Charmonium-like states at COMPASS

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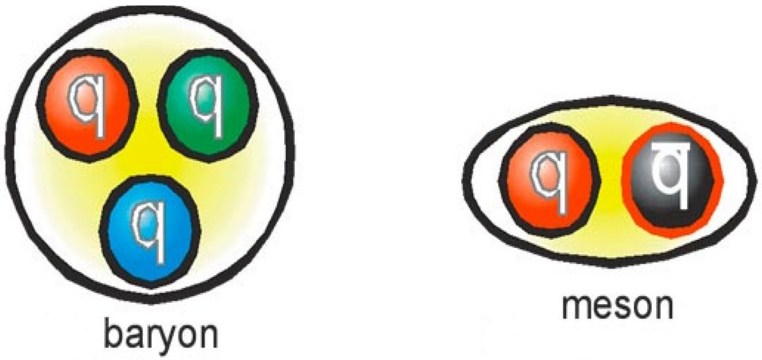
121st session of the Scientific Council

24 February 2017

Quark model

- 1964 – Gell-Mann and Zweig proposed that all hadrons are built from quarks.

  2 groups of hadrons:

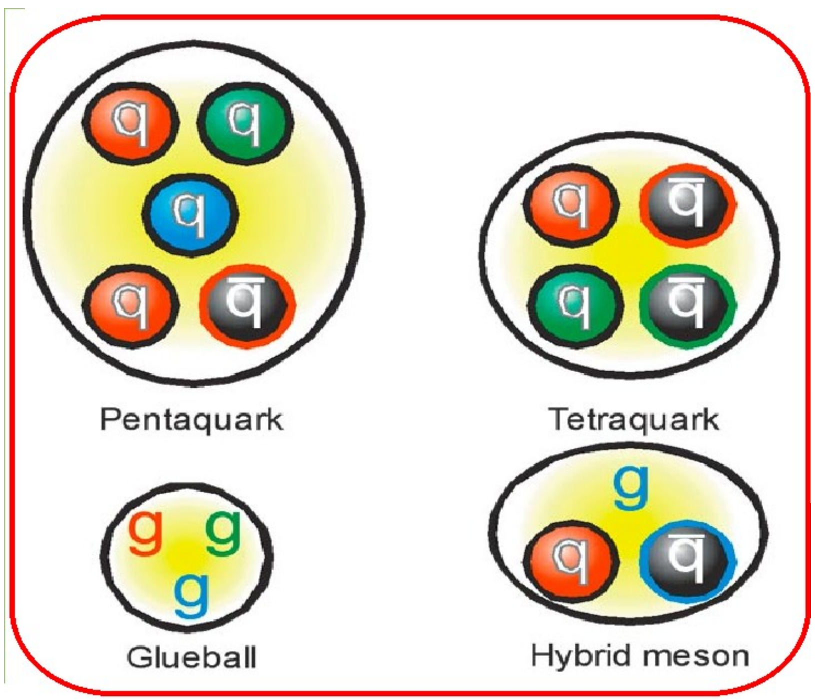


Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964



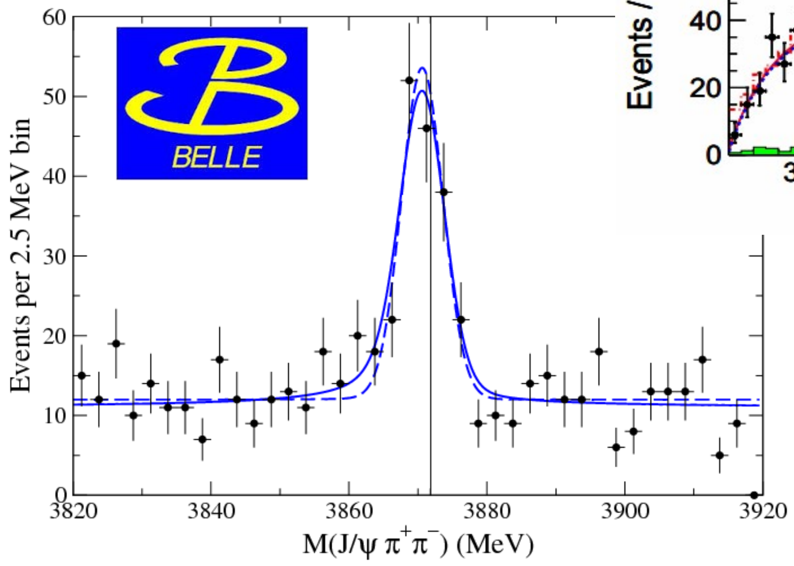
We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

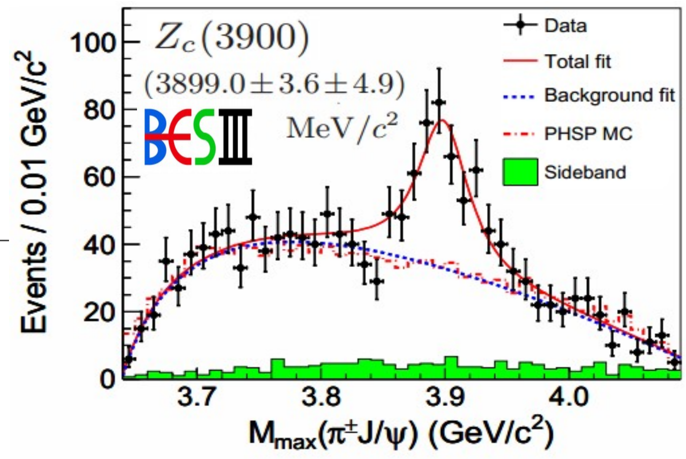
1st wave

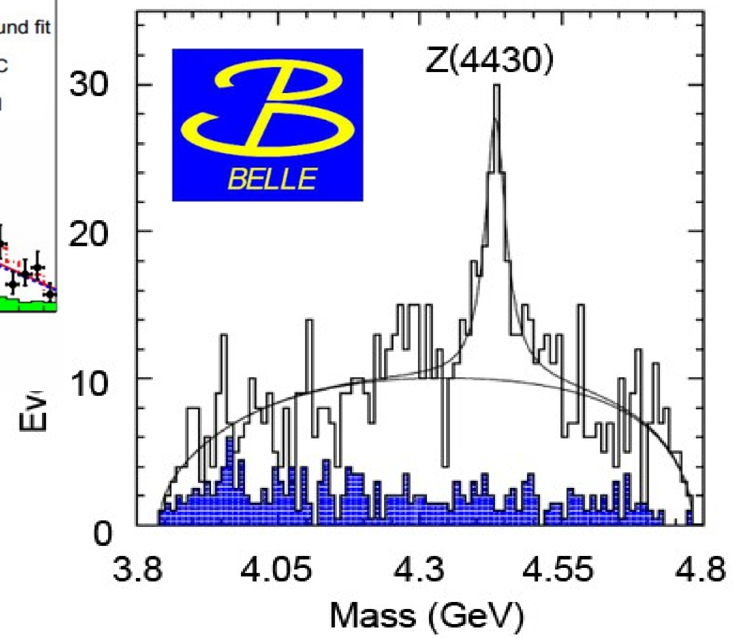
- First wave of multiquark particles: ~1990th – 2000th

  Several experiments in the mid-2000s reported discoveries of pentaquark states. CLAS, Belle, BaBar, HERA-B and COMPASS have closed these observations.

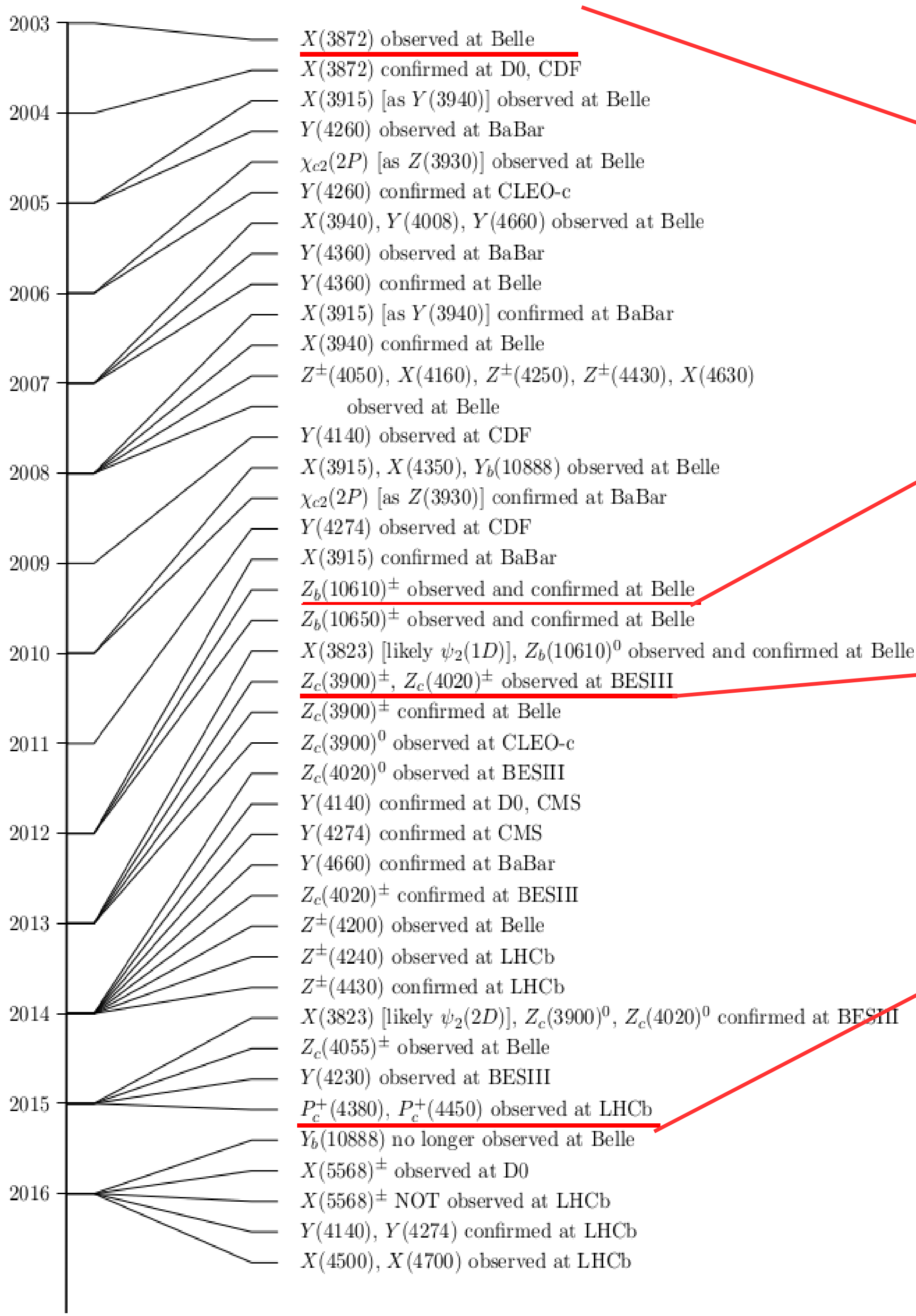
- Second wave: 2003 – now – observation of X(3872) by Belle.







2^{nd} wave



Long and rich history:

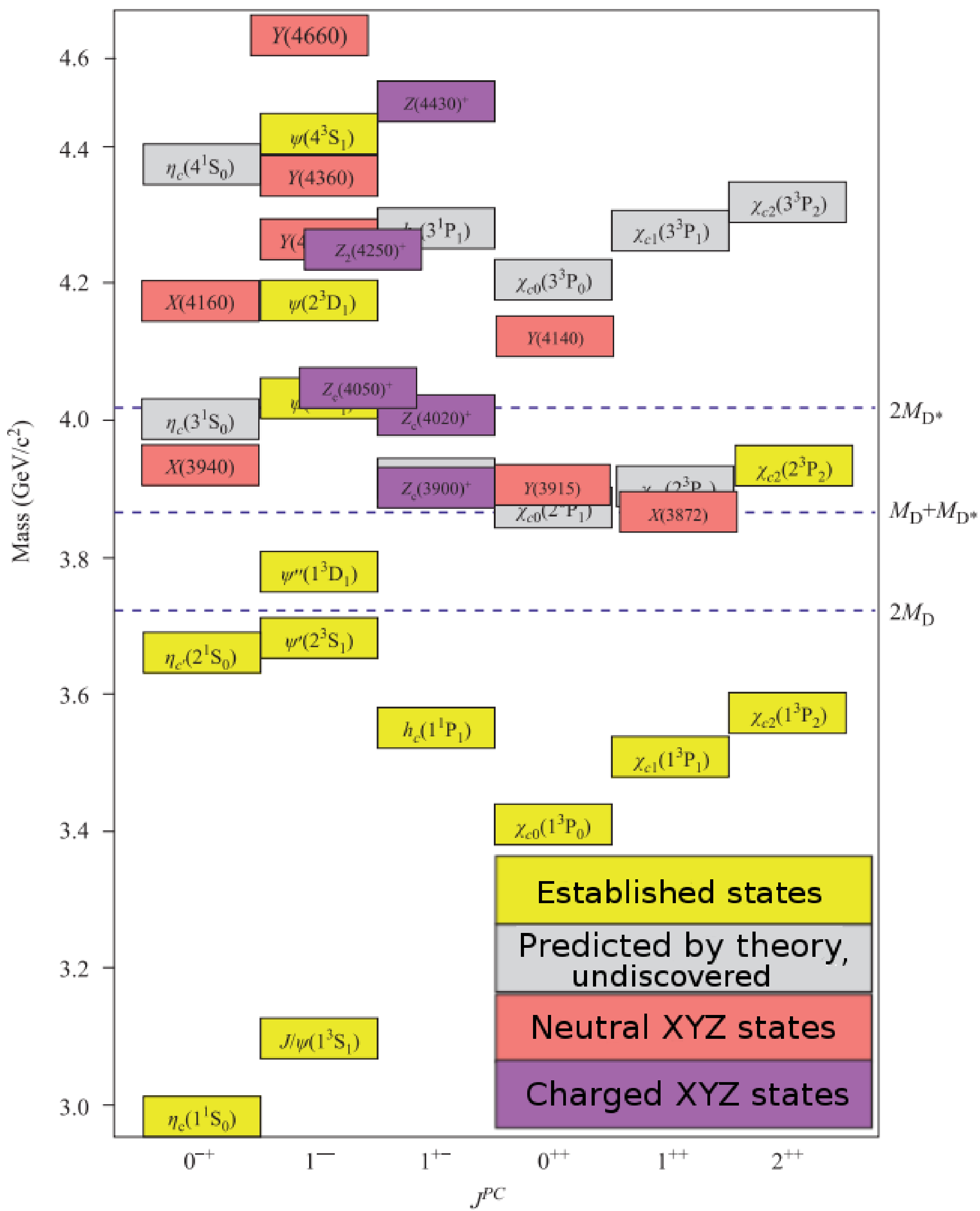
X(3872) observed by Belle

$\mathbf{Z_b^{\pm}(10610)}$ (Belle) – first charged bottomium-like state.

$\mathbf{Z_c^{\pm}(3900)}$ and $\mathbf{Z_c^{\pm}(4020)}$ (BESIII) – first charged charmonium-like states

$\mathbf{P_c^{+}(4380)}$ and $\mathbf{P_c^{+}(4450)}$ pentaquarks (LHCb)

Production of charmonium-like states



Charmonium-like states are observed in:

direct production in e^+e^- collisions;

direct production in hadron collisions;

B decays;

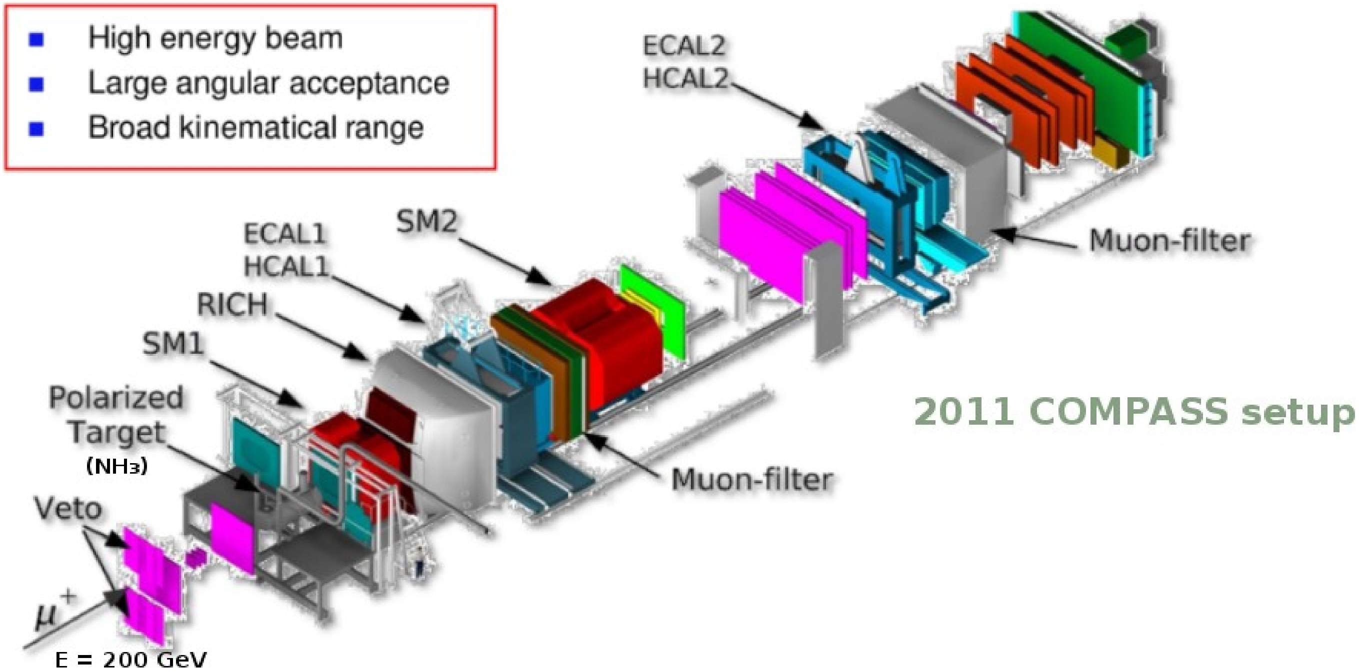
γ*γ* collisions;

but haven't searched in ***photoproduction.***

The COMPASS experiment

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

COMPASS setup

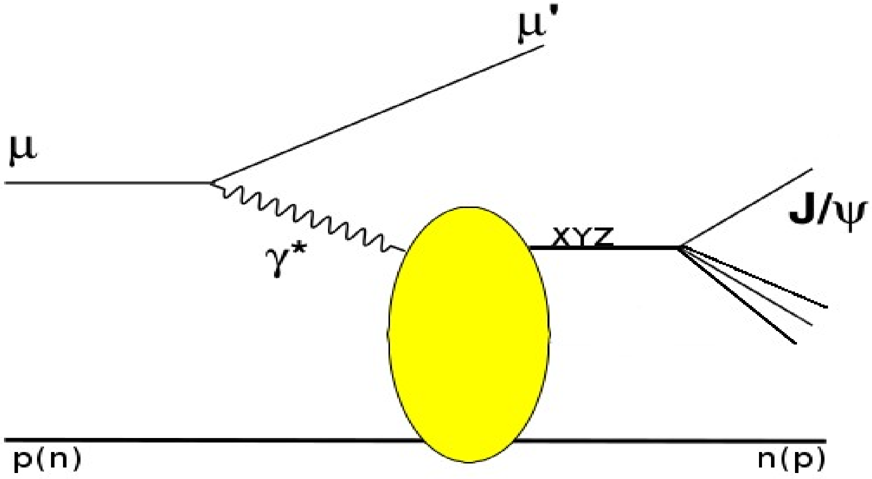


Year	Target	Beam particle	Beam momentum, GeV/c
2002	^{6}LiD	μ^+	160
2003	^{6}LiD	μ^+	160
2004	^{6}LiD	μ^+	160
2006	^{6}LiD	μ^+	160
2007	NH_3	μ^+	160
2008	Liquid H_2	π^-, K^-	190
2009	Liquid H_2, Ni, W, Pb	π^-, K^-, μ^-	190
2010	NH_3	μ^+	160
2011	NH_3	μ^+	200
2012	Ni, C, W, Pb	π^-, K^-, μ^-	190
2014	NH_3, W, Al	π^-	190
2015	NH_3, W, Al	π^-	190
2016	Liquid H_2	$\mu^\pm$	160
2017	Liquid H_2	$\mu^\pm$	160 (planned)

Physics program:

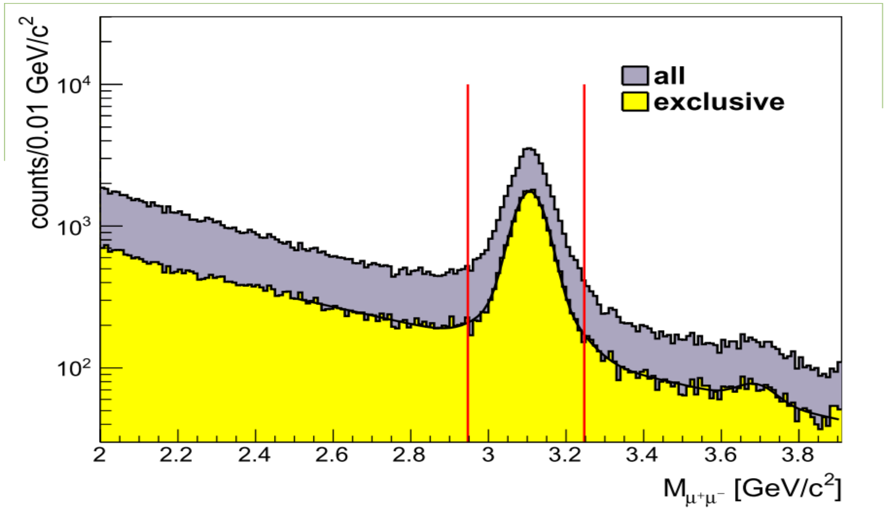
- ***nucleon spin structure (gluon and quark helicities, SIDIS)***
- ***Primakoff reactions***
- ***light meson and baryon spectroscopy***
- ***GPDs (DVCS, exclusive lepton production, SIDIS)***
- ***polarized Drell-Yan***
- ***Photoproduction of XYZ states (new!)***

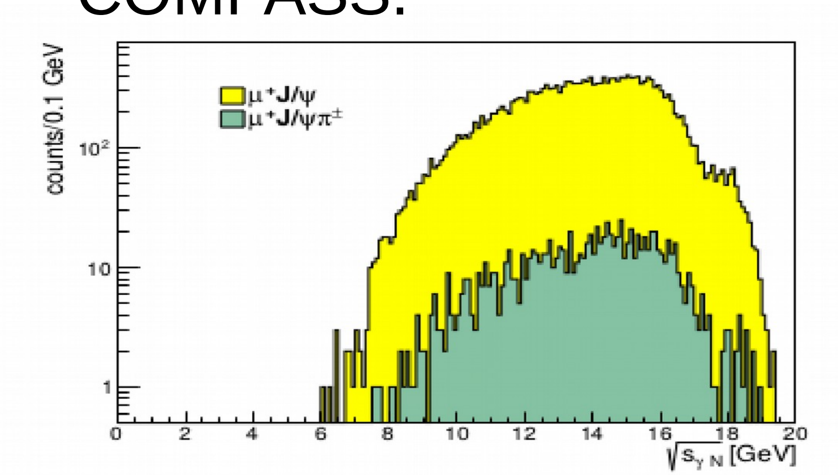
Photo(lepto)production mechanism



Various experiments – GlueX and CLAS12 use photon beam for photoproduciton. COMPASS can produce γ* which interacts with the target. The produced XYZ state decays to J/ψ and other particles which could be detected by COMPASS.

- COMPASS already has 50k J/psi via photoproduction (huge statistics)





The spectroscopy of exotic charmonia was introduced to COMPASS by JINR in 2013

$Z^{\pm}_{c}(3900)$: general information

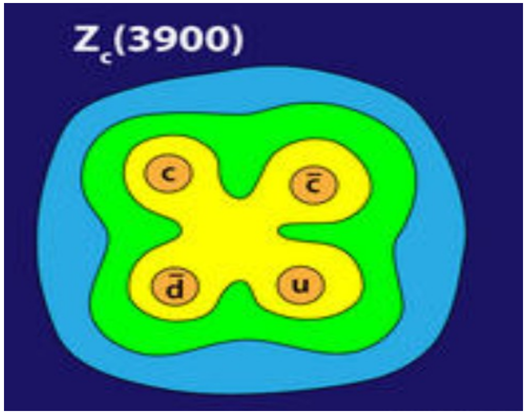
$X(3900)$ $I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 3886.6 \pm 2.4$ MeV (S = 1.6)
Full width $\Gamma = 28.1 \pm 2.6$ MeV

$X(3900)$ DECAY MODES	Fraction (Γ_i/Γ)
$J/\psi\pi$	seen
$h_c\pi^{\pm}$	not seen
$\eta_c\pi^+\pi^-$	not seen
$(D\overline{D}^*)^{\pm}$	seen
$D^0 D^{*-}$ + c.c.	seen
$D^- D^{*0}$ + c.c.	seen
$\omega\pi^{\pm}$	not seen
$J/\psi\eta$	not seen
$D^+ D^{*-}$ + c.c	seen
$D^0 \overline{D}^{*0}$ + c.c	seen

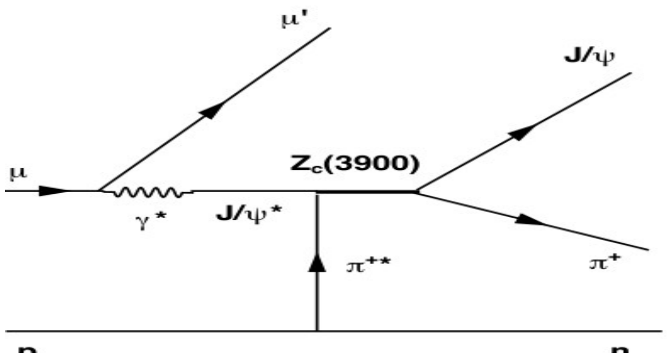
Tetraquark $c\bar{c}u\bar{d}$ state - the most suitable explanation of $Z^{\pm}_{c}(3900)$.

A lot of other explanations exist: kinematical effect, Didiquark, $D\overline{D}^*$ molecule...



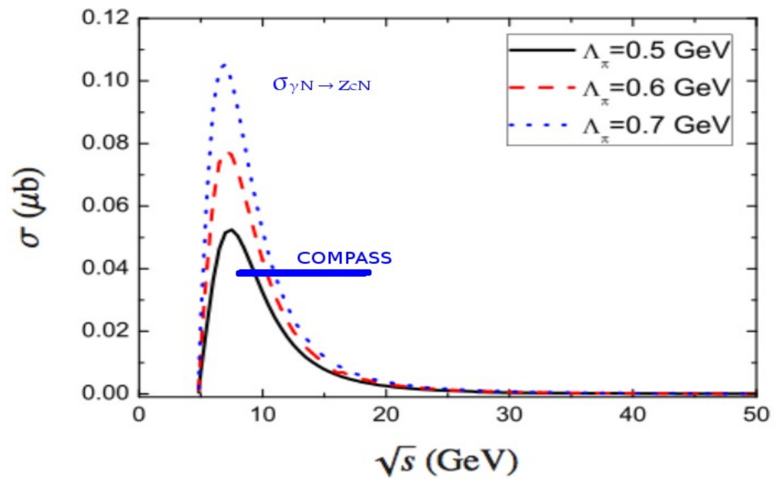
Exclusive photoproduction of $Z^{\pm}_{c}(3900)$ and $Z^{\pm}_{c}(4200)$

$$\mu^{+}N \rightarrow \mu^{+}\, Z^{\pm}_{c}(3900)N' \rightarrow \mu^{+}J/\psi\pi^{\pm}N'$$



Model for $Z^{\pm}_{c}(3900)$ photoproduction:

Phys. Rev. D88, 114009 (2013)



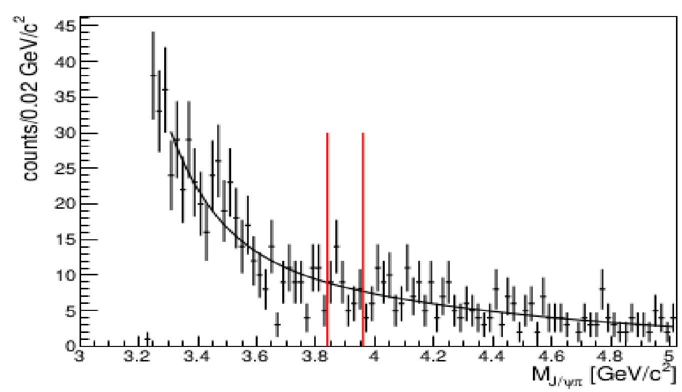
$$BR(Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}) \times \sigma_{\gamma\ N \rightarrow Z_c^{\pm}(3900)\ N}\Big|_{\langle\sqrt{s_{\gamma N}}\rangle = 13.8\ GeV} < 52\ \text{pb}$$

$$\Gamma_{J/\psi\pi} < 2.4\ MeV/c^2,\ CL = 90\%\ \ for$$
$$\Gamma_{tot} = 46\ MeV/c^2\ and\ \Lambda_{\pi} = 0.6\ \text{GeV}.$$

- **PLB 742(2015) 330-334**
- **Referenced in PDG 2016**

The same analysis for $Z^{\pm}_{c}(4200)$:

Phys. Rev. D 92, 094017 (2015)



$$BR(Z_c(4200) \rightarrow J/\psi\pi) \times \sigma_{\gamma N \rightarrow Z_c(4200)N} < 340\ \text{pb}.$$

Photoproduction of X(3872)

X(3872) $I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 3871.69 \pm 0.17$ MeV
$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
$m_{X(3872)} - m_{\psi(2S)}$
Full width $\Gamma < 1.2$ MeV, CL = 90%

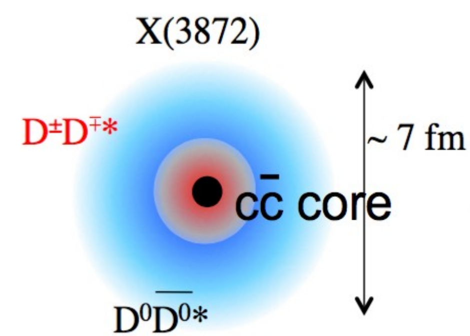
X(3872) DECAY MODES	Fraction (Γ_i/Γ)
$\pi^+\pi^- J/\psi(1S)$	> 2.6 %
$\omega J/\psi(1S)$	> 1.9 %
$D^0 \overline{D}{}^0 \pi^0$	>32 %
$\overline{D}{}^{*0} D^0$	>24 %
$\gamma J/\psi$	$> 6 \times 10^{-3}$
$\gamma \psi(2S)$	> 3.0 %
$\pi^+\pi^- \eta_c(1S)$	not seen
$p\overline{p}$	not seen

$\Gamma(\omega J/\psi(1S))/\Gamma(\pi^+\pi^- J/\psi(1S))$

VALUE
0.8±0.3

S.Takeuchi, K.Shimizu and M.Takizawa, PTEP2014(2014)123D01

We have argued that the $X(3872)$ is a hybrid state of the $c\bar{c}$ and the two-meson molecule: a superposition of the $D^0\overline{D}{}^{*0}$, D^+D^{*-}, $J/\psi\rho$, and $J/\psi\omega$ states and the $c\bar{c}(2P)$ quarkonium.

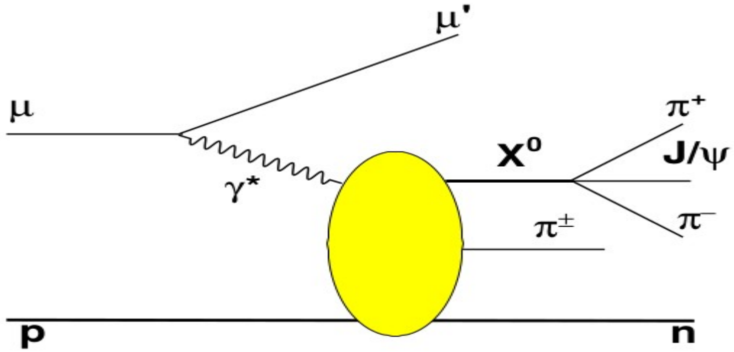


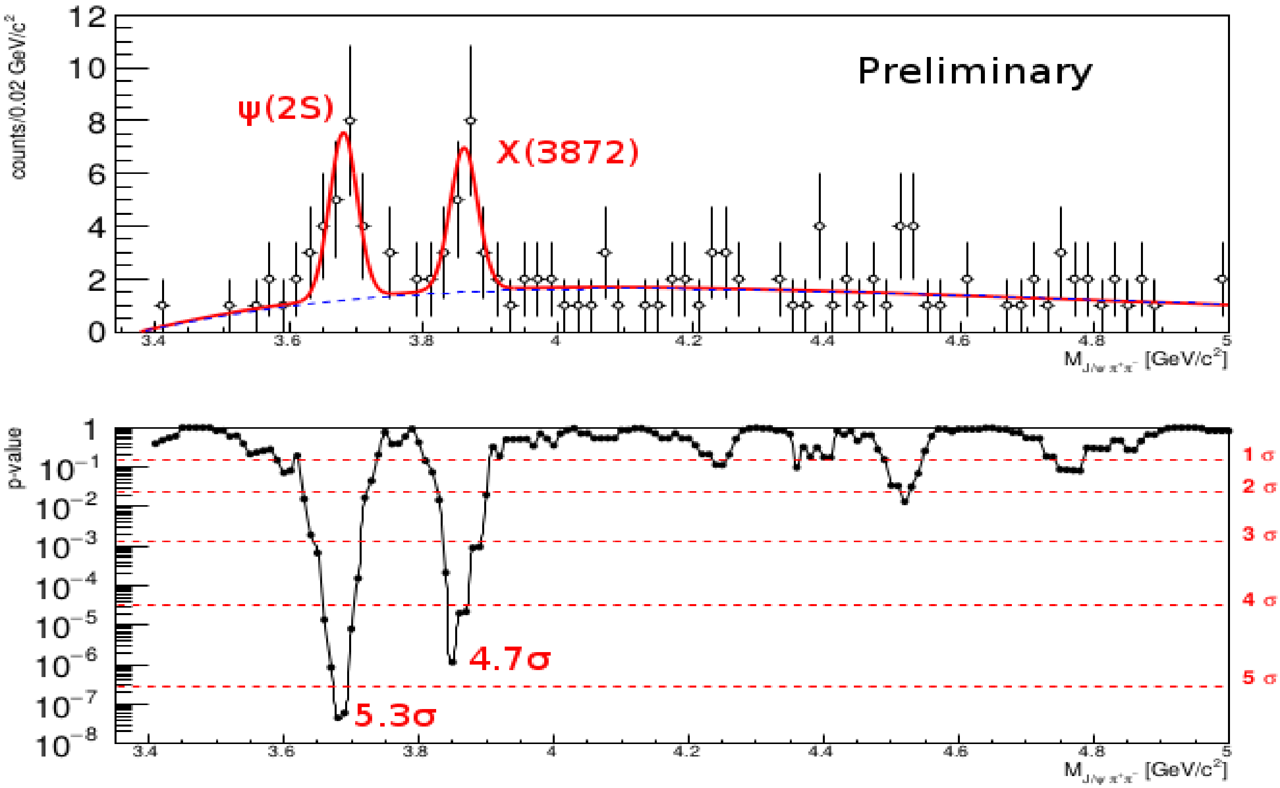
A lot of theoretical models have been developed

Photoproduction of X(3872)

$$\mu^{+}N\rightarrow\mu^{+}X(3872)\pi^{\pm}N'\rightarrow\mu^{+}(J/\psi\pi^{+}\pi^{-})\pi^{\pm}N'$$

Possibility of X(3872) photoproduction proposed in Phys.Lett.B605:306-310,2005, arXiv:hep-ph/0410264





Used muon data of 2003-2010

$N_{\psi(2S)}$ = 16.1±5.2

$N_{X(3872)}$ = 13.9±4.9

$M_{\psi(2S)}$ = 3680±8 MeV (nominal 3686.1)

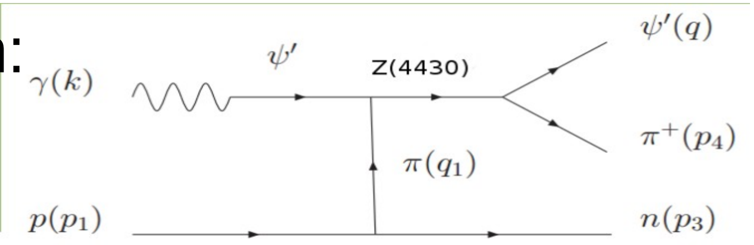
$M_{X(3872)}$ = 3860±8 MeV (nominal 3872)

σ_M = 20.6±6.1 MeV

Possible tasks

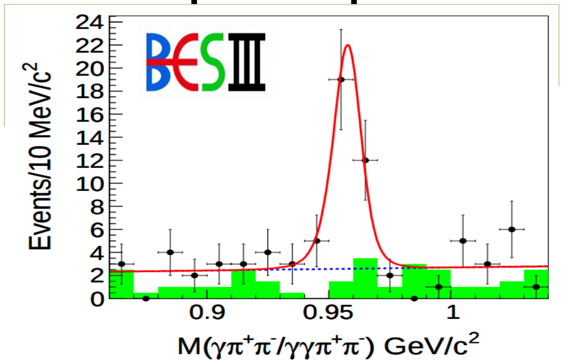
Search for photoproduction of other charmonium-like states in the collected and future data.

A lot of possible channels of photoproduction:



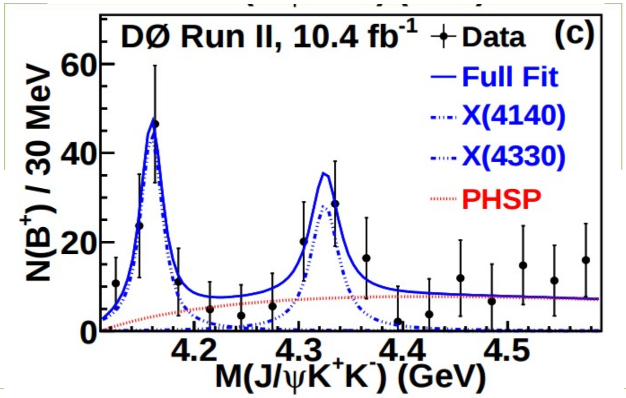
- $\mu^+ N \to \mu^+\, \eta' J/\psi\, N'$

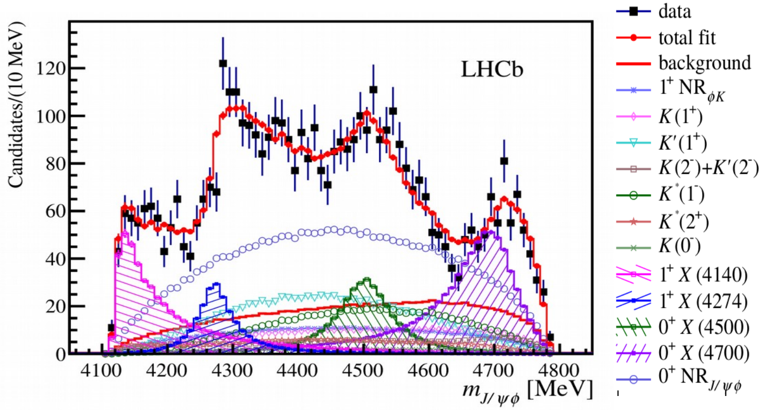
  BESIII observed significant signal



- $\mu^+ N \to \mu^+\, \phi J/\psi\, N'$

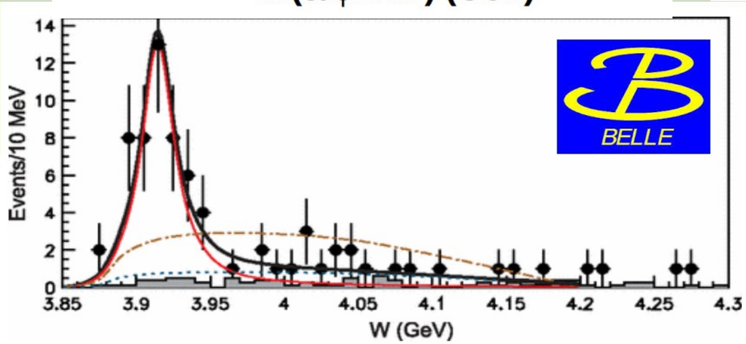
  X(4140) (Γ~15MeV)
  X(4274)(Γ~42MeV)
  observed by a lot of experiments

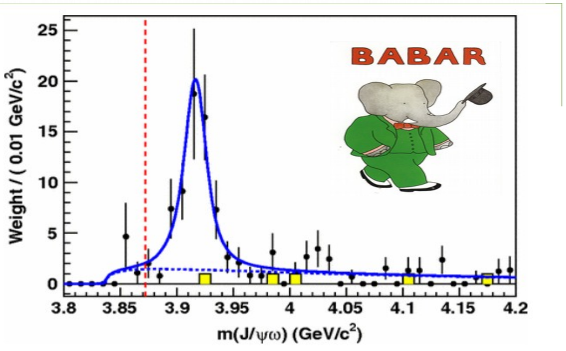




- $\mu^+ N \to \mu^+\, \omega J/\psi\, N'$

  Belle and BaBar observed Y(3940) with Γ = 37 MeV

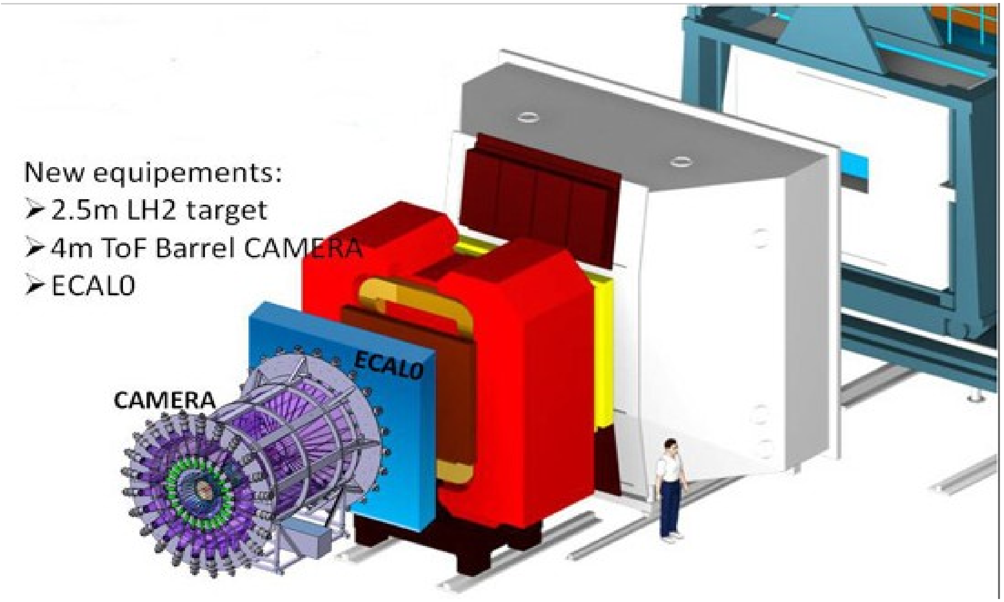




- …

Setup: new possibilities

- Liquid H_2 target: possibility to detect gamma.
- System of 3 ECALs: much better selection of exclusive events, better acceptance.
- Recoil proton detector CAMERA: improves quality of exclusive events selection.
- New set of triggers: wider kinematic range covered.

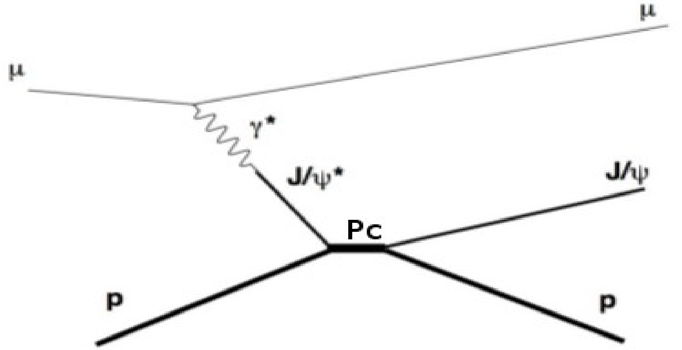


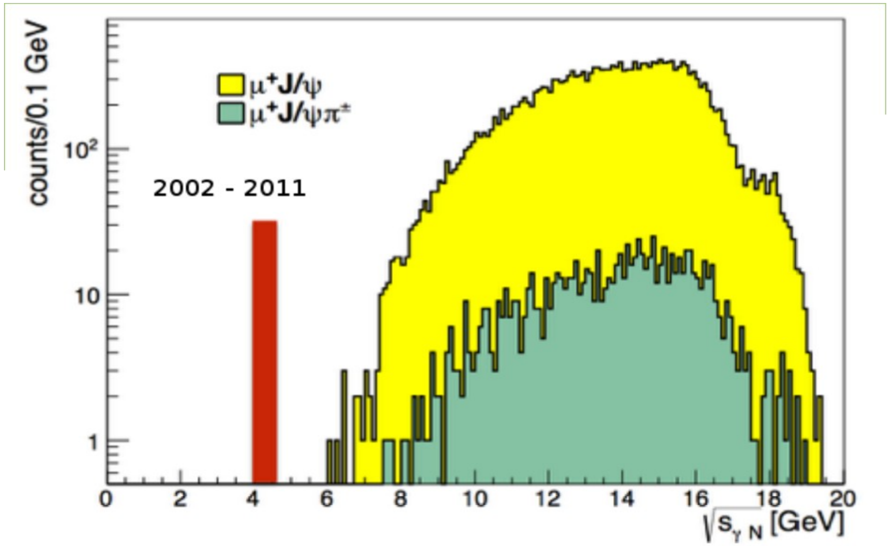
Exclusive photoproduction of pentaquarks $P_c(4380)$ and $P_c(4450)$ in s-channel

The exotic pentaquark states $P_c^+(4380)$ and $P_c^+(4450)$ have been observed by the LHCb collaboration in the $J/\psi p$ mass spectrum in the decay $\Lambda^0_b \to J/\psi p K^-$

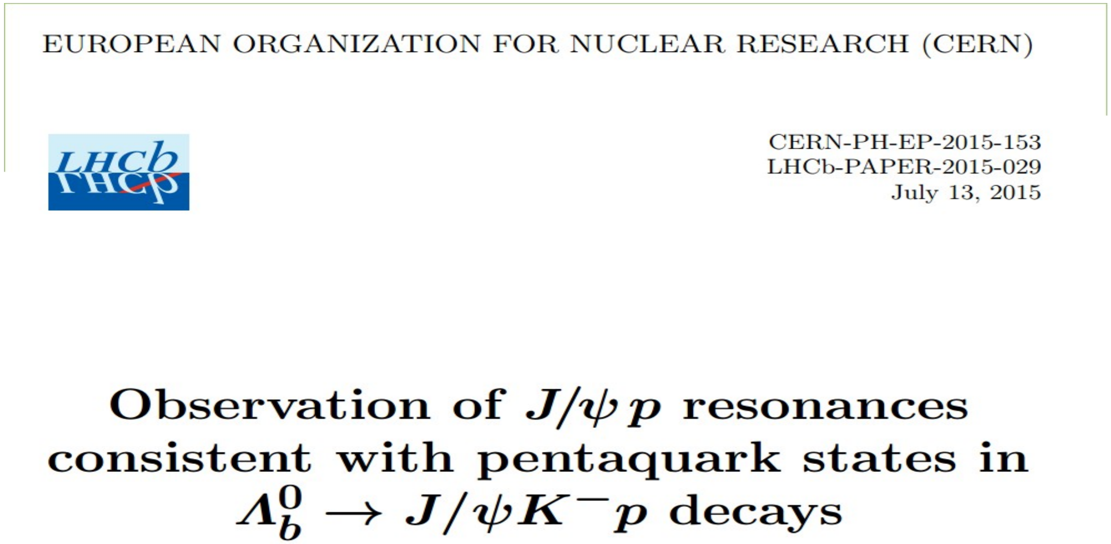
Minimal quark content $\bar{c}cuud$

$$\mu^+ p \to \mu^+ P_c \to \mu^+ J/\psi p$$





Phys. Rev. Lett. 115, 072001 (2015)


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2015-153
LHCb-PAPER-2015-029
July 13, 2015

Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda^0_b \to J/\psi K^- p$ decays

For observation of P_c COMPASS needs extended kinematic range.
In future COMPASS might cover the needed kinematic range (new triggers).

Conclusions

- Study of charmonium-like states is important for understanding of properties of hadronic matter.
- Photoproduction of exotic charmonia off a nuclear target is a new promising way to test the nature of these states.
- The COMPASS experiment performs groundbreaking studies of photoproduction of exotic XYZ states using DIS data collected in 2002-2011:

  $Z^{\pm}_{c}$(3900) - published result

  X(3872) - paper is under preparation

  XYZ$\rightarrow \phi J/\psi$ - ongoing analysis

- New data and new possibilities are expected with improved setup configuration.
- **The spectroscopy of exotic charmonia was introduced to COMPASS by JINR.**