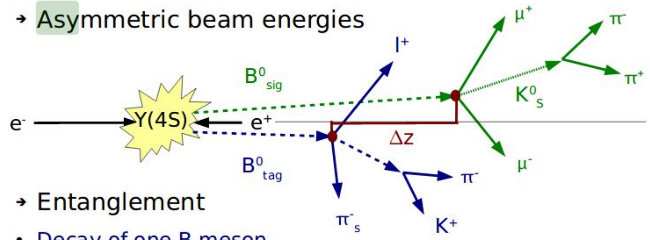


8.0 GeV e^-
3.5 GeV e^+

日本 筑波



Measurement of time-dep. CP Violation



- 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。

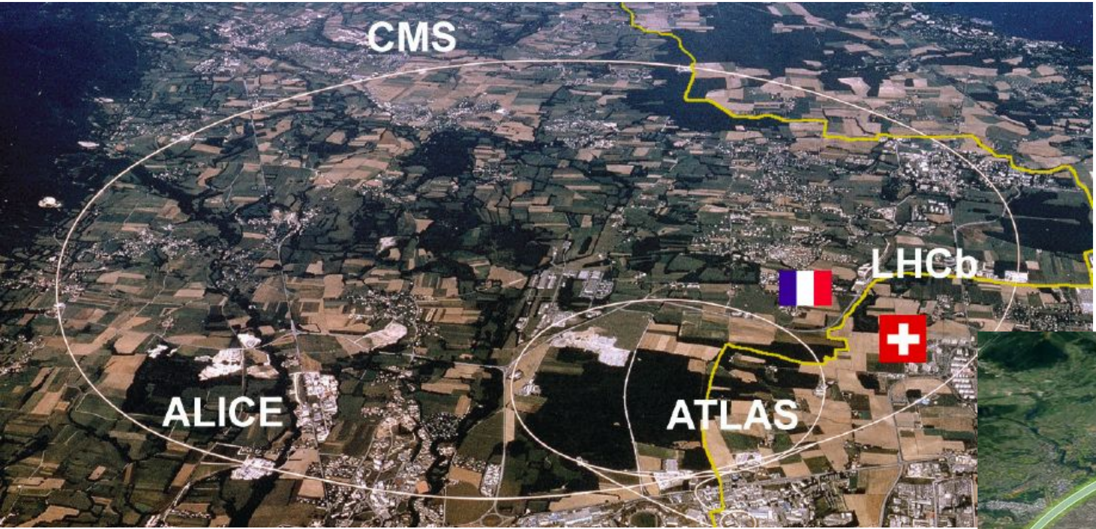
北京谱仪国际合作组发现四夸克物质Zc(3900)入选2013年物理学重要成果

Four-Quark Matter

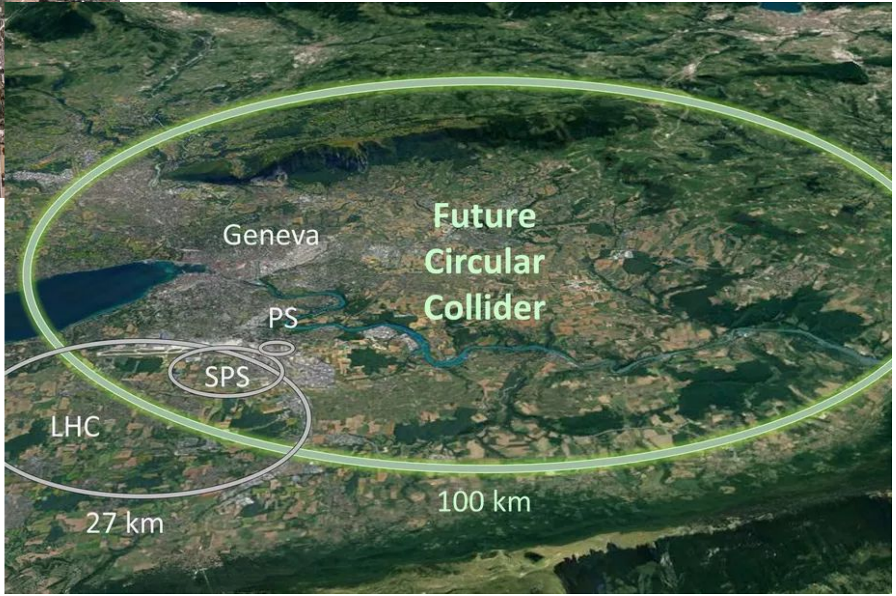
Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a **mysterious particle** that appeared to contain 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

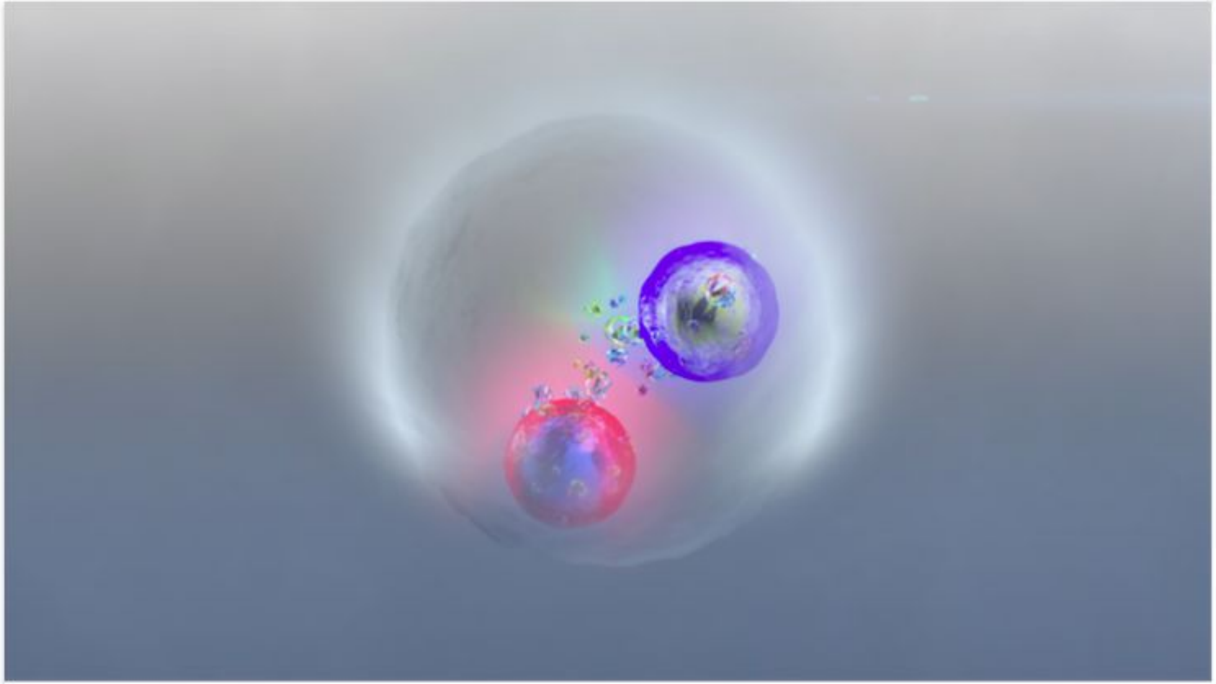


2012年Higgs发现之后，国际高能物理学界提出了**下一代对撞机方案**，包括：
欧洲的FCC-ee, FCC-hh；
中国的CEPC，SPPC。
以及国际直线加速器ILC等等。

https://home.cern/news/press-release/physics/elusive-romance-top-quark-pairs-observed-lhc

The CMS and ATLAS experiments at CERN's Large Hadron Collider have observed an unforeseen feature in the behaviour of top quarks that suggests that these heaviest of all elementary particles form a fleeting union

8 JULY, 2025



Artist's impression of the short-lived union of a top quark and a top antiquark formed by the exchange of gluons. (Image: D. Dominguez/CERN)

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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

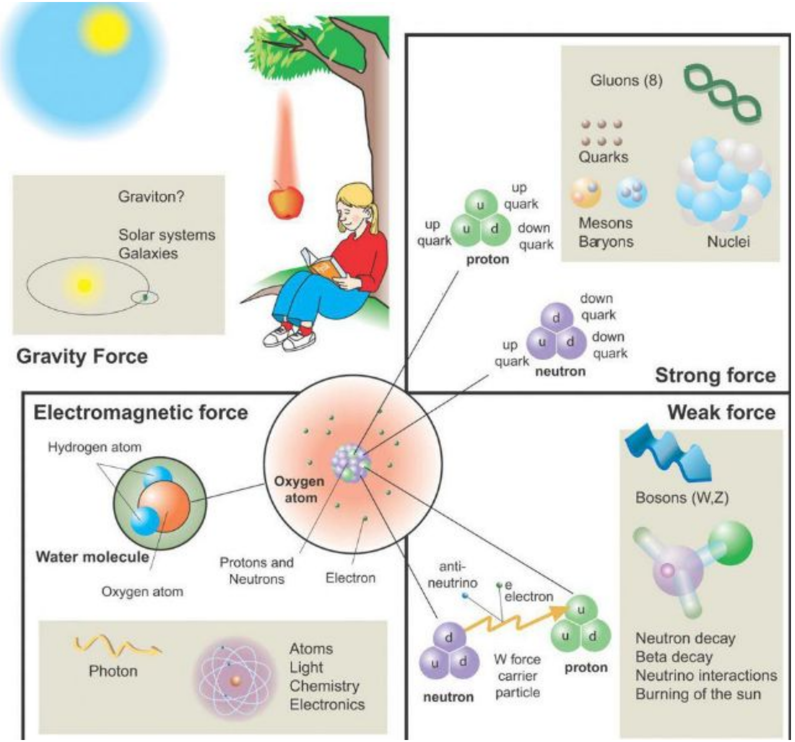
Chen Ning Yang

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

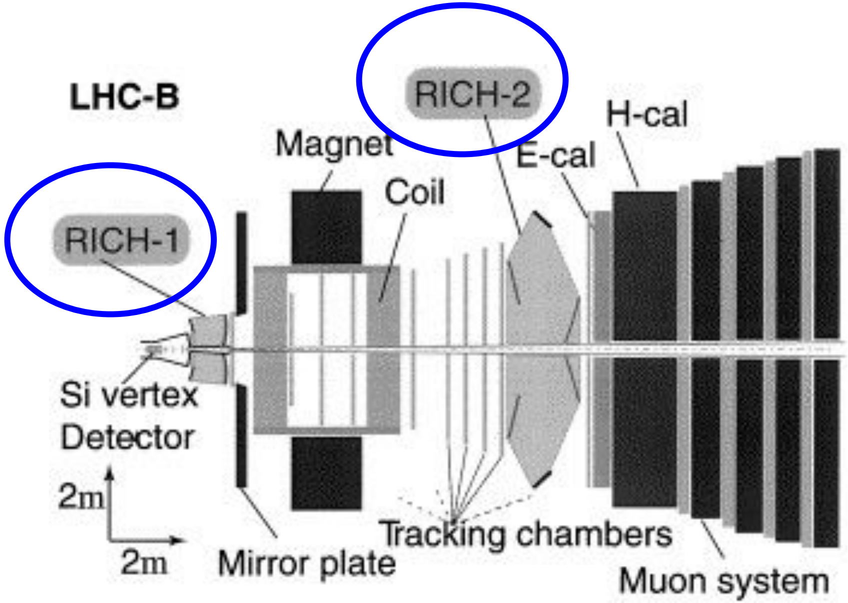
Il´ja Mikhailovich Frank

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

- 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。

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"*

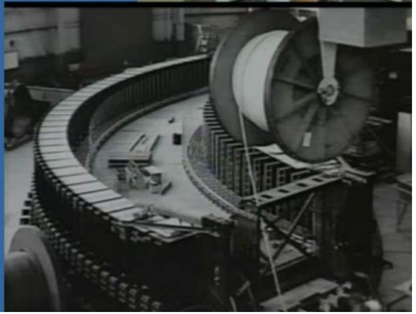
Observation of Antiprotons

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

质子打靶

The Beginning

- Design started in 1947 under the direction of Ernest Lawrence. The primary designer was engineer William Brobeck.
- Construction began in 1949 at The University of California Radiation Laboratory at Berkeley. (The lab was later named the Lawrence Berkeley National Laboratory).
- The first beam at the full energy of 6.2 BeV (GeV) was delivered on April 1, 1954.



The Nobel Prize in Physics 1960

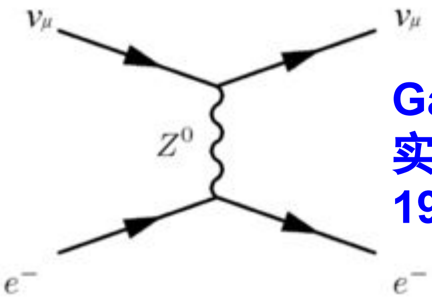
气泡室：弱中性流

Donald Arthur Glaser

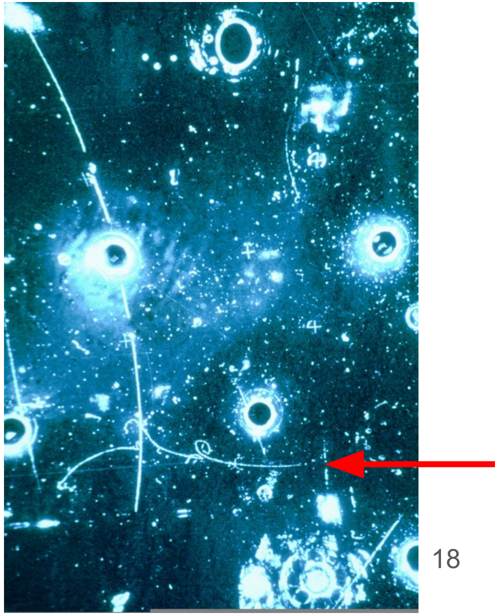
Prize share: 1/1

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



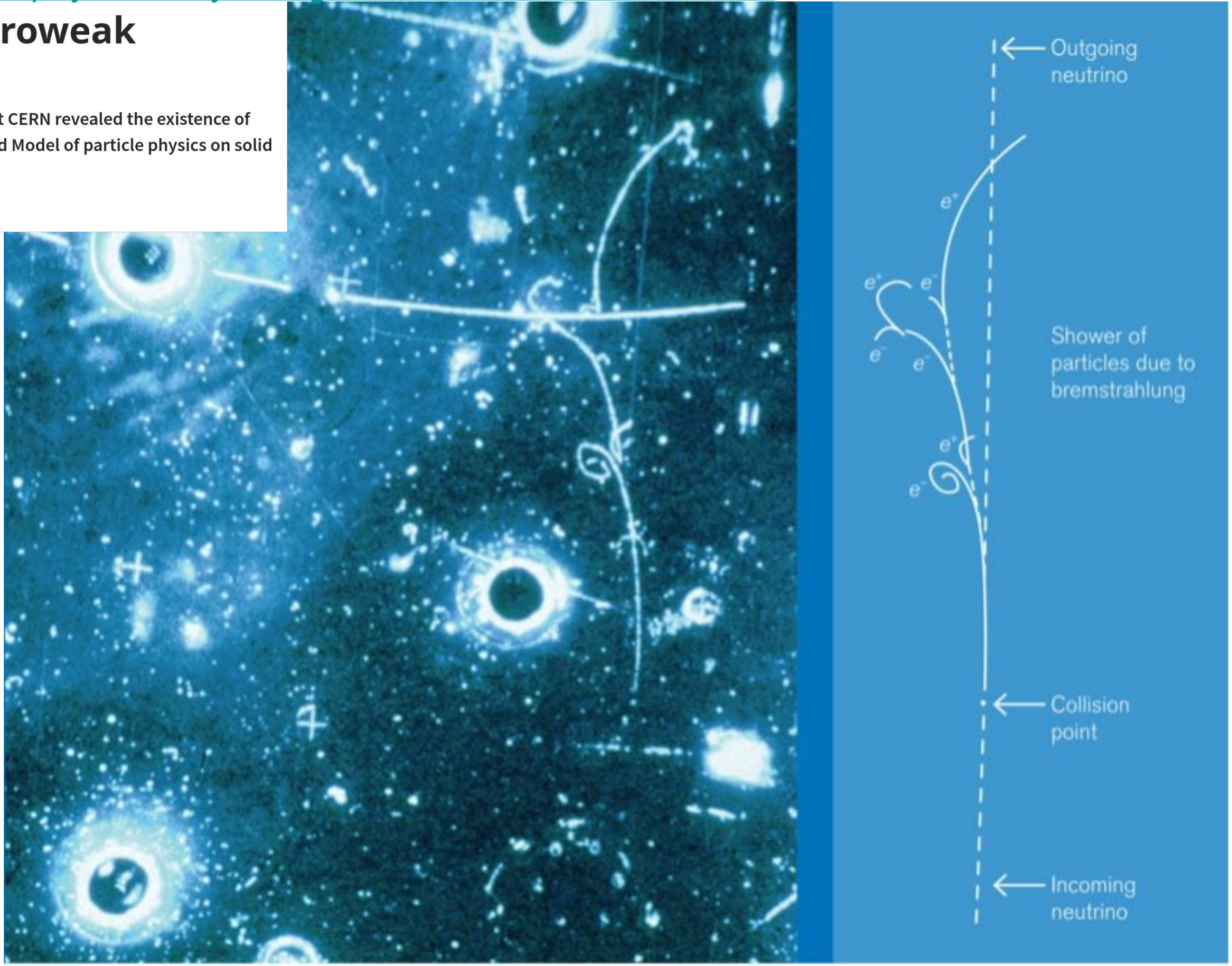
https://cerncourier.com/a/neutral-currents-a-perfect-experimental-discovery/

https://home.cern/news/news/physics/50-years-giant-electroweak-discoveries

50 years of giant electroweak discoveries

On 19 July 1973, the Gargamelle bubble chamber at CERN revealed the existence of weak neutral currents and put the nascent Standard Model of particle physics on solid ground

19 JULY, 2023 | By Matthew Chalmers



The Nobel Prize in Physics 1965

量子电动力学

Sin-Itiro Tomonaga

Prize share: 1/3

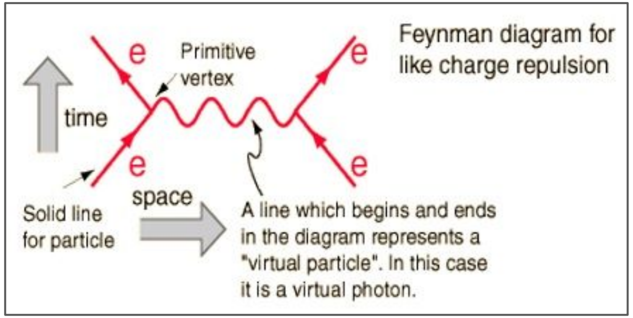
Julian Schwinger

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".*



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."

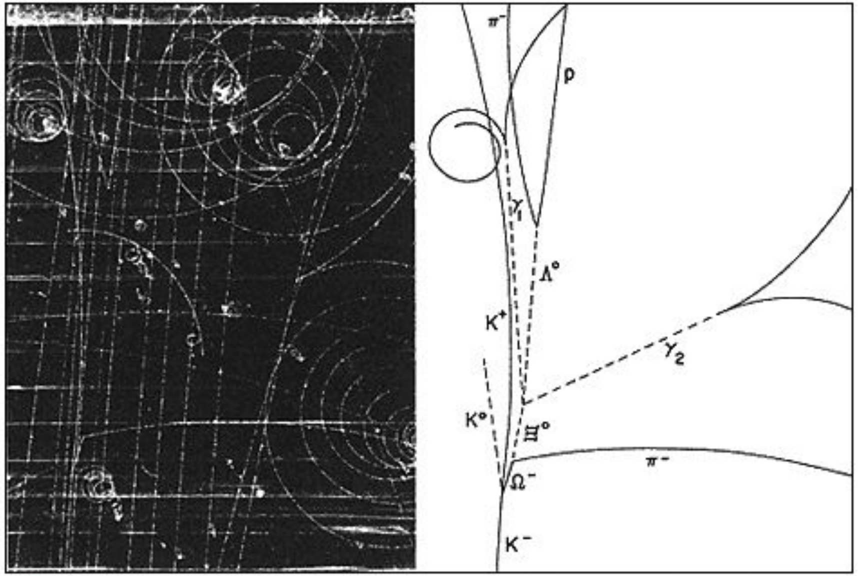
Particle	Symbol	Makeup	Rest mass MeV/c^2	Spin	B	S	Lifetime	Decay Modes
Omega	Ω^-	sss	1672	3/2	+1	-3	0.82 x10^{-10}	$\Xi^0\pi^-$, Λ^0K^-

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

盖尔曼 八重道

(The Eightfold Way)

Brookhaven in 1964.

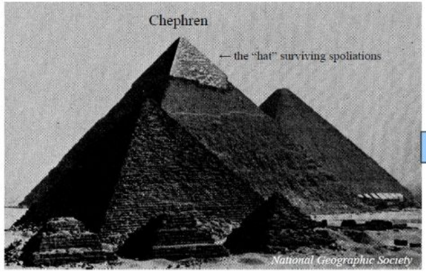


The bubble chamber picture of the first omega-minus. An incoming K- meson interacts with a proton in the liquid hydrogen of the bubble chamber and produces an

https://indico.cern.ch/event/1303471/contributions/5481927/attachments/2683461/4655397/muography-iisc-2023.pdf

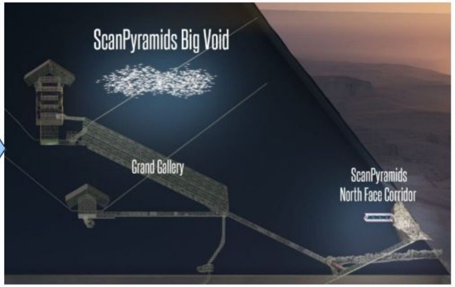
Fast-forward by 50 years

Nature volume 552, pages 386–390 (2017)



Search for hidden chambers in the Chephren's Pyramid

L.W. Alvarez et al. Science 167 (1970) 832



Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons
Morishima et al., Nature 552 (2017) 386

Alvarez chose the wrong pyramid...

(But would have he been able to spot this void?)

LETTER

doi:10.1038/nature2464

Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

Kunihiro Morishima[1], Mitsuaki Kuno[1], Akira Nishio[1], Nobuko Kitagawa[1], Yuta Manabe[1], Masaki Moto[1], Fumihiko Takasaki[2], Hirofumi Fujii[2], Kotaro Satoh[2], Hideyo Kodama[2], Kohei Hayashi[2], Shigeru Odaka[2], Sébastien Procureur[3], David Attié[3], Simon Bouteille[3], Denis Calvet[3], Christopher Filosa[3], Patrick Magnier[3], Irakli Mandjavidze[3], Marc Riallot[3], Benoit Marini[4], Pierre Gable[5], Yoshikatsu Date[6], Makiko Sugiura[7], Yasser Elshayeb[8], Tamer Elnady[9], Mustapha Ezzy[8], Emmanuel Guerriero[5], Vincent Steiger[4], Nicolas Serikoff[4], Jean-Baptiste Mouret[10,11,12], Bernard Charlès[13], Hany Helal[4,8] & Mehdi Tayoubi[4,13]

The Great Pyramid, or Khufu's Pyramid, was built on the Giza plateau in Egypt during the fourth dynasty by the pharaoh Khufu (Cheops)[1], who reigned from 2509 BC to 2483 BC. Despite being one of the oldest and largest monuments on Earth, there is no consensus about how it was built[2,3]. To understand its internal structure better, we imaged the pyramid using muons, which are by-products of cosmic rays that are only partially absorbed by stone[4–6]. The resulting cosmic-ray muon radiography allows us to visualize the known and any unknown voids in the pyramid in a non-invasive way. Here we report the discovery of a large void (with a cross-section similar to that of the Grand Gallery and a minimum length of 30 metres) situated above the Grand Gallery. This constitutes the first major inner structure found in the Great Pyramid since the nineteenth century[1]. The void, named ScanPyramids' Big Void, was first observed with nuclear emulsion films[7–9] installed in the Queen's chamber, then confirmed with scintillator hodoscopes[10,11] set u in the same chamber and finally re-confirmed with gas detectors outside the pyramid. This large void has therefore been detected wit high confidence by three different muon detection technologies an three independent analyses. These results constitute a breakthroug for the understanding of the internal structure of Khufu's Pyramid Although there is currently no information about the intende purpose of this void, these findings show how modern particl physics can shed new light on the world's archaeological heritage.

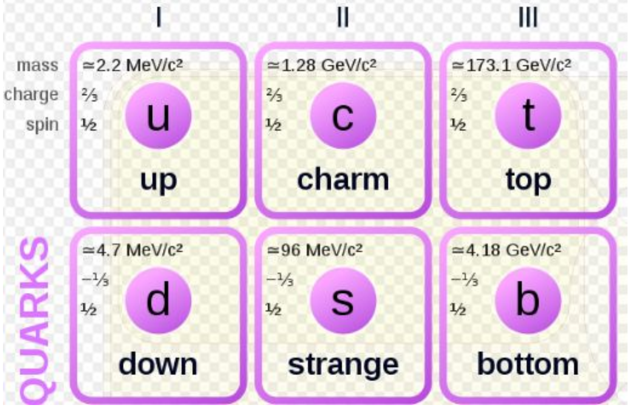
The pyramid of Khufu is 139 m high and 230 m wide[1,13]. There ar three known chambers (Fig. 1), at different heights of the pyramid, whic all lie in the north–south vertical plane[1]: the subterranean chambe the Queen's chamber, and the King's chamber. These chambers ar connected by several corridors, the most notable one being the Gran Gallery (8.6 m high × 46.7 m long × 2.1–1.0 m wide). The Queen

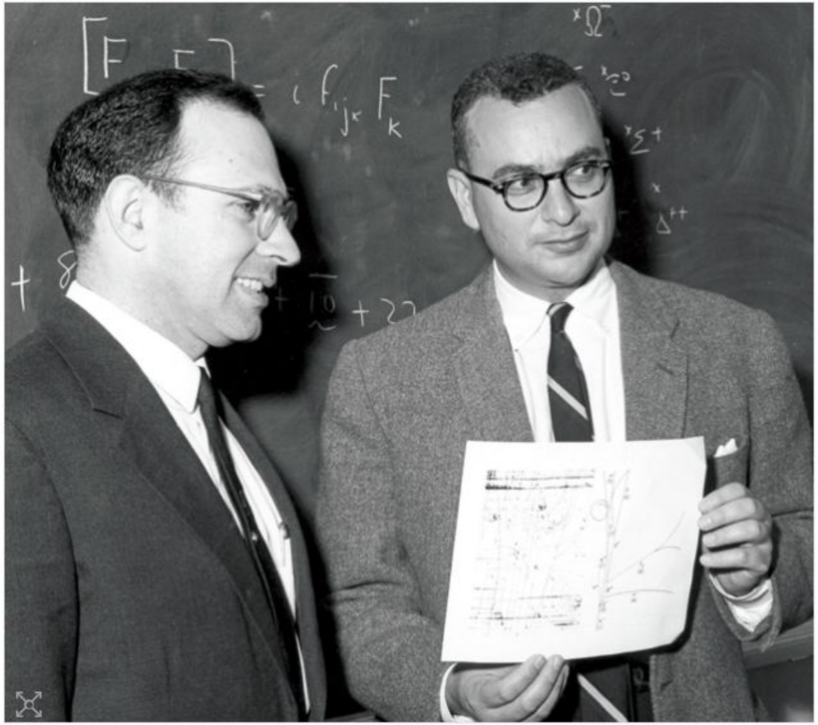
The Nobel Prize in Physics 1969

QCD，夸克

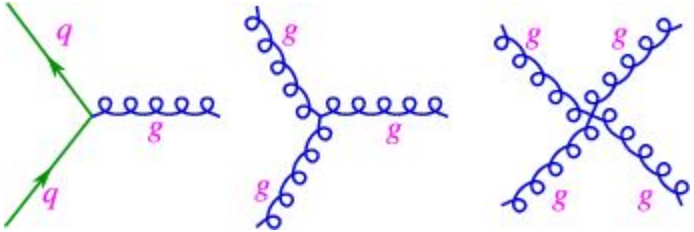
Murray Gell-Mann

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

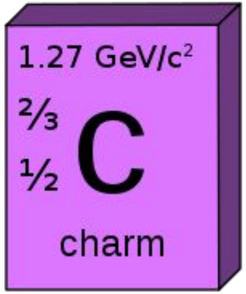
J/ψ，粲夸克

Burton Richter

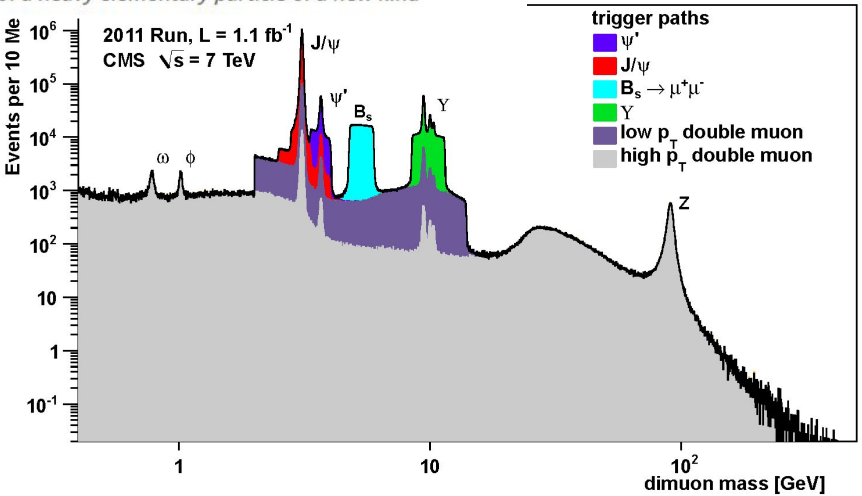
Prize share: 1/2

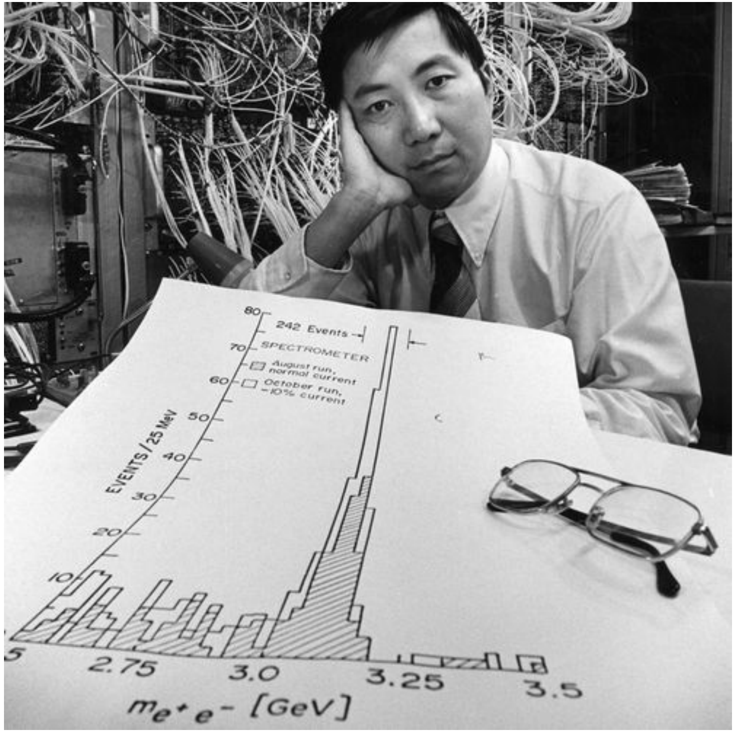
Samuel Chao Chung Ting

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"*





https://www.aip.org/history-programs/niels-bohr-library/oral-histories/44898

Uhlenbeck, after I was with him about a month or two, had an afternoon meeting with all of his graduate students. There were three or four of us. He said, "If I were to live my life over again, I would be an experimentalist rather than a theorist." I was very surprised. I discovered that one of the great theorists of the 20th century wanted to be an experimentalist. I asked him why? He said, " Whereas an average experimentalist is very useful because every measurement is useful, an average theorist is not. You can count on your fingers how many theorists made a difference in the 20th century." A few hours after this conversation, I went back to see him and said, "You're right. I should leave you, and I should try to do experiments." That's how I became an experimentalist.

乌伦贝克在我(丁肇中)和他在一起大约一两个月后，与他所有的研究生进行了一次下午的会面。我们有三四个人。他说:“如果我的人生能够重来一次，我会成为一名实验家，而不是一名理论家。”我很惊讶。我发现 20 世纪一位伟大的理论家想成为一名实验家。我问他为什么？他说:“普通的实验学家非常有用，因为每一次测量都是有用的，而普通的理论家则不然。你可以用手指头数出有多少理论家在 20 世纪做出了贡献。”这次谈话几个小时后，我回去见他，说:“你是对的。我应该离开你，我应该尝试做实验。”就这样我成为了一名实验家。

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.

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

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

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

$$A = W_3 \sin\theta_W + B \cos\theta_W \qquad \theta_W \text{ Weak Mixing Angle}$$

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

标准模型 Standard Model

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

The Nobel Prize in Physics 1984

W，Z玻色子

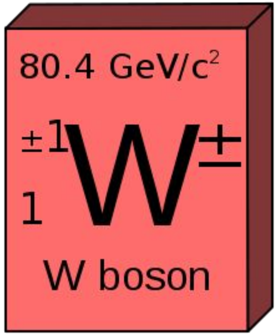
Carlo Rubbia

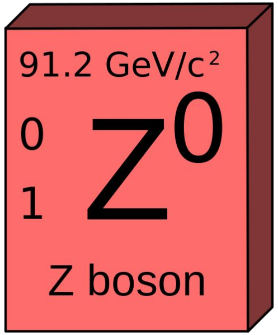
Prize share: 1/2

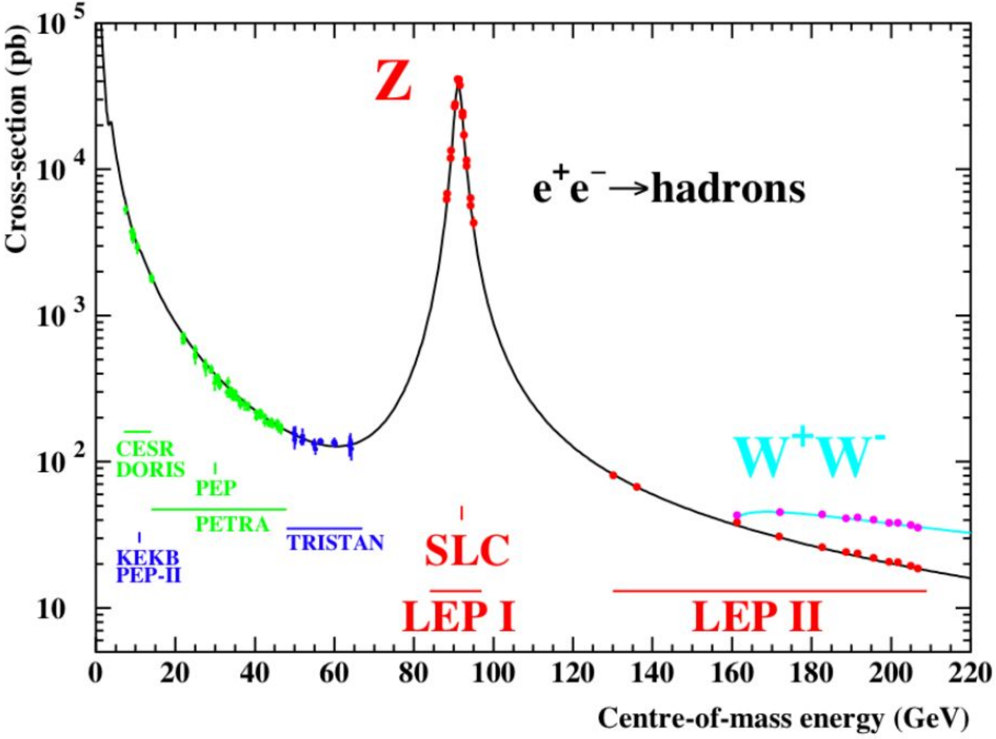
Simon van der Meer

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"*







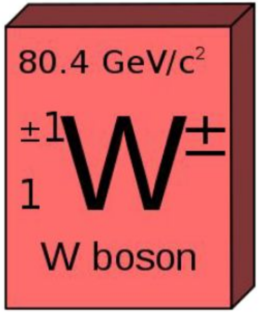
The Nobel Prize in Physics 1984

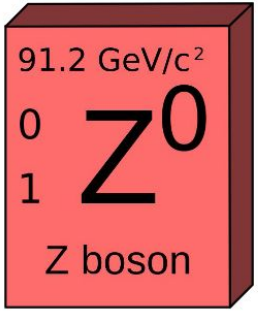
W，Z玻色子

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"*





缪子中微子

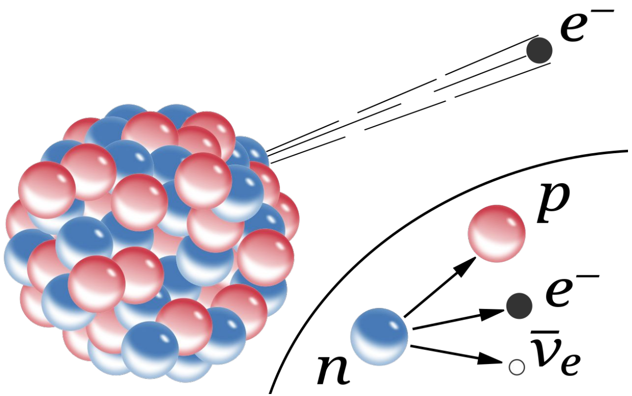
The Nobel Prize in Physics 1988

Leon M. Lederman
Prize share: 1/3

Melvin Schwartz
Prize share: 1/3

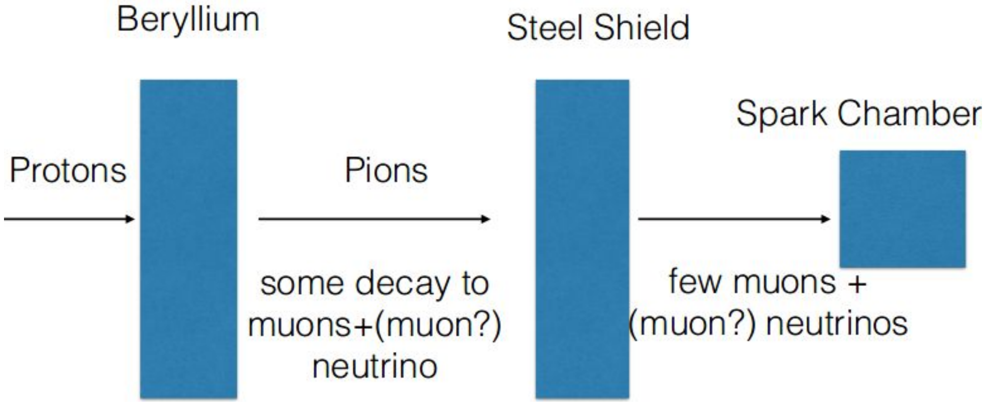
Jack Steinberger
Prize share: 1/3

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

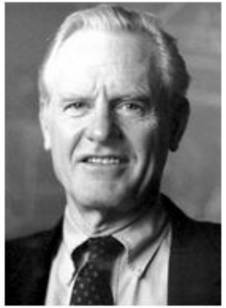


1930
Pauli
预言
中微子

深度非弹，夸克模型

The Nobel Prize in Physics 1990

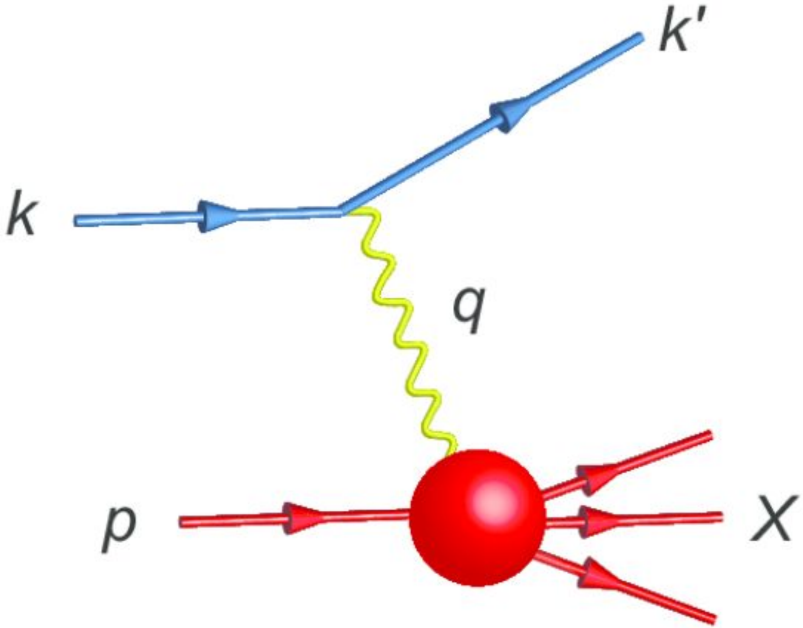
Jerome I. Friedman
Prize share: 1/3



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

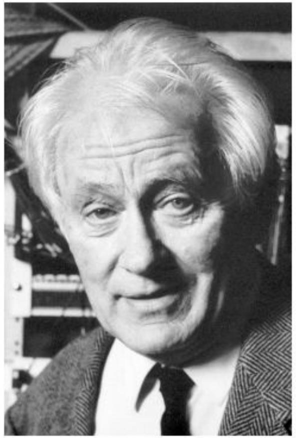
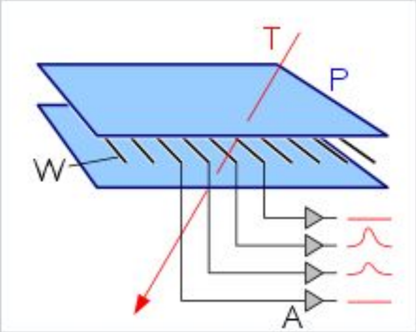


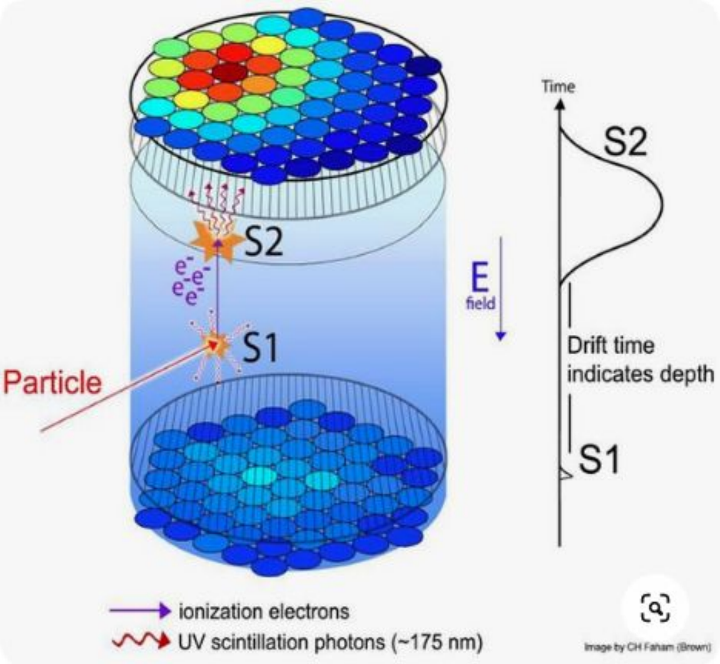
Photo from the Nobel Foundation archive.

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

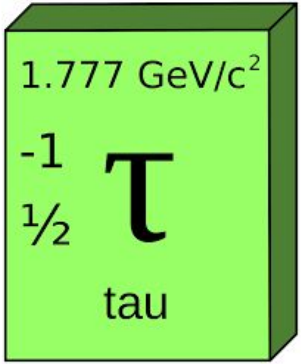
Martin L. Perl

Prize share: 1/2

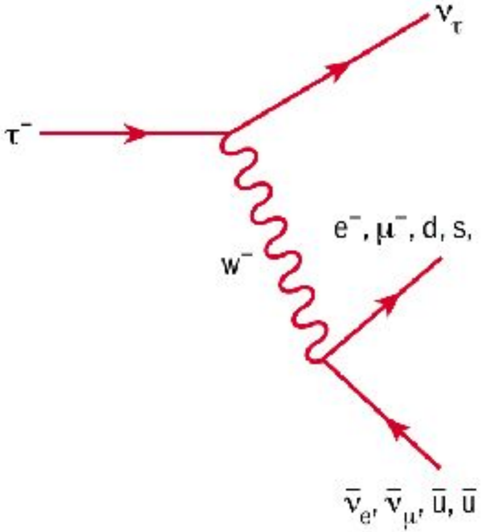
© University of California Regents

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.

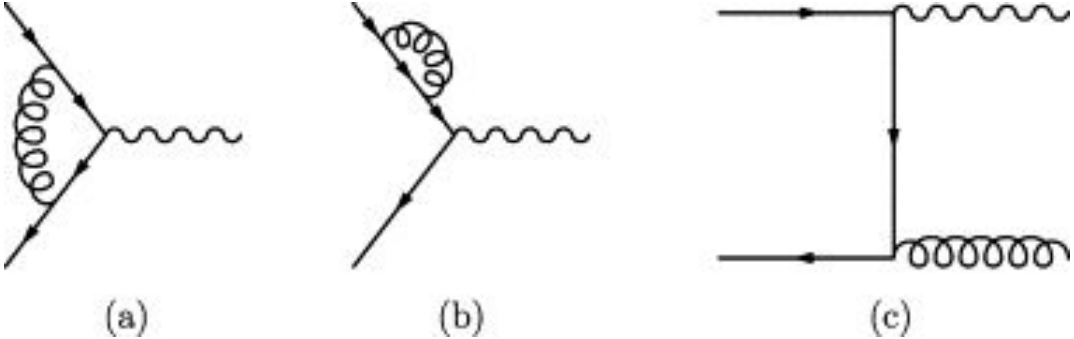
The Nobel Prize in Physics 1999

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

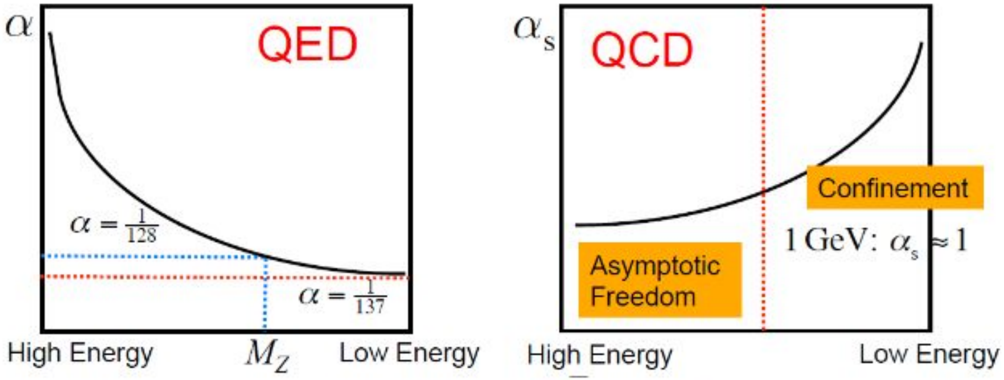
QCD渐进自由

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"*.



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

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

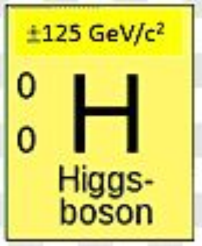
François Englert

Prize share: 1/2

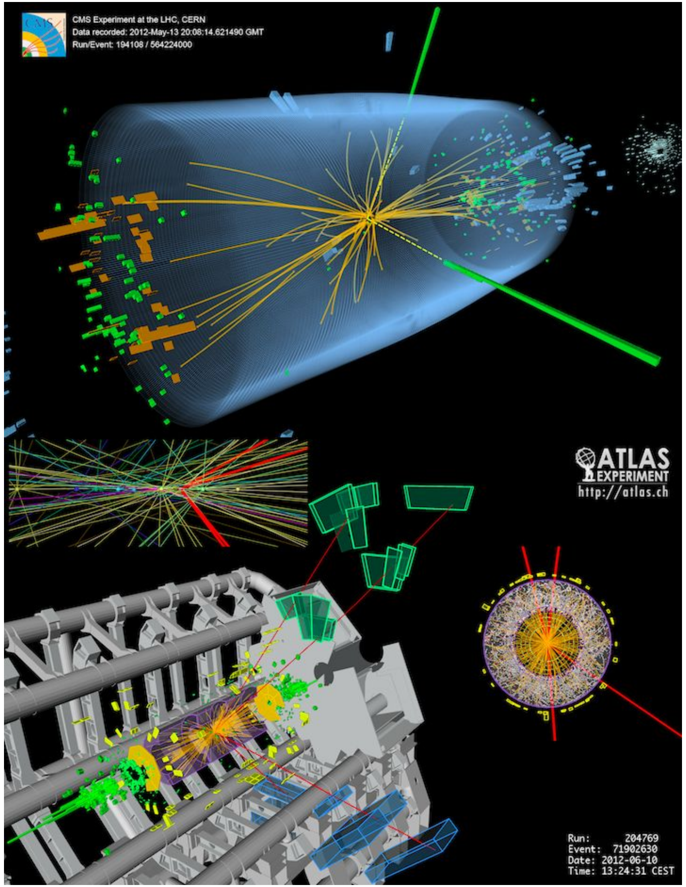
Photo: A. Mahmoud

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

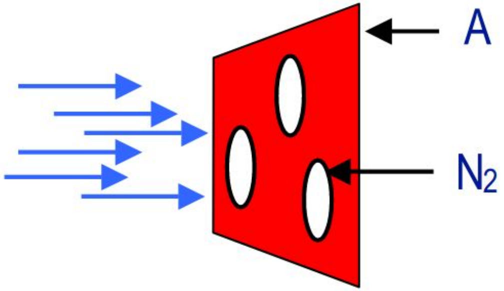
https://videos.cern.ch/

束流打靶

Cross Section and Luminosity

$$R(t) = \mathcal{L}(t) \cdot \sigma_{\text{vis}}$$

Number of beam particles: N_1



Number of target particles: N_2

Target thickness: dx

Target density: $n_2 = N_2/(A \cdot dx)$

Number of interactions / time: $$R = \frac{dN_1}{dt} \cdot n_2 \cdot dx \cdot \sigma$$

- The number of interactions per time, i.e. the rate R, is proportional to the material-specific cross section σ.
- The proportionality factor $\mathcal{L} = \frac{dN_1}{dt} \cdot n_2 \cdot dx$ is called luminosity

Joscha knolle FSP Colloquium 2022

束流碰撞

What is luminosity?

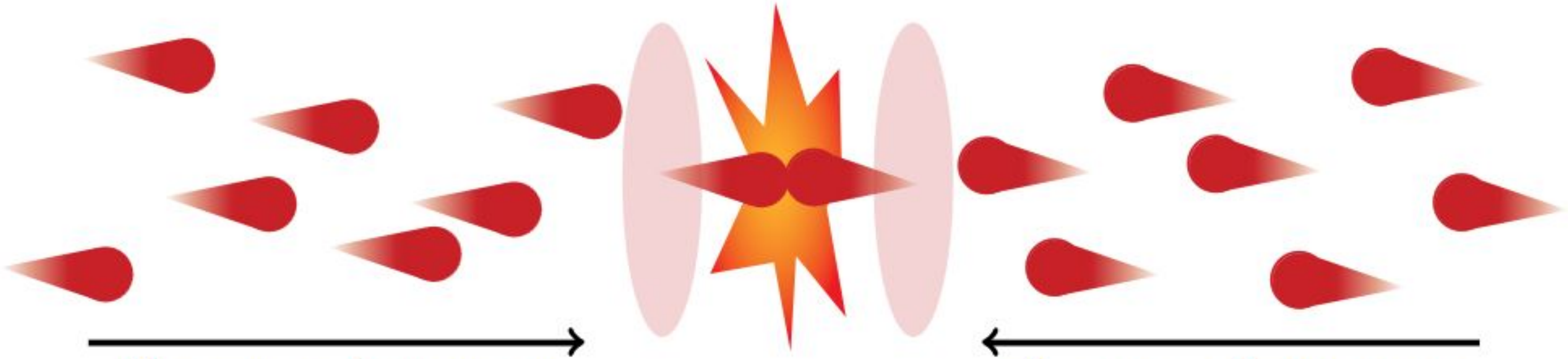
- measure of collision rate:

$$\frac{\mathrm{d}N}{\mathrm{d}t}(pp \to X) = \mathcal{L} \cdot \sigma(pp \to X)$$

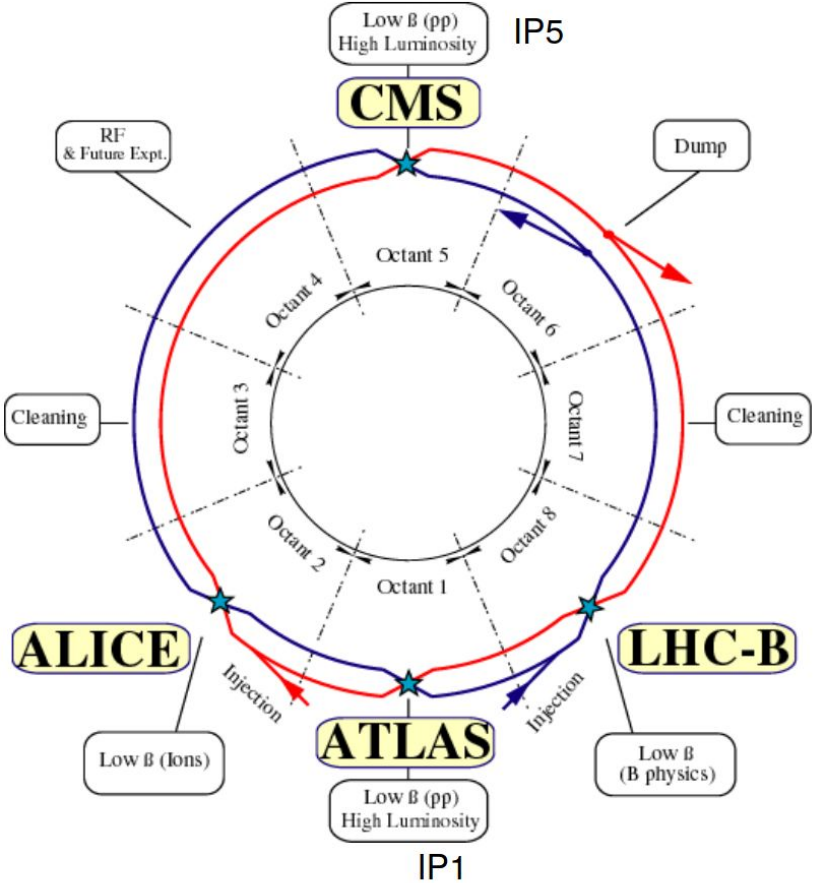
- luminosity from beam parameters:

$$\mathcal{L} = \frac{\nu N_1 N_2}{A_{\text{luminous}}}$$

- units of luminosity: $(\text{area} \cdot \text{time})^{-1}$
  - instantaneous luminosity: Hz/μb
  - integrated luminosity $\int \mathrm{d}t\, \mathcal{L}$: fb^{-1}



https://www-conf.slac.stanford.edu/ssi/2012/Presentations/Zimmermann.pdf



- luminosity from beam parameters:

$$\mathcal{L} = \frac{\nu N_1 N_2}{A_{\text{luminous}}}$$

c.m. energy = 14 TeV
luminosity $=10^{34}$ cm^{-2}s^{-1}

1.15×10^{11} p/bunch
2808 bunches/beam

$\gamma\varepsilon=3.75\ \mu m$
$\beta^*=0.55$ m
$\theta_c=285\ \mu rad$
$\sigma_z=7.55$ cm
$\sigma^*=16.6\mu m$ (IP1 & 5)

$L \sim N^2/(t \cdot S_{eff})$

Now, with $N^2 = (1{,}15\cdot10^{11})^2$

$t = 25\cdot10^{-9}$ s , $S_{eff} = 4\cdot\pi(16\cdot10^{-4})^2$ cm^2

$L \sim 10^{34}$ cm$^{-2}\cdot$s^{-1}

Unit	Symbol	m^2	cm^2
megabarn	Mb	10^{-22}	10^{-18}
kilobarn	kb	10^{-25}	10^{-21}
barn	b	10^{-28}	10^{-24}
millibarn	mb	10^{-31}	10^{-27}
microbarn	μb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}
zeptobarn	zb	10^{-49}	10^{-45}
yoctobarn	yb	10^{-52}	10^{-48}

Higgs cross section ~ 50pb ~5*10^{-35} cm^2

1 year ~ 10^7 sec effectively

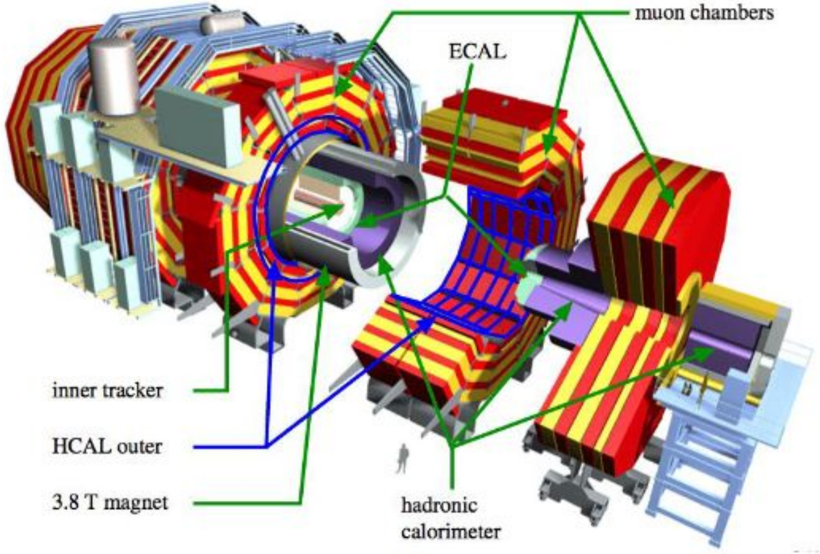
→

5*10^{-35} * 10^7 * 10^-34 ~ 1 Million Higgs

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. 机器学习、量子纠缠
8. 总结与展望

Large Hadron Collider

CMS探测器：直径15米，长28米，重14000吨

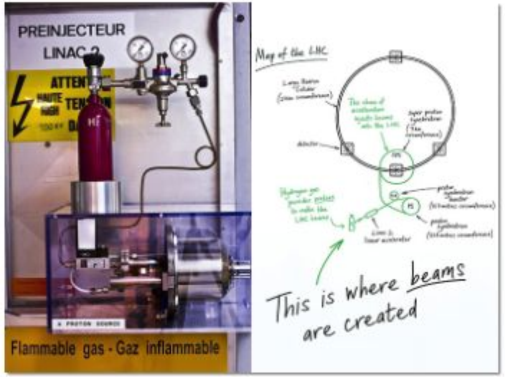


CMS是LHC上4个大型对撞点实验之一。

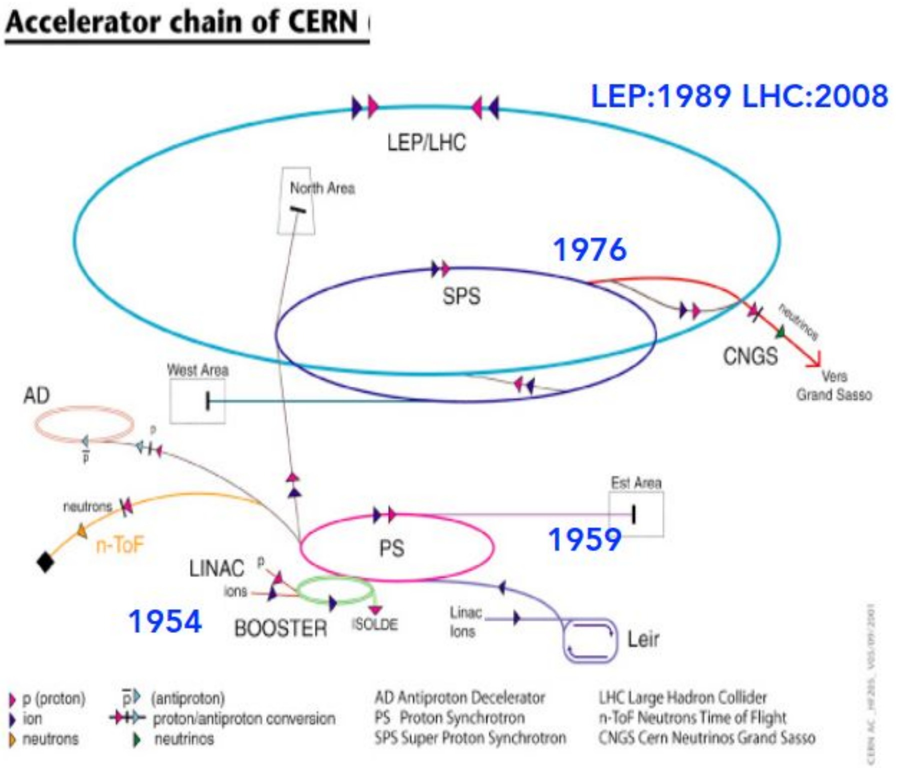
成员：约55个国家, 210个研究单位, 4000多人员。北大1996年加入CMS组。

Large Hadron Collider

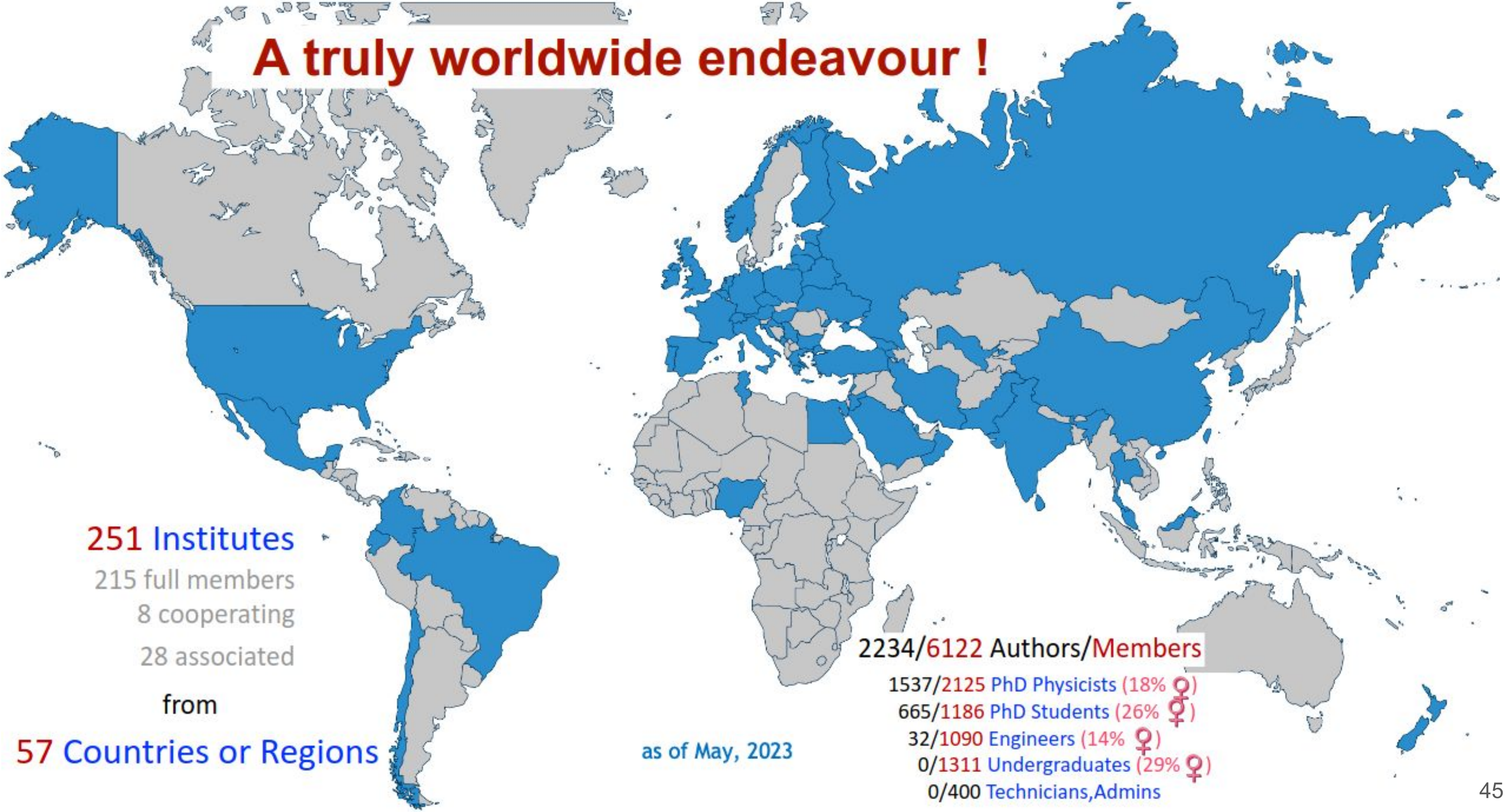
The CERN accelerator complex is formed by a succession of accelerators of increasing energy



- PS Booster : 1.4 GeV
- PS : 25 GeV
- SPS : 450 GeV
- LHC : 6.5 TeV



A truly worldwide endeavour !



251 Institutes

215 full members
8 cooperating
28 associated

from

57 Countries or Regions

as of May, 2023

2234/6122 Authors/Members

1537/2125 PhD Physicists (18% ♀)
665/1186 PhD Students (26% ♀)
32/1090 Engineers (14% ♀)
0/1311 Undergraduates (29% ♀)
0/400 Technicians,Admins

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高能所
北大
清华
北航
山大
复旦
浙大
科大
南师大
中山
华南师大

CMS structure & management

"The Parliament"

Collaboration Board

"The Government"

Management Board

Committees

Conference Committee

etc.

Publications Committee

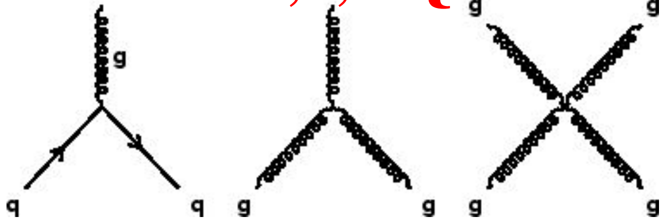
Extended Executive Board

QED vs QCD

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

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

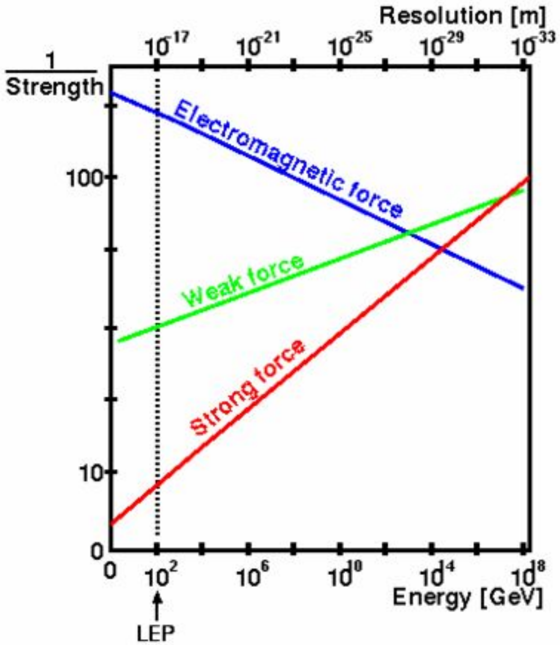
a=1…8,
i=1,2,3 QCD colors



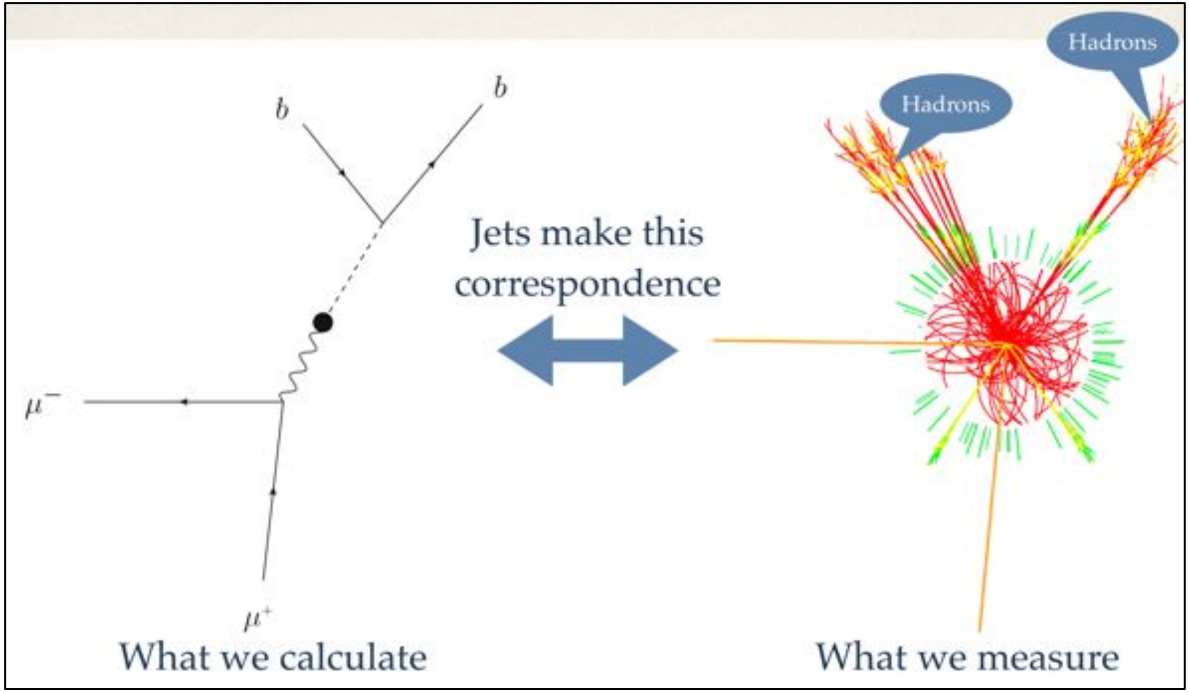
Self-interactions

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

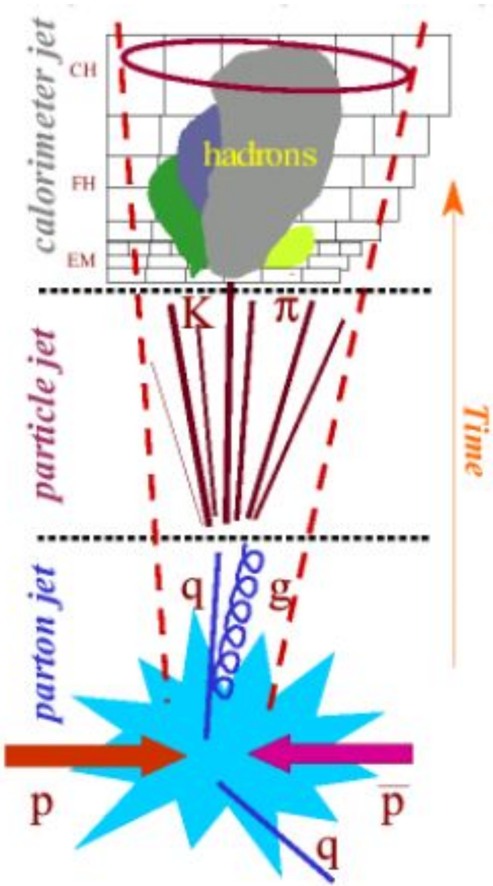
$$\alpha_{QCD}(100GeV) = \frac{g_s{}^2}{4\pi} \sim 0.13$$



Parton, Jet



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

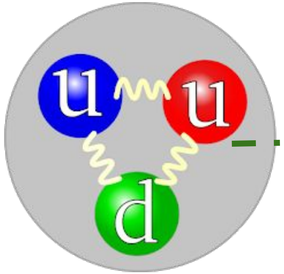


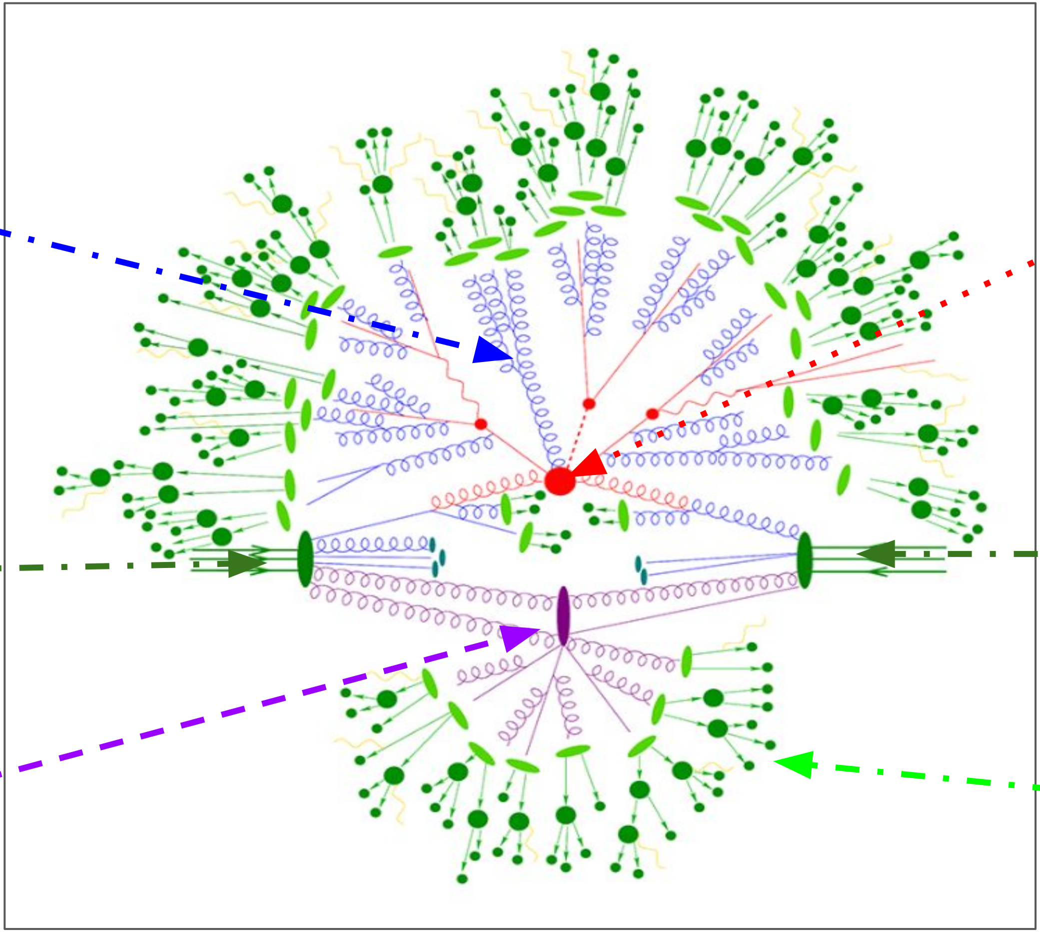
calorimeter jet
CH
FH
EM
hadrons
K
π
particle jet
Time
parton jet
q
g
p
p̄
q

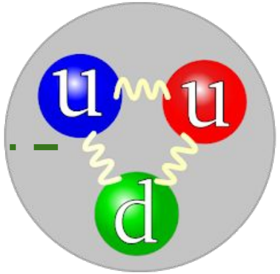
高能对撞

QCD演化
: Parton
Shower

硬散射



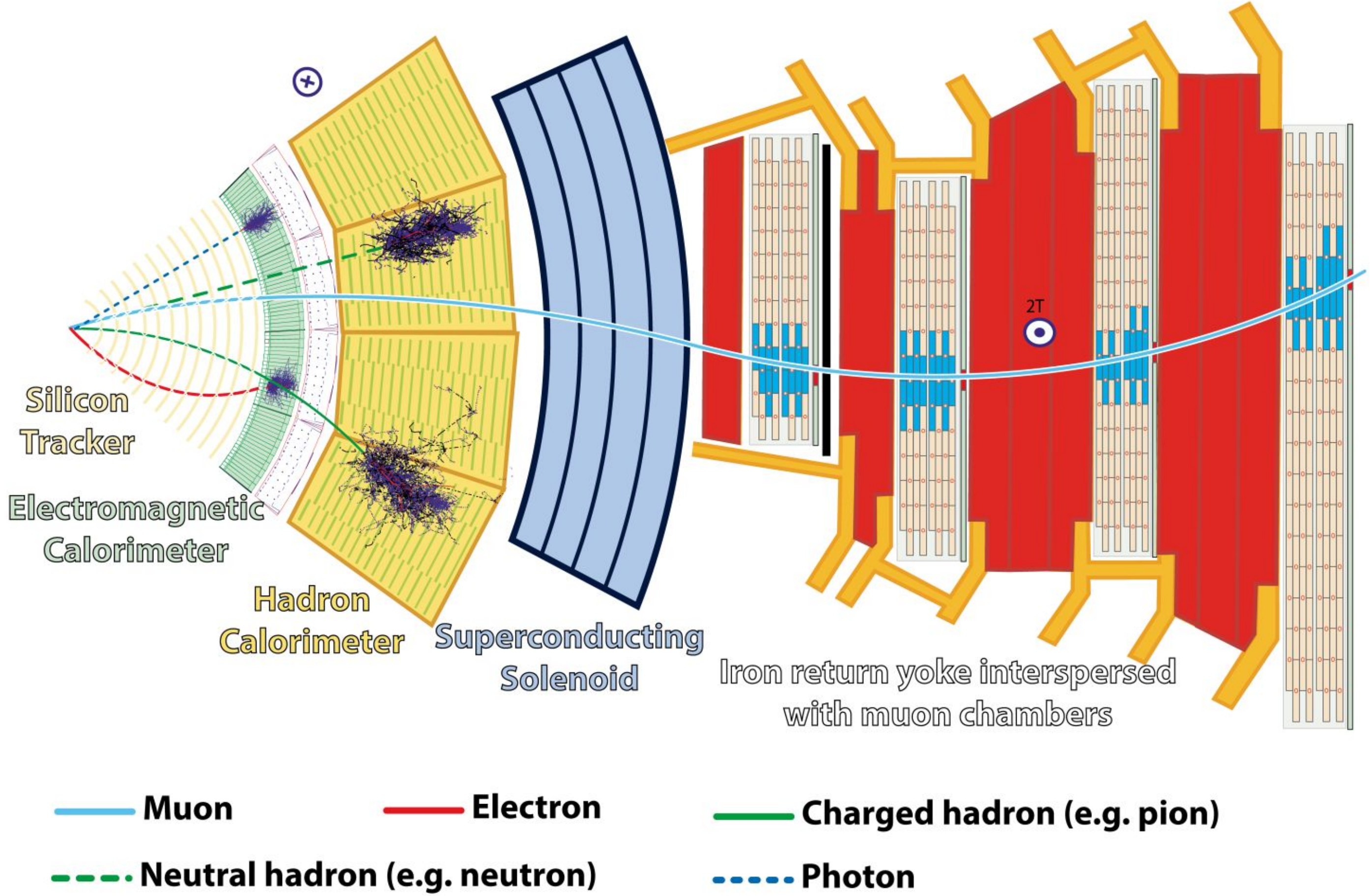


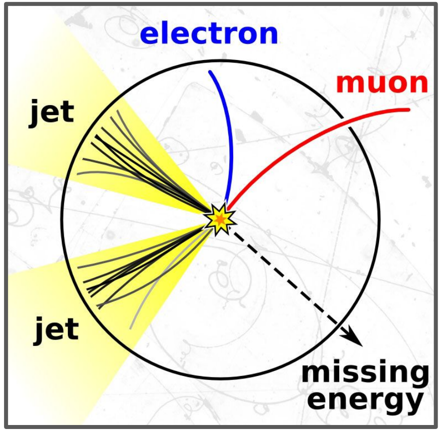


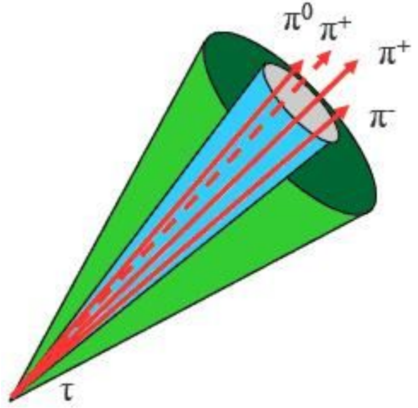
多重散射

强子化

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

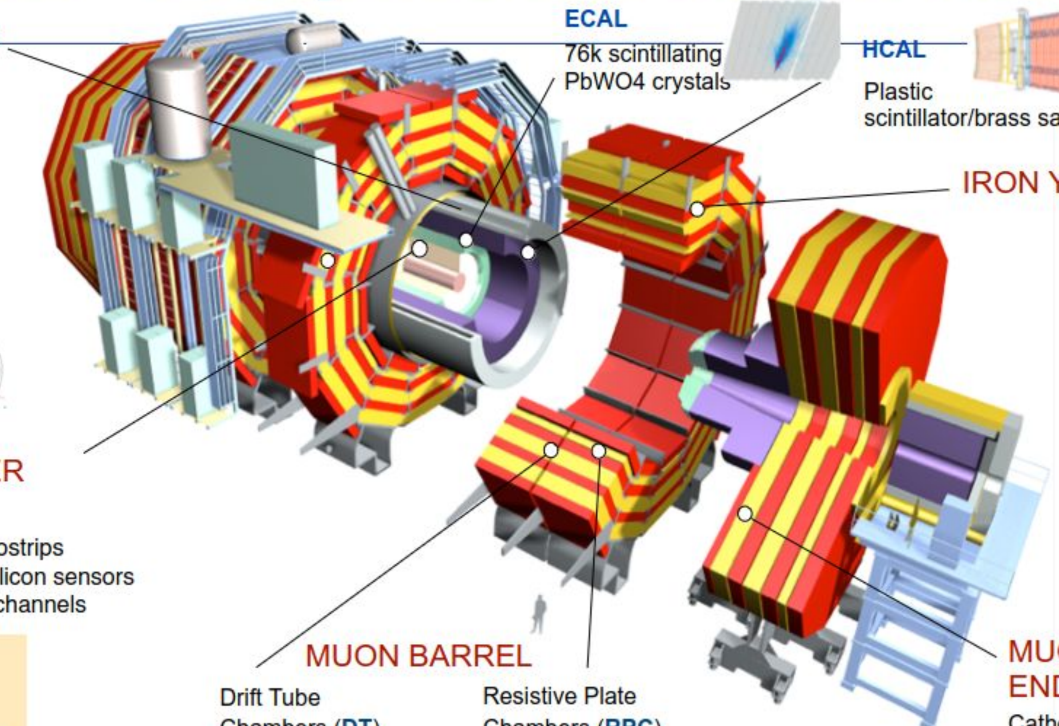

electron
muon
jet
jet
missing energy


π^0 π^+
π^+
π^-
τ

What: the Compact Muon Solenoid

Superconducting Coil, 3.8 Tesla

Total weight	14000 t
Overall diameter	15 m
Overall length	21 m



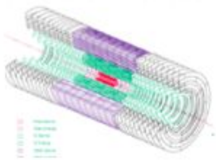
ECAL
76k scintillating $PbWO_4$ crystals

HCAL
Plastic scintillator/brass sandwich

CALORIMETERS

IRON YOKE

Most parts of CMS "easily" accessible during shutdowns (incl. pixels)



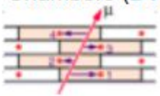
TRACKER

Pixels
Silicon Microstrips
202 m² of silicon sensors
124+9.6 M channels

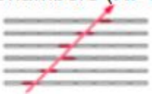
Modular structure
- Barrel (13-m long)
  5 independent wheels
- 2 endcaps (3 rings)

MUON BARREL

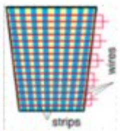
Drift Tube Chambers (**DT**)



Resistive Plate Chambers (**RPC**)



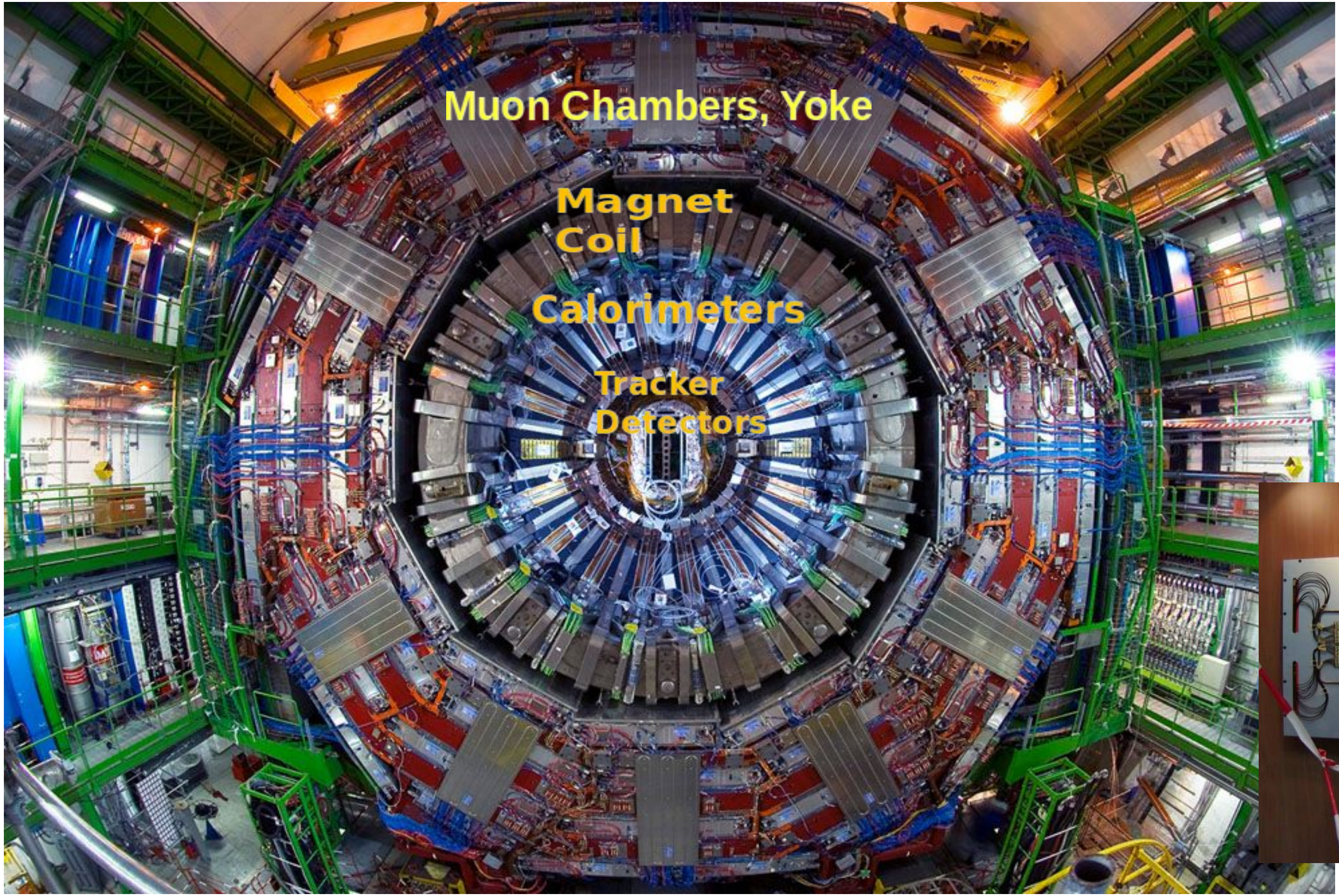
MUON ENDCAPS



Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

+ BRIL (luminosity & beam conditions)
+ PPS (precision proton spectrometer)

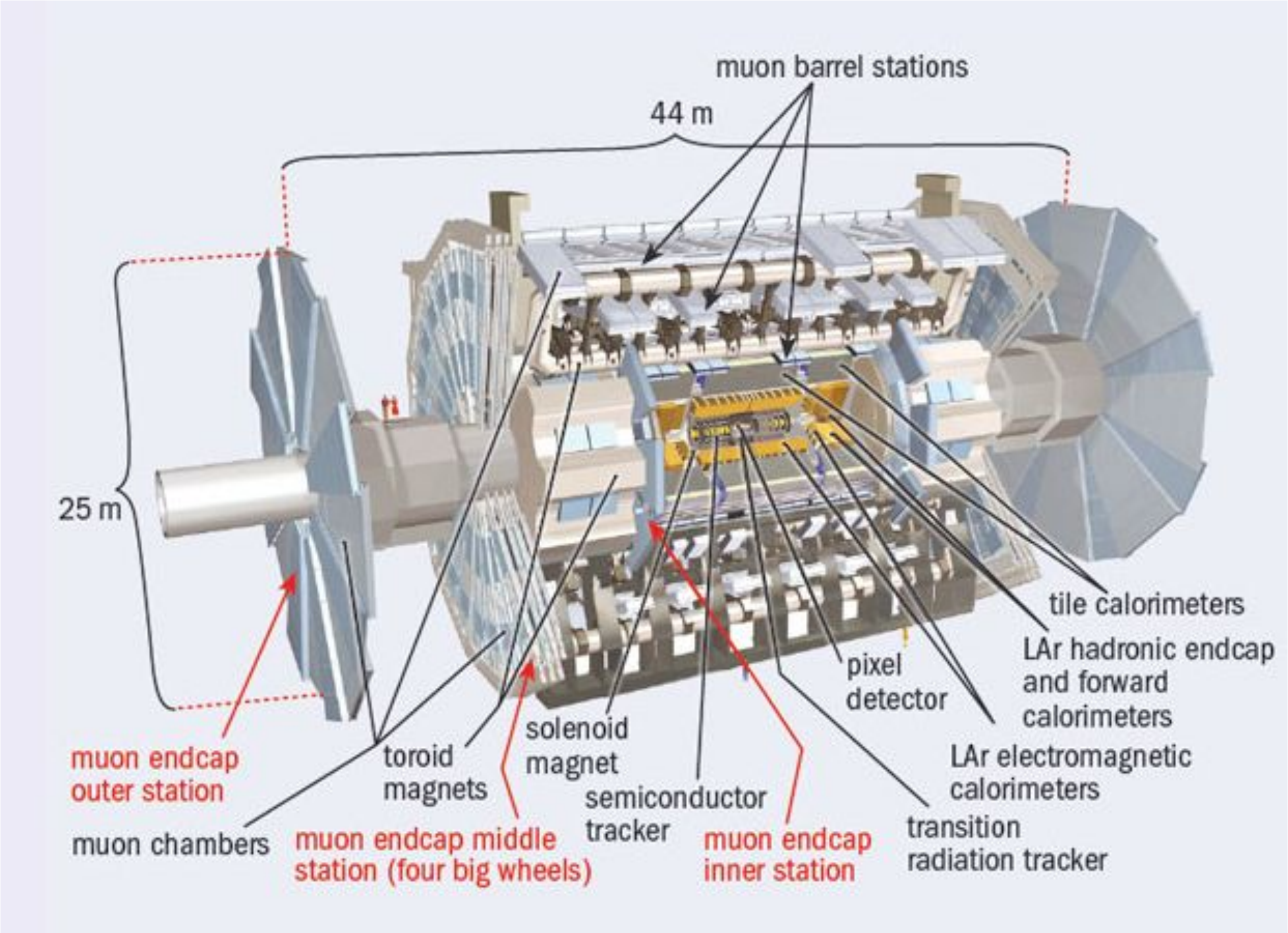
高能对撞机：CMS探测器



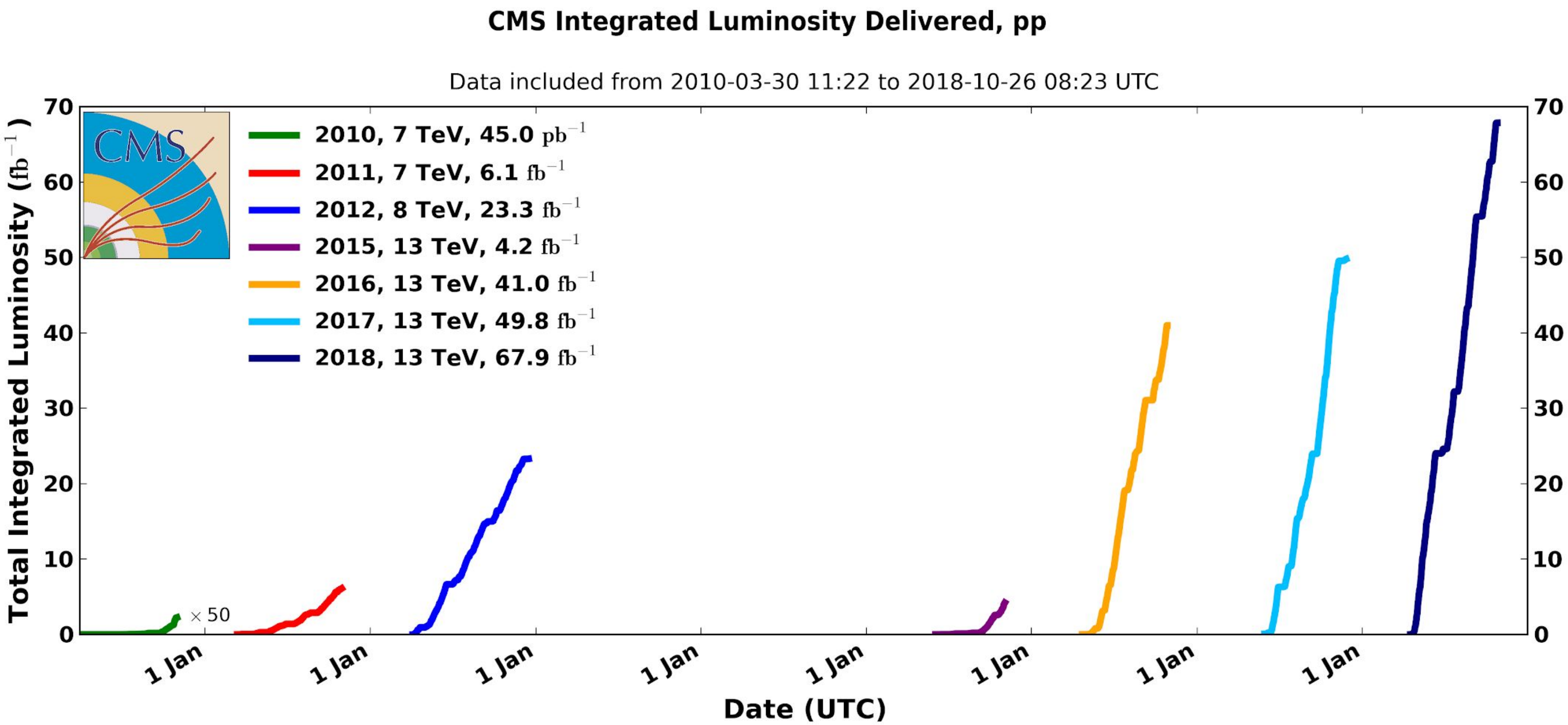
weight: 12500 t
overall diameter: 15 m
overall length: 21.6 m

照相机？
录音机？

高能对撞机：ATLAS探测器

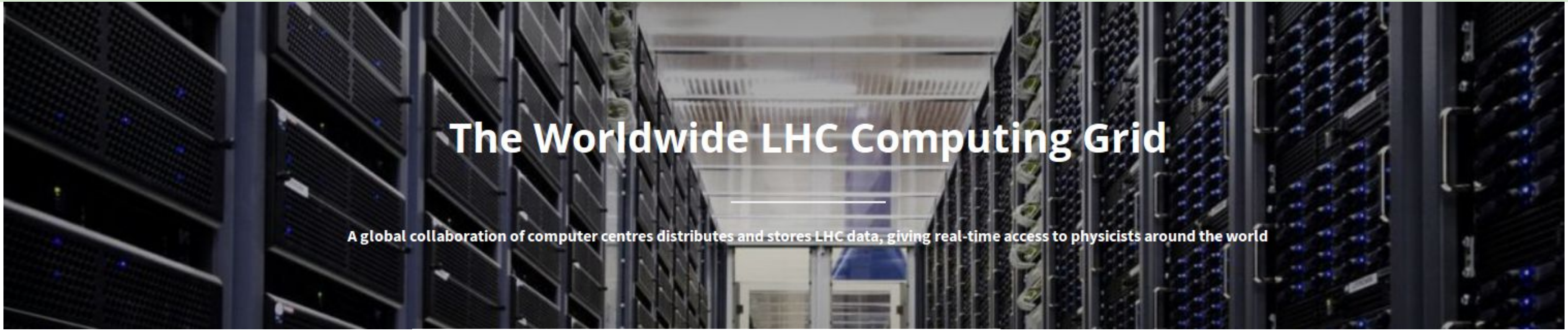


LHC数据亮度

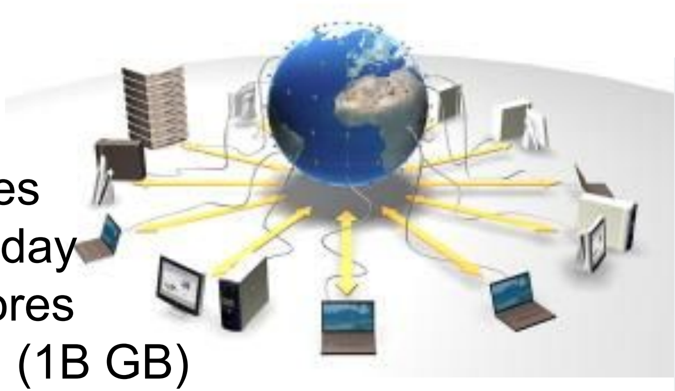


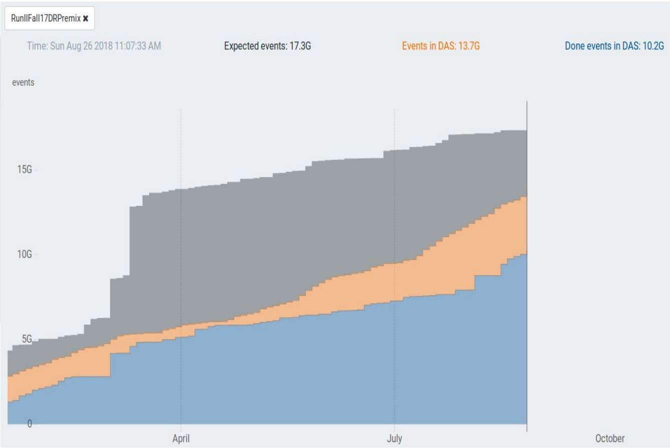
CMS Integrated Luminosity Delivered, pp
Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC
CMS
2010, 7 TeV, 45.0 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
2015, 13 TeV, 4.2 fb⁻¹
2016, 13 TeV, 41.0 fb⁻¹
2017, 13 TeV, 49.8 fb⁻¹
2018, 13 TeV, 67.9 fb⁻¹
× 50
Total Integrated Luminosity (fb⁻¹)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

高能对撞机：大数据



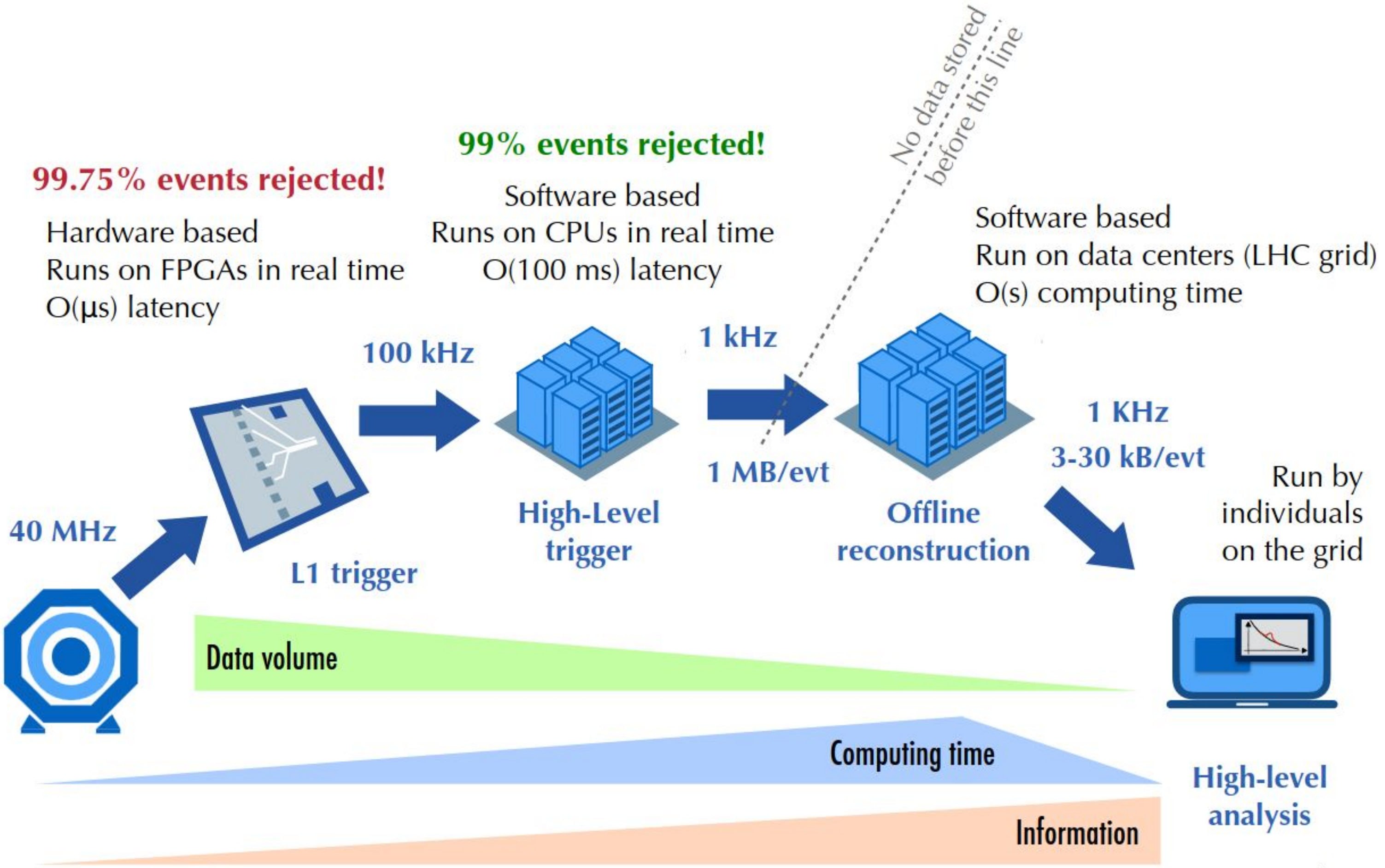
42 countries
170 computing centres
Over 2 million tasks/ day
1 million computer cores
1 exabyte of storage (1B GB)



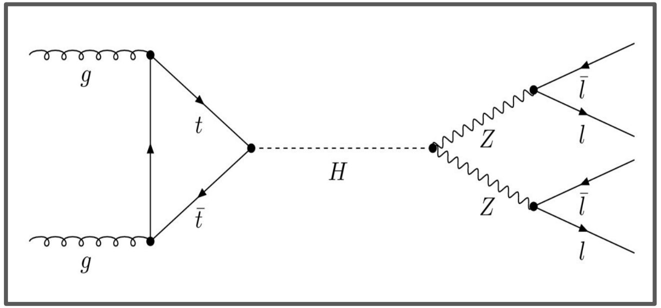


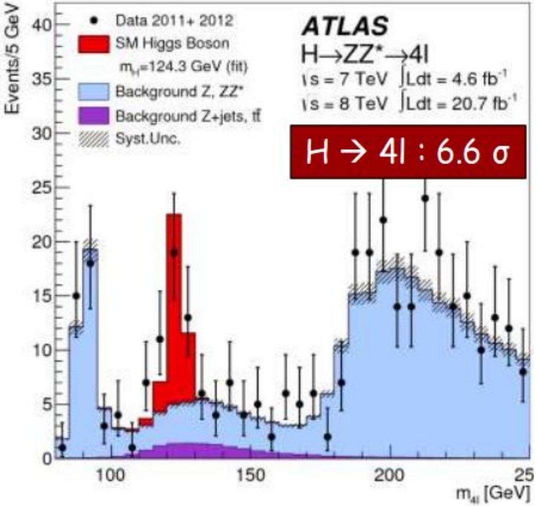
CMS： 15B events in 8 months

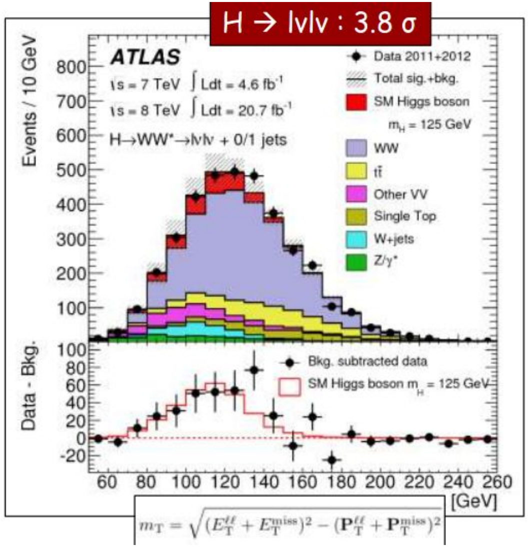
Data reduction workflow @ LHC



高能对撞机：大数据







Needles in a haystack

In ATLAS, up to July 4, 2012:

A million billion collisions

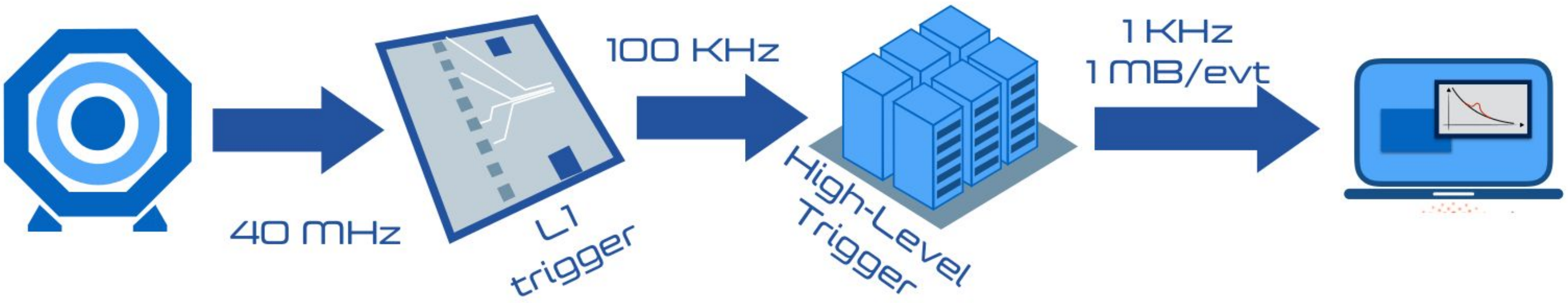
4.2 billion events analyzed

240,000 Higgs particles produced

~350 diphoton Higgs events detected

~8 four-lepton Higgs events detected

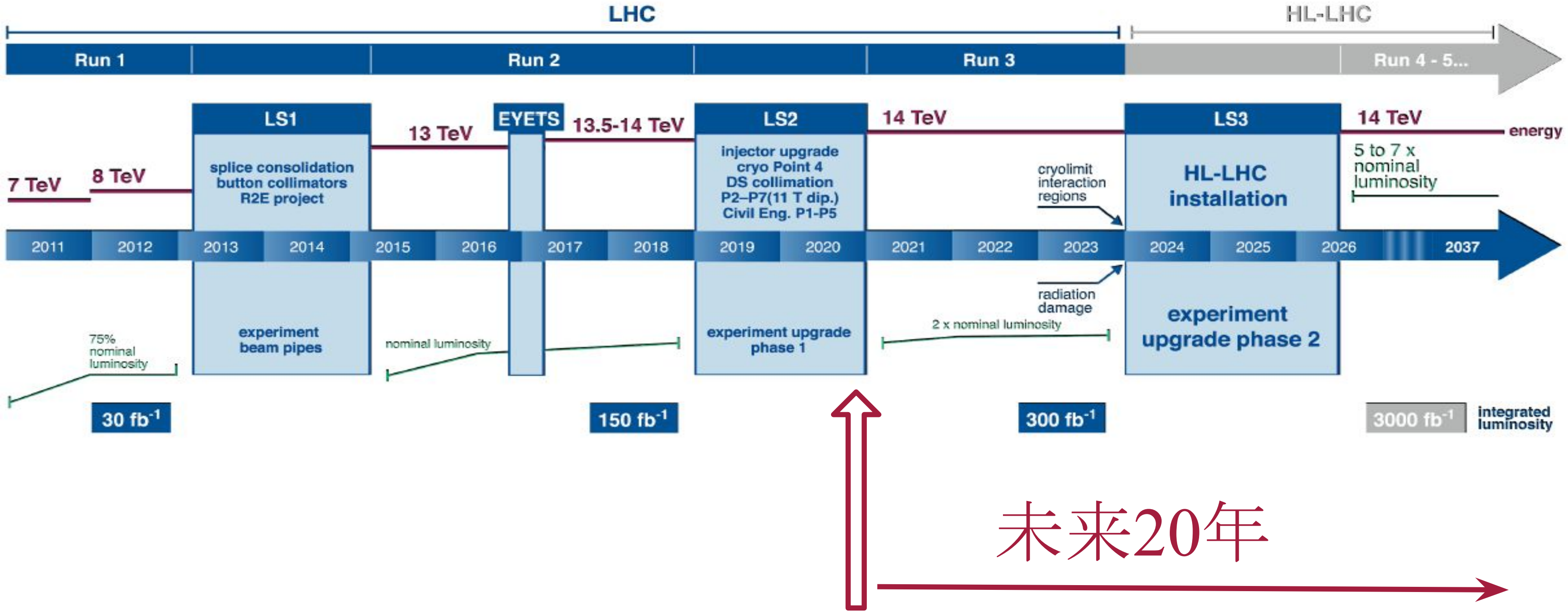
LHC数据流



- **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
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. 机器学习、量子纠缠
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

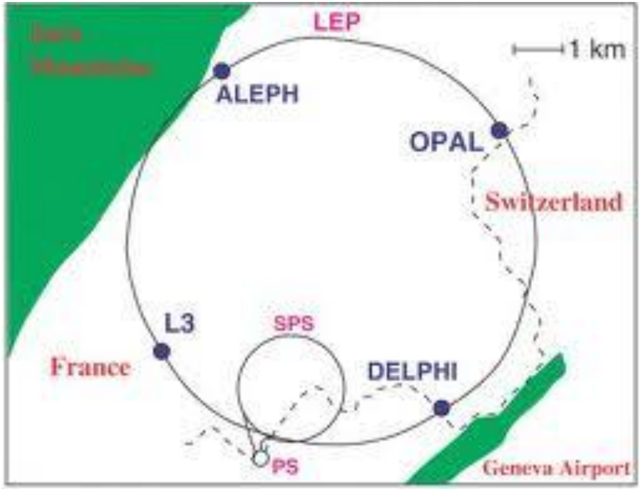
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

4

Volume 13, Number 20 PHYSICAL REVIEW LETTERS 16 November 1964

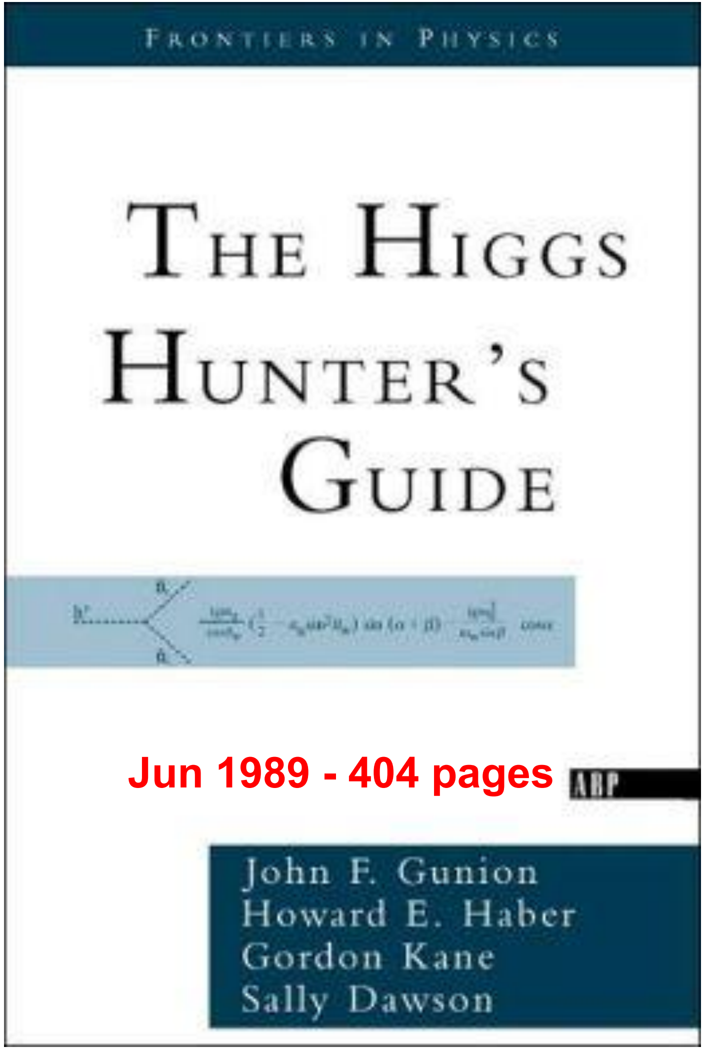
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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

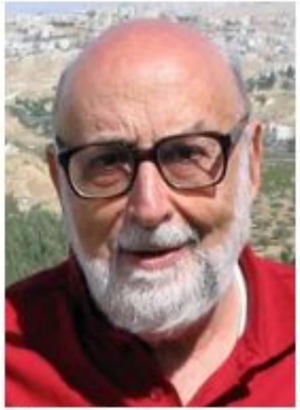


Photo: Pnicolet via Wikimedia Commons

François Englert

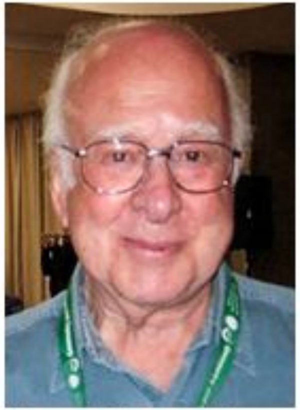
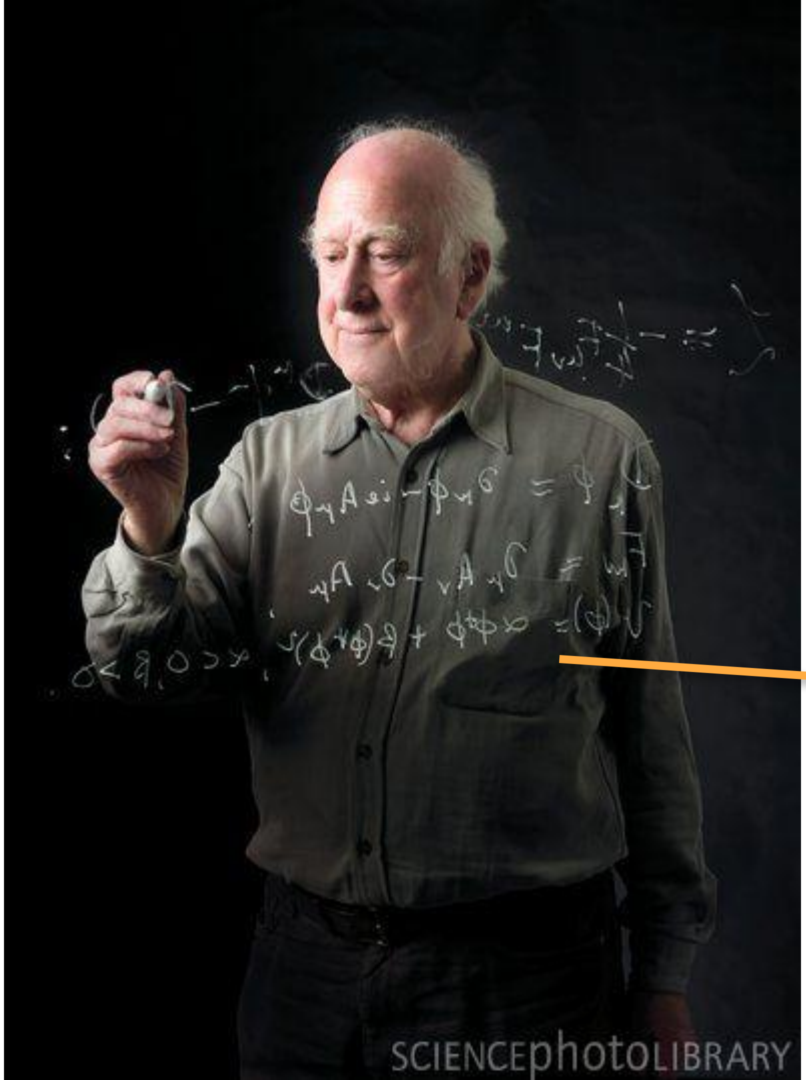


Photo: G-M Greuel via Wikimedia Commons

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"*

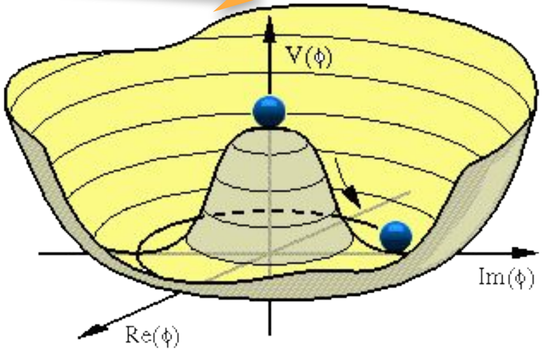
An accepted definition for a "discovery": a 5-sigma level of certainty 99.99994 %.

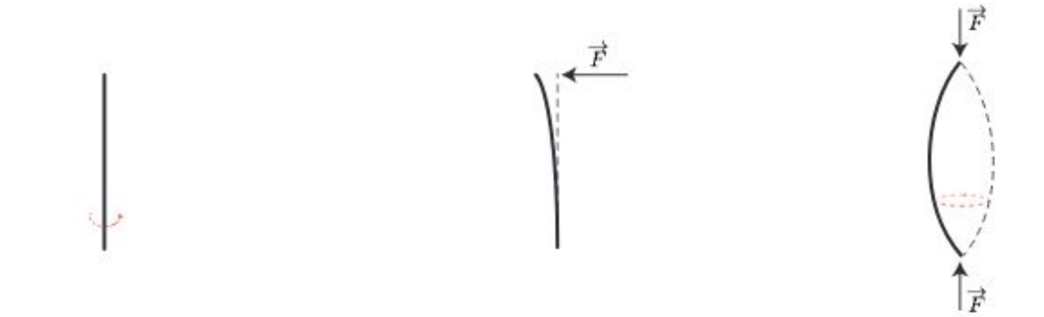


Spontaneous Symmetry Breaking
in
Quantum Gauge Field Theory

Generating V mass
while keeping Gauge Symmetry
and
avoiding massless goldstone

$$Higgs - Potential:$$
$$\alpha\phi\phi^* + \beta(\phi\phi^*)^2, \alpha < 0, \beta > 0$$



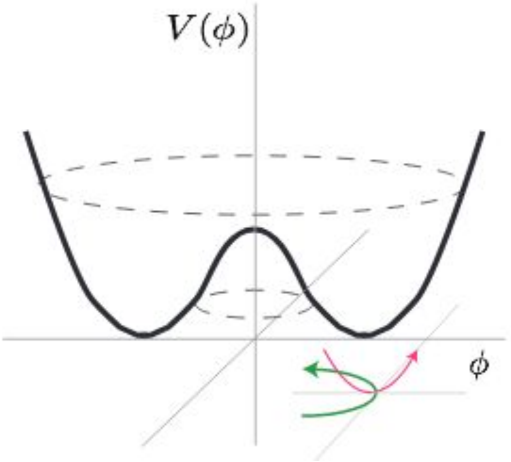


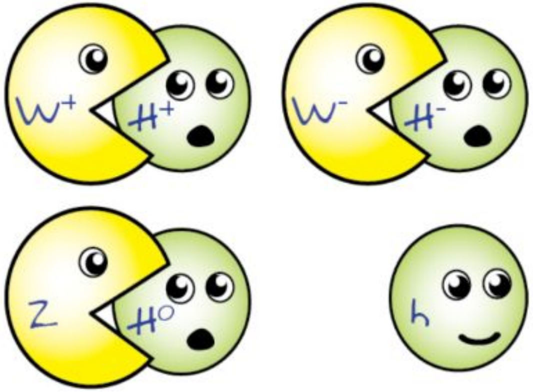
(a) Unbroken symmetry: the rod in its original state is rotationally invariant

(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

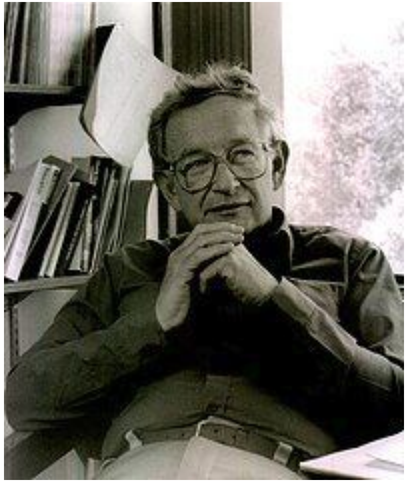
Deep root from Condensed Matter Physics

My life as a boson
by Peter Higgs

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

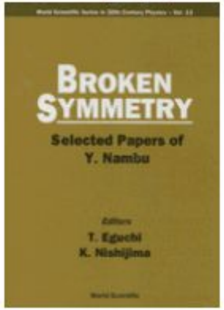


Philip W. Anderson
1977 Nobel Physics Prize

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

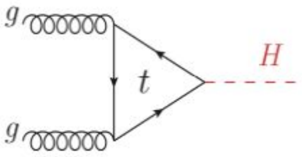
240,000 Higgs particles produced

~350 diphoton Higgs events detected

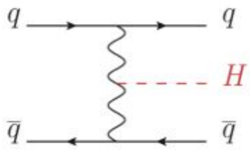
~8 four-lepton Higgs events detected

Higgs Production and Decay Processes

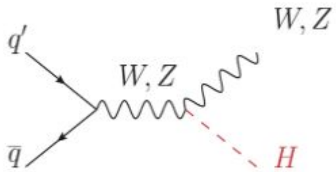
Production rates at Run 2 (13 TeV) for ~150 fb^{-1}



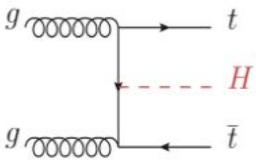
Gluon fusion process
~8 M events produced



Vector Boson Fusion
Two forward jets and a large rapidity gap
~600 k events produced

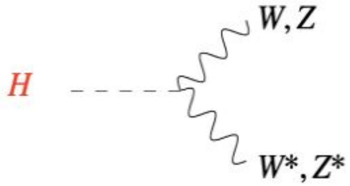


W and Z Associated Production
~400 k events produced



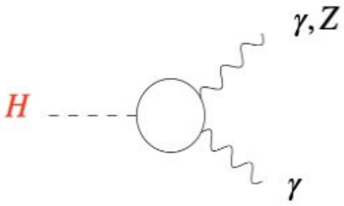
Top Assoc. Prod.
~80 k evts produced

Decay branching fractions



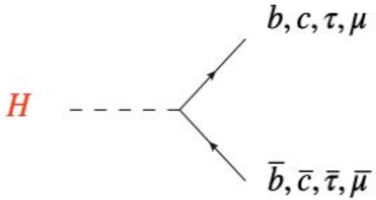
$\mathrm{Br}(H \to WW^*) = 22\,\%$

$\mathrm{Br}(H \to ZZ^*) = 3\,\%$



$\mathrm{Br}(H \to \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \to Z\gamma) = 0.2\,\%$



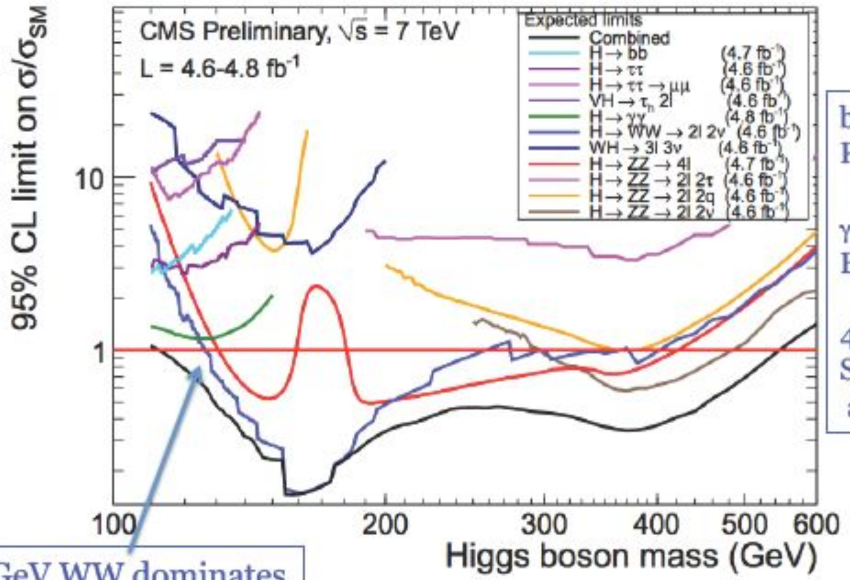
$\mathrm{Br}(H \to b\bar{b}) = 57\,\%$

$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

$\mathrm{Br}(H \to c\bar{c}) = 3\,\%$

$\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%$

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 S. L. 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

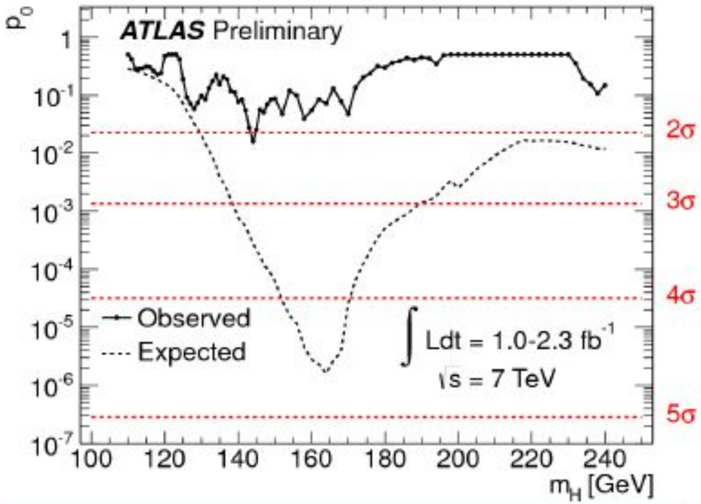
EPS-HEP 2011 (July)
Lepton-Photon 2011 (August)

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

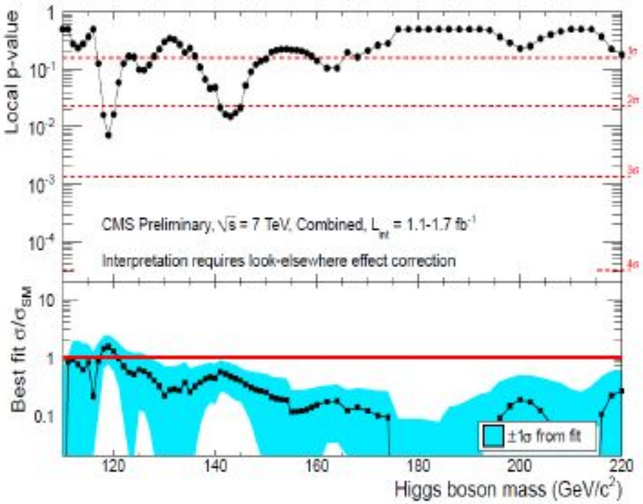
p_0: probability that the background fluctuates to the observed data (or higher)

p_0 = Local p-value

ATLAS H→γγ, ττ, WW(lvlv), ZZ(4l, llvv, llqq)



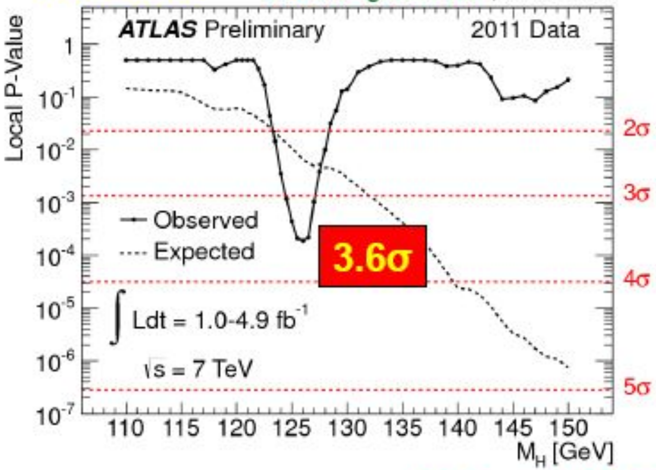
H→γγ, bb, ττ, WW(lvlv), ZZ(4l, llττ, llvv, llqq)



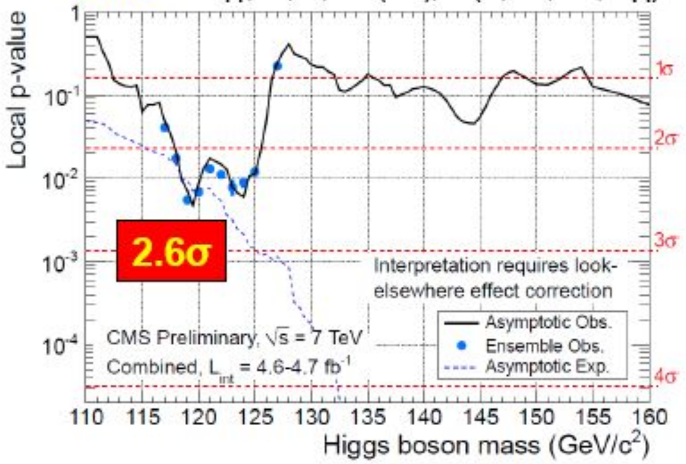
ATLAS (LP11)	CMS (LP11)
largest local excess: 2.1σ at 145 GeV	largest local excess: 2.3σ at 120 GeV

LHC ERA CERN Council (Dec 2011) Higgs combined

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



CMS $H \to \gamma\gamma$, bb, $\tau\tau$, WW(lvlv), ZZ(4l, ll$\tau\tau$, llvv, llqq)



Largest local excess: 3.6σ at 126 GeV

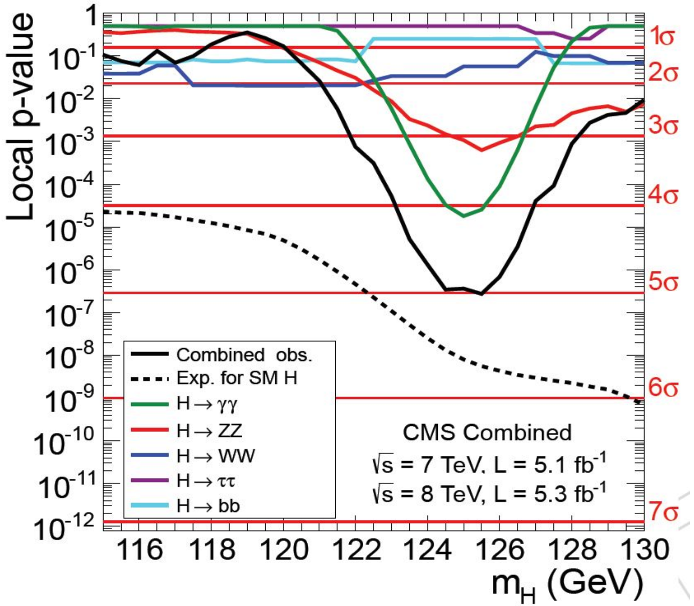
Largest local excess: 2.6σ at ~120 GeV

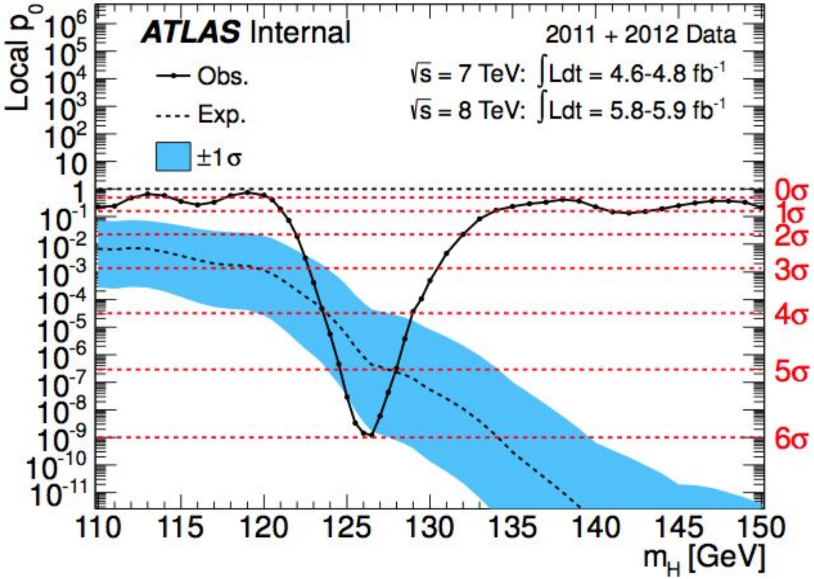
Fabiola Gianotti

"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)

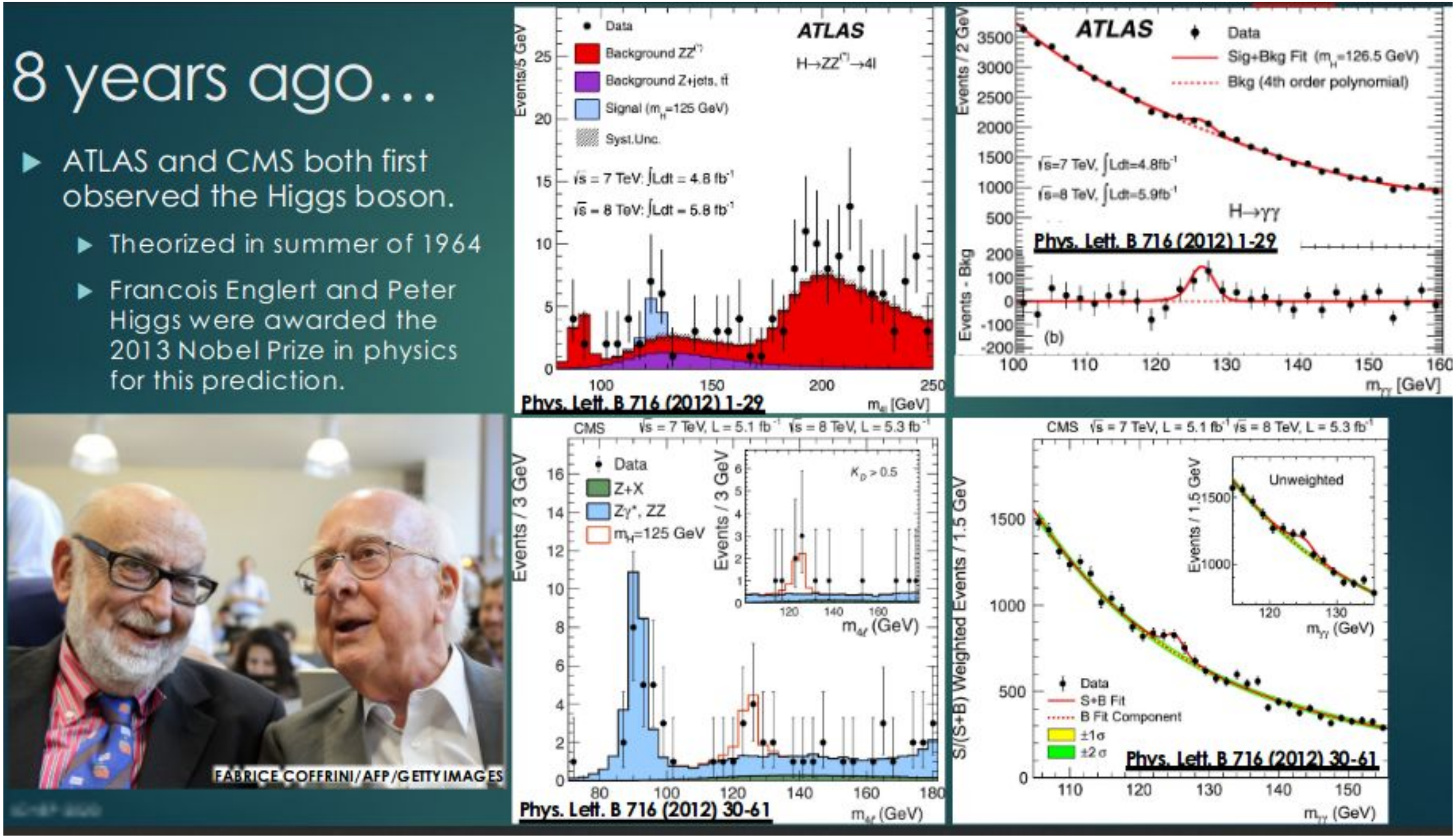
Results are presented from searches for the standard model Higgs boson in proton-proton collisions at sqrt(s)=7 and 8 TeV in the CMS experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 inverse femtobarns at 7 TeV and 5.3 inverse femtobarns at 8 TeV. The search 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

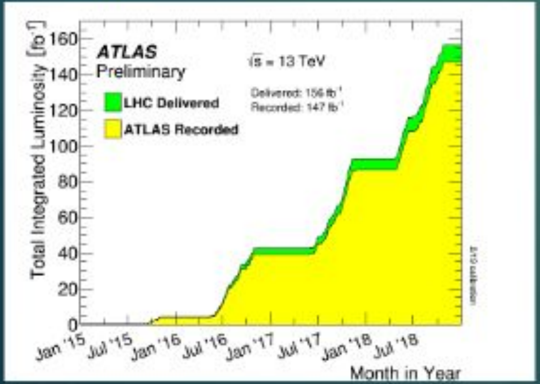
2012

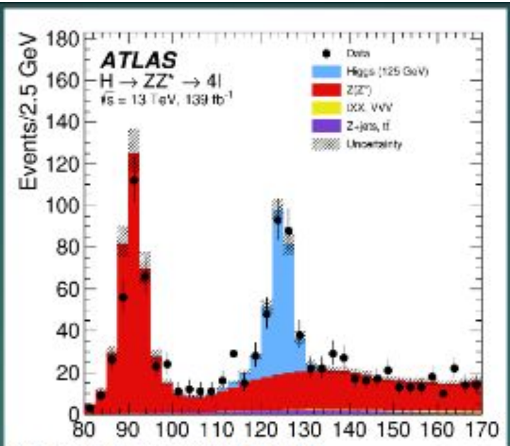

8 years ago…
ATLAS and CMS both first observed the Higgs boson.
Theorized in summer of 1964
Francois Englert and Peter Higgs were awarded the 2013 Nobel Prize in physics for this prediction.
FABRICE COFFRINI/AFP/GETTY IMAGES
ATLAS
H→ZZ(*)→4l
Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (mH=125 GeV)
Syst.Unc.
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/5 GeV
m4l [GeV]
Phys. Lett. B 716 (2012) 1-29
ATLAS
Data
Sig+Bkg Fit (mH=126.5 GeV)
Bkg (4th order polynomial)
√s=7 TeV, ∫Ldt=4.8fb-1
√s=8 TeV, ∫Ldt=5.9fb-1
H→γγ
Phys. Lett. B 716 (2012) 1-29
Events / 2 GeV
Events - Bkg
(b)
mγγ [GeV]
CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
Data
Z+X
Zγ*, ZZ
mH=125 GeV
KD > 0.5
Events / 3 GeV
m4l (GeV)
Phys. Lett. B 716 (2012) 30-61
CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
Unweighted
Events / 1.5 GeV
S/(S+B) Weighted Events / 1.5 GeV
Data
S+B Fit
B Fit Component
±1σ
±2σ
mγγ (GeV)
Phys. Lett. B 716 (2012) 30-61

2020

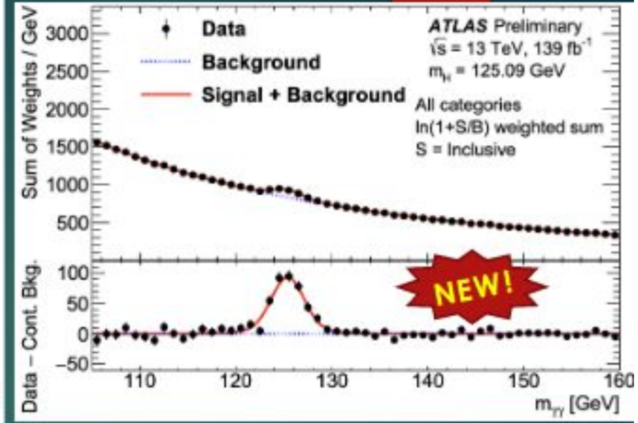
Full LHC Run 2

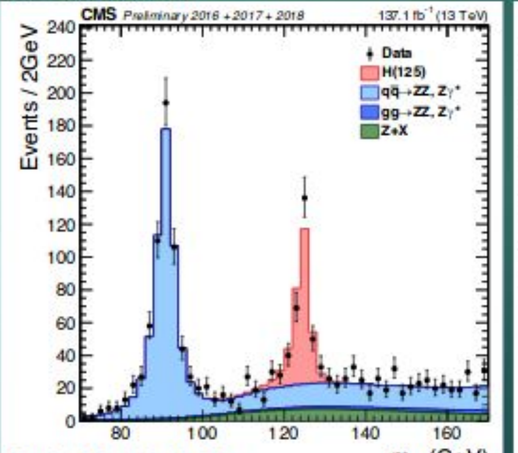
- With LHC's exceptional performance from 2015-2018 each experiment has ~140/fb of proton-proton collision data at 13 TeV, from which to harvest Higgs bosons!
  - LHC operated at twice design (!) luminosity in 2018!
  - Very impressive! Thank you LHC!



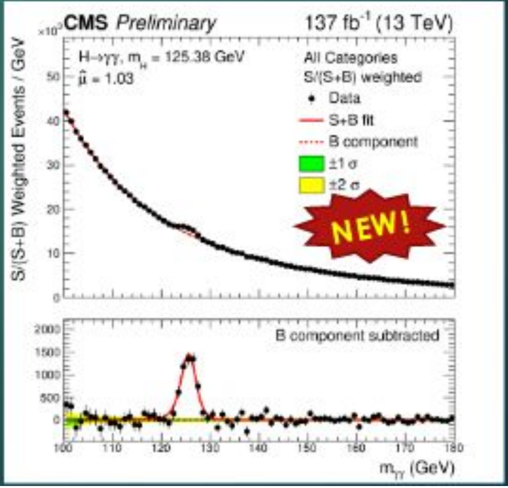


https://arxiv.org/abs/2004.03447
(Accepted in EPJC)

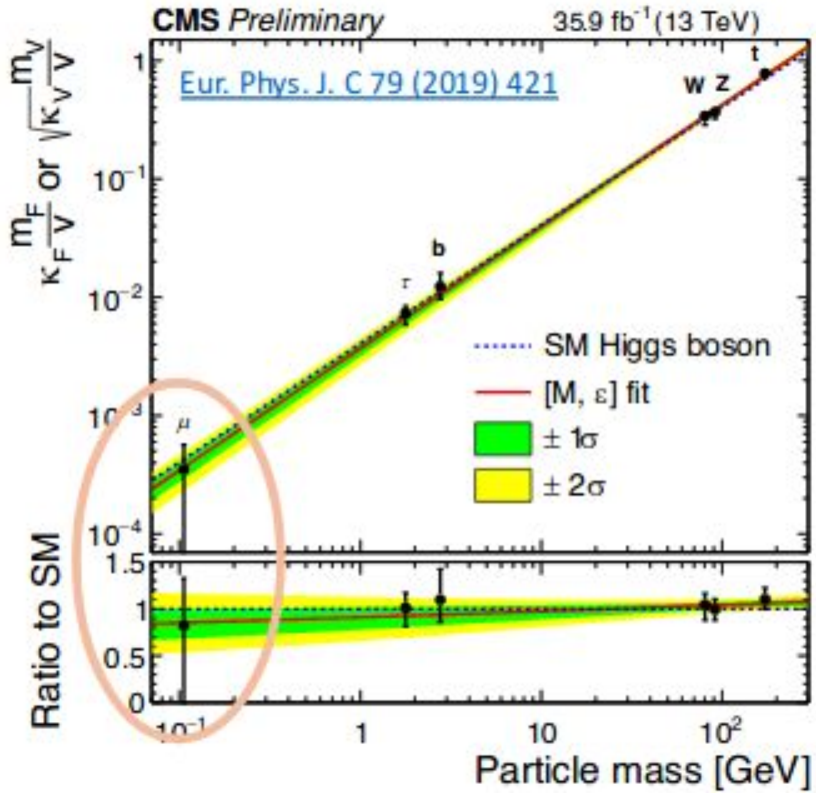


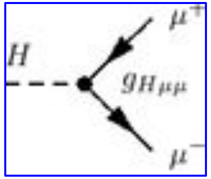


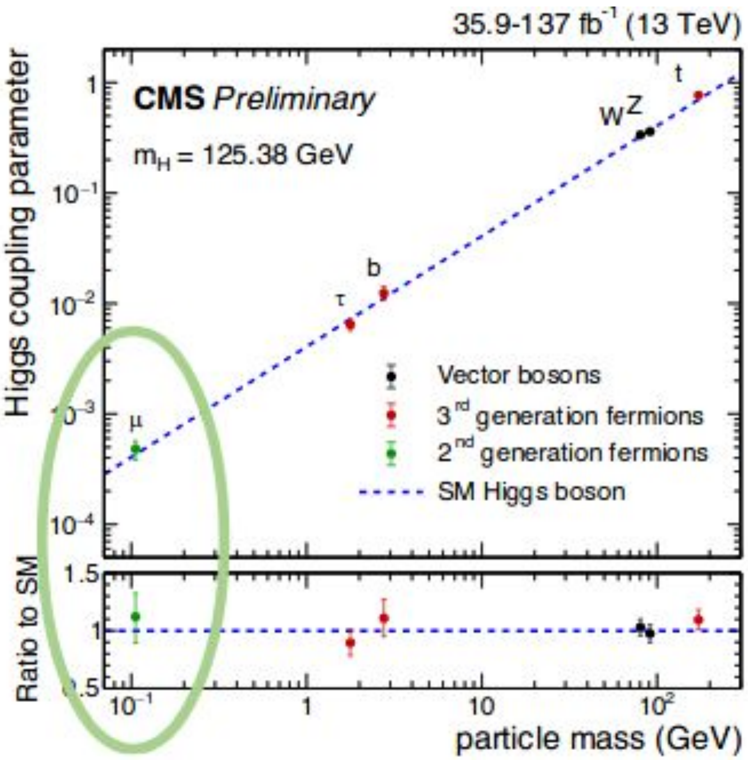
CMS-PAS-HIG-19-001



2020.8 Higgs与第二代费米子相互作用的证据！







周辰、冒亚军课题组发表希格斯玻色子衰变为Z玻色子和光子的首个实验证据

发布日期：2024-01-16　浏览次数：　662
供稿：技术物理系｜ 编辑：曲音璇 ｜ 审核：李强

在2023年大型强子对撞机物理学会议上，超环面仪器实验（ATLAS）和 紧凑缪子线圈实验（CMS）团队汇报了希格斯玻色子衰变为一个Z玻色子和一个光子过程的首个证据。《科技日报》和欧洲核子研究中心官方网站等对此进行了新闻报道。近日，该重要结果由两个实验组携手以“大型强子对撞机上希格斯玻色子衰变为一个Z玻色子和一个光子过程的证据”（Evidence for the Higgs Boson Decay to a Z Boson and a Photon at the LHC）为题于2024年1月发表在《物理评论快报》（Physical Review Letters），并被选为“物理亮点”（Featured in Physics）和“编辑推荐”（Editors' Suggestion）。北京大学物理学院技术物理系周辰、冒亚军课题组对该结果起了关键作用。在CMS合作组内部，北京大学物理学院博士研究生张铭滔被选做预审核报告，周辰被选做审核报告、并担任分析文档负责人。2023年9月，周辰获选担任大型强子对撞机（LHC）希格斯联合分析工作组召集人。

2012年希格斯玻色子的发现是粒子物理的一座重要里程碑。自此以来，欧洲核子研究中心LHC的ATLAS和CMS实验致力于研究希格斯玻色子产生和衰变的各种方式，从而检验产生基本粒子质量的希格斯机制。其中，希格斯玻色子衰变为Z玻色子和光子的过程需要通过量子圈进行。由于量子圈中可能存在尚未被发现的新粒子，该稀有衰变过程有望提供新物理的线索。相关理论研究包括北京大学物理学院曹庆宏等人工作（Phys. Lett. B 789 (2019) 233）等。

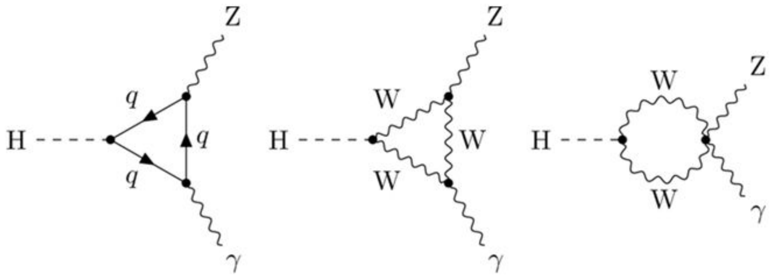


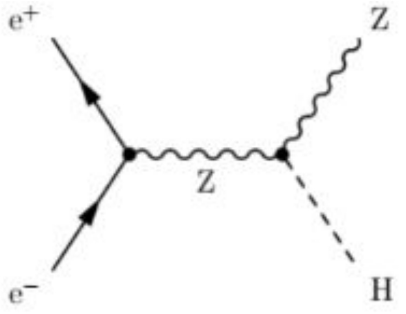
图1:标准模型中希格斯玻色子衰变为Z玻色子和光子过程的费曼图

视频 two PKU Students@CERN in 2009

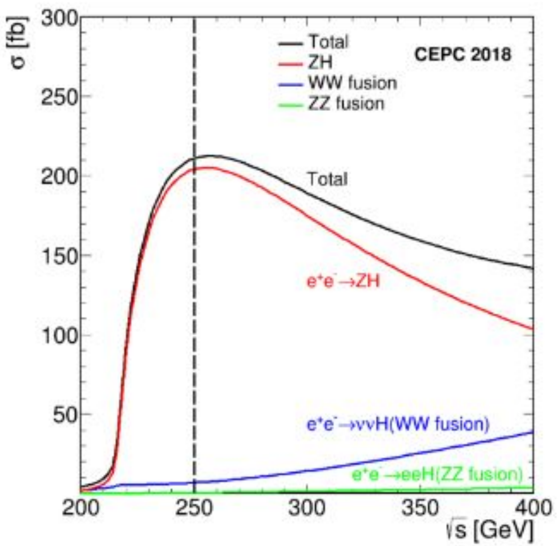
https://www.youtube.com/watch?v=dJEwyPO5PYE

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. 机器学习、量子纠缠
8. 总结与展望

中国环形正负电子对撞机CEPC



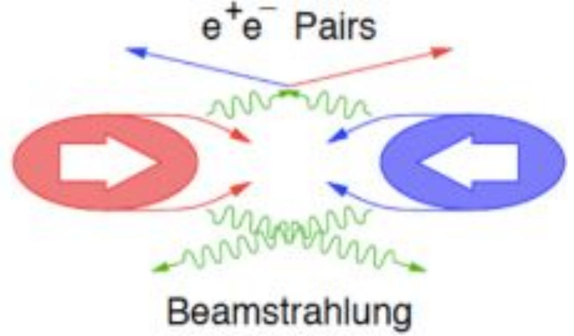
Production cross sections



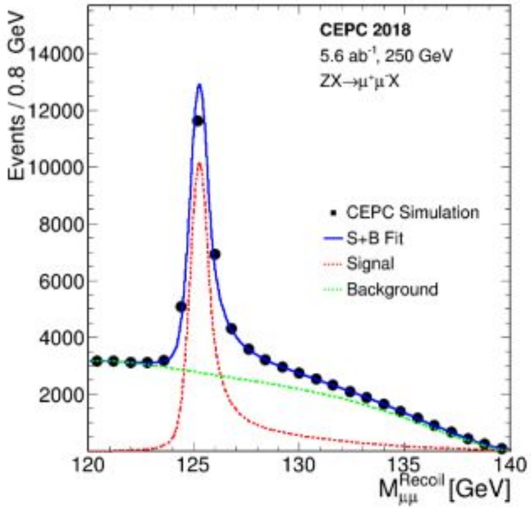
2018.11 发布概念设计报告CDR。
100公里隧道；
240-250GeV 正负电子对撞；
产生约100万Higgs；
Higgs工厂： 精确测量Higgs性质。

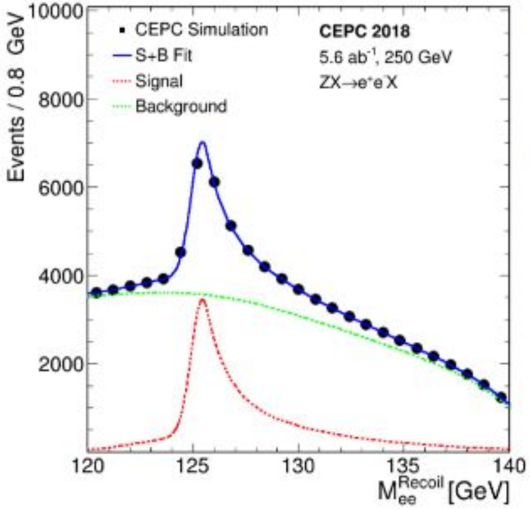
与pp对撞机相比：

- 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；

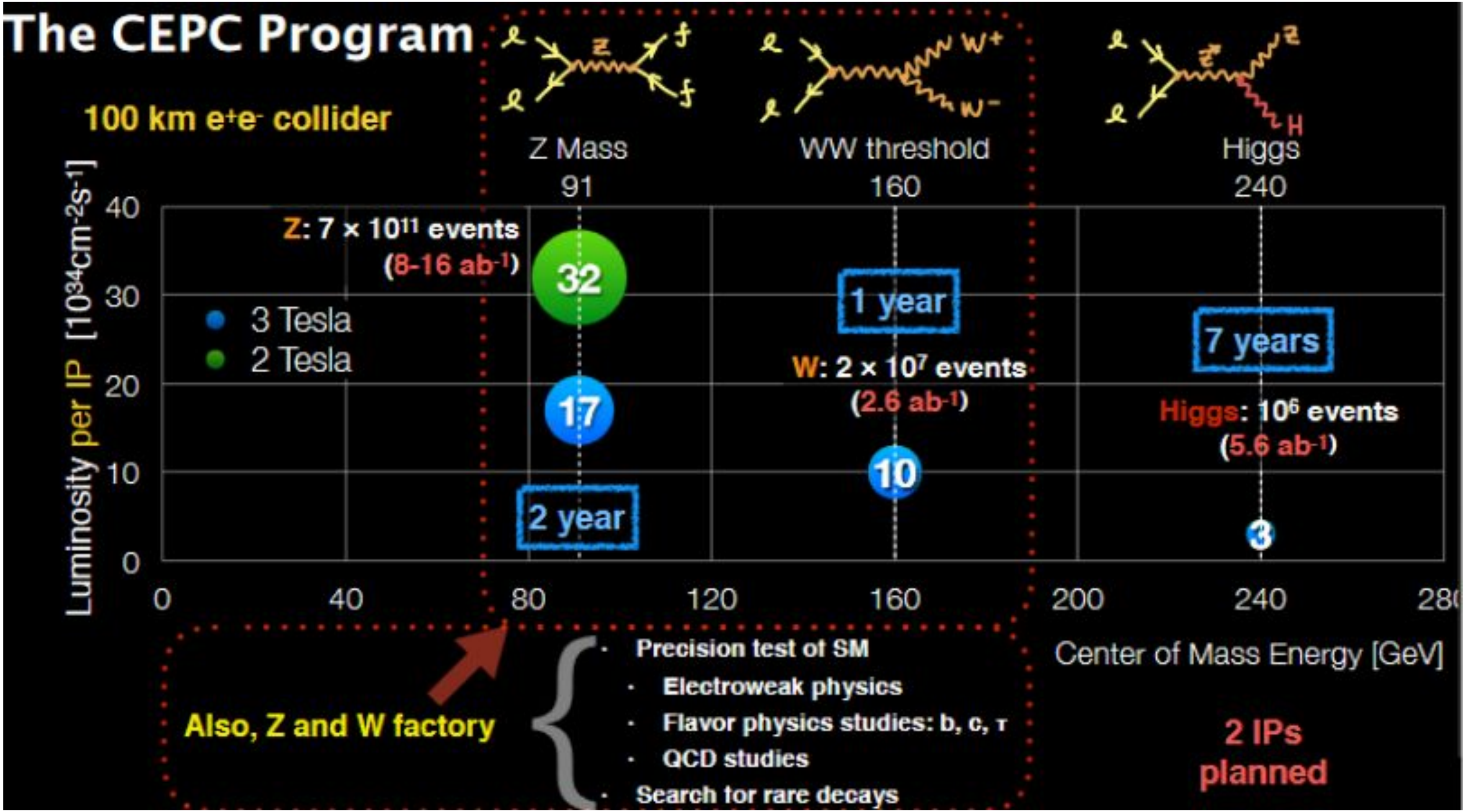


- Higgsstrahlung (ee->ZH), Z decays to a pair of visible fermions(ff), the recoil mass against the Z: $M^2_{\mathrm{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$





- 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}


The CEPC Program
100 km e+e- collider
Z Mass
91
WW threshold
160
Higgs
240
Luminosity per IP [10^34cm^-2s^-1]
Z: 7 × 10^11 events
(8-16 ab^-1)
32
17
2 year
1 year
W: 2 × 10^7 events
(2.6 ab^-1)
10
7 years
Higgs: 10^6 events
(5.6 ab^-1)
3
3 Tesla
2 Tesla
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

Milestones and activities of CEPC physics studies

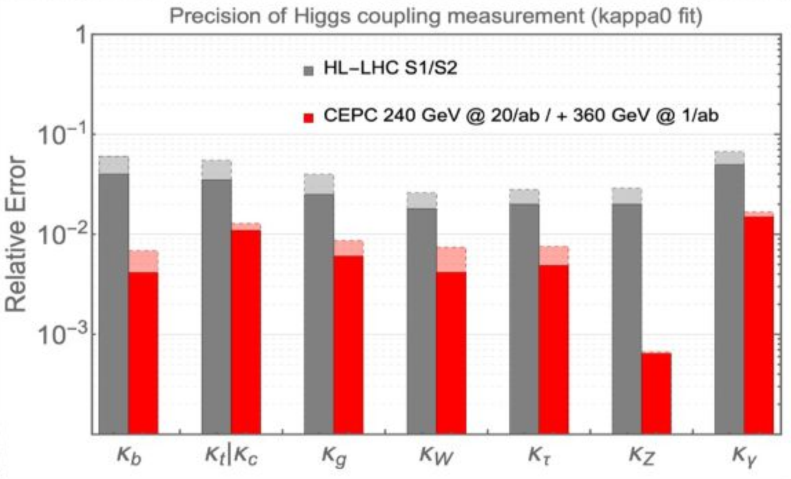
- Public documents released: CDR(2018) → Higgs white paper (2019) → Snowmass white paper (2022) → Flavor white paper to come out soon → more in preparation (EWK white paper, New physics white paper)
- CEPC physics and detector workshops in series: May 2019, April 2021, August 2023
- Physics studies for the IAS-HEP program and Snowmass exercise
- Communication and collaboration with international partners: ECFA studies ...

- **O(100) Journal / arXiv papers**

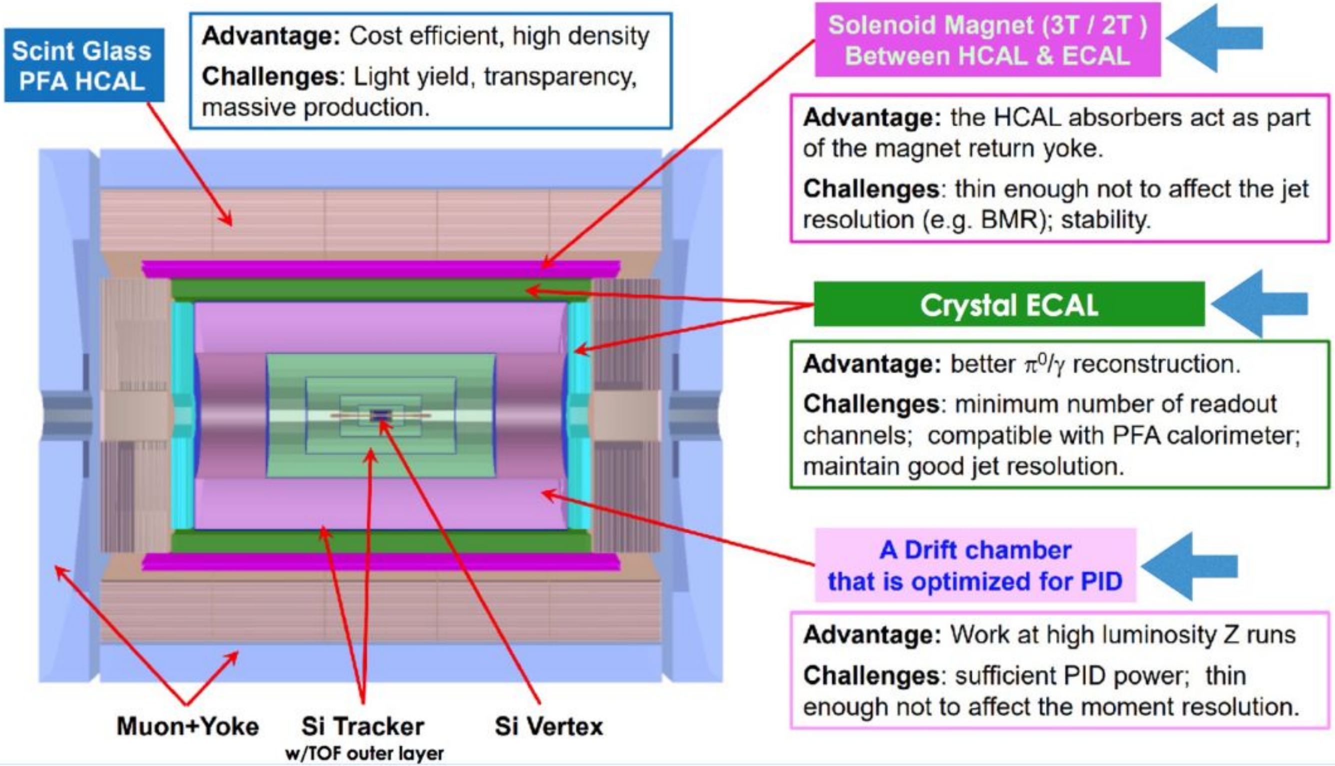
https://indico.ph.ed.ac.uk/event/259/contributions/2534/attachments/1395/2106/cepc-physics-murray-23.pdf https://arxiv.org/pdf/1810.09037.pdf

	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	vvH	ZH	vvH	eeH
inclusive	0.26%		1.40%	\	\
H→bb	0.14%	1.59%	0.90%	1.10%	4.30%
H→cc	2.02%		8.80%	16%	20%
H→gg	0.81%		3.40%	4.50%	12%
H→WW	0.53%		2.80%	4.40%	6.50%
H→ZZ	4.17%		20%	21%	
$H \to \tau\tau$	0.42%		2.10%	4.20%	7.50%
$H \to \gamma\gamma$	3.02%		11%	16%	
$H \to \mu\mu$	6.36%		41%	57%	
$H \to Z\gamma$	8.50%		35%		
$Br_{upper}(H \to inv.)$	0.07%				
Γ_H	1.65%		1.10%		

- Higgs coupling precision factor ~10 better than LHC
- Where many models predict deviations



The 4th Detector Concept



Excellent e/gamma energy resolution;

PID capability;

Better hadronic energy resolution;

Magnet in much reduced size.

BMR: 4% → 3%


CEPC
The 2023 international workshop on the Circular Electron Positron Collider [European Edition]
THE UNIVERS DINBURGH

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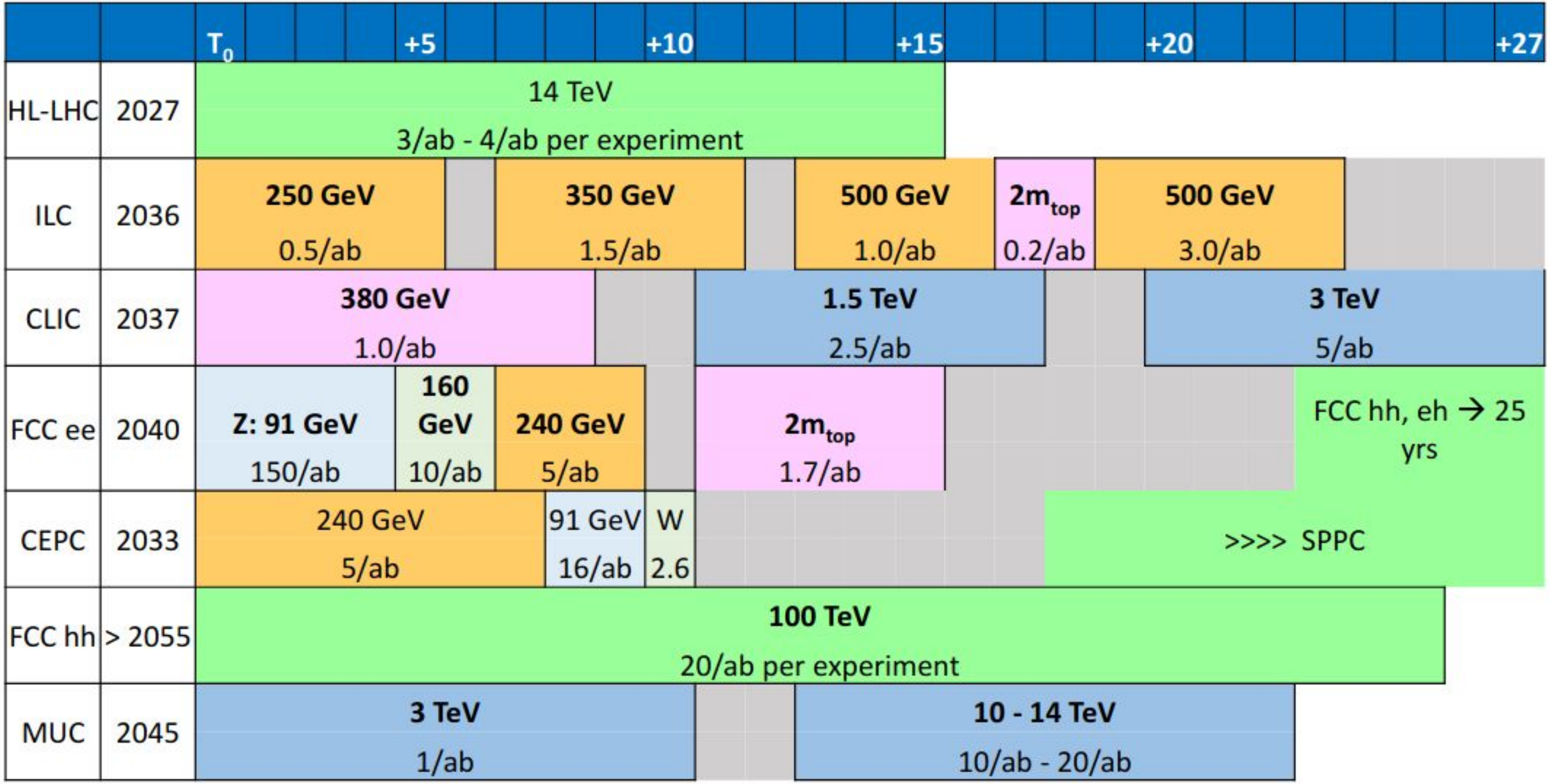
Future colliders with earliest feasible start date



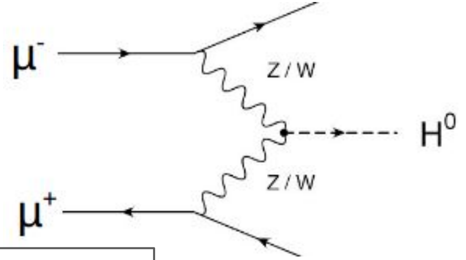
https://indico.desy.de/event/28202/contributions/102729/attachments/67953/85077/FutureColliders_LRivkin.pdf

Muon Collider interest Revived upon Muon Anomalies

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.



Parameter	Units	Higgs		Multi-TeV	
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13'500	37'500	200'000	820'000
Circumference	km	0.3	2.5	4.5	6
No. of IP's		1	2	2	2
Repetition Rate	Hz	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1	0.5	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, $\varepsilon_{\mathrm{TN}}$	μm-rad	200	25	25	25
Norm. Long. Emittance, $\varepsilon_{\mathrm{LN}}$	μm-rad	1.5	70	70	70
Bunch Length, σ_S	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

link

Muon Collider Community

MoC and Design Study Partners

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
IT	**INFN**
	INFN, Univ., Polit. Torino
	INFN, Univ. Milano
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
Mal	**Univ. of Malta**
BE	***Louvain***

UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham
SE	**ESS**
	University of Uppsala
PT	**LIP**
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical Univers.**

US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	Old Dominion
	BNL
China	***Sun Yat-sen University***
	IHEP
	Peking University
EST	***Tartu University***
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
CH	**PSI**
	University of Geneva
	EPFL

KO	**KEU**
	Yonsei University
India	***CHEP***
IT	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
US	FNAL
	LBL
	JLAB
	Chicago
	Tenessee

Muon Collider Status, Annual Meeting, Orsay, June 2023

IMCC Annual Meeting 2023

19 Jun 2023, 12:00 → 22 Jun 2023, 14:00

Many thanks to

- Alexia Augier, Michela Lancellotti, Valérie Brunner (CERN secrétariat)
- Séverine Candau, Armelle Le Noa (CEA Saclay secretariat)
- Gregory Perrin, Yoann Kermaidic (IJCLab)
- The local and scientific committees
- All helping/funding entities (EU, Saclay, IJCLab, CERN)
- All of you !

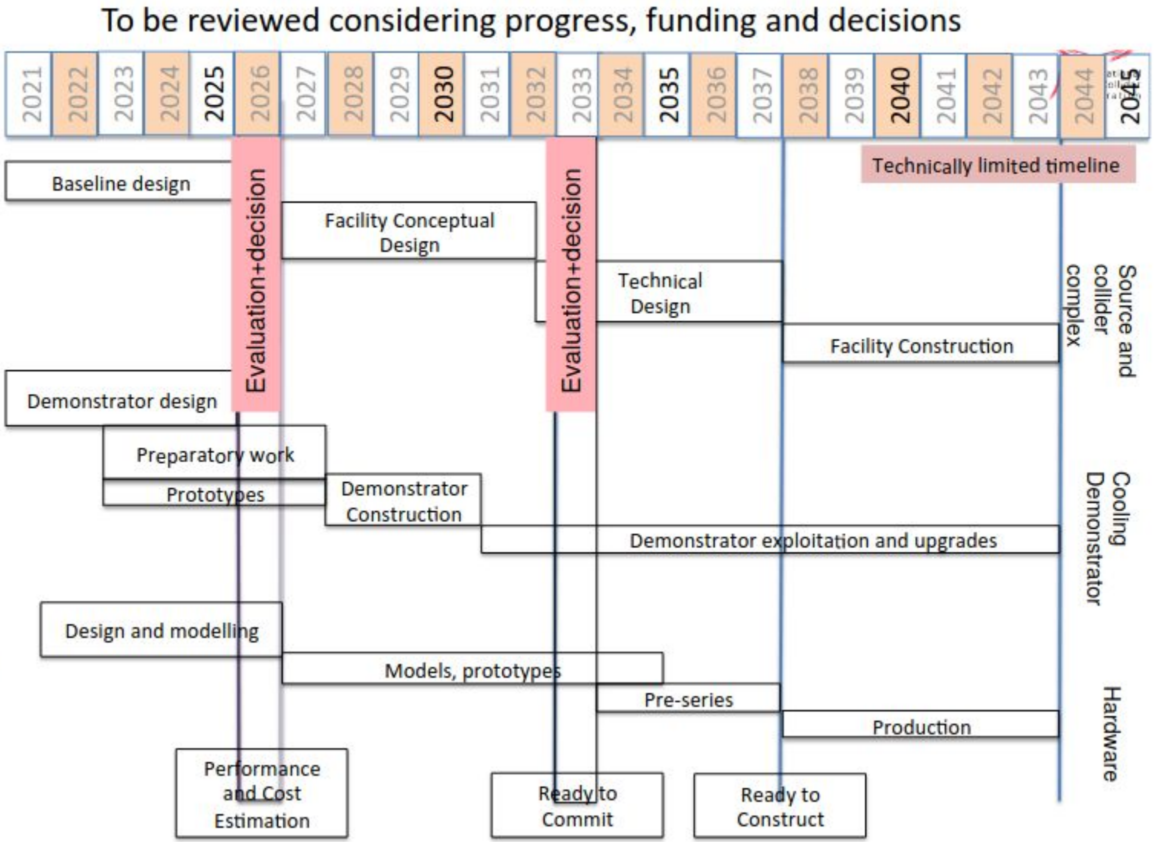
Roadmap: Technically Limited Timeline

Muon collider important in the long term

Fastest track option with important ramp-up of resources to see if muon collider could come directly after HL-LHC

- Compromises in performance, e.g. 3 TeV

Needs to be revised but do not have enough information at this point for final plan

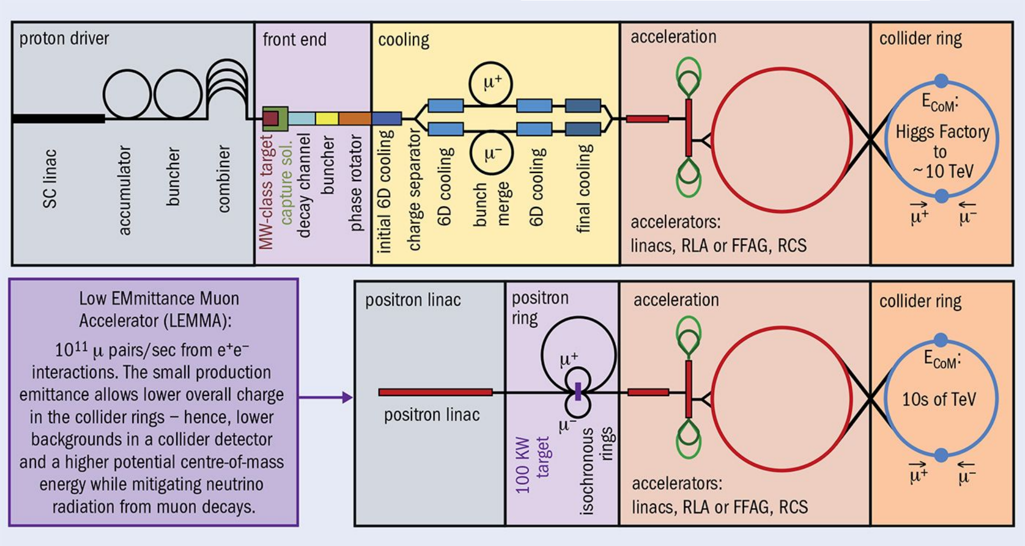


Muon Collider: beam and background

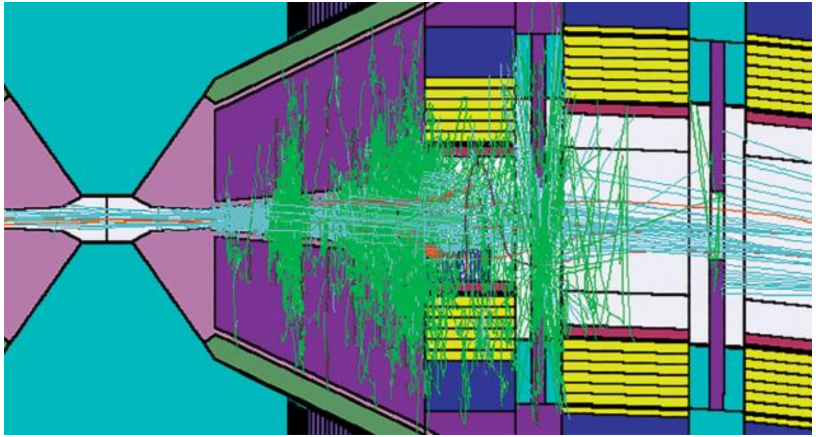
1) Muon Source

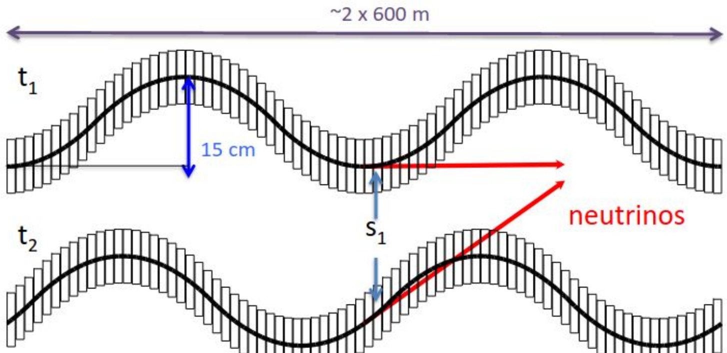
$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy; High field in collider ring; Large energy acceptance; Dense beam; High beam power



2) Muon Beam Induced background

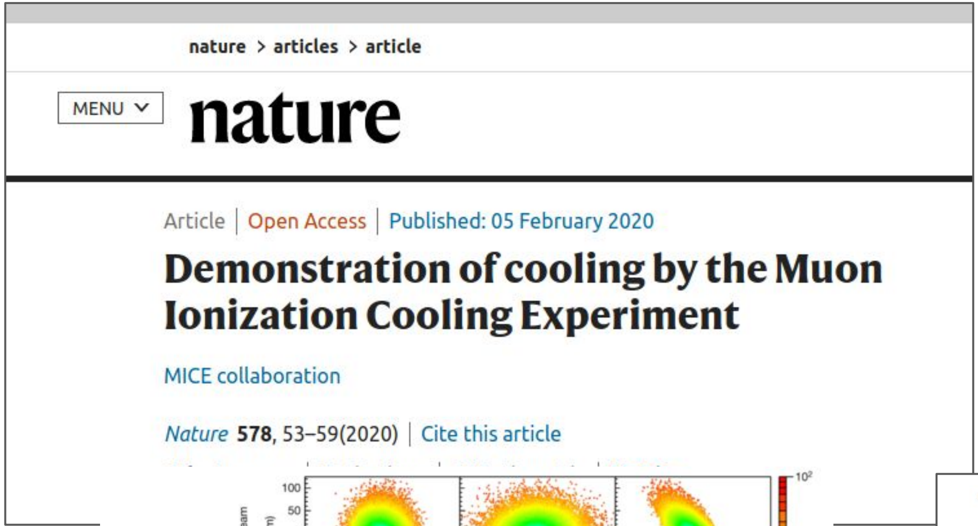




3) Neutrino Flux Mitigation:

move collider ring components, e.g. vertical bending with 1% of main field

Muon Ionisation Cooling Experiment (MICE)


nature > articles > article

MENU

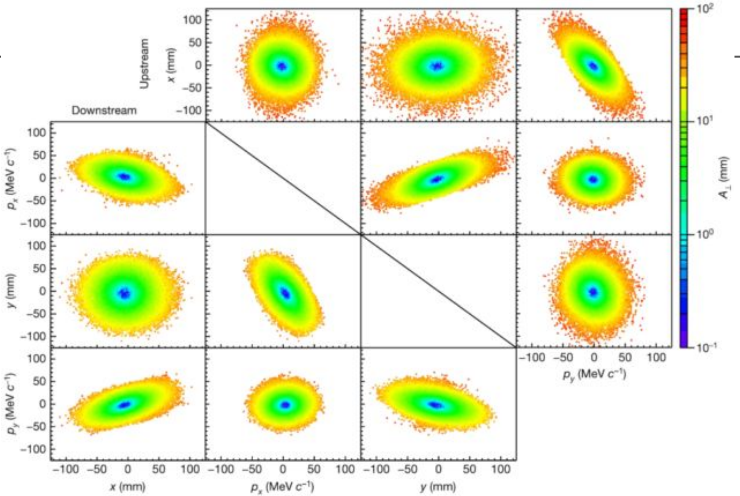
nature

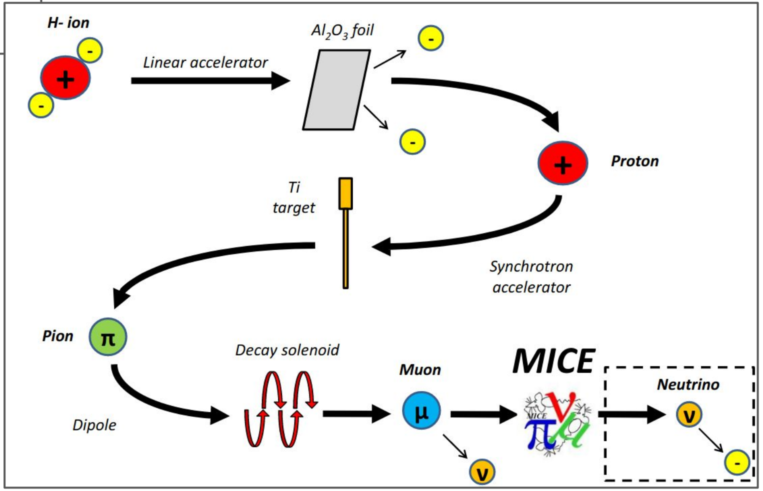
Article | Open Access | Published: 05 February 2020

Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

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

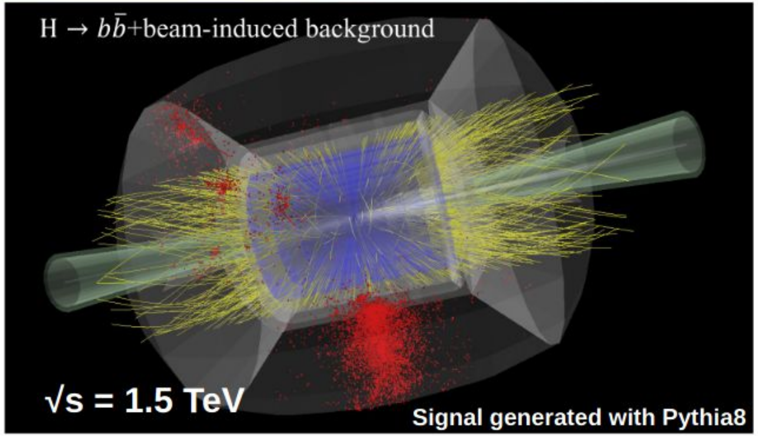


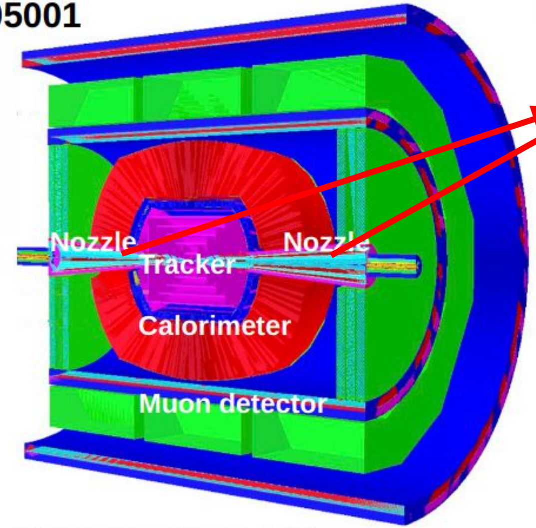


Higgs Physics at Muon Collider

$\mu^+\mu^- \rightarrow \nu\bar{\nu}\, H(\rightarrow b\bar{b})$

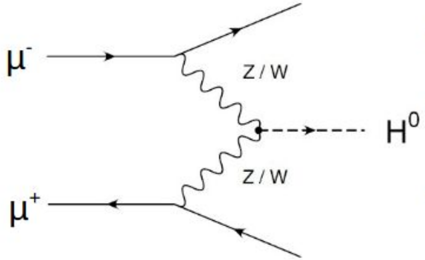
2020 JINST 15 P05001





To Suppress BIB

Lorenzo Sestini @ICHEP2020



- We studied the $\mu\mu \rightarrow \nu\nu\, H(\rightarrow bb)$ production at a MC
- The goal is to determine the **sensitivity to the cross section measurement and to the Hbb couping determination**
- In the full simulation (Geant4) we used the detector developed by the MAP collaboration → not optimized for the full event reconstruction

7

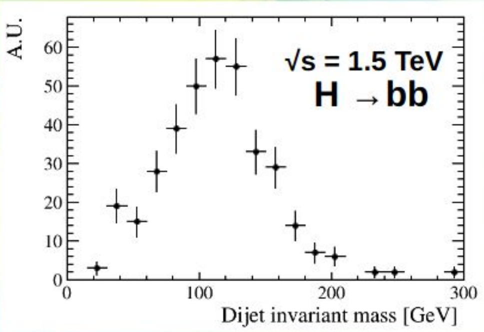
https://indico.cern.ch/event/868940/contributions/3813545/attachments/2083147/3499196/higgs_mc_ichep.pdf

Higgs Physics at Muon Collider

Cross section and Hbb coupling

2020 JINST 15 P05001

INFN
Istituto Nazionale di Fisica Nucleare



Two b-tagged jets with p_T>40 GeV, |η|<2.5 are selected

- **As a conservative approach we applied the efficiencies obtained at √s = 1.5 TeV to the 3.0 and 10 TeV case → BUT the BIB yield is expected to be lower at higher energies.**
- We assumed **4 Snowmass years of data taking**, at the luminosities expected by MAP.
- Cross section sensitivity obtained with $\frac{\Delta\sigma}{\sigma} \simeq \frac{\sqrt{N+B}}{N}$,
- Hbb coupling sensitivity $\frac{\Delta g_{Hbb}}{g_{Hbb}} = \frac{1}{2}\sqrt{\left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta\frac{g^2_{HWW}}{\Gamma_H}}{\frac{g^2_{HWW}}{\Gamma_H}}\right)^2}$, → Taken from CLIC expectation

Lorenzo Sestini @ICHEP2020

$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [$cm^{-2}s^{-1}$]	$\mathcal{L}_{int}$ [ab^{-1}]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot 10^{35}$	8.0	549	270000	4400	0.20	0.91

At 3 TeV the Hbb coupling sensitivity is compatible with the one expected by CLIC, but very conservative assumptions have been done!

10

No such bkgs at e-mu collider!

Physics backgrounds

Process
$\mu^+\mu^- \to \gamma^*/Z \to q\bar{q}$
$\mu^+\mu^- \to \gamma^*/Z\gamma^*/Z \to q\bar{q}$ +X
$\mu^+\mu^- \to \gamma^*/Z\gamma \to q\bar{q}\gamma$

https://indico.cern.ch/event/868940/contributions/3813545/attachments/2083147/3499196/higgs_mc_ichep.pdf

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. **机器学习、量子纠缠**
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)

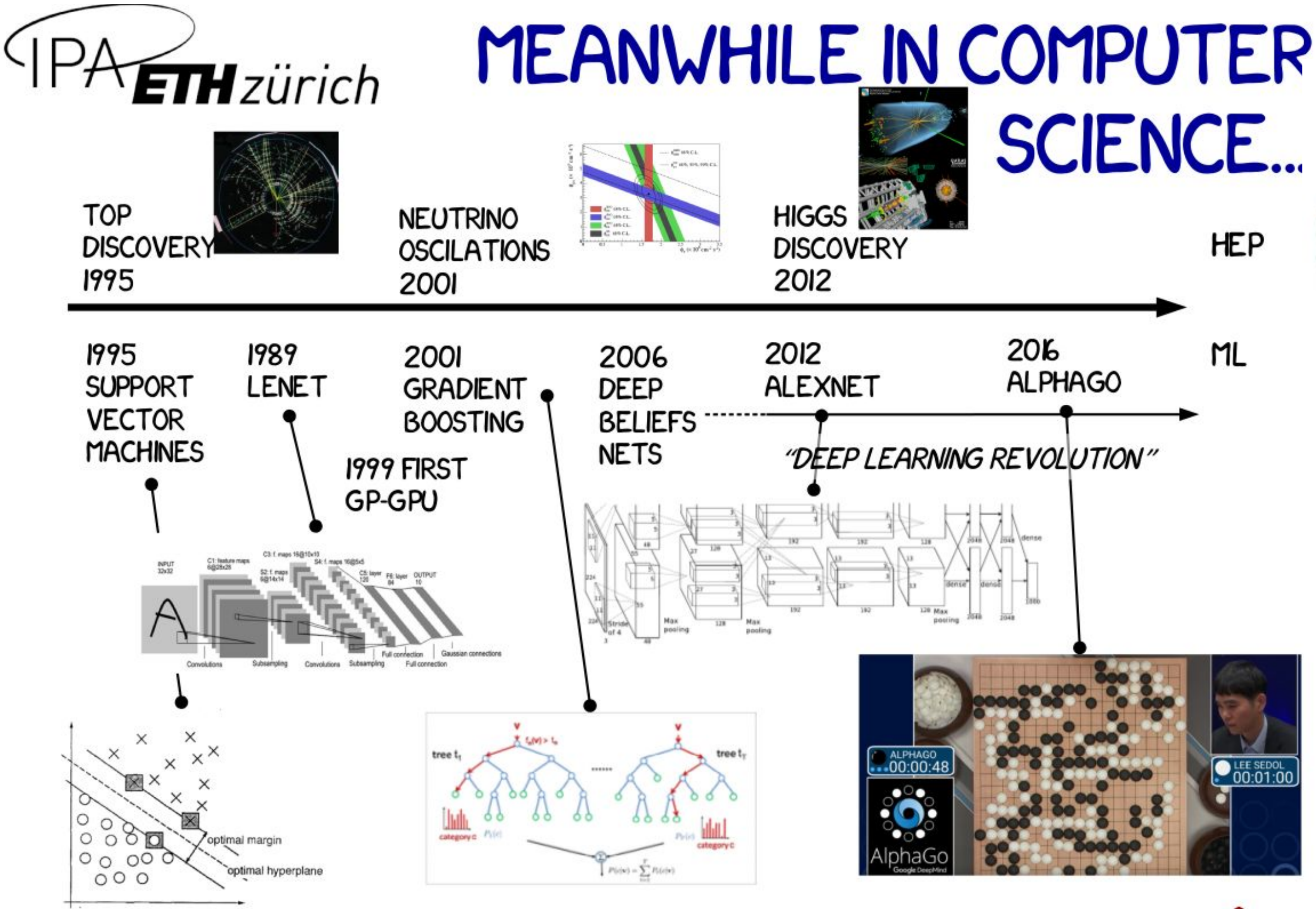
Geoffrey Hinton

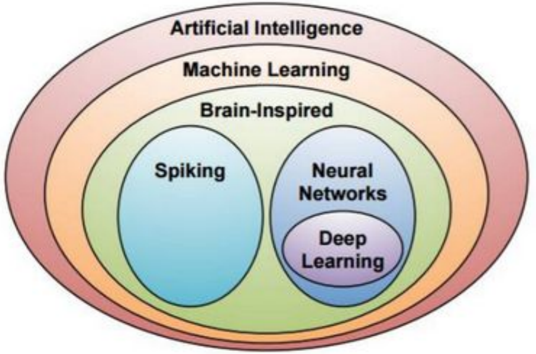
FRS FRSC CC

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)

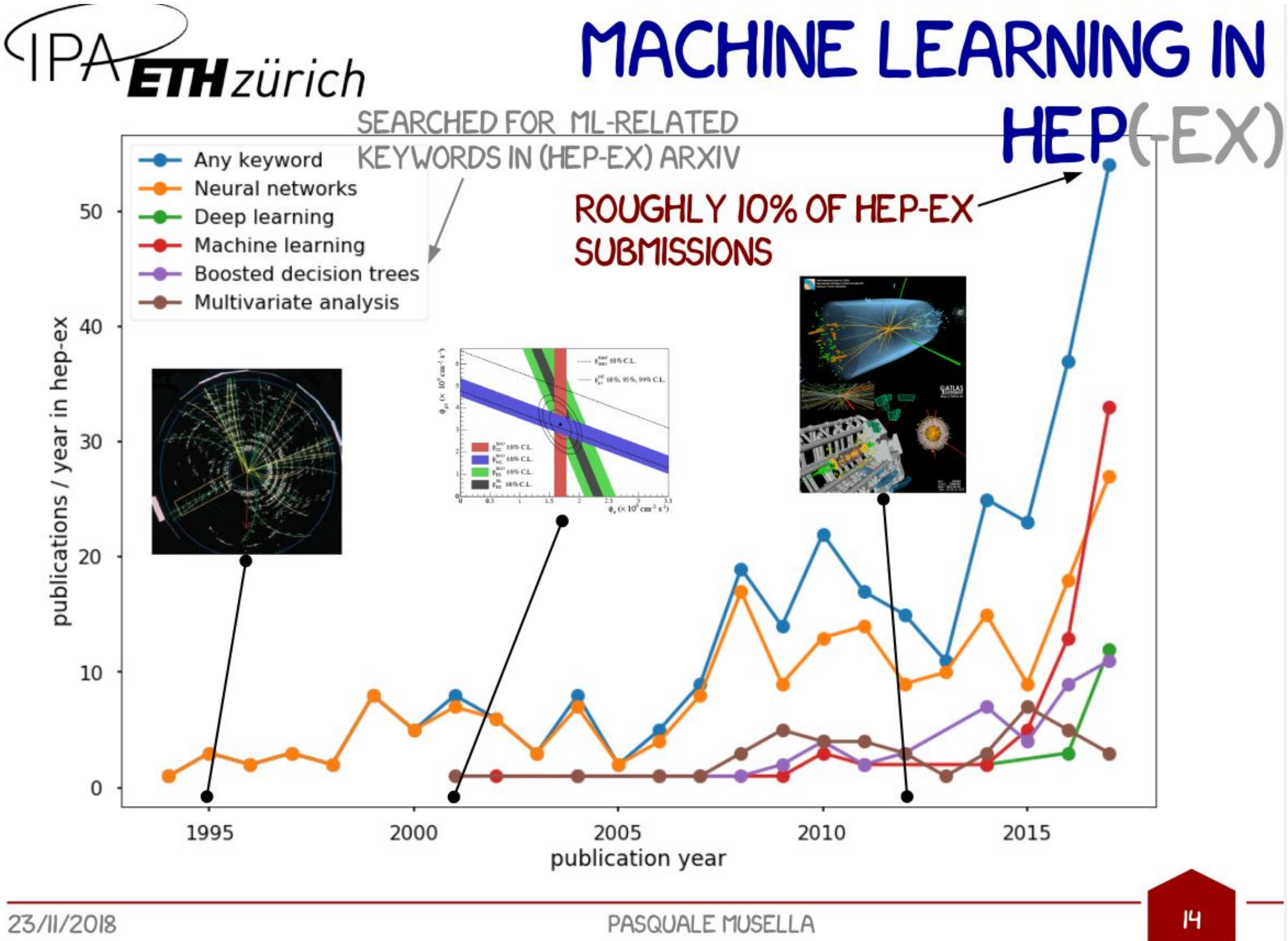
机器学习简史

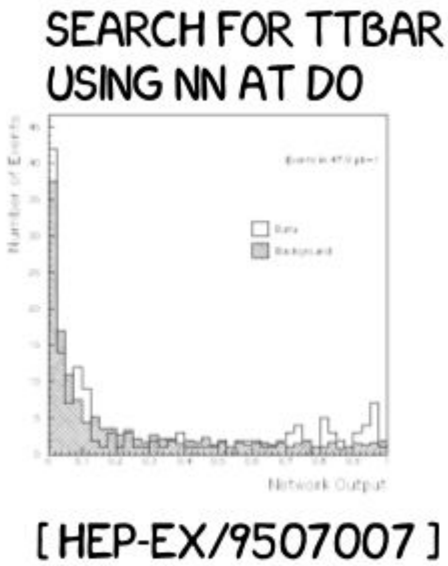




2018年图灵奖

高能物理机器学 习应用简史



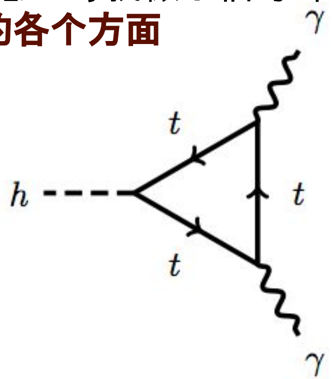


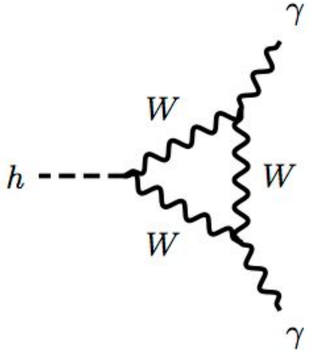
Tevatron：Top夸克
LHC: Higgs发现
miniBOONE: 粒子鉴别

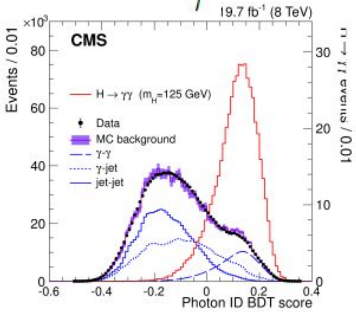
机器学习应用：Higgs粒子寻找

CMS实验中Higgs双光子道的寻找：

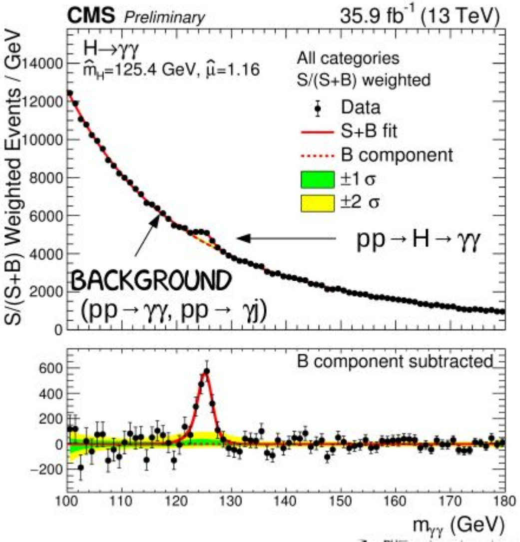
- 分支比10^{-3}: 在本底上寻找微小信号峰；
- **BDT应用于分析的各个方面**
  - 光子鉴别
  - 事例分类
  - 光子能量
  - 双光子顶点

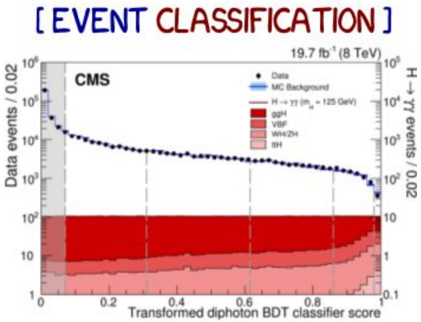




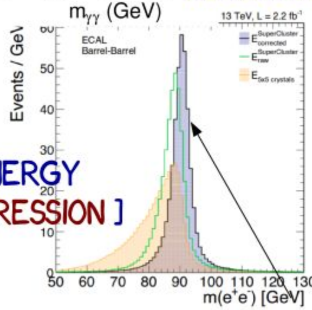


[PARTICLE-ID: SEPARATE PROMPT γ FROM HADRONIC JETS]

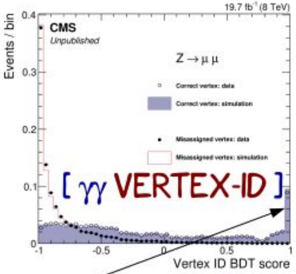




[INVARIANT MASS ESTIMATION]



[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

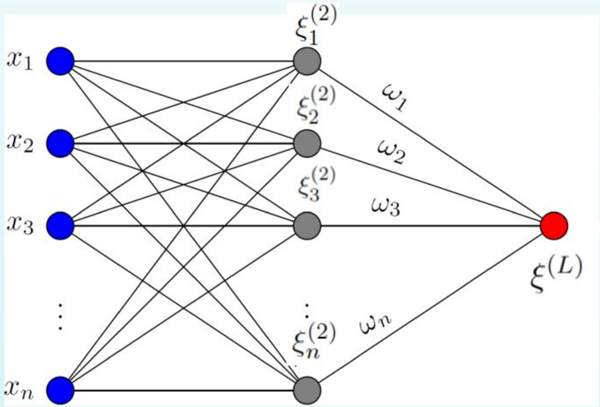
not from QCD!

Traditional approach

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

NNPDF approach

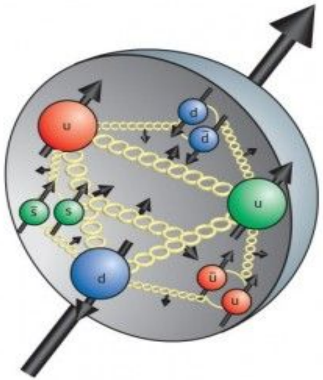
$$g(x,Q_0) = A_g \mathrm{ANN}_g(x)$$

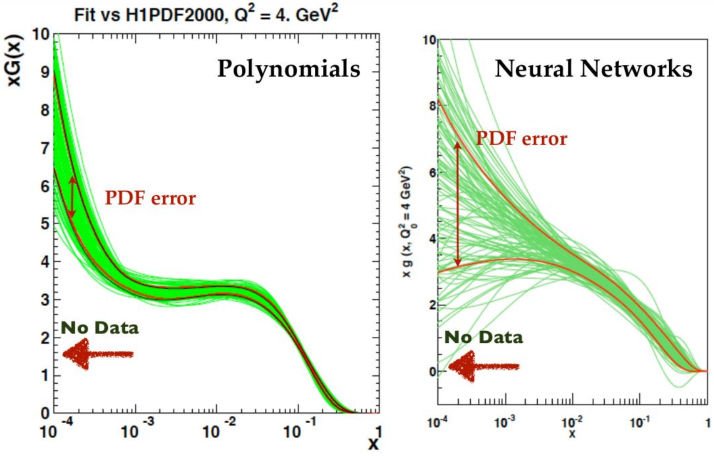


$$\mathrm{ANN}_g(x) = \xi^{(L)} = \mathcal{F}\left[\xi^{(1)}, \{\omega_{ij}^{(l)}\}, \{\theta_i^{(l)}\}\right]$$

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

- 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!**



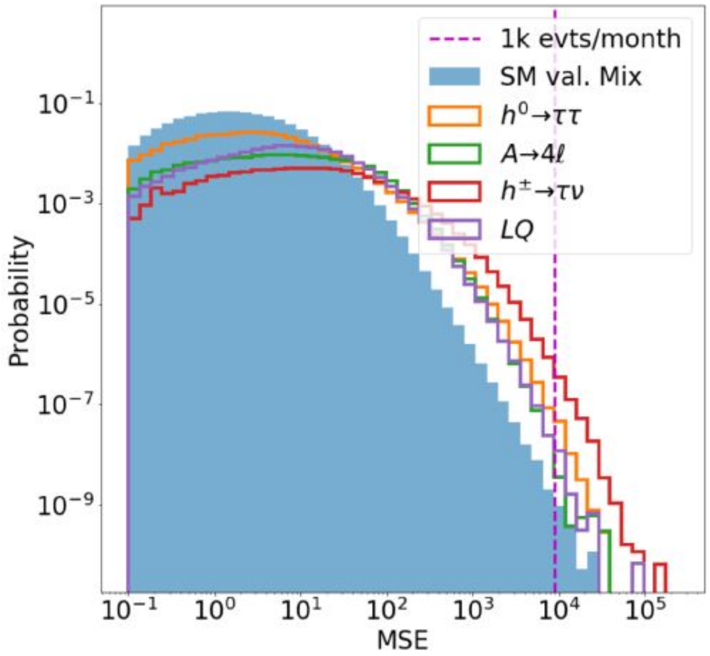


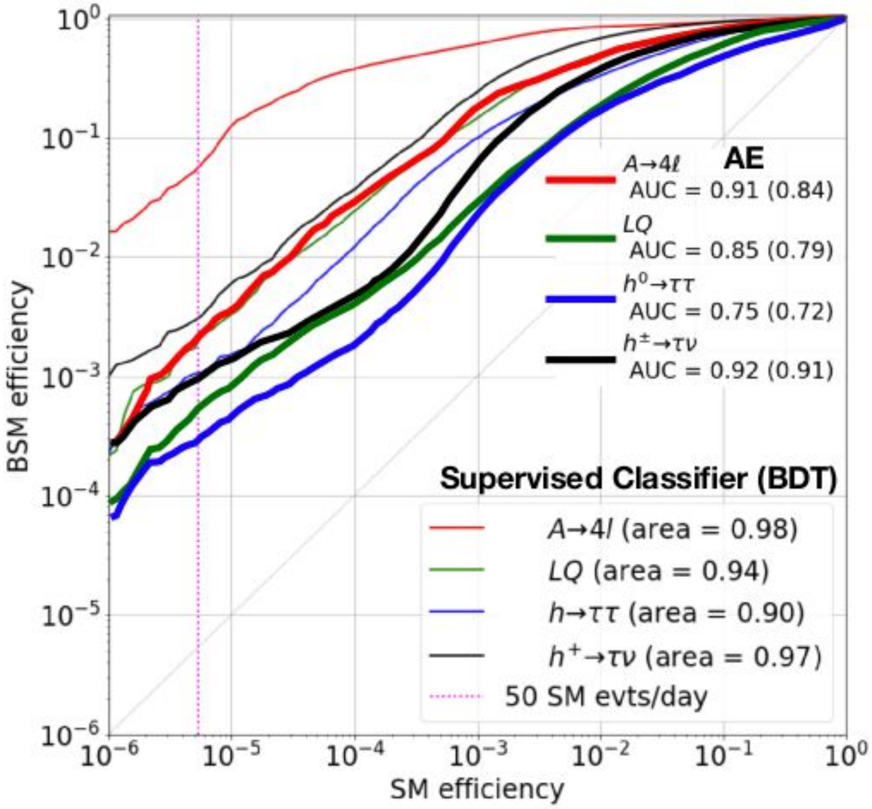
ANNs avoid biasing the PDFs, faithful extrapolation at small-x (very few data, thus error blow up)

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

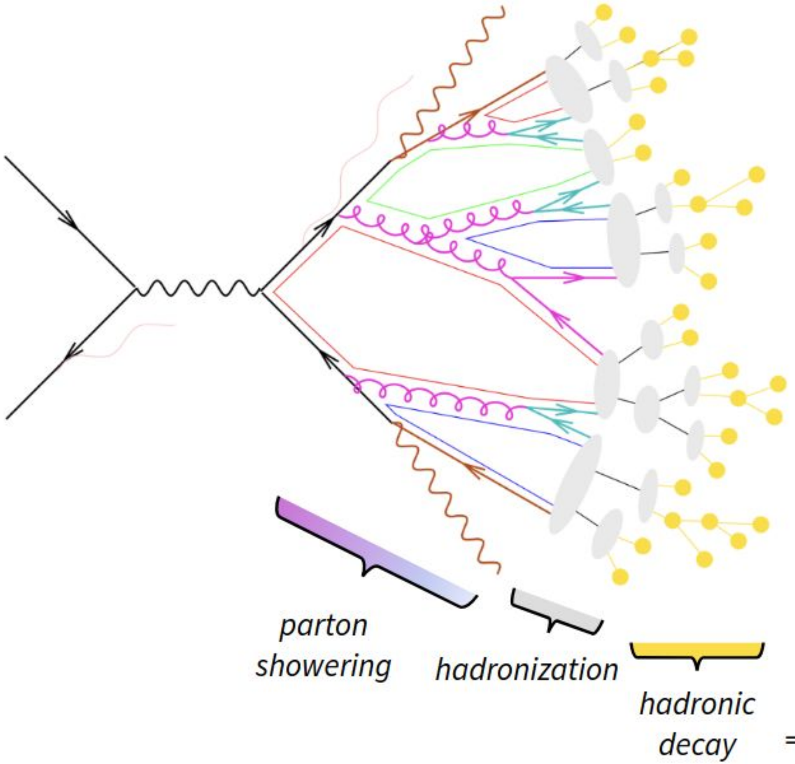
Worse than Supervised but results encouraging



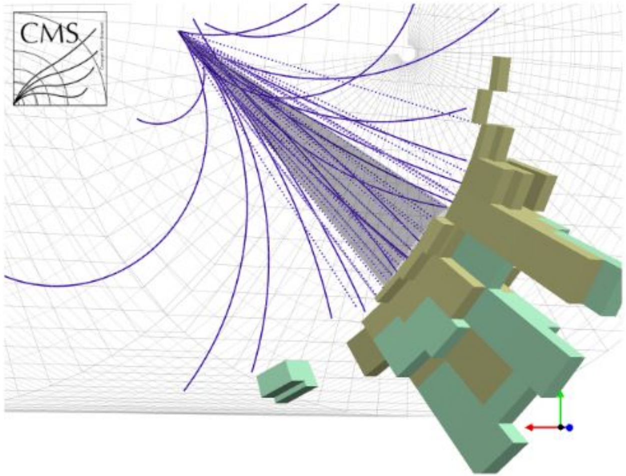


Jets in particle physics

Jets are collinear sprays of particles initiated by quark/gluons



⇒ stable hadrons



raw data from tracker & calorimeter
→ reconstruct to particle records (particle-flow candidates in CMS) to cluster jets

Jet identification (jet tagging): identify the origin of the jet

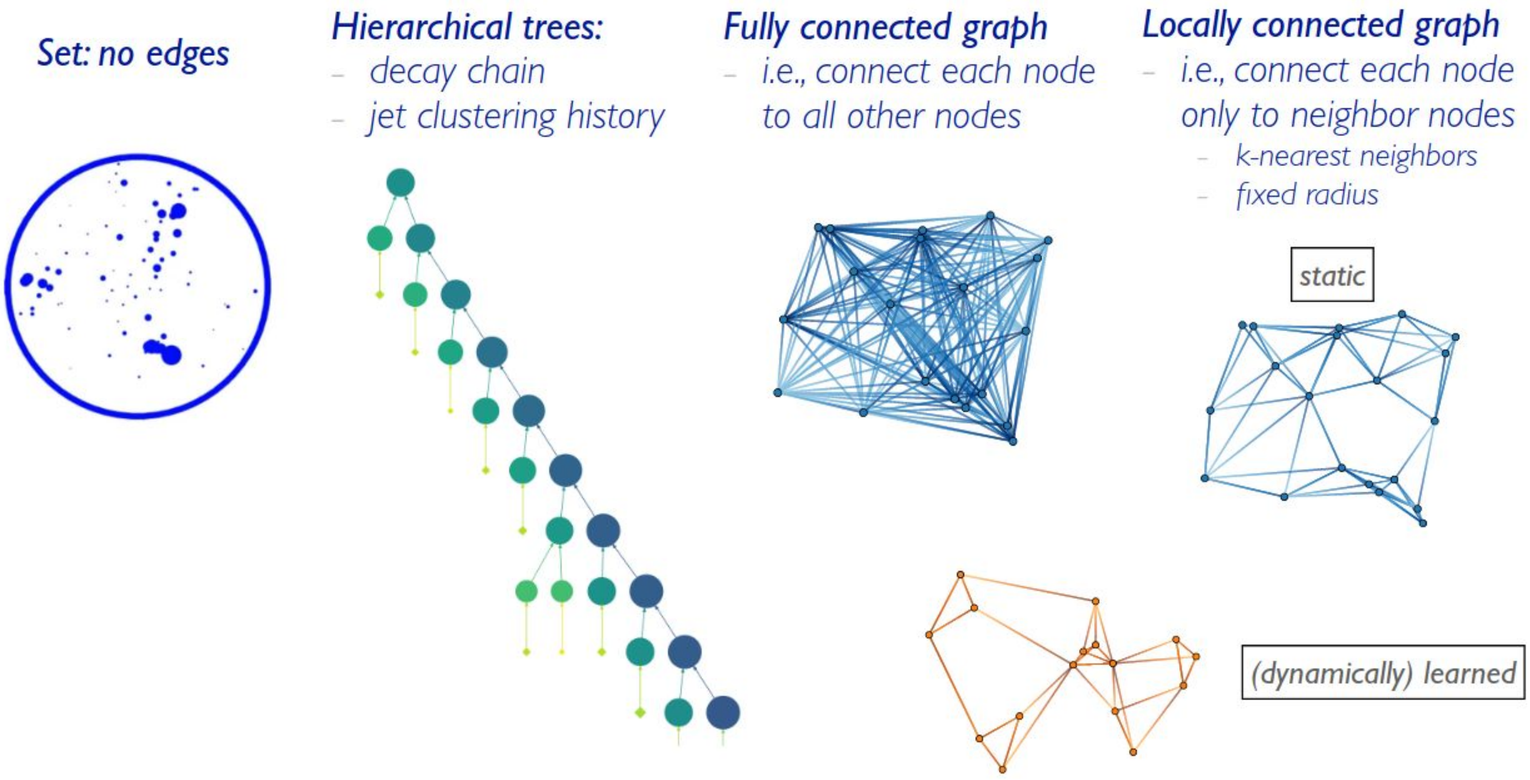
How to design a most performant jet NN?

➔ This is a highly physics-ML interdisciplinary subject

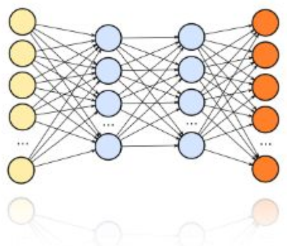
research objective:
design a most performant jet NN

Set/graph representations

View input particles as a set/graph: guarantee the permutational invariance of input particles
The edges of graph: enable communication between pairs of particles

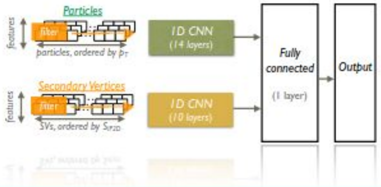


THE EVOLUTION OF JET TAGGERS



"Shallow" ML

- Inputs: O(10) hand-crafted features
  - tracks, SVs, (soft leptons)
- Model: BDTs or feedforward NNs



"Deep" ML

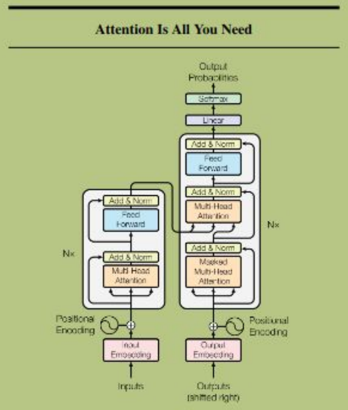
- Inputs:
  - O(10-100) particles
  - O(1-10) SVs
  - O(~1000) low-level features in total
- Model: sequence-based deep NNs
  - 1D CNNs, RNNs, …

Particle Cloud / GNNs

- Inputs:
  - O(10-100) particles
  - O(1-10) SVs
  - but viewed as an unordered "cloud"
- Model:
  - Graph Neural Networks (e.g., ParticleNet)

Transformers

- Inputs:
  - O(10-100) particles
  - O(1-10) SVs
- Model:

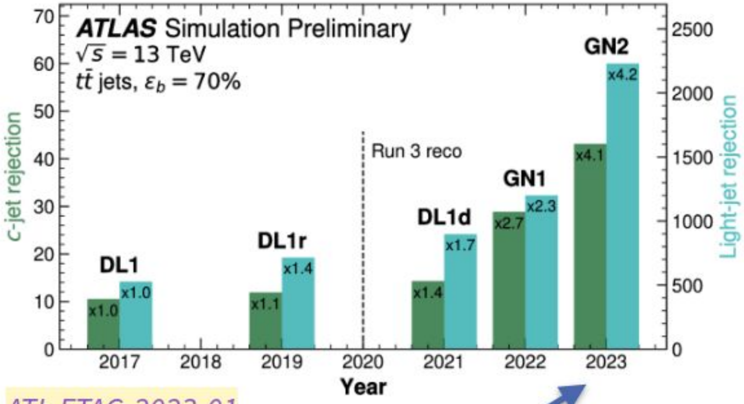


2015 2017 2019 2021 2023

Experimental impact - small radius jets

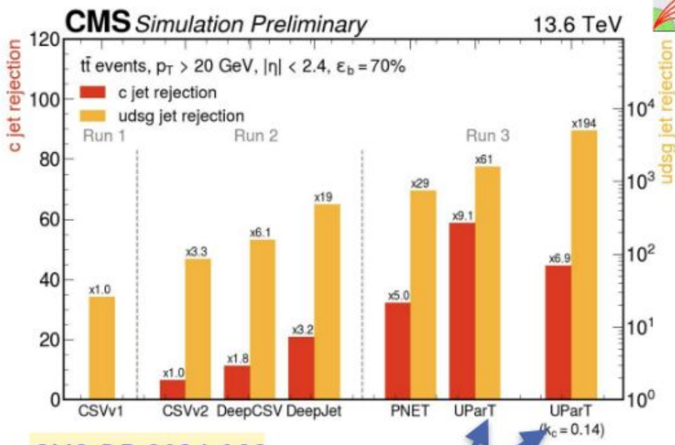
- Huge progress seen from 2016 (early Run-2) to 2024 (mid-Run3), in building jet models for b/c flavour tagging (nearly half of the analyses will use these models)
- ATLAS/CMS "flagship" models all switched to the **Transformers**
  - w/ training dataset size reaching o(100M)

ATLAS EXPERIMENT



ATL-FTAG-2023-01

Latest ATLAS tagger for small-R jets: Transformer-based GN2

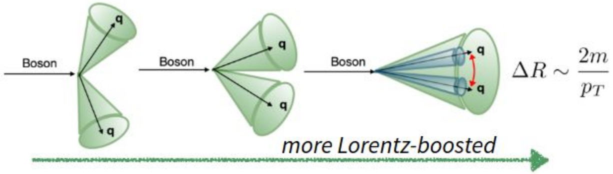


CMS-DP-2024-066

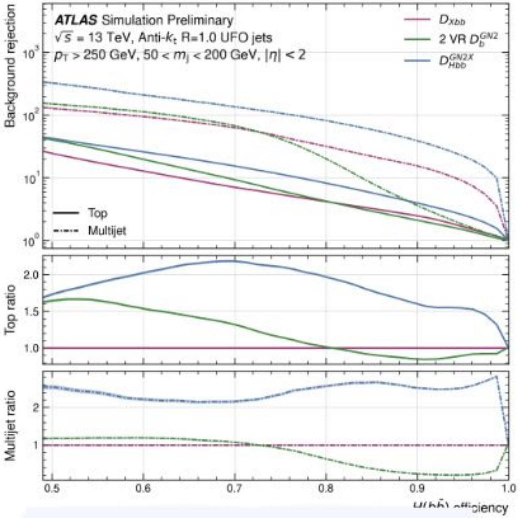
Latest CMS tagger for small-R jets: Unified Particle Transformer (UParT)

Experimental impact - large radius jets

- ➔ Similar cases for large-R jet tagging
  - ❖ more complex tasks! (o(30-100) particles within a large cone size)
  - ❖ believed to have larger benefits from DNN algorithm improvements

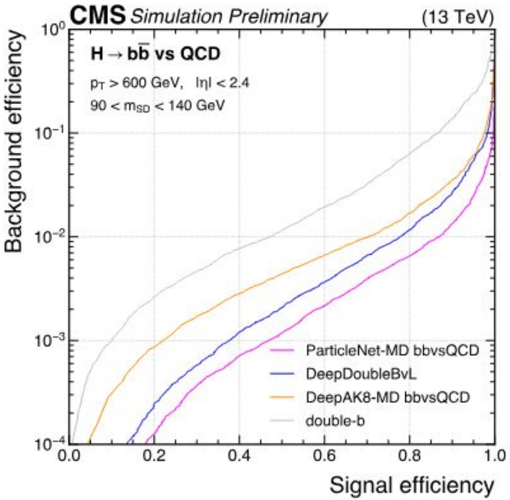


ATL-PHYS-PUB-2023-021



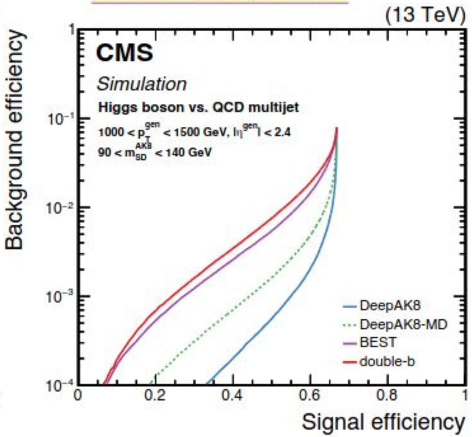
Transformer-based GN2X tagger:
~x3 📈 QCD and x2 top background rejection

CMS-PAS-BTV-22-001



DeepAK8 → ParticleNet:
x5 📈 QCD background rejection

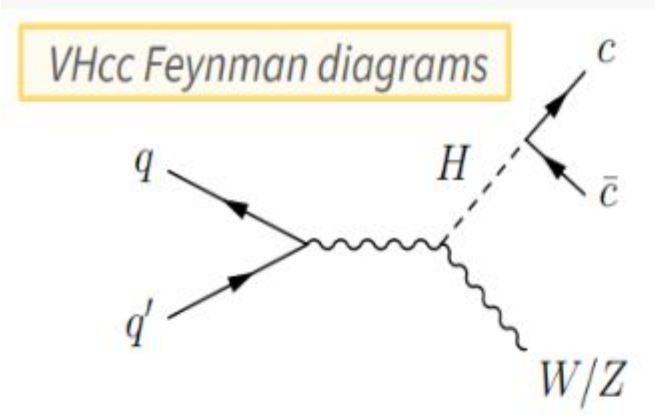
JINST 15 (2020) P06005

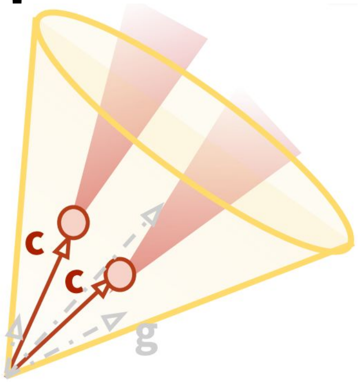


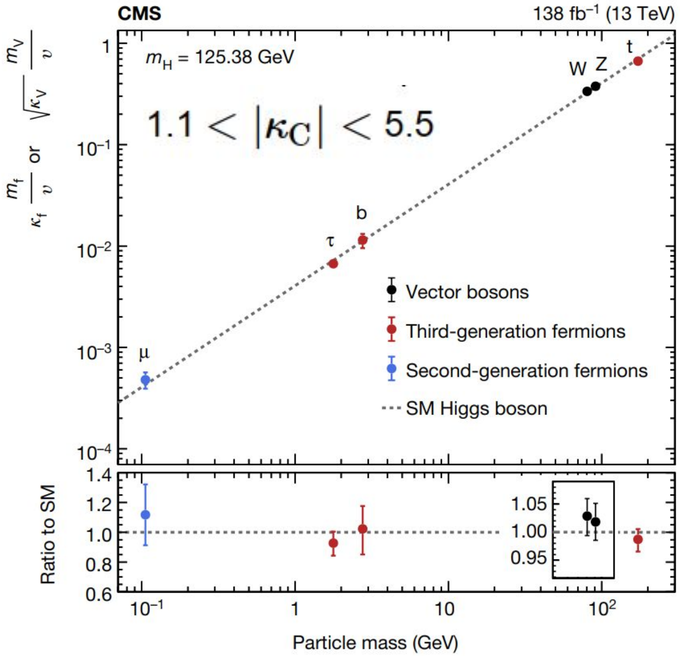
Comparing with early approaches
Another **~x5** 📈 improvement achieved

探测希格斯玻色子与粲夸克耦合

北京大学与 CERN合作开发了基于图神经网络深度算法标记技术，获得Higgs与第二代费米子即粲夸克 汤川耦合的最强实验限制,超过ATLAS同期结果近2倍！







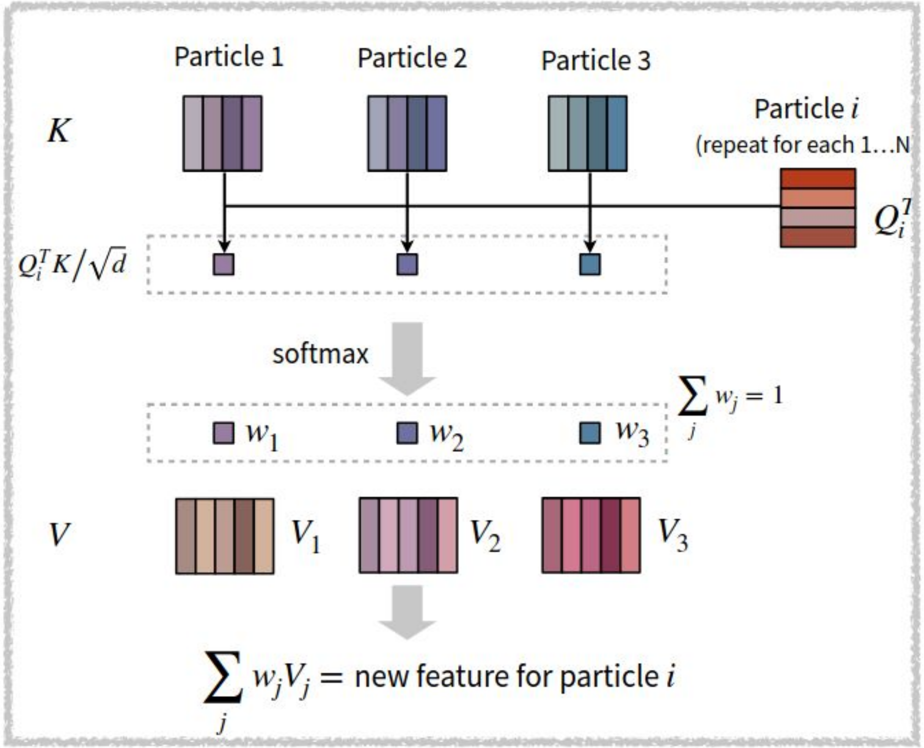
PRL 2023，Editors' suggestion

Transformer × jet network?

arXiv:2202.03772

- ➔ Transformer (Google, 2017): unifies the architecture designs across the tasks
  - ❖ initiated in NLP, then extended to computer vision (started by ViTs)
- ➔ Benefits:
  - ❖ efficiently learn relations of tokens
  - ❖ scale well on larger datasets
  - ❖ → achieve new state-of-the-art performance

Attention in Transformers



Each token (particle) talks to every other token

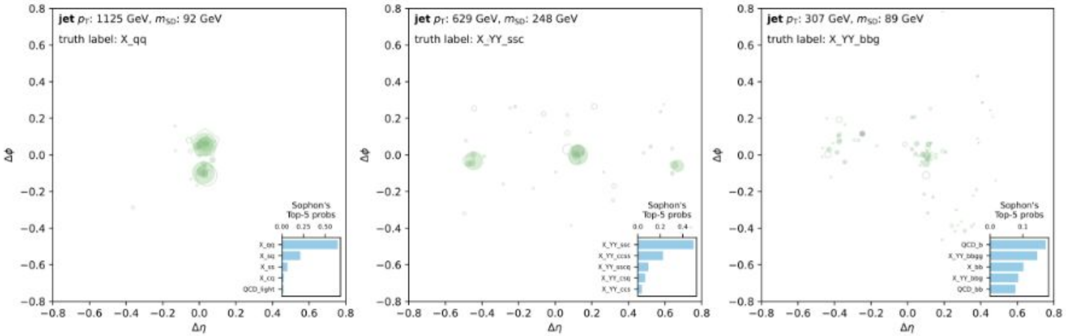
Same prototype across the fields

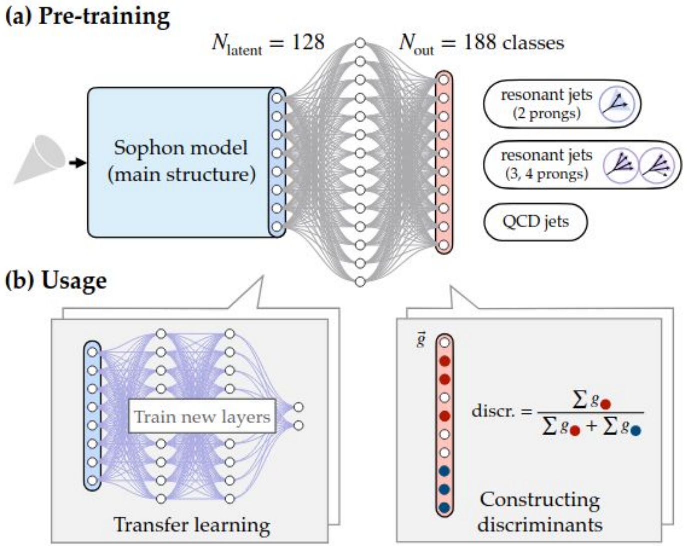
Global tagger

- For large-R jets: from specific SM resonance (W/Z/H/top) tagging to **generic signature-based tagging**
  - a proof-of-concept "*Sophon*": Particle Transformer trained on a wide range of boosted jet signatures (QCD + 2-, 3-, and 4-prong), decay modes, and resonance masses (up to 500 GeV)

TABLE I. Summary of the 188 jet labels in the JETCLASS-II dataset.

Major types	Index range	Label names
Resonant jets: $X \to 2$ prong	0–14	$bb, cc, ss, qq, bc, cs, bq, cq, sq, gg, ee, \mu\mu, \tau_\mathrm{h}\tau_e, \tau_\mathrm{h}\tau_\mu, \tau_\mathrm{h}\tau_\mathrm{h}$
Resonant jets: $X \to 3$ or 4 prong	15–160	$bbbb, bbcc, bbss, bbqq, bbgg, bbee, bb\mu\mu, bb\tau_\mathrm{h}\tau_e, bb\tau_\mathrm{h}\tau_\mu, bb\tau_\mathrm{h}\tau_\mathrm{h}, bbb, bbc, bbs, bbq, bbg, bbe, bb\mu, cccc, ccss, ccqq, ccgg, ccee, cc\mu\mu, cc\tau_\mathrm{h}\tau_e, cc\tau_\mathrm{h}\tau_\mu, cc\tau_\mathrm{h}\tau_\mathrm{h}, ccb, ccc, ccs, ccq, ccg, cce, cc\mu, ssss, ssqq, ssgg, ssee, ss\mu\mu, ss\tau_\mathrm{h}\tau_e, ss\tau_\mathrm{h}\tau_\mu, ss\tau_\mathrm{h}\tau_\mathrm{h}, ssb, ssc, sss, ssq, ssg, sse, ss\mu, qqqq, qqgg, qqee, qq\mu\mu, qq\tau_\mathrm{h}\tau_e, qq\tau_\mathrm{h}\tau_\mu, qq\tau_\mathrm{h}\tau_\mathrm{h}, qqb, qqc, qqs, qqq, qqg, qqe, qq\mu, gggg, ggee, gg\mu\mu, gg\tau_\mathrm{h}\tau_e, gg\tau_\mathrm{h}\tau_\mu, gg\tau_\mathrm{h}\tau_\mathrm{h}, ggb, ggc, ggs, ggq, ggg, gge, gg\mu, bee, cee, see, qee, gee, b\mu\mu, c\mu\mu, s\mu\mu, q\mu\mu, g\mu\mu, b\tau_\mathrm{h}\tau_e, c\tau_\mathrm{h}\tau_e, s\tau_\mathrm{h}\tau_e, q\tau_\mathrm{h}\tau_e, g\tau_\mathrm{h}\tau_e, b\tau_\mathrm{h}\tau_\mu, c\tau_\mathrm{h}\tau_\mu, s\tau_\mathrm{h}\tau_\mu, q\tau_\mathrm{h}\tau_\mu, g\tau_\mathrm{h}\tau_\mu, b\tau_\mathrm{h}\tau_\mathrm{h}, c\tau_\mathrm{h}\tau_\mathrm{h}, s\tau_\mathrm{h}\tau_\mathrm{h}, q\tau_\mathrm{h}\tau_\mathrm{h}, g\tau_\mathrm{h}\tau_\mathrm{h}, qqqb, qqqc, qqqs, bbcq, ccbs, ccbq, ccsq, sscq, qqbc, qqbs, qqcs, bcsq, bcs, bcq, bsq, csq, bce\nu, cse\nu, bqe\nu, cqe\nu, sqe\nu, qqe\nu, bc\mu\nu, cs\mu\nu, bq\mu\nu, cq\mu\nu, sq\mu\nu, qq\mu\nu, bc\tau_e\nu, cs\tau_e\nu, bq\tau_e\nu, cq\tau_e\nu, sq\tau_e\nu, qq\tau_e\nu, bc\tau_\mu\nu, cs\tau_\mu\nu, bq\tau_\mu\nu, cq\tau_\mu\nu, sq\tau_\mu\nu, qq\tau_\mu\nu, bc\tau_\mathrm{h}\nu, cs\tau_\mathrm{h}\nu, bq\tau_\mathrm{h}\nu, cq\tau_\mathrm{h}\nu, sq\tau_\mathrm{h}\nu, qq\tau_\mathrm{h}\nu$
QCD jets	161–187	$bbccss, bbccs, bbcc, bbcss, bbcs, bbc, bbss, bbs, bb, bccss, bccs, bcc, bcss, bcs, bc, bss, bs, b, ccss, ccs, cc, css, cs, c, ss, s,$ others





C. Li et. al., arXiv:2405.12972

Spooky action at a distance!

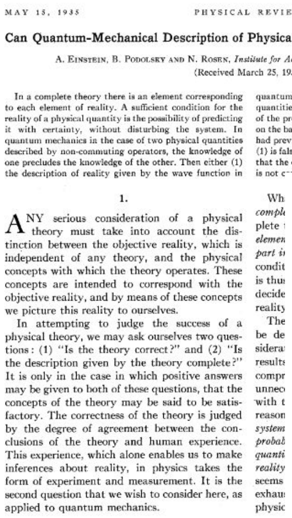
ref

"Can Quantum Mechanical Description of Physical Reality Be Considered Complete?"

A. Einstein   B. Podolski   N. Rosen

Physical reality must be local! - Podolsky

EPR Paradox


MAY 15, 1935   PHYSICAL REVIEW   VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)

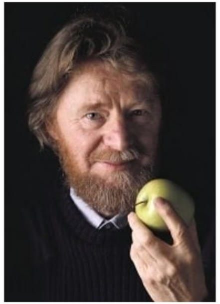
In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not c…

1.

ANY serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves.

In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) "Is the theory correct?" and (2) "Is the description given by the theory complete?" It is only in the case in which positive answers may be given to both of these questions, that the concepts of the theory may be said to be satisfactory. The correctness of the theory is judged by the degree of agreement between the conclusions of the theory and human experience. This experience, which alone enables us to make inferences about reality, in physics takes the form of experiment and measurement. It is the second question that we wish to consider here, as applied to quantum mechanics.

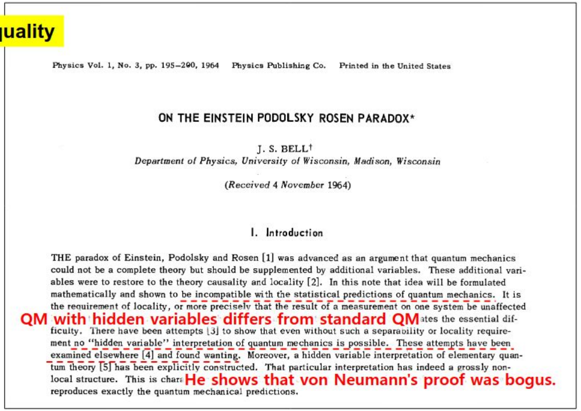
1964 **QM with hidden variables differs from QM**



1928~1990
John Stewart Bell

In the 1980s, he was always mentioned as a candidate for the Nobel Prize.

Bell's Inequality


Physics Vol. 1, No. 3, pp. 195–200, 1964   Physics Publishing Co.   Printed in the United States

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

J. S. BELL†
Department of Physics, University of Wisconsin, Madison, Wisconsin

(*Received* 4 *November* 1964)

I. Introduction

THE paradox of Einstein, Podolsky and Rosen [1] was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality [2]. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected … ates the essential difficulty. There have been attempts [3] to show that even without such a separability or locality requirement no "hidden variable" interpretation of quantum mechanics is possible. These attempts have been examined elsewhere [4] and found wanting. Moreover, a hidden variable interpretation of elementary quantum theory [5] has been explicitly constructed. That particular interpretation has indeed a grossly nonlocal structure. This is chara… reproduces exactly the quantum mechanical predictions.

QM with hidden variables differs from standard QM

He shows that von Neumann's proof was bogus.

Quantum mechanics is nonlocal

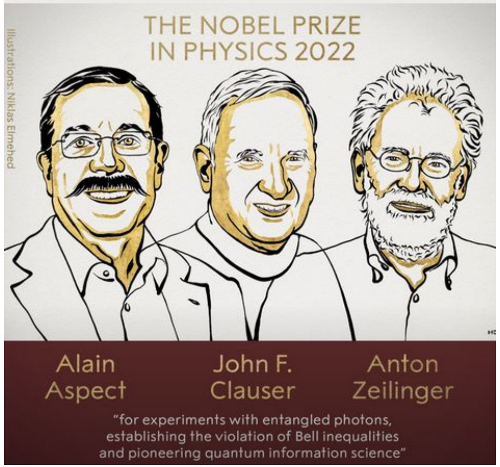
Upon observation, the cat was found to be alive.   Huh? The cat suddenly died.

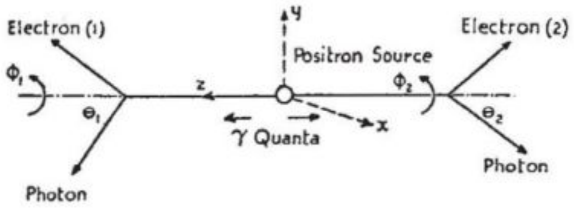
Planet A   Planet B

However, it still takes 1 light year for A and B to exchange answers.

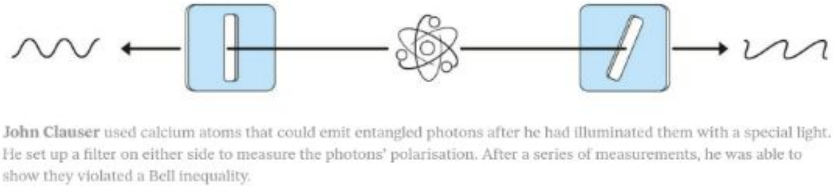
Quantum entanglement tests

- As reviewed by C. N. Yang, the first experiment on quantum entanglement is the Wu-Shaknov Experiment published in 1950 in which the angular correlation of two Compton scattered photons arising from $e+e-$ annihilation are measured.
- The violation of Bell inequality was demonstrated in 1970s using entangled photons, confirming the non-locality of our universe.
- Alain Aspect, John Clauser and Anton Zeilinger won Nobel Prize in Physics in 2022 for demonstrating the potential to investigate and control particles (photons) that are in entangled states





Wu-Shaknov Experiment



Clauser's photon entanglement experiment

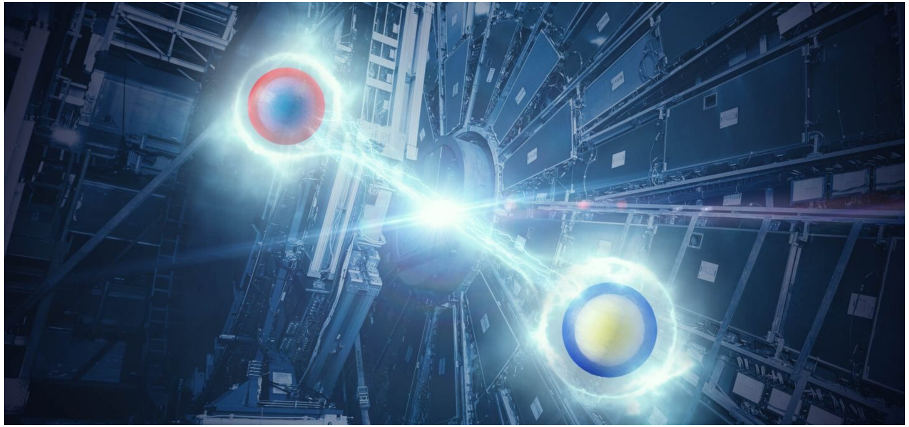
Quantum entanglement at high energy

Nature volume 633, pages 542–547 (2024)

LHC experiments at CERN observe quantum entanglement at the highest energy yet

The results open up a new perspective on the complex world of quantum physics

18 SEPTEMBER, 2024



Article

Observation of quantum entanglement with top quarks at the ATLAS detector

https://doi.org/10.1038/s41586-024-07824-z

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Open access

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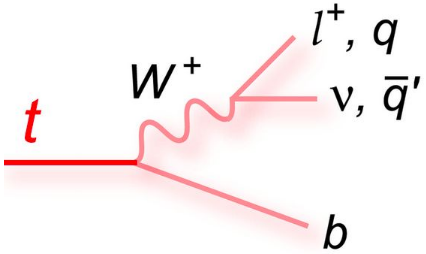
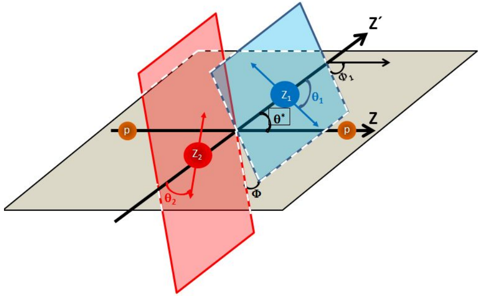
The ATLAS Collaboration*✉

Entanglement is a key feature of quantum mechanics[1–3], with applications in fields such as metrology, cryptography, quantum information and quantum computation[4–8]. It has been observed in a wide variety of systems and length scales, ranging from the microscopic[9–13] to the macroscopic[14–16]. However, entanglement remains largely unexplored at the highest accessible energy scales. Here we report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision dataset with a centre-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 140 inverse femtobarns $(\mathrm{fb})^{-1}$ recorded with the ATLAS experiment. Spin entanglement is detected from the measurement of a single observable D, inferred from the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured in a narrow interval around the top–antitop quark production threshold, at which the entanglement detection is expected to be significant. It is reported in a fiducial phase space defined with stable particles to minimize the uncertainties that stem from the limitations of the Monte Carlo event generators and the parton shower model in modelling top-quark pair production. The entanglement marker is measured to be $D = -0.537 \pm 0.002\,(\mathrm{stat.}) \pm 0.019\,(\mathrm{syst.})$ for $340\ \mathrm{GeV} < m_{t\bar{t}} < 380\ \mathrm{GeV}$. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement so far.

Why QE at high energy?

- **Understand quantum nature & seek for BSM effects.**
- Particle scattering/decay of unstable particles provide **a natural laboratory**
  - the momenta of observed particles are essentially commuting observables. Therefore, there is always some hidden variable theory that can explain the observed momentum data
  - However, one can focus on **spin correlation** emerges in different phase-space region
- It is plausible that **quantum mechanics undergoes modifications at some short distance scales** to achieve compatibility with gravity. Such modifications could, in principle, **be (only) detected by measuring Bell-type observables** or through quantum process tomography (ref)
- offers the potential to uncover **new insights into quantum field theory**.





https://scipost.org/10.21468/SciPostPhys.3.5.036


Sci|Post

SciPost Phys. 3, 036 (2017)

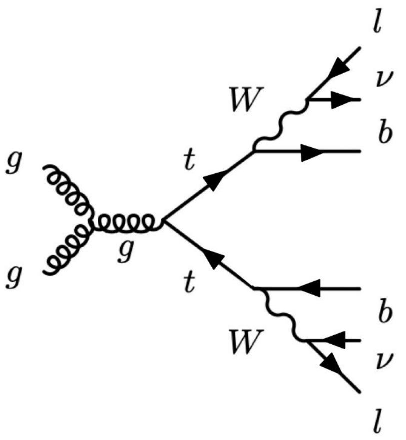
Maximal entanglement in high energy physics

Alba Cervera-Lierta[1], José I. Latorre[1,2], Juan Rojo[3] and Luca Rottoli[4]

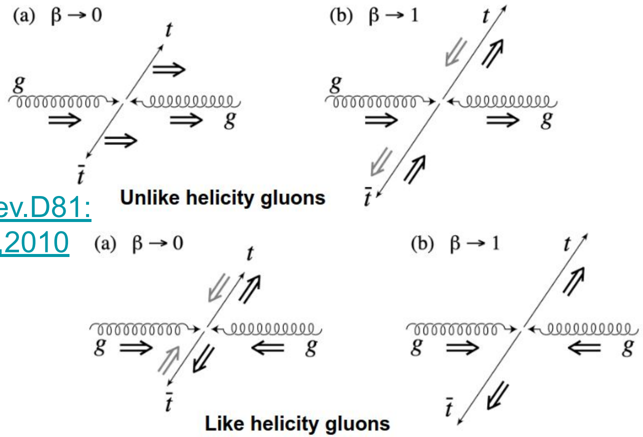
Top quark

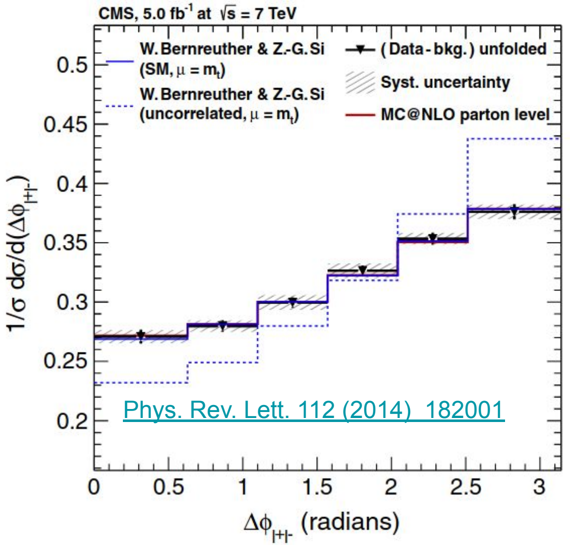
- The most massive fundamental particle : $m_t \approx 173$ GeV
- Large width : $\Gamma_t \sim 1$ GeV
  - Short lifetime : $\tau = 1/\Gamma_t \sim 10^{-25}$ s
    - ✓ decay before hadronisation : $\sim 10^{-23}$ s
      - In case of top pair production, $t\bar{t}$ spins can be measured from decay products
      - The effect due to spin correlation has already been measured in several experiments.

BR(t→Wb)~100% + weak interaction is maximally parity-violating
→ correlations are observable!



Phys.Rev.D81: 074024,2010





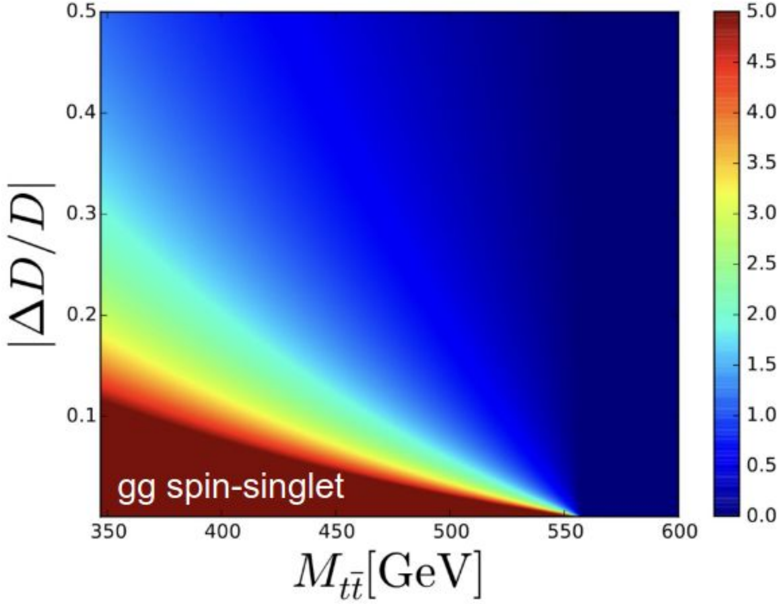
Phys. Rev. Lett. 112 (2014) 182001

(Quantum) Top quark beyond spin correlations

Eur. Phys. J. Plus (2021) 136 (March 2020) → first analysis of top quark pair production from the quantum information point of view: "bipartite qubit system"

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1 + \alpha_1\,\mathbf{B}_1 \cdot \hat{\ell}_1 + \alpha_2\,\mathbf{B}_2 \cdot \hat{\ell}_2 + \alpha_1\alpha_2\,\hat{\ell}_1\,\mathbb{C}\,\hat{\ell}_2\right)$$

($\mathbf{B}_1 \to 0$, $\mathbf{B}_2 \to 0$)



$$\mathrm{Tr}\,[\mathbb{C}] < -1$$ *Peres-Horodecki criterion*

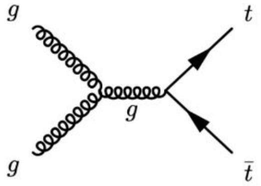
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$ *a simple observable*

$$D = \frac{\mathrm{Tr}\,[\mathbb{C}]}{3} \Rightarrow D < -\frac{1}{3}$$ *a quantum entanglement marker!*

Density matrix, Peres-Horodecki criterion ref

	pure state	mixed states
wavefunction	$\lvert\psi\rangle$	$f(\lvert\psi_i\rangle)$
density matrix	$\rho = \lvert\psi\rangle\langle\psi\rvert$	$\rho = \sum_i p_i \lvert\psi_i\rangle\langle\psi_i\rvert$
trace of ρ	$Tr(\rho) = 1$	$Tr(\rho) = 1$
trace of ρ^2	$Tr(\rho^2) = 1$	$Tr(\rho^2) < 1$
entropy	$S(\rho) = 0$	$S(\rho) = -Tr(\rho \ln \rho) > 0$

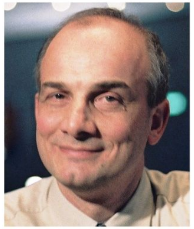
- **density matrix for 1 spin**
  - $\rho = \frac{1}{2}\left(I_2 + \sum_i B_i \sigma^i \otimes I_2\right)$
    - ✓ $B_i = \langle \sigma^i \rangle$
      - B_i **3 parameters → Polarization**
- **density matrix for 2 spins**
  - $\rho = \frac{1}{4}\left(I_4 + \sum_i (B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i)\right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j)$
    - ✓ $B_i^{\pm} = \langle \boldsymbol{\sigma}_{\pm}^{i} \rangle$
      - **6 paramters → Polarizations**
    - ✓ $C_{ij} = \langle \boldsymbol{\sigma}_{+}^{i} \boldsymbol{\sigma}_{-}^{j} \rangle$
      - **9 parameters → Correlations**



- From pure state to mixed state.

"A quantitatively characterization of the degree of the entanglement between the subsystems of a system in a mixed state, is not unique! "

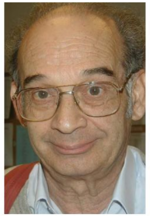
$$\rho_{AB} \overset{?}{=} \sum_{i=1}^{N} p_i \rho_A^{(i)} \otimes \rho_B^{(i)}, \quad \left(\sum_i^N p_i = 1,\ p_i > 0 \right)$$



"Finally, we prove that the weak membership problem for the convex set of separable normalized bipartite density matrices is ***NP-HARD***. "

——Leonid Gurvits

- For 2×2 and 2×3 system, it is solved by Peres, and Horodeckis 1996 (Peres-Horodecki criterion, concurrence).



Asher Peres
(1934/01/30-2005/01/01)

Ryszard Horodecki
(1943/09/30-)

Paweł Horodecki
(1971-)

Michał Horodecki
(1973-)

Top quark Entanglement Discovery

Nature volume 633, pages 542–547 (2024)

Article

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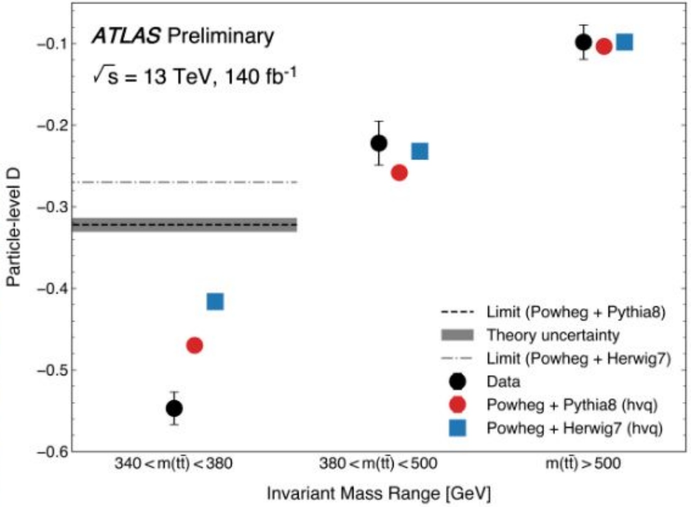
$$D = -3\langle \cos \varphi \rangle$$

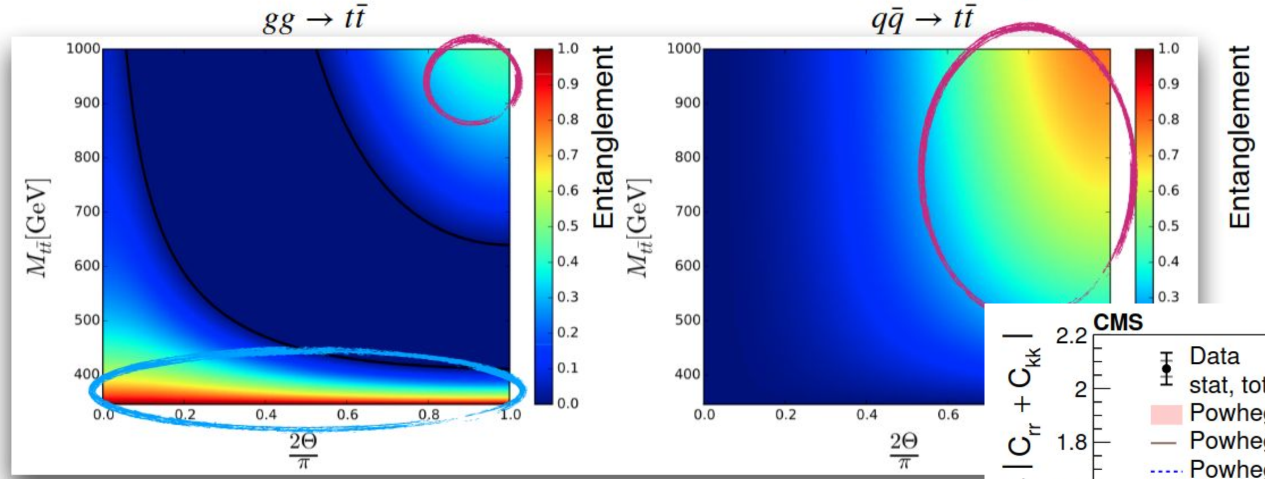


Entangled state : ***D* < −1/3**
(derived from the Peres–Horodecki criterion)

Top quark Entanglement Discovery

- SM predicts entangled states:
  - at the production threshold region in gg fusion production
  - at the boosted region for central production of the $t\bar{t}$ system

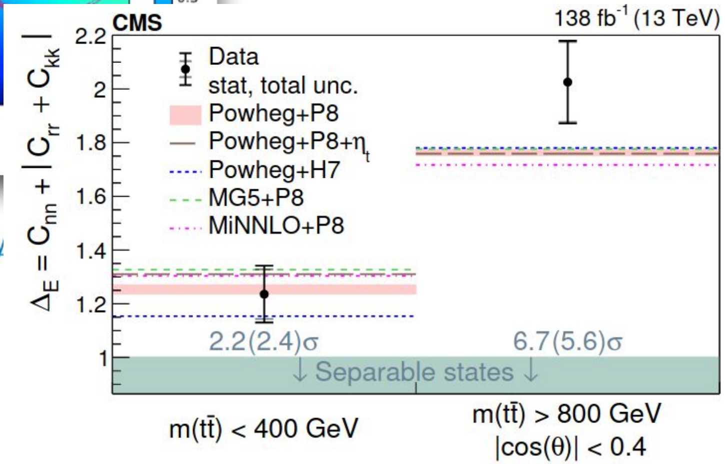
high relative velocity of top quarks → space-like separated events



top2024

low relative velocity of top quarks → time-like separated events

Eur. Phy



Rep. Prog. Phys. 87 (2024) 117801
Phys. Rev. D 110 (2024) 112016

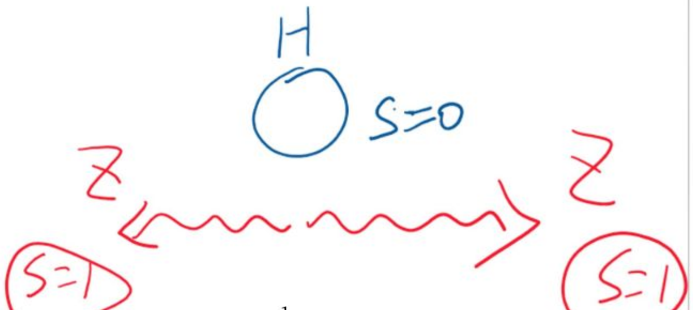
QE between Triplets: H→ VV

- The polarization density matrix(PDM) can be reconstructed from the angular distributions of the decay products:

$$\rho = |\Psi_{ZZ}\rangle\langle\Psi_{ZZ}| = |\Phi\rangle\langle\Phi|$$

$$|\Phi\rangle = \sum c_{ij}|ij\rangle \to \sum \mathcal{M}(\lambda_1,\lambda_2)|\lambda_1,\lambda_2\rangle$$

Ψ_Z has three polarization states: +1, 0, -1



$$|\psi_{ZZ}\rangle = \frac{1}{\sqrt{2+\beta^2}}(|+-\rangle - \beta|00\rangle + |-+\rangle),$$

For two-triplet system, we can expand the density matrix as

$$\rho = \frac{1}{9}\left[\mathbb{1}\otimes\mathbb{1}\right] + \sum_{a=1}^{8} f_a\left[T^a\otimes\mathbb{1}\right] + \sum_{a=1}^{8} g_a\left[\mathbb{1}\otimes T^a\right] + \sum_{a,b=1}^{8} h_{ab}\left[T^a\otimes T^b\right]$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+\,d\Omega_-} = \left(\frac{3}{4\pi}\right)^2 \mathrm{Tr}\left[\rho_{V_1V_2}\left(\Gamma_1\otimes\Gamma_2\right)\right]$$

Production ($\rho_{V_1V_2}$) **Decay** ($\Gamma_1\otimes\Gamma_2$)

All coefficients → Quantum Tomography

- No direct spin measurements: inferred by angular distributions.
- Both the state before decay & the final state decay products inherit the SAME quantum information.

Quantum Tomography

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+\,d\Omega_-} = \left(\frac{3}{4\pi}\right)^2 \mathrm{Tr}\left[\rho_{V_1V_2}\left(\Gamma_1 \otimes \Gamma_2\right)\right],$$

$$\Gamma(\theta,\phi) = \frac{1}{4}\begin{pmatrix} 1+\cos^2\theta - 2\eta_\ell\cos\theta & \frac{1}{\sqrt{2}}(\sin 2\theta - 2\eta_\ell \sin\theta)e^{i\phi} & (1-\cos^2\theta)e^{i2\phi} \\ \frac{1}{\sqrt{2}}(\sin 2\theta - 2\eta_\ell\sin\theta)e^{-i\phi} & 2\sin^2\theta & -\frac{1}{\sqrt{2}}(\sin 2\theta + 2\eta_\ell\sin\theta)e^{i\phi} \\ (1-\cos^2\theta)e^{-i2\phi} & -\frac{1}{\sqrt{2}}(\sin 2\theta + 2\eta_\ell\sin\theta)e^{-i\phi} & 1+\cos^2\theta - 2\eta_\ell\cos\theta \end{pmatrix};$$

→

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\big[1 + A^1_{LM} Y^M_L(\theta_1,\phi_1) + A^2_{LM} B_L Y^M_L(\theta_2,\phi_2) + C_{L_1M_1L_2M_2} B_{L_1} B_{L_2} Y^{M_1}_{L_1}(\theta_1,\phi_1) Y^{M_2}_{L_2}(\theta_2,\phi_2)\big],$$

$$\int \frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} Y^M_L(\Omega_j) d\Omega_j = \frac{B_L}{4\pi} A^j_{LM}, \qquad j = 1,2;$$

$$\int \frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} Y^{M_1}_{L_1}(\Omega_1) Y^{M_2}_{L_2}(\Omega_1) d\Omega_1 d\Omega_2 = \frac{B_{L_1}B_{L_2}}{4\pi} C_{L_1M_1L_2M_2}.$$

Integral ⟶ events summed

More details in

PRD 107 (2023) 1, 016012

JHEP 10 (2024) 211

PRD 111 (2025) 3, 036008

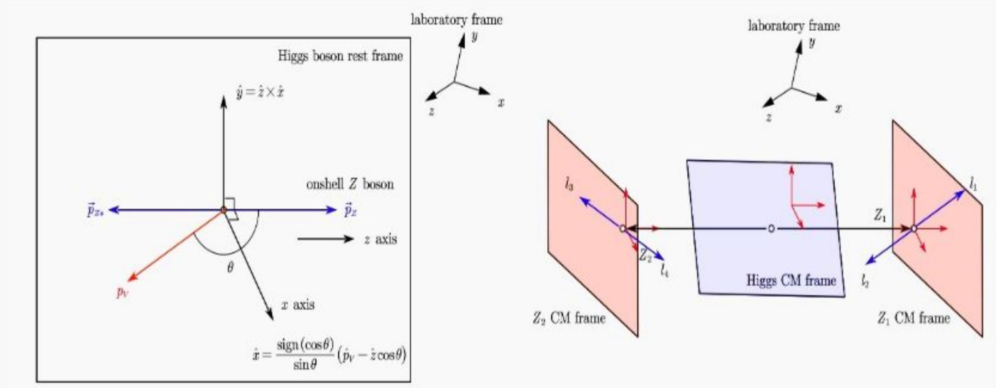
Notice that the theoretical form of the density matrix imposes strong constraints on the various coefficients: this assumption can be relaxed though

$$\rho = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{6}\left(\sqrt{2}A^1_{2,0}+2\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}\left(1-\sqrt{2}A^1_{2,0}\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{6}\left(\sqrt{2}A^1_{2,0}+2\right) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Quantum Tomography in Operation

In two spin-1 massive bosons' system:

- The z-axis is the direction of the on-shell Z boson's 3-momentum.
- The $\hat{x}$ axis is in the production plane: $\hat{x} = \frac{sign(cos\theta)(\hat{p}_p - cos\theta\hat{z})}{sin\theta}, \hat{p}_p = (0,0,1)$
- The $\hat{y} = \hat{z} \times \hat{x}$
- J_Z is the polarization operator.
- The eigenstates of J_Z is the basis of the spin space.



Two Lorentz Transformation:

- Higgs rest frame → determine Z axis
- Z boson rest frame(boost along Z vector) → lepton's polar angles

Obtain :(θ_1, φ_1) in Z_1 rest frame, (θ_2, φ_2) in Z_2 rest frame. The coefficients can A^l_{LM} *and* $C_{L_1M_1L_2M_2}$ can be calculated

$$\rho = \frac{1}{9}\left[\mathbb{1}_3 \otimes \mathbb{1}_3 + A^1_{LM} T^L_M \otimes \mathbb{1}_3 + A^2_{LM} \mathbb{1}_3 \otimes T^L_M + C_{L_1M_1L_2M_2} T^{L_1}_{M_1} \otimes T^{L_2}_{M_2}\right]$$

Quantum Tomography → Bell Inequality

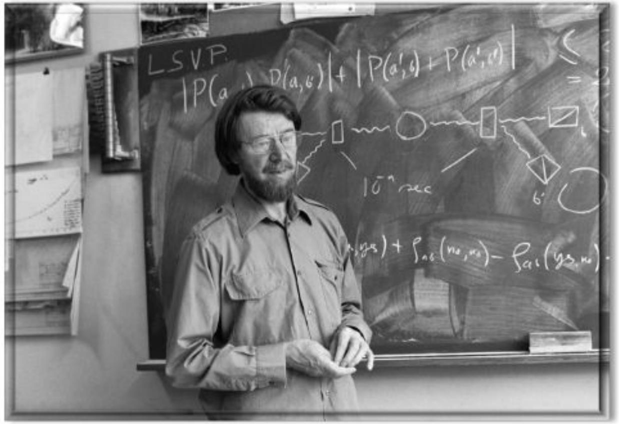
- The most original form of Bell inequalities (Clauser-Horne-Shimony-Holt Inequality):

$$P(A_1 B_1 | AB, \lambda) = P(A_1 | A, \lambda) P(B_1 | B, \lambda)$$

Classical local hidden variable theory:

$$I_3 = \langle O_{Bell} \rangle = Tr\{\rho O_{Bell}\} \le 2$$

ρ **: Polarization density matrix (PDM)**



- More general form (Collins-Gisin-Linden-Massar-Popescu Inequality)

$$\mathcal{I}_d = \sum_{k-0}^{[d/2]-1} \left(1 - \frac{2k}{d-1}\right)\{+[P(A_1 = B_1 + k) + P(B_1 = A_2 + k + 1) + P(A_2 = B_2 + k) + P(B_2 = A_1 + k) - [P(A_1 = B_1 - k - 1) + P(B_1 = A_2 - k) + P(A_2 = B_2 - k - 1) + P(B_2 = A_1 - k - 1)]\}$$

3-dimensional form:

$$\mathcal{I}_3 = P(A_1 = B_1) + P(B_1 = A_2 + 1) + P(A_2 = B_2) + P(B_2 = A_1) - [P(A_1 = B_1 - 1) + P(B_1 = A_2) + P(A_2 = B_2 - 1) + P(B_2 = A_1 - 1)].$$

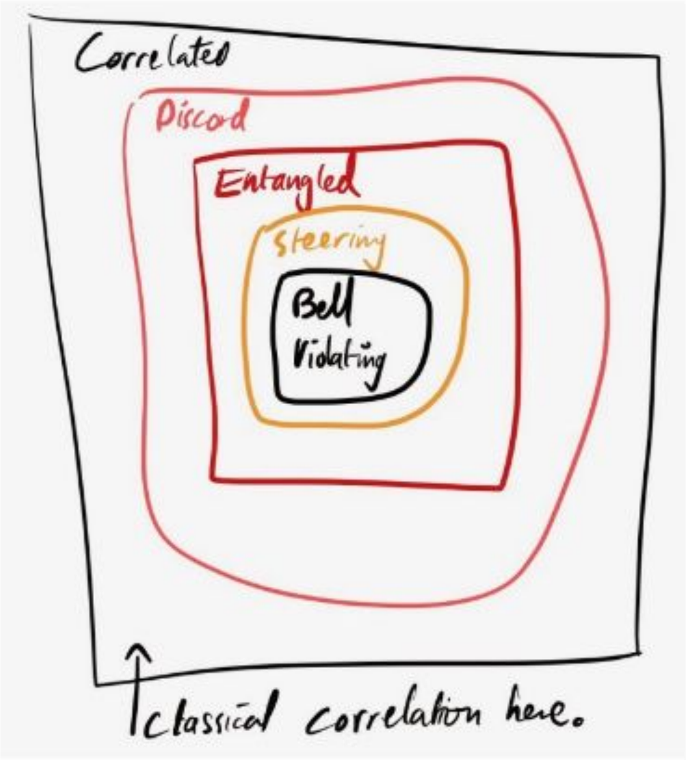
- The expectation value of the Bell operator can be written as:

$$\mathcal{B} = \left[\frac{2}{3\sqrt{3}}\left(T_1^1 \otimes T_1^1 - T_0^1 \otimes T_0^1 + T_1^1 \otimes T_{-1}^1\right) + \frac{1}{12}\left(T_2^2 \otimes T_2^2 + T_2^2 \otimes T_{-2}^2\right) + \frac{1}{2\sqrt{6}}\left(T_2^2 \otimes T_0^2 + T_0^2 \otimes T_2^2\right) - \frac{1}{3}\left(T_1^2 \otimes T_1^2 + T_1^2 \otimes T_{-1}^2\right) + \frac{1}{4} T_0^2 \otimes T_0^2\right] + \text{h.c.}.$$

- Bell inequality expectation value can be calculated:

$$\mathcal{I}_3 = \frac{1}{36}\left(18 + 16\sqrt{3} - \sqrt{2}\left(9 - 8\sqrt{3}\right) A_{2,0}^1 - 8\left(3 + 2\sqrt{3}\right) C_{2,1,2,-1} + 6 C_{2,2,2,-2}\right)$$

Quantum Tomography → Entanglement Criteria



SUSY2024

The theoretical form of the density matrix imposes strong constraints and leads to a entanglement criteria

$$\rho = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & c \\ 0 & 0 & 0 & 0 & 0 & b & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & f & 0 \\ 0 & 0 & 0 & 0 & d & 0 & 0 & 0 & 0 \\ 0 & b^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & g & 0 & 0 \\ 0 & 0 & 0 & f^* & 0 & 0 & 0 & 0 & 0 \\ c^* & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \quad (29)$$

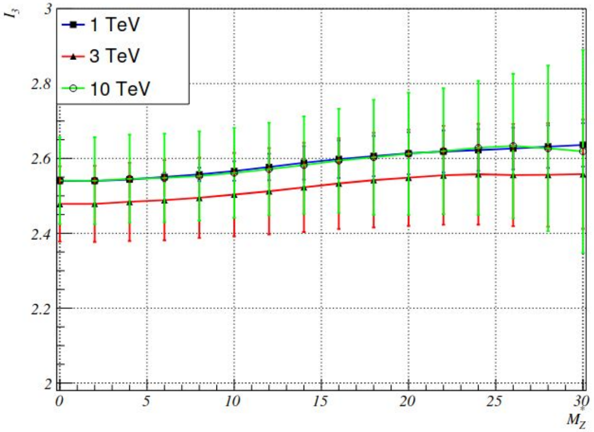
which has eigenvalues $a, d, g, \pm|b|, \pm|c|, \pm|f|$. Therefore if $b \neq 0$, $c \neq 0$ or $f \neq 0$ the density matrix is entangled. Note that the reverse is also true: if $b = c = f = 0$ the state is obviously separable, as ρ is diagonal in the separable basis. This represents a noteworthy example beyond a two-qubit system, where, thanks to an underlying symmetry, the Peres-Horodecki condition for entanglement is not just sufficient, but also necessary.

When applied this condition to our density matrix (26), it turns out that the ZZ system is entangled if and only if

$$C_{2,1,2,-1} \neq 0 \quad \text{or} \quad C_{2,2,2,-2} \neq 0 .$$

Prospects@LHC, MuC, CEPC

- The numerical analysis shows that with a luminosity of L =300 fb−1 entanglement can be probed at >3σ level. For $\boldsymbol{L}$**=3 ab−1 (HL-LHC) entanglement** can be probed beyond the **5$\boldsymbol{\sigma}$** level, while the sensitivity to **Bell inequalities** violation is at the **4.5$\boldsymbol{\sigma}$** level.
- At Muon Collider, **Quantum entanglement** can be probed up to **4σ** of significance with lower MZ2 cut or 2σ ~ 3σ with higher MZ2 cut, using either one of the correlation coefficients C2,1,2,−1 and C2,2,2,−2. The significance of the **violation of Bell inequality** can be obtained up to **2σ**.

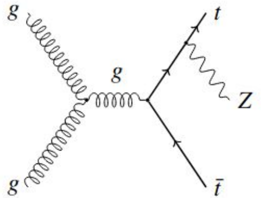


$\sqrt{s} = 1\,\mathrm{TeV}$

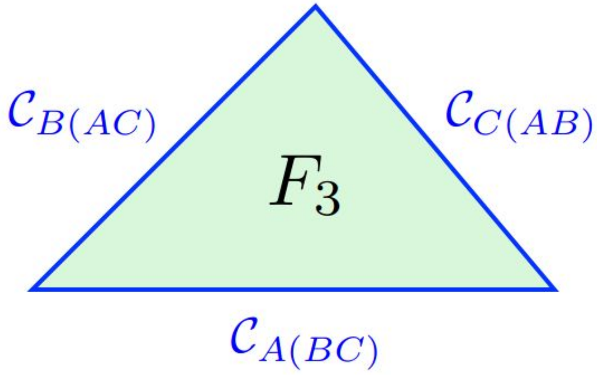
M_{Z_2} (GeV)	I_3	$C_{2,1,2,-1}$	$C_{2,2,2,-2}$
0.000	2.563 ± 0.325	-0.928 ± 0.216	0.527 ± 0.164
10.000	2.596 ± 0.335	-0.943 ± 0.220	0.553 ± 0.179
20.000	2.654 ± 0.373	-0.977 ± 0.248	0.574 ± 0.192
30.000	2.663 ± 0.508	-0.979 ± 0.334	0.589 ± 0.248

Table 2. Values of the correlation coefficients $C_{2,1,2,-1}$ and $C_{2,2,2,-2}$ as the signal for quantum entanglement and also the expectation value of the Bell operator I_3. The expected target luminosity is $30\mathrm{ab}^{-1}$ and $\sqrt{s} = 1\,\mathrm{TeV}$.

Quantum Collisions: more funs



- **Three-partite entanglement**
  - 3-body Decay: *Phys.Rev.Lett.* 132 (2024) 15, 151602; arXiv:2502.19470
  - 2 to 3 process (ttZ): arXiv:2404.03292
- **Quantum Process Tomography** (operating initial particles' flavor and spin)
  - arXiv:2412.01892



concurrence triangle

PHYSICAL REVIEW A, VOLUME 62, 062314

Three qubits can be entangled in two inequivalent ways

W. Dür, G. Vidal, and J. I. Cirac
Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria
(Received 26 May 2000; published 14 November 2000)

PHYSICAL REVIEW A, VOLUME 65, 052112

Four qubits can be entangled in nine different ways

F. Verstraete,[1,2] J. Dehaene,[2] B. De Moor,[2] and H. Verschelde[1]
[1]*Department of Mathematical Physics and Astronomy, Ghent University, Krijgslaan 281 (S9), B-9000 Gent, Belgium*
[2]*Department of Electrical Engineering, Katholieke Universiteit Leuven, Research Group SISTA Kasteelpark Arenberg 10, B-3001 Leuven, Belgium*
(Received 29 November 2001; published 25 April 2002)

Quantum Process Tomography: one further step

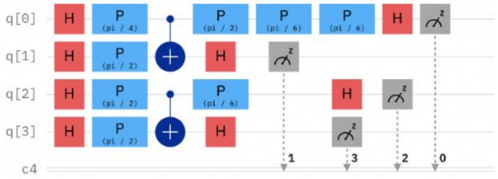
- **Spin and flavour measurements** in collider experiments as a **quantum instrument**
- **Choi matrix**, which completely determines input-output transitions, can be both **theoretically computed** and **experimentally reconstructed**
- **Polarized Beam collisions, or,**

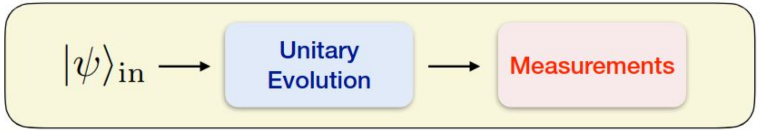
ref **lepton scattering on polarized target experiments (see next)**

Particle Collider = Quantum Computer

=

C. Altomonte, A.Barr [2312.02242]





Reconstruction of Choi matrix $e^-e^+ \to t\bar{t}$

- Reconstruction of the diagonal part:

$$\widetilde{\mathcal{I}}_x = \frac{1}{4}\begin{pmatrix} \mathcal{I}_x(|++\rangle\langle++|) & \mathcal{I}_x(|++\rangle\langle+-|) & \mathcal{I}_x(|++\rangle\langle-+|) & \mathcal{I}_x(|++\rangle\langle--|) \\ \mathcal{I}_x(|+-\rangle\langle++|) & \mathcal{I}_x(|+-\rangle\langle+-|) & \mathcal{I}_x(|+-\rangle\langle-+|) & \mathcal{I}_x(|+-\rangle\langle--|) \\ \mathcal{I}_x(|-+\rangle\langle++|) & \mathcal{I}_x(|-+\rangle\langle+-|) & \mathcal{I}_x(|-+\rangle\langle-+|) & \mathcal{I}_x(|-+\rangle\langle--|) \\ \mathcal{I}_x(|--\rangle\langle++|) & \mathcal{I}_x(|--\rangle\langle+-|) & \mathcal{I}_x(|--\rangle\langle-+|) & \mathcal{I}_x(|--\rangle\langle--|) \end{pmatrix}$$

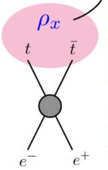
- Consider 4 purely polarised beam settings:

$$\{|i\rangle\} = \{|++\rangle, |+-\rangle, |-+\rangle, |--\rangle\} \qquad \rho_0^i = |i\rangle\langle i|$$

$$\mathcal{I}_x(|i\rangle\langle i|) = \varrho_x^i = \mathrm{Tr}\varrho_x^i \cdot \frac{\varrho_x^i}{\mathrm{Tr}\varrho_x^i}$$

measurable

$$\frac{\sigma_x[e^-e^+(\rho_0^i) \to t\bar{t}]}{\sigma[e^-e^+(\rho_0^{\text{mix}}) \to t\bar{t}]}$$



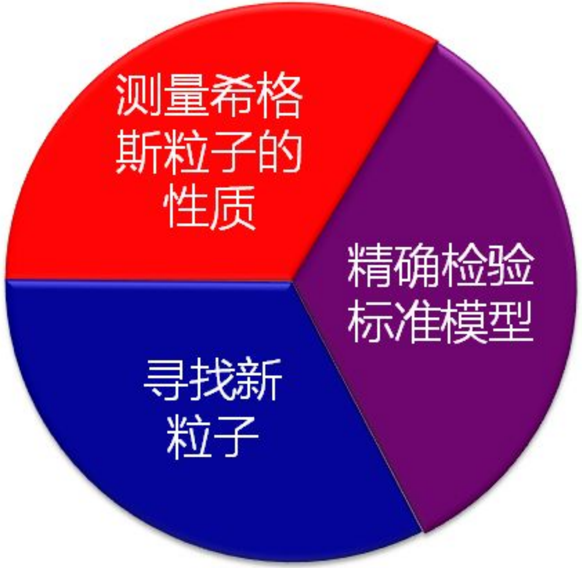
Reconstruction of spin-density matrix is possible

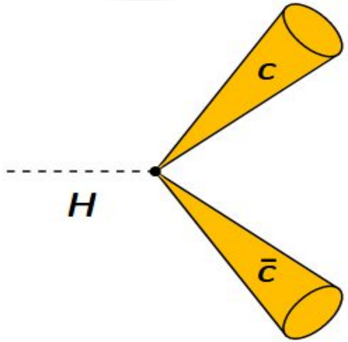
Quantum State Tomography

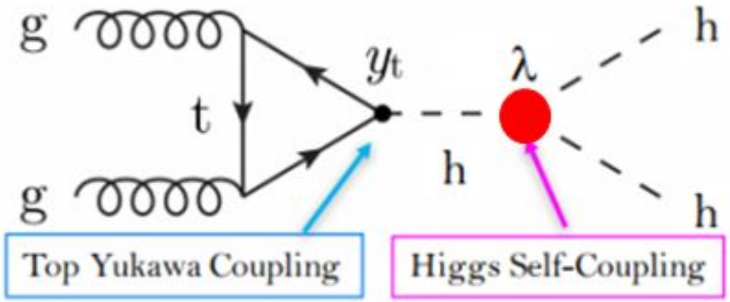
Y.Afik, J.Nova [2003.02280], Ashby-Pickering, Barr, Wierzchucka [2209.13990]

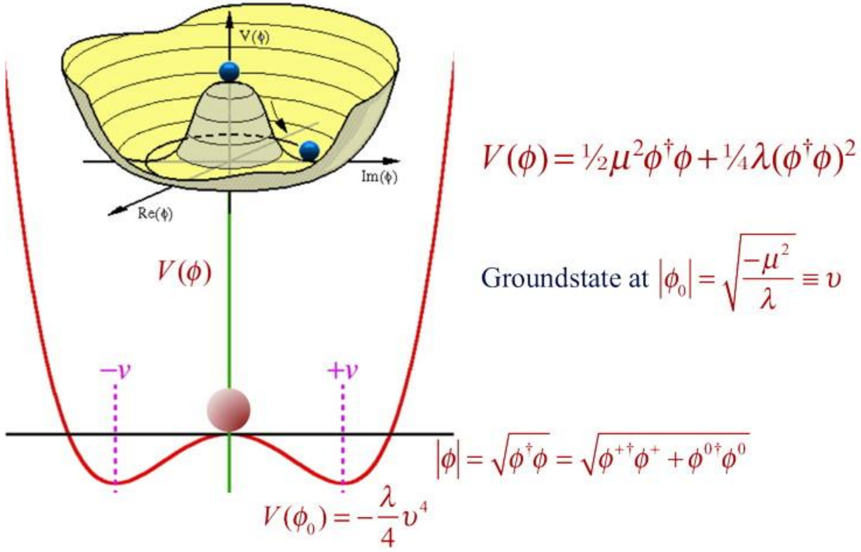
1. 前言
2. 高能物理简介
3. 大型强子对撞机(LHC)
4. Higgs的发现
5. 中国未来对撞机(CEPC)
6. 其他对撞机
7. 机器学习、量子纠缠
8. **总结与展望**

Summary

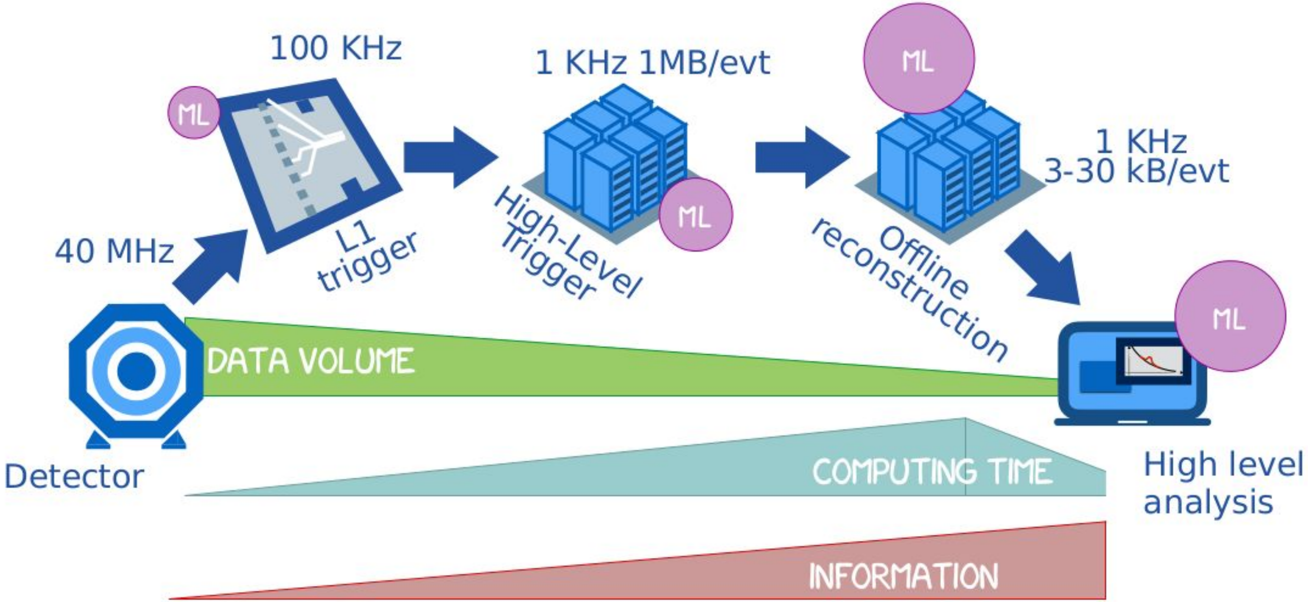

测量希格斯粒子的性质
精确检验标准模型
寻找新粒子


c
c̄
H


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 $|\phi_0|=\sqrt{\frac{-\mu^2}{\lambda}}\equiv\upsilon$
$|\phi|=\sqrt{\phi^\dagger\phi}=\sqrt{\phi^{+\dagger}\phi^{+}+\phi^{0\dagger}\phi^{0}}$
$V(\phi_0)=-\frac{\lambda}{4}\upsilon^4$

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

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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"*.

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PT and (pseudo-)Rapidity

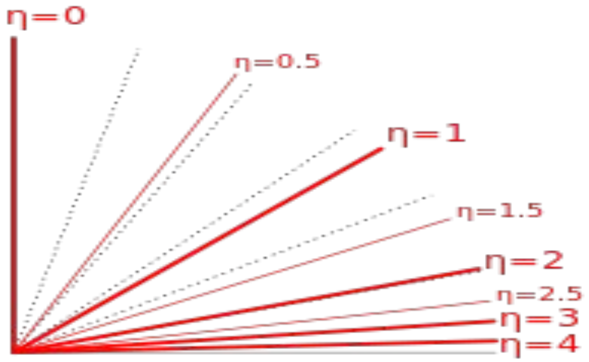
$$y \equiv \frac{1}{2} \ln \left(\frac{E + p_{\mathrm{L}}}{E - p_{\mathrm{L}}} \right)$$

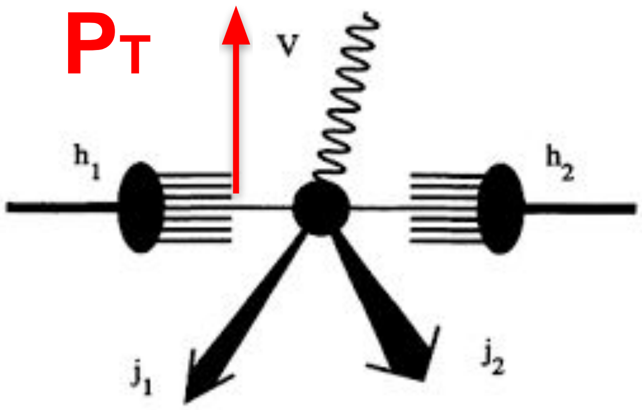
$$\eta = \frac{1}{2} \ln \left(\frac{|\mathbf{p}| + p_{\mathrm{L}}}{|\mathbf{p}| - p_{\mathrm{L}}} \right) = \quad - \ln \left[\tan \left(\frac{\theta}{2} \right) \right]$$

$$p_{\mathrm{T}} \equiv \sqrt{p_x^2 + p_y^2}$$

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

Lorentz Invariant Distance





LHC typical:

PT>20-30GeV

$|\eta|$<2.5, 4.7

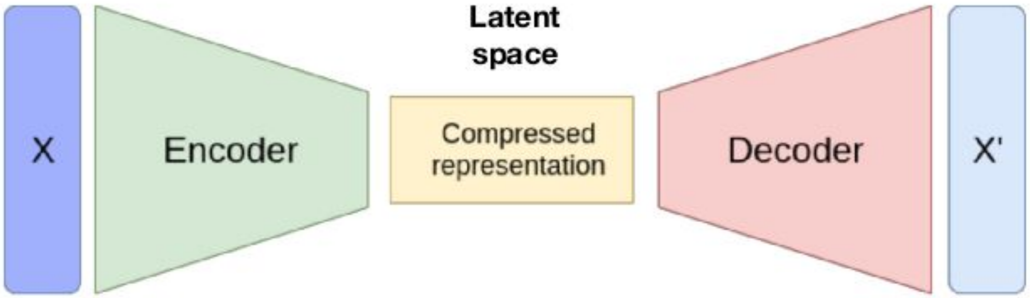
$\Delta R > 0.3, 0.4, 0.5, 0.7, 0.8$

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

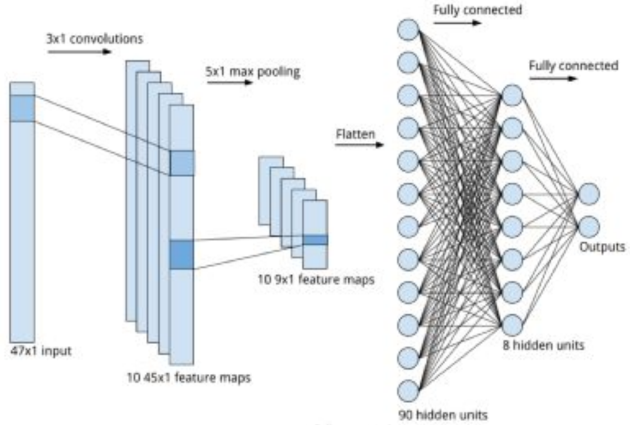
- *Autoencoders are essential tools for unsupervised studies*

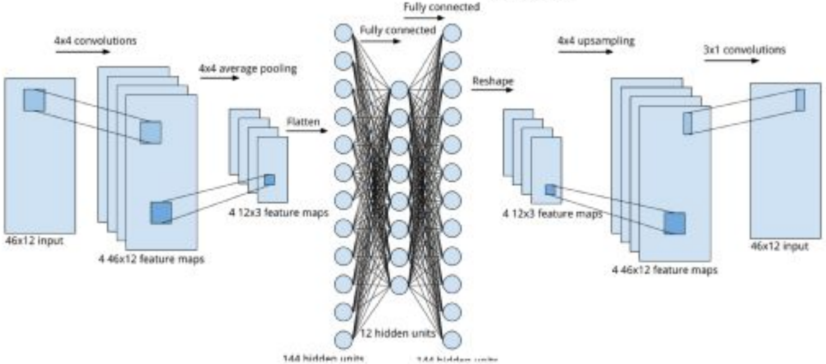


自编码：数据监控

- *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