对撞机物理实验

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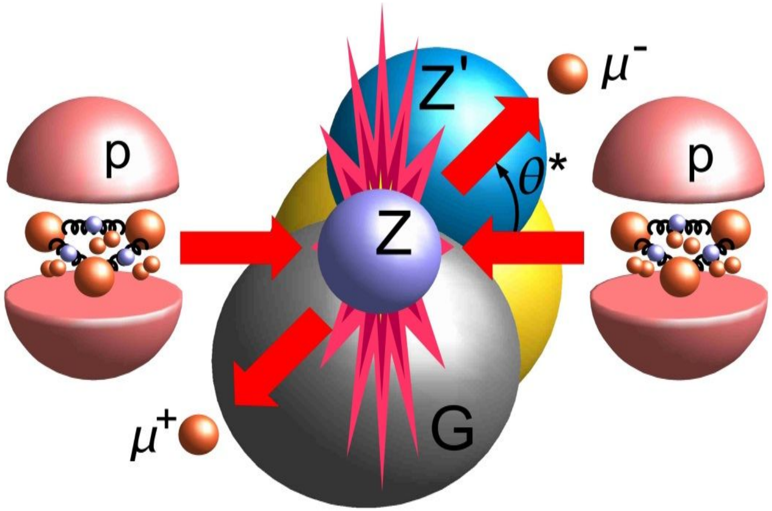
1. 前言
2. 高能物理简介
3. 大型强子对撞机(LHC)
4. Higgs的发现
5. 中国未来对撞机(CEPC)
6. 其他对撞机
7. 高能物理中的机器学习
8. 总结与展望



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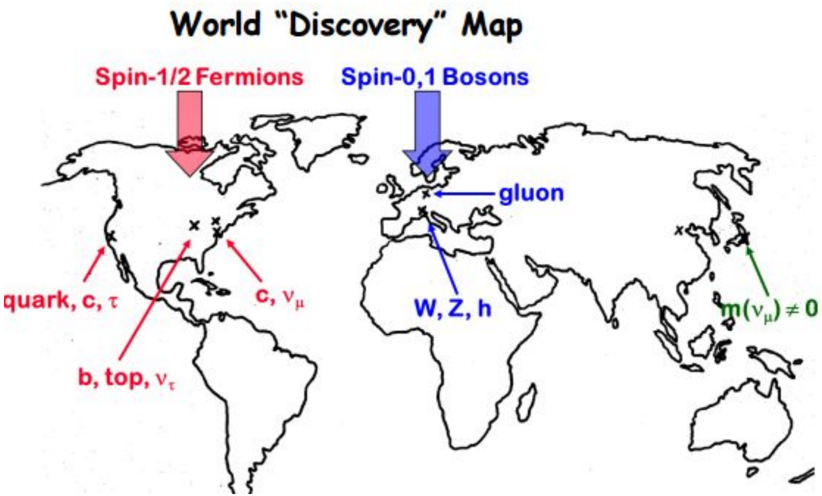
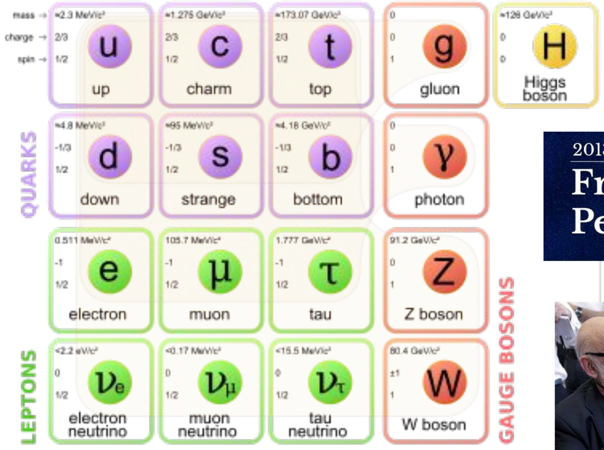
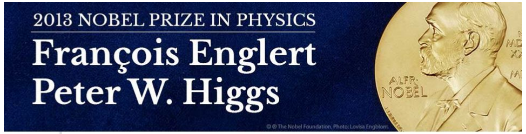
高能物理简介







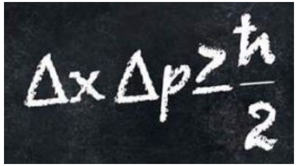
8 October 2013

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

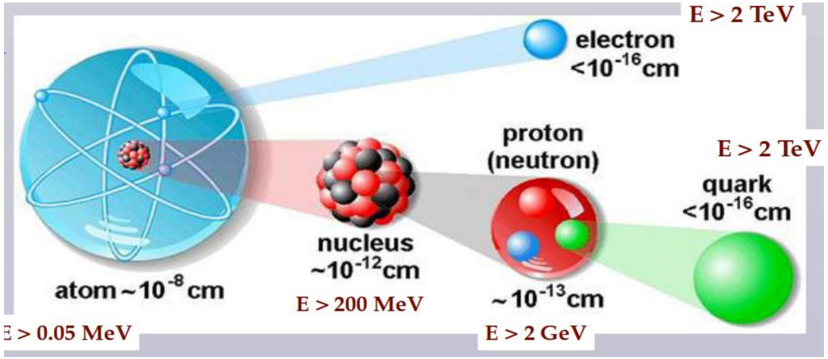
François Englert and Peter Higgs

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

小尺度，
大能量



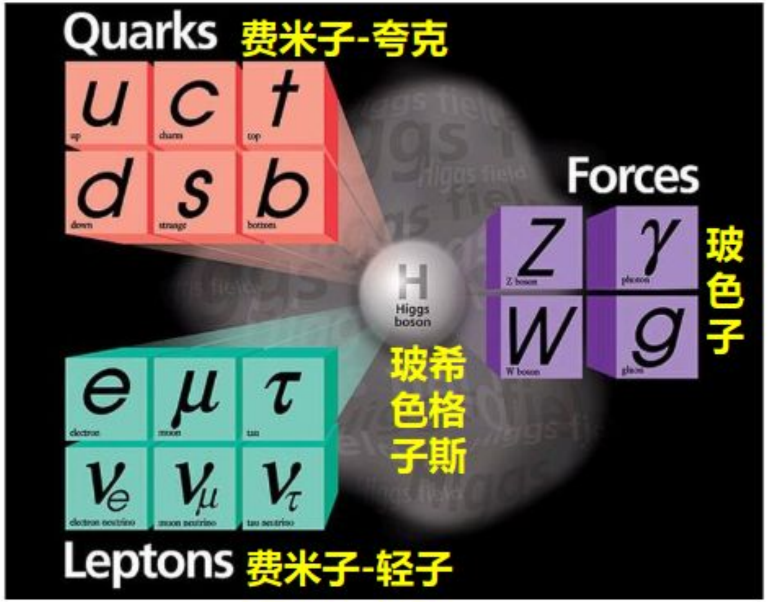
$$(1\ \mathrm{GeV})^{-1} = 0.2\ \mathrm{fm} = 0.2\ 10^{-15}\ \mathrm{m}$$



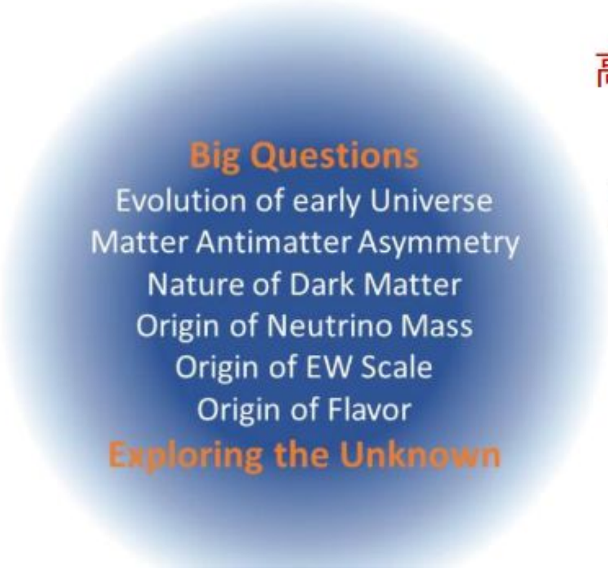
探索深层次物质规律

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、

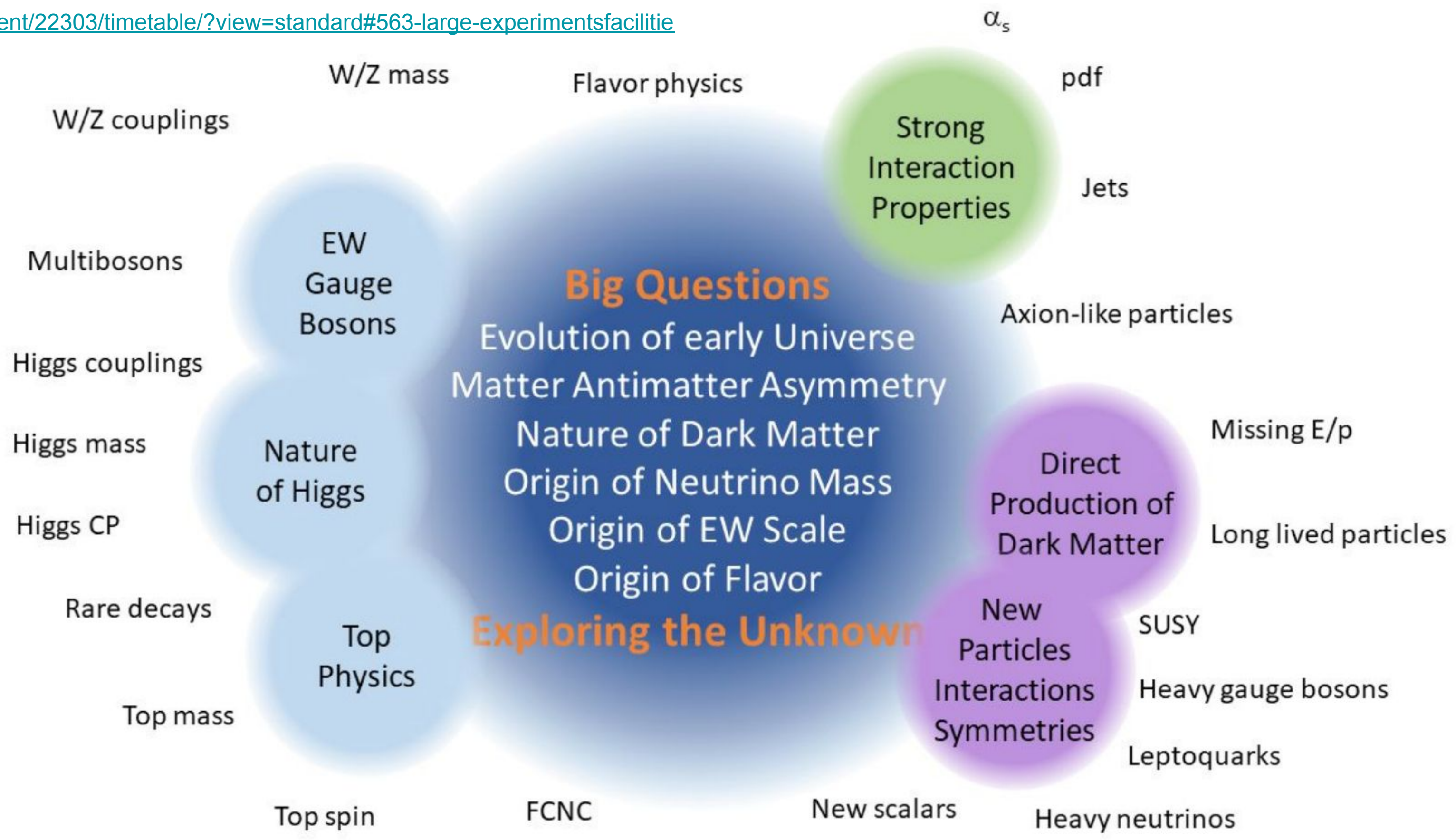
中微子质量起源、

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



U.S. Particle Physics

About Particle Physics | Resources for Physicists | Particle Physics in the United States | 2023 P5

2023 P5

P5 (Particle Physics Projects Prioritization Panel) reports to HEPAP (High-Energy Physics Advisory Panel) that advises High-Energy Physics of DOE Office of Science and Division of Physics of NSF. We will build on the "Snowmass" community study to hash out priorities for the next 10 years within 20-year context.

U.S. DEPARTMENT OF ENERGY | Office of Science

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Home | Programs | High Energy Physics (HEP) | Research | Snowmass / P5 Planning Process

About

Research

Science Drivers of Particle Physics

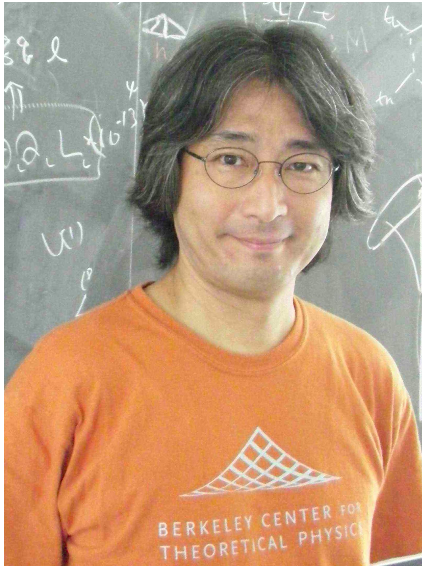
Energy Frontier

Snowmass / P5 Planning Process

The high energy physics research community is currently engaged in developing a ten-year plan for U.S. particle physics. The goal of this planning process is to identify the most compelling scientific opportunities at the Energy, Intensity, and Cosmic Frontiers, and to identify those technologies required for frontier research. This multi-step process requires broad input from all members of the community.

https://www.symmetrymagazine.org/article/hitoshi-murayama-brings-people-together?language_content_entity=und
https://indico.fnal.gov/event/22303/timetable/?view=standard#833-my-personal-experience

Hitoshi Murayama brings people together



Leaving his rock star dreams behind, Murayama rekindled his love of physics as he studied for graduate school entrance exams. He applied to study particle physics at the University of Tokyo.

Murayama was especially excited about studying aspects of particle physics that could be observed and tested through experimentation. But once he arrived at University of Tokyo, he soon realized his research interests didn't align with those around him. "Everybody in grad school was studying string theory except me," he says. "I felt very isolated."

He was considering quitting when a visiting scientist gave him new hope. Kaoru Hagiwara, a physicist from the High Energy Accelerator Research Organization, or KEK, in Tsukuba, Japan, delivered a series of lectures on subatomic particle research. Murayama was hooked. "I asked him right away–I begged him–to work with me," Murayama says.

Hagiwara said he couldn't teach until he returned from a two-year sabbatical in the UK. For the next two years, Murayama continued through his graduate program, studying condensed-matter physics and superconductors and clinging to the hope that Hagiwara would return and mentor him through the end of his doctorate research.

电磁学内容

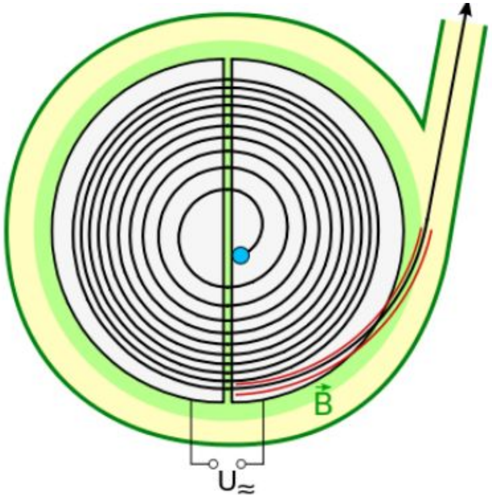
The Nobel Prize in Physics 1939

Photo from the Nobel Foundation archive.

Ernest Orlando Lawrence

Prize share: 1/1

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



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

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

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

考虑相对论效应，粒子质量及回旋周期都会随速度增大而增大

同步加速器：变化磁场

同步回旋加速器：改变交变电压频率

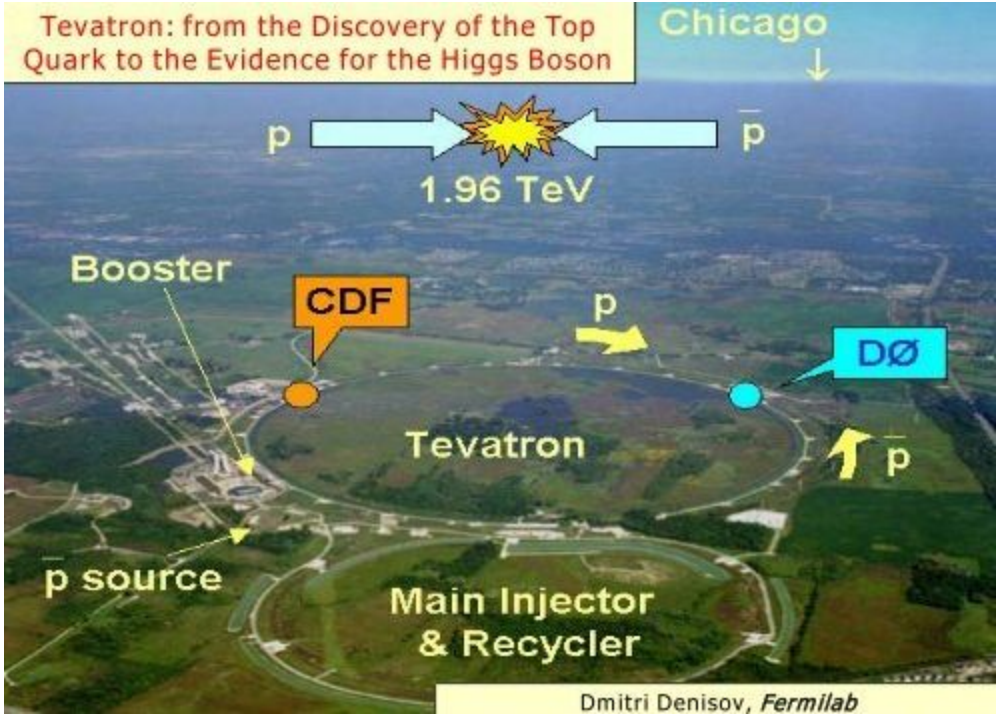
$$E = \gamma M c^2$$

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

Synchrotron

对撞机:过去、现在及未来

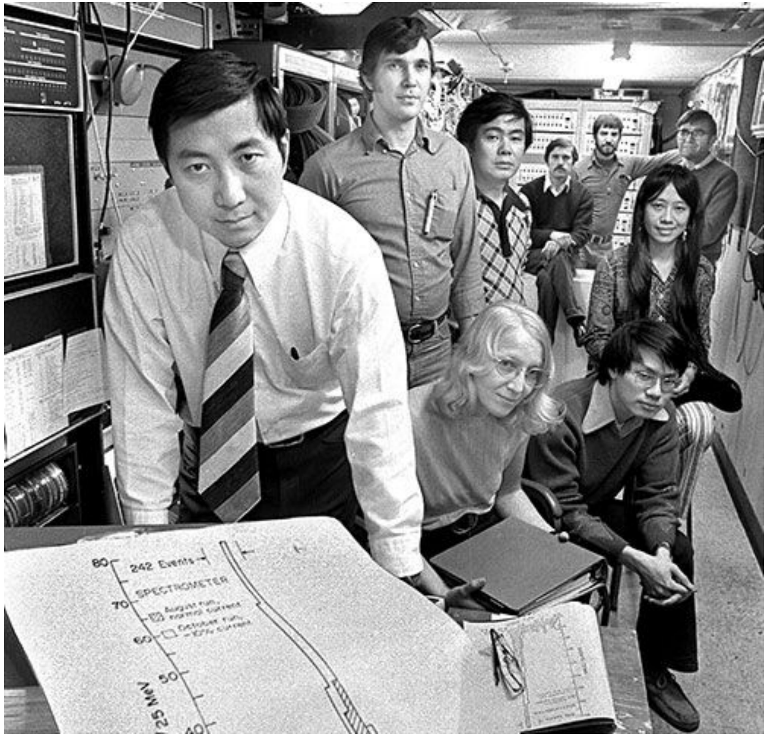
CERN Super Proton Synchrotron
正负质子对撞
1983年1月25日 宣布发现W玻色子

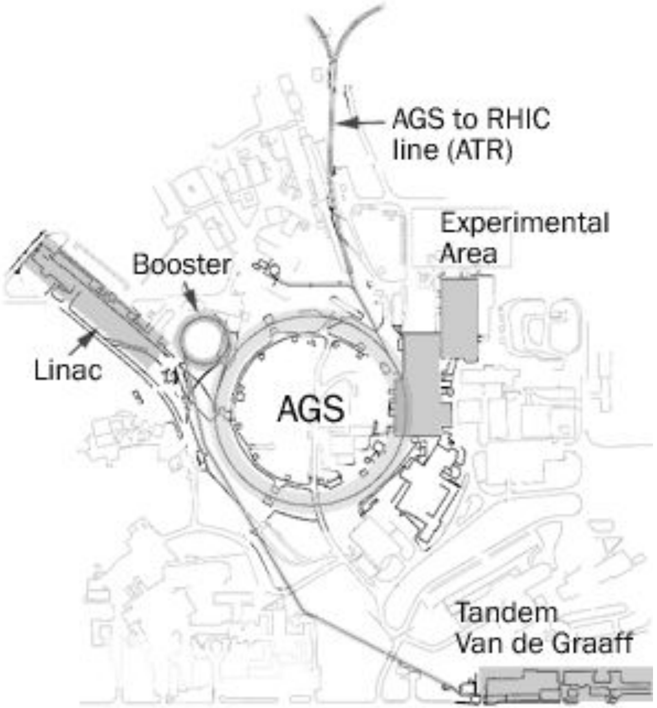


美国Tevatron 1992-2011 正负质子对撞
1995年发现Top夸克

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

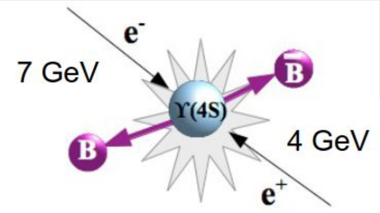
对撞机:过去、现在及未来





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

对撞机:过去、现在及未来



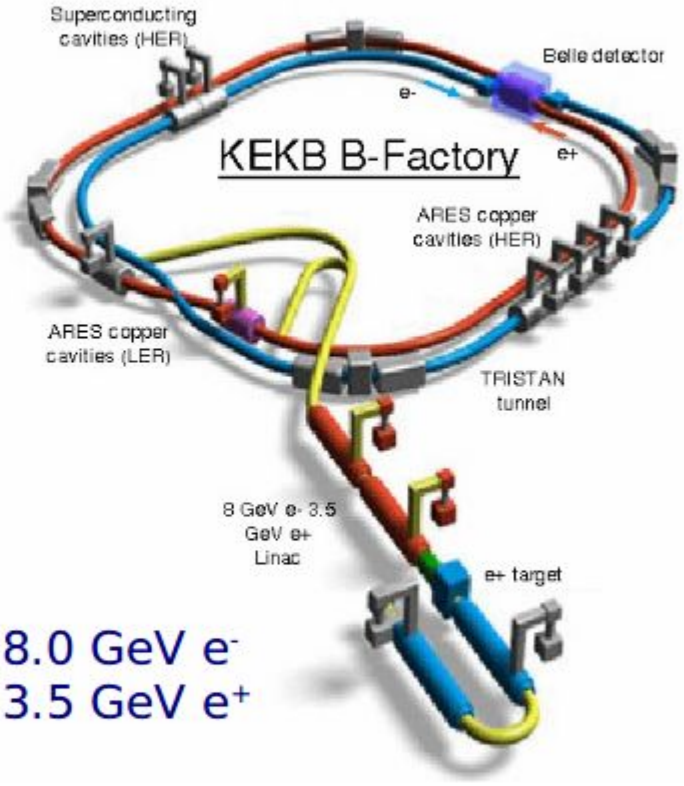
现役对撞机

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

sqrt(112)~=10.58GeV

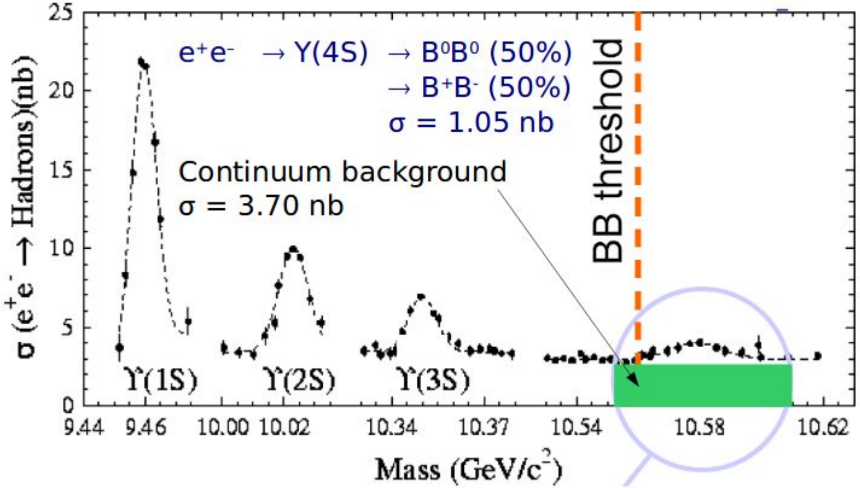
Accelerator	Centre, city, country	First operation	accelerated particles	max energy per beam, GeV	Luminosity, 10^{30} cm^{-2} s^{-1}	Perimeter (length), km
VEPP-2000	INP, Novosibirsk, Russia	2006	e^+e^-	1.0	100	0.024
VEPP-4M	INP, Novosibirsk, Russia	1994	e^+e^-	6	20	0.366
BEPC II	IHEP, Beijing, China	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



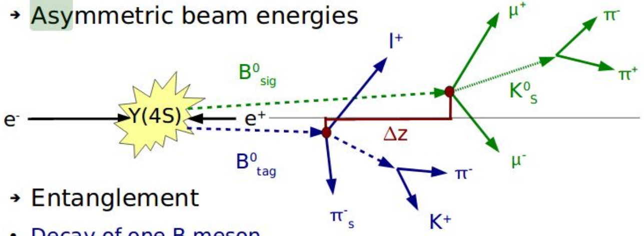
8.0 GeV e^-
3.5 GeV e^+

日本 筑波



Measurement of time-dep. CP Violation

- Asymmetric beam energies



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

对撞机:过去、现在及未来

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

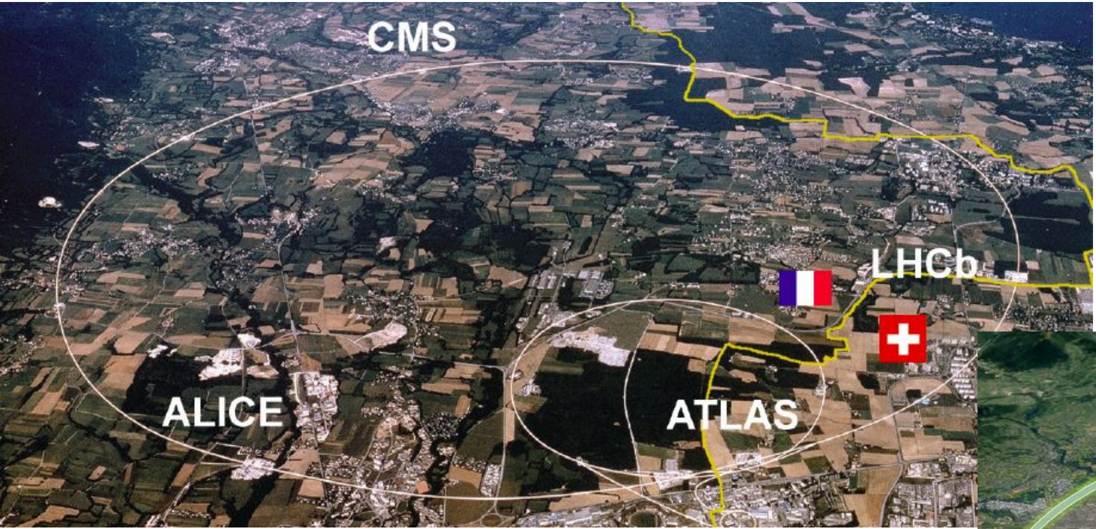
北京谱仪国际合作组发现四夸克物质Zc(3900)入选2013年物理学重要成果

Four-Quark Matter

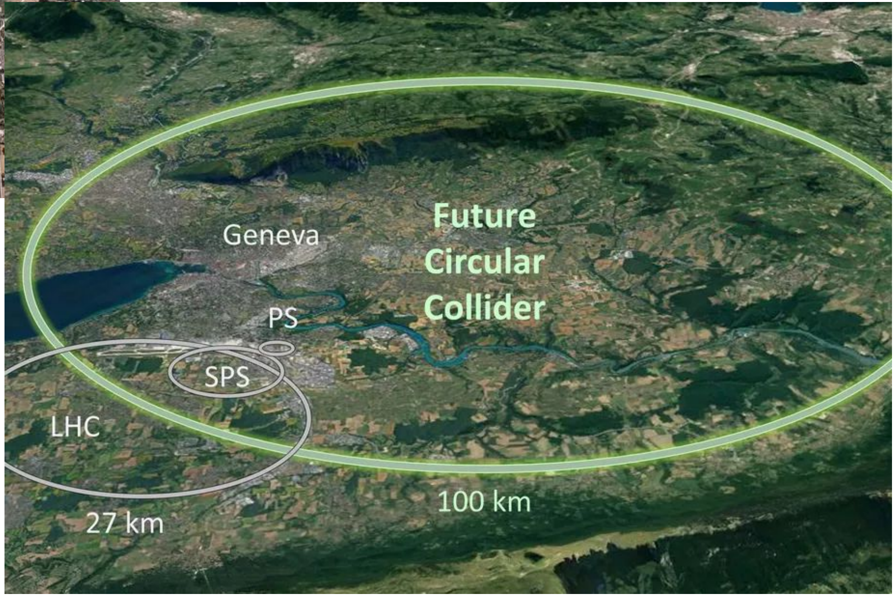
Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a **mysterious particle** that appeared to contain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

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

对撞机:过去、现在及未来



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



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。

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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

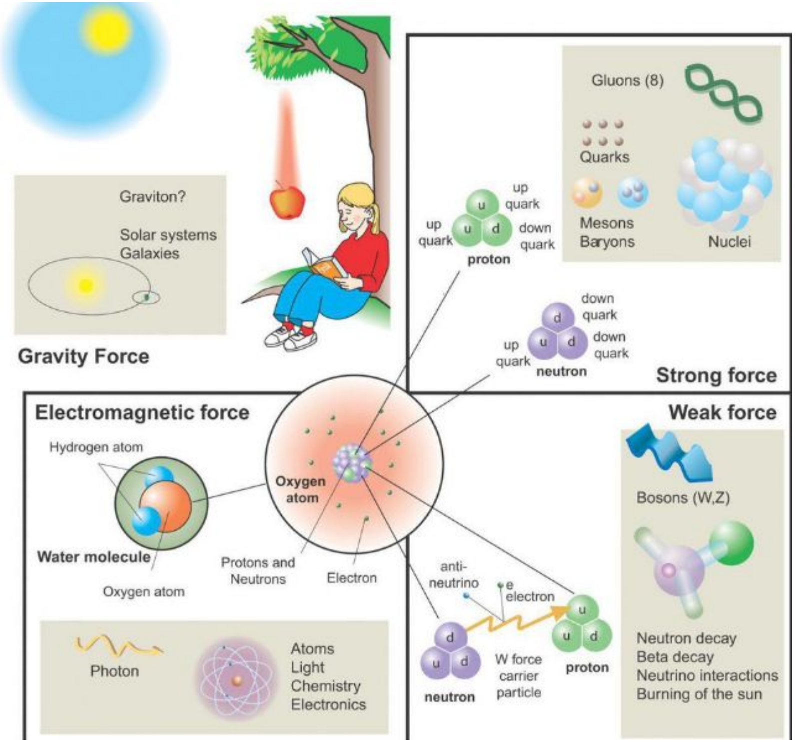
Chen Ning Yang

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

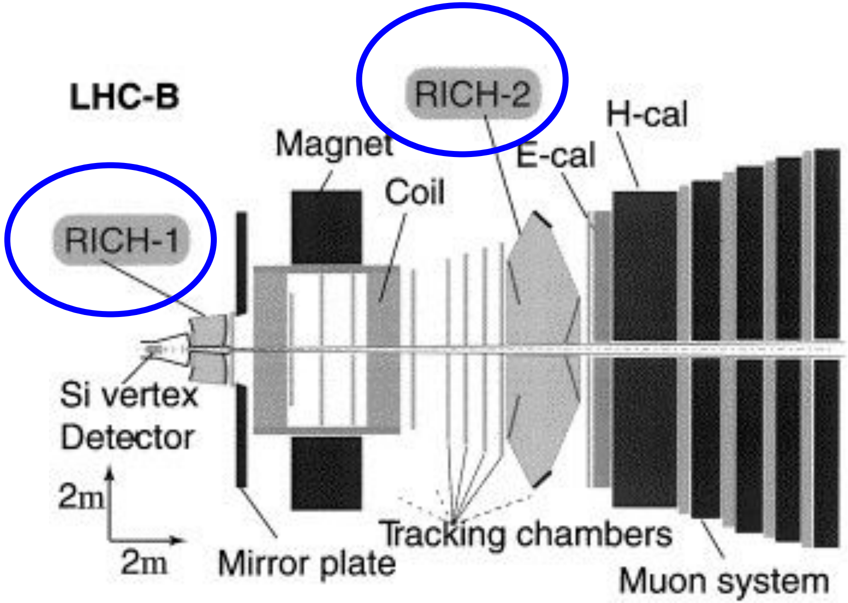
Il´ja Mikhailovich Frank

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"*.

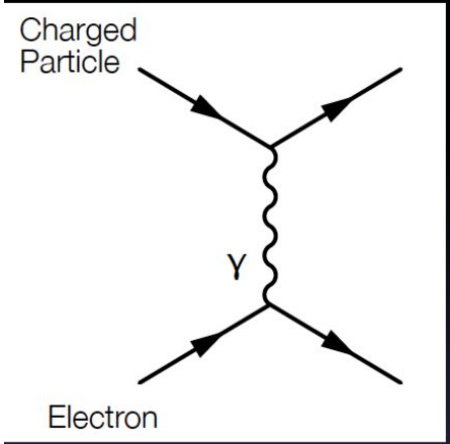


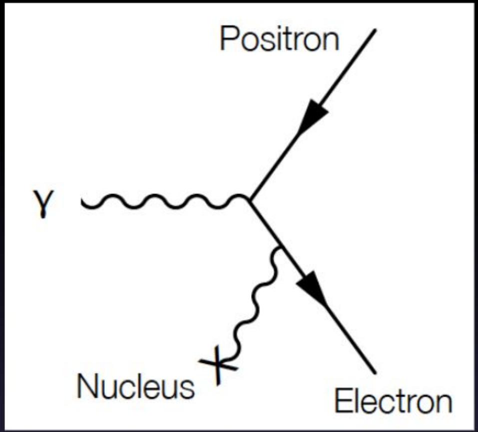
When a charged particle travels faster than light does through a given medium, it emits Cherenkov radiation at an angle that depends on its velocity. The particle's velocity can be calculated from this angle. Velocity can then be combined with a measure of the particle's momentum to determine its mass,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

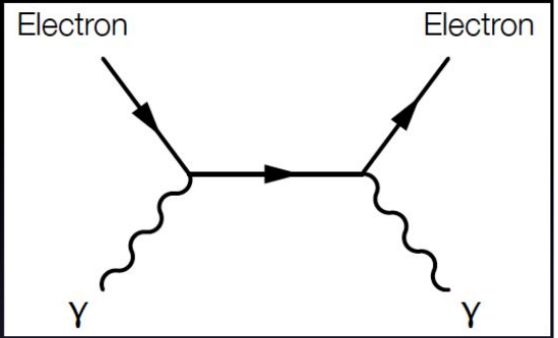
https://indico.cern.ch/event/387976/attachments/1124401/1605557/daniela_l2.pdf

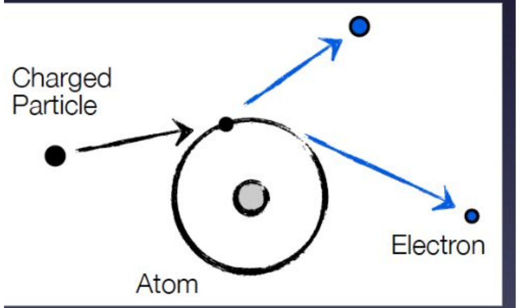
Example of particle interactions

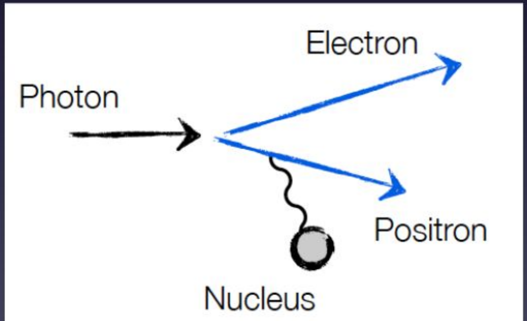
- Ionization
- Pair production
- Compton scattering

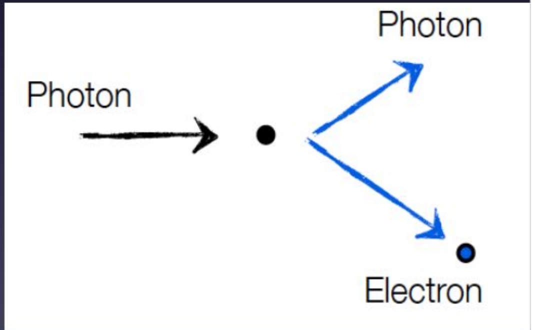






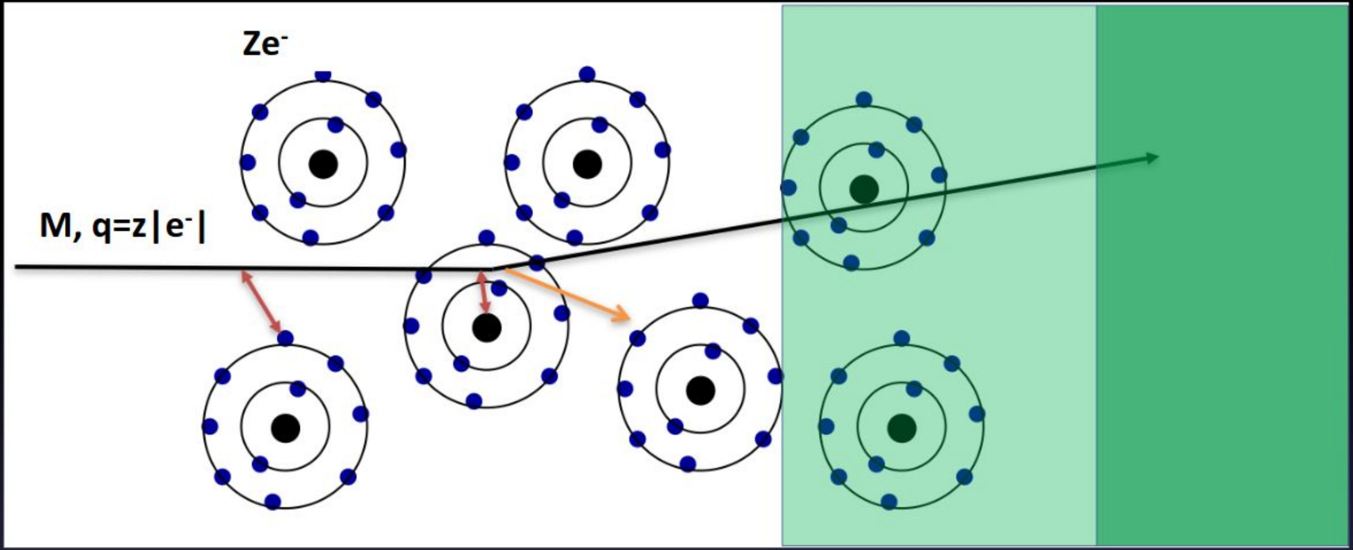






https://indico.cern.ch/event/387976/attachments/1124401/1605557/daniela_l2.pdf

EM interaction of charged particles with matter



Interaction with the atomic electrons. Incoming particles lose energy and atoms are excited or ionized.

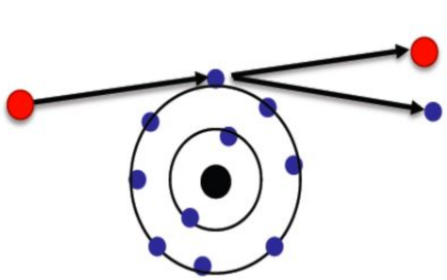
Interaction with the atomic nucleus. Particles are deflected and a Bremsstrahlung photon can be emitted.

If the particle's velocity is > the velocity of light in the medium → Cherenkov Radiation.
When a particle crosses the boundary between two media, there is a probability ≈1% to produce an X ray photon

https://indico.cern.ch/event/387976/attachments/1124401/1605557/daniela_l2.pdf https://people.phys.ethz.ch/~mdonega/slides/passageOfParticlesThroughMatter.pdf

Energy Loss by Ionization

- Assume: $Mc^2 \gg m_e c^2$ (calculation for electrons and muons are more complex)
- Interaction is dominated by elastic collisions with electrons
  - The trajectory of the charged particle is unchanged after scattering
- Energy is transferred to the electrons

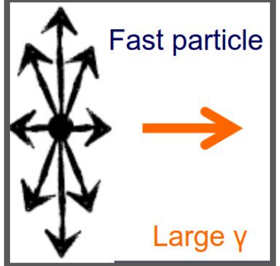


$$\Delta p_{\perp} = \int F_{\perp} dt = \int F_{\perp} \frac{dt}{dx} dx = \int F_{\perp} \frac{dx}{v}$$

Energy loss (- sign)

Bethe-Bloch Formula

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



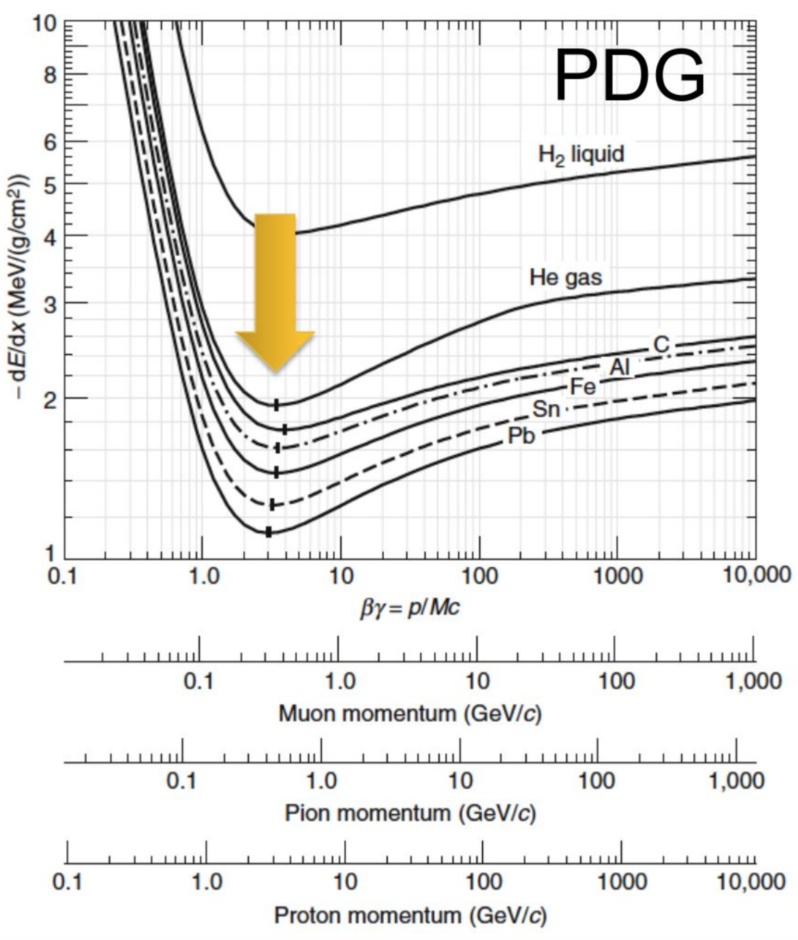
Classical derivation in backup slides agrees with QM within a factor of 2

$\propto 1/\beta^2 \cdot \ln(\text{const} \cdot \beta^2\gamma^2)$

https://indico.cern.ch/event/387976/attachments/1124401/1605557/daniela_l2.pdf https://people.phys.ethz.ch/~mdonega/slides/passageOfParticlesThroughMatter.pdf

The Bethe-Bloch Formula

- Common features:
  - fast growth, as $1/\beta^2$, at low energy
  - wide minimum in the range $3 \leq \beta\gamma \leq 4$,
  - slow increase at high $\beta\gamma$.
- A particle with dE/dx near the minimum is a minimum-ionizing particle or mip.
- The mip's ionization losses for all materials except hydrogen are in the range 1-2 MeV/(g/cm²)
  - increasing from large to low Z of the absorber.



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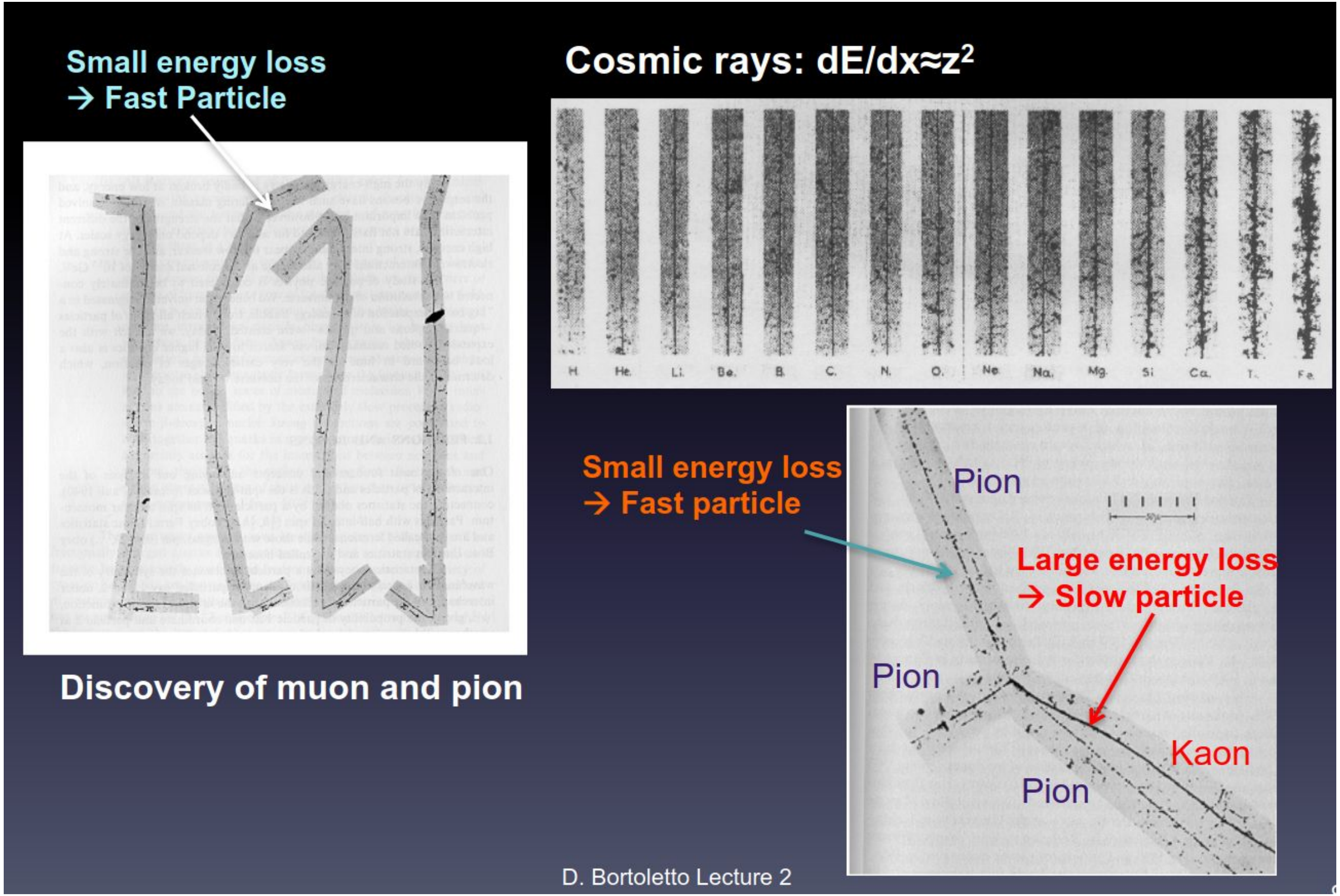


Jungfraujoch

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

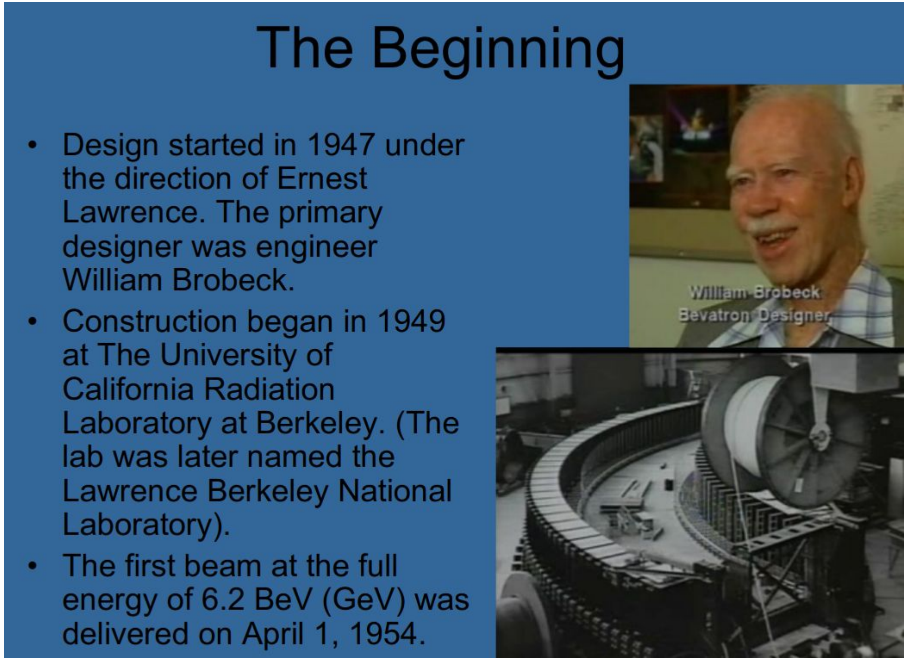
Owen Chamberlain
Prize share: 1/2

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

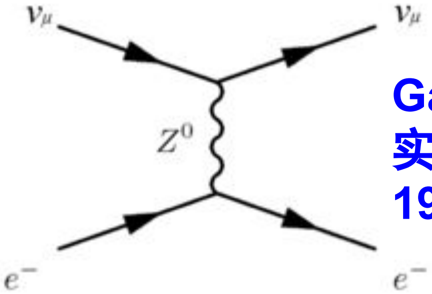
气泡室：弱中性流

Donald Arthur Glaser

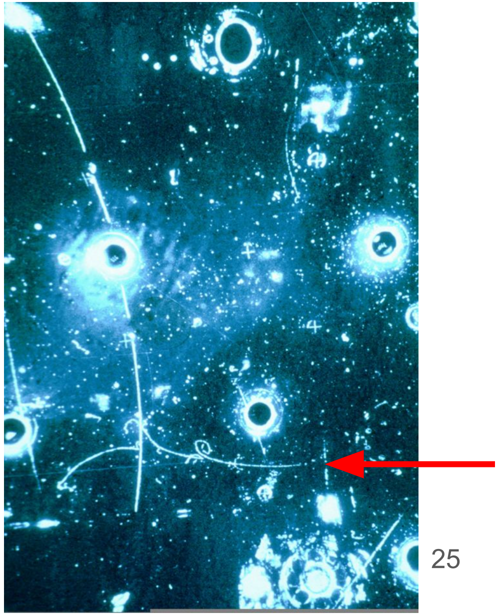
Prize share: 1/1

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



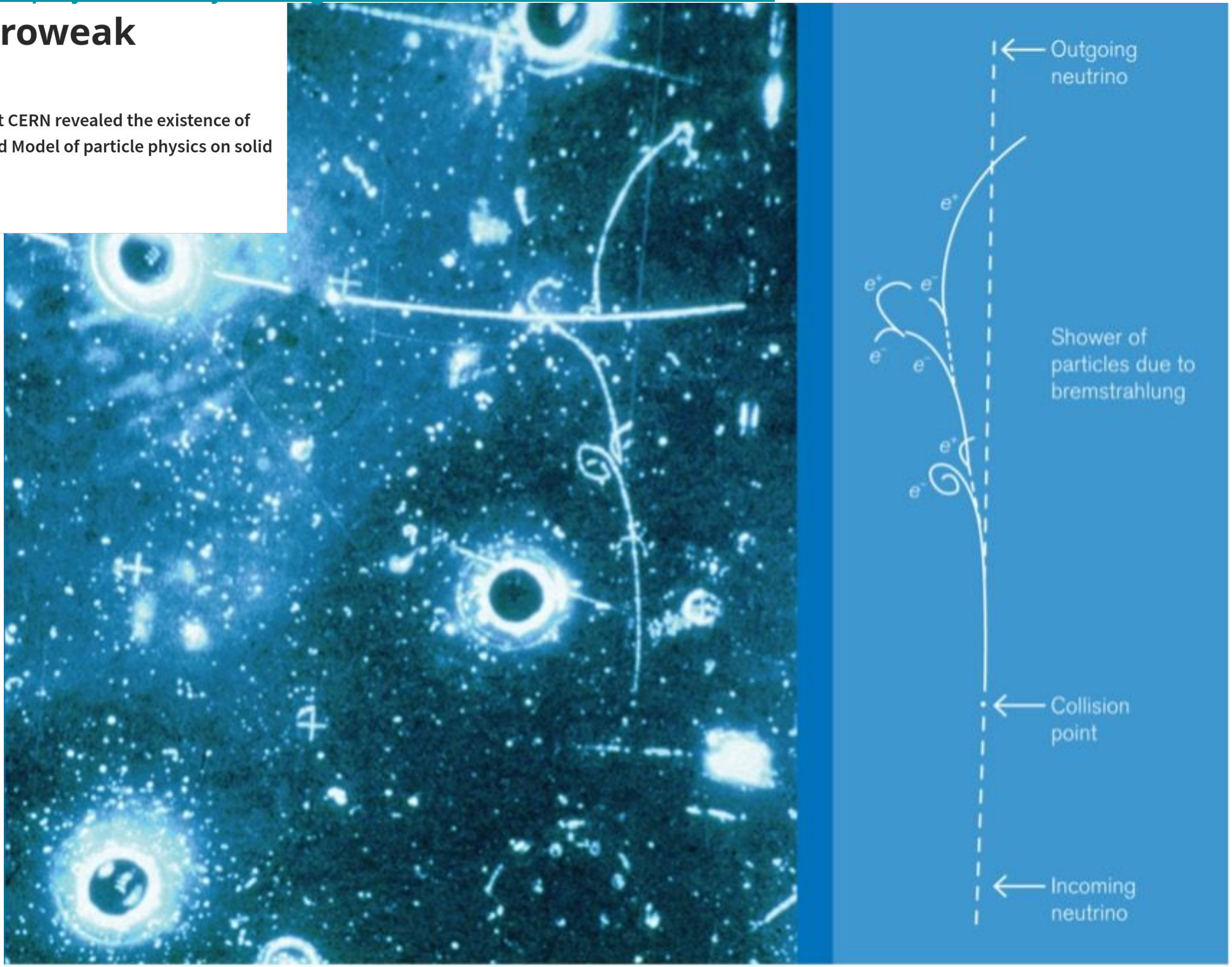
https://cerncourier.com/a/neutral-currents-a-perfect-experimental-discovery/

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



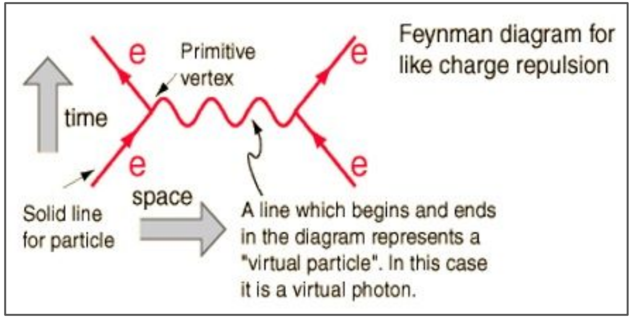
The Nobel Prize in Physics 1965

Sin-Itiro Tomonaga
Prize share: 1/3

Julian Schwinger
Prize share: 1/3

Richard P. Feynman
Prize share: 1/3

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



量子电动力学

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

电子磁矩

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

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

D. Hanneke, S. Fogwell, and G. Gabrielse*
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 4 January 2008; published 26 March 2008)

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

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

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

Rym Bouchendira,[1] Pierre Cladé,[1] Saïda Guellati-Khélifa,[2] François Nez,[1] and François Biraben[1]
[1] *Laboratoire Kastler Brossel, Ecole Normale Supérieure, Université Pierre et Marie Curie, CNRS, 4 place Jussieu, 75252 Paris Cedex 05, France*
[2] *Conservatoire National des Arts et Métiers, 292 rue Saint Martin, 75141 Paris Cedex 03, France*

We report a new measurement of the ratio $h/m_{\rm Rb}$ 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."

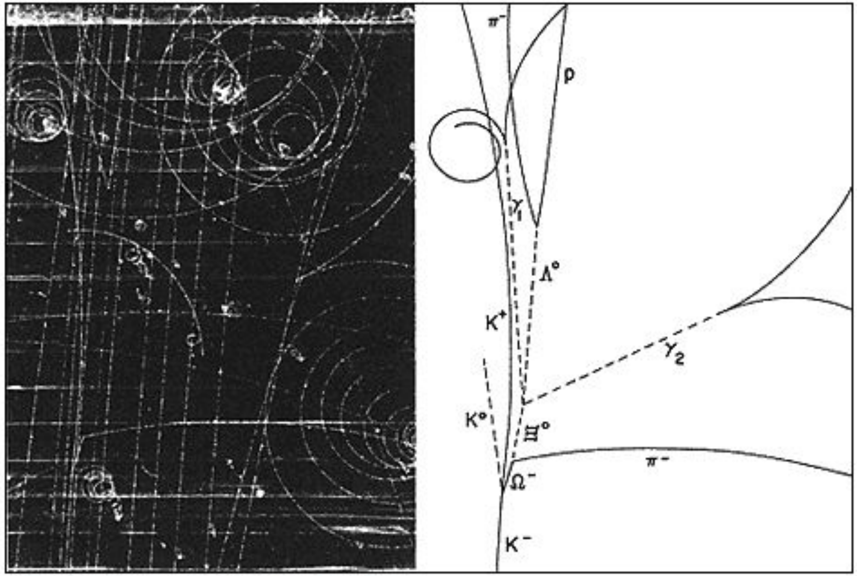
Particle	Symbol	Makeup	Rest mass MeV/c^2	Spin	B	S	Lifetime	Decay Modes
Omega	Ω^-	sss	1672	3/2	+1	-3	0.82 $\times 10^{-10}$	$\Xi^0\pi^-$, Λ^0K^-

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

盖尔曼 八重道

(The Eightfold Way)

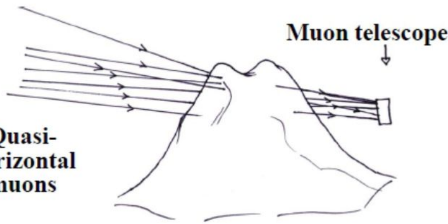
Brookhaven in 1964.

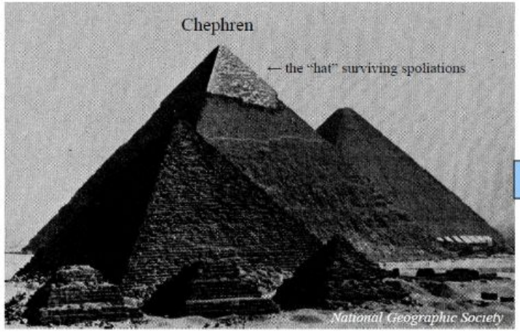


The bubble chamber picture of the first omega-minus. An incoming K- meson interacts with a proton in the liquid hydrogen of the bubble chamber and produces an

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

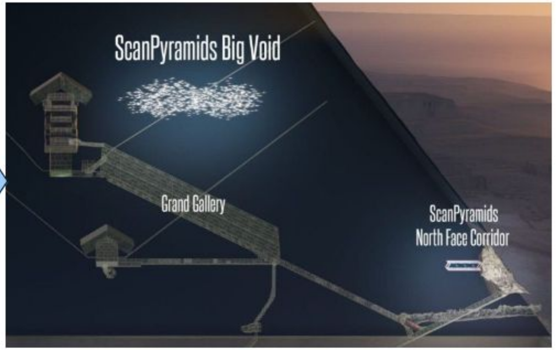
Fast-forward by 50 years





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...

30

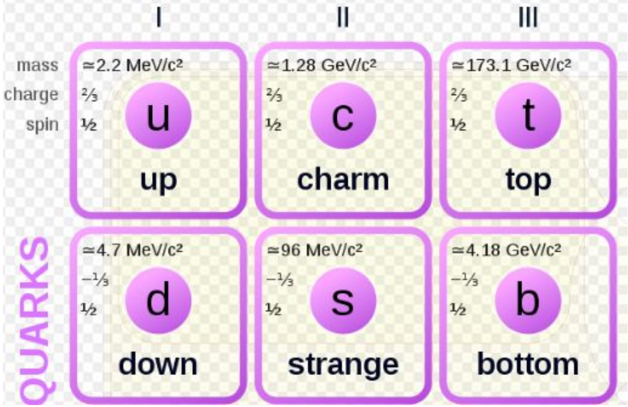
(But would have he been able to spot this void?)

The Nobel Prize in Physics 1969

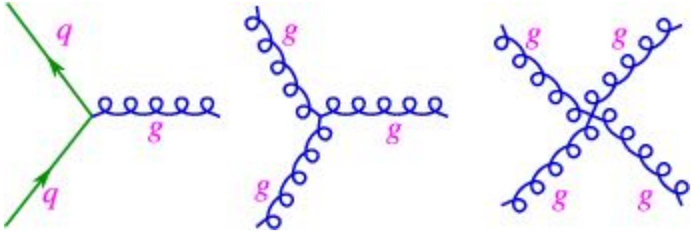
QCD，夸克

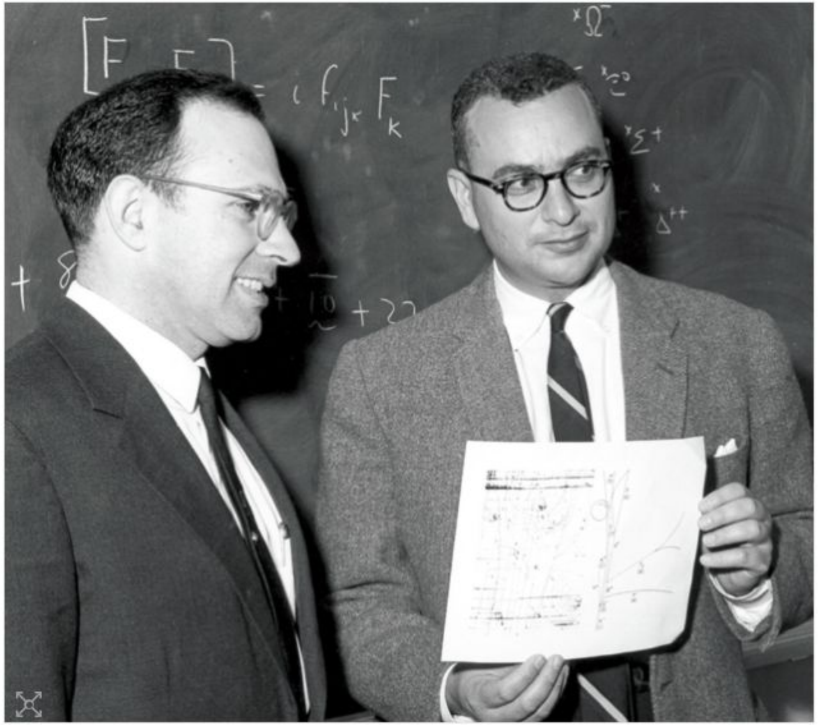
Murray Gell-Mann

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".*





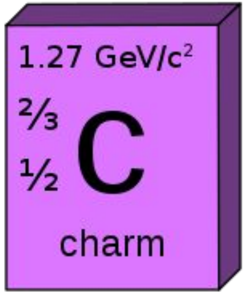
Triply strange Yuval Ne'eman (left) and Gell-Mann in March 1964, holding a copy of the event display that proved the existence of the Ω^- baryon that was predicted by Gell-Mann's "eightfold way". Credit: Courtesy of the Archives, California Institute of Technology.

The Nobel Prize in Physics 1976

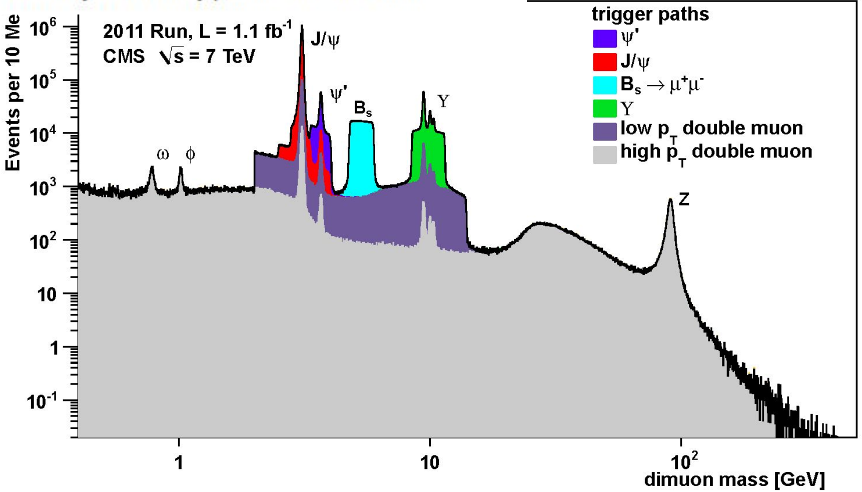
J/ψ，粲夸克

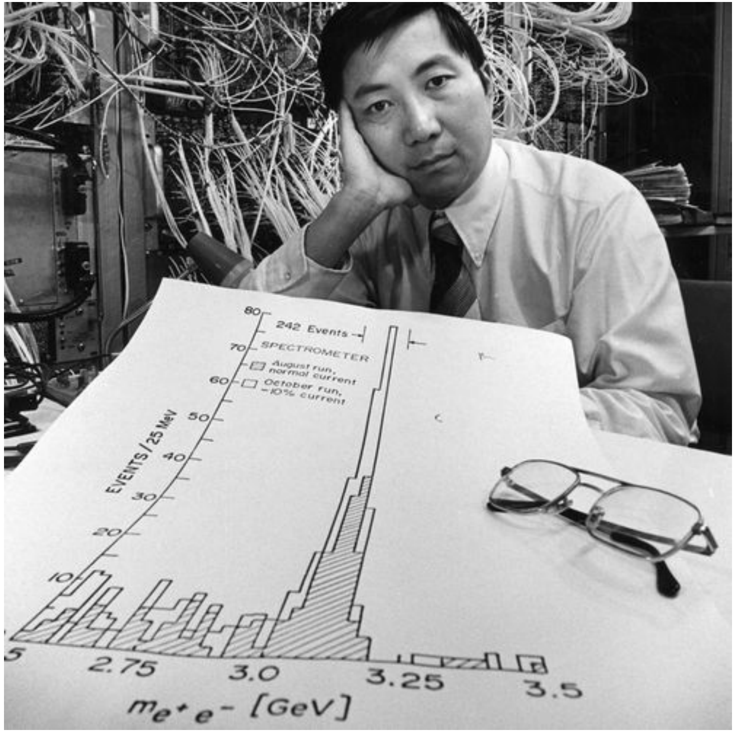
Burton Richter
Prize share: 1/2

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.

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

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

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

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

θ_W Weak Mixing Angle

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

标准模型 Standard Model

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

The Nobel Prize in Physics 1984

W, Z玻色子

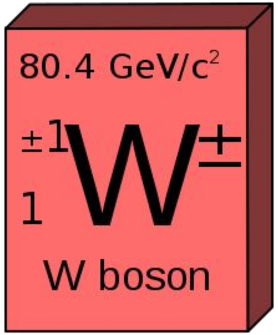
Carlo Rubbia

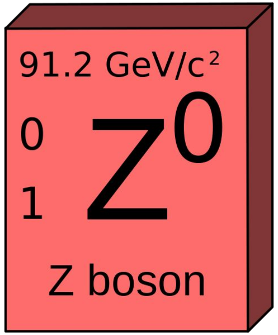
Prize share: 1/2

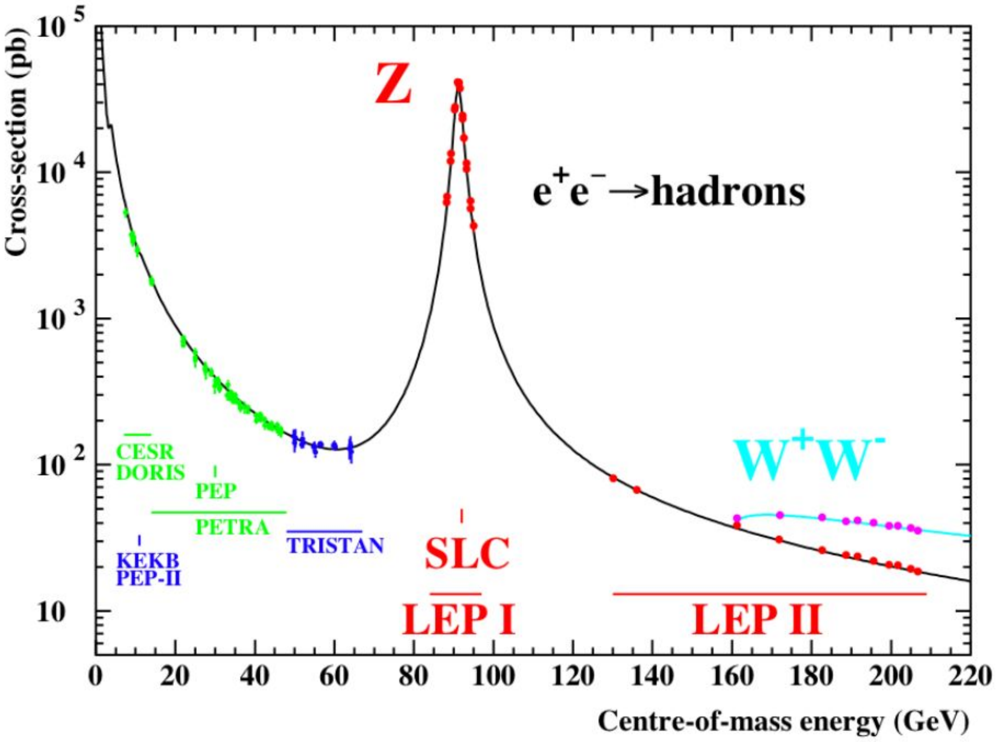
Simon van der Meer

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"*







缪子中微子

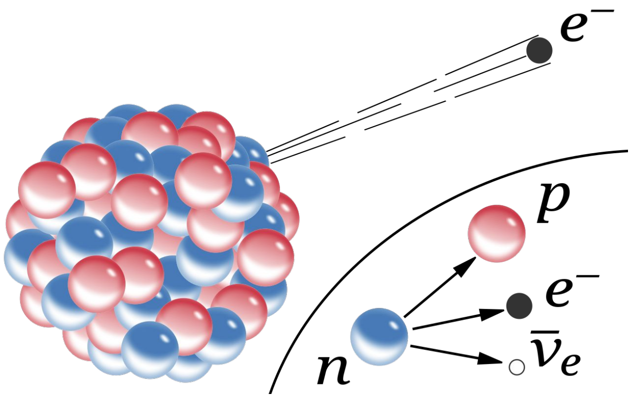
The Nobel Prize in Physics 1988

Leon M. Lederman
Prize share: 1/3

Melvin Schwartz
Prize share: 1/3

Jack Steinberger
Prize share: 1/3

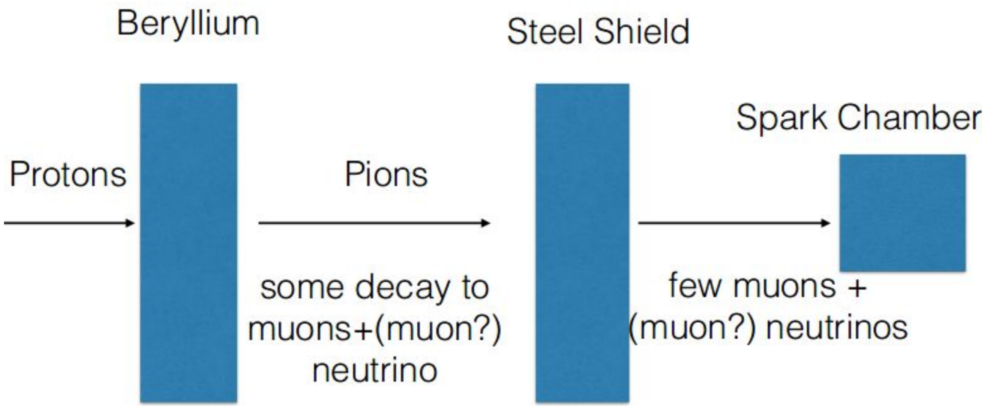
The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz and Jack Steinberger *"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino".*



Pauli, Nobel Prize portrait

1930
Pauli
预言
中微子

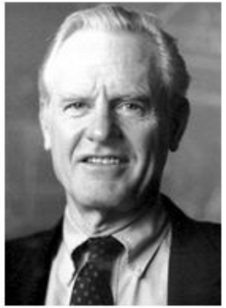
The AGS Neutrino Experiment at Brookhaven, 1962



The Nobel Prize in Physics 1990

深度非弹，夸克模型

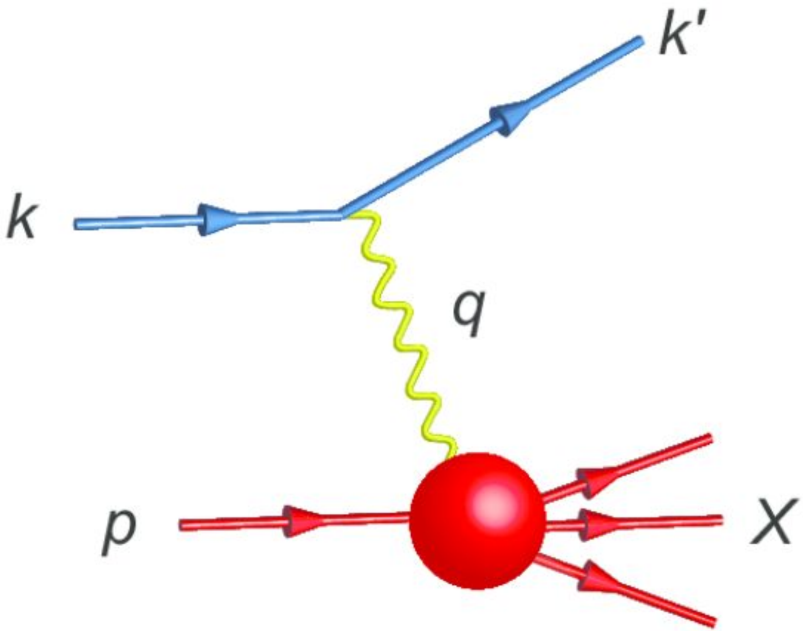
Jerome I. Friedman
Prize share: 1/3



Henry W. Kendall
Prize share: 1/3

Photo: T. Nakashima
Richard E. Taylor
Prize share: 1/3

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



电子、质子碰撞

The Nobel Prize in Physics 1992

多丝正比室

Drift Tube, Time Projection Chamber

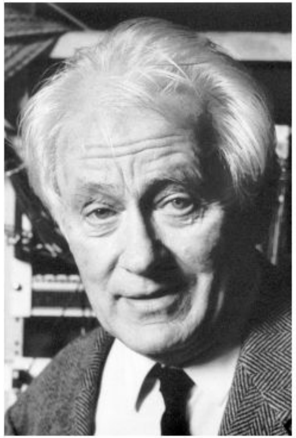
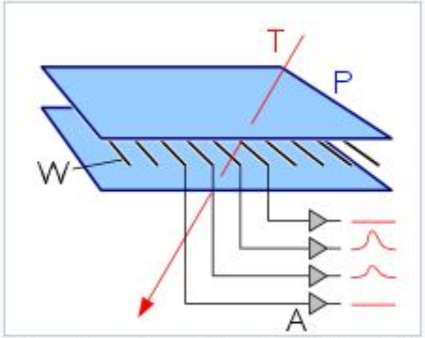


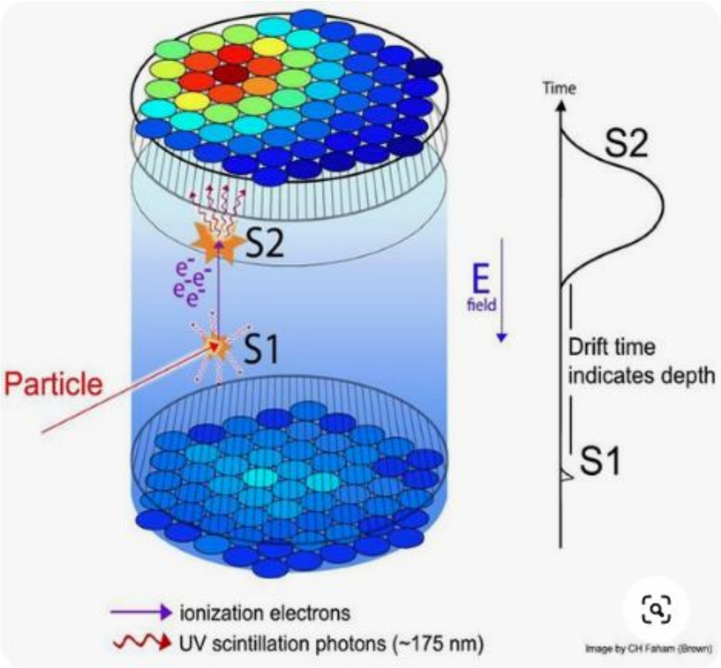
Photo from the Nobel Foundation archive.

Georges Charpak

Prize share: 1/1



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



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

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

The Nobel Prize in Physics 1995

Tau轻子 1977

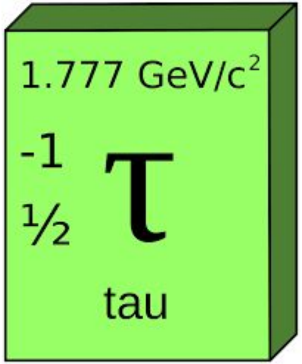
探测中微子 电子反中微子 1956

Martin L. Perl

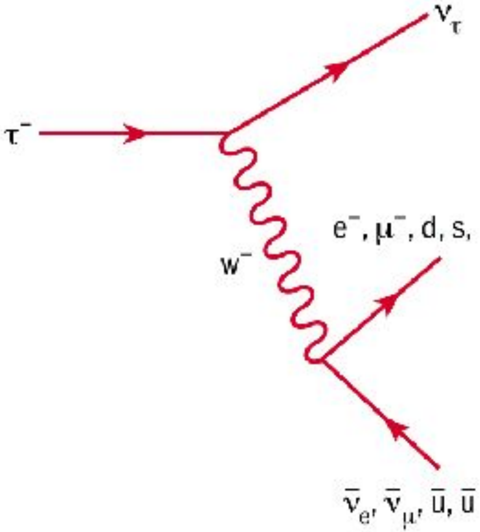
Prize share: 1/2

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"*.

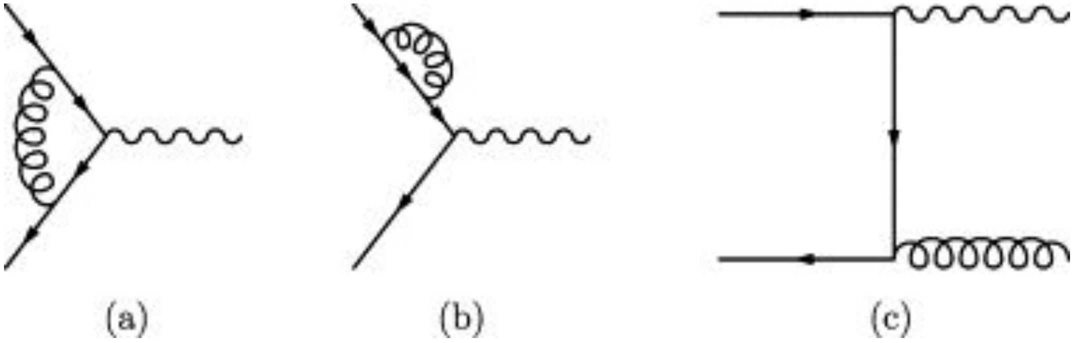
Stanford Positron Electron Asymmetric Rings, 1977.

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

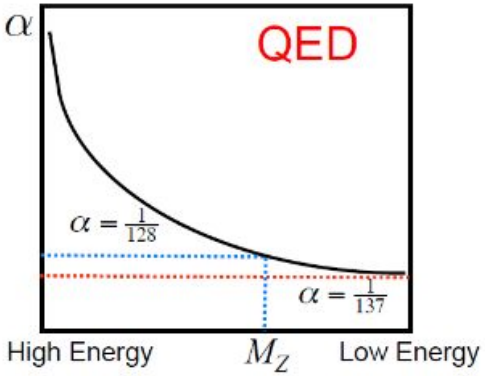
QCD渐进自由

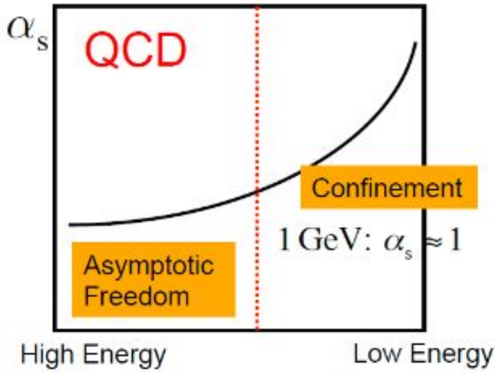
David J. Gross
Prize share: 1/3

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

对称性自发破缺
CKM, top夸克

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"*.

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

质量本征态 ！= 弱相互作用本征态

The Nobel Prize in Physics 2013

Higgs Boson

Photo: A. Mahmoud

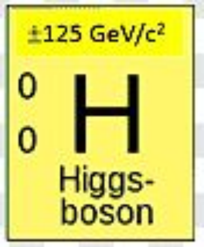
François Englert

Prize share: 1/2

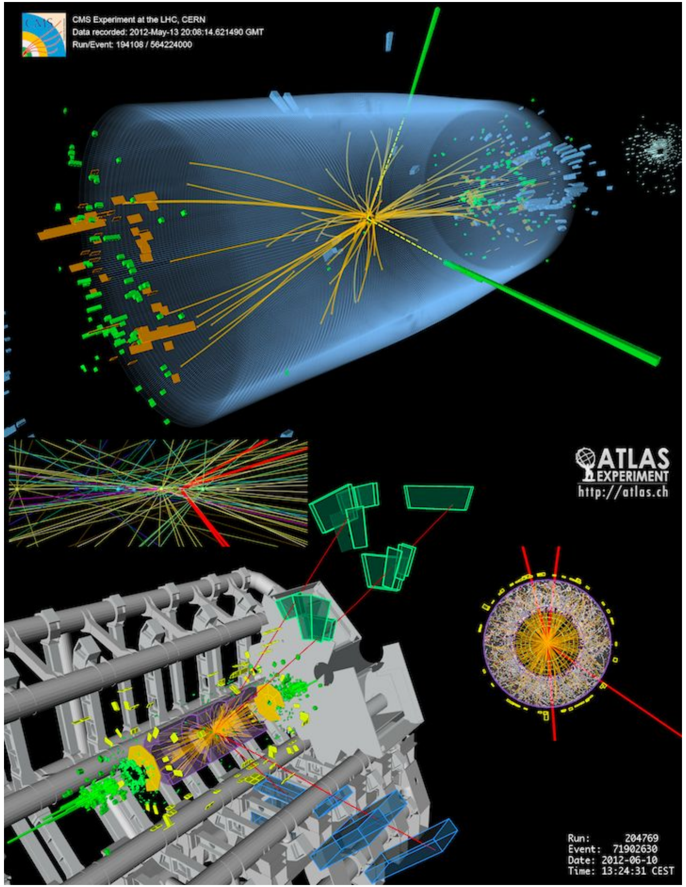
Photo: A. Mahmoud

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

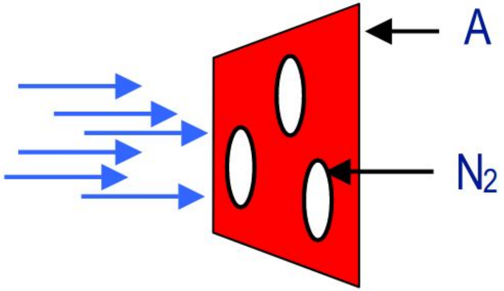
https://videos.cern.ch/

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

束流碰撞

What is luminosity?

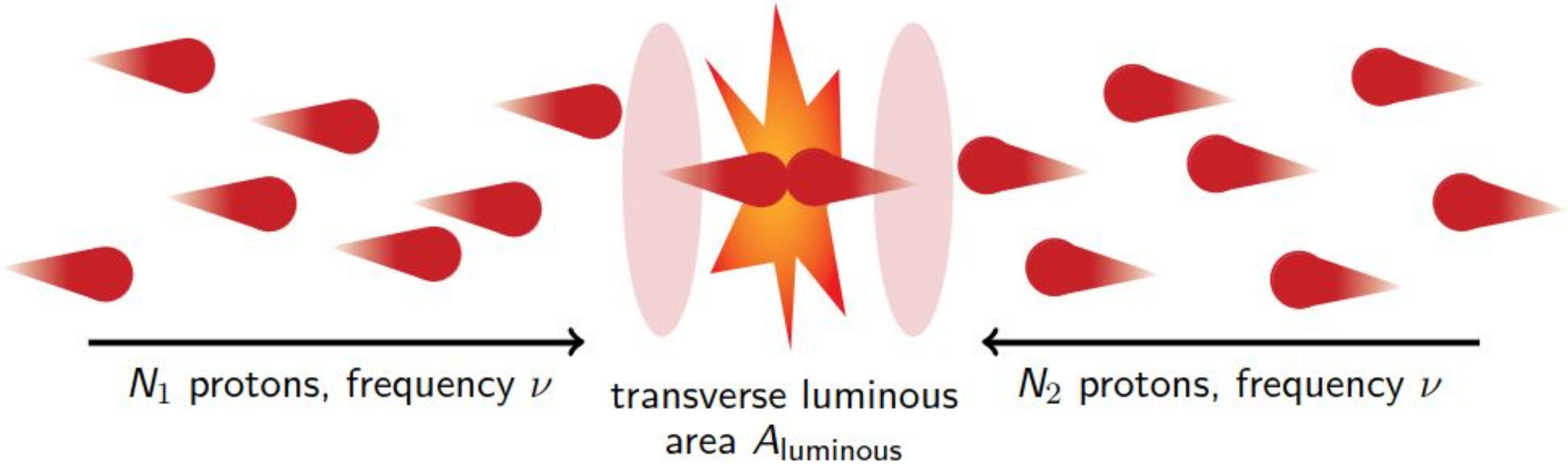
- measure of collision rate:

$$\frac{dN}{dt}(pp \to X) = \mathcal{L} \cdot \sigma(pp \to X)$$

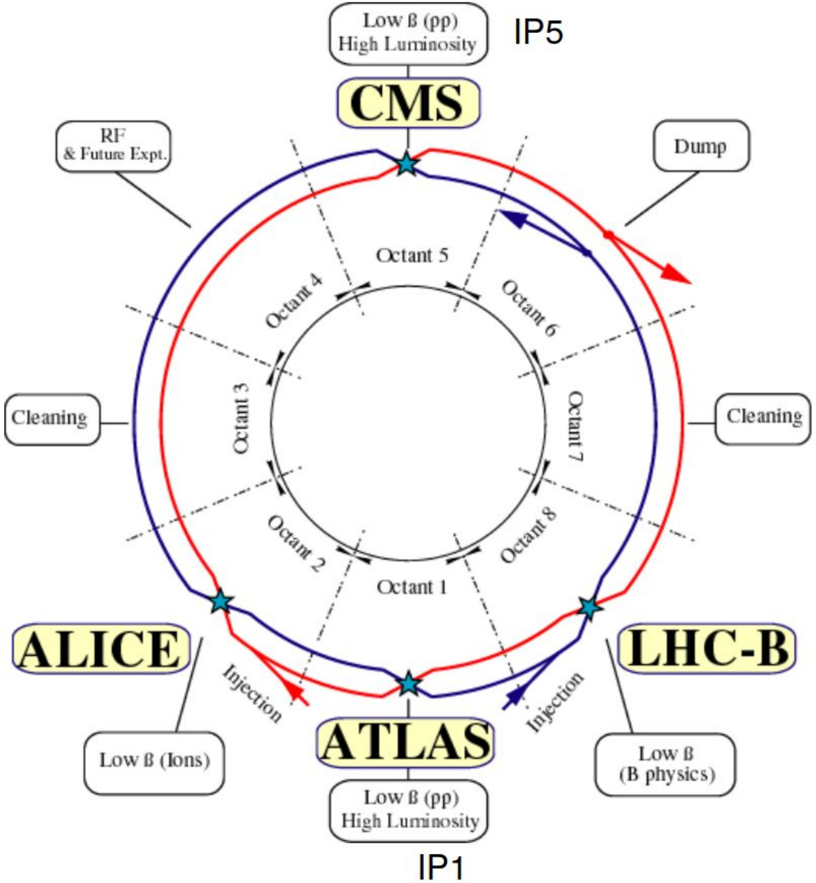
- luminosity from beam parameters:

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

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



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



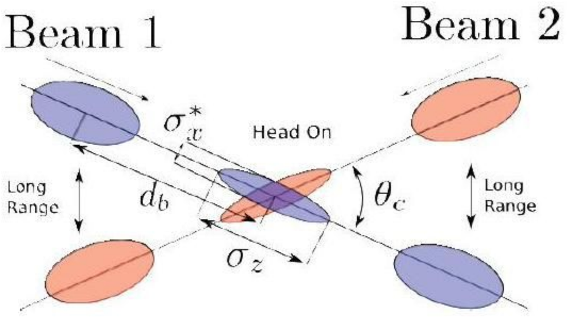
- luminosity from beam parameters:

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

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

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

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



σ_z is constant over the machine (~7,5 cm), σ_x varies and assumes its minimum in the Interaction Points.

25ns → 40MHZ
O(25) pileup → 1GHZ

- luminosity from beam parameters:

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

Between each consecutive bunch there are 7,5 m. Taking *bunches* moving at almost the *speed of light* around the 27 kilometre ring of the *LHC*, we can easily calculate other important parameter:

time between bunches = $7{,}5/3\cdot10^{8}$
Bunch spacing = $2{,}5\cdot10^{-8}$ s

Bunch spacing = 25 ns

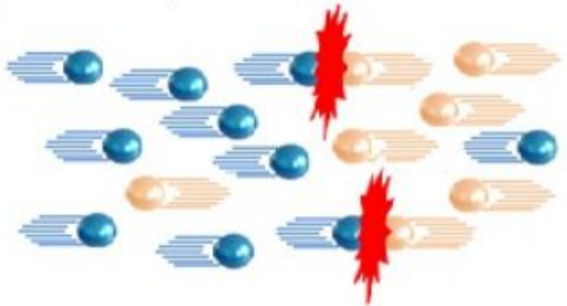
Besides, with that circumference of 27 km there should be:

26659 / 7,5 ~ 3550 bunches.

https://lhc-closer.es/taking_a_closer_look_at_lhc/0.lhc_p_collisions

For the calculation we take into account the fact that there are **$1{,}15 \cdot 10^{11}$ protons** per bunch (in **LHC Run 3 -from 2022 to 2026- up to 1.8×10^{11} protons** per bunch are reached). In order to understand this value, it should be noted that 1 cm^3 STP of hydrogen has ~10^{19} protons).

Each bunch gets squeezed down (using magnetics lenses) to **16 x16** μm section at an interaction point, where collisions take place.



- 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 $\int dt\, \mathcal{L}$: fb^{-1}

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

Now, with $N^2 = (1{,}15 \cdot 10^{11})^2$

$t = 25 \cdot 10^{-9}$ s , $S_{eff} = 4 \cdot \pi (16 \cdot 10^{-4})^2$ 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}

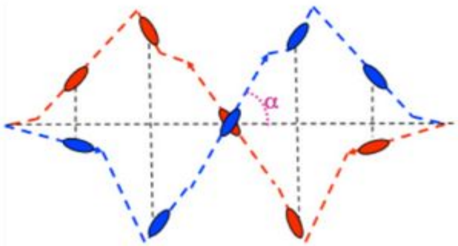
Higgs cross section ~ 50pb ~5*10^{-35} cm^2

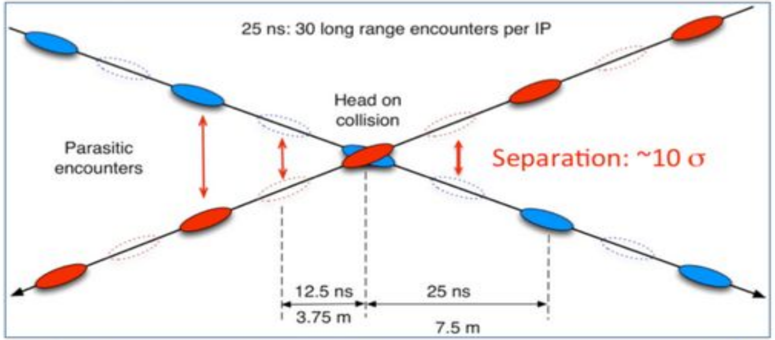
1 year ~ 10^7 sec effectively

→

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

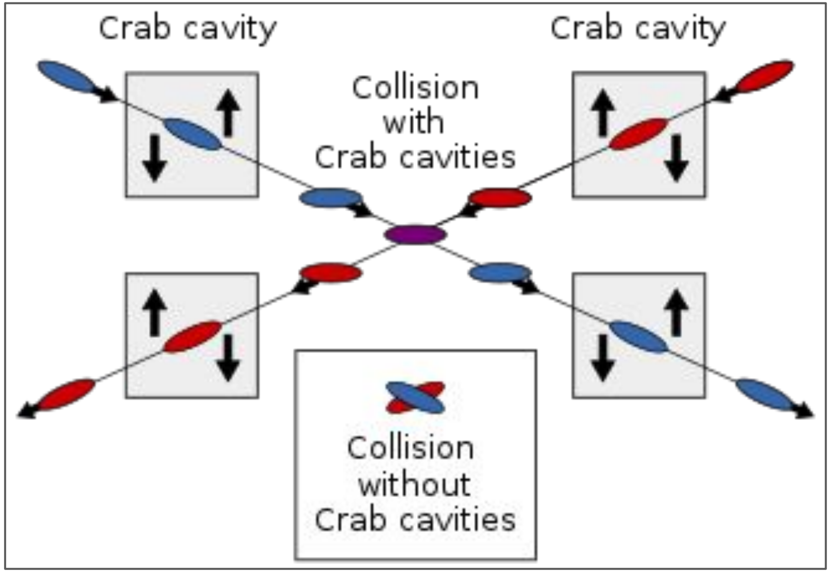
https://cds.cern.ch/journal/CERNBulletin/2016/38/News%20Articles/2216373
https://en.wikipedia.org/wiki/Crab_cavity





The crossing angles are an essential feature of the machine set-up. They have to be big enough to reduce the long-range beam-beam effect.

"The aim is to restart physics in the last few months of the year with the crossing angle reduced from **370 to 280 microradians**. This should increase the peak luminosity by around 15%. "



https://www.worldscientific.com/doi/10.1142/S0217751X23500331

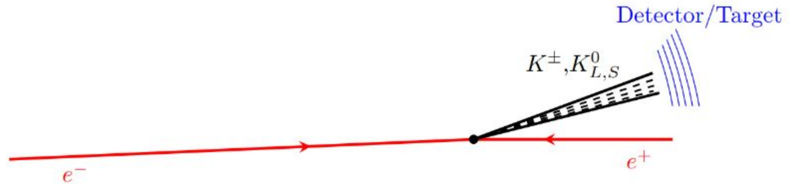


Fig. 1. Kaons produced at a rate of 10^{4-5}/s from asymmetric electron–positron collisions at e.g. 1020 MeV.

不对称碰撞

$$e^+e^- \to \phi(1020) \to K^+K^-, K^0_L K^0_S$$

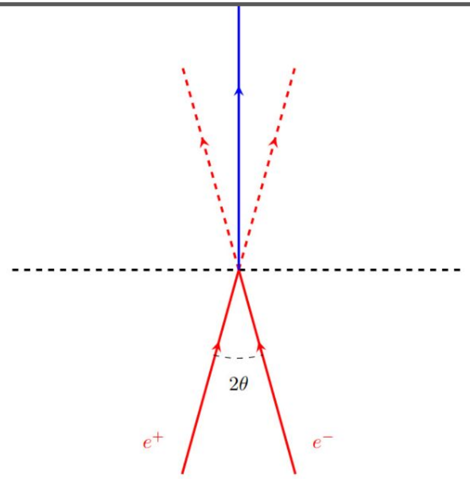


Fig. 3. Collisions between electron and positron beams separated by an angle 2θ. The two beams are symmetric in energy, while asymmetric in space. For electron and positron beams with energy of 5 (or 10) GeV, to achieve $\phi(1020)$ resonant productions, the angle is $\theta \sim 0.102$ (or 0.051) radius.

https://www.worldscientific.com/doi/10.1142/S0217751X23500331

$$e^+e^- \to \phi(1020) \to K^+K^-, K^0_L K^0_S$$

New methods to achieve meson, muon and gamma light sources through asymmetric electron positron collisions

Dawei Fu, Alim Ruzi,
Qiang Li, and Meng Lu

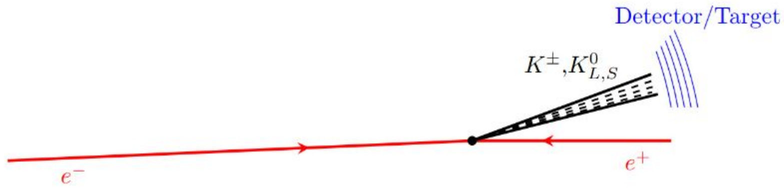
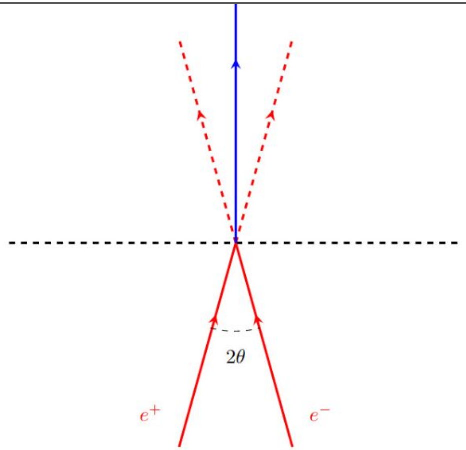


Fig. 1. Kaons produced at a rate of 10^{4-5}/s from asymmetric electron–positron collisions at e.g. 1020 MeV.

不对称碰撞



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https://arxiv.org/abs/2306.12480

A boosted muon collider

Daniele Barducci, Alessandro Strumia

Dipartimento di Fisica, Università di Pisa, Italia

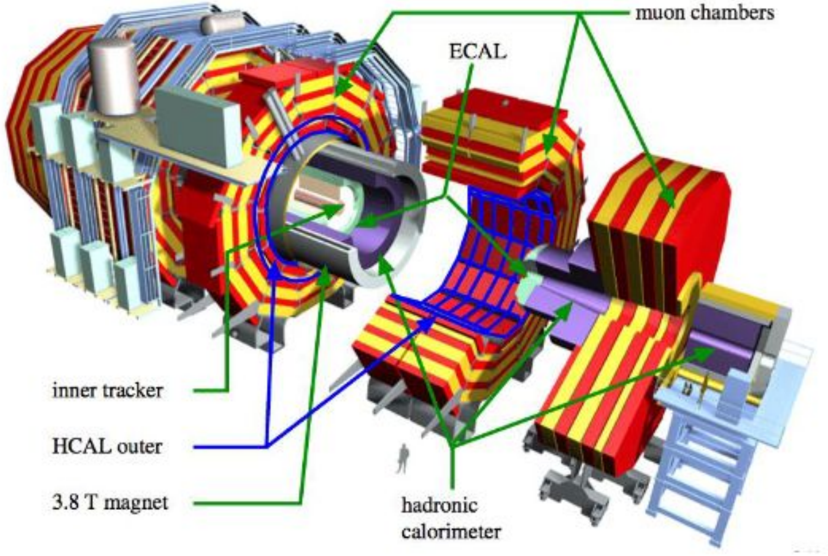
Abstract

A muon collider could produce the heavier Standard Model particles with a boost, for example in resonant processes such as $\mu^-\mu^+ \to h$ or $\mu^-\mu^+ \to Z$. We discuss possible geometries that produce the boost (asymmetric beam energies, tilted beams) and estimate how much the luminosity is reduced or perhaps enhanced. The boost provides new observational opportunities. For example it can significantly enhance the sensitivity to long-lived new particles decaying in a far-away detector, such as dark higgses or sterile neutrinos produced in h or Z decays.

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

Large Hadron Collider

CMS探测器：直径15米，长28米，重14000吨

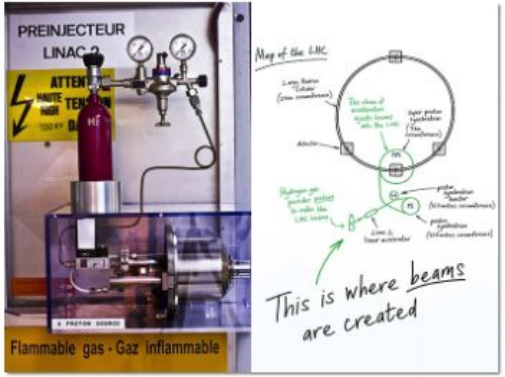


CMS是LHC上4个大型对撞点实验之一。

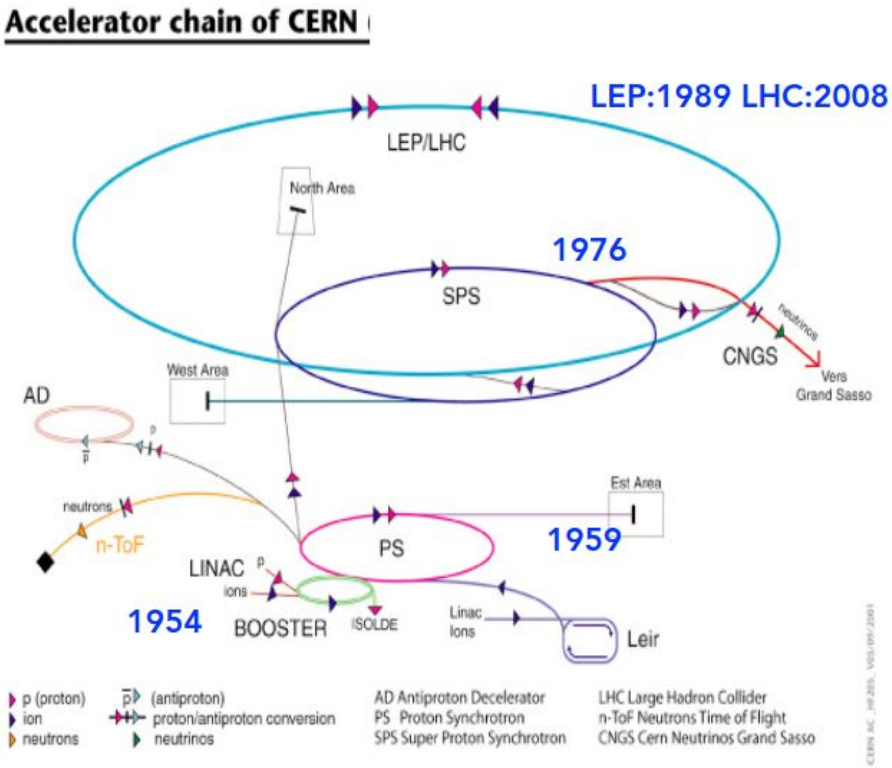
成员：约55个国家，210个研究单位，4000多人员。北大1996年加入CMS组。

Large Hadron Collider

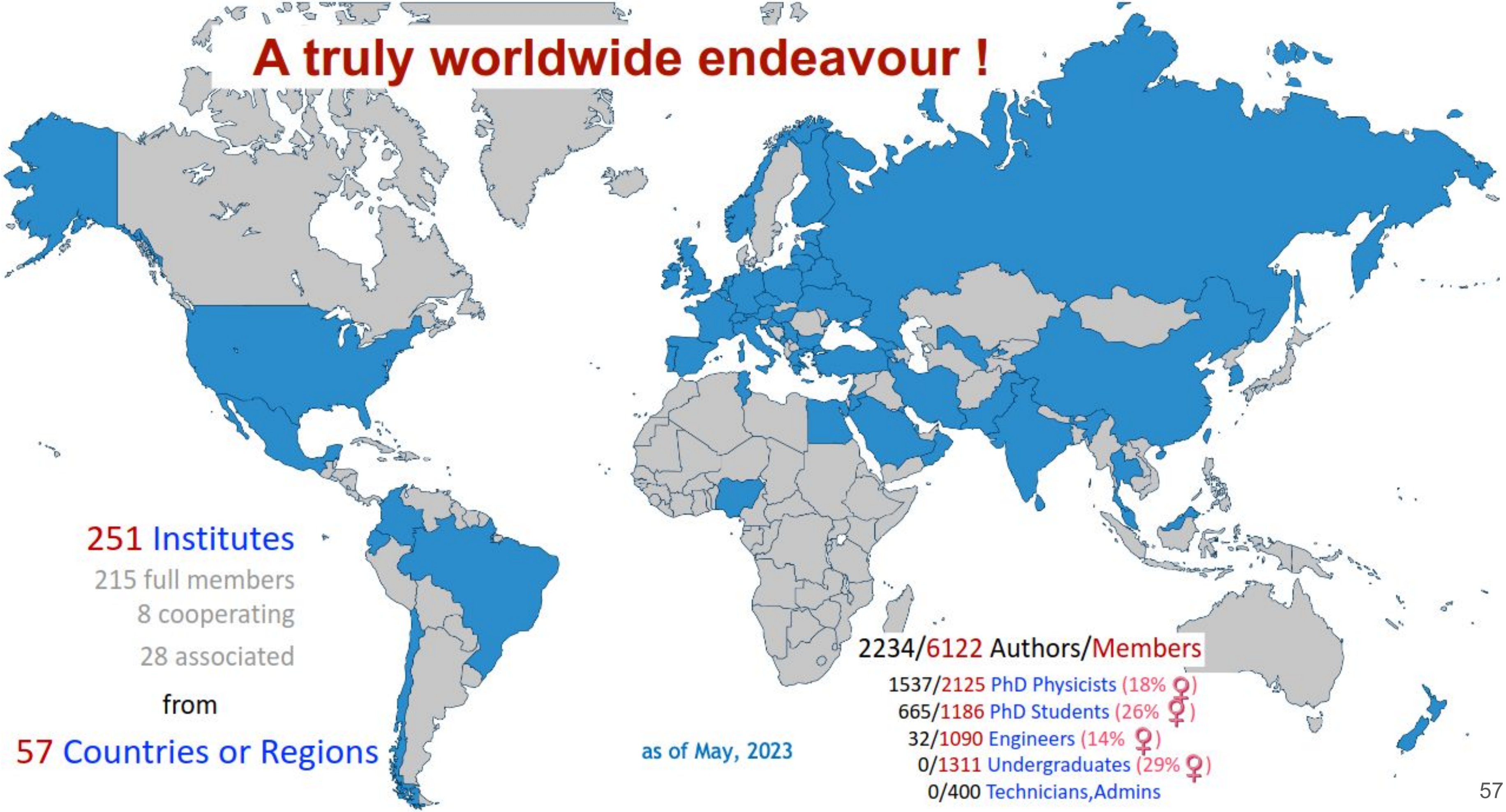
The CERN accelerator complex is formed by a succession of accelerators of increasing energy



- 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


CMS WEEK
April 17-21, 2023
Saint Malo

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"

"The Government"

Collaboration Board

Management Board

Committees

Conference Committee

etc.

Publications Committee

Extended Executive Board

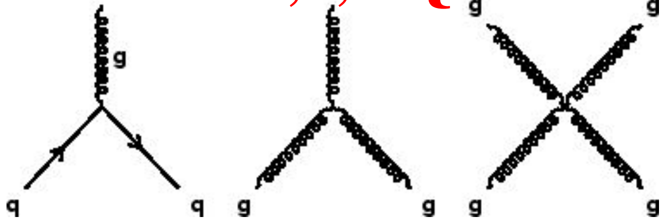
QED vs QCD

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

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

a=1…8,

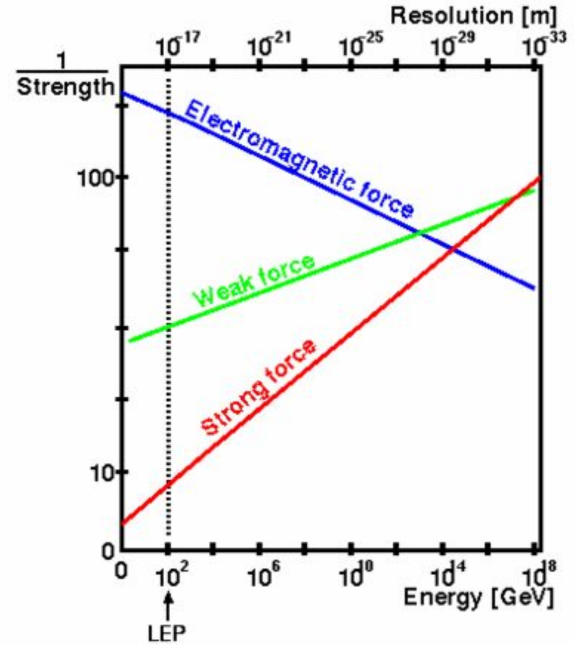
i=1,2,3 QCD colors



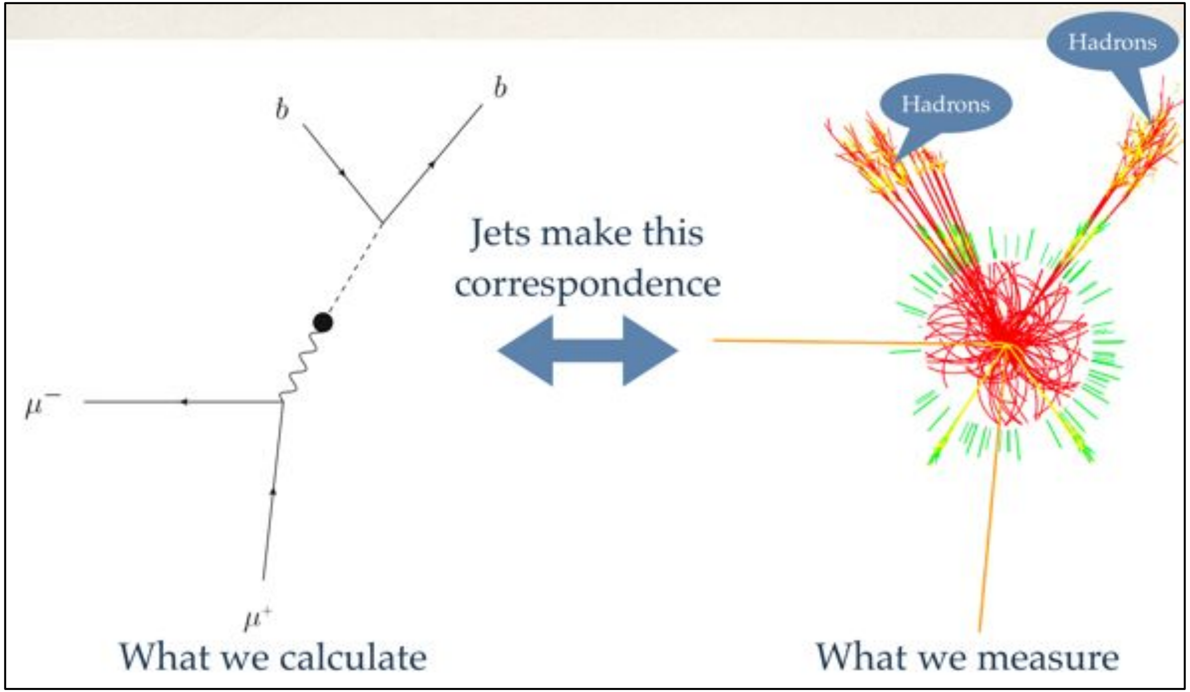
Self-interactions

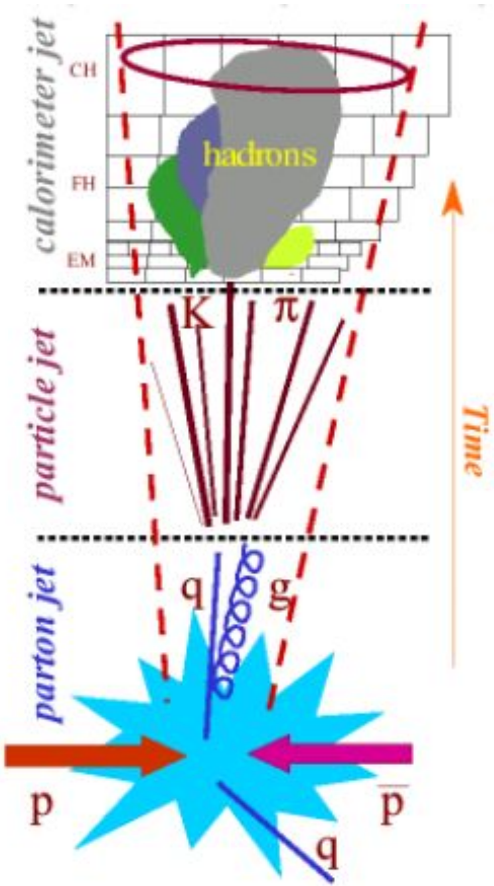
$$\alpha_{em} = \frac{e^2}{4\pi} \sim \frac{1}{137}$$

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

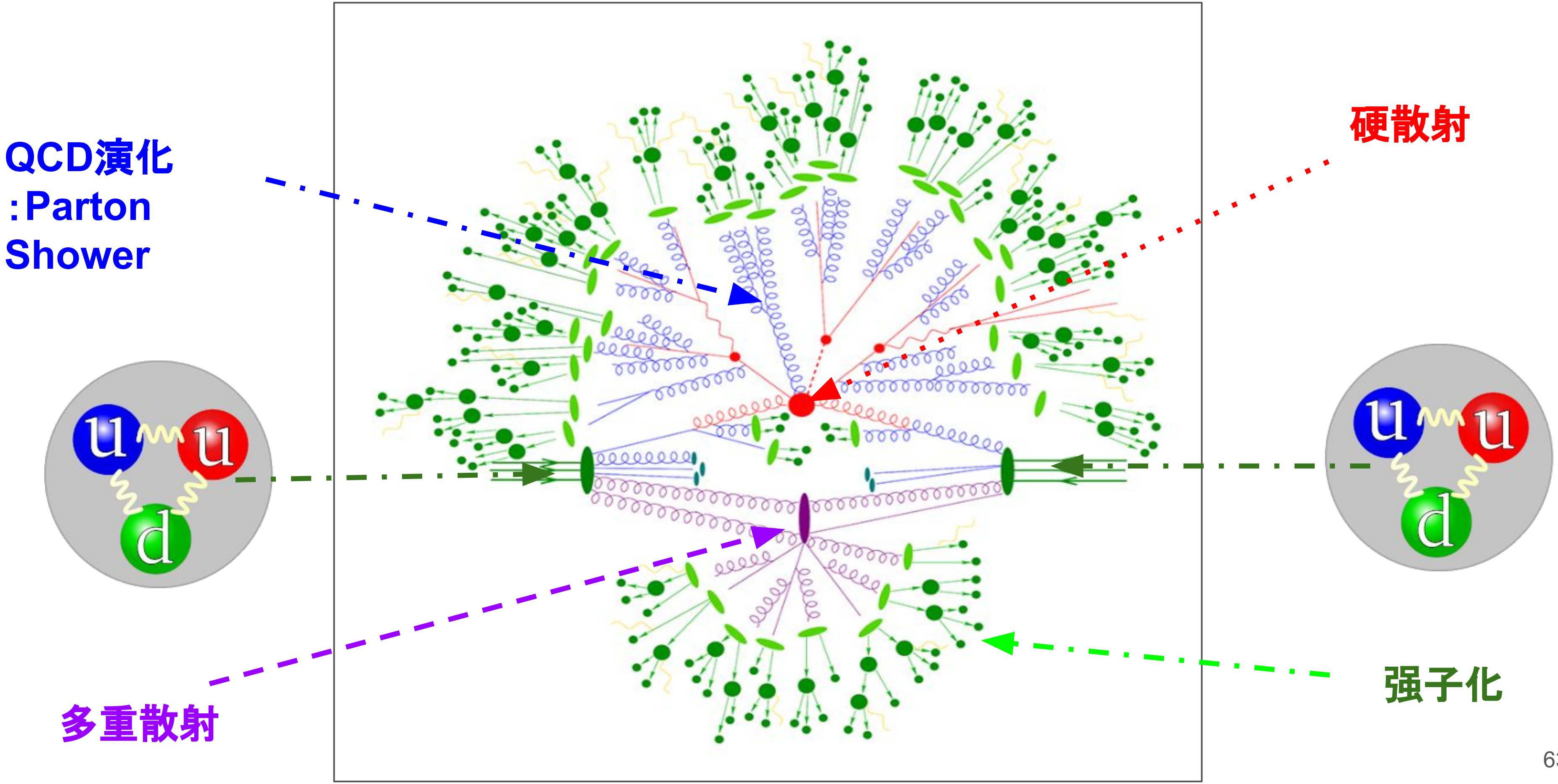


Parton, Jet

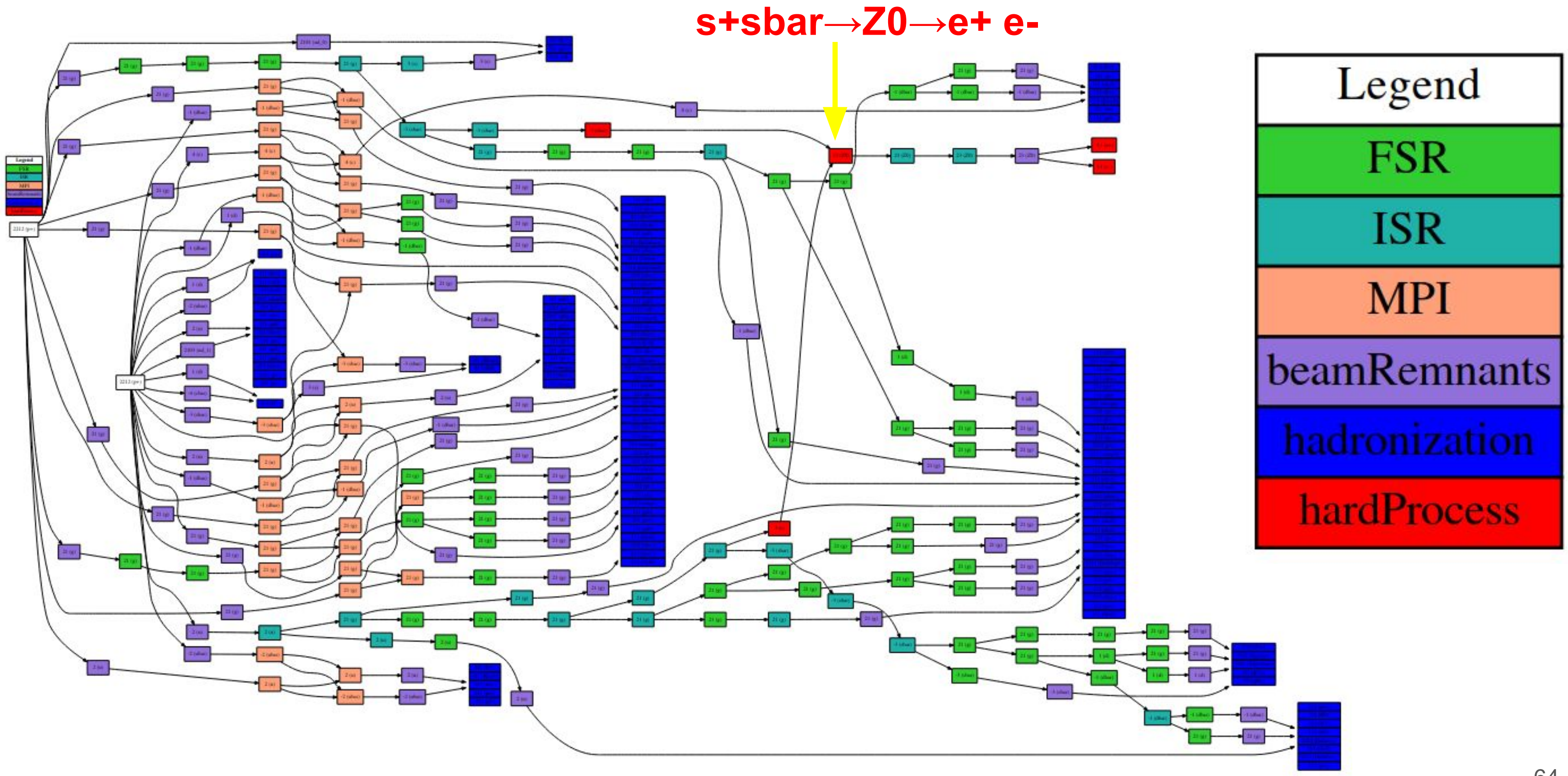

Hadrons
Hadrons
b
b
Jets make this correspondence
μ^-
μ^+
What we calculate
What we measure


calorimeter jet
CH
FH
EM
hadrons
K
π
particle jet
Time
parton jet
q
g
p
$\bar{p}$
q

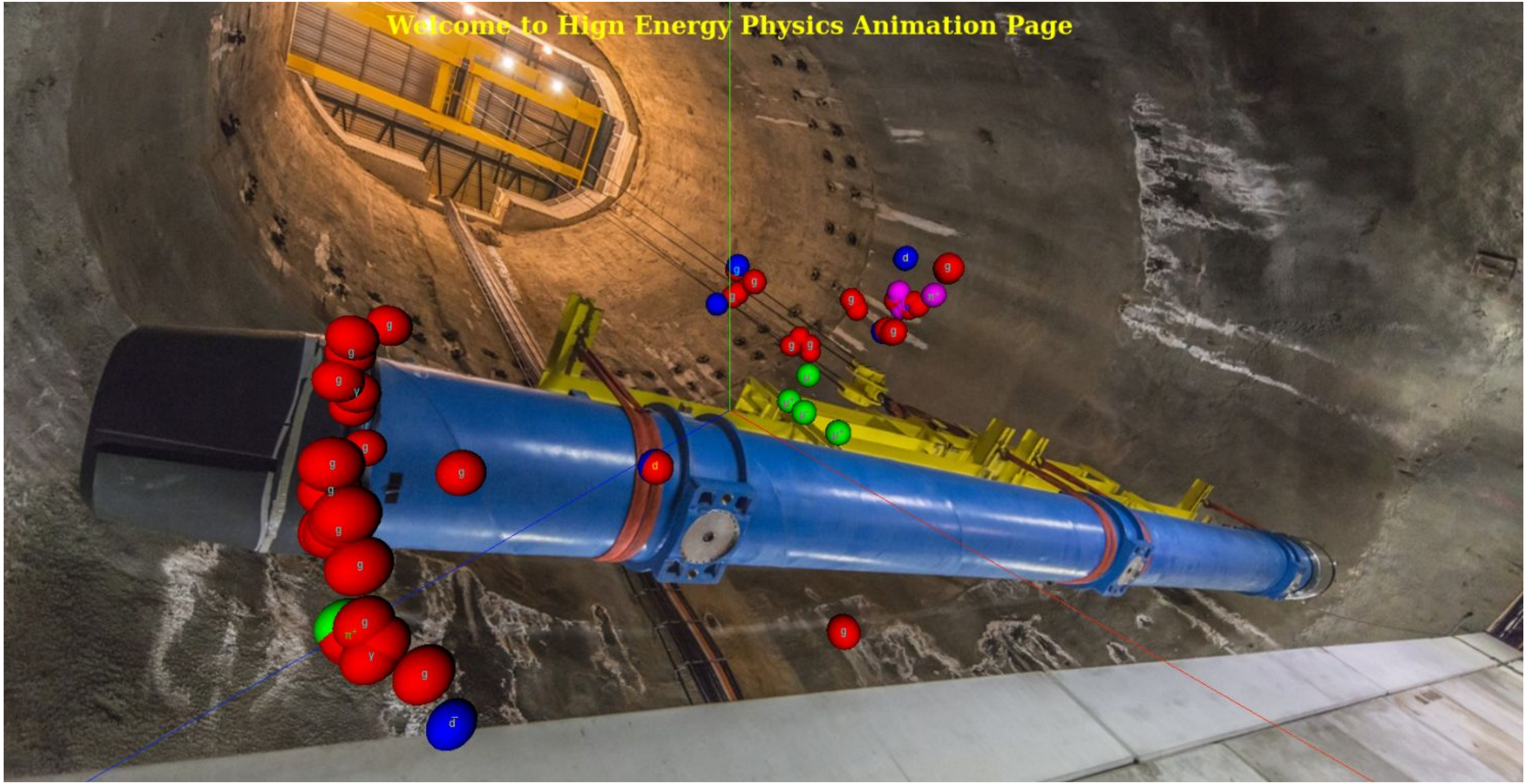
高能对撞



高能对撞

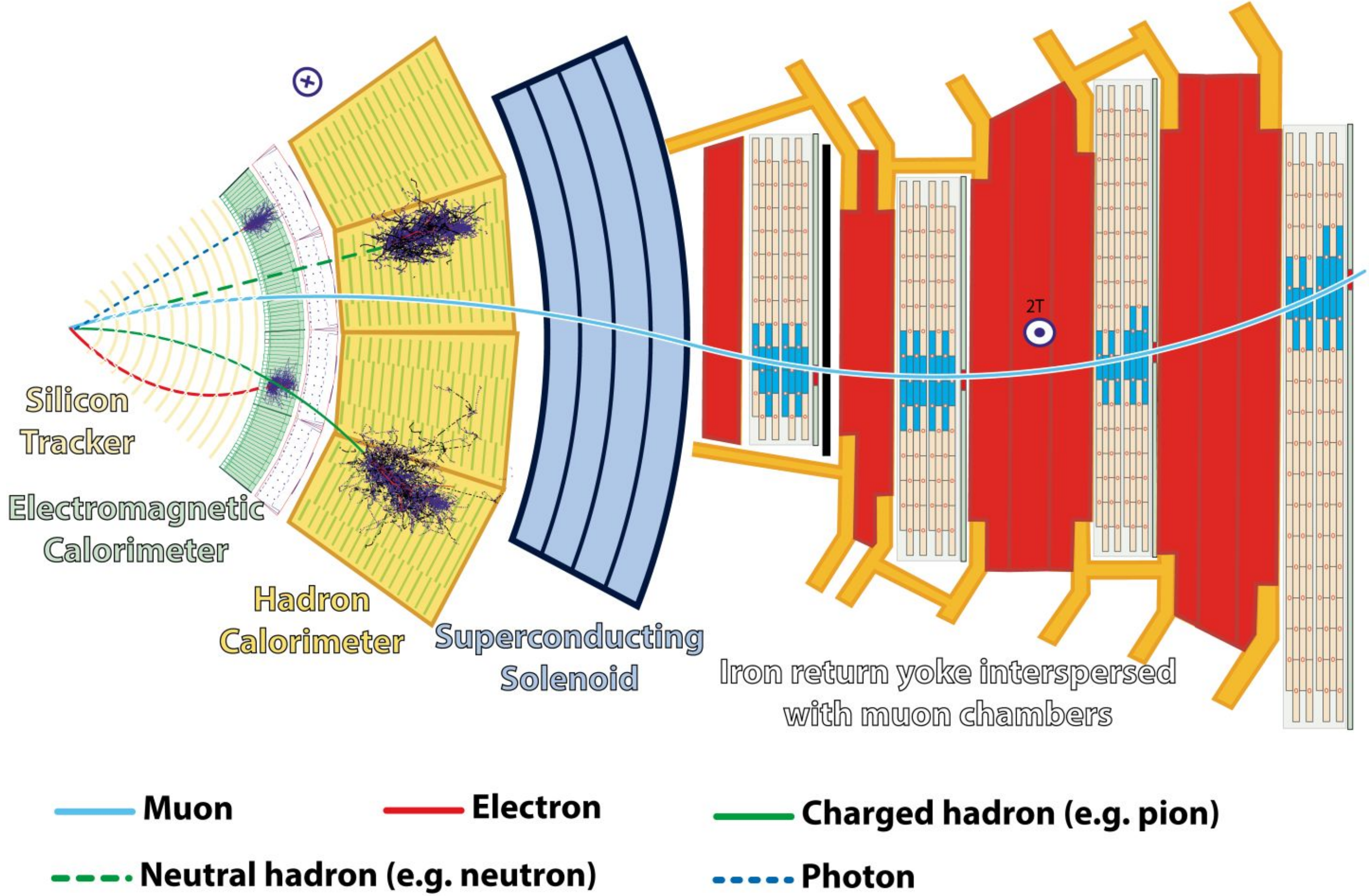

s+sbar→Z0→e+ e-
Legend
FSR
ISR
MPI
beamRemnants
hadronization
hardProcess

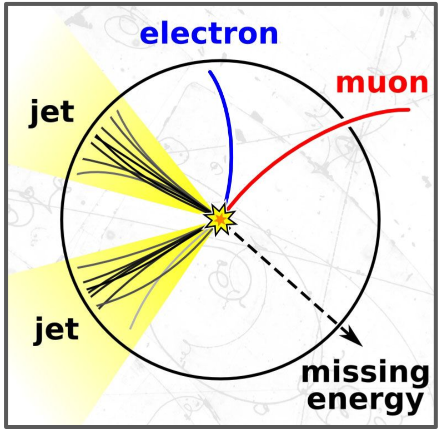
高能对撞动画

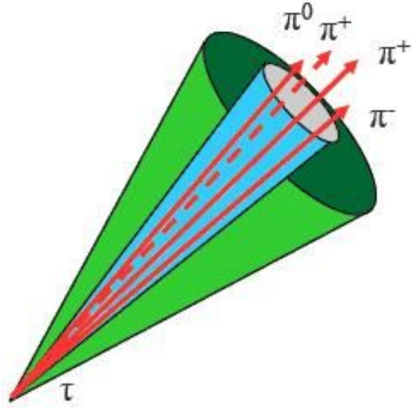


北大本科生高乐耘的科研工作成果

高能对撞机：探测⟶信息

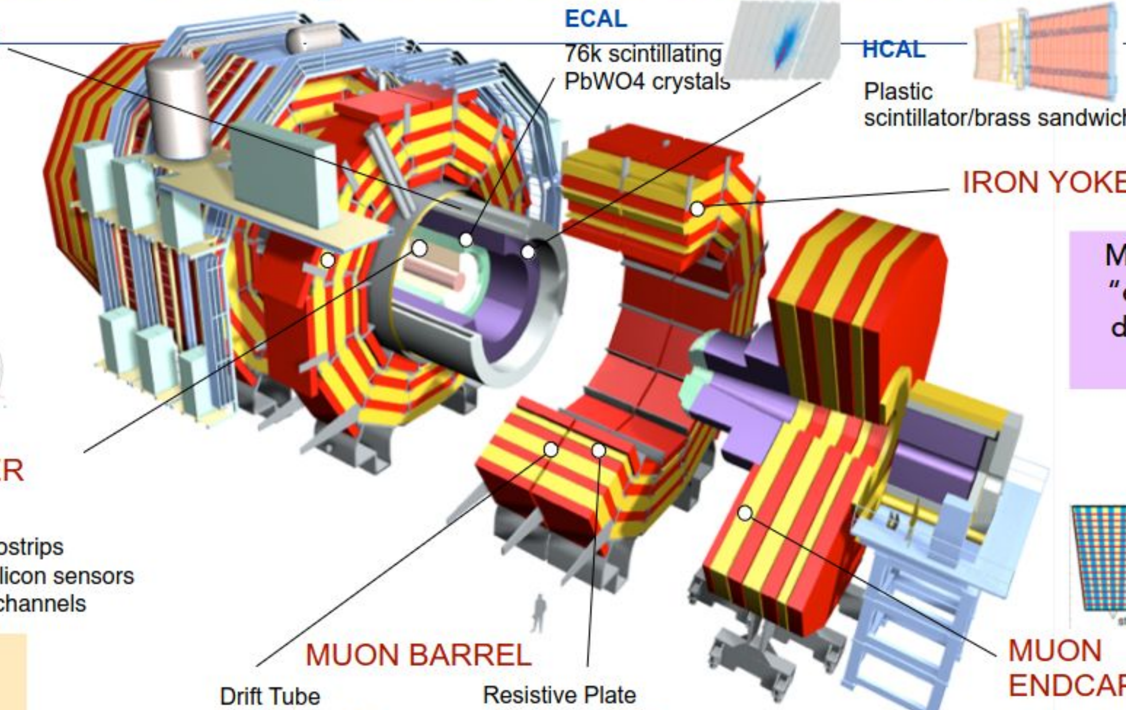

2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with muon chambers
Muon
Electron
Charged hadron (e.g. pion)
Neutral hadron (e.g. neutron)
Photon

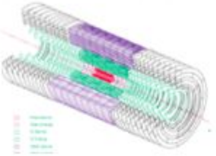

electron
muon
jet
jet
missing energy

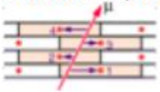

π^0 π^+
π^+
π^-
τ

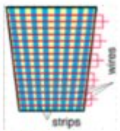
What: the Compact Muon Solenoid

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









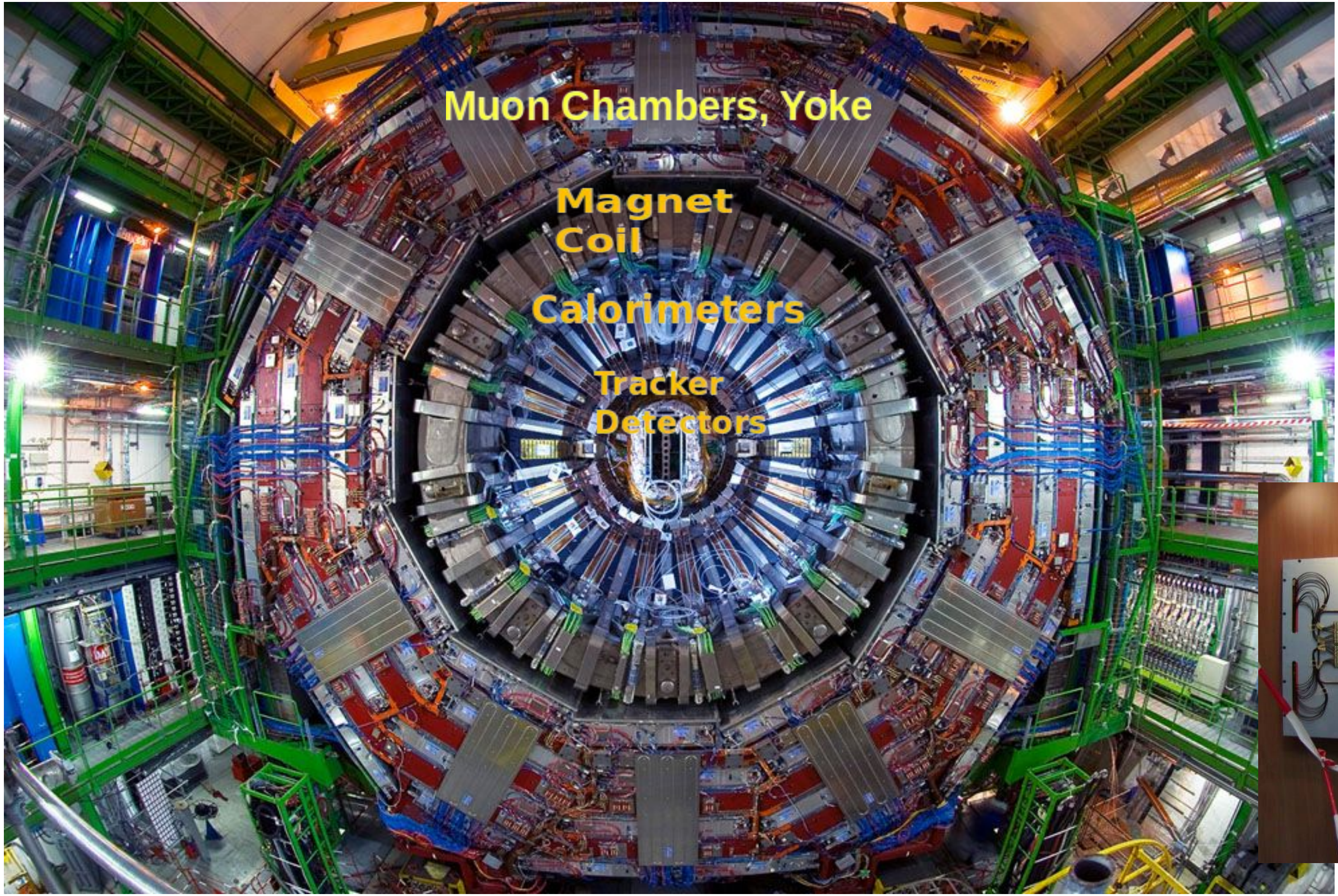
Most parts of CMS "easily" accessible during shutdowns (incl. pixels)

Modular structure

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

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

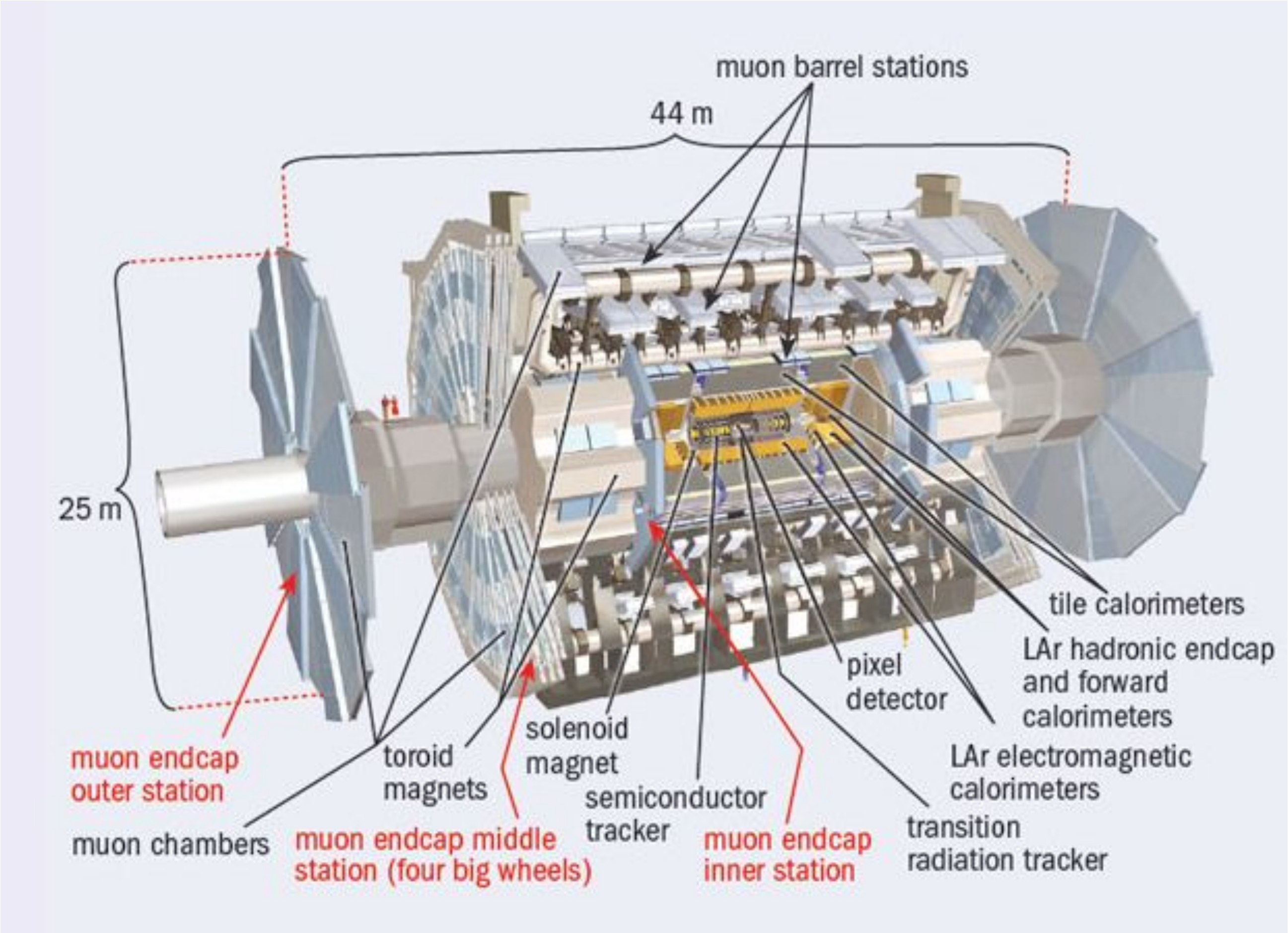
高能对撞机：CMS探测器



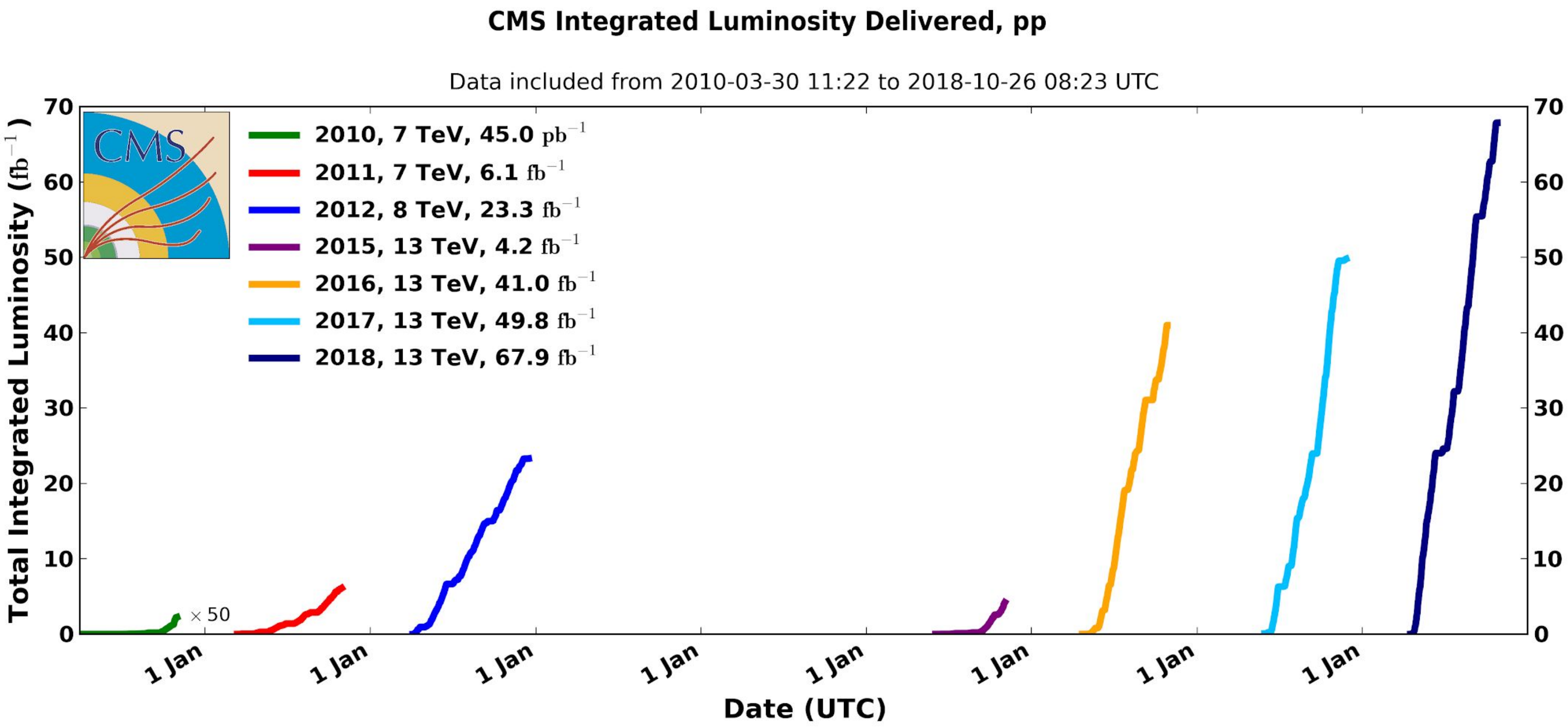
weight: 12500 t
overall diameter: 15 m
overall length: 21.6 m

照相机？
录音机？

高能对撞机：ATLAS探测器

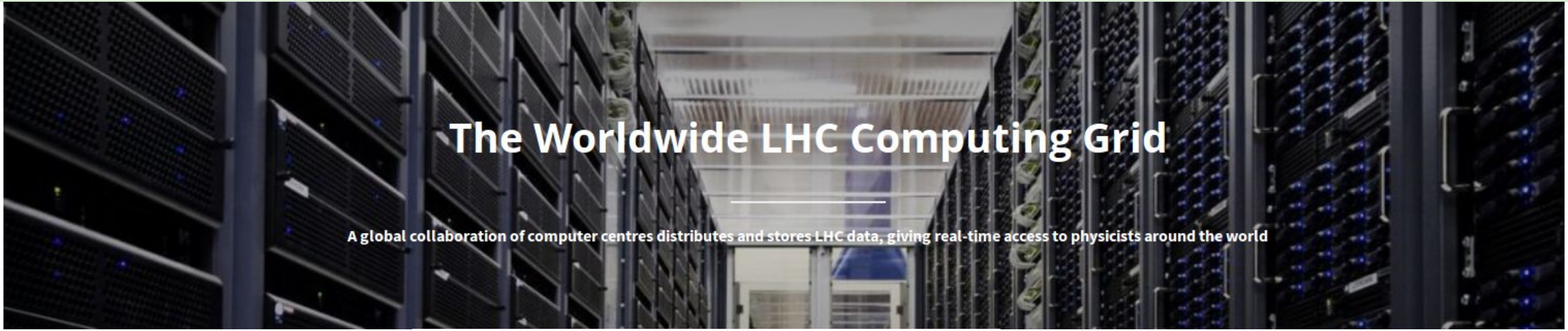


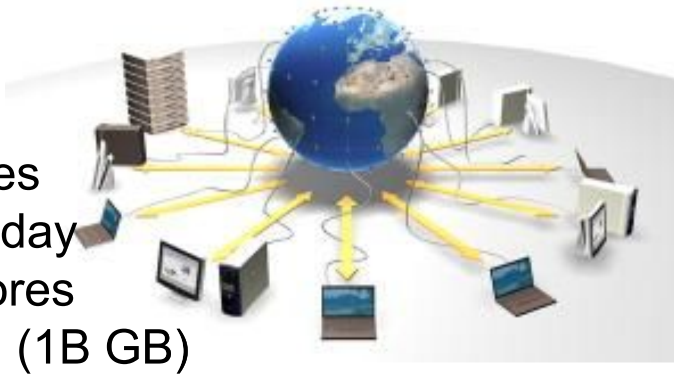
LHC数据亮度



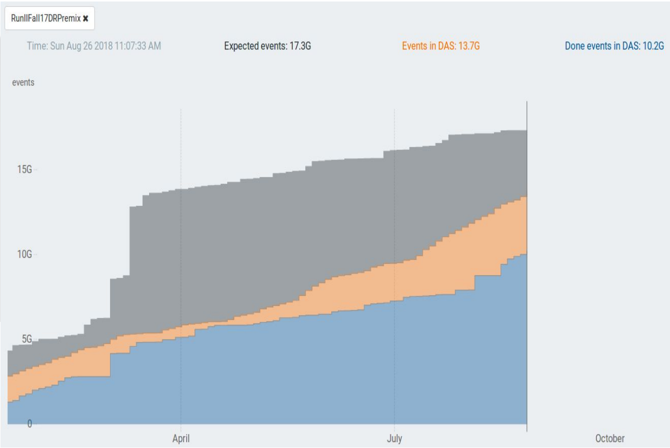
CMS Integrated Luminosity Delivered, pp
Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC
CMS
2010, 7 TeV, 45.0 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
2015, 13 TeV, 4.2 fb^{-1}
2016, 13 TeV, 41.0 fb^{-1}
2017, 13 TeV, 49.8 fb^{-1}
2018, 13 TeV, 67.9 fb^{-1}
× 50
Total Integrated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

高能对撞机：大数据



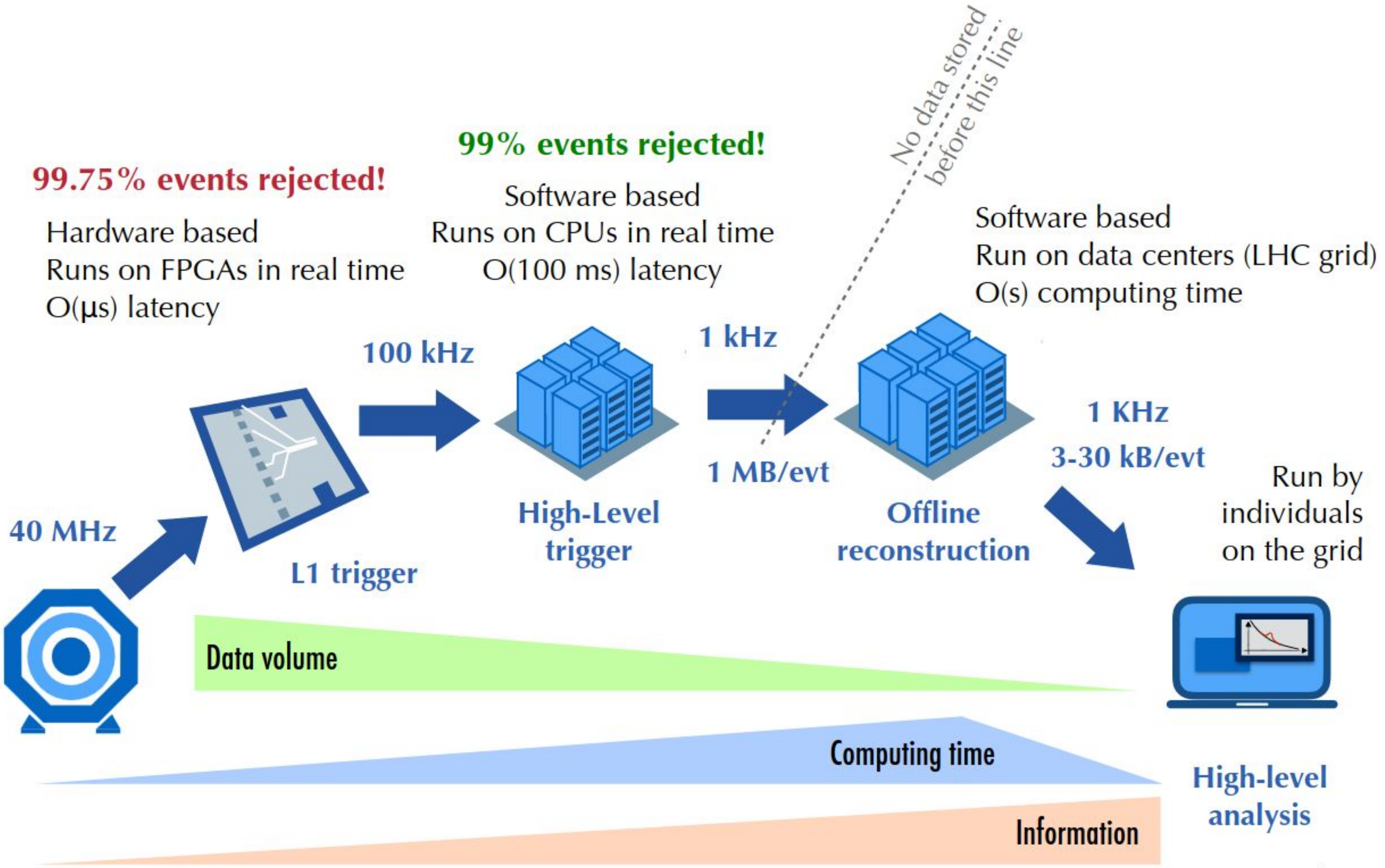


42 countries
170 computing centres
Over 2 million tasks/ day
1 million computer cores
1 exabyte of storage (1B GB)

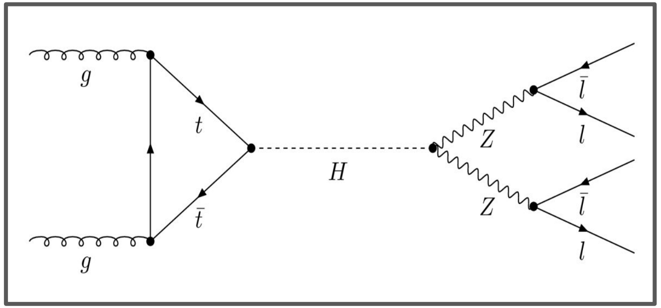


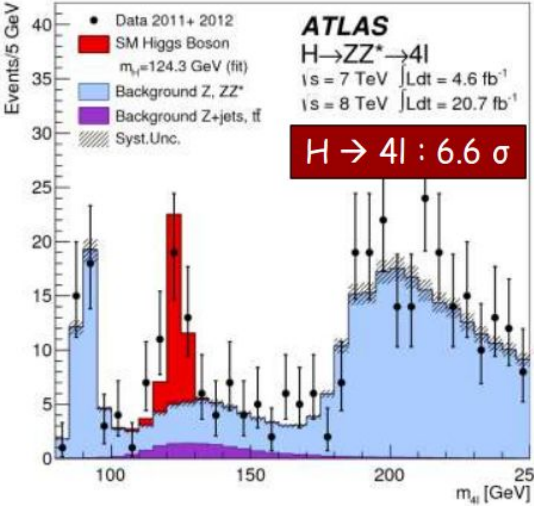
CMS： 15B events in 8 months

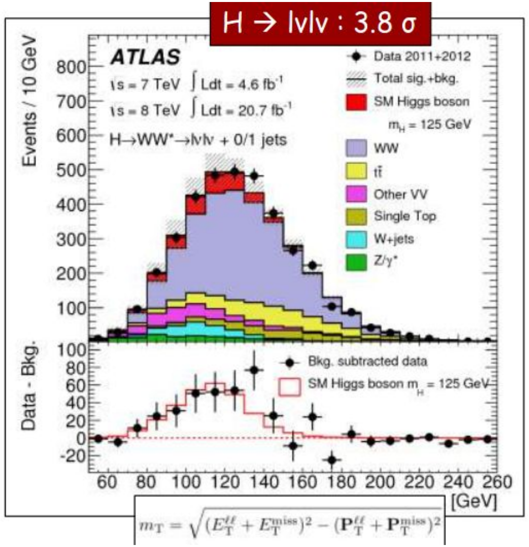
Data reduction workflow @ LHC



高能对撞机：大数据







Needles in a haystack

In ATLAS, up to July 4, 2012:

A million billion collisions

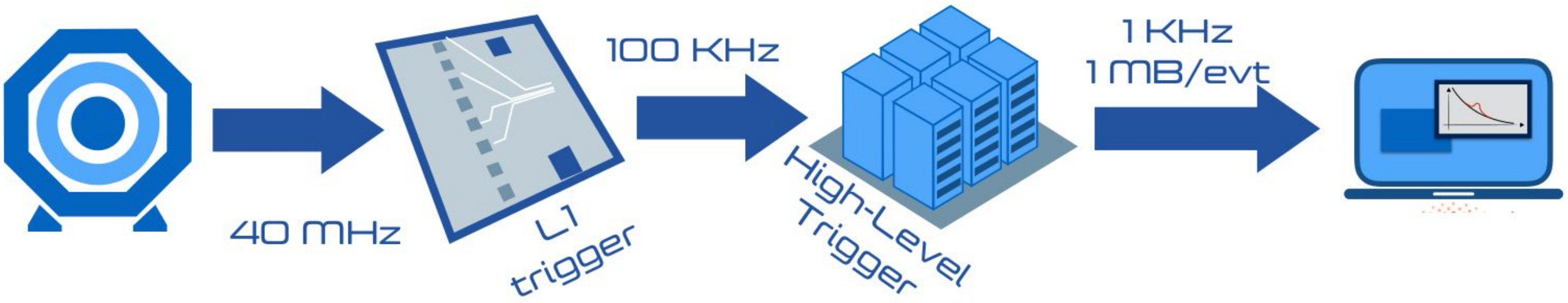
4.2 billion events analyzed

240,000 Higgs particles produced

~350 diphoton Higgs events detected

~8 four-lepton Higgs events detected

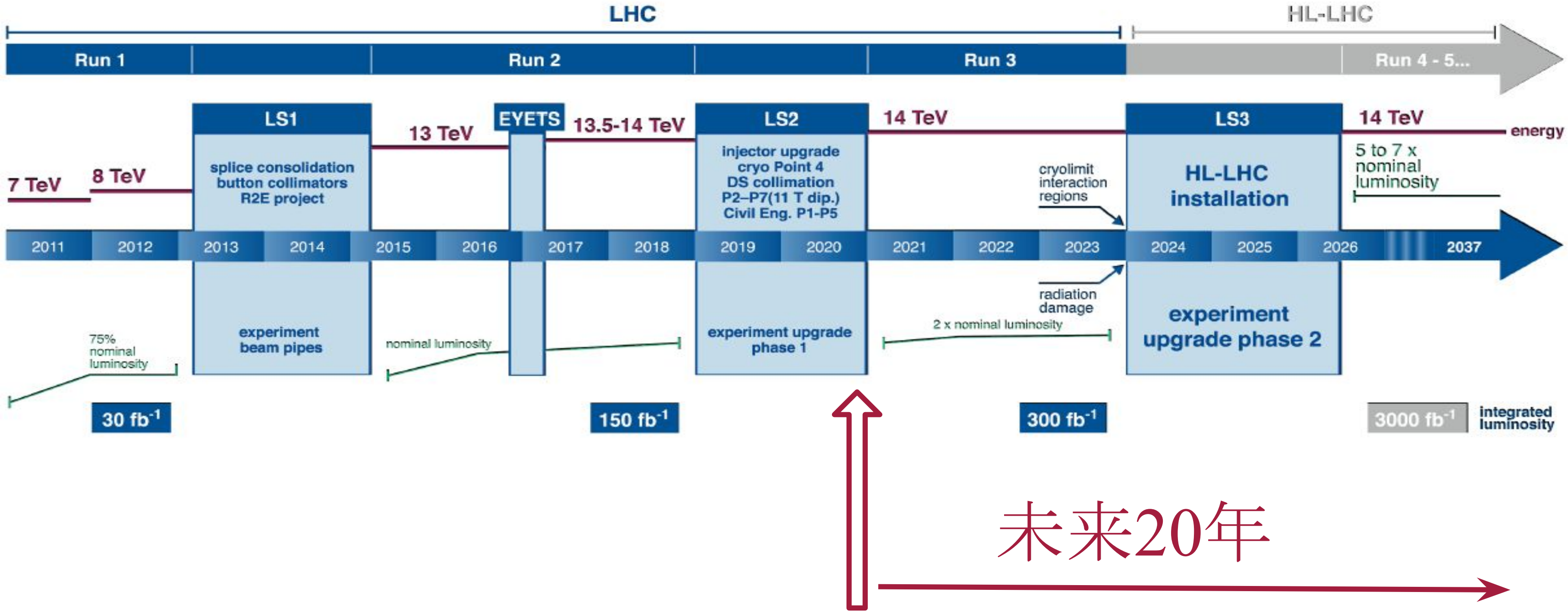
LHC数据流



- **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. 高能物理中的机器学习
8. 总结与展望

1964年

1

Volume 13, Number 9 — PHYSICAL REVIEW LETTERS — 31 August 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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

2

Volume 12, number 2 — PHYSICS LETTERS — 15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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

Received 27 July 1964

3

Volume 13, Number 16 — PHYSICAL REVIEW LETTERS — 19 October 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

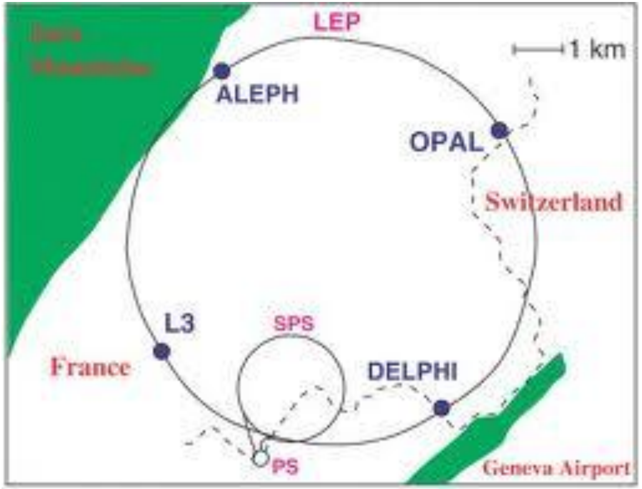
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

4

Volume 13, Number 20 — PHYSICAL REVIEW LETTERS — 16 November 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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



CERN LEP

(The Large Electron-Positron Collider)

1989.7-2000.11: 91-209GeV

115GeV Higgs hint before shutdown?

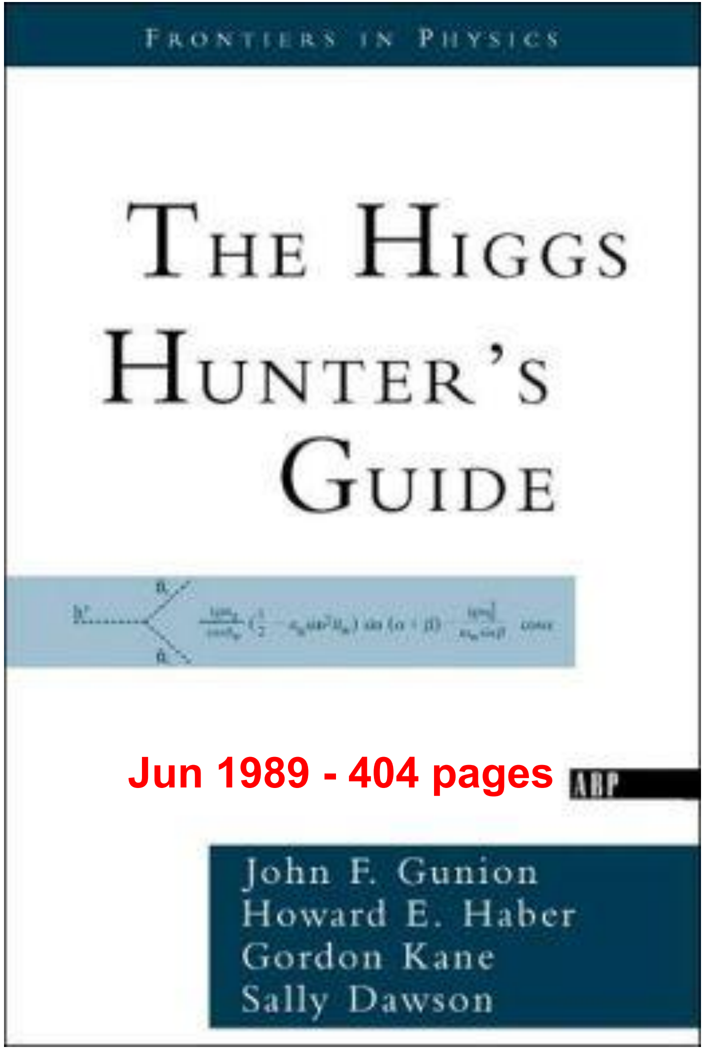
Fermilab Tevatron, US

1983-2011

Proton-antiproton collider

1.8/1.96TeV

1995 Top quark discovery



Jun 1989 - 404 pages

A Phenomenological Profile of the Higgs Boson

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

Oct 1975 - 62 pages

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

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

The Nobel Prize in Physics 2013

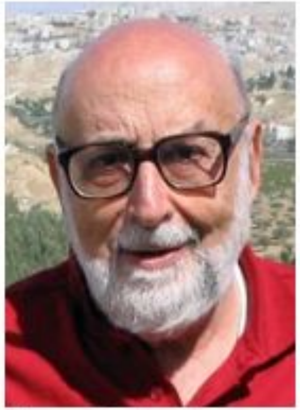


Photo: Pnicolet via Wikimedia Commons

François Englert

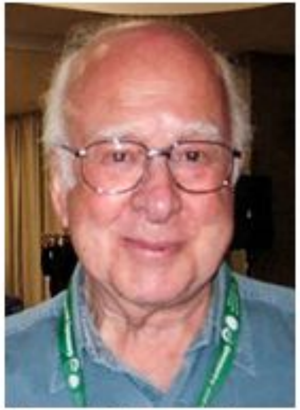


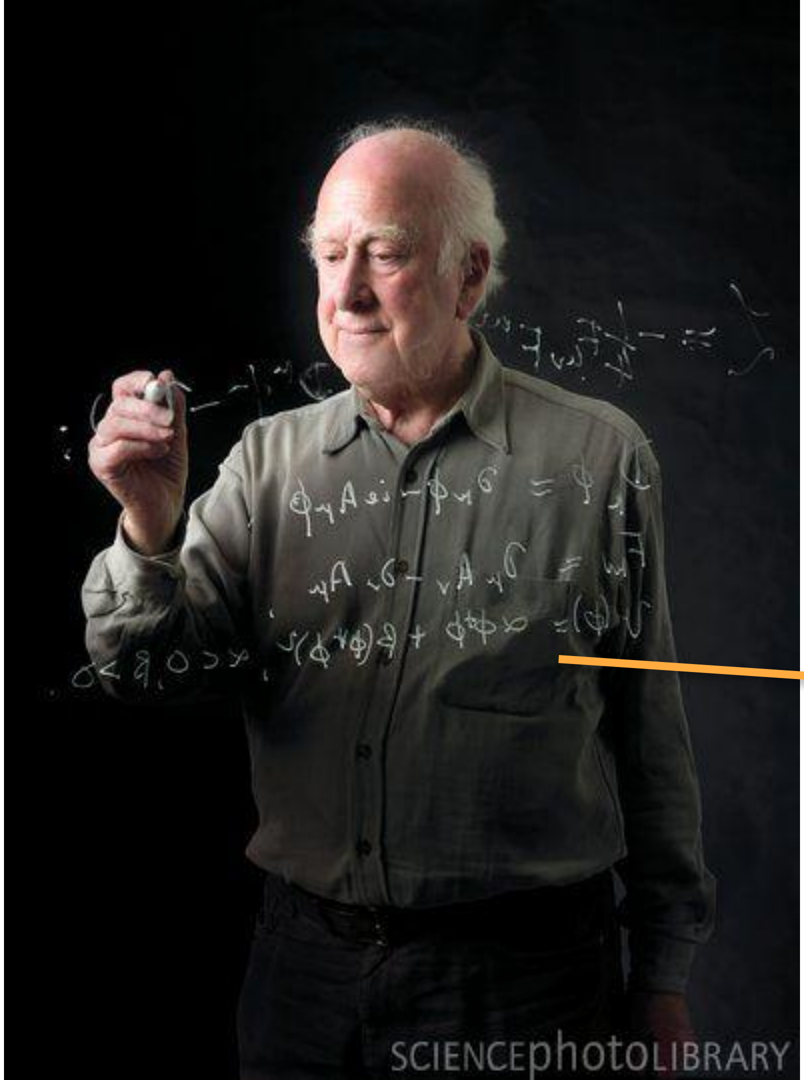
Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

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

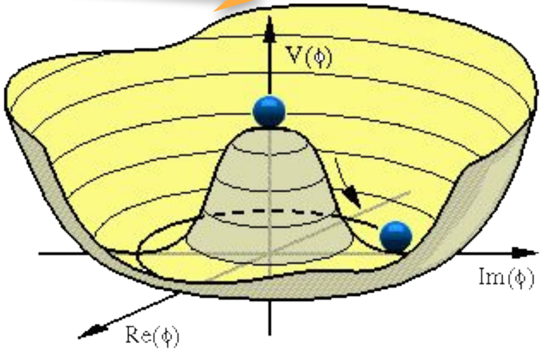
An accepted definition for a "discovery": a 5-sigma level of certainty 99.99994 %.

Spontaneous Symmetry Breaking
in
Quantum Gauge Field Theory



Generating V mass
while keeping Gauge Symmetry
and
avoiding massless goldstone

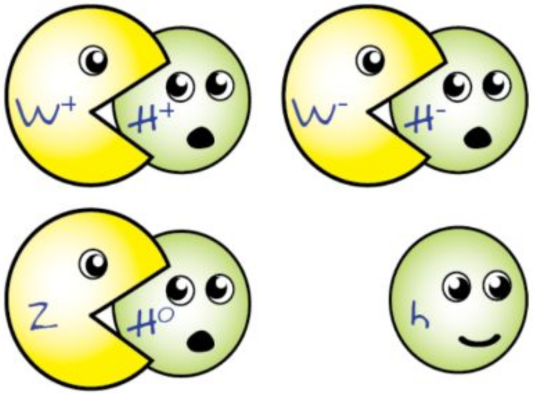
$$Higgs - Potential:$$
$$\alpha\phi\phi^* + \beta(\phi\phi^*)^2, \alpha < 0, \beta > 0$$



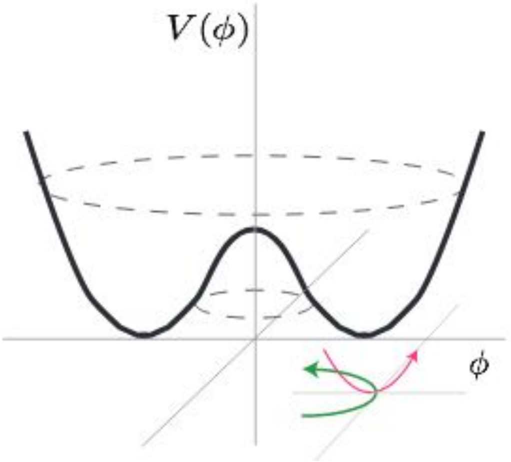
(a) Unbroken symmetry: the rod in its original state is rotationally invariant

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

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



无质量
Goldstone



规范场情形，W、Z吞并了Higgs分量

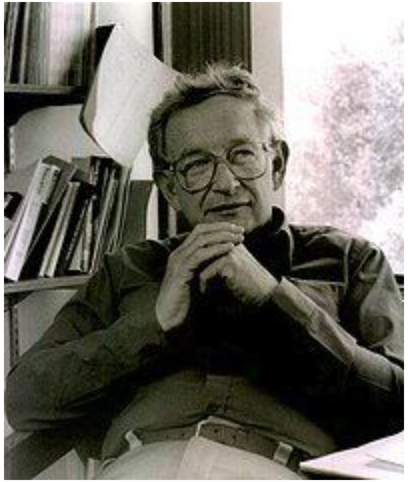
Deep root from Condensed Matter Physics

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

My life as a boson
by Peter Higgs

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

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

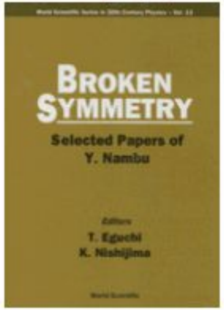


Philip W. Anderson
1977 Nobel Physics Prize

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

Deep root from Condensed Matter Physics

Autobiography in



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

Schrieffer joined Chicago faculty for a year

PHYSICAL REVIEW VOLUME 117, NUMBER 3 FEBRUARY 1, 1960

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

YOICHIRO NAMBU
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois
(Received July 23, 1959)

it took him two years

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

6. THE COLLECTIVE EXCITATIONS

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

...

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

"zero modes"

ACKNOWLEDGMENT

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

Photo: University of Chicago

Yoichiro Nambu

Prize share: 1/2

2008 Nobel Physics Prize

How to search for a Higgs particle?

Not so easy!

Needles in a haystack

In ATLAS, up to July 4, 2012:

A million billion collisions

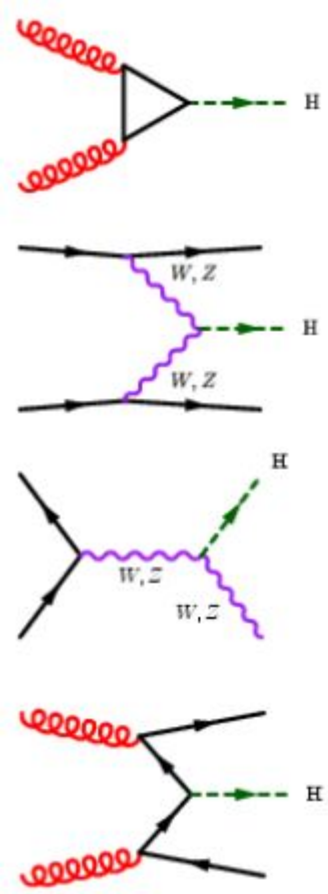
4.2 billion events analyzed

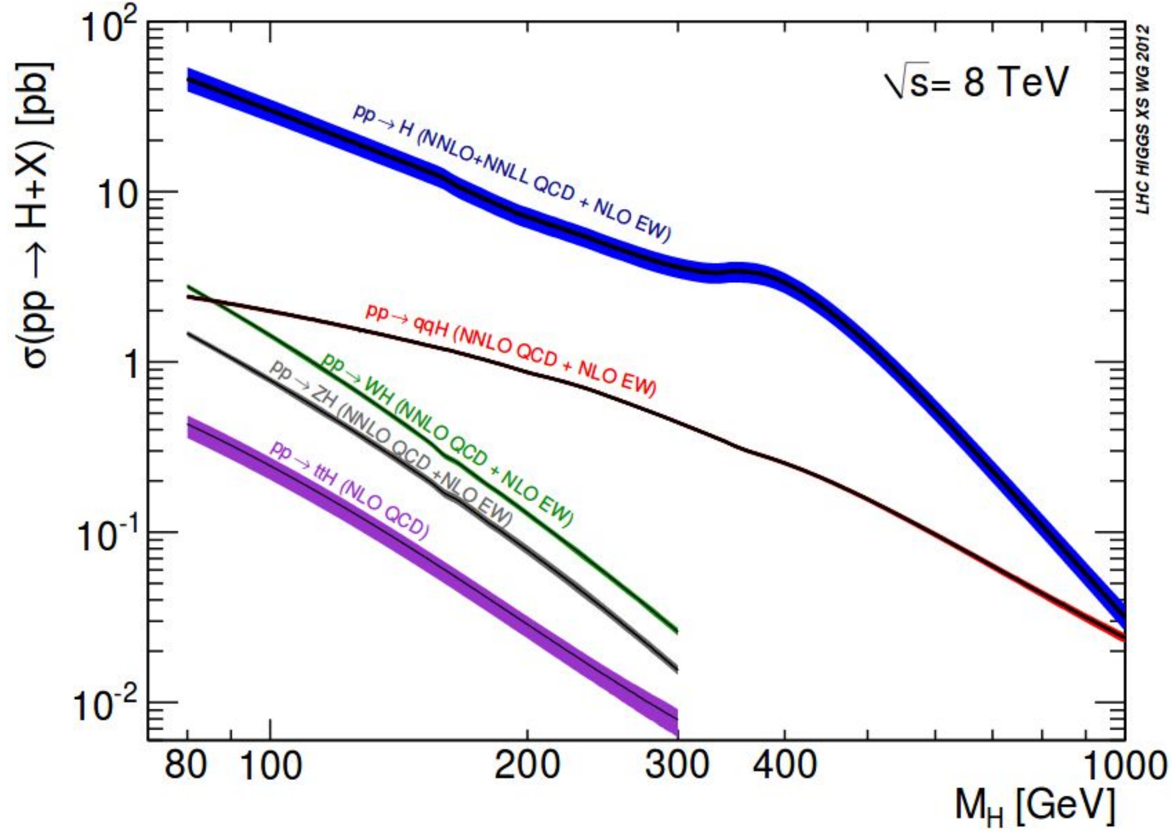
240,000 Higgs particles produced

~350 diphoton Higgs events detected

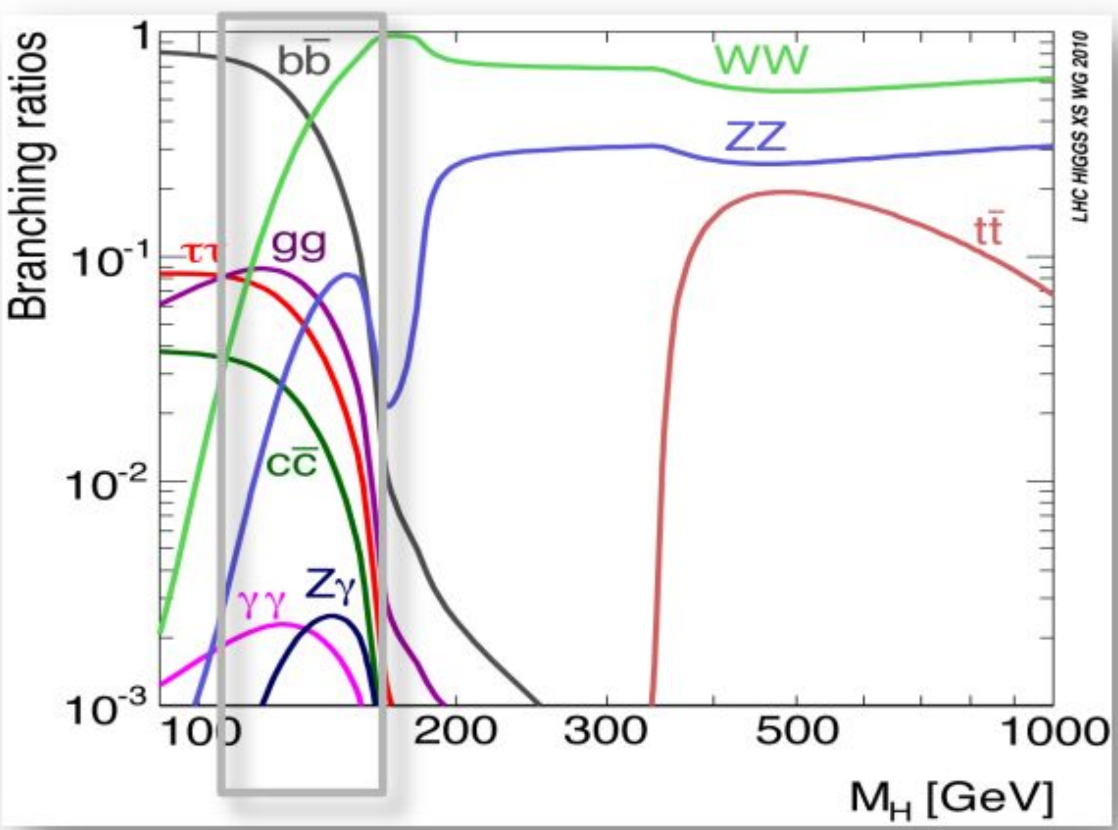
~8 four-lepton Higgs events detected

Higgs Production



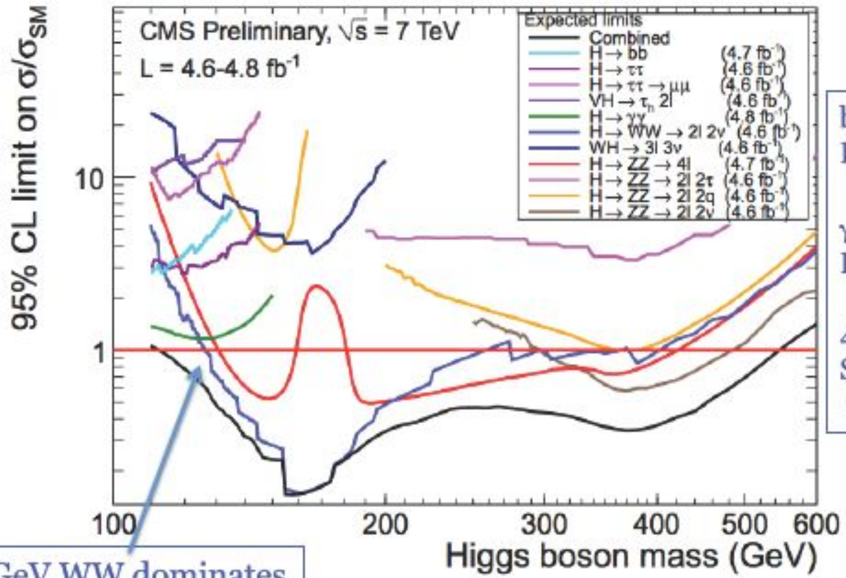


Higgs Decay



Branching ratios
1
10^-1
10^-2
10^-3
bb̄
WW
ZZ
tt̄
ττ
gg
cc̄
γγ
Zγ
100
200
300
500
1000
M_H [GeV]
LHC HIGGS XS WG 2010

Higgs search strategy



bb/ττ/WW
Poor mass resol

γγ and 4l
Excellent mass resol

4l is ~backg free
Single event has
an impact

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

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

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

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

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

LHC 上的重大进展 —— 发现 Higgs 粒子

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

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

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

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

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

LHC ERA — The path to Higgs discovery

From C.S. Wu

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

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

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

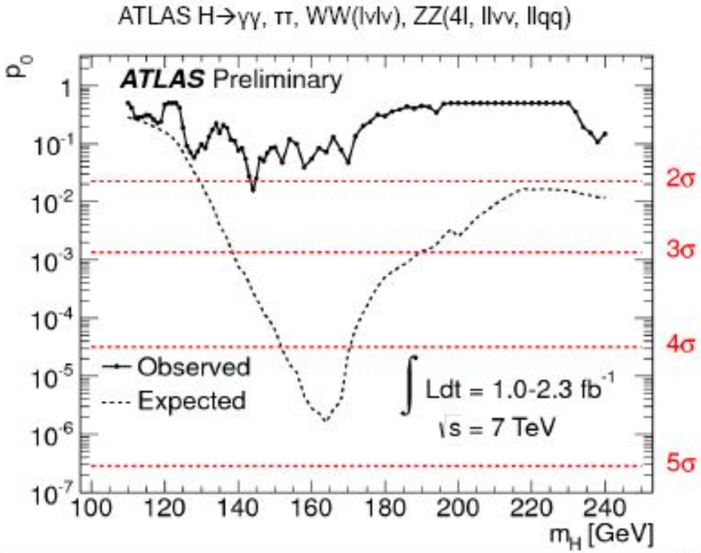
LHC ERA

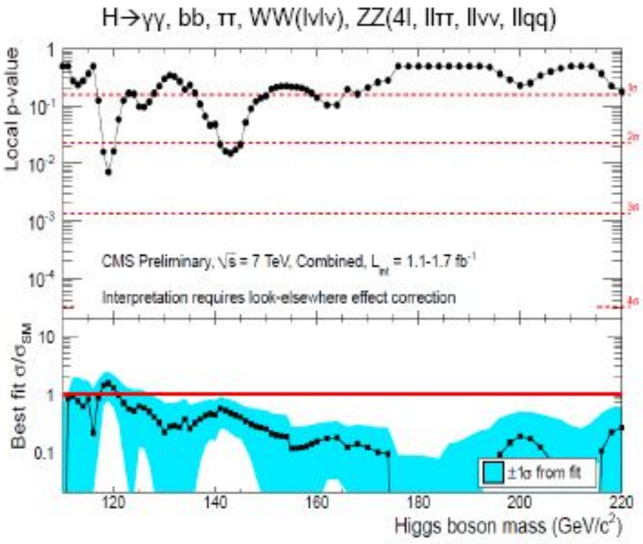
EPS-HEP 2011 (July)
Lepton-Photon 2011 (August)

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

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

p_0 = Local p-value

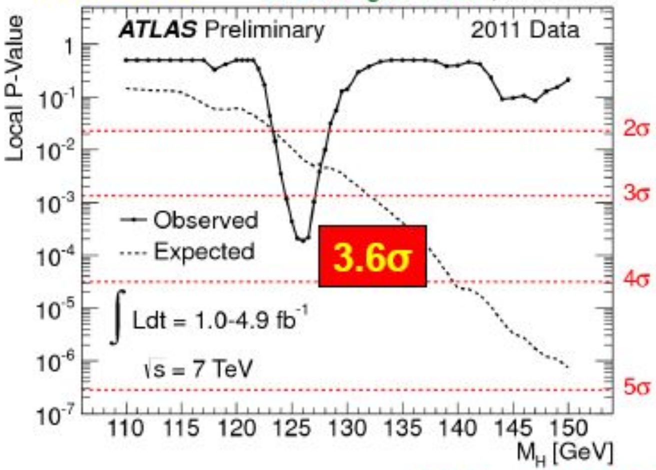




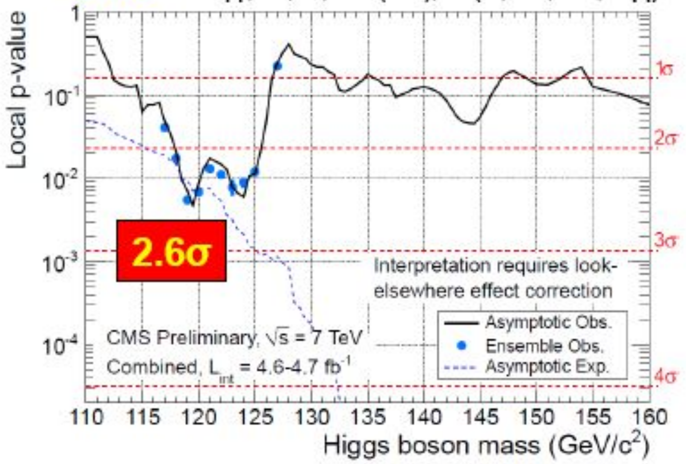
ATLAS (LP11)	**CMS (LP11)**
largest local excess: 2.1σ at 145 GeV	***largest local excess: 2.3σ at 120 GeV***

LHC ERA CERN Council (Dec 2011) Higgs combined

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



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



Largest local excess: 3.6σ at 126 GeV

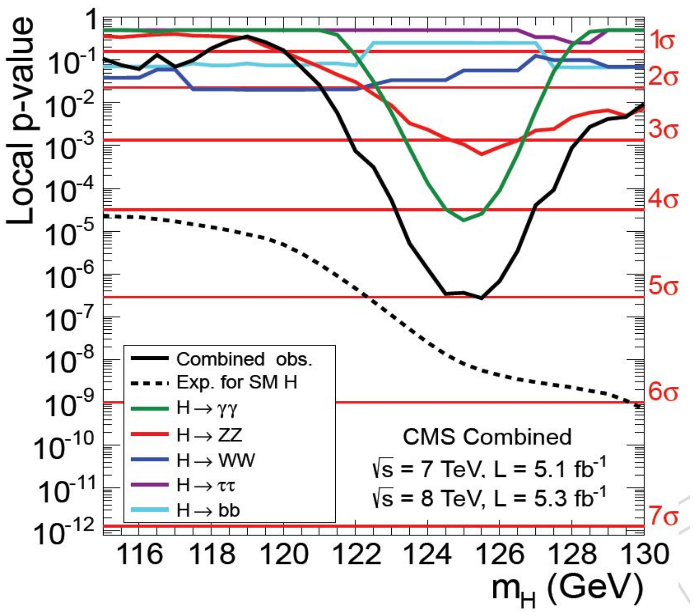
Largest local excess: 2.6σ at ~120 GeV

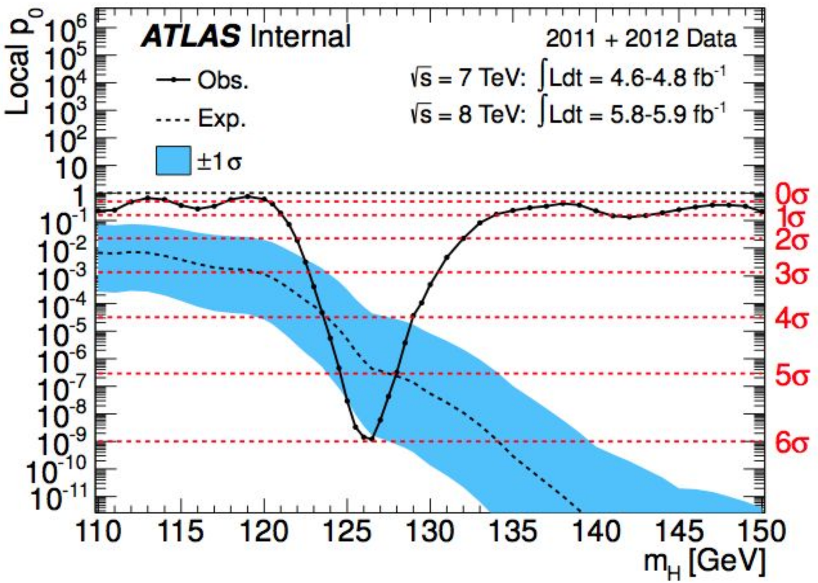
Fabiola Gianotti

"Tantalizing hints"

Guido Tonelli

July 4th, 2012: Discovery of a new boson





Combined significance 5.0σ for CMS and 5.9σ for ATLAS

125.3+-0.4+-0.5GeV

0.87+-0.23

126.0+-0.4+-0.4GeV

1.4+-0.3

2012.07 Big Discovery

arXiv.org > hep-ex > arXiv:1207.7214

Search or

High Energy Physics - Experiment

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

The ATLAS Collaboration

(Submitted on 31 Jul 2012)

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

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

5.9sigma

Phys.Lett. B716 (2012) 1-29

arXiv.org > hep-ex > arXiv:1207.7235

Search or Art

High Energy Physics - Experiment

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

The CMS Collaboration

(Submitted on 31 Jul 2012)

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

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

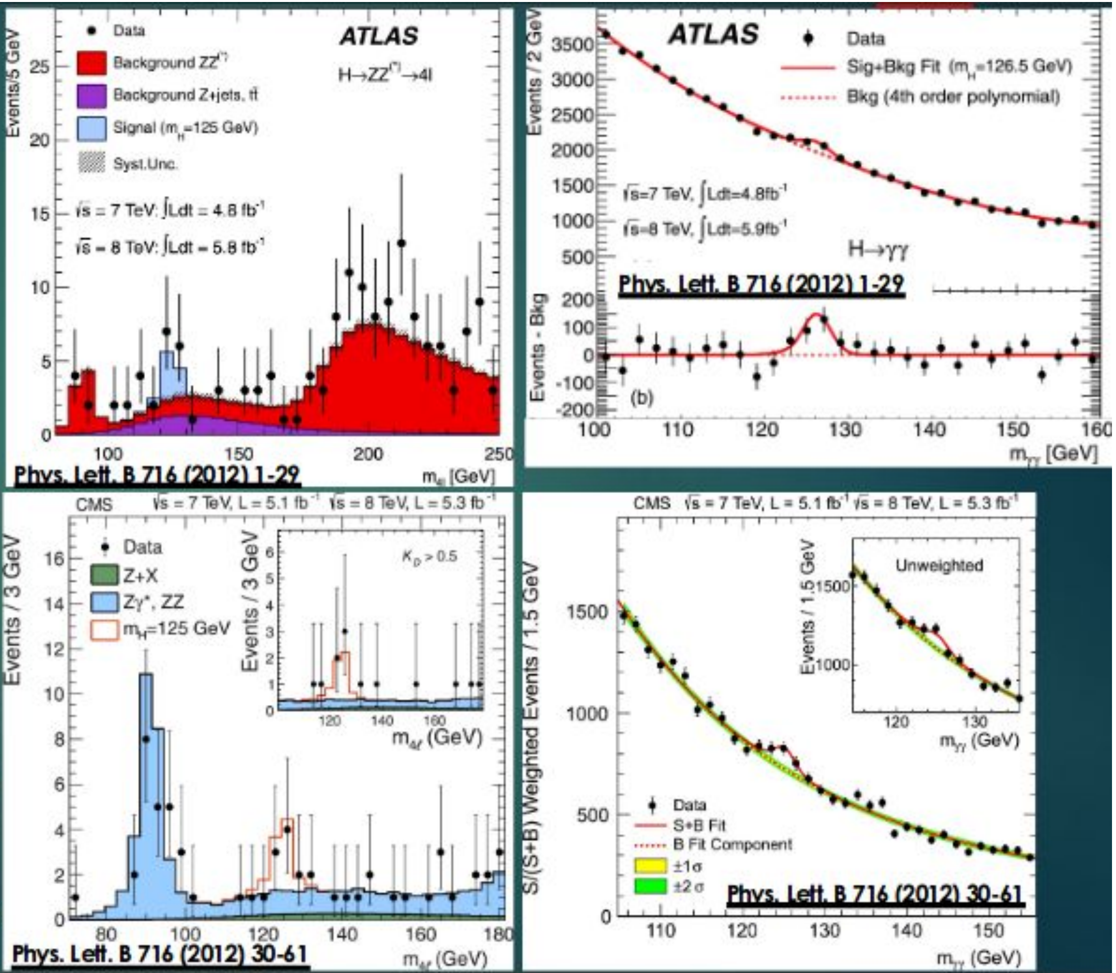
5.0sigma

Phys. Lett. B 716 (2012) 30

2012

8 years ago…

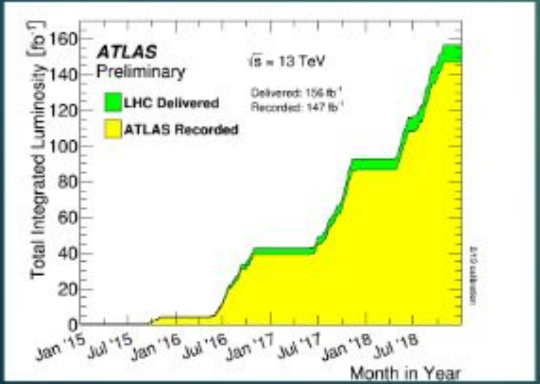
- ATLAS and CMS both first observed the Higgs boson.
  - Theorized in summer of 1964
  - Francois Englert and Peter Higgs were awarded the 2013 Nobel Prize in physics for this prediction.

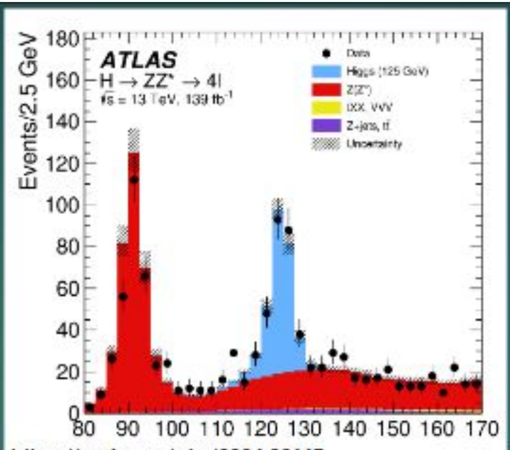


2020

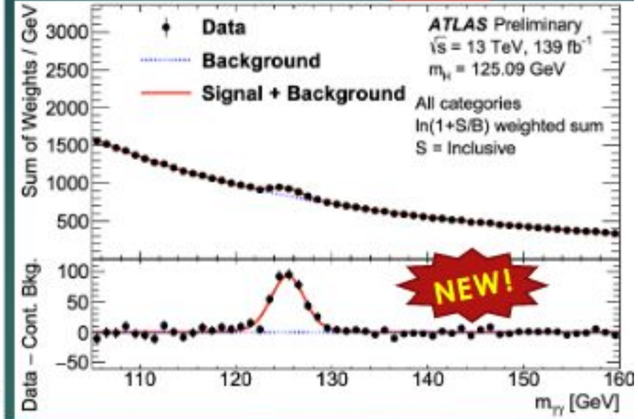
Full LHC Run 2

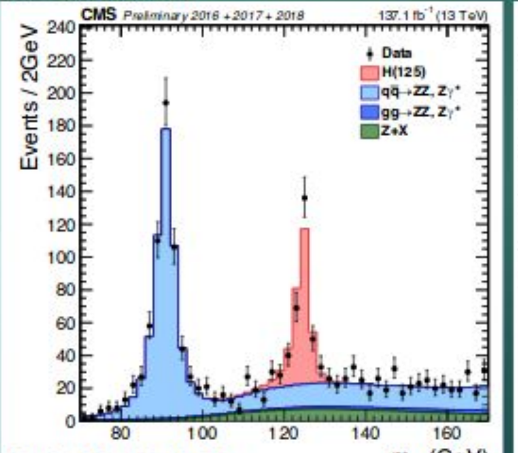
- With LHC's exceptional performance from 2015-2018 each experiment has ~140/fb of proton-proton collision data at 13 TeV, from which to harvest Higgs bosons!
  - LHC operated at twice design (!) luminosity in 2018!
  - Very impressive! Thank you LHC!



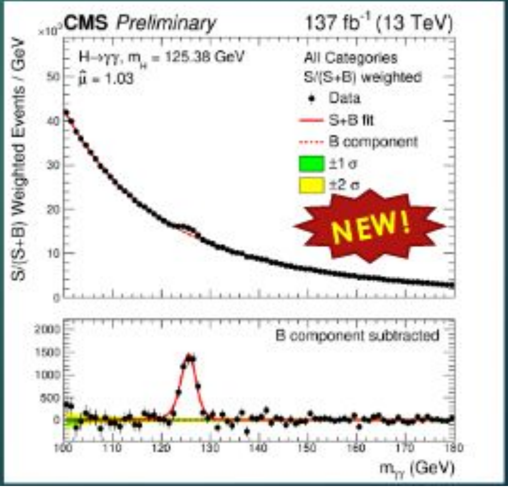


https://arxiv.org/abs/2004.03447
(Accepted in EPJC)

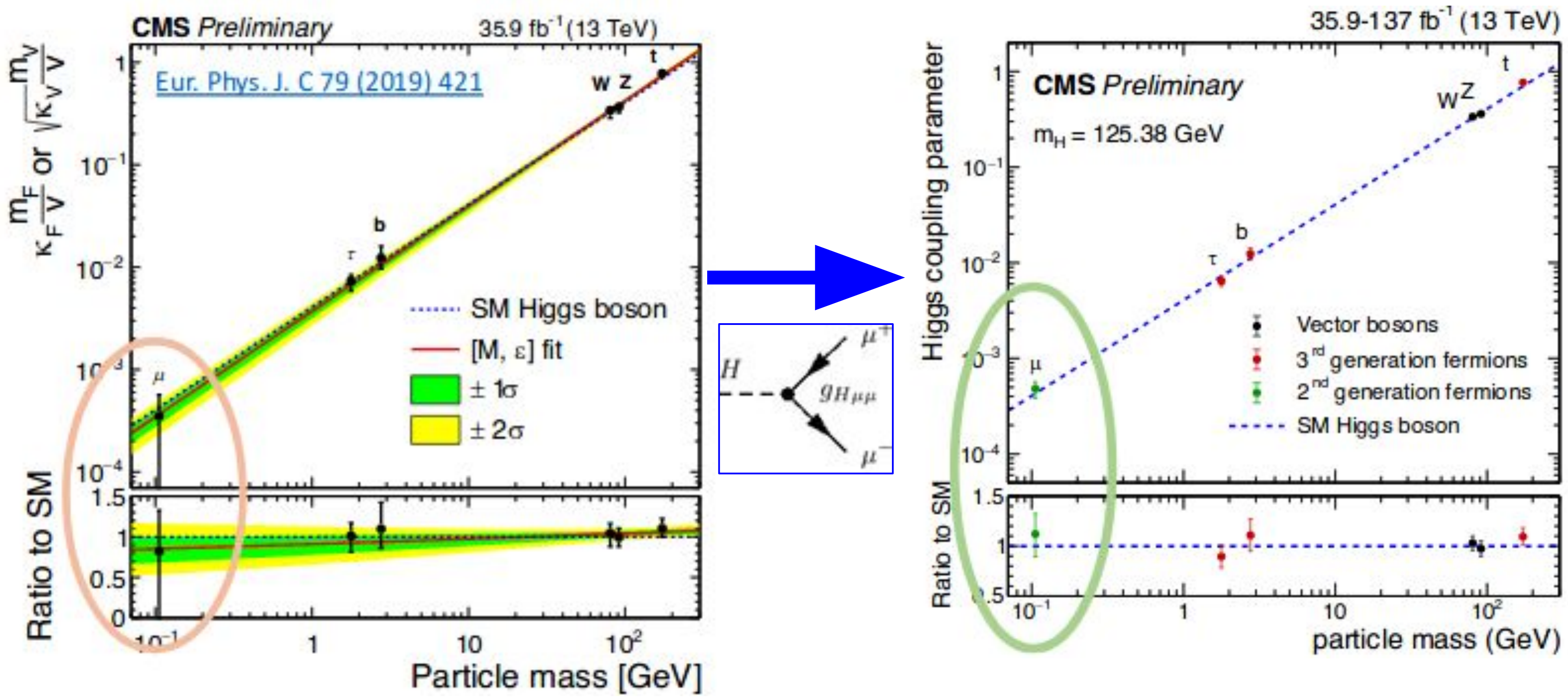




CMS-PAS-HIG-19-001



2020.8 Higgs与第二代费米子相互作用的证据！

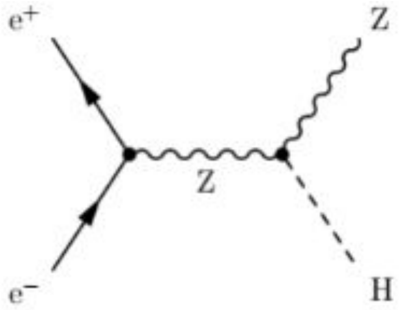


视频 two PKU Students@CERN in 2009

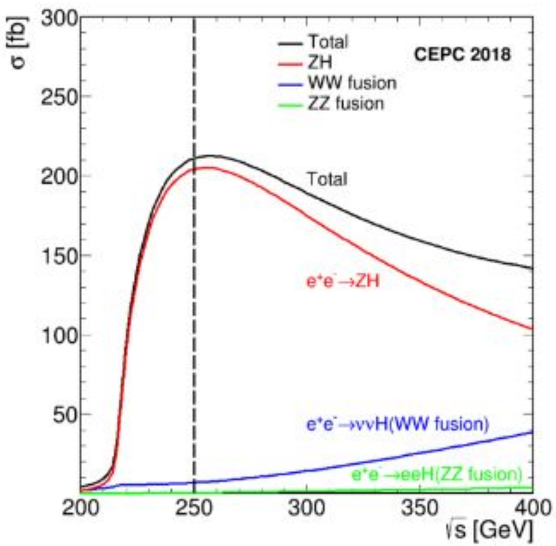
https://www.youtube.com/watch?v=dJEwyPO5PYE

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

中国环形正负电子对撞机CEPC



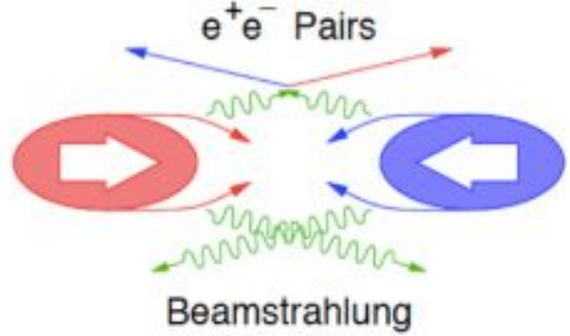
Production cross sections



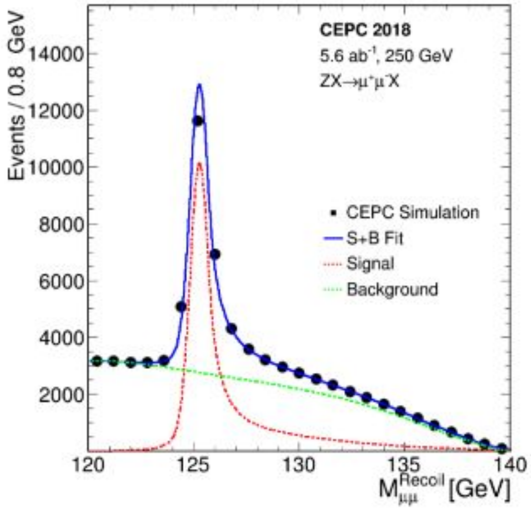
2018.11 发布概念设计报告CDR。
100公里隧道；
240-250GeV 正负电子对撞；
产生约100万Higgs；
Higgs工厂： 精确测量Higgs性质。

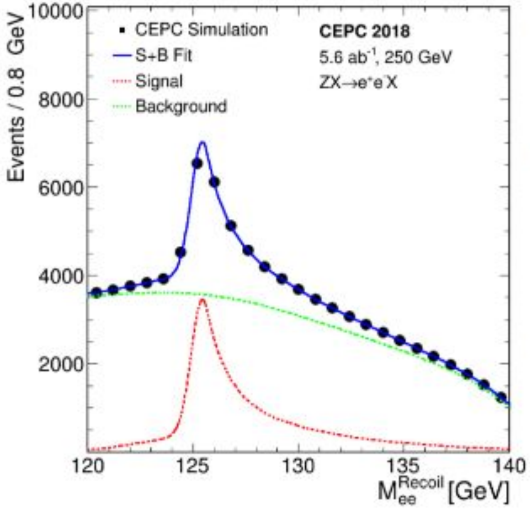
与pp对撞机相比：

- 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；

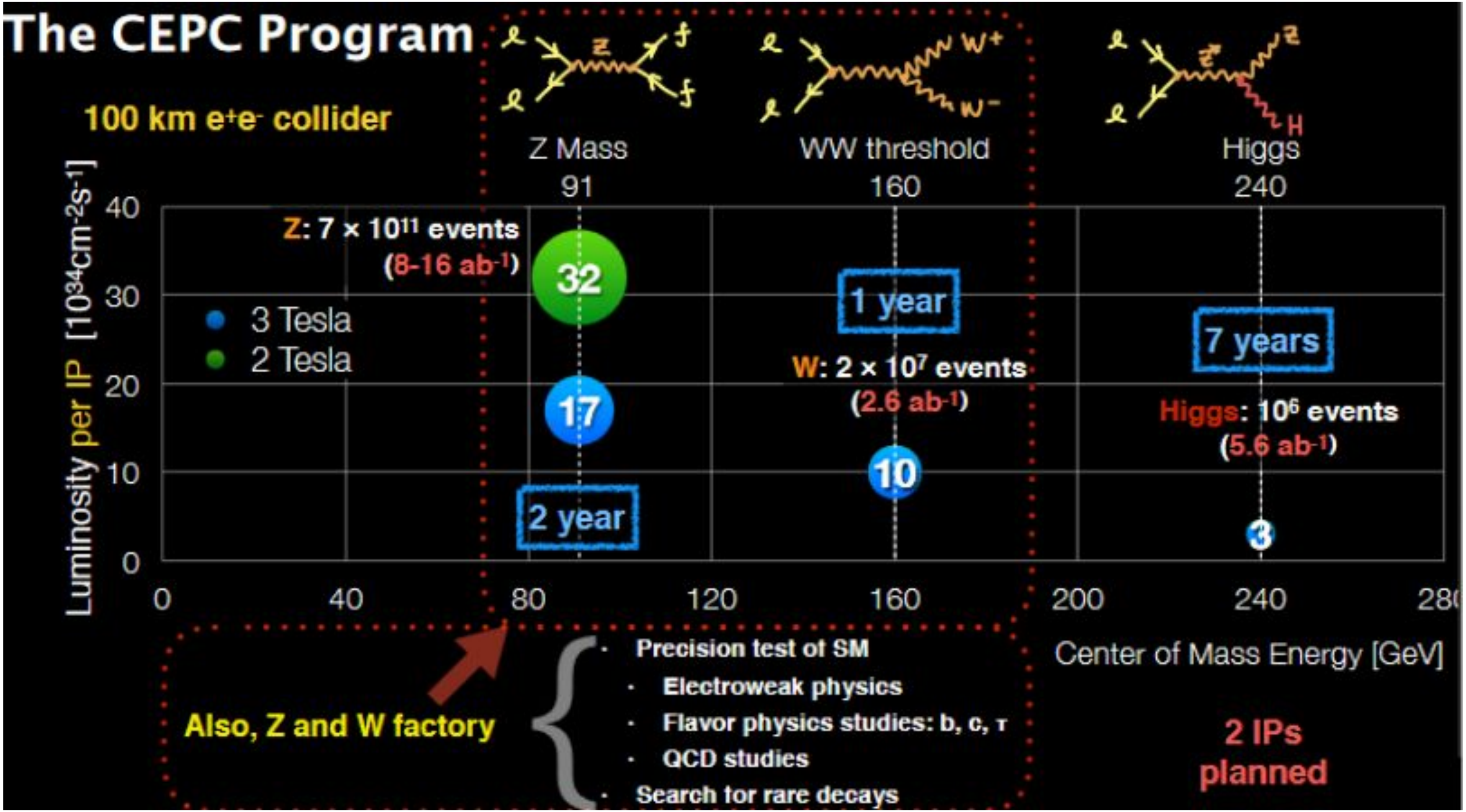


- Higgsstrahlung (ee->ZH), Z decays to a pair of visible fermions(ff), the recoil mass against the Z: $M^2_{\text{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$





- 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
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
Luminosity per IP [10^34cm^-2s^-1]
Center of Mass Energy [GeV]
Also, Z and W factory
Precision test of SM
Electroweak physics
Flavor physics studies: b, c, τ
QCD studies
Search for rare decays
2 IPs planned

https://indico.ph.ed.ac.uk/event/259/timetable/?view=standard

Milestones and activities of CEPC physics studies

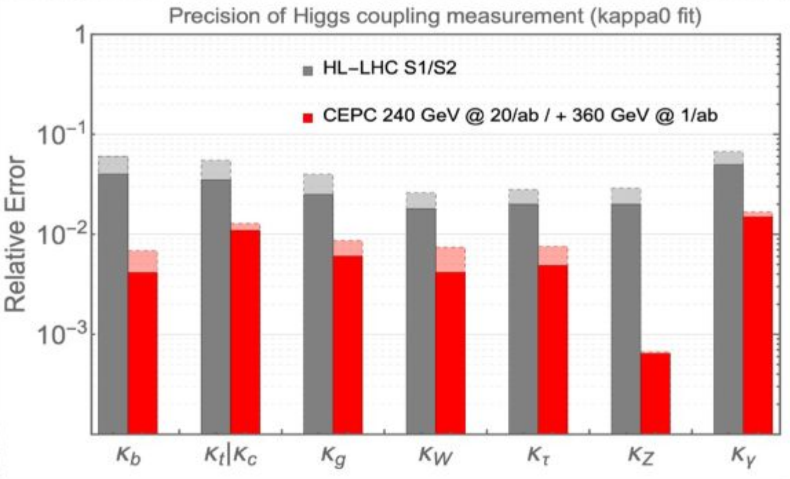
- ❖ Public documents released: CDR(2018) → Higgs white paper (2019) → Snowmass white paper (2022) → Flavor white paper to come out soon → more in preparation (EWK white paper, New physics white paper)
- ❖ CEPC physics and detector workshops in series: May 2019, April 2021, August 2023
- ❖ Physics studies 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

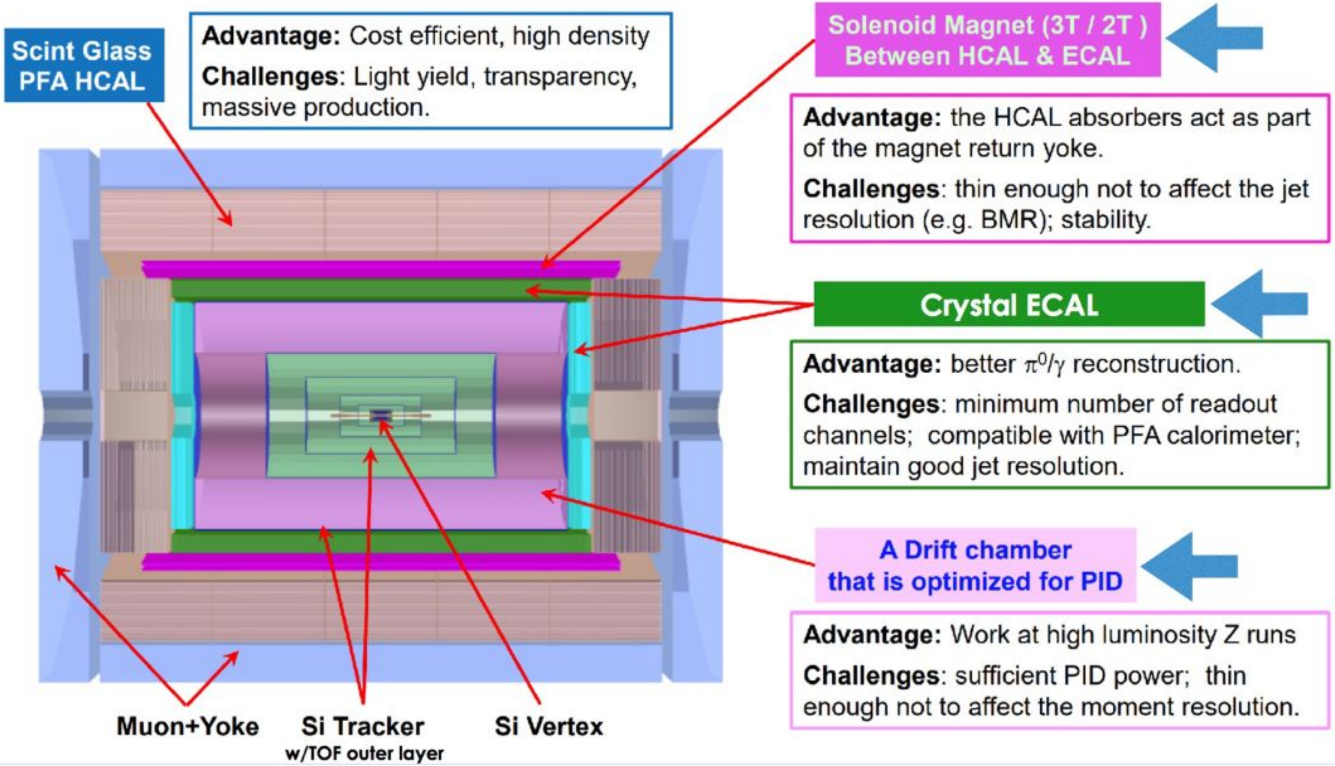
	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	vvH	ZH	vvH	eeH
inclusive	0.26%		1.40%	\	\
H→bb	0.14%	1.59%	0.90%	1.10%	4.30%
H→cc	2.02%		8.80%	16%	20%
H→gg	0.81%		3.40%	4.50%	12%
H→WW	0.53%		2.80%	4.40%	6.50%
H→ZZ	4.17%		20%	21%	
$H \to \tau\tau$	0.42%		2.10%	4.20%	7.50%
$H \to \gamma\gamma$	3.02%		11%	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



https://indico.ph.ed.ac.uk/event/259/timetable/?view=standard

The 4th Detector Concept



Excellent e/gamma energy resolution;

PID capability;

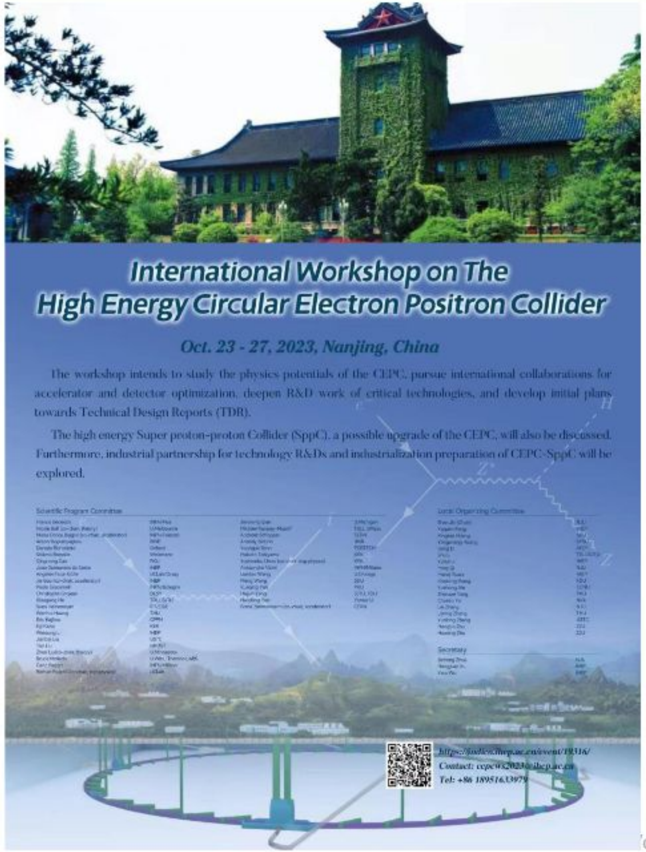
Better hadronic energy resolution;

Magnet in much reduced size.

BMR: 4% → 3%


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

Next CEPC workshop in China



International Workshop on CEPC

at Nanjing University, China

October 23-27, 2023

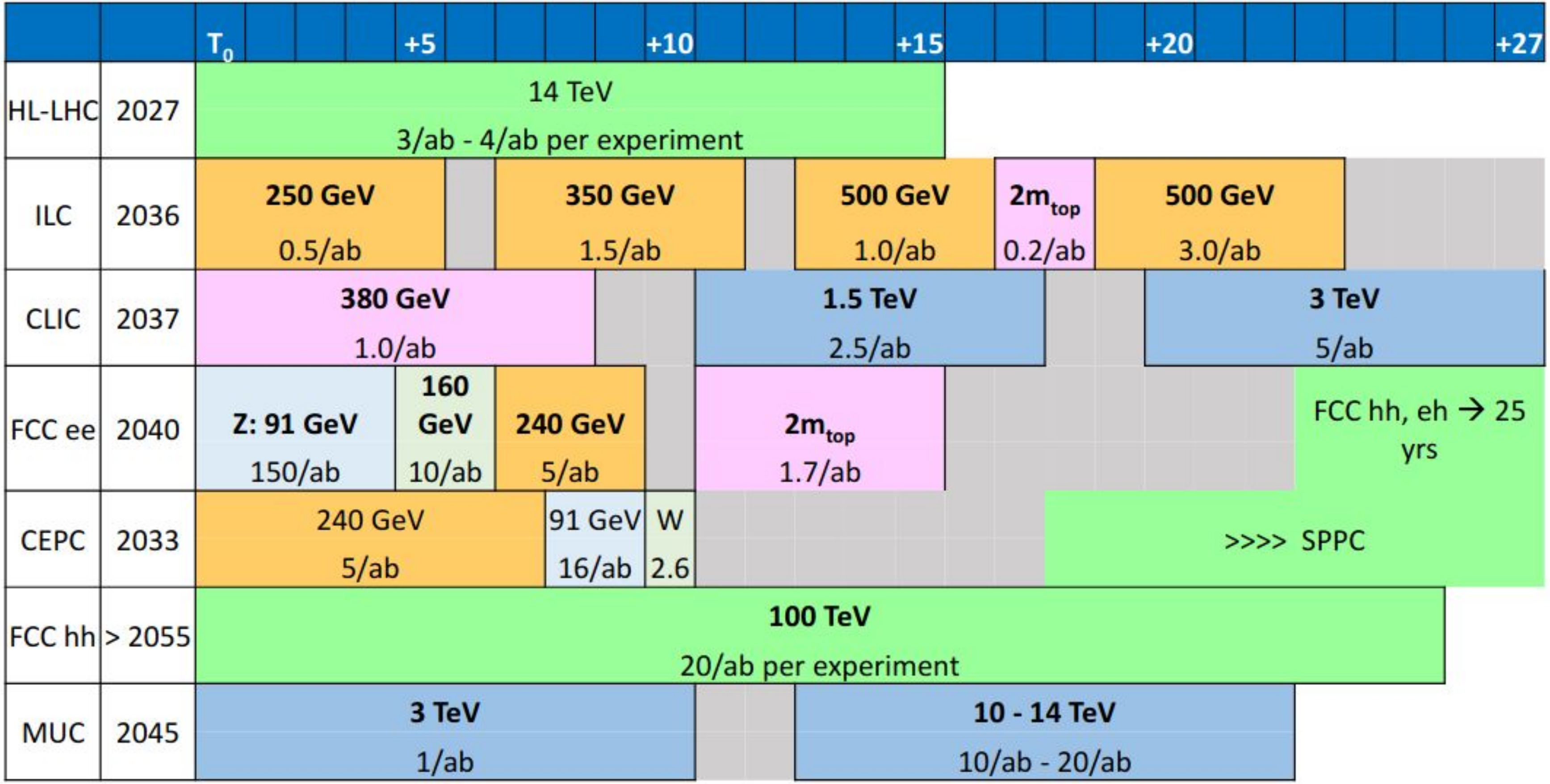
https://indico.ihep.ac.cn/event/19316/

cepcws2023@ihep.ac.cn

Please come to this workshop

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

Future colliders with earliest feasible start date



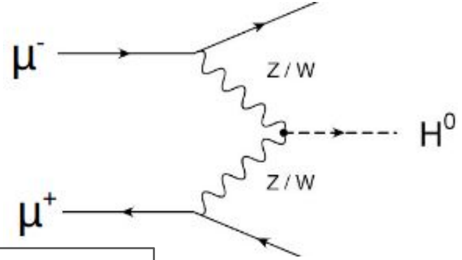
https://indico.desy.de/event/28202/contributions/102729/attachments/67953/85077/FutureColliders_LRivkin.pdf

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 <u>lifetime</u> at rest only 2.2 μs.



Parameter	Units	Higgs		Multi-TeV	
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	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, ε_{TN}	μm-rad	200	25	25	25
Norm. Long. Emittance, ε_{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

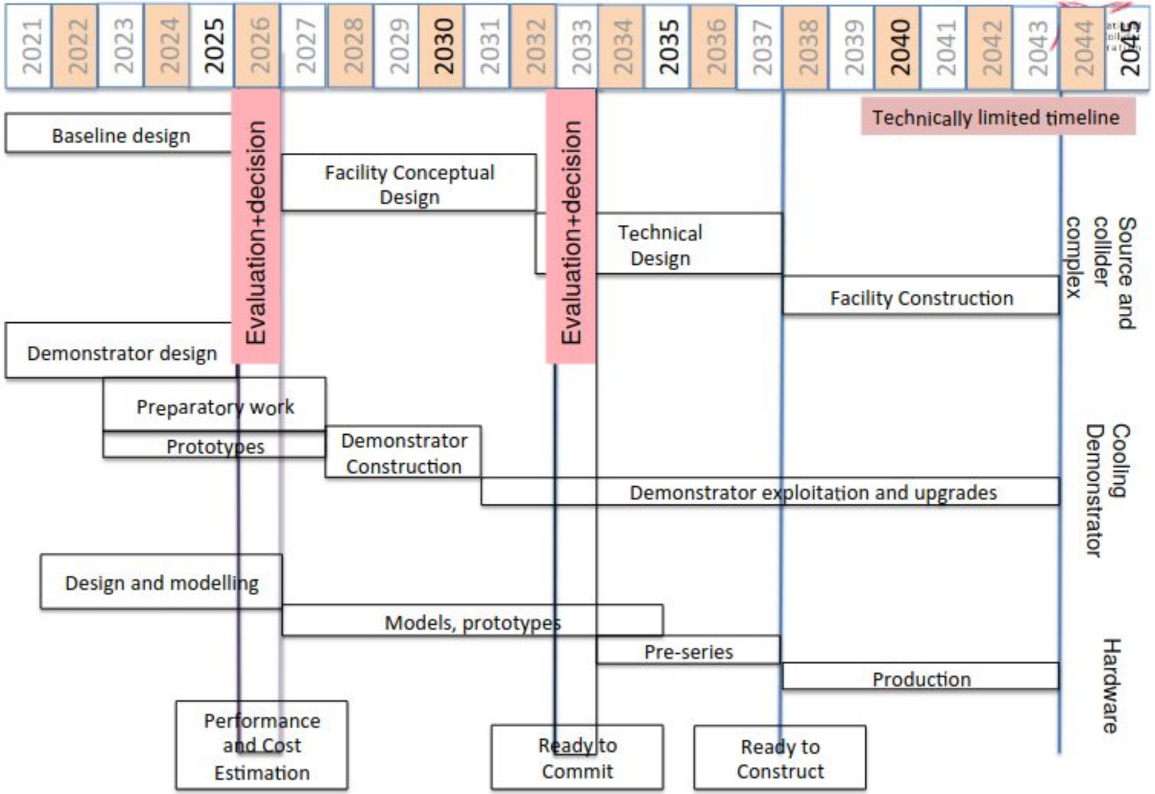
To be reviewed considering progress, funding and decisions

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

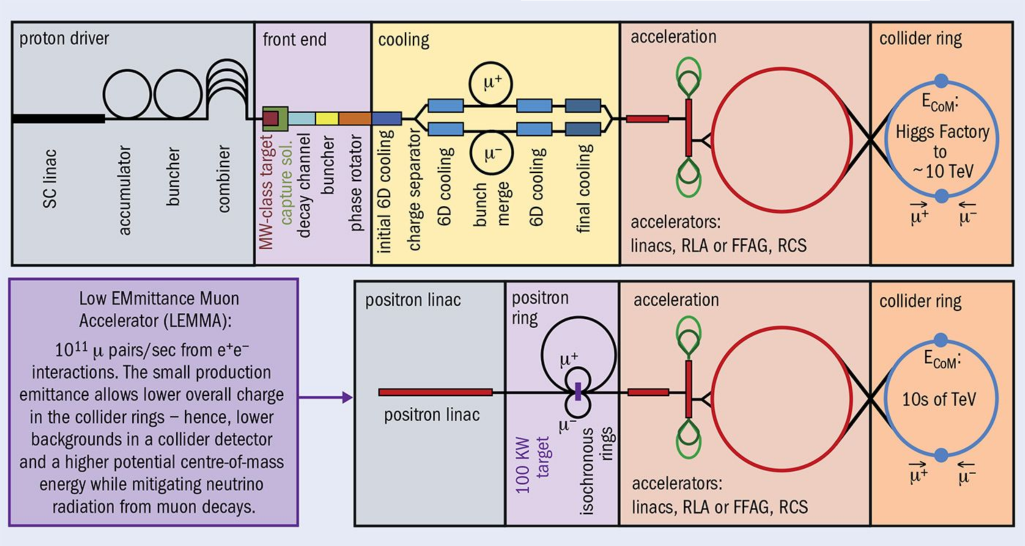


Muon Collider: beam and background

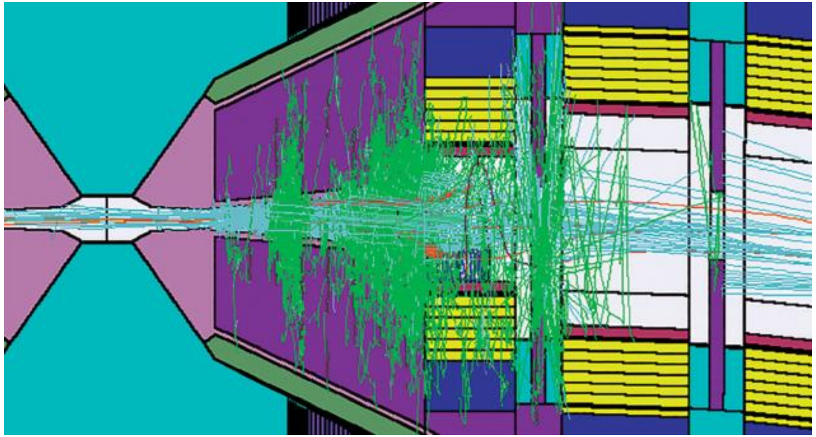
1) Muon Source

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

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

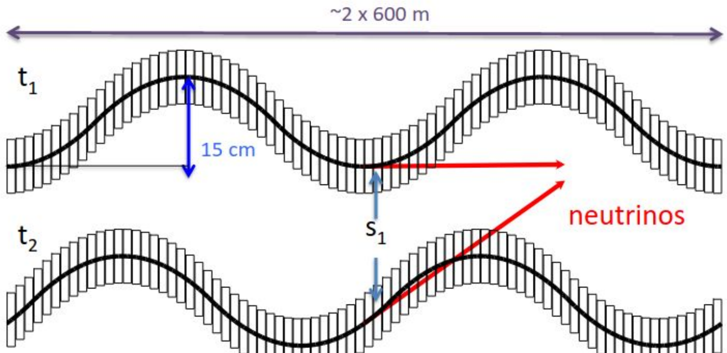


2) Muon Beam Induced background



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

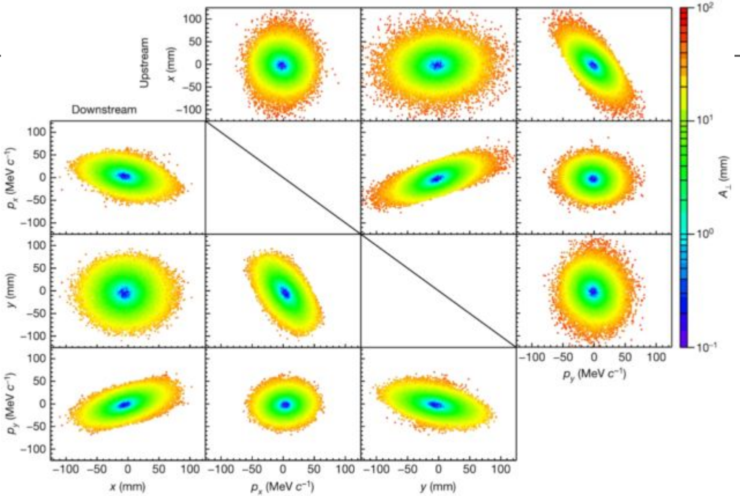
nature

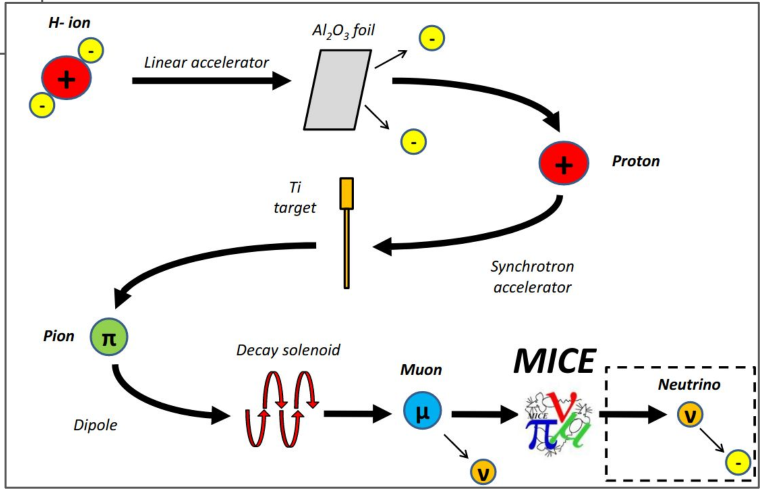
Article | Open Access | Published: 05 February 2020

Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

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

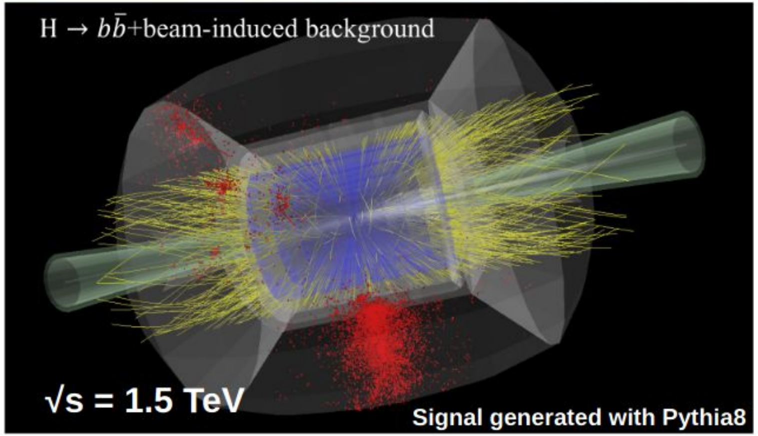


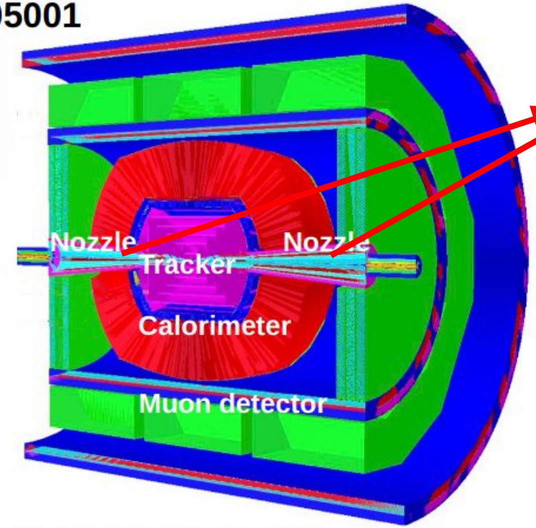


Higgs Physics at Muon Collider

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

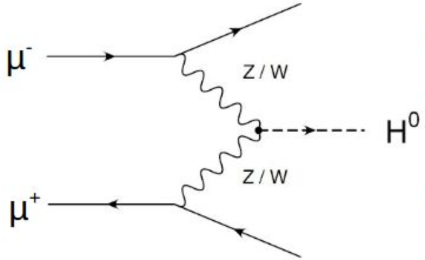
2020 JINST 15 P05001





To Suppress BIB

Lorenzo Sestini @ICHEP2020



- We studied the $\mu\mu \rightarrow \nu\nu$ H(→ 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

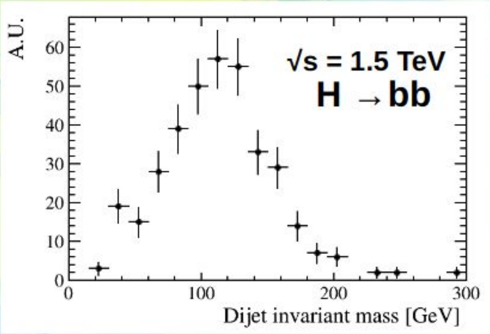
https://indico.cern.ch/event/868940/contributions/3813545/attachments/2083147/3499196/higgs_mc_ichep.pdf

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

电子-缪子对撞机

The Physics Case for an Electron-Muon Collider

Meng Lu,[1] Andrew Michael Levin,[1] Congqiao Li,[1] Antonios Agapitos,[1] **Qiang Li**,[1] Fanqiang Meng,[1] Sitian Qian,[1] Jie Xiao,[1] and Tianyi Yang[1]
Show more

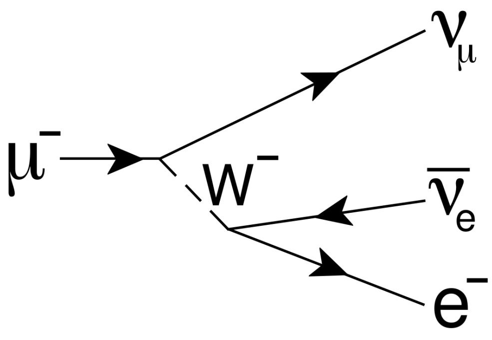
Academic Editor: Mariana Frank

Received	Accepted	Published
10 Dec 2020	08 Feb 2021	26 Feb 2021

Novel collider concept
Peking University physicists urge the community to consider the merits of a novel electron–muon collider (arXiv:2010.15144). Collisions between different species of lepton could reduce physics backgrounds for studies of charged-lepton flavour violation and Higgs-boson properties, and the asymmetric nature of the collisions could be used to control troublesome backgrounds caused by muon decays inside the accelerator, argue the authors. The preprint proposes 10 GeV electron and muon beams initially, and upgrades culminating in a TeV-scale muon–muon collider.

提出了电子缪子对撞机是矢量玻色子散射类型的对撞机的新概念！

Neutrino Beam



B. J. King hep-ex/0005007

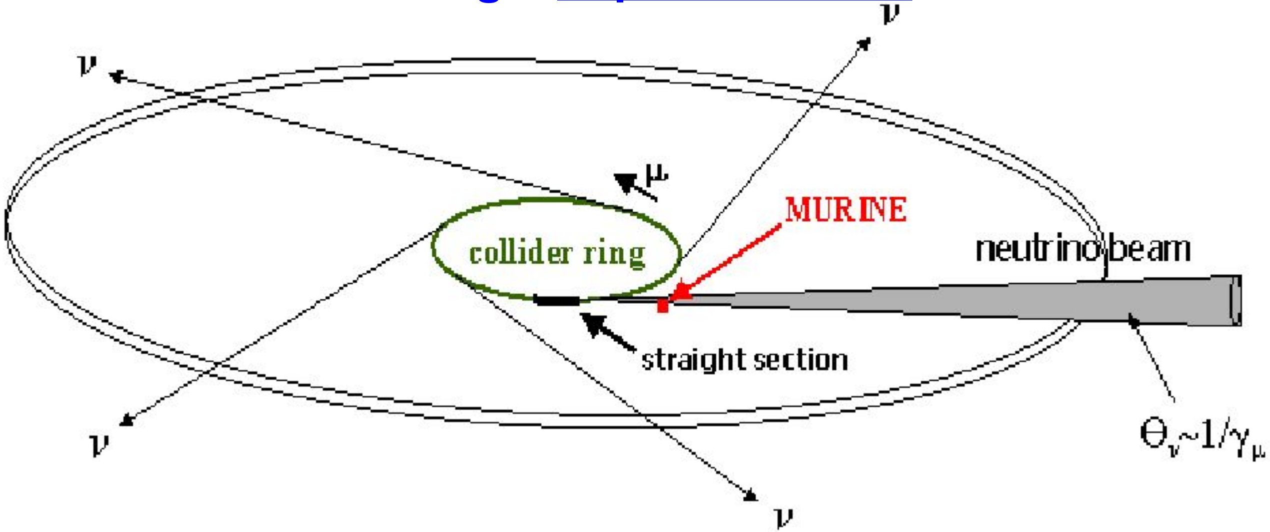


FIGURE 1. The decays of muons in a muon collider will produce a disk of neutrinos emanating out tangentially from the collider ring. The neutrinos from decays in straight sections will line up into beams suitable for experiments. The MURINEs will be sited in the center of the most intense beam and as close as is feasible to the production straight section.

NuTeV
Neutrino-Nucleon Scattering
NuMAX
NuSOnG
Neutrino Scattering on Glass
nuSTORM
"Neutrinos from STORed Muons," …for neutrino oscillation searches

很多中微子打靶实验，但是没有head-on对撞构想

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

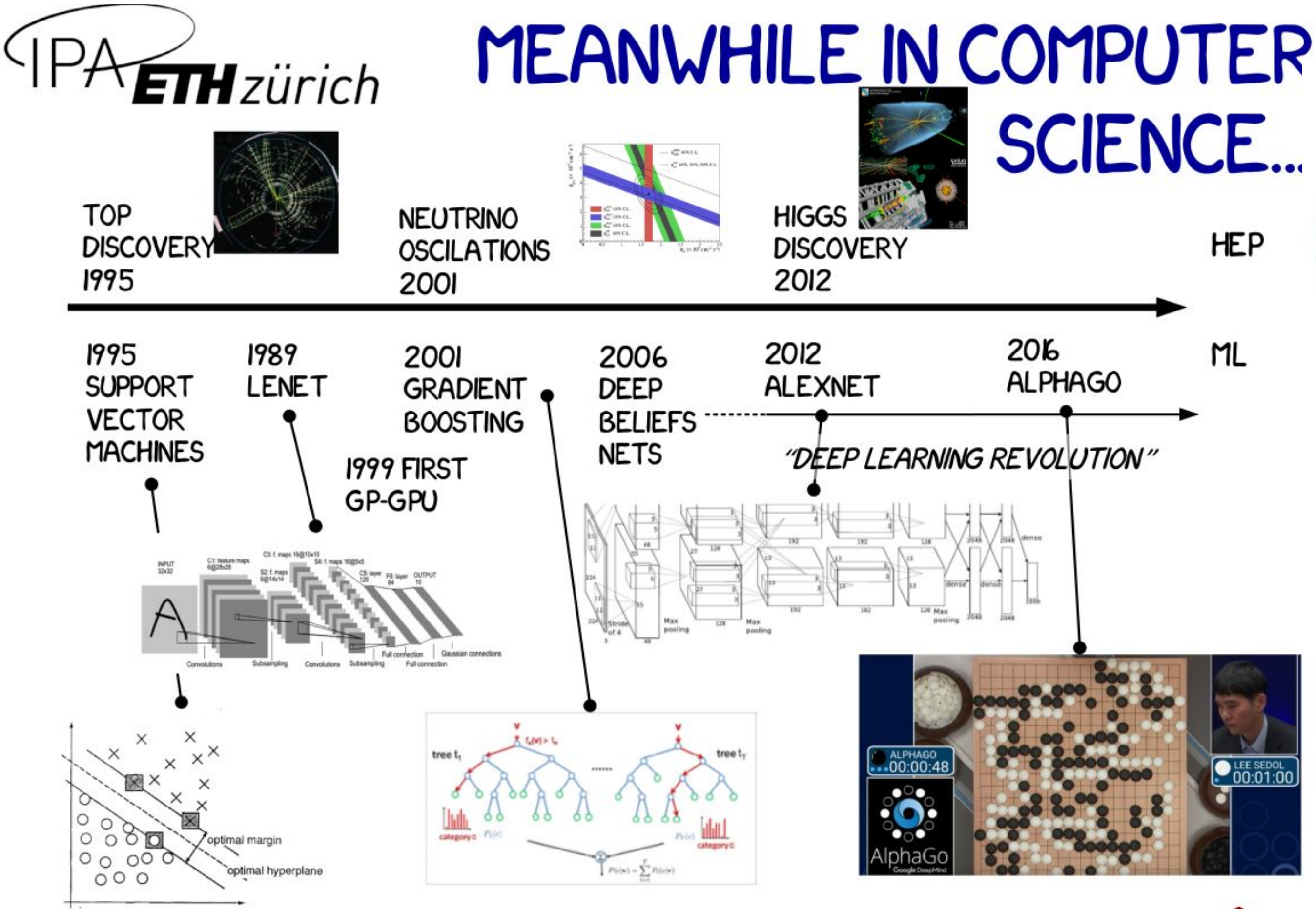
Doctoral advisor	Christopher Longuet-Higgins[3][4][5]
Doctoral students	Richard Zemel[6] Brendan Frey[7] Radford M. Neal[8] Ruslan Salakhutdinov[9] Ilya Sutskever[10]
Other notable students	Yann LeCun (postdoc) Peter Dayan (postdoc) Zoubin Ghahramani (postdoc)

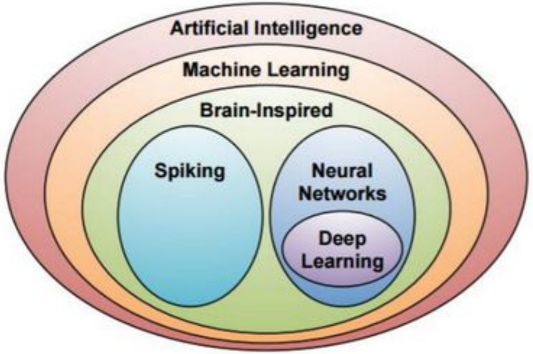
Geoffrey Hinton
FRS FRSC CC

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)

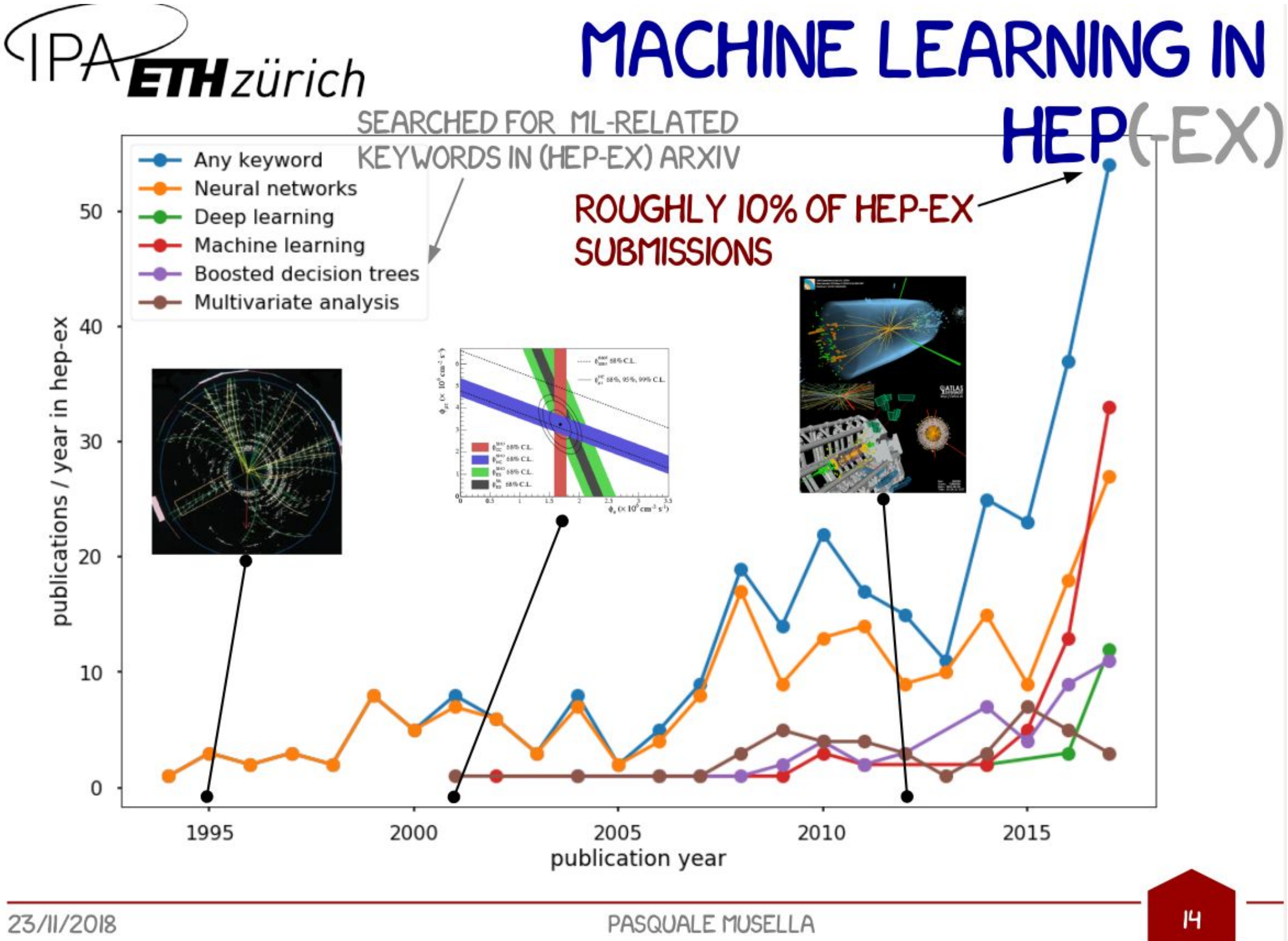
机器学习简史



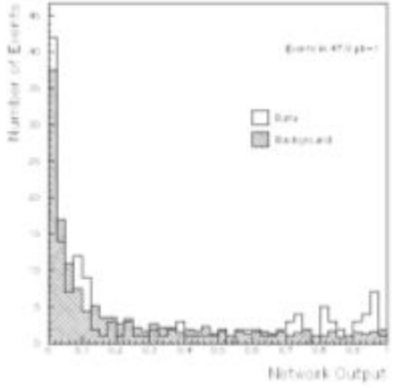


2018年图灵奖

高能物理机器学习应用简史



SEARCH FOR TTBAR USING NN AT D0



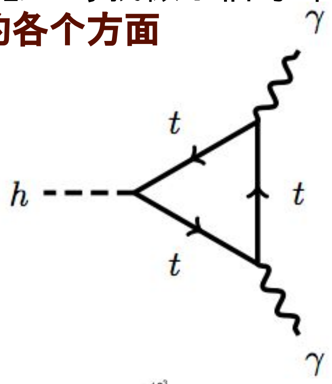
[HEP-EX/9507007]

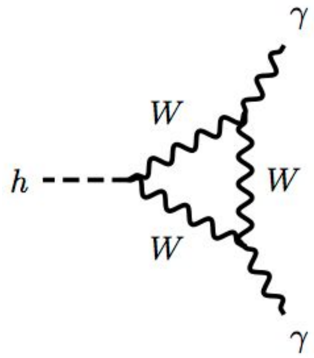
Tevatron：Top夸克
LHC: Higgs发现
miniBOONE: 粒子鉴别

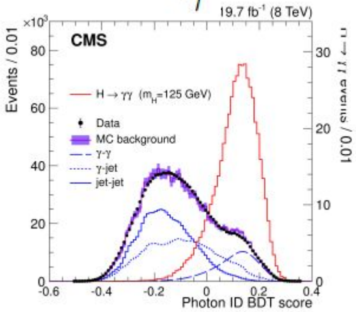
机器学习应用：Higgs粒子寻找

CMS实验中Higgs双光子道的寻找：

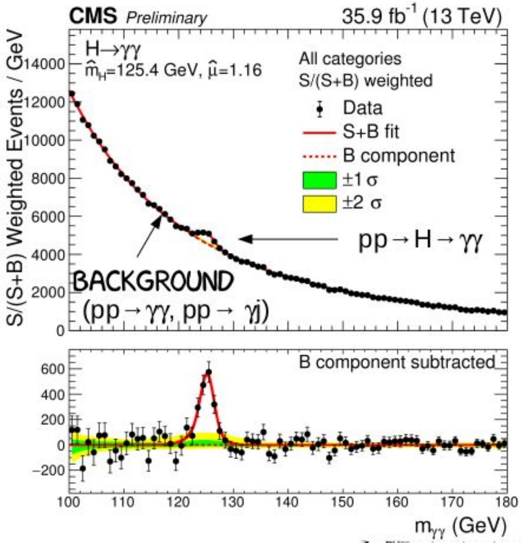
- 分支比10^{-3}: 在本底上寻找微小信号峰；
- **BDT应用于分析的各个方面**
  - 光子鉴别
  - 事例分类
  - 光子能量
  - 双光子顶点



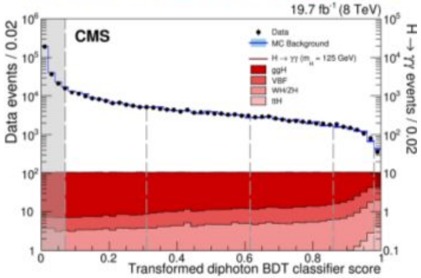




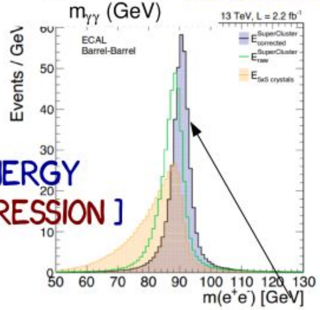
[PARTICLE-ID: SEPARATE PROMPT γ FROM HADRONIC JETS]



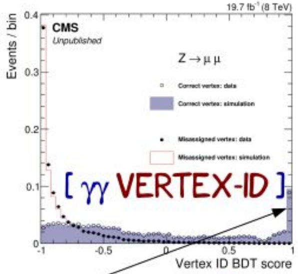
[EVENT CLASSIFICATION]



[INVARIANT MASS ESTIMATION]



[γ ENERGY REGRESSION]



[γγ VERTEX-ID]

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

机器学习应用：NNPDF

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

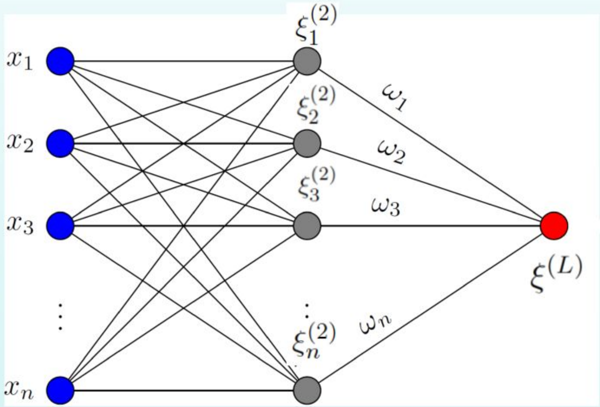
Traditional approach

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

← not from QCD!

NNPDF approach

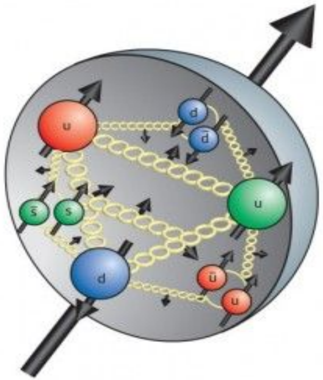
$$g(x, Q_0) = A_g \mathrm{ANN}_g(x)$$

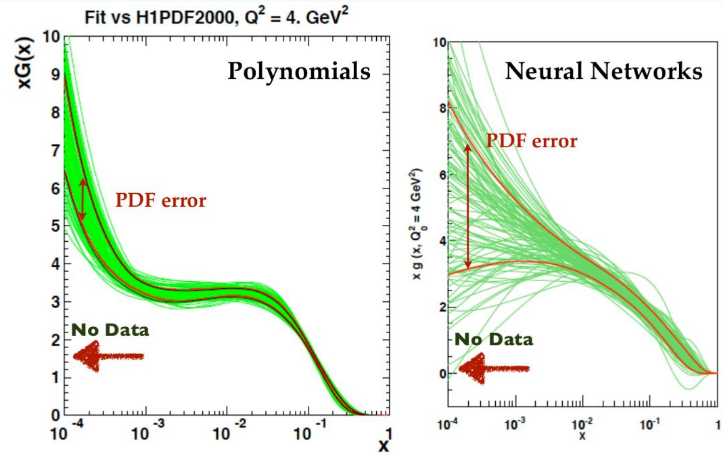


$$\mathrm{ANN}_g(x) = \xi^{(L)} = \mathcal{F}\left[\xi^{(1)}, \{\omega_{ij}^{(l)}\}, \{\theta_i^{(l)}\}\right]$$

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

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



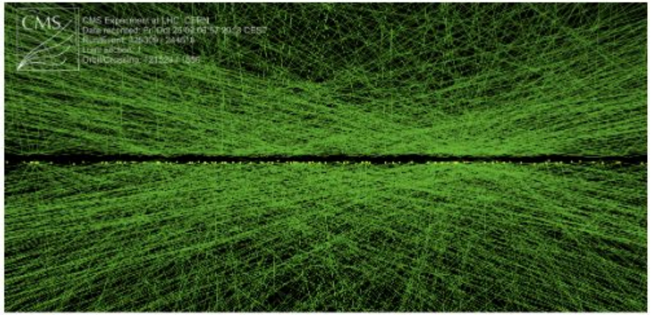


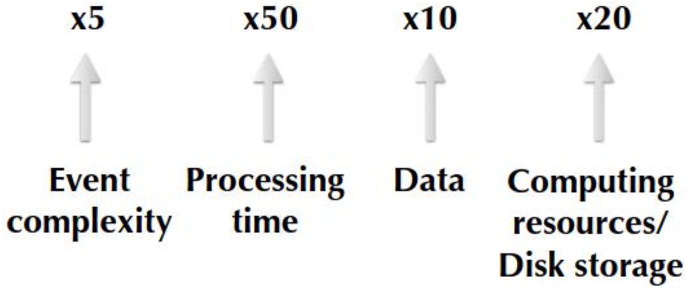
ANNs avoid biasing the PDFs, faithful extrapolation at small-x (very few data, thus error blow up)

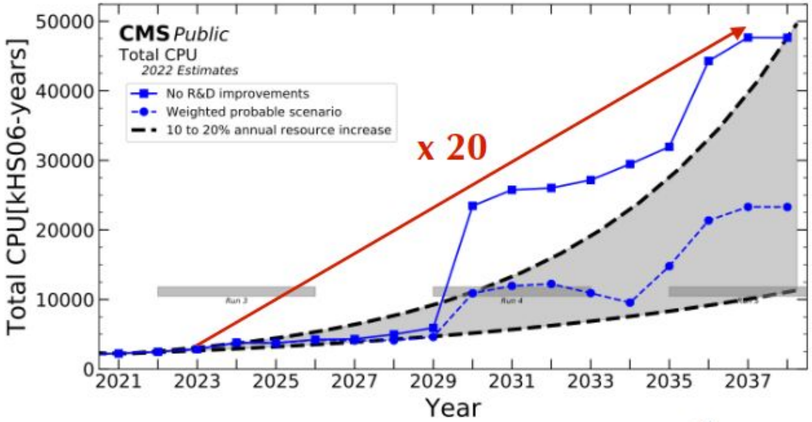
The HL-LHC challenge

With more particles per collision and more readout channels to combine, the reconstruction to become even more computing intensive

We cannot throw away more data
We must increase the throughput
with at most flat budget for computing resources
We must do more with less
to preserve the physics!

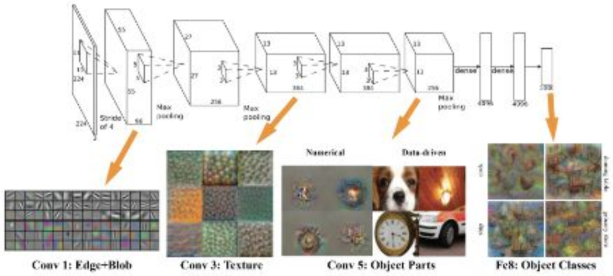




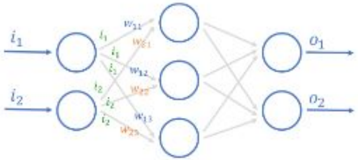


Source

ML as a solution



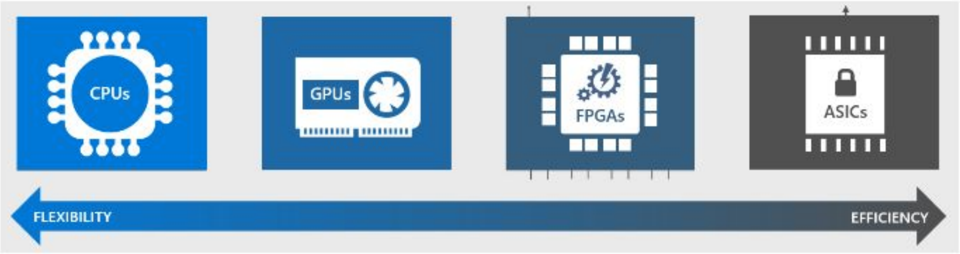
- **High accuracy**
  - improved physics performance: capacity to extract most useful info from complex datasets
  - better scaling with data complexity (HL-LHC)
  - enables novel strategies (e.g., anomaly detection)



- **Fast speed**
  - reduced development time
  - matrix multiplication can be massively parallelized
  - take advantage of reduced precision

$$\begin{bmatrix} w_{11} & w_{21} \\ w_{12} & w_{22} \\ w_{13} & w_{23} \end{bmatrix} \cdot \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} (w_{11} \times i_1) + (w_{21} \times i_2) \\ (w_{12} \times i_1) + (w_{22} \times i_2) \\ (w_{13} \times i_1) + (w_{23} \times i_2) \end{bmatrix}$$

- **Better portability**
  - many dedicated processors: GPUs, FPGAs, TPU, IPU, …
  - large investment in tools to compile and optimize ML models for the hardware

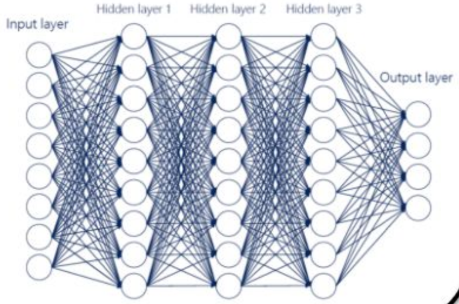


Where ML is (will be) used in CMS

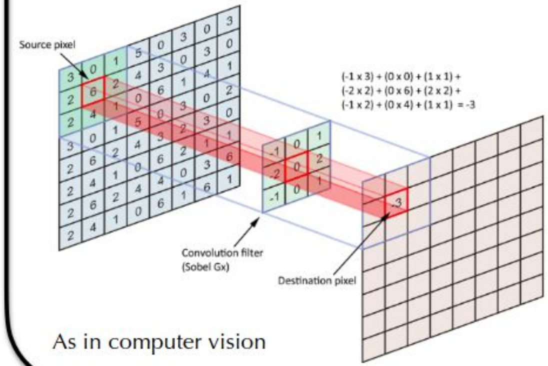
Operations	• Monitoring and anomaly detection for logs • Automated decision making for grid jobs and data management
Front-end electronics	• Fast ML on ASICs for data compression in Phase 2 HGCAL
Trigger	• Fast ML on FPGAs for Run 3 & Phase 2 L1 trigger and 40 MHz scouting
DQM	• Automated data certification • Online anomaly detection (ECAL, HCAL, muon system)
Simulation	• Calorimeter/jet simulation with generative adversarial networks, variational autoencoders, normalizing flows, diffusion models
Calibrations	• Jet energy corrections and scale factors
Reconstruction	• Energy and mass regression (e.g., MET, photons, electrons, jets) • PU mitigation • Clustering (e.g., calorimeter, jets, vertexing) • Particle flow
Analysis / object ID	• Tau leptons, heavy flavour / boosted / displace jets tagging • Event classification • Background estimation • Uncertainties evaluation

Data representations

High level/tabular: fully connected NN, BDTs

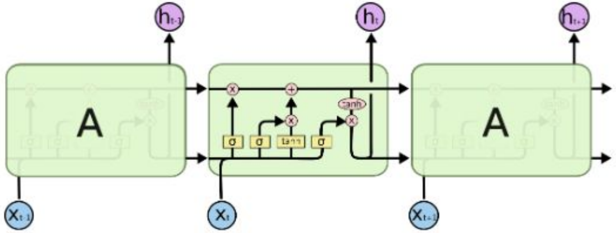


Regular grid: convolutional NN



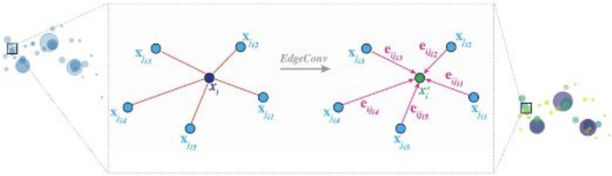
As in computer vision

Ordered sequence/time series: recurrent NN, transformers



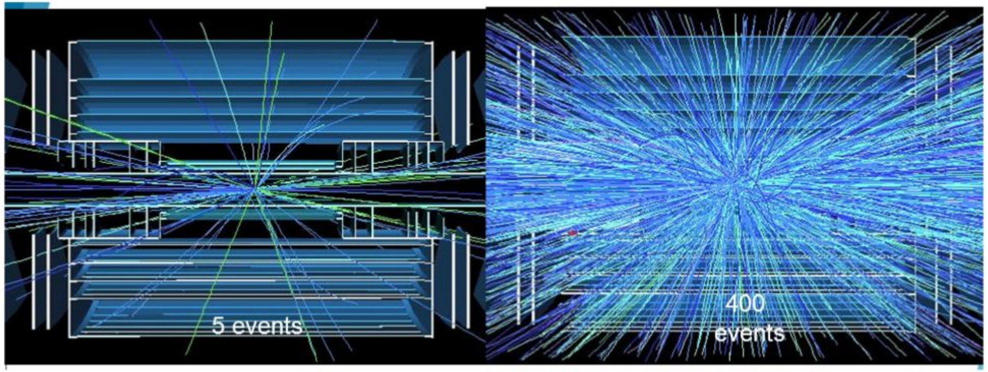
As in natural language processing

Point cloud: Deep sets, graph NN, transformers

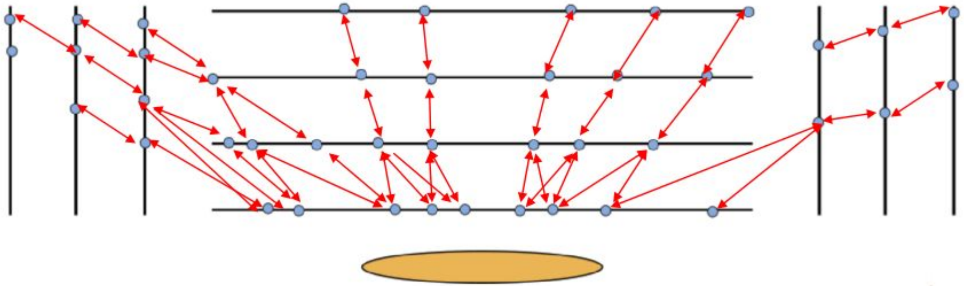


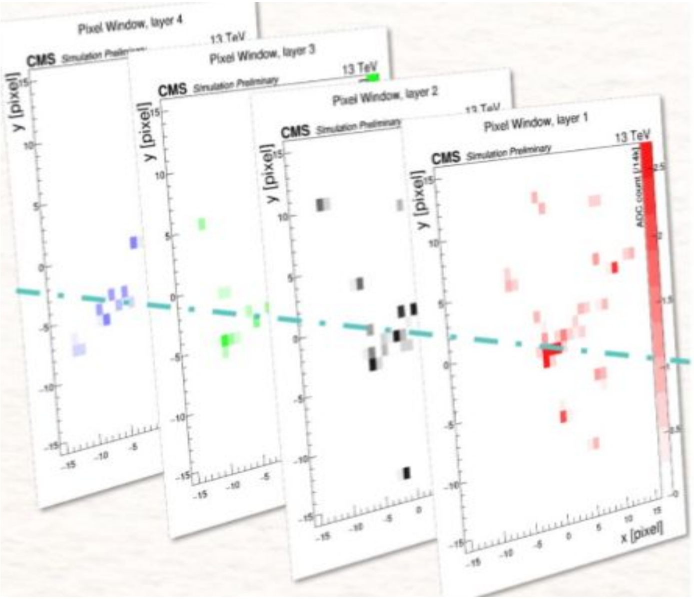
As in social media analysis

CNN应用： 径迹重建



嘈杂环境中重建带电粒子径迹，具有挑战性：
误组合，假种子

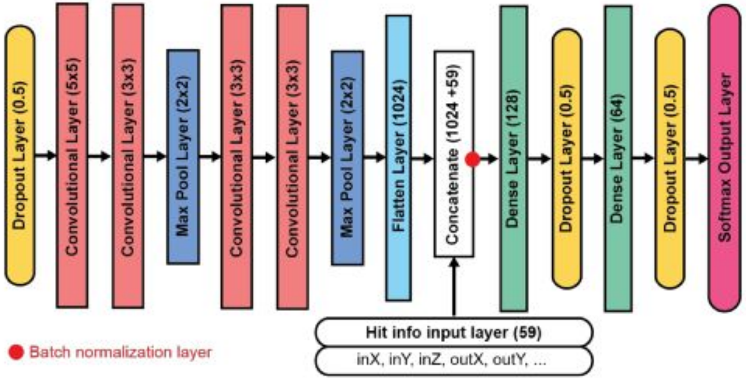




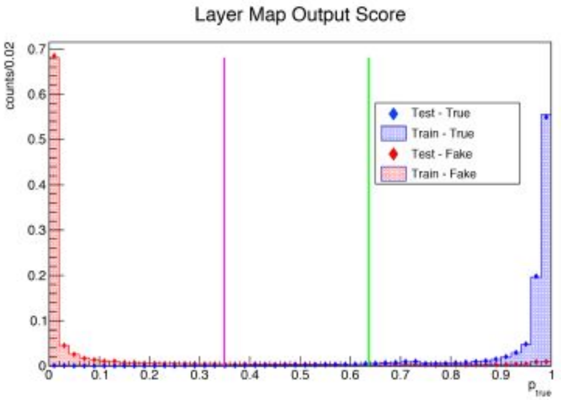
CNN应用：径迹重建

PixelSeed ConvNN

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



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



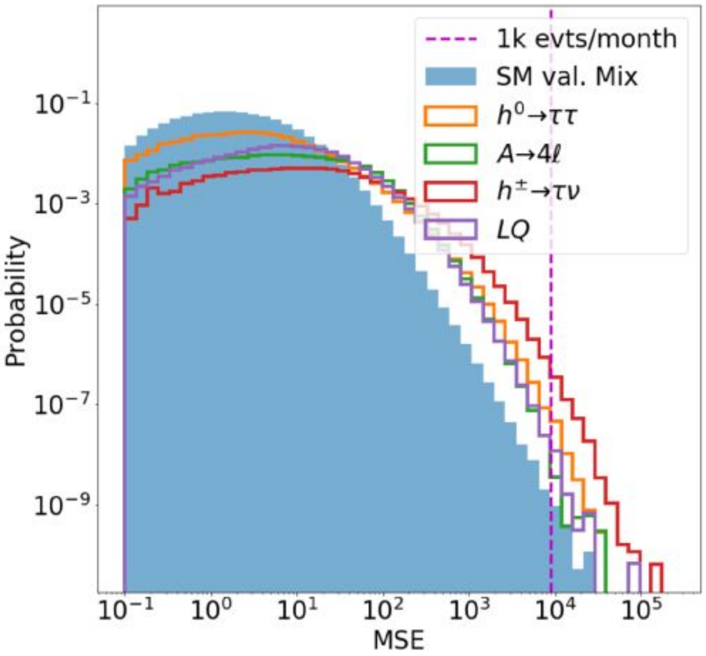
- **One can reduce the fake rate by one order of magnitude with a few % loss in efficiency**

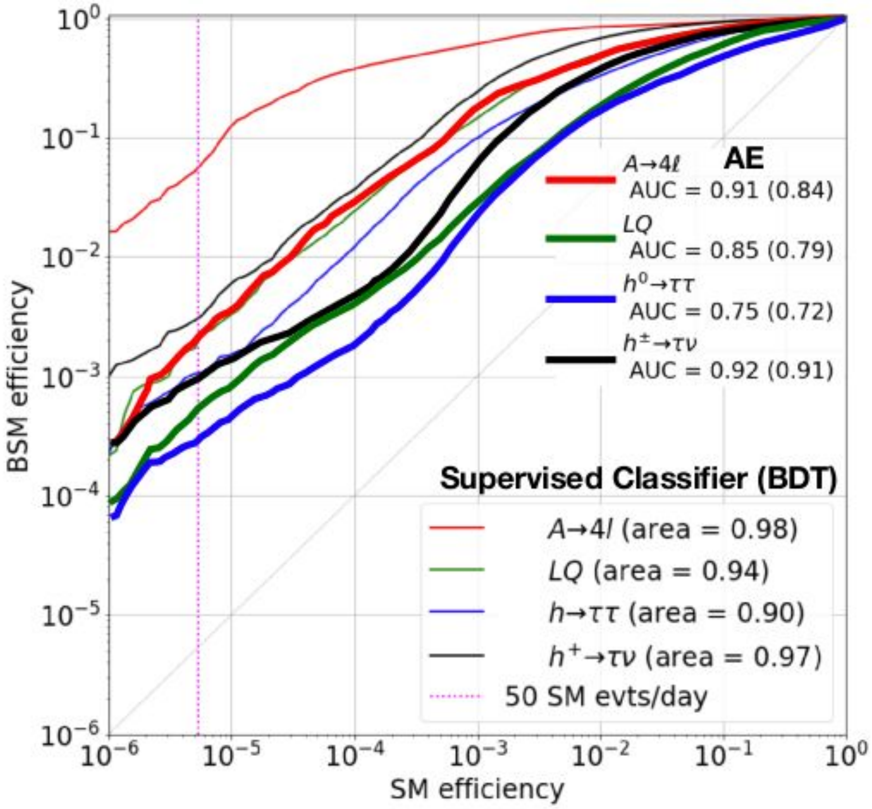
```
Efficiency (tpr) @ fake rejection
tpr @ rej 50%: 0.998996700259
tpr @ rej 75%: 0.990524391331
tpr @ rej 90%: 0.922210826719
tpr @ rej 99%: 0.338669401587
```

自编码:自动寻找新物理

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

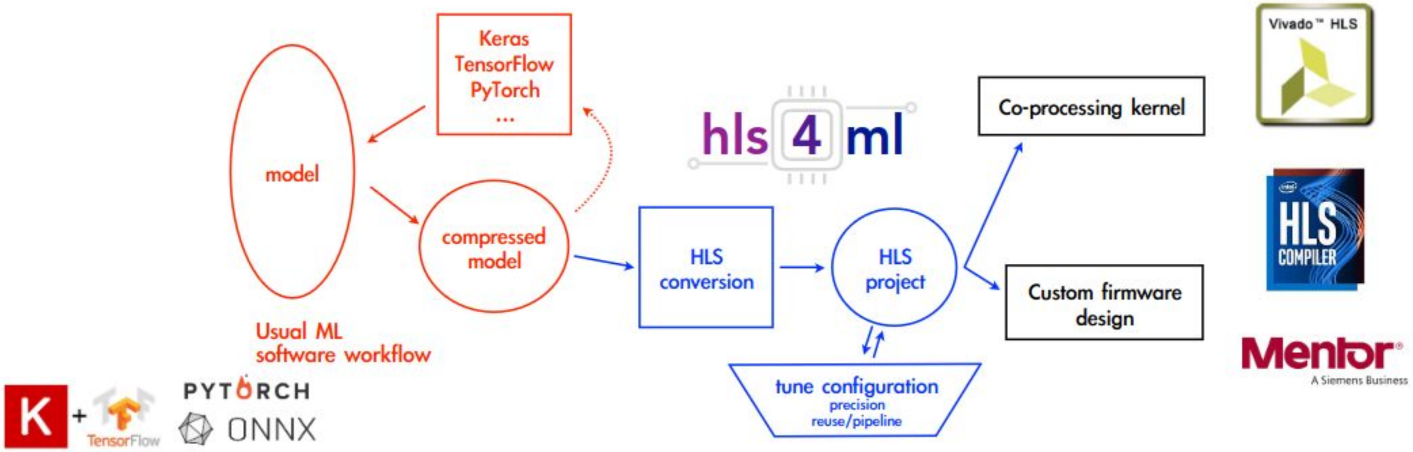
Worse than Supervised but results encouraging





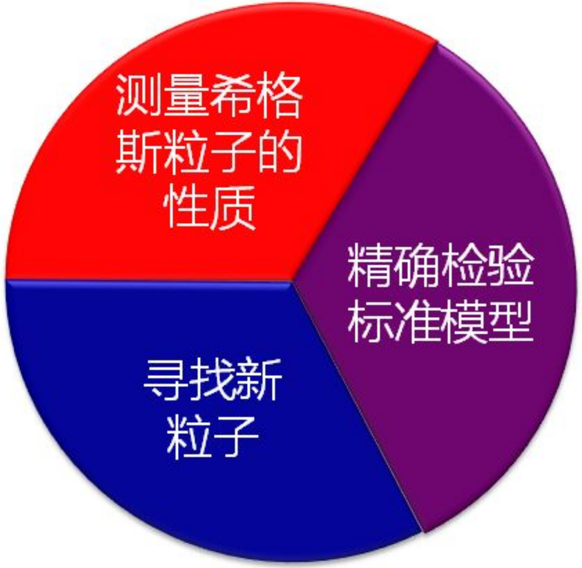
ML @ CMS: triggering

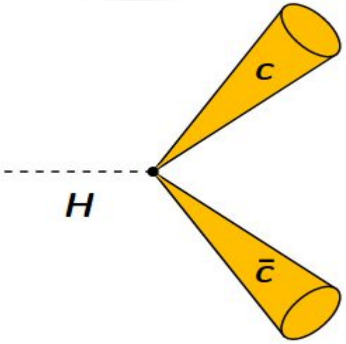
- The L1 trigger must achieve orders of magnitude of data reduction while preserving the interesting physics
- The challenge: it must do it as fast as **a few microseconds → algorithms run on FPGAs**
- CMS physicists developed **hls4ml** to automatically translate NNs to FPGA firmware for users with limited knowledge in firmware development
  - internal optimization to meet the strict latency and hardware resources constraints
- Many interesting use cases that were once possible only offline are now being developed for Run 3 and Phase 2 L1 trigger system! **(see CMS-TDR-021)**

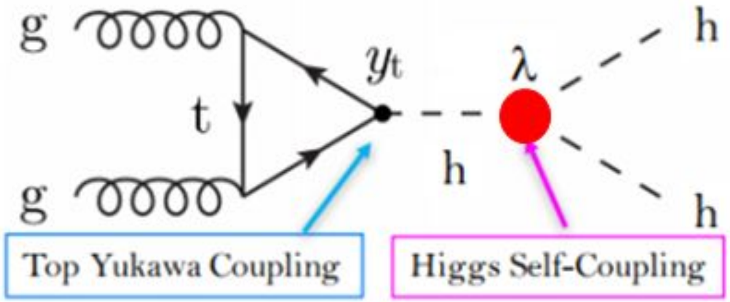


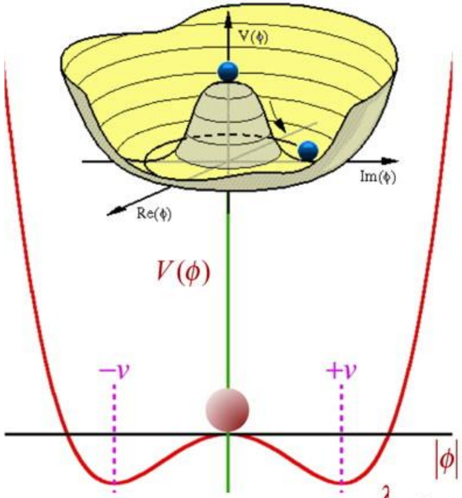
1. 前言
2. 高能物理简介
3. 大型强子对撞机(LHC)
4. Higgs的发现
5. 中国未来对撞机(CEPC)
6. 其他对撞机
7. 高能物理中的机器学习
8. **总结与展望**

Summary









$$V(\phi) = \tfrac{1}{2}\mu^2\phi^\dagger\phi + \tfrac{1}{4}\lambda(\phi^\dagger\phi)^2$$

Groundstate at $|\phi_0| = \sqrt{\frac{-\mu^2}{\lambda}} \equiv \upsilon$

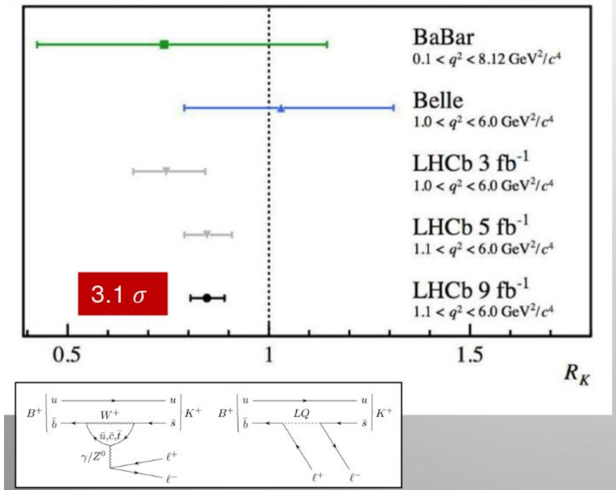
$$|\phi| = \sqrt{\phi^\dagger\phi} = \sqrt{\phi^{+\dagger}\phi^+ + \phi^{0\dagger}\phi^0}$$

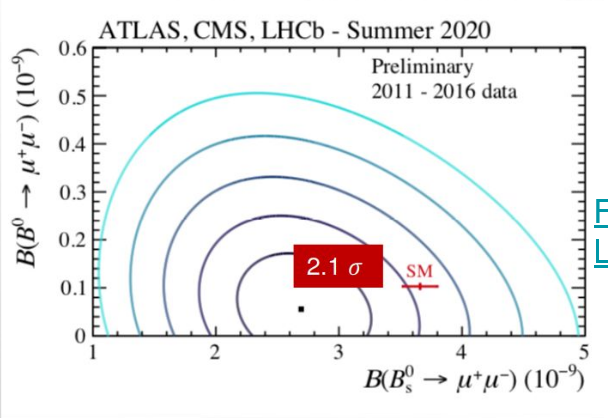
$$V(\phi_0) = -\frac{\lambda}{4}\upsilon^4$$

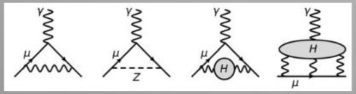
Summary

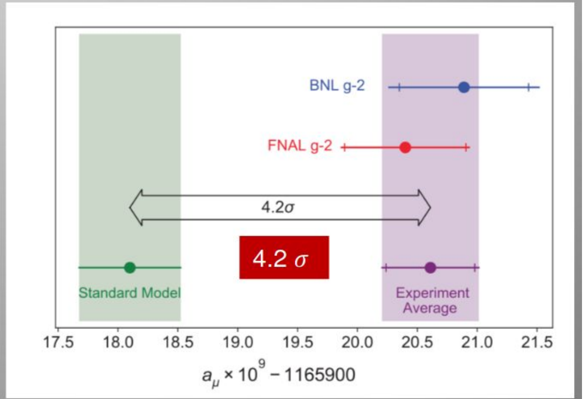
Recent muon anomalies, IF confirmed, may indicate (a close) scale of new physics (and drive a paradigm shift in particle physics)

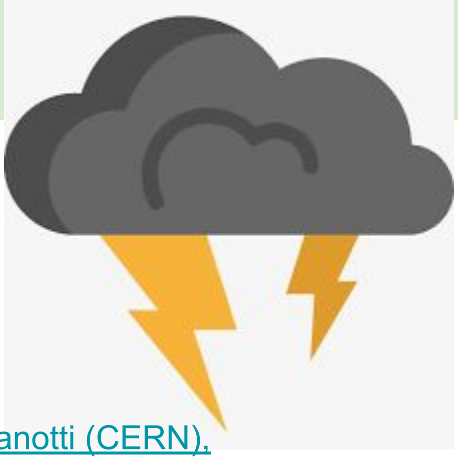
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$











Fabiola Gianotti (CERN), LHCP, 7 June 2021

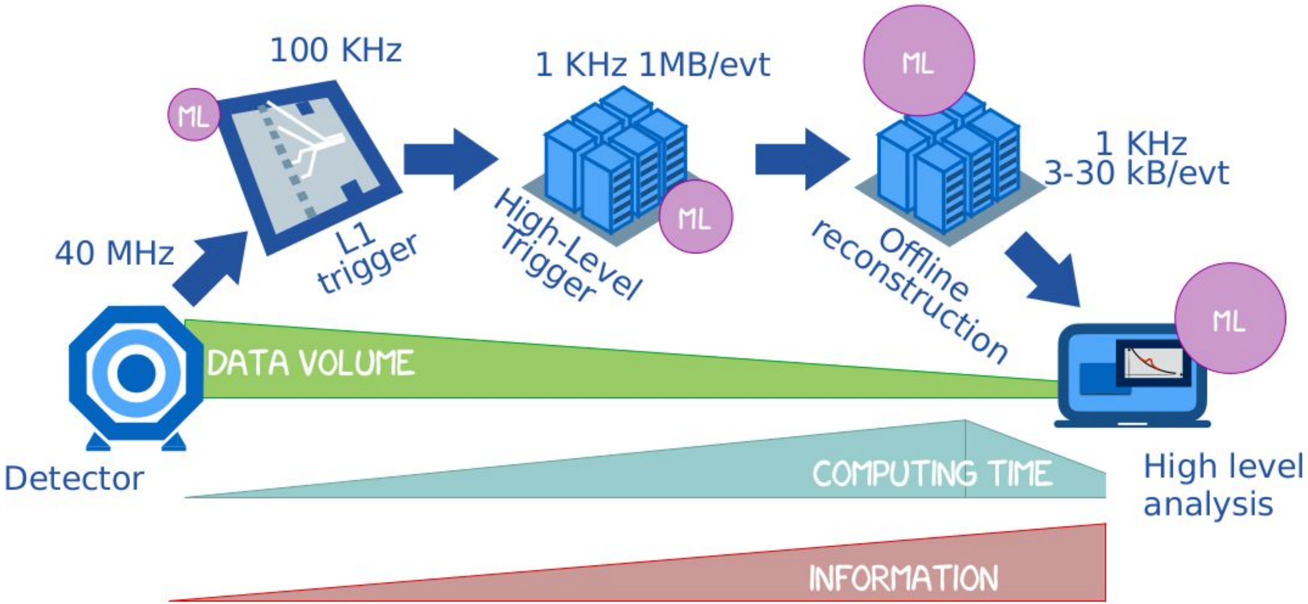
2021年，与缪子相关的'反常'

LHCb轻子味道普适性破坏

费米实验室缪子反常磁矩

可能的新物理迹象！

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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P_T and (pseudo-)Rapidity

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

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

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

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

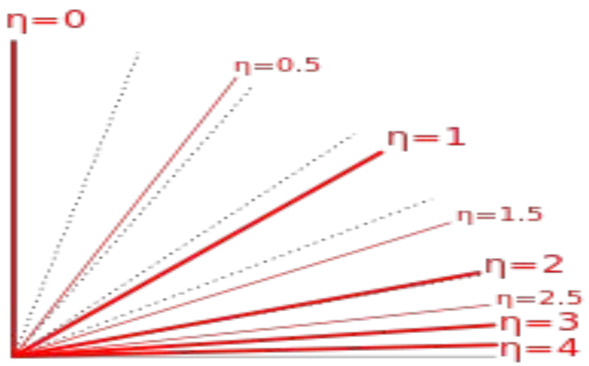
Lorentz Invariant Distance

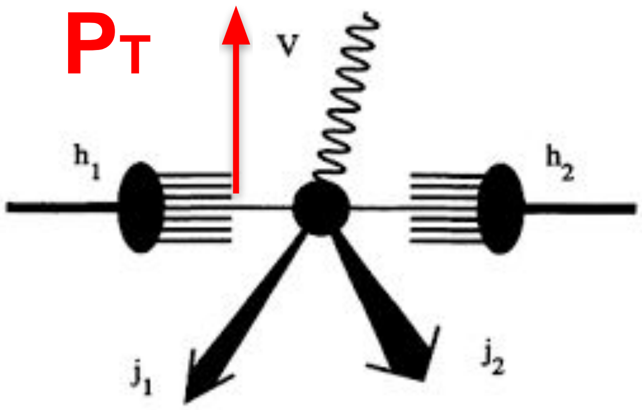
LHC typical:

PT>20-30GeV

$|\eta|$<2.5, 4.7

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



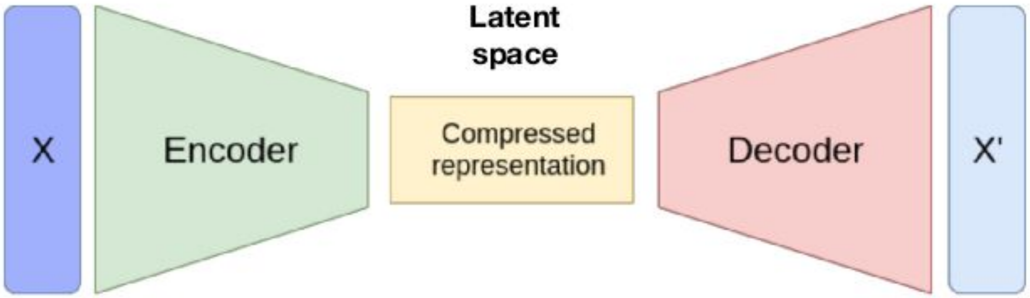


自编码Autoencoders

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

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

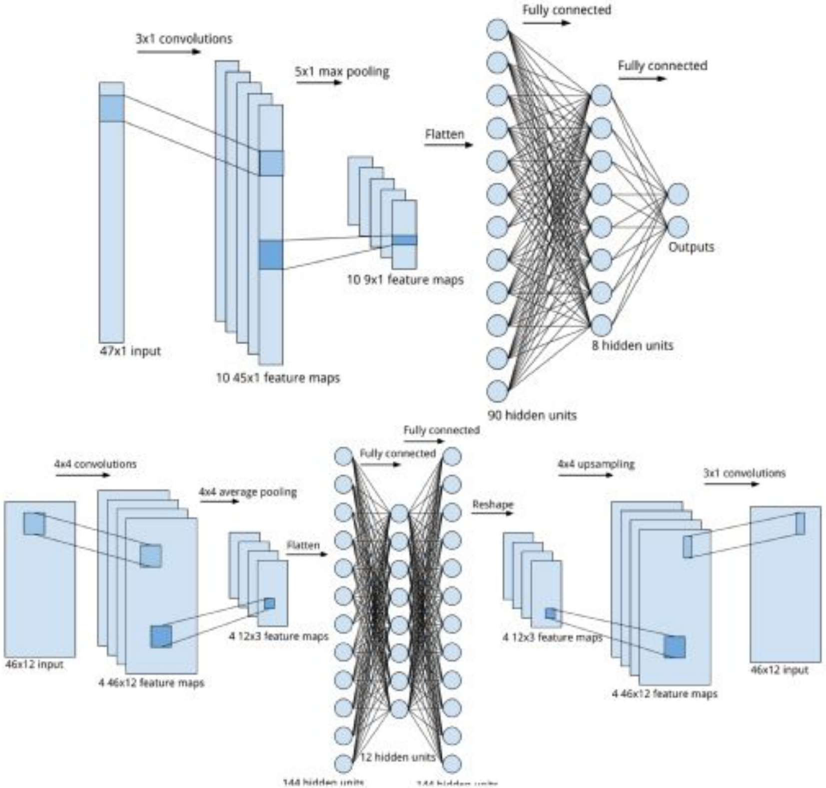
- *Autoencoders are essential tools for unsupervised studies*



自编码：数据监控

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

A. Pol et al., to appear soon



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