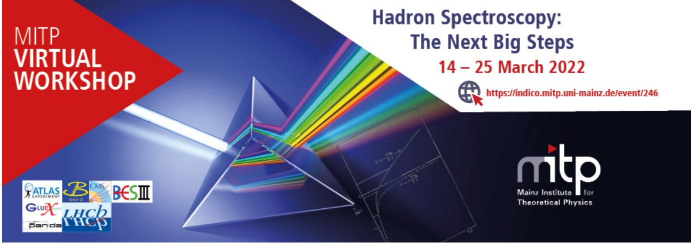


Experimental summary
Multiquark states: 20 years later

Claudia Patrignani

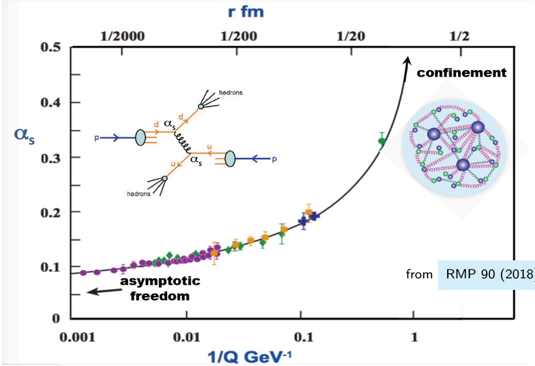
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
CAMPUS DI RIMINI

Università di Bologna and I.N.F.N.
Claudia.Patrignani@bo.infn.it

INFN

Facts:

- QCD *is* part of the Standard Model



from RMP 90 (2018) 015003

unfortunately perturbative only at small distance

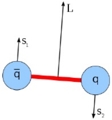
- precision tests of Standard Model rely on controlling QCD corrections
- the primary observable of QCD is the hadron spectrum
- level splittings $\Longrightarrow$ probe the region between long and short distance

Spectroscopy is a tool to test understanding short and medium range dynamics

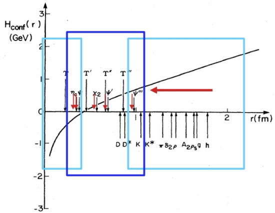
A flashback: heavy quark spectroscopy circa A.D. 2000

Mesons:

The quantum numbers are determined from the relative angular momentum L and the quark spin relative orientation $\vec{s}_1$ and $\vec{s}_2$:



- $P = (-1)^{L+1}$
- $|L - S| \leqslant J \leqslant |L + S|$
- C only defined for flavor-less mesons



Quarkonium: charmonium and bottomonium

Heavy quarks $\longrightarrow$ non relativistic
relativistic corrections in $b\bar{b}$ smaller than in $c\bar{c}$ (?)

- Potential models: Cornell (Coulomb +linear term)
  but also
- Lattice NRQCD, pNRQCD: α_s, m_b/m_c, lattice spacing, ...

$c\bar{c}$ or $b\bar{b}$ bound states: spectroscopic notation: $n^{2S+1}L_J$

fermion-antifermion: $P = (-1)^{L+1}$ $\quad C = (-1)^{L+S}$

$$\psi(nS), \Upsilon(nS) = n^3S_1 \qquad \eta_Q(nS) = n^1S_0$$
$$\chi_{QJ}(nP) = n^3P_J \qquad h_Q(nP) = n^1P_1$$

Quarkonium physics

Decay widths:
above open $D\bar{D}$ or $B\bar{B}$ threshold dominant decay to heavy mesons unless forbidden by quantum numbers broad states
below open $D\bar{D}$ or $B\bar{B}$ threshold, $Q\bar{Q}$ annihilate to gluons (or virtual photon) OZI-rule $\longrightarrow$ narrow states:

- $\psi(nS), \Upsilon(nS) \to ggg,\ \gamma gg$ [$\approx$ %] or $\gamma*$ [$\ell^+\ell^- \approx$ %]
- other states decay to ggg or gg depending on J odd/even
  $\eta_Q(nS), \chi_{Q0}(nP), \chi_{Q2}(nP) \to gg$
  $h_Q(nP), \chi_{Q1}(nP) \to ggg$ or $gq\bar{q}$
- very few exclusive hadronic modes observed especially in $b\bar{b}$

Radiative and hadronic transitions:

- photon or gluons radiation from $Q\bar{Q}$ state
  multipole expansion if radius $\ll$ wavelength

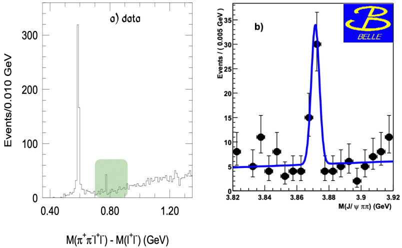
Spectroscopy:

- fine and hyperfine splitting (spin-dependent terms)
  mass splitting between n^3S_1 and n^1S_0 depend strongly on α_s

Focus: precisely understand spectrum below open charm/bottom threshold

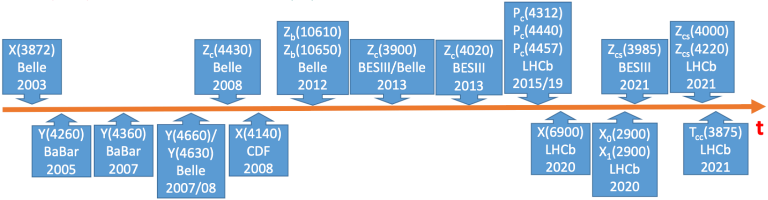
A.D. 2003: $X(3872)$ – now $\chi_{c_1}(3872)$ just the first in a new kind of hadrons

Unexpected mass&Unique properties.



Phys.Rev.Lett. 91 (2003) 262001 *Most cited Belle paper!*

- Ever since the discovery of $X(3872)$, we have a golden era in the discovery of the exotic states.
- No solid explanations for these exotics.

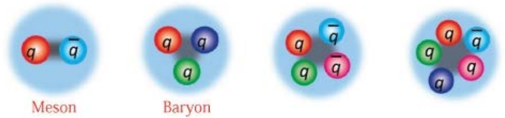


4

From Junhao Yin's talk, (Tue,15)

Standard and Exotic Hadrons

Mesons and baryons with other than $q\bar{q}$ or qqq configurations not forbidden by QCD (as long as they remain colour-less)



possibility admitted as early as the quark model was introduced

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING II *)

G. Zweig **)
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

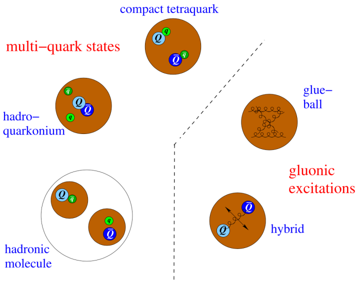
6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

no undisputed evidence yet in light hadrons

pretty well established by now in heavy hadrons

Multiquark states

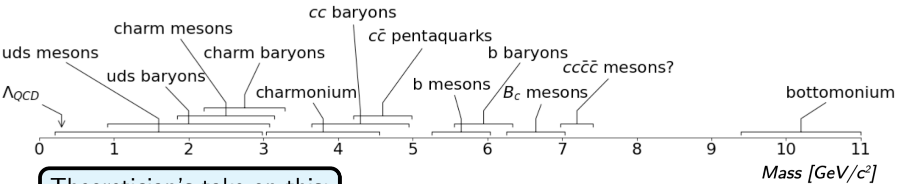
N. Brambilla, S. Eidelman, C. Hanhart et al. / Physics Reports 873 (2020) 1–154



From Junhao Yin's talk, (Tue,15)

hadron spectroscopy

- New knowledge feeds back to theory.
- Perfect ground to test theoretical models.
- New viewing angle towards QCD.



Theoretician's take on this:

Need to understand the role of nearby thresholds

not always easy, plenty of thresholds...

Need to understand the relevance of diquark approximation

Experimenter's take on this: measure as many multiquark states as possible

What are we looking for?

Manifestly exotic

- quantum numbers not allowed for $q\bar{q}'$ or $qq'q$"
- >3 valence quarks required

Undisputed

many possible exotic states would not fit

"Cryptoexotic"

- mass/width not fitting in meson or baryon spectra
- overpopulation of the spectra
- production or decay properties incompatible with standard mesons/baryons

identification can be disputed

possible mixing with conventional states

CAVEAT:Peaking structures can also be due to rescattering / threshold effects,. . .

for heavy constituent quarks the mass itself is a clue!

Outline

. . . too many results!

disclaimer: just a personal selection

And be lenient if I misunderstood your work :)

Heavy (exotic?) mesons

$\chi_{c1}(3872)$

In nearly 20 years we have learnt a lot:

- $J^{PC} = 1^{++}$ (LHCb)
- absolute branching fractions (*BABAR*) albeit with large errors
  $\approx 90\%$ to $D^0\ \bar{D}^{*0}$ and $D^0\ \bar{D}^0\ \pi^0$
- lower limit on the natural width (LHCb)
  still not able to test the expected deviation from BW shape
- mass determined with increased precision
  but still compatible with $D^0\ \bar{D}^{*0}$ threshold
- sizeable I-spin violation in $\chi_{c1}(3872) \to J/\psi\,\pi^+\pi^-$
- large prompt production in pp and $p\bar{p}$ high energy collisions

yet, we are far from understanding its nature

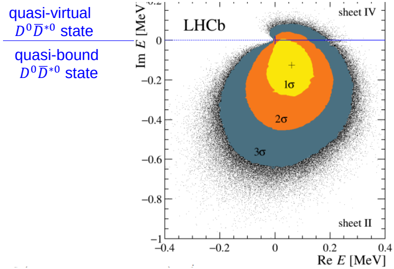
plenty of recent and new results, as well as future perspectives presented in Thursday 17th session by

- Tomasz Skwarnicki (LHCb)
- Daniele Fasanella (CMS)
- Jens Sören Lange (Belle,BelleII)
- Frank Nerling (PANDA)

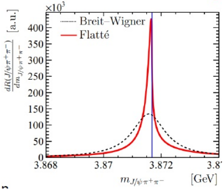
A few picks on $\chi_{c1}(3872)$: Proximity to threshold & width

close to threshold BW is not appropriate; decay dominated by $D^0\ \bar{D}^{*0} \implies$ Flattè inspired amplitude parametrization

- (T. Skwarnicki): quasi-bound state preferred over quasi-virtual state

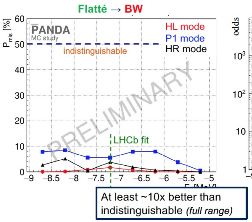


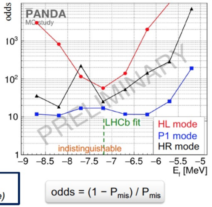
excellent LHCb resolution gives sensitivity to natural width, yet it's not enough (nor will likely be..)



- (F. Nerling) PANDA

should be able to pin down the correct lineshape and achieve a sensitivity $\Gamma/\Delta\Gamma > 5$ for $\Gamma \gtrsim 50 \div 120$ keV provided $\mathcal{B}_{p\bar{p}}$ not too small...



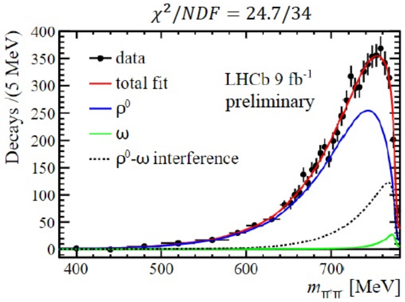


A few picks on $\chi_{c1}(3872)$: I-spin violating decays

- (T. Skwarnicki) Determination of sizeable ω contribution in $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$

Decay NOT completely dominated by ρ^0

:



ω, which is small on its own, but is enhanced to a sizeable contribution via $\rho - \omega$ interference!

Significance of ω contributions is 7.1σ

ρ ~ 79%

$\rho - \omega$ ~ 19%

ω ~ 2%

$(21.4 \pm 2.3 \pm 2.0)\%$

$(1.9 \pm 0.4 \pm 0.3)\%$
In agreement with the expectations from the
$\Gamma(X(3872) \to \omega J/\psi,\ \omega \to \pi^+\pi^-\pi^0)\ /\ \Gamma(X(3872) \to \pi^+\pi^- J/\psi)$
measurements by Belle, BaBar and BESIII

phase space effects on resonance masses in decay chains NOT simulated in EvtGen

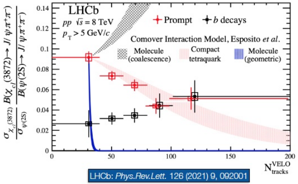
Implications for I-spin violating contribution:

$$\frac{g_{X(3872)\to\rho^0 J/\psi}}{g_{X(3872)\to\omega J/\psi}} = 0.29 \pm 0.04 \quad \text{vs} \quad \frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = 0.045 \pm 0.001$$

A few picks on $\chi_{c1}(3872)$: prompt production

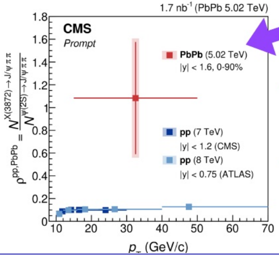
Compare to $\psi(2S) \to \pi^+\pi^- J/\psi$; prompt/non-prompt via tranverse distance from primary vertex

- (T. Skwarnicki) event-multiplicity dependence of prompt production in pp markedly different from $\psi(2S)$



seem to support compact tetraquark (comover interaction m.)

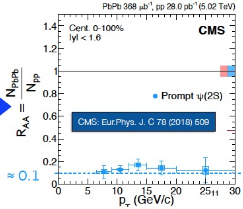
- (D. Fasanella) PbPb collisions (CMS, first measurement) and pp



Indication of R enhancement in PbPb w.r.t. pp

- Better precision and accuracy needed to draw conclusions

- CMS also measured the strong suppression of ψ(2S) in PbPb collision
- X(3872) less suppressed than ψ(2S) in PbPb



seem to support coalescence model!

A few picks on $\chi_{c1}(3872)$: b-hadron, $\gamma\gamma$ production

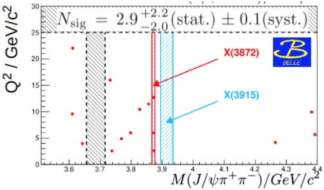
- (J.S. Lange) First evidence of $\chi_{c1}(3872)$ in $\gamma\gamma$ (Belle)

at least one photon is virtual

$$\Gamma_{\gamma\gamma}^{X(3872)} \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 5.5^{+4.1}_{-3.8} \pm 0.7\ eV$$

Belle, Phys. Rev. Lett. 126 (2021) 122001 (825 fb^{-1})

Significance 3.2σ
(background
0.11±0.10 events)



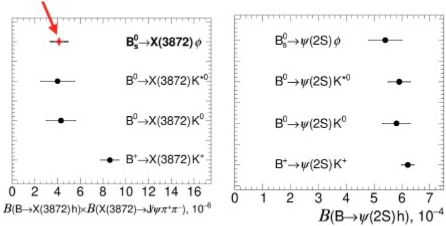
compatible with quarkonium prediction

- (D. Fasanella) $B_s \to \chi_{c1}(3872)\phi$ from CMS

confirms that formation mechanism in $B_{(s)}$ mesons different from $\psi(2S)$

consistent with 4 compact tetraquark states $X_u, X_d, X^{\pm}$?

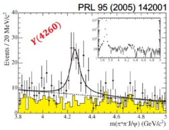
(no charged partner...)

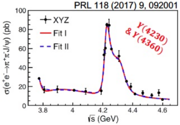


$$\mathcal{B}(B_s^0 \to \phi X \to \phi J/\psi\pi^+\pi^-) \simeq \mathcal{B}(B^0 \to K^0 X \to K^0 J/\psi\pi^+\pi^-) \simeq \frac{1}{2}\mathcal{B}(B^+ \to K^+ X \to K^+ J/\psi\pi^+\pi^-)$$

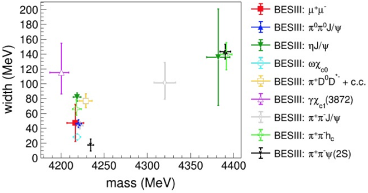
Vector states: $\psi(4230)$; $\psi(4360)$; $\psi(4660)$

Junhao Yin and Nils Huesken's talks, Tue 15th

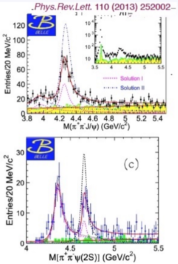




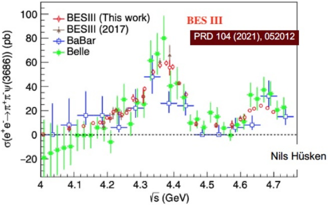
- $Y(4260)$ first observed by BaBar, we find two states $\psi(4230)$ & $\psi(4360)$



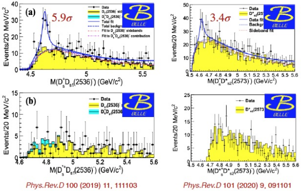
- different channels show (slightly) different masses and widths



date of $e^+e^- \to \pi^+\pi^-\psi(2S)$ with improved precision



Recent: A new vector state in $e^+e^- \to D_s^+ D_{s1}(2536)^-$, $D_s^+ D^*_{s2}(2573)^-$



$Y(4620) = Y(4660)$**?**

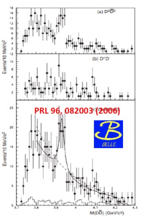
Experiments	Mass (MeV/c^2)	Width (MeV)
Belle, $\Lambda_c^+\Lambda_c^-$	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}
Belle, $\pi^+\pi^-J/\psi$	$4652 \pm 10 \pm 8$	$68 \pm 11 \pm 1$
BaBar, $\pi^+\pi^-J/\psi$	$4669 \pm 21 \pm 3$	$104 \pm 48 \pm 10$
Belle, $D_s^+ D_{s1}(2536)^-$	$4625.9^{+6.2}_{-6.0} \pm 0.4$	$49.8^{+13.9}_{-11.5} \pm 4.0$
Belle, $D_s^+ D^*_{s1}(2573)^-$	$4619.8^{+8.9}_{-8.0} \pm 2.3$	$47.0^{+31.3}_{-14.8} \pm 4.6$

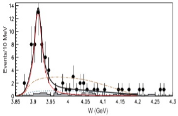
CAVEAT: lineshape is not always a BW ...

$\chi_{cJ}(2P)$ candidates around 3.9 GeV

Wenjing Zhu, Thur 18;
Ruiting Ma, Wed 16

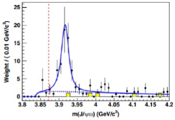
Many candidates: assignment as 0^{++} or 2^{++} not clear





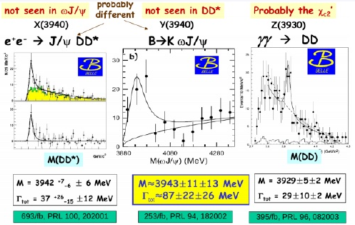
$X(3915)$ from Belle:

- $M = (3915 \pm 3 \pm 2)$ MeV;
- $\Gamma = (17 \pm 10 \pm 3)$ MeV



$X(3915)$ From BaBar:

- $M = (3919.4 \pm 2.2 \pm 1.6)$ MeV$/c^2$;
- $\Gamma = (13 \pm 6 \pm 3)$ MeV;



And one more result: two overlapping 0^{++} or 2^{++} in $B \to D\bar{D}K$

plus another candidate at lower mass: is this a better 0^{++}?

$\chi_{c0}(3860)$ $I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

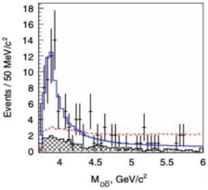
The assignment $J^P = 0^+$ is preferred over 2^+ by 2.5 sigma.

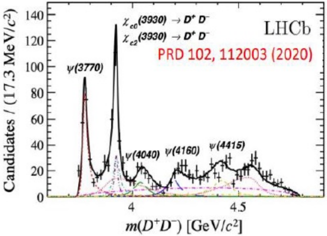
Observed by CHILIKIN 17 using full amplitude analysis of the process $e^+e^- \to J/\psi D\bar{D}$, where $D = D^0, D^+$.

✓ X(3860) observed at Belle Experiment only.

[Phys. Rev. D 95, 112003 (2017)]

J^{PC}	Mass, MeV/c^2	Width, MeV	Significance
0^{++}	3862^{+26}_{-32}	201^{+154}_{-67}	6.5σ



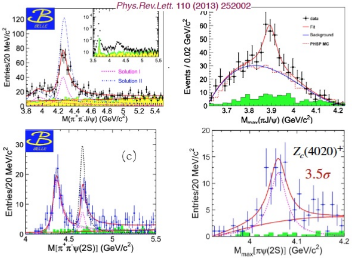


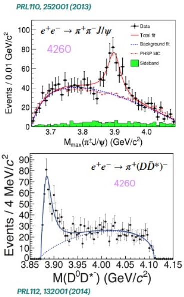
Need to clarify..

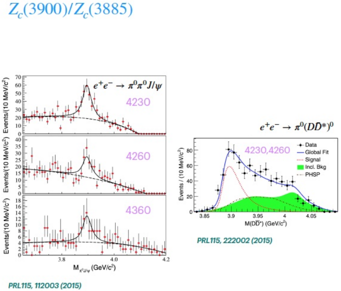
Charged hidden charm candidates: $Z_c^{\pm,0}$

see Yuping Guo's talk, Thurs 17

$Z_c^+(3900)$







Many more observed in the large BESIII datasets

in a variety of final states

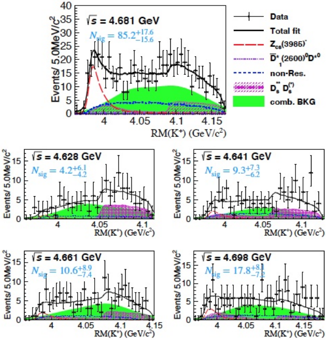
Charged hidden charm **strange** candidates: $Z_{cs}(3985)$

see Yuping Guo's talk, Thurs 17

$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D0)$

Observation of $Z_{cs}(3985)$

PRL126, 102001 (2021)



- Assume $J^P=1^+$
- Simultaneous fit to five data samples
- Signal component:

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

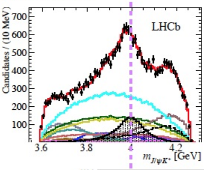
$f = 0.5$ represents the fraction of the two decay modes

- Pole position:

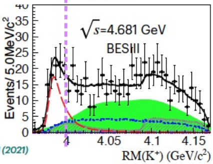
$$M = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ \mathrm{MeV}/c^2$$
$$\Gamma = (12.8^{+5.3}_{-4.4} \pm 3.0)\ \mathrm{MeV}$$

- Significance: 5.3σ
- At least four quarks $(c\bar{c}s\bar{u})$

PRL127, 082001 (2021)



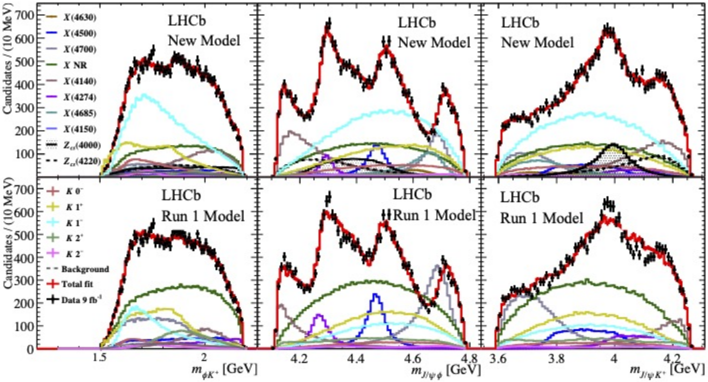
same state?



PRL126, 102001 (2021)

Exotics in $B^+ \to J/\psi\phi K$ decays

talk: Capriotti, Tue 15



Confirmed states: $X(4150)$, $X(4500)$, $X(4700)$, $X(4140)$, $X(4274)$

New states: $X(4630)$, $X(4685)$, $Z_{cs}(4000)$, $Z_{cs}(4220)$

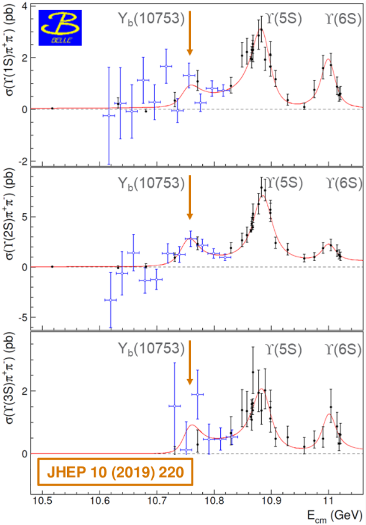
First observation of exotic states with $c\bar{c}u\bar{s}$ content in the $J/\psi K^+$ final state

---

[PRL 127 (2021) 082001]

$Y_b(10750)$

- Seven scan points below $\Upsilon(5S)$ at Belle, each $\simeq 1\ \mathrm{fb}^{-1}$
- New structure observed in $\Upsilon(nS)\pi\pi$



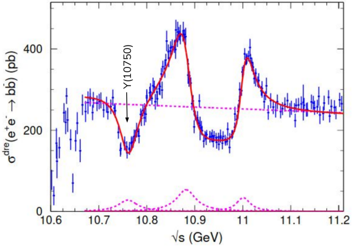
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}{}^{+1.0}_{-1.3}$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}{}^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}{}^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$

Further evidence in destructive interference

Re t of BaBar and Belle scan data

Dong et al., Chin. Phys. C 44 (2020) 8, 083001

Parameter	$Y(10750)$	$\Upsilon(5S)$	$\Upsilon(6S)$
Mass/(MeV/c^2)	10761 ± 2	10882 ± 1	11001 ± 1
Width/MeV	48.5 ± 3.0	49.5 ± 1.5	35.1 ± 1.2



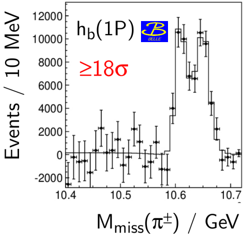
Bottomonium search at Belle and Belle II | MITP Mainz, 24.03.2022 1

No competition!!

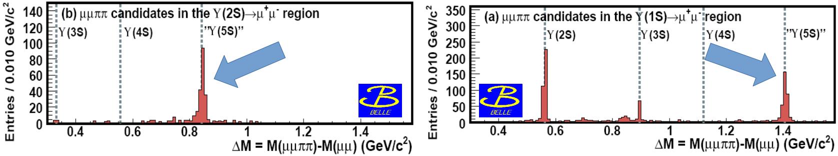
talk by J.S. Lange, Thur 24

BOTTOMONIUM

- $\Upsilon(5S)$ never observed at LHC
- Branching of $\Upsilon(5S)$ $\Upsilon(nS)\pi\pi$ is factor $\simeq$1000 larger than $\Upsilon(4S)$ $\Upsilon(nS)\pi\pi$
  $\Upsilon(5S)$ exotic itself?
- Charged Z_b states observed in $\Upsilon(5S)$ decays
  Belle, Phys. Rev. D91 (2015) 072003
  (not seen at LHC either)
  peculiar properties:
  spin ip in decays not suppressed
- New state observed: $Y_b(10750)$



$Z_b(10610)^{\pm}$ m=10607.2±2.0 MeV
2.6 MeV above $\bar{B}B^*$ threshold
$Z_b'(10650)^{\pm}$ m=10652.2±1.5 MeV
2.0 MeV above $\bar{B}^*B^*$ threshold
confirmed in 5 decay modes



Belle Phys. Rev. Lett. 100, 112001 (2008)

Bottomonium search at Belle and Belle II | MITP Mainz, 24.03.2022 1

No competition!!

talk by J.S. Lange, Thur 24

Charged charm strange candidates?

see talk by Ruiting Ma, Wed 16

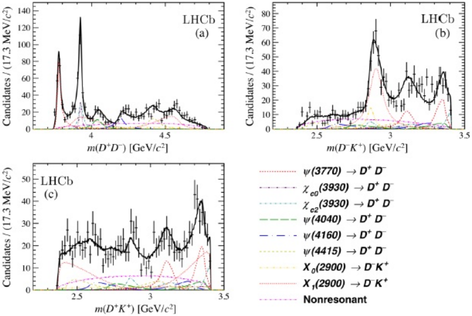
$B \to D^+ D^- K^+$

Model independent and model dependent analysis

Need two overlapping $D^- K^+$ components $c\bar{s}u\bar{d}$

Very large significance for both

- **Results after add $D^- K^+$ resonances:**
  - Two $D^- K^+$ resonances are added:
    - **$X_0(2900)$, $J^P = 0^+$**
      - Mass: $2866 \pm 7 \pm 2$ MeV/c^2
      - Width: $57 \pm 12 \pm 4$ MeV
    - **$X_1(2900)$, $J^P = 1^-$**
      - Mass: $2904 \pm 5 \pm 1$ MeV/c^2
      - Width: $110 \pm 11 \pm 4$ MeV
  - Also test other models, this model gives the best description.



PRL 125, 242001 (2021); PRD 102, 112003 (2020)

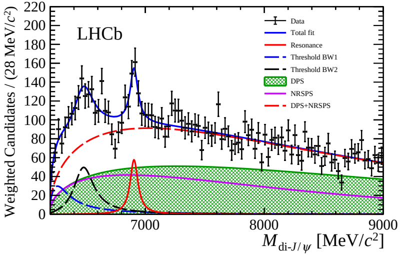
would be the first meson with 4 different flavours..

talk: Capriotti, Tue 15

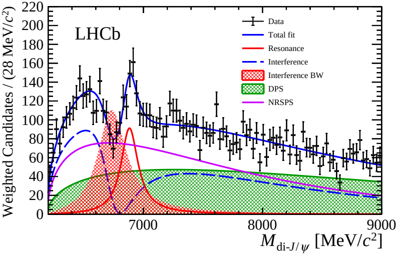
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Structure in J/ψ-pair mass spectrum

No interference



SPS-BW interference



- Threshold enhancement described by two resonances
- S-wave BW $\times$ 2-body phase space
- $m_{X(6900)} = 6905 \pm 11 \pm 7$ MeV
- $\Gamma_{X(6900)} = 80 \pm 19 \pm 33$ MeV
- Significance $>5\sigma$

- Threshold enhancement described by interference
- One BW, interference with SPS
- $m_{X(6900)} = 6886 \pm 11 \pm 11$ MeV
- $\Gamma_{X(6900)} = 168 \pm 33 \pm 69$ MeV
- Significance $>5\sigma$

Further studies are required to investigate the nature of X(6900). If confirmed:
First observation of exotic hadron composed by heavy quarks of the same flavour

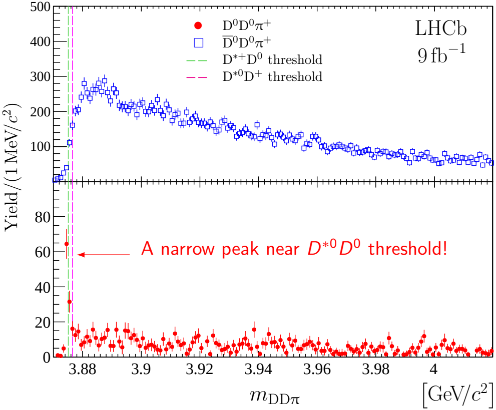
[Sci. Bull. 2020 65(23) 1983]

Double the charm? T_{cc}^{+}

talk: Polyakov, Mikhasenko,Wed 16

Having observed doubly charmed baryons ccu and hiddden charm $cc\bar{c}\bar{c}$ tetraquark, why not search for doubly charmed $cc\bar{q}_1\bar{q}_2$ tetraquarks?

The first hint of the signal: $D^0D^0\pi^+$ and $D^0\bar{D}^0\pi^+$



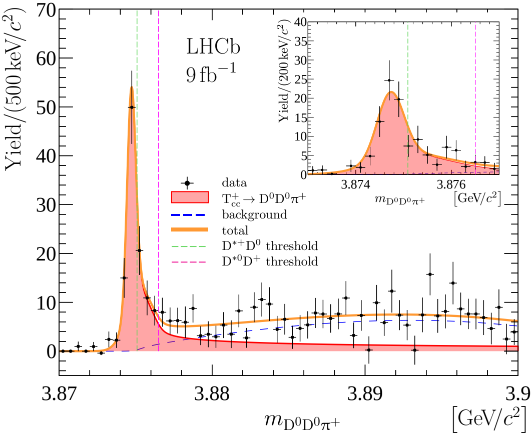
talk: Polyakov, Mikhasenko,Wed 16

Fit to the spectrum

Unitarized model

- The signal shape does not depend on $|g|$ for $|g| \to \infty$.
- The lower limit: $|g| > 7.7(6.2)\,\mathrm{GeV}$ at 90(95)% CL
- δm_U is the only parameter

Parameter	Value
N	186 ± 24
δm_{U}	$-359 \pm 40\,\mathrm{keV}/c^2$
$\lvert g \rvert$	$3 \times 10^4\,\mathrm{GeV}$ (fixed)

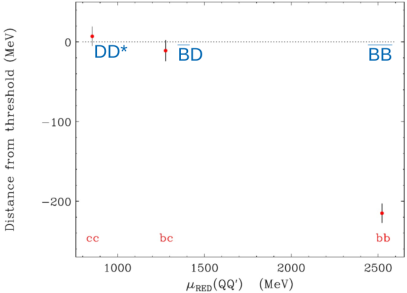


No direct sensitivity to the width, the value is driven by the model talk: Polyakov, Mikhasenko,Wed 16

Do other hadrons of the $(QQ'qq')$ family exist?

- Exists? Now, we are sure they do, all of them.
- Can be observed? Certainly some. Some might be too broad.

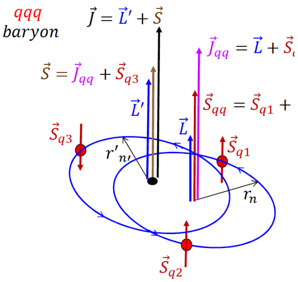
- $T_{bb}^{-}(bb\bar{u}\bar{d})$ are likely stable wrt QCD
- $T_{cb}^{0}(cb\bar{u}\bar{d})$ is either stable or almost, like T_{cc}^{+}
- ? Radial and orbital excitations of isoscalar T_{QQ}^{*}
- ? Isovector T_{QQ} and its family

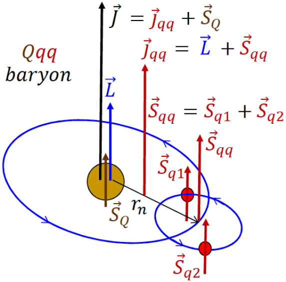


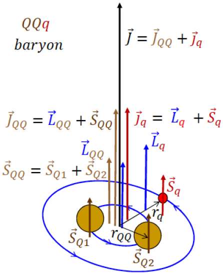
[Karliner, Rosner (2017)]

Baryon excitations

Also for baryons when at least one of the quarks is heavy the problem is simplified by the decoupling between heavy and light quark's spins







very complicated!

Heavy-light-light

$\Longrightarrow$ light diquarks

Heavy-Heavy-light

$\Longrightarrow$ heavy diquarks

Heavy baryon excitations provide a keyhole into diquarks

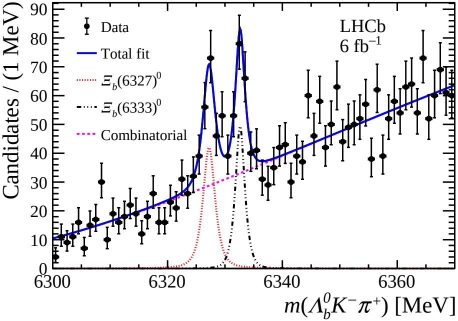
Ξ_{cc}^{++} and Ξ_{cc}^{+} have been observed ... hope in LHC Run3?

Heavy (exotic/excited) baryons

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

New excited Ξ_b^0 states

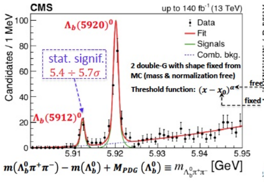
- Two narrow peaks observed in the $\Lambda_b^0 K^- \pi^+$ spectrum
- Large significance wrt one and no peak hypotheses
- $m(\Xi_b(6327)^0) = 6327.28^{+0.23}_{-0.21} \pm 0.08 \pm 0.24$ MeV, $\Gamma(\Xi_b(6327)^0) < 2.20$ MeV
- $m(\Xi_b(6333)^0) = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22$ MeV, $\Gamma(\Xi_b(6333)^0) < 1.55$ MeV
- Consistent with the predicted 1D Ξ_b^0 doublet, $J^P = 3/2^+$ and $J^P = 5/2^+$

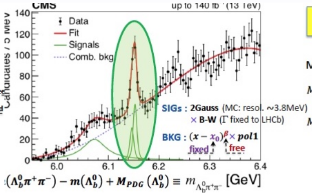


[arXiv:2110.04497], submitted to Phys. Rev. Lett.

New excited Λ_b^0 states

talk: Pompili, Tue 15





First confirmation of $\Lambda_b(6146)^0$ & $\Lambda_b(6152)^0$

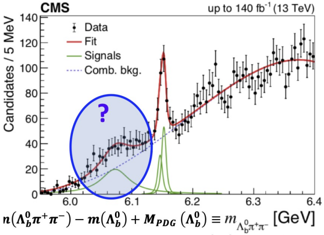
Mass measurements:

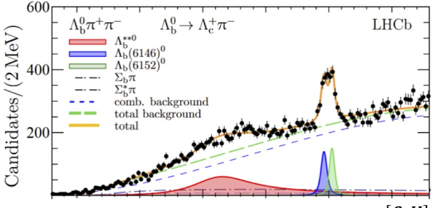
$M(\Lambda_b(6146)^0) = [6146.5 \pm 1.9(stat) \pm 0.8(syst) \pm 0.2(m_{PDG}(\Lambda_b^0))]$MeV

$M(\Lambda_b(6152)^0) = [6152.7 \pm 1.1(stat) \pm 0.4(syst) \pm 0.2(m_{PDG}(\Lambda_b^0))]$MeV

... in agreement with LHCb values (but not as precise as theirs)

. . . and another broad bump later confirmed by LHCb



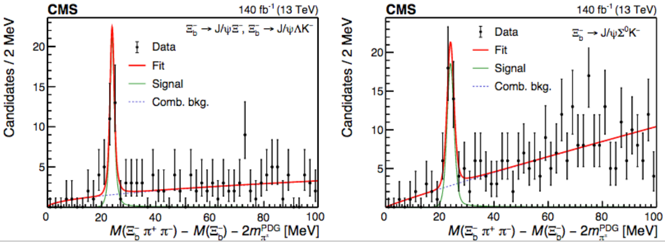


[JHEP 06 (2020) 136]

talk:Pompili, Tue 15

Observation of the excited beauty baryon $\Xi_b^{**}(6100)^-$

- The invariant mass of the final state is build combining the fully reconstructed decays (left) with identical mass resolutions and the partially reconstructed channel (right) with a 30% larger mass resolution.
The projections of the **simultaneous** extended UML fit (mass parameter is common due to Δm definition):



(local stat. signif. ~6.2-6.7σ

$m(\Xi_b^{**-}) = [\,6100.3$
$\pm 0.2(\text{stat}) \pm 0.1(\text{sys})$
$\pm 0.6(\Xi_b^-)\,]$ MeV

- **The natural width** (signal model: RBW⊗2Gauss-resolution) is **too small (consistent with 0) to be measured** with the present data sample and experimental resolution. An Upper Limit $\Gamma(\Xi_b^{**-}) < 1.9\text{MeV}$ @95%CL is obtained (systematics included) through the scan of the profiled likelihood.

- The low yield does not allow a measurement of the quantum numbers.
However following analogies with the established Ξ_c baryon states …
… **the new $\Xi_b^{**}(6100)^-$ resonance is the analogue of Ξ_c(2815) and its decay sequence are consistent with lightest the orbitally excited Ξ_b^- baryon with $J^P = 3/2^-$** [L=1 between b-quark and (ds)-diquark]

Study of Excited Baryons via the $\Xi^{+}\Lambda K^{-}$ Final State

arXiv: 2201.03852

- Baryon studies especially interesting at $\bar{\text{P}}$ANDA due to high production cross sections
- Knowledge in strange baryon sector very sparse
- All decay modes - charged and neutral - accessible
- Feasibility study performed to determine the spin and parity QN for specific Ξ resonances
- Ξ(1690)⁻ and Ξ(1820)⁻ were simulated including detector response
- Model includes interference effects, proper angular distributions and barrier factors

➡ Fit was able to identify the correct spin and parity quantum numbers and resonance parameters

- Of course, the models used are a limited representation of reality and can be improved

$p_{\bar{p}}$ (GeV/c)	Reaction	Rate (s^{-1}) at $10^{31}\text{cm}^{-2}\text{s}^{-1}$
1.64	$\bar{p}p \to \bar{\Lambda}\Lambda$	44
1.77	$\bar{p}p \to \bar{\Sigma}^0\Lambda$	2.4
6.0	$\bar{p}p \to \bar{\Sigma}^0\Lambda$	5.0
4.6	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	0.3
7.0	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	0.1
4.6	$\bar{p}p \to \bar{\Lambda}K^+\Xi^- + \text{c.c}$	0.2

Eur. Phys. J. A (2021) **57**: 184

Δ AIC values for Ξ(1690)⁻

Gen. ↓ / Fit →	$1/2^+$	$1/2^-$	$3/2^+$	$3/2^-$
$1/2^+$	0.0	2,550.6	2,310.6	2,706.8
$1/2^-$	316.7	0.0	328.2	2,332.2
$3/2^+$	4,973.9	5,228.0	0.0	584.6
$3/2^-$	5,345.6	3,118.6	833.1	0.0

Δ (AIC+BIC) values for Ξ(1820)⁻

Gen. ↓ / Fit →	$1/2^+$	$1/2^-$	$3/2^+$	$3/2^-$
$1/2^+$	0.0	139.9	158.7	208.1
$1/2^-$	96.8	0.0	211.1	887.4
$3/2^+$	7473.3	7604.5	0.0	198.4
$3/2^-$	7617.6	6900.8	490.2	0.0

Panda simulations also give hope See talk M. Kussner, Mon 21

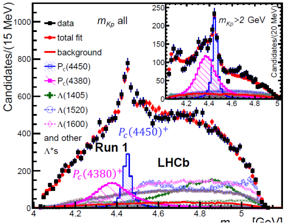
Pentaquarks

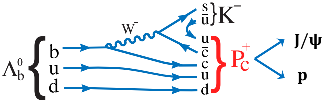
LHCb observation in 2015

- **Two $J/\psi p$ resonant structures** are revealed by a full 6D amplitude analysis
  - $P_c(4450)^+$ ← the prominent peak
  - $P_c(4380)^+$ ← required to obtain a good fit to the data
  - Consistent with **pentaquarks** with minimal quark content of $uudc\bar{c}$

See talk Liming Zhang, Thur 18
more in overflow...

26k Λ_b signals **PRL 115 (2015) 072001 (most cited paper at LHCb so far)**

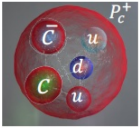




	$P_c(4380)^{\pm}$	$P_c(4450)^{\pm}$
Mass (MeV)	4380 ± 8 ± 29	4449.8 ± 1.7 ± 2.5
Width (MeV)	205 ± 18 ± 86	39 ± 5 ± 19
Fit Fraction (%)	8.4 ± 0.7 ± 4.2	4.1 ± 0.5 ± 1.1

$M_{J/\psi} + M_p + \sim 400\text{MeV}$

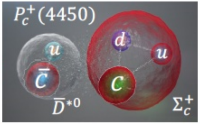
Tightly-bound pentaquark?



Maiani, Polosa, Riquer, PLB 749 (2015) 289
Lebed, PLB 749 (2015) 454
Anisovich, Matveev, Nyiri, Sarantsev PLB 749 (2015) 454

$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim\text{few MeV}$

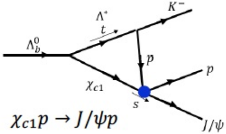
Loosely-bound pentaquark?



Wu, Molina, Oset, Zou, PRL105 (2010) 232001
Wang, Huang, Zhang, Zou, PRC84 (2011) 015203
Karliner, Rosner, PRL 115 (2015)

$P_c(4450)^+ = \chi_{c1}p$ threshold?

Kinematical effect: triangle diagram?



Guo, Meissner, Wang, Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552

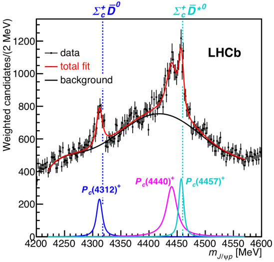
Fine structures from update

See talk Liming Zhang, Thur 18

- Run1+Run2, x10 $\Lambda_b^0 \to J/\psi p K^-$ yield
  - Inclusion of Run 2 data (x 5)
  - Improved data selection (x 2)
- $P_c(4312)^+$ is observed
- $P_c(4450)^+$ peak structure is an overlap of two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$
- Their near-threshold masses **favour** "molecular" pentaquarks with meson-baryon substructure, but **other hypotheses are not ruled out**

246k Λ_b signals

PRL 122 (2019) 222001



State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

1D $m_{J/\psi p}$ is fitted, full amplitude study is very advanced

Liming Zhang 5

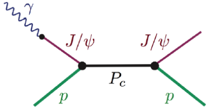
J/ψ Photoproduction Near Threshold

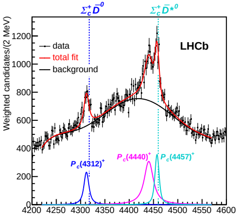
See talk Credé, Wed 23

Photoproduction of J/ψ (near threshold) provides clean laboratory to study $c\bar{c}$:

- Probes gluon distribution in proton
- Sensitive to multi-quark correlations
- Intriguing possibility of five-quark interaction

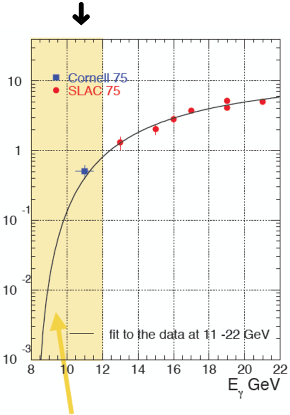
$P_c(4450)$





$m_{J/\psi\, p}$ [GeV]

R. Aaij *et al.*, PRL **122**, 222001 (2019)

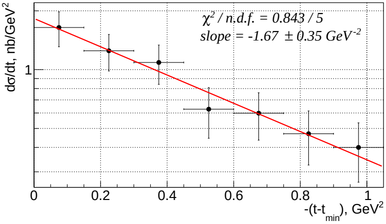


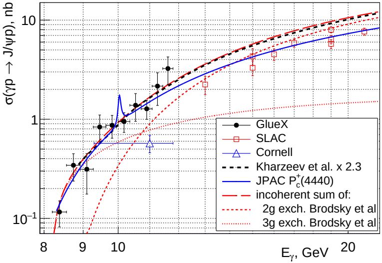
GlueX energy range

Observation of J/ψ at GlueX

See talk Credé, Wed 23

A. Ali *et al.* [GlueX], Phys. Rev. Lett. **123**, no.7, 072001 (2019)





First observation of J/ψ at Jefferson Lab in $\gamma p \rightarrow p J/\psi \rightarrow p e^+ e^-$

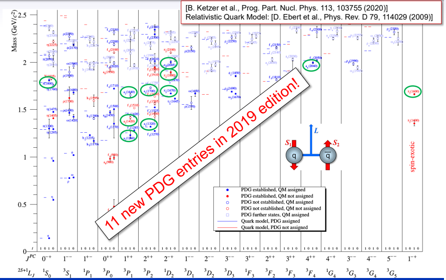
- First detailed look at cross section near threshold
- Measurement of t slope (at 10.7 GeV avg. E_γ): (-1.67 ± 0.39) GeV^{-2}
- Limits on pentaquark production

Light mesons

PWA ⟹ resonance parameters See B. Ketzer; Tue 22

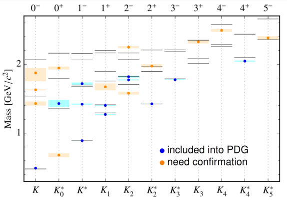
Light-Meson Spectrum

UNIVERSITÄT BONN



Kaon Excitation Spectrum

UNIVERSITÄT BONN

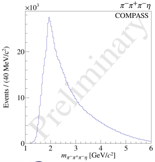


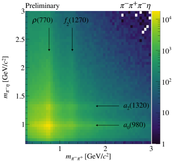
- 25 kaon states listed by PDG ($M < 3.1$ GeV), 13 of those need confirmation
- many predicted quark-model states still missing
- some hints for supernumerary states

$\pi^-\pi^+\pi^-\eta$ Final State

UNIVERSITÄT BONN

- PWA to be performed in full mass range
- $\eta'\pi$ excluded
- in addition: $\pi^+\pi^-$ and $\eta\pi$ isobars



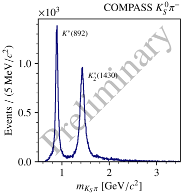


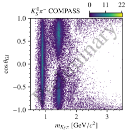
Dominant decays:

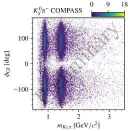
- $X^- \to f_1(1285) + \pi^-$
- $X^- \to a_2(1320) + \eta$
- $X^- \to a_0(980) + \rho$
- $X^- \to a_0(980) + f_2(1270)$
- $X^- \to a_2(1320) + \rho$

$K_S^0\pi^-$ Final State

UNIVERSITÄT BONN



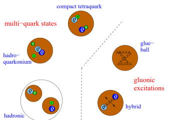




exotic $J^{PC} = 1^{-+}$ in $J/\psi \to \gamma\eta\eta'$

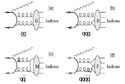
See B.J.Liu; Mon 21

Charmonium decays provide an ideal lab for light hadron physics



Phys.Rept. 873 (2020) 1

- Clean high statistics data samples
- Well defined initial and final states
  - Kinematic constraints
  - $I(J^{PC})$ filter
- "Gluon-rich" process



What's the role of gluonic excitation and how does it connect to the confinement?

3

Baseline set of amplitudes by adding the η_1 state

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	$M_{\rm PDG}$ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	1992	442	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
	$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	2314	144	$0.10\pm0.02^{+0.01}_{-0.02}$	13.2σ
	$\eta_1(1855)$	$1855\pm9^{+6}_{-1}$	$188\pm18^{+3}_{-8}$	-	-	$0.27\pm0.04^{+0.02}_{-0.04}$	21.4σ
	$f_2(1565)$	1542	122	1542	122	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
	$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	2011	202	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
	$f_4(2050)$	2018	237	2018	237	$0.06\pm0.01^{+0.03}_{-0.01}$	4.6σ
	0^{++} PHSP	-	-	-	-	$1.44\pm0.15^{+0.10}_{-0.20}$	15.7σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
	$h_1(1595)$	1584	384	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ

Comparing to the PDG-optimized set, ln L of the baseline set is improved by 32 and the number of free parameters is reduced by 16

Contributions from the $f_0(2100)$, $h_1(1595)(\gamma\eta')$, $\rho(1700)(\gamma\eta')$, $\phi(2170)(\gamma\eta)$, $f_2(1810)$, and $f_2(2340)$, in the PDG-optimized set become insignificant (< 3σ), omitted
Significance of the $f_4(2050)$ is reduced from 5.6σ to 4.6σ, but is still retained

13

Scalar glueball candidate: production properties

$$\Gamma(J/\psi \to \gamma G_{0^+}) = \frac{4}{27}\alpha\frac{|p|}{M^2_{J/\psi}}|E_1(0)|^2 = 0.35(8) keV$$
$$\Gamma/\Gamma_{tot} = 0.33(7)/93.2 = 3.8(9)\times 10^{-3}$$

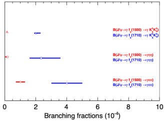
CLQCD, Phys. Rev. Lett. 110, 021601 (2013)

Experimental results

- ➢ $B(J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K}) = (8.5^{+1.2}_{-0.9})\times 10^{-4}$
- ➢ $B(J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi) = (4.0\pm1.0)\times 10^{-4}$
- ➢ $B(J/\psi \to \gamma f_0(1710) \to \gamma\omega\omega) = (3.1\pm1.0)\times 10^{-4}$
- ➢ $B(J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta) = (2.35^{+0.13+1.24}_{-0.11-0.74})\times 10^{-4}$

$\Rightarrow$ $B(J/\psi \to \gamma f_0(1710)) > 1.7\times 10^{-3}$

$B(J/\psi \to \gamma f_0(1710))$ is x10 large than that of $f_0(1500)$



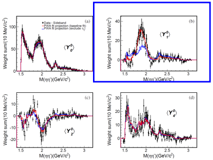
$f_0(1710)$ largely overlapped with scalar glueball

Recent coupled channel phenomenology analyses
Phys.Lett.B 816 (2021) 136227 *Eur.Phys.J.C 82 (2022) 1, 80*

4

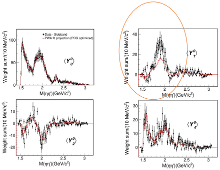
For comparison

need for the $\eta_1(1855)$ P-wave



Baseline set of amplitudes

Can not be described only with 1^{+-} and 1^{--} states in $\gamma\eta(')$



PDG-optimized set of amplitudes

22

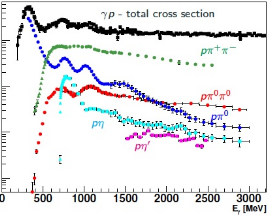
- An isoscalar 1^{-+}, $\eta_1(1855)$, has been observed in $J/\psi \to \gamma\eta\eta'$ (>19σ)

$$M = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV}/c^2,\ \Gamma = (188 \pm 18^{+3}_{-8})\ \mathrm{MeV}/c^2$$
$$B(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = \left(2.70 \pm 0.41^{+0.16}_{-0.35}\right)\times 10^{-6}$$

arXiv:2202.00621, 2202.00623

See A. Thiel; Wed 23

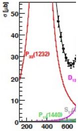
Exploit polarization to determine amplitudes

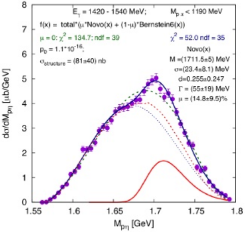


al wave analysis needed to disentangle the
ances.

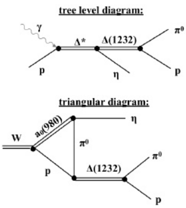
Resonar
different

→ Weal
difficult





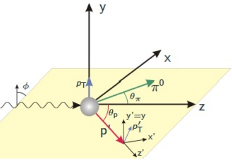
[V. Metag et al. Eur.Phys.J.A 57 (2021) 12, 325]



Structure obser
$p\eta$ invariant ma

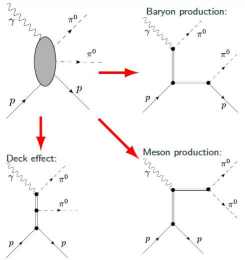
Triangle singula
describe this str

Observation of
singularity in ba
spectroscopy?



16 Polarization Observables in
photoproduction of pseudoscalar mesons

Baryon and Meson Production in the t-channel



		Target			Recoil			Target+Recoil			
		–	–	–	x'	y'	z'	x'	x'	z'	z'
ton		x	y	z	–	–	–	x	z	x	z
olarized	σ	–	T	–	–	P	–	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
rly pol.	Σ	H	(-P)	-G	$O_{x'}$	(-T)	$O_{z'}$	–	–	–	–
ularly pol.	–	F	–	-E	$-C_{x'}$	–	$-C_{z'}$	–	–	–	–

ery complicated, polarization observables can help disentangling "weak"

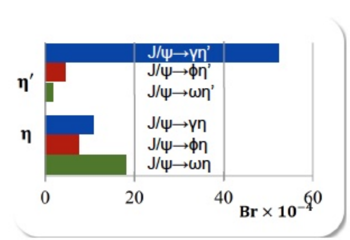
See X. Yuan; Mon 21

Not just spectroscopy..

10 billions J/ψ.... huge samples of η and η'

some analyses just use 1.3 billions at present . . .)

- $\eta' \to \pi^0\pi^0\pi^0\pi^0$
- $\eta' \to \gamma\gamma\eta$
- $\eta' \to \pi^+\pi^-e^+e^-$
- $\eta' \to \pi^+\pi^-\mu^+\mu^-$
- Absolute Branching Fractions of η Decay Modes



$\eta' \to \pi^+\pi^-e^+e^-$

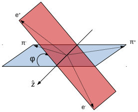
Branching fraction of $\eta' \to \pi^+\pi^-e^+e^-$:

- Theoretical predictions:
  - Two different VMD models[6]: $(2.17 \pm 0.21) \times 10^{-3}$ and $(2.27 \pm 0.13) \times 10^{-3}$
  - ChPT model[7]: $(2.13^{+0.17}_{-0.31}) \times 10^{-3}$
- Most precise measurement before[8]: $(2.11 \pm 0.12_{stat.} \pm 0.15_{syst.}) \times 10^{-3}$

Possible CP-violating contribution[9−11]:

- An electric dipole type transition
- Manifest itself as an asymmetry of $\sin 2\varphi$:

$$\mathcal{A}_\varphi = \frac{N(\sin 2\varphi > 0) - N(\sin 2\varphi < 0)}{N(\sin 2\varphi > 0) + N(\sin 2\varphi < 0)} \quad (1)$$



- Previous measurement of $\mathcal{A}_\varphi$: consistent with zero

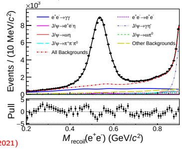
[6] T. Petri, PhD thesis, Forschungszentrum Julich, (2010), arXiv:1010.2378[nucl-th].
[7] B. Borasoy and R. Nissler, Eur. Phys. J. A 33, 95 (2007).
[8] M. Ablikim *et al.*, (BESIII Collaboration), Phys. Rev. D 87, 092011 (2013).
[9] C. Q. Geng, J. N. Ng, and T. H. Wu, Mod. Phys. Lett. A 17, 1489 (2002).
[10] D.-N. Gao, Mod. Phys. Lett. A 17, 1583 (2002).
[11] L. Gan, B. Kubis, E. Passemar, and S. Tulin, (2020), arXiv:2007.00664hep-ph.

Absolute Branching Fractions of η Decay Modes

- Step 1: Inclusive decays

$$B(J/\psi \to \gamma\eta) = \frac{N^{obs}_{J/\psi\to\gamma\eta}}{N_{J/\psi} \cdot \varepsilon f} \quad (4)$$

$N^{obs}_{J/\psi\to\gamma\eta}$ and $N_{J/\psi}$: observed η yield and number of J/ψ events.
ε: detection efficiency obtained from MC simulation
f: correct the difference in γ conversion efficiencies between data and MC



Phys. Rev. D 104, 092004 (2021)

$$B(J/\psi \to \gamma\eta) = (1.067 \pm 0.005_{stat.} \pm 0.023_{syst.}) \times 10^{-3}$$

PDG: $(1.108 \pm 0.027) \times 10^{-3}$(before this work)

Summary

. . . too many results!

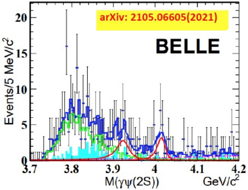
disclaimer: just a personal selection

Overflow

. . . all other interesting things for which I had no time

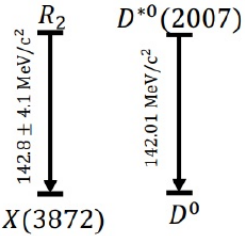
An intriguing coincidence?

$\gamma\gamma \to \gamma\psi(2S)$



significance not large

R_1 can be (any of) the states at 3.9 GeV



Resonant parameters	$J = 0$	$J = 2$
M_{R_1}	$3922.4 \pm 6.5 \pm 2.0$	
Γ_{R_1}	$22 \pm 17 \pm 4$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	$9.8 \pm 3.6 \pm 1.2$	$2.0 \pm 0.7 \pm 0.2$
M_{R_2}	$4014.3 \pm 4.0 \pm 1.5$	
Γ_{R_2}	$4 \pm 11 \pm 6$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$6.2 \pm 2.2 \pm 0.8$	$1.2 \pm 0.4 \pm 0.2$

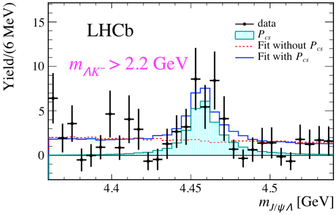
R_2 ?? 2^{++} partner of $\chi_{c1}(3872)$??

Evidence of $J/\psi\Lambda$ structure

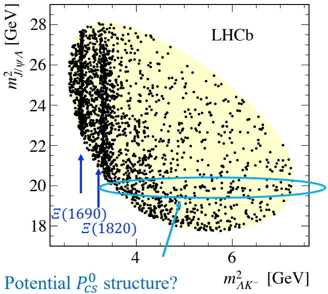
[Science Bulletin 66 (2021) 1278]

See talk Liming Zhang, Thur 18

- Hidden-charm pentaquark with strangeness P_{cs} is predicted, and suggested to search for in $\Xi_b^- \to J/\psi\Lambda K^-$
  [JJ Wu PRL 105 (2010) 232001; HX Chen PRC 93(2016) 064203]
- Amplitude analysis with improved helicity formalism
  - $P_{cs}(4459)^0$ found, significance >3.1σ



~1750 $\Xi_b^- \to J/\psi\Lambda K^-$ signals (purity ~80%)

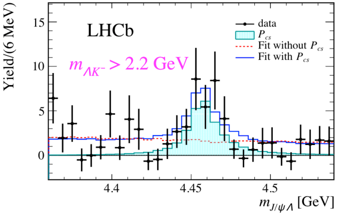


Liming Zhang 6

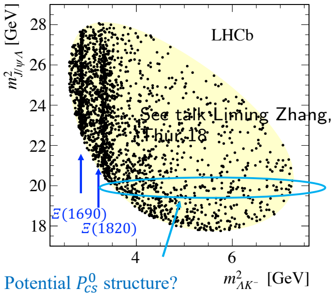
Evidence of $J/\psi\Lambda$ structure

[Science Bulletin 66 (2021) 1278]

- Hidden-charm pentaquark with strangeness P_{cs} is predicted, and suggested to search for in $\Xi_b^- \to J/\psi\Lambda K^-$
  [JJ Wu PRL 105 (2010) 232001; HX Chen PRC 93(2016) 064203]
- Amplitude analysis with improved helicity formalism
  - $P_{cs}(4459)^0$ found, significance >3.1σ



~1750 $\Xi_b^- \to J/\psi\Lambda K^-$ signals (purity ~80%)



Potential P_{cs}^0 structure?

Liming Zhang 6