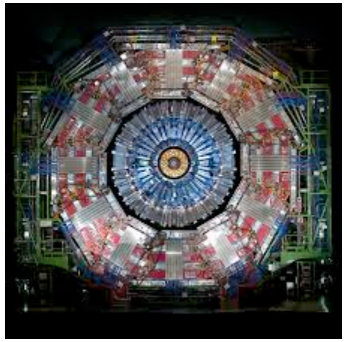


J/ψJ/ψ Mass Spectrum at LHC & CEPC

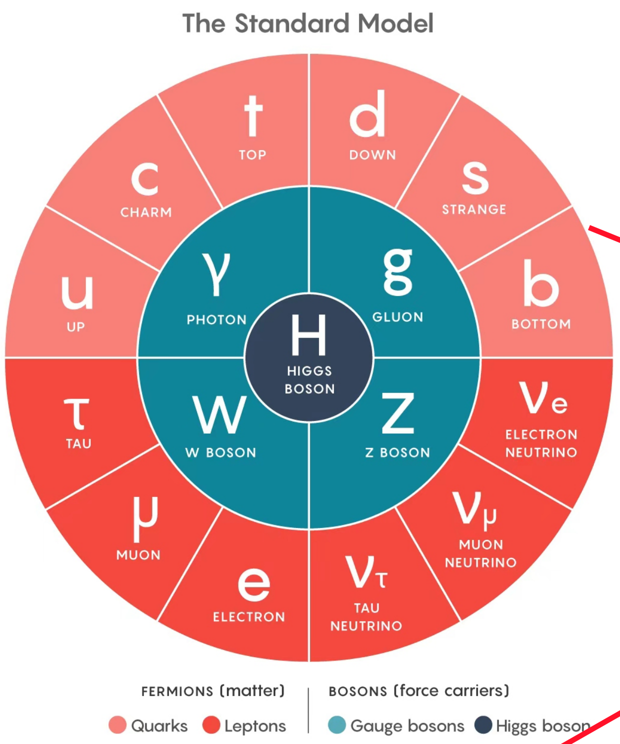
Kai Yi

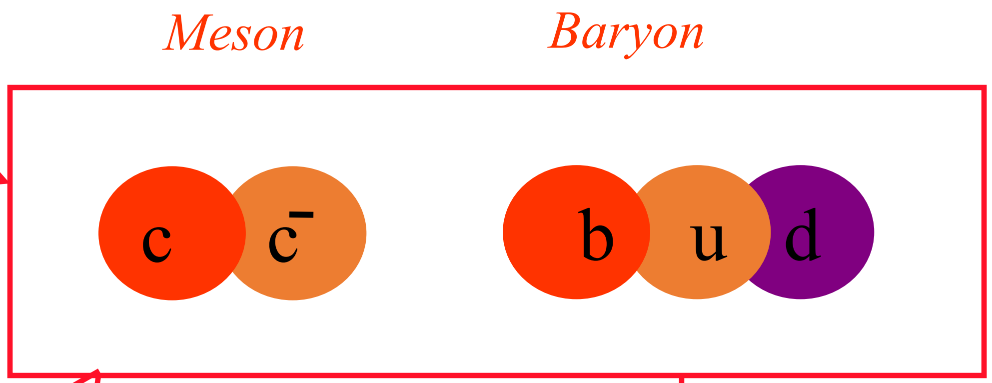
Nanjing Normal University & Tsinghua University

Outline

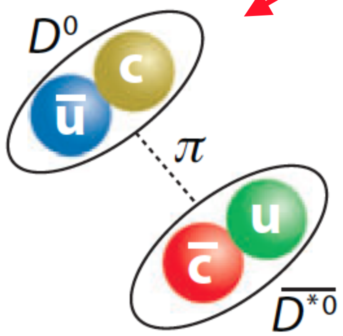
- About exotic hadron
- CMS contribution to heavy exotic hadron
- New Domain of Exotics: All-Heavy Tetra-quarks
- Discussion and future (CEPC)
- Summary

Quark model

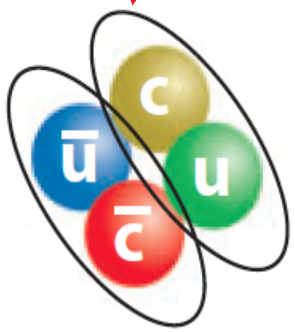




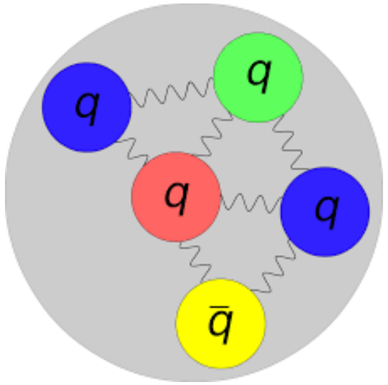
"exotic" hadron



D^0–$\overline{D}^{*0}$ "molecule"



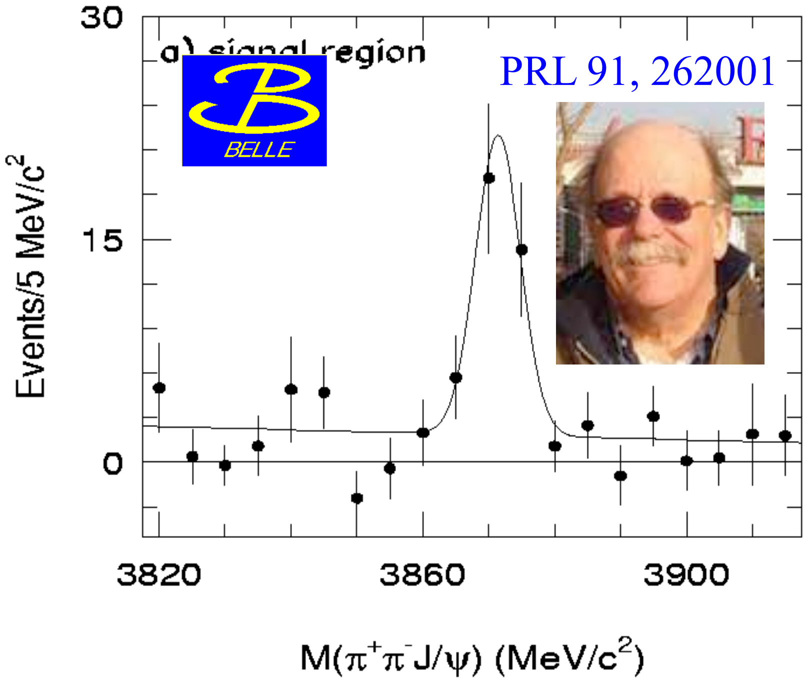
Diquark–diantiquark

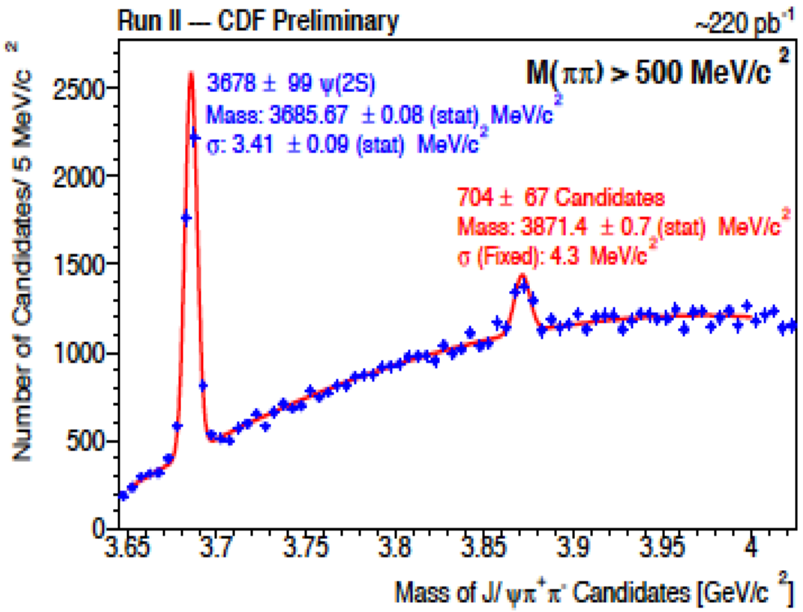


Two possible extensions of meson to tetra-quark states

Possible penta-quark state

X(3872) (Belle)--2003





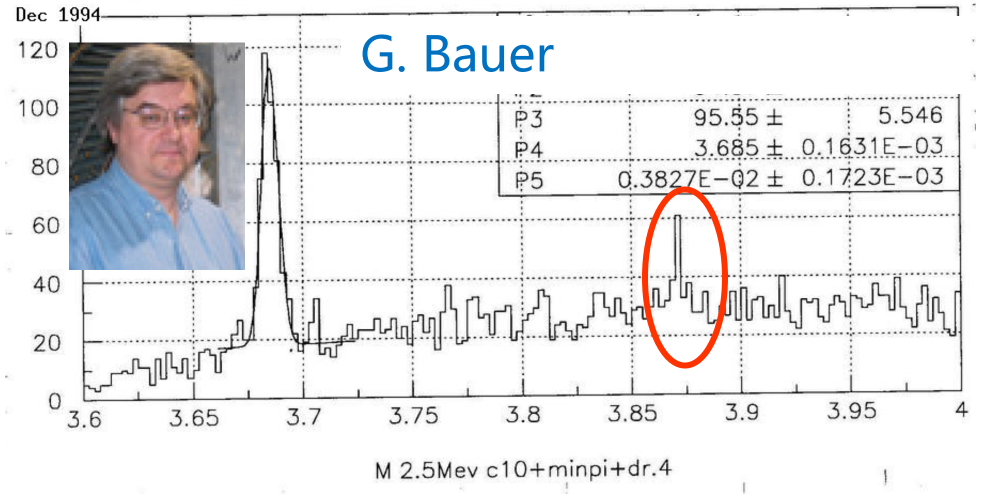
2017 Laureates

"…The X(3872) was discovered by Dr. Sookyung Choi and Dr. Stephen Olsen with their colleagues in the Belle experiment among the final states of the decay of B mesons. The X(3872) was confirmed by seven other experimental groups thereafter and is the first example of a new type of XYZ meson and the most well-established state among them. …"

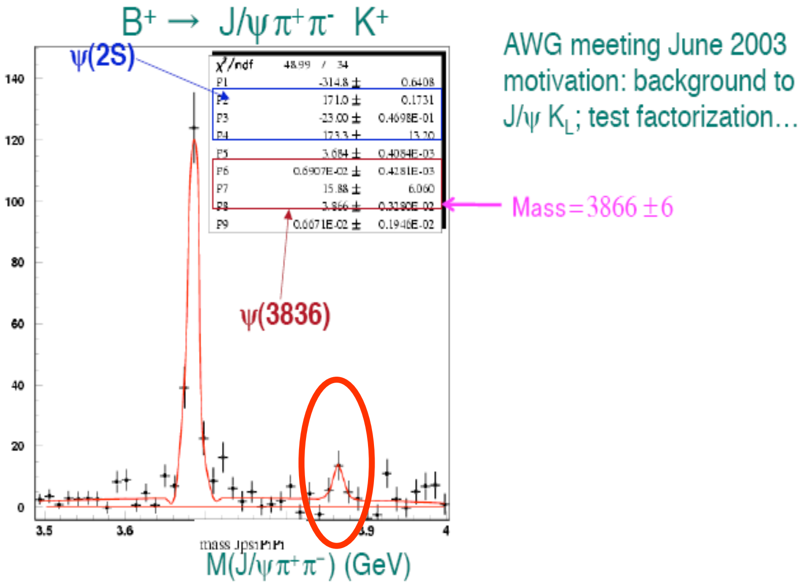
2017 Korean Ho-Am Science Prize

Hints before the discovery of $X(3872) \to J/\psi\pi^+\pi^-$

CDF internal, 1994



BaBar internal, 2003



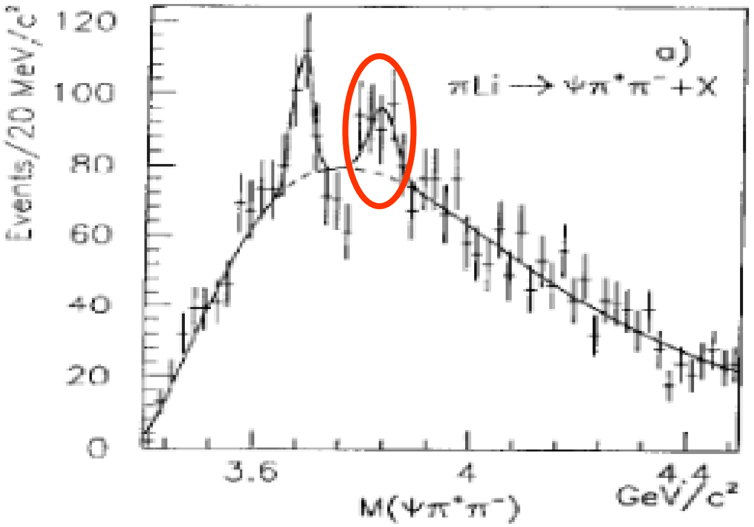
From BaBar B-Factory Symposium (C. Hearty)

http://www-conf.slac.stanford.edu/b-factory-symposium/talks.asp

E705, PRD 50, 4258 (1994)

E705 saw ψ(3836) (2^{--})in 1994, 3.836±0.013 GeV

PRL 115 011803, PRL 111 032001



CDF saw a hint in 1994, unpublished

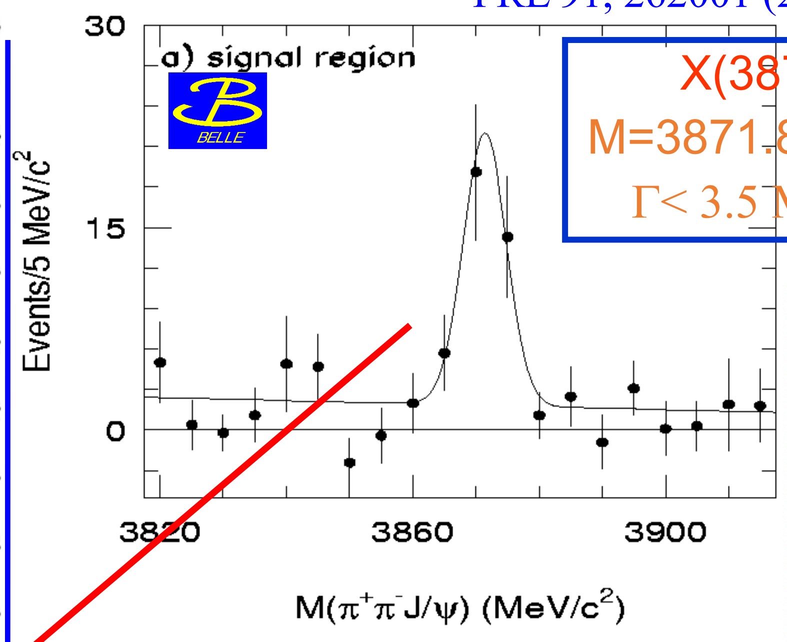
BaBar saw a hint in 2003, unpublished

Both CDF and Babar spotted hints of X(3872) before its discovery!

History: X(3872)—2003 (a slide from 2003)

$N\,^{2S+1}L_J$	J^{PC}	$u\bar{d}, u\bar{u}, d\bar{d}$ $I=1$	$u\bar{u}, d\bar{d}, s\bar{s}$ $I=0$	$c\bar{c}$ (CC̄) $I=0$
$1\,^1S_0$	0^{-+}	π	η, η'	$\eta_c(1S)$
$1\,^3S_1$	1^{--}	ρ	ω, ϕ	$J/\psi(1S)$
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$h_1(1170), h_1(1380)$	$h_c(1P)$
$1\,^3P_0$	0^{++}	$a_0(1450)^*$	$f_0(1370)^*, f_0(1710)^*$	$\chi_{c0}(1P)$
$1\,^3P_1$	1^{++}	$a_1(1260)$	$f_1(1285), f_1(1420)$	$\chi_{c1}(1P)$
$1\,^3P_2$	2^{++}	$a_2(1320)$	$f_2(1270), f_2'(1525)$	$\chi_{c2}(1P)$
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$\eta_2(1645), \eta_2(1870)$	
$1\,^3D_1$	1^{--}	$\rho(1700)$	$\omega(1650)$	$\psi(3770)$
$1\,^3D_2$	2^{--}			??
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$\omega_3(1670), \phi_3(1850)$	
$1\,^3F_4$	4^{++}	$a_4(2040)$	$f_4(2050), f_4(2220)$	
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$\eta(1295), \eta(1440)$	$\eta_c(2S)$
$2\,^3S_1$	1^{--}	$\rho(1450)$	$\omega(1420), \phi(1680)$	$\psi(2S)$
$2\,^3P_2$	2^{++}	$a_2(1700)$	$f_2(1950), f_2(2010)$	
$3\,^1S_0$	0^{-+}	$\pi(1800)$	$\eta(1760)$	

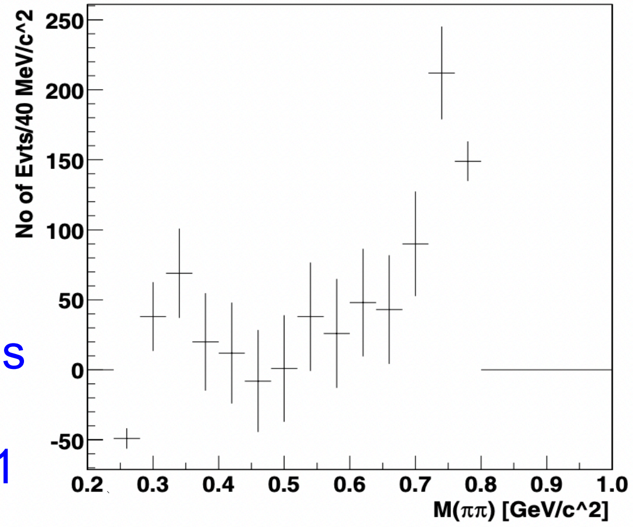
PRL 91, 262001 (2003)



$X(3872) \to J/\psi\pi^+\pi^-$

M=3871.8±0.7±0.4 MeV

$\Gamma <$ 3.5 MeV @ 90% CL



(Problematic) features

mass ~70 MeV > 1^3D_2 charmonium

$M(\pi^+\pi^-)$ peaks as a ρ, C=+, isospin=1

(charmonium--0)

Mass close to DD*, molecule is speculated

First particle challenging charmonium model,

Revitalized exotic meson study

Heavy—a factor to make us easier to identify “exotic”

Back to 2015

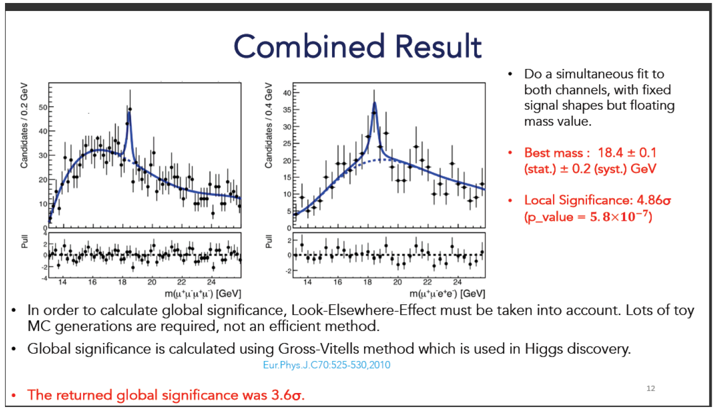
Prospects of New Physics Search below Z Mass in Multiple Lepton Final State

Kai Yi (University of Iowa)
for the working group

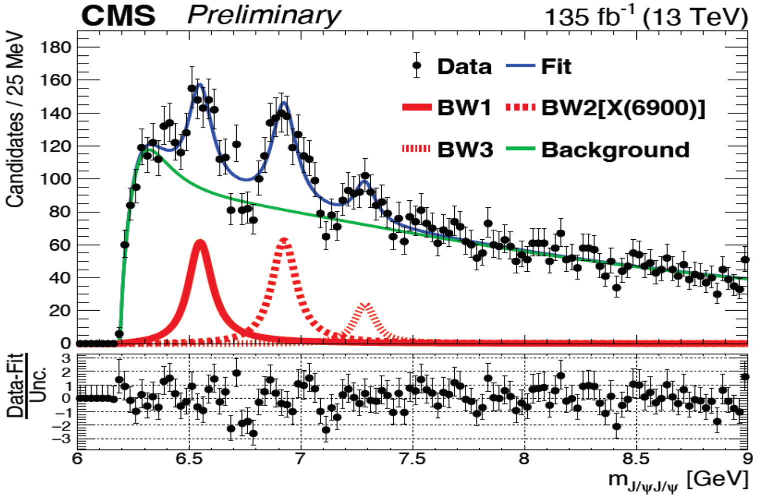
Involved US Institutions:
Iowa, Fermilab, Tennessee, Notre Dame, …

USCMS Annual Meeting, May 28, 2015, Cornell

Finally some progress in 2022

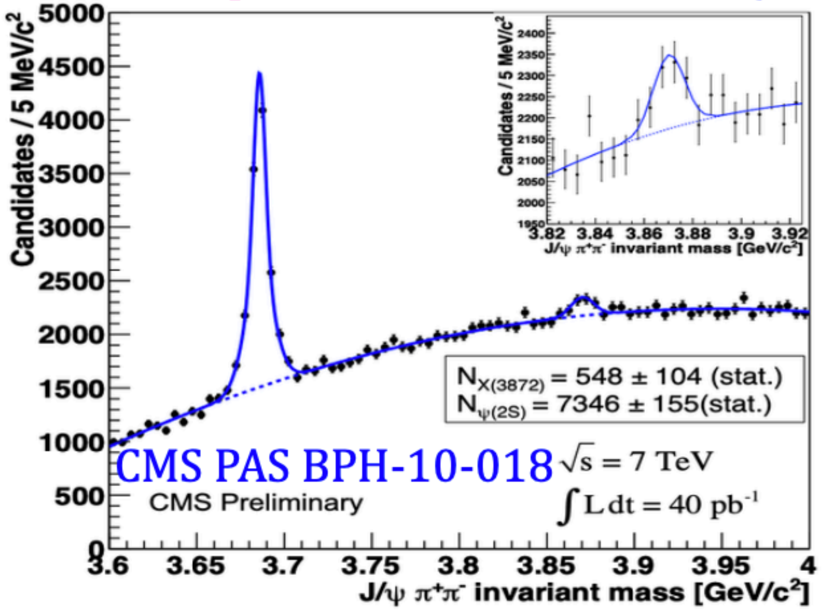


2012—2018—2022

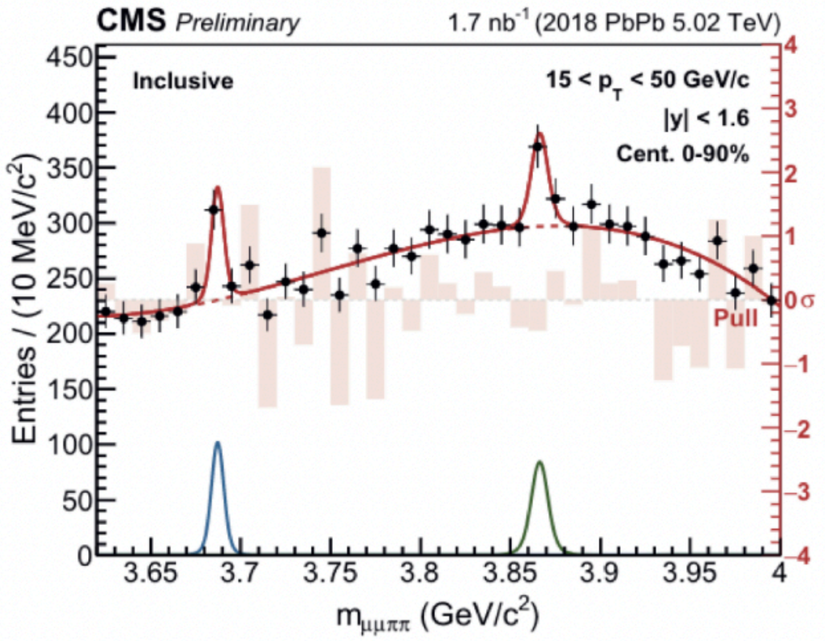


Selected CMS contributions to heavy exotic states

First LHC experiment re-discovered X(3872)



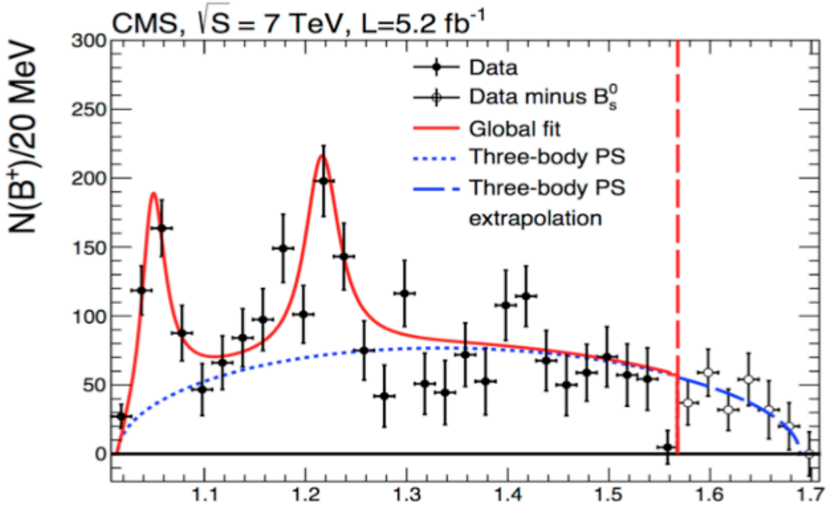
CMS PAS BPH-10-018



First X(3872) signal in PbPb

Nucl. Phys. Vol 1005 (2021)121781

First confirmation of Y(4140)



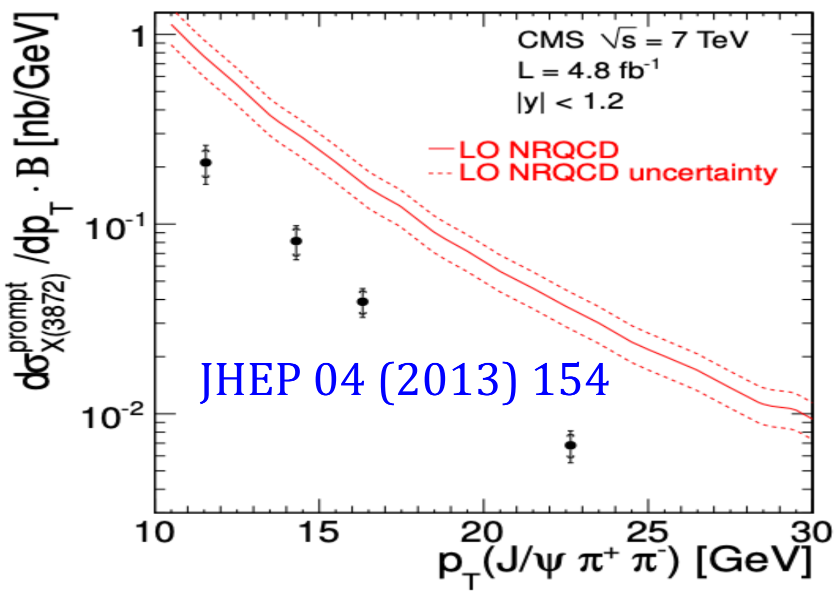
PLB 734 261 (2014)

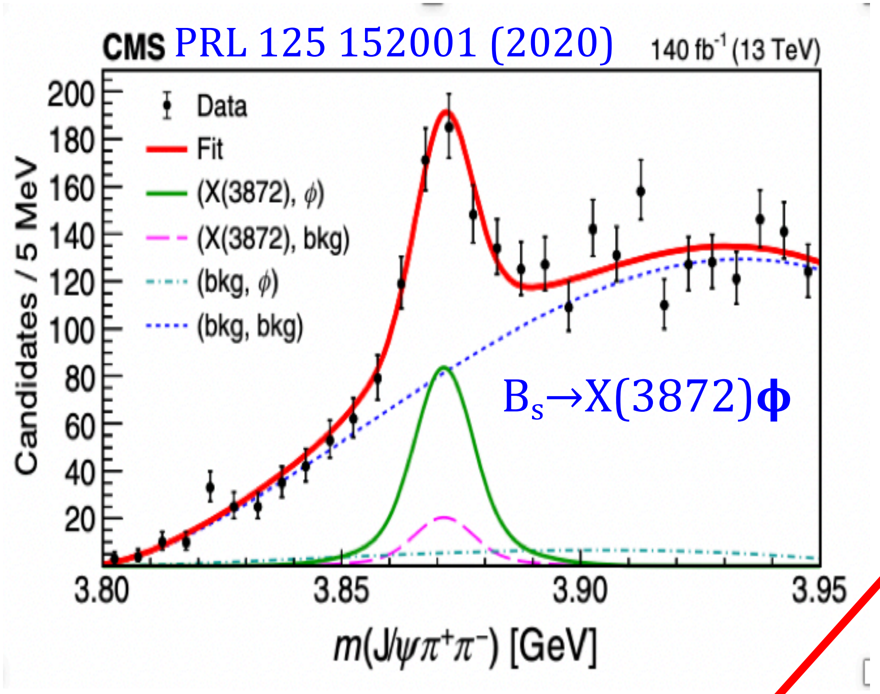
CMS played the following leading roles

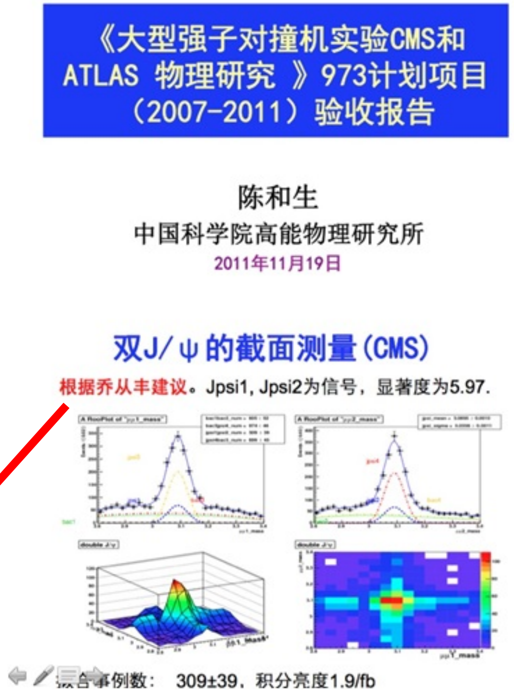
- First LHC experiment to see X(3872)
- First LHC experiment to see exotic hadron
- First LHC experiment to see X(3872) in PbPb data

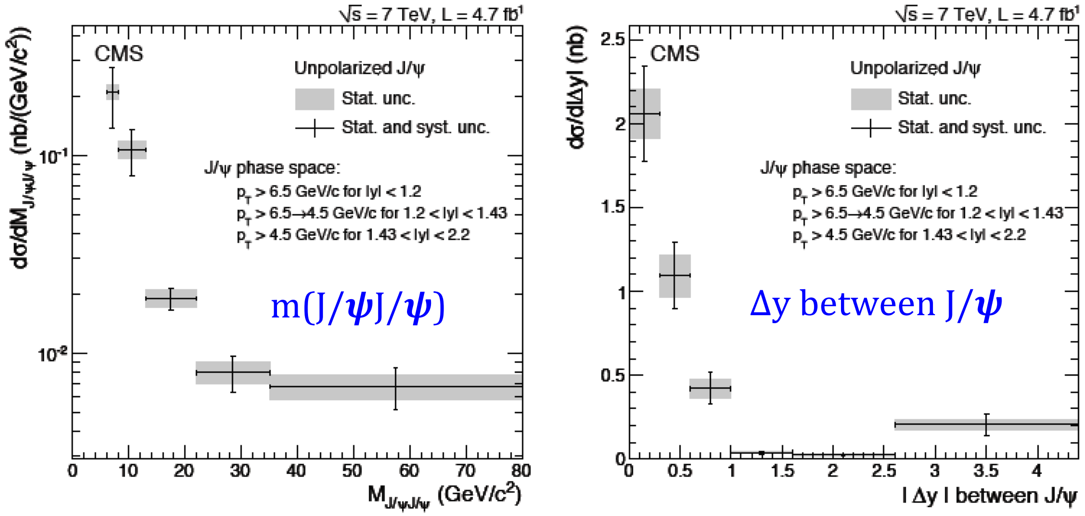
Other selected CMS contributions to heavy exotic states

X(3872) measurement









JHEP 1409 (2014) 094

- **Jianguo Bian** initialized di-J/ψ cross section analysis
- CMS has large di-J/ψ sample
- Any surprise in di-J/ψ mass spectrum?

New Domain of Exotics: All-Heavy Tetra-quarks

- First mention of 4c states at 6.2 GeV (1975): Prog. of Theo. Phys. Vol. 54, No. 2

  (Just one year after the discovery of J/ψ)
- First calculation of 4c states (1981): Z. Phys. C 7 (1981) 317

L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.55
	1	$0^{-+}, 1^{-+}, 2^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}$	
2	0	2^{++}	6.78
	1	$1^{+-}, 2^{+-}, 3^{+-}$	
	2	$0^{++}, 1^{++}, 2^{++}, 3^{++}, 4^{++}$	
3	0	3^{--}	6.98
	1	$2^{-+}, 3^{-+}, 4^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}, 4^{--}, 5^{--}$	

$\leftarrow (cc)_{\underline{3}^*} - (\overline{cc})_{\underline{3}}$

$(cc)_{\underline{6}} - (\overline{cc})_{\underline{6}^*}$

L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.82
2	0	2^{++}	7.15
3	0	3^{--}	7.41

Linked by color electric flux in a bag

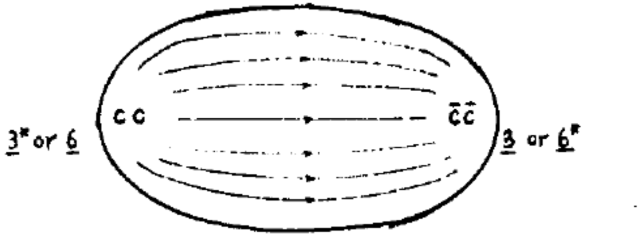


Fig.2

Possible two-body decays

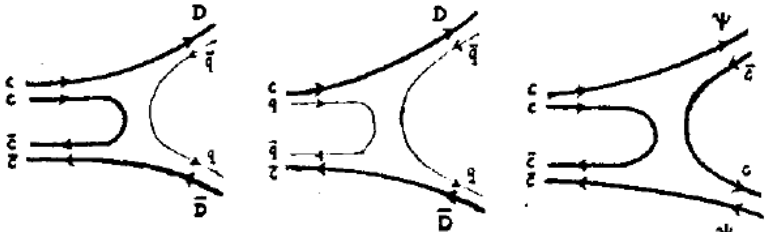


Fig.3(a) Fig.3(b) Fig.3(c)

Possible P-wave to S-wave decays

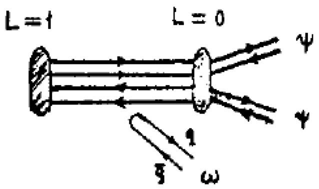
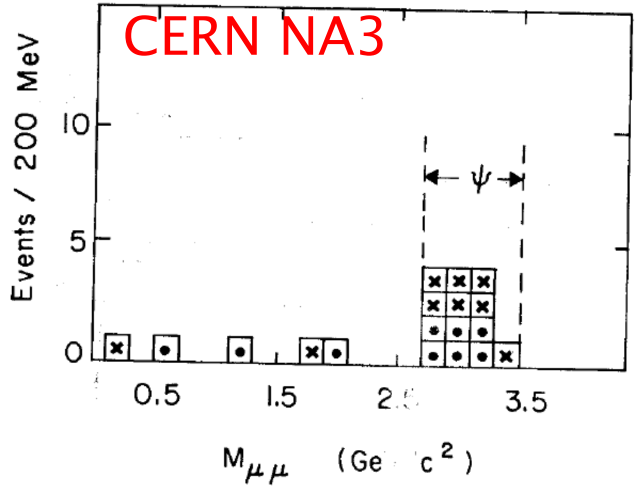
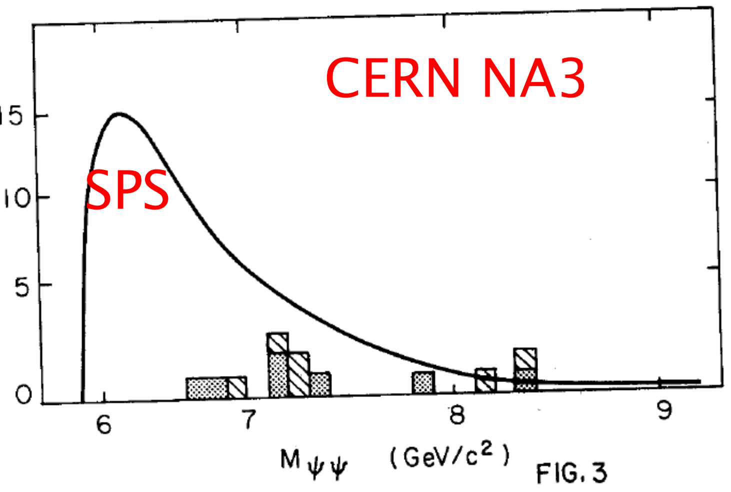


Fig.4

- A different exotic system comparing to exotic with light quarks

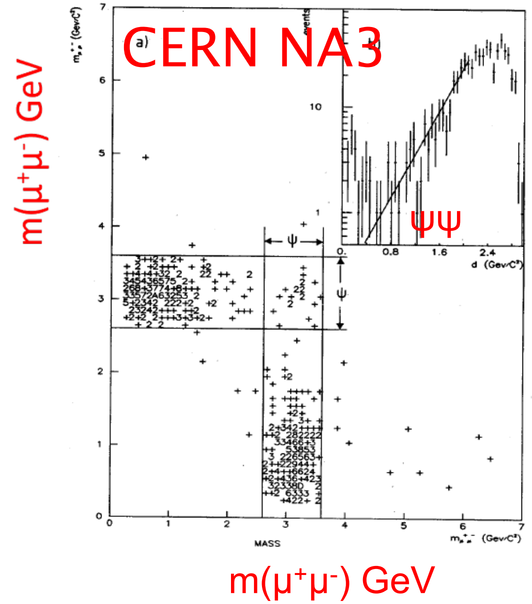
J/ψJ/ψ events—first evidence

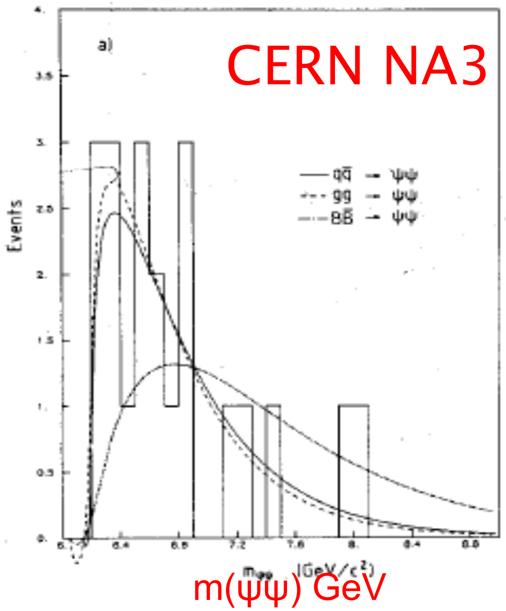


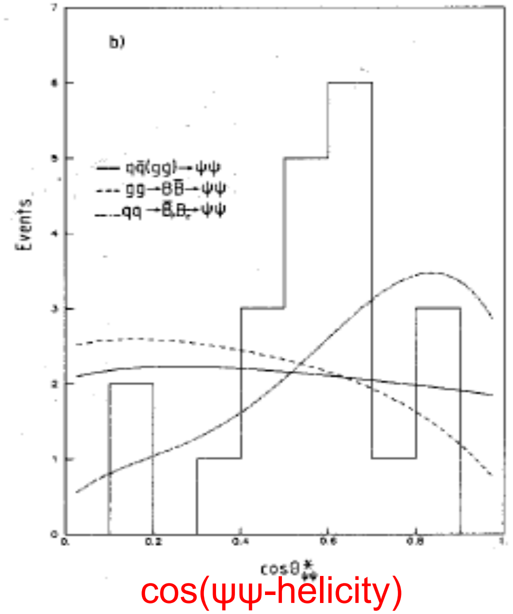


PLB114 (1982) 457

Was interoperated as 2^{++} 4-quark state







PLB158 (1985) 85

Possible explanations of J/ψ-J/ψ states

2^{++} four-quark states, PRD29 (1984) 426

TABLE I. Parameters used in Eq. (8) to calculate the cross sections for vector-meson pair production. (+) and (−) denote two degenerate 2^{++} $Q^2\bar{Q}^2$ states. Except in the case of JJ, we take $4\pi/f_J^2=0.03$, due to the fact that the 2^{++} $Q^2\bar{Q}^2$ are expected to lie not far above the threshold. α_s is determined from Eq. (11).

V_1V_2	$a^j_{V_1V_2}/a$	$b^j_{\alpha\beta}\Big/\alpha_s\frac{a}{\sqrt{8}}\delta_{\alpha\beta}$	M_j (GeV)	α_s	m_1
$J\phi^{(+)}$	$-1/\sqrt{6}$	$\frac{-1}{\sqrt{3}}\frac{4\pi}{f_J f_\phi}$	4.40	0.2	
$J\phi^{(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2}\frac{4\pi}{f_J f_\phi}$	4.40	0.2	
$J\omega^{(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2}\frac{4\pi}{f_J f_\omega}$	4.05	0.2	
$\Upsilon J^{(+)}$	$1/\sqrt{6}$	$\frac{-1}{\sqrt{3}}\frac{4\pi}{f_\Upsilon f_J}$	13.5	0.167	
$\Upsilon J^{(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2}\frac{4\pi}{f_\Upsilon f_J}$	13.5	0.167	
$B_c^*\bar{B}_c^{*(+)}$	$-1/\sqrt{6}$	$\frac{-1}{\sqrt{3}}\frac{4\pi}{f_\Upsilon f_J}$	13.5	0.167	6.60
$B_c^*\bar{B}_c^{*(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2}\frac{4\pi}{f_\Upsilon f_J}$	13.5	0.167	

There were other attempts

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New Domain of Exotics: All-Heavy Tetra-quarks

(cccc) *Phys. Rev. D 86, 034004 (2012)*

$0^{++\prime}$: $M = 5.966$ GeV, $M - M_{\rm th} = -228.$ MeV,
$1^{+-\prime}$: $M = 6.051$ GeV, $M - M_{\rm th} = -142.$ MeV,
2^{++} : $M = 6.223$ GeV, $M - M_{\rm th} = 29.5$ MeV.

Below double J/ψ threshold
Search via $J/\psi\mu^+\mu^-$, J/ψ^*

Above double J/ψ threshold
Search via $J/\psi J/\psi$

(bbcc)

$0^{++}a$: $M = 12.359$ GeV, $M - M_{\rm th} = -191.$ MeV
$0^{++}b$: $M = 12.471$ GeV, $M - M_{\rm th} = -78.7$ MeV,
$1^{+-}a$: $M = 12.424$ GeV, $M - M_{\rm th} = -126.$ MeV
$1^{+-}b$: $M = 12.488$ GeV, $M - M_{\rm th} = -62.5$ MeV,
1^{++} : $M = 12.485$ GeV, $M - M_{\rm th} = -64.9$ MeV,
2^{++} : $M = 12.566$ GeV, $M - M_{\rm th} = 16.1$ MeV.

Below double B_c threshold
$J/\psi Y(1S)$ threshold
? …

(bbbb)

$0^{++\prime}$: $M = 18.754$ GeV, $M - M_{\rm th} = -544.$ MeV,
$1^{+-\prime}$: $M = 18.808$ GeV, $M - M_{\rm th} = -490.$ MeV,
2^{++} : $M = 18.916$ GeV, $M - M_{\rm th} = -382.$ MeV.

Above double B_c threshold
$J/\psi Y(1S)$ threshold
Search via the above two channels

Below double Y(1S) threshold
Search via $Y(1S)\mu^+\mu^-$

Many recent theoretical studies on $(c\bar{c}c\bar{c})$, $(b\bar{b}b\bar{b})$, $(b\bar{b}c\bar{c})$:

controversial on existence of bound states below $\eta_b\eta_b$ threshold;

consistent on existence of resonant states above $\eta_b\eta_b$ threshold.

Re-cap, mini summary of previous presentations

- Feb 21, 2013 exotic state kick-off meeting—first proposed:
https://indico.cern.ch/getFile.py/access?contribId=4&resId=0&materialId=slides&confId=237108
- March 13, 2013, B WG meeting—Showed VV mass distributions:
https://indico.cern.ch/getFile.py/access?contribId=3&resId=2&materialId=slides&confId=238055
https://indico.cern.ch/getFile.py/access?contribId=3&resId=0&materialId=slides&confId=238055
- March 27, 2013, B WG meeting—2D fit result for J/ψJ/ψ:
https://indico.cern.ch/getFile.py/access?contribId=2&resId=0&materialId=slides&confId=238057
- April 3, 2013, B WG meeting—Follow-up on 2D fit:
https://indico.cern.ch/getFile.py/access?contribId=2&resId=0&materialId=slides&confId=238058
- July 24, 2013, B WG meeting—Tried μμee channel:
https://indico.cern.ch/getFile.py/access?contribId=2&resId=0&materialId=slides&confId=238058
- March 21, 2013, **CMS Statistics Committee—Consulate search windows & LEE:**
https://indico.cern.ch/getFile.py/access?contribId=0&resId=0&materialId=slides&confId=242367

& minute: **https://twiki.cern.ch/twiki/bin/view/CMS/SCM20130321** proposed near threshold search windows [GeV]:

- J/ψ+J/ψ--[6.2, 9.0], J/ψ+ϒ(1S)--[12.5, 14.5], ϒ(1S)+ϒ(1S)--[18.9,21.0]
- SC suggests to define two regions: near threshold region; beyond the near threshold region

- January 17, 2014, **X->VV meeting—Revealed some VV mass distributions:**
https://indico.cern.ch/event/297970/

…

- **October 8, 2019, B PAG meeting—Re-start of J/ψJ/ψ analysis using Run II data**

…

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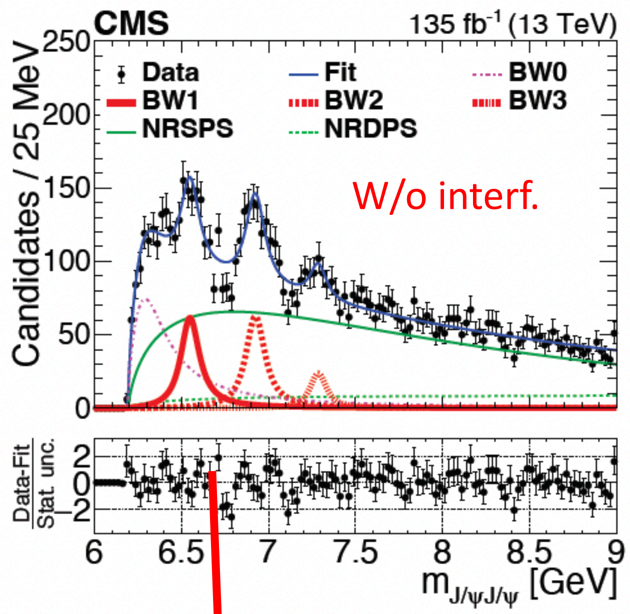
CMS $J/\psi J/\psi$



W/ interf.

Table 1. Predictions of the masses (MeV) of S-wave fully heavy $T_{4Q}(nS)$ tetraquarks. Only 0^{++} and 2^{++} are considered for $T_{bc\bar{b}\bar{c}}$. The uncertainty is from the coupling constant $\alpha_s = 0.35 \pm 0.05$.

Nucl. Phys. B 966 (2021) 115393

$T_{4Q}(nS)$ states	J^P	Mass(n=1)	Mass(n=2)	Mass(n=3)	Mass(n=4)
$T_{cc\bar{c}\bar{c}}$	0^{++}	6055^{+69}_{-74}	6555^{+36}_{-37}	6883^{+27}_{-27}	7154^{+22}_{-22}
	2^{++}	6090^{+62}_{-66}	6566^{+34}_{-35}	6890^{+27}_{-26}	7160^{+21}_{-22}
$T'_{cc\bar{c}\bar{c}}$	0^{++}	5984^{+64}_{-67}	6468[illegible]	67[illegible]5$^{+26}_{-26}$	[illegible]66$^{+21}_{-22}$
$T_{bc\bar{b}\bar{c}}$	0^{++}	12387^{+109}_{-120}	12911[illegible]	13[illegible]00$^{+35}_{-36}$	13429^{+29}_{-30}
	2^{++}	12401^{+117}_{-106}	12914^{+49}_{-49}	13[illegible]02$^{+35}_{-36}$	13430^{+29}_{-29}
$T'_{bc\bar{b}\bar{c}}$	0^{++}	12300^{+106}_{-117}	12816^{+48}_{-50}	13[illegible]04$^{+35}_{-35}$	13333^{+29}_{-29}
$T_{bb\bar{b}\bar{b}}$	0^{++}	18475^{+151}_{-169}	19073^{+59}_{-63}	19[illegible]53$^{+42}_{-42}$	19566^{+33}_{-35}
	2^{++}	18483^{+149}_{-168}	19075^{+59}_{-62}	19[illegible]55$^{+41}_{-43}$	19567^{+33}_{-35}
$T'_{bb\bar{b}\bar{b}}$	0^{++}	18383^{+149}_{-167}	18976^{+59}_{-62}	19[illegible]56$^{+43}_{-42}$	19468^{+34}_{-34}

S-wave

1^1P_1	1^{--}	363.9	320.3	-366.7	337.5	-14.4	0	0	-2.6	6553	-	-
1^3P_0	0^{-+}	356.7	320.2	-366.7	337.5	-7.2	-56.9	-43.1	-2.6	6460	6398.1	$\eta_c(1S)\chi_{c0}(1P)$
1^3P_1	1^{-+}	356.6	320.3	-366.7	337.5	-7.2	-28.4	21.5	-2.7	6554	6494.1	$\eta_c(1S)\chi_{c1}(1P)$
1^3P_2	2^{-+}	356.6	320.2	-366.7	337.5	-7.2	28.4	-2.1	-2.4	6587	6539.6	$\eta_c(1S)\chi_{c2}(1P)$
1^5P_1	1^{--}	342.4	320.4	-366.7	337.5	7.2	-85.3	-30.2	-2.7	64[illegible]9	6508.8	$\eta_c(1S)h_{c1}(1P)$
1^5P_2	2^{--}	342.2	320.2	-366.7	337.5	7.2	-28.4	30.2	-2.5	657[illegible]	6607.6	$J/\psi(1S)\chi_{c1}(1P)$
1^5P_3	3^{--}	342.3	320.3	-366.7	337.5	7.2	56.9	-8.6	-2.5	6623	6653.1	$J/\psi(1S)\chi_{c2}(1P)$
2^1P_1	1^{--}	414.7	688.7	-263.4	548.6	-11.2	0	0	-1.6	6925	-	-
2^3P_0	0^{-+}	410.0	689.6	-263.4	548.6	-5.6	-46.2	-34.5	-1.7	6851	-	-
2^3P_1	1^{-+}	410.0	689.6	-263.4	548.6	-5.6	-23.1	17.2	-1.6	6926	-	-
2^3P_2	2^{-+}	410.0	689.6	-263.4	548.7	-5.6	23.1	-3.4	-1.7	69[illegible]1	-	-
2^5P_1	1^{--}	398.7	689.5	-263.4	548.6	-5.6	-69.3	-24.2	-1.7	684[illegible]	-	-
2^5P_2	2^{--}	398.7	689.5	-263.4	548.6	5.6	-23.1	24.2	-1.5	6944	-	-
2^5P_3	3^{--}	398.8	689.7	-263.4	548.6	5.6	46.2	-6.9	-1.6	6982	-	-
3^1P_1	1^{--}	479.8	982.2	-215.5	727.8	-9.3	0	0	-1.1	7221	-	-
3^3P_0	0^{-+}	475.2	982.7	-215.5	727.7	-4.6	-41.9	-31.0	-1.2	7153	-	-
3^3P_1	1^{-+}	475.1	982.6	-215.5	727.7	-4.6	-20.9	15.5	-1.2	7220	-	-
3^3P_2	2^{-+}	475.1	982.6	-215.5	727.8	-4.6	20.9	-3.1	-1.0	7243	-	-

arXiv:2108.04017 [hep-ph]

P-wave

M[BW1] = 6552 ± 10 ± 12 MeV

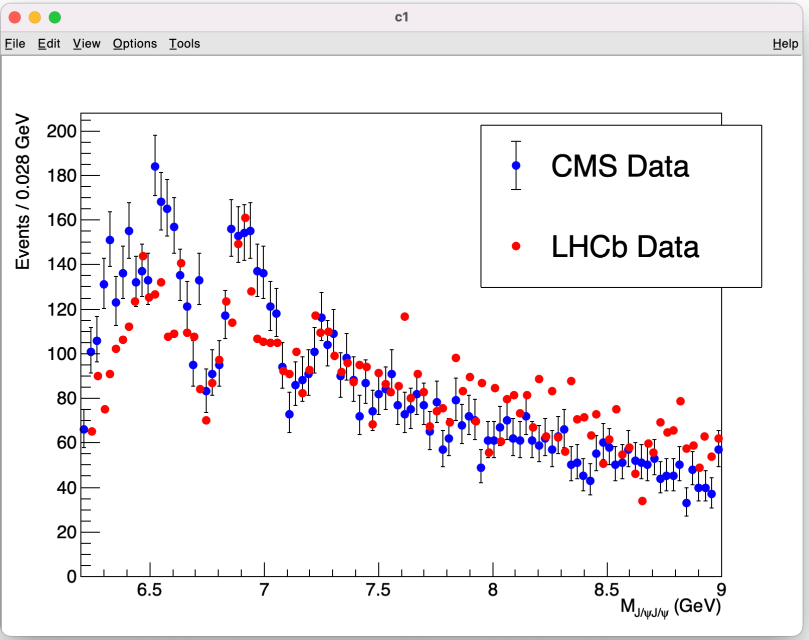
M[BW2] = 6927 ± 9 ± 5 MeV

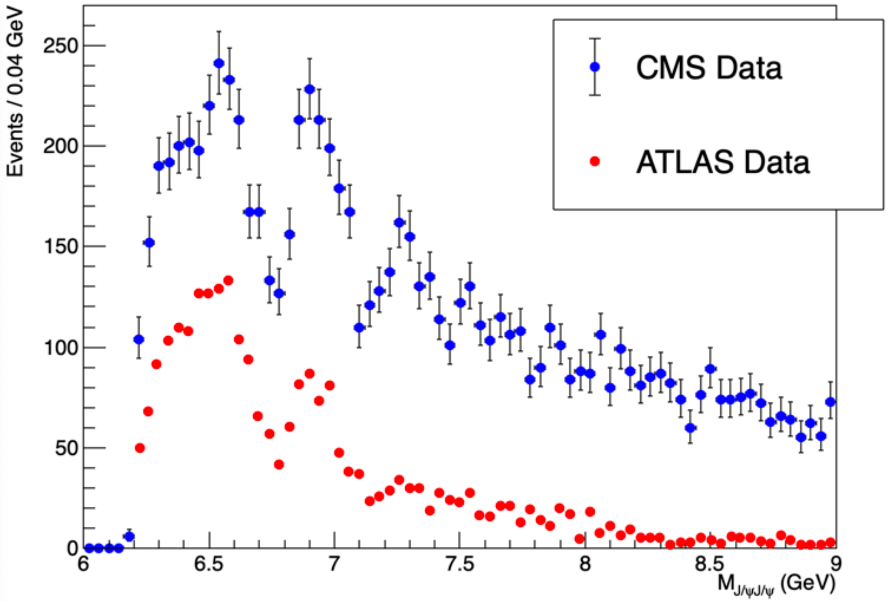
M[BW3] = 7287 ± 19 ± 5 MeV

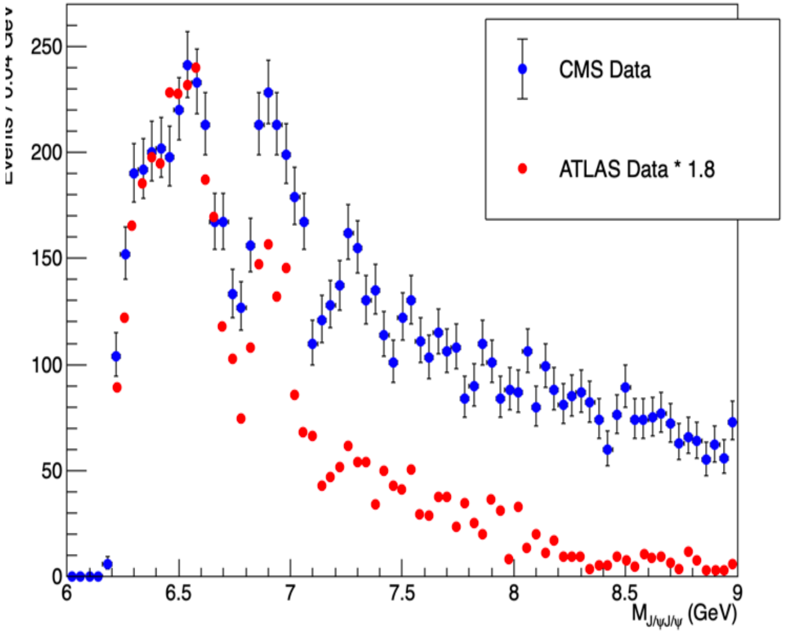
- Radial excited p-wave states like J/ψ series?
- Or Radial excited S-wave states?
- Important next step: measure J^{PC}
- Interf. effect also indicate same J^{PC}

- Natural question: what about YY final state?

$J/\psi J/\psi$ comparison with LHCb & ATLAS







- CMS vs LHCb comparisons:
  - 135/9 ≈ 15X (int. lum.)
  - $(5/3)^4$ ≈ 8X (muon acceptance)
  - Higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
  - Similar number of final events
  - 2X yield @CMS for X(6900)

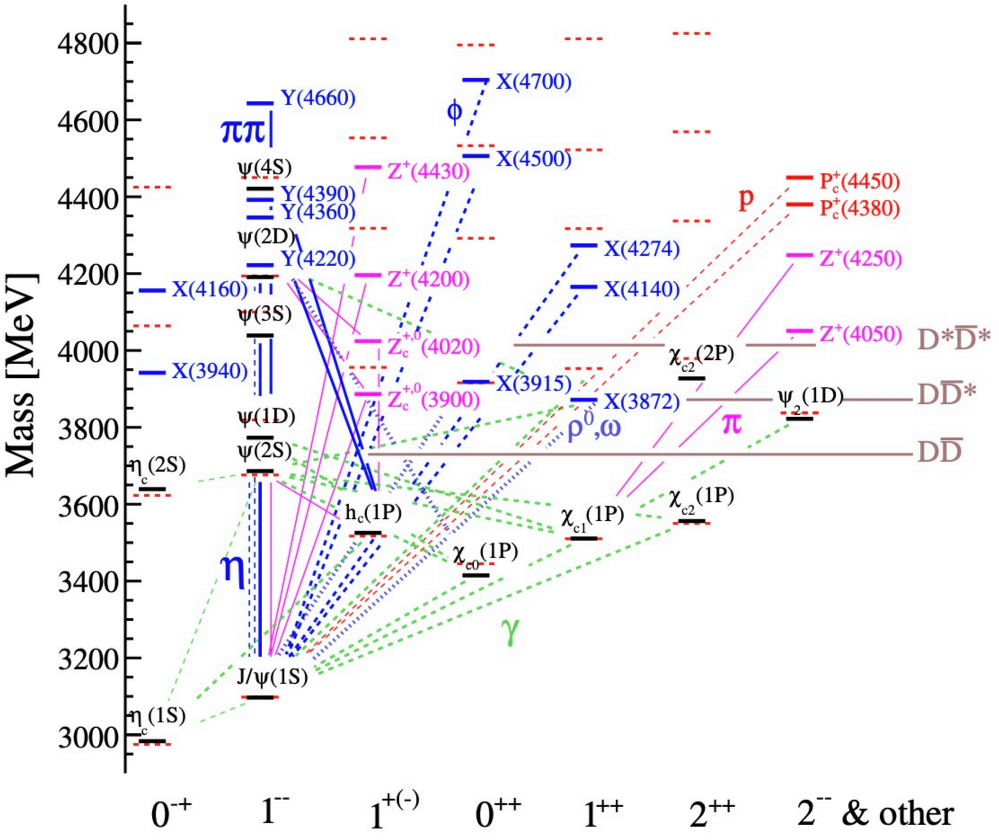
- CMS vs ATLAS comparisons:
  - ATLAS is 1/3 –1/2 of CMS data (trigger?)
  - ATLAS used dR cut—remove high mass events
  - ATLAS has slightly worse resolution

CMS has some advantage

Exotic zoo

X(bbbb)?
X(bbbb)?
X(bbbb)?

Up to 2018



X(7300)
X(6900)
X(6600)

J^{PC}=??+

Many theoretical studies on $(c\bar{c}c\bar{c})$, $(b\bar{b}b\bar{b})$, $(b\bar{b}c\bar{c})$:

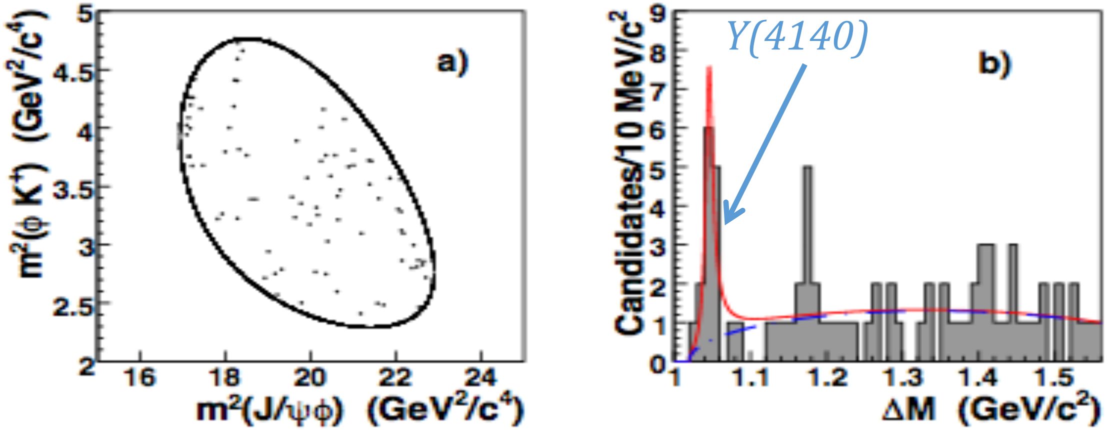
controversial on bound states below $\eta_b\eta_b$ threshold

consistent on resonant states above $\eta_b\eta_b$ threshold

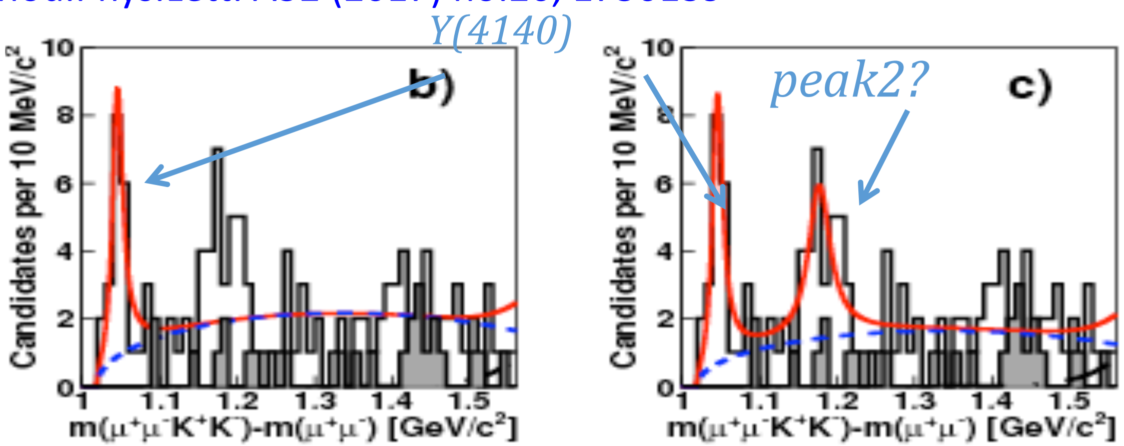
Expect similar structures in b sector

What are they?

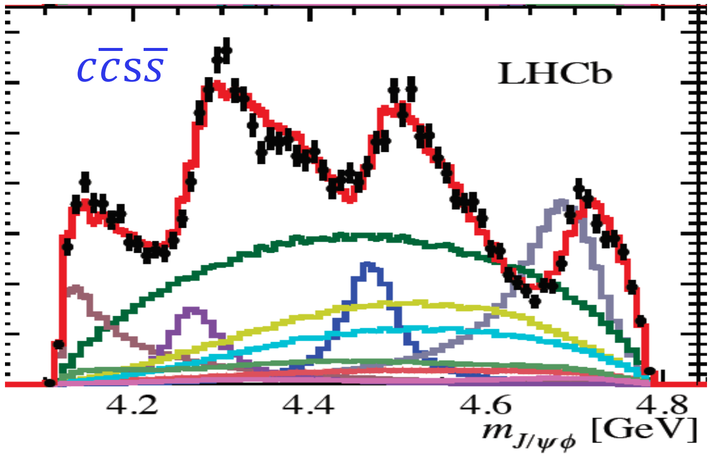
CDF—PRL102:242002 (2009)

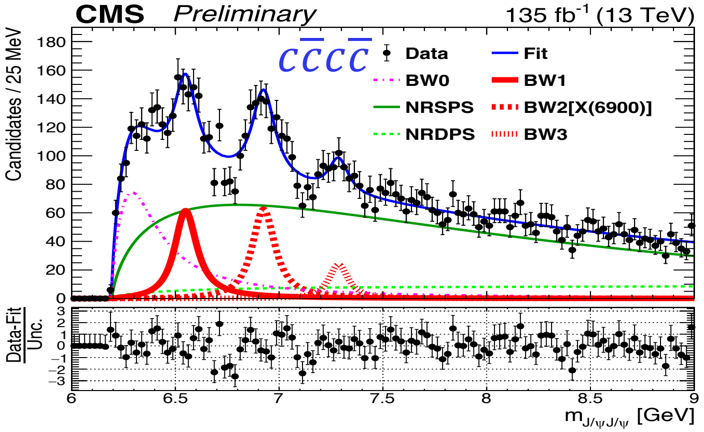


Mod.Phys.Lett. A32 (2017) no.26, 1750139



PRL 127, 082001 (2001)





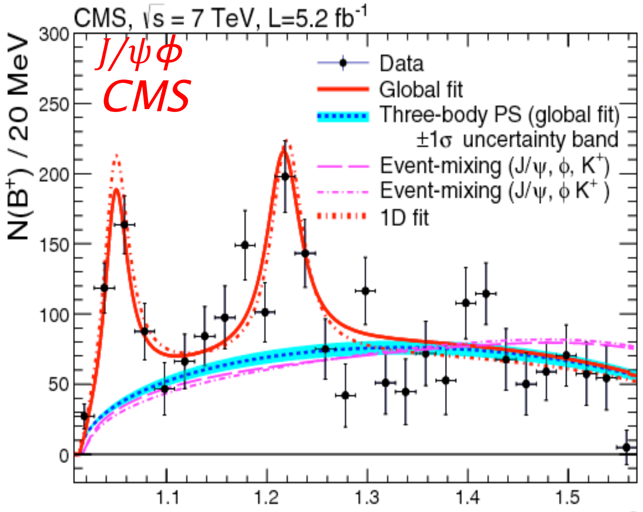
Similar $X \to 1^{-}\ 1^{--}$
how about $b\bar{b}c\bar{c}$, $b\bar{b}b\bar{b}$?

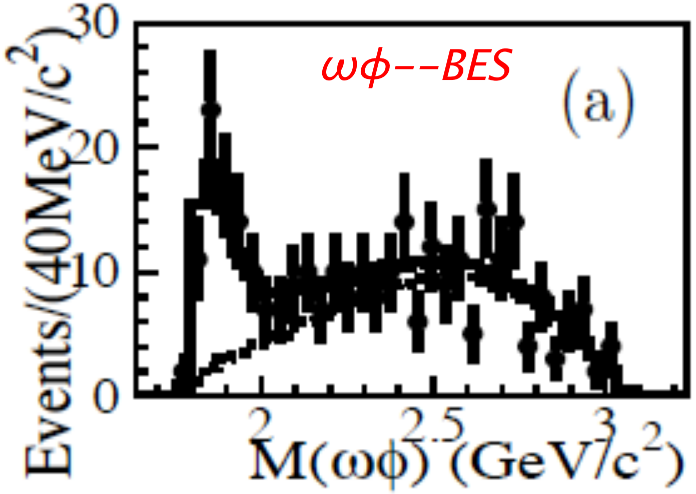
Belle II can contribute to $c\bar{c}s\bar{s}$

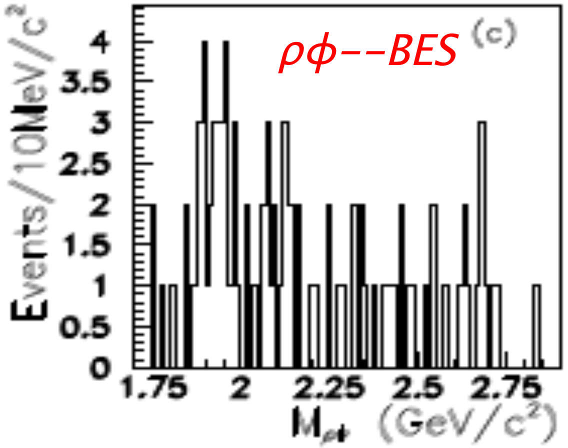
"It will also be interesting to search for vector–vector structures composed entirely of c and b quarks near threshold because they may offer simpler systems to model theoretically."

IJMPA Vol. 28, No. 18 (2013) 1330020

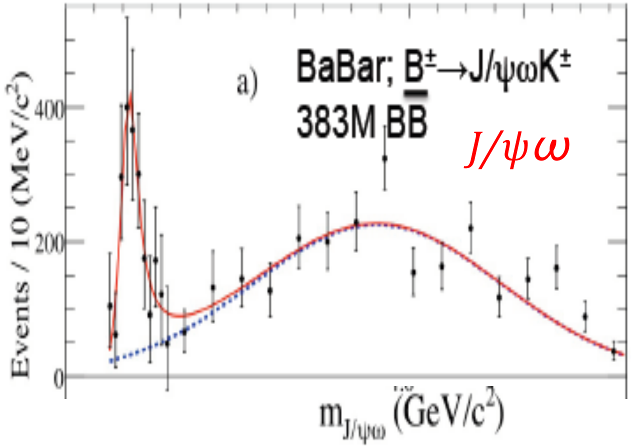
Motivation--Near Threshold puzzle

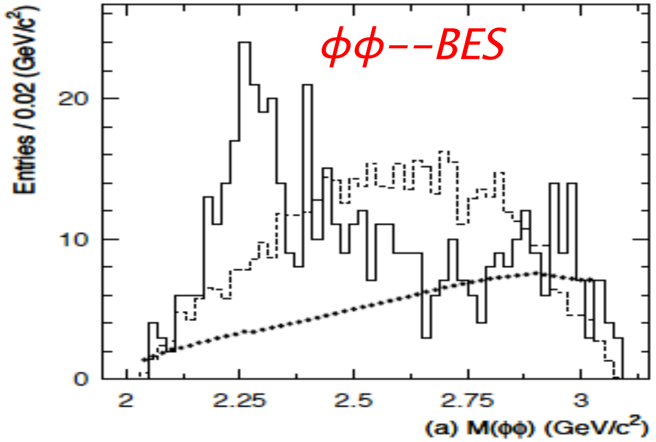


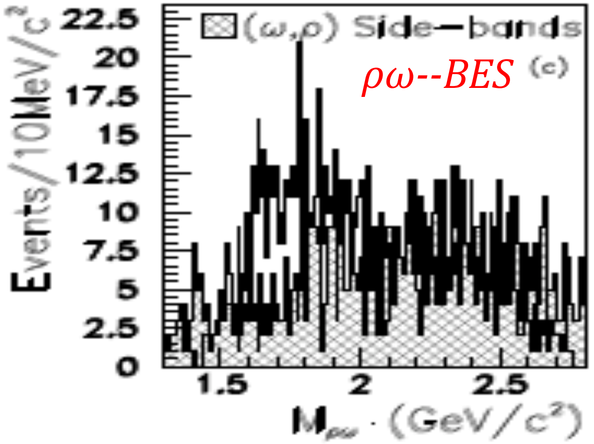




PRD 77, 012001(2008)







IJMPA Vol. 28, No. 18 (2013) 1330020

Clean vector-vector (VV) system:

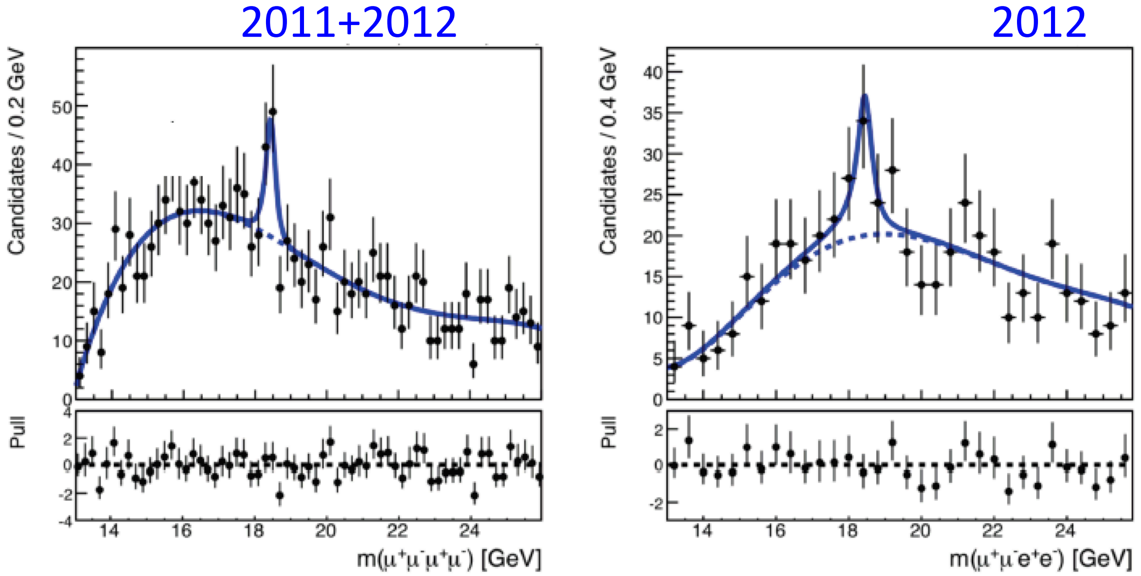
--excesses when both V has no isospin

--not clear when one V has isospin

extend to other VV system, where V is composed of heavy quark such as $J/\psi J/\psi$ and YY?

Anything below $\eta_b\eta_b$ or Y(1s)Y(1S) threshold?

Combined Result



- Do a simultaneous fit to both channels, with fixed signal shapes but floating mass value.
- Best mass : 18.4 ± 0.1 (stat.) ± 0.2 (syst.) GeV
- Local Significance: 4.86σ ($p\_value = 5.8\times10^{-7}$)

- In order to calculate global significance, Look-Elsewhere-Effect must be taken into account. Lots of toy MC generations are required, not an efficient method.
- Global significance is calculated using Gross-Vitells method which is used in Higgs discovery.

Eur.Phys.J.C70:525-530,2010

- The returned global significance was 3.6σ.

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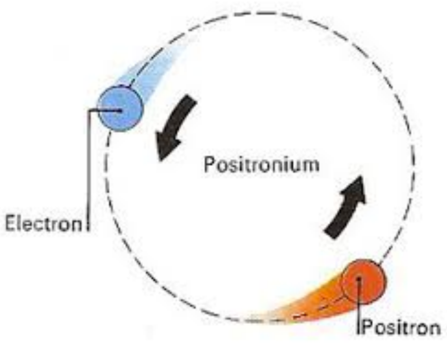
Taken from: http://meetings.aps.org/Meeting/APR18/Session/U09.6

This can be studied in LHC experiments, and future circular/linear e^+e^- colliders

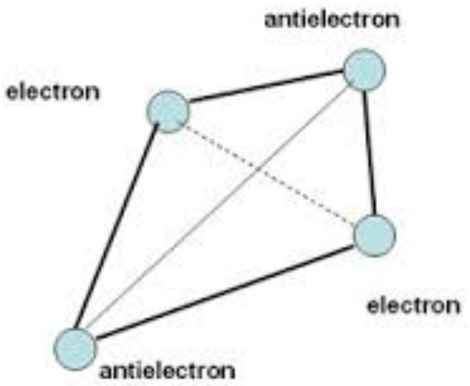
If true, can be a breakthrough in QCD , or even something more exciting

Something analogue to positronium molecule

Positronium (1951)



positronium molecule (2007)



Vol 449|13 September 2007|doi:10.1038/nature06094 nature

Nature letter

LETTERS

The production of molecular positronium

D. B. Cassidy[1] & A. P. Mills Jr[1]

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Last Updated: Wednesday, 12 September 2007, 17:03 GMT 18:03 UK

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Mirror particles form new matter

By Jonathan Fildes
Science and technology reporter, BBC News

Fragile particles rarely seen in our Universe have been merged with ordinary electrons to make a new form of matter.

Antiparticles are the mirror image of ordinary particles

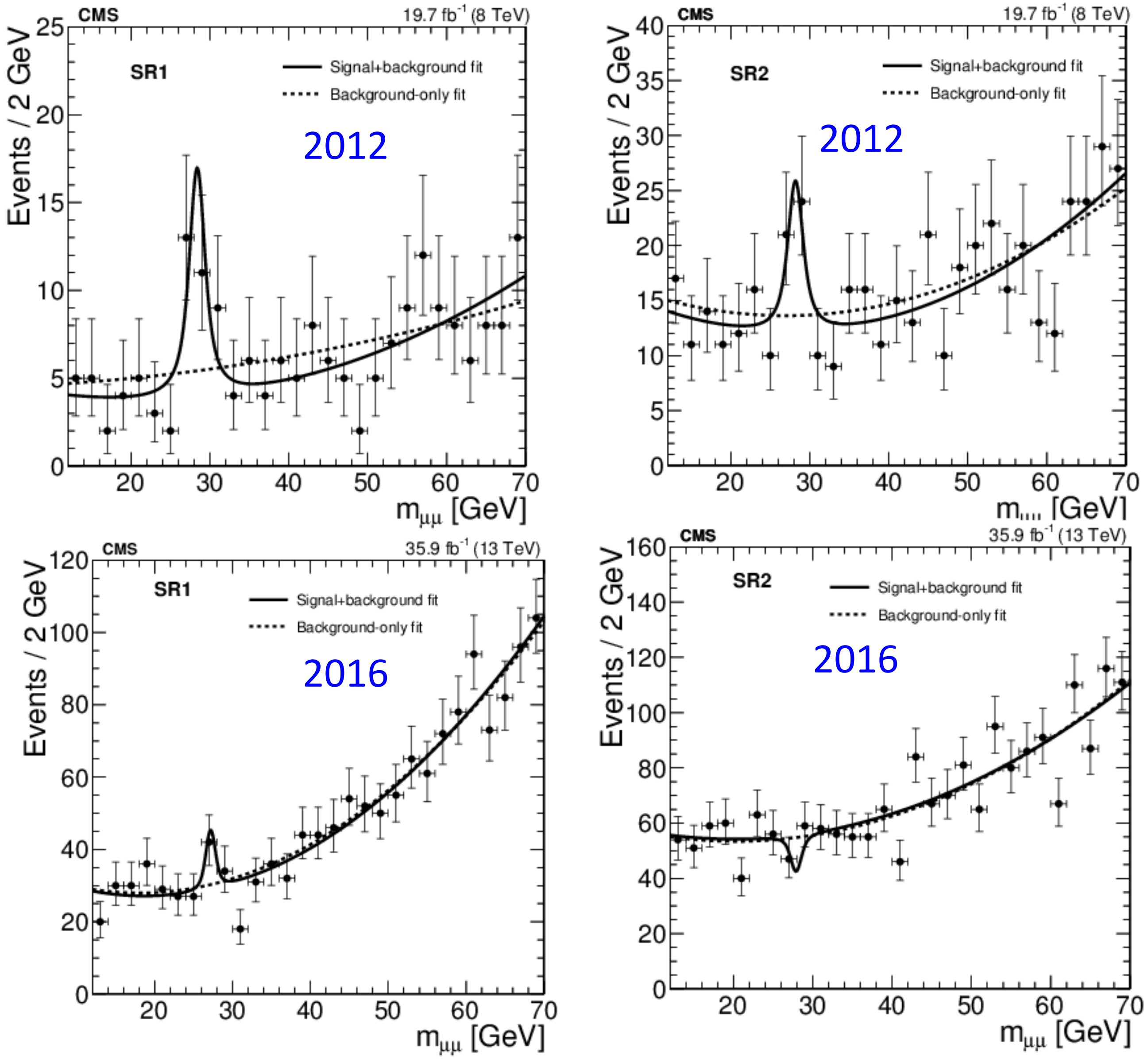
Di-positronium, as the new molecule is known, was predicted to exist in 1946 but has remained elusive to science.

Now, a US team has created thousands of the molecules by merging electrons with their antimatter equivalent: positrons.

The discovery, reported in the journal Nature, is a key step in the creation of ultra-powerful lasers known as gamma-ray annihilation lasers.

21

Dimuon result from CMS



JHEP 11 (2018) 161

ATLAS does not see
Same sensitivity?

How about 2017 ?

How about 2018?

If true → BSM

An exploration in the low mass region at LHC

never fully explored (GeVs-Z mass) Multiple-lepton final states

http://arxiv.org/abs/hep-ph/0312114

Experiment	E_{cm} [GeV]
* ADONE-MEA	2.23
BEPC-BES	2.0 - 4.8
BEPC-BES	2.6 - 5.0
* SPEAR-SMAG †	2.4 - 5.0
* SPEAR-SMAG+LGW	3.598 - 3.886
SPEAR-Crystal Ball	3.670 - 4.496
SPEAR-Crystal Ball	5.0 - 7.4
SLAC-MARK-II	3.670 - 3.872
DORIS-DASP	3.6025 - 5.1950
DORIS-II-LENA	7.440 - 9.415
* DORIS-II-ARGUS	9.360
DORIS-II-Crystal Ball	9.39 - 9.46
* DORIS-II-DHHM	9.45 - 10.04
DORIS-II-DASP	9.51
VEPP-4-MD1	7.30 - 10.29
CESR-CUSB	10.43 - 11.09
CESR-CLEO	10.49
CESR-CLEO ††	10.60 - 11.20
CESR-CLEO II	10.52
DORIS/PETRA-PLUTO	3.6 - 30.8
* PETRA-TASSO	12.0 - 41.4
* PETRA-TASSO	12.00 - 31.25
* PETRA-TASSO	14.03 - 43.70
PETRA-TASSO	41.45 - 44.20
PETRA-JADE	12.00 - 46.47
PETRA-MARK-J	12.00 - 46.47
* PETRA-MARK-J	31.57
* PETRA-MARK-J	34.85
PETRA-CELLO	14.0 - 46.6
PEP-MAC	29.0
* PEP-MARK-II	29.0
* TRISTAN-AMY	50.0 - 61.4
* TRISTAN-TOPAZ	50.0 - 61.4
* TRISTAN-TOPAZ	57.77
* TRISTAN-TOPAZ	57.37 - 59.84
* TRISTAN-VENUS	50.0 - 52.0
* TRISTAN-VENUS	63.6 - 64.0

A) Not enough energy (associated production)

B) Not enough data

C) Opportunity comes with LHC
Enough energy and luminosity

D) Rich physics motivation + curiosity,
BSM—new scalar, Higgs-like,...
QCD—new dynamics, 4b states,...
anything else unexpected?

m_Z=90 GeV

23

Motivation—Beyond Standard Model

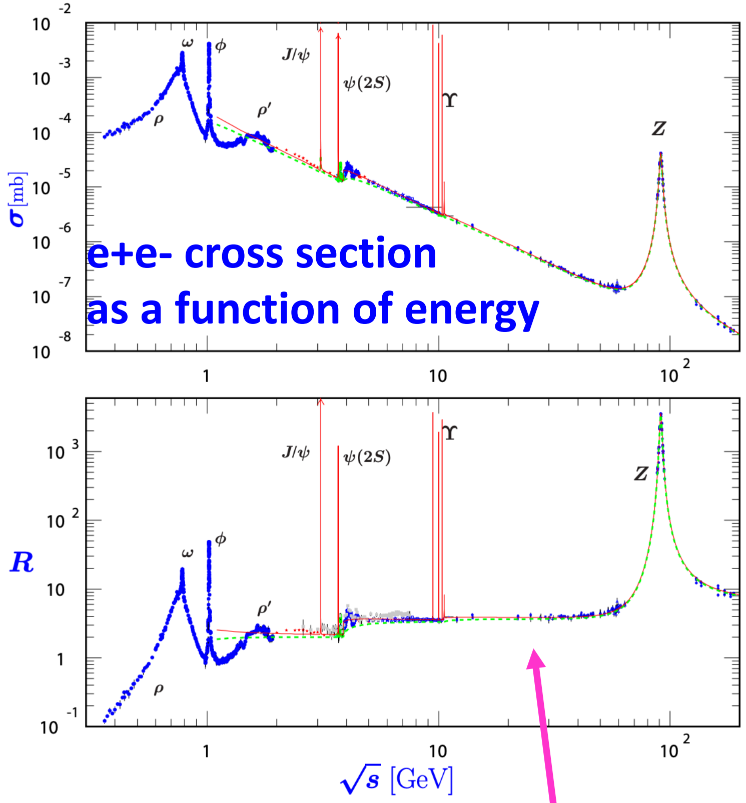
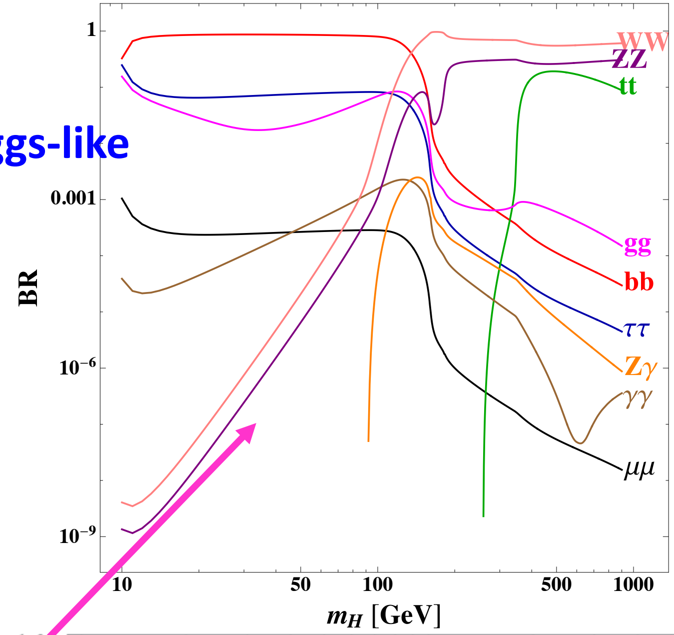
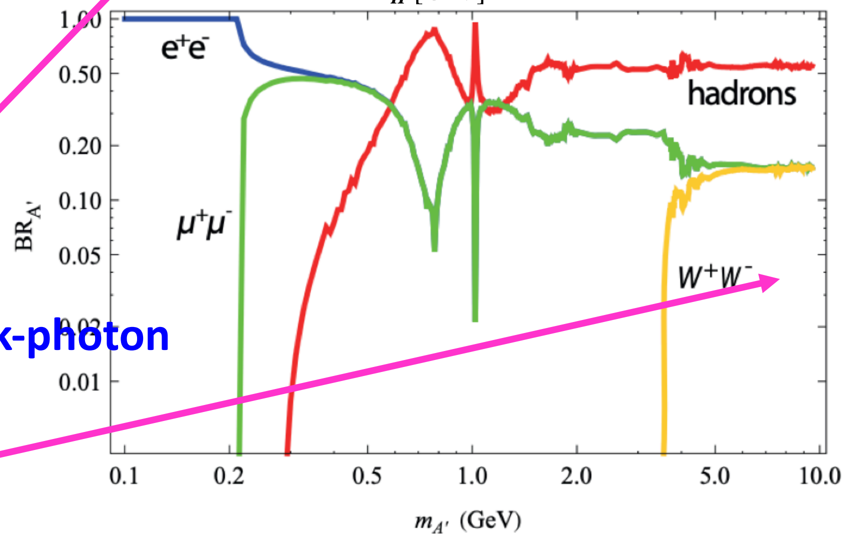


Figure 51.2: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s)$. $\sigma(e^+e^- \to hadrons, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \to \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model prediction, and the solid one (red) is 3-loop pQCD prediction (see "Quantum Chromodynamics" section of this *Review*, Eq. (9.7) or, for more details, K. G. Chetyrkin *et al.*, Nucl. Phys. **B586**, 56 (2000) (Erratum *ibid.* **B634**, 413 (2002)). Breit-Wigner

Higgs-like



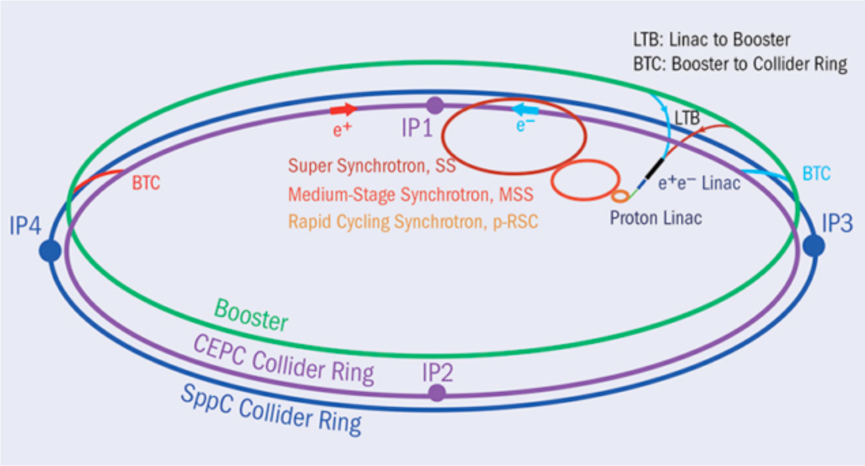


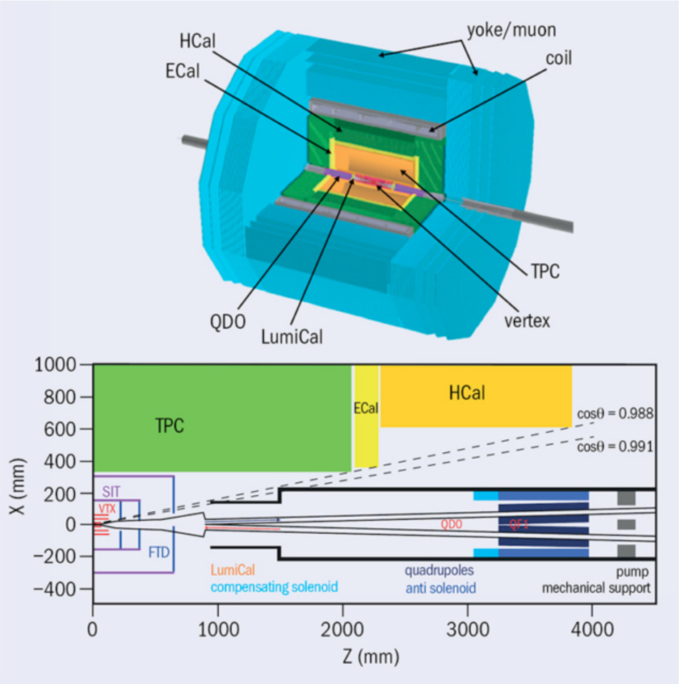
Dark-photon

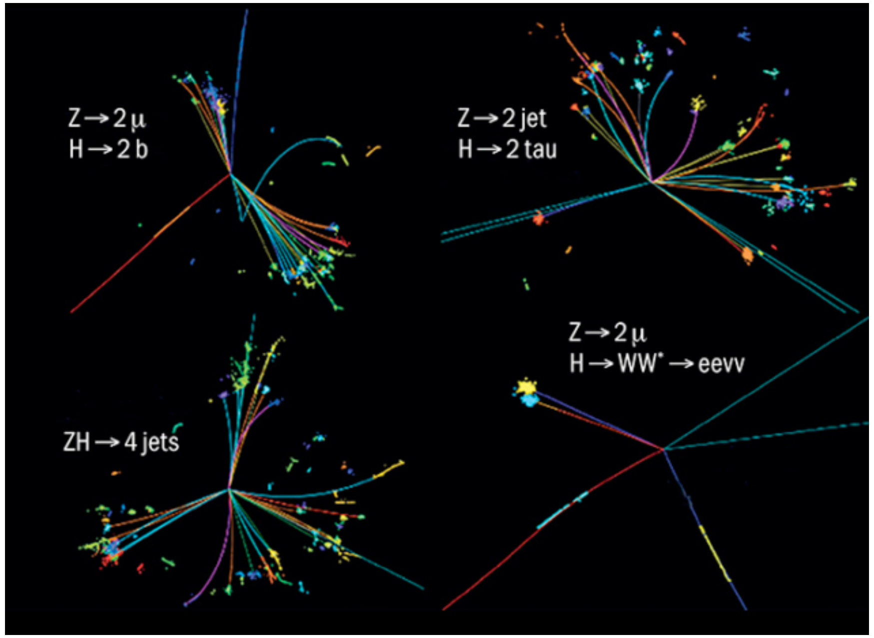
never fully explored region

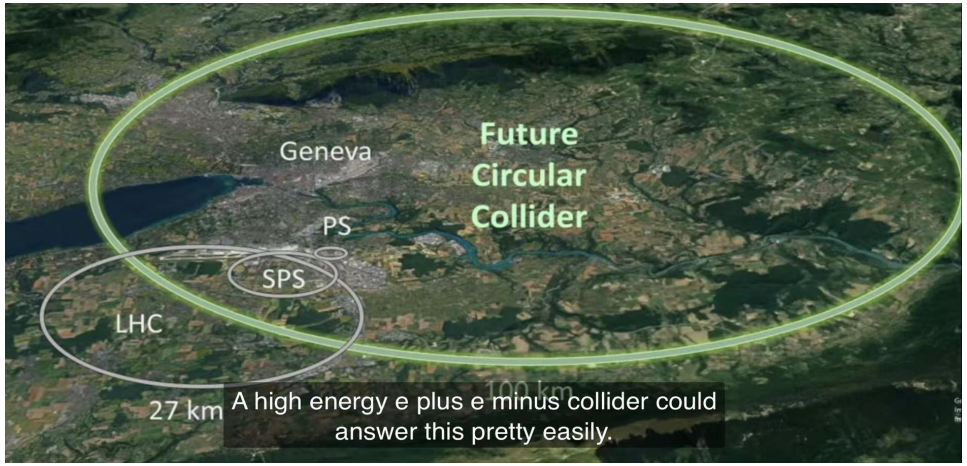
24

CEPC/FCC


LTB: Linac to Booster
BTC: Booster to Collider Ring
IP1
IP2
IP3
IP4
e+
e−
LTB
BTC
BTC
Super Synchrotron, SS
Medium-Stage Synchrotron, MSS
Rapid Cycling Synchrotron, p-RSC
e+e− Linac
Proton Linac
Booster
CEPC Collider Ring
SppC Collider Ring


HCal
ECal
yoke/muon
coil
TPC
vertex
QD0
LumiCal
TPC
ECal
HCal
cosθ = 0.988
cosθ = 0.991
SIT
VTX
FTD
LumiCal
compensating solenoid
quadrupoles
anti solenoid
pump
mechanical support
X (mm)
Z (mm)
1000
800
600
400
200
0
−200
−400
0
1000
2000
3000
4000


Z→2μ
H→2b
Z→2jet
H→2tau
ZH→4jets
Z→2μ
H→WW*→eevv


Geneva
Future
Circular
Collider
PS
SPS
LHC
27 km
100 km
A high energy e plus e minus collider could
answer this pretty easily.

25

CEPC/FCC

LHC

- Double J/ψ : observation of multiple peaks (4c)
- Double Upsilon: hints at 18 GeV

directly produced by pp

CEPC/FCC

- Associated with Z/gamma
- Produced by two photon process

cannot be directly produced by ee (1--)

- Have been looking for theorists to collaborate on various productions

IJMA, vol.33, 1850224

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Recoil masses at CEPC

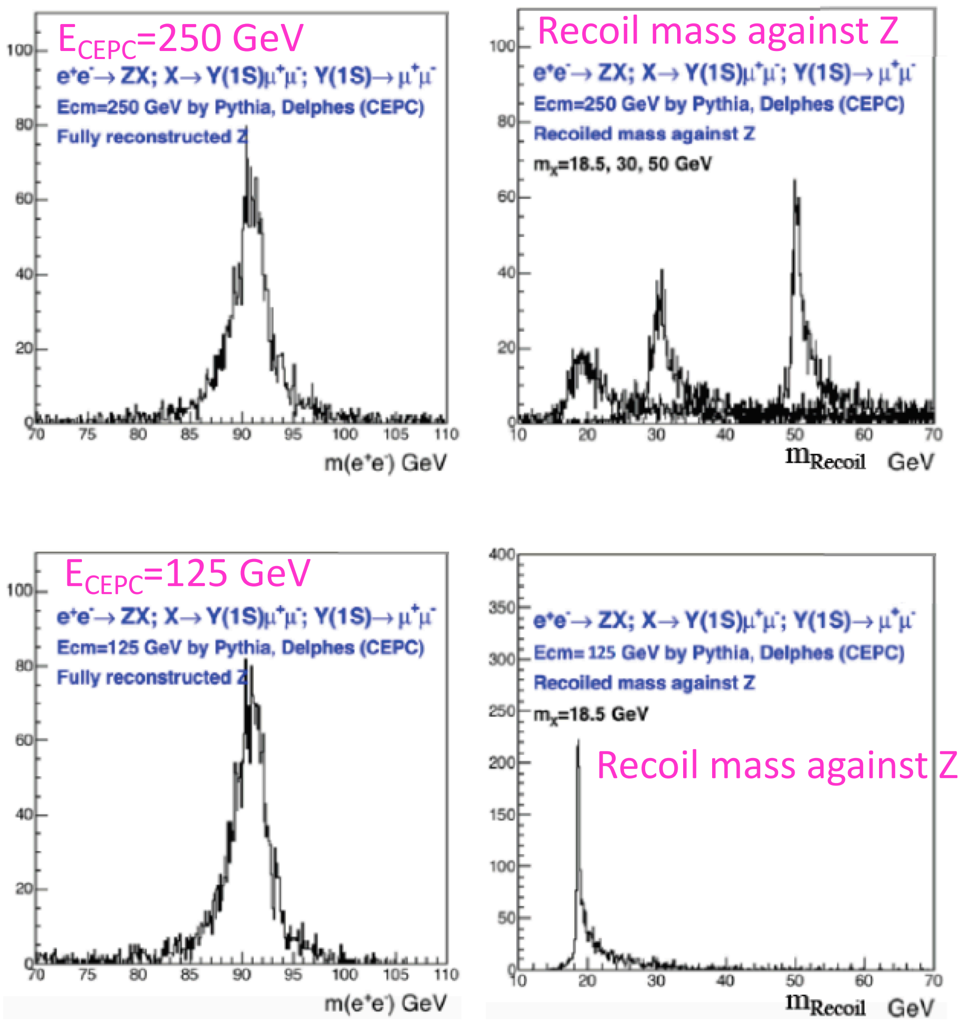

Fig. 2. The fully reconstructed Z mass and its recoiled mass against Z particle at the CEPC with different collision energy by assuming X particle mass as 18.5, 30 and 50 GeV produced in the process of $e^+e^- \to ZX$; $X \to Y(1S)\mu^+\mu^-$; $Y(1S) \to \mu^+\mu^-$. These events are simulated by Delphes with CEPC configuration.

IJMA, vol.33, 1850224

Simulated using Delphes CEPC detector with different collision energy values.

An unique approach at CEPC e^+e^- collider

It is sensitive to all final states

It is useful to measure BFs

Other $\tau^+\tau^-$ final state at CEPC

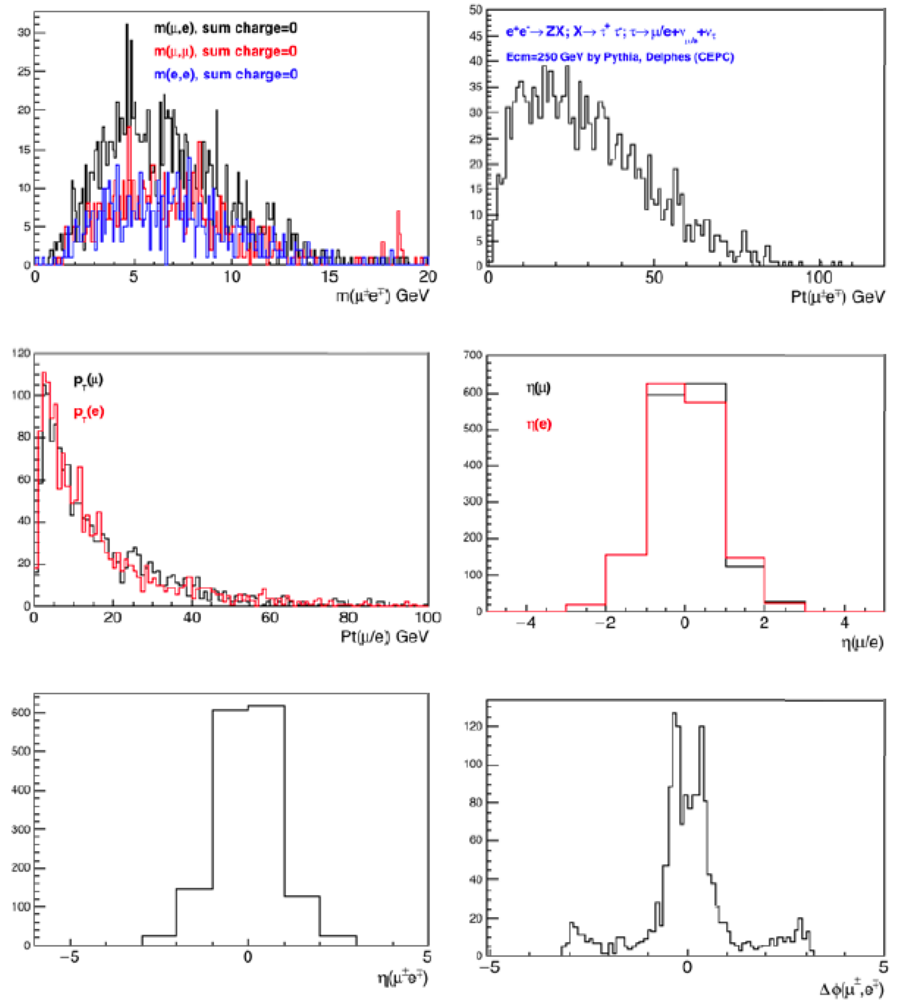

Fig. 7. The features of the $\mu^{\pm}e^{\mp}$ ($\tau^{\pm}\tau^{\mp}$) system in the $e^+e^- \to ZX$; $X \to \tau^{\pm}\tau^{\mp}$; $\tau^{\pm} \to \ell^{\pm}$ + anything-else, $\tau^{\mp} \to \ell^{\mp}$ + anything-else, where $\ell = \mu, e$ process at the CEPC: (top left) the $\mu^{\pm}e^{\mp}/\mu^{\pm}\mu^{\mp}/e^{\pm}e^{\mp}$ mass distributions; (top right) the p_T distributions of $\mu^{\pm}e^{\mp}$; (middle left) the p_T distribution of muon and electron; (middle right) the η distribution of muon and electron; (bottom left) the η distribution of $\mu^{\pm}e^{\mp}$; (bottom right) the $\Delta\phi$ distribution between muon and electron. These events are simulated by Delphes with CEPC configuration.

IJMA, vol.33, 1850224

Simulated using Delphes CEPC detector

Another approach for $\tau^+\tau^-$ final state through opposite u e channel at CEPC e^+e^- collider

Two photon process at CEPC

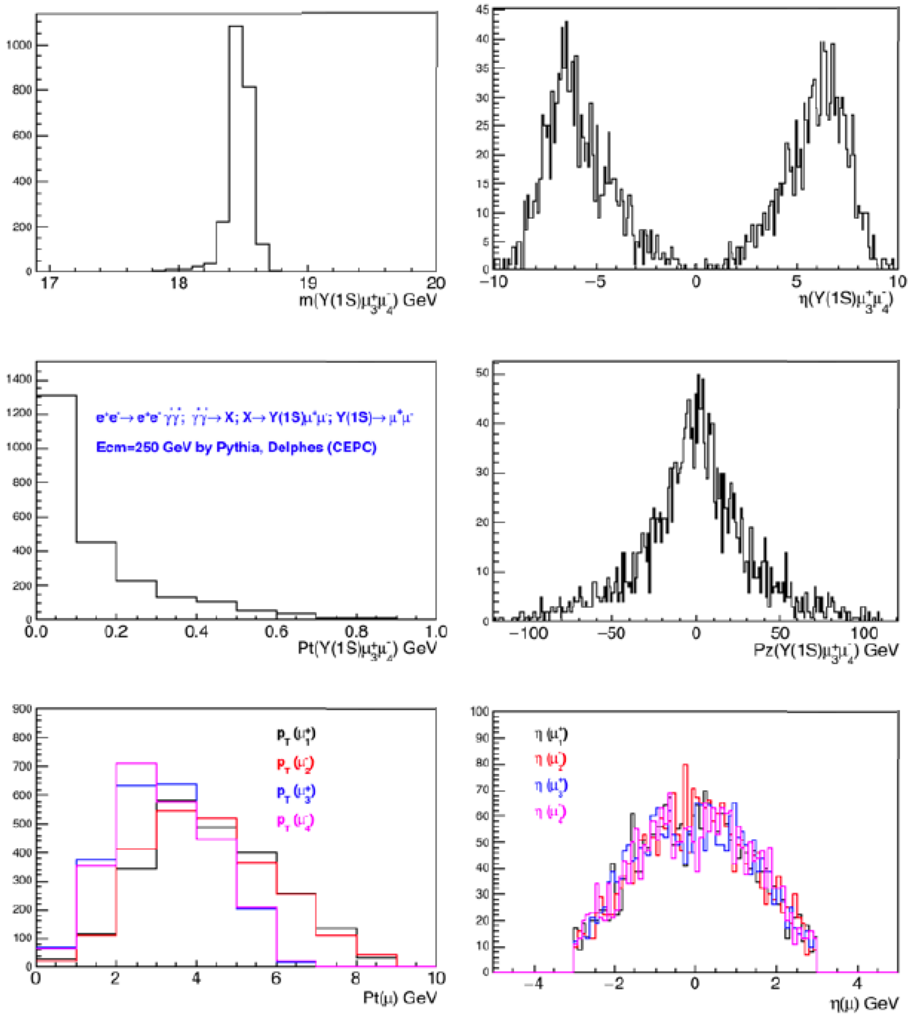

Fig. 8. The features of the four-muon system in the $e^+e^- \to e^+e^-X$; $X \to Y(1S)\mu^+\mu^-$; $Y(1S) \to \mu^+\mu^-$ process at the CEPC: (top left) the invariant mass of the four muons; (top right) the η distribution of the four muons; (middle left) p_T of the four muons; (middle right) p_Z of the four muons; (bottom left) p_T of each muon; (bottom right) η of each muon. These events are simulated by Delphes with CEPC configuration.

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Simulated using Delphes CEPC detector

Another unique approach to study multiple lepton final state at CEPC e^+e^- collider

Summary

- CMS found a potential family of structures X(6600) X(6900), X(7200)
  - Confirms the existence of X(6900) observed by LHCb
  - which are candidates for all-charm tetra-quarks!

- More data/knowledge needed to understand nature of near threshold region

- ***All-heavy quark exotic structures offer system easier to understand***
- ***A new window to understand strong interaction***
- ***May extend for BSM in multiple lepton final state***

- CEPC/FCC offers new opportunities to study heavy exotic hadrons, even BSM

Backup

BSM—light Z', light Higgs

1404.3947 [hep-ex]

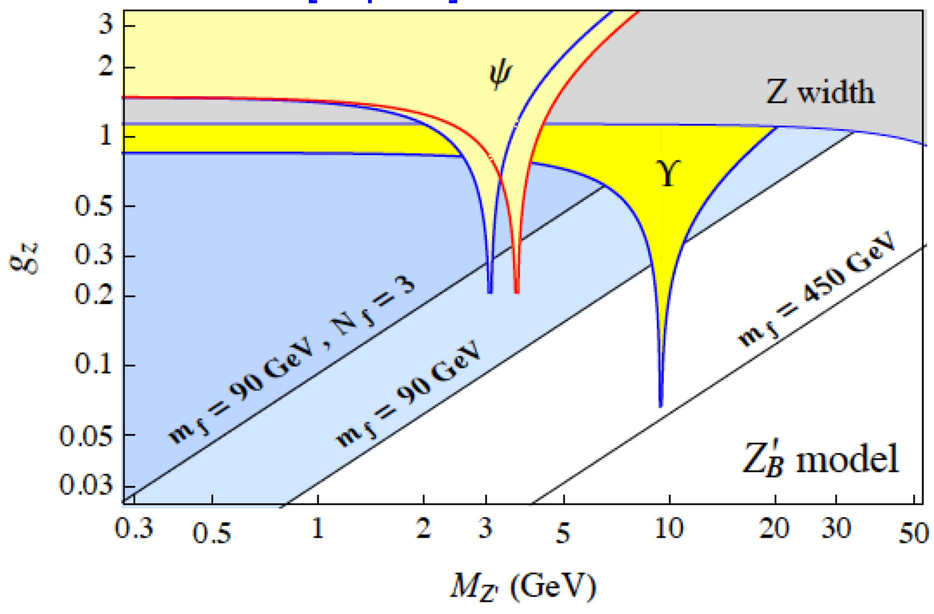


FIG. 1. Limits in the gauge coupling versus mass plane for Z'_B. Values of g_z above the straight lines are excluded by the anomaly cancellation conditions in conjunction with collider searches for new fermions, for $N_f = 1$ or 3, $m_f > 90$ GeV, and for $N_f = 1$, $m_f > 450$ GeV. The top regions are excluded by quarkonium and hadronic Z decays.

For g_z<1.0 case,
Light Z' mass region between upsilon and 50 GeV is not constrained at all.

Main decay channel is jj, but difficult to search at hadron colliders.

This mass region is not explored before, can we explore now?

How?

How about possible light Higgs?

g_z—gauge coupling

BSM—dark sector

- **Physics Beyond Standard Model, i.e., a new particle Z_d** *Phys. Rev. D 88, 015022 (2013)*

---Associated with dark sector including dark matter, no direct coupling to SM particles

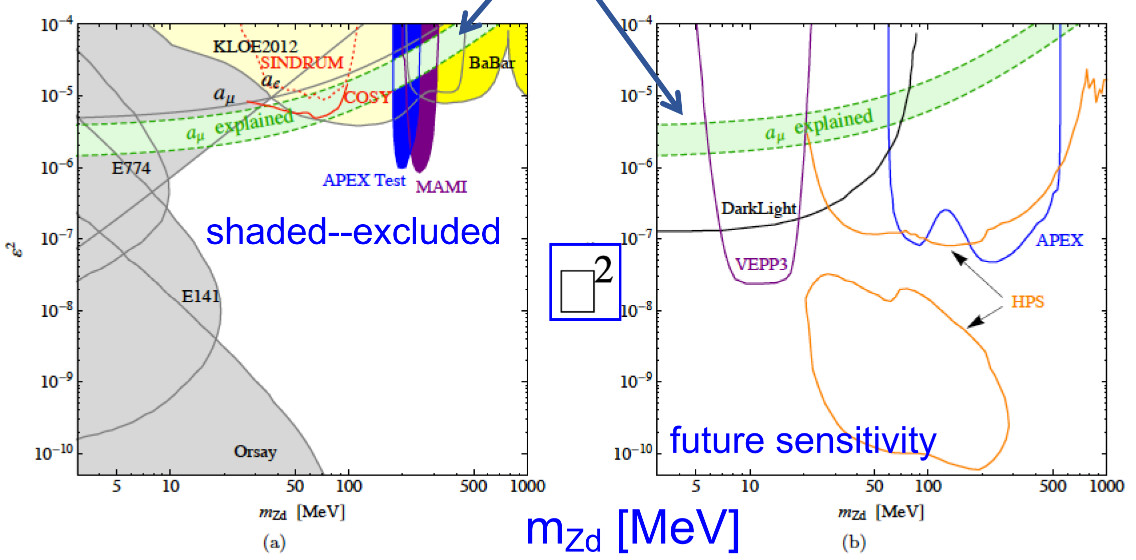
---Coupled to Higgs via mass-mixing, or new heavy fermion loops

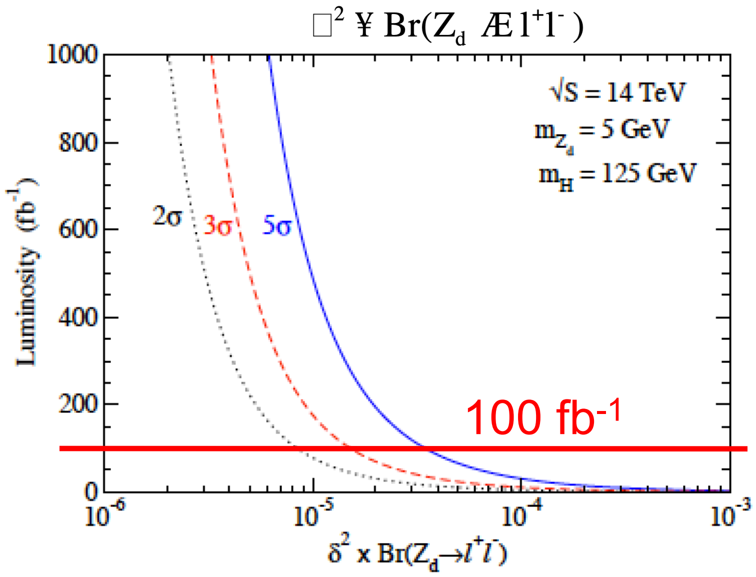
---Higgs➔XZ_d, X=Z, Z_d, or γ, four-lepton final state, $u^+u^-u^+u^-$, $e^+e^-u^+u^-$

$$\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta$$ δ is a model dependent parameter

Explain g-2 discrepancy

LHC sensitivity for H➔XZ_d





Direct search at low mass region < 1 GeV

Z_d 5-10 GeV, complementary to low mass direct search

Charmonium States

Notation:

$^{2S+1}[L]_J$

L=S,P,D (0,1,2)
(No cand. *with* L>=3)

J = L+S

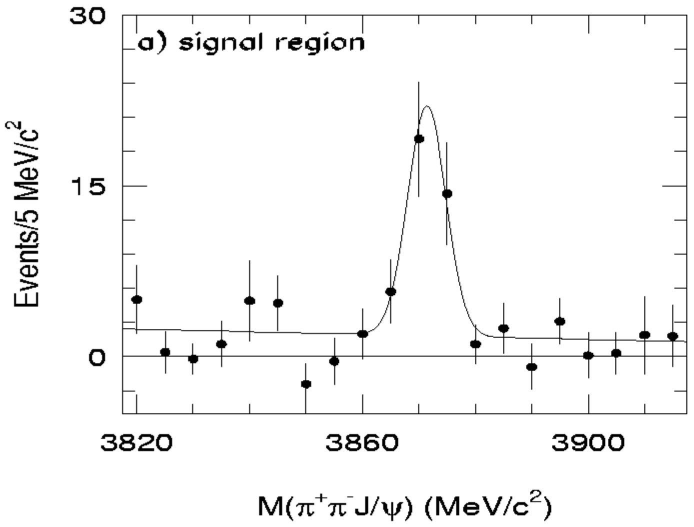
S(qq) = 0 or 1

Parity: **P = (-1)$^{L+1}$**

Charge conjugation *eigenvales:* **C=(-1)$^{L+S}$**

***N**: Radial Quantum Numbers*

Quantum numbers				Name	Mass (MeV/c^2)	width(MeV)
N	L	J^{PC}	$N^{2S+1}L_J$			
1	0	0^{-+}	1^1S_0	$\eta_c(1S)$	2980.4±1.2	26.7±3
1	0	1^{--}	1^3S_1	J/ψ	3096.916±0.011	93.2±0.02 ×10^{-3}
1	1	0^{++}	1^3P_0	χ_{c0} (1P)	3414.75±0.31	10.2±0.7
1	1	1^{++}	1^3P_1	χ_{c1}(1P)	3510.66±0.07	0.89±0.05
1	1	2^{++}	1^3P_2	χ_{c2}(1P)	3556.20±0.09	2.03±0.12
1	1	1^{+-}	1^1P_1	h_c(1P)	3525.93±0.27	<1
1	2	1^{--}	1^3D_1	ψ(3770)	3772.92±0.35	27.3±1.0
2	0	0^{-+}	2^1S_0	η_c(2S)	3637±4	14±7
2	0	1^{--}	2^3S_1	ψ(2S)	3686.09±0.04	317±9 ×10^{-3}
2	1	2^{++}	2^3P_2	χ_{c2}(2P)	3929±5	29±10
3	0	1^{--}	3^3S_1	ψ(4040)	4039±1	80±10
2	2	1^{--}	2^3D_1	ψ(4160)	4153±3	103±8
4	0	1^{--}	4^3S_1	ψ(4415)	4421±4	62±20



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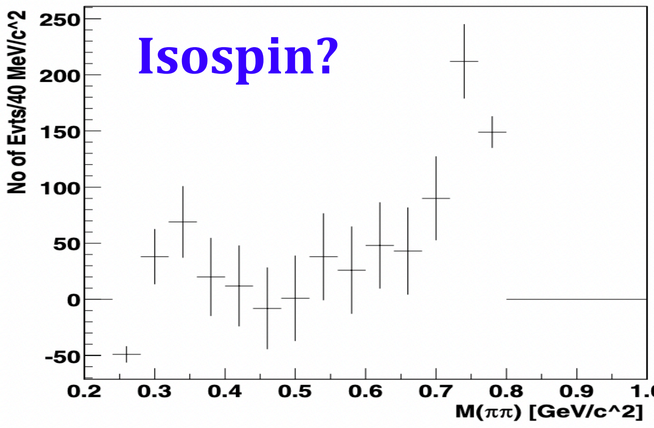

π π mass ρ *like*

Heavy—a factor to make us easier to identify "exotic"