TeV 高能实验物理 暑期学校 iSTEP2023

粒子物理 和 标准模型

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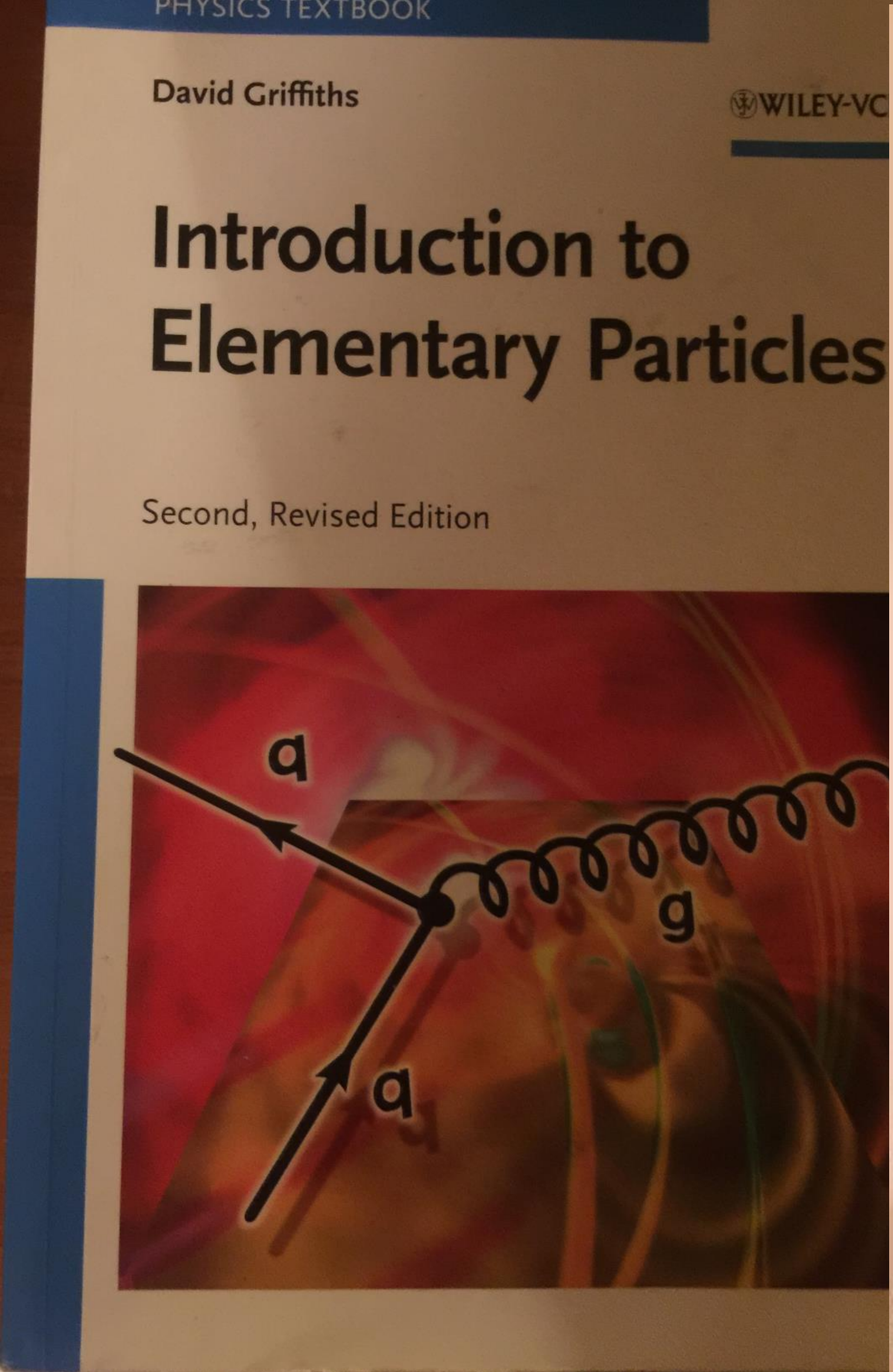
2023年8月22日上午，浙江大学紫金港校区物理学院



Preface to the First Edition

第一版是1986年

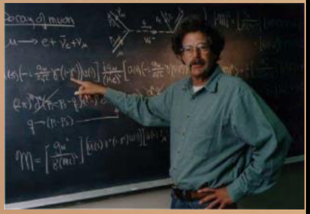
This introduction to the theory of elementary particles is intended primarily for advanced undergraduates who are majoring in physics. Most of my colleagues consider this subject inappropriate for such an audience – mathematically too sophisticated, phenomenologically too cluttered, insecure in its foundations, and uncertain in its future. Ten years ago I would have agreed. But in the last decade the dust has settled to an astonishing degree, and it is fair to say that elementary particle physics has come of age. Although we obviously have much more to learn, there now exists a coherent and unified theoretical structure that is simply too exciting and important to save for graduate school or to serve up in diluted qualitative form as a subunit of modern physics. I believe the time has come to integrate elementary particle physics into the standard undergraduate curriculum.

Unfortunately, the research literature in this field is clearly inaccessible to undergraduates, and although there are now several excellent graduate texts, these call for a strong preparation in advanced quantum mechanics, if not quantum field theory. At the other extreme, there are many fine popular books and a number of outstanding *Scientific American* articles. But very little has been written specifically for the undergraduate. This book is an effort to fill that need. It grew out of a one-semester elementary particles course I have taught from time to time at Reed College. The students typically had under their belts a semester of electromagnetism (at the level of Lorrain and Corson), a semester of quantum mechanics (at the level of Park), and a fairly strong background in special relativity.

In addition to its principal audience, I hope this book will be of use to beginning graduate students, either as a primary text, or as preparation for a more sophisticated treatment. With this in mind, and in the interest of greater completeness and flexibility, I have included more material here than one can comfortably cover in a single semester. (In my own courses I ask the students to read Chapters 1 and 2 on their own, and begin the lectures with Chapter 3. I skip Chapter 5 altogether, concentrate on Chapters 6 and 7, discuss the first two sections of Chapter 8, and then jump to Chapter 10.) To assist the reader (and the teacher) I begin each chapter with a brief indication of its purpose and content, its prerequisites, and its role in what follows.

Introduction to Elementary Particles, Second Edition. David Griffiths

ISBN: 978-3-527-40601-2




WILEY
[美] 大卫 J.格里菲斯（David J. Griffiths）著
Introduction to Elementary Particles
粒子物理导论
翻译版
原书第2版
清华大学 王 青 译
机械工业出版社
CHINA MACHINE PRESS
WILEY
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1. PageIII Line5：“标准模型永远会作为一个为实验”应改为“标准模型永远会是一个为实验”

2.PageIII 第二段第10行：“稍微涉猎一点点，”应改为“稍微涉猎一点，”

3.PageV 第三段第2行最后开始：“比一个单一学期能够舒适地涵盖所更多的内容。”应改为“比一个学期能够轻松地涵盖的更多内容。”

4.PageV 第三段第4行：“聚焦于第6和第7章，”应改为“聚焦第6和第7章，”

5.PageXI 费曼规则中自旋1/2的传播子公式中的分子pslashi应改为qslashi

6.Page1 第一段最后一行：“不非得是”应改为“并不真是”

7.Page1 第五段最后一行“但这个需求在这里”应改为“但这个过程在这里”

8.Page7 标题“进一步阅读”下面一段的第三行“of Physics G)上，”后加“译者注：最近这些年还发表在国内外的其他不同杂志上，具体可从后面给出的网址上查到。”

9.Page9 标题“经典时代（1897-1932）”下面第一行：“它可通过人为去准确确定这些事，”应改为“这虽可以认为确定，”

10.Page11 第三行“普朗克发现可以逃避紫外灾难—拟合实验曲线—如果假设”应改为“普朗克通过拟合实验曲线发现可以逃避紫外灾难，如果假设”

11.Page11 公式（1.3）中的w改成大写

12.Page11 脚注一“erg（尔格）为非法”应改为“erg（尔格）现在已为非法”

13.Page12 图1.2后第1行：“一个不被接受物理学家群体，”应改为“一个不被物理学家接受的群体，”

14.Page12 图1.2后第1段倒数第2行最后：“引力子之前它的”应改为“引力子之前，它的”

15.Page13 第二段第11行：“。现在汤川知道”应改为“。当时汤川知道”

16.Page19 脚注“ft（英尺）为非法”应改为“ft（英尺）现在已为非法”

17.Page20 1.6节第二段第2行：“发布了1.8所示的云室照片。”应改为“发布了1.7所示的云室照片。”

18.Page22 公式（1.26）后第3行：“，它们不像轻子”应改为“，不像轻子”

19.Page23 最后一行，在“S=-2。”前面加一个逗号。

20.Page30 第二段第9行：“大约比差不多粒子长约”应改为“大约比其它粒子长约”

21.Page30 倒数第三段最后一行：“不寻常多余其作者”应改为“不寻常多于其作者”

22.Page30 倒数第二段第7行：“第一个双粲重子的迹象。）”在句号后加“译者注：这个结果分别被LHCb上2012年√s=8TeV和2016年√s=13TeV的数据所否认，但LHCb的中国组在对后来的这些数据分析中确认了另一个双粲重子，详细见Phys. Rev. Lett. 119. 112001(2017)。”

23.Page31 注的最后：“2010年6月30日关机。”后面补充“译者注：升级改造后的SuperKEKB的Belle II实验将于2019年开始物理取数。”

24.Page48 最后一行的最后：“的数字实际”应改为“的数值实际”

25.Page51 注三倒数第2行："代表自旋为-1/2的粒子，"应改为"代表自旋为1/2的粒子，"

26.Page55 倒数第5行："我们永远不希望引起"应改为"我们永远看不到引起"

27.Page62 最后一行2.10："3686MeV/c2就具有"把"就"字去掉

28.Page68 公式（3.24）中最后一个a2中的a改为黑体。注意等号左边的a2不改！

29.Page78 标题"参考文献"前最后一行："将会具有4000GeV"应该改为"将会具有4GeV"

30.Page78 习题3.2（b）中第3行："在相对论中总是那样的，"应改为"在相对论中总是这样的，"

31.Page87 Line2: "因此，如果我说氢原子中的电子占据轨道态|3 1〉和自旋态|1/2 1/2〉，我再告诉你l=2，…"应改为"因此，如果一个氢原子中的电子占据轨道态|3 -1〉和自旋态|1/2 1/2〉，那么它的l=3， ml = -1，…"；

32.Page101 Line1："赝矢量"应为"赝标量"；

33.Page103 Line3："右手反中微子"应为"左手反中微子"；

34.Page105 (4.72)式第二行"10-11s"应为"10-8s"

35.Page106 注3倒数第2行："这是B系统即一个"应改为"这使得B系统成为一个"

36.Page131 标题"5.6重子"后第一段第3行："更不用说三个了，"后补充"注二：双粲重子已在LHCb实验上被发现，见第30页最后的译者注。"

37.Page133 注的最后一行："自旋1/2的组合：|>=|>13+|>12。"应改为"自旋1/2的组合：|>=|>13+|>23。"

38.Page145 标题"6.1.2截面"后第2行："靶的尺寸或更精确地"应改为"靶的尺寸或其更精确地"

39.Page149 公式（6.15）后第8行："它为零除自变量是零外。"应改为"它除了自变量是零的情形，都为零。"

40.Page176 外线Feynman Rule入射正电子\bar{\nu} 出射正电子\nu;

41.Page180 脚注中的\slash{epsilon}符号要补充上标*。

42.Page228 (9.30)后第一行，"当粒子3和4图像上与粒子2反向时"改为"当粒子3和4与粒子2截然反向时"

43.Page233 第一行，"而给定若衰变"改为"考虑到弱衰变"；第二行"大概能满意"改为"应该满意"

44.Page235 脚注一倒数第二行："因此我们可以承担起直接在"应改为"因此我们可以直接在"

45.Page239 公式（9.82）前一行："使用的态势d'"应改为"使用的态是d'"

46.Page249 第一行文字应为table9.2的注解文字而非正文，"为零"二字多余；

47.Page271 公式（10.95）分子上的"i"改为"-i"

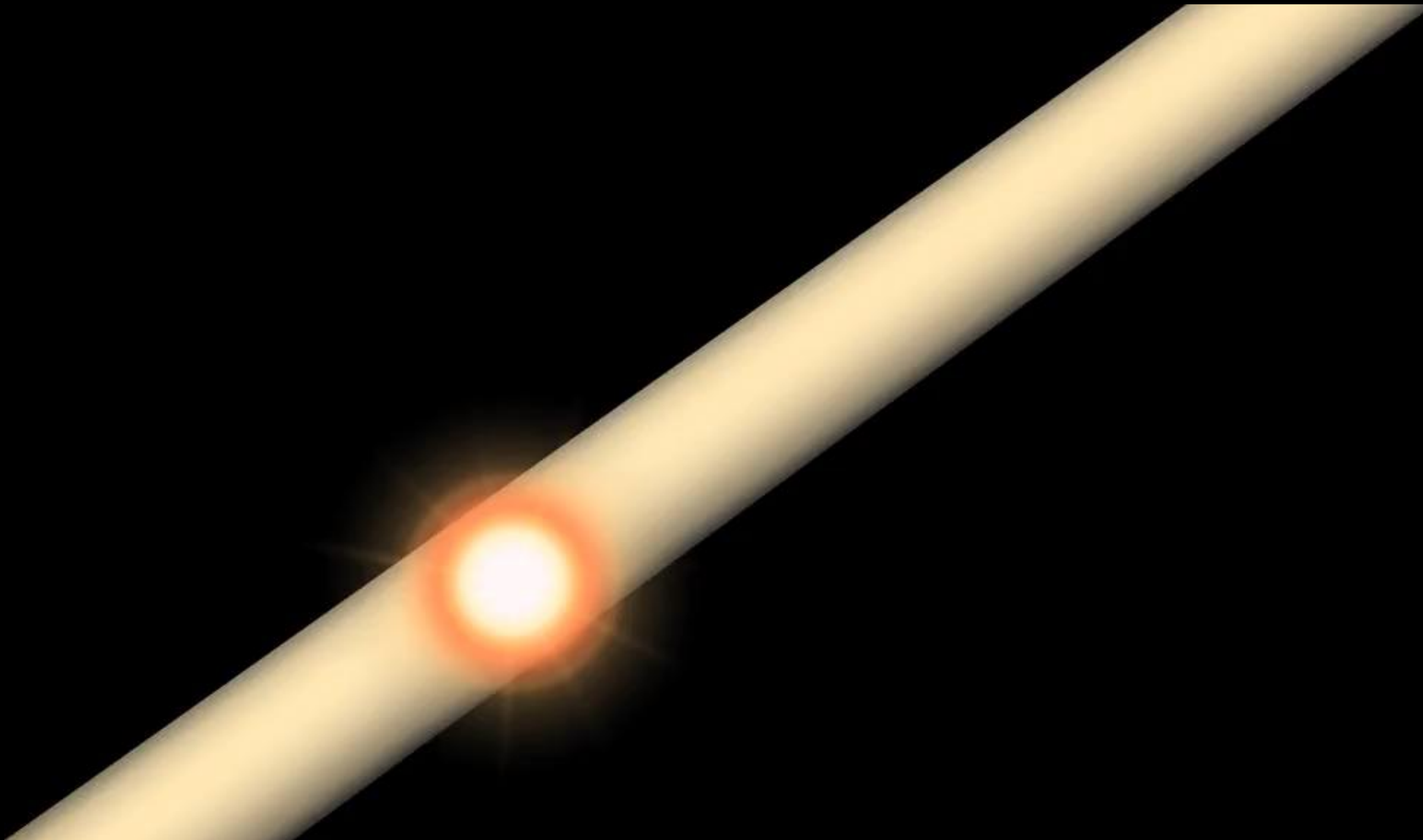
48.Page279 第二行："而这是我们的许可相信"应改为"而这使得我们可以相信"

以后使用此书时发现新的错误，请告知：

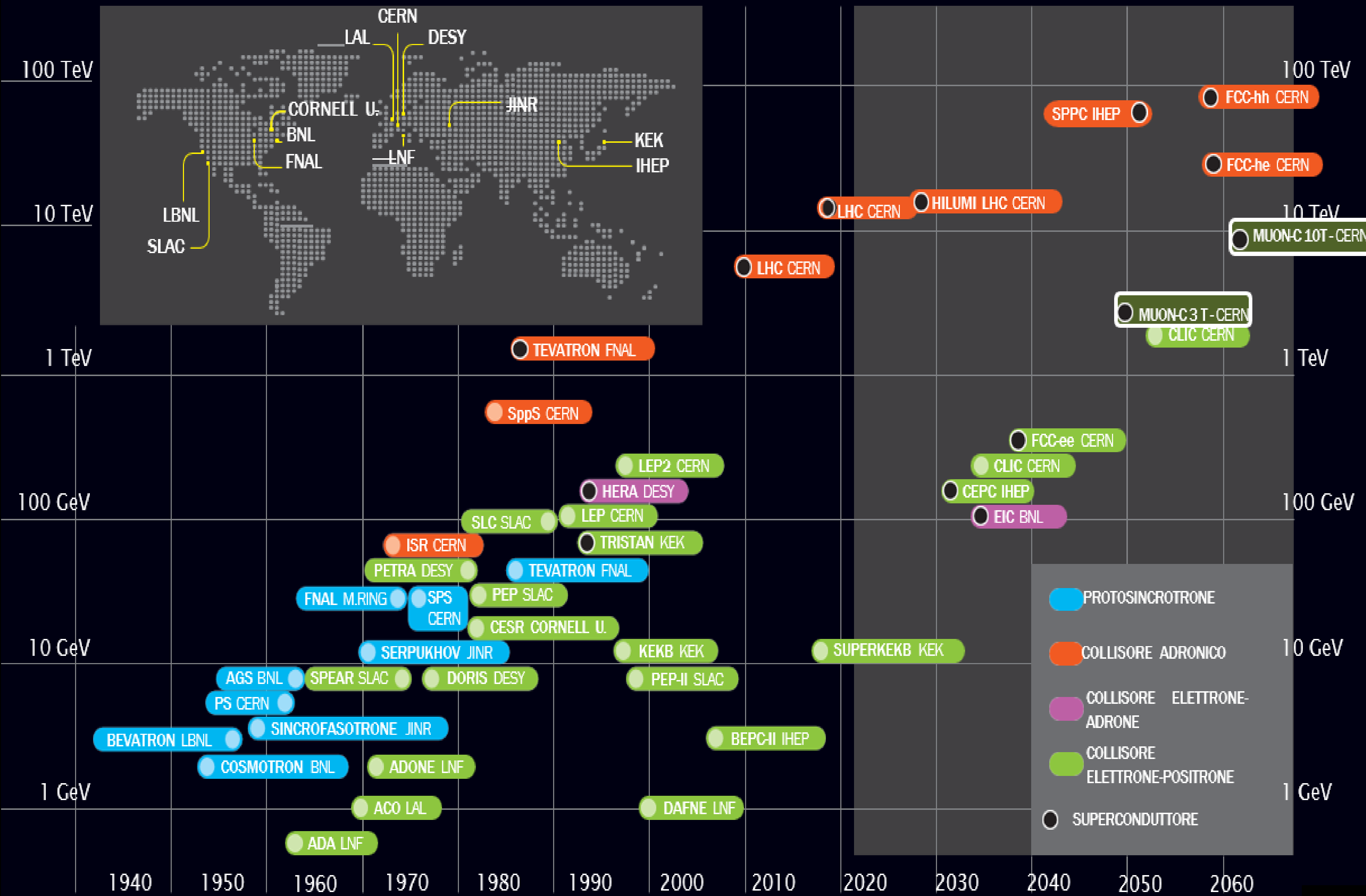
wangq@mail.tsinghua.edu.cn

王青　　　13910515916

- 自然科学与其它学科的差别在实验
- 粒子物理前沿理论方面当前十分迷茫
- 粒子物理的发展迫切需要实验提供信息
- 高能实验是未来基础科学发展的重要推手
- 本讲座是开场白，主要给一个宏观图景加八卦



20230818 CMS组装厂房



CERN
LAL
DESY
CORNELL U.
BNL
FNAL
LNF
JINR
KEK
IHEP
LBNL
SLAC
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
FCC-hh CERN
SPPC IHEP
FCC-he CERN
LHC CERN
HILUMI LHC CERN
MUON-C 10T - CERN
LHC CERN
MUON-C 3 T - CERN
CLIC CERN
TEVATRON FNAL
SppS CERN
FCC-ee CERN
LEP2 CERN
CLIC CERN
HERA DESY
CEPC IHEP
SLC SLAC
LEP CERN
EIC BNL
ISR CERN
TRISTAN KEK
PETRA DESY
TEVATRON FNAL
FNAL M.RING
SPS CERN
PEP SLAC
CESR CORNELL U.
SERPUKHOV JINR
KEKB KEK
SUPERKEKB KEK
AGS BNL
SPEAR SLAC
DORIS DESY
PEP-II SLAC
PS CERN
SINCROFASOTRONE JINR
BEVATRON LBNL
BEPC-II IHEP
COSMOTRON BNL
ADONE LNF
ACO LAL
DAFNE LNF
ADA LNF
PROTOSINCROTRONE
COLLISORE ADRONICO
COLLISORE ELETTRONE-ADRONE
COLLISORE ELETTRONE-POSITRONE
SUPERCONDUTTORE
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
year


参数控制
宇宙射线仿真
EAST FORCE
SUPERCONDUCTING

大纲

- 现状
- 未来
- 真空

现 状

基本粒子物理（Elementary Paticle Physics）

研究的对象 $\Rightarrow$ particles

$\equiv$ 高能物理（High Energy Physics）

研究的手段 $\Rightarrow$ high energy $\Delta x \cdot \Delta p \geq \hbar$

自然单位制： 10^{-17}厘米 $=10^{-4}$费米 = 1/1.97TeV 玻尔半径= $5.3 * 10^{-9}$ 厘米 电子的经典半径= $2.8 * 10^{-13}$ 厘米

目标：自然界的基本组分及其相互作用

牛顿在他著名的《31问》中写道

我认为似乎这是很可能的：上帝最初用实心的、有质量的、坚硬的、不可穿透的和可运动的粒子构造物质，这些物质具有那样的尺度和外形并具有那样的一些其他性质，与空间如此相称，以致最有利于达到上帝通过构造它们所要实现的终极目标；并且这些原始的固态的粒子与任何由它们复合成的可渗透的物体相比是无比坚硬的，甚至坚硬到绝不可能磨损和破碎；没有什么普通力量能分割上帝自己在首次创造中造出的粒子。

法拉第
Michael Faraday

1791.9.22
生于伦敦郊外Newington
1867.8.25
卒于伦敦郊外Hampton Court
终年76岁

吴国盛教授导读《法拉第传》

https://www.koushare.com/lives/room/941341

法拉第的挑战小结

- 从1832年开始，法拉第自觉遵循场论，而明确反对牛顿主义
  - 场既不是物质、也不是空间、也不是物的属性。场独立存在。空间与物质在“场”中统一。
  - 物质（原子）只是场的属性（力线的节点、场包围的力心）
  - “对光来说，空间也就是物质”，并不是“以太”传播光
  - 惯性不是公理，可以从场论推导出来
  - 各种力之间可以相互直接转化

	BIG	SMALL 高能一定小距离
FAST 高能可以快速也可慢速	Rocketship near lightspeed, no need for QM	The marriage of quantum mechanics & special relativity
SLOW	Classical physics	Slow moving electron scattering off a proton, no need for special relativity

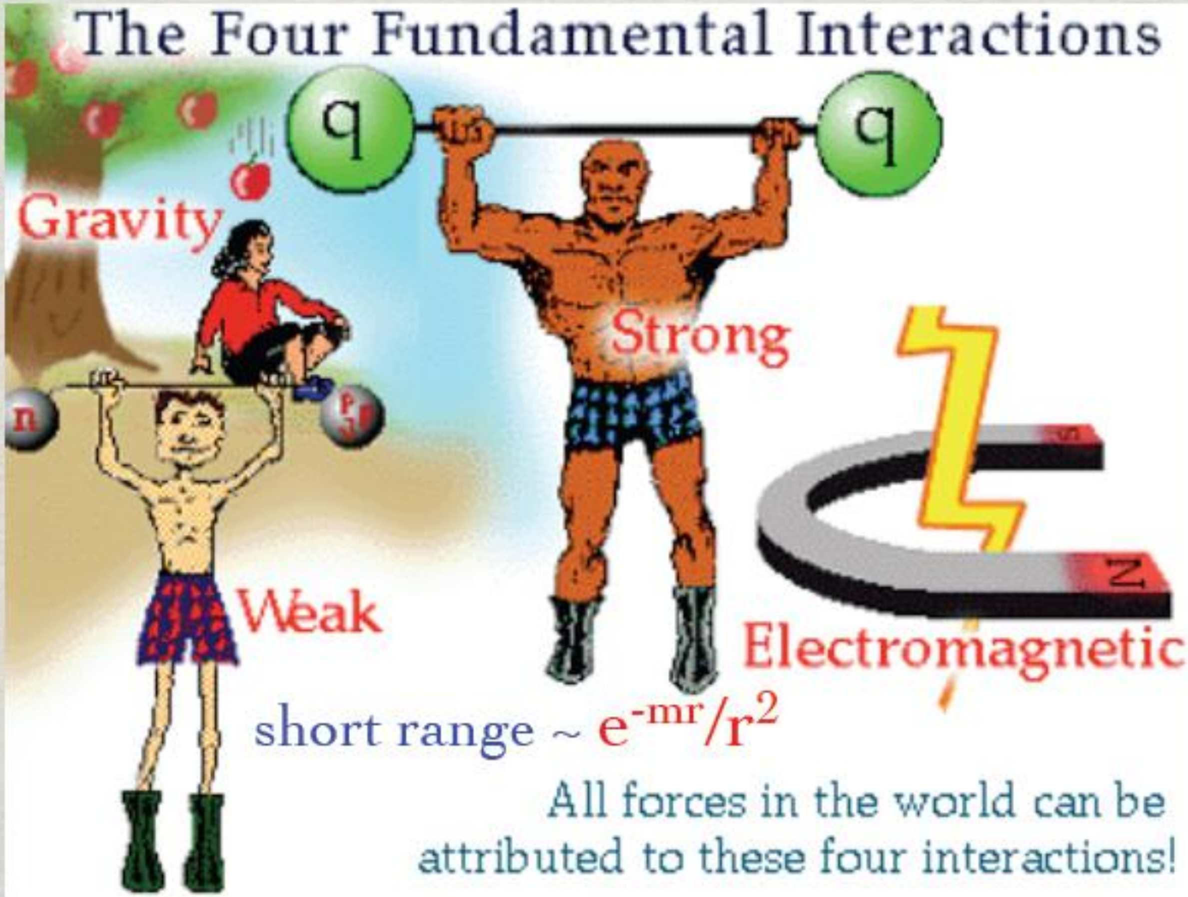
$$E = \frac{mc^2}{\sqrt{1 - v^2/c^2}}$$

In the peculiar confluence of special relativity & quantum mechanics a new set of phenomena arises: particles can be born & particles can die.

A new subject in physics, quantum field theory, is needed to describe birth & death, & some kind of life in between.

THE NATURE OF FORCES:

long range
$\sim(G_N\, m_1 m_2)/r^2$
$\rightarrow$ GR



long range
$\sim(\alpha\, e_1 e_2)/r^2$
$\rightarrow$E&M

Why are they so different?
It is the topic of "elementary particle physics"

世界上任何东西都是由原子组成的（包括物质和灵魂）。原子是不可分割的。

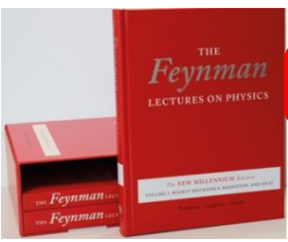
还原论

Democritus
BC460-370
古希腊哲学家
公元前440年

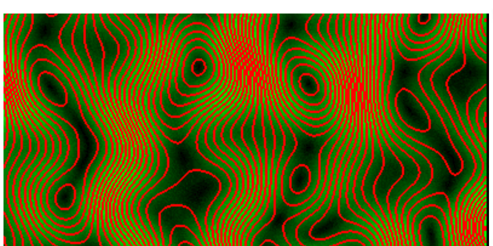
德谟克利特

金、木、水、火、土

《庄子．天下篇》
一尺之棰
日取其半
万世不竭

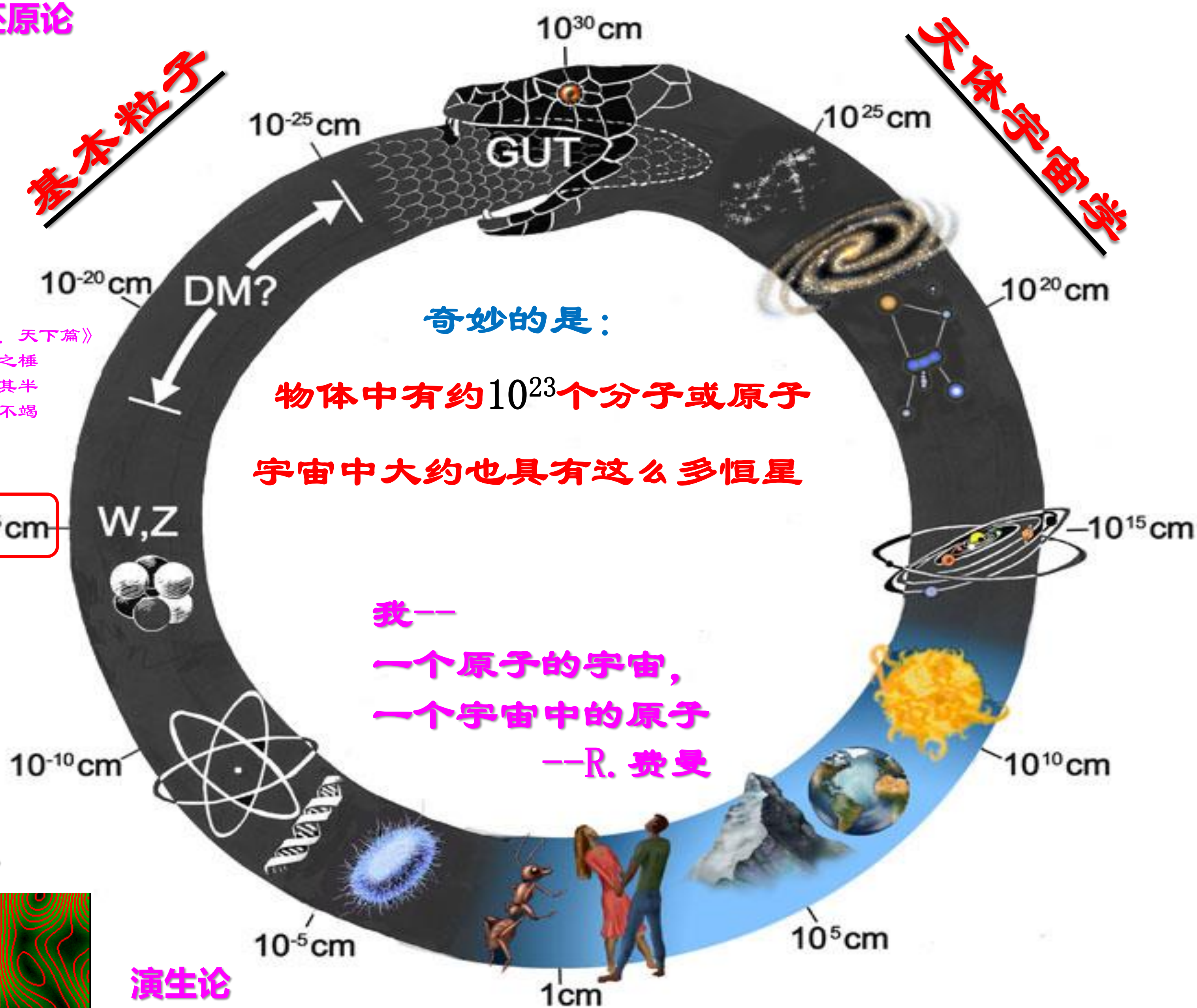


费曼物理学讲义
第一册第一章第2节
（第一节是序言）
的标题是：
《物质是由原子构成的》



基本粒子

天体宇宙学

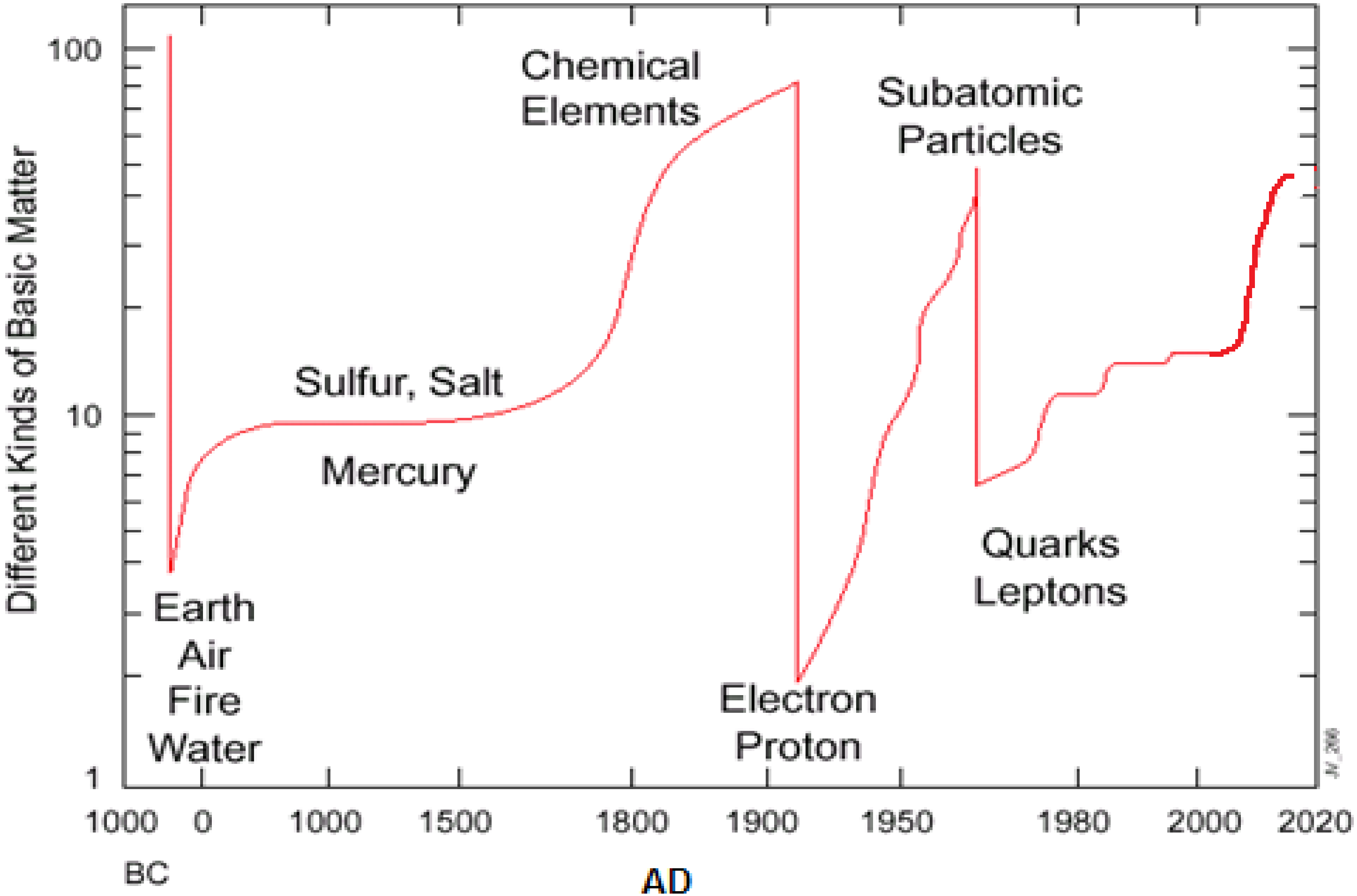


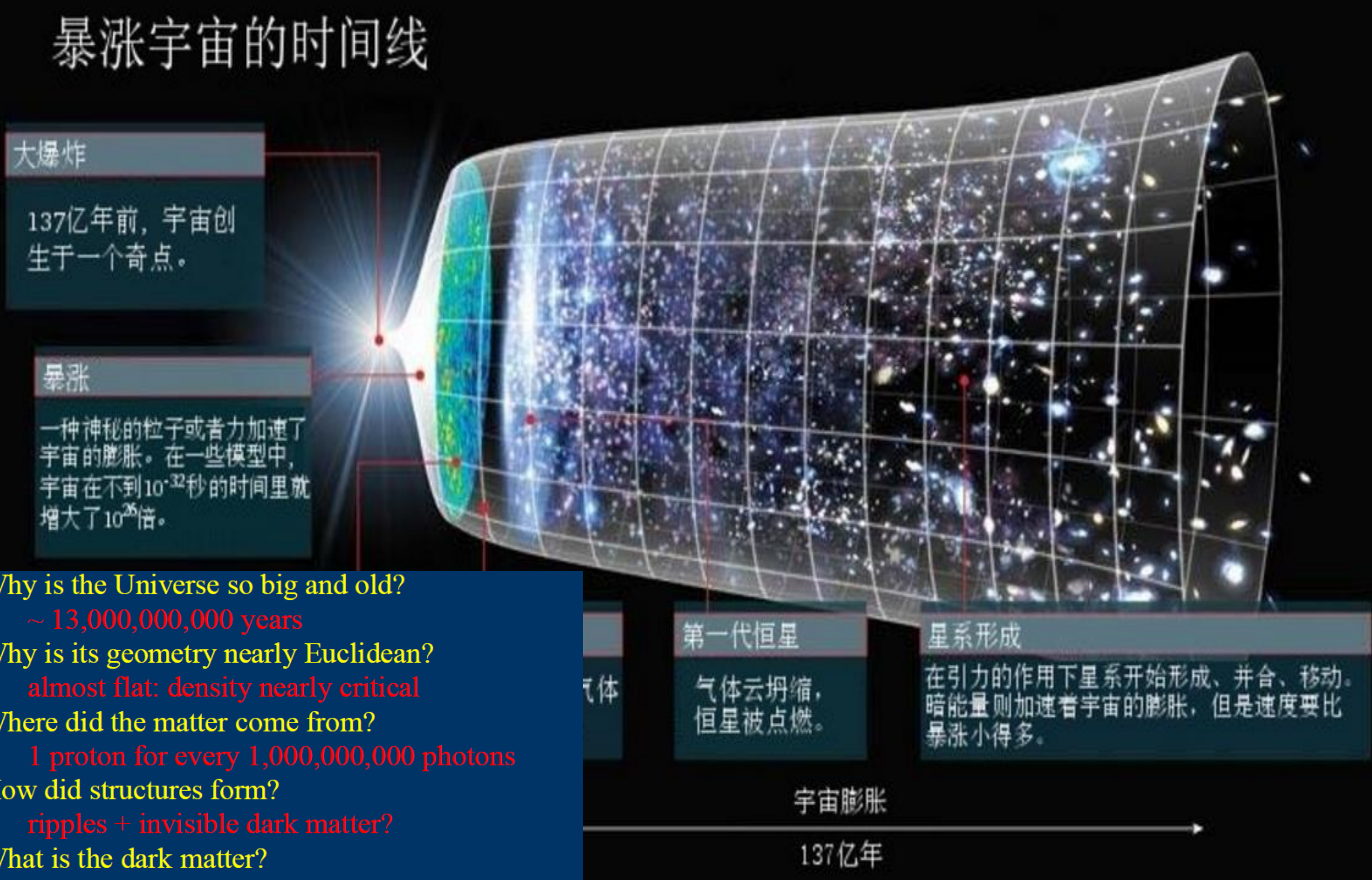
演生论

AMO；凝聚态

The Cosmic Uroboros

History of Constituents of Matter





- Why is the Universe so big and old?
  - ~ 13,000,000,000 years
- Why is its geometry nearly Euclidean?
  - almost flat: density nearly critical
- Where did the matter come from?
  - 1 proton for every 1,000,000,000 photons
- How did structures form?
  - ripples + invisible dark matter?
- What is the dark matter?
- What is the dark energy?

Need particle physics to answer these questions

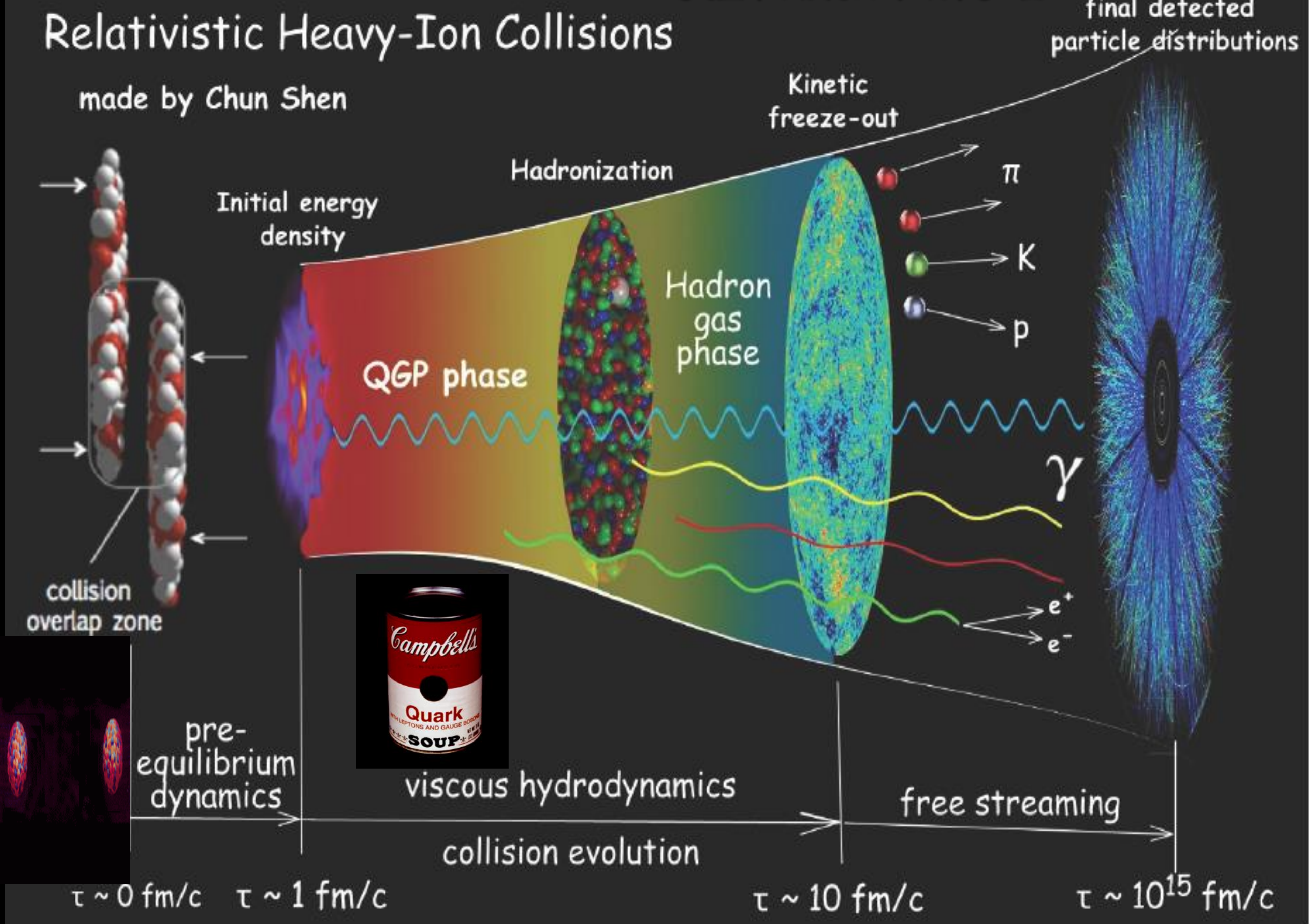
Quantum Fluctuations become seeds for galaxies

1. What is Dark Matter?
2. What is the Nature of Dark Energy?
3. How Did the Universe Begin?
4. Did Einstein Have the Last Word on Gravity?
5. What are the Masses of the Neutrinos and How Have They Shaped the Evolution of the Universe?
6. How do Cosmic Accelerators Work and What are They Accelerating?
7. Are Protons Unstable?
8. What Are the New States of Matter at Exceedingly High Density and Temperature?
9. Are There Additional Space-Time Dimensions?
10. How Were the Elements from Iron to Uranium Made?
11. Is a New Theory of Light and Matter Needed at the Highest Energies?

2002年美国国家研究委员会确定的研究前沿:

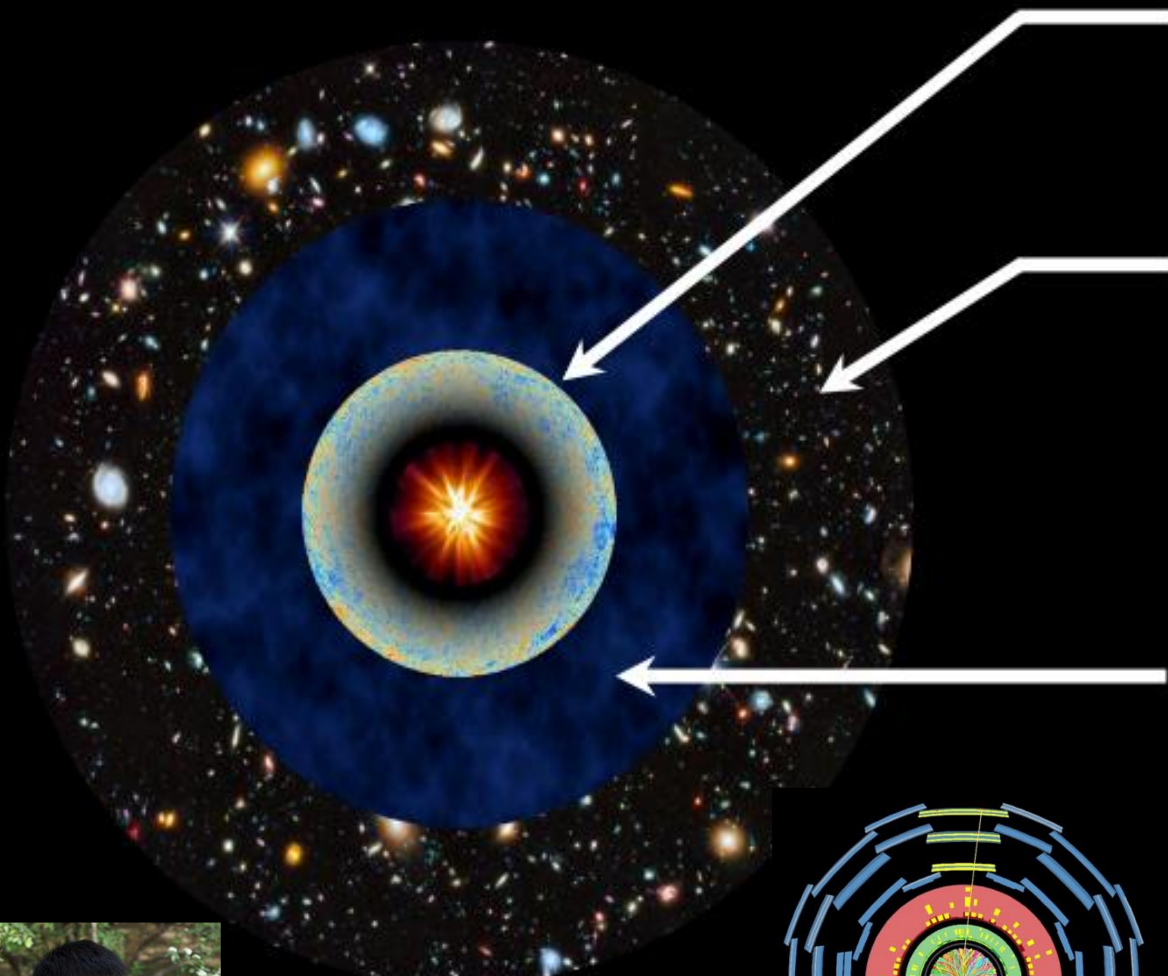
《联结夸克和宇宙：新世纪11个科学问题》

对撞机模拟早期宇宙

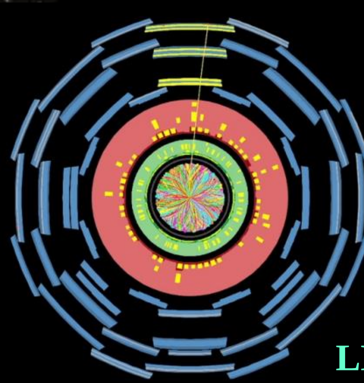

Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
K
p
γ
e+
e-
collision overlap zone
Campbell's
Quark
SOUP
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

Cosmological Collider – The Universe

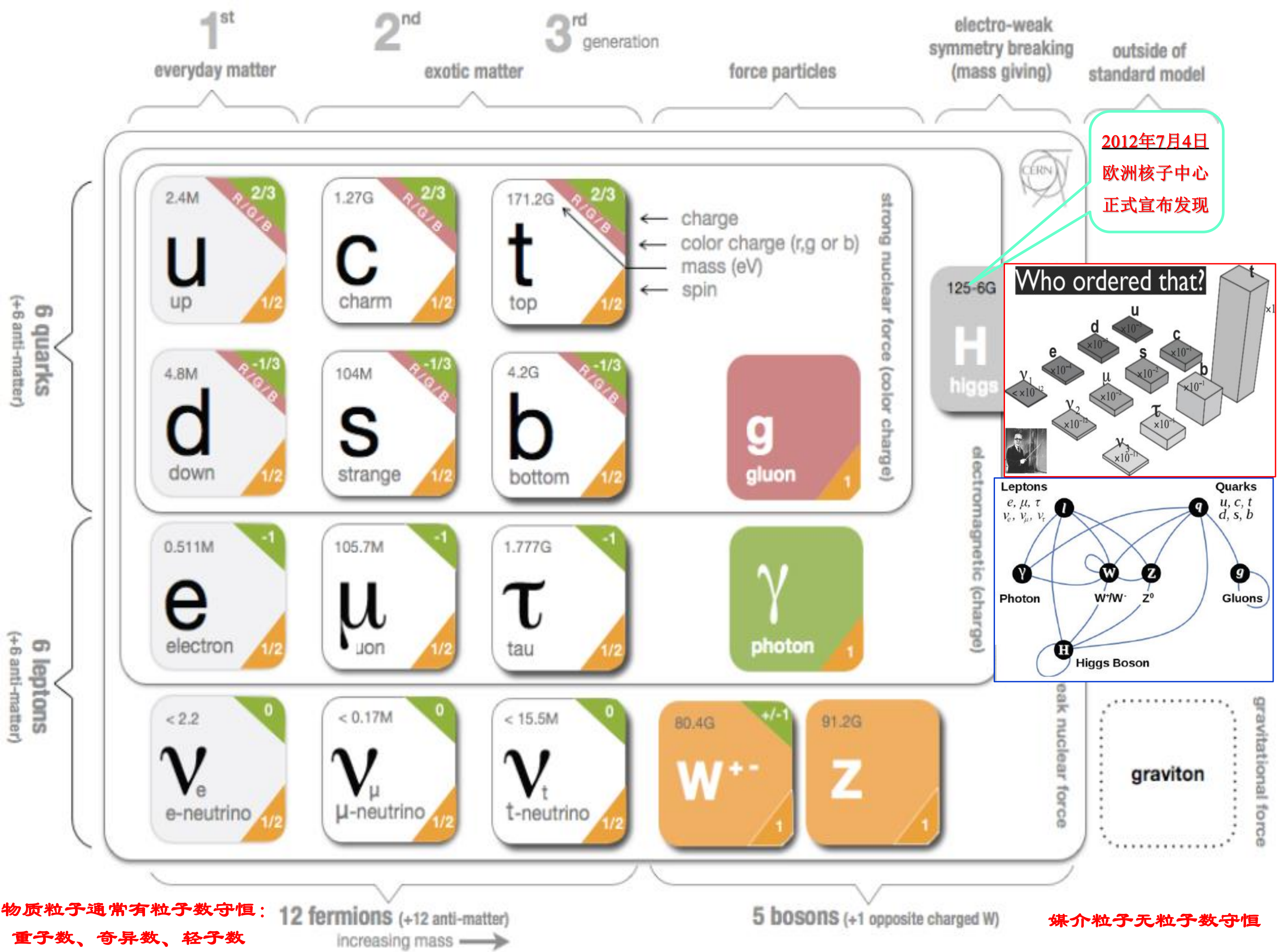
--把宇宙看成是对撞机



Gravitational waves
Neutrinos ...



LHC Atlas detector



物质粒子通常有粒子数守恒：

重子数、奇异数、轻子数

媒介粒子无粒子数守恒

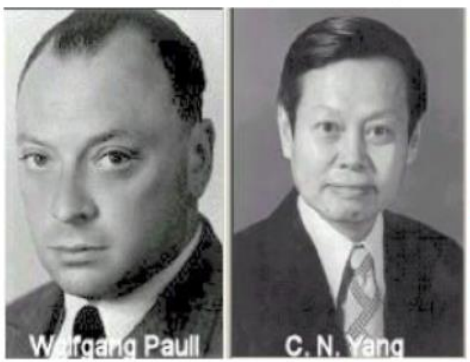
Gauge Symmetry (Gravity is not included)

$$\underbrace{SU(3)_{\text{Color}}}_{\text{QCD}} \otimes \underbrace{SU(2)_{\text{Left}} \otimes U(1)_{\text{Hyper charge}}}_{\text{WEAK} \oplus \text{QED}}$$

(Strong Interaction)

(Unification of Weak and Electromagnetic)

Wolfgang Pauli (1900-1958) was spending the year in Princeton, and was deeply interested in symmetries and interactions.... Soon after my seminar began, when I had written on the blackboard,



Wolfgang Pauli and C. N. Yang

$(\partial_\mu - i\epsilon \mathbf{B}_\mu)\psi$

Pauli asked, "What is the mass of this field $\mathbf{B}_\mu$?" I said we did not know. Then I resumed my presentation but soon Pauli asked the same question again. I said something to the effect that it was a very complicated problem, we had worked on it and had come to no definite conclusions. I still remember his repartee: "That is not sufficient excuse". I was so taken aback that I decided, after a few moments' hesitation, to sit down. There was general embarrassment. Finally Oppenheimer, who was chairman of the seminar, said "We should let Frank proceed". I then resumed and Pauli did not ask any more questions during the seminar.

Spontaneously Broken
(Higgs Mechanism)

$U(1)_{\text{E.M.}}$ QED

(Electromagnetic Interaction)

杨振宁在1947年在芝加哥大学做研究生时做实验不成功，对此事开始尝试越做越复杂，以后几年又多次尝试仍不成功，1953–54年到BNL访问一年，同办公室一个年轻人Robert Mills，他们修改了场强的定义，越做越简单，他们知道挖到宝贝了，找到突破口了，写了一篇文章。杨先生说：这篇文章后来被称为Yang-Mills理论变成我一生最重要的工作。我一生研究经历中，有没有大差错，失去机会呢？当然有。其中最重要的是：1970年代我对对称破缺注意不够，所以失去了在此方面做出贡献的机会。我当时的工作转向规范场的数学结构方面。

2023年8月12日，北京大学物理学院

The birth of the Standard Model:

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

[12]M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282

bra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta \to \pi^+\pi^-\gamma)/$) calculated in Refs. 12 and 14.

. M. Brown and P. Singer, Phys. Rev. Letters 8, (1962).

A MODEL OF LEPTONS*

Steven Weinberg†

Physics Department,
ambridge, Massachusetts
1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences

on a right-handed singlet

$$R = [\tfrac{1}{2}(1-\gamma_5)]e.$$

$$
\begin{aligned}
\mathcal{L}_{SM} = & -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
& M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
& igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
& W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
& Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
& \beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
& g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
& \tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
& gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
& \tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
& \tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
& M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
& W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
& \tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
& \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
& W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
& g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m_\nu^\lambda)\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial + \\
& m_u^\lambda)u_j^\lambda - \bar{d}_j^\lambda(\gamma\partial + m_d^\lambda)d_j^\lambda + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}_j^\lambda\gamma^\mu u_j^\lambda) - \tfrac{1}{3}(\bar{d}_j^\lambda\gamma^\mu d_j^\lambda)\right) + \\
& \tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}_j^\lambda\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d_j^\lambda) + \\
& (\bar{u}_j^\lambda\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u_j^\lambda)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)\right) + \\
& \tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}_j^\kappa C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u_j^\lambda)\right) + \\
& \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m_e^\kappa(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m_\nu^\lambda(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \\
& \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m_e^\lambda(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m_\nu^\kappa(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m_\nu^\lambda}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
& \tfrac{g}{2}\tfrac{m_e^\lambda}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m_\nu^\lambda}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m_e^\lambda}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
& \tfrac{1}{4}\overline{\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) + m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa)\right) + \\
& \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m_d^\lambda(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1-\gamma^5)u_j^\kappa)\right) - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda) - \\
& \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}_j^\lambda\gamma^5 d_j^\lambda) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
& \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
& \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
& \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
& \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
& \partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \\
& \tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \\
& \tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).
\end{aligned}
$$

All known physics

$$
W = \int_{k<\Lambda}[\mathcal{D}g\ldots]\ \exp\left\{\frac{i}{\hbar}\int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}R - \frac{1}{4}F^2 + \bar{\psi}i\not{D}\psi - \lambda\phi\bar{\psi}\psi + |D\phi|^2 - V(\phi)\right]\right\}
$$

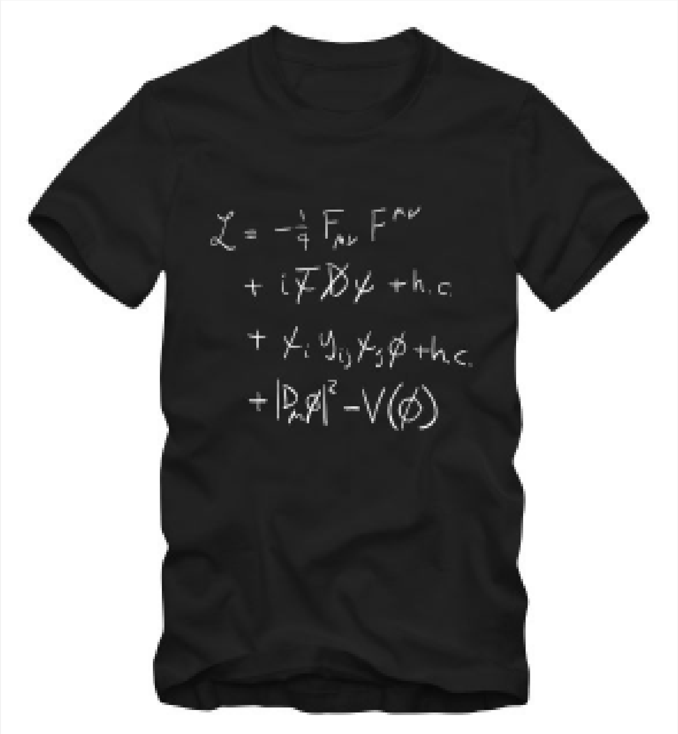
amplitude | current understanding | quantum mechanics | spacetime | gravity | strong & electroweak | matter | Higgs

年过半百---粒子物理标准模型：量子色动力学+电弱统一理论

Modern Physics Landscape

■ Standard Model

quantum field theory



■ General Relativity

gravitation and spacetime

Free Parameters in Standard Model

$SU(3)_{\text{color}} \times SU(2)_{\text{Left}} \times U(1)_{\text{Hypercharge}}$

g_3, g_2, g_1
λ, μ

$$\left\{ \begin{array}{l} \alpha_S, \alpha_{em}, \theta_{\text{Weak mixing}} \\ V\,(\text{vacuum expectation value}) \\ m_H\,(\text{Higgs Boson mass}) \end{array} \right\}$$

This set can be traded by
$\alpha_S, \alpha_{em}, G_F, m_Z, m_H$

(3) Lepton masses
$(e, \mu, \tau) \quad m_\nu\text{'s}=0$

(6) Quark masses
(u, d, s, c, b, t)

Mixing of quark weak eigenstates and mass eigenstates → 3 angles and 1 phase (CP violation)

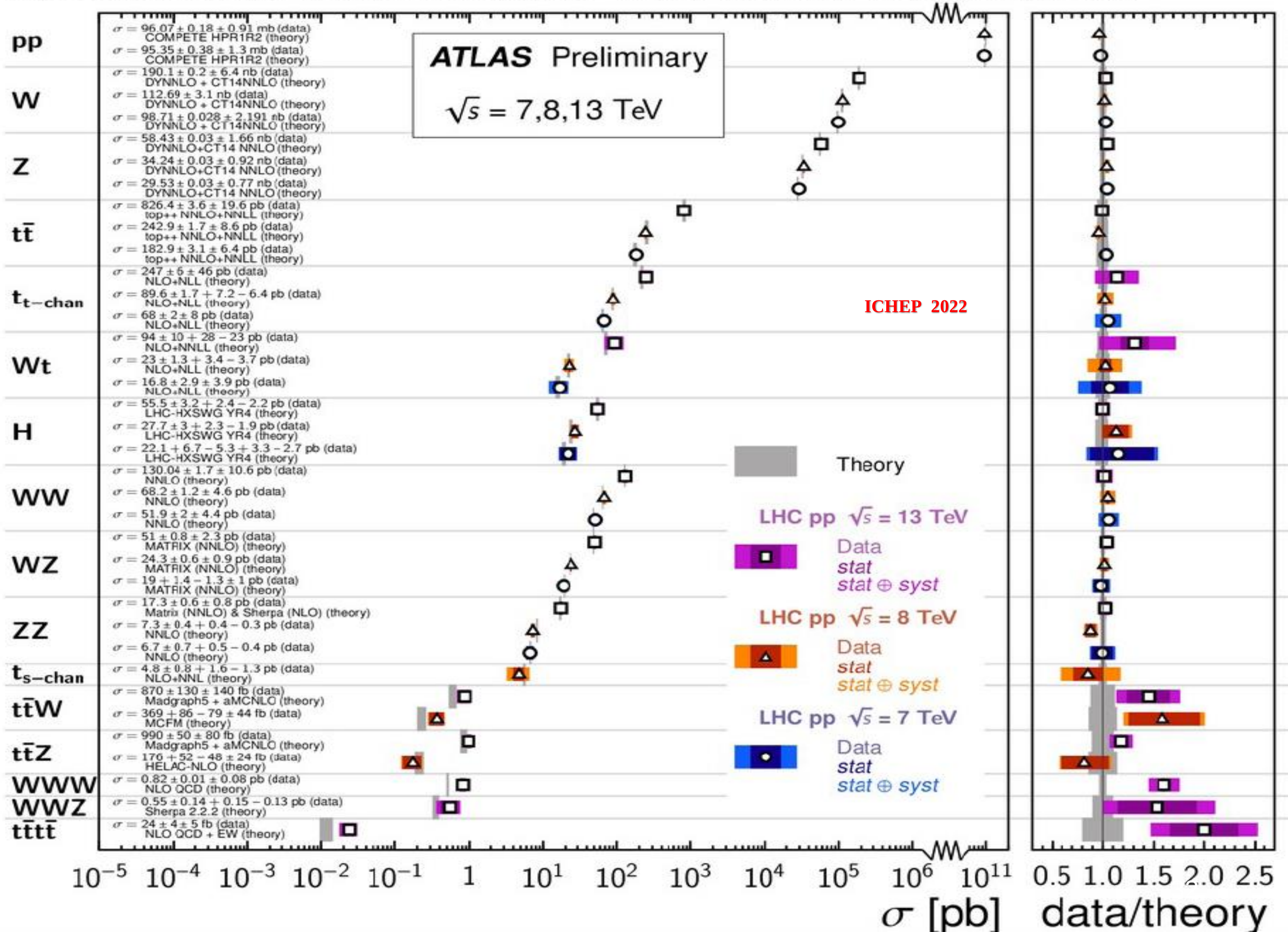
(1) Strong CP phase

→ Total of 19 free parameters.
So far, all experimental data agree with the prediction of SM.

To include neutrino masses (suggested by Neutrino Oscillation data) in the SM

- For Dirac Neutrinos
  → Add 3 masses and 3 mixing angles with 1 CP violation phase
- For Majorana Neutrinos
  → Add 3 masses and 3 mixing angles with 3 CP violation phase

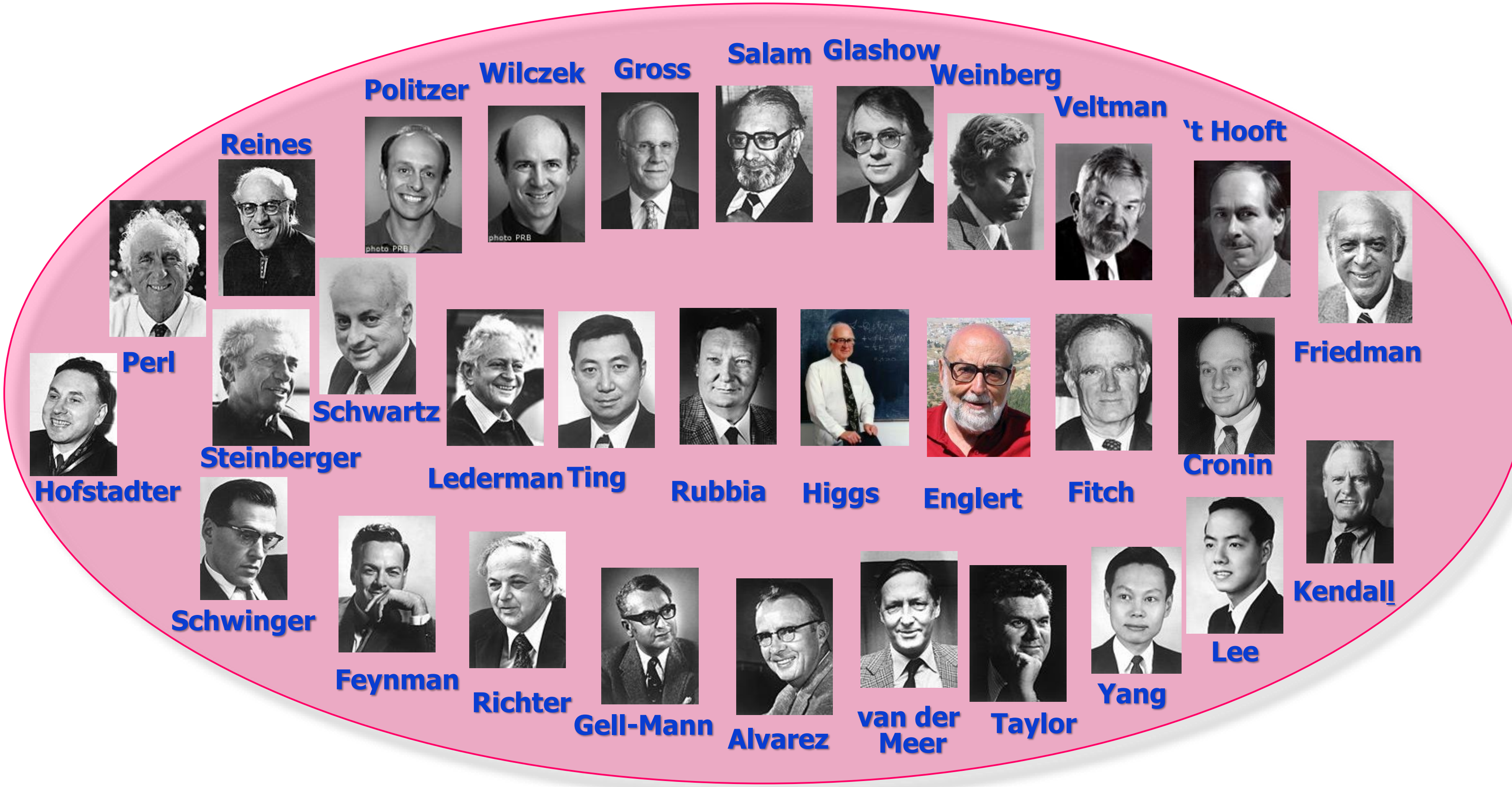
Standard Model Total Production Cross Section Measurements



Happy 50th birthday Standard Model!

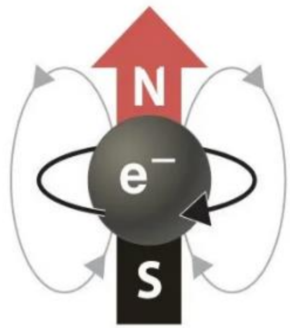
- **Successes**
  (theory, experiment, accelerator, …)
  - Describes ordinary matter/ interactions to < 10^{-16} cm
  - Mathematically consistent
  - Many predictions/tests (often exquisite precision)
  - (Approximate) accidental symmetries (B, L, FCNC, EDM)
- **BSM**
  (avoid new large FCNC, EDM)
  - Conventional ideas
  - Paradigms?
  - Is Nature *just right*?
- **Problems/missing/questions**
  - Complicated gauge interactions (27-29 parameters, 3 groups, charge quantization)
  - Fermion spectrum, masses, mixings (neutrino type and magnitude)
  - Fine tunings (Higgs mass, Θ_{QCD}, Λ)
  - Quantum gravity
  - Initial conditions on big bang
  - Baryon asymmetry
  - Dark matter and energy
- **Possible anomalies**
  (flavor, g_μ-2, sterile, …)

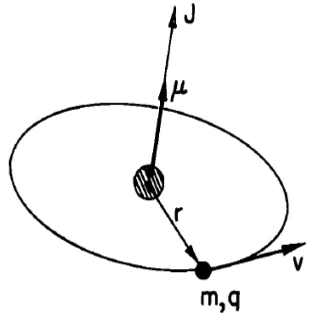
Standard Model



successful for ever ??

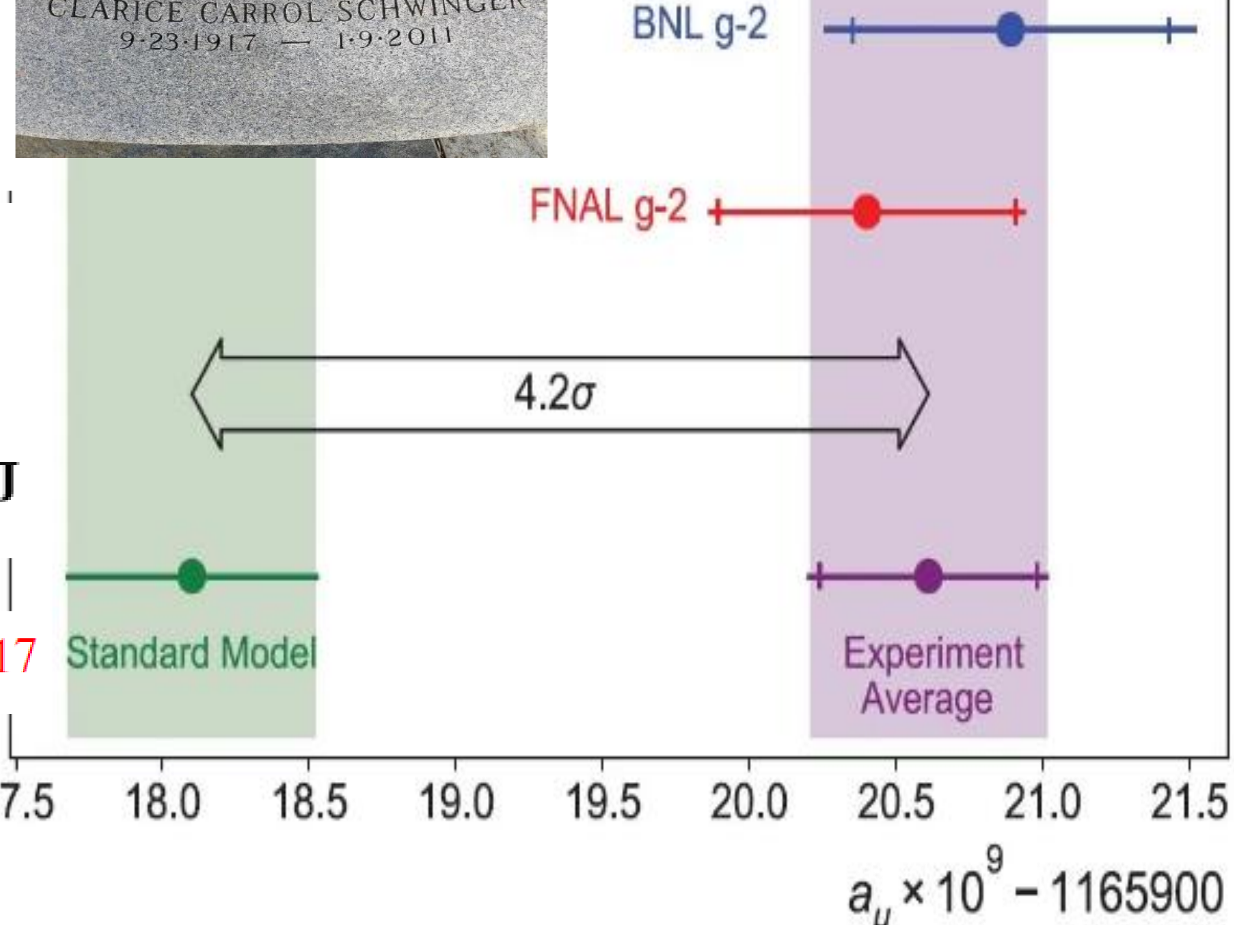

SM





$$J = mvr \qquad I = q\frac{v}{2\pi r}$$

$$\mu = I\pi r^2 = \frac{qvr}{2} = \gamma\frac{q}{2m}J$$



$$\delta\mu_e = \frac{e}{2M}\frac{\alpha}{2\pi} = \frac{e}{2M} \times 0.0011617$$

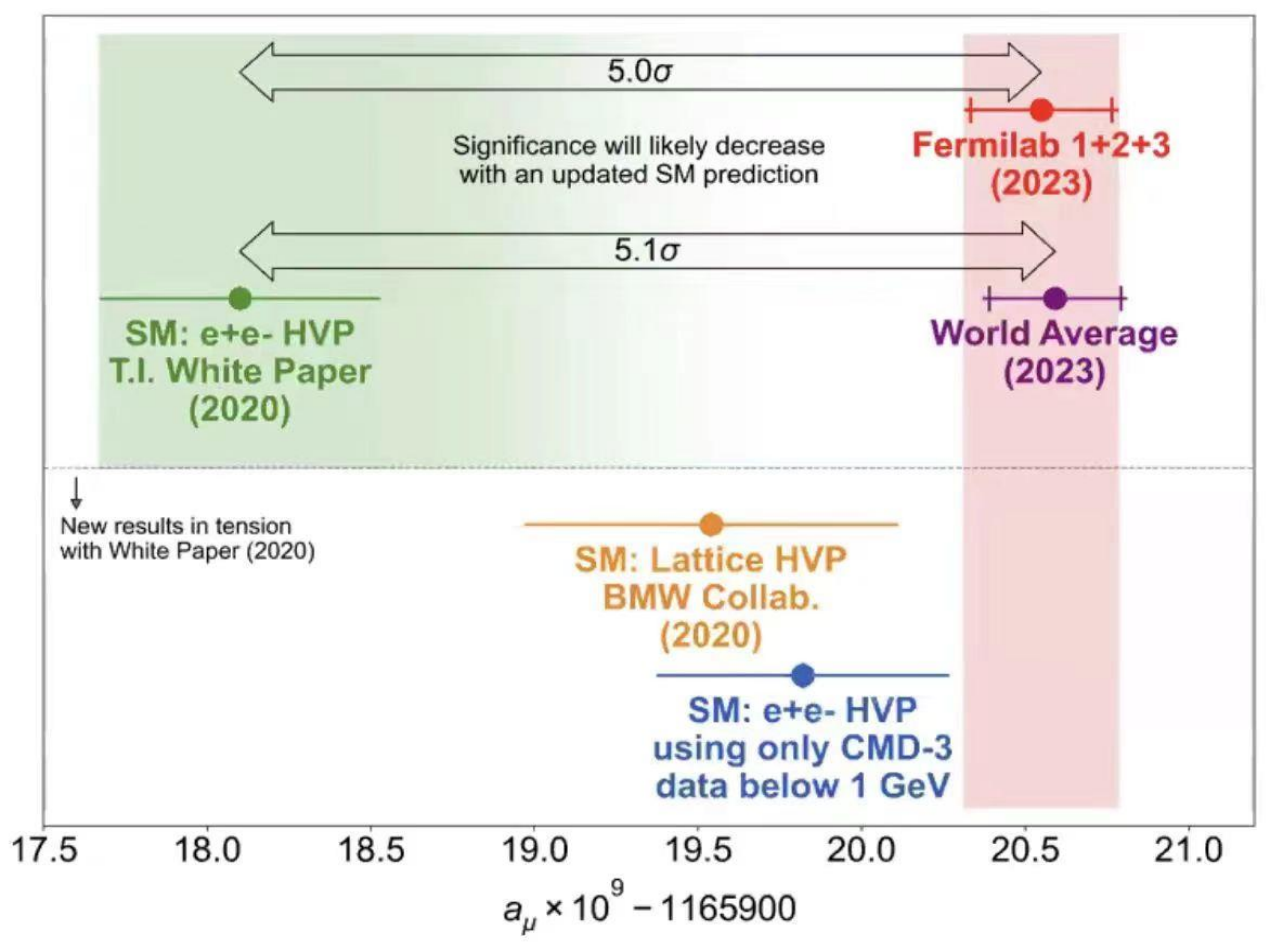
1947 年 12 月，著名物理学家

朱利安 • 施温格Julian Seymour Schwinger

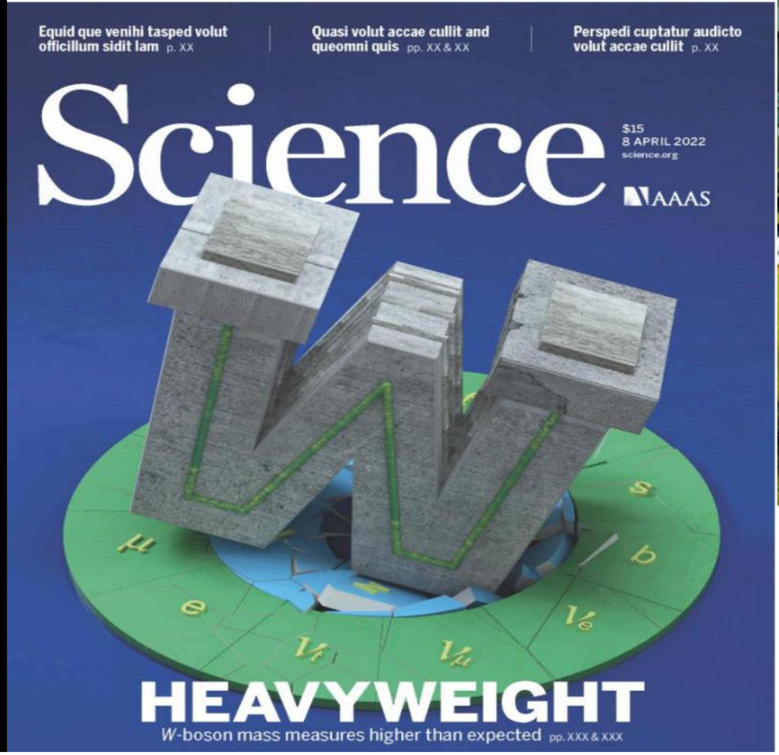
首次次给出上面结果

2016 PDG $\delta\mu_e = \frac{e}{2M}[0.00115965218091 \pm 0.00000000000026]$

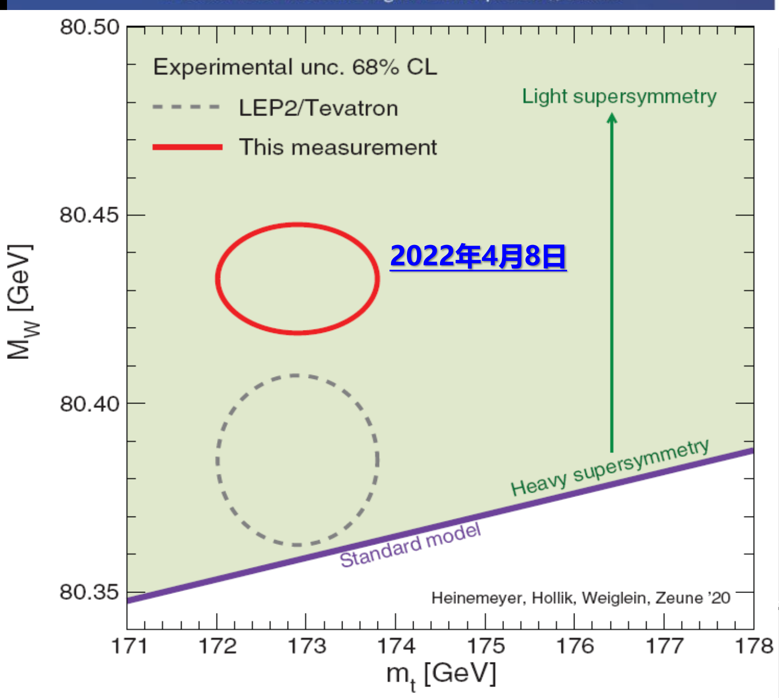
2021 年 4 月 7 日上午，美国费米国家加速器实验室（Fermi National Accalorator Laboratory, FNAL）选择召开网络视频发布会，公布了缪子 g-2 实验组对于缪子反常磁矩的首个测量结果。B.Abi et al. (Muon g-2 Collaboration), ΠΡΛ. 126 (2021) 141801

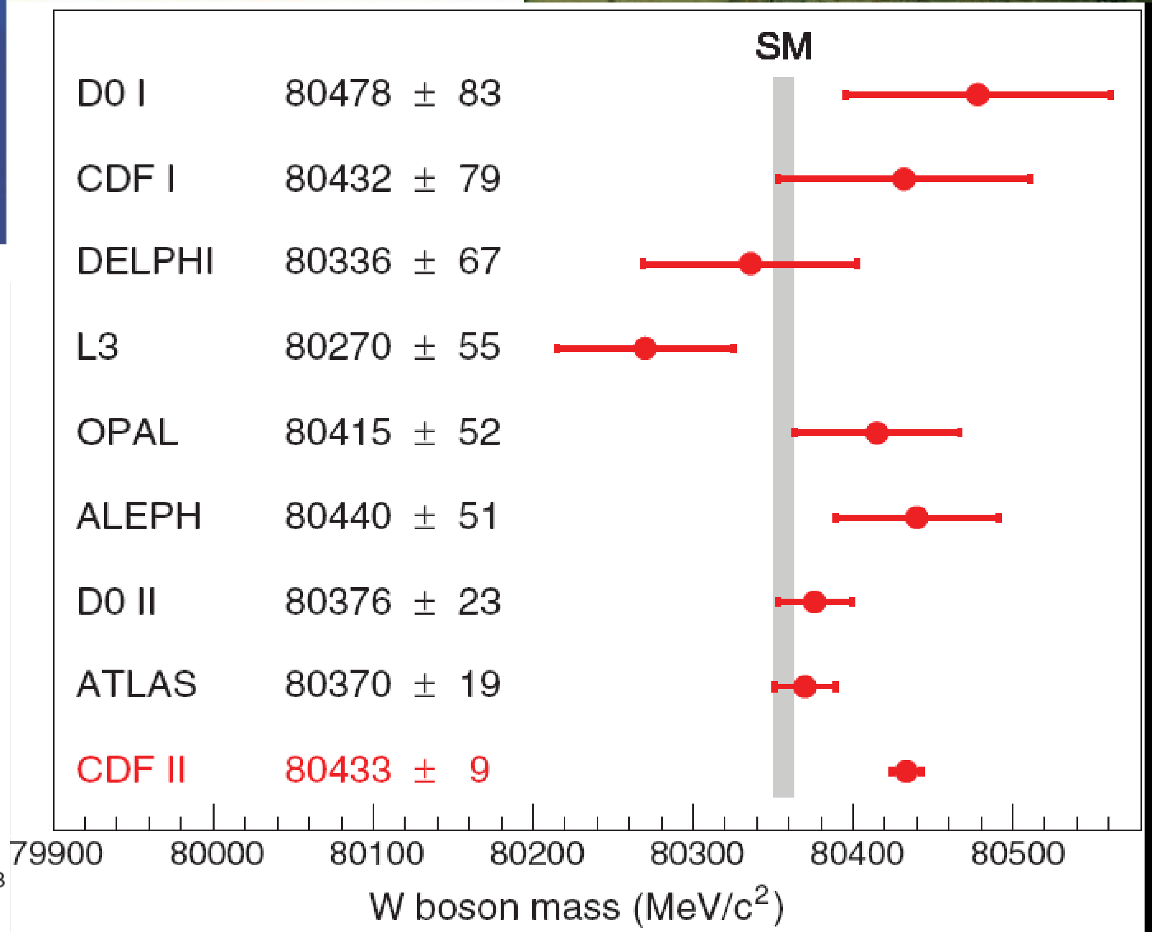


5.0σ
Significance will likely decrease
with an updated SM prediction
Fermilab 1+2+3
(2023)
5.1σ
SM: e+e- HVP
T.I. White Paper
(2020)
World Average
(2023)
New results in tension
with White Paper (2020)
SM: Lattice HVP
BMW Collab.
(2020)
SM: e+e- HVP
using only CMD-3
data below 1 GeV
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
$a_\mu \times 10^9 - 1165900$


Equid que venihi tasped volut officillum sidit lam p. XX
Quasi volut accae cullit and queomni quis pp. XX & XX
Perspedi cuptatur audicto volut accae cullit p. XX
Science
$15
8 APRIL 2022
science.org
AAAS
HEAVYWEIGHT
W-boson mass measures higher than expected pp. XXX & XXX

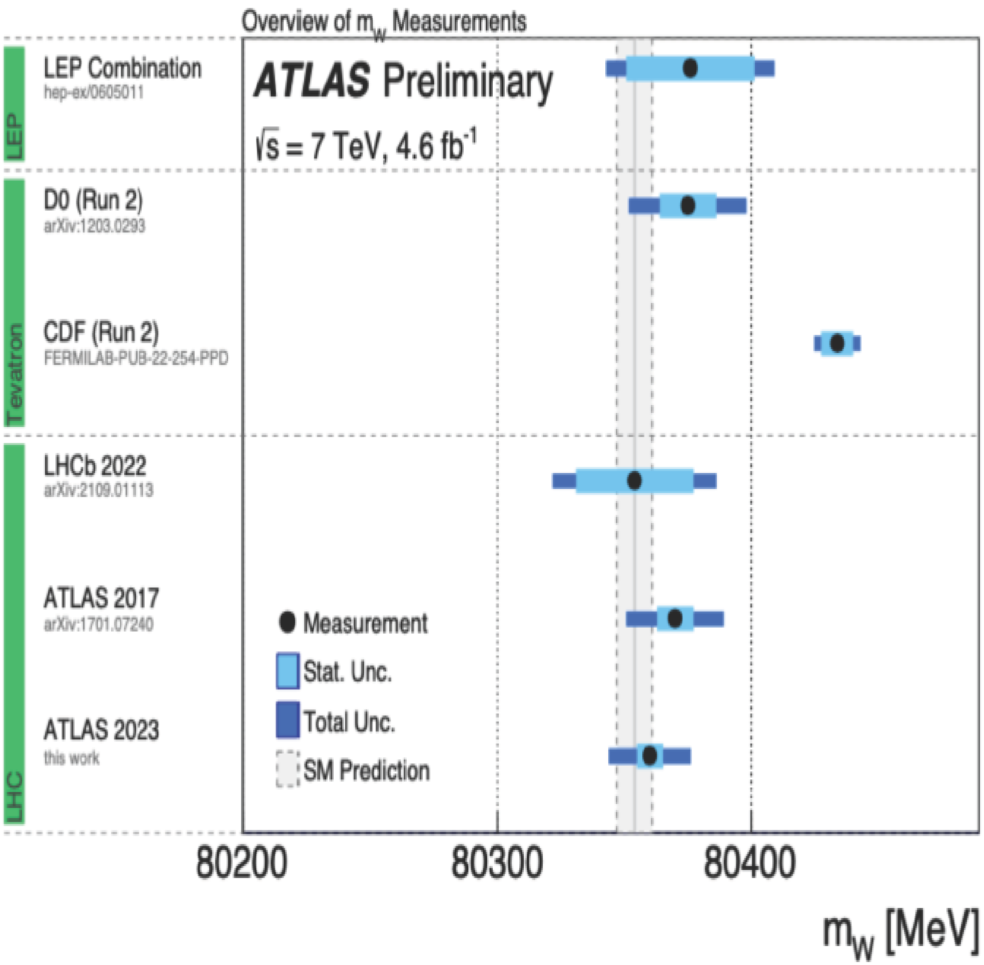

2011年9月30日关闭


Experimental unc. 68% CL
LEP2/Tevatron
This measurement
Light supersymmetry
2022年4月8日
Heavy supersymmetry
Standard model
Heinemeyer, Hollik, Weiglein, Zeune '20
80.50
80.45
80.40
80.35
M_W [GeV]
171 172 173 174 175 176 177 178
m_t [GeV]


SM
D0 I 80478 ± 83
CDF I 80432 ± 79
DELPHI 80336 ± 67
L3 80270 ± 55
OPAL 80415 ± 52
ALEPH 80440 ± 51
D0 II 80376 ± 23
ATLAS 80370 ± 19
CDF II 80433 ± 9
79900 80000 80100 80200 80300 80400 80500
W boson mass (MeV/c^2)

Observed shift 10 MeV and precision improved by 16 MeV!

New for Moriond EW 2023



- New W mass measurement from ATLAS is agreeing even ore with the SM prediction
- The tension with the CDF W mass is larger between ATLAS (only) and CDF 3.4σ now 4σ
- (Tension of CDF measurement with the SM 7σ)

Where do we go from here?

Significant evidence of measurement systematic bias: need a collective effort to understand this puzzle!

$m_W = 80360 \pm 5_{(stat.)} \pm 15_{(syst.)} = 80360 \pm 16$ MeV

$m_W = 80370 \pm 19$ MeV

未　来

2014年2月23日晚（春季学期上课周之前的周五）

清华大学主楼后厅

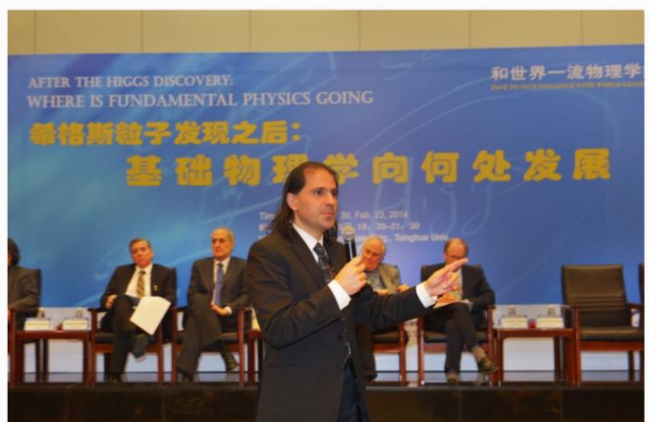
菲尔兹奖获得者、清华大学教授丘成桐主持论坛

八位世界一流的物理学家作为嘉宾参加论坛

日本东京大学卡弗里宇宙物理学与数学研究所所长

Hitoshi Murayama

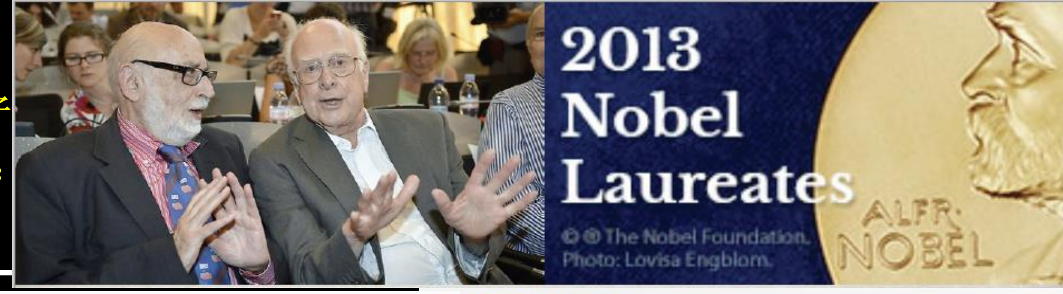
论坛现场气氛热烈，座无虚席



基础物理学奖获得者Nima Arkani-Hamed

清华大学陈吉宁校长出席论坛并致辞

2013年10月8日诺贝尔物理奖授予“上帝粒子”—希格斯粒子（粒子物理标准模型中最后一个未被发现的粒子）的提出人：



及基础物理学奖
潘诺夫斯基实验粒子物理学奖获得者王贻芳

诺贝尔物理奖获得者Gerard’t Hooft

立克奖和樱井奖获得者Luciano Maiani

诺贝尔物理奖获得者David Gross

菲尔兹奖和基础物理学奖获得者Edward Witten

出物理学奖获得者Joseph Incandela

2014年2月23日晚（春季学期上课周之前的周五），清华大学主楼后厅

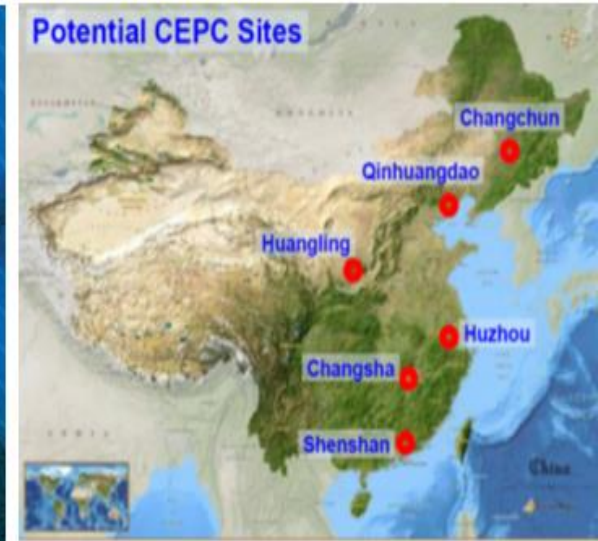
2016年6月26日（周五）晚上7：30
清华大学主楼后厅，丘成桐数学中心
设立“叶承耀-叶家祺冠名讲座”
王贻芳院士首讲“探索无穷”

编 辑　删 除

讲座》的通知 [文化素质教育基地办公室 2016-10-06]

办、清华大学国家大学生文化素质教育基地等协办的“工物学术论坛”暨
《环形正负电子对撞机——未来我国科学发展的一个重大机遇》讲座，因

CEPC → SPPC projet in China



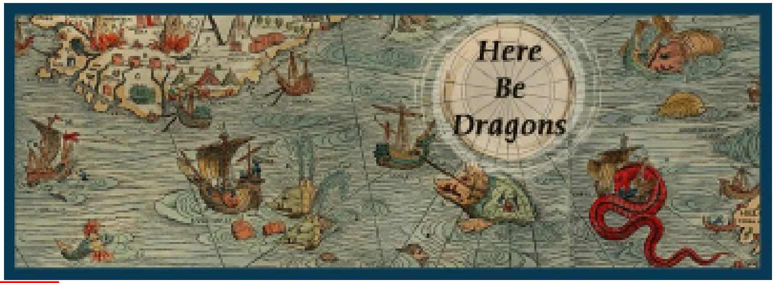
- 2013-2025: Key technology R&D, from CDR to TDR, site selection, international collaboration etc.
- Ideal case: Approval in the 15th Five-Year Plan, and start construction (~8 years)

Technically very similar project to FCC
The start with lepton collider followed then by Hadron Collider **has been always the plan of China since 2013.**

The choice for SC Magnet R&D is unique: IBS –iron based SC
an HTS potentially **much lower cost,** but lower performance than REBCO.

Ideas (conventional and not)

- Symmetries
  - Supersymmetry, family, …
- Compositeness
  - Higgs, fermions, …
- Extra dimensions
  - large, warped, …
- Dark or hidden sectors
  - Dark, SUSY-breaking, random, …
- Unification
  - GUT, string, …



- New dynamical ideas
  - Relaxion, nnaturalness, clockwork, string instantons, …
- Random or environmental
  - multiverse
- String remnants (need not solve SM problem)
  - *Z'*, vector fermions, extended Higgs, dark, moduli, axions, …
- Here be dragons
  - emergent dimensions or interactions, hidden variables, …

19世纪初的经典物理学	当今的基础物理学 粒子物理与宇宙学
There is nothing new to be discovered in physics . All that remains is more and more precise measurement,… William Thompson 1900 经典物理的大厦完美无缺	Are we in a Michelson moment ? Veronica Sanz in ICHEP2022 粒子物理标准模型+ **ΛCDM** 与实验符合很好
物理学再没新东西了	基础物理物理再没新东西了 新物理；修改引力.....
只有两朵乌云  	若干问题
经典真空：一直在寻找以太	量子?真空： 一直在寻找新东西
苦苦探寻未果导致 狭义相对论	若真苦苦探寻未果导致？？？
大厦建成后没多久就有了新的发展	能否重现百年前的物理学历史？

What happens during the scattering process of elementary particles?

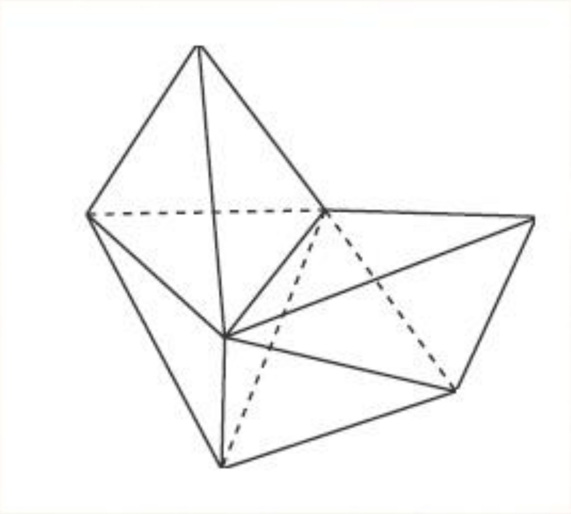
振幅可以约化为某个辅助空间的积分因而是体积

量子场论是否需要重塑：

①是否仍需以拉氏量为基础？

②数学上不严格

③向非局域推广



颠覆传统量子场论计算原则！

甚至超越弦理论

整数

∩

有理数　　实数

∩

代数数可数,超越数不可数

有理系数方程解定义 ∩

周期通常是超越数，但可数 ∩

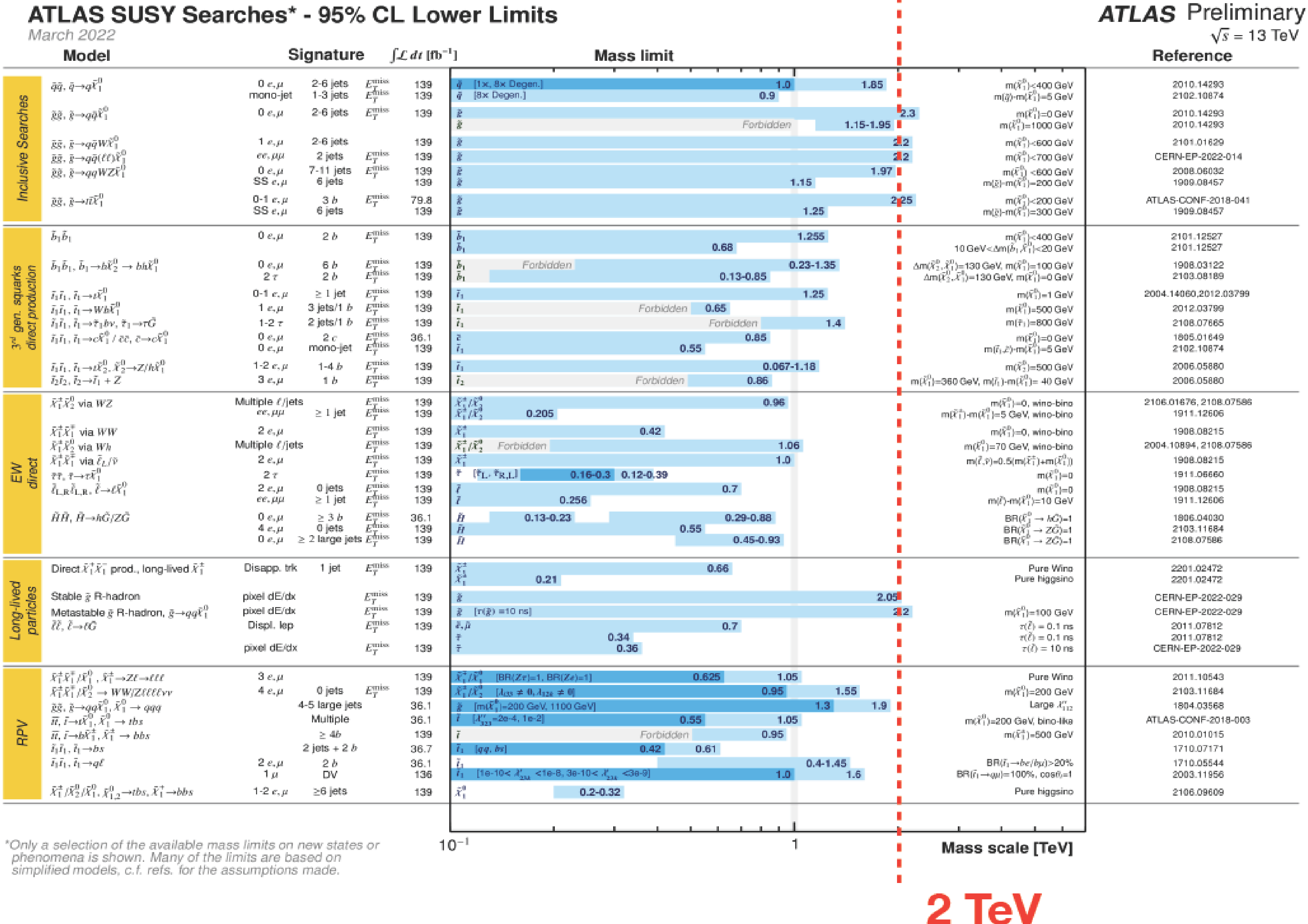
通过定积分定义 ∩

复数

$$\pi = \iint_{x^2+y^2\leq 1} dx\, dy$$

$$\sqrt{2} = \int_{2x^2\leq 1} dx$$

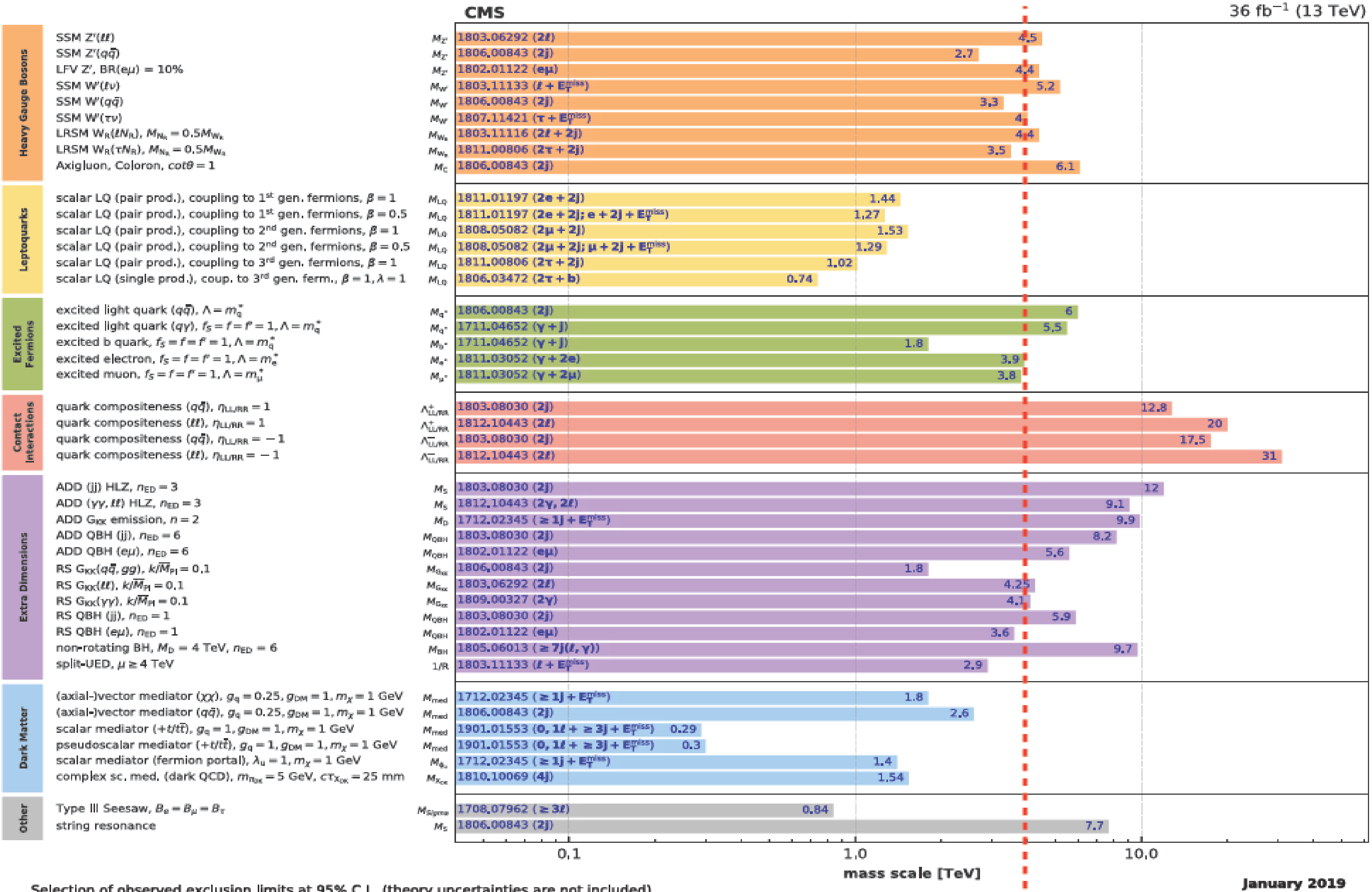
Big goal: find a new formulation of QFT where the picture of interacting particles in spacetime, locality and unitarity is replaced by other principles



Moriond 2023

Example from ATLAS (similar for CMS)

Overview of CMS EXO results



4 TeV

Moriond 2023

Example from CMS (similar for ATLAS)

A era of precision measurement

Collider

EXP: Higgs property, VBS (aQGCs, dim-8 operators, ...)

TH: NLO -> NNLO -> NNNLO ->

Neutrino: Mass ordering, CPV, Majorana?

Dark Matter: Neutrino floor

Cosmology: GW, BH ...

1974：c quark observed （SLAC,BNL)
1974-77：τ lepton observed （SLAC)
1977：b quark observed （FNAL)
1983：W and Z observed （CERN)
1995：t quark observed （FNAL)
2000：ν_τ observed FNAL)
2012：H observed （CERN）
2024：dark matter？

- 非渐近自由的规范作用
- 唯一的标量场
- 负责所有粒子质量产生

玛雅历2012.12.21结束后

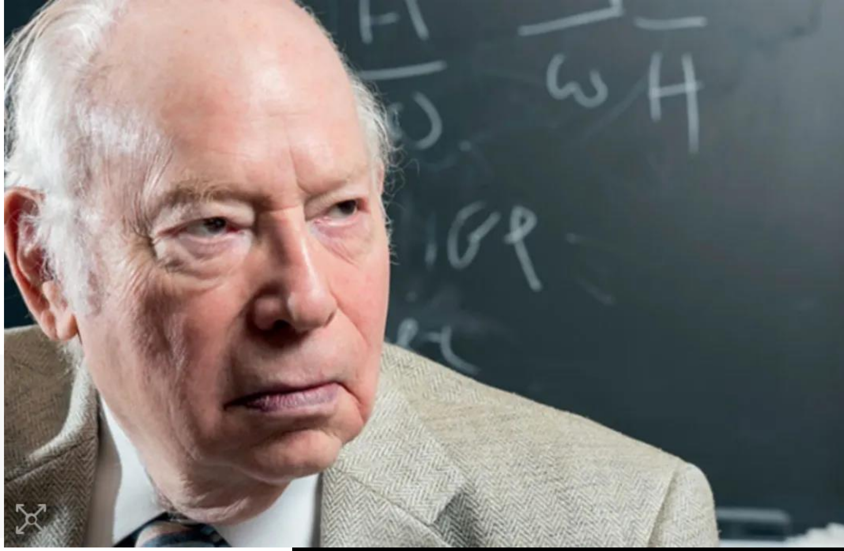
开启了 **后希格斯** 时代

模型缔造者温伯格，带着未见新物理的遗憾走了

中国物理学会期刊网 今天

以下文章来源于返朴 ，作者Matt Valentine

返朴
溯源守拙·问学求新

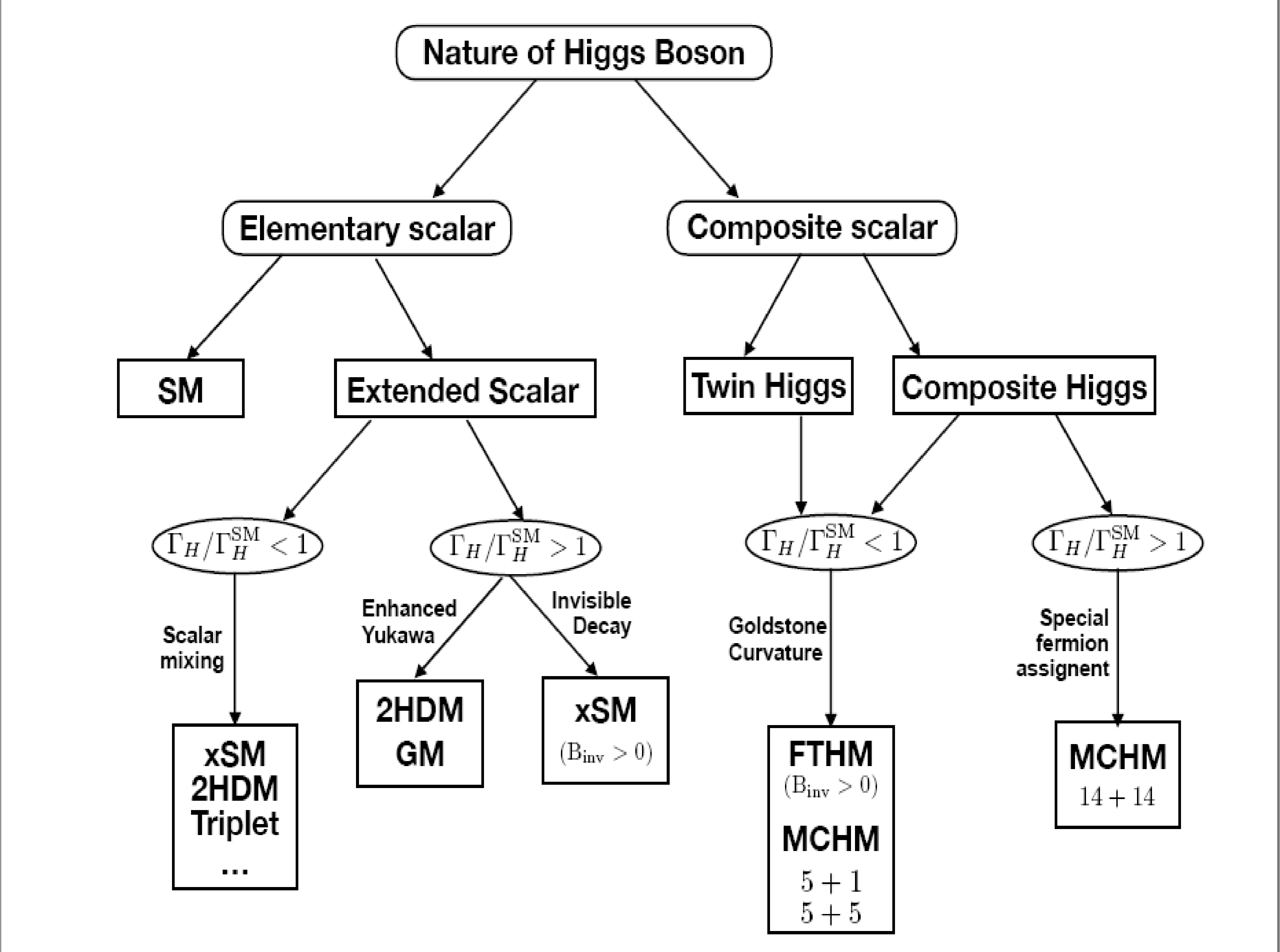


一般认为：温伯格所提的基本粒子中的费米子质量的问题是下一个时代的粒子物理才有可能予以考虑研究的内容。目前是研究基本粒子中的玻色子的规范粒子的质量的时代，连玻色子中的希格斯玻色子的质量也是无法研究的。规范玻色子的质量的起源在粒子物理标准模型中通过引入希格斯场建立希格斯机制得以实现，只是2013年诺贝尔物理奖的核心。这个对规范玻色子质量的解释是否就满意了呢？ 否！

人们相信目前的希格斯场及其相互作用很可能只是一个有效的理论，并不是背后真正的基本相互作用，这是当今探索新物理的主要考虑。

当被问及如果可以选择，他希望在有生之年解开什么谜团时，

温伯格无需多想：他希望能够解释观测到的夸克和轻子质量的模式。



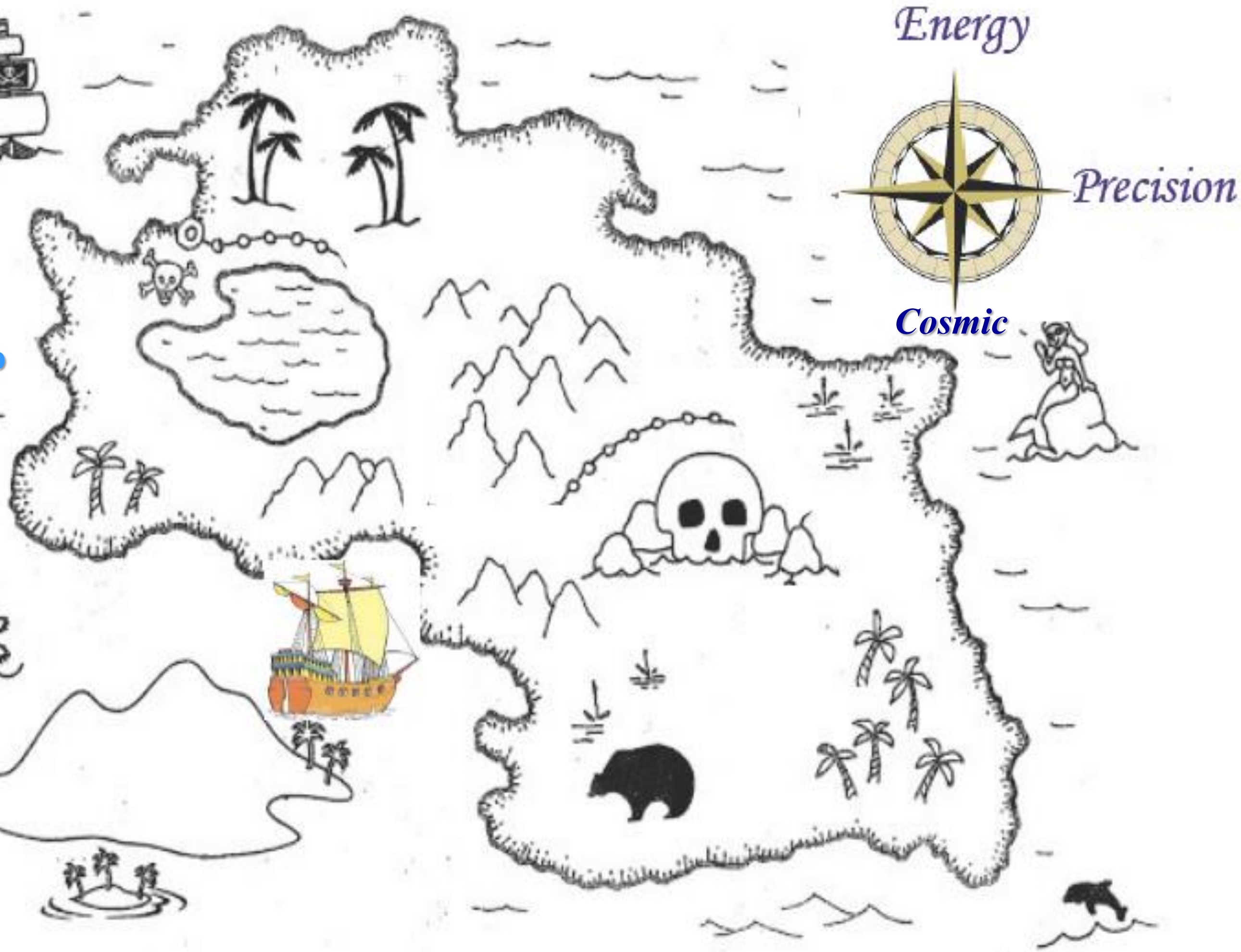
Nature of Higgs Boson
Elementary scalar
Composite scalar
SM
Extended Scalar
Twin Higgs
Composite Higgs
$\Gamma_H/\Gamma_H^{SM} < 1$
$\Gamma_H/\Gamma_H^{SM} > 1$
$\Gamma_H/\Gamma_H^{SM} < 1$
$\Gamma_H/\Gamma_H^{SM} > 1$
Scalar mixing
Enhanced Yukawa
Invisible Decay
Goldstone Curvature
Special fermion assignent
xSM
2HDM
Triplet
...
2HDM
GM
xSM
$(B_{inv} > 0)$
FTHM
$(B_{inv} > 0)$
MCHM
$5 + 1$
$5 + 5$
MCHM
$14 + 14$

在理论处于茫然的时期
实验的指示尤显重要

TERRA INCOGNITA

Unfortunately we do not have a ❌ in the map to know where the treasure is, as we had for the Higgs Boson. We have to explore the whole territory.

Actually, we are not even sure that the BSM treasure is in the territory to be explored, or even if it does exist at all.

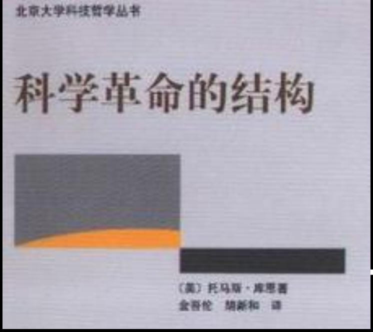


The whole history of physics proves that a new discovery is quite likely lurking at the next decimal places,…
F.K. Richtmeyer 1931

XXVII International Symposium on Lepton Photon Interactions at High Energies

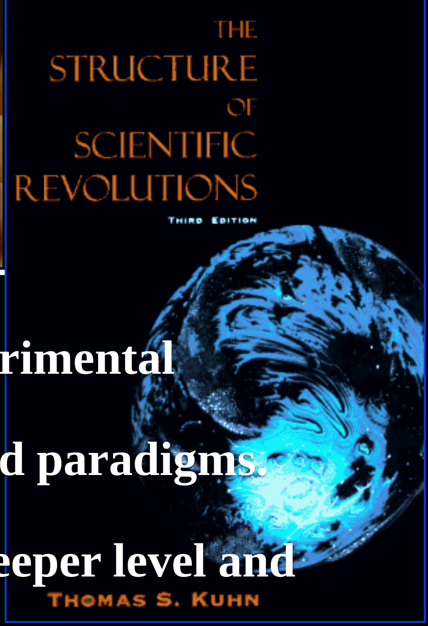
17–22 Aug 2015 Slovenia

New Physics： Dusk or Dawn ?




固态氩液化与气化


Thomas Samuel Kuhn

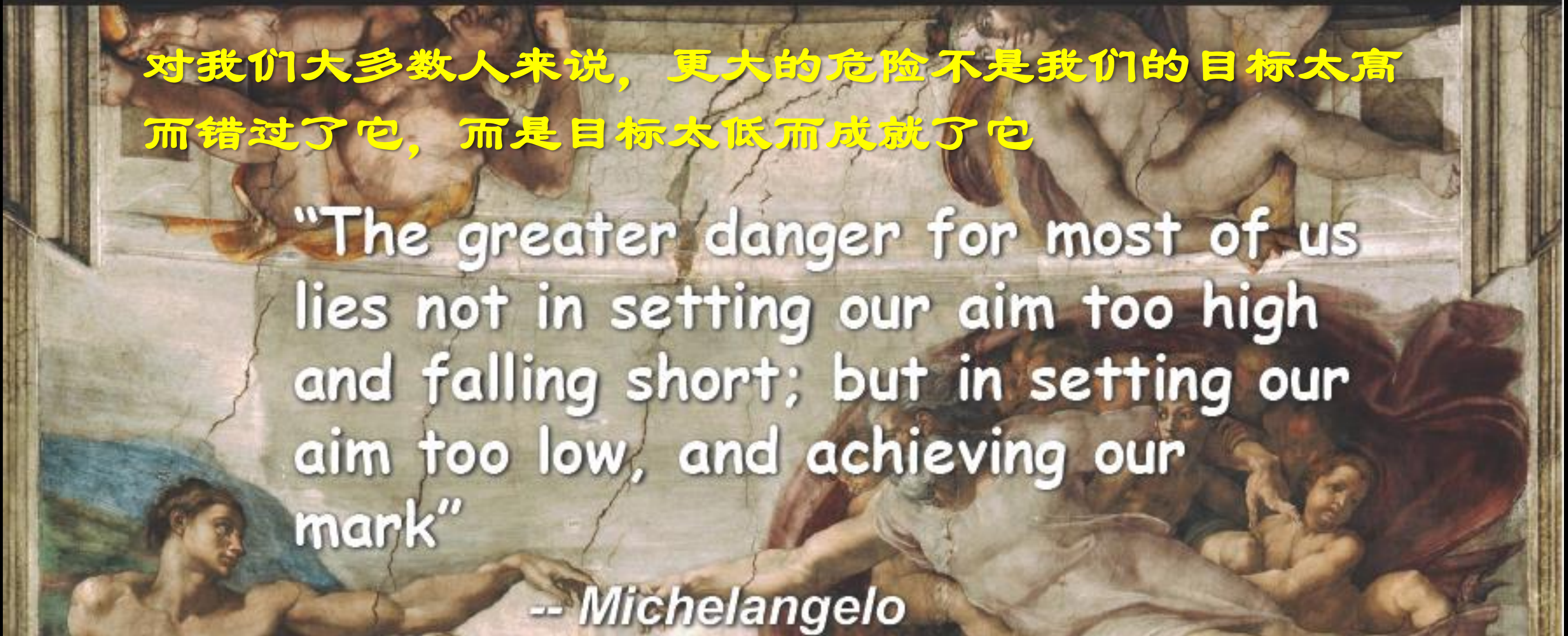


The phase of discovery : new conceptual breakthroughs and experimental results lead to the emergence of a new theory that departs from old paradigms.

The phase of consolidation : the theory is understood at a much deeper level and confirmed by precise measurements. This process has the effct of trasforming the new theory into the established paradigm of **normal science**.

The phase of crisis : the normal theory can no longer address new conceptual questions or explain experimental data. This phase is characterised by the search for new paradigms and marked by periods of confusion and frustration.

Finally a paradigm shift occurs, which results in a departure from normal science, activating a new phase of discovery and marking the beginning of a new cycle.



It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair, we had everything before us, we had nothing before us, we were all going direct to Heaven, we were all going direct the other way.

— Charles Dickens

这是一个最好的时代，这是一个最坏的时代；这是一个智慧的时代，这是一个愚蠢的时代
这是一个信仰的时期，这是一个怀疑的时期；这是一个光明的季节，这是一个黑暗的季节
人们面前应有尽有，人们面前一无所有；人们正踏上天堂之路，人们正走向地狱之门 《双城记》

真　空

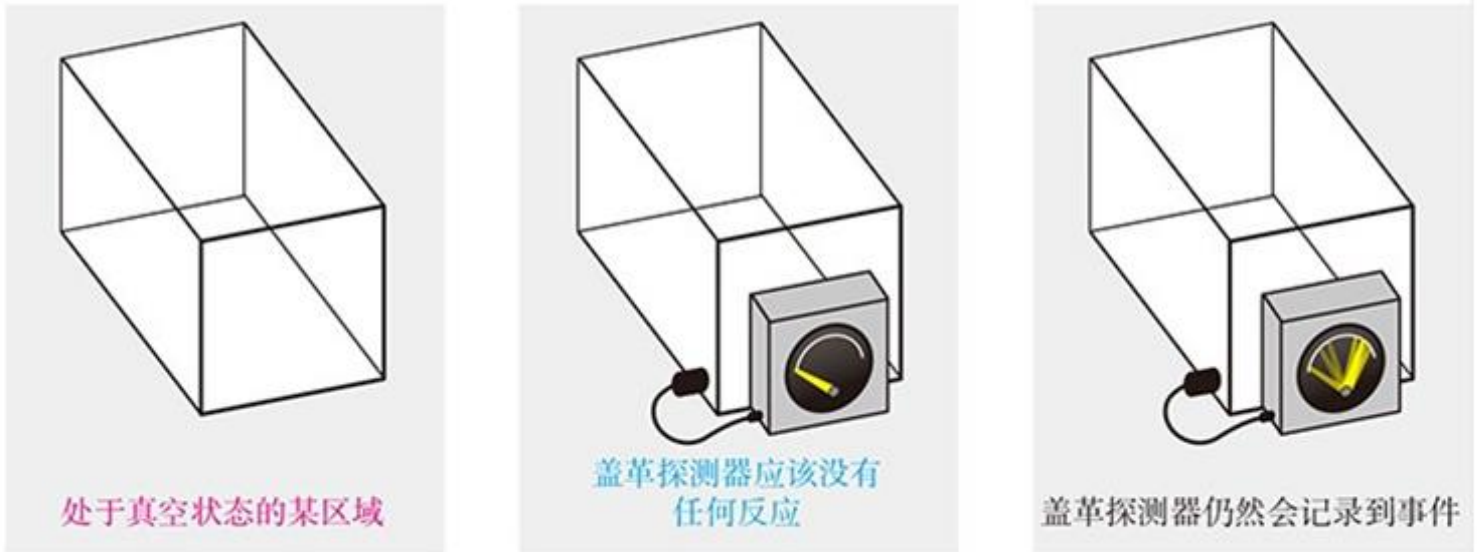
真空不空！

亚里士多德：
自然厌恶真空

老子道德经：
万物生于有
有生于无

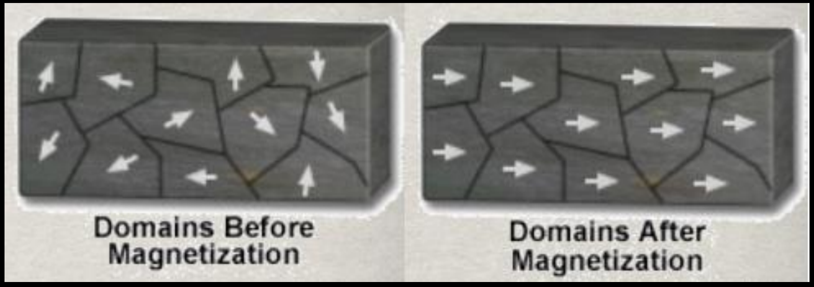
没有粒子就一无所有

如果物质由粒子构成，那么作为零粒子状态的真空，就应该是一片死寂。但量子理论预言，放置在真空中的盖革探测器或类似的粒子探测器，仍然能记录到物质存在的事件。因此，物质不可能由我们理解中的经典"粒子"构成。



- 量子系统的真空就是其最低能量状态（若有简并，就会发生自发破缺）
- 真空具有复杂的结构，类似介质
- 真空在引力场中会发生形变，类似介质

  为什么非得是引力？
- 但真空这种介质 <u>不存在绝对参考系</u>



Two gold-plated equations of physics

QM: uncertainty principle

$$\Delta E \sim 1/\,\Delta t$$

"Accounting errors could be tolerated for a short time"

Special relativity: energy = matter

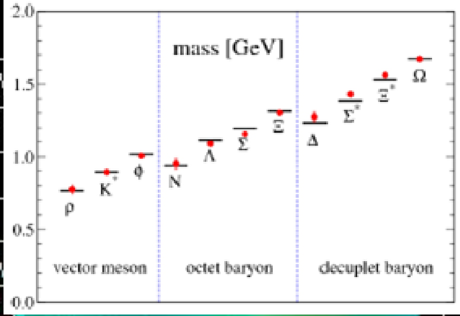
$$E = mc^2$$

"Accounting errors could be turned into stuff"

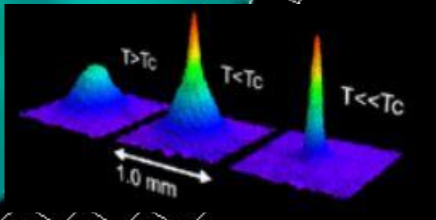
If both of these principles, then for an instant, particles could pop out of and pop back into the vacuum

You need both quantum physics and special relativity!

No matter how you shake and bake the Schrödinger equation of one electron, always one electron

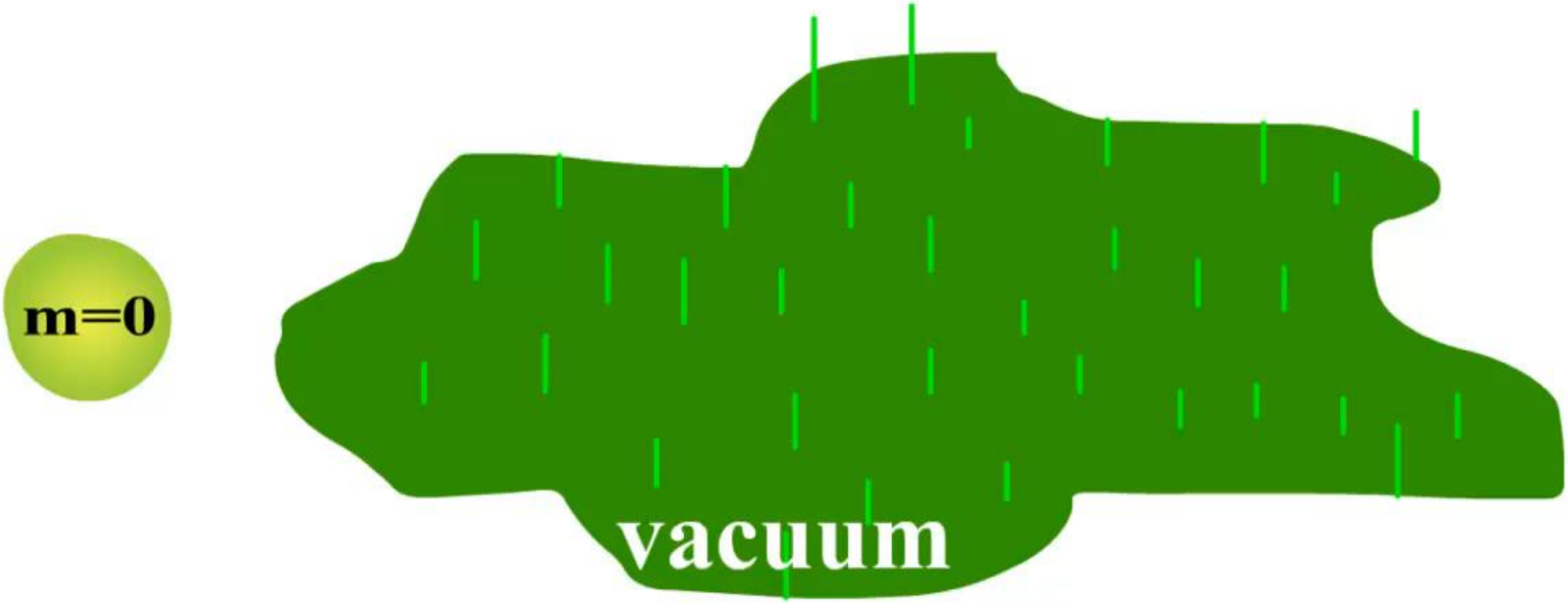


强作用真空与夸克对凝聚



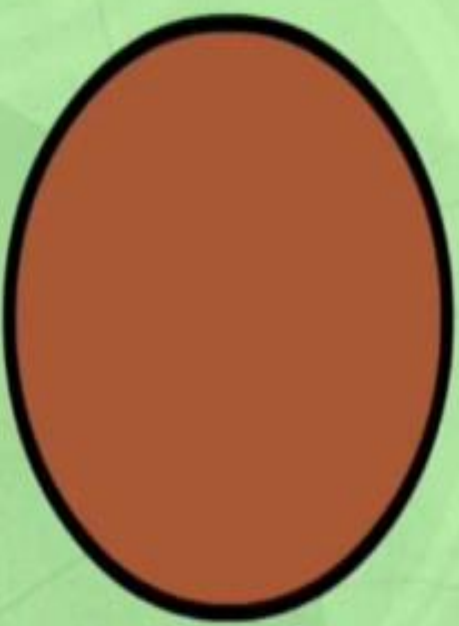
$$M_N = g < \bar{q}q >$$

质子和中子在强作用真空中穿行，
和真空发生复杂的相互作用，
产生夸克对的玻色爱因斯坦凝聚，
导致质量产生。


m=0
vacuum

有些粒子和真空中的希格斯场无作用，保持无质量！

有些粒子和真空发生作用，产生凝聚，获得质量！



Massless

希格斯场自己还可能会激发出粒子,它是希格斯场存在的标志！

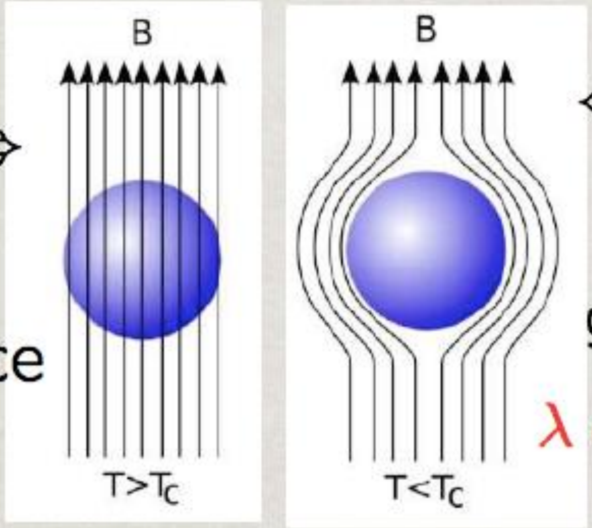
电弱真空是第二类超导体

$M_H > \frac{M_W}{\sqrt{2}}$

Normal phase⇒

$E^2 = p^2c^2$

Long-range force



⇐Superconducting phase

$E^2 = p^2c^2 + m^2c^4$

gap leads to $\sim exp(-r/\lambda)$

$\lambda \sim m^{-1}$ penetration depth

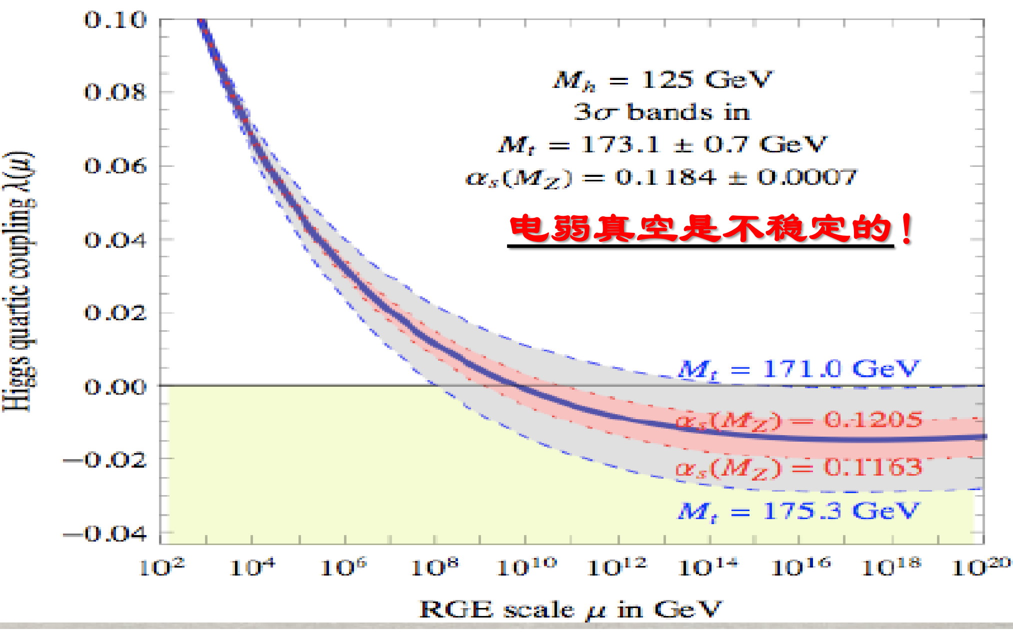
In "conventional" electro-magnetic superconductivity:

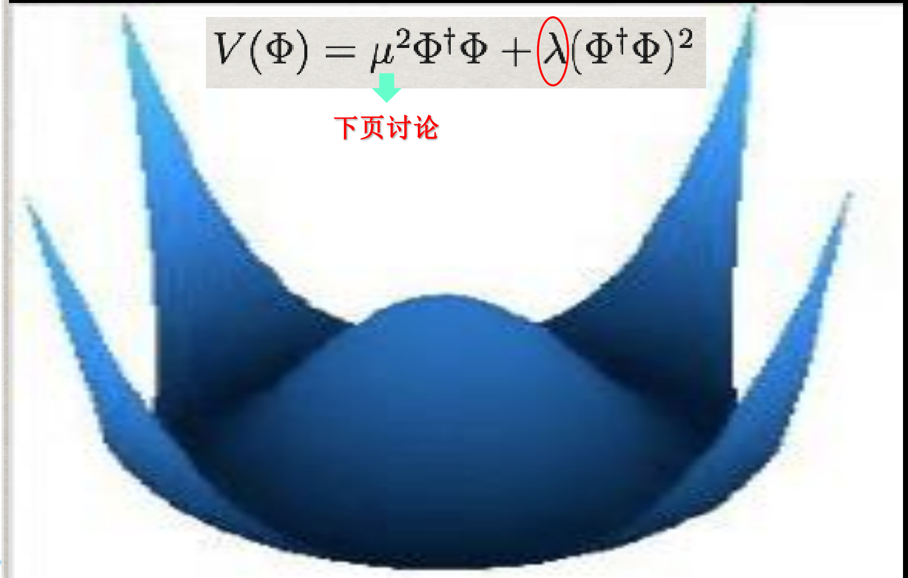
$m_\gamma \sim m_e/1000$, $T_c^{em} \sim \mathcal{O}(\text{few } K)$. BCS theory.

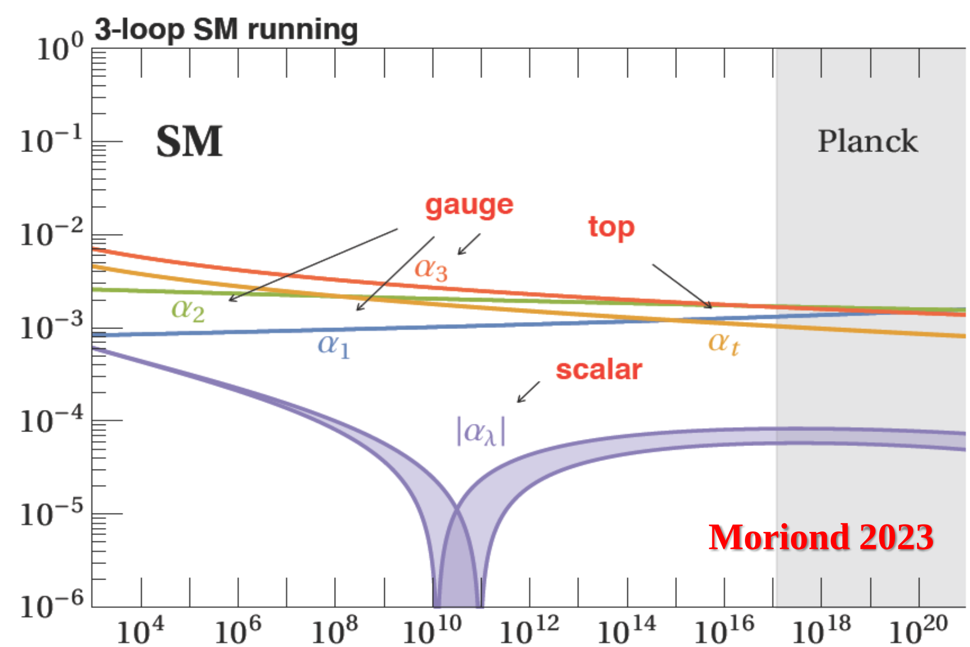
In "electro-weak superconductivity":

$m_w \sim G_F^{-\frac{1}{2}} \sim 100$ GeV, $T_c^w \sim 10^{15}K$!

We are living in a EW superconducting phase!

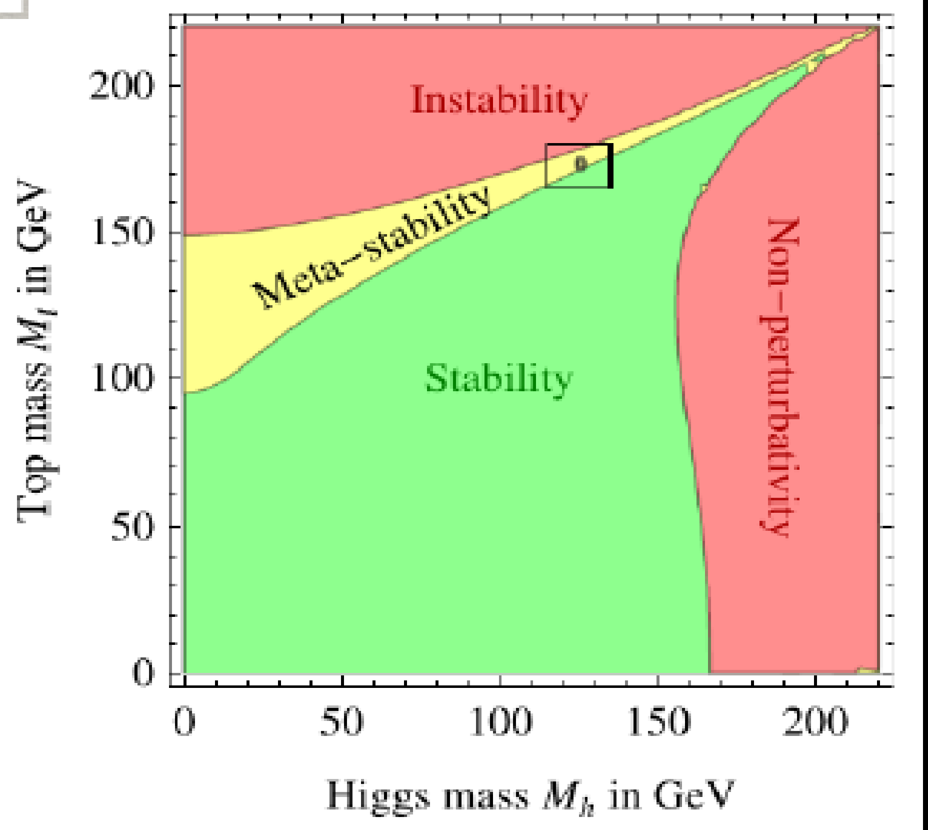






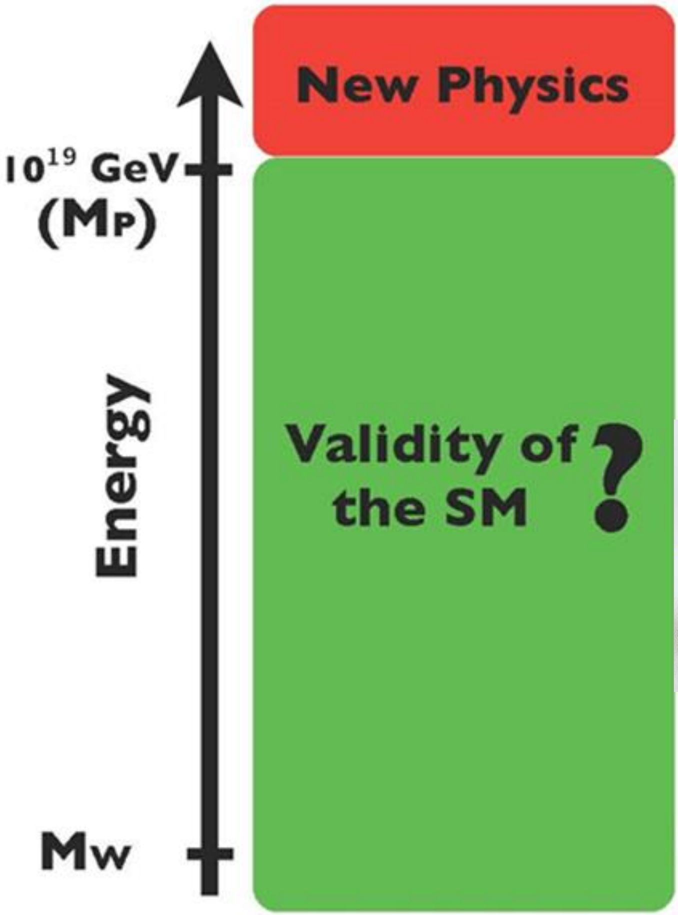
$$\alpha_\lambda = \frac{\lambda}{(4\pi)^2}$$ ← Higgs quartic

Uncertainty bands:
1-sigma top pole mass
$m_t = 172.76 \pm 0.30$ GeV



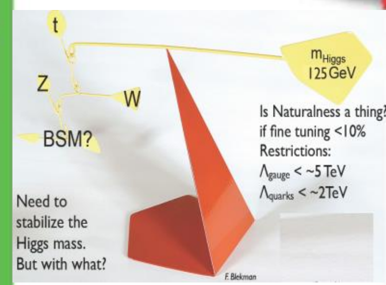
Although consistent, we think (and hope) the SM is not the full story

At the quantum level "slim" scalars cannot survive in the presence of "fat" states



Heavy states
Strings/GUT

保持苗条需要"健身"



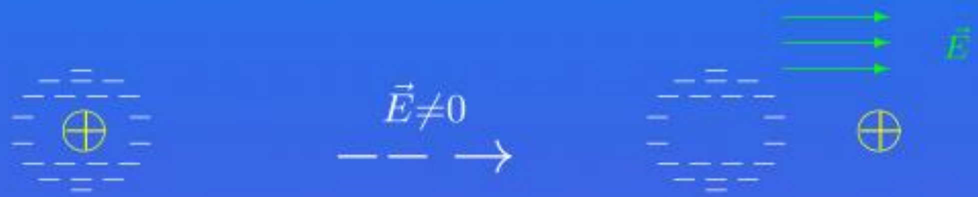
Higgs = Scalar

电子预期质量比实际至少大了4个量级（导致量子力学出现）：$r_e = \frac{\mu_0 e^2}{4\pi m_e} = 2.817 \times 10^{-15}$米 >质子的电荷半径0.8*10^-15^米

考虑真空极化的效应后：

$$m_e = \frac{\mu_0 e^2}{4\pi r_e} \xrightarrow{\text{真空极化效应}} \frac{\mu_0 e^2}{4\pi r_e} \times \frac{m c r_e}{h} \ln\left[\frac{h}{m c r_e} + \sqrt{1 + \left(\frac{h}{m c r_e}\right)^2}\right]$$

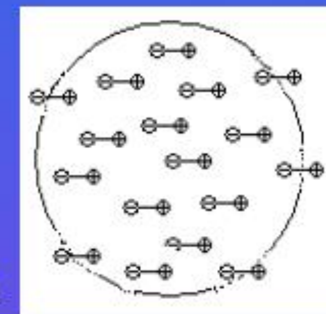
介质极化：



极化强度：

$$\vec{P} = \lim_{\Delta\tau\to 0}\frac{\sum\vec{p}}{\Delta\tau} = n_p\vec{p}$$

n_p ： 单位体积的电偶极距



$$\vec{P} = \chi_e\epsilon_0\vec{E}$$

χ_e： 极化率　　物质的电磁性质方程

一各向同性非均匀无穷大介质球的球心放置一个电量为q的点电荷,介质球介电常数 $\epsilon=\epsilon_0[1+\chi_e(r)]$是半径r的函数，求半径为r的区域内的总电荷Q(r) (裸电荷加极化电荷)?

按照高斯定理： $\vec{E} = \dfrac{\vec{D}}{\epsilon} = \dfrac{q}{4\pi r^2\epsilon}$　　$Q(r) = \epsilon_0\oint_r d\vec{S}\cdot\vec{E} = \dfrac{q\epsilon_0}{\epsilon} = \dfrac{q}{1+\chi_e(r)}$

- 正常情形下极化强度和电场强度是同方向的，因此$\chi_e>0$,这时 $Q(r)<q$，称 屏蔽！
- 如果真出现极化强度和电场强度是反方向的情况，$\chi_e<0$, 这时 $Q(r)>q$，称 反屏蔽！
- 量子场论中真空体现出介质的性质，真空极化导致人们实际测量到的是Q(r),而不是q！

Running of coupling with energies

$$\alpha(r) = \frac{\alpha(r\ )}{1 + \frac{\alpha(r_0)}{3\pi}\ln(r^2/r_0^2)}$$

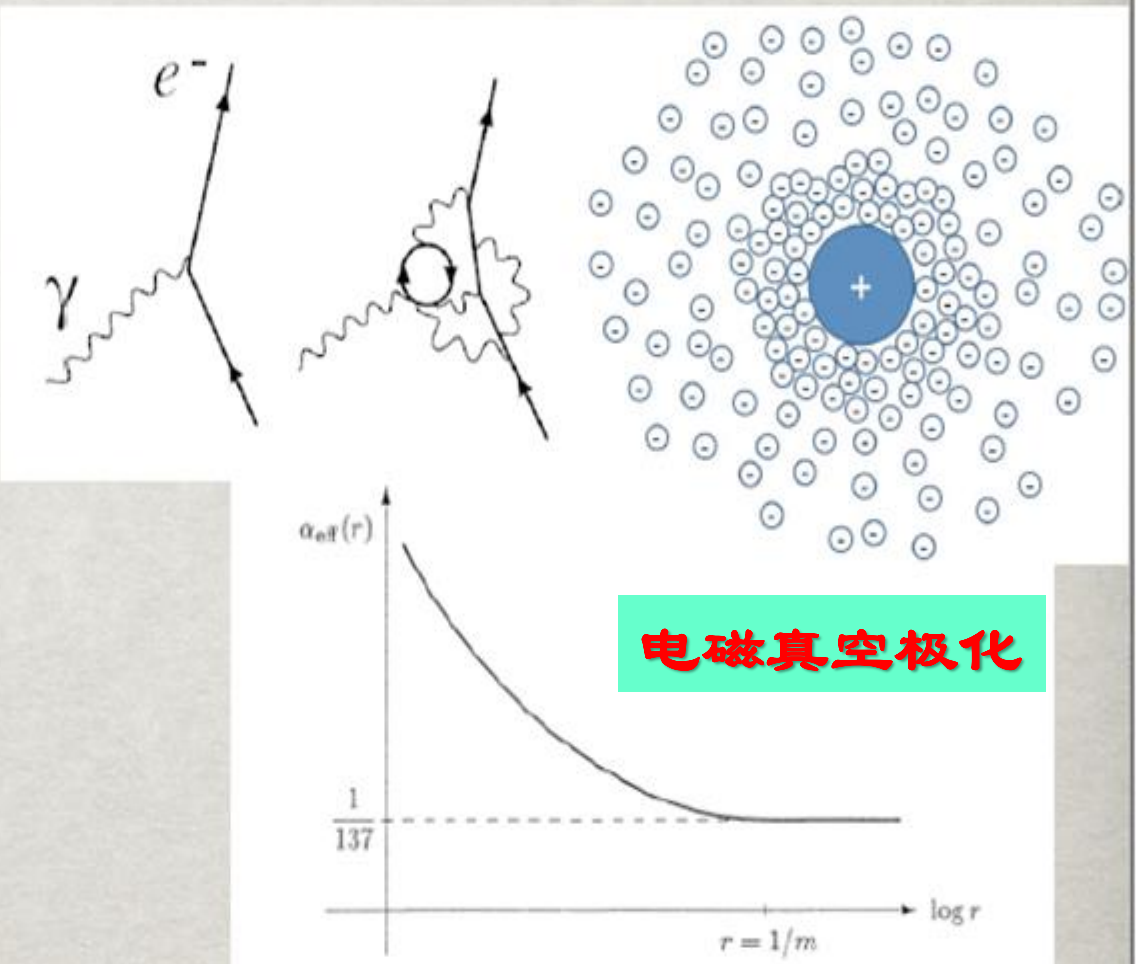


Figure 7.10. A qualitative sketch of the effective electromagnetic coupling constant generated by the one-loop vacuum polarization diagram, as a function of distance. The horizontal scale covers many orders of magnitude.

$$\alpha_{QED}(keV) = 1/137$$

$$\alpha_{QED}(M_Z) = 1/128$$

The Landau pole:

It blows up at high energies!

Must be modified at UV.

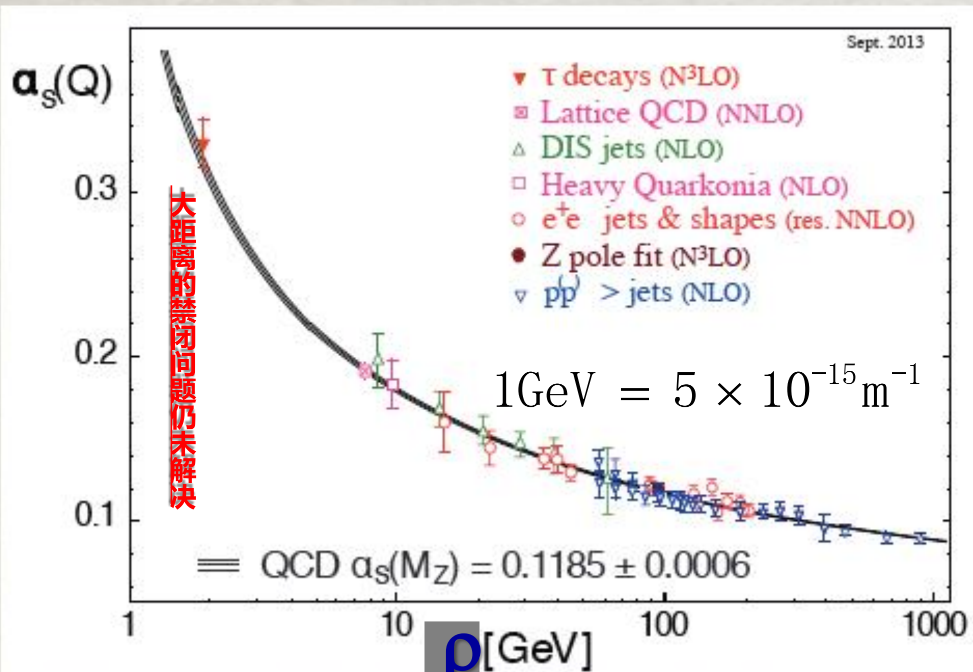
非阿贝尔规范场产生反屏蔽效应催生 渐近自由

IR confinement & UV asymptotic freedom

Interaction strength changes fast with energy/distance scale:

裸电荷（裸强精细结构常数）趋近于零!

$$\alpha(r) = \frac{\alpha(r_0)}{1 + \frac{\alpha(r_0)}{3\pi}\ln(r^2/r_0^2)}$$



强作用真空极化

D. Gross, F. Wilczek, D. Politzer (2004)

非阿贝尔规范理论是唯一在小距离自洽的可重整量子场论!

V.S.Vanyashin and M.V.Terentev， ZhETF 48(1965)565 [Sov.Phy.JETP 21(1965)375]

I.B.Khriplovich, Yad.Fiz.10(1969)409 [Sov. J. Nucl.Phys.10 (1970)235]

A.Zee Phys.Rev.D7, June 15, 1973 (received March 12)

"Study of the Renormalization Group for Small Coupling Constants"

A renormalizable quantum field theory is said to be stagnant if it is asymptotically free. ....We show that Cartan's four families A,B,C,D and exceptional algebra G_2 possess no stagnant representation. On the basis of this result we conjecture that there are no assymptotically free quantum field theories in four dimensions.

D.J.Gross and F.Wilczek PRL, 30, June 25 1973 (Received April 27)

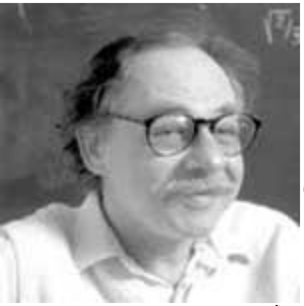
"Ultraviolet Behavior of Non-Abelian Gauge Theories"

It is shown that a wide class of non-abelian gauge theories have, up to calculate logarithmic corrections, free-field-theory asymptotic behavior.

David Politzer Phys.Rev.Lett, 30, 25 June 1973 (Received 3 May)

"Reliable Purturbative Results for Strong Interactions?"

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions.



Price of Asymptotic Freedom*

Sidney Coleman† and David J. Gross‡
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 13 July 1973)

A renormalizable field theory is said to be asymptotically free if the origin of coupli constant space is an ultraviolet-stable fixed point in the sense of Wilson. Asymptotically free theories are of great interest because they have almost-canonical light-cone singularities, and thus predict phenomena very close to Bjorken scaling. All known examples of asymptotically free theories involve non-Abelian gauge fields. We show that this is not coincidence: No renormalizable field theory without non-Abelian gauge fields can be asymptotically free.

In recent years, the renormalization group of Gell-Mann and Low[1] has played a central part in the investigation of some important asymptotic properties of renormalizable field theories.[2] In particular, the renormalization group is the key to the asymptotic behavior of the coefficient functions in Wilson's operator-product expansion,[3] and the related behavior of electroproduction structure functions in the Bjorken region.[4]

To establish notation, and as an aid to the reader of imperfect memory, let us briefly summarize how this machinery works[5]: In a general re-

erned by that of the theory at the fixed point. Of special interest is the case where the origin is an ultraviolet-stable fixed point, that is to say, where there exists a family of solutions to the Eqs. (1) such that

$$\lim_{M\to\infty} g^{\alpha}(M)=0. \qquad (3)$$

In this case, we say the theory is asymptotically free. The coefficient functions in the operator-product expansion display canonical scaling behavior, except for occasional logarithmic factors,

渐近自由发现过程中的三对师徒：

1. Martinus J.G Veltman & G.’ t Hooft：

  荣获1999年诺贝尔物理奖

71年tHooft算出了负号，没意识到其对强作用的重要性。72年发展出了计算规范理论重整化的方法，并发现了能给出跑动耦合常数的方法。但Veltman认为这都是欧式空间的结果，和在闵氏空间的物理观测结果无关。tHooft曾几次跟Veltman谈及纯规范理论对强作用的作用，但Veltman认为只要禁闭问题不解决，其它的想法都无用，评审人不会接受这些想法的发表。

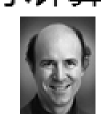
在72年在马赛开了一个小会，重整化群大咖Symanzik在到达的机场和tHooft谈及他的工作：具有渐近自由的负耦合常数的$\lambda\varphi^4$理论。tHooft问如何处理理论没下界问题，Symanzik说寄希望非微扰效应。tHooft告诉他在非阿贝尔规范理论里有渐近自由，Symanzik吃惊又怀疑地说： “如果是真的，这很重要，你应该赶紧发表你的结果。如果你不这么做，别人将来也会做”。会上Symanzik在讲了他的负耦合常数的$\lambda\varphi^4$理论后就强调进一步需要在非阿贝尔规范理论的研究，然后就有了传说中著名的tHooft在会场的黑板上写下了他自己的计算的渐近自由的结果！tHooft给出的他没发表结果的原因：①Weinberg对规范理论的红外结构有详细的讨论，是tHooft相信红外奴役作为渐近自由的红外预研应该是Weinberg很清楚知道的②Gross告诉tHooft说强作用的标度行为在任何场论里都解释不了③给出渐近自由的深度欧式空间是非物理、无趣的。

2. Sidney Coleman & H.D.Politzer：

Coleman当时正访问Princeton；Politzer做其研究生被要求计算非阿贝尔规范场的高能行为，算出负号到处问...

3. David Gross & Frank Wilczek：

Gross在Princeton教量子场论，72年当教授；原计划证明无渐近自由，不想做了相反的发现；Wilczek原是学数学的学生，对粒子物理感兴趣转入物理系；71年听场论课，做Gross的研究生，72年开始跟Gross做工作，与Gross合作计算非阿贝尔规范场理论的高能行为。 Wilczek现在是麻省理工学院教授，李政道研究所首任所长。

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