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Production of Exotic Hadrons at LHC

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8/11/2014 杭州

13th LHC Physics Mini-Workshop

With Feng-Kun Guo, Ulf-G. Meissner and Zhi Yang

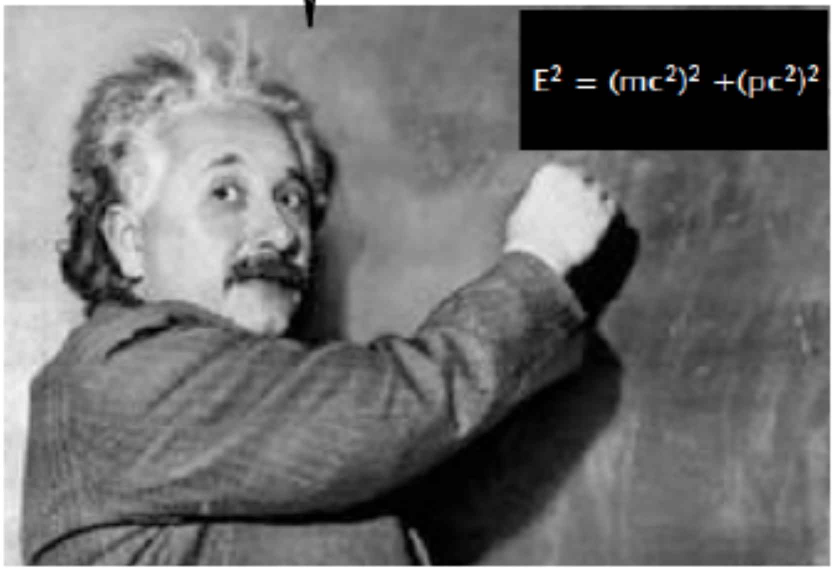
Large Hadron Collider

Content

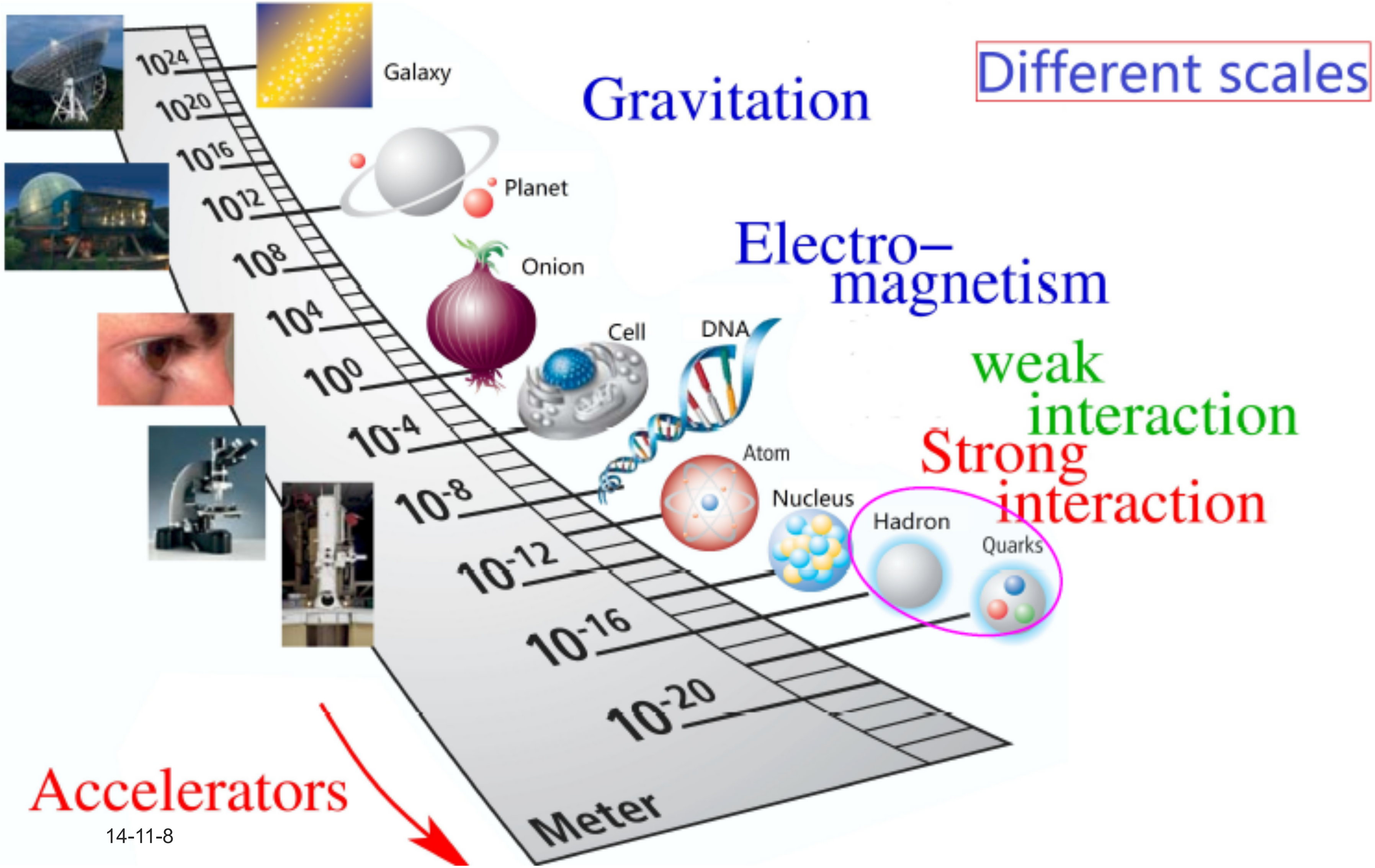
- Motivation for Hadron exotics
- How to reliably study exotic states?
  A: Effective Field Theory, ….
- Hadron molecule
- Production at LHC
- Summary

What do particle physicist pursue?

What makes up the Universe?
How did it come to be?

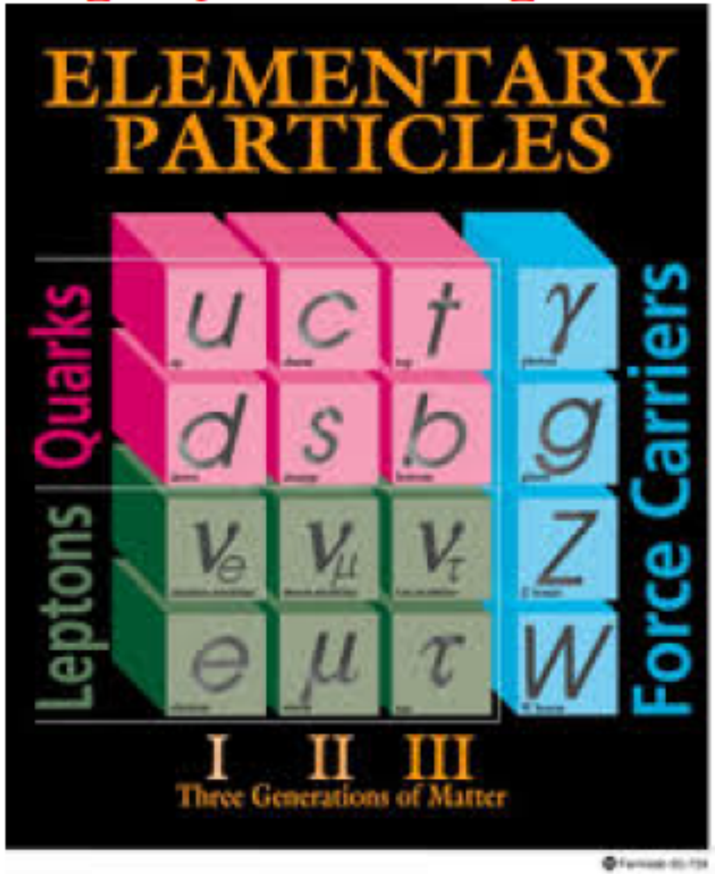


Introduction: fundamental interactions



What makes up this world?

- particle physicist: quarks, leptons



Standard model

Mass Origin

- Gauge boson: Higgs Mechanism
- Quarks and Leptons: Yukawa Coupling
- Matter in this world:

  p/n: 1GeV u/d: a few MeV

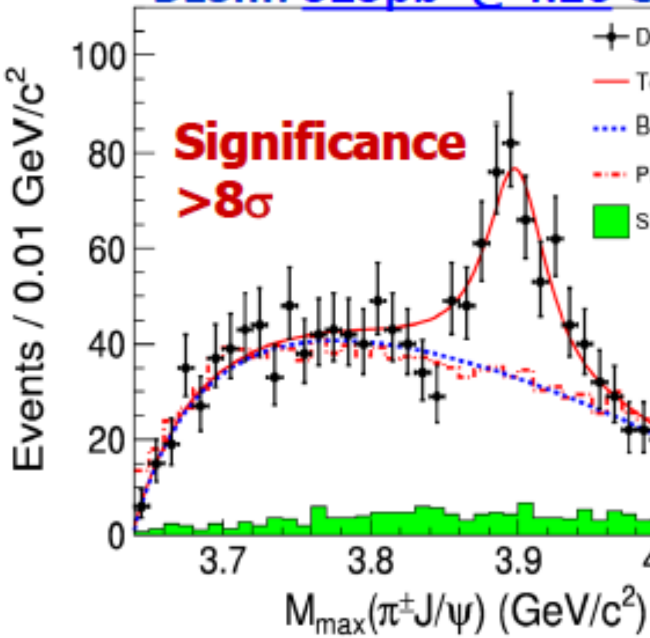
  strong interaction: important to understand but difficult..

Great Progress in Particle Physics

- Higgs boson: ATLAS,CMS, …
- Neutrino: θ_{13} Daya-Bay, …
- Hadron Exotics: BES, Belle, LHCb, BaBar, CLEO,…
- …..

Observation of Zc(3900) at BESIII

BESIII: 525pb^{-1}@4.26 GeV

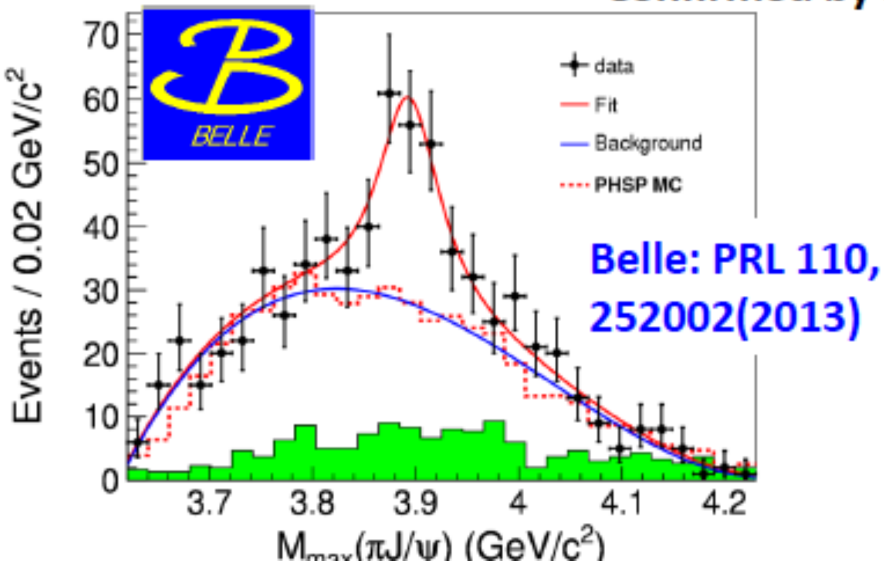


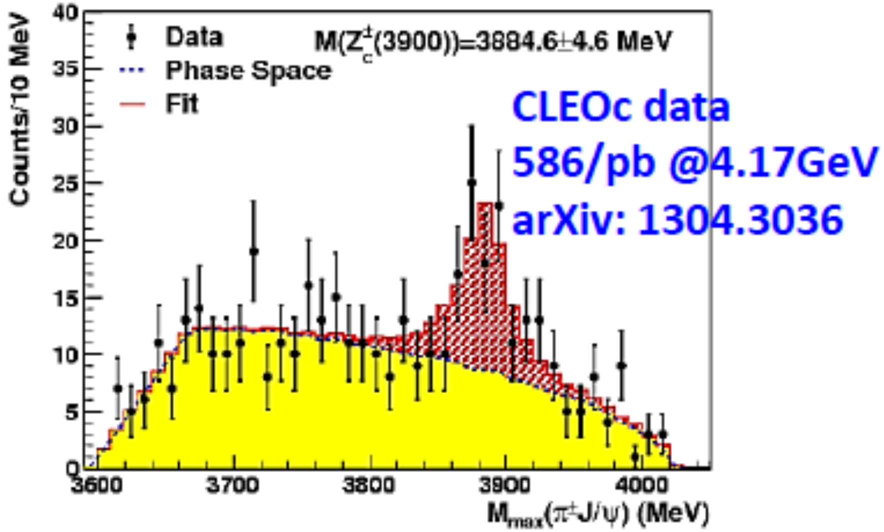
BESIII: PRL110, 252001 (2013)

- M = 3899.0±3.6±4.9 MeV
- Γ = 46±10±20 MeV
- 307 ± 48 events

The mass position is 24 MeV away from DD* threshold!
A partial wave analysis is on going!

Confirmed by Belle and CLEOc: established!



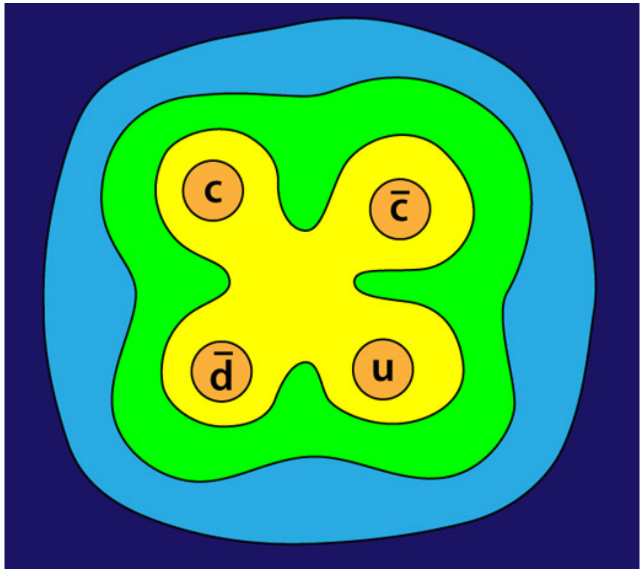


$Z_c(3900)$ is exotic!

$Z_c \rightarrow J/psi\pi \rightarrow Z_c$ state contains a cc quark pair

charge = ± 1 ➔ Z_c must contain additional light quarks

$Z_c^+=$



“minimal” quark configuration : Four-quark states!

Physics
spotlighting exceptional research

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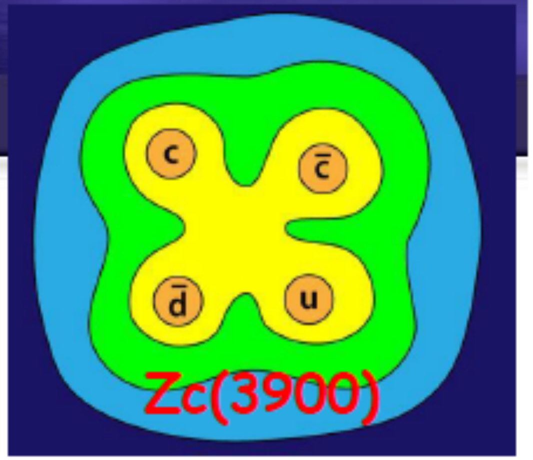


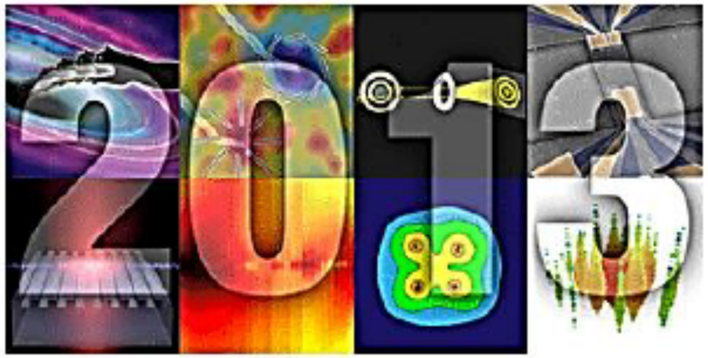
Notes from the Editors: Highlights of the Year

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

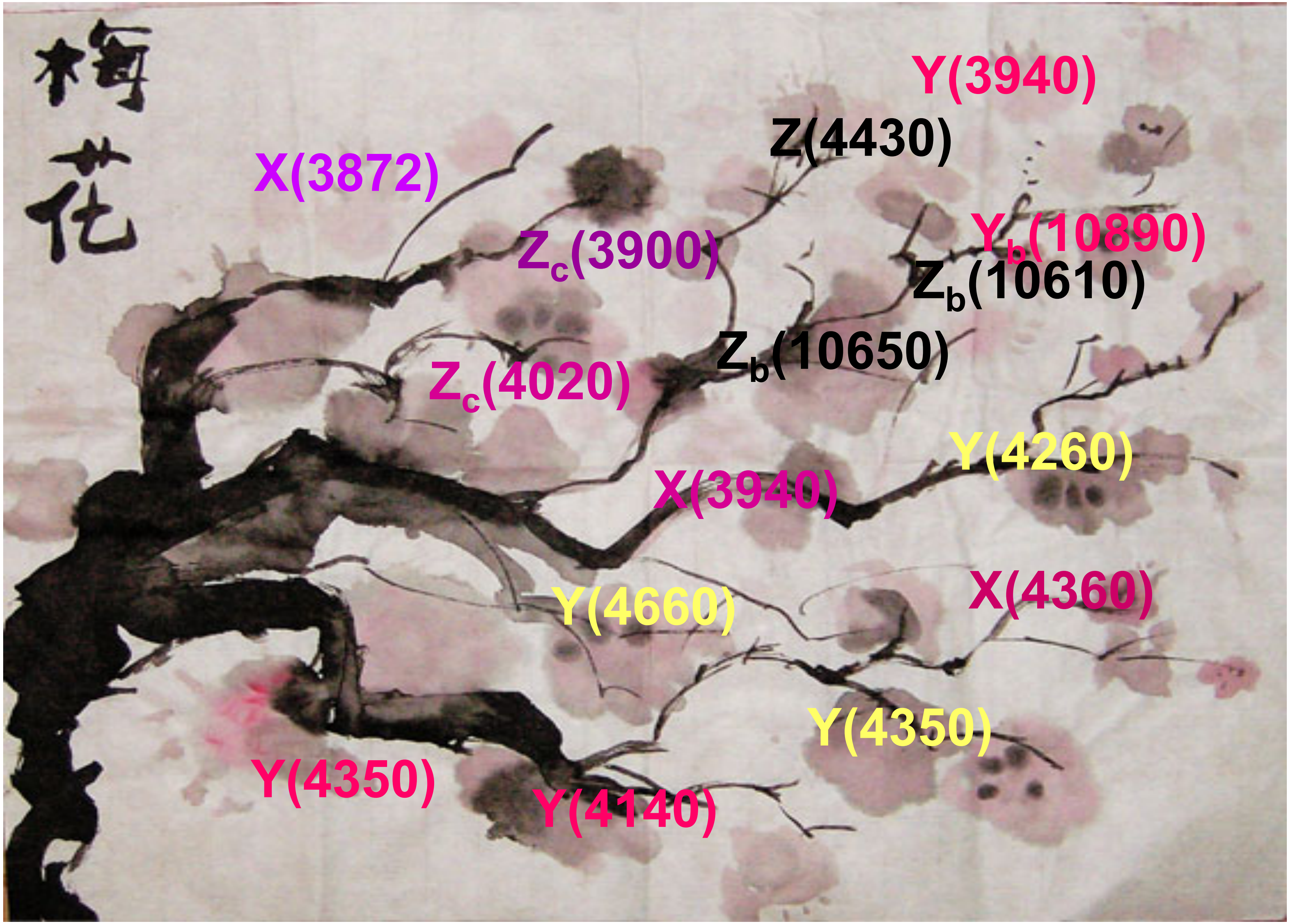


Images from popular *Physics* stories in 2013.

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.

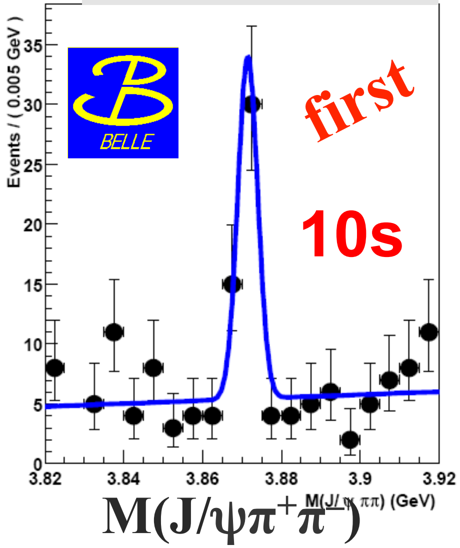
$Z_c(3900)$ is not alone



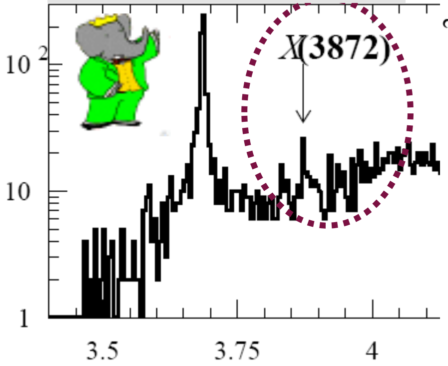
X(3872) observation

X(3872) first seen in $B \to K\, J/\psi \pi^+\pi^-$

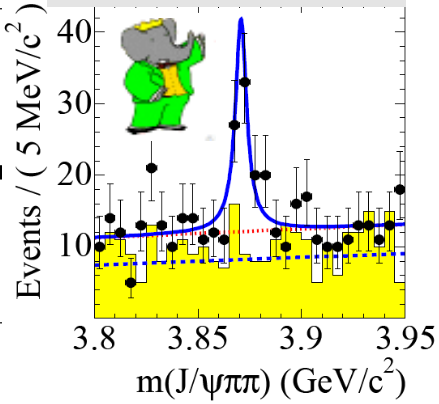
PRL91,262001,2003



PRD71,071103,2005



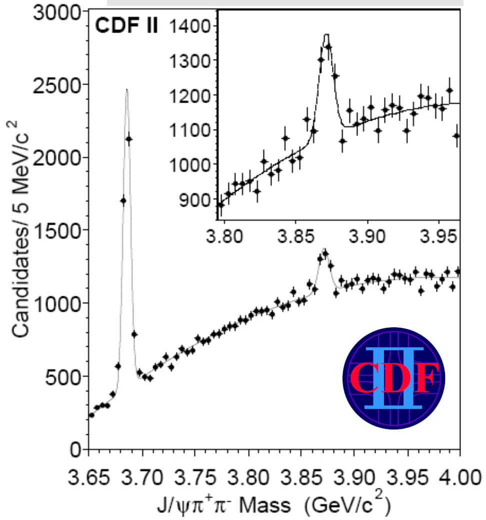
PRD73,011101,2006



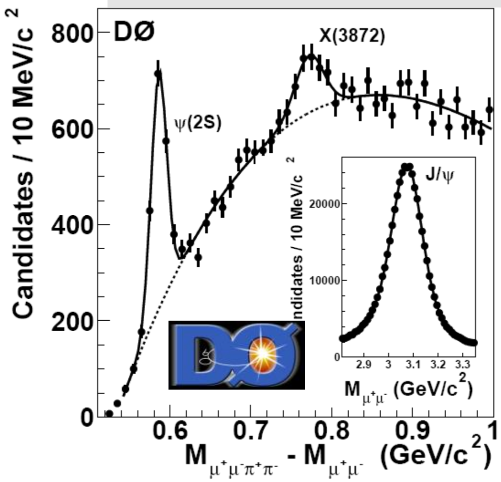
Tevatron: in $p\bar{p}$ collisions

- prompt production
- B decays (16.1±4.9±1.0)% *similar to ψ(2S)*

PRL93,072001,2004



PRL93,162002,2004



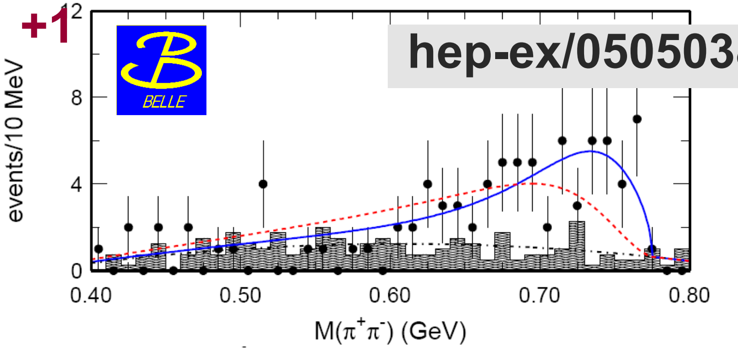
- close to D^0D^{*0} threshold (not clear below or above)

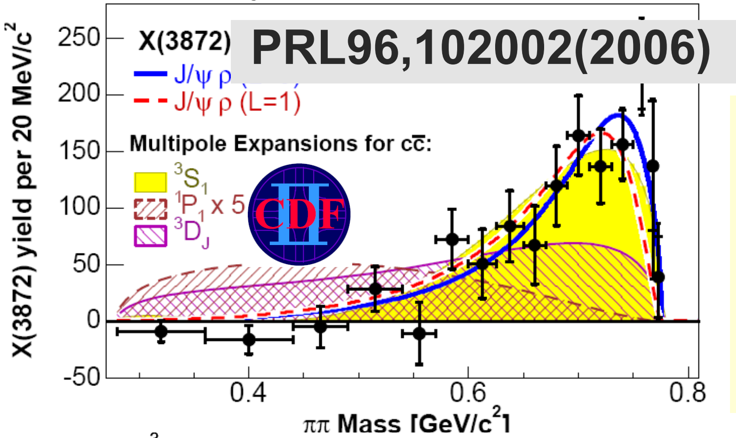
$M_X = 3871.68 \pm 0.17$ MeV

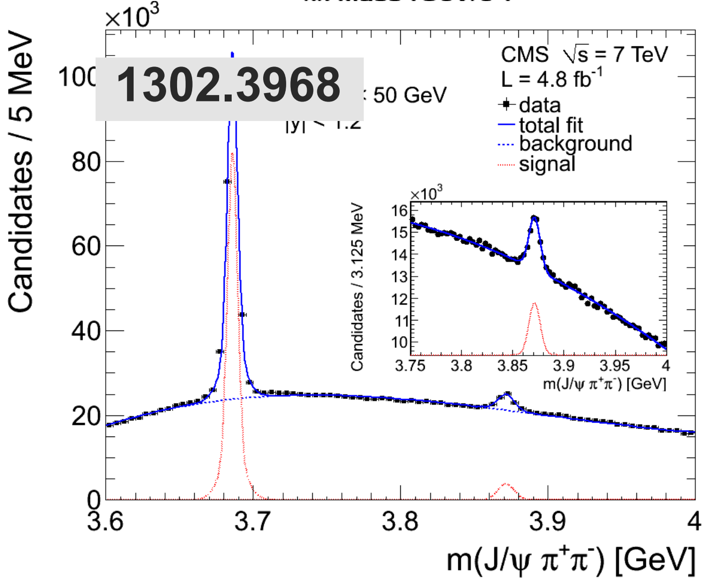
$M_X - M_{DD^*}$
$= (-0.12 \pm 0.24)$ MeV

- surprisingly narrow: $\Gamma_{tot} < 1.2$ MeV at 90% CL
- $M(\pi\pi)$ tends to kinematic limit **Large Isospin violation!**

Fit to M(ππ) favors L = 0; P_X = +1







J^{PC} of the X(3872)

X(3872)→J/ψ γ observation fixes C_X= +1
confirms that in the X→J/ψ ππ decay (ππ)=ρ
Γ(X→J ψ γ) / Γ(X→J/ψ $\pi^+\pi^-$) = 0.14 ± 0.05 small

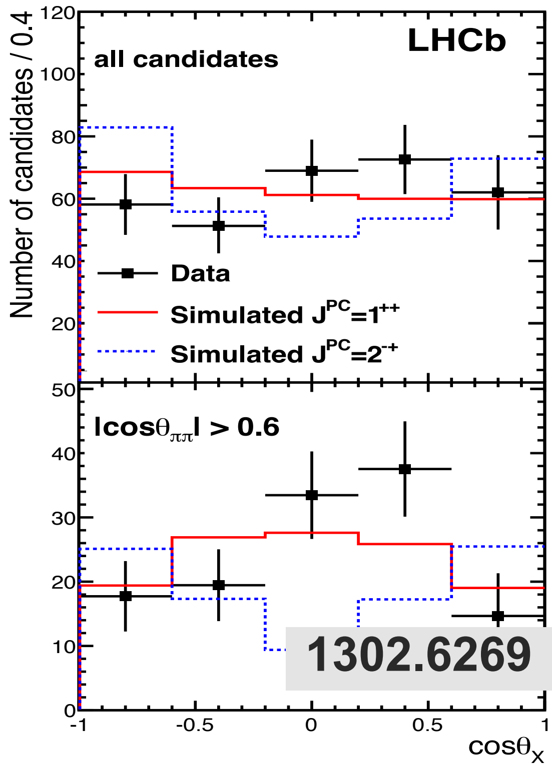
- X → J/ψ ω observation

Br (X → J/ψ ω) / Br (X→J/ψ $\pi^+\pi^-$) = 1.0 ± 0.4 ± 0.3
large isospin violation

CDF 790fb^{-1}: PRL98, 132002(2007)
X → J/ψ ππ angular analysis $J^{PC} = 1^{++}$ or 2^{-+}

LHCb 1fb^{-1} 1302.6269

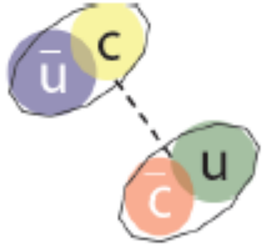
$J^{PC} = 1^{++}$



What is the nature?

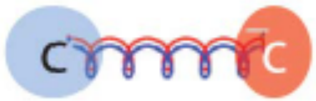
Many new charmonium(–like) do not fit into quark model spectrum easily. Theoretical speculations include:

- **Molecular states:** loosely bound states composed of a pair of mesons, probably bound by the long-range color-singlet pion exchange



- **Tetraquarks:** bound states of four quarks, bound by colored-force between quarks, decay through rearrangement, some are charged or carry strangeness, there are many states within the same multiplet

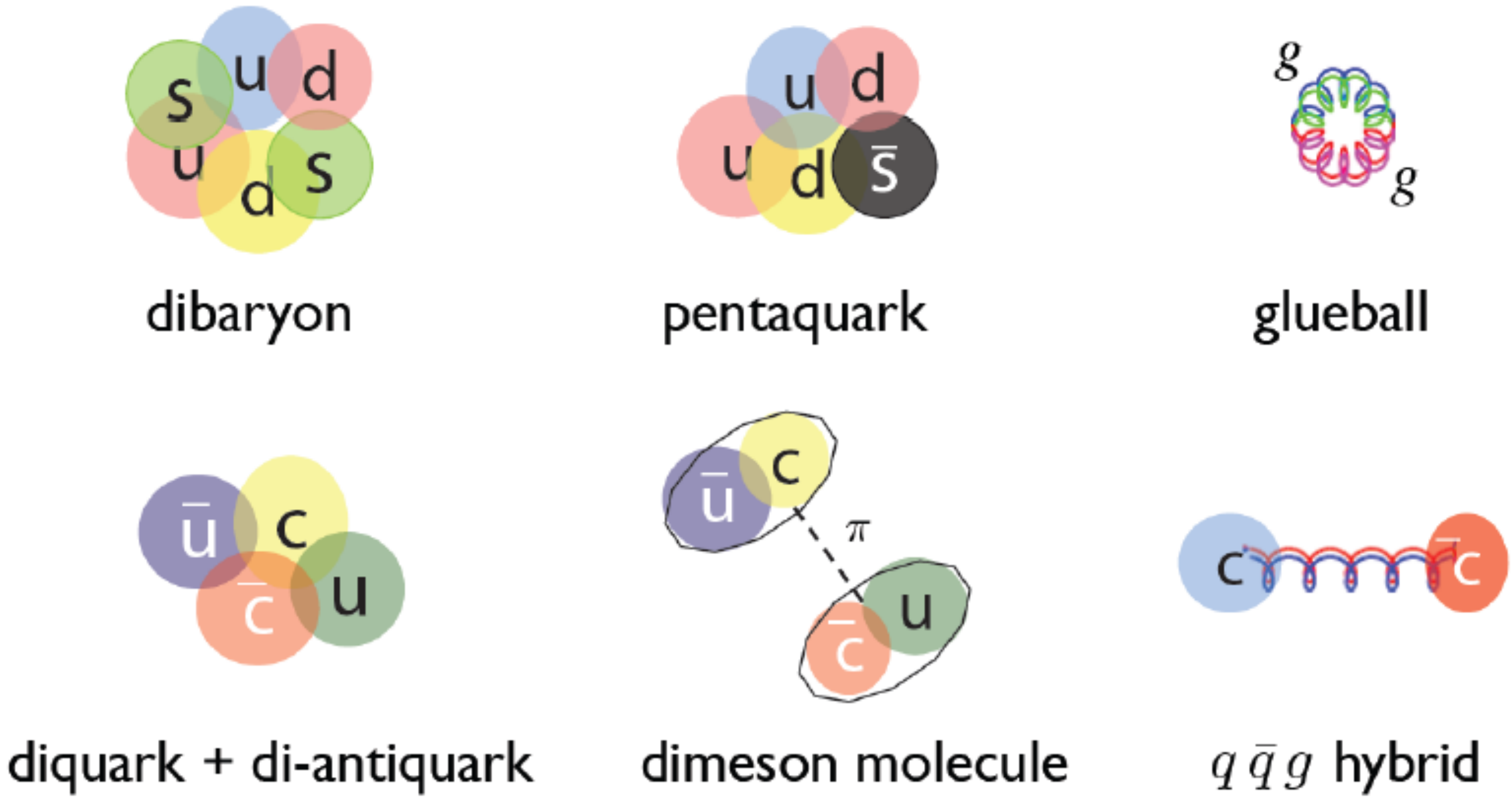
- **Hybrid charmonium:** bound states composed of a pair of quarks and one excited gluon



- **Conventional charmonium:** quark model spectrum could be distorted by the coupled-channel effects

More Exotics

QCD: There are many other possible color singlets.



How to study exotics?

- Effective field theory is an approximation to an underlying physical theory.
- EFT includes the appropriate degrees of freedom to describe physical phenomena occurring at a chosen length scale or energy scale: scale separation

At Low Energy, Quark-hadron duality:

QCD degrees of freedom are equivalent to hadron degrees of freedom.

Chiral perturbation theory!

Chiral Perturbation Theory

χPT effective field theory based on the two assumptions

- π's are the Goldstone boson of $SU(3)_L \otimes SU(3)_R \rightarrow SU(3)_V$
- *(chiral) power counting* i.e. the theory has a small expansion parameter: $p^2/\ \Lambda^2_{\chi SB}$: $\Lambda_{\chi SB} \sim 4\pi F_\pi \sim 1.2$ GeV

$$\mathcal{L}_{\Delta S=0} = \mathcal{L}^2_{\Delta S=0} + \mathcal{L}^4_{\Delta S=0} + \cdots = \frac{F_\pi{}^2}{4} \overbrace{\langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + U \chi^\dagger \rangle}^{\pi\to l\nu,\ \pi\pi\to\pi\pi,\ K\to\pi..} + \overbrace{\sum_i L_i O_i}^{K\to\pi..} + \cdots$$

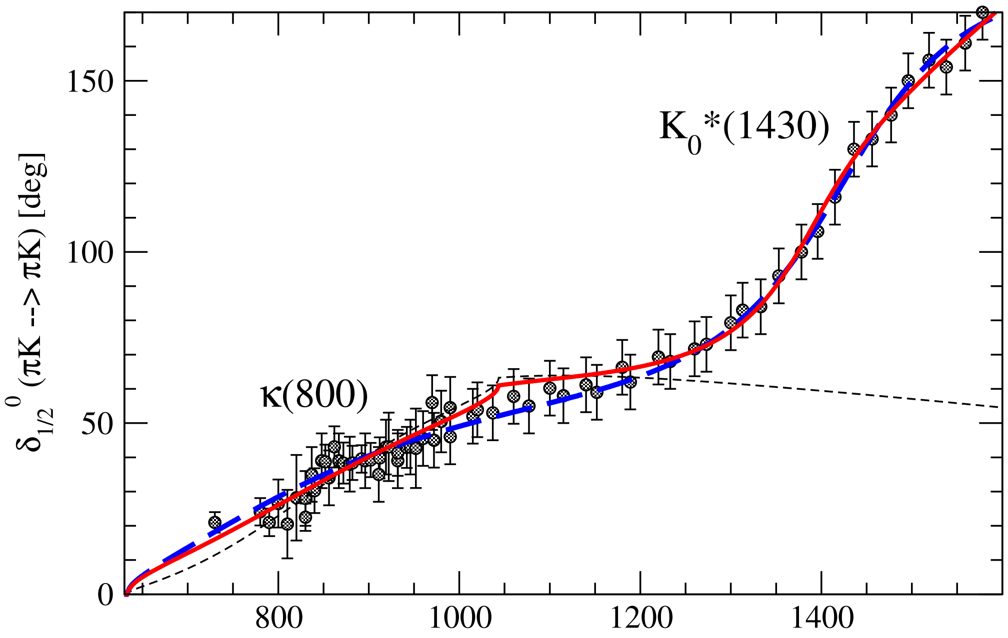
Fantastic chiral prediction $A_{\pi\pi} \sim (s - m^2_\pi)/F_\pi{}^2$ Weinberg, Colangelo *et al*

$$\mathcal{L}_{\Delta S=1} = \mathcal{L}^2_{\Delta S=1} + \mathcal{L}^4_{\Delta S=1} + \cdots = G_8 F^4 \underbrace{\langle \lambda_6 D_\mu U^\dagger D^\mu U \rangle}_{K\to 2\pi/3\pi} + \underbrace{G_8 F^2 \sum_i N_i W_i}_{K^+\to\pi^+\gamma\gamma,\,K\to\pi l^+ l^-} + \cdots$$

ChiPT limited to low energies

ChiPT and data

Recent update in unitarized ChiPT from M.Döring,U.-G.Meißner,WW, 1307.0947



Scattering Phase

		z_0 [MeV]	$a_{-1}(K\eta)$ $[M_\pi]$	$a_{-1}(K\pi)$ $[M_\pi]$
$\kappa(800)$	this work (2-ch.)	$792-i\,279$		$-29-i\,57$
	this work (1-ch.)	$715-i\,283$		$-45-i\,62$
	Ref. [32] (χU)	$815-i\,226$		$-30-i\,57$
	Ref. [65] (Roy-S.)	$658-i\,279$		

Mass Pole

重夸克对称性

- 重强子由重夸克Q、轻夸克q组成
- 康普顿波长：$\lambda_Q \sim 1/m_Q$，$\lambda_q \sim 1/\Lambda_{QCD}$
- $m_Q >> \Lambda_{QCD}$，$\lambda_q >> \lambda_Q$
- 轻夸克感受不到重夸克的性质，轻夸克的相互作用与λ_Q的大小无关
- 重夸克自旋1/2，色磁矩$\mu_Q \propto g / 2m_Q$
- $m_Q \to \infty$时，$\mu_Q \to 0$，重轻夸克之间的自旋相互作用是压低的

重夸克对称性

- 轻夸克对于S_Q不敏感，不依赖于$S_Q^z=1/2$或者$S_Q^z= -1/2$
- 轻夸克在与以下四种重夸克态组成的强子中是一样的：

  b(↑), b(↓); c(↑), c(↓)
- 如果，轻夸克系统的角动量是J_l，那么，与重夸克组成的强子角动量是

  $J=|J_l\pm 1/2|$
- 构造一个重强子有效理论

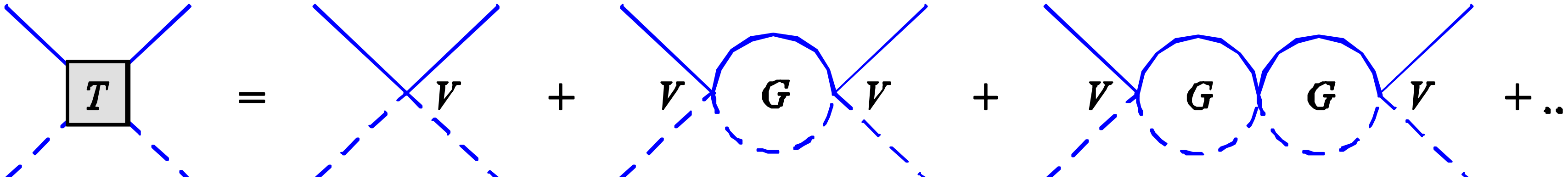
Heavy Meson Chiral Perturbation Theory

$$\mathscr{L}_{\rm LO} = -i\mathrm{Tr}[\bar{H}_a v_\mu D^\mu_{ba} H_b] + g_\pi \mathrm{Tr}[\bar{H}_a H_b \gamma_\nu \gamma_5] u^\nu_{ba} + \frac{\lambda}{m_Q}\mathrm{Tr}[\bar{H}_a \sigma_{\mu\nu} H_a \sigma^{\mu\nu}]$$

$$H = \frac{1+\not{v}}{2}\left[\not{V} + iP\gamma_5\right], \quad \bar{H} = \gamma^0 H^\dagger \gamma^0,$$

- **Heavy Meson pair: DD^*, BB^***
- **Heavy Meson plus a Pseudo-Scalar: DK**
- **Two Pseudo-Scalar**

Scattering in EFT

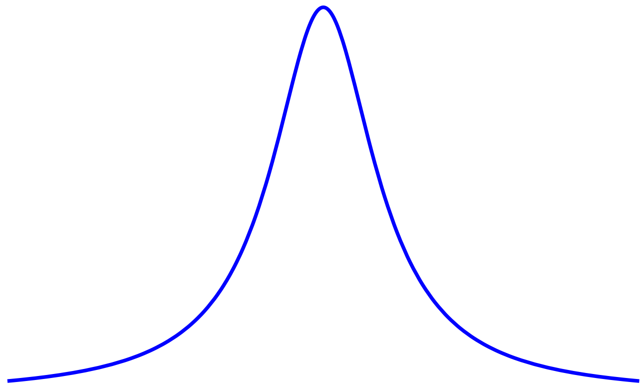


Summing All order contributions:

V+ VGV + VGVGV+…. = V(s)/(1-GV)

1-GV＝0

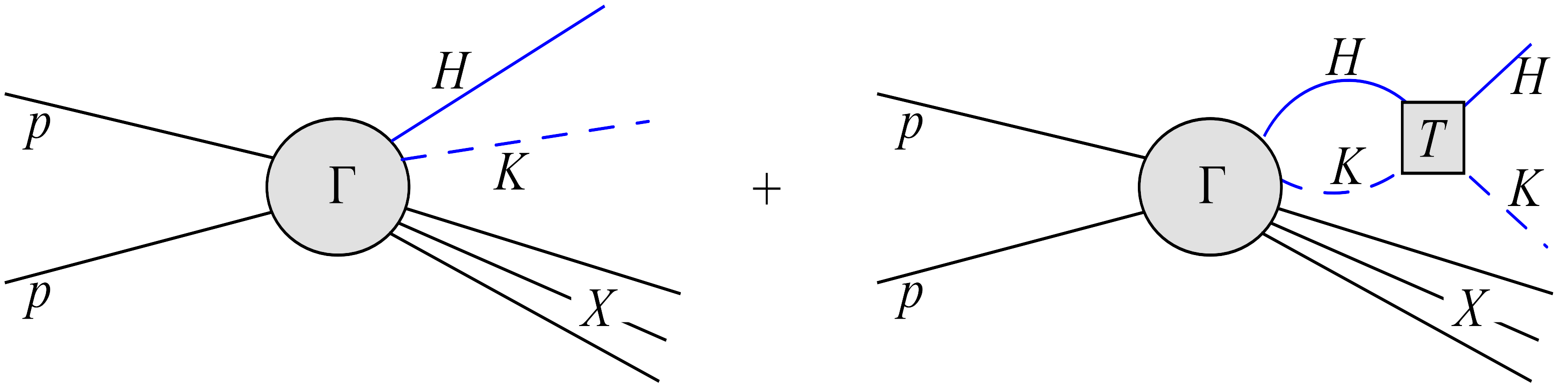
$s=s_0$



Mass pole corresponds to a resonance structure

→ Hadron Molecule

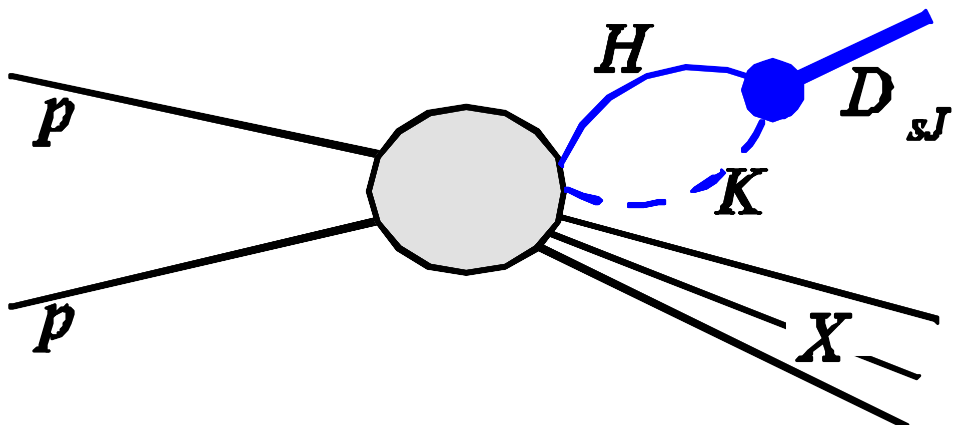
Production at LHC



$\Gamma + \Gamma GV + \Gamma GVGV + \ldots. = \Gamma /(1-GV)$

Γ is tree-level amplitude.

$1-GV = 0$

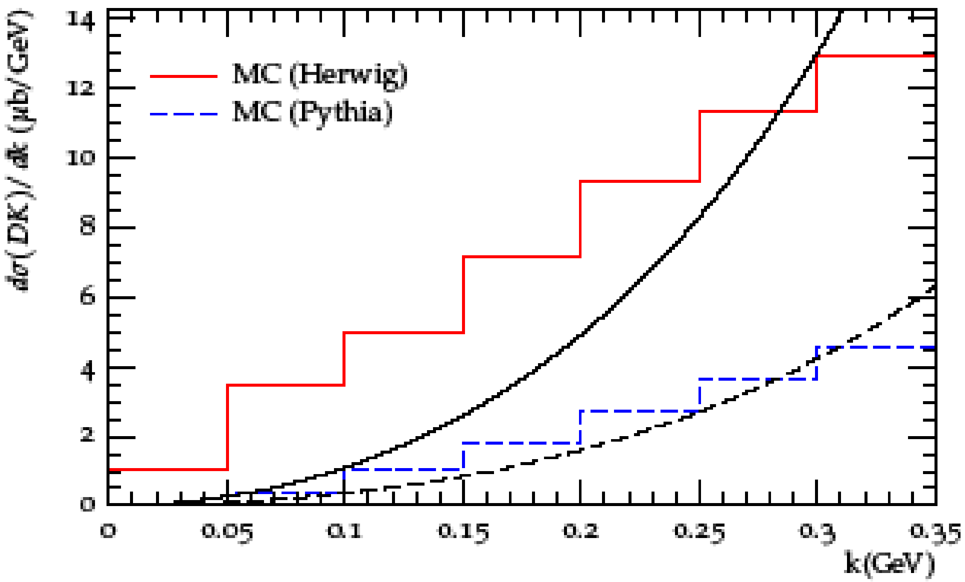


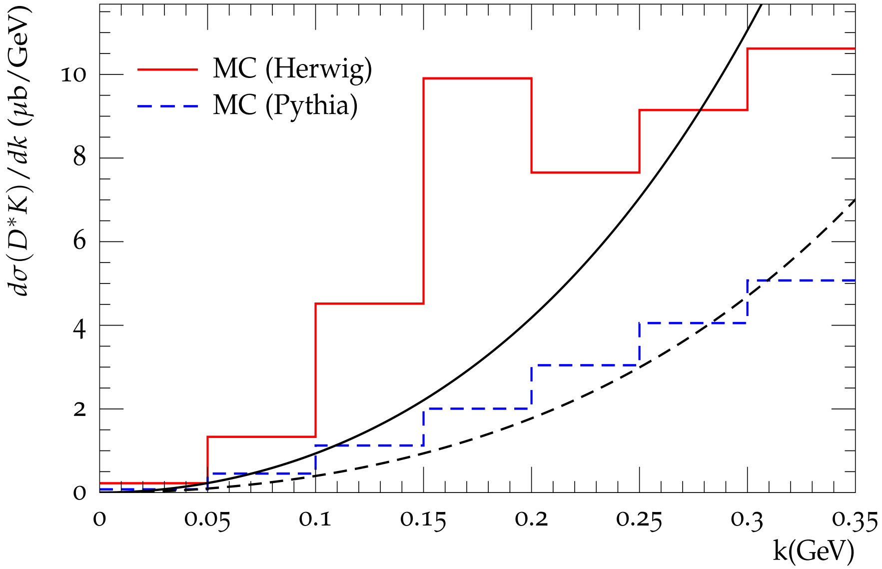
Monte Carlo Event Generators

- **Herwig/Pythia:** simulate production rates of constituents, Γ
- For charmonium/bottomonium-like states, heavy quarks move together, and a third parton is requested. 2->3 process: use **Madgraph** to improve efficiency
- Use **Rivet** to analyze the hadronic events from Herwig/Pythia.

Test of EFT: LO and MC

F.K. Guo, U.G. Meissner, WW, Z.Yang 1403.4032





Histograms: MC event generators Curves: fit according to EFT.

$\sigma(pp/p\bar{p} \to X(3872))$	Ref. [16]	Ref. [18]	$\Lambda = 0.5$ GeV	$\Lambda = 1$ GeV	Experiment
Tevatron	< 0.085	1.5–23	10(7)	47(33)	37–115 [43]
LHC7	–	45–100 [a]	16(7)	72(32)	13–39 [6]

Not bad for factorization.

Production rates of charged Z_b/Z_c

TABLE II: Integrated normalized cross sections (in units of nb) for the reactions $pp/\bar{p} \to Z_b(10610), Z_b(10650), Z_c(3900)$, and $Z_c(4020)$ at the LHC and the Tevatron. Results are obtained using Herwig (Pythia). The rapidity range $|y| < 2.5$ has been assumed for the LHC experiments (ATLAS and CMS) at 7, 8 and 14 TeV, respectively, for the Tevatron experiments (CDF and D0) at 1.96 TeV, we use $|y| < 0.6$; the rapidity range $2.0 < y < 4.5$ is used for LHCb.

	$Z_b(10610)$	$Z_b(10650)$	$Z_c(3900)$	$Z_c(4020)$
Tevatron	0.26(0.47)	0.06(0.17)	11(13)	1.7(2.0)
LHC 7	4.8(8.0)	1.2(3.0)	187(211)	29(31)
LHCb 7	0.76(1.3)	0.18(0.47)	33(39)	5.5(5.8)
LHC 8	5.9(9.5)	1.4(3.5)	220(240)	34(36)
LHCb 8	0.9(1.4)	0.22(0.56)	40(48)	6.3(6.9)
LHC 14	11(17)	2.6(6.5)	382(423)	61(63)
LHCb 14	1.9(3.0)	0.52(1.2)	84(88)	14(14)

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WW
1308.0193

Is it likely to observe Z_b/Z_c?

Z_c decays into $J/\psi\ \pi^+$. To estimate background

$$\sigma(pp \to \psi\pi^{\pm} + anything) < \sigma(pp \to \psi + anything).$$

ATLAS data on pp→J/ψ: Nucl. Phys. B 850, 387 (2011)

$$\sigma(pp \to \psi(\to \mu^+\mu^-) + anything) = (81^{+27}_{-22})\ \mathrm{nb},$$

With 22fb^{-1} data, the signal/background ratio is

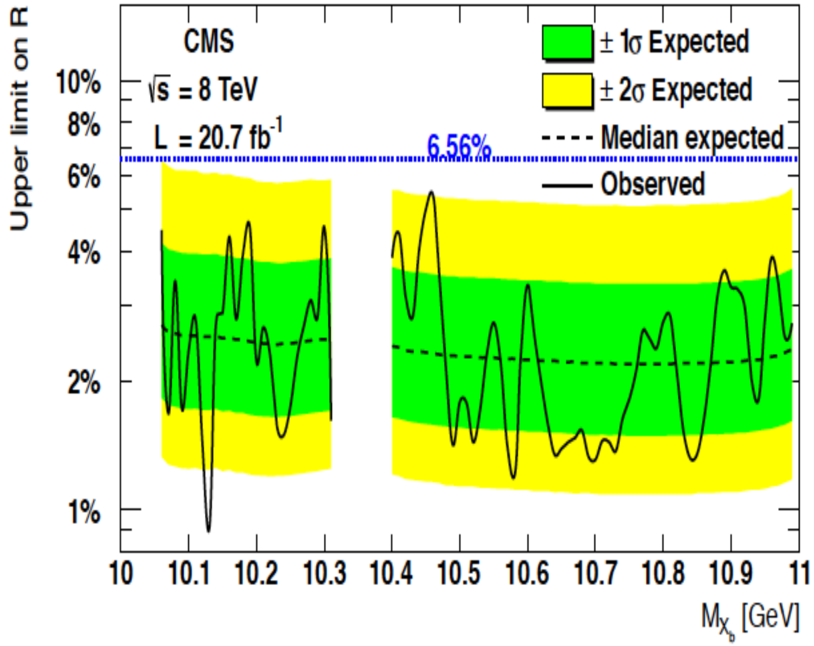
$$\frac{S}{\sqrt{B}} \sim \frac{200 \times 22 \times 10^6 \times 10\% \times 5.9\%}{\sqrt{81 \times 22 \times 10^6}} \sim 600,$$

X_b

- **Counterpart of X(3872):** **$J^{PC}=1^{++}$; BB^* molecule state**
- **Very heavy (11 GeV), difficult to directly produce at electron-positron collider.**

- **CMS made an attempt:**

Phys.Lett. B727 (2013) 57-76



$$\frac{\sigma(pp \to X_b \to \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-)} < (0.009, 0.054) \,,$$

$$\sigma(pp \to X_b)\mathcal{B}(X_b \to \Upsilon(1S)\pi^+\pi^-) < (0.18, 1.11) \text{ nb.}$$

Integrated cross sections (in units of nb) for the $pp/\bar{p} \to X_b$

X_b	$E_{X_b} = 1$ MeV	$E_{X_b} = 2$ MeV	$E_{X_b} = 5$ MeV
Tevatron	0.04(0.09)	0.06(0.13)	0.09(0.2)
LHC 7	0.77(1.5)	1.1(2.2)	1.7(3.5)
LHCb 7	0.12(0.24)	0.18(0.34)	0.28(0.54)
LHC 8	0.9(1.8)	1.3(2.5)	2.(4.)
LHCb 8	0.15(0.31)	0.21(0.43)	0.33(0.68)
LHC 14	1.6(3.4)	2.2(4.8)	3.6(7.5)
LHCb 14	0.32(0.64)	0.46(0.91)	0.72(1.4)

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U.G. Meissner
WW
1402.6236

X_b decays into $\Upsilon\pi^+\pi^-$ violates isospin → tiny BR.

One may look at $\Upsilon\gamma$, $\Upsilon\pi^+\pi^-\pi^0$, $\chi_b\pi^+\pi^-$.

Radiative decays width are about 1 keV *G.Li WW 1402.6463*

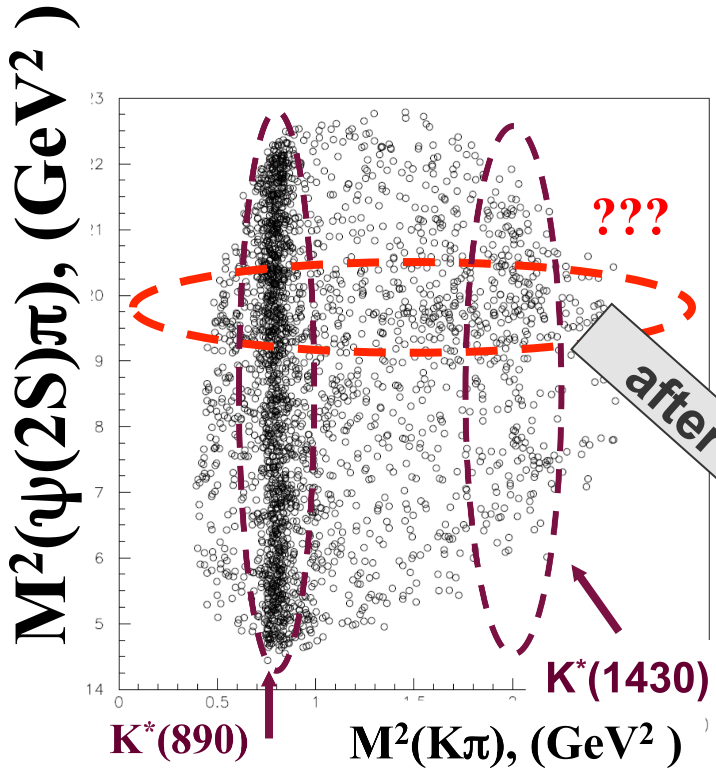
Summary

- LHC physics is rich.
- Exotic Hadron is a fast-developing branch.
- EFT can be used to explore hadron molecules.
- We have studied the production of exotic states at the LHC:

  a) X-sections; b) decay modes

Thank you for your attention!

Z(4430)$^+$ first charged charmoniumlike state



Cannot be conventional charmonium or hybrid

$B \to KZ$, $Z(4430)^+ \to \pi^+\psi(2S)$

$K=K^-, K^0_s$; $\psi(2S) \to \ell^+\ell^-$, $\pi^+\pi^- J/\psi$

Fit: S-wave BW + phase space like func

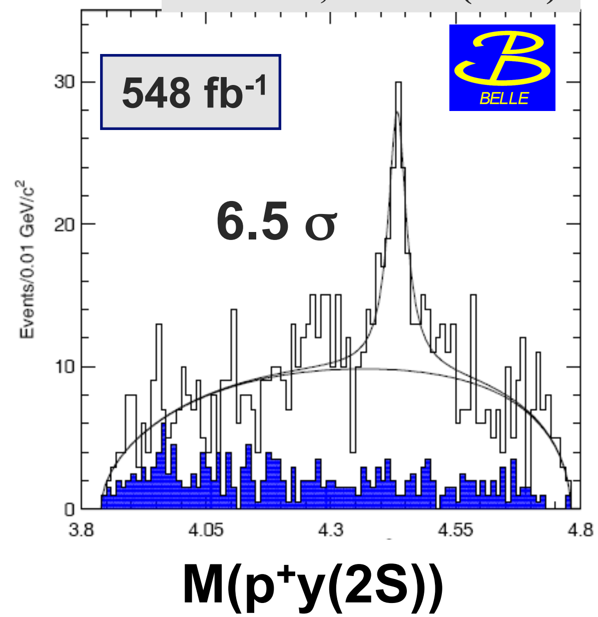
$M = (4433 \pm 4 \pm 2)$ MeV

$\Gamma = (45^{+18}_{-13}\,^{+30}_{-13})$ MeV

$Br(B \to KZ) \times Br(Z \to \psi(2S)\pi) = (4.1 \pm 1.0 \pm 1.3) \times 10^{-5}$

$Br_{\pm}/Br_0 = 1.0 \pm 0.4$

PRL 100, 142001 (2008)




Microscopic
black holes
Extra dimensions
Supersymmetry
Compositeness
LHC expectations


LHC results...
125 GeV
palm tree