BESIII实验上的奇特强子物质

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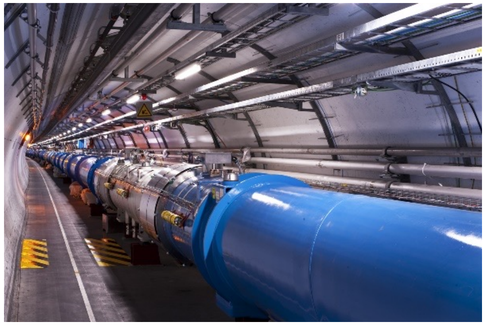
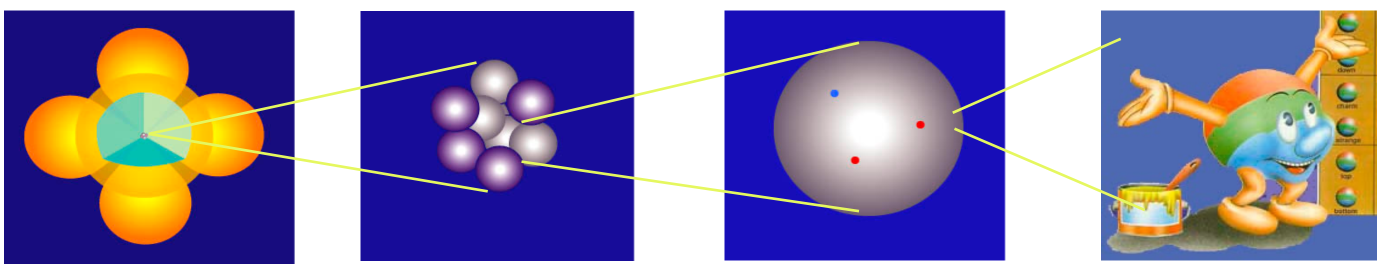


粒子物理

粒子物理，也称高能物理, 是对分子(➔化学)、原子(➔原子物理、凝聚态物理)、原子核（ ➔ 核物理 ）研究的自然发展与深化



Atom 原子 10^{-10} m

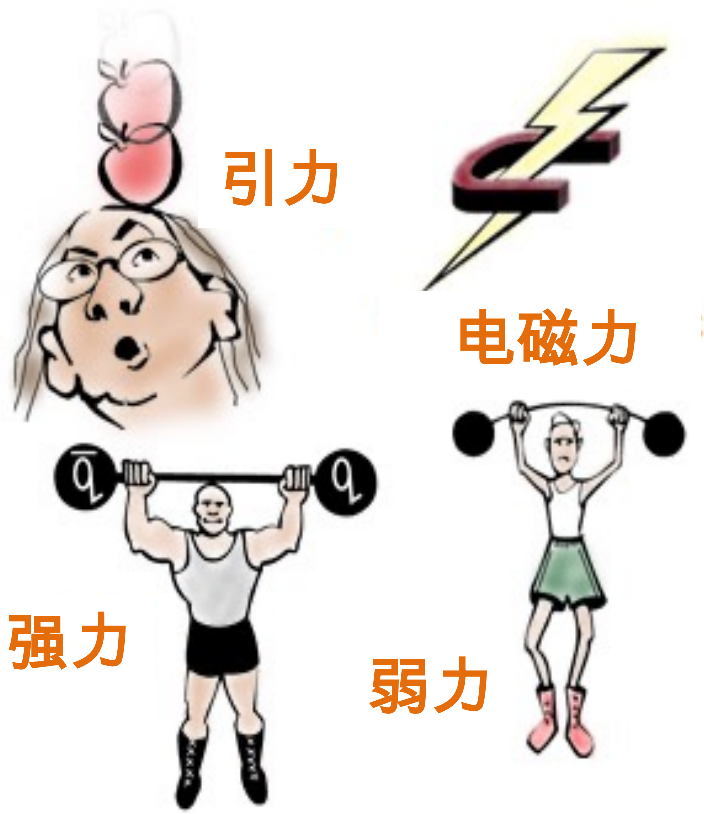
nucleus 原子核 10^{-14} m

nucleon 核子(质子、中子） 10^{-15} m

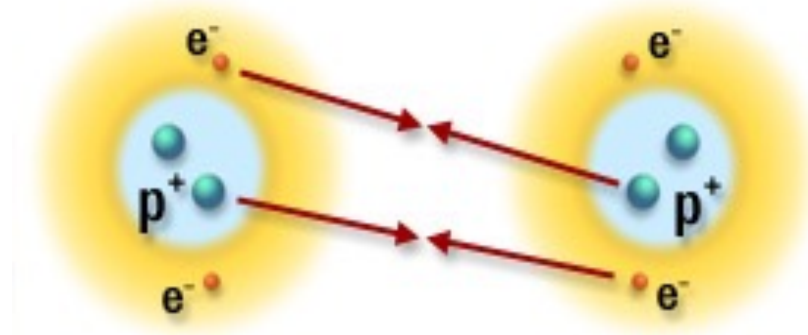
quark 夸克 $<10^{-17}$ m

对物质世界的基本组分及其相互作用研究是近代科学发展的根本动力之一

基本粒子间的相互作用

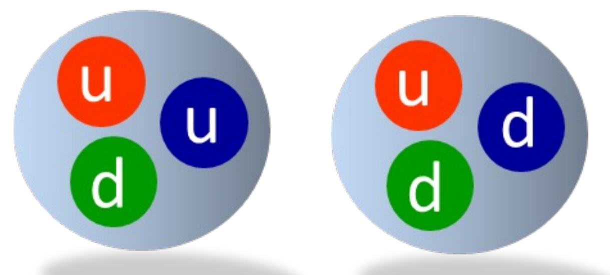


相互作用即一般所说的“力”



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。



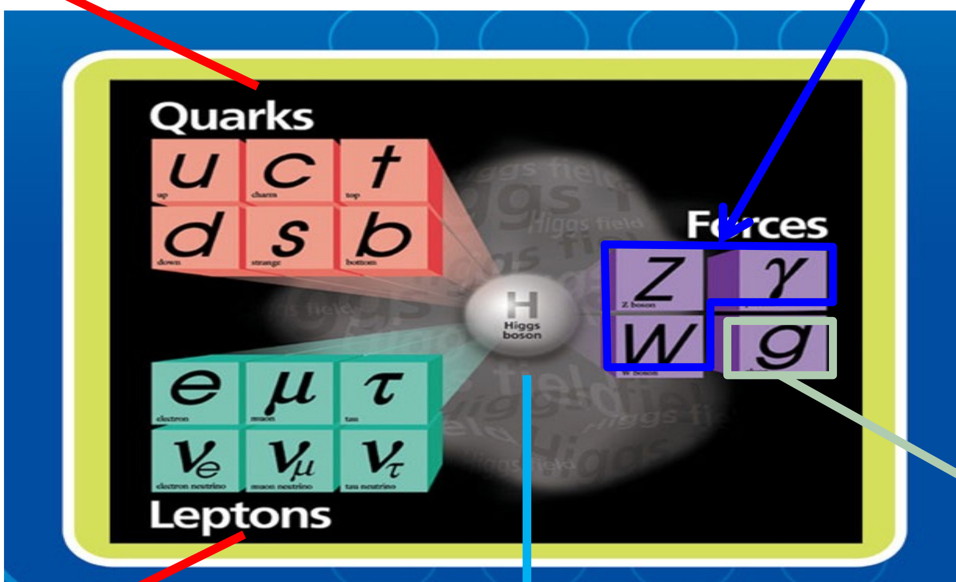
质子　　中子

物质构成的基本理论—标准模型

- 构成物质的基本单元：6种轻子 + 6种夸克

具有强相互作用

电磁、弱相互作用
(电弱统一理论 (EW))

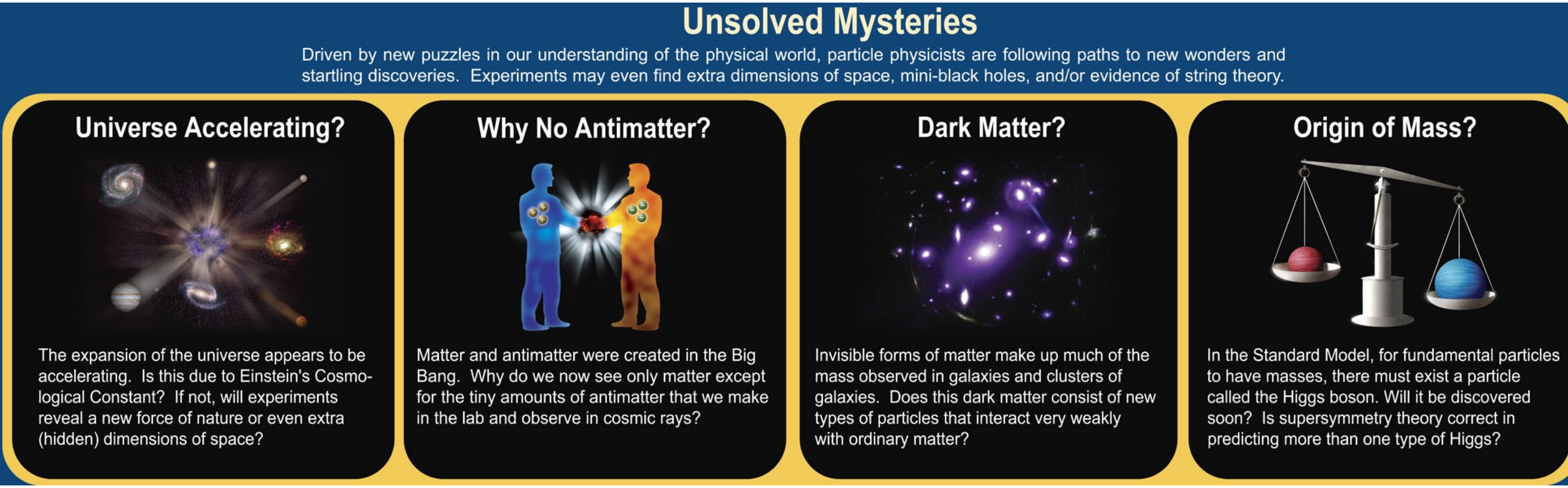


不具有强相互作用

基本粒子
的质量来源

强相互作用
（量子色动力学(QCD)）

但是，仍然存在的热点前沿问题

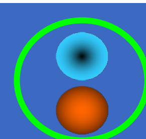


- Matter-antimatter asymmetry
- Gravity
- The origin of the Mass
- New form of matter (exotic states) ⟵ **新型物质形态（奇特物质）**
- Dark matter/energy
- Neutrino mixing
- …

寻找构成物质世界的基本元素

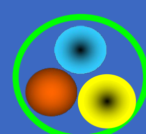
- 50-60年代，实验上发现了大量新粒子
- 1963年,盖尔曼等猜测这些新粒子具有内部结构(夸克),类似元素周期表。
- 盖尔曼的夸克模型共有三种夸克 u, d, s

介子由（$q\ \bar{q}$）构成



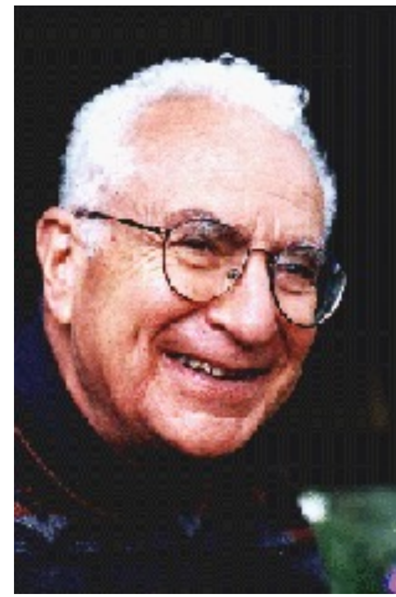
$\pi^+(u\bar{d})$
$K^+(u\bar{s})$

重子由（qqq）构成



质子(uud)
中子(udd)

为什么只有这两大类粒子？还有更多吗？
为什么只有三种夸克？还有更多吗？



M. Gell-Mann

强相互作用——重要前沿课题

研究强子的结构，回答**自然界中是否存在超出夸克模型的新型强子**这一基本问题。

常规的

有，极少

实验上没有确凿证据

理论上都是允许的

粒子物理实验

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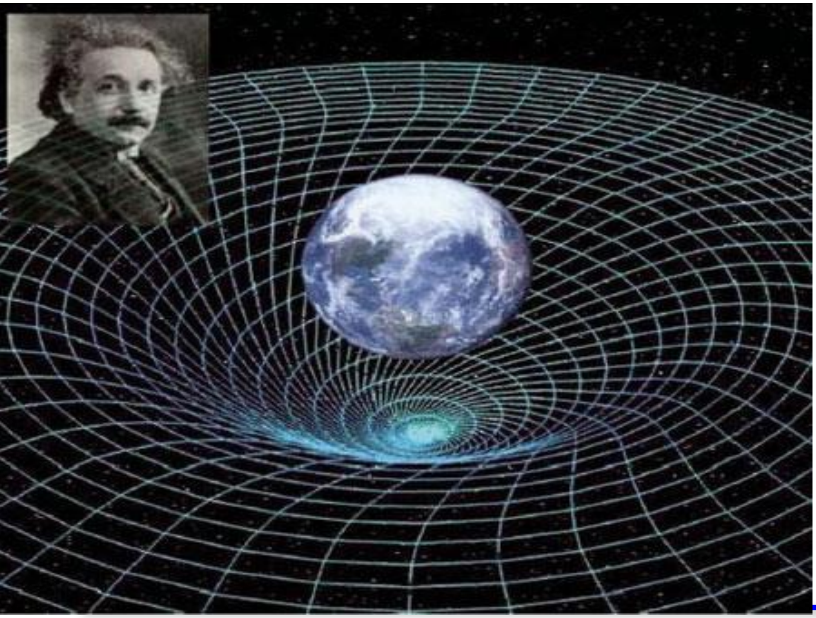
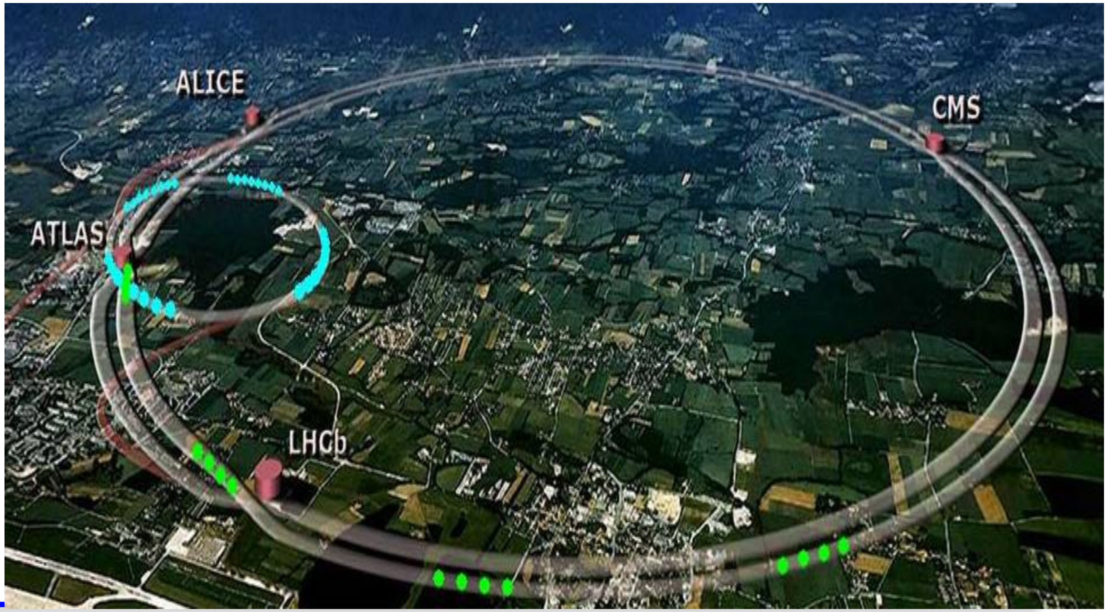
世界由什么组成？

世界如何组成？

世界如何演化？

我们如何知道？

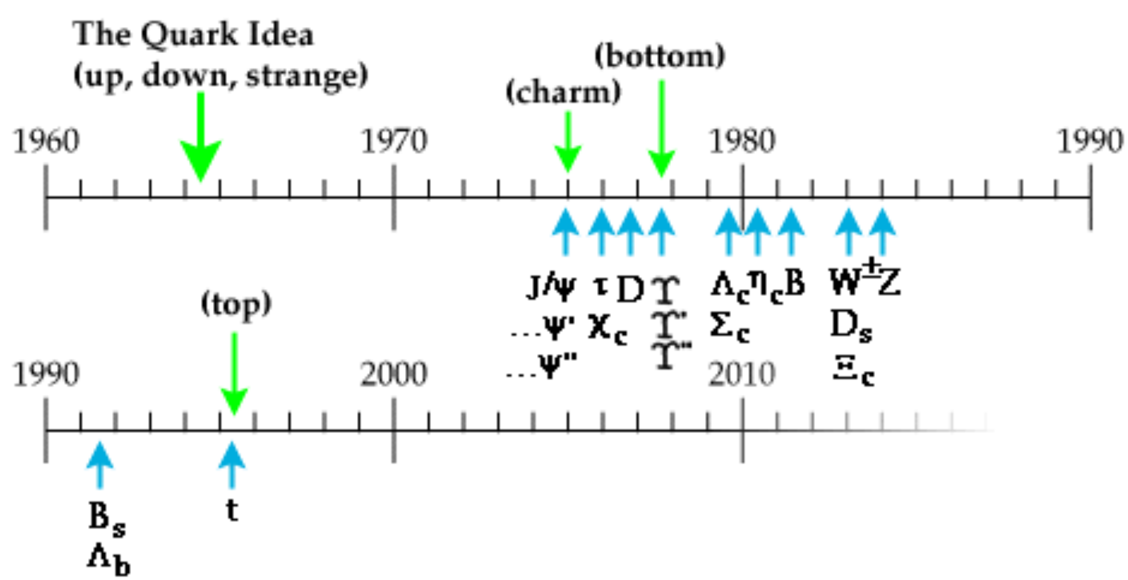




通过实验进行研究

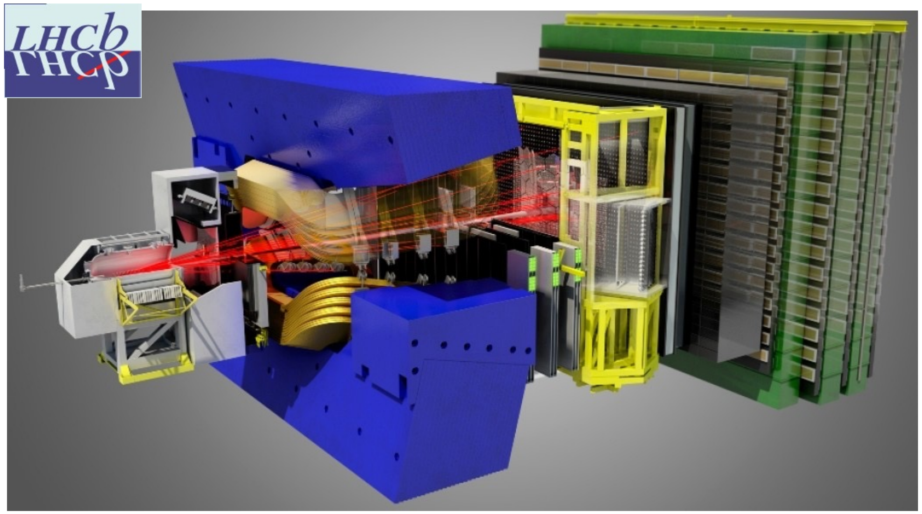
- 今天知道的粒子的绝大部分都是不稳定的粒子，它们在宇宙形成的初期都曾经存在过，但很快就衰变掉了，要研究粒子物理，就必须产生出这些粒子，并用探测器研究这些粒子的性质。

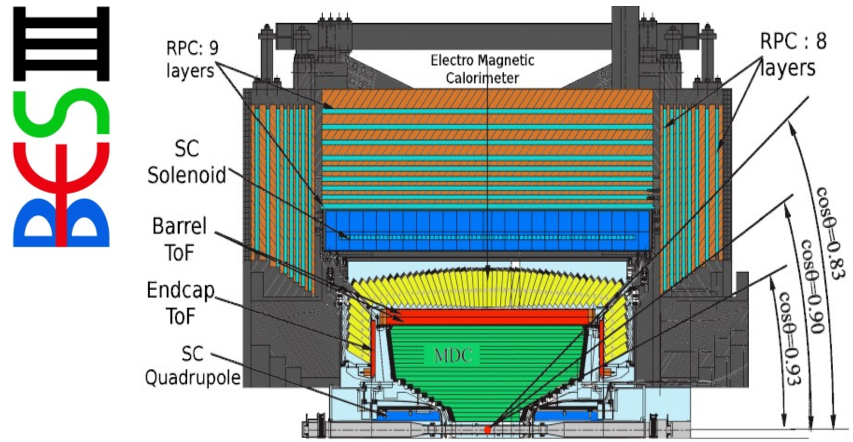
- 粒子产生的方法：
  - 来自宇宙
  - 来自对撞机



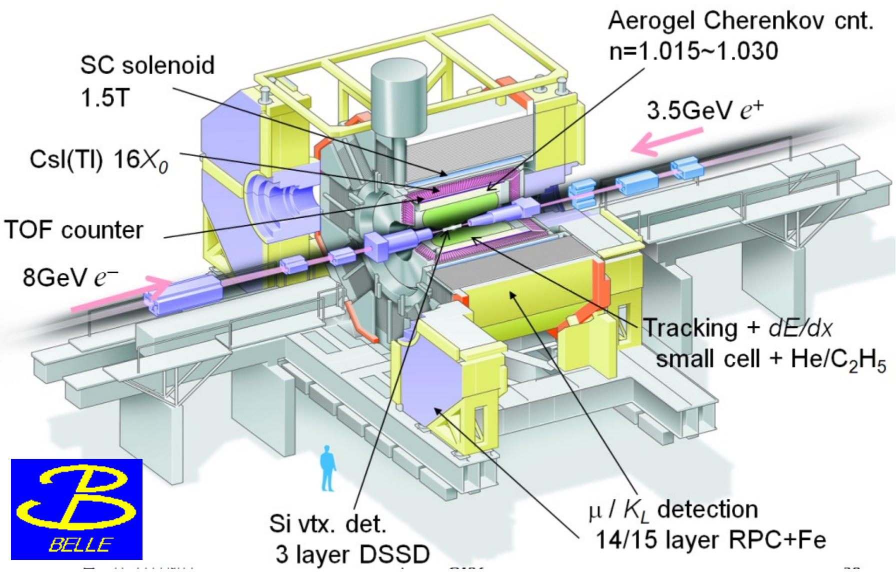
- 粒子探测的工具：
  - 探测器

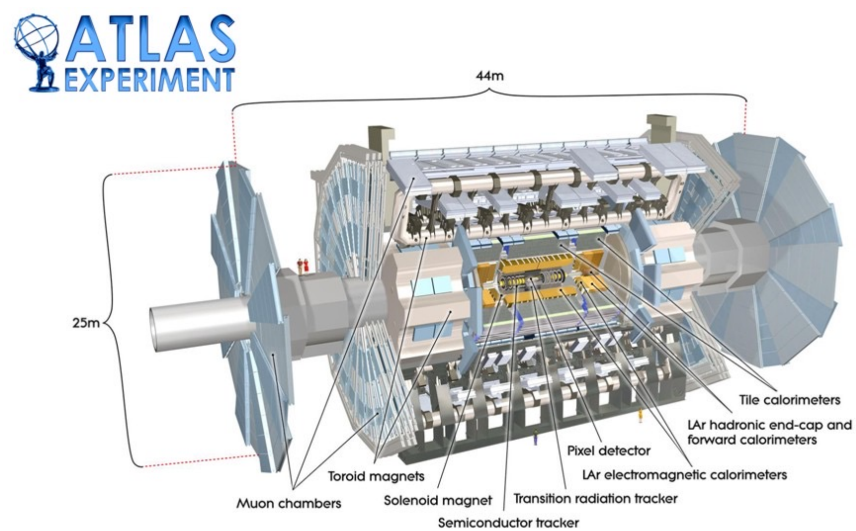
探测器





Wire tracker (no Si); TOF + dE/dx for PID; CsI Ecal; RPC muon

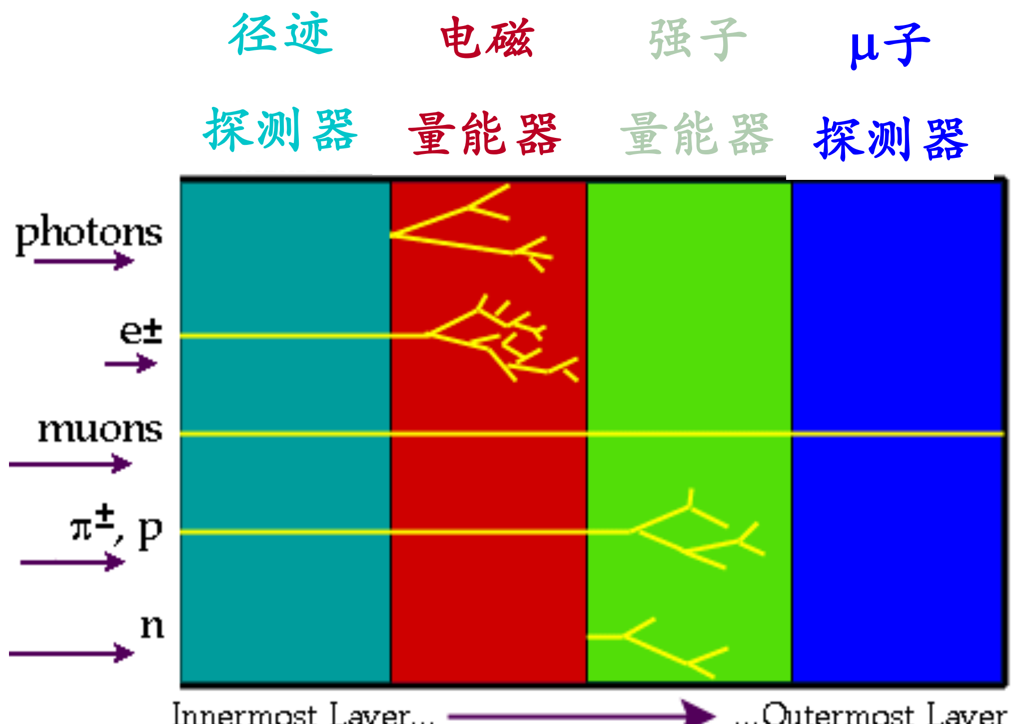




粒子是如何被探测的？

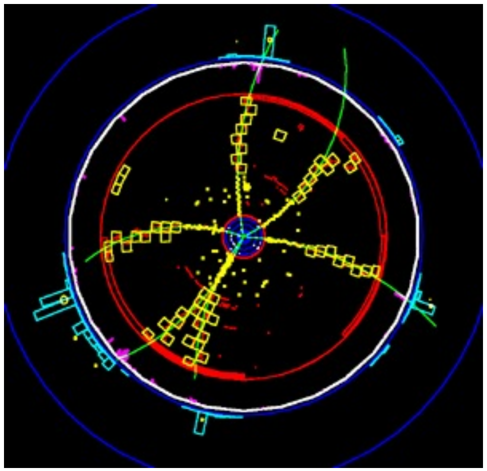
- 粒子是通过与探测器发生**相互作用**来探测的
- 对撞机所产生的绝大部分粒子的寿命都很短，会衰变到长寿命的稳定粒子：
  - 带电荷稳定粒子：电子, μ, K, π, 质子
  - 中性稳定粒子：光子, 中子
- 不稳定粒子可以从对稳定粒子的测量中重建

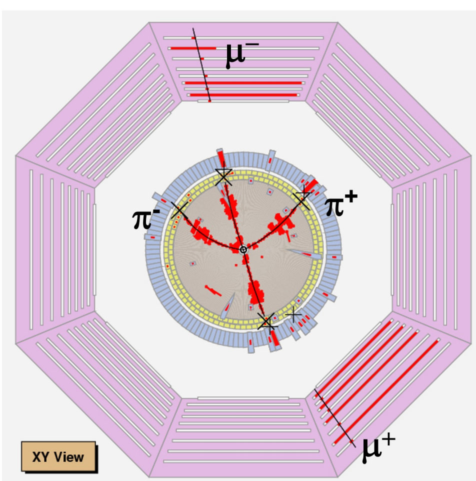
✦ 利用粒子在气体中的电离、飞行时间、穿透性以及能量簇射等效应来分辨粒子种类



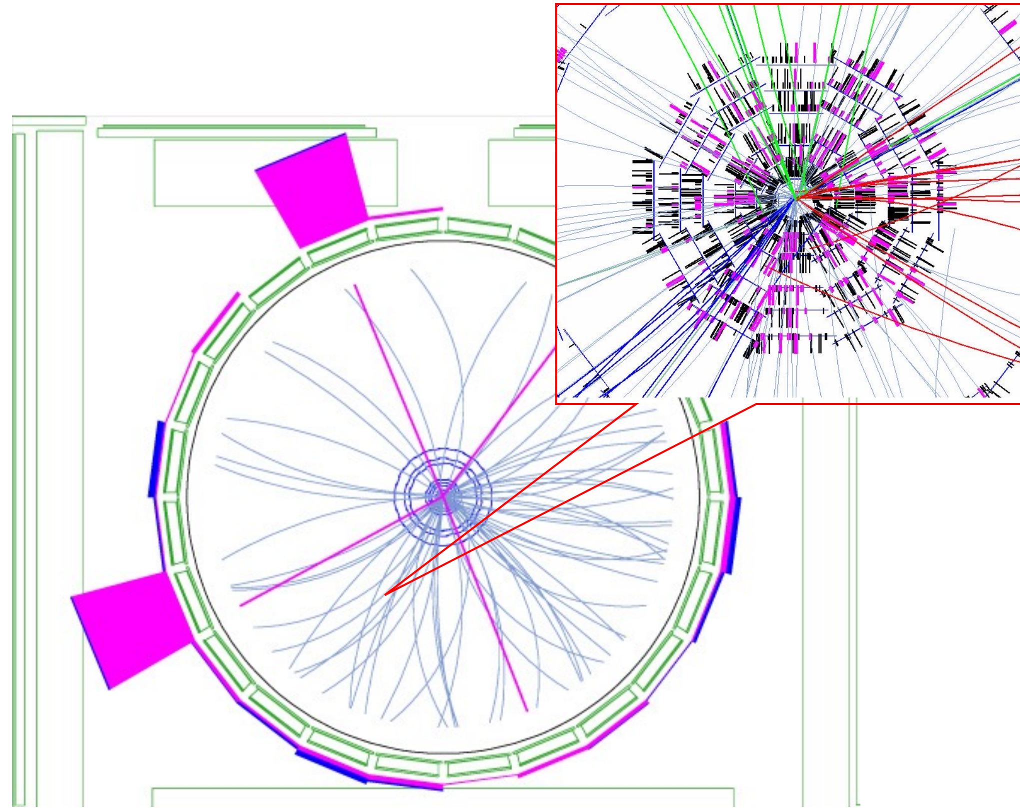
典型的对撞事例

正负电子对撞

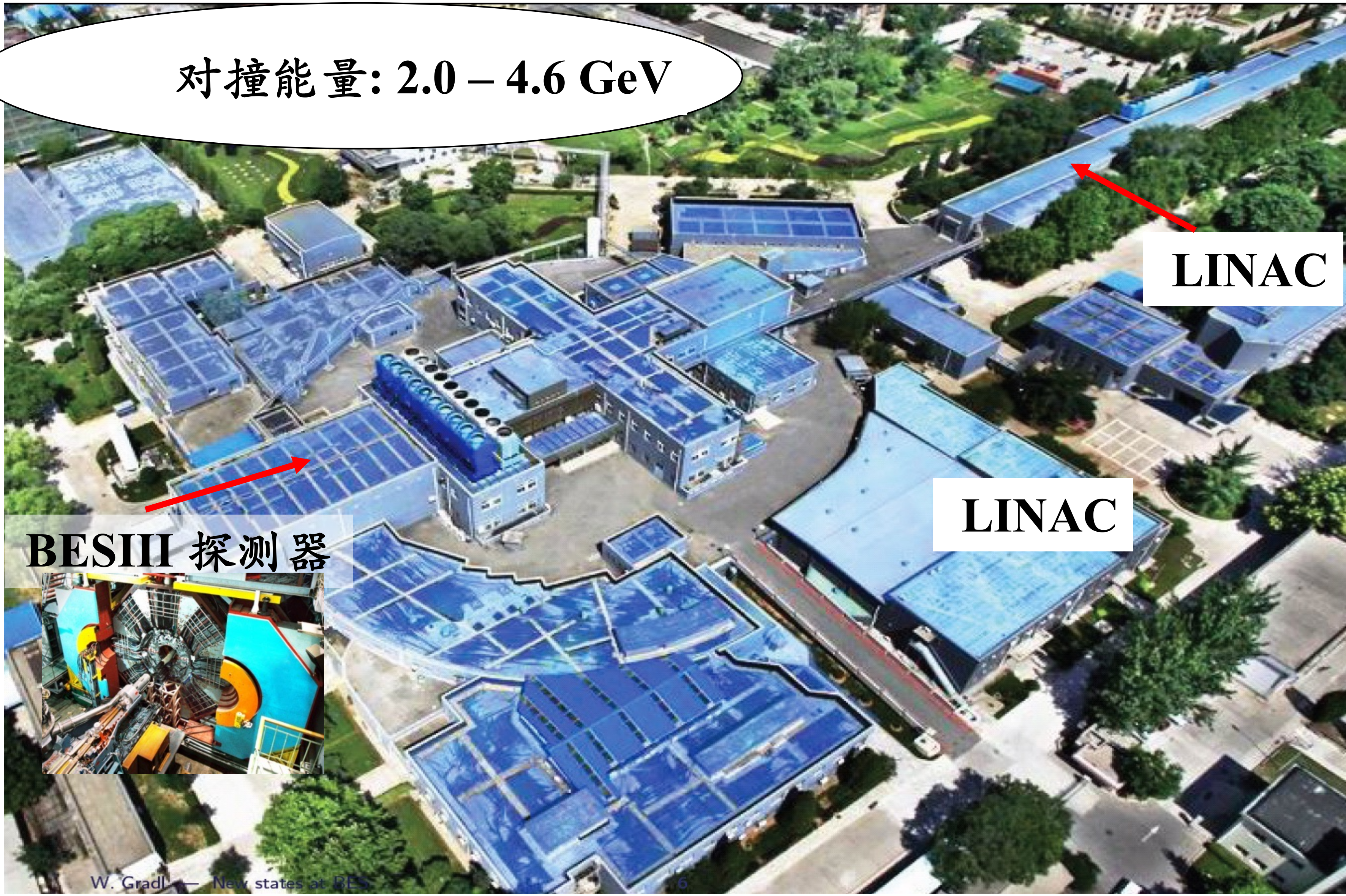




质子反质子对撞

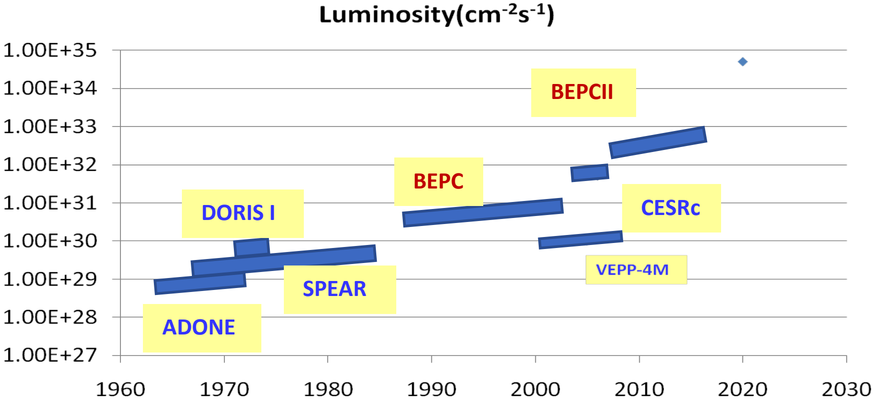


北京正负电子对撞机BESIII实验

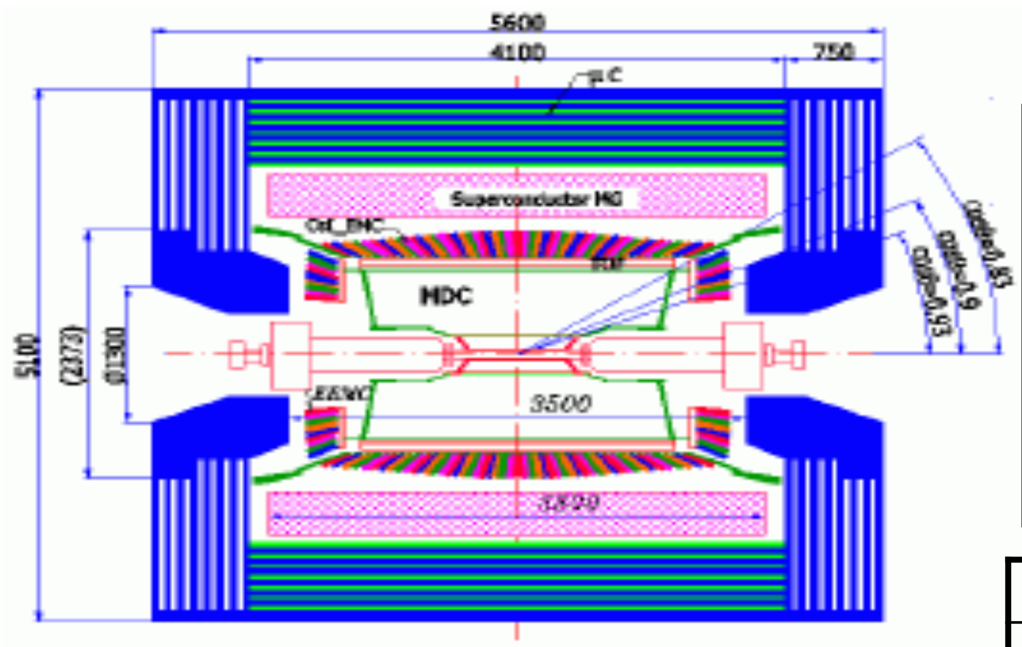


北京正负电子对撞机

- 中国的粒子物理80年代才起步
- 北京正负电子对撞机（BEPC/BES）1984年开工，1988年实现对撞
- 北京正负电子对撞机重大改造工程（BEPCII/BESIII）2009年完成
- BEPCII/BESIII还有10年的科学寿命，即将开始再一次改造，亮度提高~3倍@4GeV



BESIII探测器性能达到世界先进水平



Exps.	MDC 单丝分辨	MDC dE/dx 分辨	EMC 能量分辨
CLEO	110 μm	5%	2.2-2.4 %
Babar	125 μm	7%	2.67 %
Belle	130 μm	5.6%	2.2 %
BESIII	115 μm	<5%	2.3%

Exps.	TOF 时间分辨
CDFII	100 ps
Belle	90 ps
BESIII	68 ps (桶部) 50ps (端盖)

国内最大的单体超导磁铁：

- 1 Tesla
- 3米直径，3.5米长

物理分析

- 事例选择与分析:多维变量分析与选择
- 信号提取,研究本底,确定信号显著性
- 多变量分析、神经元网络技术、机器学习技术
- 必要的修正
  – 利用模拟数据,计算接收度,重建效率,…
  – 数据与模拟不一致时,改进分析,并做必要的效率修正
- 物理量的计算
  – 质量,宽度,寿命,物理截面,分支比,自旋宇称,…

统计与误差估计

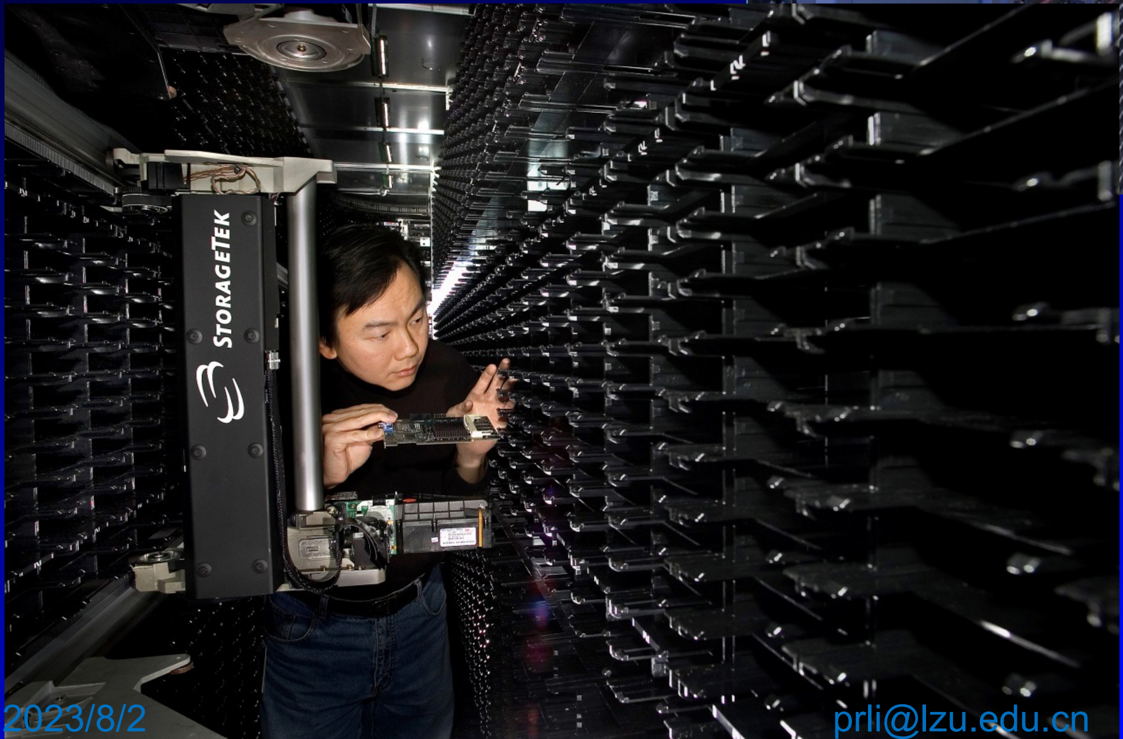
- 实验测量永远是不完美的
- 相应的测量误差分析与误差来源
  - 统计误差：样本的有限性造成的统计涨落
  - 系统误差：由于对物理规律和探测器性能认识的局限性，所做的一些关键的假设。由此造成的不确定性，称为“系统误差”。包括：探测器模型，理论模型，本底研究，探测器分辨能力，等等
- 误差传递
- 结果的统计诠释

挑战计算能力、存储能力

网格计算

高性能计算集群

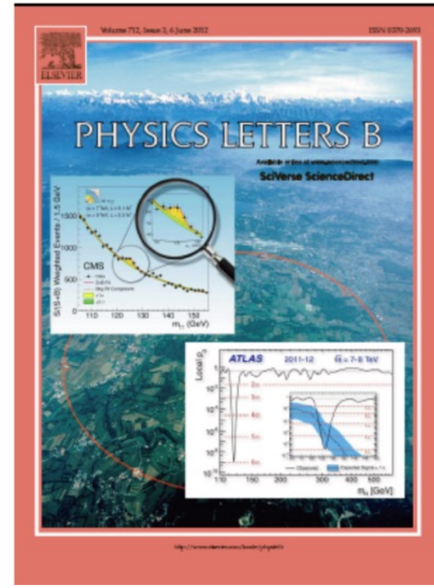
海量存储



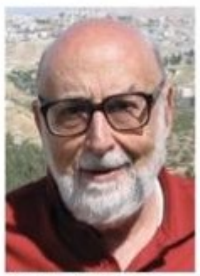
奇特物质的寻找

标准模型理论的两个研究热点

- 实验对EW理论有很多精确测量和检验
- 2012年7月LHC实验发现Higgs粒子



Physics 2013



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François Englert

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Peter W. Higgs

➔ EW 理论的巨大成功 ！

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

- 高能下的QCD得到实验的大量检验

  QCD 的渐进自由 ➔2004年诺贝尔奖

Physics 2004

David J. Gross

H. David Politzer

Frank Wilczek

- 在低能下, QCD 还有待进一步的检验.

四夸克物质研究背景

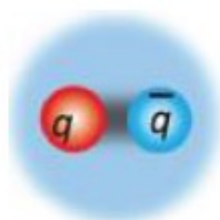
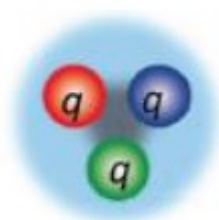
LANZHOU UNIVERSITY 蘭州大學

- 量子色动力学（QCD）是描述自然界强相互作用的基本理论。高能下QCD检验获得成功而获2004年诺贝尔奖，然而，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）？

描述强子结构的理论：夸克模型

<table>
<tr><td colspan="2">强子（主要由强相互作用绑定，QCD理论描述）</td></tr>
<tr><td>介子</td><td>重子</td></tr>
<tr><td>夸克数=2
（正反夸克对）</td><td>夸克数=3</td></tr>
<tr><td></td><td></td></tr>
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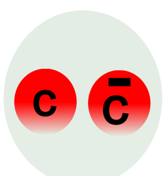
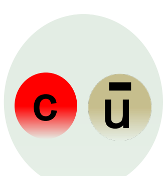
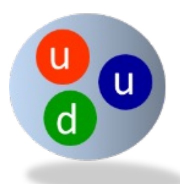
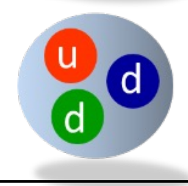
粲偶素 
粲介子 </td><td>举例：
质子 
中子 </td></tr>
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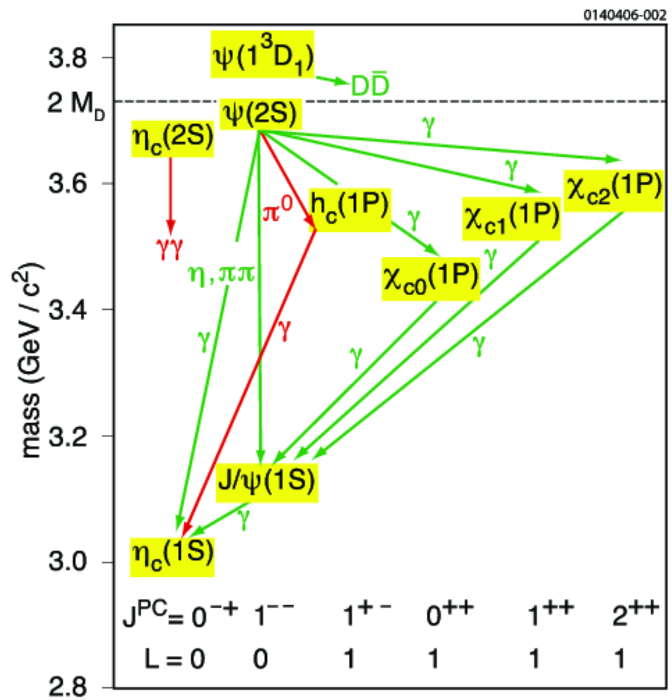
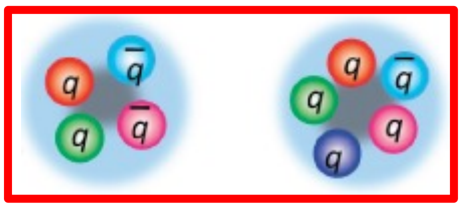
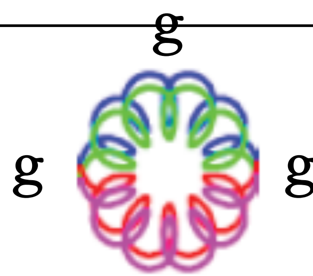
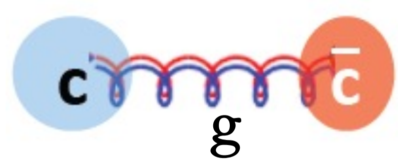
- 1964年提出模型
- 介子和重子的夸克结构早已被实验确认

具体实例：

- 粲偶素：类比于氢原子系统
  - 质量谱 ⇔ 氢原子能级



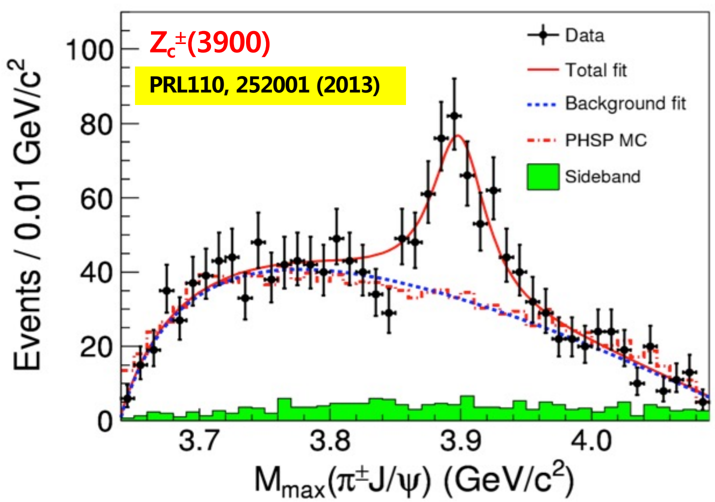
奇特强子态

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…
		

- 实验上还未确认新型强子态的存在 ！

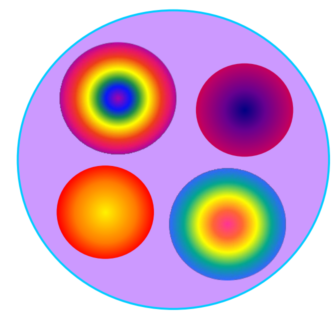
北京谱仪的重大成果：发现多夸克粒子态

- 过去50年，人们一直在寻找超出传统夸克模型的新型强子态
- BESIII实验2013年发现了**$Z_c^{\pm}$(3900)** ，其后又发现了其伴随态**Z_c^0(3900)**和**Z_c^0(4020)** ，提供了奇特强子态存在的有力证据
- 此后欧洲核子中心LHCb实验的清华大学小组发现了5夸克态**Pc(4380)**和**Pc(4450)**



许多理论解释：

- **$\bar{D}D^*$ 分子态?**
- **四夸克态?**
- **阈效应?**
- **…**



BESIII实验上发现的系列Z_c

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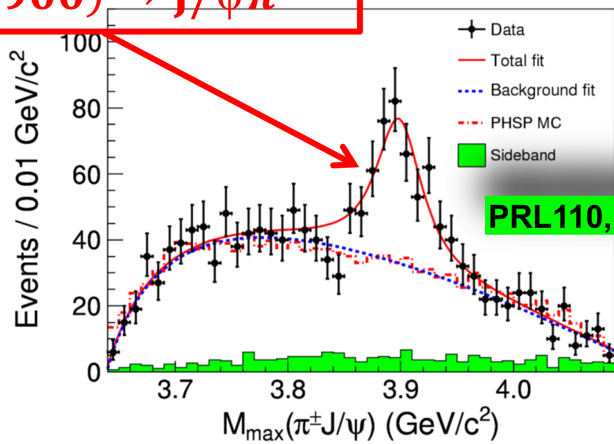
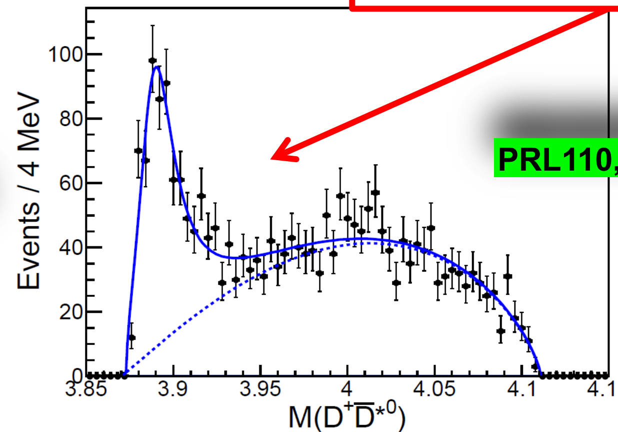
$Z_c(3900) \to J/\psi\pi^+$



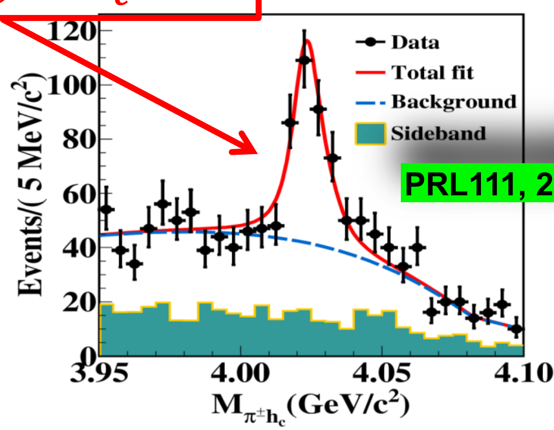
PRL110, 252001 (2013)

$Z_c(3883) \to D^+\bar{D}^{*0}$



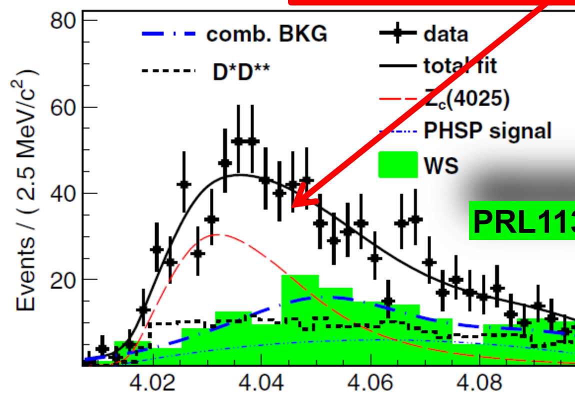
PRL110, 252001 (2013)

$Z_c(4020) \to h_c\pi^+$



PRL111, 242001 (2013)

$Z_c(4025) \to D^{*+}\bar{D}^{*0}$

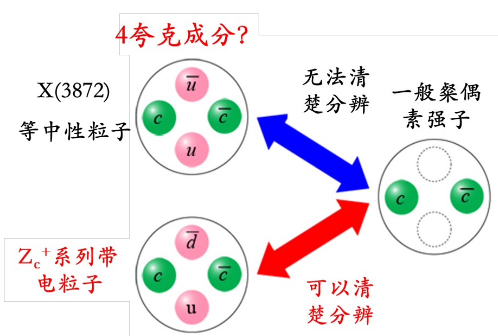


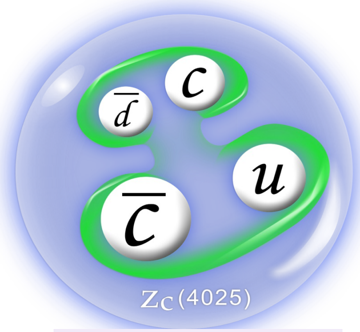
PRL113, 132001 (2014)

- 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！

四夸克物质的实验确认关键

- 确认关键：携带**电荷**⇒一对**额外**的夸克
  - 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CLEOc实验证实
  - 2013年7月在一对激发的粲介子末态$(D^{*}\bar{D}^{*})^{\pm}$中观测到$Z_c^{\pm}(4025)$

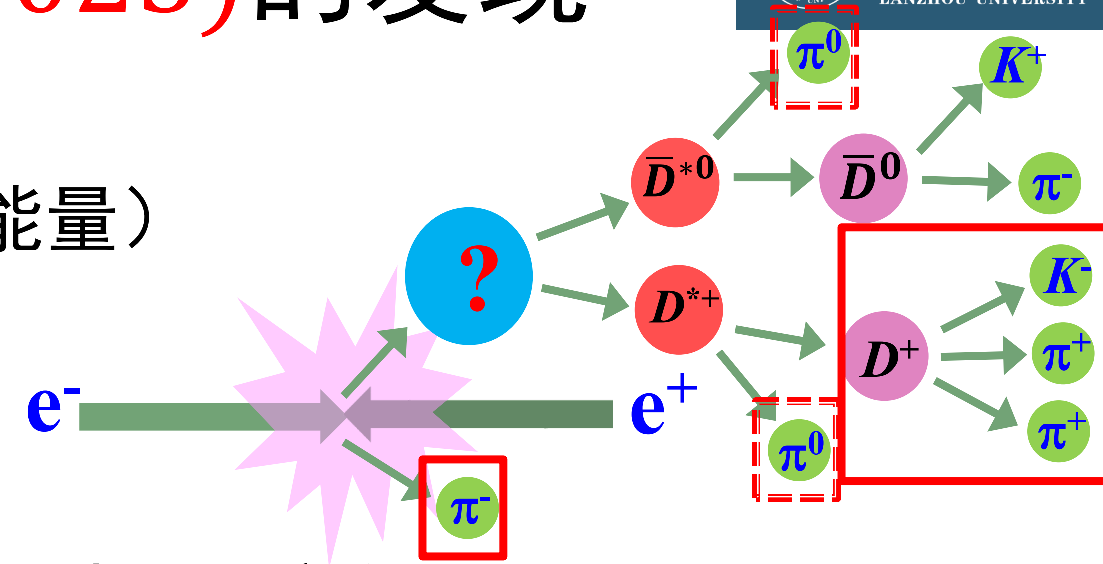




Zc四夸克态

Zc(4025)的发现

- $e^+e^-\rightarrow\bar{D}^{*0}D^{*+}\pi^-$
  （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：创新的信号重建方法
  - 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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The New York Times PREMIUM CROSSWORDS
MASTER
THE ULTIMATE PUZZLE.
SCIENCE physics
BY ADAM MANN 06.17.13
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18 June 2013
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Mögliche neue Mat
Teilchen
Fotos
Es ist viermal so schwer wie ein Pro
Beschleunigern nachgewiesenes Tei
Quarks bestehen - das wäre ein Novu
livescience
TRENDING: Hurricane Season 2013
New 'Char
Rare Stat
Clara Moskowitz, LiveS
The Beijing Spectrometer Experiment
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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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.

入选2013年物理学领域重要成果

兰州大学 LANZHOU UNIVERSITY

- 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！

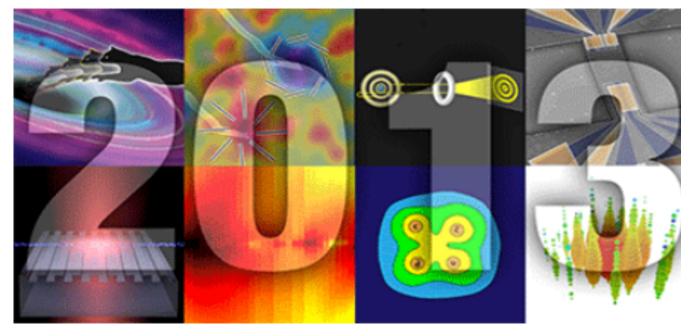
Notes from the Editors: Highlights of the Year

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

发现Zc(3900)的国际影响

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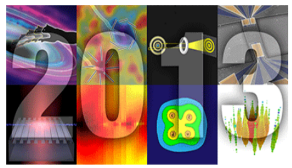

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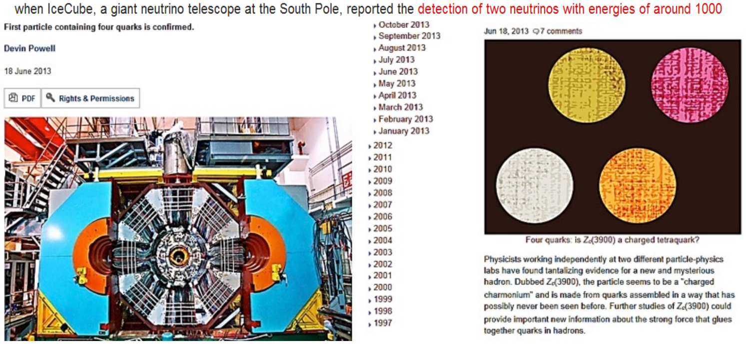
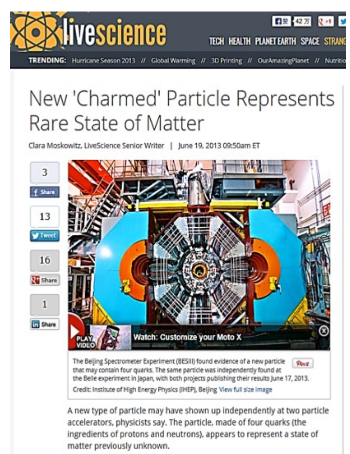
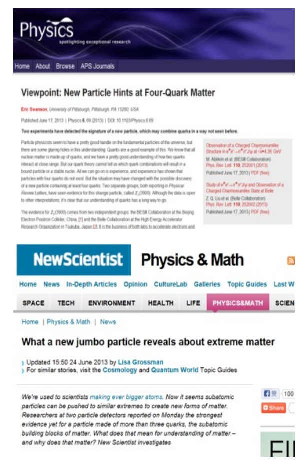
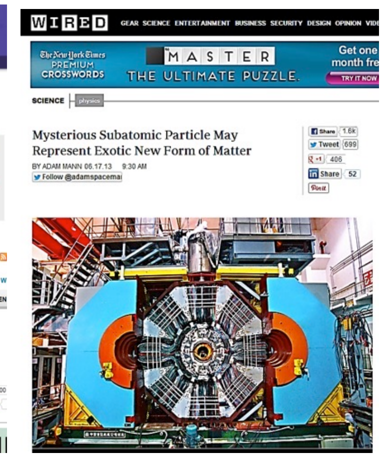


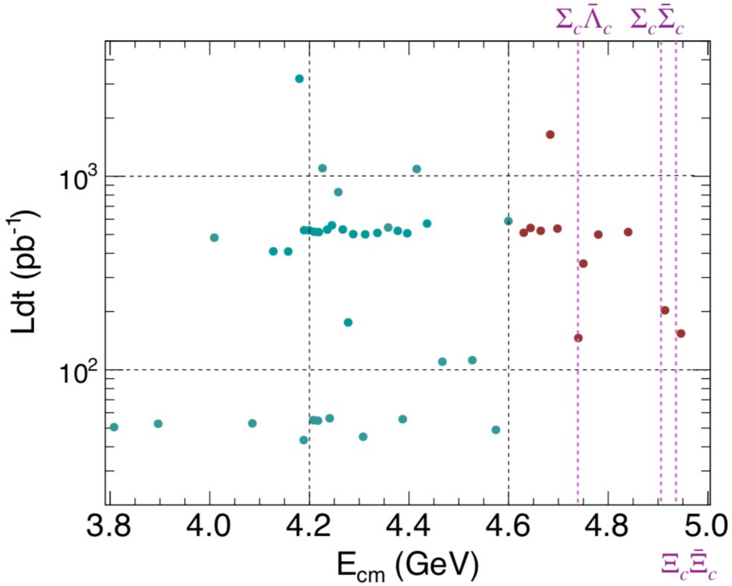
- 被国外科学杂志广泛报道。美国物理学会《物理》配发评论文章
- 入选美国物理学会《物理》杂志2013年国际物理学十一项重要成果，位列榜首。
- 入选2013年度“中国科学十大进展”

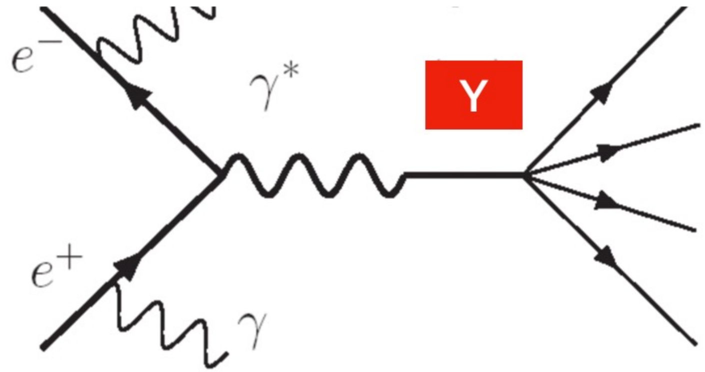






BESIII data Samples for XYZ study

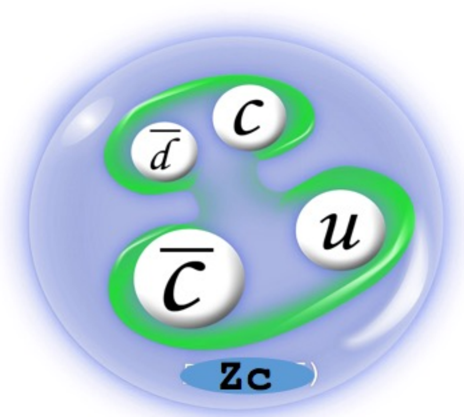


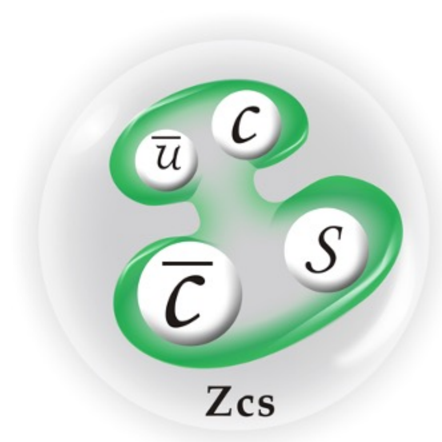


- BESIII can directly generate Y(1^{--}) states by e^+e^- annihilation.
- Study X and Z by radiative decay or hadronic transition from Y.
- BESIII accumulate ~24fb^{-1} e^+e^- collision data events from 3.8-4.946GeV.
- Data sample taken above 4.6GeV has been finished in 2020=>Y(4660) study.
- Search for more XYZ states, study their properties and new decays modes.
- Look for transitions between different states.

The $Z_{c(s)}$ states

Charmonium-like states **carrying** electric charge;
must contain at least $c\bar{c}$ and a light $q\bar{q}$ pair

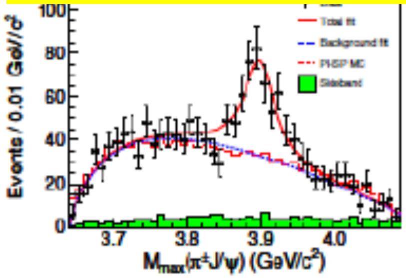




The Zc Family at BESIII

Zc(3900)$^+$

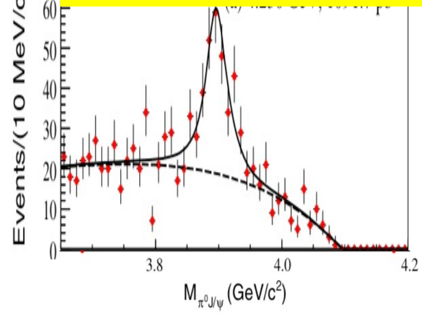
PRL 110, 252001 (2013)



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

Zc(3900)^0

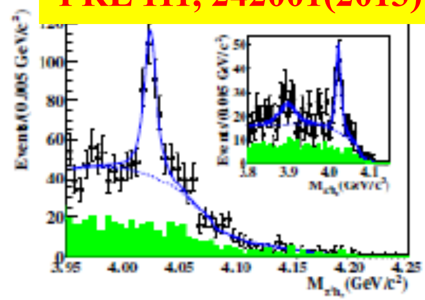
PRL 115, 112003 (2015)



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

Zc(4020)$^+$

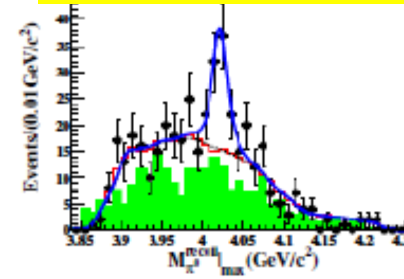
PRL 111, 242001(2013)



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

Zc(4020)^0

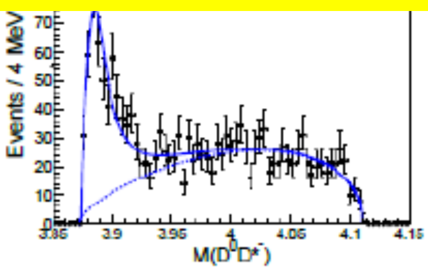
PRL113,212002 (2014)



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

Zc(3885)$^+$

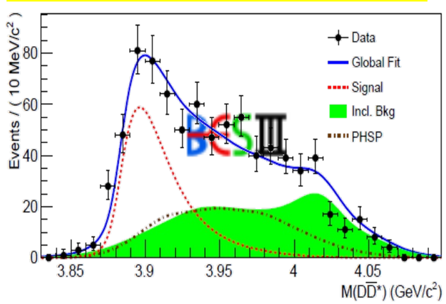
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



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

Zc(3885)^0

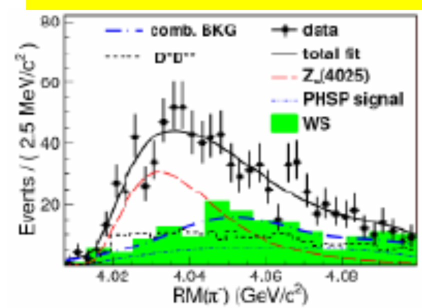
PRL115, 222002 (2015)



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

Zc(4025)$^+$

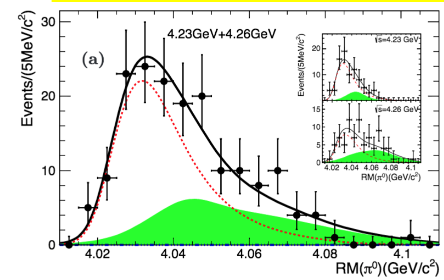
PRL 112, 132001 (2014)



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

Zc(4025)^0

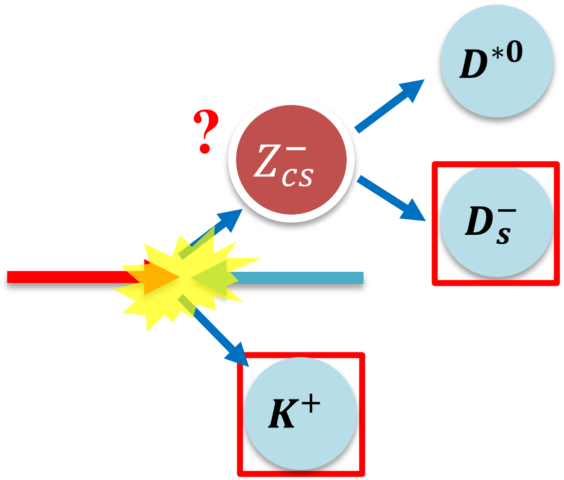
PRL115, 182002 (2015)



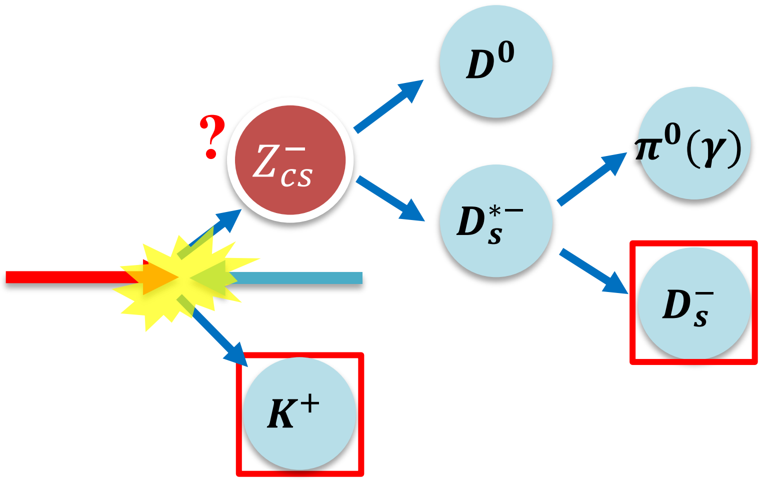
$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

- What is the nature of these states?
- Different decay channels of the same observed states? Other decay modes? J^P?
- Searches for Z_{cs} partners were proposed few years ago. e.g., $Z_{cs}/Z'_{cs} \to KJ/\psi$, D_sD^*, D_s^*D, $D_s^*D^*$ etc. => decay rate of Z_{cs} to open-charm final states is supposed to be larger than hidden-charm.

How to identify $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$



$e^+e^- \to K^+ D_s^- D^{*0}$

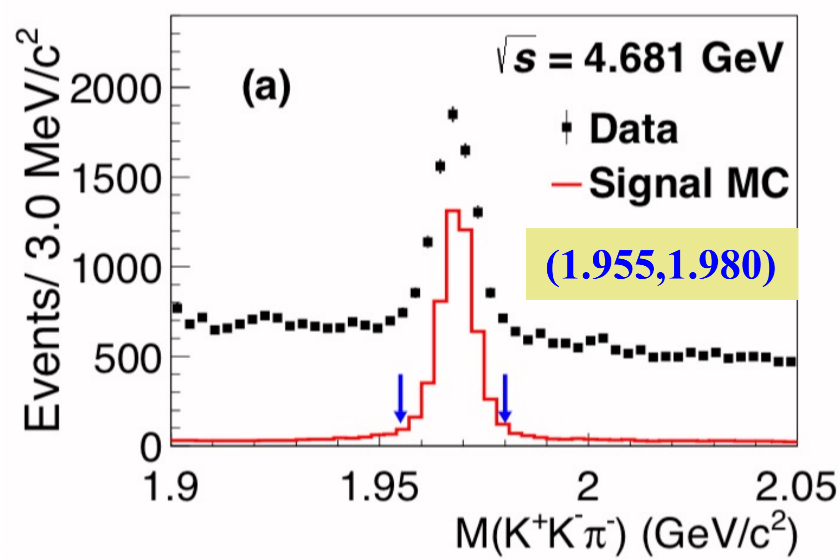


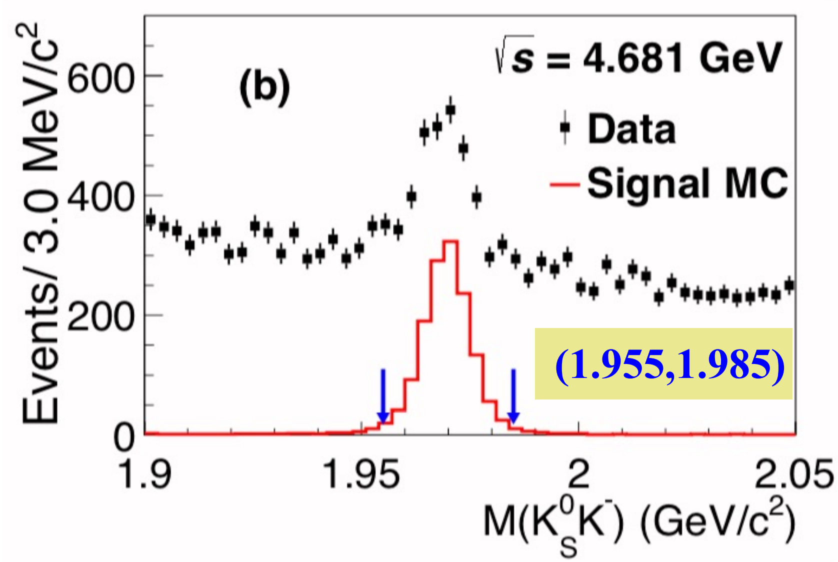
$e^+e^- \to K^+ D_s^{*-} D^0$

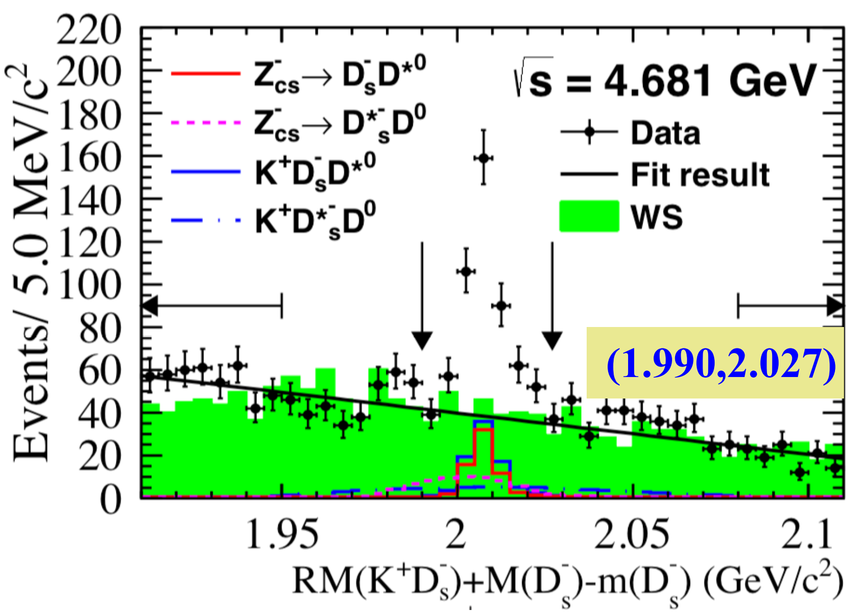
- **Partial reconstruction** of the process $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$
  - Reconstruct a D_s^- with two tag modes: $D_s^- \to K_S^0 K^-$ and $D_s^- \to K^+ K^- \pi^-$.
  - Tag a bachelor charged K^+.
  - Use signature in the **recoil mass spectrum of $K^+ D_s^-$** to identify the process of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$.
  - Study the mass spectrum of recoil mass of K^+.
  - The charge conjugated channels are also implied.

Similar technique with the paper of **Zc(4025)$^+$** observation.
PRL 112, 132001 (2014)

Tag a D_s^- and select $K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ signals







For $D_s^- \to K^+K^-\pi^-$ process, keep the events only in

1) $D_s^- \to \pi^-\phi(K^-K^+)$: $M(K^-K^+) < 1.05$ GeV/c^2.

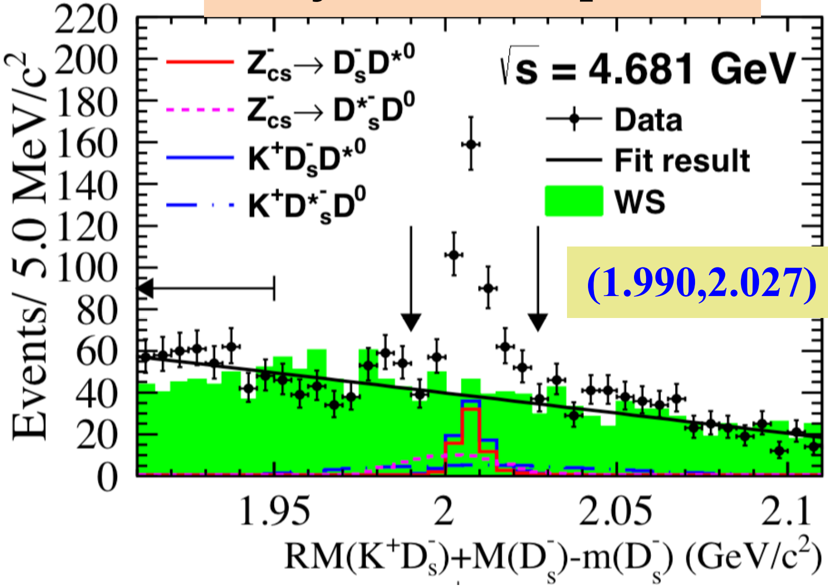
2) $D_s^- \to K^-K^*(892)(K^+\pi^-)$:

$M(K^+\pi^-) \in (0.85, 0.93)$ GeV/c^2.

- $RM(K^+D_s^-)$: the recoil mass of $K^+D_s^-$.
- $M(D_s^-)$: the reconstructed mass.
- $m(D_s^-)$: the mass taken from PDG.

Select candidates for $K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

very evident peak

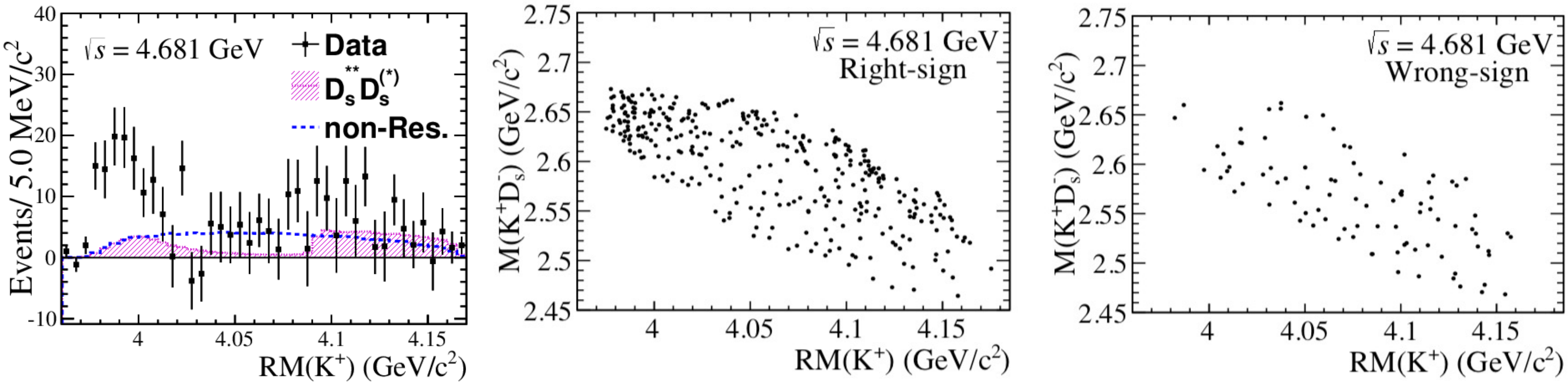


(1.990,2.027)

- Data-driven technique to describe combinatorial background.
- Right Sign(RS): combination of D_s^- and K^+.
- Wrong Sign(WS): combination of D_s^- and K^- to mimic combinatorial background.

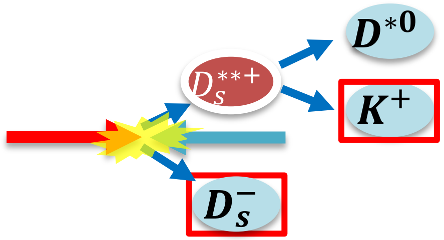
- No peaking background observed in WS events; => **WS technique is well validated by MC simulations and data sideband events.**
- Both $e^+e^- \to K^+ D_s^- D^{*0}$ and $e^+e^- \to K^+ D_s^{*-} D^0$ can survive with this criterion.
- Fitting to $RM(K^+ D_s^-)$ sideband events give number of WS in signal region: 282.6 ± 12.0;
- This WS number will be fixed in $RM(K^+)$ spectrum fitting.

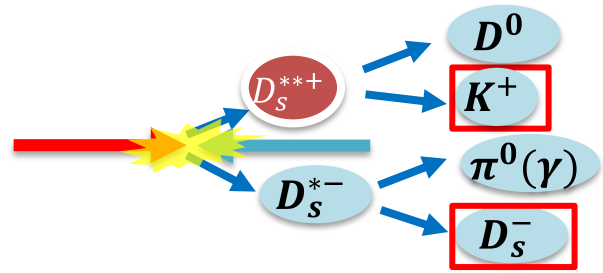
Recoil-mass spectra of K^+ and two-dimensional distributions of $M(K^+D_s^-)$ vs. $RM(K^+)$



- The K^+ recoil-mass spectrum in data at 4.681GeV.
- Combinatorial backgrounds are subtracted.
- A structure next to threshold raging from 3.96 to 4.02GeV/c^2.
- The enhancement cannot be attributed to the non-resonant (NR) signal process $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$.

Check with high excited D_s^{**} states



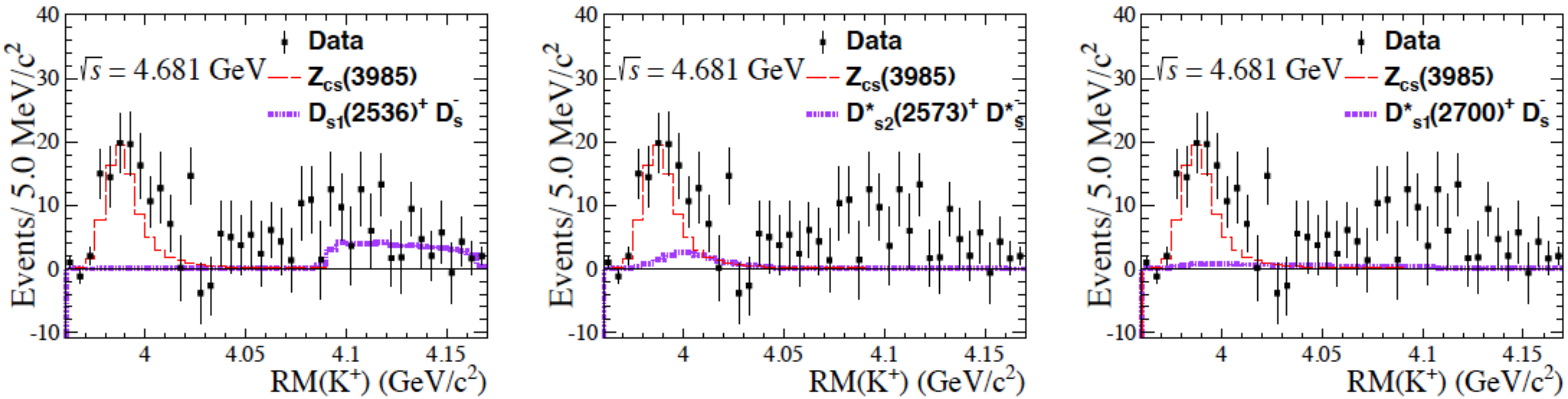


D_s^{**+}	mass(MeV/c²)	width(MeV)	J^P	$D_s^{**+}(K^+D^{*0})D_s^-$	$D_s^{**+}(K^+D^0)D_s^{*-}$
$D_{s1}(2536)^+$	2535.11±0.06	0.92±0.05	1^+	(*) Fixed in nominal fitting	Parity Violation in decay
$D_{s2}^*(2573)^+$	2569.1±0.8	16.9±0.7	2^+	Not decay to KD*	(*) Fixed in nominal fitting
$D_{s1}^*(2700)^+$	$2708.3^{+4.0}_{-3.4}$	120±11	1^-	(*) Fixed in nominal fitting	Q=-139.3MeV P-wave suppression in production.
$D_{s1}^*(2860)^+$	2859±27	159±80	1^-	(*)less contribution than $D_{s1}^*(2700)^+$; Q=-146MeV.	Q=-290MeV; P-wave suppression in production.
$D_{s3}^*(2860)^+$	2860±7	53±10	3^-	(*)F-wave suppression; Q=-147MeV	Q=-291MeV

• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}^*(2573)$	$0(2^+)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{s1}^*(2860)^\pm$	$0(1^-)$
$D_{s3}^*(2860)^\pm$	$0(3^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

- Most high excited D_s^{**} states have negative Q value or forbidden due to Parity Violation.
- $D_{s1}^*(2536)^+(K^+D^{*0})D_s^-$, $D_{s2}^*(2573)^+(K^+D^0)D_s^{*-}$ and $D_{s1}^*(2700)^+(K^+D^{*0})D_s^-$ are studied using control sample.
- Most high excited $D_{(s)}^{**}$ states contribute a broad peak around 4 GeV which could not describe the enhancement in $RM(K^+)$.

Check with high excited D_s^{**} states



(a) $D_{s1}(2536)^+(\to D^{*0}K^+)D_s^-$ (b) $D^*_{s2}(2573)^+(\to D^0K^+)D_s^{*-}$ (c) $D^*_{s1}(2700)^+(\to D^{*0}K^+)D_s^-$

$e^+e^- \to D_{s1}(2536)^+(D^{*0}K^+)\, D_s^-$
$e^+e^- \to D_{s1}(2536)^+(D^{*0}K^+)\, D_s^-$

$e^+e^- \to D^*_{s2}(2573)^+(K^+D^0)D_s^{*-}(\gamma D_s^-)$
$e^+e^- \to D^*_{s2}(2573)^+(K^+D^0)D_s^{*-}(\gamma D_s^-)$

$e^+e^- \to D^*_{s1}(2700)^+D_s^- \to K^+D^0D_s^-$.

$$\frac{\mathcal{B}(D^*_{s1}(2700)^+ \to D^{*0}K^+)}{\mathcal{B}(D^*_{s1}(2700)^+ \to D^0K^+)} = 0.91 \pm 0.18,$$

BaBar_PhysRevD.80.092003(2009)

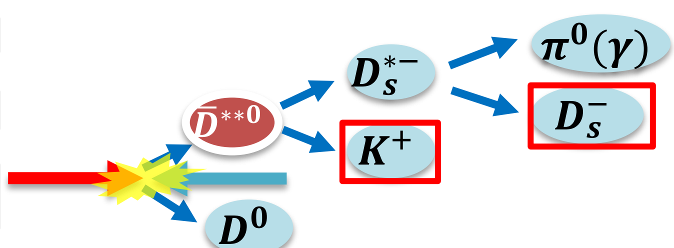
$\sqrt{s}$(GeV)	4.628	4.641	4.661	4.681	4.698
$D_{s1}(2536)^+(K^+D^{*0})D_s^-$	41.2 ± 6.3	26.2 ± 5.4	23.9 ± 5.6	54.4 ± 8.0	15.3 ± 4.2
$D^*_{s2}(2573)^+(K^+D^0)D_s^{*-}$	–	–	–	19.1 ± 7.6	17.3 ± 7.3
$D^*_{s1}(2700)^+(K^+D^{*0})D_s^-$	0.0 ± 1.8	18.6 ± 8.7	16.6 ± 7.8	15.0 ± 13.3	7.7 ± 8.4

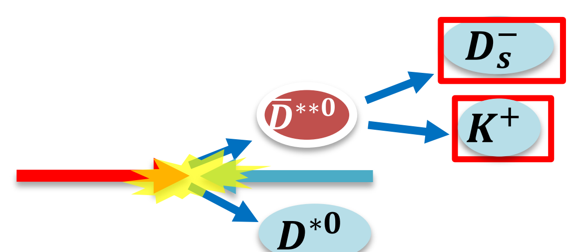
- The estimated sizes of excited D_s^{**} contributions at each energy point.
- “-” means the production is not allowed kinematically.

Check with high excited $\bar{D}^{**0}$ states

$\bar{D}^{**0}$	mass(MeV/c²)	width(MeV)	J^P	$\bar{D}^{**0}(K^+D_s^{*-})D^0$	$\bar{D}^{**0}(K^+D_s^-)D^{*0}$
$\bar{D}_1(2430)^0$	2427±40	384^{+130}_{-110}	1^+	below KDs* threshold; Q=-72.22MeV soft Kaon	Parity Violation decay
$\bar{D}_2^*(2460)^0$	2460.7±0.4	47.5±1.1	2^+	below KDs* threshold; Q=-39.52MeV soft Kaon	(*)Test fit
$\bar{D}(2550)^0$	2564±20	135±17	0-	(*)Test fit	Parity Violation in decay
$\bar{D}_J^*(2600)^0$	2623±12	139±31	1^-	(*)Test fit	(*)Control sample & nominal fit
$\bar{D}^*(2640)^0$	2637±6	<15	?	(*)Test fit	(*)Test fit
$\bar{D}(2740)^0$	2737±12	73±28	2^-	(*)Test fit	Parity Violation in decay
$\bar{D}_3^*(2750)^0$	2763±3.4	66±5	3-	(*)Control sample	P-wave suppressed. Q=-89.8MeV

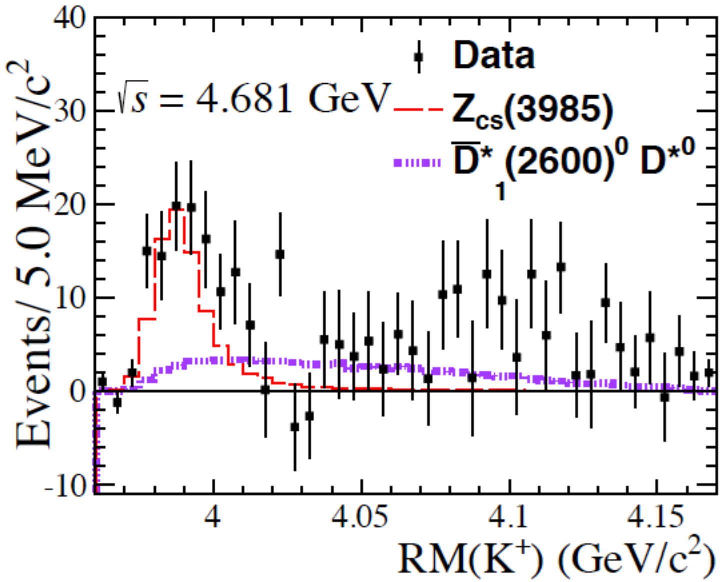
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(?^?)$
$D_J^*(2600)$	$1/2(?^?)$
was $D(2600)$	
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2740)^0$	$1/2(?^?)$
$D_3^*(2750)$	$1/2(3^-)$
$D(3000)^0$	$1/2(?^?)$





- ◆ $D(2640)$ is quite narrow and not confirmed by any high statistic experiment including LHCb.
- ◆ Most $\bar{D}^{**0}$ states are not favored from the check of test fit.=>Systematic uncertainties.

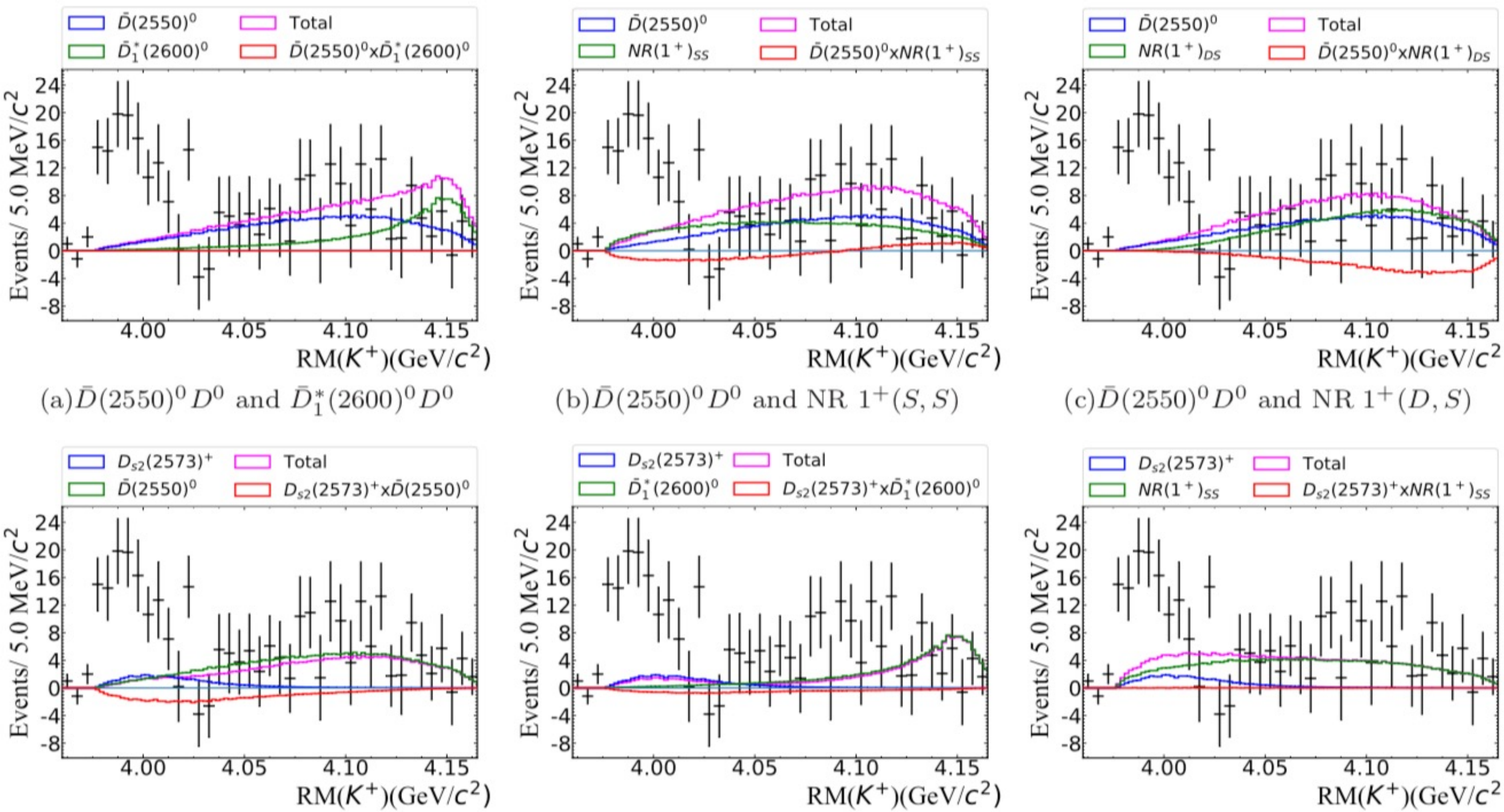
Check with high excited non-strange $\bar{D}_1^*(2600)^0$ states



(c) $\bar{D}_1^*(2600)^0(\to D_s^- K^+)D^{*0}$

- The $RM(K^+)$ spectrum is distorted due to limited production phase space. However, it is much broader than the observed enhancement.
- $e^+e^- \to D^{*0}\bar{D}_1^*(2600)^0(\to D_s^- K^+)$ is studied using an PWA of control sample $e^+e^- \to D^{*0}\bar{D}_1^*(2600)^0(\to D^-\pi^+)$.
- The ratio R= $B(\bar{D}_1^*(2600)^0 \to D_s^- K^+)/B(\bar{D}_1^*(2600)^0 \to D^-\pi^+)$ is unknown.
  => difficult to produce absolute size.
- Determine the ratio in nominal simultaneous fit, providing constraint on its size.

Interference effect of $K^+ D_s^{*-} D^0$ final states (1)

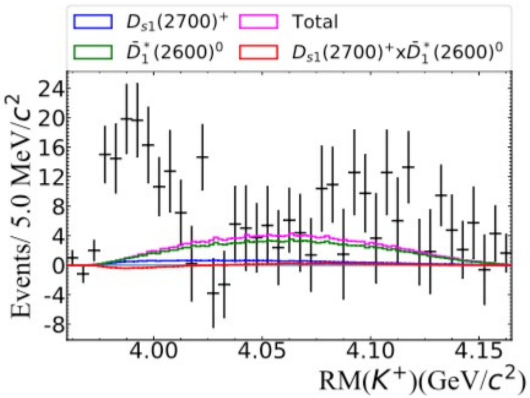


(a) $\bar{D}(2550)^0 D^0$ and $\bar{D}_1^*(2600)^0 D^0$ (b) $\bar{D}(2550)^0 D^0$ and NR $1^+(S,S)$ (c) $\bar{D}(2550)^0 D^0$ and NR $1^+(D,S)$

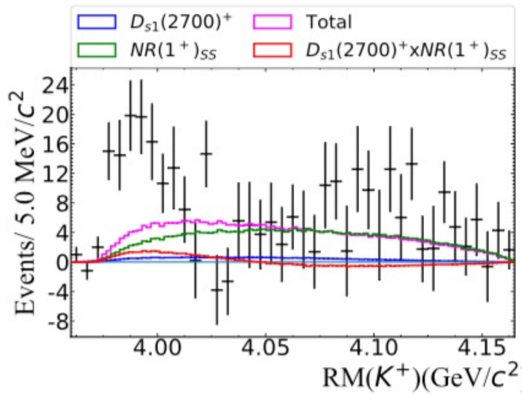
(d) $D_{s2}^*(2573)^+ D_s^{*-}$ and $\bar{D}(2550)^0 D^0$ (e) $D_{s2}^*(2573)^+ D_s^{*-}$ and $\bar{D}_1^*(2600)^0 D^0$ (f) $D_{s2}^*(2573)^+ D_s^{*-}$ and NR $1^+(S,S)$

- Data subtracted with WS backgrounds.
- Any two MC simulated backgrounds with interferences are taken into account.
- The interference angle is tuned to give the largest interference effect around 4.0GeV/c^2.

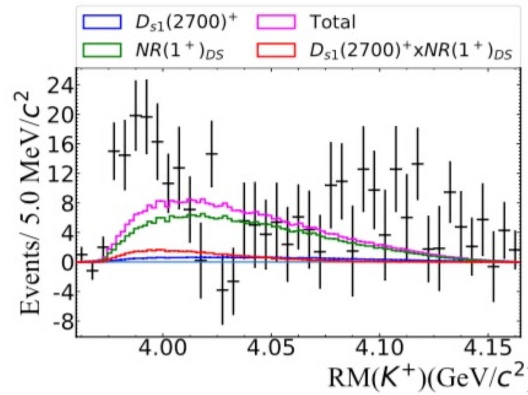
Interference effect of $K^+ D_s^- D^{*0}$ final states (2)



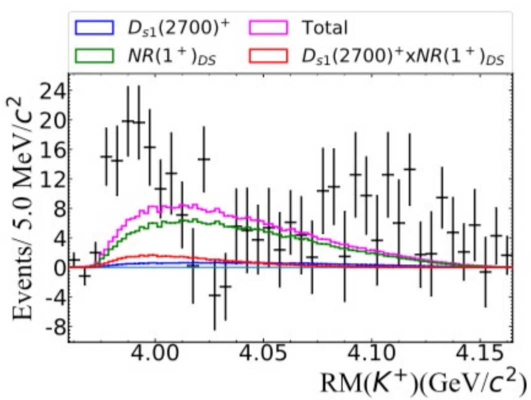
(g)$D_{s1}^*(2700)^+ D_s^-$ and $\bar{D}_1^*(2600)^0 D^{*0}$



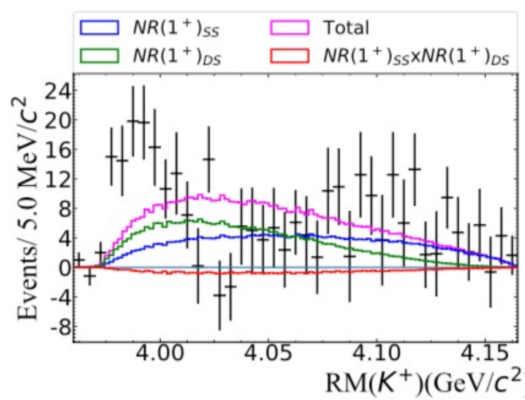
(h)$D_{s1}^*(2700)^+ D_s^-$ and NR $1^+(S, S)$



(i)$D_{s1}^*(2700)^+ D_s^-$ and NR $1^+(D, S)$



(j)$D_{s1}^*(2700)^+ D_s^-$ and NR $1^+(D, S)$



(k)NR $1^+(S, S)$ and NR $1^+(D, S)$

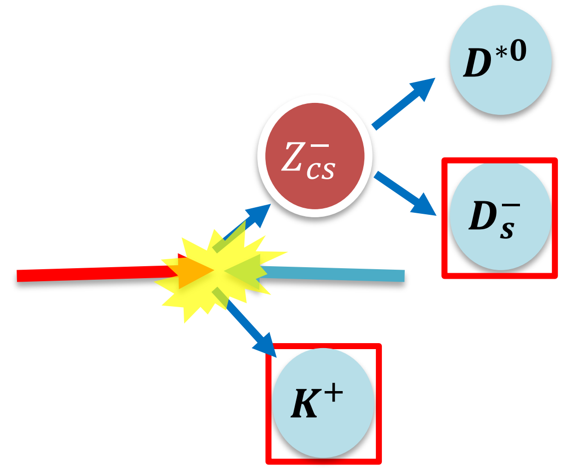
Interference between any two $D_{(s)}^{**}$/NR will not produce such a narrow peak we observed in data.

What do we studied?

- Do you clearly see $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ events? **Yes**
- Can the WS shape represent the combinatorial backgrounds? **Yes**
- Do you see an excess of data over the backgrounds? **Yes**
- Is the enhancement due to the $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ non-resonant process? **NO**
- Is the enhancement due to the $D_{(s)}^{**}$ resonant process? **NO**
- Is the enhancement due to interference effect between any $D_{(s)}^{**}$/NR? **NO**
- Can we try the assumption of $e^+e^- \to K^+ Z_{cs}^-, Z_{cs}^- \to D_s^- D^{*0}/D_s^{*-} D^0$ to interpret it? **Yes, we could.**

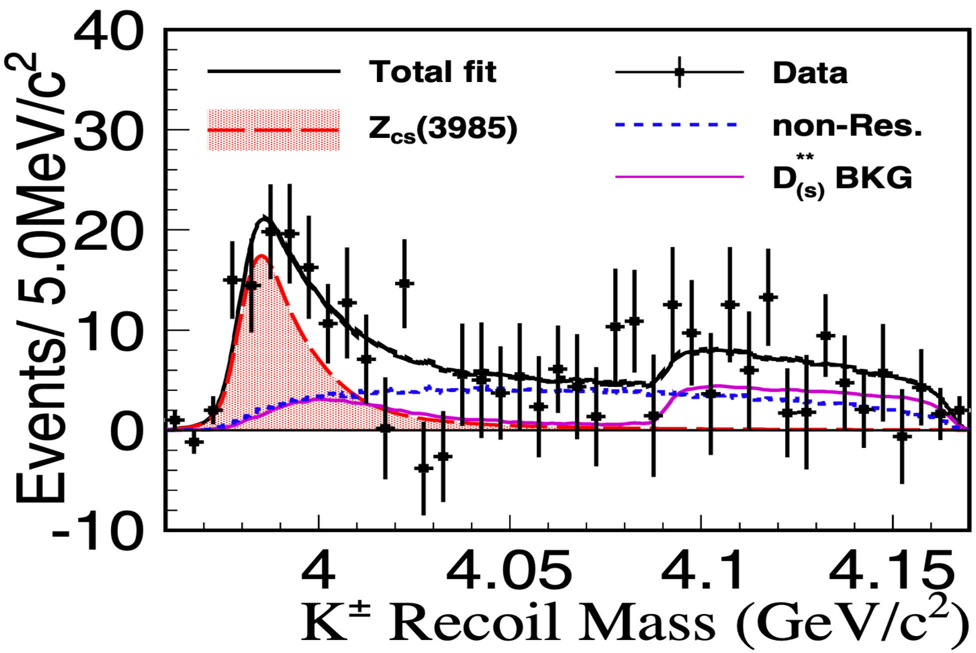
Observation of $Z_{cs}(3985)^-$

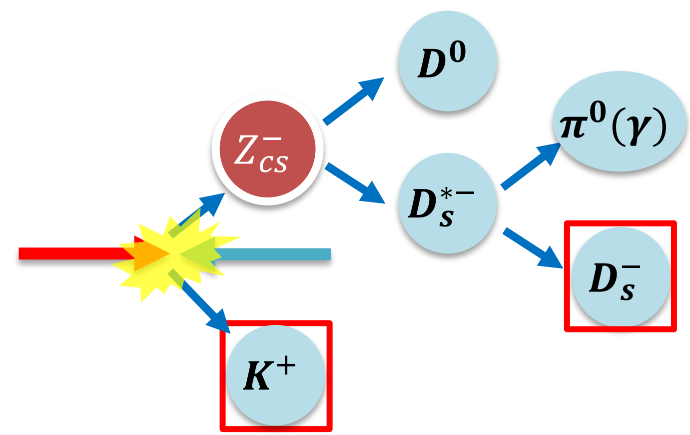
- $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$.
- 3.7fb^{-1} data between 4.62 and 4.7GeV.
- Partial reconstruction of the process, tag K^+ and D_s^-.
- Study the mass spectrum of **recoil mass of K$^+$**.



$e^+e^- \to K^+D_s^-D^{*0}$

PRL126.102001(2021)

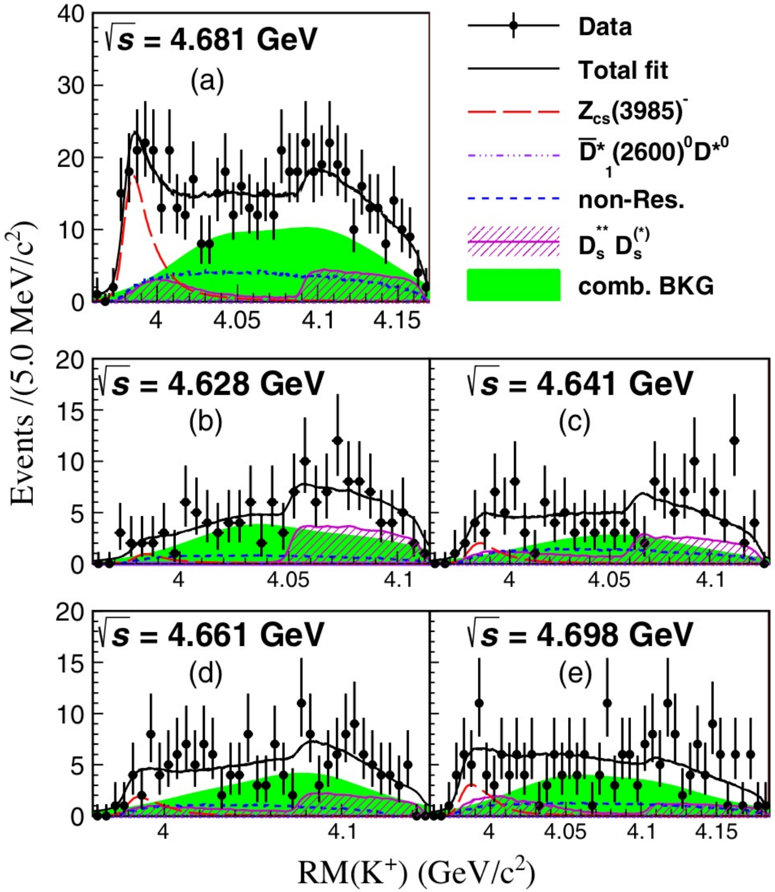




$e^+e^- \to K^+D_s^{*-}D^0$

Observation of $Z_{cs}(3985)^-$

PRL126.102001(2021)



- The J^P of $Z_{cs}(3985)^-$ is assumed as 1^+; =>(S,S) is the most promising configuration.
- Simultaneous unbinned maximum likelihood fit to five data samples.
- $Z_{cs}(3985)^-$ signal shape: S-wave Breit-Wigner with mass dependent width with phase-space factor.

$$\mathcal{F}_j(M) \propto \left| \frac{\sqrt{q \cdot p_j}}{M^2 - m_0^2 + i m_0 (f \Gamma_1(M) + (1-f)\Gamma_2(M))} \right|^2$$

$$\Gamma_j(M) = \Gamma_0 \cdot \frac{p_j}{p_j^*} \cdot \frac{m_0}{M}$$

$$m_0(Z_{cs}(3985)^-) = 3985.2^{+2.1}_{-2.0}(stat.) \pm 1.7(sys.)\ \mathrm{MeV/c^2}$$

$$\Gamma_0(Z_{cs}(3985)^-) = 13.8^{+8.1}_{-5.2}(stat.) \pm 4.9(\mathrm{sys.})\mathrm{MeV}.$$

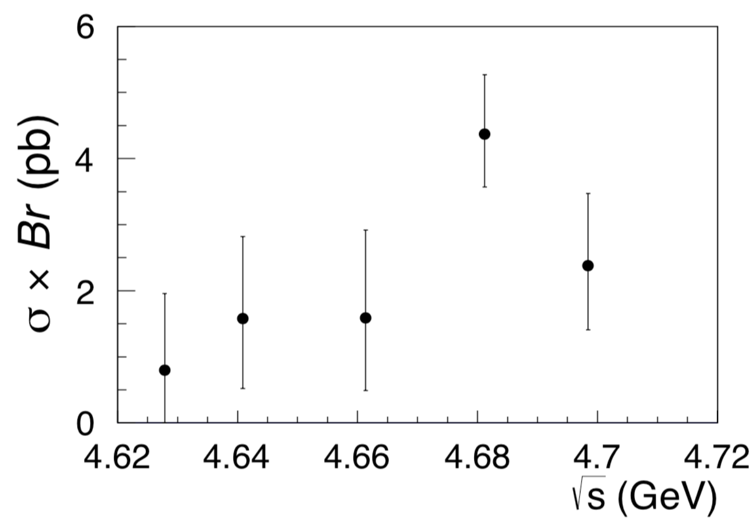
- The significance with systematic uncertainties and look-elsewhere effect considered is evaluated to **5.3σ.**
- At least four quark state (***$c\bar{c}s\bar{u}$***).
- Only a few MeV higher than the threshold of $D_s^- D^{*0}/D_s^{*-} D^0$ (3975.2/3977.0)MeV.

Cross-section measurement at each energy point

- Born cross section:

$$\sigma^{Born}(e^+e^- \to K^+ Z_{cs}^- + c.c.) \cdot \mathfrak{B}\left(Z_{cs}^- \to (D_s^- D^{*0} + D_s^{*-} D^0)\right)$$
$$= \frac{N_{obs}}{\mathcal{L}_{int} \cdot (1+\delta) \cdot f_{vp} \cdot (\tilde{\epsilon}_1 + \tilde{\epsilon}_2)/2}.$$

$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}$ ($\rm pb^{-1}$)	$n_{\rm sig}$	$f_{\rm corr}\bar{\varepsilon}$(%)	$\sigma^B \cdot \mathcal{B}$ (pb)
4.628	511.1	$4.2^{+6.1}_{-4.2}$	1.03	$0.8^{+1.2}_{-0.8} \pm 0.6\,(< 3.0)$
4.641	541.4	$9.3^{+7.3}_{-6.2}$	1.09	$1.6^{+1.2}_{-1.1} \pm 1.3\,(< 4.4)$
4.661	523.6	$10.6^{+8.9}_{-7.4}$	1.28	$1.6^{+1.3}_{-1.1} \pm 0.8\,(< 4.0)$
4.681	1643.4	$85.2^{+17.6}_{-15.6}$	1.18	$4.4^{+0.9}_{-0.8} \pm 1.4$
4.698	526.2	$17.8^{+8.1}_{-7.2}$	1.42	$2.4^{+1.1}_{-1.0} \pm 1.2\,(< 4.7)$



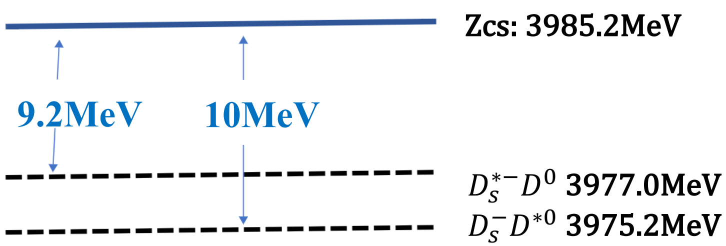
- Uncertainty is quite large,

- Any Y states around 4.68GeV?

Interpretation on the nature of $Z_{cs}(3985)^-$

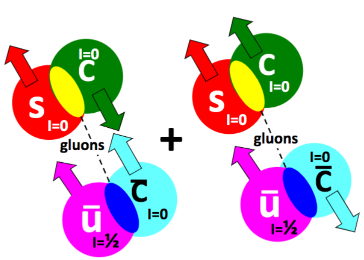
- **Various interpretations are possible for the structure**
  - 1) Tetraquark state
  - 2) Molecule
  - 3) $D_{s2}^*(2573)^+ D_s^{*-}$ threshold kinematic effects
    (Re-scattering , Reflection, Triangle singularity)
  - 4) Mixture of molecular and tetraquark
  - 5) …

arXiv:2011.08501
arXiv:2011.08628
arXiv:2011.08656
arXiv:2011.08725
arXiv:2011.08747
arXiv:2011.09156
arXiv:2011.09225
arXiv:2011.09244
arXiv:2011.09404
arXiv:2011.10495
arXiv:2011.10922
arXiv:2011.10959
arXiv:2011.11488
arXiv:2011.12230
arXiv:2011.12326

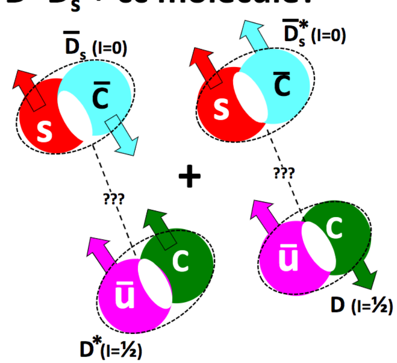


~10 MeV above D_sD^*/D_sD thresholds
similar to $Z_c(3900)$ & $Z_b(10,610)$
(DD*) (BB*)

diquark-antidiquark?



$D^*\bar{D}_s$ + cc molecule?



奇特强子态Zcs寻找

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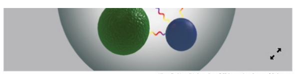
SYNOPSIS

New Tetraquark Spotted in Electron-Positron Collisions

March 11, 2021 • *Physics* 14, s33

The detection of a new particle containing both charm and strange quarks could offer new insights into how hadrons form.

美国物理学会《物理》杂志专题报道Zcs(3985)的发现



Xiao-Rui Lyu/University of Chinese Academy of Sciences

Creating particles composed of novel combinations of quarks in high-energy particle collisions lets physicists develop theories of quantum chromodynamics, which describe how quarks and gluons interact. Now, the BESIII Collaboration at the Beijing Electron Positron Collider in China has detected another example of such a combination—a "tetraquark" called Z_{cs} [1]. The result offers insight into how quarks are distributed inside a hadron.

Highlights

Observation of the Zcs(3985) strange four-quark meson

2021-03-12 Print Text Size A A

- the first hidden-charm tetraquark state with non-zero strangeness -

In the March 12th, 2021 issue of Physical Review Letters, the BESIII collaboration reports the discovery of an exoti multi-quark structure, dubbed the Zcs(3985), that is produced in the process of $e^+e^-\to K^+ (D_s^- D^{*0}+D_s^{*-}D^0)$ at an e^+ e center-of-mass energy of 4.68 GeV. The Zcs(3985) is observed to decay to a charged strange-charmed meson plus neutral charmed meson, i.e., $D_s^- D^{*0}+D_s^{*-}D^0$, and has a mass of 3.98 GeV/c^2. This is the first candidate for a tetra quark meson containing hidden-charm with non-zero strangeness. This paper was selected as an "Editors' Suggestion for that issue of the journal and was prominently featured on the APS synopsis website.

中国物理学会高能物理分会
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前沿热点 重要研究进展 CPC封面文章解读

北京谱仪III实验首次发现含奇异夸克的隐粲四夸克候选态Zcs(3985)

发布时间：2021/03/15

3月11日，《物理评论快报》(Physics Review Letters)发表了北京正负电子对撞机上北京谱仪(BESIII)实验新发现的首个含奇异夸克的隐粲四夸克候选态Zcs(3985)的成果[Phys. Rev. Lett. 126, 102001 (2021)]。相关研究成果论文被PRL选为当期"Feature in Physics"和编辑推荐文章，并在美国物理学会网站上以" New Tetraquark Spotted in Electron-Positron Collisions"为题报道。这是国际上首次发现含有奇异夸克的隐粲四夸克候选态Zcs信号。该成果在arXiv预印本网站发表不久后便引发了30多次相关研究工作的引用。

实验团队通过分析BESIII实验2020年新采集的46.8亿电子伏特(4.68 GeV)对撞能量的数据，在含有奇异夸克的粲介子衰变末态中发现了全新的四夸克候选态Zcs(3985)的信号，质量约为39.8亿电子伏特，相当于质子质量的4倍还多，其带有1个单位电荷，且衰变到1个中性粲介子(夸克成份$c\bar{u}$)和1个带电且含奇异夸克(s)的粲介子(夸克成份$\bar{c}s$)，所以它必然包含至少四个夸克成份($c\bar{c}s\bar{u}$)。

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Observation of a Near-Threshold Structure in the K^+ Recoil-Mass Spectra in $e^+e^-\to K^+(D_s^-D^{*0}+D_s^{*-}D^0)$

M. Ablikim *et al.* (BESIII Collaboration)
Phys. Rev. Lett. **126**, 102001 – Published 11 March 2021

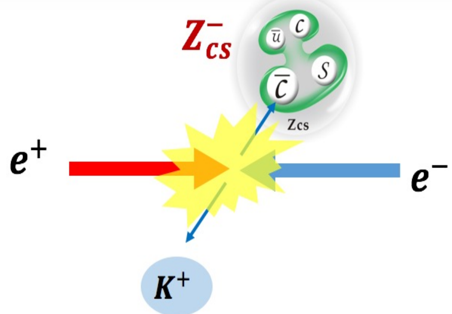
Physics See synopsis: New Tetraquark Spotted in Electron-Positron Collisions

Article References Citing Articles (23) Supplemental Material PDF HTML Export Citation

ABSTRACT

We report a study of the processes of $e^+e^-\to K^+D_s^-D^{*0}$ and $K^+D_s^{*-}D^0$ based on e^+e^- annihilation samples collected with the BESIII detector operating at BEPCII at five center-of-mass energies

《物理评论快报》选为当期“编辑推荐”(Editors’ Suggestion)和“物理特色”(Featured in Physics)论文



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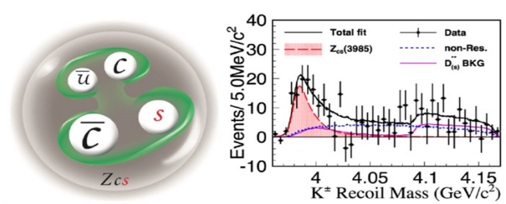
兰州大学粒子物理核物理团队首次发现含有奇异夸克的隐粲四夸克态信号

日期：2021-03-18 阅读：4175 来源：核科学与技术学院



北京谱仪III实验上发现四夸克态Zcs(3985)信号（红色阴影部分）

3月11日，《物理评论快报》（Physical Review Letters）发表了由兰州大学团队与中国科学院大学团队合作，主导完成的北京谱仪III实验含奇异夸克的隐粲四夸克态物理结果，并被选为当期编辑推荐文章(Editors’ Suggestion)和“Featurein Physics”。美国物理学会网站以“New Tetraquark Spotted in Electron-Positron Collisions”为标题对其进行了报道。本研究工作获得了国家自然科学基金委、科技部以及兰州大学人才建设经费及基本科研业务费的大力支持。

团队通过分析北京谱仪III实验2020年采集的对撞数据，在含有奇异夸克的粲介子衰变末态中发现了四夸克粒子Zcs(3985)的信号。这是国际上首次发现含有奇异夸克的隐粲四夸克粒子Zcs信号。该成果在arXiv预印本网站发表后不久，就引发了30余篇相关研究工作对此进行讨论。

实验上首次发现了一类全新的带电四夸克粒子Zcs(3985)，其夸克成分包含奇异夸克。

对于理解低能区非微扰量子色力学的行为具有重要的意义。引用率达170余次。

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e-Print: 2011.08725 [hep-ph]
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$Z_{cs}(3985)^-$ as the U-spin partner of $Z_c(3900)^-$ and implication of other states in the $\mathrm{SU}(3)_F$ symmetry and heavy quark symmetry #2
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Published in: *Eur.Phys.J.C* 81 (2021) 1, 51 • e-Print: 2011.08628 [hep-ph]
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About the exotic structure of Z_{cs} #4
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e-Print: 2011.08747 [hep-ph]
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The nature of charged charmonium-like states $Z_c(3900)$ and its strange partner $Z_{cs}(3982)$ #5
Meng-Chuan Du (South China Normal U. and Beijing, Inst. High Energy Phys.), Qian Wang (South China Normal U.), Qiang Zhao (South China Normal U. and Beijing, Inst. High Energy Phys. and Beijing, GUCAS) (Nov 18, 2020)
e-Print: 2011.09225 [hep-ph]
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$Z_{cs}(3985)^-$: A strange hidden-charm tetraquark resonance or not? #6
Rui Chen (Peking U., CHEP and Peking U. and Peking U., SKLNPT), Qi Huang (Beijing, GUCAS) (Nov 18, 2020)
Published in: *Phys.Rev.D* 103 (2021) 3, 034008 • e-Print: 2011.09156 [hep-ph]
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Explanation of the newly obseaved $Z_{cs}^-(3985)$ as a $D_s^{(*)-}D^{(*)0}$ molecular state #7
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Xiang-Kun Dong (SKLTP, Beijing and Beijing, GUCAS), Feng-Kun Guo (SKLTP, Beijing and Beijing, GUCAS), Bing-Song Zou (SKLTP, Beijing and Beijing, GUCAS and Central South U., Changsha) (Jan 4, 2021)
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Exotic $\bar{D}_s^{(*)}D^{(*)}$ molecular states and $sc\bar{q}\bar{c}$ tetraquark states with $J^P = 0^+, 1^+, 2^+$ #9
Qi-Nan Wang (Zhongshan U.), Wei Chen (Zhongshan U.), Hua-Xing Chen (Southeast U., Nanjing) (Nov 20, 2020)
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$Z_{cs}(3985)^-$ as the U-spin partner of $Z_c(3900)^-$ and implication of other states in the $\mathrm{SU}(3)_F$ symmetry and heavy quark symmetry #1
Lu Meng (Peking U., CHEP and Peking U. and Peking U., SKLNPT and Ruhr U., Bochum), Bo Wang (Peking U., CHEP and Peking U. and Peking U., SKLNPT), Shi-Lin Zhu (Peking U., CHEP and Peking U. and Peking U., SKLNPT) (Nov 17, 2020)
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Toward charged $Z_{cs}(3985)$ structure under a reflection mechanism #2
Jun-Zhang Wang (Lanzhou U. and Lanzhou, Inst. Modern Phys.), Qing-Song Zhou (Lanzhou U. and Lanzhou, Inst. Modern Phys.), Xiang Liu (Lanzhou U. and Lanzhou, Inst. Modern Phys.), Takayuki Matsuki (Tokyo Kasei U.) (Nov 17, 2020)
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$Z_{cs}(3985)^-$: A strange hidden-charm tetraquark resonance or not? #3
Rui Chen (Peking U., CHEP and Peking U. and Peking U., SKLNPT), Qi Huang (Beijing, GUCAS) (Nov 18, 2020)
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A survey of heavy-antiheavy hadronic molecules #4
Xiang-Kun Dong (SKLTP, Beijing and Beijing, GUCAS), Feng-Kun Guo (SKLTP, Beijing and Beijing, GUCAS), Bing-Song Zou (SKLTP, Beijing and Beijing, GUCAS and Central South U., Changsha) (Jan 4, 2021)
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Photoproduction of strange hidden-charm and hidden-bottom states #5
Xu Cao (Lanzhou, Inst. Modern Phys. and Beijing, GUCAS), Jian-Ping Dai (Yunnan U.), Zhi Yang (UESTC, Chengdu) (Nov 18, 2020)
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The newly observed $Z_{cs}(3985)^-$ state: in vacuum and a dense medium #6
K. Azizi (Tehran U. and Dogus U., Kadikoy), N. Er (Abant Izzet Baysal U.) (Nov 23, 2020)
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Xiang-Kun Dong (Beijing, Inst. Theor. Phys. and Beijing, GUCAS), Feng-Kun Guo (Beijing, Inst. Theor. Phys. and Beijing, GUCAS), Bing-Song Zou (Beijing, Inst. Theor. Phys. and Beijing, GUCAS) (Nov 29, 2020)
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Natsumi Ikeno (Tottori U. and Valencia U., IFIC), Raquel Molina (Valencia U., IFIC), Eulogio Oset (Valencia U., IFIC) (Nov 26, 2020)
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Decoding the nature of $Z_{cs}(3985)$ and establishing the spectrum of charged heavy quarkoniumlike states in chiral effective field theory #9
Bo Wang (Peking U., CHEP and Peking U. and Peking U., SKLNPT), Lu Meng (Ruhr U., Bochum), Shi-Lin Zhu (Peking U., CHEP and Peking U. and Peking U., SKLNPT) (Nov 21, 2020)
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Unified description of the hidden-charm tetraquark states $Z_{cs}(3985)$, $Z_c(3900)$, and $X(4020)$ #10
Zhi-Hui Guo (Southeast U., Nanjing and Hebei Normal U.), J.A. Oller (Murcia U.) (Dec 22, 2020)
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Yu.A. Simonov (Kurchatov Inst., Moscow) (Nov 24, 2020)
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Xiao-Dong Shi (CUST, SKLPDE and Hefei, CUST), Xiao-Rong Zhou (CUST, SKLPDE and Hefei, CUST), Xiao-Shuai Qin (SDU, Qingdao and Key Laboratory of Particle Physics and Particle Irradiation,Ministry of Education,Qingdao 266237, China), Hai-Ping Peng (CUST, SKLPDE and Hefei, CUST) (Nov 3, 2020)
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- **Full discussion from different models**
  - ✓ SU(3)F symmetry
  - ✓ Reflection
  - ✓ OBE model (vector, axial)
  - ✓ QCD Sum Rules
  - ✓ Threshold cusps
  - ✓ Chiral effective field theory
  - ✓ Effective range expansion
  - ✓ Recoupling
  - ✓ …

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Mar 22, 2021 by News Staff / Source
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Observation of Zcs(3985) Strange Four-quark Meson: First Hidden-charm Tetraquark State with Non-zero Strangeness
Editor: LIU Jia | Mar 12, 2021
In the March 12, the BESIII collaboration reports the discovery of an exotic multiquark structure, dubbed Zcs(3985), that is produced in the process of e+e-→K+(Ds-D*0+Ds*-D0) at an e+e- center-of-mass energy of 4.68 GeV. Zcs(3985) is observed to decay to a charged strange-charmed meson plus a neutral charmed meson, i.e., Ds-D*0+Ds*-D0, and has a mass of 3.98 GeV/c2.
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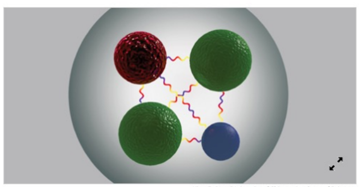
SYNOPSIS

New Tetraquark Spotted in Electron-Positron Collisions

March 11, 2021 • *Physics* 14, s33

The detection of a new particle containing both charm and strange quarks could offer new insights into how hadrons form.



Creating particles composed of novel combinations of quarks in high-energy particle collisions lets physicists develop theories of quantum chromodynamics, which describe how quarks and gluons interact. Now, the BESIII Collaboration at the Beijing Electron Positron Collider in China has detected another example of such a combination—a "tetraquark" called Z_{cs} [1]. The result offers insight into how quarks are distributed inside a hadron.

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兰州大学粒子物理核物理团队首次发现含有奇异夸克的隐粲四夸克态信

日期: 2021-03-18 阅读: 4175 来源: 核科学与技术学院

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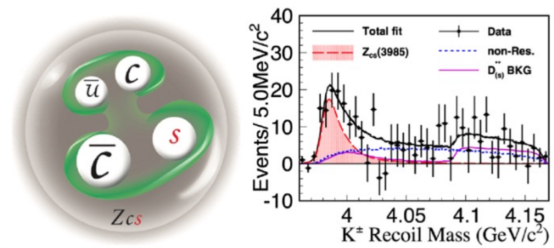


北京谱仪III实验上发现四夸克态Zcs(3985)信号（红色阴影部分）

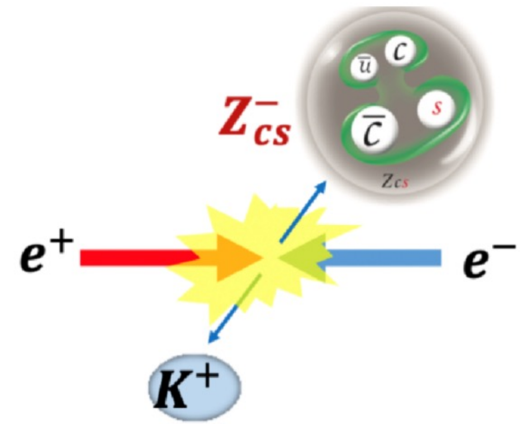
3月11日，《物理评论快报》（Physical Review Letters）发表了由兰州大学团队与中国科学院大学团队合作，主导完成的北京谱仪III实验含奇异夸克的隐粲四夸克态物理结果，并被选为当期编辑推荐文章(Editors' Suggestion)和"Featurein Physics"。美国物理学会网站以"New Tetraquark Spotted in Electron-Positron Collisions"为标题对其进行了报道。本研究工作获得了国家自然科学基金委、科技部以及兰州大学人才建设经费及基本科研业务费的大力支持。

020年采集的对撞数据，在含有奇异夸克的粲介子衰变末态中发现了四夸克粒
首次发现含有奇异夸克的隐粲四夸克粒子Zcs信号。该成果在arXiv预印本网站
研究工作对此进行讨论。

兰大故事 | 兰州大学粒子物理核物理团队首次发现含有奇异夸克的隐粲四夸克态信号

兰小招 兰州大学本科招生 3月25日

兰州大学粒子物理核物理团队首次发现含有奇异夸克的隐粲四夸克态信号。



四夸克态Zcs在正负电子对撞机上产生示意图

负责人介绍一

多夸克强子的实验研究对完善人们对于宇宙中物质最基本结构的理解具有重要科学意义，是国际粒子物理界当前的热点问题。针对这一基础前沿问题，兰州大学核科学与技术学院、稀有同位素前沿科学中心青年研究员李培荣带领团队成员深度参与北京谱仪III实验项目。"在2020年疫情期间，团队成员积极参与实验数据获取及离线数据质量监测。在保证数据质量的基础上，深入理解对撞产生的实验数据，精心设计分析算法和筛选逻辑，对Zcs产生以及衰变链条进行有针对性的寻找和测量。通过一年多时间的连续奋战，反复验证，排除了所有可能性，最终确认了Zcs的存在。Zcs信号的产率低，本底复杂，观测难度非常大。"北京谱仪III实验合作组兰州大学团队负责人李培荣介绍道。

Highlights

Observation of the Zcs(3985) strange four-quark meson

2021-03-12 Print Text Size A A

- the first hidden-charm tetraquark state with non-zero strangeness -

In the March 12th, 2021 issue of Physical Review Letters, the BESIII collaboration reports the discovery of an exotic multi-quark structure, dubbed the Zcs(3985), that is produced in the process of $e^+e^- \to K^+(D_s^- D^{*0}+D_s^{*-}D^0)$ at an e^+e^- center-of-mass energy of 4.68 GeV. The Zcs(3985) is observed to decay to a charged strange-charmed meson plus a neutral charmed meson, i.e., $D_s^- D^{*0}+D_s^{*-}D^0$, and has a mass of 3.98 GeV/c^2. This is the first candidate for a tetra-quark meson containing hidden-charm with non-zero strangeness. This paper was selected as an "Editors' Suggestion" for that issue of the journal and was prominently featured on the APS synopsis website.

Zcs(3985)的发现引发国内外的广泛关注，短时间内40余篇理论文章引用解释。多次在国际会议报告。

中性奇特强子态Zcs0的发现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兰州大学粒子物理核物理团队首次寻找到含奇异夸克的中性隐粲四夸克态的存在证据

日期: 2022-10-04 阅读: 1476 来源: 核科学与技术学院

近日，《物理评论快报》（Physical Review Letters）正式发表了由兰州大学核科学与技术学院、稀有同位素前沿科学中心粒子物理核物理团队与印第安纳大学、中国科学院高能物理研究所、山东大学、中国科学院大学合作完成的北京谱仪III实验含奇异夸克的中性隐粲四夸克态物理结果。这是对中性含奇异夸克隐粲四夸克态的首次实验报道，是奇特强子态实验研究的又一进展。

同位旋伴随的中性Z_{cs}^0粒子

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物理前沿

发现新型四夸克态Zcs(3985)

李培荣[1] 吕晓睿[2] 郑阳恒[2]

（1. 兰州大学 730000；2. 中国科学院大学 100049）

DOI:10.13405/j.cnki.xdwz.2021.03.011

2020年11月16日，北京谱仪 III(BESIII) 实验国际合作组利用在疫情期间采集的实验数据，发现了一个新型的奇特态，命名为Z_{cs}(3985)。该成果在arXiv预印本网站发表不久后便被引用近40次。该结果最终于2021年3月11日发表在国际权威物理期刊*Physics Review Letters* (PRL)上，并被PRL选为当期编辑推荐文章，在美国物理学会网站做推广介绍。这是国际上首次发现含有奇异夸克的隐粲四夸克态信号。该发现之所以如此吸引人们的关注，还得从粒子物理中量子色动力学(QCD)和奇特强子态说起。

从公元前4世纪古希腊的德谟克里特和亚里士多德开始就对物质的基本结构开始了思考和探索。我国在战国时期以公孙龙为代表的思想家提出了物质无限可分的思想。在19世纪，科学家逐渐了解到，组成我们周围物质的基本单元是由原子构成并且不同元素的物理化学性质具有周期性，进而

的。描述物质最基本组成结构和基本粒子间相互作用的理论被称为标准模型，它已经被大量实验证实。在标准模型的框架下，参与强作用的基本粒子包含了三代共6味夸克和它们的反夸克(图2)。强力把多个夸克束缚在一起形成强子，包括在实验上确认的含2个夸克的介子(如J/ψ粒子、D介子)和含3个夸克的重子(图3)。我们熟悉的质子和中子就属于重子。1974年丁肇中先生因为发现J/ψ粒子，

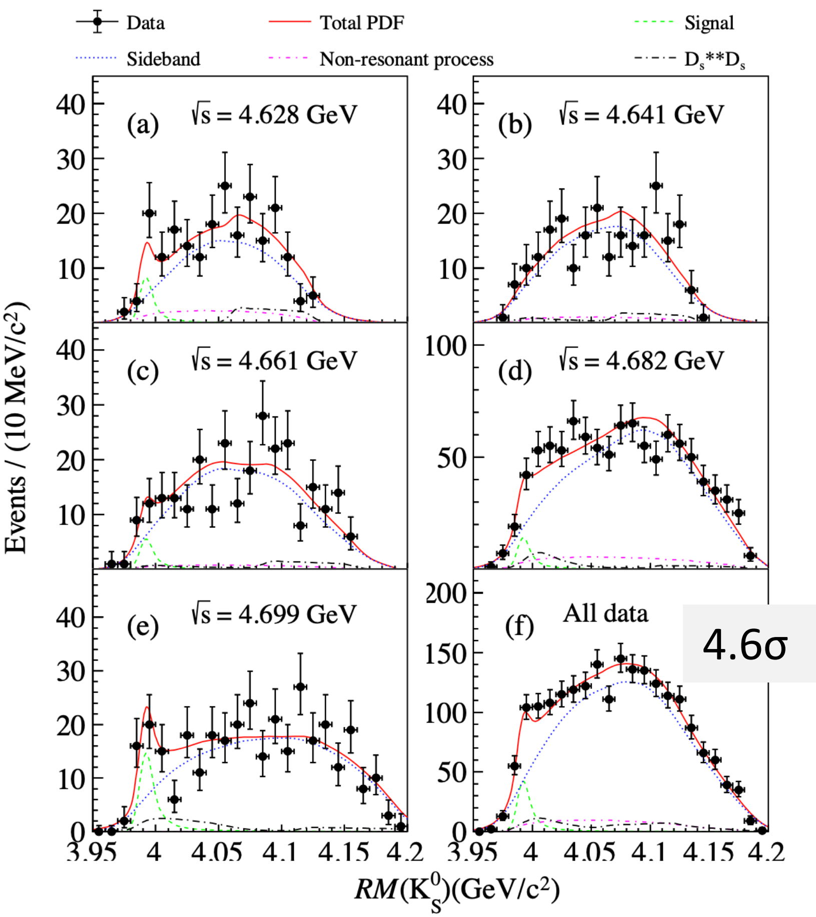
国际著名理论物理学家、 欧洲核子研究中心前所长、狄拉克奖章获得者 、意大利罗马大学Luciano Maiani 教授在Science Bulletin 66.1616(2021) 以及中科院理论所邹冰松院士Phys. Rev. Lett. 126 (2021) 152001上高度评价

实验上首次发现了带电四夸克粒子Zcs(3985) 的中性伴随态，其夸克成分包含奇异夸克。

确定了Zcs粒子的同位旋性质。国际上引起了广泛的讨论和研究。

$Z_{cs}(3985)^0$

PRL129.112003(2022)



- $e^+e^- \rightarrow K_S^0(D_s^+D^{*-} + D_s^{*+}D^-)$
- Similar technique, check in the recoil against K_S^0

$m_0(Z_{cs}(3985)^-) = 3985.2^{+2.1}_{-2.0}(stat.) \pm 1.7(sys.)\ MeV/c^2$

$\Gamma_0(Z_{cs}(3985)^-) = 13.8^{+8.1}_{-5.2}(stat.) \pm 4.9(\text{sys.})MeV.$

$m_0(Z_{cs}(3985)^0) = 3992.2 \pm 1.7(stat.) \pm 1.6(sys.)\ \text{MeV/c}^2$

$\Gamma_0(Z_{cs}(3985)^0) = 7.7^{+4.1}_{-3.8}(stat.) \pm 4.3(\text{sys.})MeV$

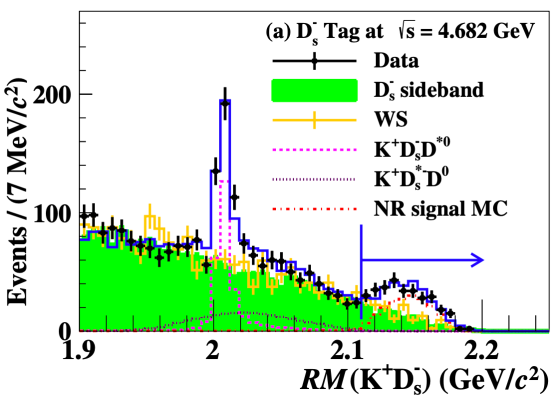
TABLE V. Born cross sections multiplied by branching fraction of $\bar{K}^0 Z_{cs}(3985)^0$ and $K^- Z_{cs}(3985)^+$ at the five energy points. The χ^2/ndf quantifies the compatibility of the five measurements.

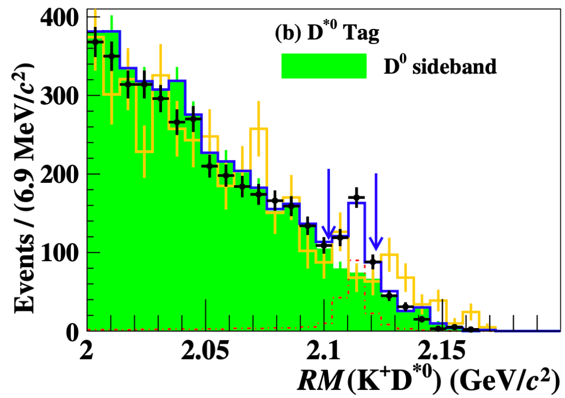
$\sqrt{s}$ (MeV)	$\sigma^{\text{Born}} \times \mathcal{B}$(pb) $\bar{K}^0 Z_{cs}(3985)^0$	$K^- Z_{cs}(3985)^+$	χ^2	χ^2_{total}/ndf
4628	$4.4^{+2.6}_{-2.2} \pm 2.0$	$0.8^{+1.2}_{-0.8} \pm 0.6$	1.2	
4641	$0.0^{+1.6}_{-0.0} \pm 0.2$	$1.6^{+1.2}_{-1.1} \pm 1.3$	0.5	
4661	$2.8^{+1.8}_{-1.6} \pm 0.6$	$1.6^{+1.3}_{-1.1} \pm 0.8$	0.3	5.1/5
4682	$2.2^{+1.2}_{-1.0} \pm 0.8$	$4.4^{+0.9}_{-0.8} \pm 1.4$	1.0	
4699	$7.0^{+2.2}_{-2.0} \pm 1.8$	$2.4^{+1.1}_{-1.0} \pm 1.2$	2.1	

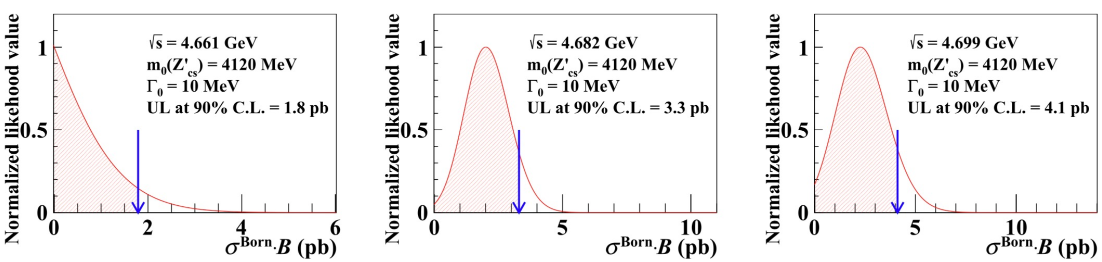
We conclude $Z_{cs}(3985)^0$ is the isospin partner of the $Z_{cs}(3985)^+$

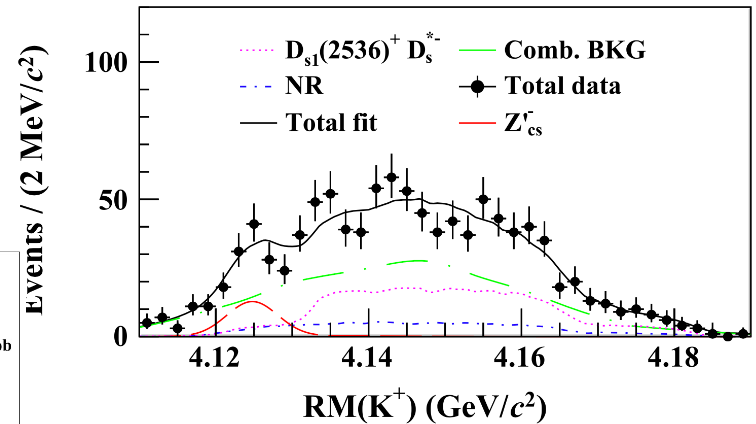
The charged Z'^{-}_{cs}

Chin. Phys. C 47, 033001 (2023)







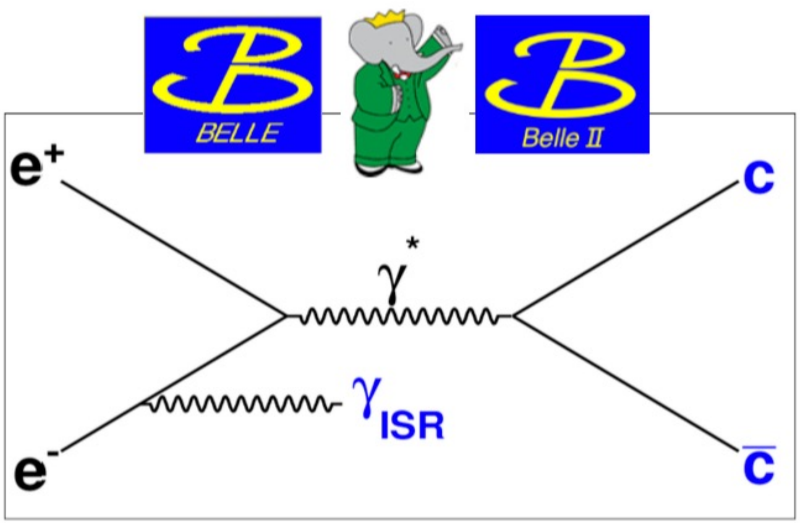


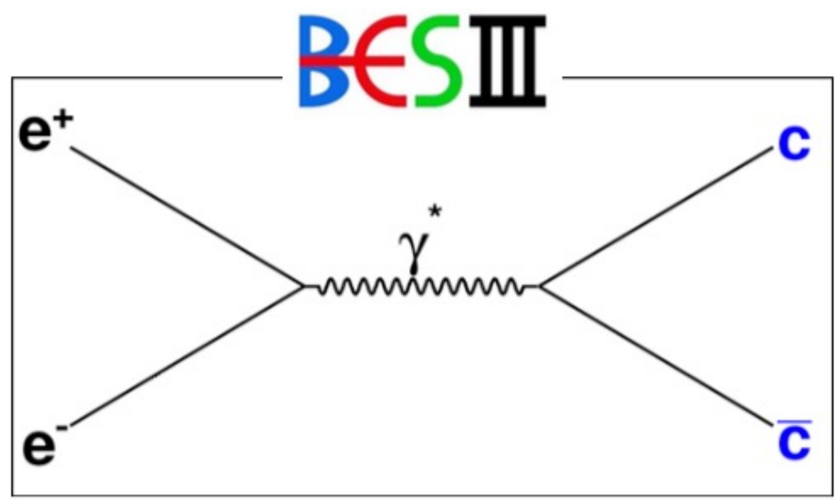
- Search for excited partner of $Z_{cs}(3985)^+$ in $e^+e^- \to K^+D_s^{*-}D^{*0}$+c.c.
- Two different tag-methods (D_s^--tag and D^{*0}-tag) are adopted.
- Evidence for Z'^{-}_{cs} state $M(Z'^{-}_{cs}) = 4123.5 \pm 0.7(stat.) \pm 4.7(sys.)$ MeV/c^2
- Significance is 2.1σ (3.9σ) w/o considering systematic uncertainties.
- Statistics limited, decay width hypotheses are tested.

  =>$M(Z'^{-}_{cs}) = 4124.1$MeV/c^2 under 10MeV decay width with local significance 4.1σ.
- Cross section upper limit @C.L.90% are estimated to $\mathcal{O}(1)$ pb.

The Y states

Measurements of more final states for the Y and ψ states

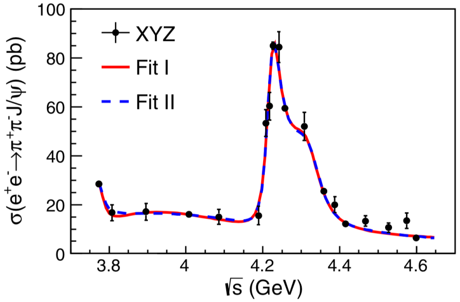




Y(4220)

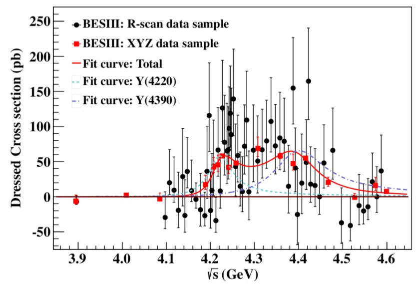
PRL.118.092001(2017)

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



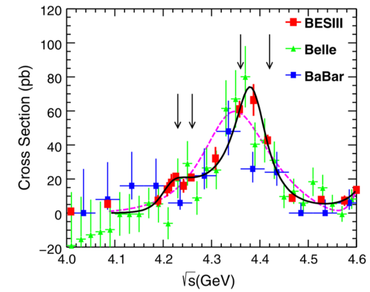
PRL.118.092002(2017)

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



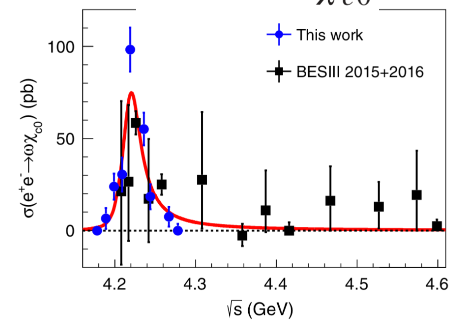
PRD.96.032004(2017)

$e^+e^- \to \pi^+\pi^- \psi(3686)$

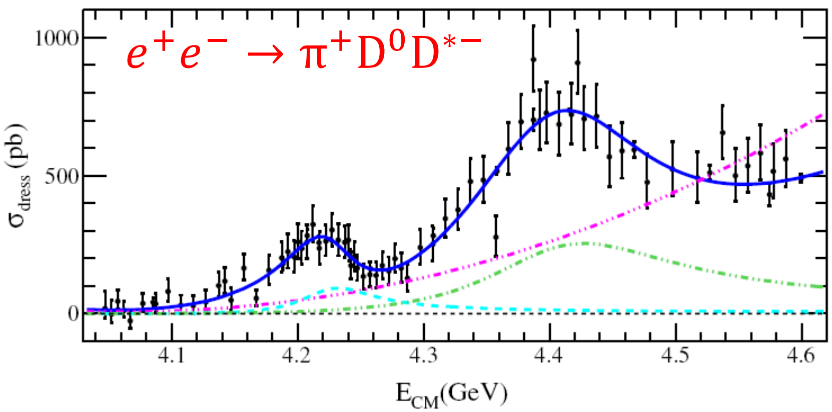


PRD.99. 091103(2019)

$e^+e^- \to \omega\chi_{c0}$



PRL. 122, 102002 (2019)



Y(4220) appeared in above processes.
Mass:4220MeV, Width~60 MeV!

- Y(4260) has been discovered by BaBar experiment in the mass spectrum m($\pi^+\pi^- J/\psi$) and confirmed by Belle.
- BESIII measured the cross section of different processes.
- The mass and width of Y(4220) and Y(4360) from the different processes are measured.
- Two resonances describe the data with high significance than the fit with single peak.
- The intrinsic scenario for the difference on width is still unknown.

Recent progress on Y studies at BESIII

$e^+e^- \to \pi^0\pi^0 J/\psi$ PRD.102.012009(2020)

$e^+e^- \to \eta J/\psi$ PRD.102.031101(RC)(2021)

$e^+e^- \to \eta' J/\psi$ PRD101.012008(2020)

$e^+e^- \to \eta_c\pi^+\pi^-\pi^0$ PRD103.032006(2021)

$e^+e^- \to K^+K^- J/\psi$ Chin. Phys. C 46, 111002 (2022)

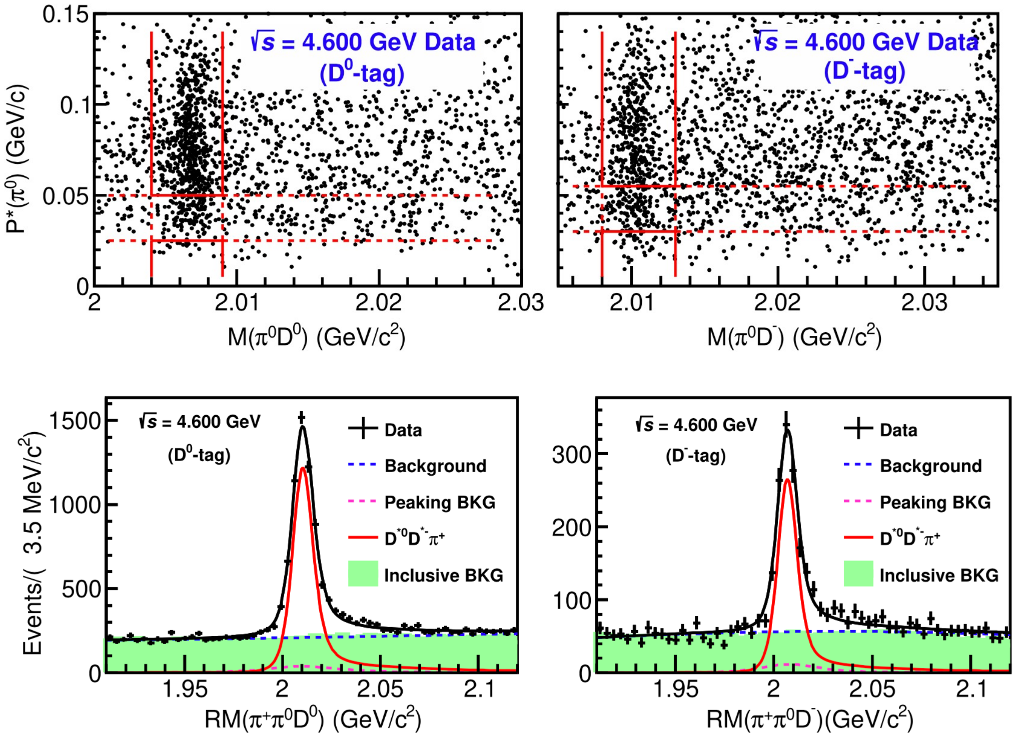
$e^+e^- \to \pi^+\pi^- D^+D^-$ PRD106.052012(2022)

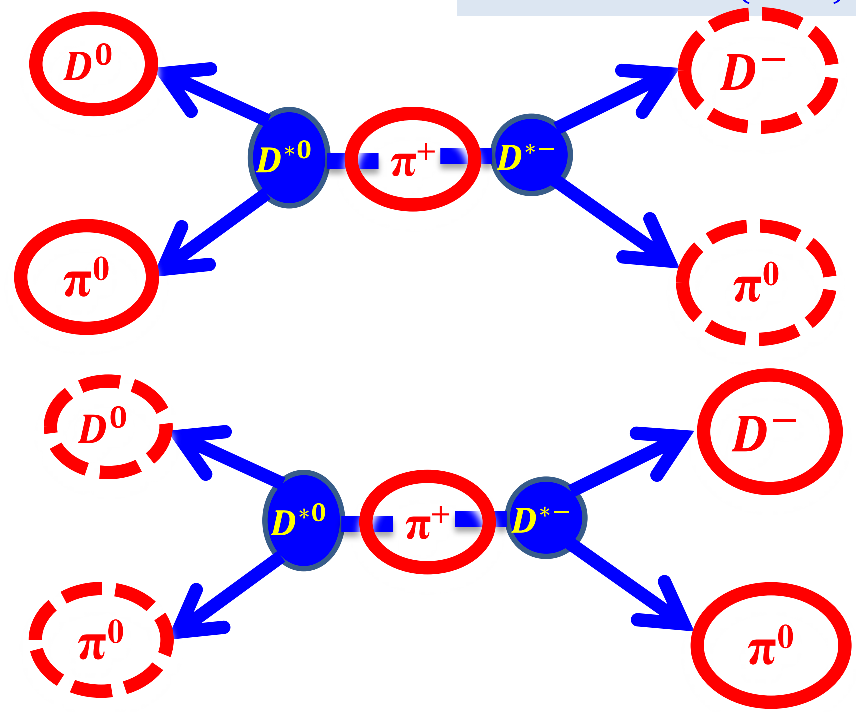
$e^+e^- \to D^{*+}D^{*-}$、 $D^{*+}D^-$ JHEP05.155(2022)

Y(4220) couple to hidden-charm final states more easier?

Cross section of $e^+e^- \to D^{*0}D^{*-}\pi^+$

PRL130.121901(2023)

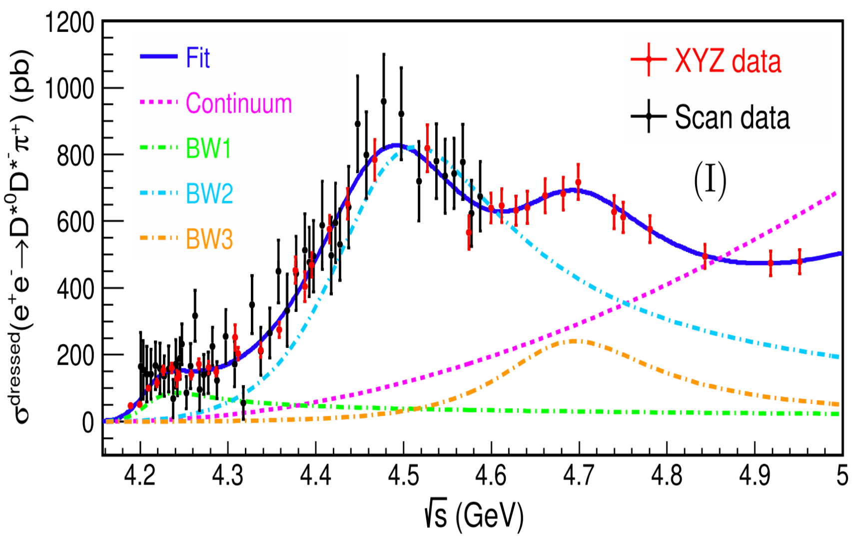




- Similar technique is adopted with the paper on $Z_c(4025)^+$ in $e^+e^- \to \pi^+D^{*0}D^{*-}$+c.c.
- Two different tag-methods (D^{*0}-tag and D^{*-}-tag) are simultaneously considered.
- Evident $e^+e^- \to \pi^+D^{*0}D^{*-}$ signals.
- No peaking background observed in background MC samples but some low level unmatched events from fake photon;

Three charmonium-like structures are observed in $D^{*0}D^{*-}\pi^{+}$

PRL130.121901(2023)



$m_1 = 4209.6 \pm 4.7 \pm 5.9$ MeV/c^2
$\Gamma_1 = 81.6 \pm 17.8 \pm 9.0$ MeV

$m_2 = 4469.1 \pm 26.2 \pm 3.6$ MeV/c^2
$\Gamma_2 = 246.3 \pm 36.7 \pm 9.4$ MeV

$m_3 = 4675.3 \pm 29.5 \pm 3.5$ MeV/c^2
$\Gamma_3 = 218.3 \pm 72.9 \pm 9.3$ MeV

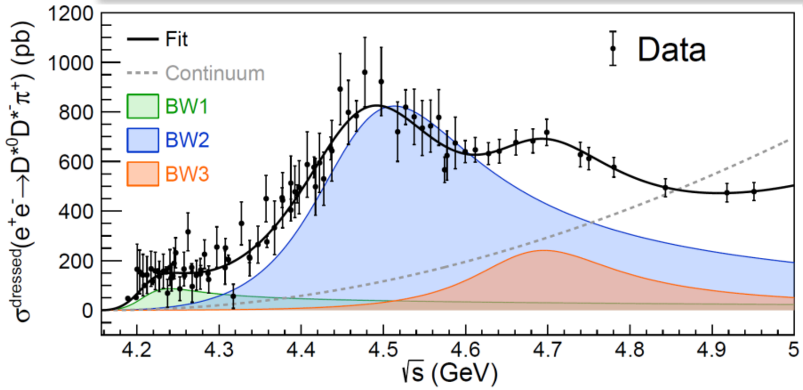
- Cross section at 86 energy points are measured.
- Three charmonium-like structures found in $D^{*0}D^{*-}\pi^{+}$ final state(>10σ).
- Left and right structures consistent with Y(4230) and Y(4660)

  =>Disfavor hybrid interpretation of Y(4230). Same order with $D^{0}D^{*-}\pi^{+}$.

  =>First observation of Y(4660) in open charm final states.
- Center structure compatible with Y(4500) observed in $K^{+}K^{-}J/\psi$

  =>two order lager coupling, disfavor hidden-strangeness tetraquark nature

奇特强子态寻找



截面谱上发现了三个$J^{PC}=1^{--}$的类粲偶素态

提供了丰富的共振态参数以及耦合强度信息。

PRL 审稿人高度赞扬了该工作对于理解粲偶素能区物理的重要性

Open Access

Observation of Three Charmoniumlike States with $J^{PC}=1^{--}$ in $e^+e^-\to D^{*0}D^{*-}\pi^+$

M. Ablikim *et al.* (BESIII Collaboration)

Phys. Rev. Lett. **130**, 121901 – Published 23 March 2023

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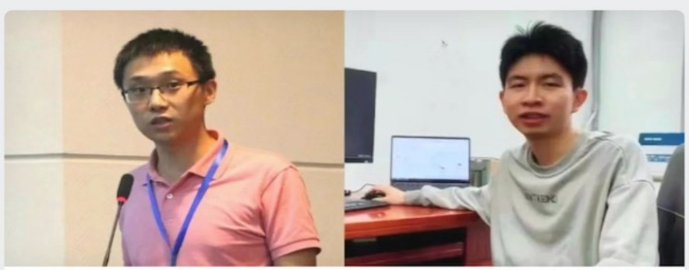
ABSTRACT

The Born cross sections of the process $e^+e^-\to D^{*0}D^{*-}\pi^+$ at center-of-mass energies from 4.189 to 4.951 GeV are measured for the first time. The data samples used correspond to an integrated luminosity of 17.9 fb^{-1} and were collected by the BESIII detector operating at the BEPCII storage ring. ...e enhancements around 4.20, 4.47, and 4.67 GeV are visible. The resonances have masses of ... with the ... are obse...

兰州大学

4月7日 14:41



兰大本科生又发top!竟和《三体》粒子对撞机是一个领域......

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原创 一流本科教育看 兰州大学 2023-04-07 14:40 发表于甘肃

自强不息 独树一帜

2023年3月23日，《物理评论快报》(Physical Review Letters) 正式发表了稀有同位素前沿科学中心、核科学与技术学院李培荣教授联合中国科学院大学粒子物理实验团队在北京谱仪III实验上主导完成的对显粲三体过程$e^+e^-\to D^{*0}D^{*-}\pi^+$的产生截面测量工作。在截面线形分布上观测到了**三个类粲偶素态**，分别位于4.21GeV，4.47GeV和4.68GeV，且宽度都大于50MeV。**这些类粲偶素态作为奇特强子态的候选者**，与夸克模型预言的粲偶素有明显的区别。

我校**2018级本科生许昭燊同学在李培荣教授**的指导下主导完成了此项工作，**许昭燊现于**中国科学院大学物理科学学院**就读研究生**。

高能物理实验的三大主要工作方向

探测器设计、建造、取数
（硬件）

↓

数据重建、模拟
（软件）

↓

物理分析 ↔ 理论研究

高能物理研究团队性强，需要各方面人才紧密配合

“四好”学生

物理好
（包括理论基础好、物理概念清楚）

计算机知识好
编程好

英语好

统计知识好

谢谢！