Photoproduction of multi-quark baryonic states: a theoretical perspective

G.C. Rossi [a)] & G. Veneziano [b)]

[a)] Dipartimento di Fisica - Università di Roma *Tor Vergata* - Italia
INFN - Sezione di Roma *Tor Vergata*, Roma - Italia
Centro Fermi, Roma - Italia

[b)] Collège de France, 11 place M. Berthelot, 75231 Paris - France
Theory Division, CERN, CH-1211 Geneva 23 - Switzerland

Outline of the talk

- Motivation and a bit of history
- A unified description of hadrons encompassing
  - ordinary mesons and baryons
  - multi-quark states $\rightarrow$ "baryonium states"
- P_c as a penta-quark
- P_c photoproduction
- Conclusions

Bibliography

- The talk is mainly based on the paper
  G. C. Rossi and G. Veneziano
  JHEP **1606** (2016) 041

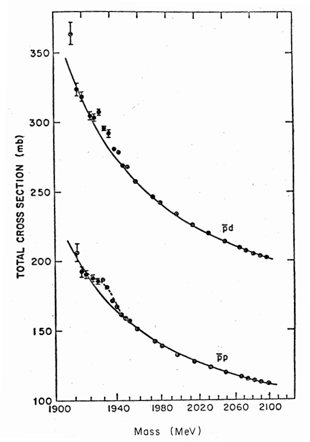
- Existence of multi-quark states were first conjectured in
  G. C. Rossi and G. Veneziano
  Nucl. Phys. B **123** (1977) 507.

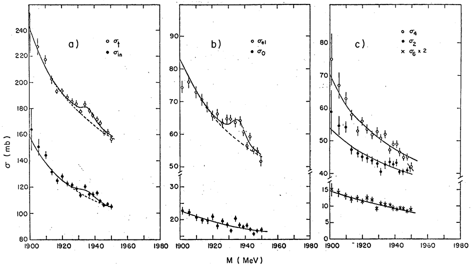
- About "Baryonium state" isospin mixing see
  G. C. Rossi and G. Veneziano
  Phys. Lett. **70B** (1977) 255
  Phys. Lett. **597B** (2004) 338

- An old experimental & theoretical review paper
  L. Montanet, G. C. Rossi and G. Veneziano
  Phys. Rept. **63** (1980) 149.

Motivation
A bit of history

A tetra-quark $qq\bar{q}\bar{q}$?





- A. S. Carroll *et al.*, PRL **32** (1974) 247 "Observation of structure in $\bar{p}p$ and $\bar{p}d$ total cross-sections below 1.1 GeV/c" @ BNL
- V. Chaloupka *et al.*, Phys. Lett. **61B** (1976) 487 "Measurement of the total and partial $\bar{p}p$ cross-section between 1901 and 1950 MeV" @ CERN

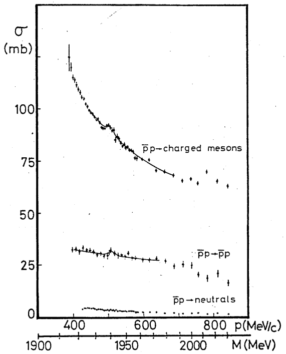


FIG. 4

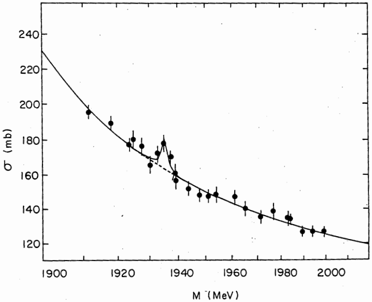
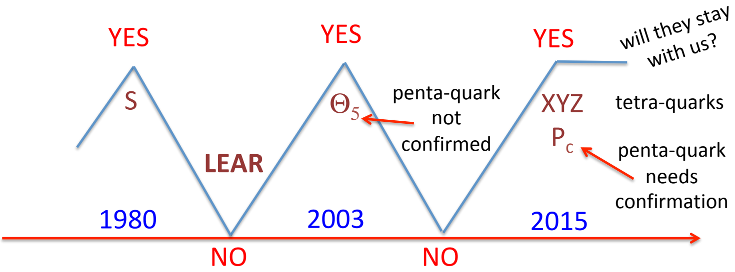


FIG. 5

- W. Bruckner *et al.*, Phys. Lett. **67B** (1977) 222 "Observation of a narrow resonance near the $\bar{p}p$ threshold" @ CERN
- S. Sakamoto *et al.*, NP B **158** (1979) 410 "Observation of a narrow resonance with a mass of 1936 Mev in $\bar{p}p$ total cross-section" @ BNL

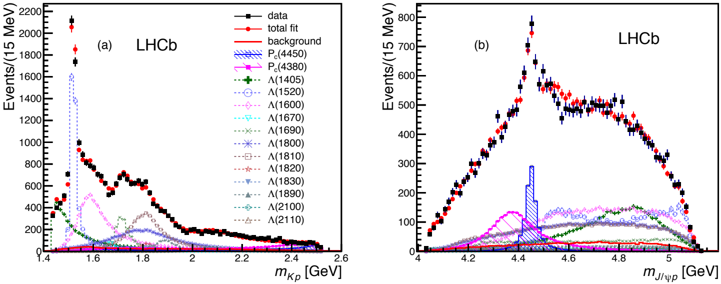
Rise and fall of multi-quark states



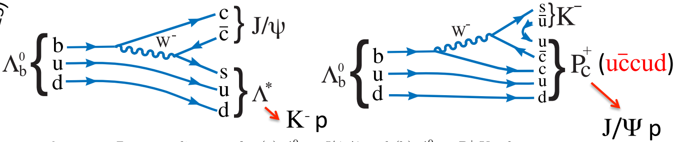
S(1930) not seen @ BNL by
V. Alston-Garnjost *et al.*, PRL 35 (1975) 1685
``Measurement of the anti-p p charge exchange
cross-section below 1 GeV/c''

Experimental evidence for the P_c 5q's state

R. Aaij *et al.* [LHCb Collaboration]



PRL **115**, 072001 (2015)



Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

$M(P_{Ic}^+) = 4450$ $J^P = 5/2^+$ $\Gamma = 39$ MeV

$M(P_{IIc}^+) = 4380$ $J^P = 3/2^-$ $\Gamma = 205$ MeV

Need for confirmation

- By the same collaboration

PRL **117**, 082003 (2016) PHYSICAL REVIEW LETTERS week ending 19 AUGUST 2016

Evidence for Exotic Hadron Contributions to $\Lambda_b^0 \to J/\psi p \pi^-$ Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

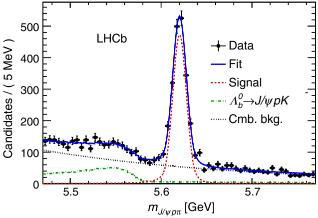


FIG. 1. Invariant mass spectrum for the selected $\Lambda_b^0 \to J/\psi p \pi^-$ candidates.

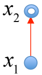
- I will concentrate on photoproduction
  - $\gamma p \to P_c^+ \to$ decay products
  - $\gamma p \to \pi^0 + P_c^+ \to \pi^0$ + decay products
  - $\gamma p \to PS + P_c \to PS$ + decay products

A unified picture of hadrons

from QCD color string + “planarity”

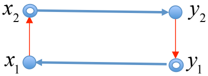
- ordinary mesons and baryons
- multi-quark states $\rightarrow$ baryonium states

Unified picture of hadrons → QCD string + "planarity"



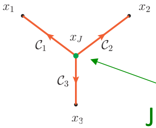
Meson → $M(x_1,x_2) = \frac{1}{\sqrt{3}} \bar{q}_k(x_1) C(x_1,x_2)^k_j q^j(x_2)$

$$C(x_1,x_2)^k_j = P\exp\left(ig\int_{x_1}^{x_2} A_\mu(z)\,dz_\mu\right)\Big|^k_j$$



Propagator → $\langle M(x_1,x_2)M^+(y_1,y_2)\rangle$

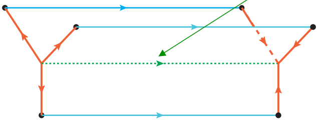
gauge invariance
+
planarity



Baryon → $B(x_1,x_2,x_3) =$

$$\frac{\varepsilon^{i_1 i_2 i_3}}{\sqrt{3!}} q_{k_1}(x_1) C(x_1,x_J)^{k_1}_{i_1} q_{k_2}(x_2) C(x_2,x_J)^{k_2}_{i_2} q_{k_3}(x_3) C(x_3,x_J)^{k_3}_{i_3}$$

Junction

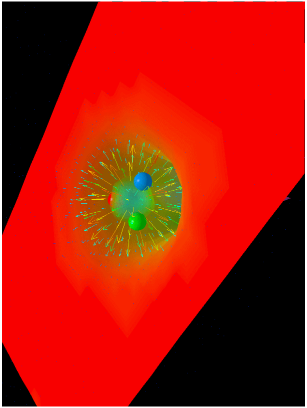


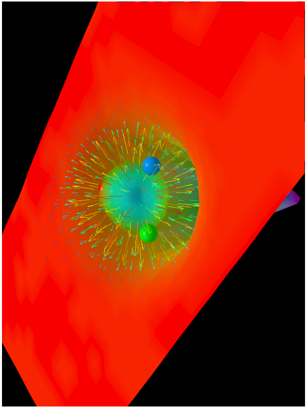
Propagator → $\langle B(x_1,x_2,x_3)B^+(y_1,y_2,y_3)\rangle$

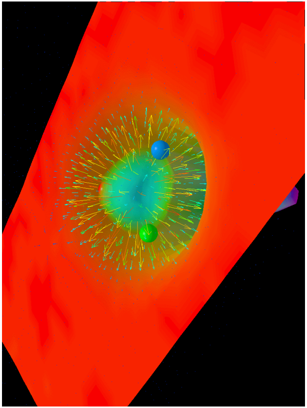
"Planarity" = dominance of "planar" diagrams

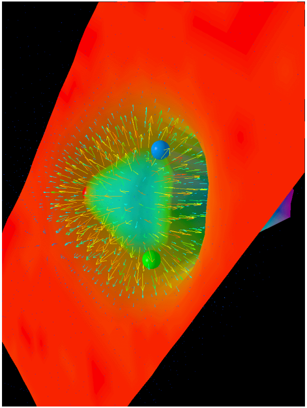
"Planarity" emerges from purely theoretical as well as lattice results

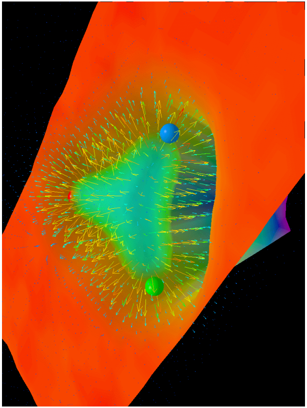
- Large N-expansions
  - from
    - large N_c @ $\lambda = g^2 N_c$ fix 't Hooft 1974
    - topological expansion Veneziano 1976
  - plus
    - duality
  - $\rightarrow$ Y-shaped baryons & baryonia Rossi & Veneziano 1977, Witten 1979
- Large $\lambda = g^2 N_c$ expansion
  - from
    - lattice strong coupling expansion Rossi & Veneziano 2016
  - $\rightarrow$ minimal "area" diagrams dominate scattering amplitudes
- Lattice data confirm
  - Y-shaped colour flux tube Bissey et al. 2006
  - Three-quark potential Koma & Koma 2017
  - Junction's position is at solution of the Fermat-Torricelli problem, i.e. is the location at minimal distance from $N(= 3)$ given points

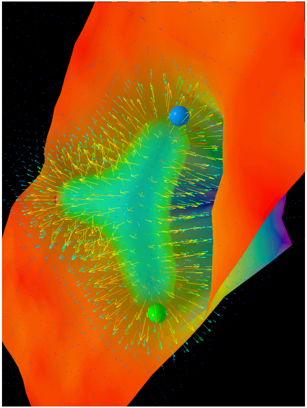


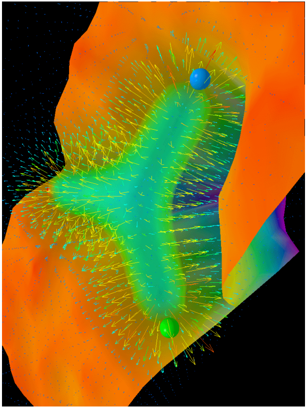


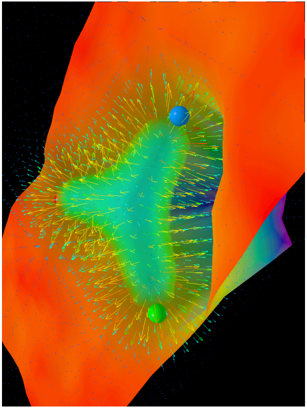


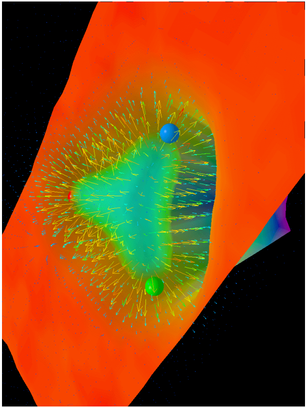


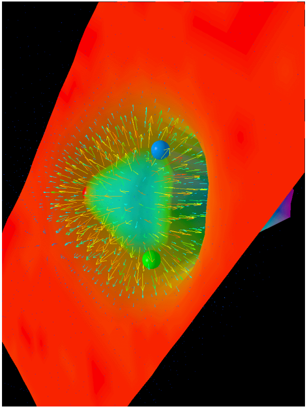


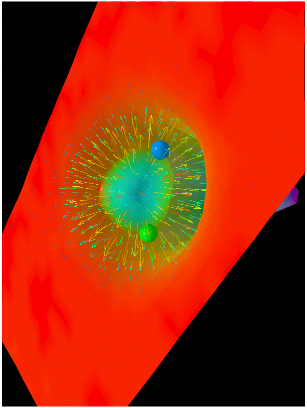


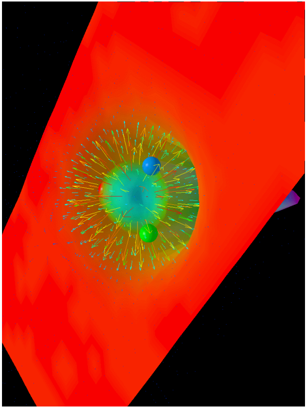






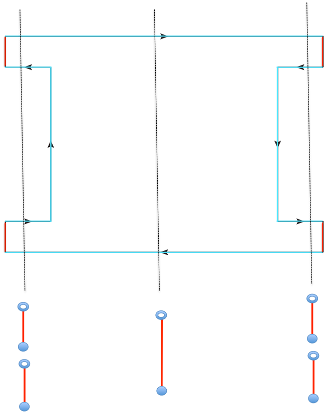






Scattering amplitudes

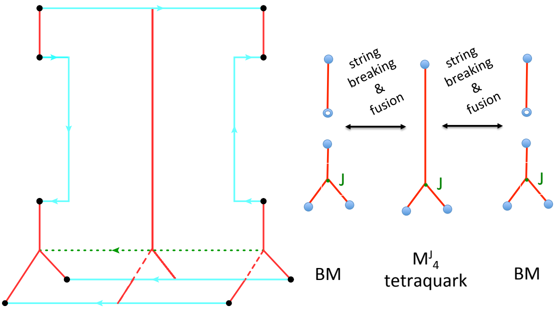
- Gluing & stretching Meson sheets $\Longrightarrow$ $MM \to MM$ amplitude



- *s*-channel mesons dual to *t*-channel mesons
- string breaking $\leftrightarrow$ string fusion

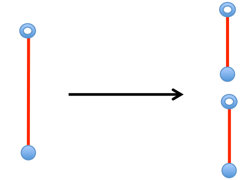
Scattering amplitudes

- Gluing Meson to Baryon sheets $\Longrightarrow$ $MB \to MB$ amplitude



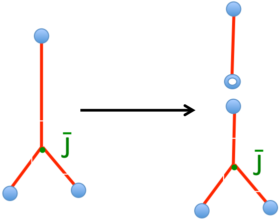
- s-channel baryons dual to t-channel mesons
- string breaking $\leftrightarrow$ string fusion

Meson & Baryon decay by string breaking



$\rho^+ \rightarrow \pi^+\pi^0$

meson decay
string breaking



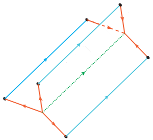
$\Delta^+ \rightarrow p\,\pi^0$

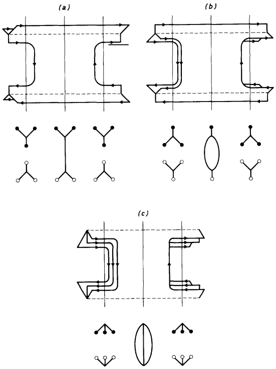
baryon decay
string breaking

$B\bar{B} \to B\bar{B}$ amplitudes

- Gluing together planar Baryon sheets $\Longrightarrow$ $B\bar{B} \to B\bar{B}$ scattering

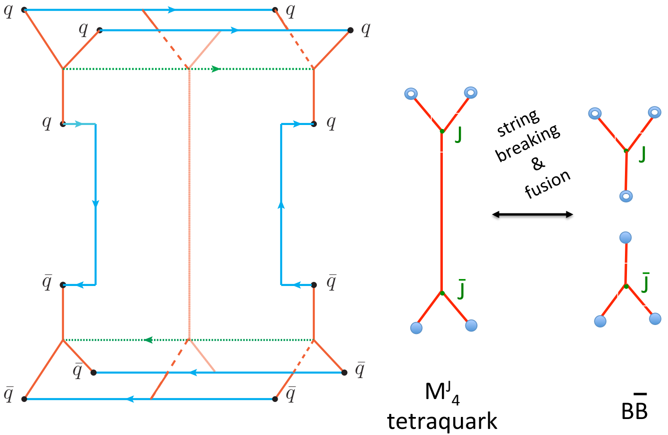
N$_c$=3





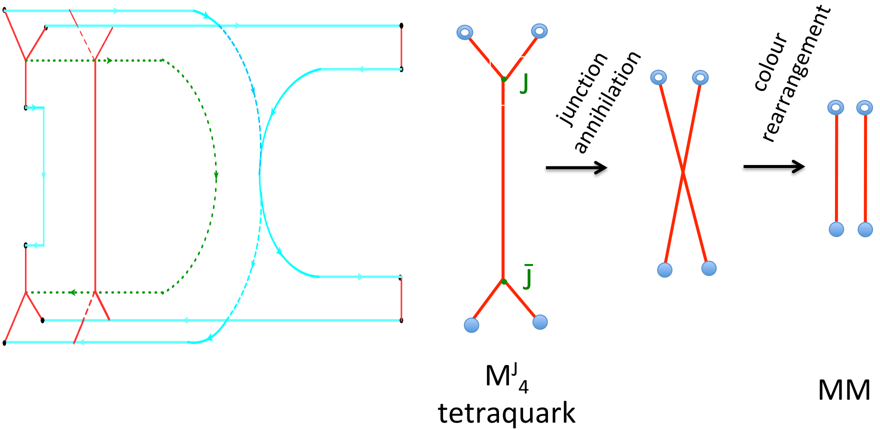
  - New intermediate *s*-channel states emerge $\to$ Baryonium states
  - *t*-channel intermediate states are 1, 2 and 3 *MM*-jets
- $B\bar{B} \to B\bar{B}$ annihilation: just turn by 90° the above diagrams

An artistic view of $B\bar{B} \to B\bar{B}$ scattering



- *s*-channel M_4^J tetra-quark dual to a *t*-channel $q\,\bar{q}$ meson
- the (preferred?) $M_4^J \to \bar{B}B$ decay (baryonium)

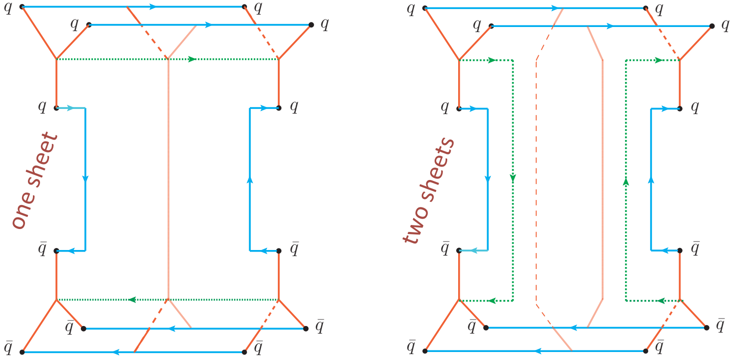
Non-planar $B\bar{B} \to MM$ annihilation



- the (dynamically disfavoured?) $M_4^J \to MM$ decay

Scattering vs. annihilation

Following flavour flow is not enough ...

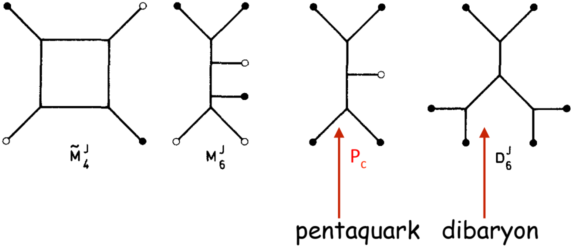


... need to also specify Junction flows (the green sewing lines)

A whole family of states is predicted

Other multiquark states

(from G. C. Rossi & GV, Phys. Rep. 1982)

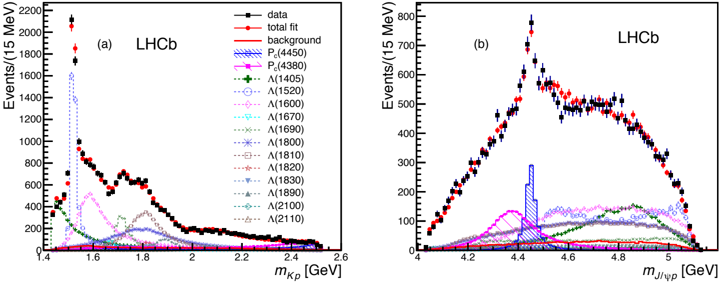


- Baryonic decay (string breaking) is dynamically favoured
- If kinematically forbidden, these states can be unusually narrow
- Other interpretations are on the market
  - Jaffe & Wilczek 2003
  - Karliner & Lipkin 2008 - Karliner & Rosner 2015
  - Maiani, Piccinini, Polosa & Riquer 2005

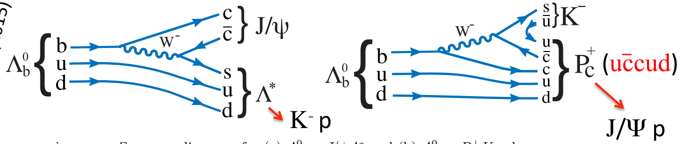
P_c as a penta-quark in the baryonium picture & Photoproduction

Experimental evidence for the P_c 5q's state

R. Aaij *et al.* [LHCb Collaboration]



PRL **115**, 072001 (2015)

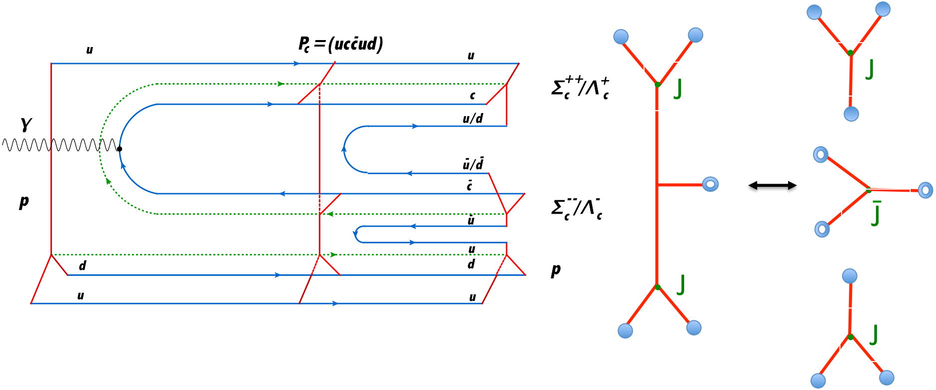


Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

$M(P_{Ic}^+) = 4450$ $J^P = 5/2^+$ $\Gamma = 39$ MeV

$M(P_{IIc}^+) = 4380$ $J^P = 3/2^-$ $\Gamma = 205$ MeV

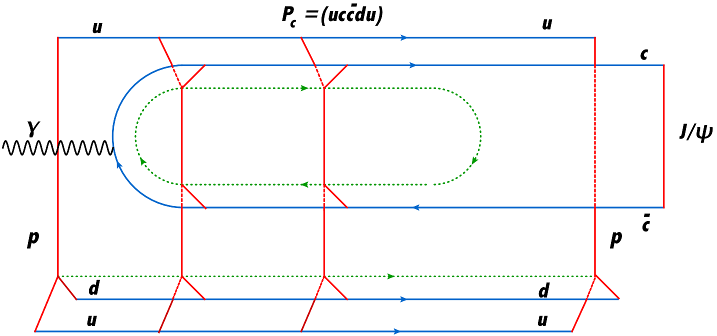
P_c photoproduction - String breaking decays



- $P_c \not\to \Lambda_c^+ + \Lambda_c^- + p$
- $P_c \not\to \Sigma_c^{++} + \Sigma_c^{--} + p$
- dynamically favoured, but kinematically forbidden
  - $M_{P_c} \sim 4450 < 2M_{\Lambda_c^+} + M_p \sim 2 \times 2286 + 938 = 5510$ MeV
  - $M_{P_c} \sim 4450 < 2M_{\Sigma_c^{++}} + M_p \sim 2 \times 2454 + 938 = 5846$ MeV

P_c photoproduction - Junction annihilation decay - I

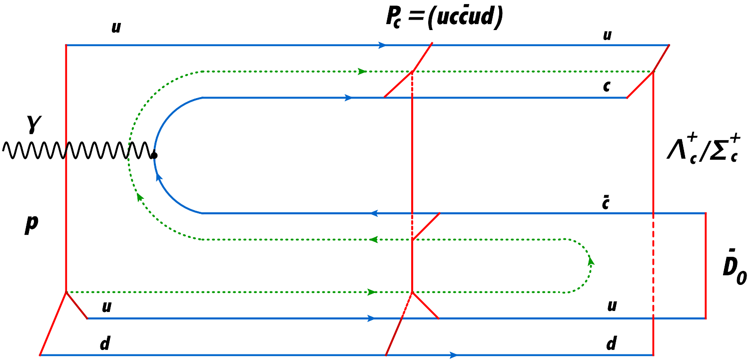
- Kinematically allowed
  - $P_c \to J/\psi + p$
  - closed Junction loop ("bathtub" diagrams)



- $M_{P_c} \sim 4450 > M_{J/\psi} + M_p \sim 3097 + 938 = 4035$ MeV
- The decay with the largest available phase-space

P_c photoproduction - Junction annihilation decay - II

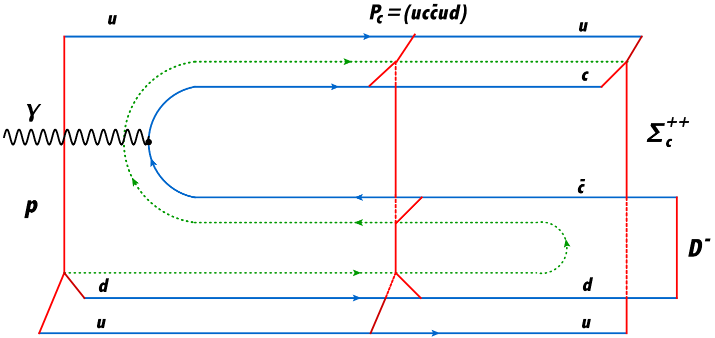
- Kinematically allowed
  - $P_c \to \Lambda_c^+/\Sigma_c^+ + \bar{D}_0$
  - no Junction loops ("snake" diagrams)



- $M_{P_c} \sim 4450 > M_{\Lambda_c^+} + M_{\bar{D}_0} \sim 2286 + 1865 = 4151$ MeV
- $M_{P_c} \sim 4450 > M_{\Sigma_c^+} + M_{\bar{D}_0} \sim 2454 + 1865 = 4319$ MeV

P_c photoproduction - Junction annihilation decay - III

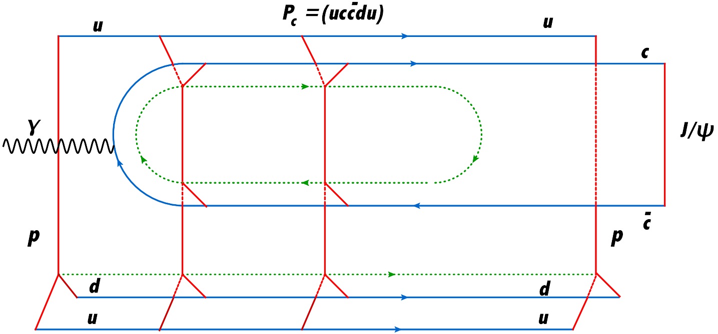
- Another kinematically allowed decay
  - $P_c \to \Sigma_c^{++} + D^-$
  - no Junction loops ("snake" diagrams)



- $M_{P_c} \sim 4450 > M_{\Sigma_c^{++}} + M_{D^-} \sim 2454 + 1865 = 4319$ MeV

P_c photoproduction - the favourite (?) decay

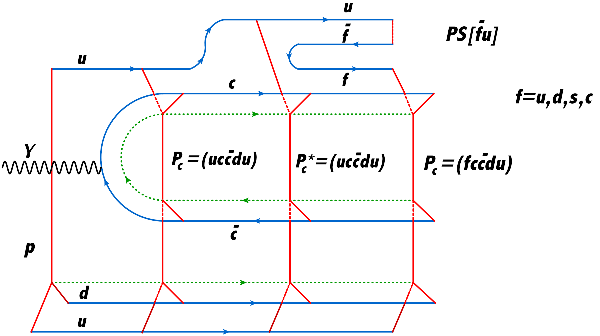
- Kinematically allowed
  - $P_c \to J/\psi + p$
  - closed Junction loop ("bathtub" diagrams)



  - $M_{P_c} \sim 4450 > M_{J/\psi} + M_p \sim 3097 + 938 = 4035$ MeV
- Perhaps the preferred P_c decay

Tagged P_c photoproduction - I

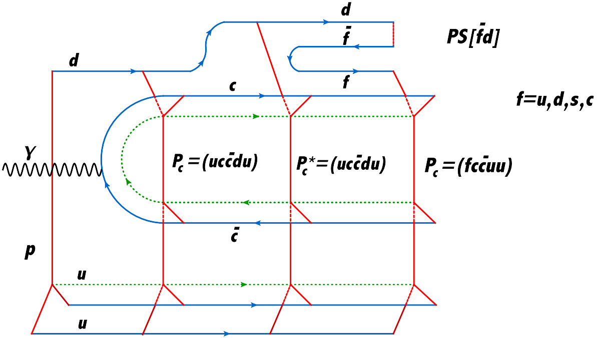
- $\gamma p \to P_c^\star(u\,c\,\bar{c}\,u\,d) \to \pi^0\, P_c^+(u\,c\,\bar{c}\,u\,d)$
- $\gamma p \to P_c^\star(u\,c\,\bar{c}\,u\,d) \to \pi^+\, P_c^0(d\,c\,\bar{c}\,u\,d)$
- if large enough E_γ available, one can more generally search for
  - $\gamma p \to P_c^\star(u\,c\,\bar{c}\,u\,d) \to K^+\, P_c^s(s\,c\,\bar{c}\,u\,d)$
  - $\gamma p \to P_c^\star(u\,c\,\bar{c}\,u\,d) \to \bar{D}^0\; P_c^c(c\,c\,\bar{c}\,u\,d)$
  - ...



- followed by the $P_c(fc\bar{c}\underline{ud})$ decay

Tagged P_c photoproduction - II

- $\gamma\, p \to P_c^\star(d\, c\, \bar{c}\, u\, u) \to \pi^-\, P_c^{++}(u\, c\, \bar{c}\, u\, u)$
- $\gamma\, p \to P_c^\star(d\, c\, \bar{c}\, u\, u) \to \pi^0\, P_c^{+}(d\, c\, \bar{c}\, u\, u)$
- if large enough E_γ available, one can more generally search for
  - $\gamma\, p \to P_c^\star(d\, c\, \bar{c}\, u\, u) \to K^0\, P_c^s(s\, c\, \bar{c}\, u\, u)$
  - $\gamma\, p \to P_c^\star(d\, c\, \bar{c}\, u\, u) \to D^-\, P_c^c(c\, c\, \bar{c}\, u\, u)$
  - $\ldots$



- followed by the $P_c(f c\bar{c}\underline{uu})$ decay

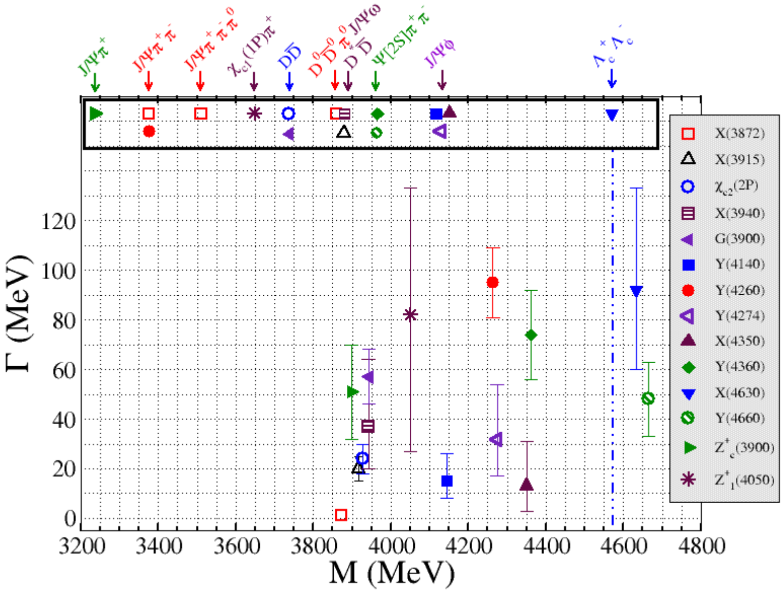
Conclusions

- Planarity + QCD string provide
- a unified picture of hadrons beyond the naïve quark model
  - the notion of Junction emerges
  - new family of multi-quark hadrons is predicted - Baryonium states
    - tetra-quarks $B = 0$
    - penta-quarks $B = 1$
    - di-baryons $B = 2$
  - their dynamically favoured decay is by string breaking (as opposed to colour rearrangement $= J - \bar{J}$ annihilation)
  - if kinematically forbidden, they can be unusually narrow
- Photoproduction: suitable tool to produce (narrow) penta-quarks
  - the preferred formation-decay processes seem to be
    - $\gamma\, p \to J/\psi\, p$
      - letting $s = (q_\gamma + q_p)^2$ sweep through $M^2_{P_c}$ by tuning E_γ
    - $\gamma\, p \to \pi^0\, J/\psi\, p$
      - sweeping through $(q_{J/\psi} + q_p)^2 = M^2_{P_c}$ with the help of q_{π^0} and/or E_γ

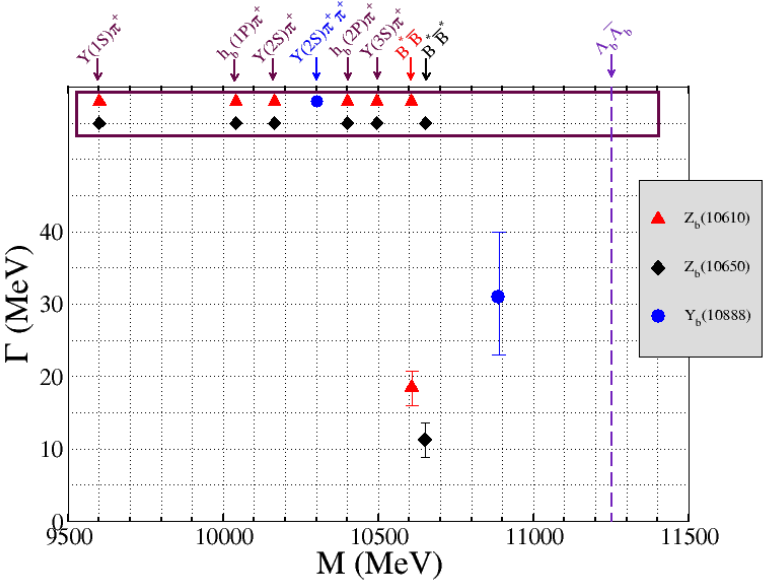
Thanks for your attention

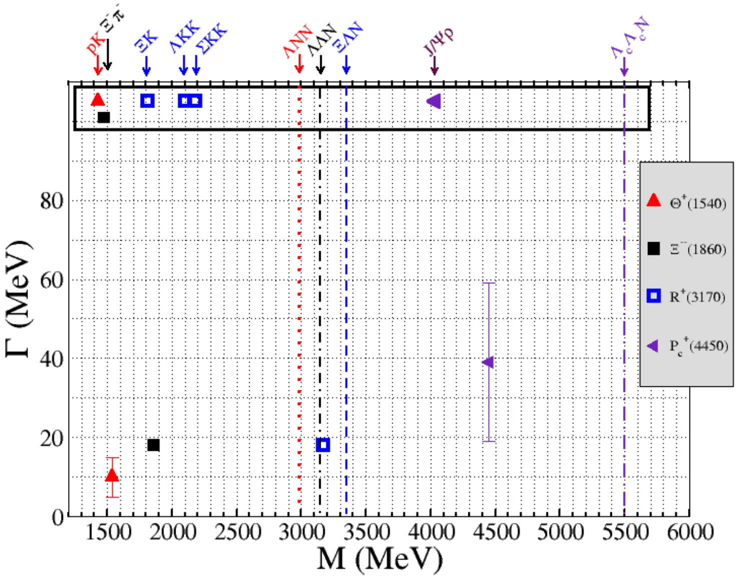
Back-up slides

II - Hidden charm tetraquarks: a (dated) compilation



III - Hidden bottom tetraquarks: a (dated) compilation





pK
Ξ⁻π⁻
ΞK
ΛKK
ΣKK
ΛNN
ΛΛN
ΞΛN
J/Ψρ
$\Lambda_c\Lambda_c N$
80
60
40
20
0
Γ (MeV)
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
M (MeV)
$\Theta^+(1540)$
$\Xi^{--}(1860)$
$R^+(3170)$
$P_c^+(4450)$

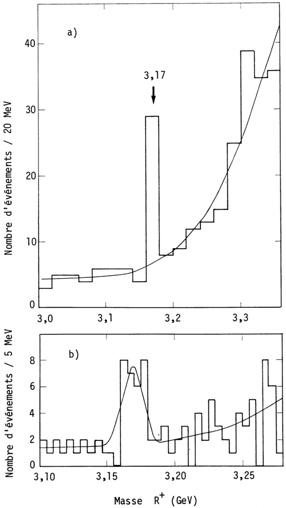


Figure 4 — a) Spectre de masse du système hypéronique R^+ pour des événements dans lesquels le π^- provenant de la réaction $K^-p \rightarrow \pi^-R^+$ se situe dans l'hémisphère arrière du système du centre de masse. La courbe en trait plein représente l'ajustement du fond avec une probabilité maximale. L'impulsion du K^- incident était de 8,25 GeV/c.
b) Spectre de masse du R^+ pour les mêmes événements que dans la figure 4a, par intervalles de 5 MeV.

$K^- p \rightarrow \pi^- R^+$

$R^+ \rightarrow \Sigma K\bar{K} / \Lambda K\bar{K} / \Xi K$

T. Amirzadeh *et al.*
CERN/EP 79-101
September 18, 1979

A narrow pentaquark?
$M \approx 3.17$ GeV