追踪反物质消失之谜

--LHCb实验探秘CP破坏

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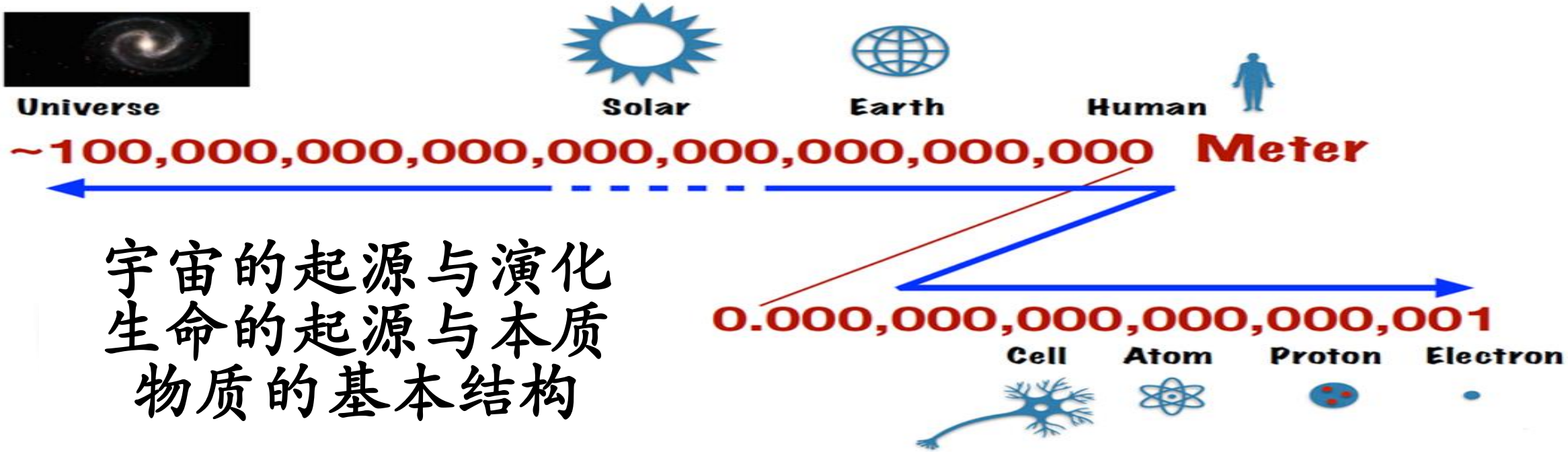
2026-01-11

物质世界的基本组成

《天问》

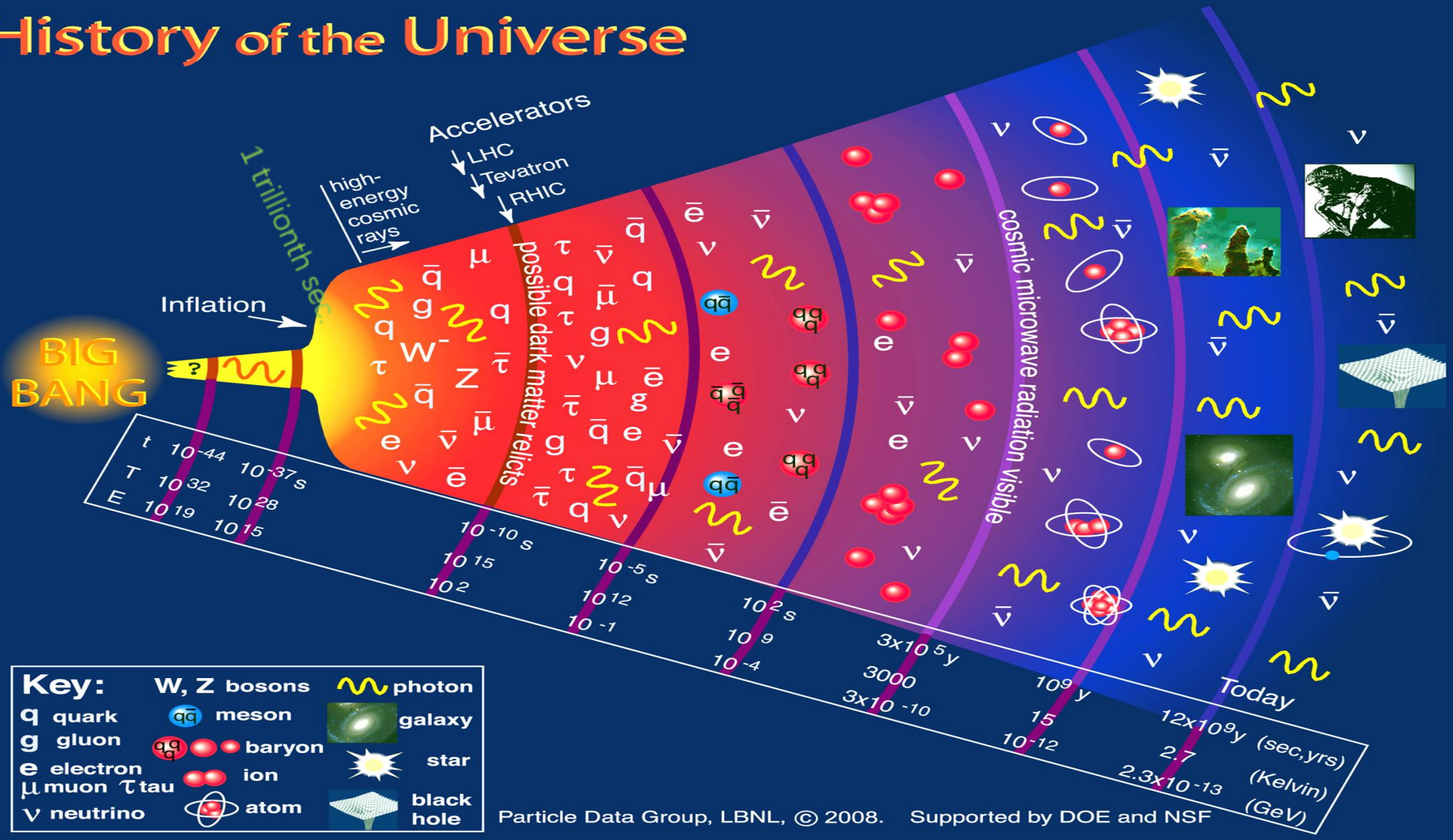
屈原

遂古之初，谁传道之？
上下未形，何由考之？
冥昭瞢暗，谁能极之？
冯翼惟象，何以识之？
明明暗暗，惟时何为？

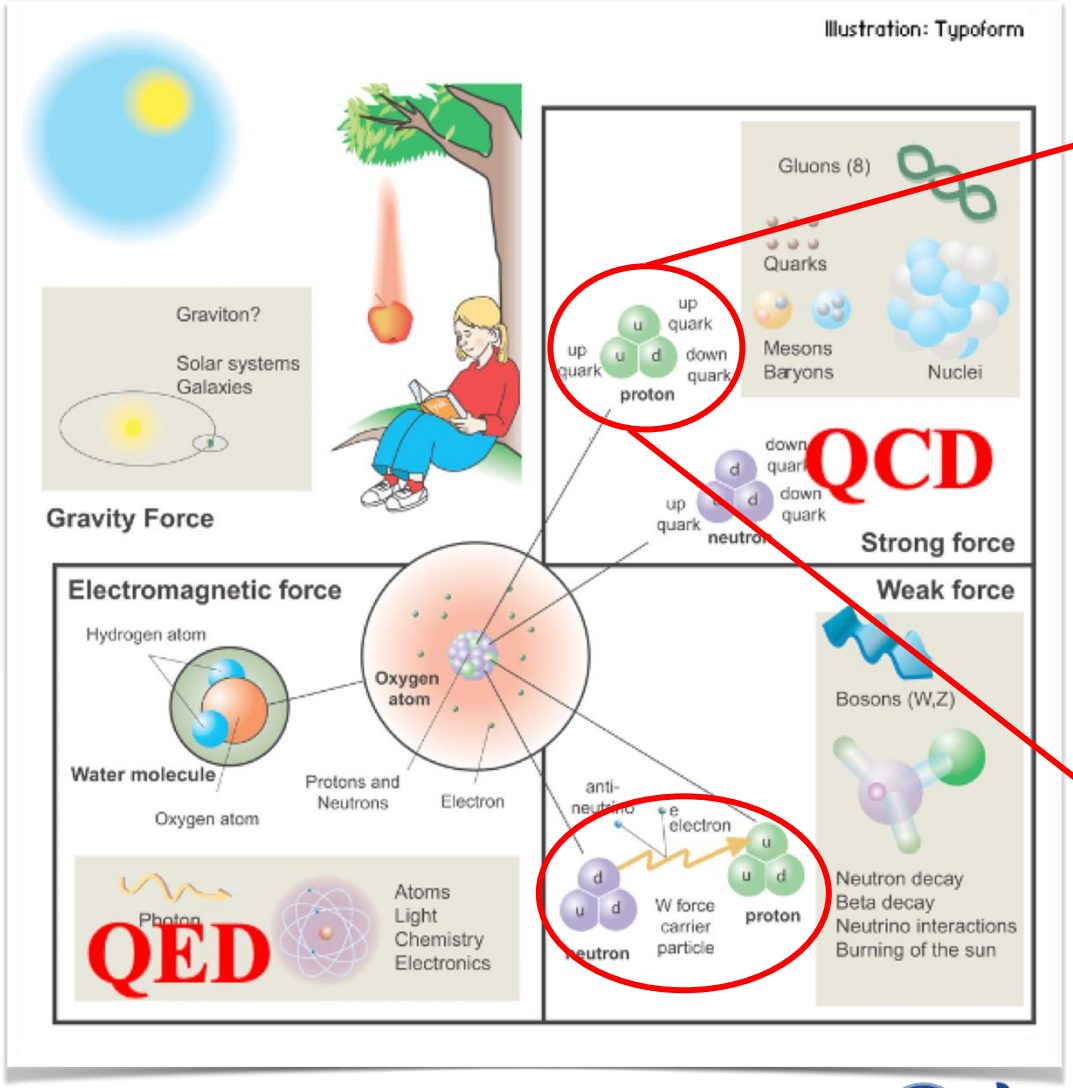


宇宙的起源与演化
生命的起源与本质
物质的基本结构

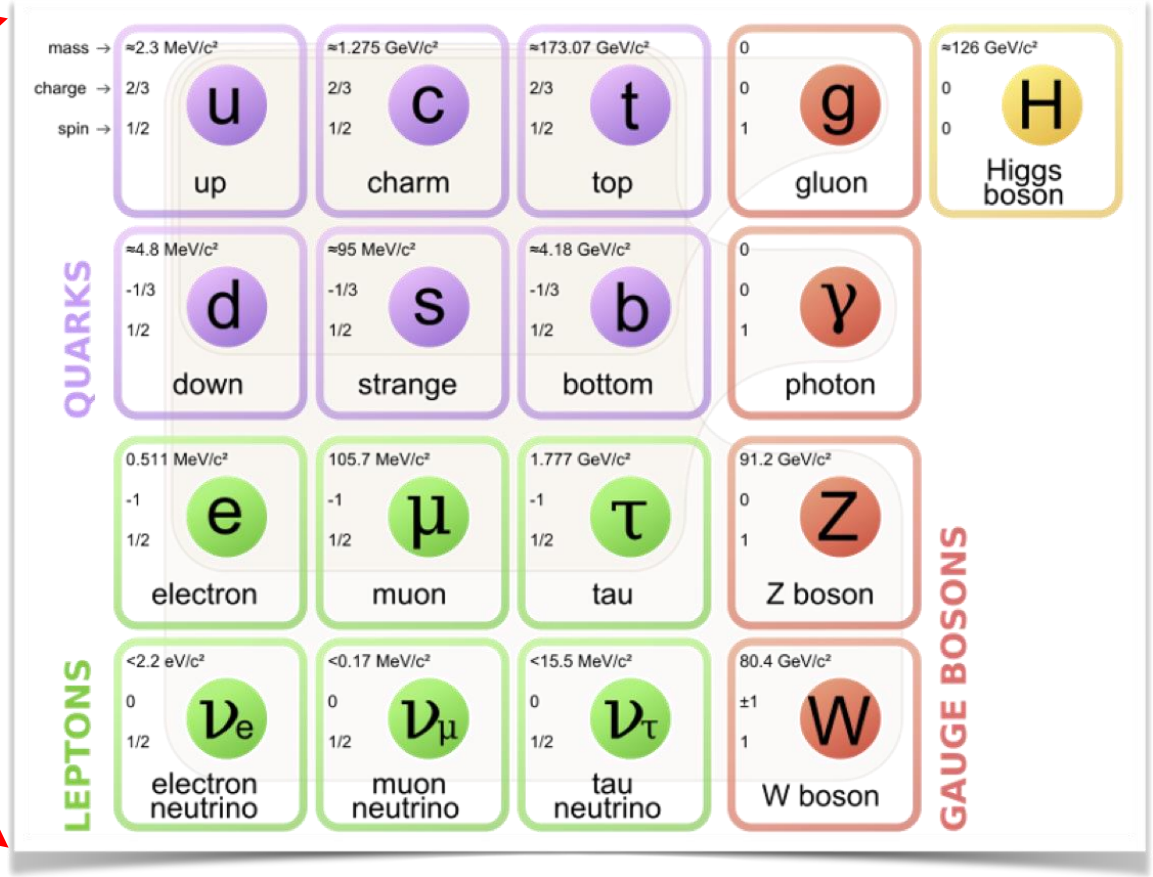
History of the Universe



标准模型 (Standard Model)

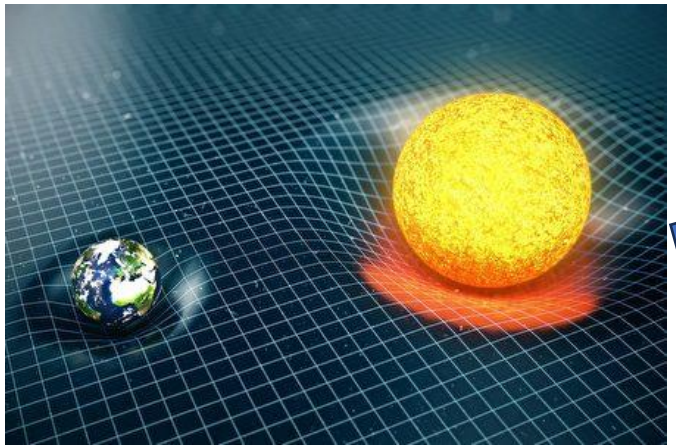


夸克、轻子、规范玻色子、希格斯粒子

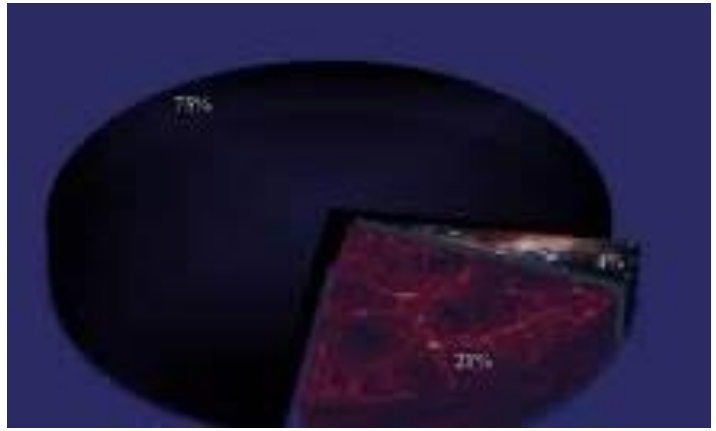


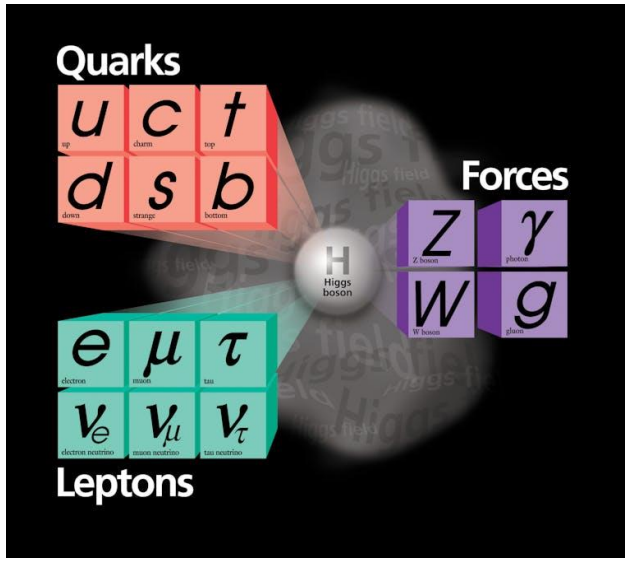
认识物质世界依然存在挑战

引力无法纳入标准模型

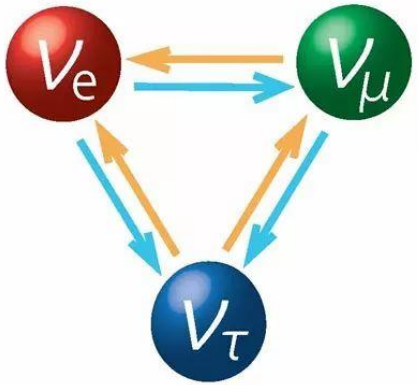


暗物质仅占宇宙5%



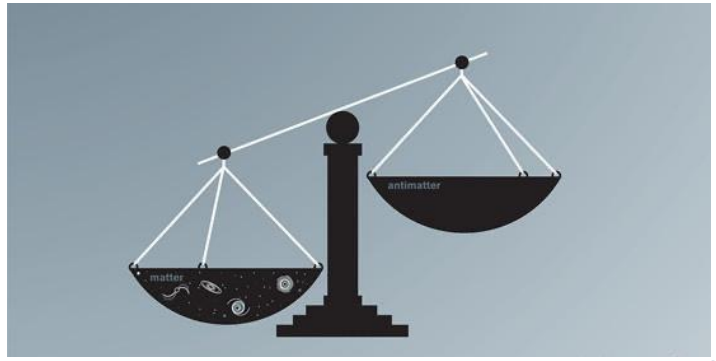


中微子质量

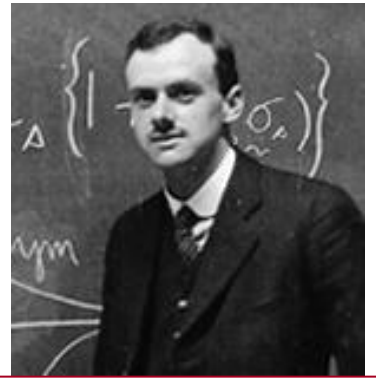


Standard Model

正反物质不对称



什么是反物质?



Dirac
1902-1984

1928年：相对论 & 量子力学

1933 诺贝尔物理学奖

Dirac equation

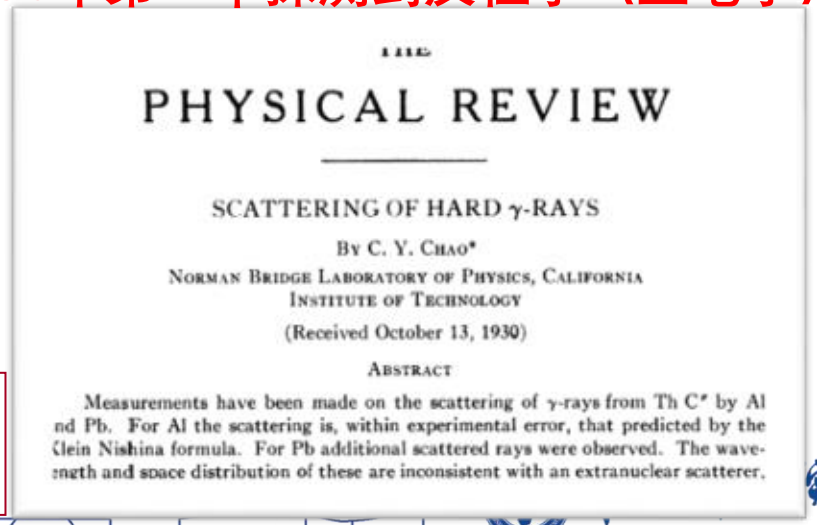
$$i\hbar\gamma^{\mu}\partial_{\mu}\psi - mc\psi = 0$$

两个正能解	**两个负能解**
$E = +\sqrt{\vec{p}^2 + m^2}$	$E = -\sqrt{\vec{p}^2 + m^2}$
$S_z = +\frac{1}{2}$ $S_z = -\frac{1}{2}$	$S_z = +\frac{1}{2}$ $S_z = -\frac{1}{2}$

1928年首次预言正电子e^+, 反物质(anti-matter)!

赵忠尧
1902-1998

1930年第一个探测到反粒子（正电子）



THE

PHYSICAL REVIEW

SCATTERING OF HARD γ-RAYS

By C. Y. Chao*

Norman Bridge Laboratory of Physics, California Institute of Technology

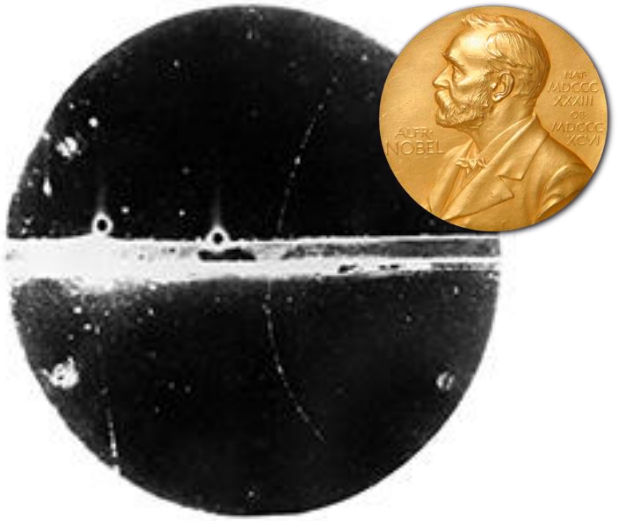
(Received October 13, 1930)

Abstract

Measurements have been made on the scattering of γ-rays from Th C″ by Al and Pb. For Al the scattering is, within experimental error, that predicted by the Klein Nishina formula. For Pb additional scattered rays were observed. The wave-length and space distribution of these are inconsistent with an extranuclear scatterer.

Carl D. Anderson
1905-1991

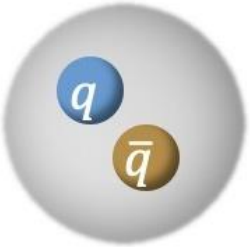
1936 诺贝尔物理学奖



Standard Model of Elementary Particles

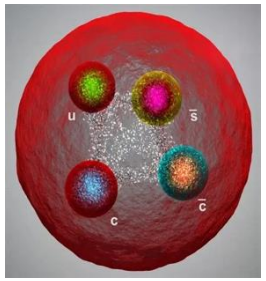
	three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)	
	I	II	III	I	II	III		
mass / charge / spin	≈2.2 MeV/c² / ⅔ / ½	≈1.28 GeV/c² / ⅔ / ½	≈173.1 GeV/c² / ⅔ / ½	≈2.2 MeV/c² / −⅔ / ½	≈1.28 GeV/c² / −⅔ / ½	≈173.1 GeV/c² / −⅔ / ½	0 / 0 / 1	≈124.97 GeV/c² / 0 / 0
QUARKS	u up	c charm	t top	ū antiup	c̄ anticharm	t̄ antitop	g gluon	H higgs
	≈4.7 MeV/c² / −⅓ / ½	≈96 MeV/c² / −⅓ / ½	≈4.18 GeV/c² / −⅓ / ½	≈4.7 MeV/c² / ⅓ / ½	≈96 MeV/c² / ⅓ / ½	≈4.18 GeV/c² / ⅓ / ½	0 / 0 / 1	
	d down	s strange	b bottom	d̄ antidown	s̄ antistrange	b̄ antibottom	γ photon	
LEPTONS	≈0.511 MeV/c² / −1 / ½	≈105.66 MeV/c² / −1 / ½	≈1.7768 GeV/c² / −1 / ½	≈0.511 MeV/c² / 1 / ½	≈105.66 MeV/c² / 1 / ½	≈1.7768 GeV/c² / 1 / ½	≈91.19 GeV/c² / 0 / 1	
	e electron	μ muon	τ tau	e⁺ positron	μ̄ antimuon	τ̄ antitau	Z Z⁰ boson	
	<2.2 eV/c² / 0 / ½	<0.17 MeV/c² / 0 / ½	<18.2 MeV/c² / 0 / ½	<2.2 eV/c² / 0 / ½	<0.17 MeV/c² / 0 / ½	<18.2 MeV/c² / 0 / ½	≈80.39 GeV/c² / 1 / 1	≈80.39 GeV/c² / −1 / 1
	νe electron neutrino	νμ muon neutrino	ντ tau neutrino	ν̄e electron antineutrino	ν̄μ muon antineutrino	ν̄τ tau antineutrino	W⁺ W⁺ boson	W⁻ W⁻ boson

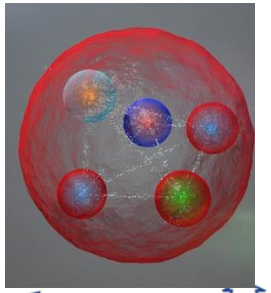
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS



介子

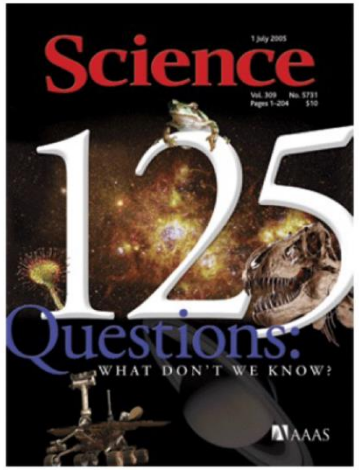
重子

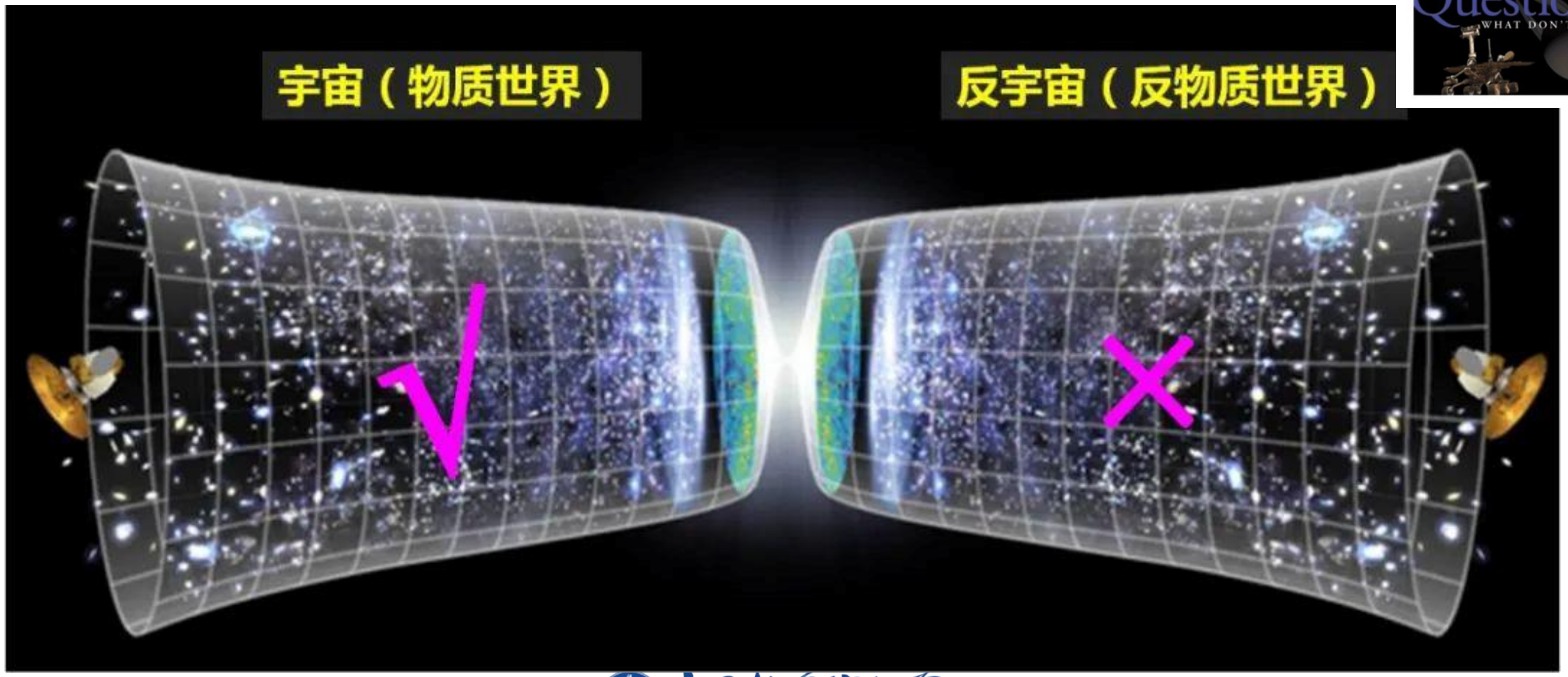




反物质宇宙存在吗？

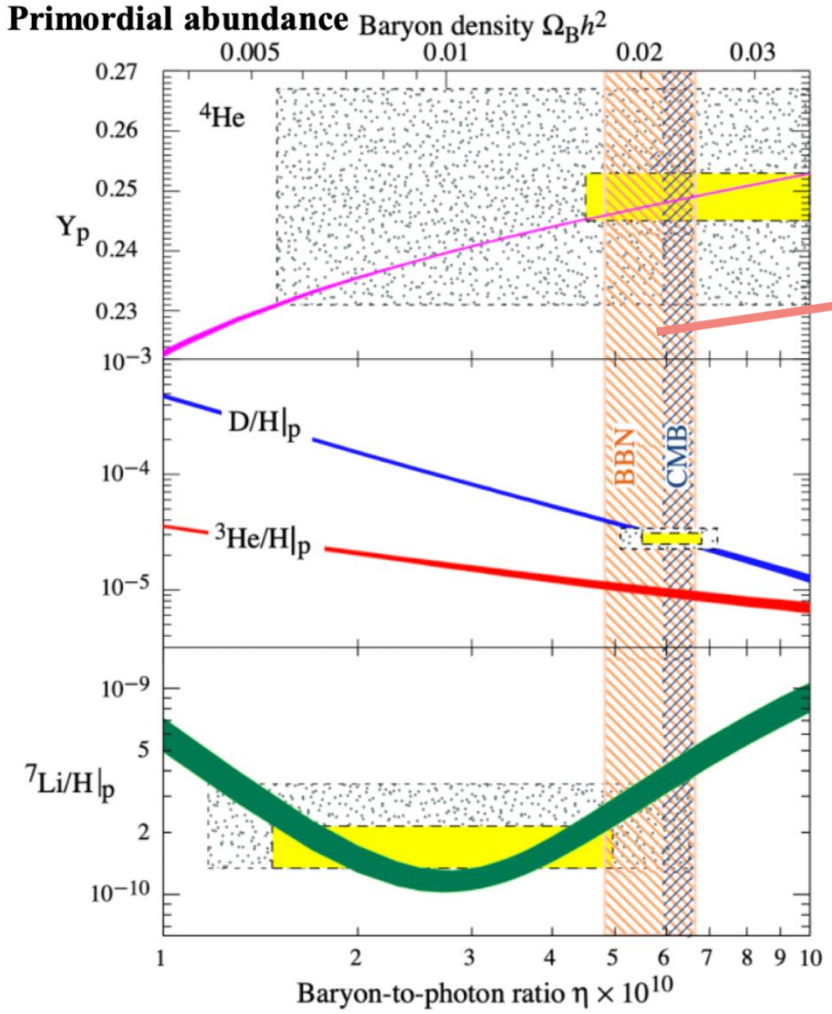
- 物质的起源：21世纪物理学重大科学问题
  - 宇宙是如何形成和演化的？
  - 反物质如何消失的？





反物质去哪儿了？

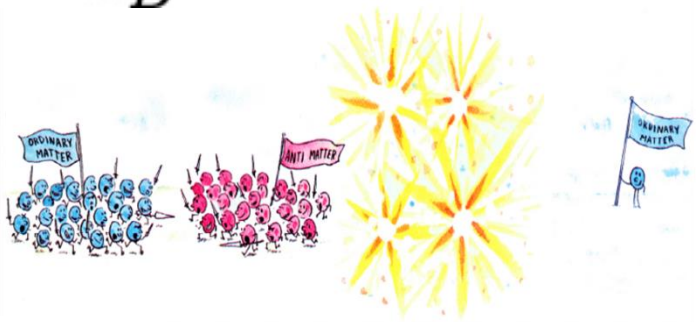
Rev. Mod. Phys. 88(2016)015004
arXiv: 1801.10059



PLB667 (2008) 1

- 宇宙暴涨后正反物质相等 $n_B = n_{\bar{B}}$
- 宇宙微博辐射背景高精度测量：

$(n_B - n_{\bar{B}})/n_\gamma \sim 6\times10^{-10}$



- 标准模型预言： $\dfrac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-18}$

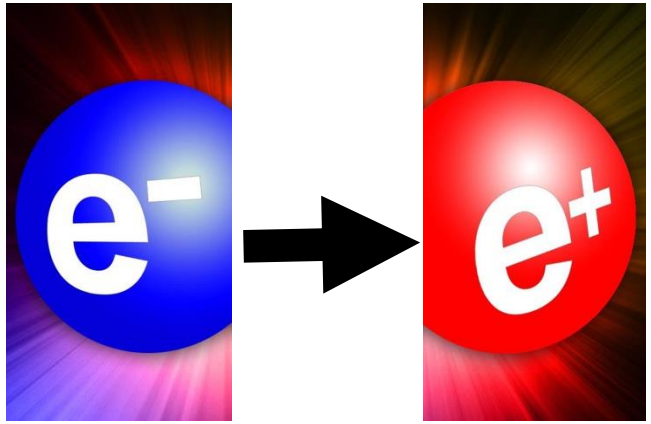
- Sakharov条件（对称性破缺）：
  - 重子数不守恒
  - C和CP破坏 $\Gamma(X \to Y + B) \neq \Gamma(\bar{X} \to \bar{Y} + \bar{B})$
  - 早期宇宙的非热平衡状态

$$\Gamma(X \to Y + B) > \Gamma(Y + B \to X)$$

电荷共轭宇称变换(CP)

- C (电荷共轭）变换： 正粒子 ⟹反粒子
- P (宇称）变换： 镜像，坐标 (x, y, z) ⟹ (-x, -y, -z)

C

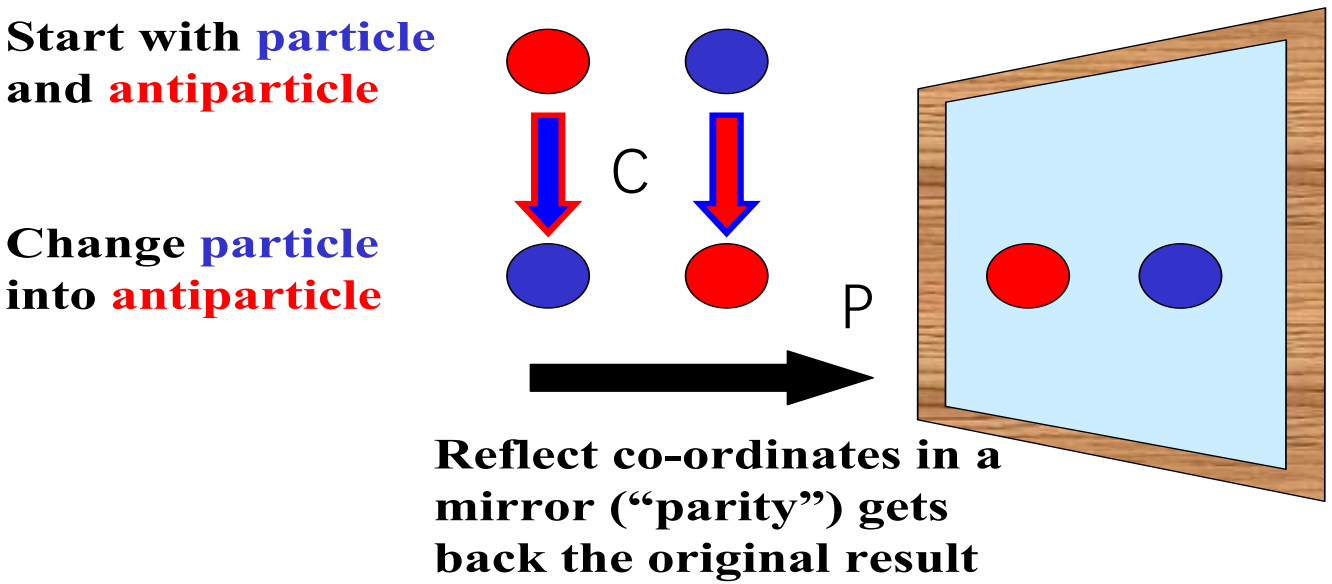


物质　　反物质

电荷宇称(CP)破坏

- C(电荷共轭)变换： 粒子 ⟹ 反粒子
- P(宇称)变换： 坐标 (x, y, z) ⟹ (-x, -y, -z) （镜像变换）

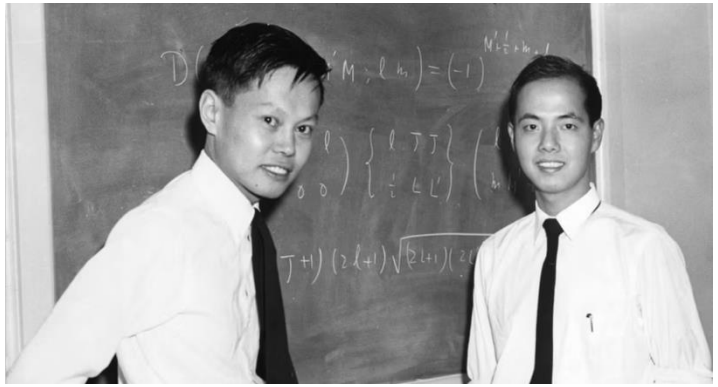
CP对称性：CP联合变换下物理规律的不变性



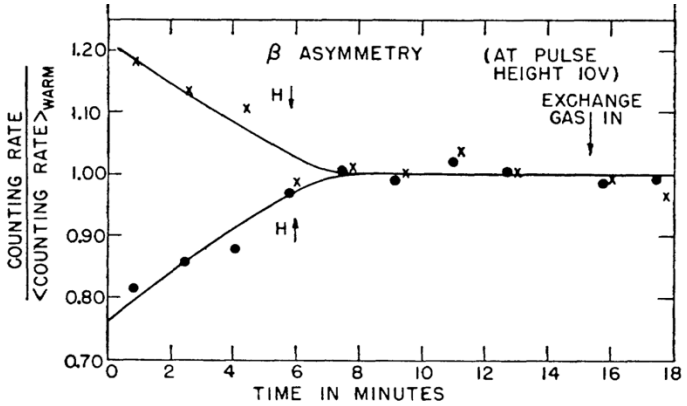
CP联合对称性的破缺简称"CP破坏"： **正反粒子的行为表现不一样！**

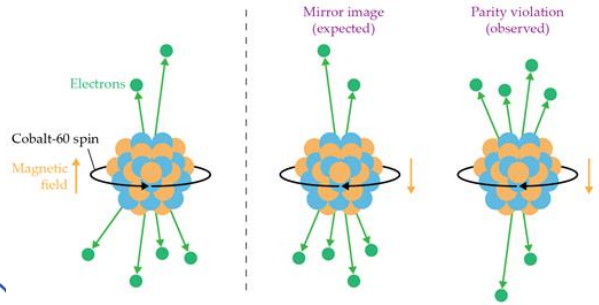
弱相互作用中宇称不守恒

- τ-θ之谜：两个质量、电荷、寿命均相等的粒子，分别衰变到三个π介子和两个，分别对应负宇称和正宇称。
- 1956年，李政道和杨振宁指出：弱相互作用过程中宇称可以不守恒.



$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$$

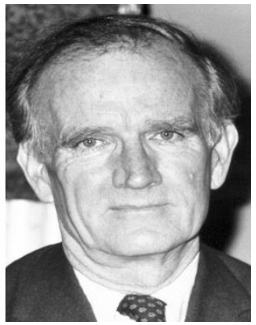




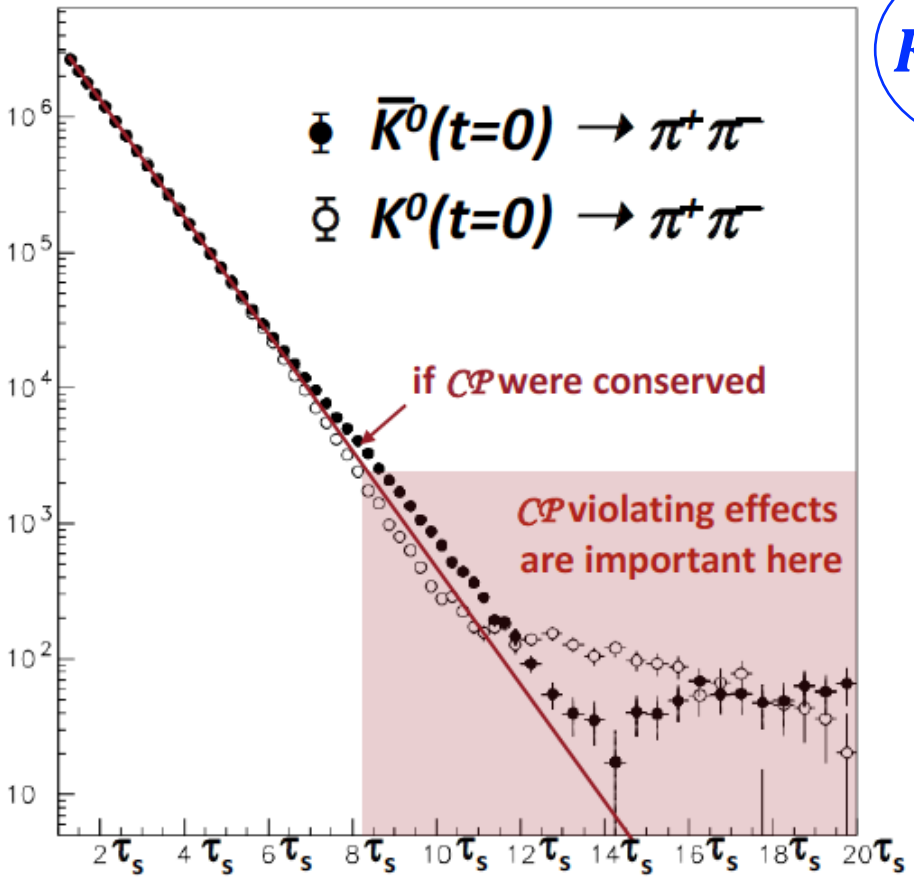
正反中性K介子衰变中发现CP破坏

Nobel prize (1980) for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons

James Watson Cronin

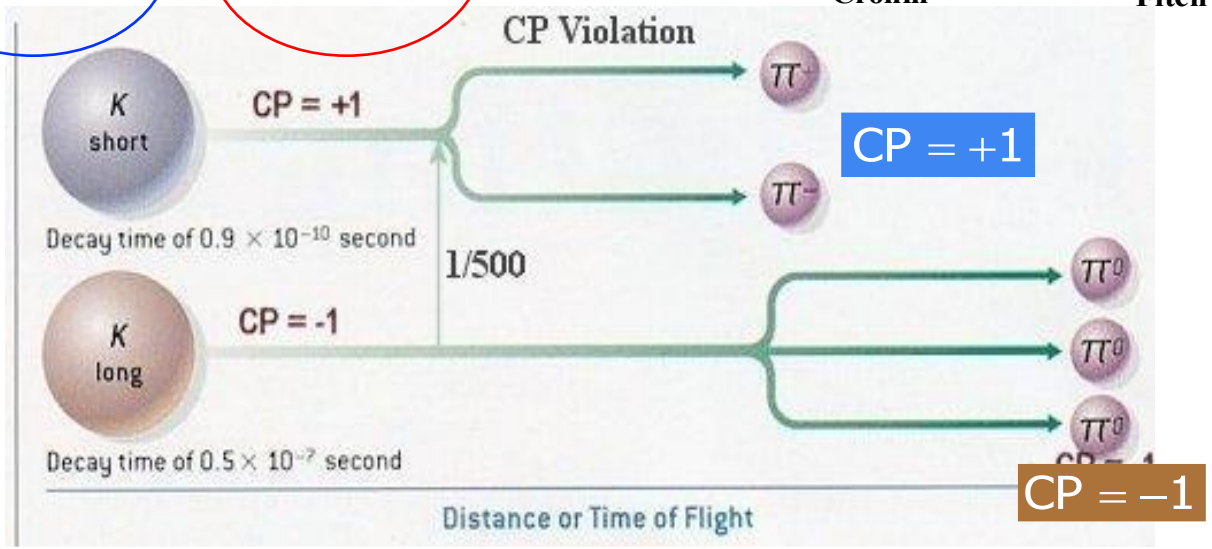


Val Logsdon Fitch



$K^0\ (d\bar{s})$

$\bar{K}^0\ (\bar{d}s)$



0.2% of the time!

$\tau_S = 1/\Gamma_S = K_S$ lifetime = 0.895 ns

CP破坏原因

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

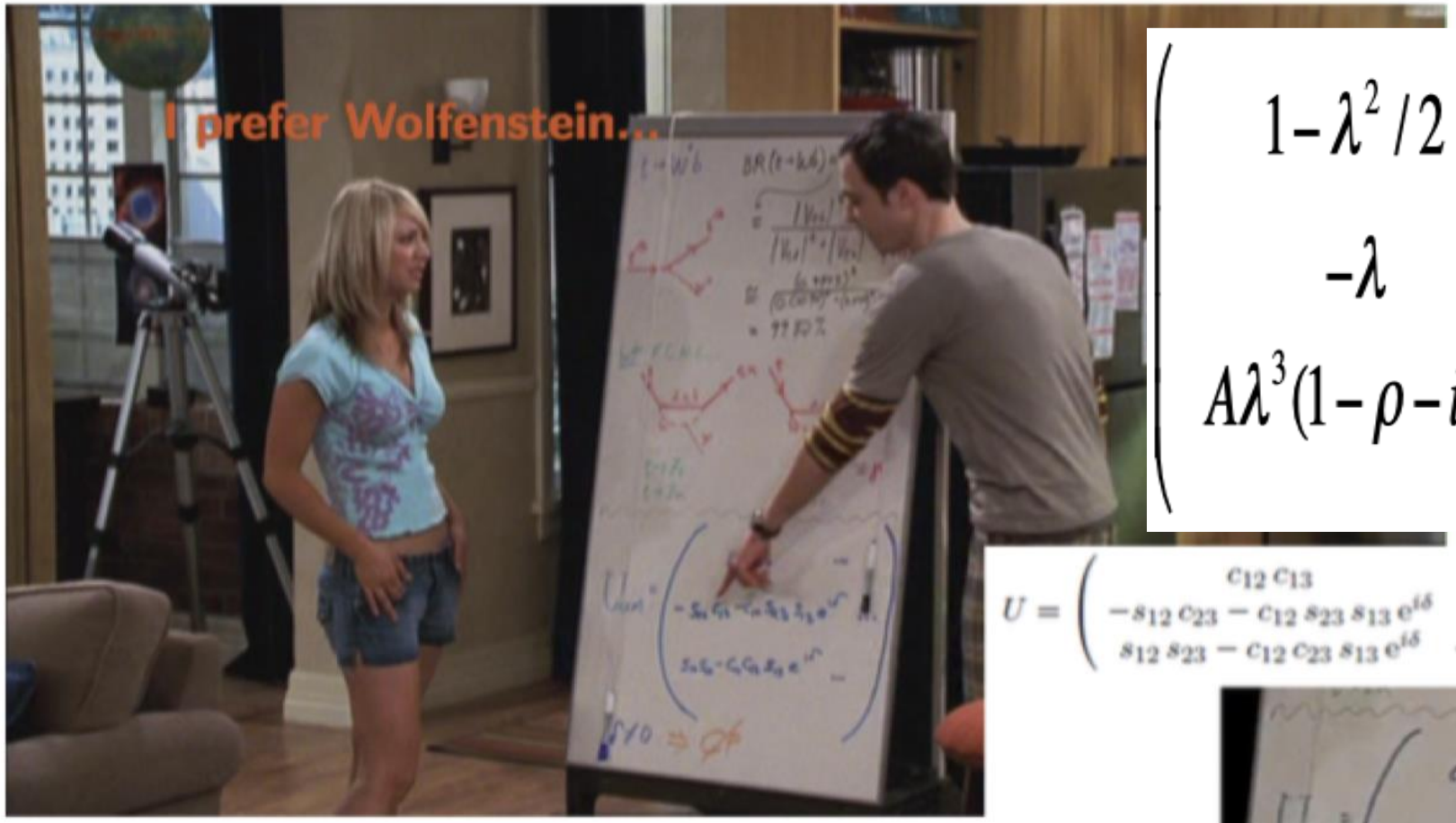
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \boxed{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM矩阵

Makoto Kobayashi Toshihide Maskawa

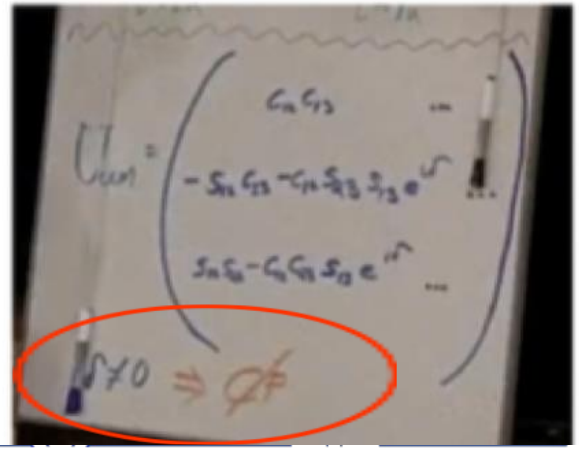
$$\hat{V}_{\mathrm{CKM}} = \begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3 - s_2s_3e^{i\delta} & c_1c_2s_3 + s_2c_3e^{i\delta} \\ s_1s_2 & c_1s_2c_3 + c_2s_3e^{i\delta} & c_1s_2s_3 - c_2c_3e^{i\delta} \end{pmatrix}$$

CP破坏的原因

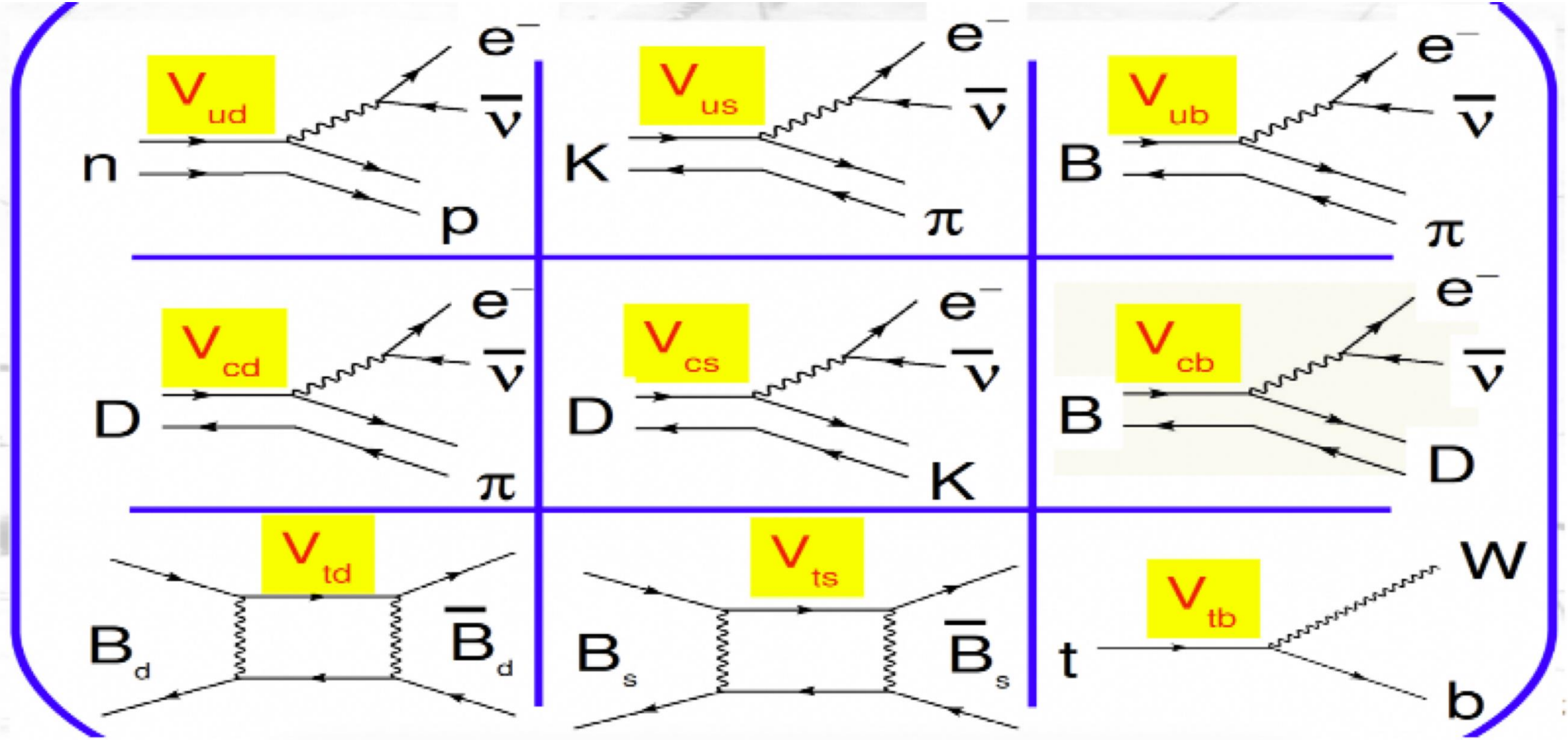


$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\delta} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\delta} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\delta} & c_{23}\,c_{13} \end{pmatrix}$$



CKM矩阵


V ud
n
p
e⁻
ν̄
V us
K
π
e⁻
ν̄
V ub
B
π
e⁻
ν̄
V cd
D
π
e⁻
ν̄
V cs
D
K
e⁻
ν̄
V cb
B
D
e⁻
ν̄
V td
B d
B̄ d
V ts
B s
B̄ s
V tb
t
b
W

CP破坏的分类

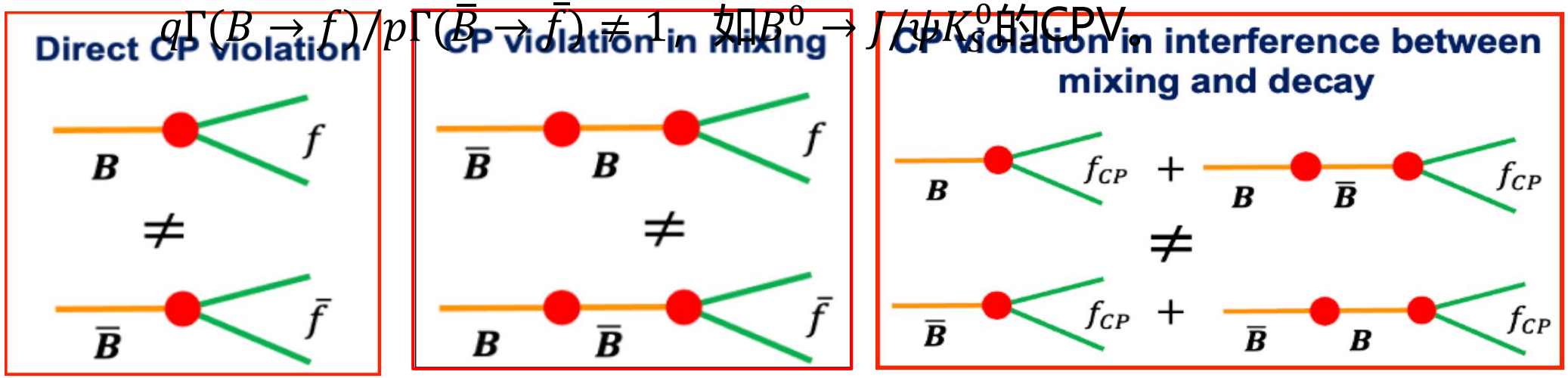
1) **Direct CPV**：正反粒子衰变的概率不相等，强弱相角都不为零，如B^+介子的CPV

2) **Indirect CPV**（或 CPV in mixing）：中性粒子混合导致的CP破坏，

混合参数 $q/p \neq 1$，如K^0和B^0的CPV。

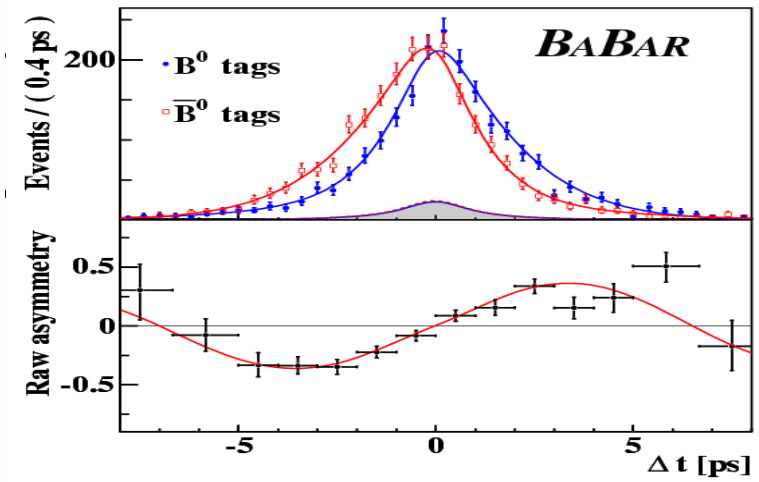
3) **Mixed CPV**（或 CPV in the interference between mixing and decay):

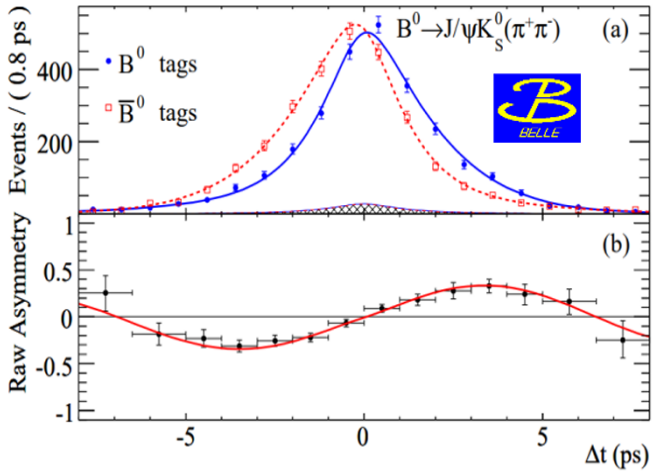
$q\Gamma(B \to f)/p\Gamma(\bar{B} \to \bar{f}) \neq 1$，如$B^0 \to J/\psi K_S^0$的CPV。

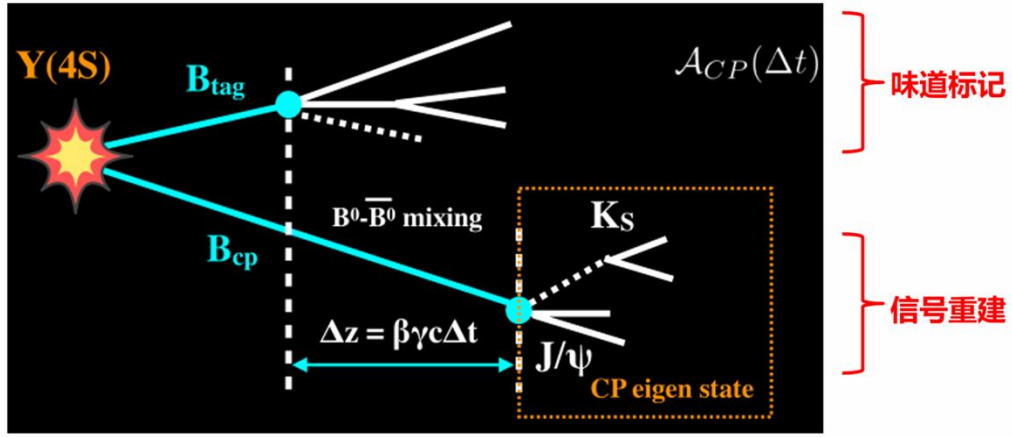


正反中性B介子中发现CP破坏

$B^0\ (d\bar{b})$ $\bar{B}^0\ (\bar{d}b)$







$$A_{CP}(t) = -\sin 2\beta \sin(\Delta m \cdot t)$$

$\sin 2\beta = 0.59 \pm 0.14 \pm 0.05$

Babar, PRL 87 (2001) 091801

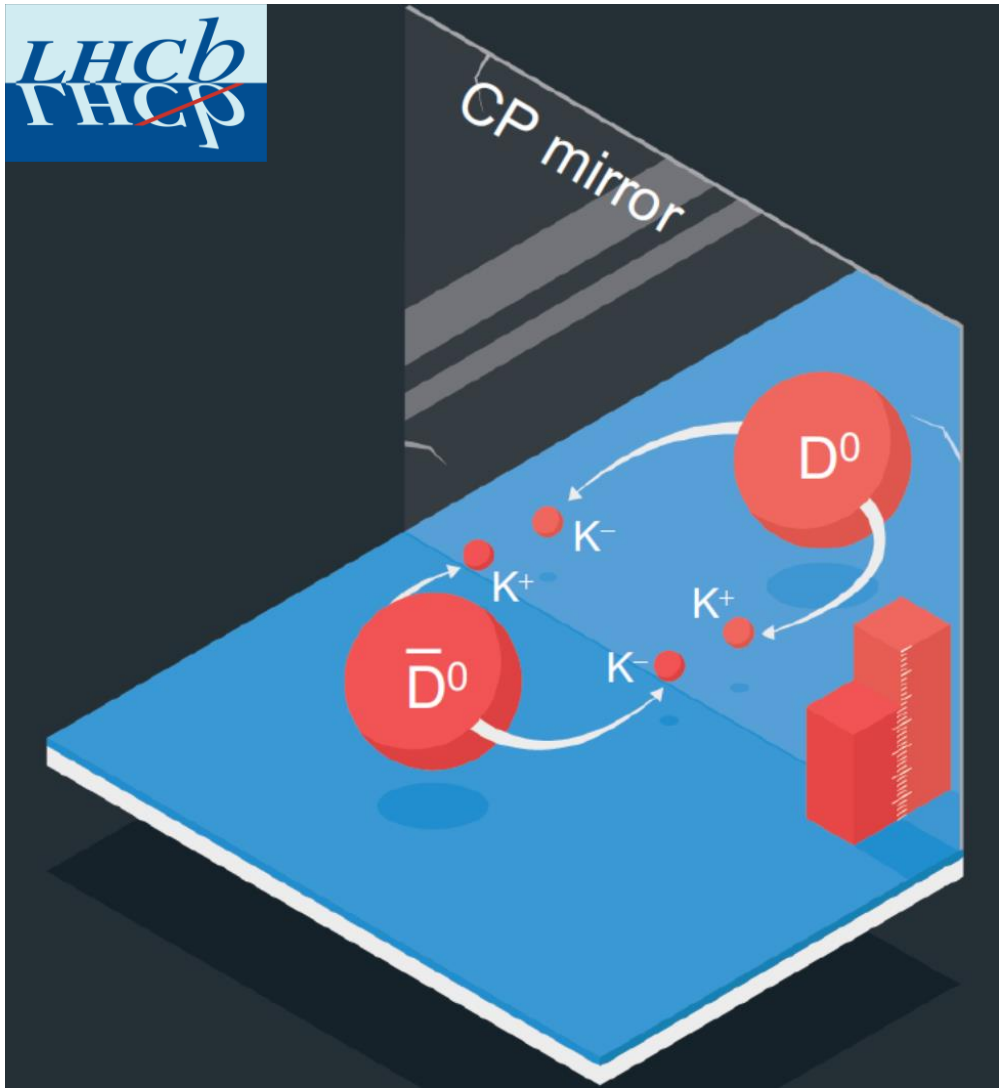
$\sin 2\beta = 0.99 \pm 0.14 \pm 0.06$

Belle, PRL 87 (2001) 091802

Makoto Kobayashi Toshihide Maskawa

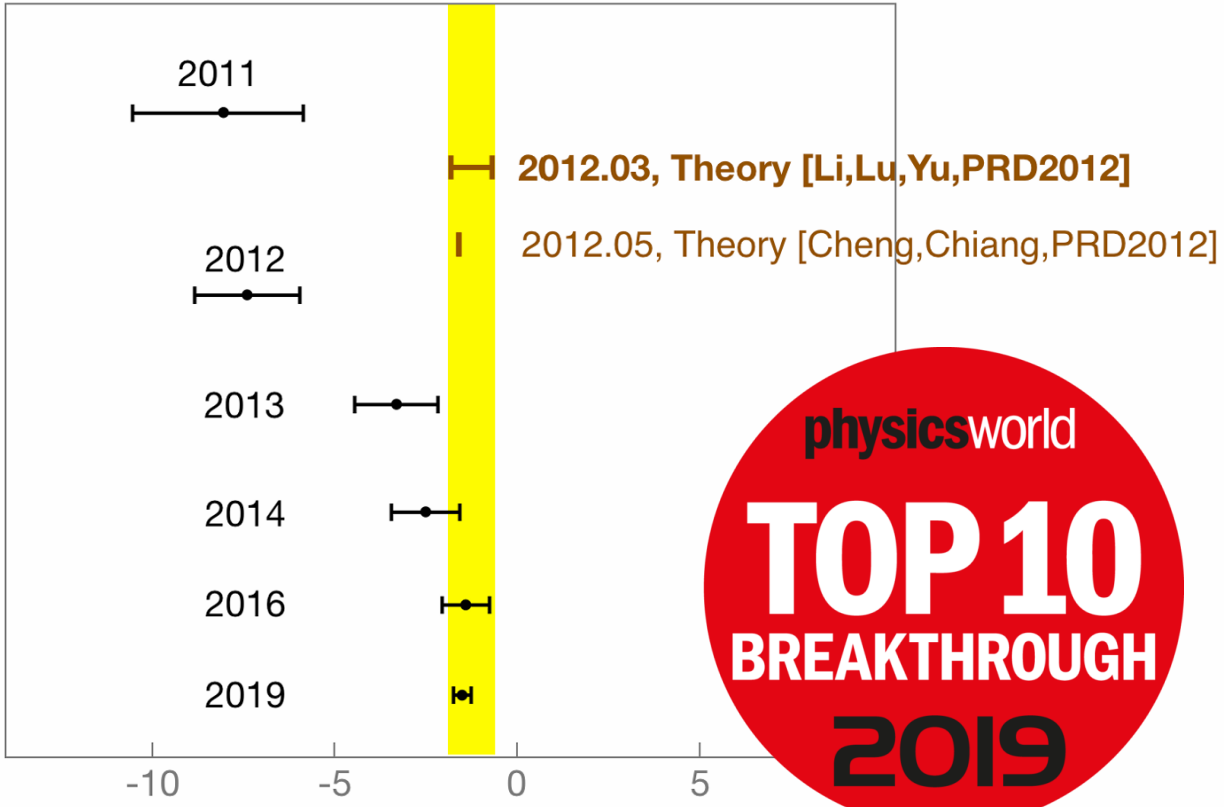
正反中性D介子中发现CP破坏

$D^0\ (c\bar{u})$ $\bar{D}^0\ (\bar{c}u)$



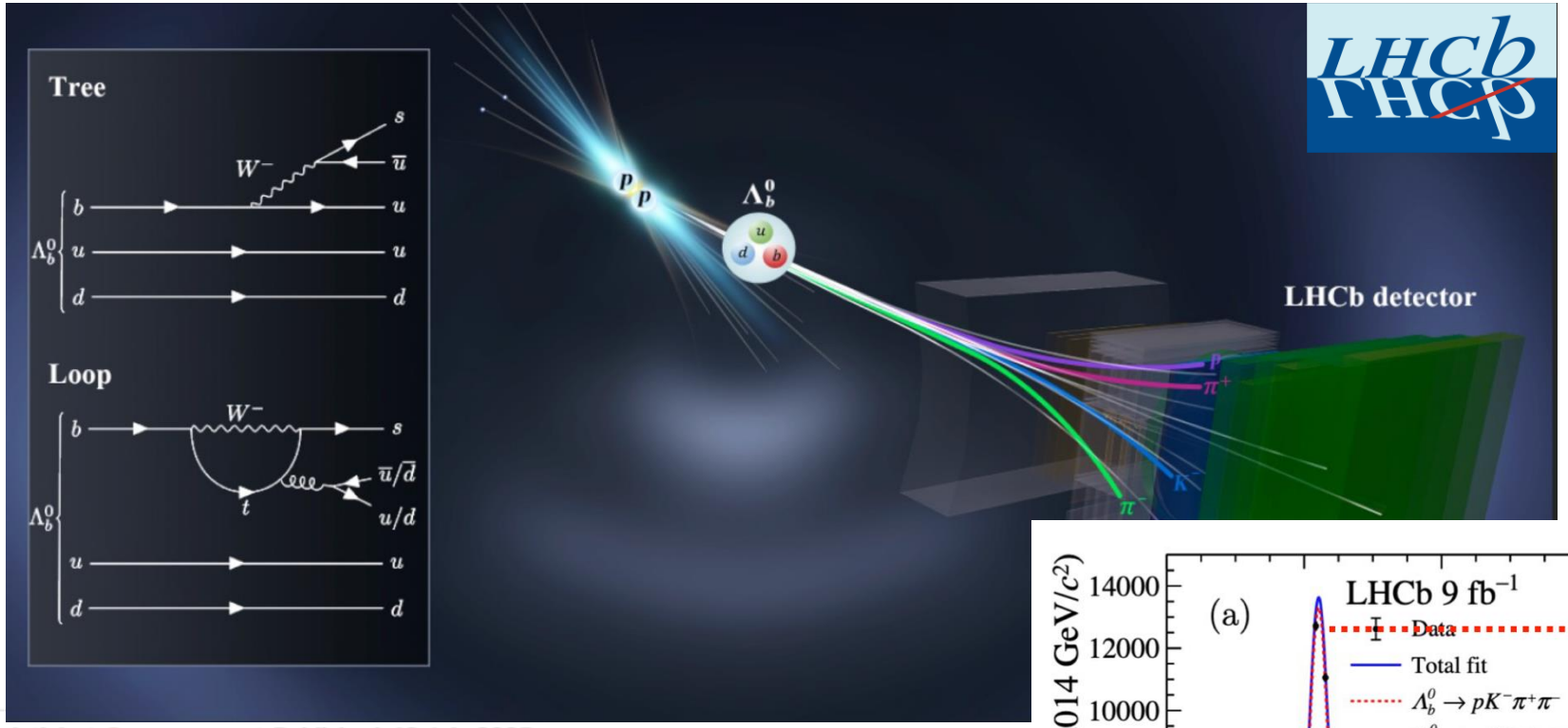
- 比较$D^0 \to h^+h^-$与$\bar{D}^0 \to h^-h^+$的衰变率

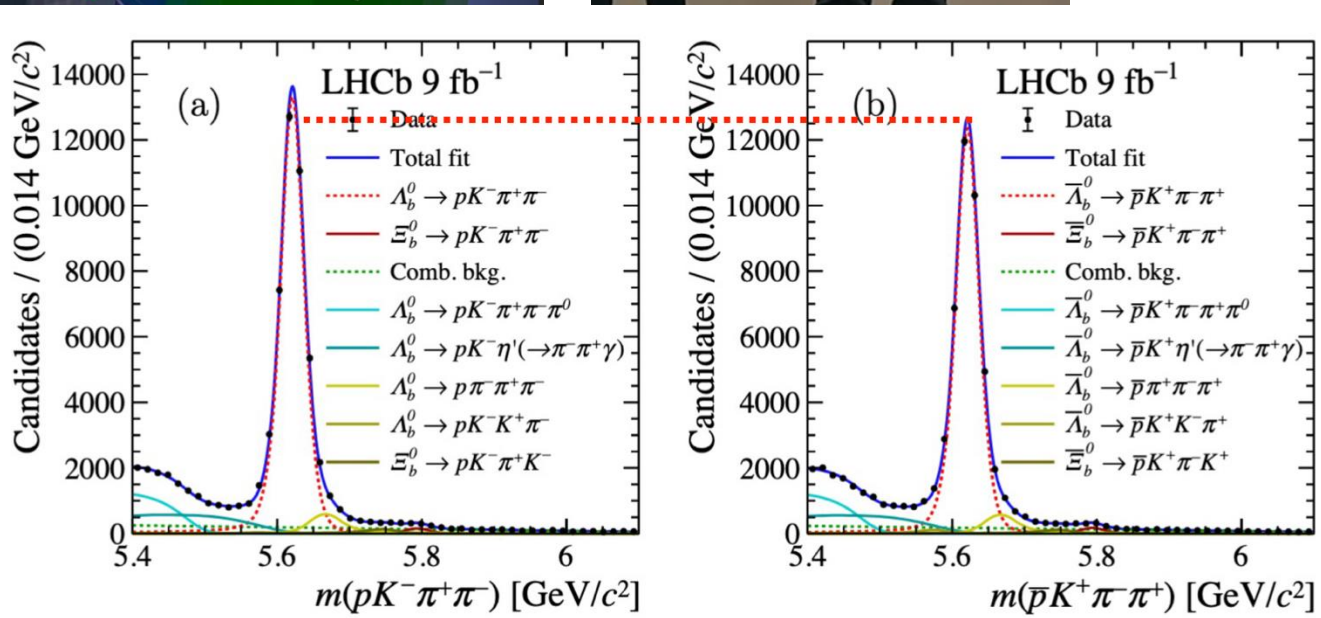
$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$= (-1.5 \pm 0.3) \times 10^{-4}$$



physicsworld TOP 10 BREAKTHROUGH 2019

首次观测到重子CP破坏！





Article | Open access | Published: 16 July 2025

Observation of charge–parity symmetry breaking baryon decays

LHCb Collaboration

Nature **643**, 1223–1228 (2025) | Cite this article

66k Accesses | **14** Citations | **1221** Altmetric | Metrics

Nature 643 (2025) 1223

Milestone, new horizon!

University of Chinese Academy of Sciences

宇宙正反物质不对称问题尚未得到理解

1928 狄拉克提出反物质

1956 李、杨提出P破坏

1963 Cabibbo 提出两代夸克混合

1970 GIM 预言粲夸克

1973 KM提出三代夸克混合机制

1932 安德森发现反物质

1957 吴健雄发现P破坏

1958 Goldhaber 发现C破坏

1964 Cronin、Fitch 发现 K^0介子 CP破坏

1974 丁肇中、里奇特 发现 c 夸克

1977 莱德曼 发现 b 夸克

1995 费米实验室 发现 t 夸克

2001 BaBar、Belle 发现 B^0介子 CP破坏

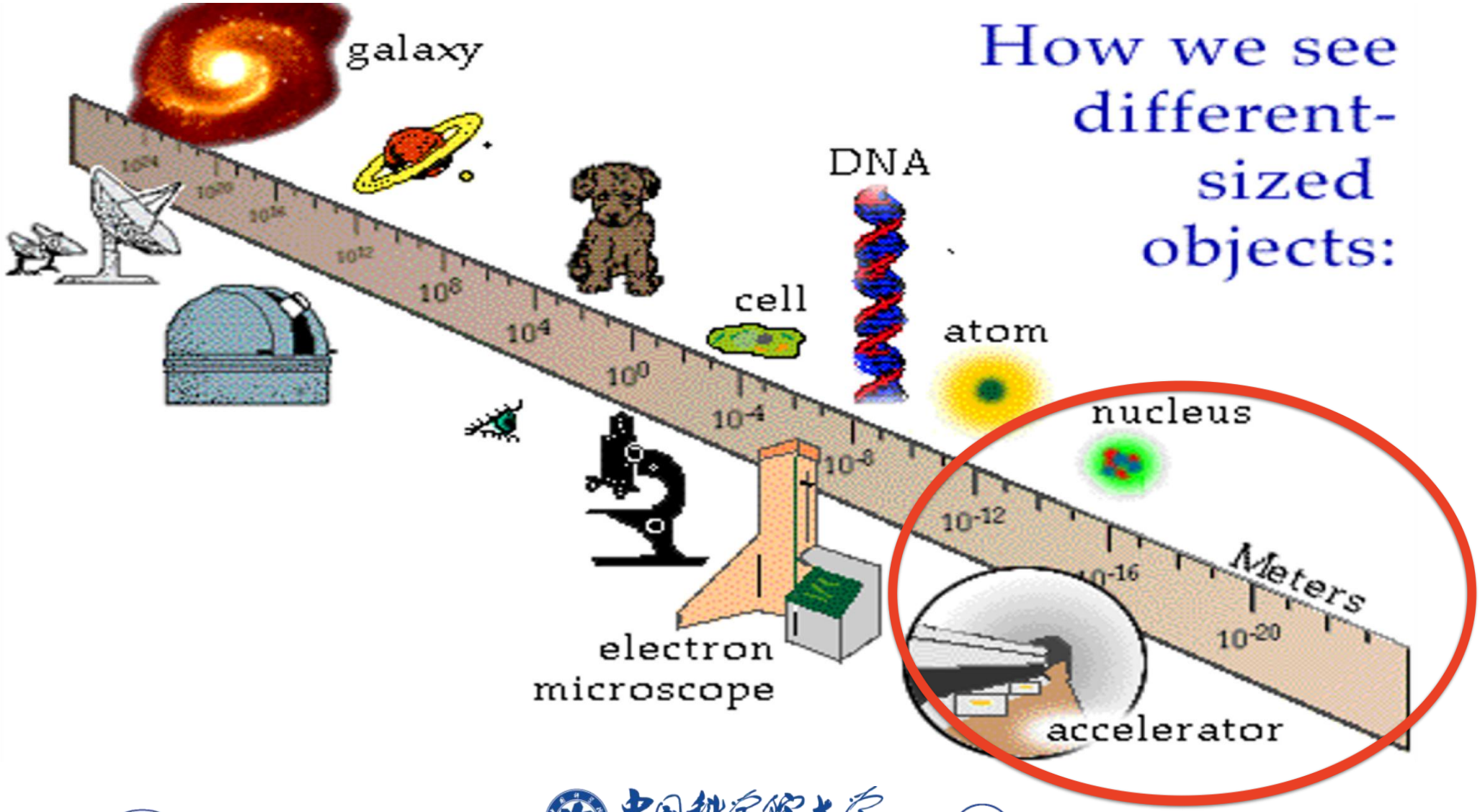
2013 LHCb 发现 B_s^0介子 CP破坏

2019 LHCb 发现 D^0介子 CP破坏

2025 LHCb 发现 Λ_b^0重子 CP破坏

新理论？ vs 新发现？

探测越小的粒子需要越高的能量

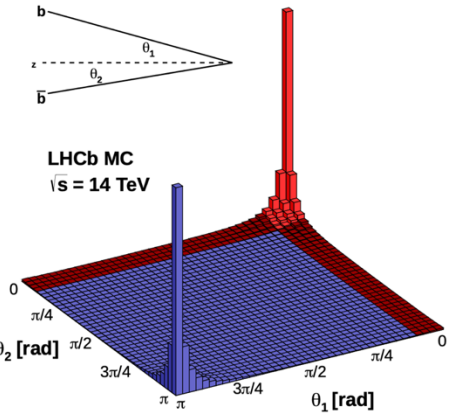


加速器与粒子探测器

LHCb 合作组：22个国家，102家单位，1700多名成员

LHCb探测器

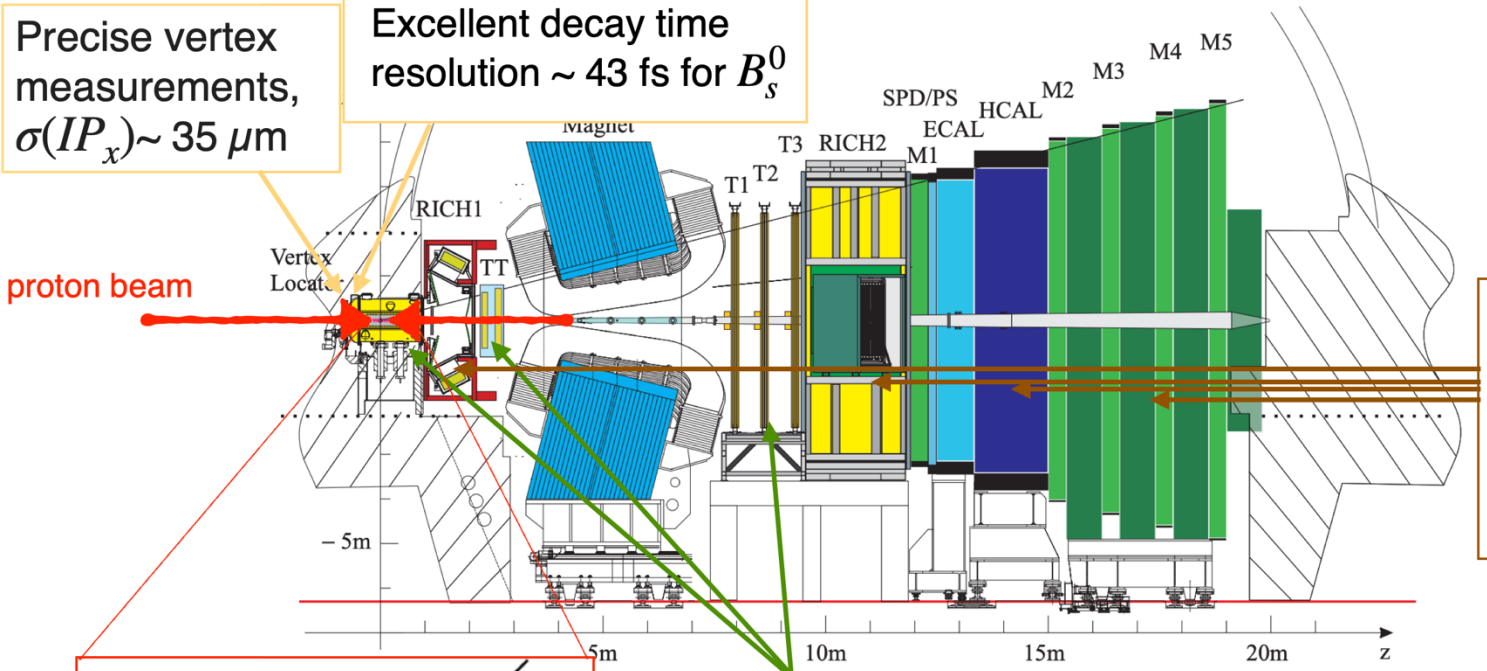
- ✓ 记录粒子飞行路径(~μm)、飞行时间(~fs)、能动量信息信息 (~MeV)
- ✓ 鉴别粒子种类： pi, K, p, e, μ



$2 < \eta < 5$

Precise vertex measurements, $\sigma(IP_x) \sim 35\ \mu m$

Excellent decay time resolution ~ 43 fs for B_s^0

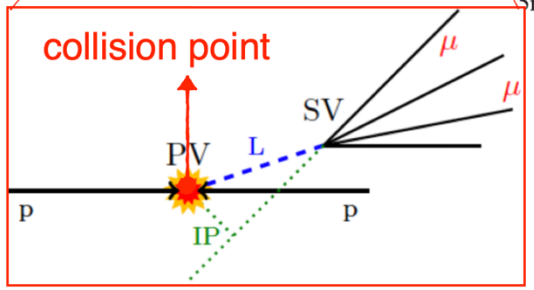


Excellent particle identification

$\epsilon(K) \approx 95\,\%$

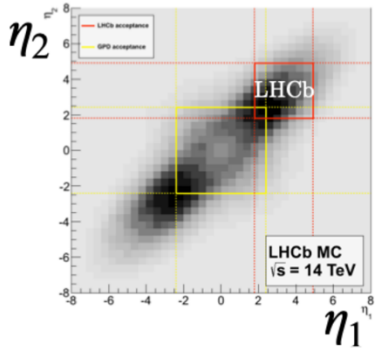
misID $p(\pi \to K) \approx 5\,\%$

$\epsilon(\mu) \approx 97\,\%$

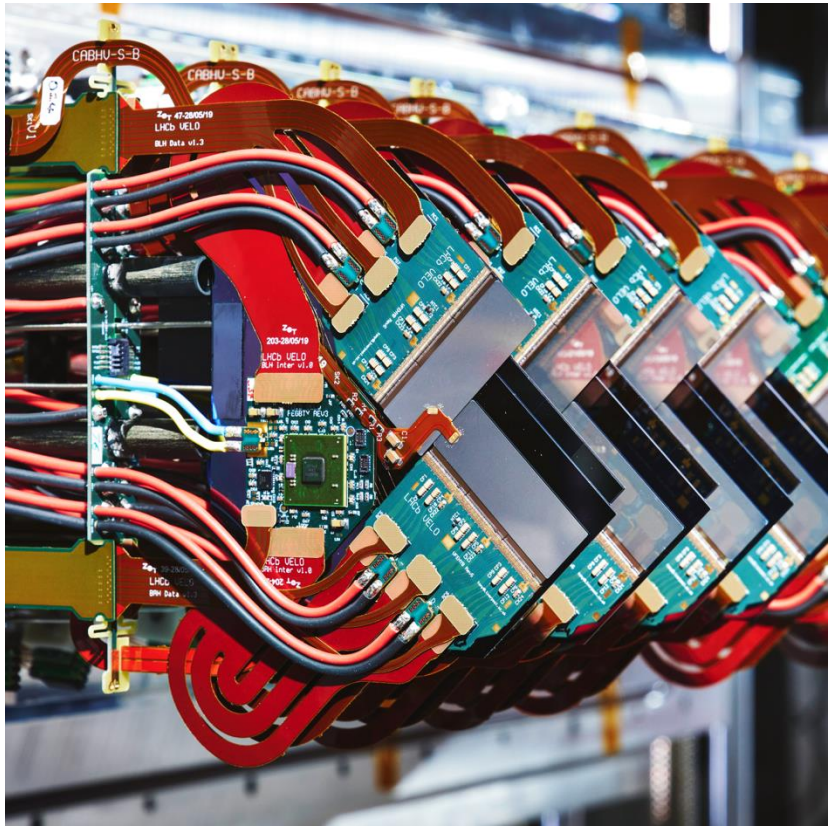


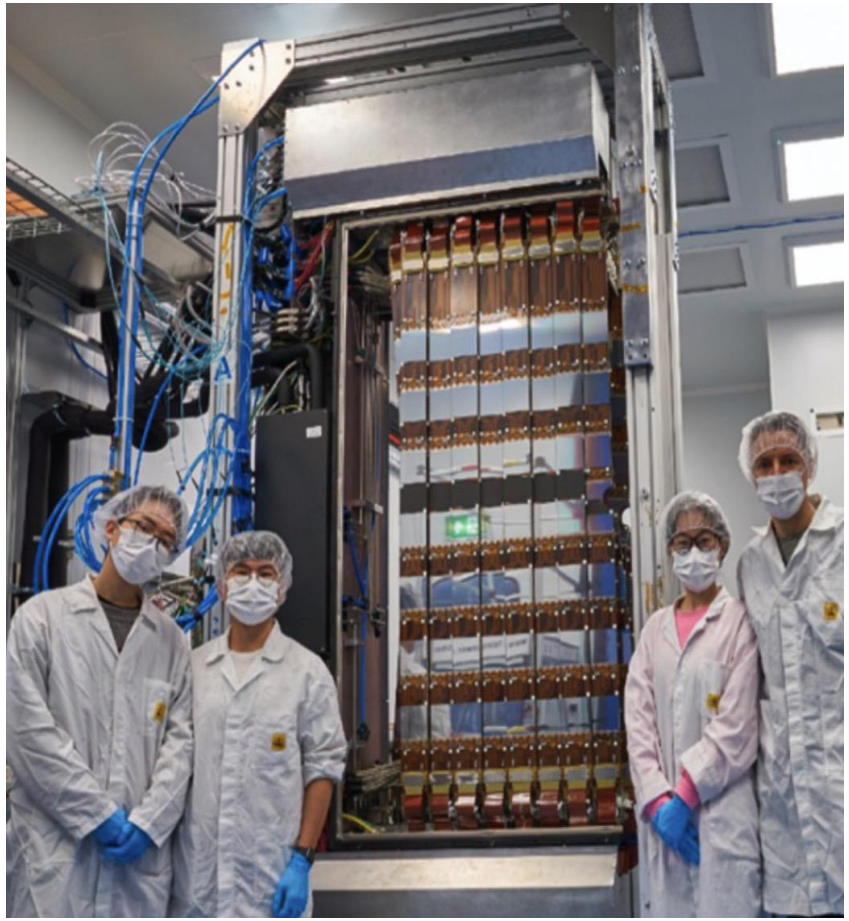
Excellent momentum resolution ~ 0.5%

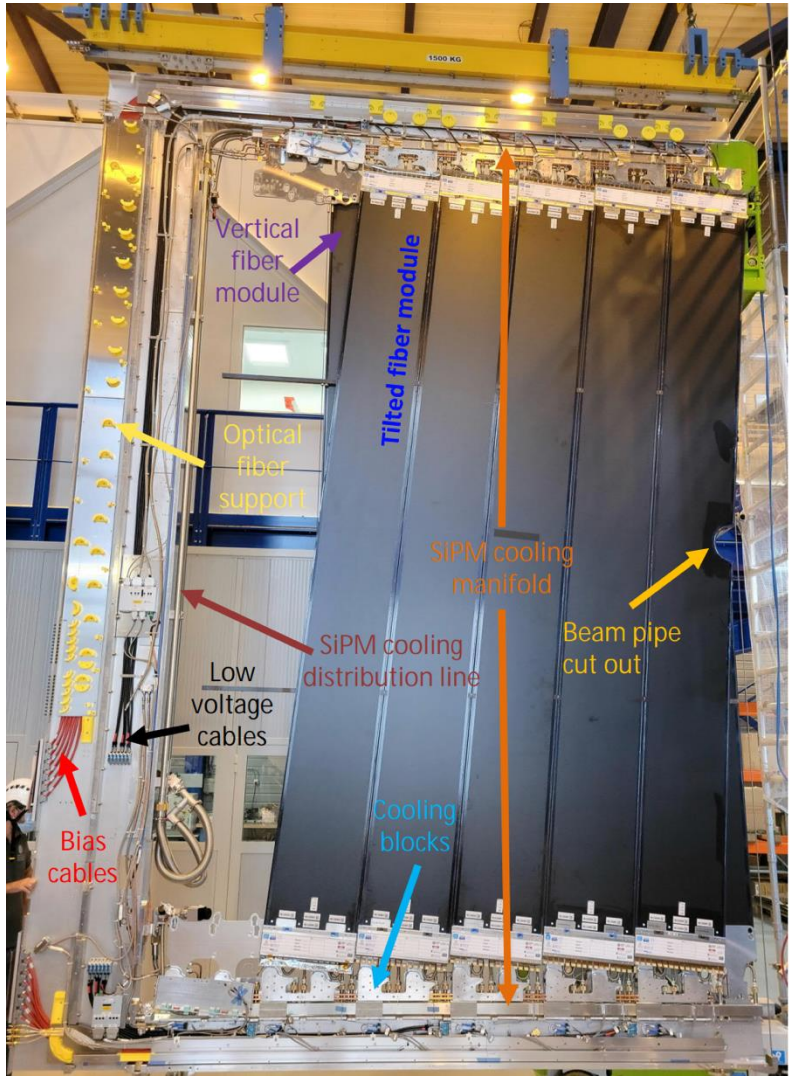
LHCb performance:
JINST 14 (2019) P04013

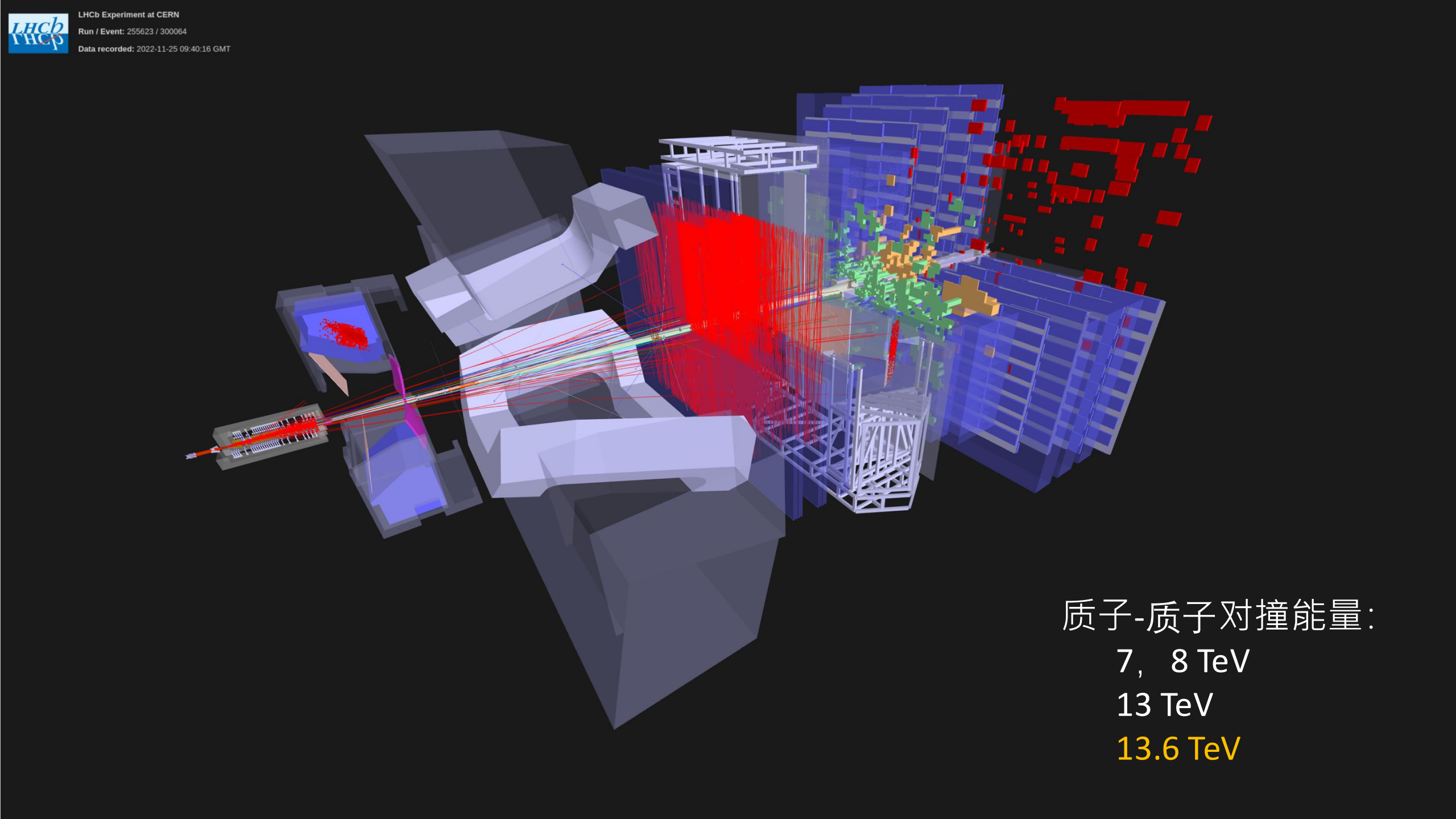


LHCb探测器


CABHU-S-B
LHCb VELO




Vertical fiber module
Tilted fiber module
Optical fiber support
SiPM cooling manifold
Beam pipe cut out
SiPM cooling distribution line
Low voltage cables
Bias cables
Cooling blocks



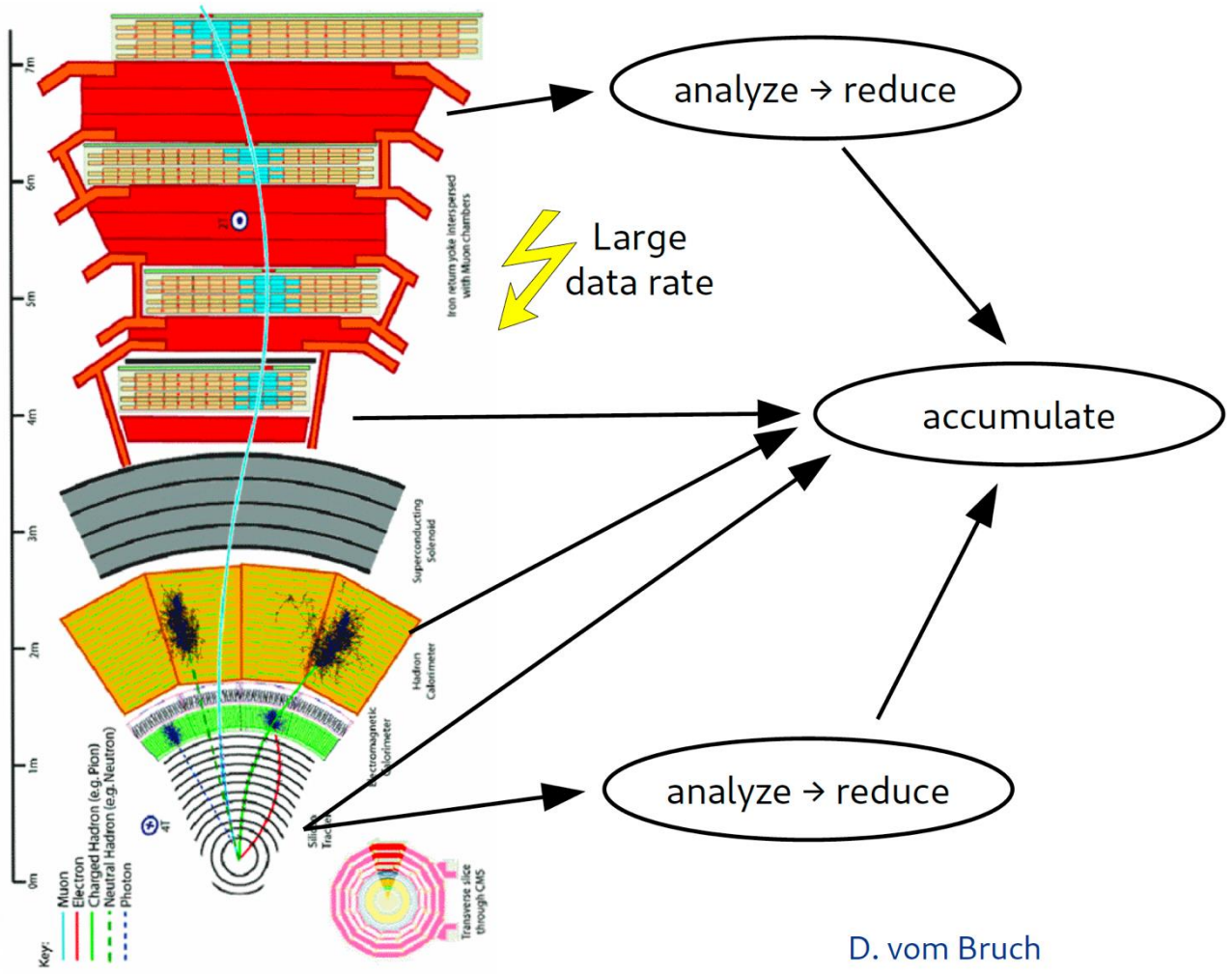
质子-质子对撞能量：

7， 8 TeV

13 TeV

13.6 TeV

Data size

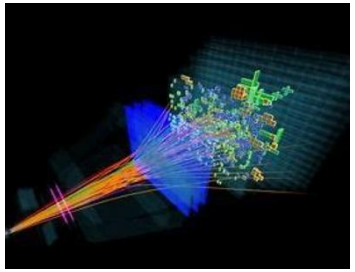


D. vom Bruch

	LHCb		CMS/ATLAS
Data volume at detector	~30 Eb/ year	Global internet dataflow 2015 ~640 Eb/ year	~1 Zb/ year
Data volume for analysts	~30 Pb/ year		~40 Pb/ year

Huge data size, good for ML/AI

数据处理流程

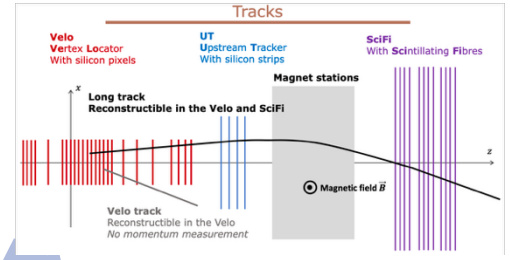


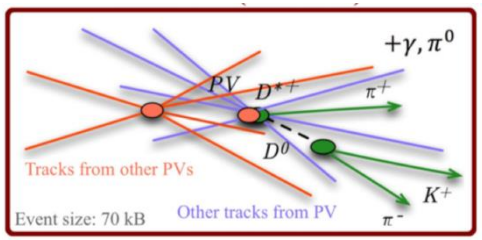
online (real-time)

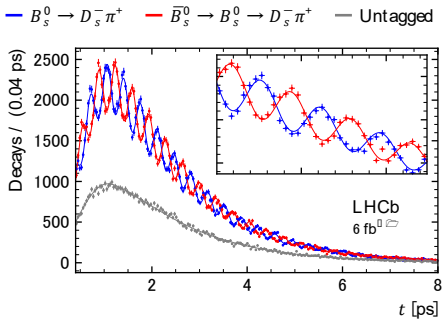
offline

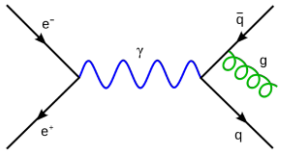
Nature
对撞数据

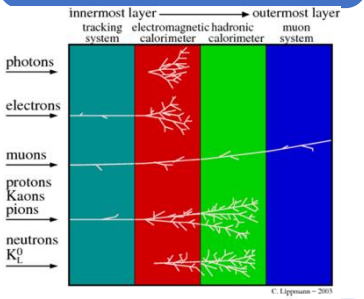
Detector
探测器采集数据











Reconstruction
重建物理事例

event selection
挑选信号事例

Physics
感兴趣的物理

event generator
模拟事例

simulation of detector response

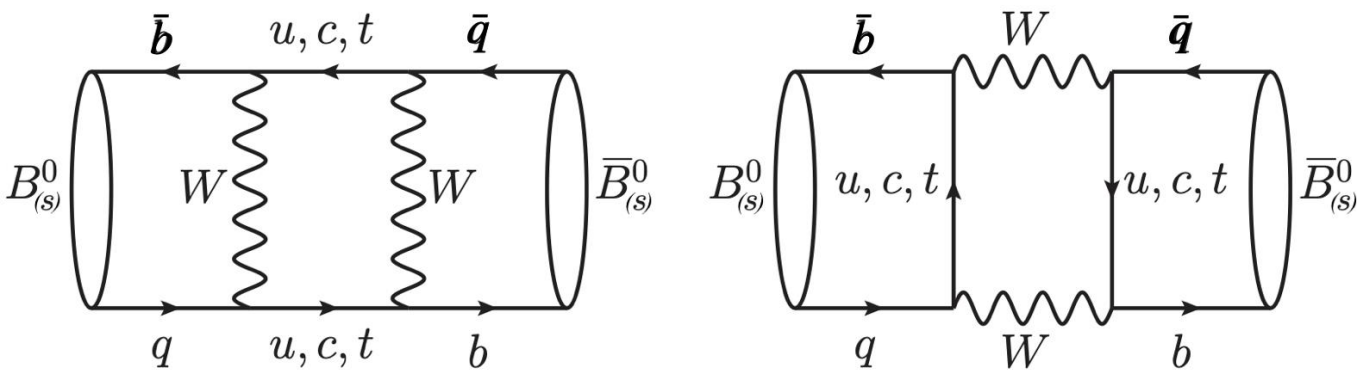
hits→ final state particle :
Cluster hits
Classify clusters as particles
Infer/regress properties

Classify
signal/background

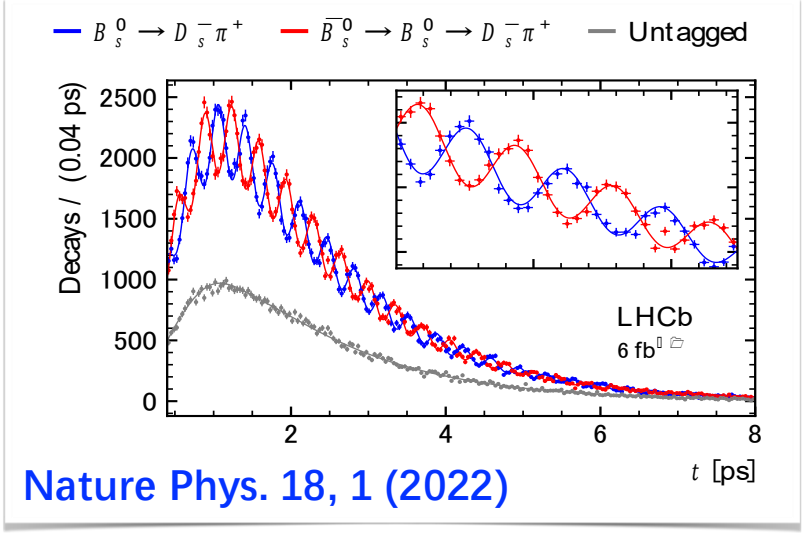
Statistical inference:
Hypothesis testing
Parameter estimation

Modeling/generation

Indirect CPV测量

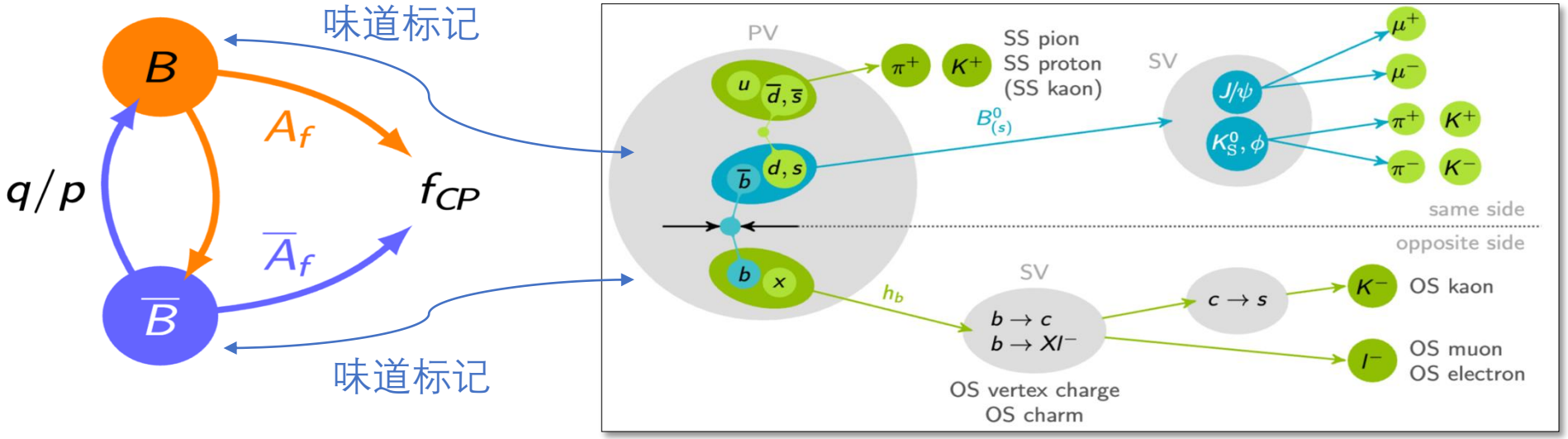


中性介子混合特性！



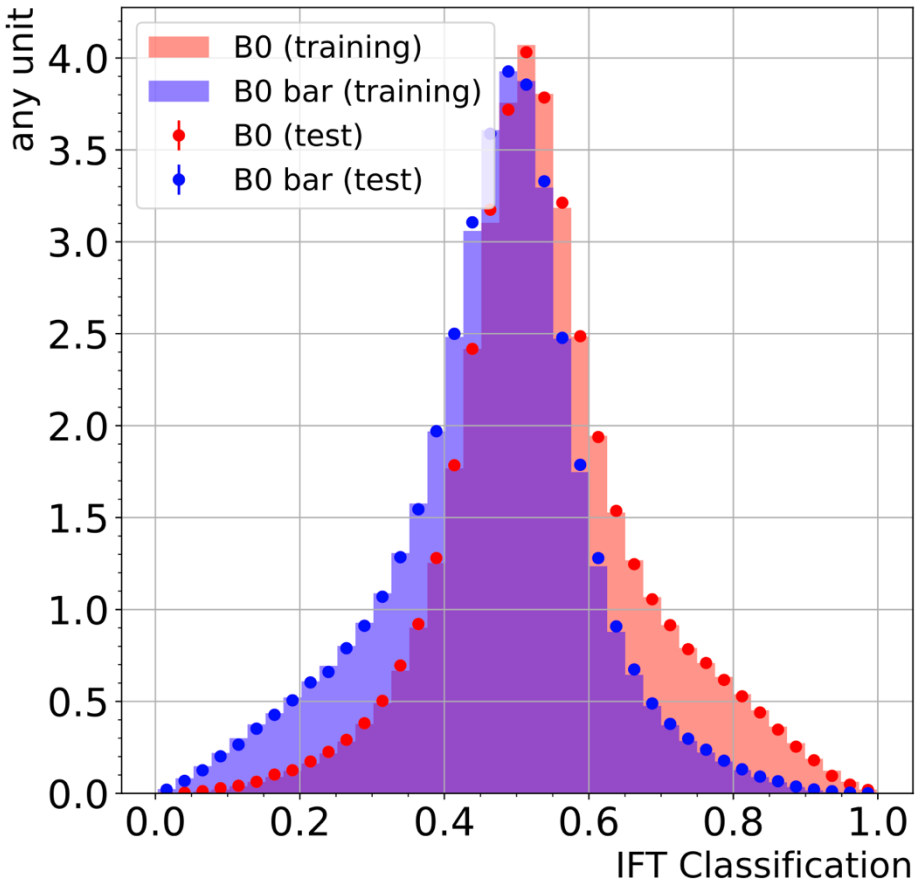
Nature Phys. 18, 1 (2022)

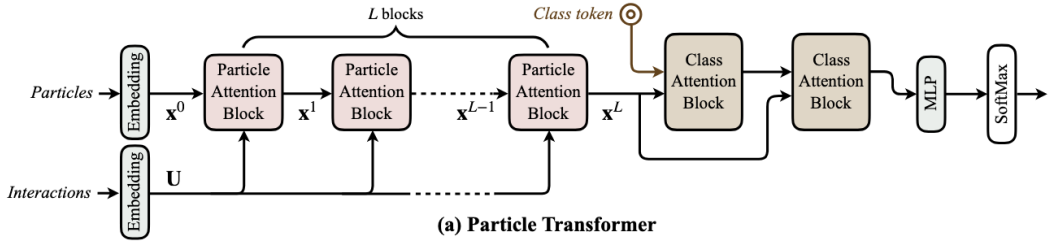
深度学习技术提高味道标记效率低



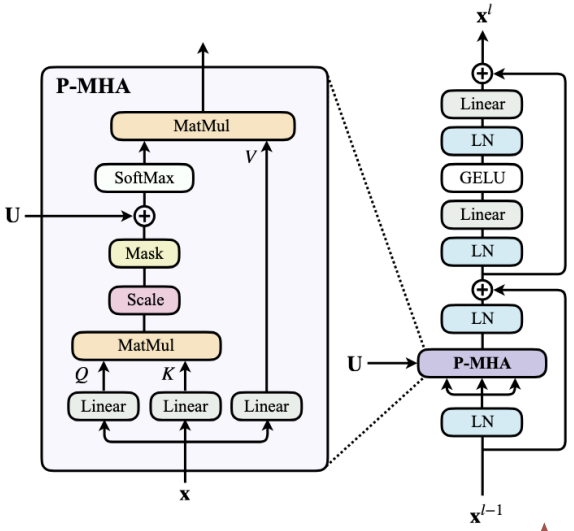
Indirect CPV测量

深度学习技术提高味道标记效率低

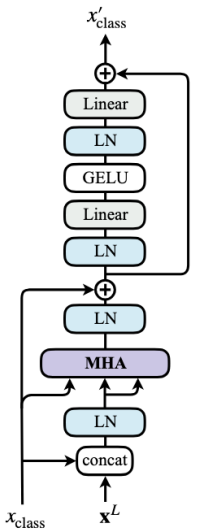




(a) Particle Transformer



(b) Particle Attention Block



(c) Class Attention Block

$$\Delta = \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2},$$

$$k_T = \min(p_{T,a}, p_{T,b})\,\Delta,$$

$$z = \min(p_{T,a}, p_{T,b}) / (p_{T,a} + p_{T,b}),$$

$$m^2 = (E_a + E_b)^2 - \|\mathbf{p}_a + \mathbf{p}_b\|^2.$$

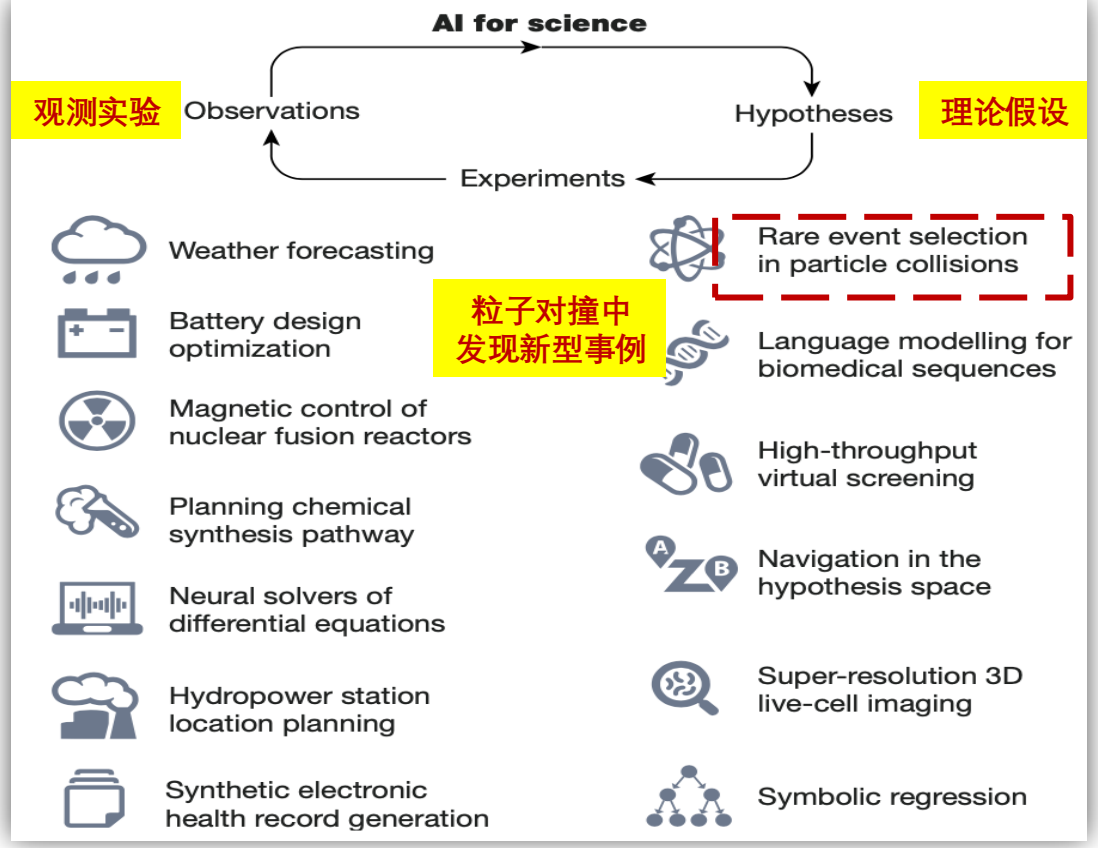
Review

Scientific discovery in the age of artificial intelligence

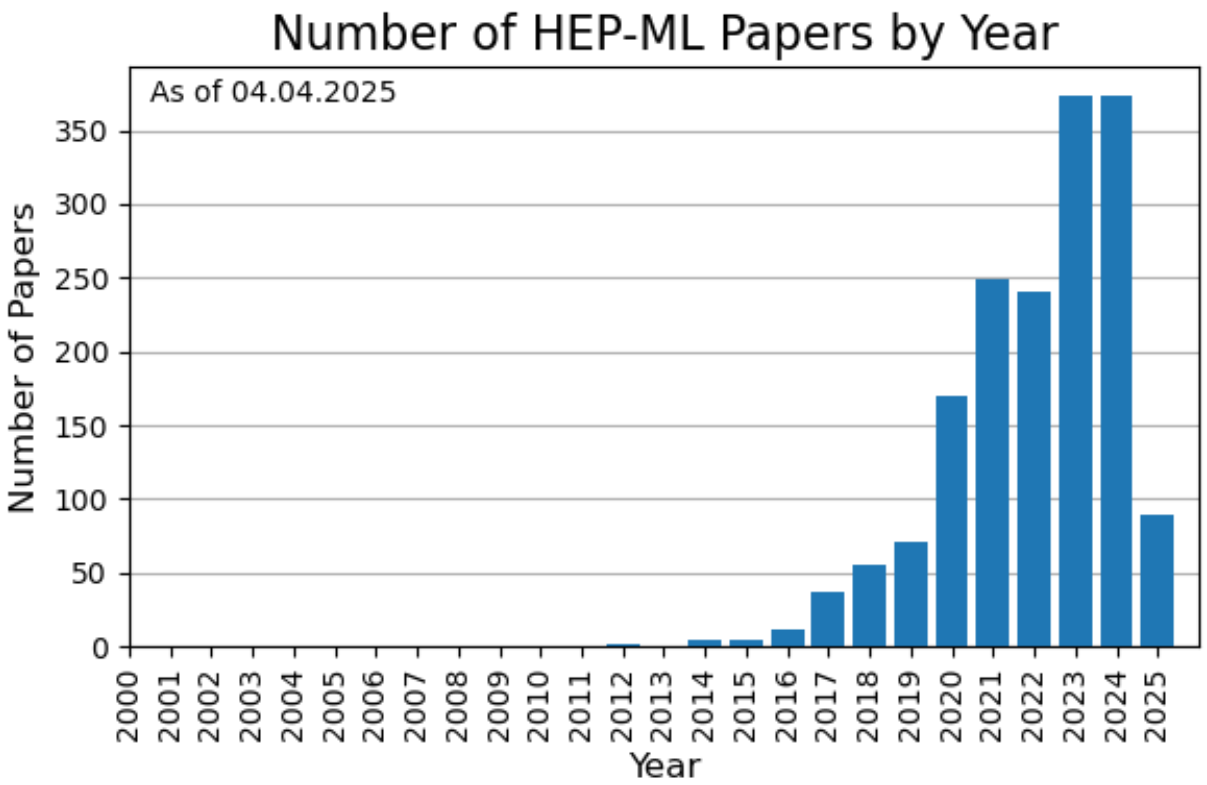
Nature, 2023

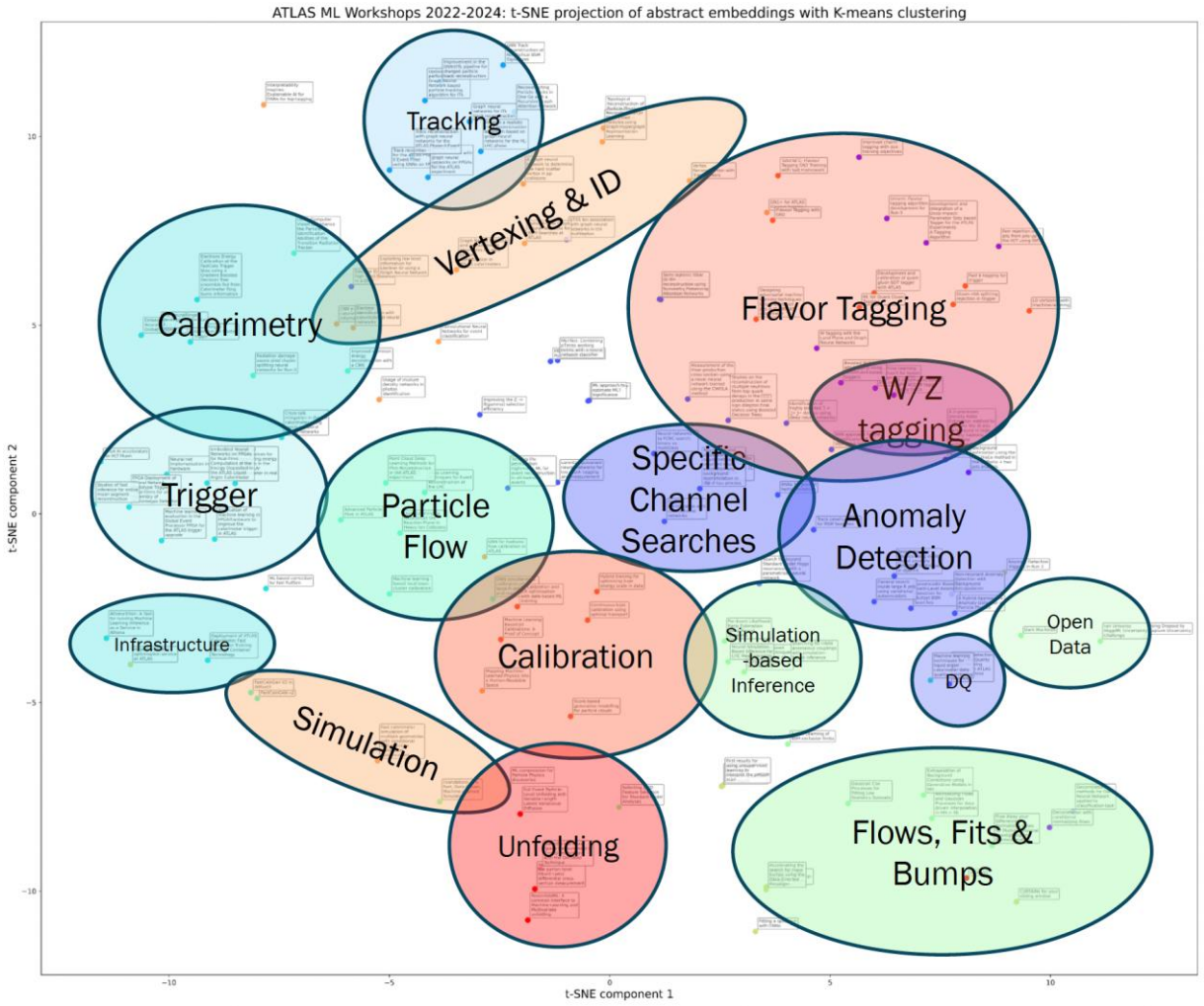
2023年，美国哈佛大学联合多家单位在《Nature》发文：

- **人工智能技术大大加速了科学研究，可以获得传统方法无法发现的科学洞见**
- 如何实现科学规律与数据驱动的模型的深度融合，**发现科学规律，仍处于研究的早期阶段。**



AI/ML in HEP

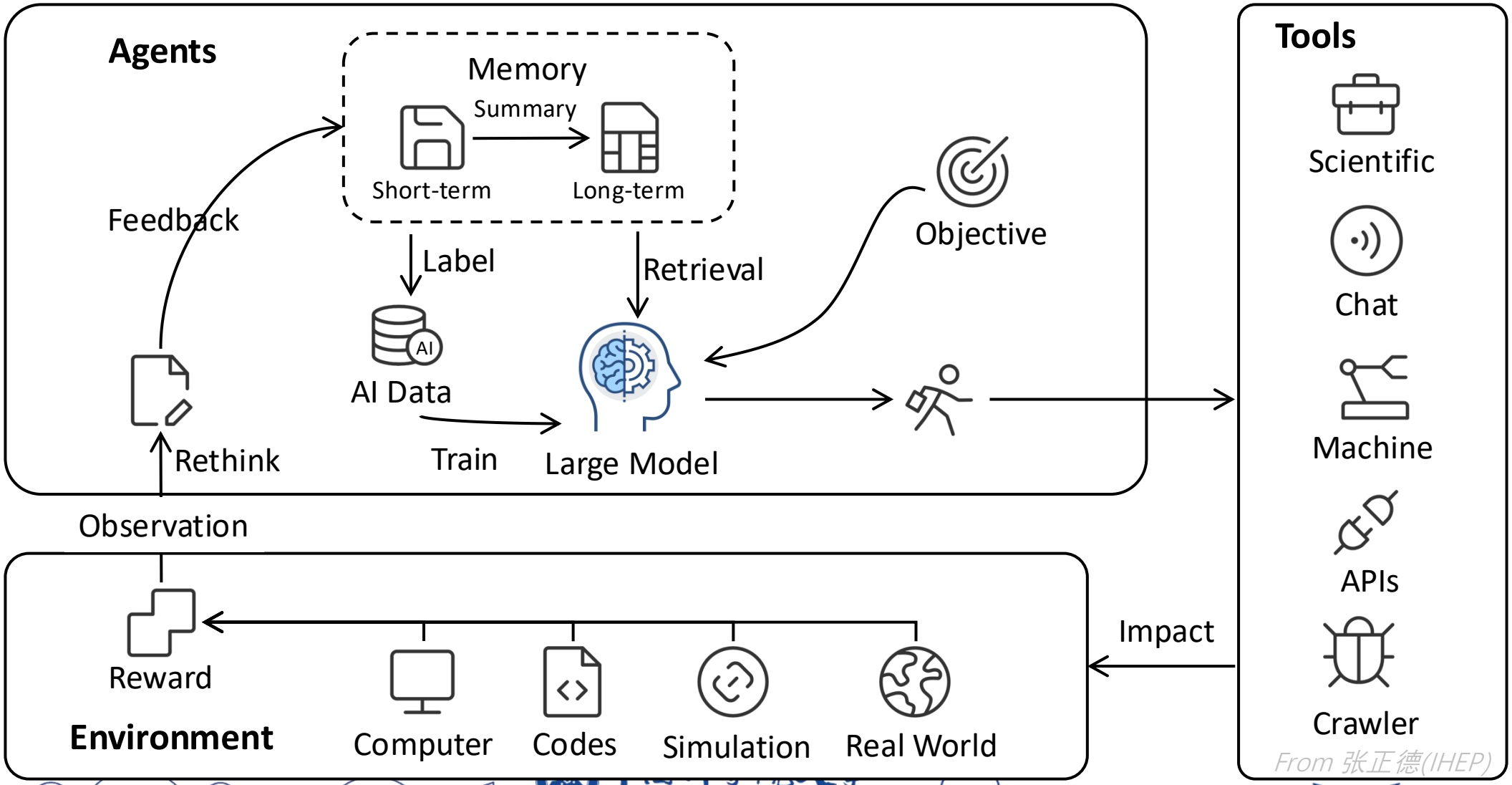




https://iml-wg.github.io/HEPML-LivingReview/

粒子物理分析智能体

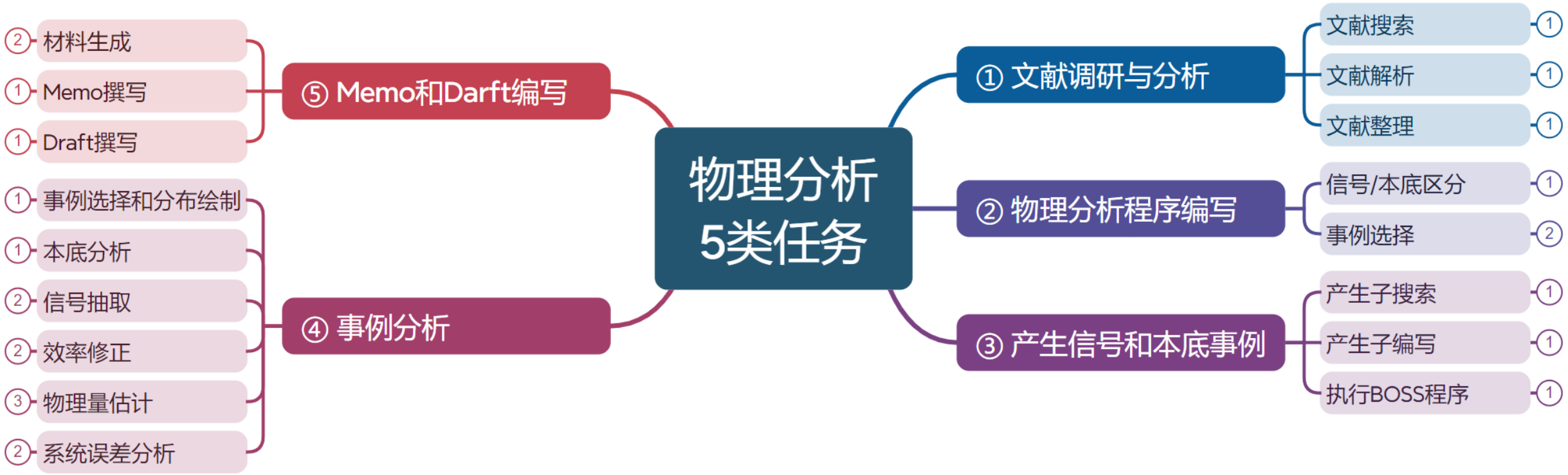
智能体是指能够根据其知识、环境和输入，自主作出决策或执行行动的系统。



From 张正德(IHEP)

粒子物理分析智能体

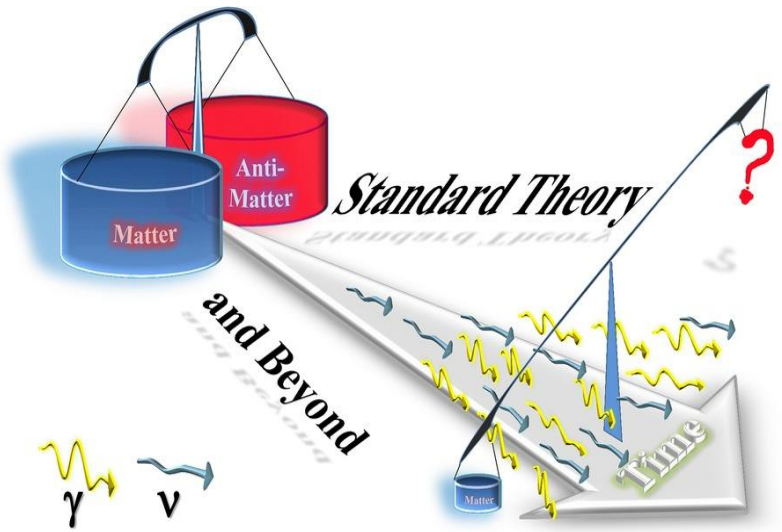
□ 物理分析是科学发现的关键环节之一



□ 让智能体来学会复杂的物理分析方法

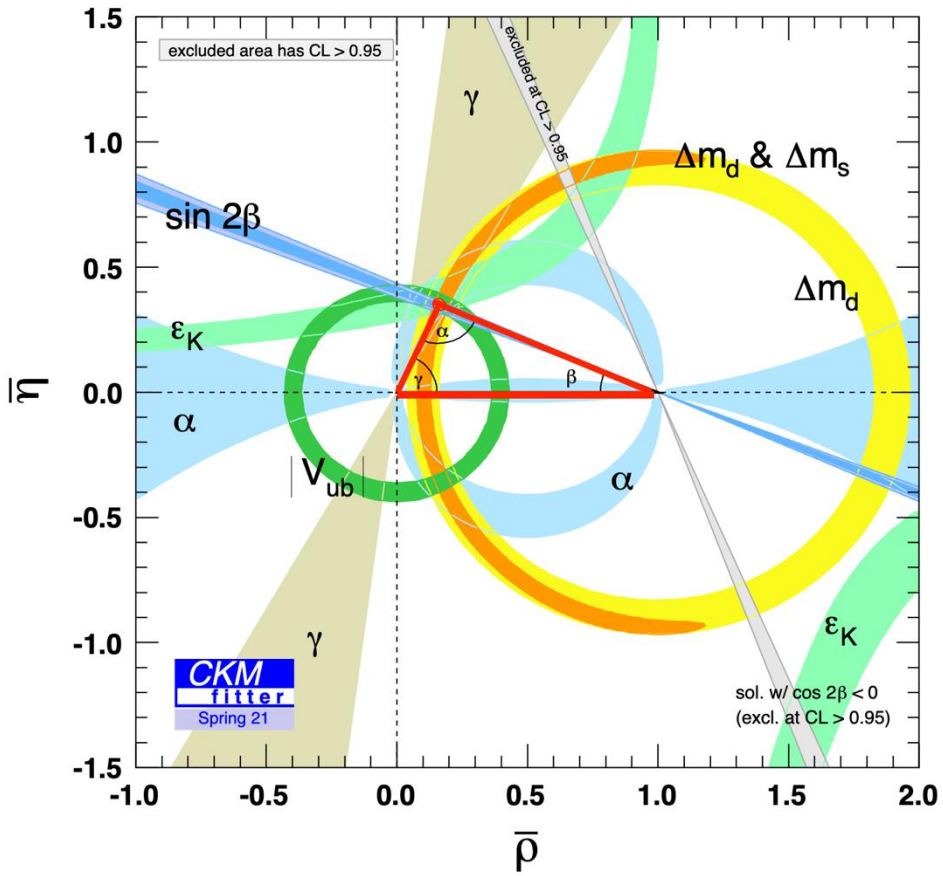
From 张正德(IHEP)

CP破坏精确测量探秘宇宙正反物质不对称性



科学难题：

正反物质不对称性



Global fit:

$\alpha+\beta+\gamma=(179.9^{+1.9}_{-1.7})$

超越标准模型的新物理？！

研究手段：CP破坏测量精度 + AI/ML for science

欢迎感兴趣的同学加入科创训练+攻读研究生！

如果你想要理解我们的物质世界，
如果你喜欢开发先进算法，
如果你喜欢ML/AI，研究大数据，
如果你喜欢探索高精尖前沿技术...

Thank you!

李佩莲课题组
lipeilian@ucas.ac.cn

Generated by ChatGPT