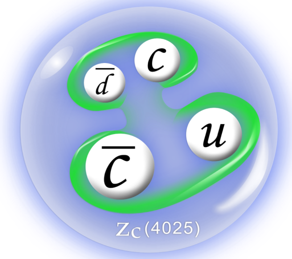
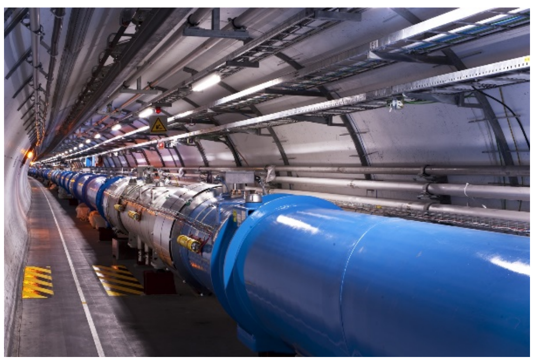
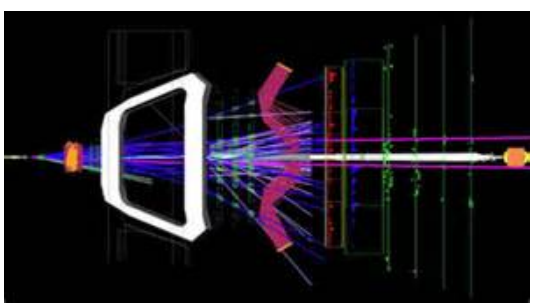


奇特四夸克物质





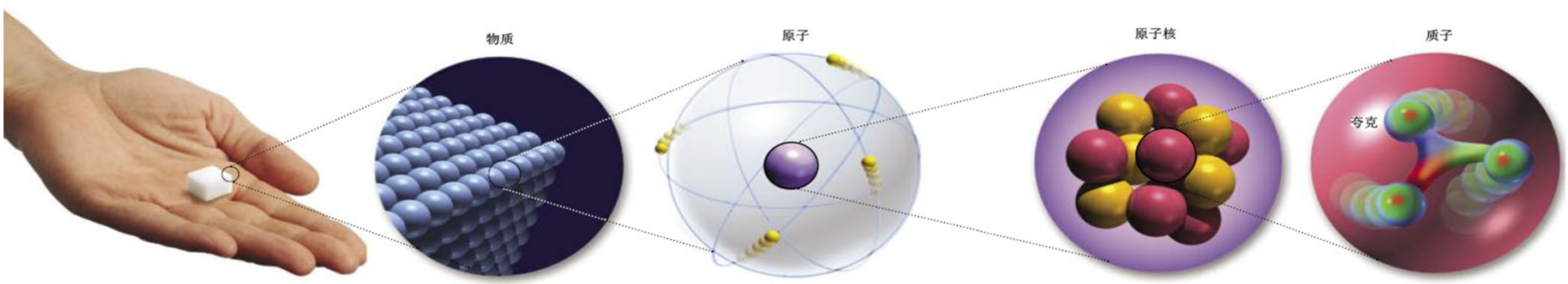
吕晓睿
中国科学院大学

电子邮件： xiaorui@ucas.ac.cn

谢耳朵的白板

✦科学顾问: David Saltzberg（UCLA）

物质的基本构成图像



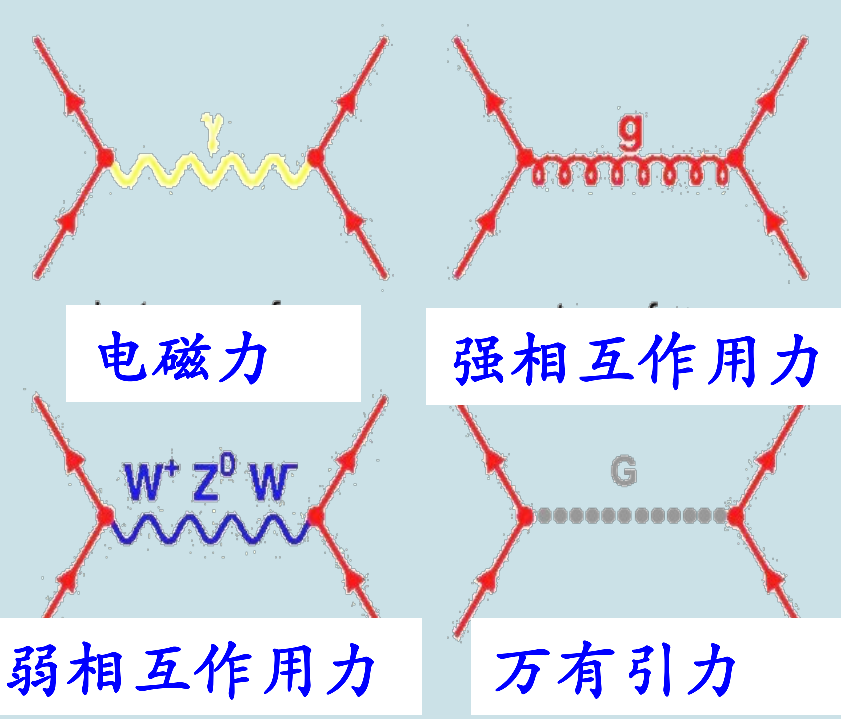
凝聚态物理 原子分子物理 原子核物理 粒子物理

化学

材料科学

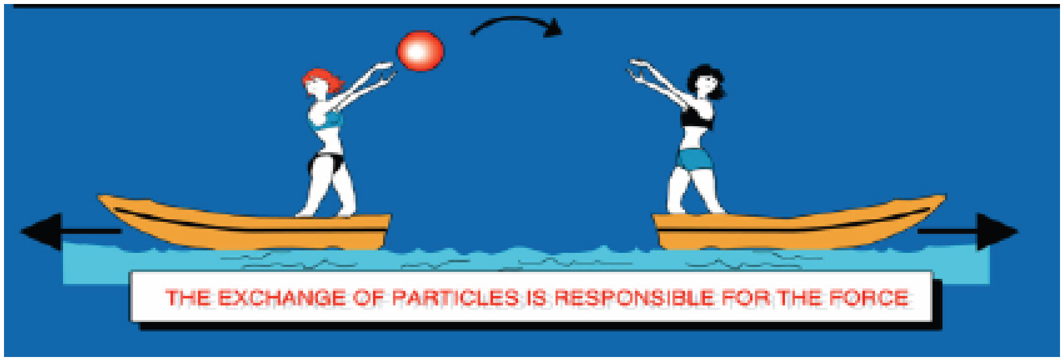
物质的基本组成--标准模型

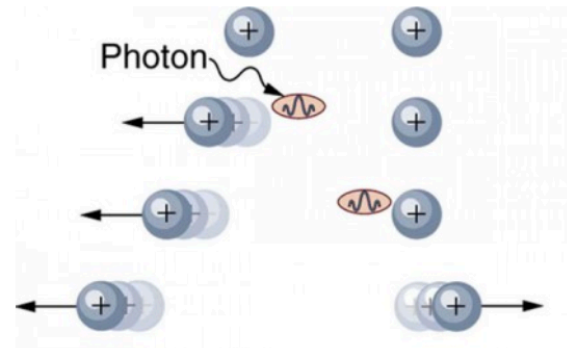
- 构成物质的基本单元：6种轻子 + 6种夸克



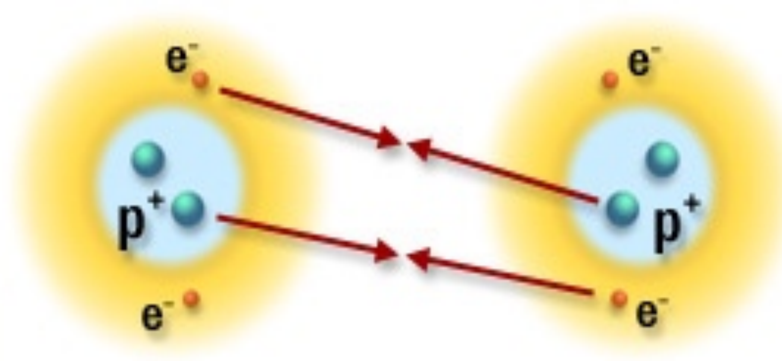
- ☐ 已知物质世界：夸克和轻子
- ☐ 强、弱、电相互作用都由规范玻色子传递
- ☐ 希格斯场赋予基本粒子质量
- ☐ 强相互作用赋予原子核等强子的大部分质量

相互作用的“标准”答案

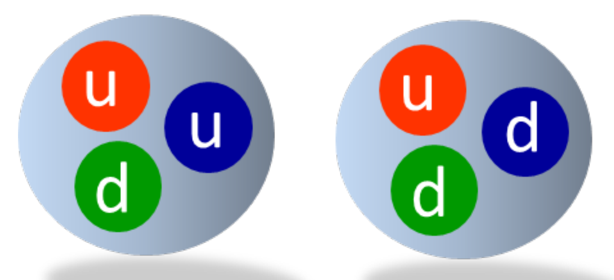




相互作用即一般所说的“力”

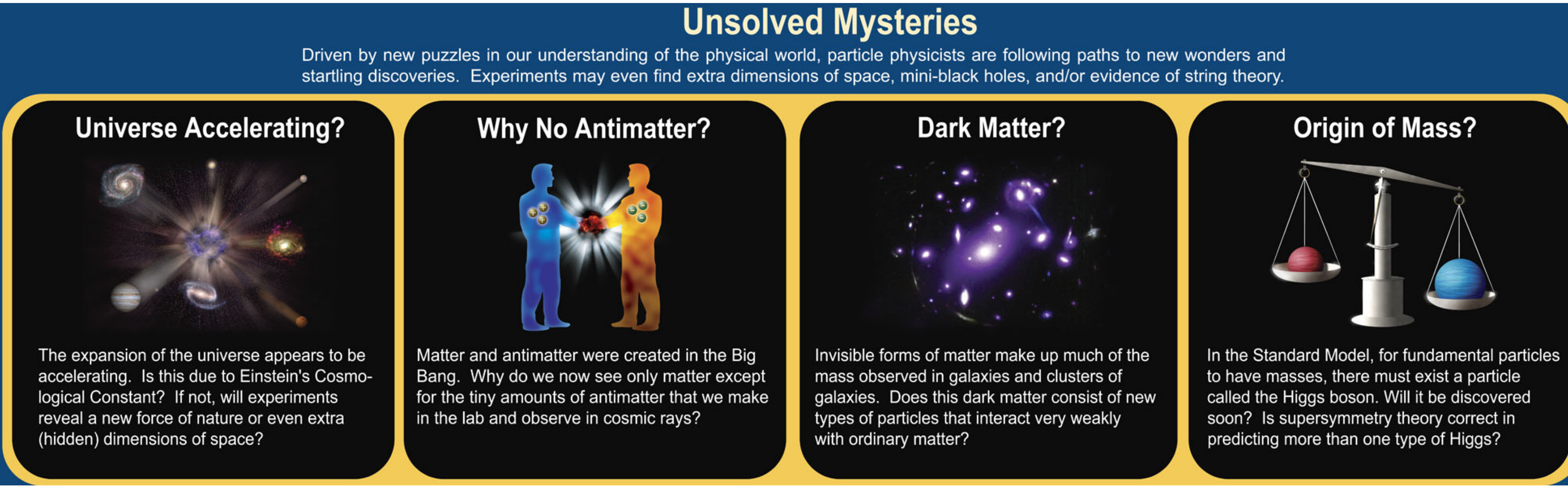


- 原子核与电子通过电磁力形成原子及万物；
- 夸克间或轻子间通过弱力互相转化；
- 夸克间通过强力形成质子和中子，
- 进而形成原子核；
- 万物通过引力相互作用形成了宇宙。



质子　中子

但是，仍然存在的热点前沿问题



- Matter-antimatter asymmetry
- Gravity
- The origin of the Mass
- New form of matter (exotic states) ⟵ 新型物质形态（奇特物质）
- Dark matter/energy
- Neutrino mixing
- …

Higgs粒子发现后的研究热点

- 实验对电弱理论的精确检验及寻找新物理
- 2012年7月LHC实验发现 Higgs粒子

Physics 2013 ➔ 电弱理论的巨大成功！

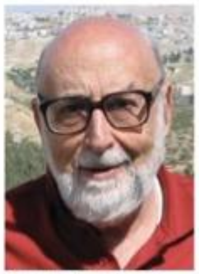
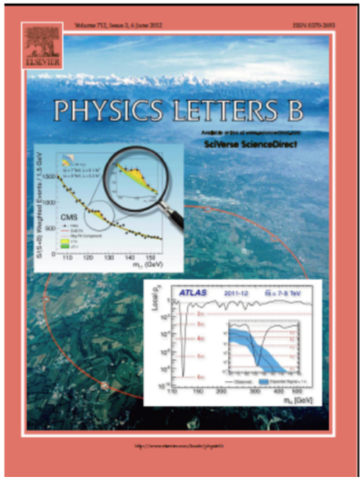


Photo: Pnicolet via Wikimedia Commons
François Englert

Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

François Englert &
Peter W. Higgs 获2013年诺贝尔奖



Physics 2004

David J. Gross

H. David Politzer

Frank Wilczek

- 高能下的QCD理论得到实验的大量检验
  QCD 的渐进自由 ➔2004年诺贝尔奖

- 低能下，强相互作用的非微扰性质、
  夸克禁闭等问题长期困扰物理学界

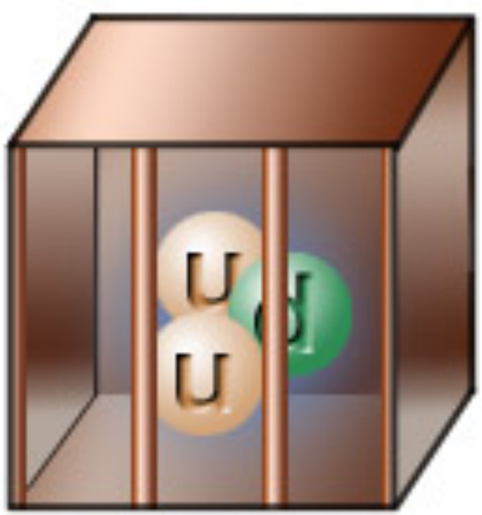
四夸克物质研究背景

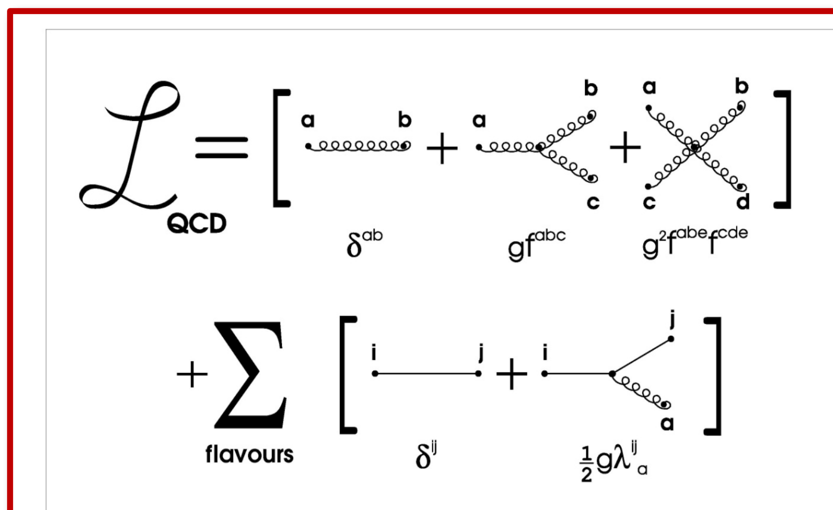
- 低能下QCD 理论尚有待进一步发展和实验检验，尤其是有许多重大科学问题亟待实验和理论共同回答，例如：

是否存在超出普通夸克模型的新型粒子?

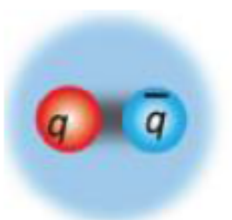
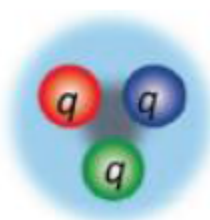
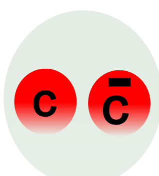
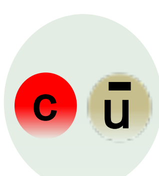
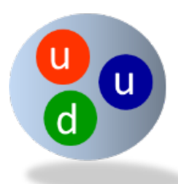
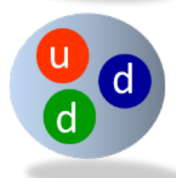
夸克如何构成粒子（夸克模型并不能回答）?

- 促进理解强相互作用的非微扰性质和夸克禁闭等问题





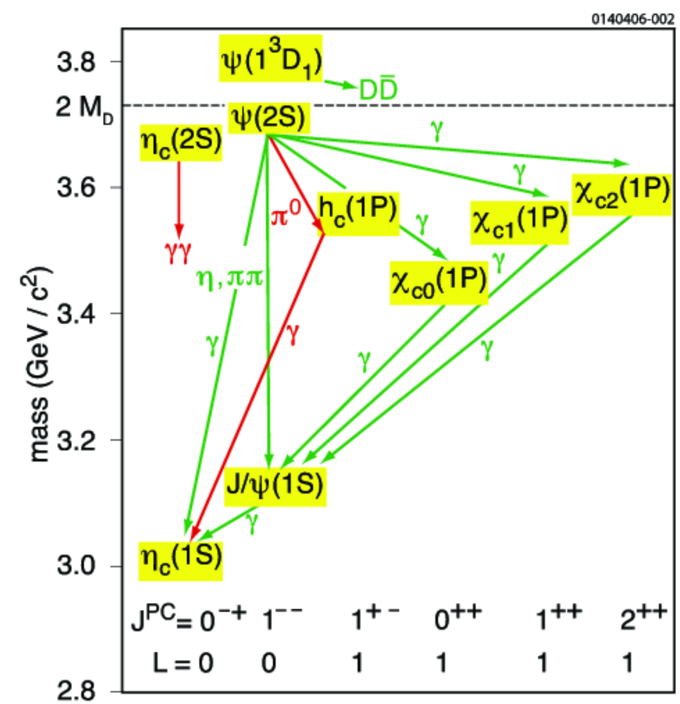
描述强子结构的理论：夸克模型

强子（主要由强相互作用绑定，QCD理论描述）	
介子	重子
夸克数=2（正反夸克对）	夸克数=3
	
举例：粲偶素  粲介子 	举例：质子  中子 

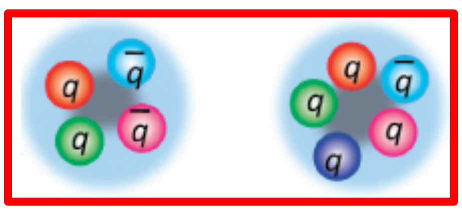
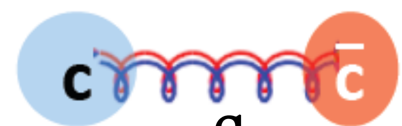
- ✦ 1964年盖尔曼提出模型
- ✦ 介子和重子的夸克结构早已被实验确认

具体实例：

- 粲偶素($c\bar{c}$)类比于氢原子系统
  - 质量谱 ⇔ 氢原子能级

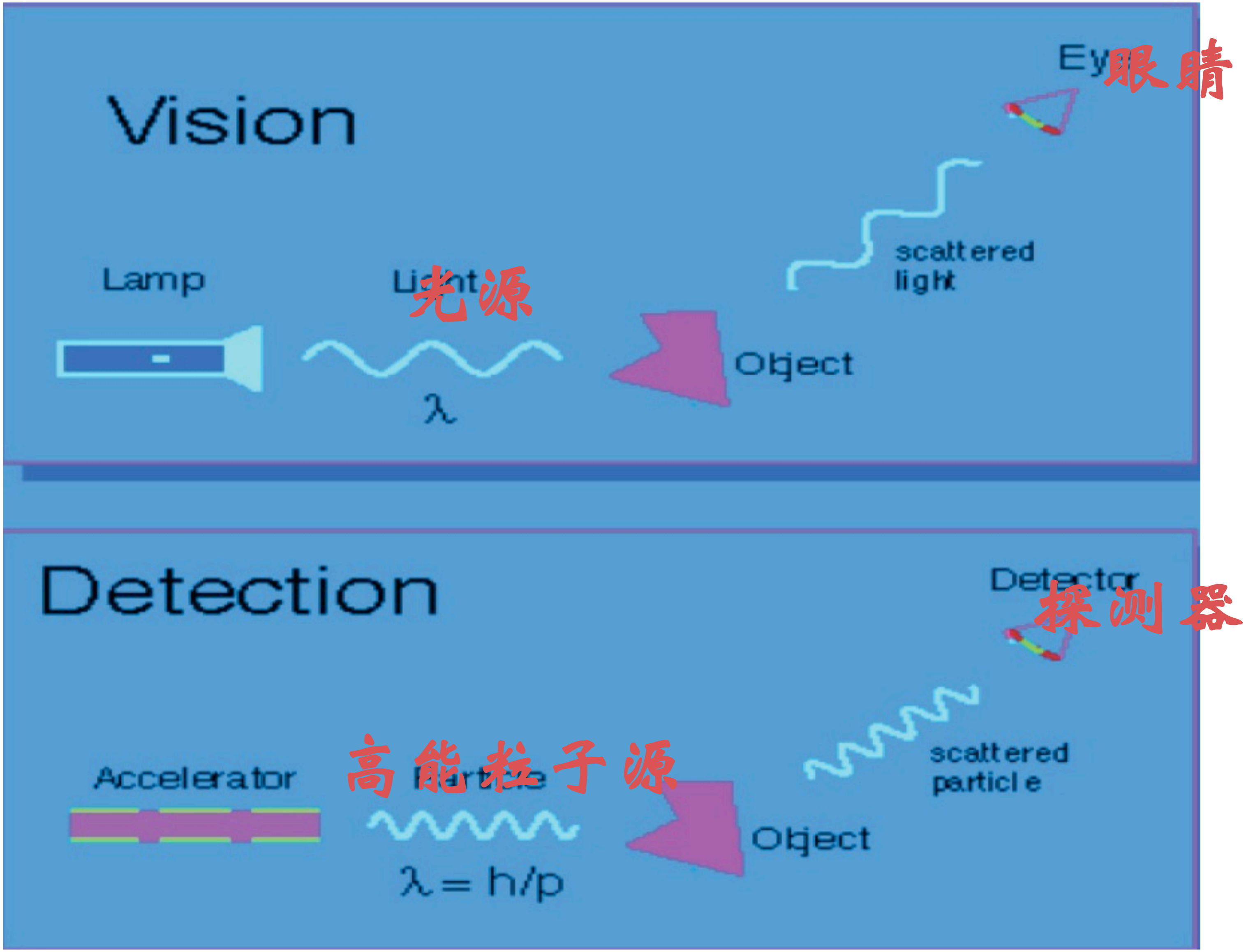


新型强子态

QCD理论允许强子的夸克数不只是2或3		
多夸克态	胶子球	混杂态
夸克数>=4	夸克数＝0，多个胶子gg，ggg …	夸克数＝2 ＋激发胶子 :qqg，qqqg …
	g g g 	 g

- 实验上还未确认新型强子态的存在！

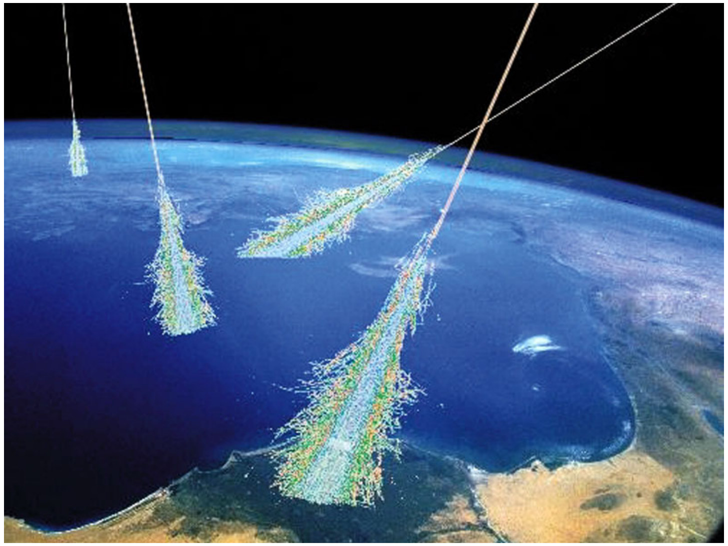
粒子物理实验研究



Vision
Eye
眼睛
Lamp
Light
光源
λ
Object
scattered light
Detection
Detector
探测器
Accelerator
Particle
高能粒子源
λ = h/p
Object
scattered particle

高能粒子源

- 放射源
- 反应堆
- 宇宙线
  - 可获超高能量粒子
  - 统计量低
  - 随机性强
- 粒子加速器
  - 电场加速，磁场偏转与聚焦
  - 能量较宇宙线低
  - 能量可调节
  - 统计量高
  - 可控制与可重复性强



粒子物理实验类比：渔网 vs 鱼枪

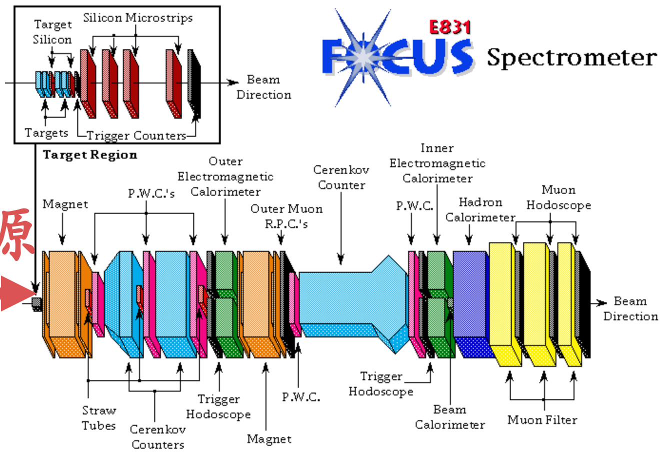
- 加速器对撞机实验（通用）
- 对撞能区 vs 捕捞海域
- 探测器能力 vs 捕捞深度
- 实验精度（$\propto$ 对撞亮度） vs 渔网的网孔尺寸

- 非加速器实验（中微子、暗物质、$0\nu\beta\beta$、g-2、引力波等实验：物理目标相对集中）

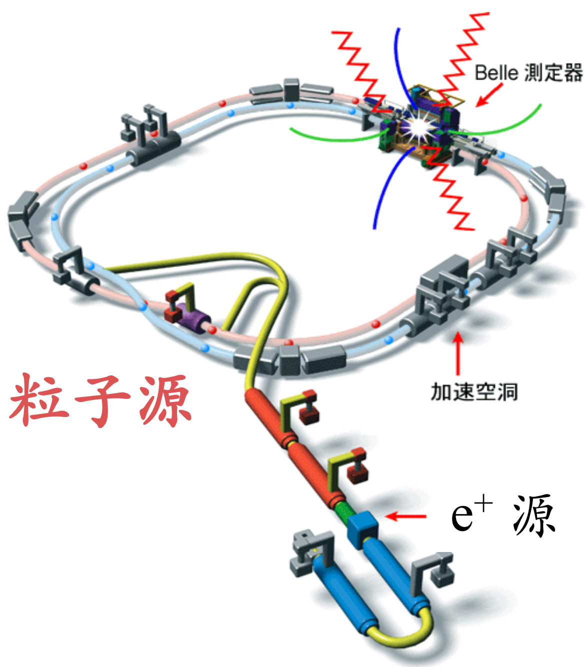
基本粒子物理实验

- 固定靶
  - 高能粒子束轰击静止的粒子靶
- 对撞机
  - 两束高能粒子对头碰撞
  - 质心系能量高

高能粒子源



高能粒子源



高能对撞：能量质量转换

- 原子弹、氢弹、核反应堆：

  $$E = mc^2$$

  物质质量 → 能量

- 对撞机物理实验：

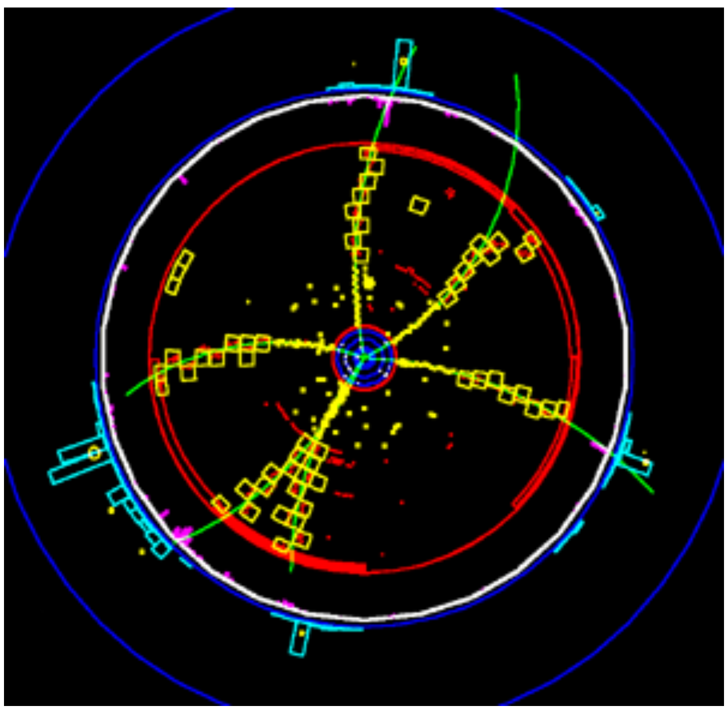
  $$m = E/c^2$$

  能量 → 粒子质量

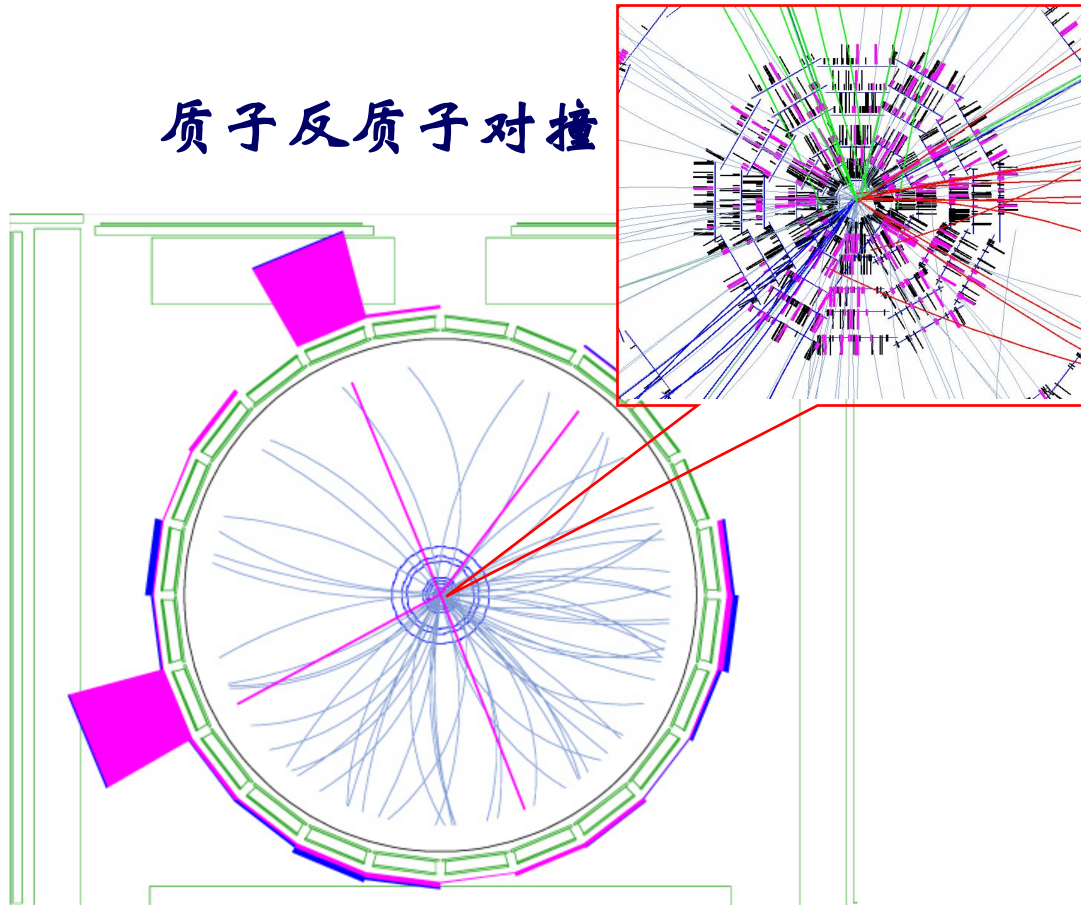
  – 动能(低质量粒子) → 粒子质量 (高质量粒子)

典型的对撞事例

正负电子对撞



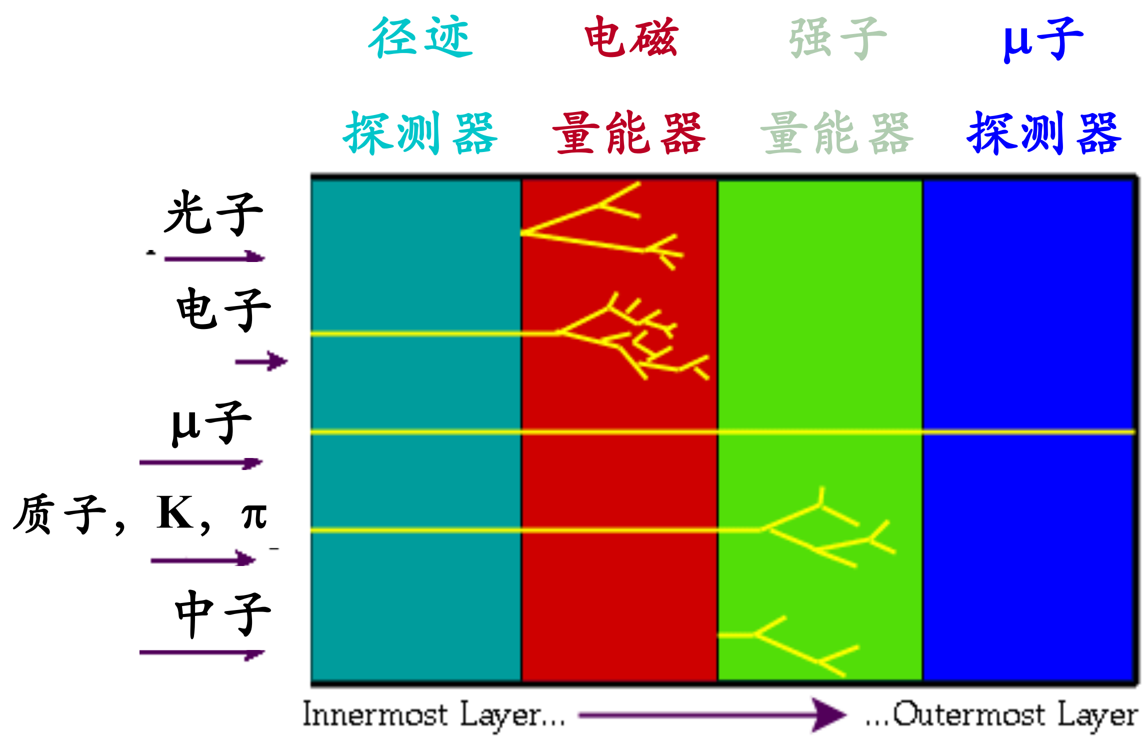
质子反质子对撞



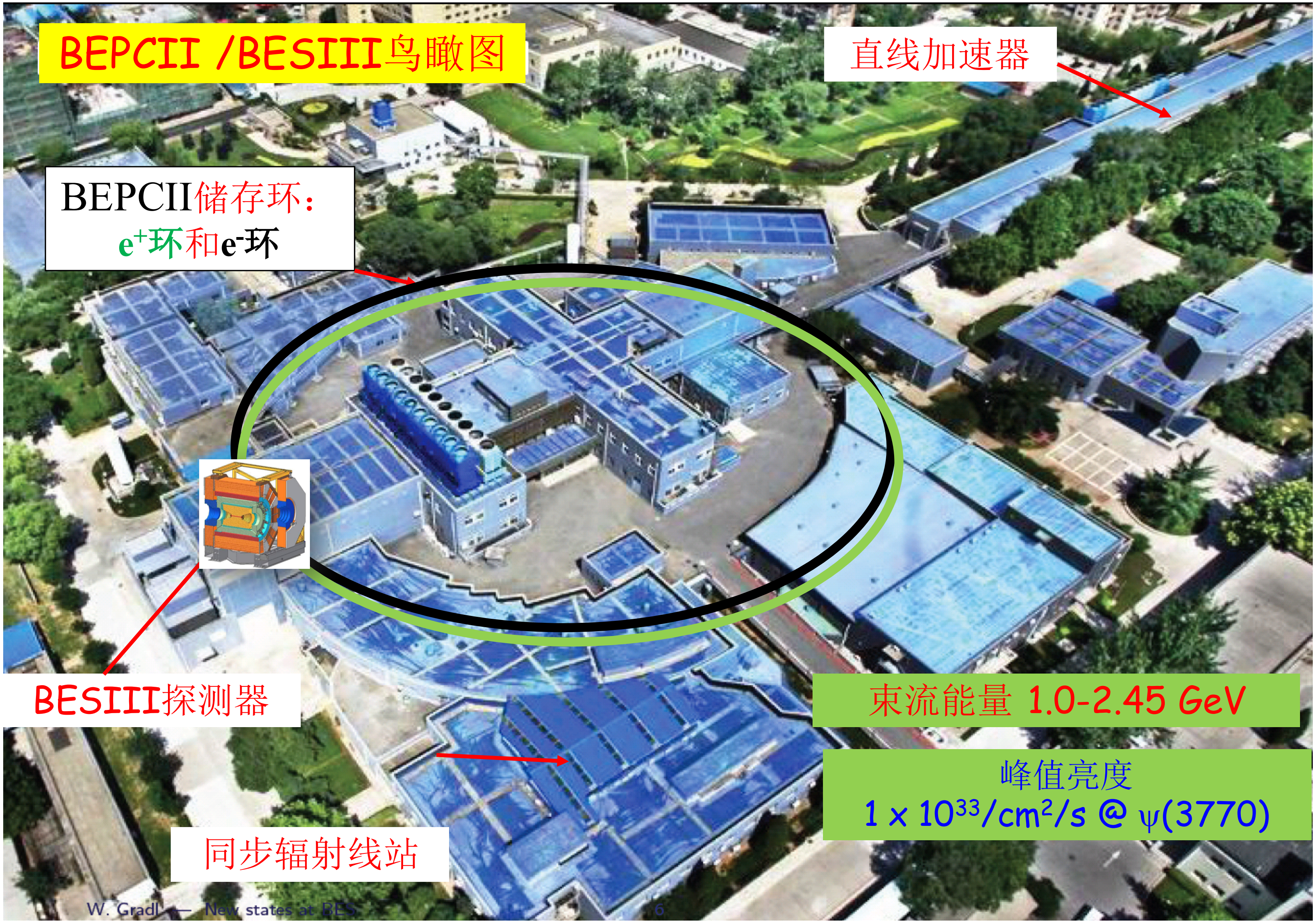
粒子是如何被探测的？

- 粒子是通过与探测器发生相互作用来探测的
- 对撞机所产生的绝大部分粒子的寿命都很短，会衰变到长寿命的稳定粒子：
  - 带电荷稳定粒子：电子, μ, K, π, 质子
  - 中性稳定粒子：光子, 中子
- 不稳定粒子可以从对稳定粒子的测量中重建

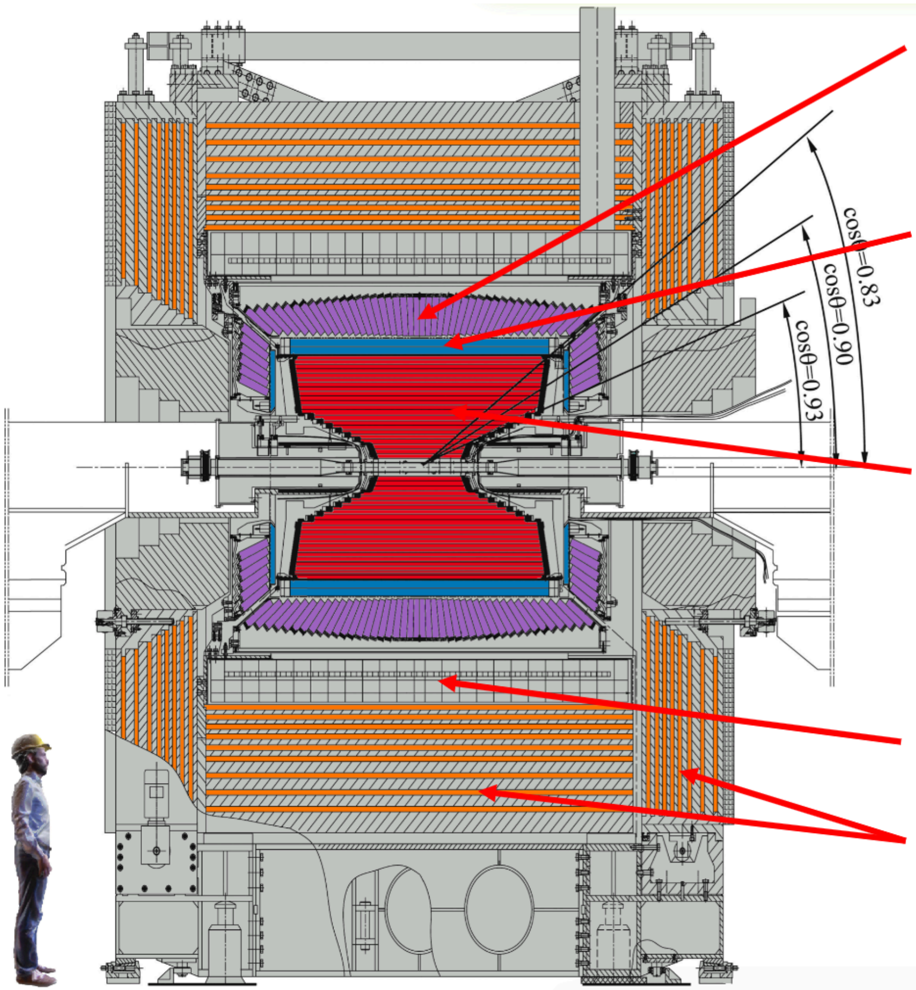
◆ 利用粒子在气体中的电离、飞行时间、穿透性以及能量簇射等效应来分辨粒子种类



北京正负电子对撞机BESIII实验



BESIII探测器：一个典型的通用谱仪



EMC: CsI crystals
$\Delta E/E$ = 2.5% @ 1 GeV - Barrel
$\Delta E/E$ = 5.0% @ 1 GeV - Endcaps

TOF:
σ_T = 80 ps Barrel
σ_T = 110 (60) ps Endcap

MDC: small cell & He gas
σ_{xy}= 130 μm
σ_p/p = 0.5% @1GeV
dE/dx = 6%

Magnet: 1T Super conducting

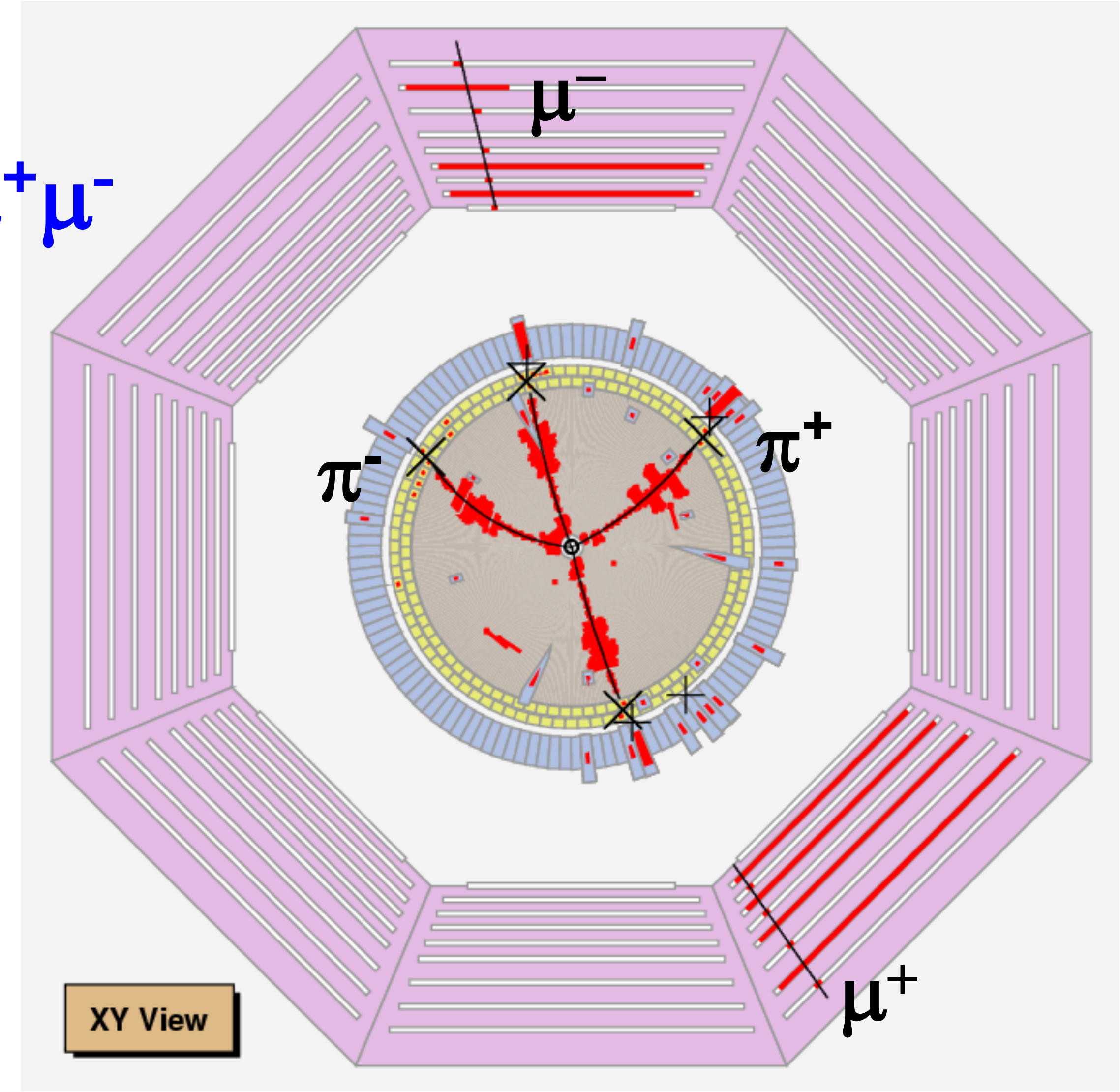
Muon ID: 9 layer RPC

Trigger: Tracks & Showers

BESIII实验上一个典型的对撞事例

$\pi^+ \pi^- J/\psi$

$\hookrightarrow \mu^+\mu^-$



BESIII国际合作组

合作组成员约500人，来自15个国家的74个科研单位。

Europe (16)

Germany: Bochum Ruhr Univ., GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg Univ. of Mainz, Justus-Liebig-Univ. Giessen, Univ. of Münster, Univ. of Giessen; Russia: Budker Institute of Nuclear Physics, Joint Institute for N… Research; It…

USA (5)

Carnegie Mellon Univ.,
Indiana Univ.,
Univ. of Hawaii,
Univ. of Mi…
Univ. …

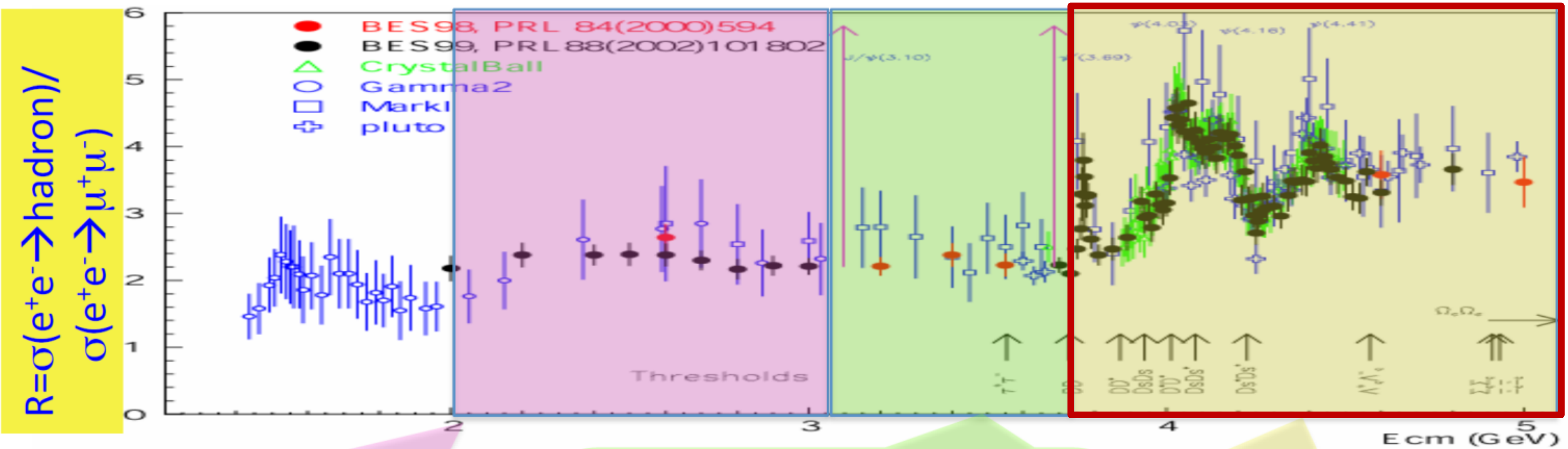
China (45)

IHEP, Beihang Univ.,
Beijing Institute of Petrochemical Technology,
CCAST, Fudan Univ., Guangxi N…rmal Univ., …rmal Univ., …iv. of Science …rmal Univ., …iv., Hunan …stitute of …hou Univ., …ng Univ., …iv., Nankai …al Univ., …, Shanxi …ng Normal …ao Tong … Normal …Yat-sen Univ., …Univ., Univ. of Chinese Academy of Sciences ,
Univ. of Jinan, Univ. of Science and Technology of China, **Univ. of Sciences and Technology Liaoning,** Univ. of South China, Wuhan Univ., Xinyang Normal Univ., Zhejiang Univ., Zhengzhou Univ.

C…

COMSATS Institute…
Indian Institut…
Institute of Phy…
Seoul …
Tokyo University, Japan
Univ. of Punjab, Pakistan
Suranaree Univ. of Technology, Thailand
University of Lahore, Pakistan

Physics at tau-charm Energy Region



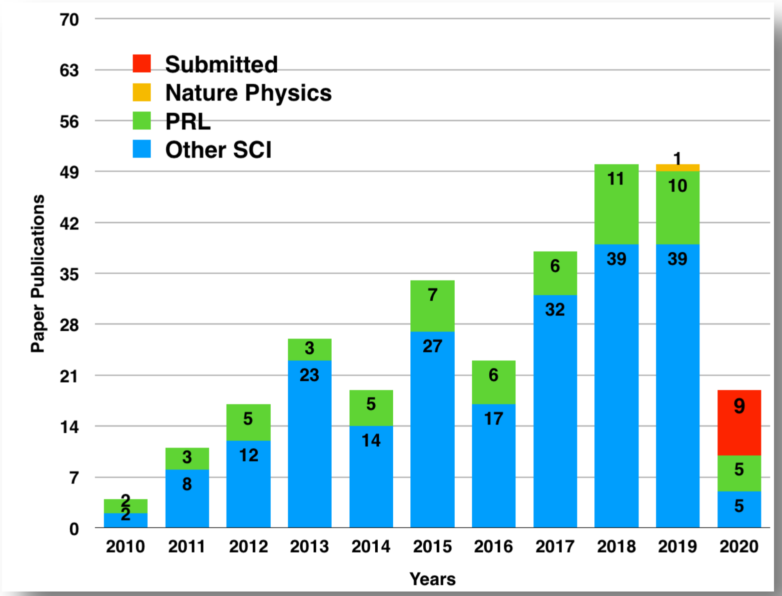
- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- D mesons
- f_D and f_{Ds}
- D_0-D_0 mixing
- Charm baryons

BES实验物理成果

- τ质量测量
- R值精确测量
- X(1835)和$X(\bar{p}p)$的发现
- Zc四夸克态的发现
- Λc产生衰变测量
- 粲强子精确测量：
  CKM、衰变常数 & 强相角测量
- J/ψ衰变到超子对极化产生
- …



Excellent in both number and quality

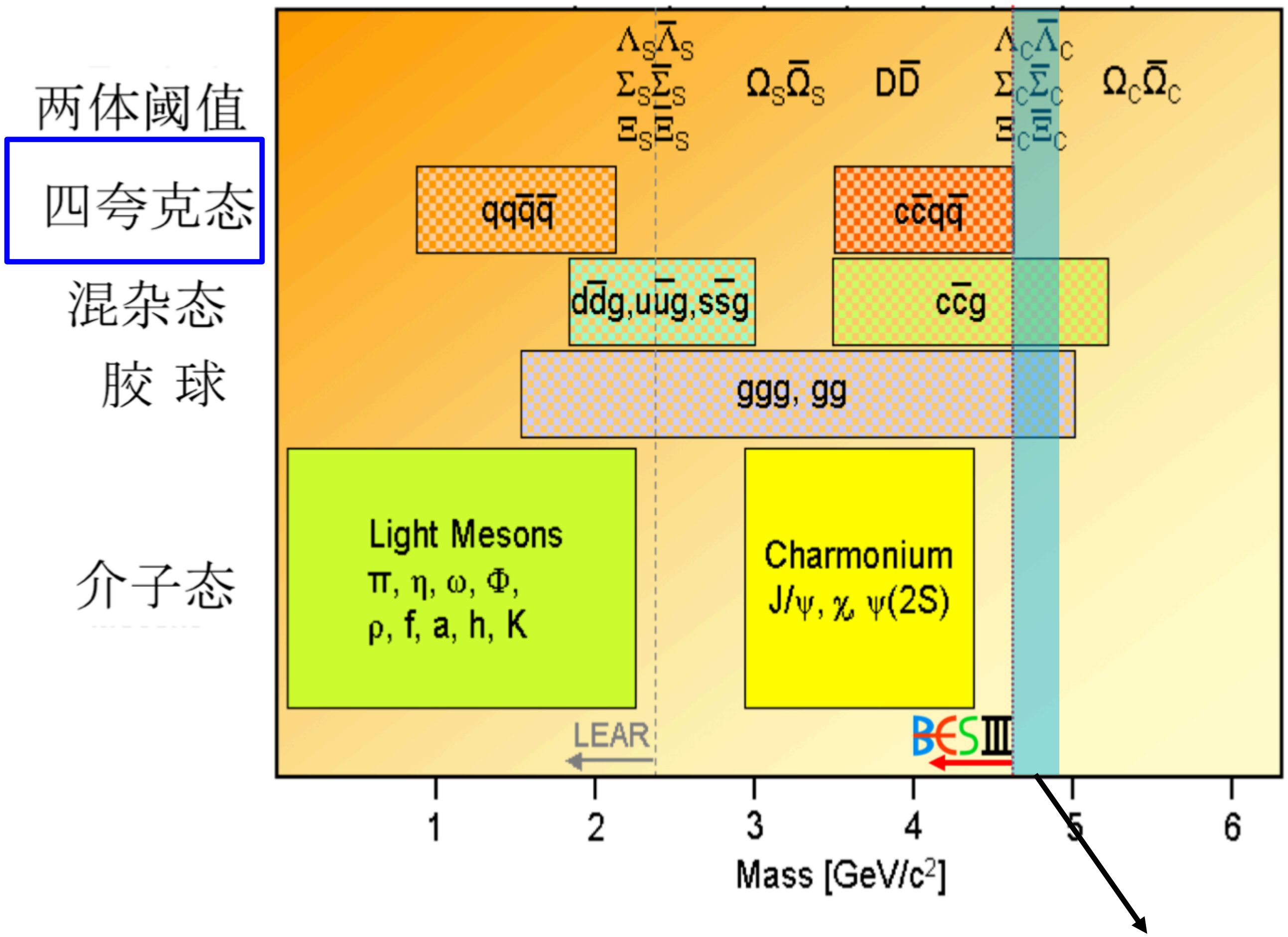
http://bes3.ihep.ac.cn/pub/physics.htm

~20 PhD / year

阈值产生⇒ 高统计量，低本底

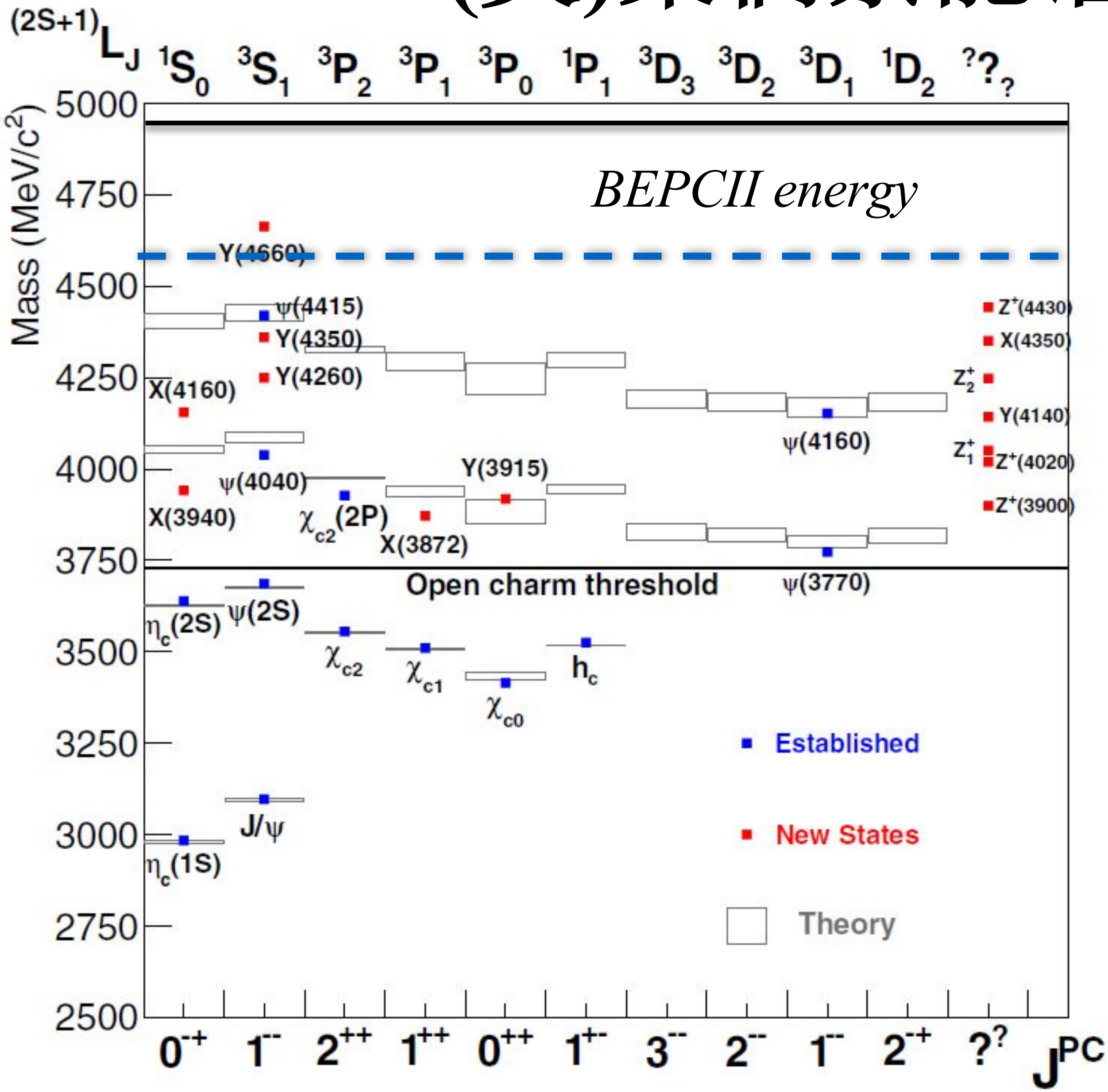
BESIII上奇特四夸克物质的寻找

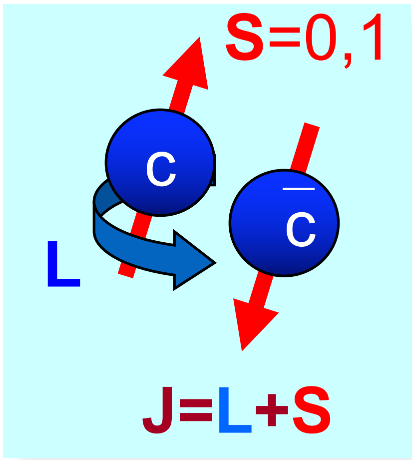
BESIII上的强子物理



2020年完成能量升级至4.9 GeV

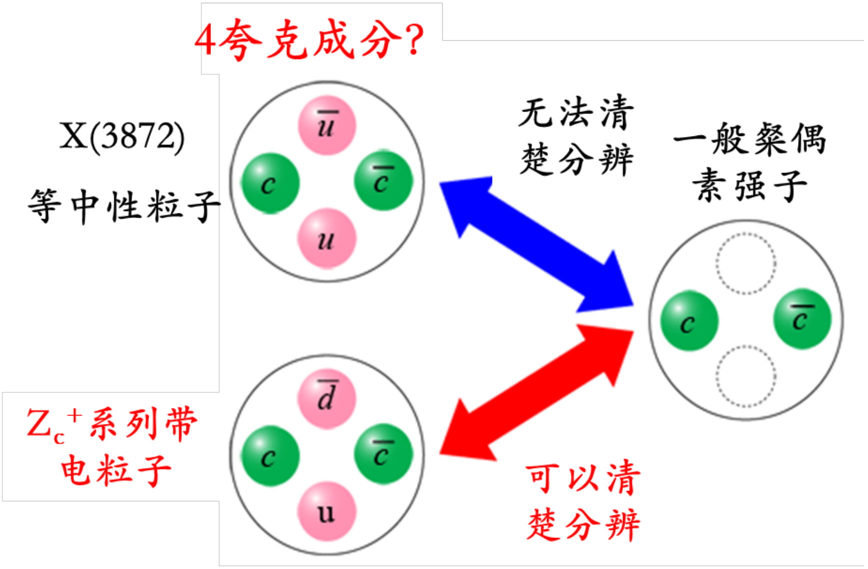
(类)粲偶素能谱





Overpopulated observed new charmonium-like states, i.e. “XYZ”.

四夸克物质的实验确认关键

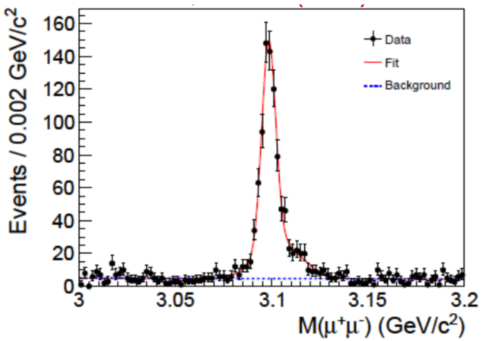


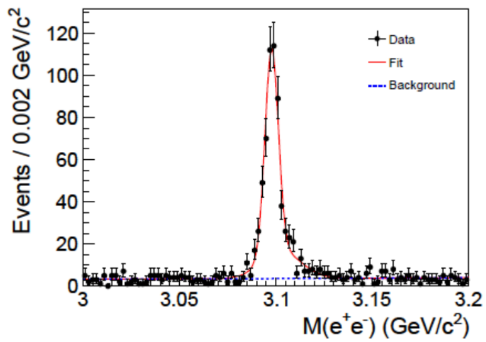
- 确认关键
  质量很重：含重夸克成份
  携带电荷：确定夸克成份
  - 2008年Belle发现带电的类粲偶素粒子：Z(4430)，Z(4250), Z(4050)
    - 未被BaBar实验证实
    - 2014年4月Z(4430)被LHCb证实
  - 2013年3月BESIII/Belle在$J/\psi\pi^{\pm}$末态中发现带电的类粲偶素粒子$Z_c^{\pm}$(3900)，随后被CLEO-c实验证实：首个被验证的类粲偶素四夸克物质
  - 2013年7月在一对激发的粲介子末态 $(D^*\bar{D}^*)^{\pm}$ 中观测到$Z_c^{\pm}$(4025), 可能是Zc(3900)的激发态

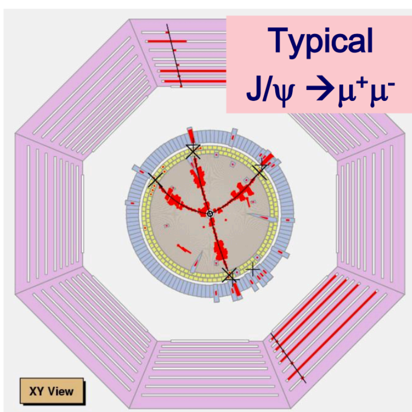
实验上发现Zc(3900)

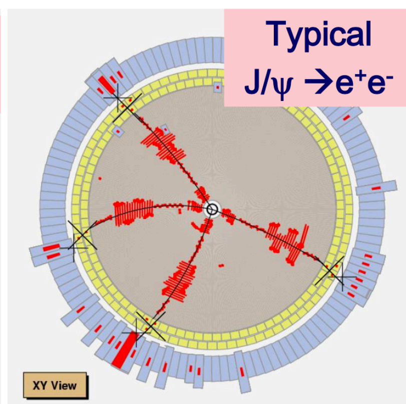
$e^+e^- \to \pi^+\pi^- J/\psi$ at 4.26 GeV

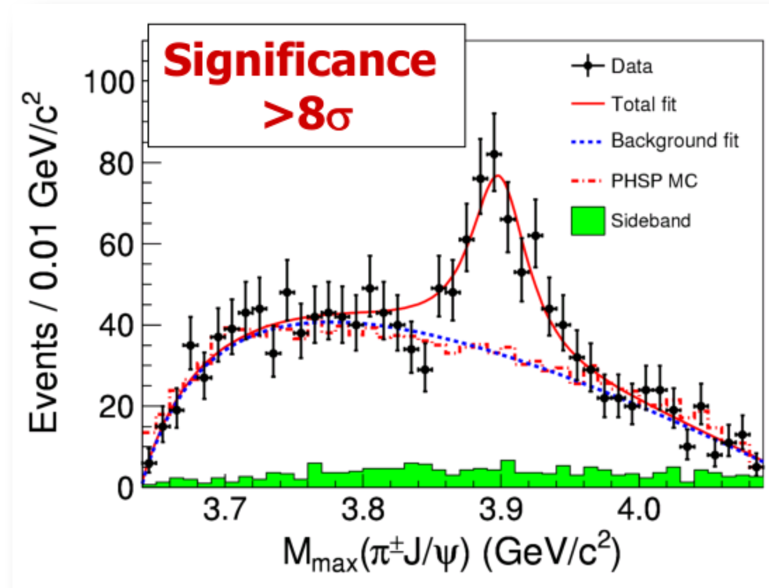
PRL110, 252001 (2013)



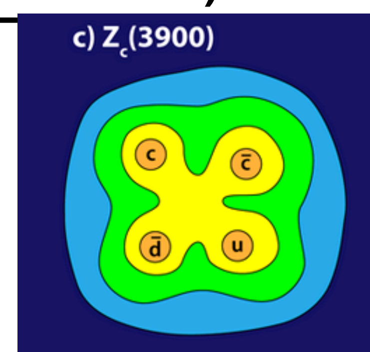








Mass = (3899.0±3.6±4.9) MeV
Width = (46±10±20) MeV



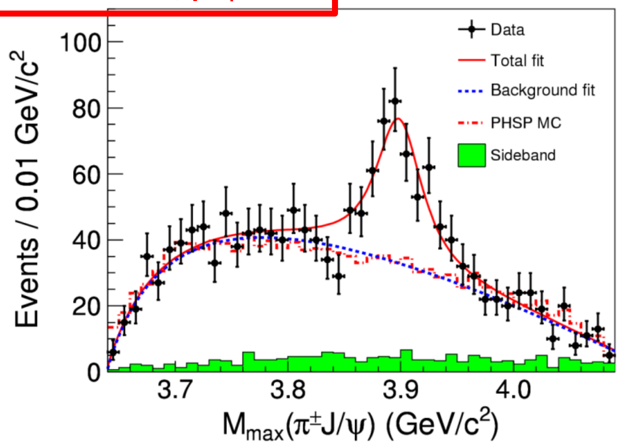
- Couples to $c\bar{c}$
- Has electric charge 1

➔ consists of at least four quarks of $c\bar{c}u\bar{d}$

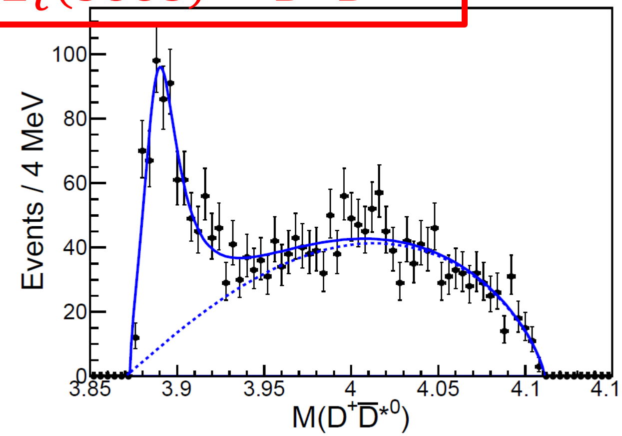
confirmed by BELLE and with CLEO-c data

BESIII实验上发现的系列带电Z_c

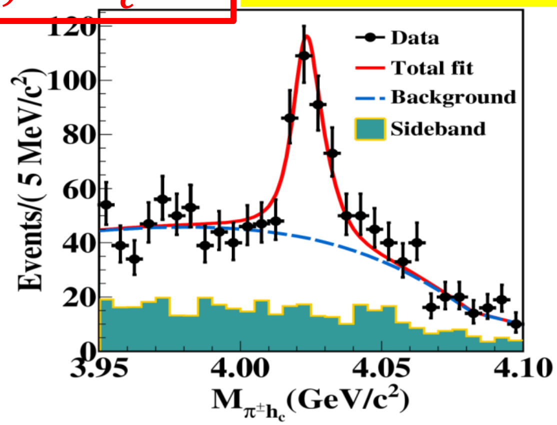
$Z_c(3900) \to J/\psi\pi^+$ PRL 110, 252001 (2013)



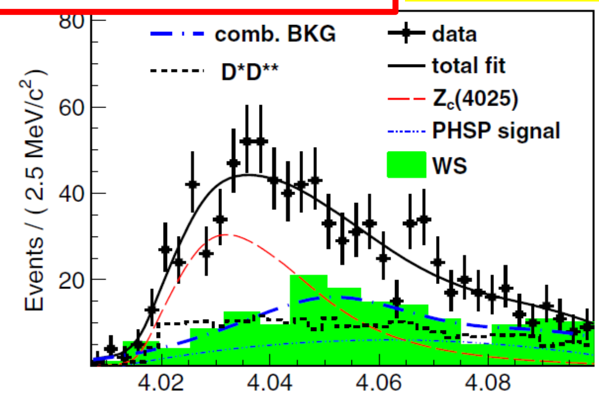
$Z_c(3885) \to D^+\bar{D}^{*0}$ PRL 111, 242001(2013)



$Z_c(4020) \to h_c\pi^+$ PRL 112, 022001(2014)



$Z_c(4025) \to D^{*+}\bar{D}^{*0}$ PRL 112, 132001 (2014)

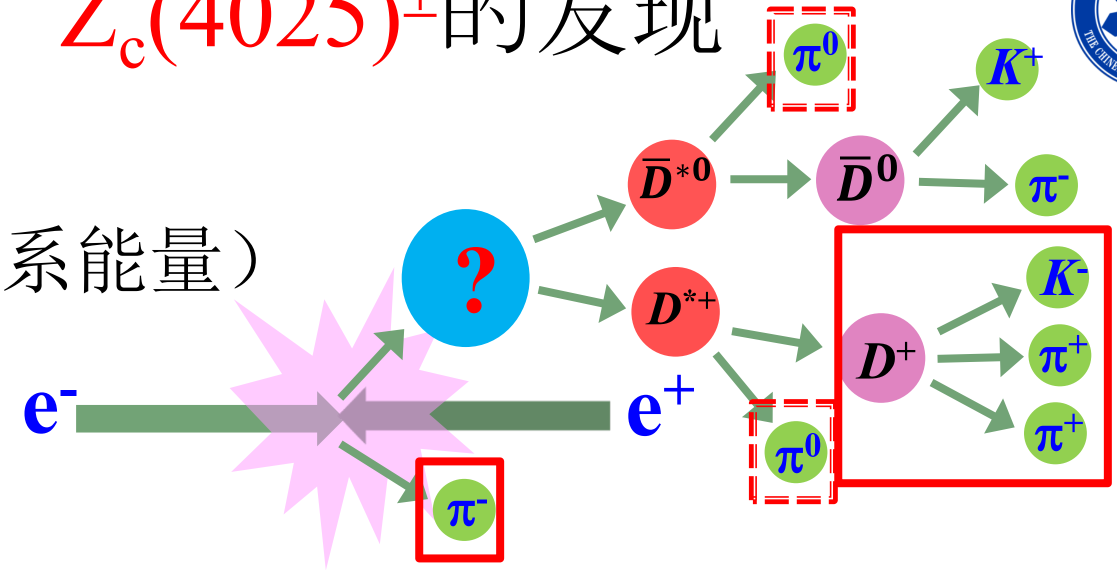


- 在测量误差范围内：Zc(3900)与Zc(3885)有可能是同一个态；Zc(4020)与Zc(4025)有可能是同一个态
- Zc(4020)/Zc(4025)很可能是Zc(3900)/Zc(3885)的激发态！

实验挑战：$Z_c(4025)^{\pm}$的发现

- $e^+e^- \to \bar{D}^{*0} D^{*+} \pi^-$

  （4260MeV对撞质心系能量）



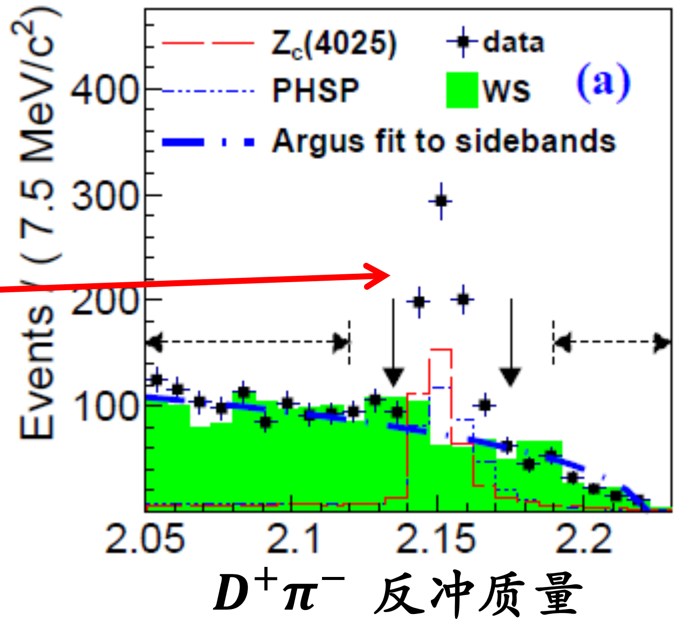
- 实验难点（一）
  - 四夸克结构产生几率小 ⇒ 相对本底高
  - 末态粒子数目众多 ⇒ 探测器接收几率小
  - 粒子种类多 ⇒ 实验辨认与分析非常困难

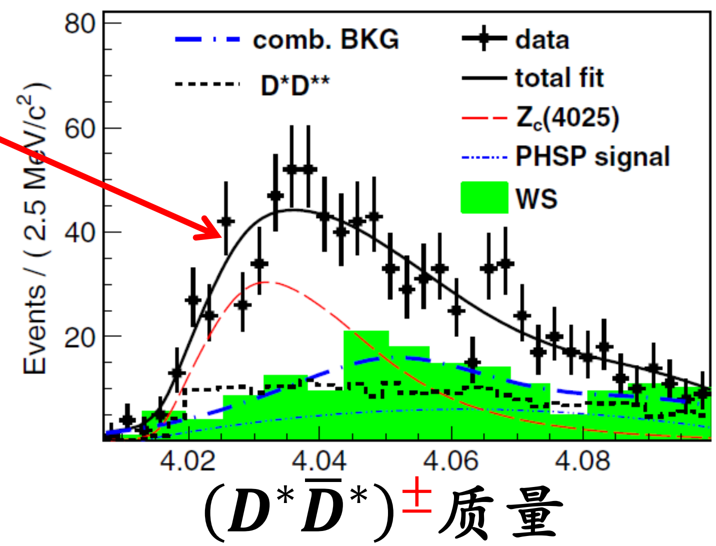
  ⇒ 常规信号重建方法效率极低

- 解决方案：
  - 正负电子对撞，质心系能、动量已知的优势 ⇒ 部分重建技术 ⇒ 重建效率提高了接近两个量级

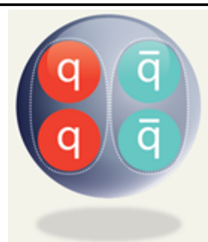
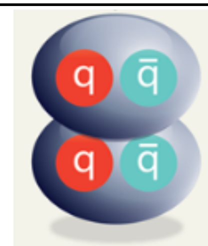
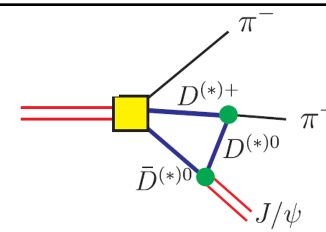
实验挑战：$Z_c^{\pm}(4025)$的发现

- 使用部分重建方法
  - 观测到了清晰的 $e^+e^-\to\bar{D}^{*0}D^{*+}\pi^-$ 信号
  - 在$\bar{D}^{*0}D^{*+}$的质量谱上观测到了一个明显的超出结构
- 实验难点（二）
  - 对出超结构本底的理解
- 解决方案：
  - 数据驱动本底分析技术
    ⇒ 各种本底均无法解释出超结构





四夸克物质发现的意义

四夸克结构Z_c的理论解释：		
四夸克强子	$D^{(*)}\bar{D}^*$分子态	阈效应、散射共振或末态相互作用等
		
四个夸克：均匀分布	两个粲介子束缚	介子间的散射，不是真实的基本粒子
类比于3夸克强子：中子、质子、N*等	类比于氘核（中子+质子 通过核力束缚）	

- 对于理解Z_c内部夸克结构 非常关键！
- 理论： $Z_c^{\pm}$到$D^{(*)}\bar{D}^*$末态的发现 ⇒ 倾向于分子态解释

（相关文献：EPJ.C73 (2013) 2635; EPJ. C73 (2013) 2561; PRD89 (2014) 034001等）

- 为发展与完善低能QCD理论提供了重要实验依据！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Mögliche neue Mat
Teilchen
Von Holger D
Fotos
Es ist viermal so schwer wie ein Pr
Beschleunigern nachgewiesenes Tei
Quarks bestehen - das wäre ein Novu
livescien
TRENDING: Hurricane Season 2013
New 'Char
Rare Stat
Clara Moskowitz, LiveS
3 Share
13 Tweet
16
1 Share
PLAY VIDEO
The Beijing Spectrometer Experiment
that may contain four quarks. The same par
the Belle experiment in Japan, with both projects
Credit: Institute of High Energy Physics (IHEP), Beijing
A new type of particle may have shown up i
accelerators, physicists say. The particle, ma
ingredients of protons and neutrons), appe
matter previously unknown.
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3sat.de Homepage Mediathek Sendung: nano Video: Rätselhaftes Partikel
Video: nano
Bericht vom Donnerstag, 20. Juni 2013
c) $Z_c(3900)$
Rätselhaftes Partikel
Menge der Quarks könnte die Ladung erklären: Physiker haben das neue Teilchen "Z(3900)" entdeckt. Das Besondere: Im Gegensatz zu anderen Teilchen besteht es vermutlich aus zwei Quarks und zwei Antiquarks.
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入选2013年物理学领域重要成果

- 美国物理学会"物理"杂志公布2013年国际物理学领域十一项重要成果，"发现四夸克物质"位列榜首！

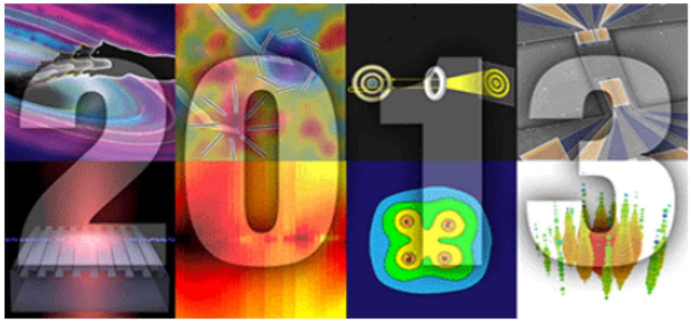
Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

Physics **looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas



Images from popular *Physics* stories in 2013.

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.

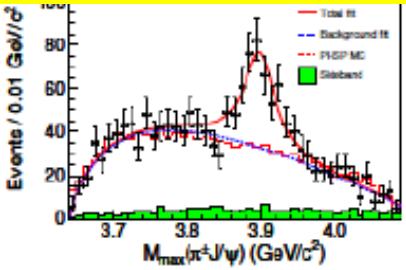
Strangers from Beyond our Solar System

Detector experiments hunting for rare events can go years and never see anything out of the ordinary. So it was cause for excitement when IceCube, a giant neutrino telescope at the South Pole, reported the detection of two neutrinos with energies of around 1000

BESIII实验上的Zc家族

Zc(3900)$^+$

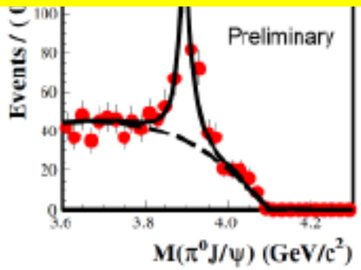
PRL 110, 252001 (2013)



$e^+e^- \to \pi^-\pi^+J/\psi$

Zc(3900)^0

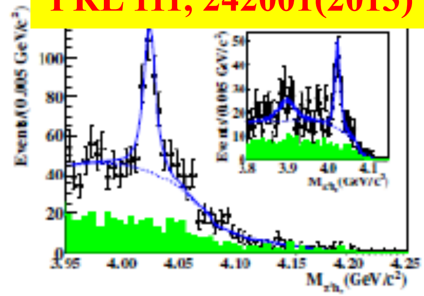
PRL 115, 112003 (2015)



$e^+e^- \to \pi^0\pi^0J/\psi$

Zc(4020)$^+$

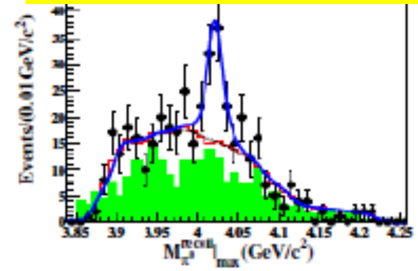
PRL 111, 242001(2013)



$e^+e^- \to \pi^-\pi^+h_c$

Zc(4020)^0

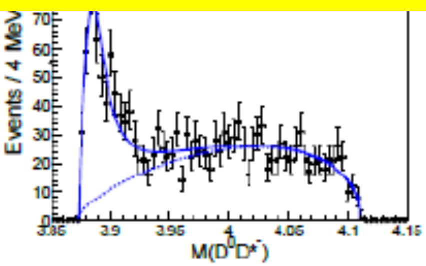
PRL113,212002 (2014)



$e^+e^- \to \pi^0\pi^0h_c$

Zc(3885)$^+$

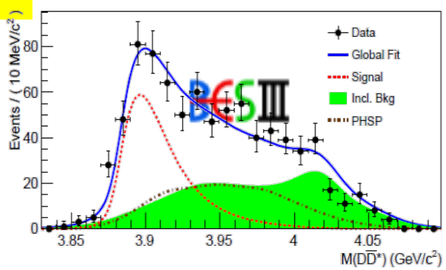
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



$e^+e^- \to \pi^-(D\bar{D}^*)^+$

Zc(3885)^0

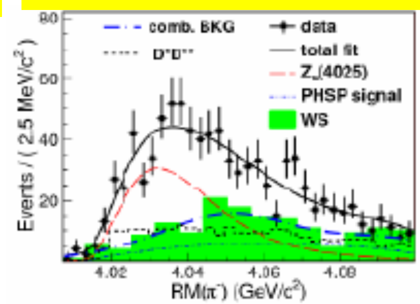
PRL 115, 222002 (2015)



✦$e^+e^- \to \pi^0(D^*\bar{D})^0$

Zc(4025)$^+$

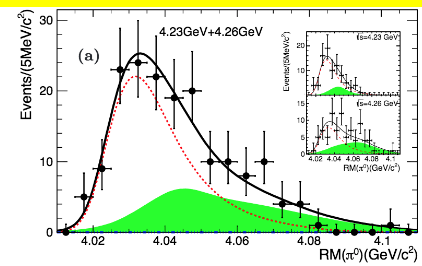
PRL 112, 132001 (2014)



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

Zc(4025)^0

PRL115, 182002 (2015)



✦$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

✦**Which is the nature of these states?**

Different decay channels of the same observed states?

Other decay modes?

BESIII实验上的Zc家族

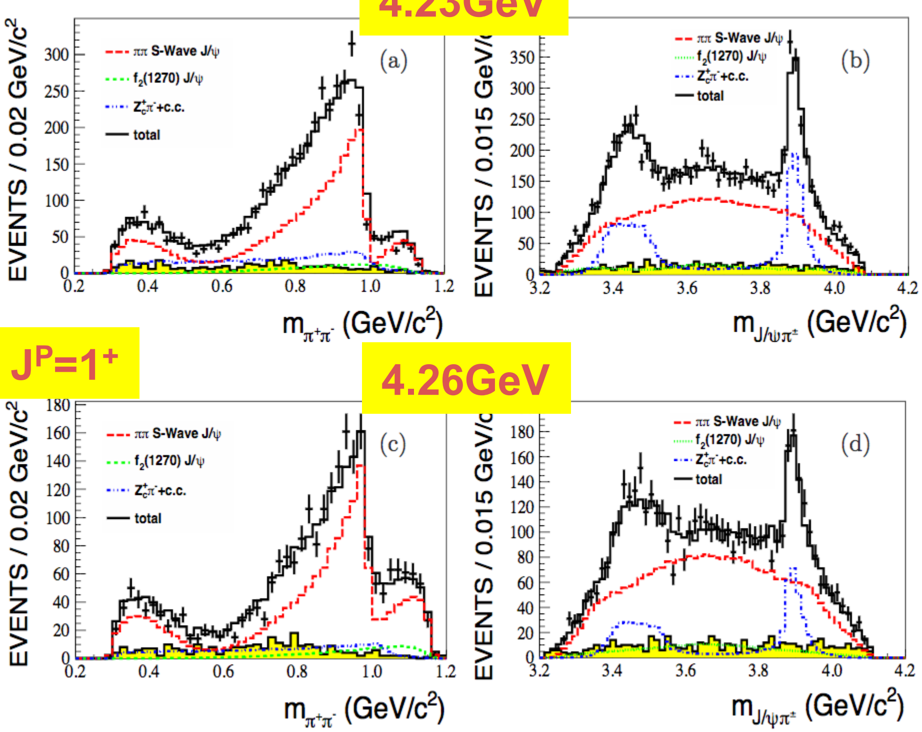
State	Mass (MeV/c²)	Width (MeV)	Decay	Process
$Z_c(3900)^{\pm}$	$3899.0\pm3.6\pm4.9$	$46\pm10\pm20$	$\pi^{\pm}J/\psi$	$e^+e^-\to\pi^+\pi^-J/\psi$
$Z_c(3900)^0$	$3894.8\pm2.3\pm2.7$	$29.6\pm8.2\pm8.2$	π^0J/ψ	$e^+e^-\to\pi^0\pi^0J/\psi$
$Z_c(3885)^{\pm}$	$3883.9\pm1.5\pm4.2$ Single D tag	$24.8\pm3.3\pm11.0$ Single D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^-\to(D\bar{D}^*)^{\pm}\pi^{\mp}$
	$3881.7\pm1.6\pm2.1$ Double D tag	$26.6\pm2.0\pm2.3$ Double D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^-\to(D\bar{D}^*)^{\pm}\pi^{\mp}$
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7}\pm8.4$	$35^{+11}_{-12}\pm15$	$(D\bar{D}^*)^0$	$e^+e^-\to(D\bar{D}^*)^0\pi^0$
$Z_c(4020)^{\pm}$	$4022.9\pm0.8\pm2.7$	$7.9\pm2.7\pm2.6$	$\pi^{\pm}h_c$	$e^+e^-\to\pi^+\pi^-h_c$
$Z_c(4020)^0$	$4023.9\pm2.2\pm3.8$	fixed	π^0h_c	$e^+e^-\to\pi^0\pi^0h_c$
$Z_c(4025)^{\pm}$	$4026.3\pm2.6\pm3.7$	$24.8\pm5.6\pm7.7$	$D^*\bar{D}^*$	$e^+e^-\to(D^*\bar{D}^*)^{\pm}\pi^{\mp}$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7}\pm3.1$	$23.0\pm6.0\pm1.0$	$D^*\bar{D}^*$	$e^+e^-\to(D^*\bar{D}^*)^0\pi^0$

BESIII Spin-parity determination of the $Z_c^+(3900)$

Amplitude analysis of $e^+e^- \to \pi^+\pi^- J/\psi$

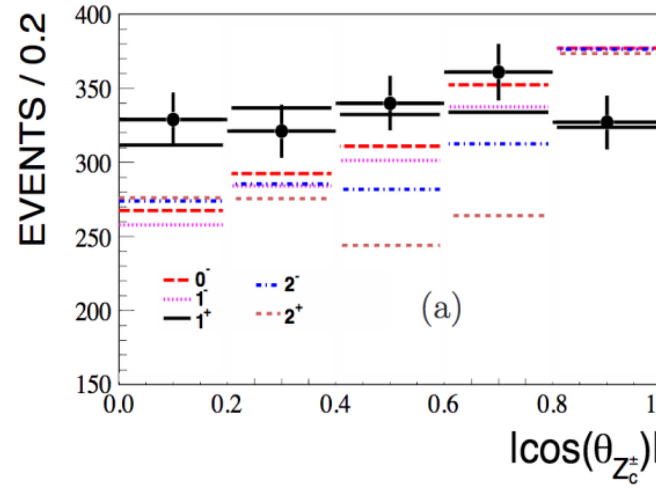
PRL 119.072001 (2017)

4.23GeV



$J^P=1^+$

4.26GeV



J^P is measured to be 1^+ with significance larger than 7.6σ

$$M_{pole} = 3881.2 \pm 4.2 \pm 52.7 \text{ MeV}, \ \Gamma_{pole} = 51.8 \pm 4.6 \pm 36.0 \text{ MeV}$$

- Born cross section for $e^+e^- \to Z_c^+\pi^- + c.c. \to \pi^+\pi^- J/\psi$

  $21.8 \pm 1.0 \pm 4.4$ pb at 4.23 GeV

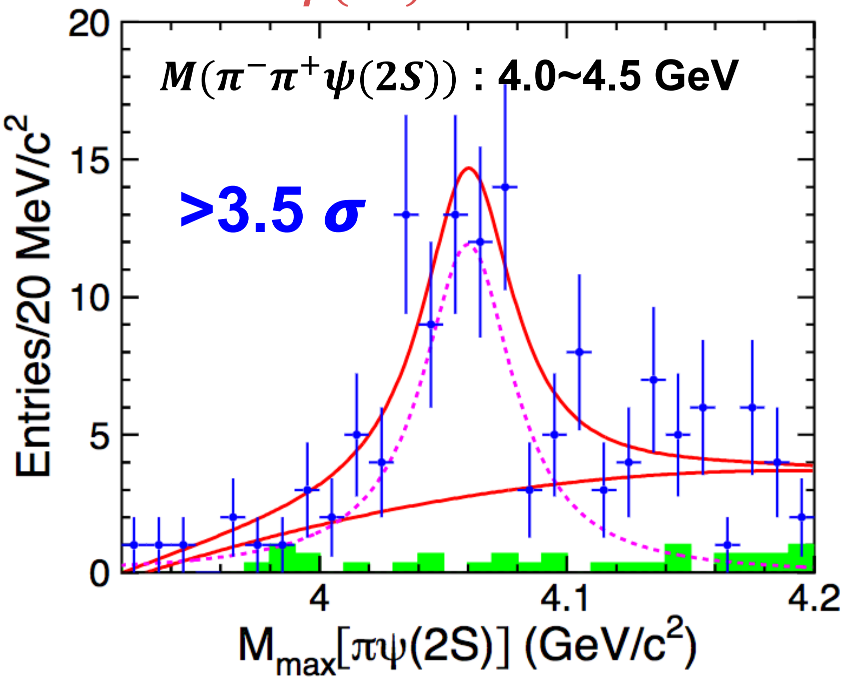
  $11.0 \pm 1.2 \pm 5.4$ pb at 4.26 GeV

$$\frac{\sigma(e^+e^- \to Z_c^+(4020)\ \pi^- + c.c \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to Z_c^+(3900)\ \pi^- + c.c \to \pi^+\pi^- J/\psi)} < 4\% \text{ at 4.23 GeV}$$

$<13\%$ at 4.26 GeV

$Z' \to \pi^+\psi(2S)$ at BESIII

ISR returned productions of $\pi^-\pi^+\psi(2S)$ at Belle

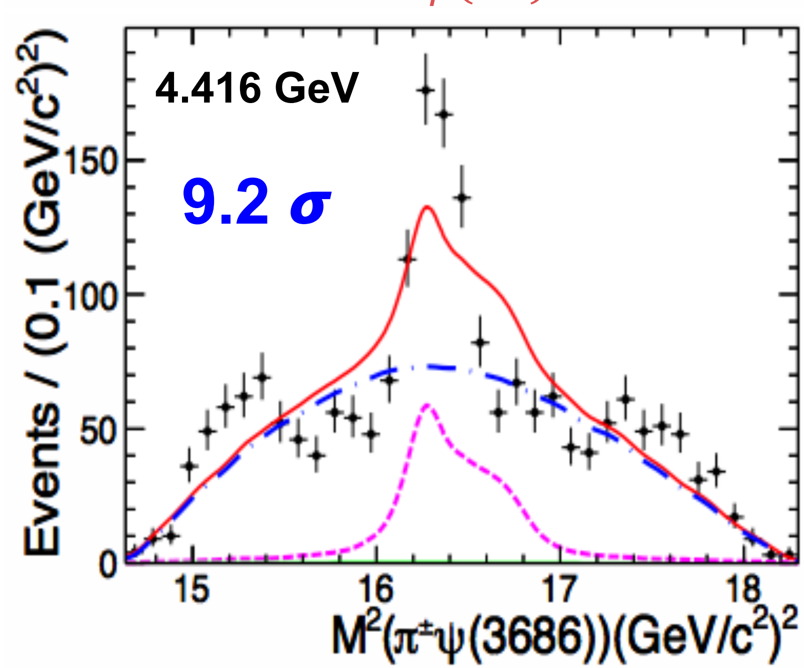


M = (4054±3±1) MeV/c²

Γ = (45±11±6) MeV

Belle, PRD91, 112007 (2015)

The charged structure in $e^+e^- \to \pi^+\pi^-\psi(2S)$ at BESIII



M = (4032.1±2.4) MeV/c²

Γ = (26.1±5.3) MeV

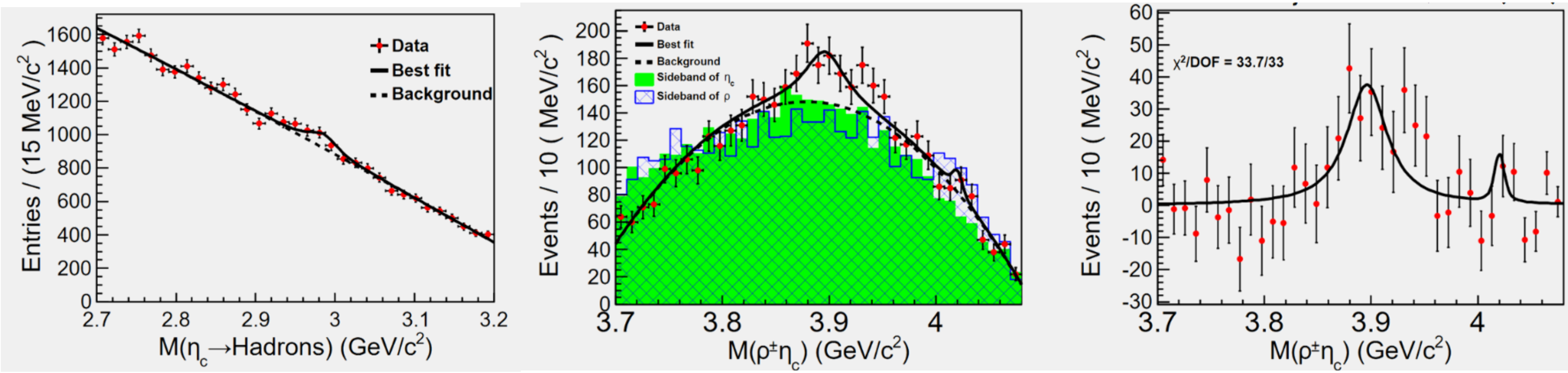
BESIII, PRD96, 032004 (2017)

BESIII's result deviates from that of the structure observed by Belle by over 3σ.

Evidence for $Z_c^{\pm} \rightarrow \rho^{\pm}\eta_c$

process $e^+e^- \rightarrow \eta_c\rho^{\pm}\pi^{\mp}$ studied at five energies between $4.23\ \mathrm{GeV} \leq \sqrt{s} \leq 4.60\ \mathrm{GeV}$

PRD 100, 111102(2019)

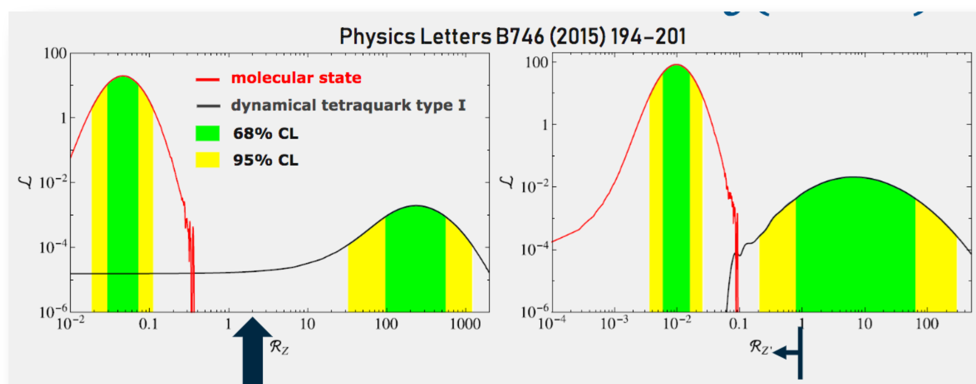


- **Nine decay channel to reconstruct η_c**
- **Strong evidence of $Z_c(3900)^{\pm} \rightarrow \rho^{\pm}\eta_c$ at $\sqrt{s} = 4.23$GeV(4.3σ)**
- **No significant $Z_c'(4020) \rightarrow \rho\eta_c$ observed**

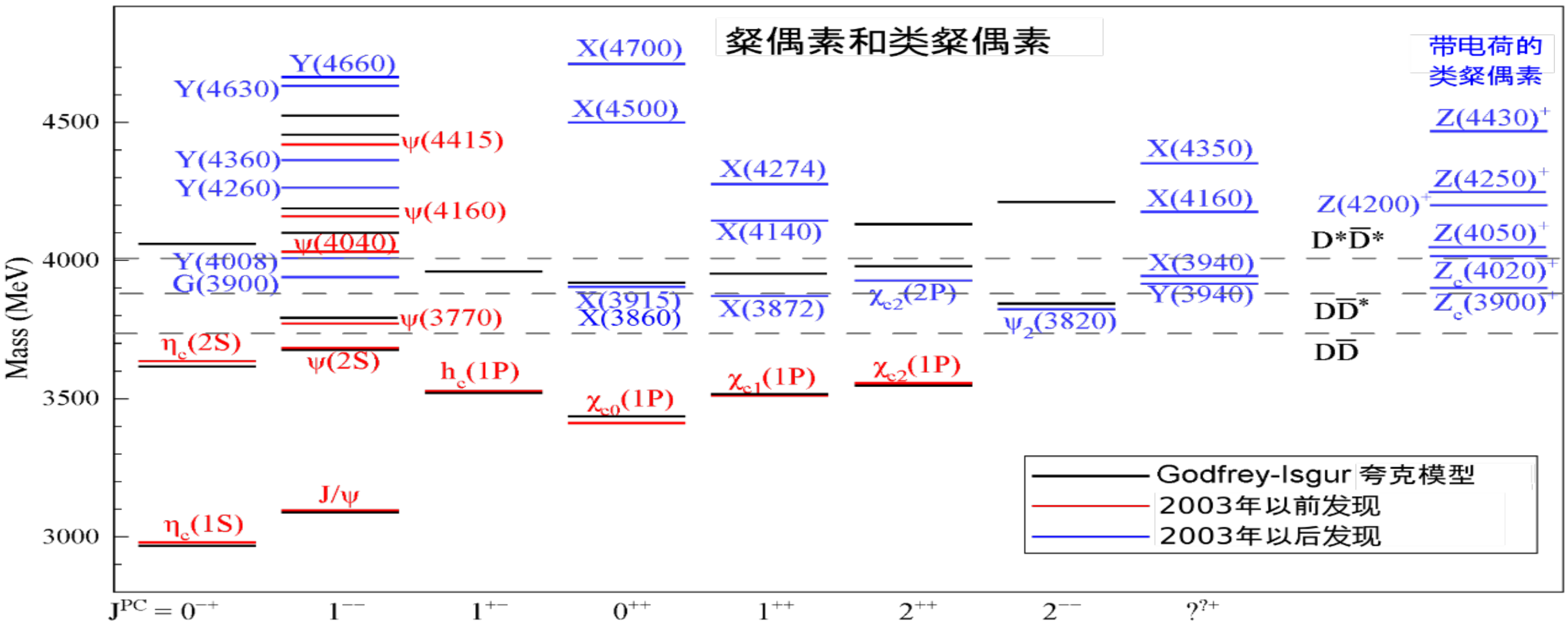
prediction:

$$R_{Z^{(\prime)}} = \frac{Br\left(Z_c^{(\prime)} \rightarrow \rho\eta_c\right)}{Br\left(Z_c^{(\prime)} \rightarrow \pi J/\psi\right)}$$

to discriminate between molecular & tetraquark assignments



更多的四夸克候选态



State	Decay modes	Seen by
$Z_c(3900)^{\pm,0}$	$\pi^{\pm}J/\psi$, $(D^*\bar{D})^{\pm}$	BESIII, Belle CLEO
$Z_c(4020)^{\pm,0}$	$\pi^{\pm}h_c$, $(D^*\bar{D}^*)^{\pm}$	BESIII
$Z_c(4430)^{\pm}$	$\pi^{\pm}\psi(2S)$ $\pi^{\pm}J/\psi$	Belle, BaBar, LHCb

in $e^+e^- \to \pi^- Zc$

in $e^+e^- \to \pi^- Zc$

in $B \to KZc$

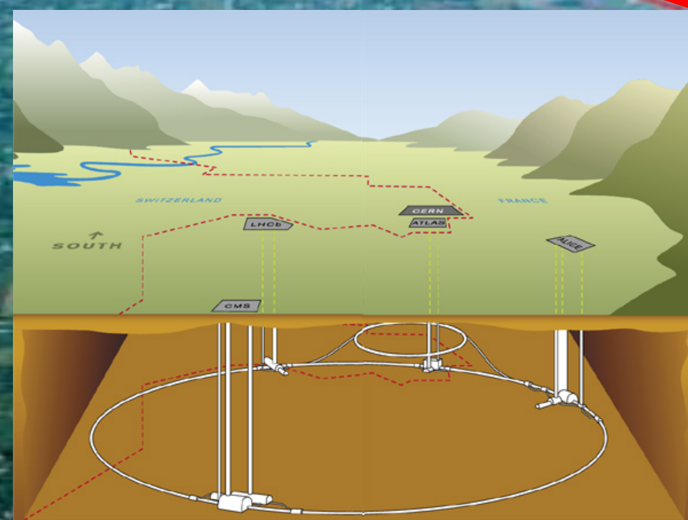
大型强子对撞机(LHC)

- 质子束流能量可达 7 TeV
- 束流对撞频率 40 MHz
- 瞬时亮度可达 $10^{34}\ cm^{-2}s^{-1}$

日内瓦机场

CERN

超导
加速器



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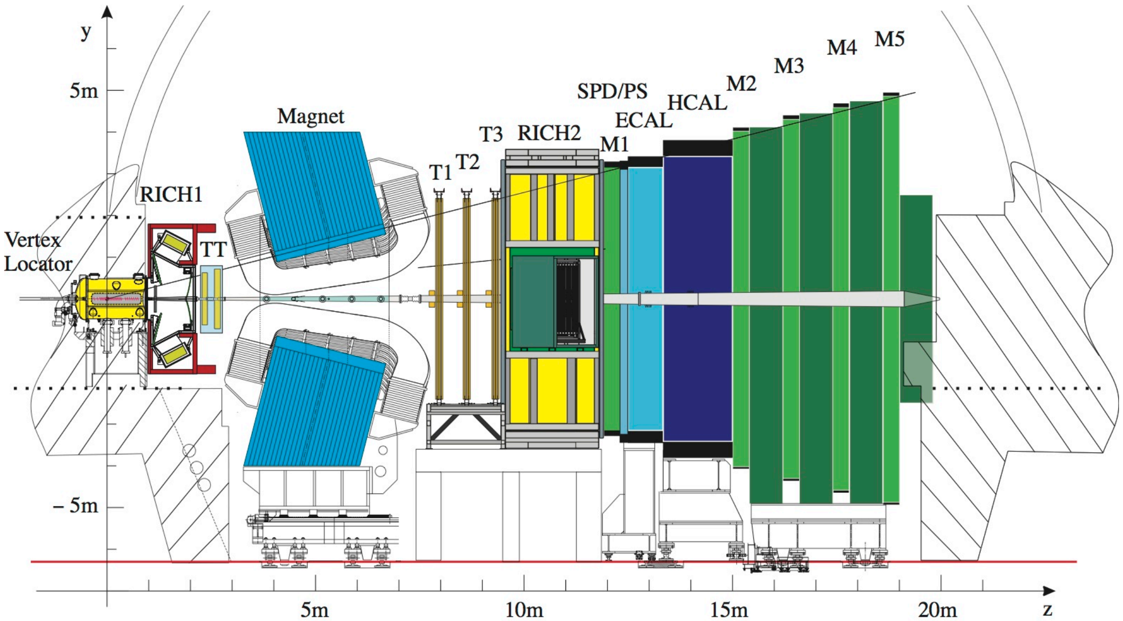
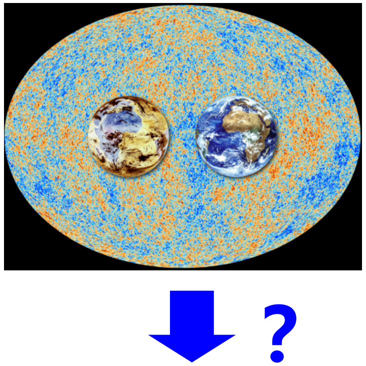
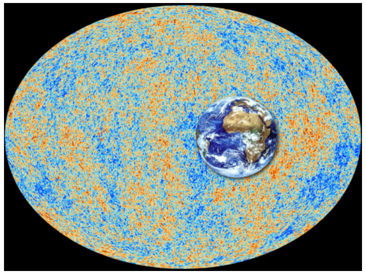
LHCb的主要科学目标

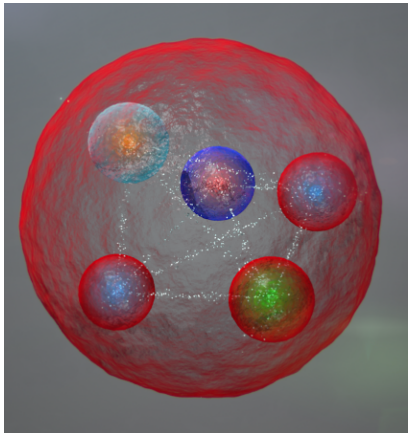




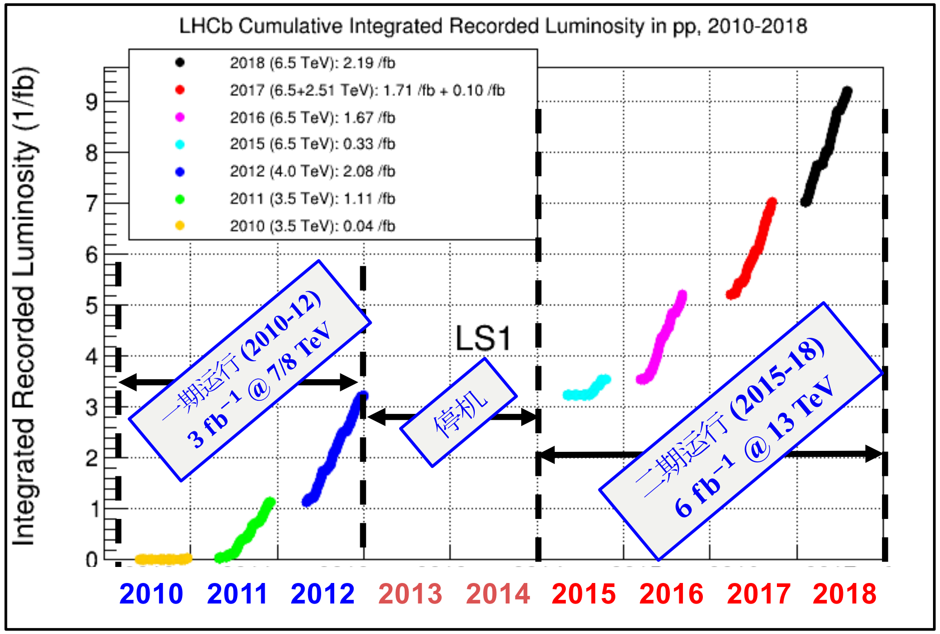


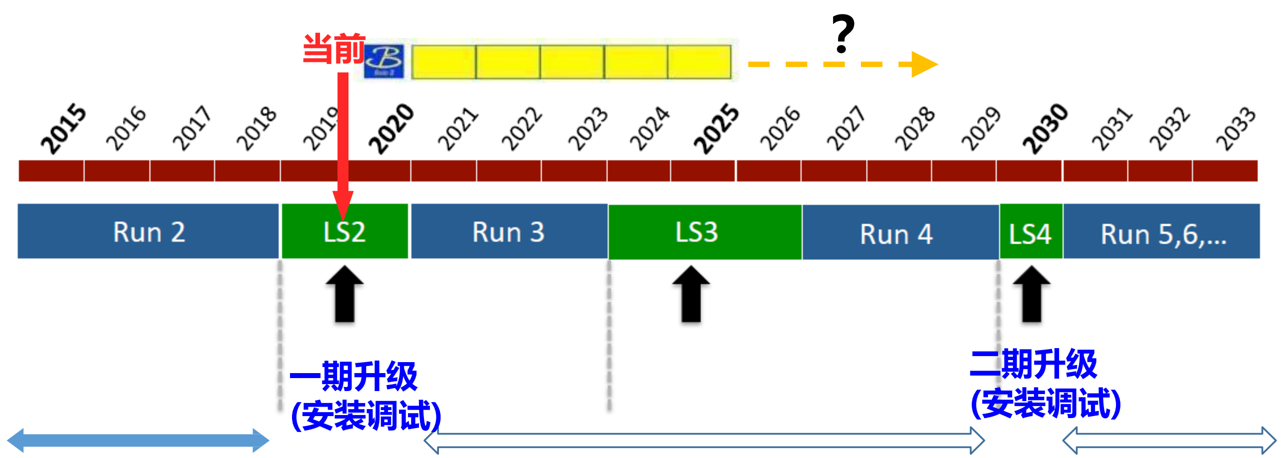
理解正反物质不对称

- **间接寻找新物理：**电荷宇称破坏+稀有衰变
- **理解强相互作用：**强子性质，新强子态
- **其它：**电弱物理，重离子物理，…



数据采集：一期运行+二期运行





$L = 4\times10^{32}\ \mathrm{cm^{-2}s^{-1}}$

已采集9 fb^{-1}

$L = 2\times10^{33}\ \mathrm{cm^{-2}s^{-1}}$

计划采集50 fb^{-1}

$L = 2\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$

计划积累~300 fb^{-1}

LHCb国际合作组

来自18个国家、80多个单位的近1400 名成员

- ✓ 2000年清华大学加入
- ✓ 2013年华中师大加入
- ✓ 2015年国科大加入
- ✓ 2016年武汉大学加入
- ✓ 2018年高能所、华南师大加入
- ✓ 2019年北京大学加入
- ✓ 2020年湖南大学加入

LHCb中国单位8个，共24名教师
单位数在合作组排名4/18

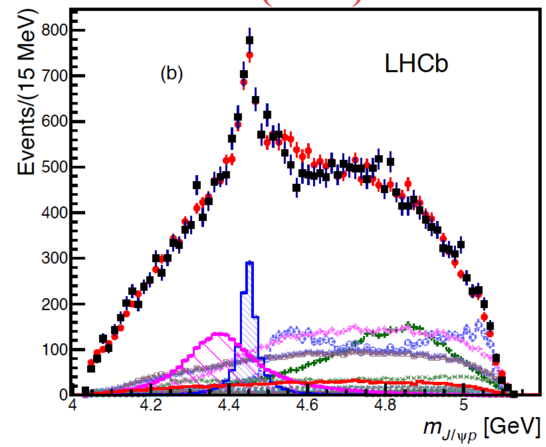
- ✦ 2015年五夸克态P_c发现
- ✦ 2017年发现双粲重子Ξ_{cc}^{++}
- ✦ $B_s^0-\bar{B}_s^0$ 混合相角 ϕ_s精确测量
- ✦ …

五夸克态Pc的发现

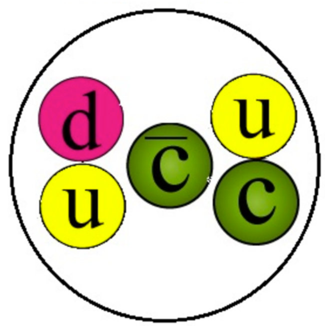
- 2015年LHCb在$\Lambda_b^0 \to J/\psi p K^-$衰变中发现五夸克态：$P_c(4380)^+$和$P_c(4450)^+$

共振态	质量 (MeV)	宽度 (MeV)
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$

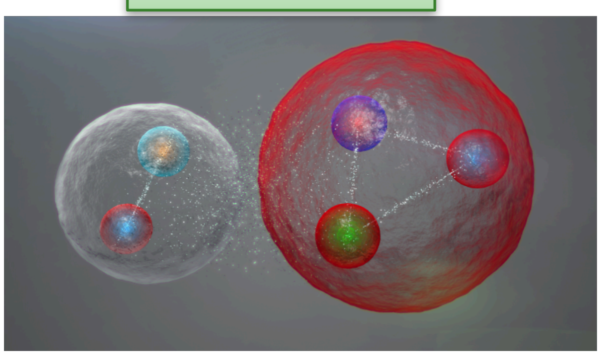
PRL 115 (2015) 072001



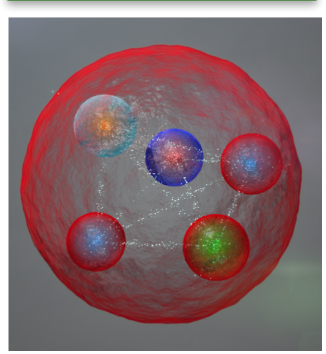
- $J/\psi p$共振态结构
- 内部至少含有5个夸克（$uudc\bar{c}$）



✦强子分子态?

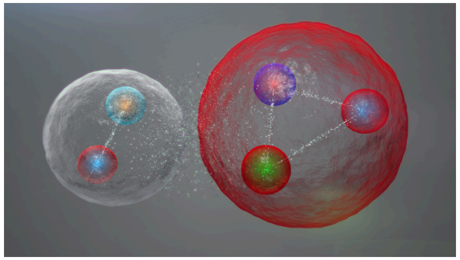


✦紧密束缚态?

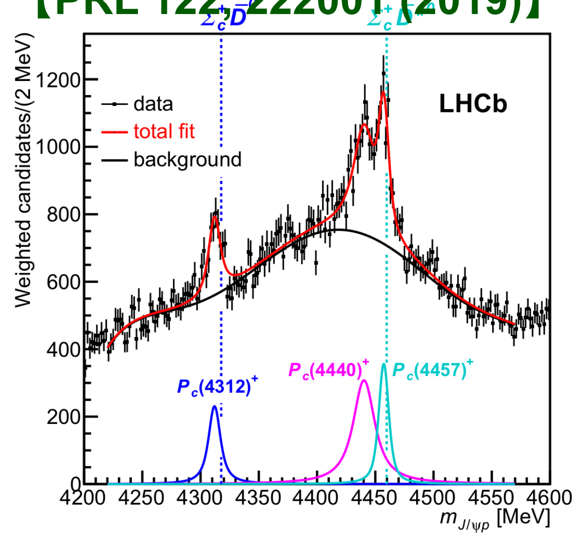


2019年发现新五夸克态

- **10倍统计量，带来了新的惊喜**
  - **接受效率提高1倍(关键一步)**
  - **使用了2015-2018采集数据**
- **发现了新的结构，有助于揭示五夸克态的本质**
  - 这三个五夸克态的宽度都很窄，质量略低于粲重子和反粲介子质量之和，有可能是粲重子和反粲介子形成的束缚态



【PRL 122, 222001 (2019)】



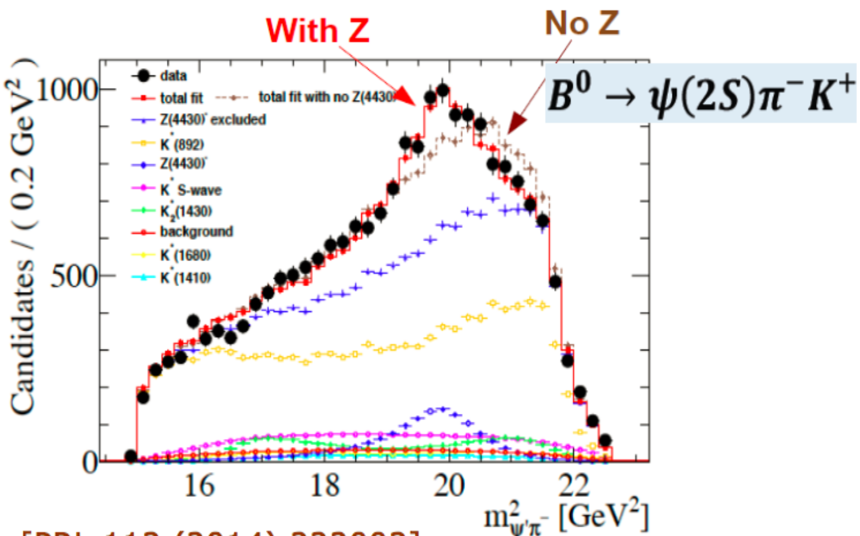
- 被选为**PRL编辑推荐(Editor Suggestion)**
- 美国《物理》杂志**提要推荐 (Viewpoint)**
- 《科学》杂志深度报道

LHCb confirms the Zc(4430)

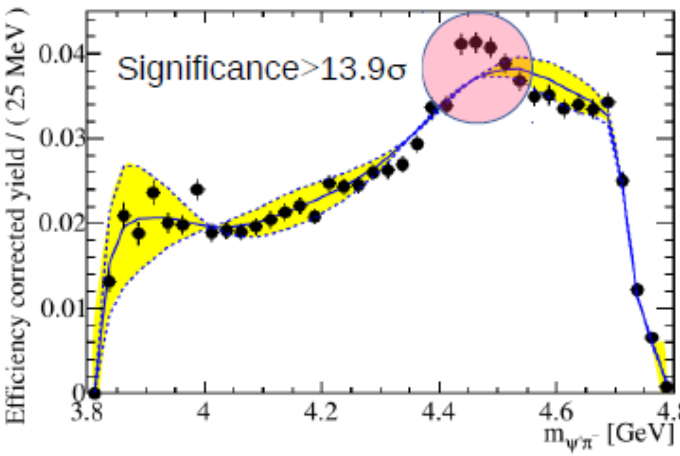
- originally found by Belle in $B \to (Z(4430)^{-} \to J/\psi\ \pi^{-}\ K$ and $B \to (Z(4430)^{-} \to \psi(2S)\ \pi^{-})\ K$

  [PRL 100(2008) 142001, PR D80(2009) 031104, PR D88(2013) 074026]

  → *not confirmed by BaBar* [PR D79 (2009) 112001]



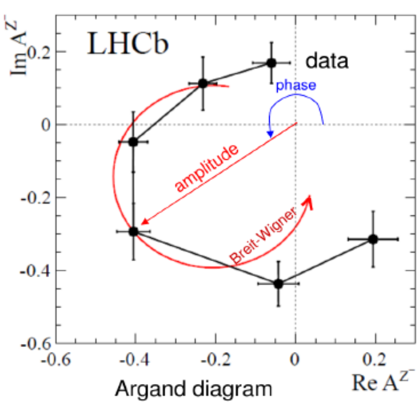
[PRL 112 (2014) 222002]



$M = 4475 \pm 7^{+15}_{-25}$ MeV/c²

$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

$J^P = 1^+$ Measured for the first time



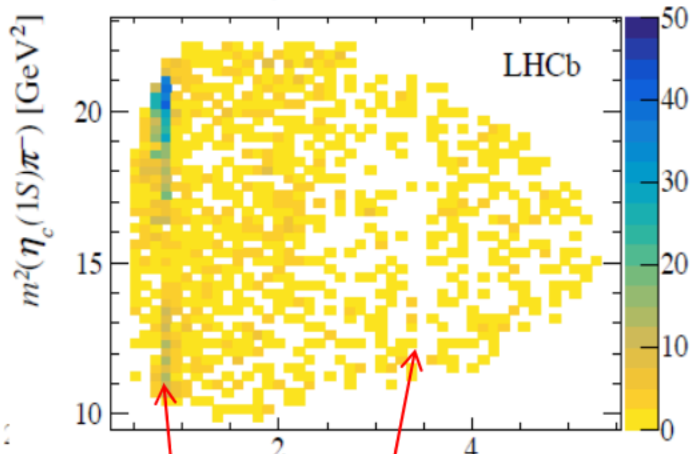
Argand plot indicates a resonance nature of the Zc(4430)

Evidence of $Z_c(4100)^-$ in $B^0 \to \eta_c \pi^- K^+$

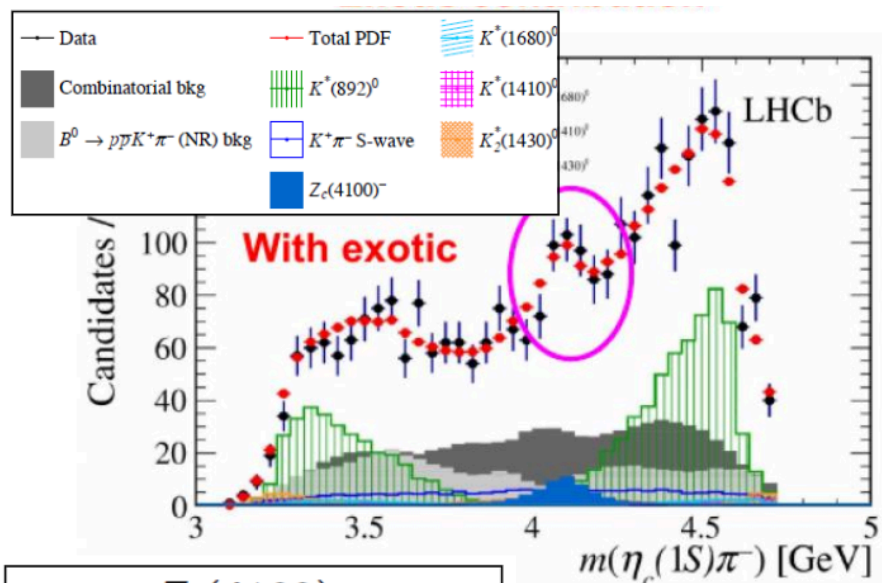
[EPJ C78, 1019 (2018)]

Dalitz plot analysis of $B^0 \to \eta_c K^+ \pi^-$ decays performed where $\eta_c(1S) \to p\bar{p}$

- $\mathcal{L}$ = 4.7 fb^{-1}, 2011-2016 data
- 2D fit to $m(p\bar{p}K^+\pi^-)$ and $m(p\bar{p})$ distribution, N_{sig} = 1870 ± 74
- Dalitz plot dominated by $K^*(892)$ signal



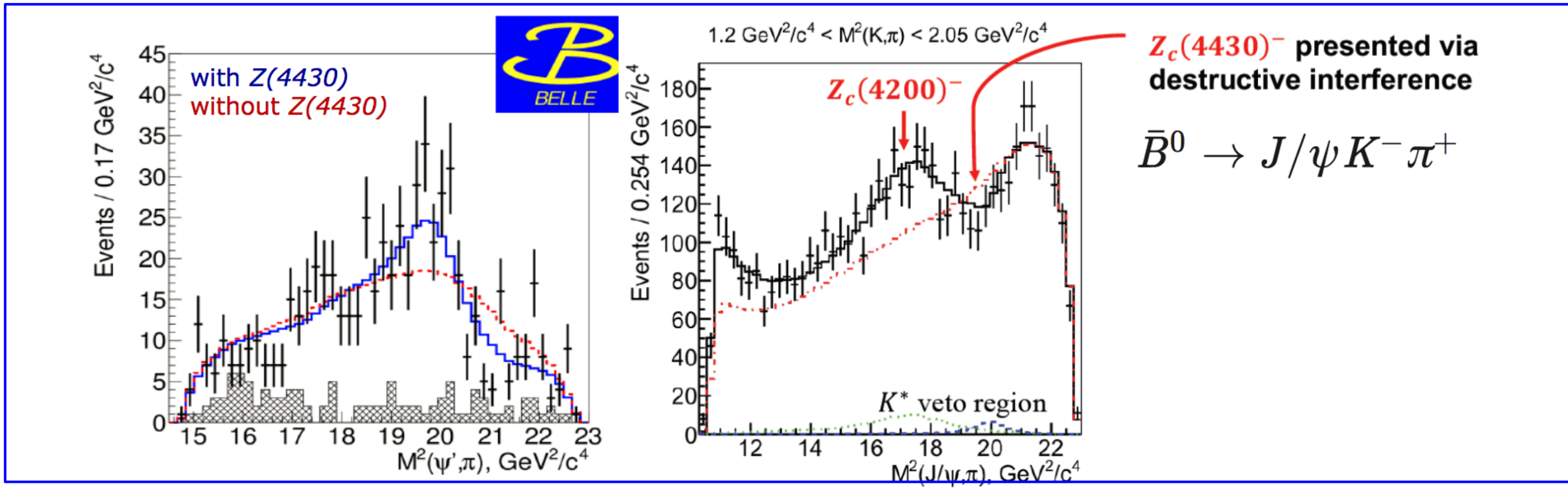
→ 3.4σ significance



$Z_c(4100)^-$
$M = 4096 \pm 20^{+18}_{-22}$ MeV
$\Gamma = 152 \pm 58^{+60}_{-35}$ MeV
$J^P = 0^+/1^-$

Exotic contributions to $B^0 \to J/\psi K^+\pi^-$

- Belle reported another exotic $Z(4200)^-$ in $J/\psi\pi^-$ system [PRD 90 (2014) 112009]

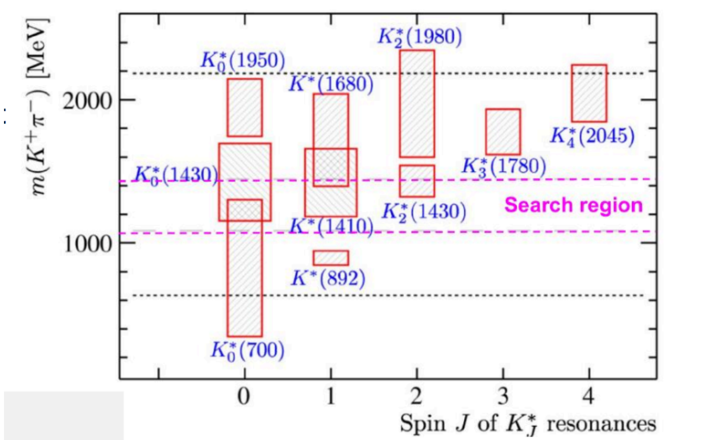


➢ LHCb implemented model-independent amplitude analysis

- $B^0 \to J/\psi K^+\pi^-$ decay dominated by many overlapping K^*_J states

[PRL 122 (2019) 152002]

- Run-1 data, x20 Belle
  → signal yield $B^0 \to J/\psi\ \pi^-\ K^+$ ~5×10^5
- dataset allows for 4D angular analysis in 35 bins of $m(K^+\pi^-)$



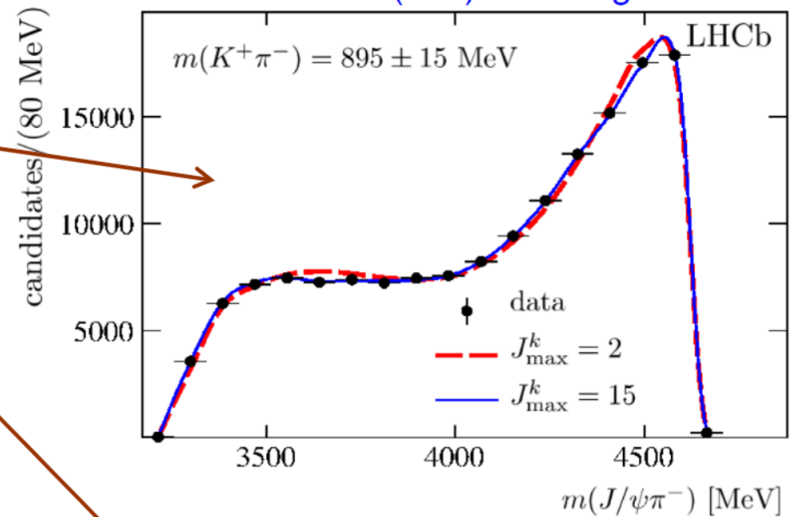
New Zc components needed

[PRL 122 (2019) 152002]

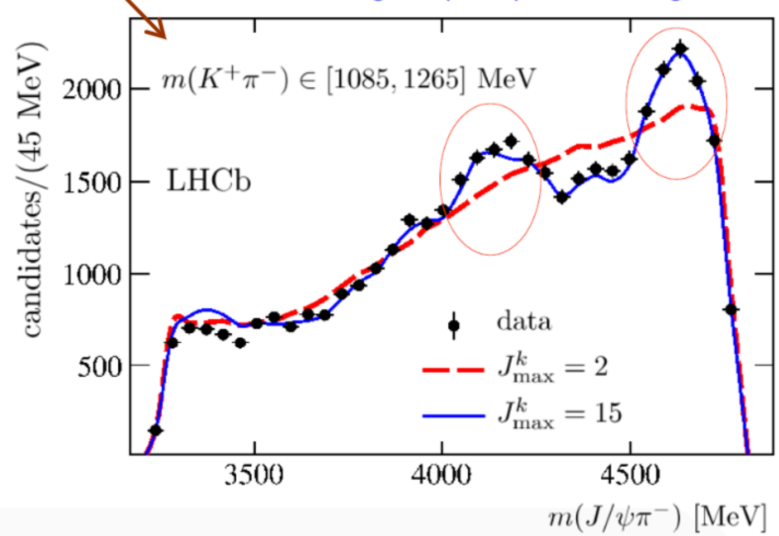
- **data inconsistent with K^*-only contributions by 10σ**
- *K*(892)* region: well described by contributions with J_{max} = 2 only
- *K*(892)* veto: unphysical J_{max} = 15 needed to describe the data

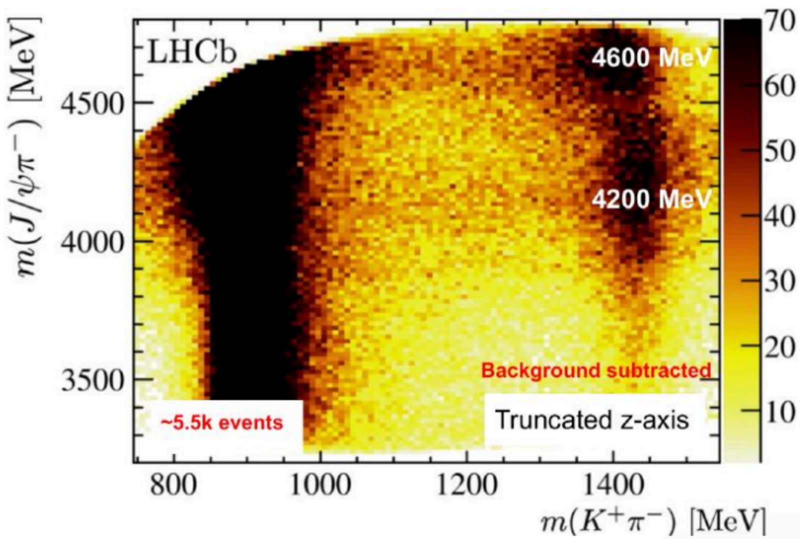
  → *m(J/ψπ) ~ 4200 and 4600 MeV regions*
- model dependent amplitude analysis needed to determine properties of these structures

In the K*(892) mass region



After vetoeing K*(892) mass region

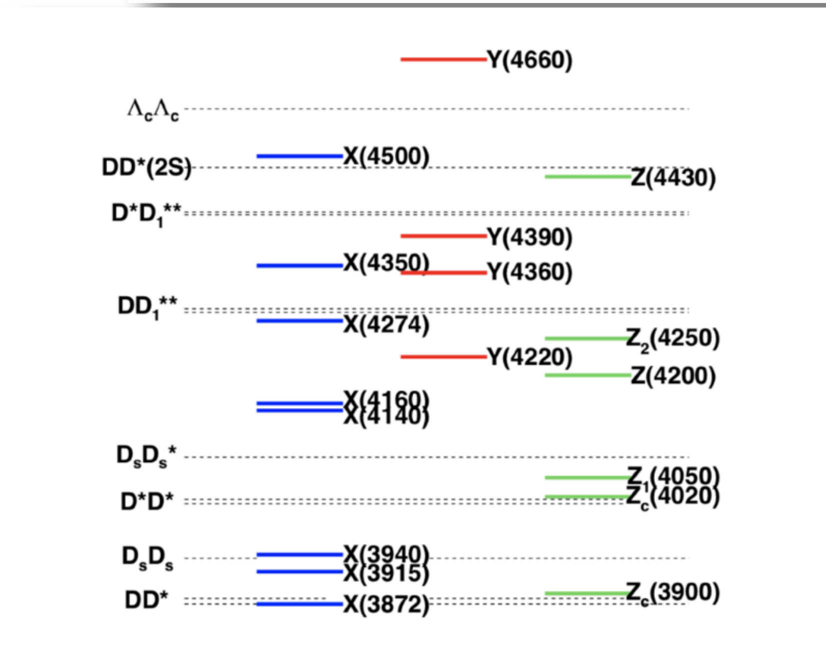




Summary of the reported Zc states

from S. L. Olsen, arXiv:1511.01589, arXiv:1812.10947

$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\, \pi^+)$	BESIII [49], Belle [50]
				$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII [69]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\, \pi^+)$	BESIII [51]
				$Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$	BESIII [52]
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\, \pi^+)$	Belle [53], BaBar [66]
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\, \pi^+)$	Belle [62]
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	$?^{?+}$	$B \to K + (\chi_{c1}\, \pi^+)$	Belle [53], BaBar [66]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi'\, \pi^+)$	Belle [54, 56, 57], LHCb [58]
				$B \to K + (J\psi\, \pi^+)$	Belle [62]



- ✦ Most of them are close to the mass thresholds of charmed meson pairs
- ✦ More efforts are needed to pin down their nature

首次发现全粲四夸克态($c\bar{c}c\bar{c}$)

- Existence of $T_{Q_1Q_2\bar{Q}_3\bar{Q}_4}$ states ($Q_i = c$ or b) is expected by many QCD models
  - Likely compactly bounded since the interaction between heavy quarks is dominantly mediated by short-range gluon exchange
  - Usually described with the attraction of a diquark (Q_1Q_2) and an anti-diquark ($\overline{Q_3Q_4}$)
  - Never observed before

•Proposed as early as 1985 ***from Maiani***

L. Heller and J. A. Tjon, *On Bound States of Heavy $Q^2\bar{Q}^2$ Systems*, Phys. Rev. **D 32**, 755 (1985);
A. V. Berezhnoy, A. V. Luchinsky and A. A. Novoselov, *Tetraquarks Composed of 4 Heavy Quarks*, Phys. Rev. **D 86**, 034004 (2012).

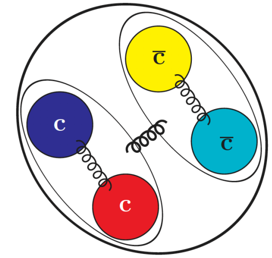
•Widely considered after the observation of doubly heavy baryons together with doubly heavy tetraquarks

W.Chen, H.X.Chen, X.Liu, T.G.Steele and S.L.Zhu, Phys. Lett. **B 773**, 247 (2017); Y.Bai, S.Lu and J.Osborne, arXiv:1612.00012 [hep-ph]; Z.G.Wang, Eur. Phys. J. **C 77**, 432 (2017); M.Karliner, S.Nussinov and J.L.Rosner, Phys. Rev. **D 95**, 034011 (2017); J.M.Richard, A.Valcarce and J.Vijande, Phys. Rev. **D 95**, 054019 (2017); J.Wu, Y.R.Liu, K.Chen, X.Liu and S.L.Zhu, Phys. Rev. **D 97**, 094015 (2018); M.N.Anwar, J.Ferretti, F.K.Guo, E.Santopinto and B.S.Zou, Eur. Phys. J. **C 78**, 647 (2018); A.Esposito and A.D.Polosa, Eur. Phys. J. **C 78** , 782 (2018); M.A.Bedolla, J.Ferretti, C.D.Roberts and E.Santopinto, arXiv:1911.00960 [hep-ph].

- $T_{bb\bar{b}\bar{b}}$ was not searched for at LHCb and CMS, but not observed
- $T_{cc\bar{c}\bar{c}}$ states predicted to have $M \in [5.8, 7.4]$ GeV$/c$, away from known quarkonia and quarkonium-like exotic states

Prompt J/ψ pair production

- Using J/ψ pair final states to reconstruct $T_{cc\bar{c}\bar{c}}$
  $J/\psi \to \mu^+\mu^-$ has good trigger efficiency



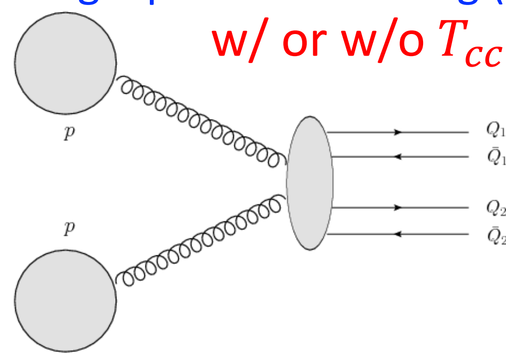
[arXiv: 1803.02522]

J^{PC}	S-wave	P-wave
0^{++}	$\eta_c(1S)\eta_c(1S)$, $J/\psi J/\psi$	$\eta_c(1S)\chi_{c1}(1P)$, $J/\psi h_c(1P)$
0^{-+}	$\eta_c(1S)\chi_{c0}(1P)$, $J/\psi h_c(1P)$	$J/\psi J/\psi$
0^{--}	$J/\psi\chi_{c1}(1P)$	$J/\psi\eta_c(1S)$
1^{++}	–	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$, $\eta_c(1S)\chi_{c0}(1P)$
1^{+-}	$J/\psi\eta_c(1S)$	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$
1^{-+}	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$	–
1^{--}	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$	$J/\psi\eta_c(1S)$

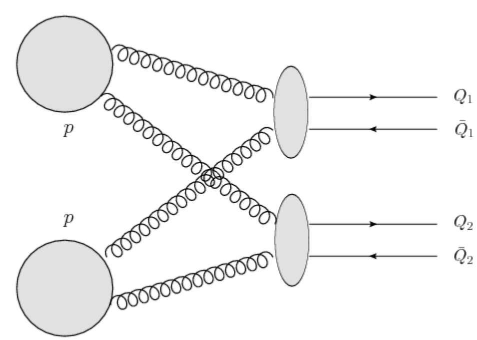
Decays in $2J/\psi$ directly or with feed-down

Single parton scattering (SPS)

w/ or w/o $T_{cc\bar{c}\bar{c}}$



Double parton scatterings (DPS)

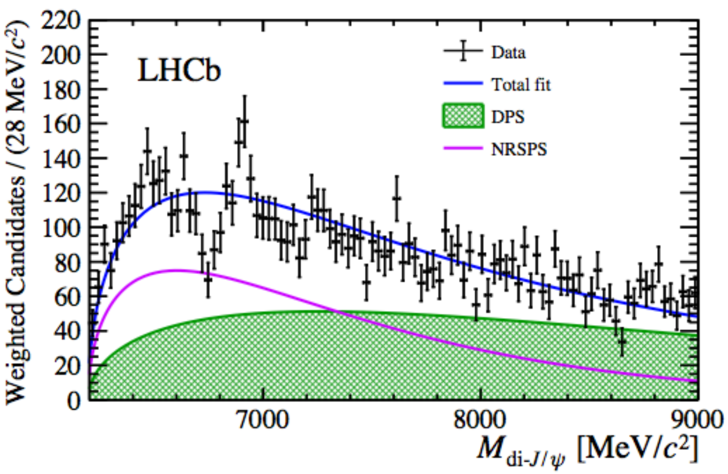


- $T_{cc\bar{c}\bar{c}}$ state production via SPS is dominant over DPS
- DPS: dominates high J/ψ pair mass region

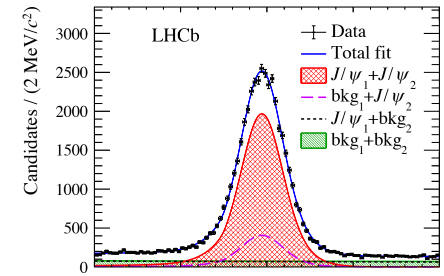
J/ψ-pair mass spectrum

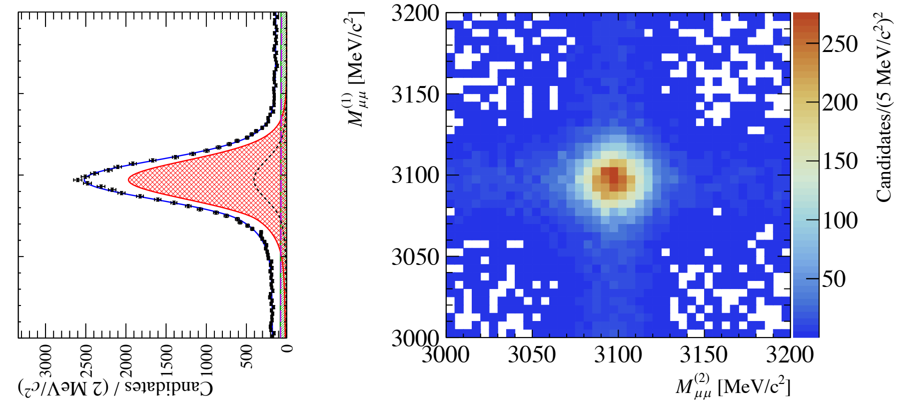
arXiv:2006.16957

- Full Run1+Run2 LHCb data corresponding to 9 fb^{-1}
- J/ψ candidates reconstructed using the $J/\psi \to \mu^+\mu^-$ decay
- SPS enhanced sample with J/ψ-pair $p_T > 5.2$ GeV$/c$



$N(J/\psi\ \text{pair}) = (33.57 \pm 0.23)\times 10^3$





- The J/ψ-pair invariant mass spectrum is inconsistent with non-resonant SPS and DPS only hypothesis by more than 5σ in the [6.2,7.4] GeV/c^2 mass region
  - ✓ A broad structure next to threshold ranging from 6.2 to 6.8 GeV$/c^2$
  - ✓ A narrower structure at about 6.9 GeV$/c^2$ ➔ X(6900)
- A narrow peaking structure matching the lineshape of a resonance and a broader structure close to the threshold are fitted in two scenarios

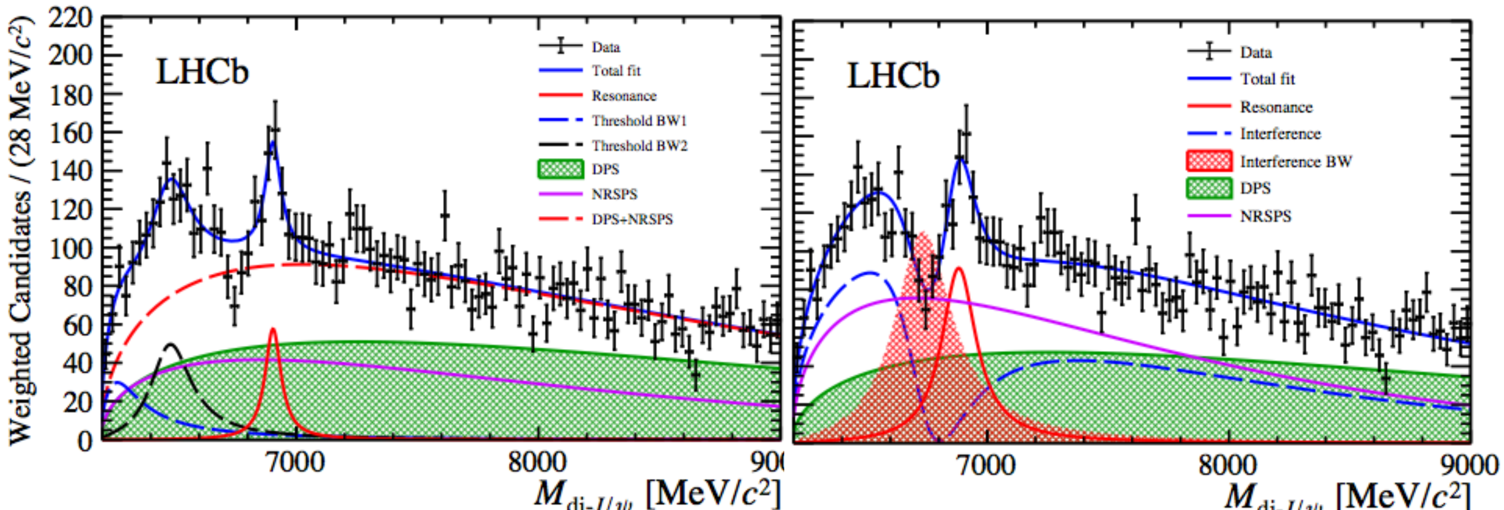
The obtained X(6900)

- Assuming X(6900) is a resonance with Breit-Wigner lineshape:
  - ✓ Model I: Based on no-interference fit (worse fitting quality) *arXiv:2006.16957*

    $$M[\mathrm{X(6900)}] = 6905 \pm 11(\mathrm{stat}) \pm 7(\mathrm{syst})\ \mathrm{MeV}/c^2$$
    $$\Gamma[\mathrm{X(6900)}] = 80 \pm 19(\mathrm{stat}) \pm 33(\mathrm{syst})\ \mathrm{MeV}/c^2$$
  - ✓ Model II:Based on the simple model with interference (better fitting quality)

    $$M[\mathrm{X(6900)}] = 6886 \pm 11(\mathrm{stat}) \pm 11(\mathrm{syst})\ \mathrm{MeV}/c^2$$
    $$\Gamma[\mathrm{X(6900)}] = 168 \pm 33(\mathrm{stat}) \pm 69(\mathrm{syst})\ \mathrm{MeV}/c^2$$

  consistent with predicted $T_{cc\bar{c}\bar{c}}$ states
- The lower broader structure is objected to many uncertainties:
  - ✓ feed-down from heavier quarkonia, e.g. $T_{cc\bar{c}\bar{c}} \to \chi_c(\to J/\psi\gamma) + J/\psi$
  - ✓ near-threshold kinematic rescattering effects



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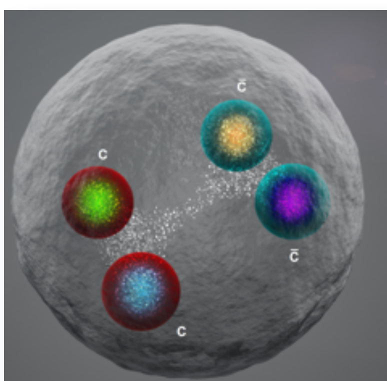
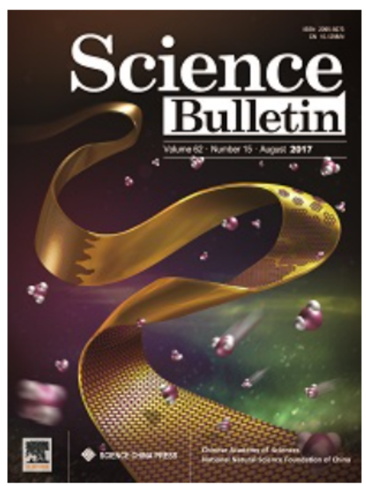
LHCb discovers a new type of tetraquark at CERN

Home

The LHCb collaboration has observed an exotic particle made up of four charm quarks for the first time.

1 JULY, 2020





Observation of structure in the J/ψ-pair mass spectrum

LHCb collaboration†

Abstract

Using proton-proton collision data at centre-of-mass energies of $\sqrt{s} = 7$, 8 and 13 TeV recorded by the LHCb experiment at the Large Hadron Collider, corresponding to an integrated luminosity of $9\,\mathrm{fb}^{-1}$, the invariant mass spectrum of J/ψ pairs is studied. A narrow structure around $6.9\,\mathrm{GeV}/c^2$ matching the lineshape of a resonance and a broad structure just above twice the J/ψ mass are observed. The deviation of the data from nonresonant J/ψ-pair production is above five standard deviations in the mass region between 6.2 and $7.4\,\mathrm{GeV}/c^2$, covering predicted masses of states composed of four charm quarks. The mass and natural width of the narrow $X(6900)$ structure are measured assuming a Breit–Wigner lineshape.

Submitted to Science Bulletin

†Authors are listed at the end of this paper.

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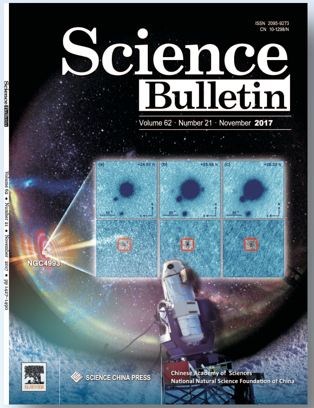

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Science Bulletin 64 (2019) 1119–1121

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News & Views

The pentaquarks observed by the LHCb experiment

Liming Zhang [a,*], Tomasz Skwarnicl

[a] Center for High Energy Physics, Tsinghua University, Beijin

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Volume 63, Issue 5, 15 March 2018, Pag

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电磁力 让我们的世界丰富多彩；

弱力 使太阳发光；

强力 给人类带来幸福，也能带来危机。

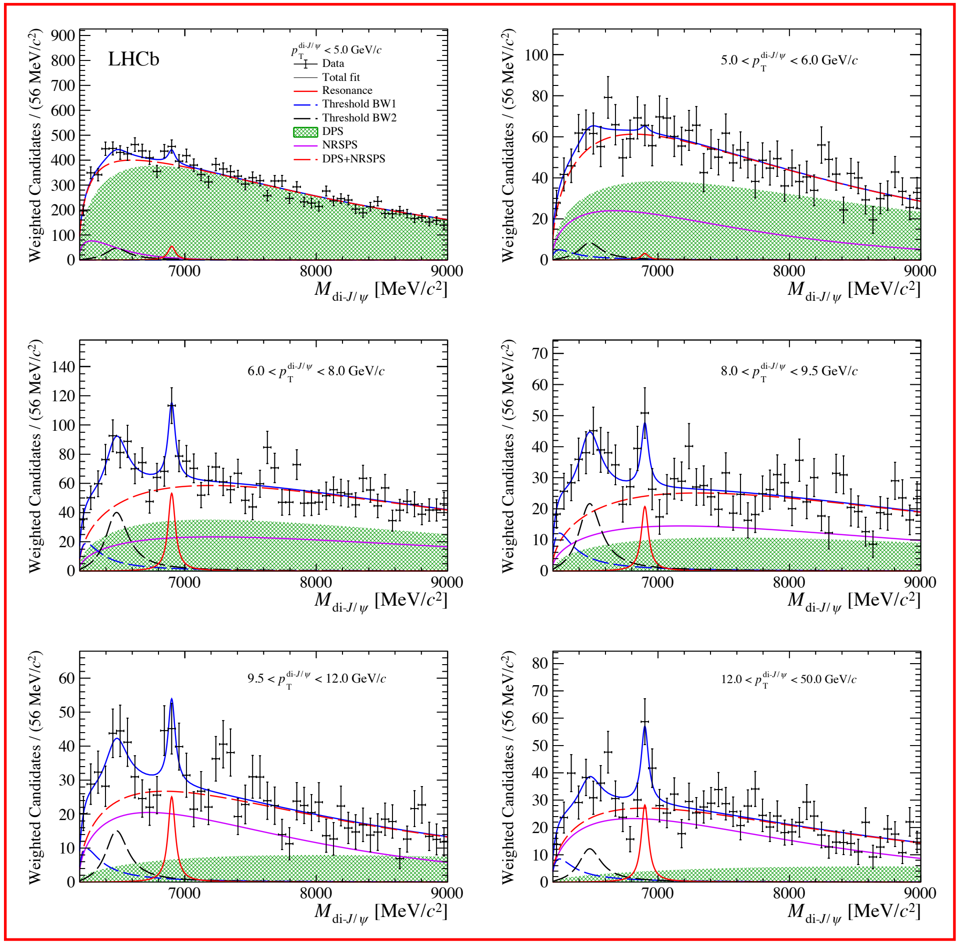
谢 谢 ！

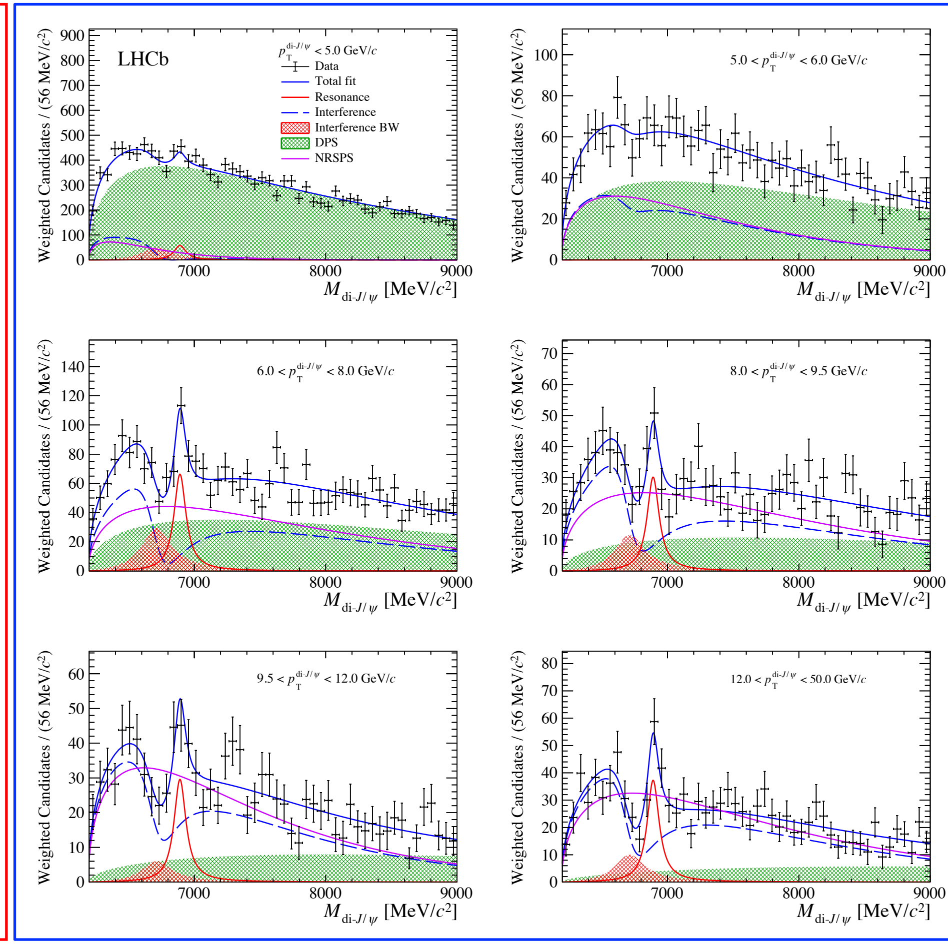
感谢安刘攀、张艳席、张黎明、杨振伟提供资料

Fits in J/ψ-pair p_{T} bins

➤ **Resonant parameters shared between J/ψ-pair p_{T} bins**

arXiv:2006.16957





Significance evaluation

Structure	Significance	
	$p_T^{\text{di-}J/\psi}$-threshold	$p_T^{\text{di-}J/\psi}$-binned
Any structure beyond NRSPS+DPS	$3.4\,\sigma$	$6.0\,\sigma$
threshold structure+6.9 GeV/c^2 peak	$6.4\,\sigma$	$6.9\,\sigma$
threshold structure	$6.0\,\sigma$	$6.5\,\sigma$
6.9 GeV/c^2 peak	$5.1\,\sigma$	$5.4\,\sigma$

Systematic uncertainties

Component	No-interference		Interference	
	M (MeV/c^2)	Γ (MeV/c^2)	M (MeV/c^2)	Γ (MeV/c^2)
sPlot weights	0.8	10.3	4.4	36.9
Mass resolution	0.0	1.4	0.0	0.6
NRSPS+DPS shape	0.8	16.1	3.5	9.3
Signal shape	0.0	0.3	0.4	0.2
$p_T^{\text{di-}J/\psi}$ cut	4.6	13.5	6.2	56.7
From-b	0.0	0.2	0.0	5.3
7.2 GeV/c^2 peak	1.3	9.2	6.7	5.2
Threshold structure shape	5.2	20.5	–	–
NRSPS phase	–	–	0.3	1.3
Total	7	33	11	69

Relative production cross-section

- Based on the no-interference fit,
  production cross-section of X(6900) times the B(X-> 2J/psi), relative to that of all prompt J/ψ pairs, $\mathcal{R}$, is measured at $\sqrt{s} = 13$ TeV

- Fiducial region: $p_{\mathrm{T}}(J/\psi) < 10$ GeV$/c$, $2.0 < y(J/\psi) < 4.5$
- Per-event efficiency-correction is applied
- For total prompt J/ψ pairs, from-b contribution is determined using simulation together with $\sigma(pp \to b\bar{b})$ and $\sigma(\text{prompt}\, J/\psi)$ then subtracted

- Systematic uncertainties
  - ✓Resonance yield: similar as the systematics on mass and width
  - ✓From-b subtraction: propagated from $\sigma(pp \to b\bar{b})$ and $\sigma(\text{prompt}\, J/\psi)$
  - ✓$(M_{\mu\mu}^{(1)}, M_{\mu\mu}^{(2)})$ fit and efficiency estimation: cancel in ratio

- $\mathcal{R} = [2.6 \pm 0.6(\text{stat}) \pm 0.8(\text{syst})]$ % for J/ψ-pair $p_{\mathrm{T}} > 5.2$ GeV$/c$
- $\mathcal{R} = [1.1 \pm 0.4(\text{stat}) \pm 0.3(\text{syst})]$ % for full J/ψ-pair p_{T} range