Charmonia and XYZ

Eric Swanson

Study the QCD portion of the Standard Model

$$
\begin{aligned}
\mathcal{L} = &-\frac{1}{4}W_a^{\mu\nu}W^a_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + (D_\mu\phi)^\dagger(D^\mu\phi) - \mu^2|\phi|^2 - \lambda|\phi|^4 \\
&+ \sum_i \left(\bar{L}^i i\not{D} L^i + \bar{R}^i i\not{D} R^i + \bar{Q}^i_L i\not{D} Q^i_L + \bar{u}^i_R i\not{D} u^i_R + \bar{d}^i_R i\not{D} d^i_R\right) \\
&- \sqrt{2}\sum_{ij}\left(\lambda^{ij}\bar{L}^i\phi R^j + \lambda^{ij}_d \bar{Q}^i_L \phi d^j_R + \lambda^{ij}_u \bar{Q}^i_L \phi^c u^j_R + \text{h.c.}\right) \\
&- \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} + \sum_f \bar{q}^f i\not{D}_{\text{QCD}} q^f
\end{aligned}
$$

Study the QCD portion of the Standard Model

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} W_a^{\mu\nu} W_{\mu\nu}^a - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} + (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 |\phi|^2 - \lambda |\phi|^4 \\
& + \sum_i \left(\bar{L}^i i \not{D} L^i + \bar{R}^i i \not{D} R^i + \bar{Q}_L^i i \not{D} Q_L^i + \bar{u}_R^i i \not{D} u_R^i + \bar{d}_R^i i \not{D} d_R^i \right) \\
& - \sqrt{2} \sum_{ij} \left(\lambda^{ij} \bar{L}^i \phi R^j + \lambda_d^{ij} \bar{Q}_L^i \phi d_R^j + \lambda_u^{ij} \bar{Q}_L^i \phi^c u_R^j + \text{h.c.} \right) \\
& \boxed{- \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a + \sum_f \bar{q}^f i \not{D}_{\text{QCD}} q^f}
\end{aligned}
$$

Murray Gell-Mann
(1929-2019)

Heinrich Leutwyler
(1938-)

Harald Fritsch
(1943-)

Study the QCD portion of the Standard Model

flavour	charge	mass	discovery
up	2/3	5 MeV	1911
down	-1/3	10 MeV	1932
charm	2/3	1600 MeV	1974
strange	-1/3	150 MeV	1947
top	2/3	174 GeV	1995
bottom	-1/3	5 GeV	1977

LeroyJackson19 · 4 hours ago

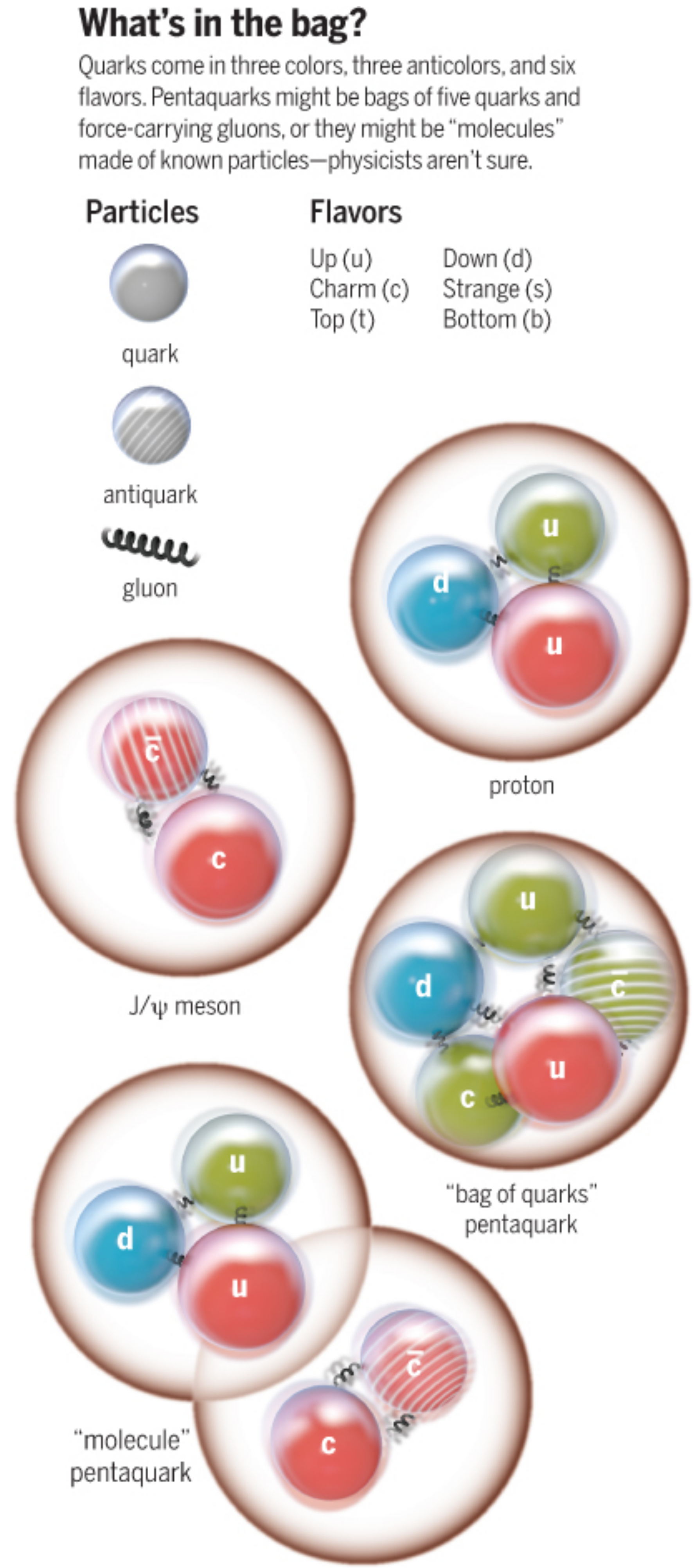
Did smart people name these particles? Cuz up, down, charm and top sounds like high school names. How bout wiz dammit, nab jones... Something along those lines.

2 ^ | v Reply Share ›

Quarks Make Things!

$$-\frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu}+\sum_f \bar{q}^f i\not{D}_{\mathrm{QCD}}q^f$$

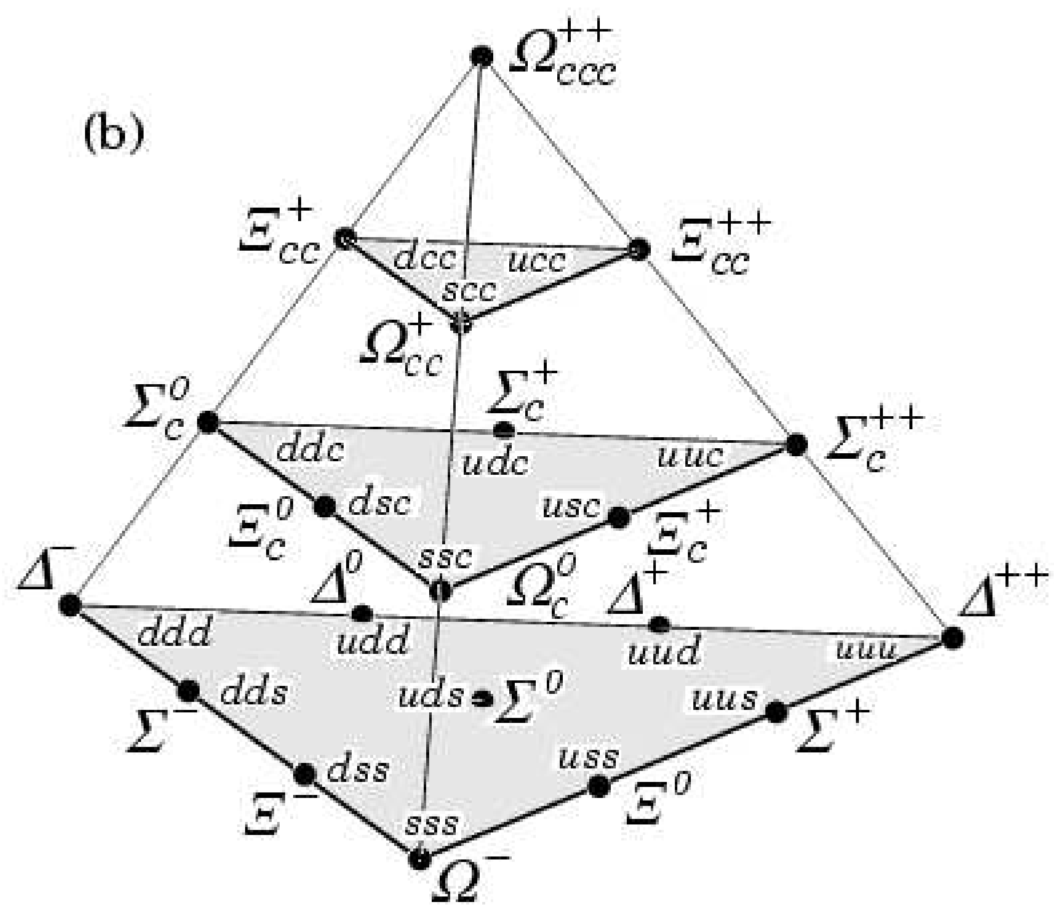
? →



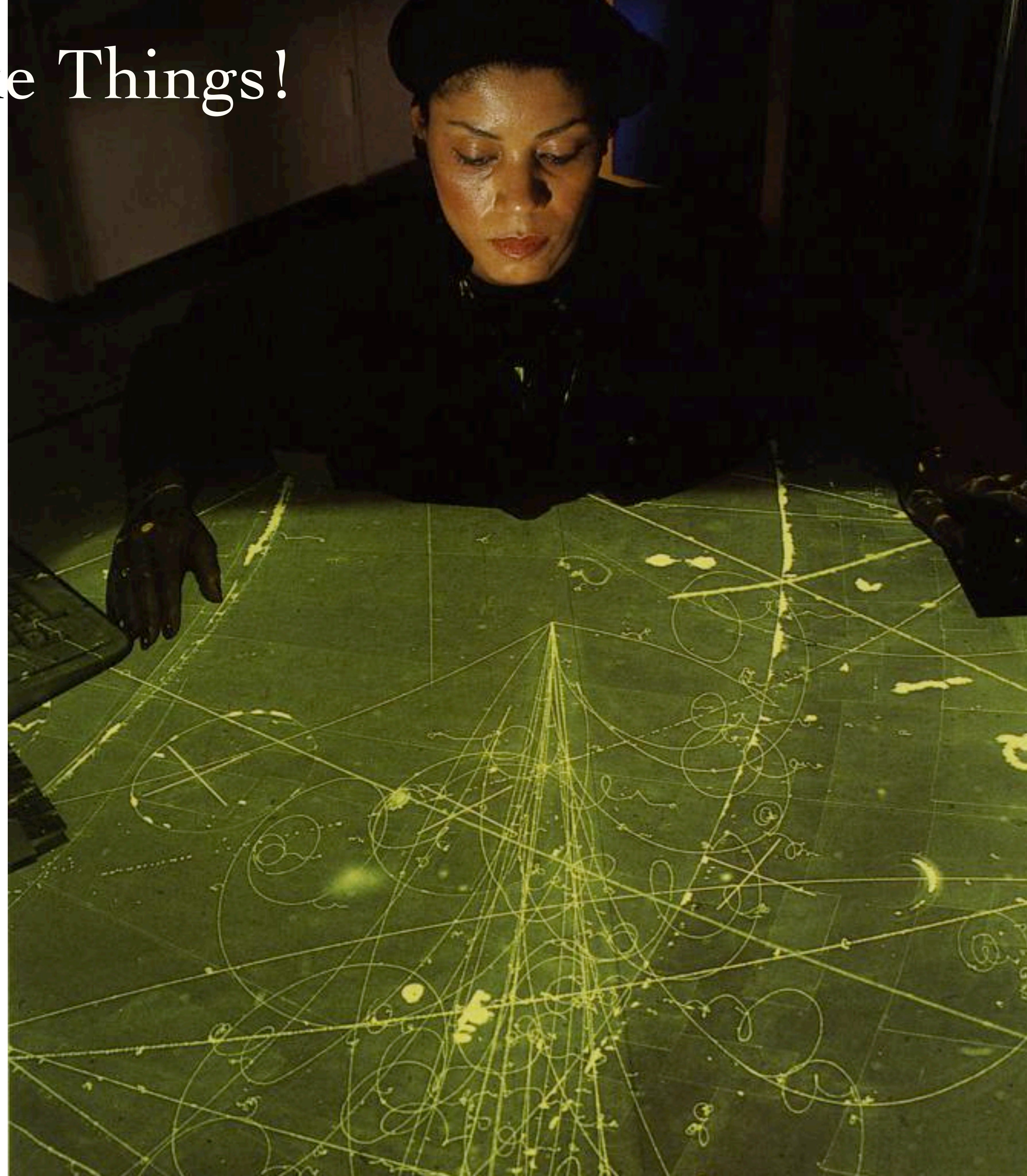
The social life of quarks, Science, 15 Jan, 2016

Quarks Make Things!

"hadrons are simple"



Quarks Make Things!

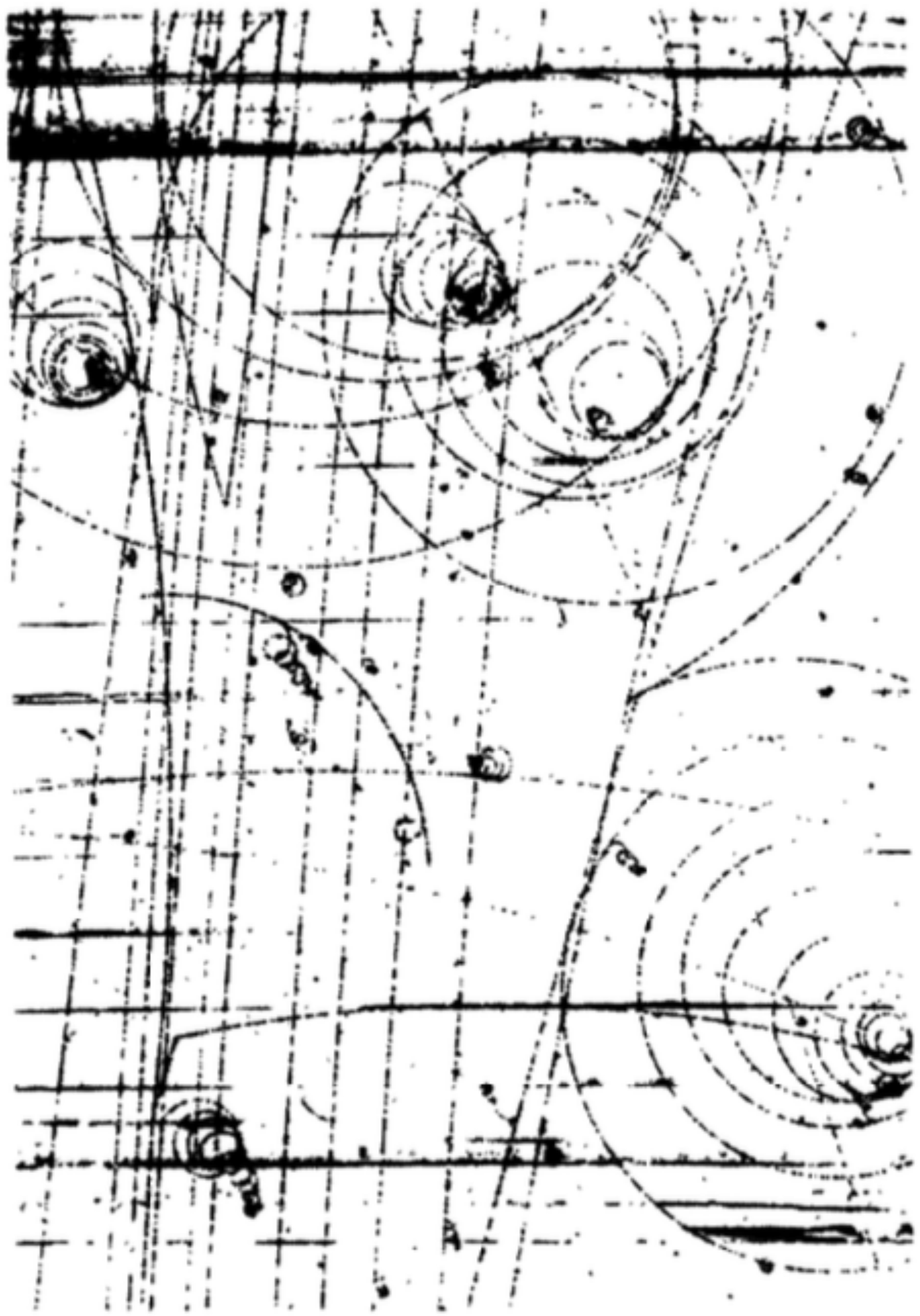


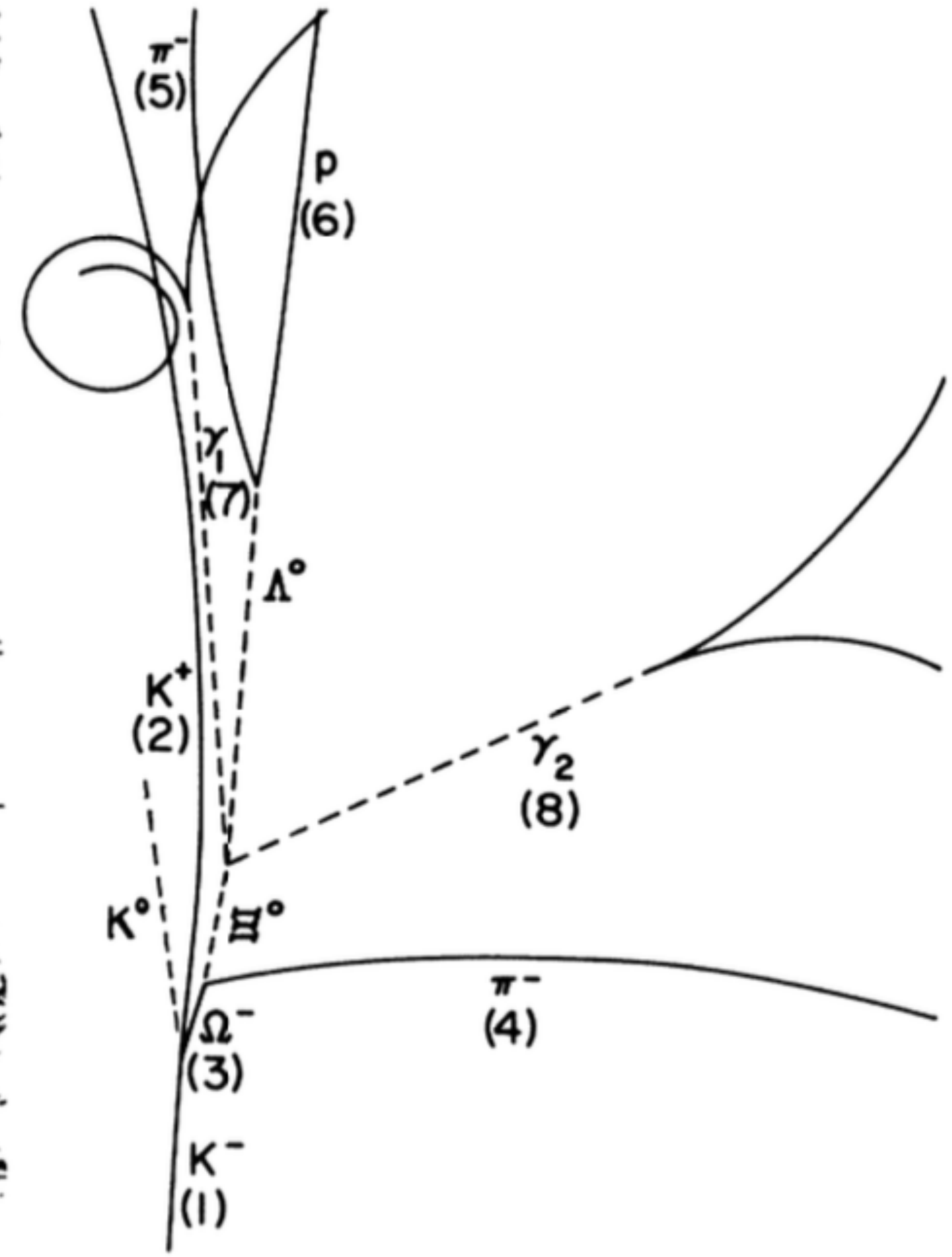
“hadrons are irreducible complexity”

Quarks Make Things!

Omega- predicted by Gell-Mann in 1962, race was on to find it. Won by BNL two years later

the Eightfold Way



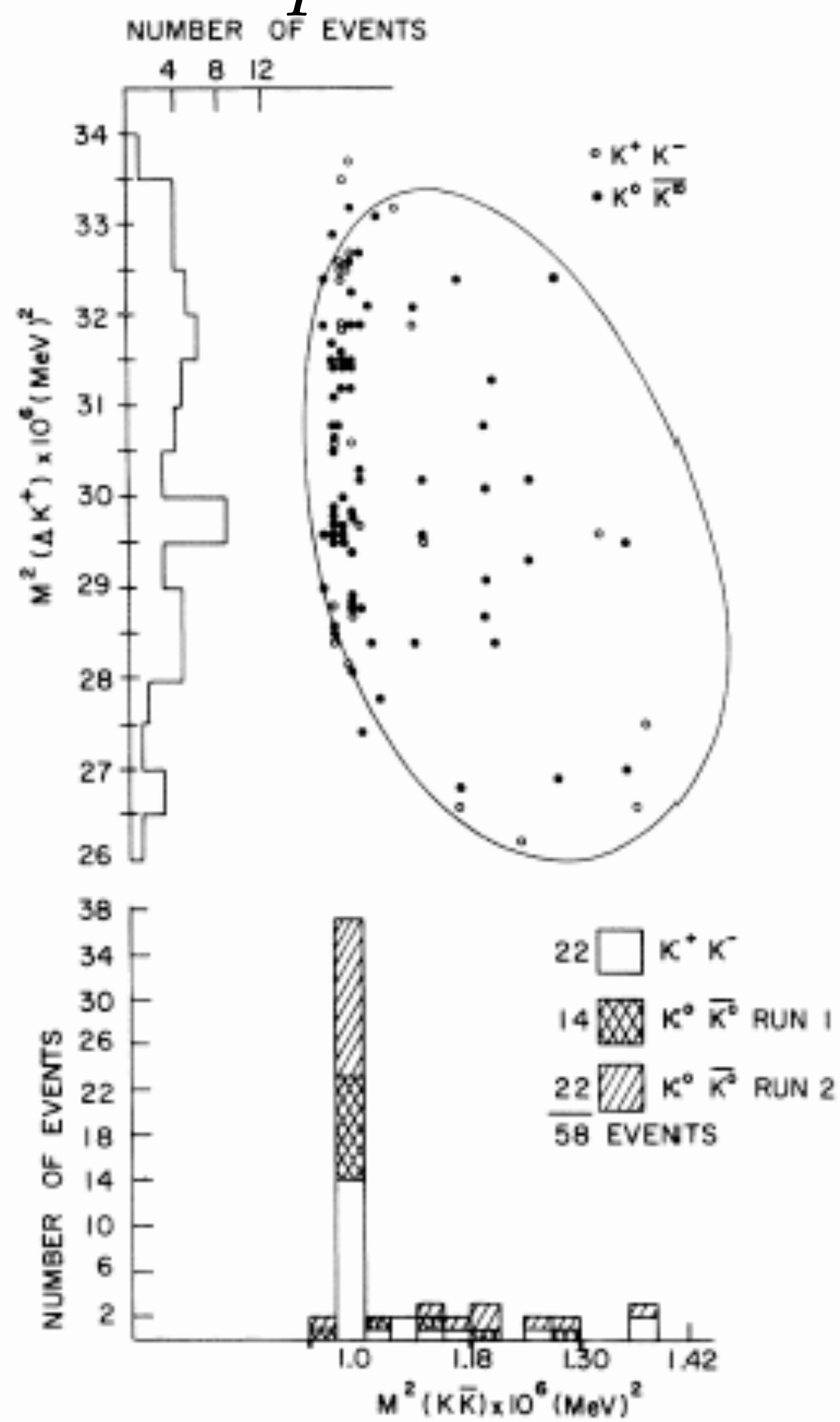


V.E. Barnes et al., PRL**12**, 204 (1964).

Quarks Make Things!

Dick Dalitz
1925-2006

$$Kp \to \Lambda K \bar{K}$$

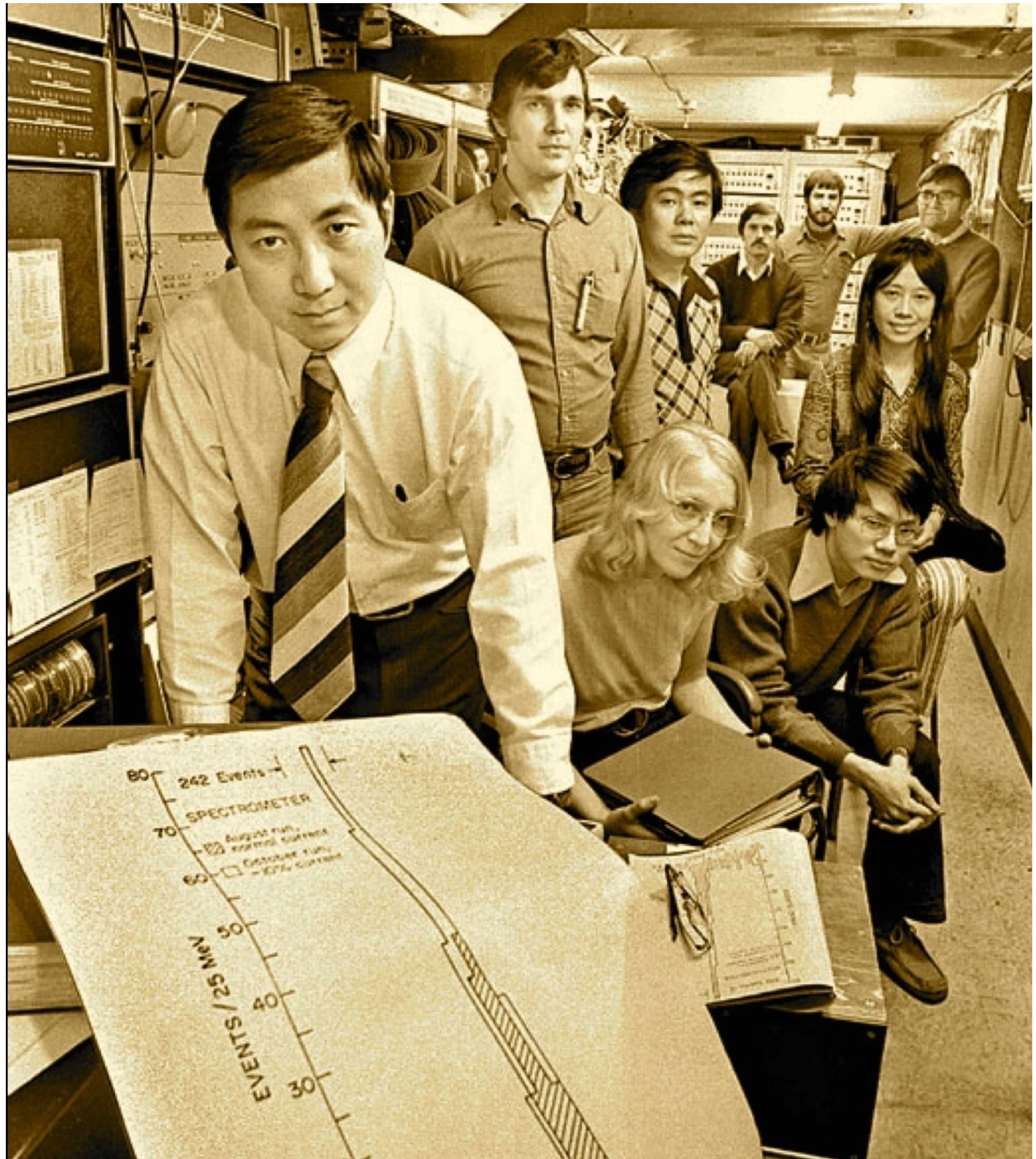


discovery of the φ

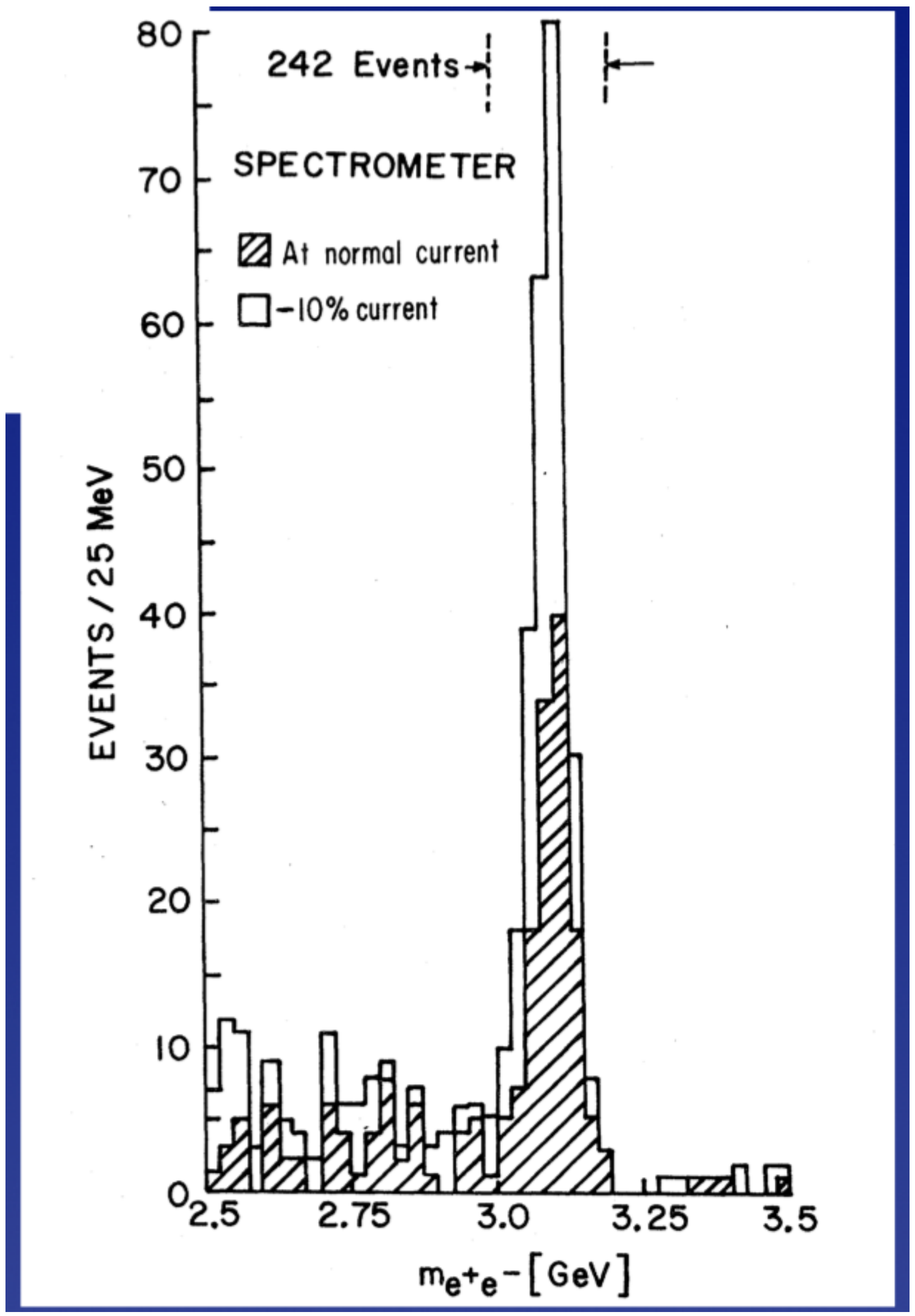
I remember being very surprised by Figure 1 …There was an enormous peak … right at the edge of phase space. The fact that the φ decayed predominantly into KK and not πρ was totally unintelligible. … Only conservation laws suppress reactions. Here was a reaction that was allowed but did not proceed! I had thought that hadrons probably have constituents and this experiment convinced me that they do, and that they are real. … This was a statement about dynamics which indicated that the constituents were not hypothetical objects carrying the symmetries of the theory, but real objects that moved in space-time from hadron to hadron.” George Zweig

P.L. Connelly et al., PRL**10**, 371 (1963).

Quarks Make Things!

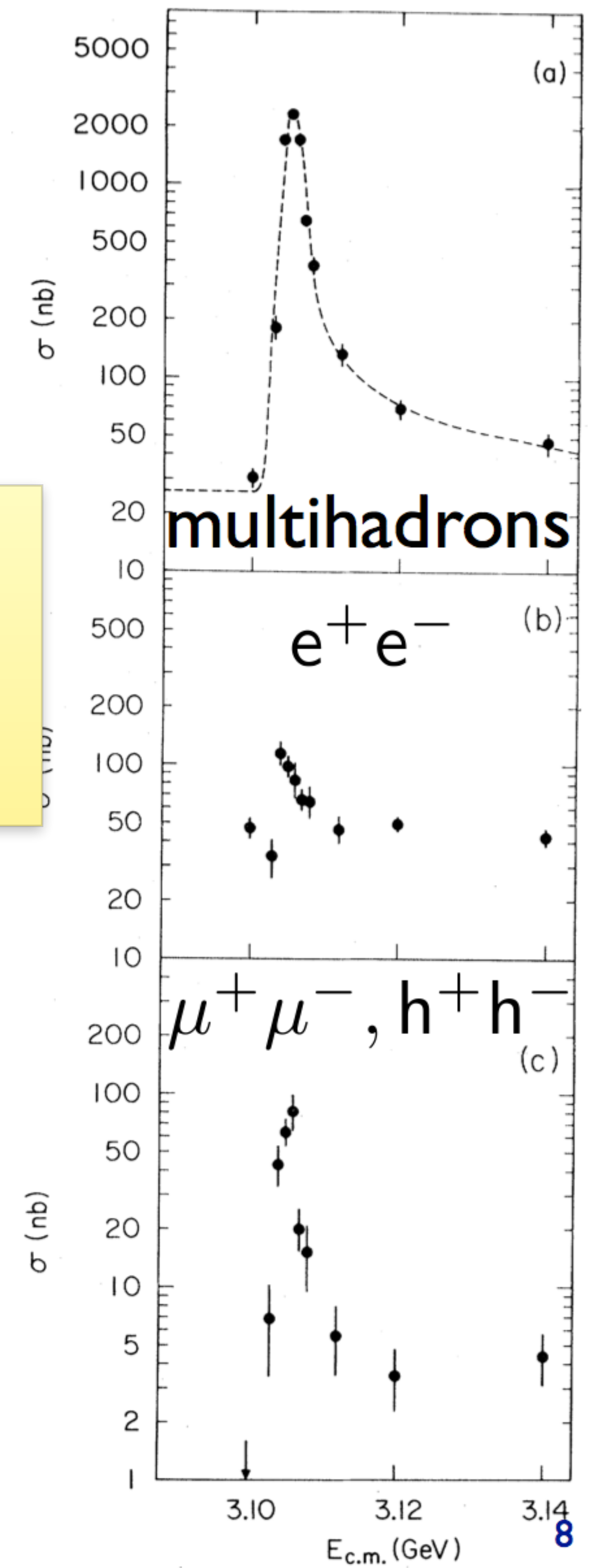


Quarks Make Things!



<- Sam Ting, at BNL

-> Burton Richter at SLAC



J.J. Aubert *et al.* Nov 12, 1974

J.-E. Augustin *et al.*, Nov 13, 1974

Quarks Make Things!

…since 2003…

$Y(4660)$
$X(4630)$
$Z^+(4430)$
$X(4350)$
$Z_2(4250)$
$X(4160)$
$Z_1(4050)$
$Y(4008)$
$X(3940)$

$Y(4320)$ $X(3915)$

$Y(4260)$ $X(3872)$ $Z_c(3900)$ $Y(4274)$ η_c' $P_c(4380)$

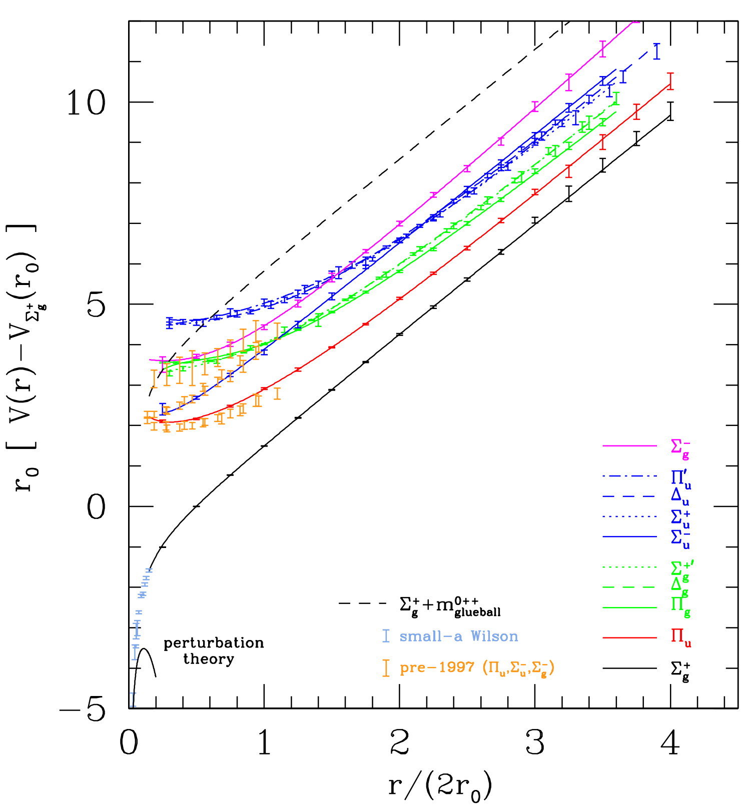
$G(3900)$ χ_{c2}' $Y(4140)$ h_c $X(5568)$ $P_c(4450)$

The Constituent Quark Model

colour

$$H = \sum_i m_i + \sum_i \frac{p_i^2}{2m_i} + C + \sum_{i<j} \left[- \left(-\frac{\alpha_s}{r_{ij}} + \frac{3}{4} b r_{ij} \right) \vec{F}_i \cdot \vec{F}_j + V_{SD}^{oge}(r_{ij}) + V_{SD}^{conf}(r_{ij}) \right]$$

variants:



running coupling

smeared delta functions

relativized

perturbative corrections

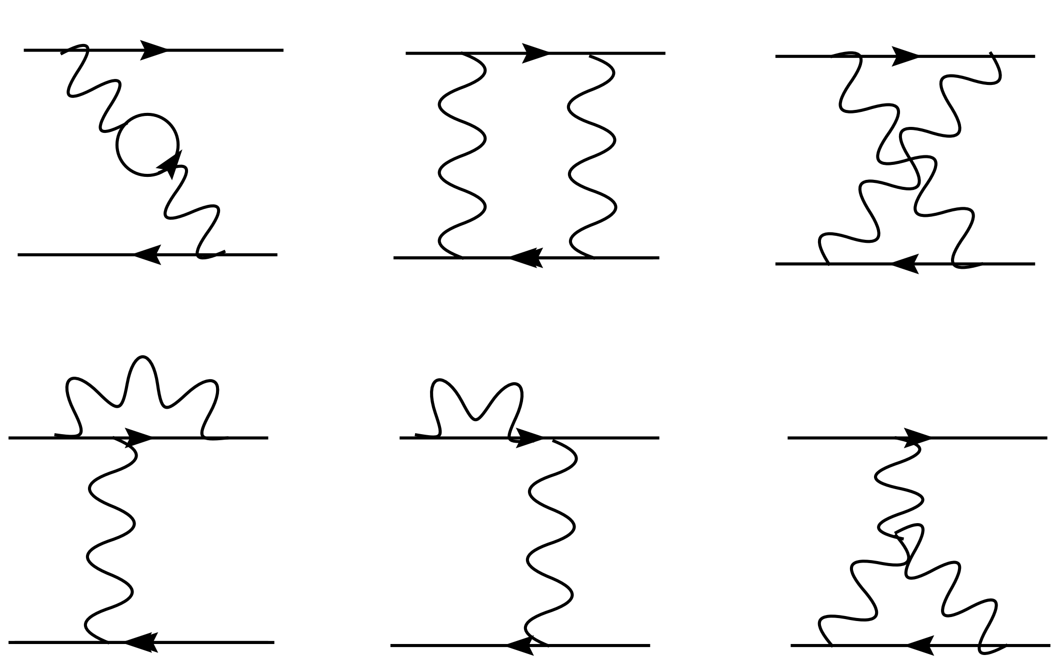
Mercedes baryon potential

instanton potential

hypercentral potential

The Constituent Quark Model

$$V_{SD}(r) = \left(\frac{\sigma_q}{4m_q^2} + \frac{\sigma_{\bar q}}{4m_{\bar q}^2}\right)\cdot \mathbf{L}\left(\frac{1}{r}\frac{dV_{conf}}{dr} + \frac{2}{r}\frac{dV_1}{dr}\right) + \left(\frac{\sigma_{\bar q} + \sigma_q}{2m_q m_{\bar q}}\right)\cdot \mathbf{L}\left(\frac{1}{r}\frac{dV_2}{dr}\right)$$
$$+\frac{1}{12 m_q m_{\bar q}}\Big(3\sigma_q\cdot\hat{\mathbf{r}}\,\sigma_{\bar q}\cdot\hat{\mathbf{r}} - \sigma_q\cdot\sigma_{\bar q}\Big)V_3 + \frac{1}{12 m_q m_{\bar q}}\sigma_q\cdot\sigma_{\bar q} V_4$$
$$+\frac{1}{2}\left[\left(\frac{\sigma_q}{m_q^2} - \frac{\sigma_{\bar q}}{m_{\bar q}^2}\right)\cdot\mathbf{L} + \left(\frac{\sigma_q - \sigma_{\bar q}}{m_q m_{\bar q}}\right)\cdot\mathbf{L}\right]V_5. \quad (1)$$



Gupta & Radford, PRD33, 777 (86)

The Constituent Quark Model

Build a Meson

$$|M(P); JM[LS]\rangle = \sum_k \sum_{M_L M_S} \sum_{m,\bar{m}} \varphi_L(k)\, \langle S M_S L M_L | JM\rangle\, Y_{LM_L}(\hat{k})\, \chi^{SM_S}_{m\bar{m}}\; b^\dagger_{P/2+k,m} d^\dagger_{P/2-k,\bar{m}} |0\rangle$$

a useful exercise: write the explicit expression for the vector current $\bar{\psi}\gamma^\mu\psi$

The Constituent Quark Model

Build a Meson

- ✓ helicity formalism: Martin and Spearman

- ✓ Dirac bra-ket formalism

$$Y_{\ell m}(\theta', \phi') = \langle \theta' \phi' | \ell m \rangle = \langle \theta \phi | R | \ell m \rangle = \sum_n \langle \theta \phi | \ell n \rangle \, \langle \ell n | R | \ell m \rangle = \sum_n Y_{\ell n}(\theta, \phi) D^{(\ell)}_{nm}(\phi^{*}, \theta^{*}, -\phi^{*})$$

The Constituent Quark Model

Meson Quantum Numbers

$$C b_{\vec{p}m} C^\dagger = \eta_C d_{\vec{p}m}$$

$$C d^\dagger_{\vec{p}m} C^\dagger = \eta_C b^\dagger_{\vec{p}m}$$

$$P d^\dagger_{\vec{p}m} P^\dagger = -\eta_P d^\dagger_{-\vec{p}m}$$

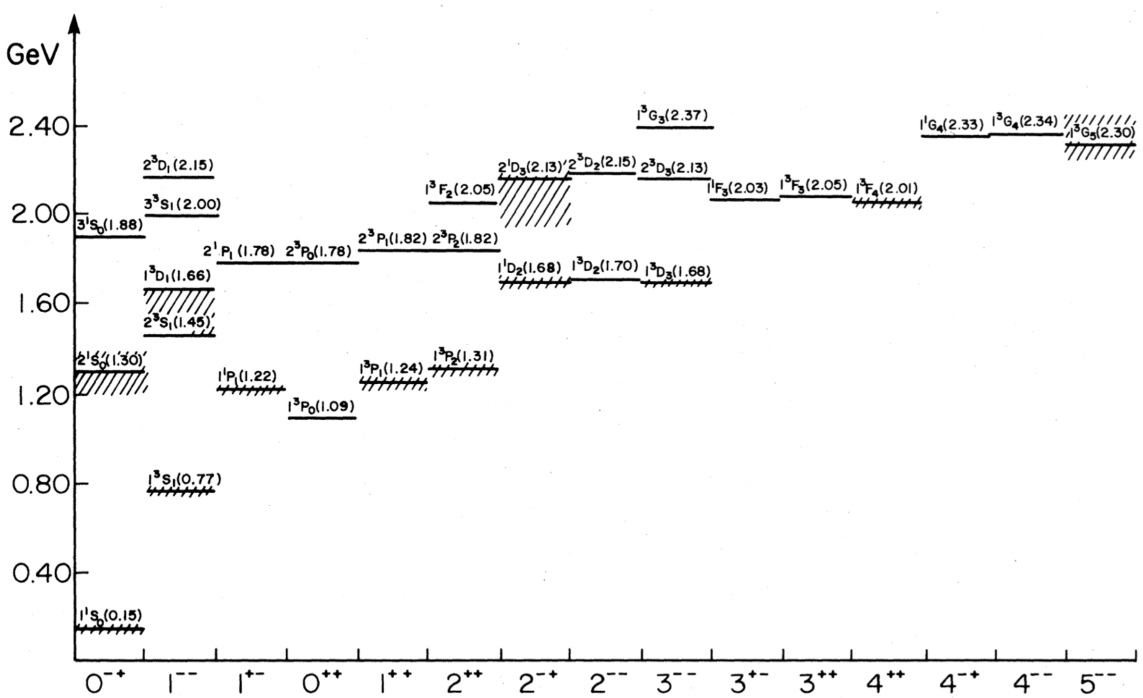
$$P b^\dagger_{\vec{p}m} P^\dagger = \eta_P^* b^\dagger_{-\vec{p}m}$$

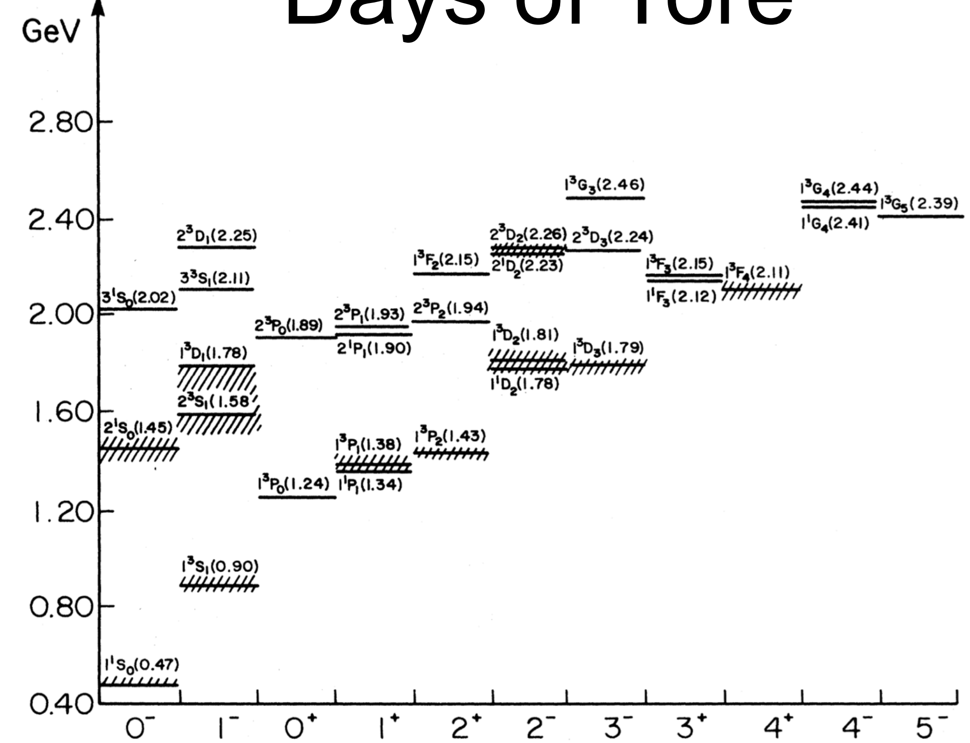
$$P|M(P); JM[LS]\rangle = (-)^{L+1}|M(-P); JM[LS]\rangle$$

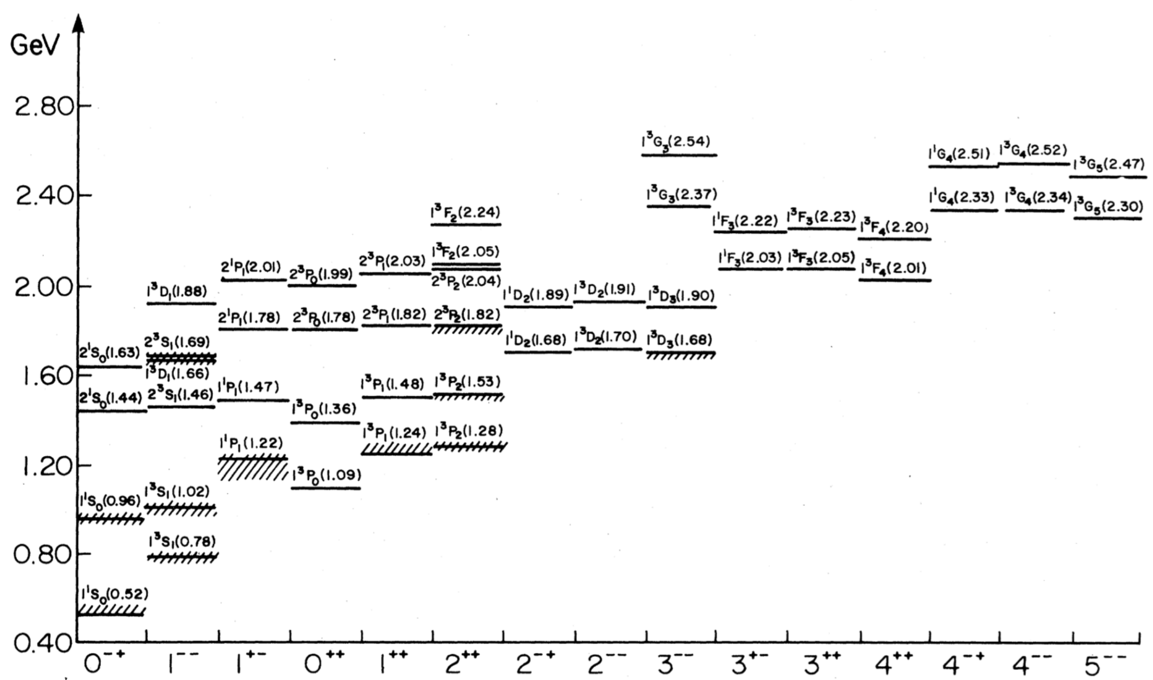
$$C|M(P); JM[LS]\rangle = (-)^{L+S}|M(P); JM[LS]\rangle$$

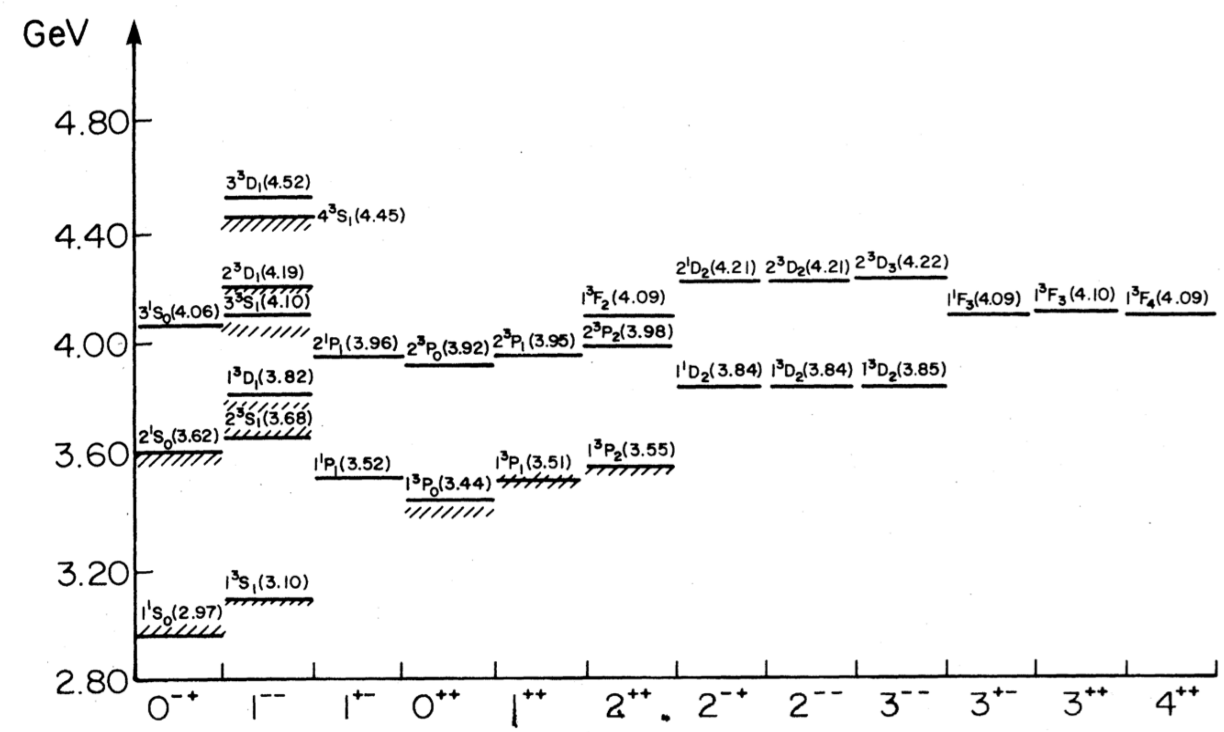
The Constituent Quark Model

Days of Yore





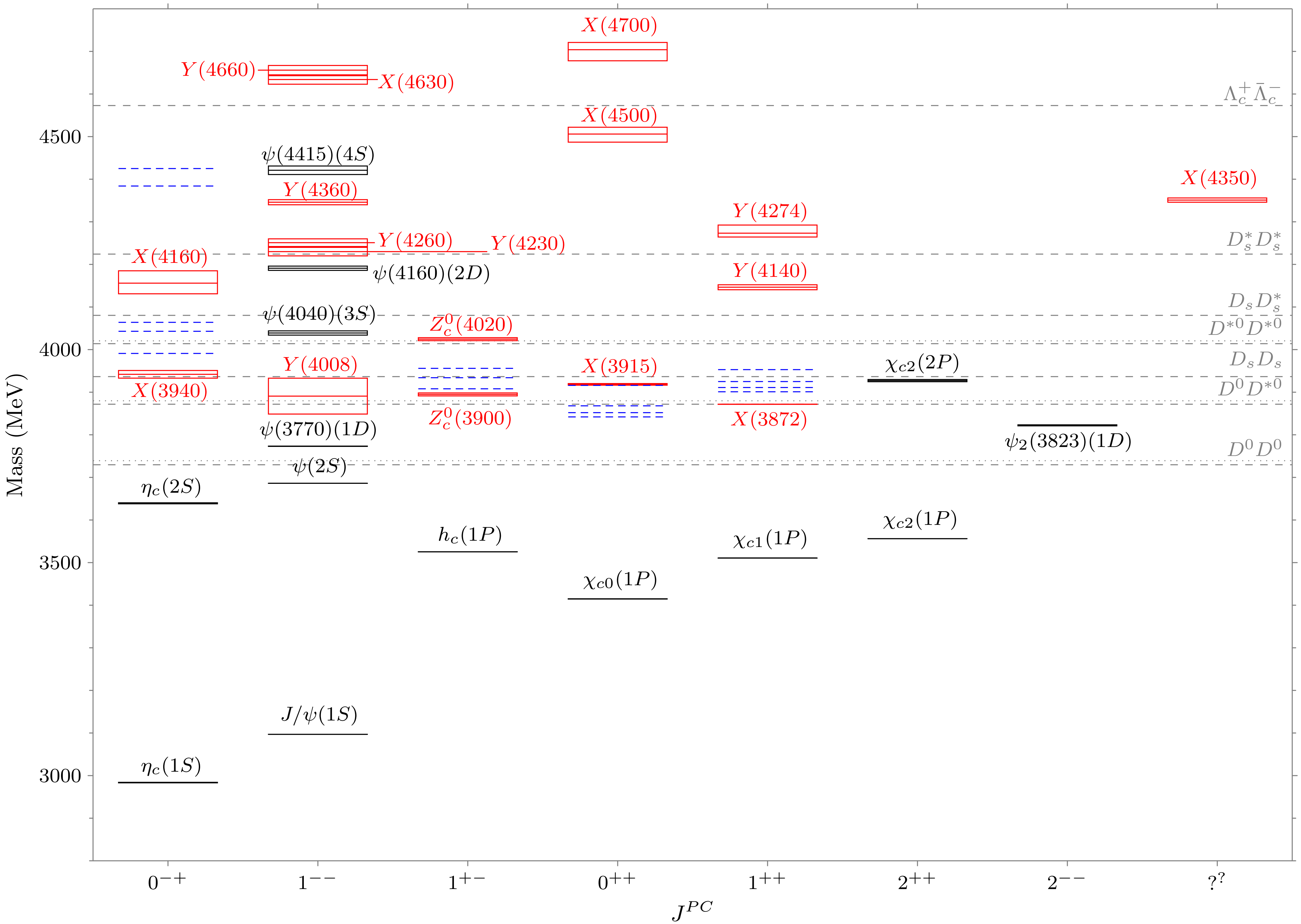




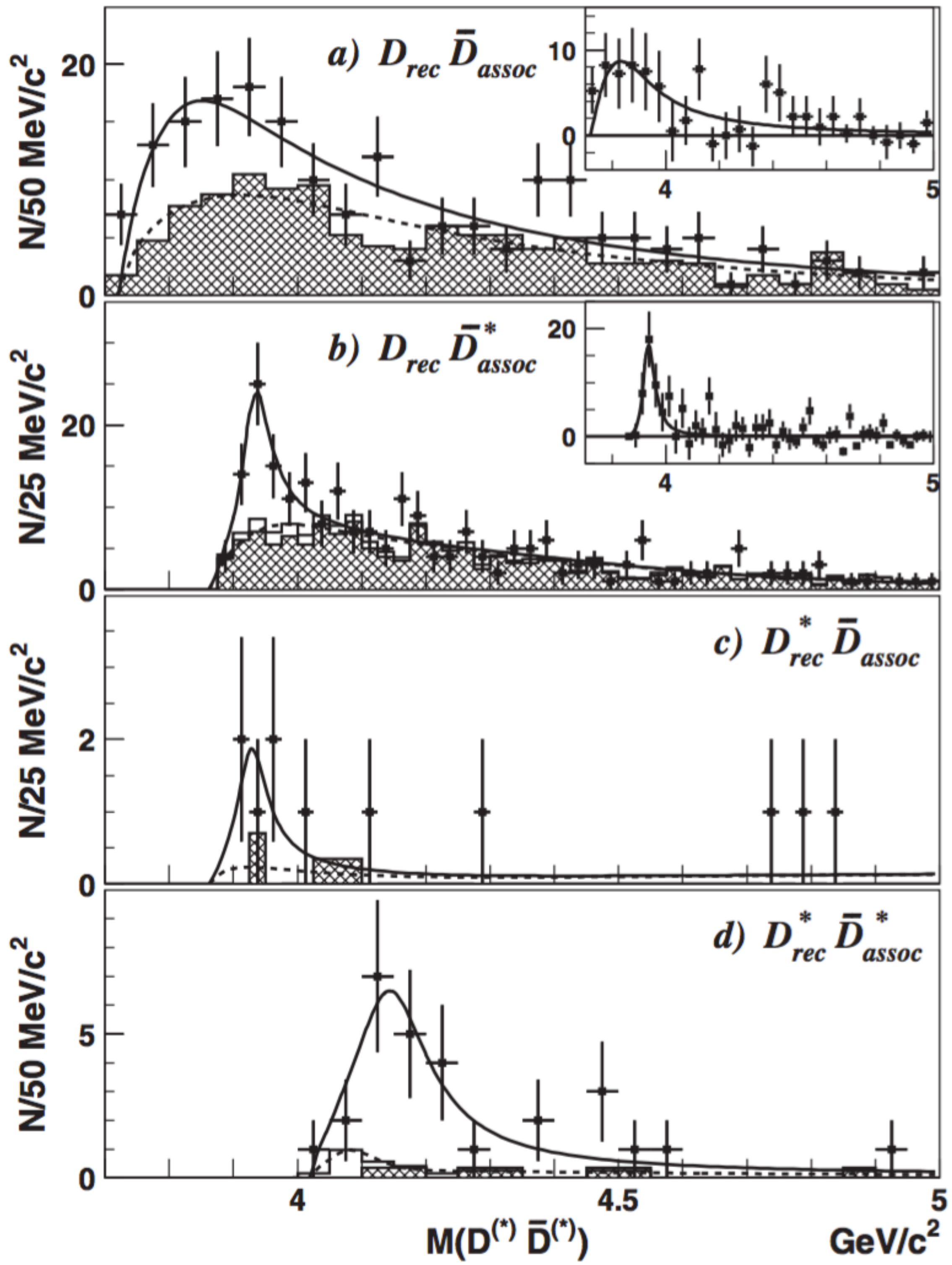
Godfrey & Isgur, 1985

The Constituent Quark Model

Days of Pain



Thresholds



[Belle] PRL100, 202001 (08)

thresholds will also move the mesons around

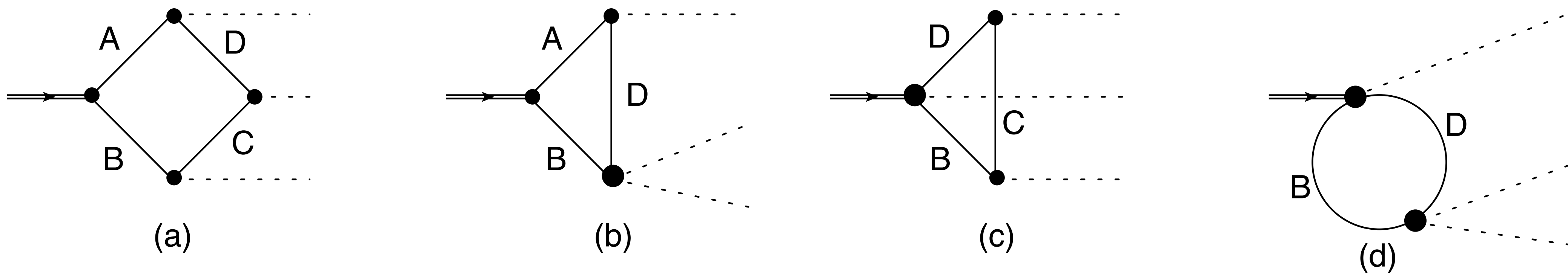
Cusps

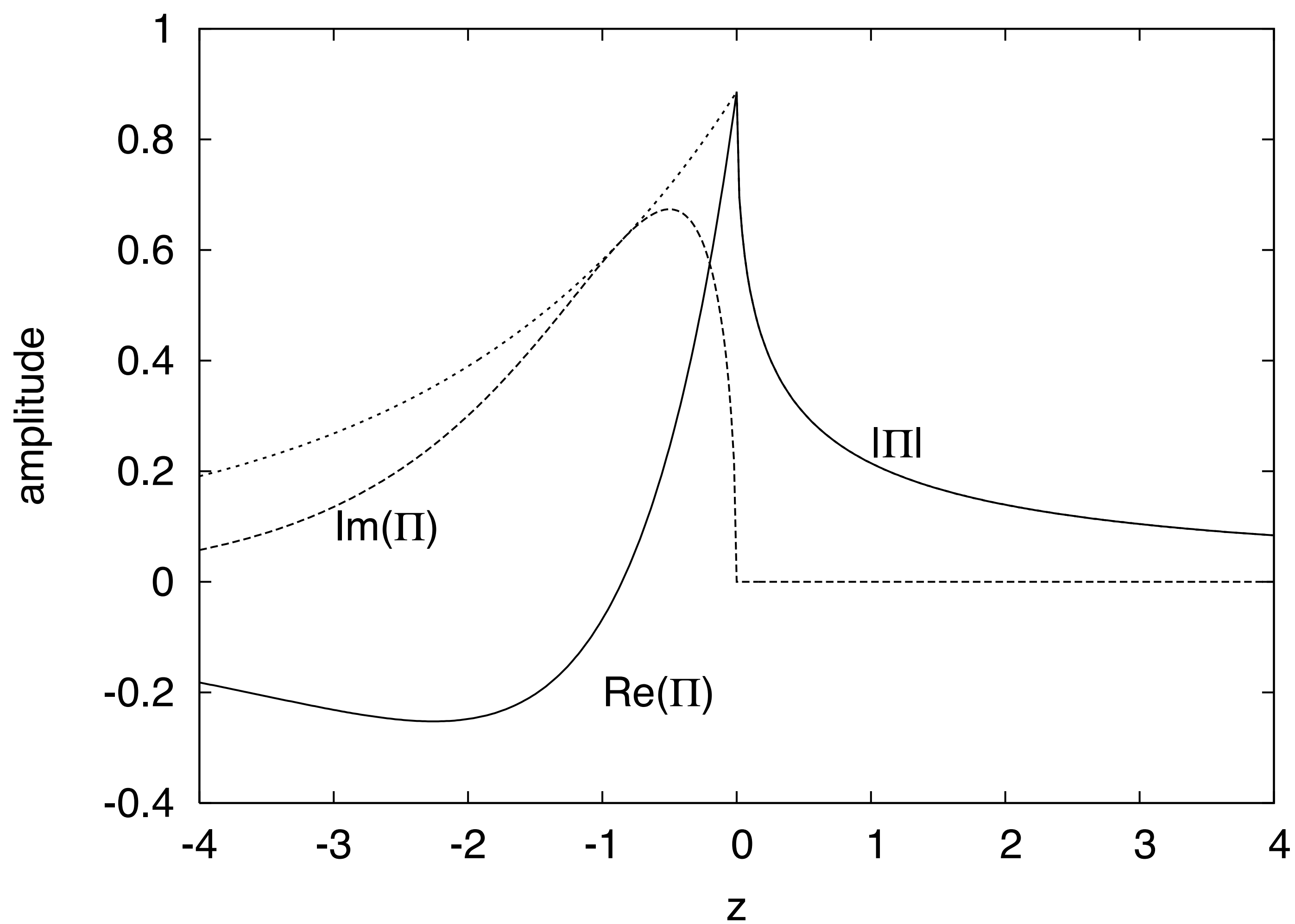
E.P. Wigner, Phys. Rev. 73 (1948) 1002

D. V. Bugg, Europhys. Lett. 96, 11002 (2011)

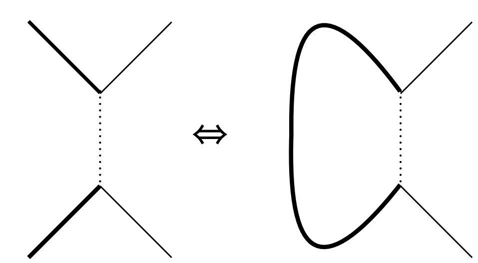
D. V. Bugg, Int. J. Mod. Phys. A 24, 394 (2009)

E.S. Swanson, arXiv:1409.3291

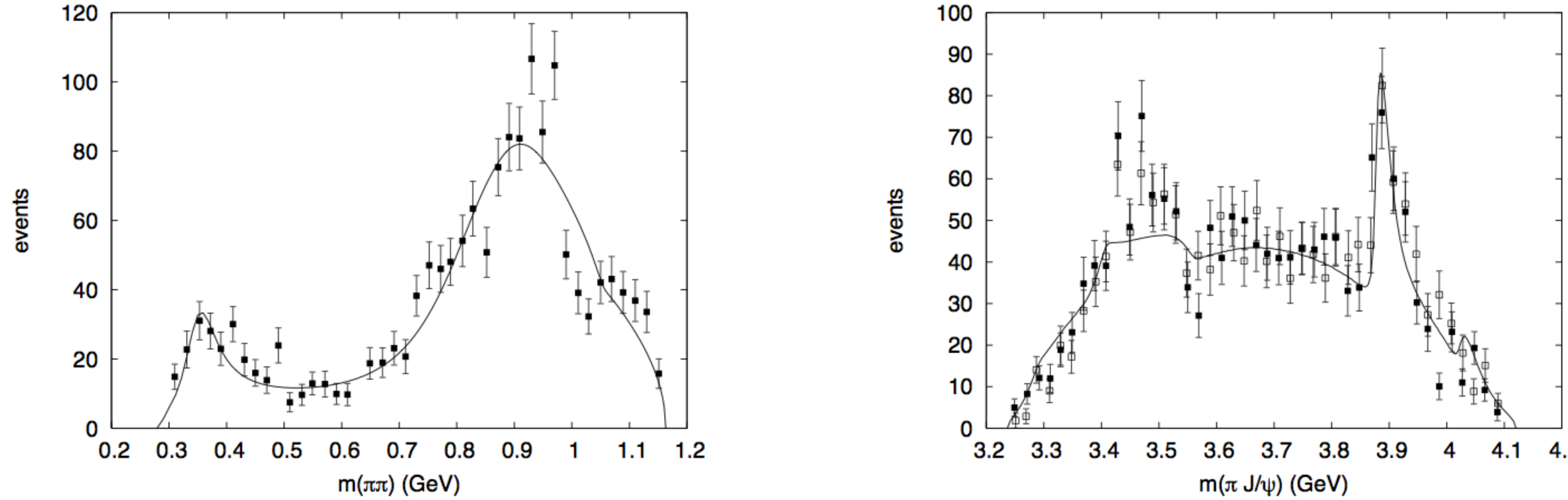




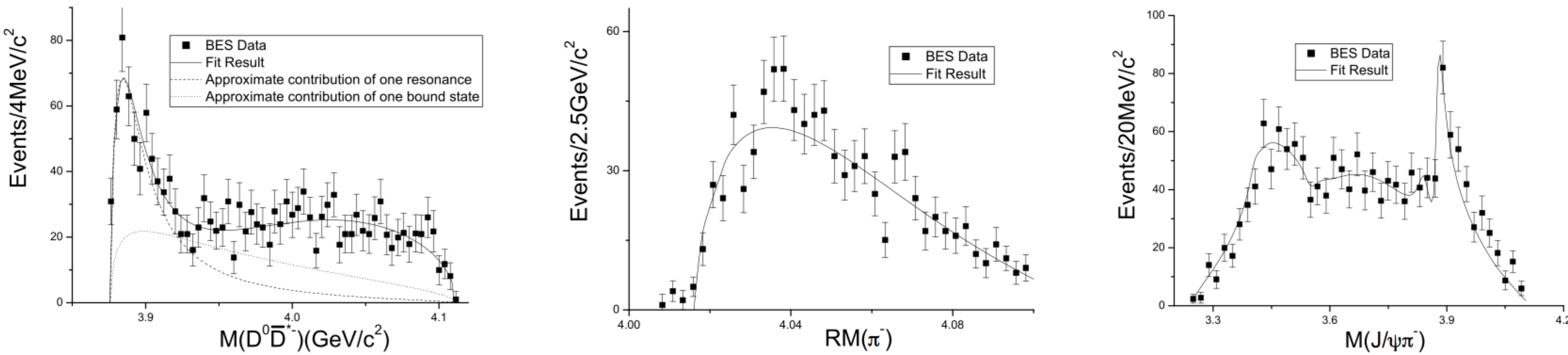
and are related to thresholds



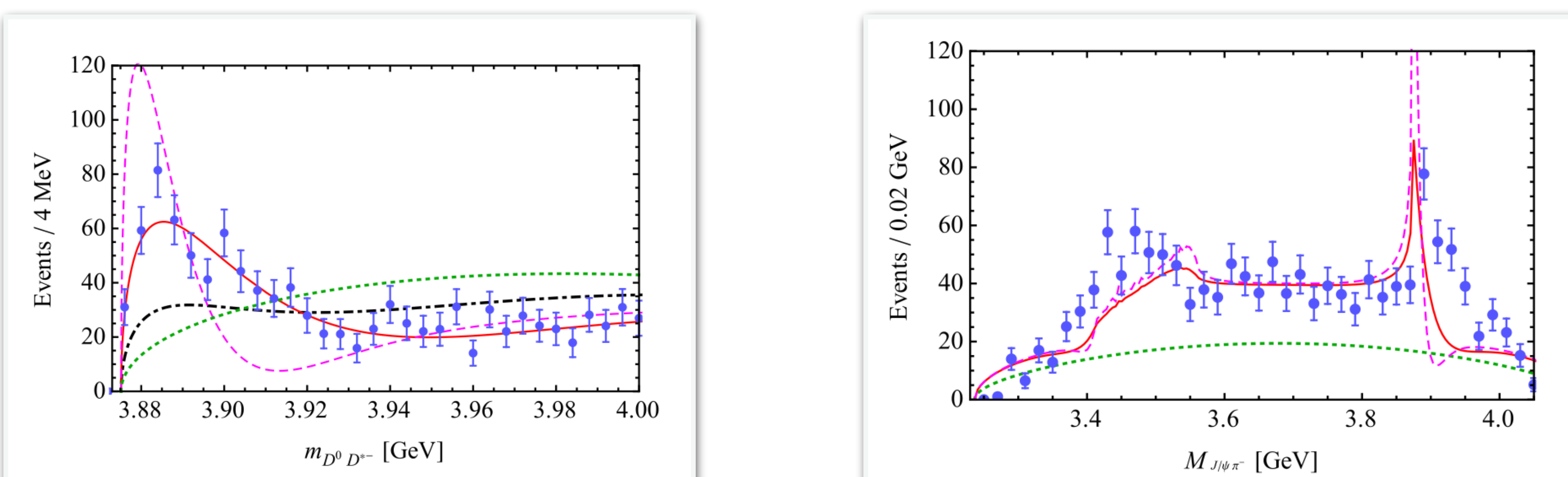
Cusps: Zc(3900)



E.S. Swanson, ``Cusps and Exotic Charmonia,'' arXiv:1504.07952 [hep-ph].



Z.Y. Zhou and Z. Xiao, ``Distinguishing cusp effects and near-threshold-pole effects,'' arXiv:1505.05761 [hep-ph].



F.K. Guo, C. Hanhart, Q. Wang and Q. Zhao, `Could the near-threshold XYZ states be simply kinematic effects?,'' Phys. Rev. D {91}, no. 5, 051504 (2015)

$Z_b^+(10610)$ $Z_b^+(10650)$

Adachi et al. [Belle] 1105.4583

$$I^G J^P = 1^+ 1^+$$

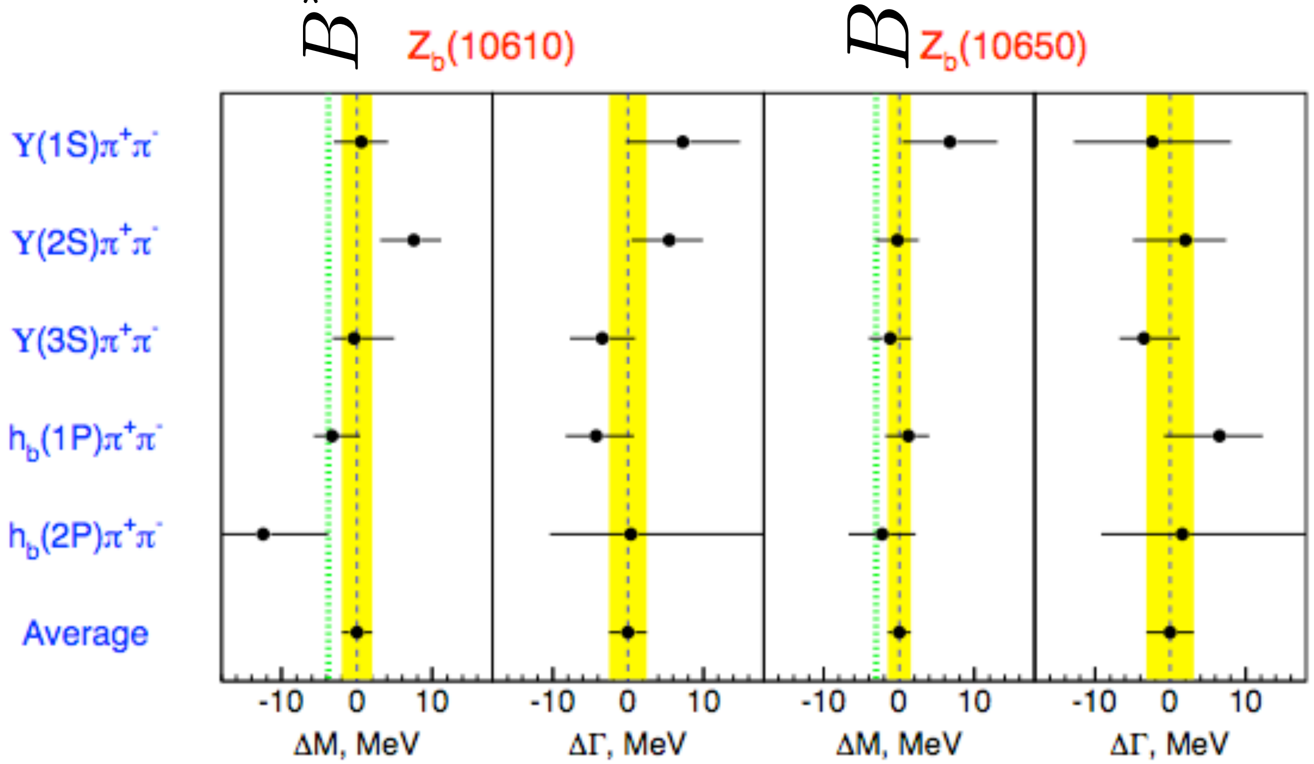
1+1+ B*B* is 5D1 and mildly attractive so likely a channel opening effect

isovector 1++ BB* is repulsive

note that both states are above threshold

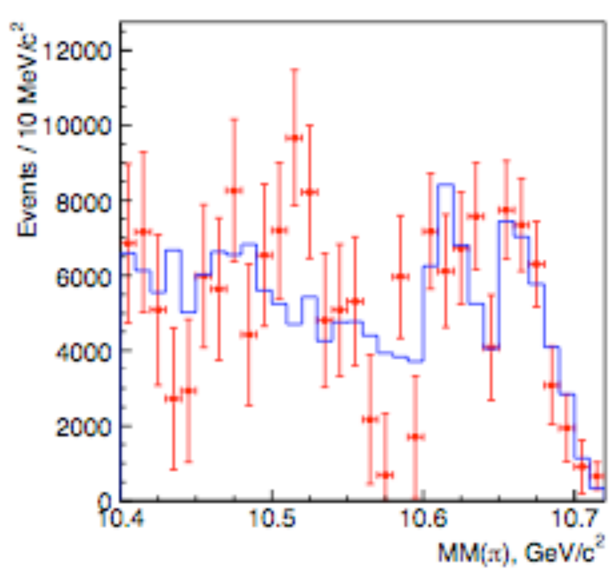
narrow (15 MeV)

$B^*\bar{B}$ $B^*\bar{B}^*$

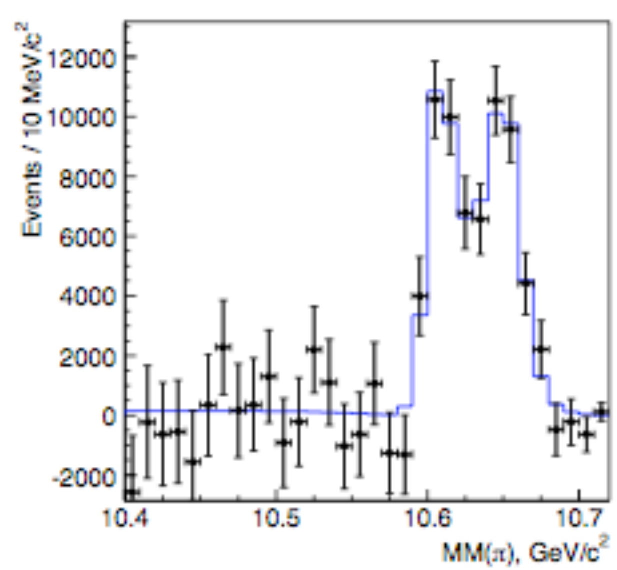


$$\Upsilon(5S) \to \pi\pi\Upsilon(nS)$$

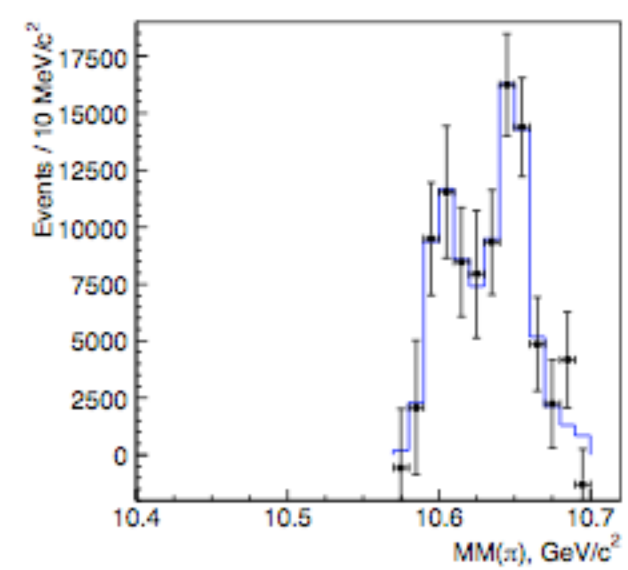
$\Upsilon(2S)$



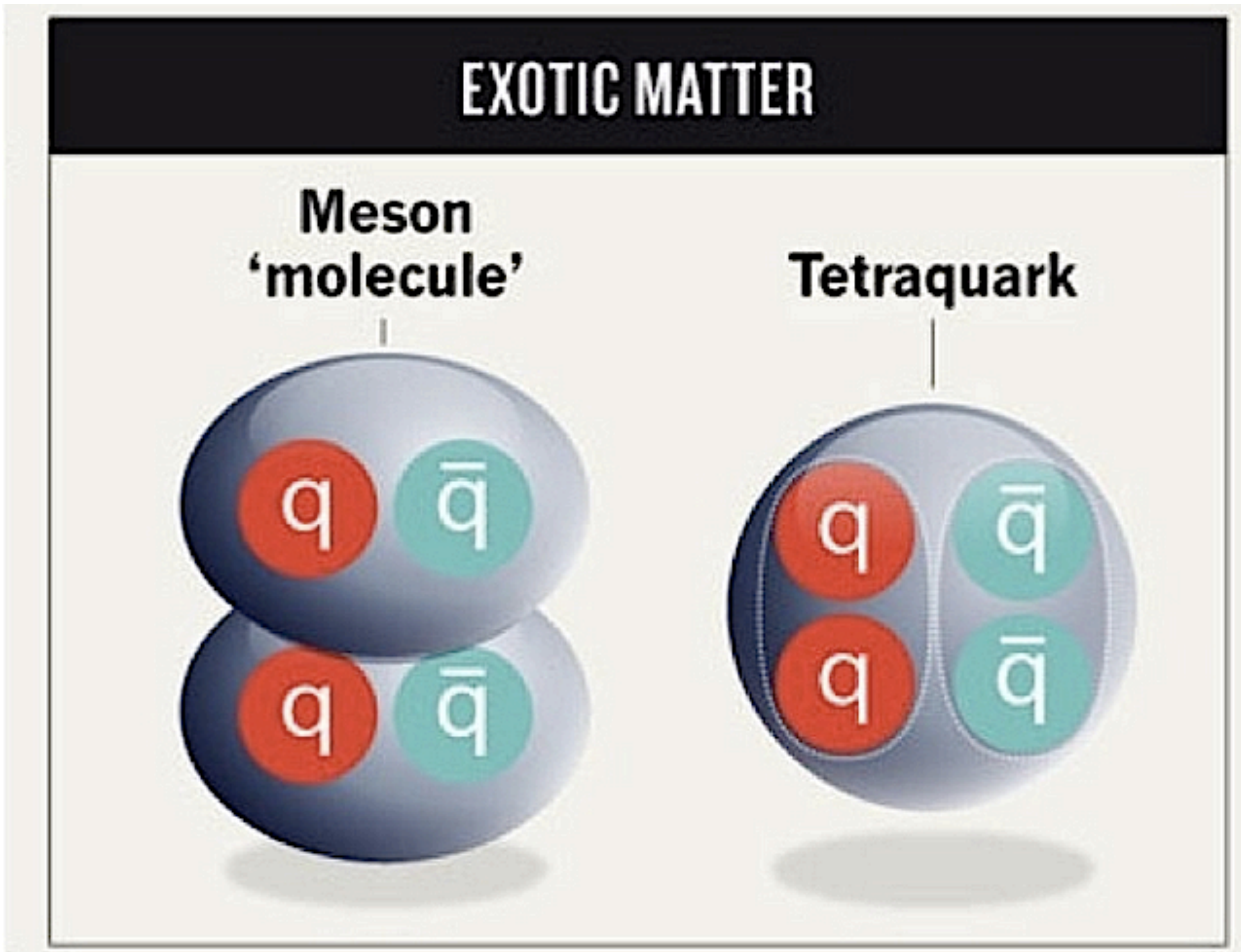
$h_b(1P)$



$h_b(2P)$



Multiquarks



Multiquarks

$\pi\pi J/\psi$
$\pi D\bar{D}^*$

$Z_c(3900)$

$\pi\pi h_c$
$\pi D^*\bar{D}^*$

$Z_c(4025)$

$K\pi\chi_{cJ}$
$\pi\psi(2S)$

$Z_1(4050)$
$Z_2(4250)$

$K\pi J/\psi$

$Z_c(4200)$

$\pi K\psi'$

$Z_c(4240)$
$Z_c(4475)$

$\pi\pi\Upsilon(nS)$
$\pi\pi h_b(nP)$
$\pi B\bar{B}^*$

$Z_b(10610)$
$Z_b(10650)$

~~Multiquarks~~ → Multielectrons

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma_\mu D^\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \rightarrow$$

$$[\frac{1}{2}(\nabla_1^2 + \nabla_2^2 + \nabla_3^2 + \nabla_4^2) + \frac{E}{4} + V]\Psi = 0$$

$$V = \frac{1}{r_{1a}} + \frac{1}{r_{2b}} + \frac{1}{r_{1b}} + \frac{1}{r_{2a}} - \frac{1}{r_{12}} - \frac{1}{r_{ab}}$$

~~Multiquarks~~ → Multielectrons

Four-electron States

1946: Wheeler suggests that Ps_2 might be bound

Wheeler, J. A. Polyelectrons. Ann. NY Acad. Sci. 48, 219–238 (1946).

1946: Ore proves it is unbound

1947: Hylleraas & Ore prove it is bound

Hylleraas, E. A. & Ore, A. Binding energy of the positronium molecule. Phys. Rev.71, 493–496 (1947).

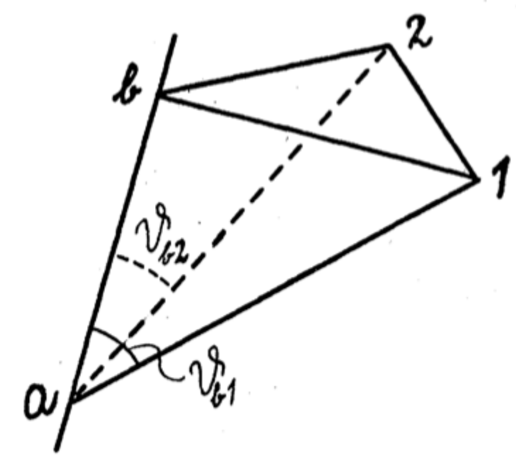


FIG. 1. Coordinate system for the positronium molecule.

2007: Ps_2 is observed

Cassidy, D.B.; Mills, A.P. (Jr.) (2007). "The production of molecular positronium". Nature 449 (7159): 195–197

Multiquarks

$$\mathcal{L}_{QCD} = \bar{\psi}_i (i\gamma_\mu D^\mu_{ij} - m\,\delta_{ij})\psi_j - \frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a \rightarrow$$

Multiquarks

$$\mathcal{L}_{QCD} = \bar{\psi}_i(i\gamma_\mu D^\mu_{ij} - m\,\delta_{ij})\psi_j - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a \rightarrow$$

Multiquarks

gluonics

hybrids
glueballs
strong decays

vacuum structure

chiral symmetry breaking
confinement
instantons/vortices/
monopoles

short range interactions

gluon exchange
pion exchange
instantons
coupled channels

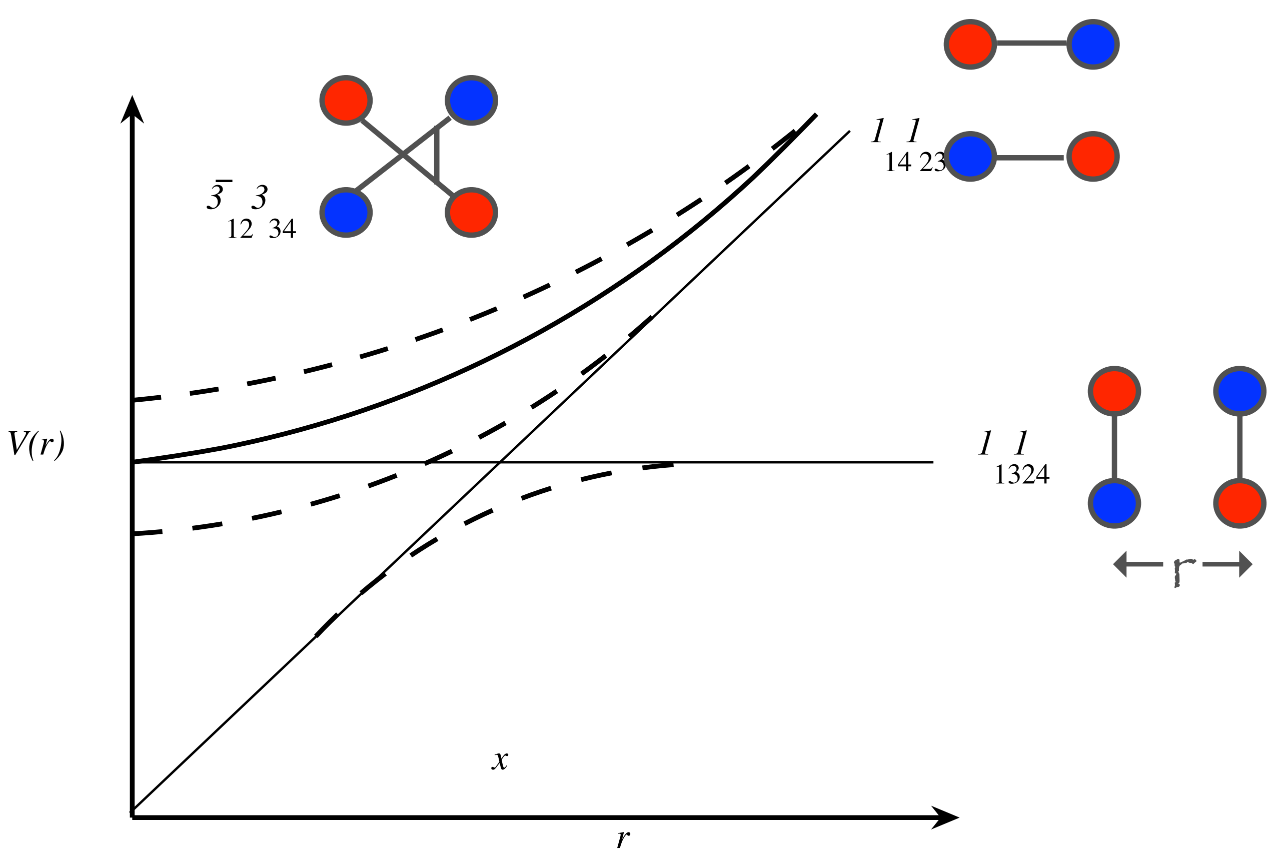
long range interactions

pomeron exchange
pion exchange
gluonic multipoles
coupled channels
confinement
emergence of nuclear physics

Multiquarks

for the first time, the colour structure becomes important.

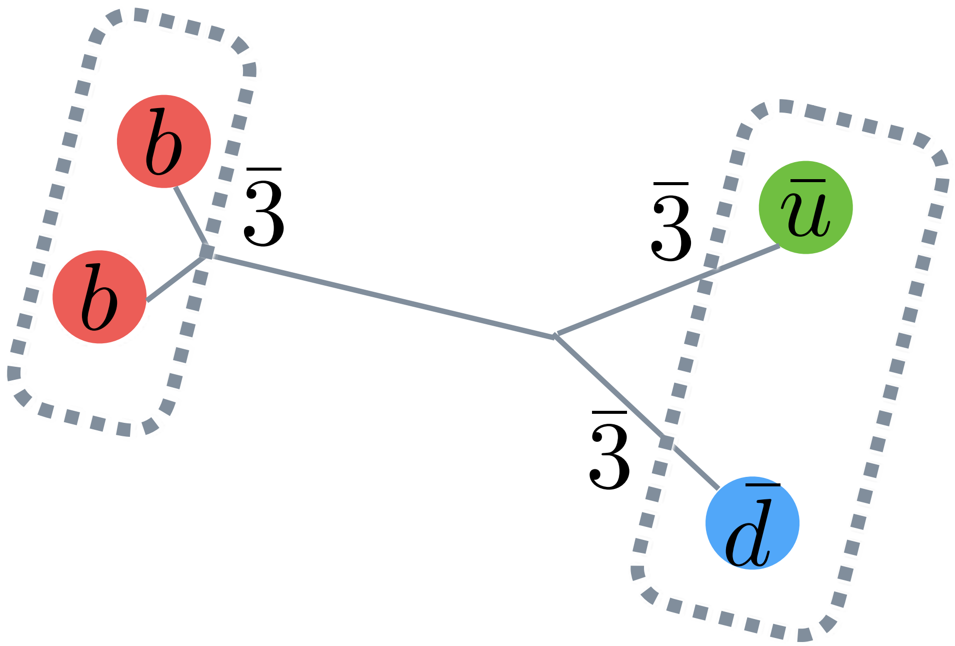
ex:



Multiquarks

Xi_{cc} & bb Tetraquarks

Marek Karliner and Jonathan L. Rosner arXiv:1707.07666



In QCD the attractive nature of the color Coulomb potential for two antiquarks in a 3c color configuration ensures the existence of strong-interaction-stable qq0Q¯ Q¯ exotics in the limit mQ → ∞
Marek and Karliner assume both pairs form diquarks, so the analogue is ~Qq. This is not necessary, just need ~Q~q~q.

Discovery of doubly-charmed Ξ_{CC} baryon implies a stable $bb\bar{u}\bar{d}$ tetraquark $J^P = 1^+$

Assume colour/space factorize (as in weak coupling) so QQ interaction strength is 1/2 QQ~ . Take (ud) w/ I=0 S=0

Multiquarks

Ξ_{cc} & bb Tetraquarks

Marek Karliner and Jonathan L. Rosner arXiv:1707.07666

State (mass in MeV)	Spin	Expression for mass [24]	Predicted mass (MeV)
$N(939)$	$1/2$	$3m_q^b - 3a/(m_q^b)^2$	939
$\Delta(1232)$	$3/2$	$3m_q^b + 3a/(m_q^b)^2$	1239
$\Lambda(1116)$	$1/2$	$2m_q^b + m_s^b - 3a/(m_q^b)^2$	1114
$\Sigma(1193)$	$1/2$	$2m_q^b + m_s^b + a/(m_q^b)^2 - 4a/m_q^b m_s^b$	1179
$\Sigma(1385)$	$3/2$	$2m_q^b + m_s^b + a/(m_q^b)^2 + 2a/m_q^b m_s^b$	1381
$\Xi(1318)$	$1/2$	$2m_s^b + m_q^b + a/(m_s^b)^2 - 4a/m_q^b m_s^b$	1327
$\Xi(1530)$	$3/2$	$2m_s^b + m_q^b + a/(m_s^b)^2 + 2a/m_q^b m_s^b$	1529
$\Omega(1672)$	$3/2$	$3m_s^b + 3a/(m_s^b)^2$	1682

- Predict a stable $bb\bar{u}\bar{d}$ 1+ state at 10389, 215 MeV below BB* and 170 MeV below BBγ
- $bc\bar{u}\bar{d}$ might be below threshold too
- Electroweak decay modes, eg $(bb\bar{u}\bar{d}) \rightarrow \bar{B}D\pi^+$

Multiquarks

Diquarks and the New Charmonia

Maiani, Piccinini,Polosa, Riquer; PRD71, 014028 (2005)

Bigi, Maiani, Piccinini,Polosa, Riquer; PRD72, 114016 (2005)

Maiani, Riquer, Piccinini, Polosa; PRD72, 031502 (2005)

Maiani, Polosa, Riquer; PRL99, 182003 (2007)

Maiani, Polosa, Riquer; arXiv:0708.3997

$$M([cq]_S) = 1933$$
$$M([cq]_V) = 1933$$

Assume a spin-spin interaction

$$|0^{++}\rangle = |[cq]_S[\bar{c}\bar{q}]_S; J=0\rangle \quad (1)$$

$$|0^{++\prime}\rangle = |[cq]_V[\bar{c}\bar{q}]_V; J=0\rangle \quad (2)$$

$$|1^{++}\rangle = \frac{1}{\sqrt{2}}\left(|[cq]_S[\bar{c}\bar{q}]_V; J=1\rangle + |[cq]_V[\bar{c}\bar{q}]_S; J=1\rangle\right) \quad (3)$$

$$|1^{+-}\rangle = \frac{1}{\sqrt{2}}\left(|[cq]_S[\bar{c}\bar{q}]_V; J=1\rangle - |[cq]_V[\bar{c}\bar{q}]_S; J=1\rangle\right) \quad (4)$$

$$|1^{+-\prime}\rangle = |[cq]_V[\bar{c}\bar{q}]_V; J=1\rangle \quad (5)$$

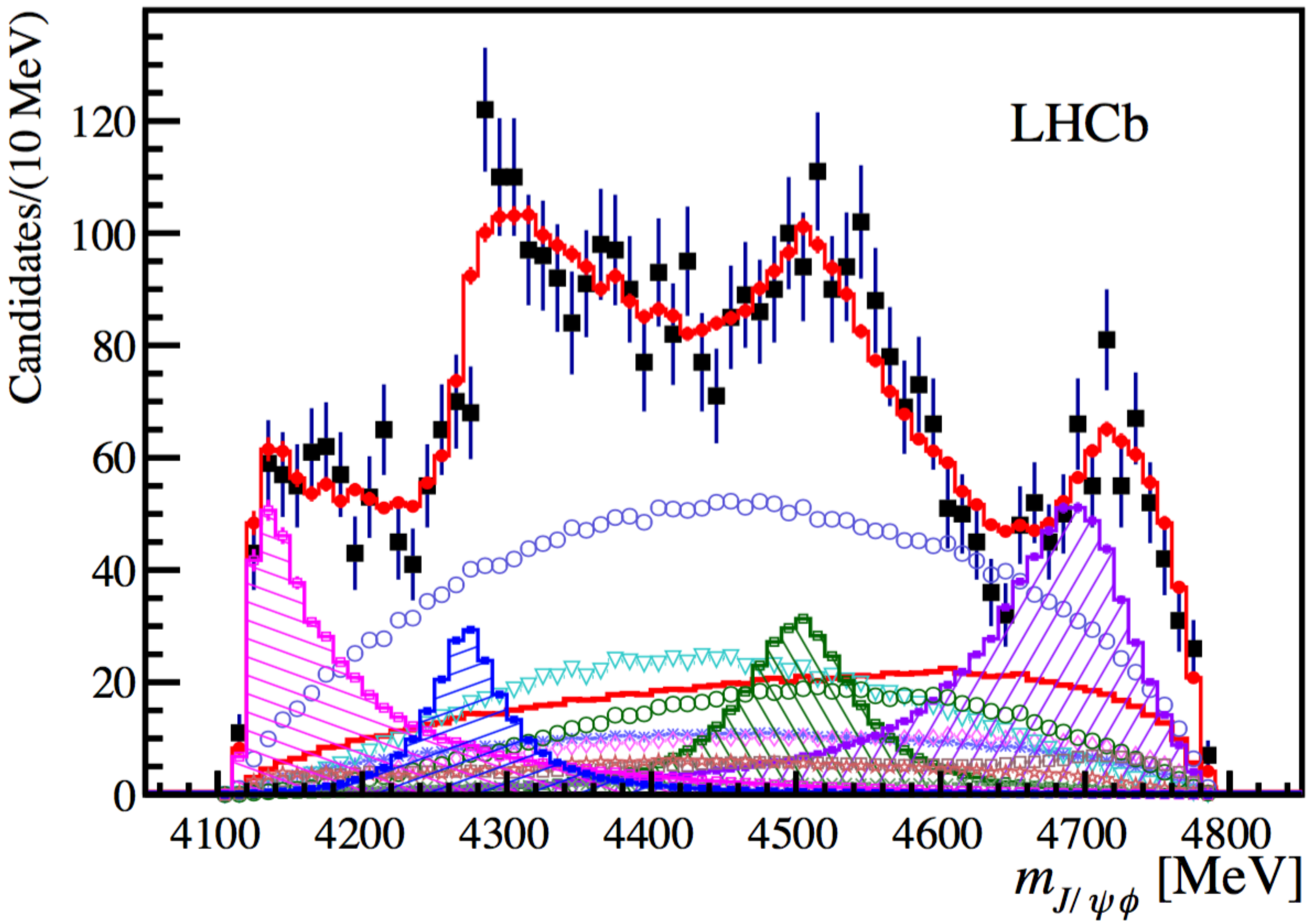
$$|2^{++}\rangle = |[cq]_V[\bar{c}\bar{q}]_V; J=2\rangle \quad (6)$$

Multiquarks

arXiv:1606.07895v1

$B \to K J/\psi \phi$

LHCb Tetraquarks



State	Mass (unct.) [MeV]	Width (unct.) [MeV]	J^{PC}
$Y(4140)$	4165.5(5,3)	83(21,16)	1^{++}
$Y(4274)$	4273.3(8,11)	56(11,10)	1^{++}
$X(4500)$	4506(11,13)	92(21,21)	0^{++}
$X(4700)$	4704(10,19)	120(31,35)	0^{++}

Multiquarks

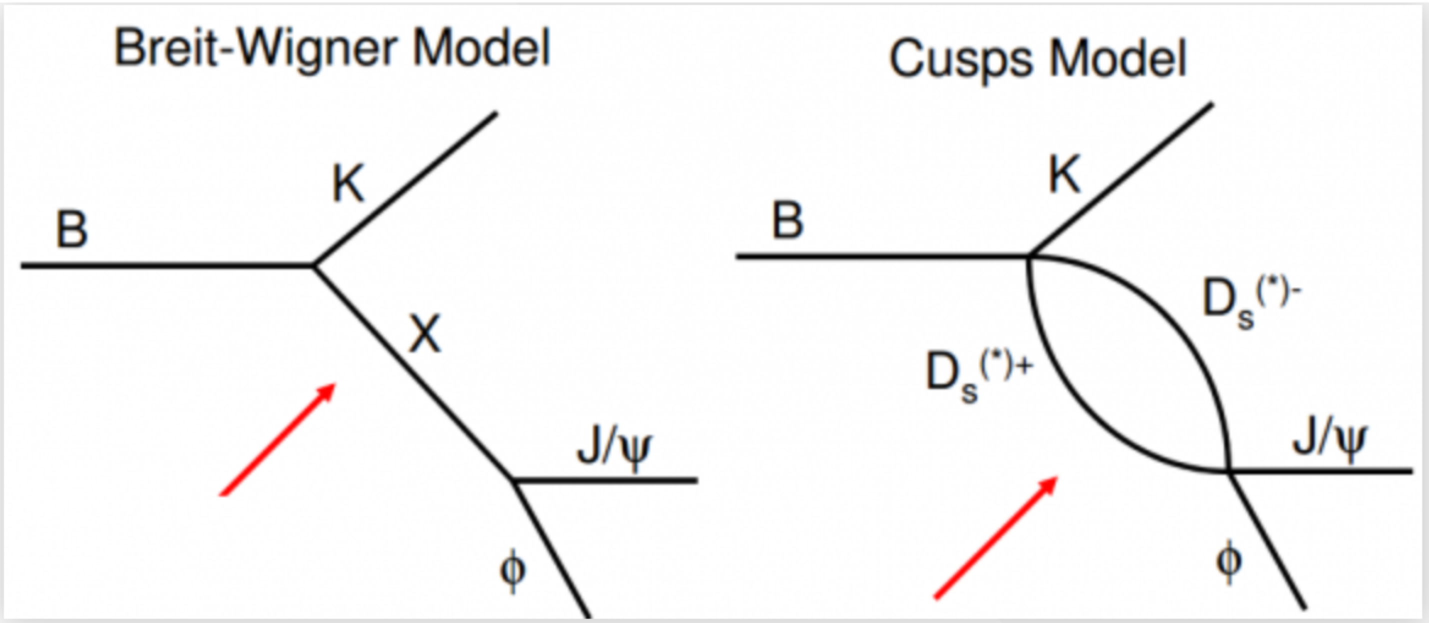
arXiv:1606.07895v1

PHYSICAL REVIEW D 91, 034009 (2015)

LHCb Tetraquarks

(v) similarly, $\bar{B}_s \to J/\psi\varphi\varphi$ and $\bar{B}_0 \to J/\psi\varphi K$ should exhibit cusp effects at $D_s\bar{D}_s^*$ and $D_s^*\bar{D}_s^*$ thresholds, while $\bar{B}_0 \to J/\psi\eta K$ will display $D\bar{D}^*$, $D^*\bar{D}^*$, $D_s\bar{D}_s^*$, and $D_s^*\bar{D}_s^*$ cusp enhancements;

http://francis.naukas.com/2016/06/04/tetraquarks-pentaquarks-observados-lhcb/



Sobre todo desde que se publicó el modelo tipo cusp Ds^+Ds^* para estos tetraquarks (E.S. Swanson, "Cusps and Exotic Charmonia," arXiv:1504.07952 [hep-ph]). Estos modelos

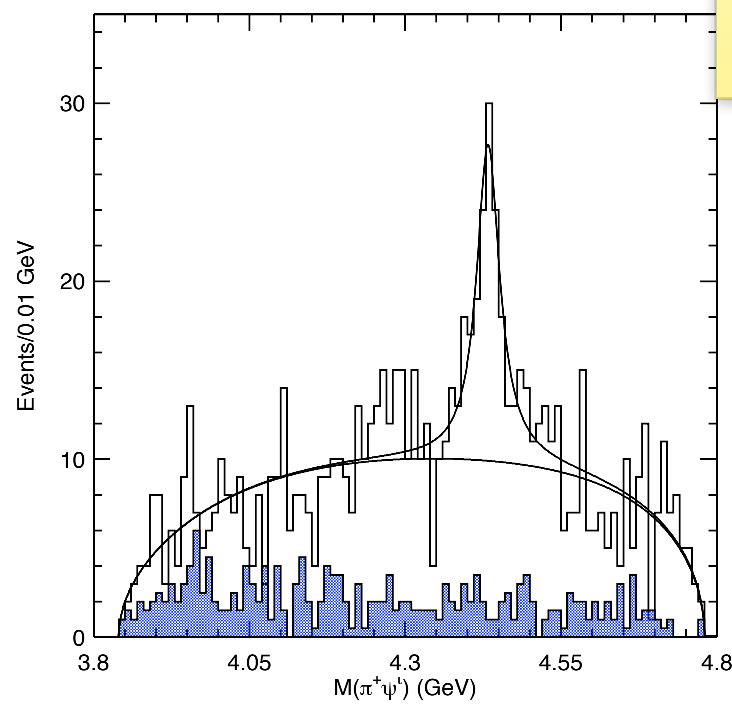
Multiquarks

D*D1(2420) threshold effect
D*D1(2420) molecule (JP = (2,1,0)-)
[cu][cd] tetraquark radial excitation (JP=1+)

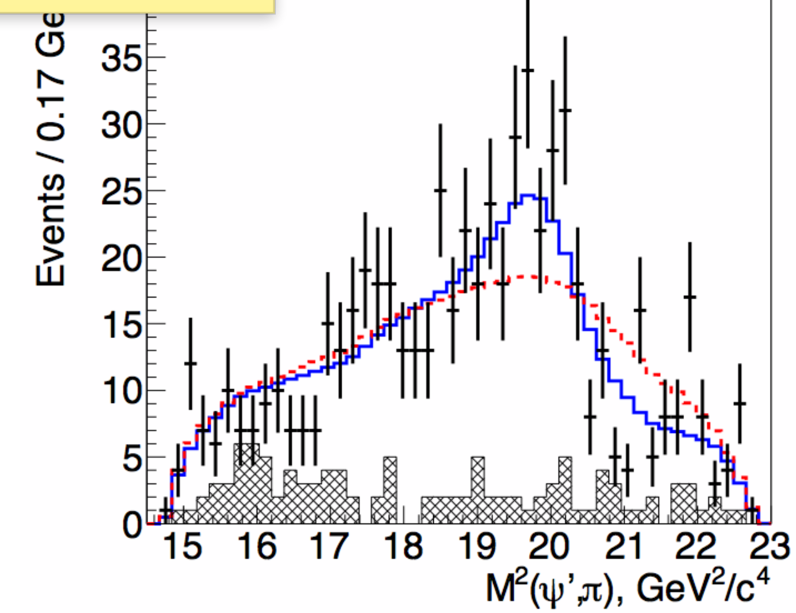
$$Z^+(4430)$$

$$B \to K\pi^\pm\psi'$$

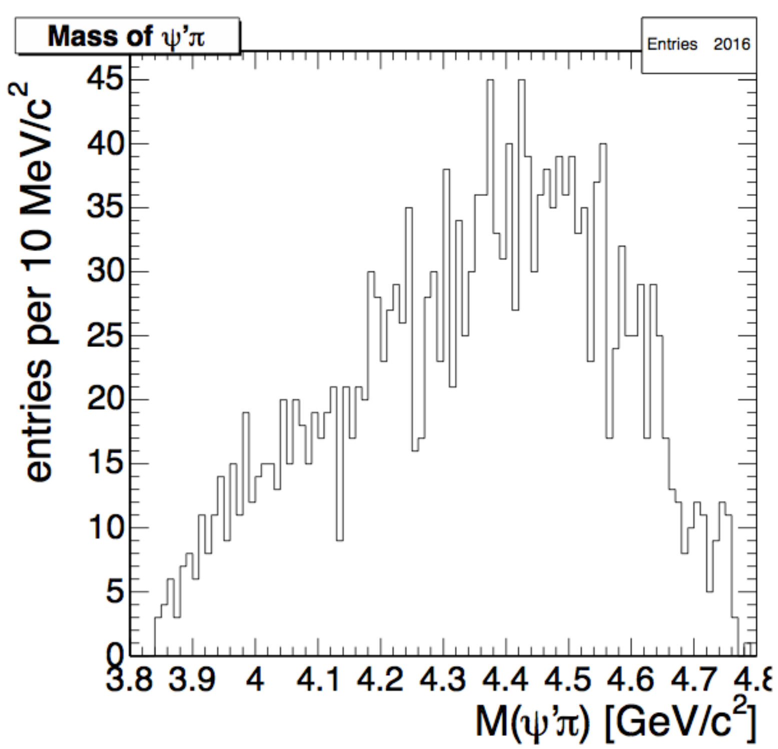
$$J^P = 1^+$$



Belle original

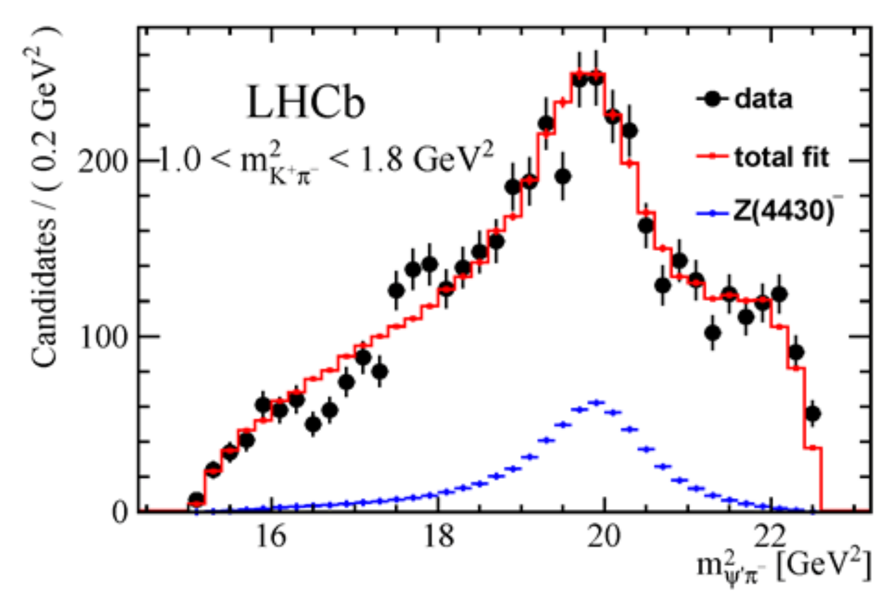


Belle re-analysis
1306.4894



F. Rubbo, Torino thesis

CDF

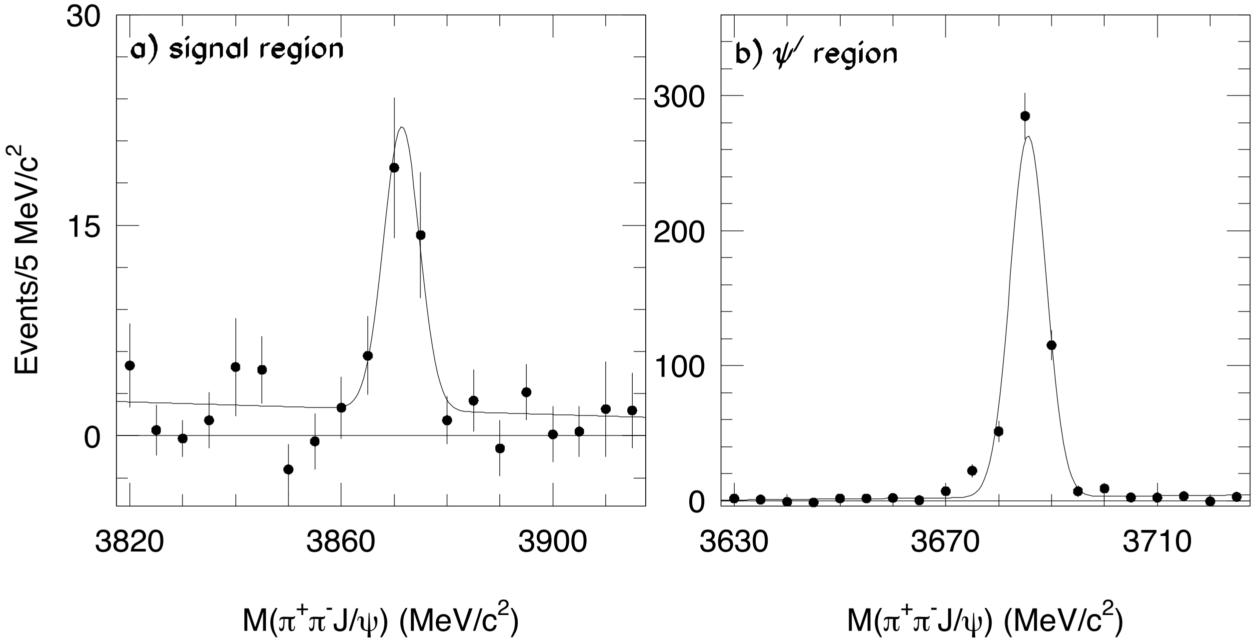


LHCb

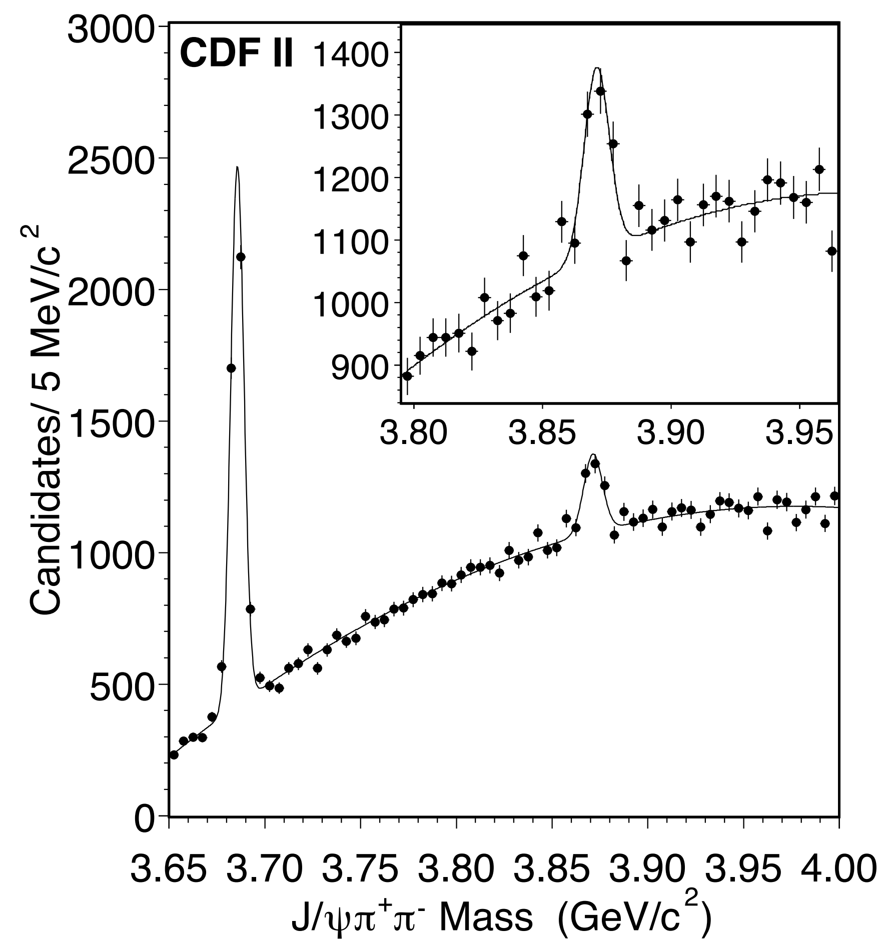
Multiquarks

X(3872)

$$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-} J/\psi$$



S.-K. Choi (Belle), hep-ex/0309032



D. Acosta (CDF) hep-ex/0312021

B. Aubert (Babar) hep-ex/0402025

Multiquarks

X(3872)

Tom LeCompte,
Northwestern thesis
E705 at FNAL
1992

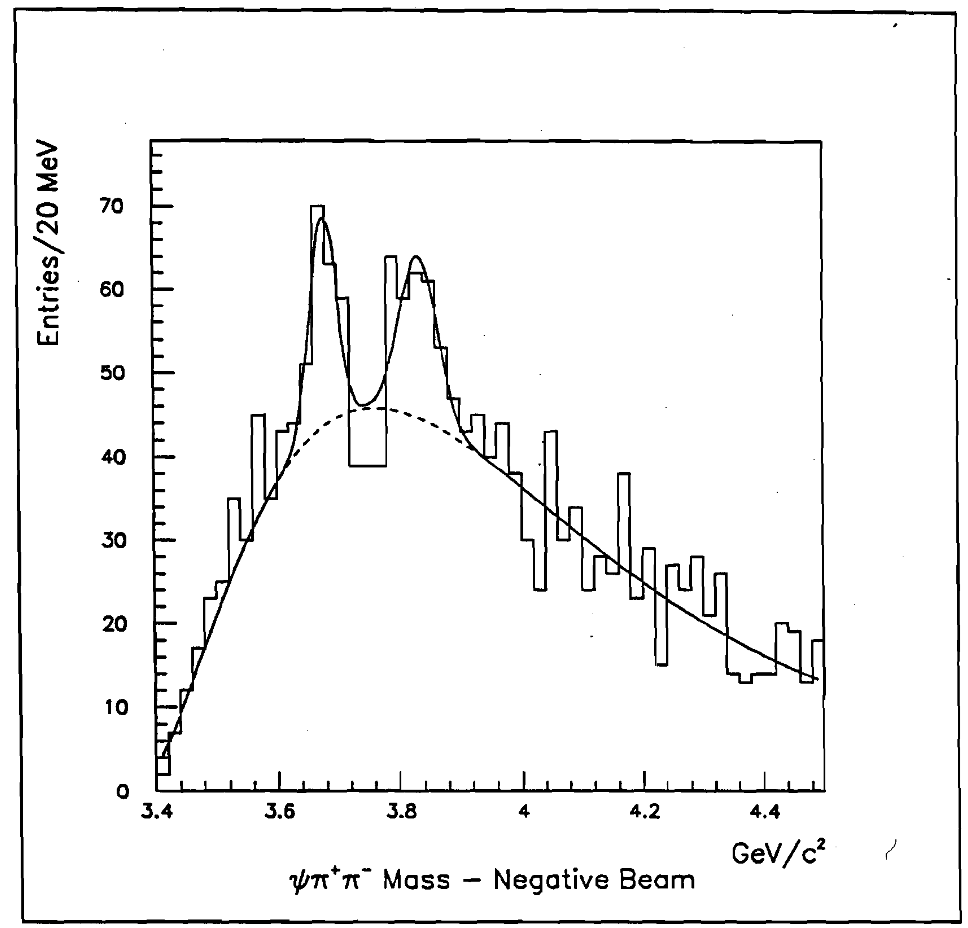


Figure 6.12 ψππ mass spectrum, standard cuts, negative beam.

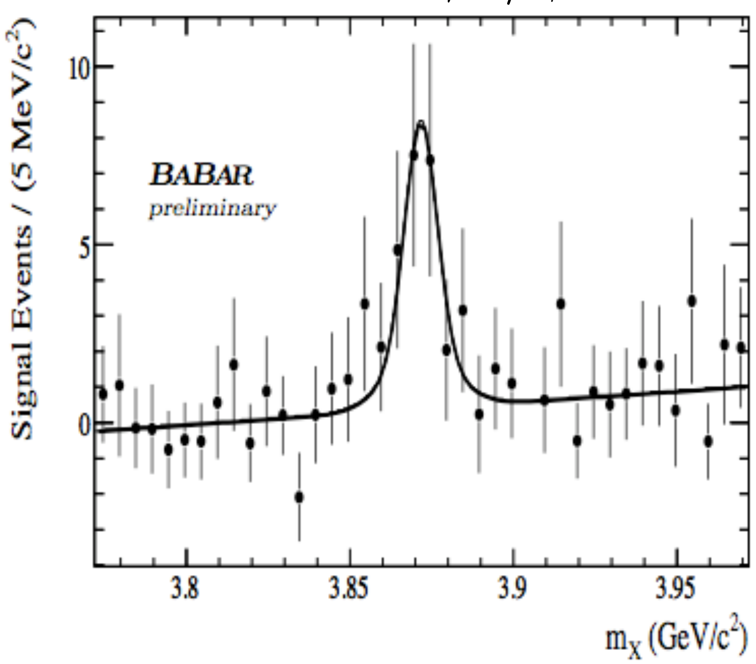
A single peak above background does not fit the observed signal well. A second peak above the ψ' was added to the fit to improve this. The fit parameters are shown on the following page:

E-705

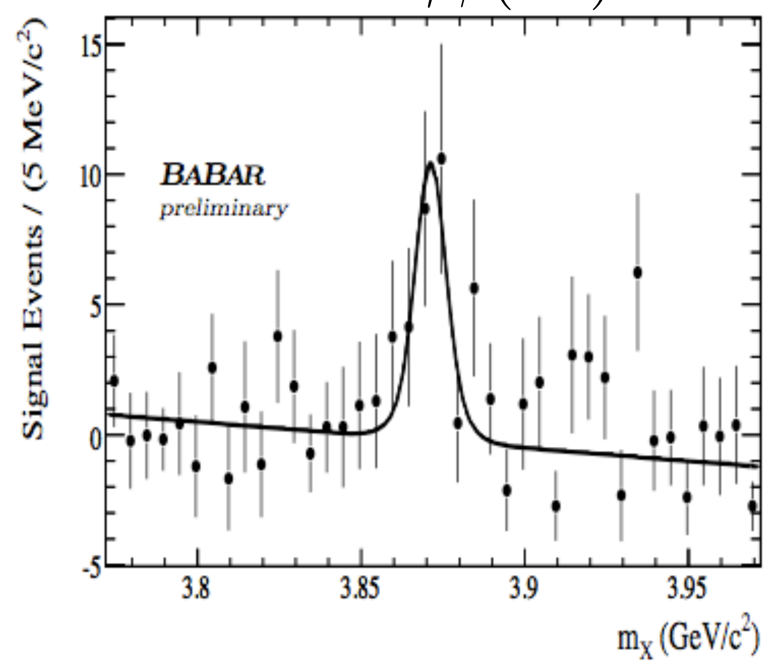
Multiquarks

X(3872)

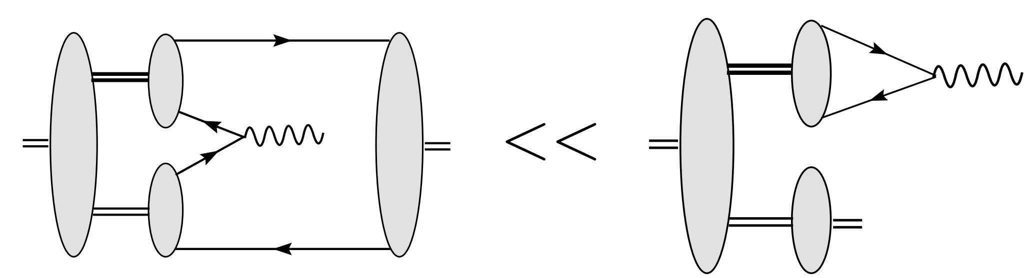
$X \to \gamma J/\psi$



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

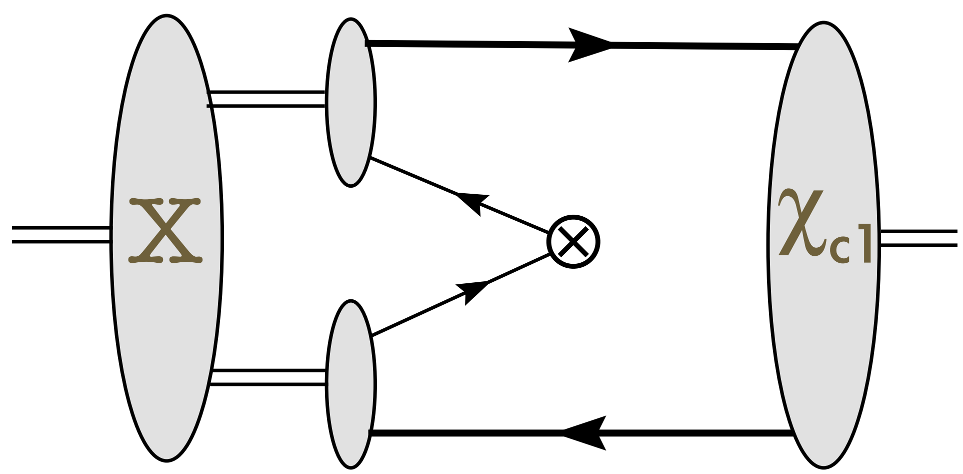


$$\frac{Bf(X \to \gamma\psi(2S))}{Bf(X \to \gamma J/\psi)} = 3.5(1.0)$$



Multiquarks

X(3872)

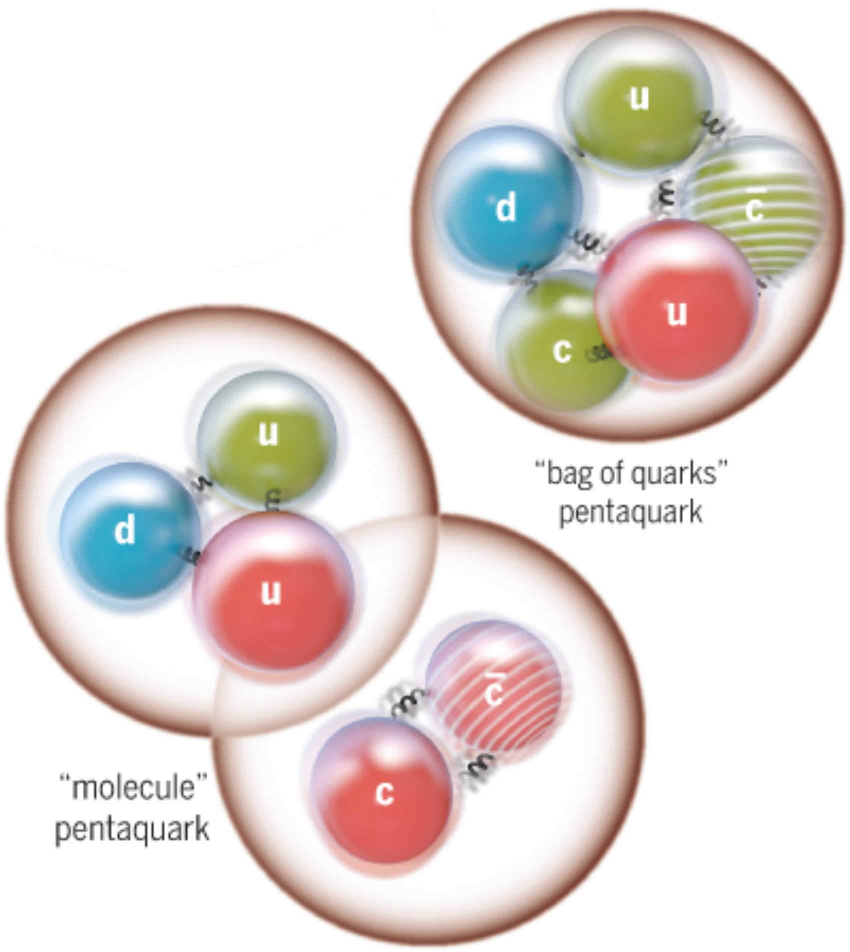


$$a_\chi = \sqrt{2} Z_{00}^{1/2} \int d^3k\, \psi_X(k) \mathcal{A}(-k)$$

state	E_B (MeV)	a (fm)	Z_{00}	a_χ (MeV)	prob
χ_{c1}	0.1	14.4	93%	94	5%
	0.5	6.4	83%	120	10%
χ'_{c1}	0.1	14.4	93%	60	100%
	0.5	6.4	83%	80	$>$ 100%

Multiquarks

Pentaquarks



Multiquarks

Pentaquarks

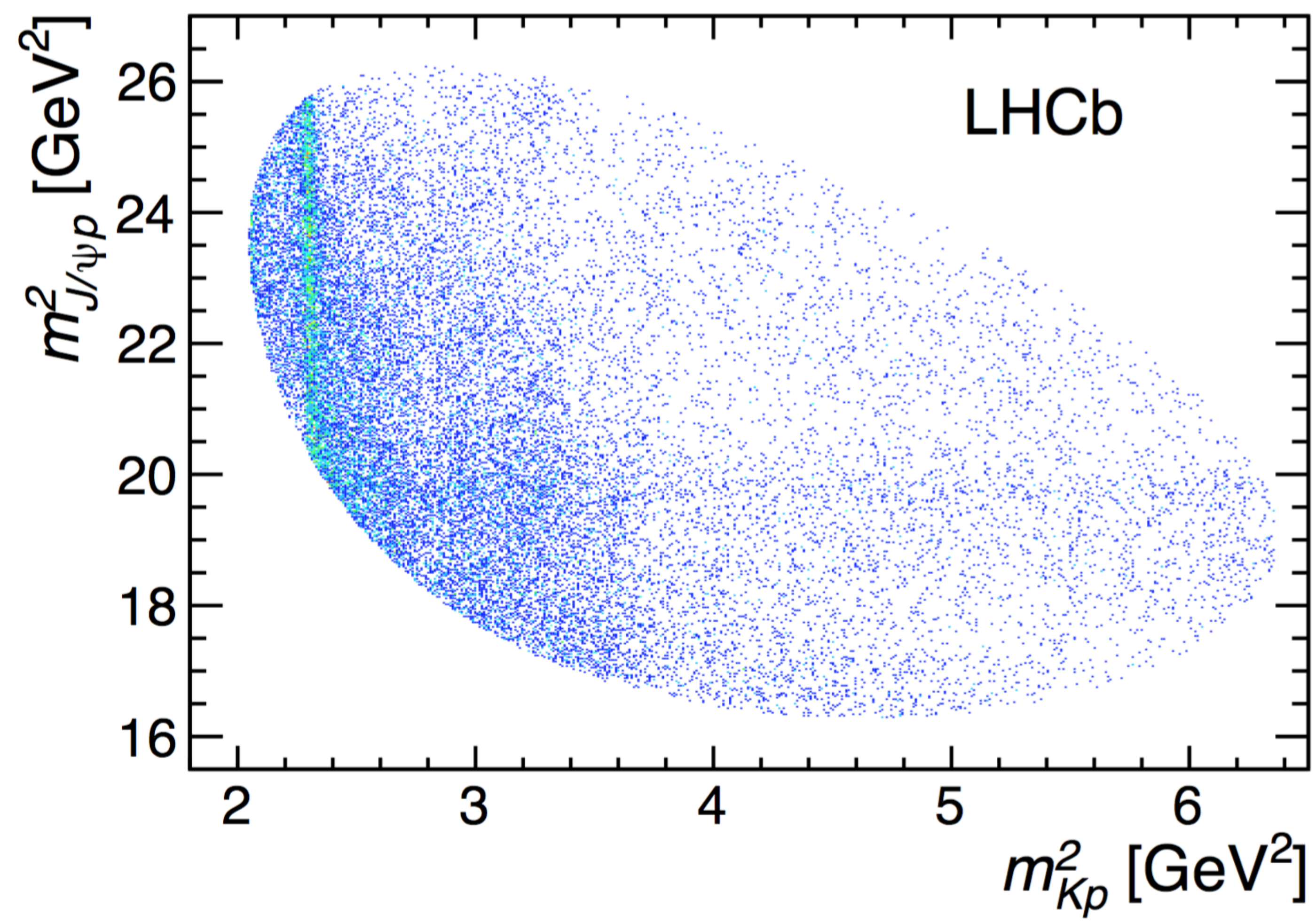
$P_c(4450) \quad \Gamma = 39 \pm 5 \pm 19 \text{ MeV}$

$P_c(4380) \quad \Gamma = 205 \pm 18 \pm 86 \text{ MeV}$

$$J^P = \frac{5}{2}^{\mp}$$

$$J^P = \frac{3}{2}^{\pm}$$

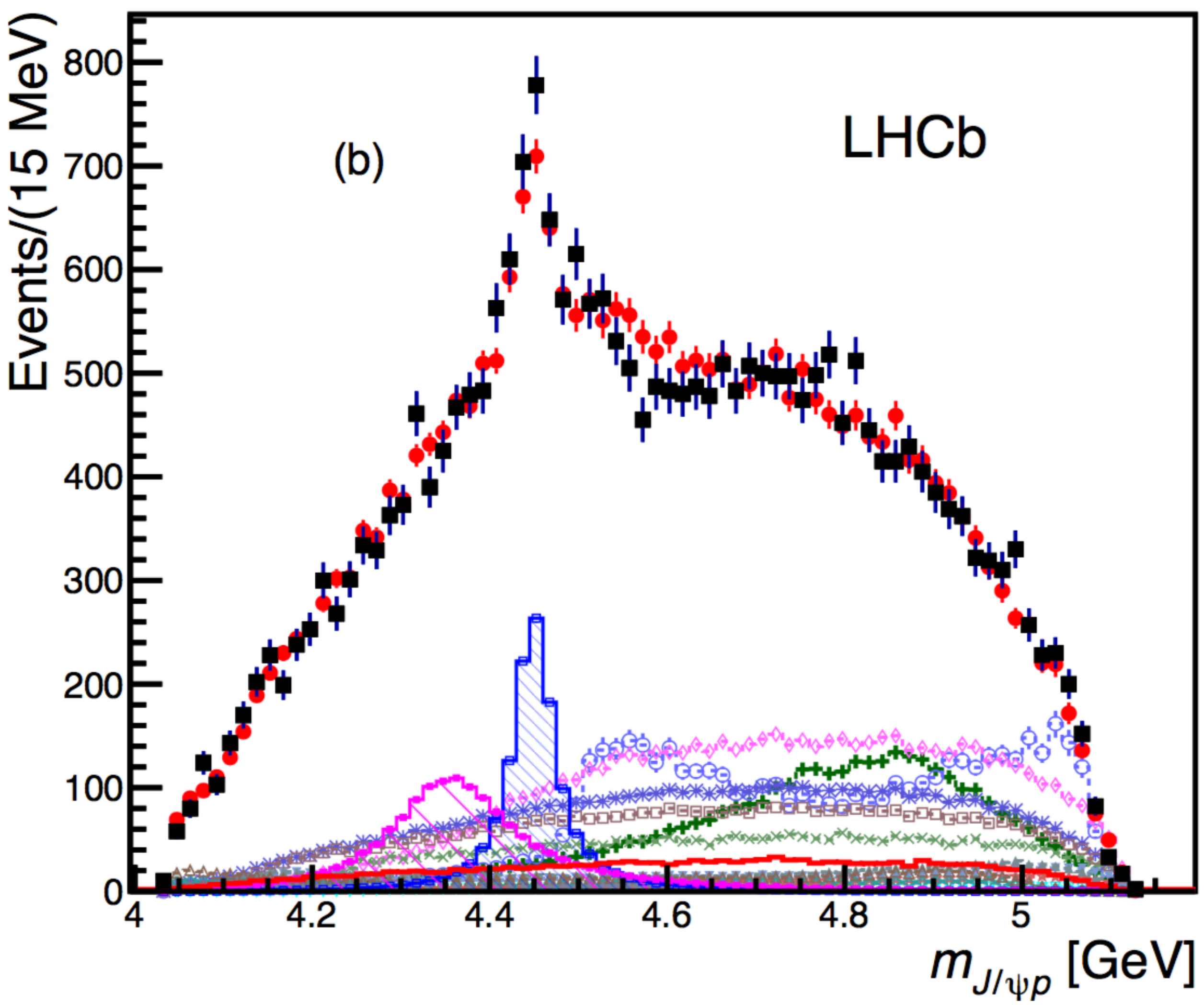
$\Lambda_b^0 \to J/\psi K^- p$



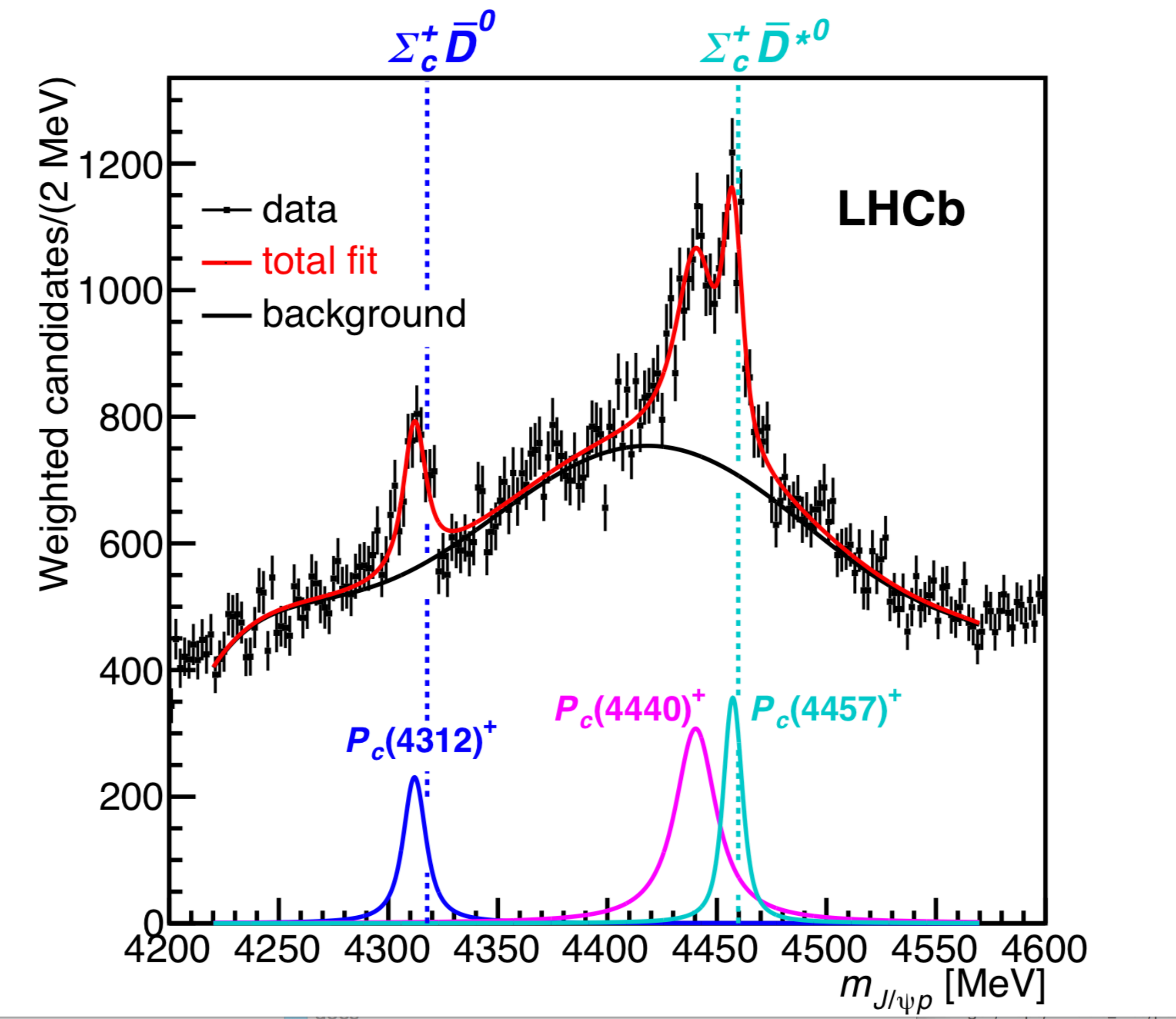
LHCb 1507.03414v2

Multiquarks

Pentaquarks



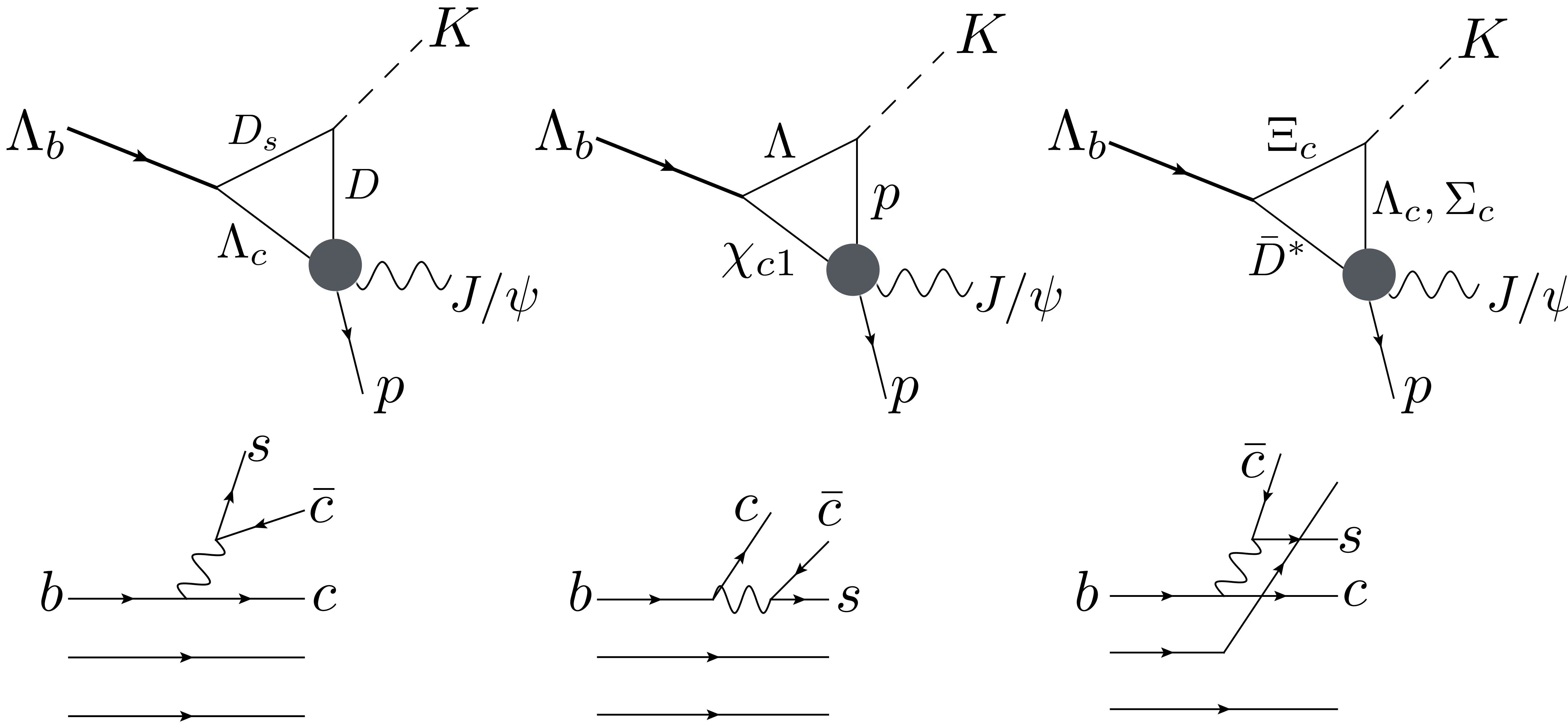
arXiv:1507.03414



arXiv:1904.03947

Multiquarks

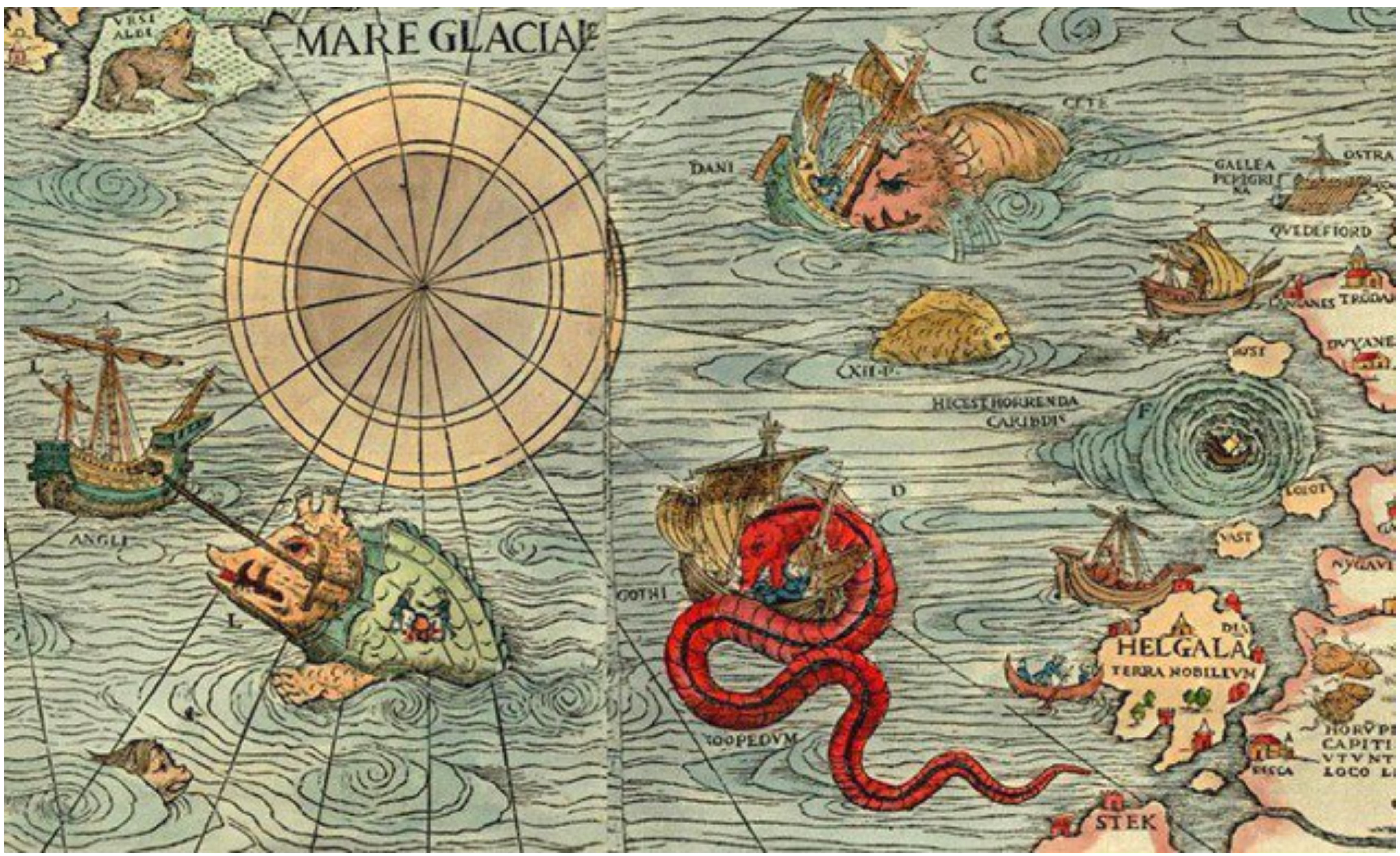
Pentaquarks



1/N

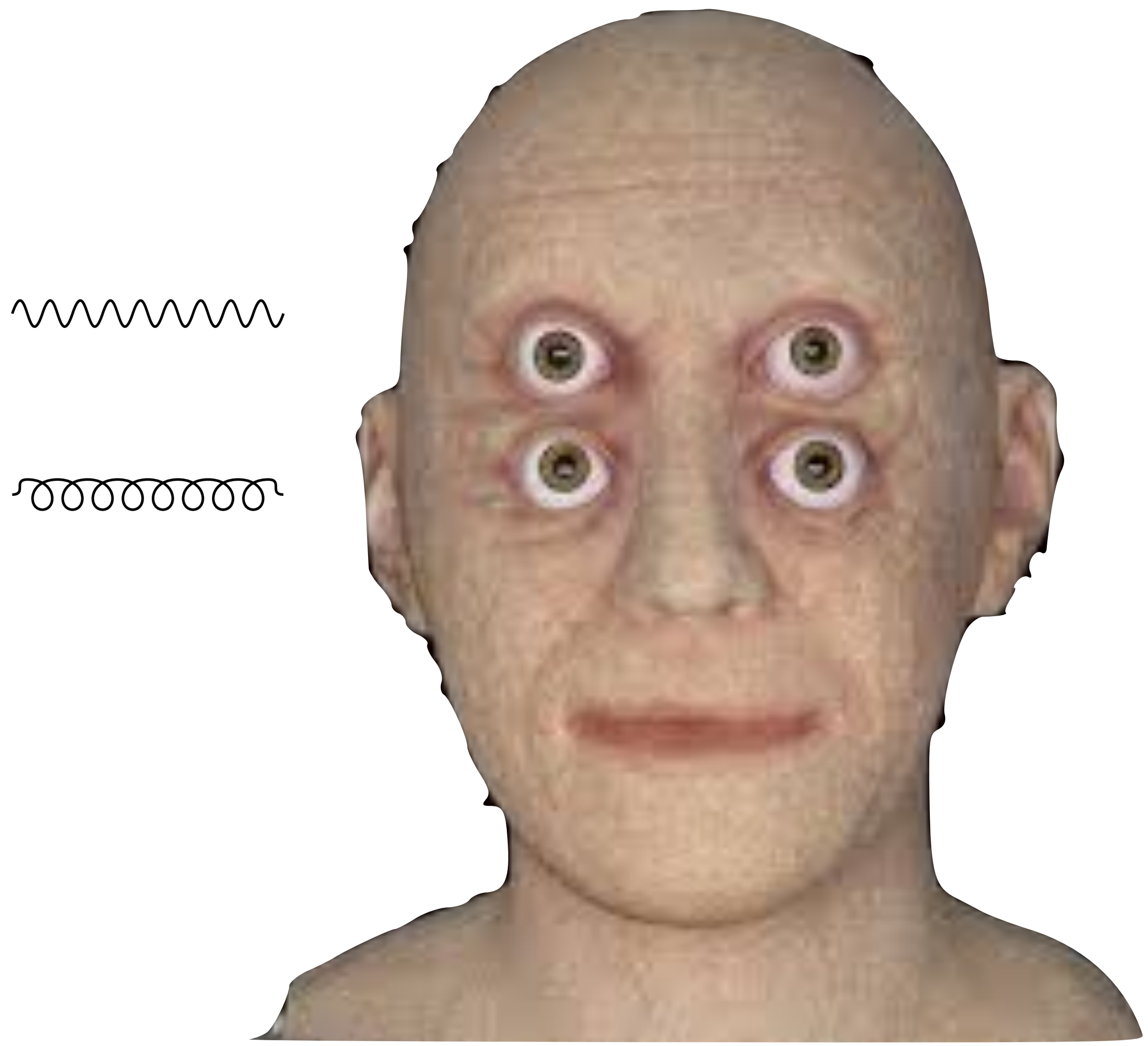
1/N
[nonfactorisable!]

the big wild card

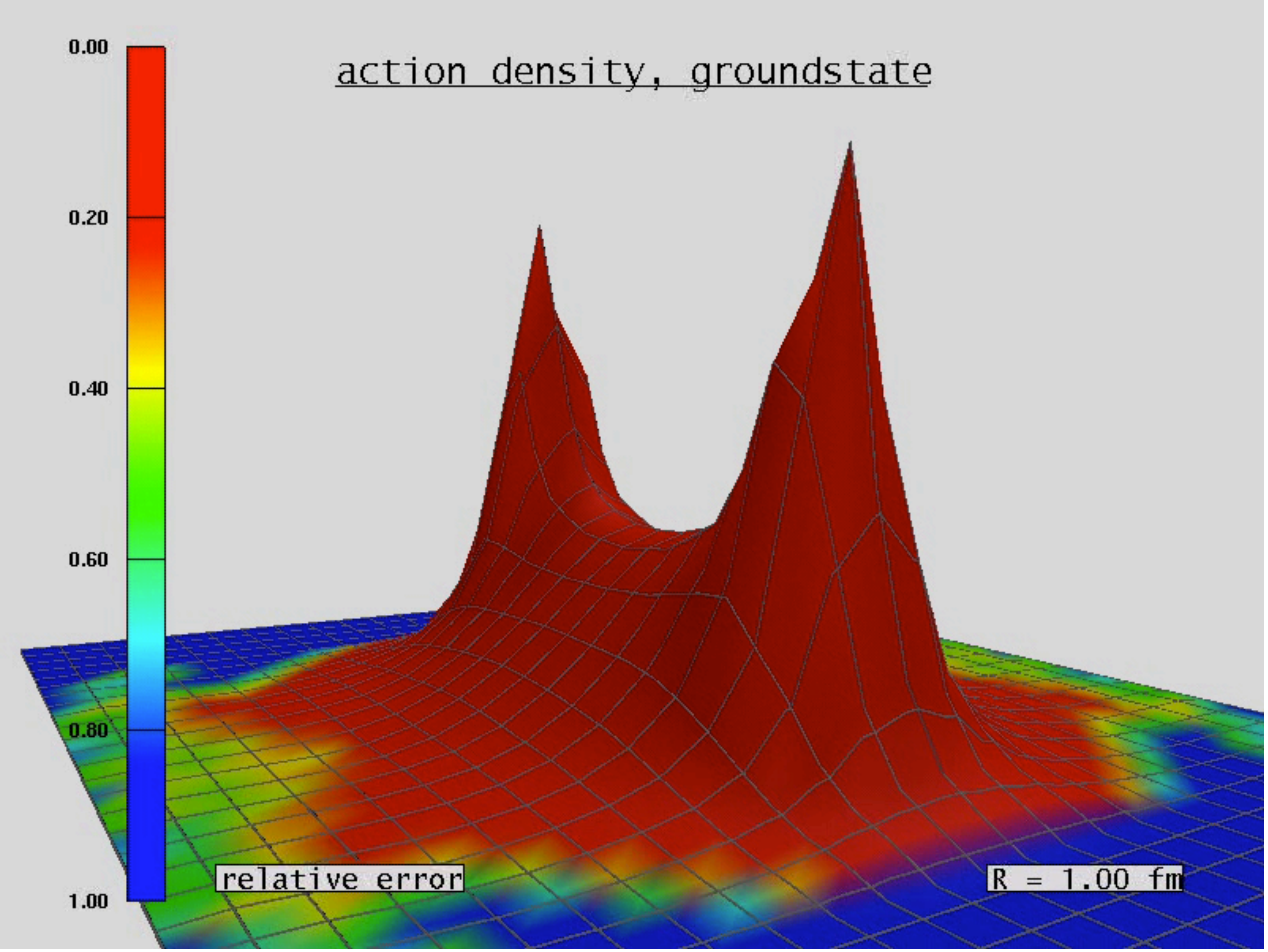


Hic dracones sunt.

glue



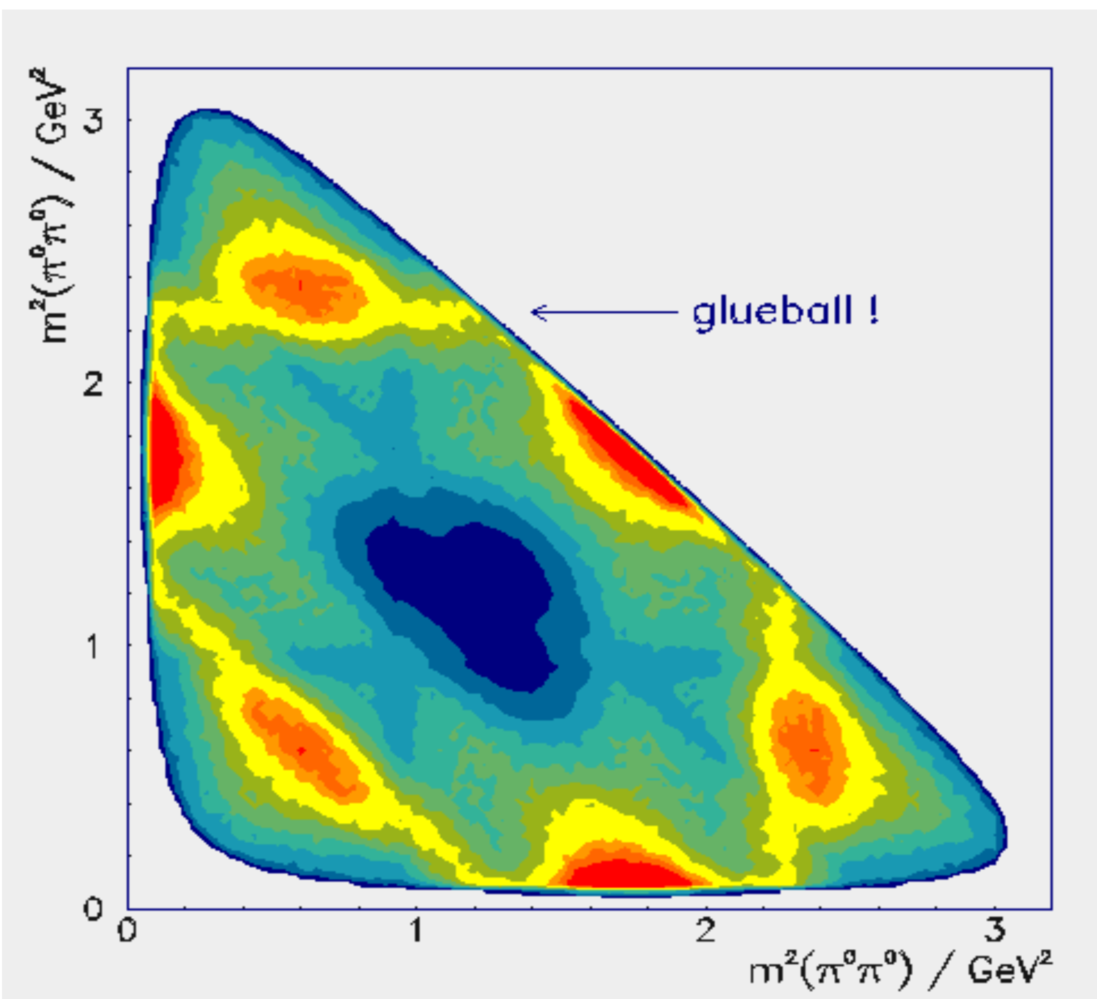
glue

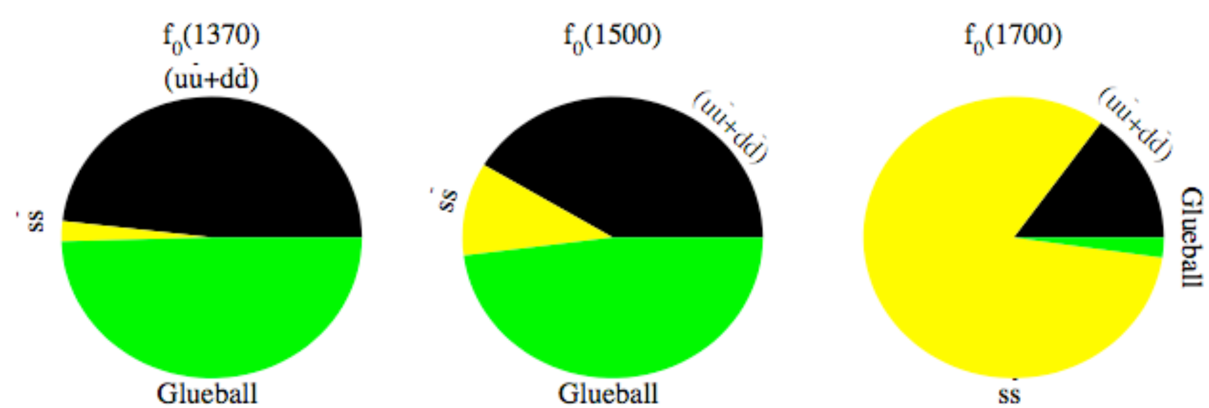


G. Bali et al., PRD71, 114513 (05)

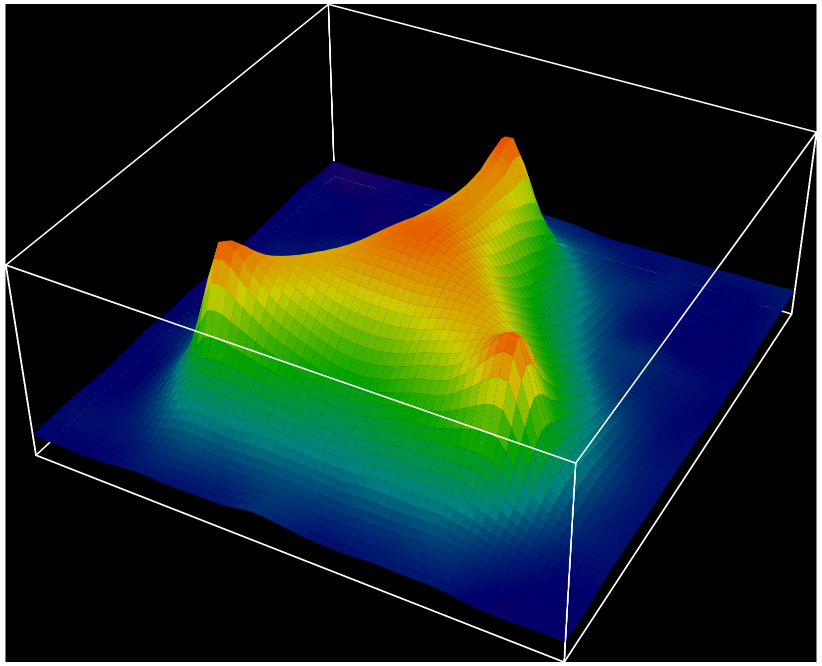
glue

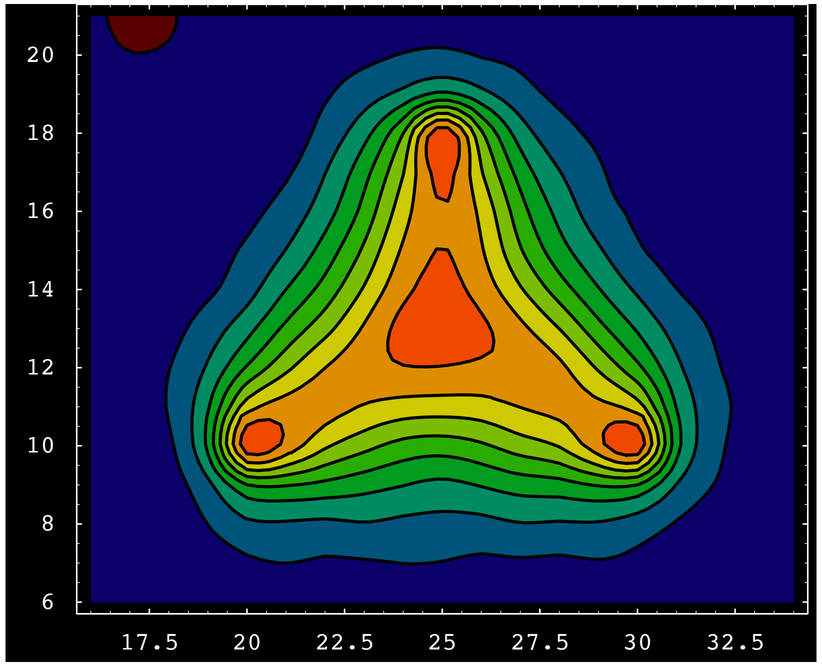
$$f_0(1500) \;\; IJ^{PC} = 0\,0^{++}$$





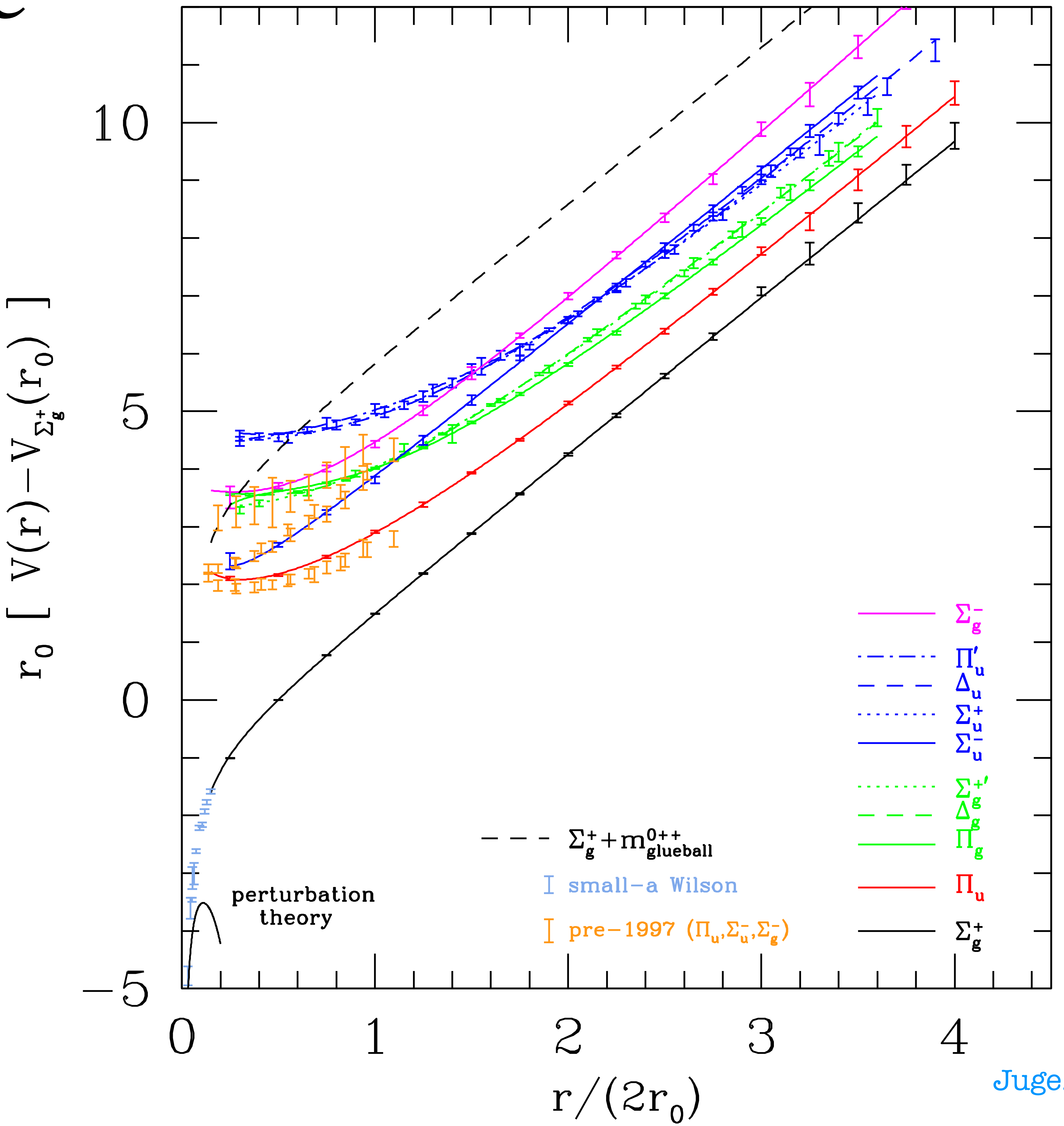
glue





Ichie, Bornyakov, Schierholz, & Streuer, hep-lat/0212036

glue



Juge, Kuti, & Morningstar.

glue - hybrid mesons

Meyer and Swanson, arXiv:1502.0727

$$P|M(P);JM[LS]\rangle = (-)^{L+1}|M(-P);JM[LS]\rangle$$

$$C|M(P);JM[LS]\rangle = (-)^{L+S}|M(P);JM[LS]\rangle$$

Not in this list:

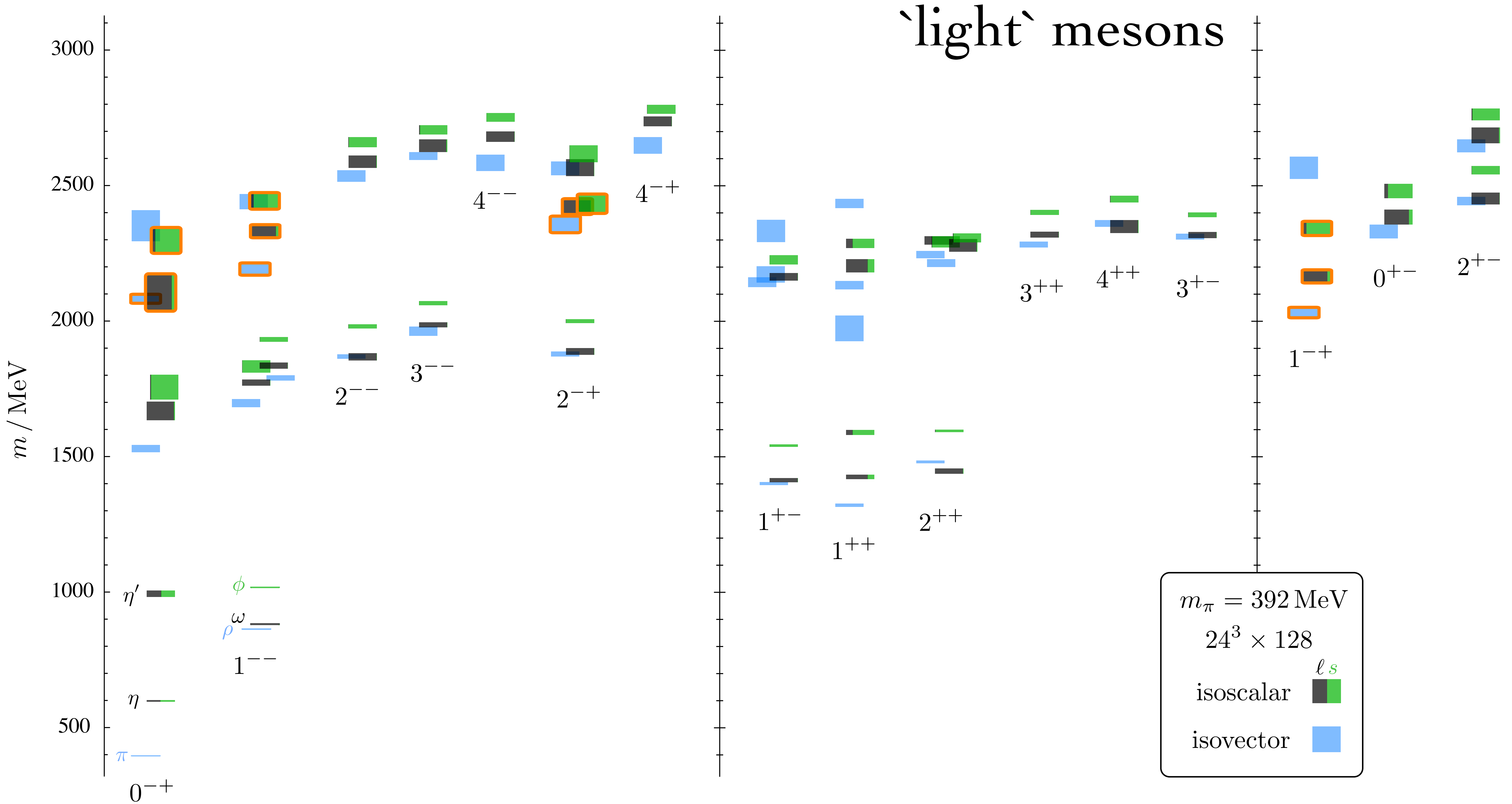
$$0^{--}$$

$$1^{-+},\ 3^{-+},\ \ldots$$

$$2^{+-},\ 4^{+-},\ \ldots$$

“quantum number exotics”

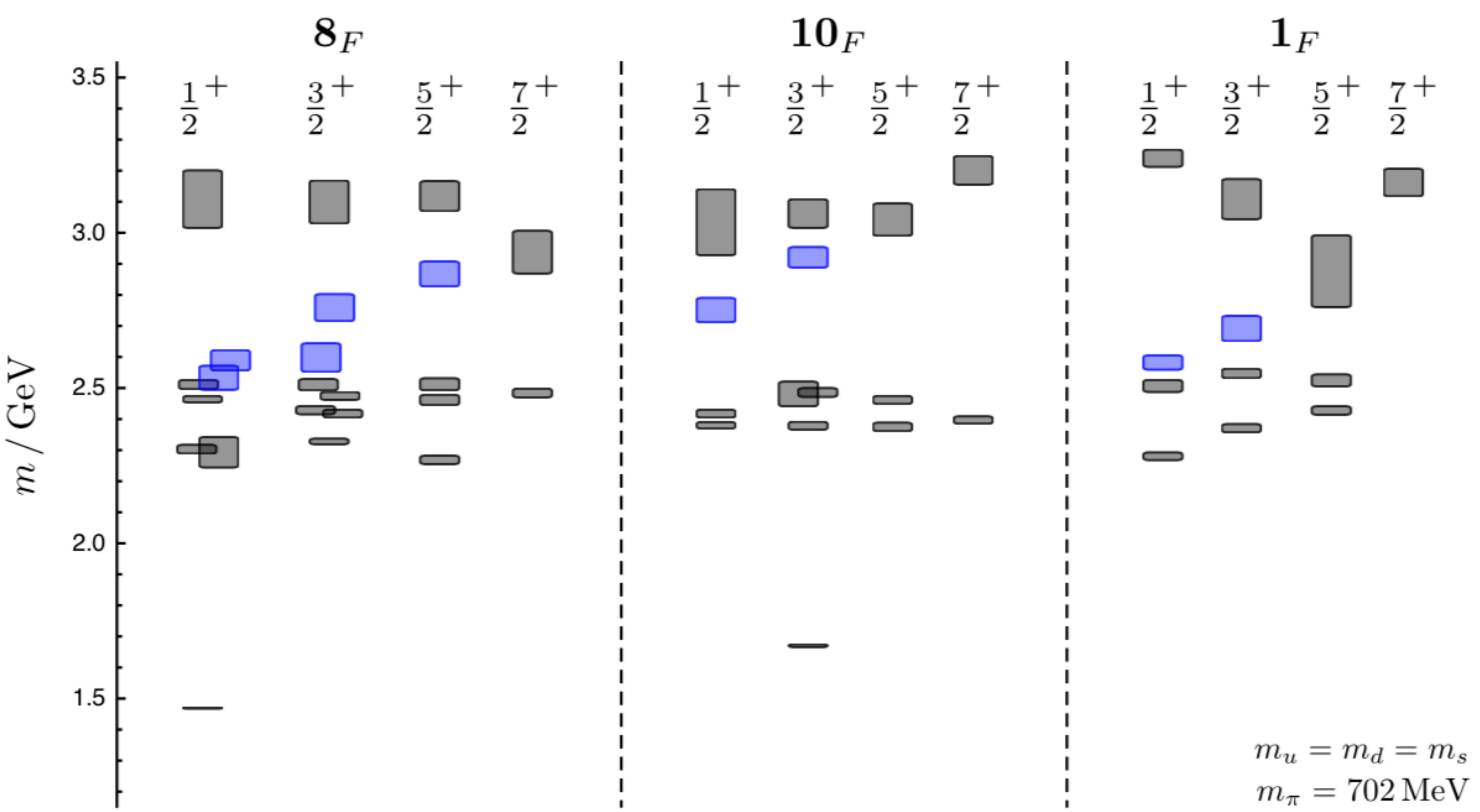
glue - hybrid mesons



arXiv:1106.5515

glue - hybrid mesons

`light` baryons

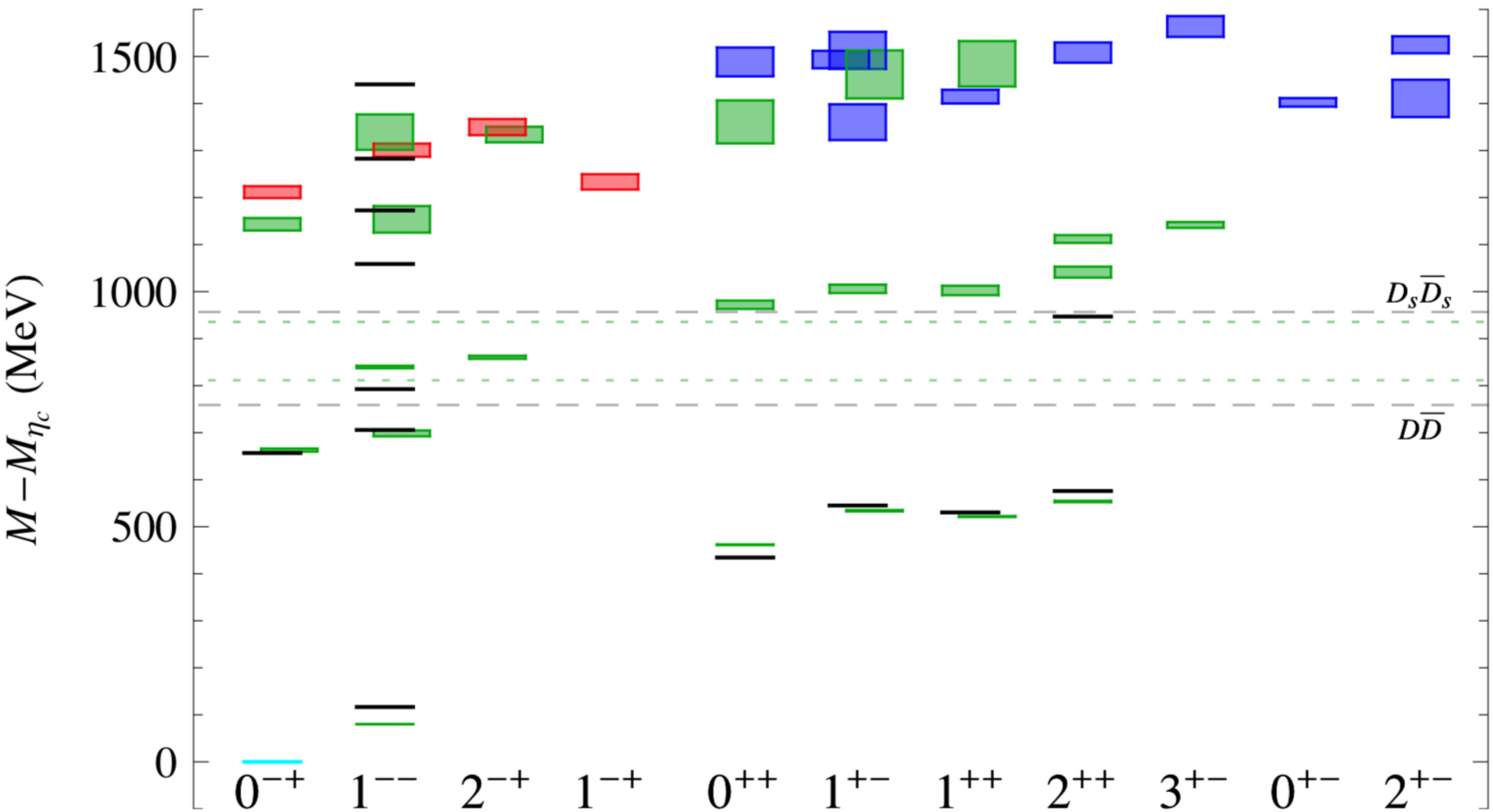


arXiv:1201.2349

flavor octet, decuplet and singlet states by J^P with three quark flavors all at the strange quark mass, corresponding to an octet pseudoscalar mass of 702 MeV. Grey boxes are conventional qqq states and blue boxes are the states identified as hybrid baryons.

glue - hybrid mesons

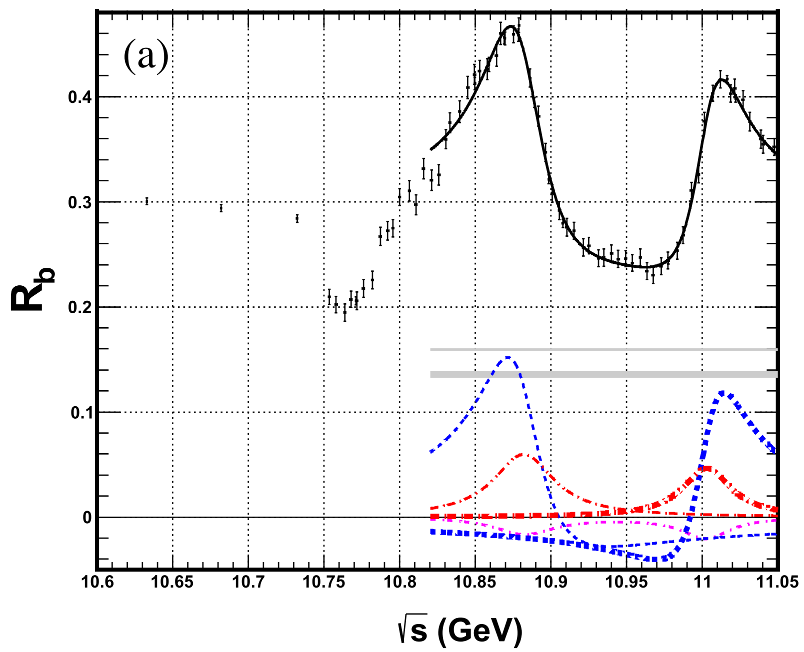
`charmonium` mesons



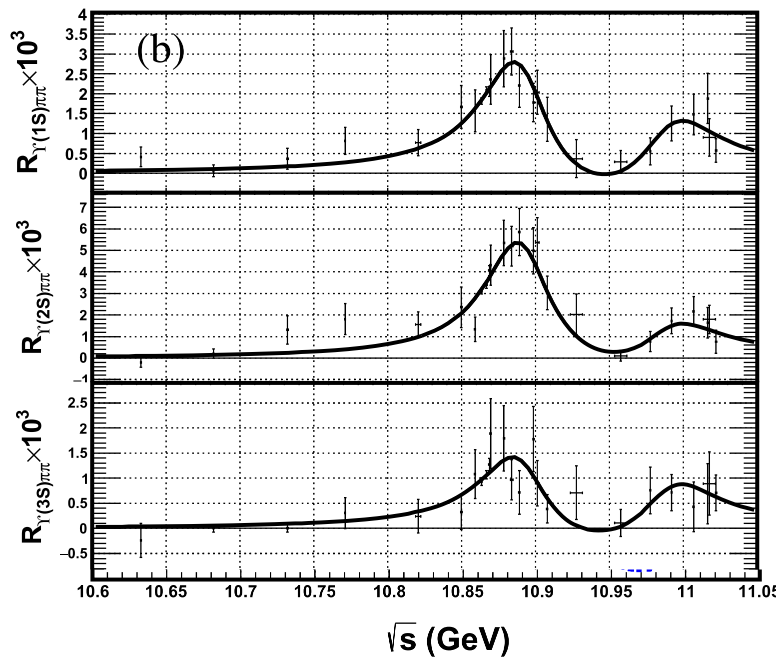
arXiv:1204.5425

The Mess in ee

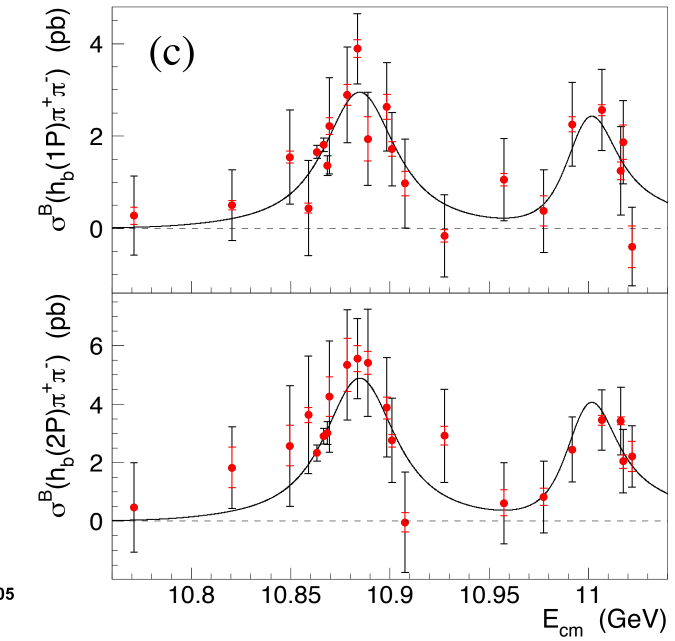
R_b



$e^+e^- \to \pi^+\pi^-\Upsilon(nS)$

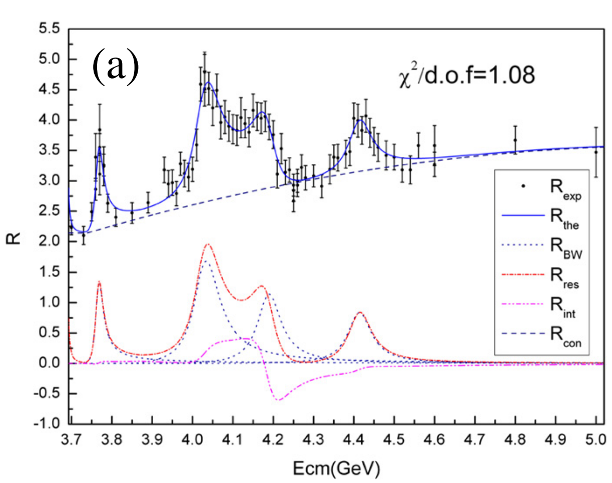


$e^+e^- \to \pi^+\pi^- h_b$

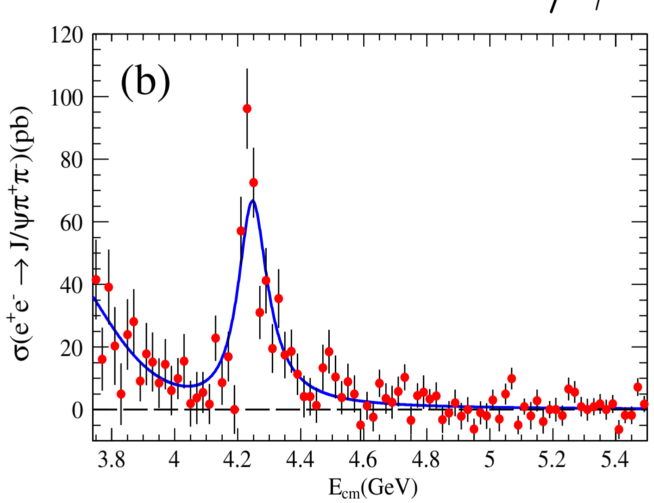


Contrast ee -> bb where the Upsilon(4S) and (5S) are clearly visible to cc:

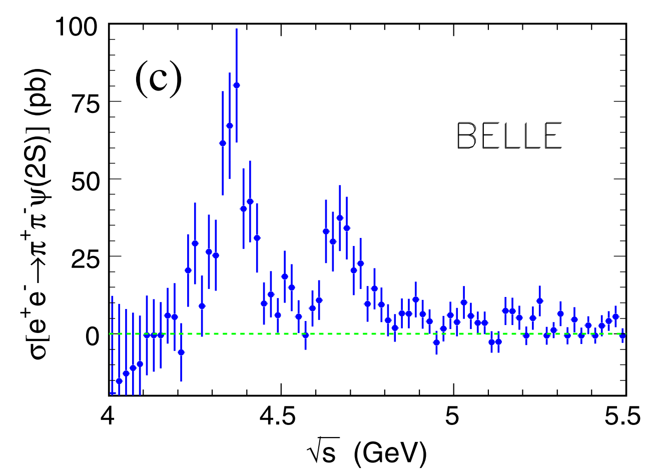
R_c



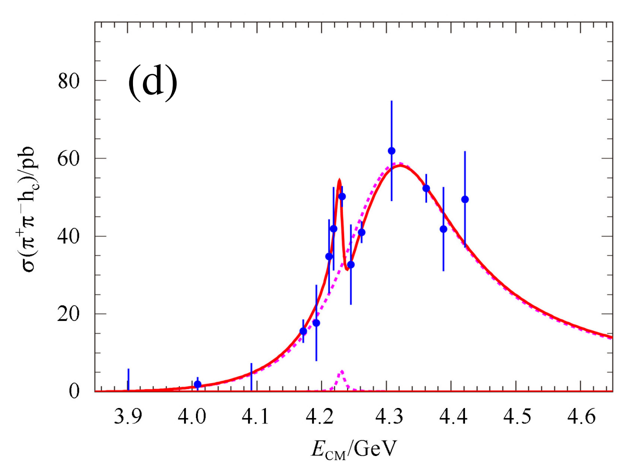
$e^+e^- \to \pi^+\pi^- J/\psi$



$e^+e^- \to \pi^+\pi^-\psi(2S)$



$e^+e^- \to \pi^+\pi^- h_c$



Conclusions

- there are a lot of new states, not all of them are ‘real’!
- cusp effects can be important and should be accounted for when modelling
- it appears likely (?) that the Z_b and Z_c states are kinematical
- cusps appear above threshold with fixed properties such as widths and phases
- channel-dependent widths, masses, and production characteristics are a clue!

Conclusions

- X(3872): likely a $c\bar{c} - \bar{D}D^*$ mixture (not a cusp!)
- Y(4260): our best candidate for a hybrid; expect many more!
- Zc(4475): 4q exotic? Much to be understood with this (and related?) states.
- 4X: more exotics/cusps?
- X(5568): likely dead.
- Pc(4450)+Pc(4380) -> Pc(4457)+Pc(4440): actual pentaquarks? Again, much remains to be understood.

Conclusions

- search for new classes of exotics: hexaquarks, double heavies, eg $cc\bar{u}\bar{d}$; exotic J^{PC}
- search for new decay modes of exotics
- clarify conventional $c\bar{c}$ in 3.8-4.0 GeV range. Zc(3930) = ?
  . $\chi_{c2}(2P)$: should be able to observe a DD* decay mode
- understand the e^+e^- charm cross sections better
- compare $p\bar{p}$ to e^+e^- production (via PANDA); photoproduction at COMPASS
- full amplitude analysis a la LHCb, more sophisticated models than isobar?

FIN

Lebed, Mitchell, Swanson arXiv:1610.04528

theoretical tools

- potential models
- Bethe-Salpeter/Schwinger-Dyson formalism
- lattice gauge theory
- effective field theories
- perturbative QCD
- operator product expansion/multipole expansion

Quantum Chromodynamics

we require a theory which

- has approximate chiral symmetry
- has approximate SU(3) flavour symmetry
- accounts for the parton model
- has colour
- and colour confinement
- is renormalizable

Cusp Diagnostics

- lie just above thresholds
- S-wave quantum numbers
- asymmetric lineshapes
- partner states of similar width – widths will depend on channel
- the reaction $\Upsilon(5S) \to K\bar{K}\Upsilon(nS)$ should reveal "states" at 10695 ($B\bar{B}_s^* + B^*\bar{B}_s$) and 10745 ($B^*\bar{B}_s^*$)

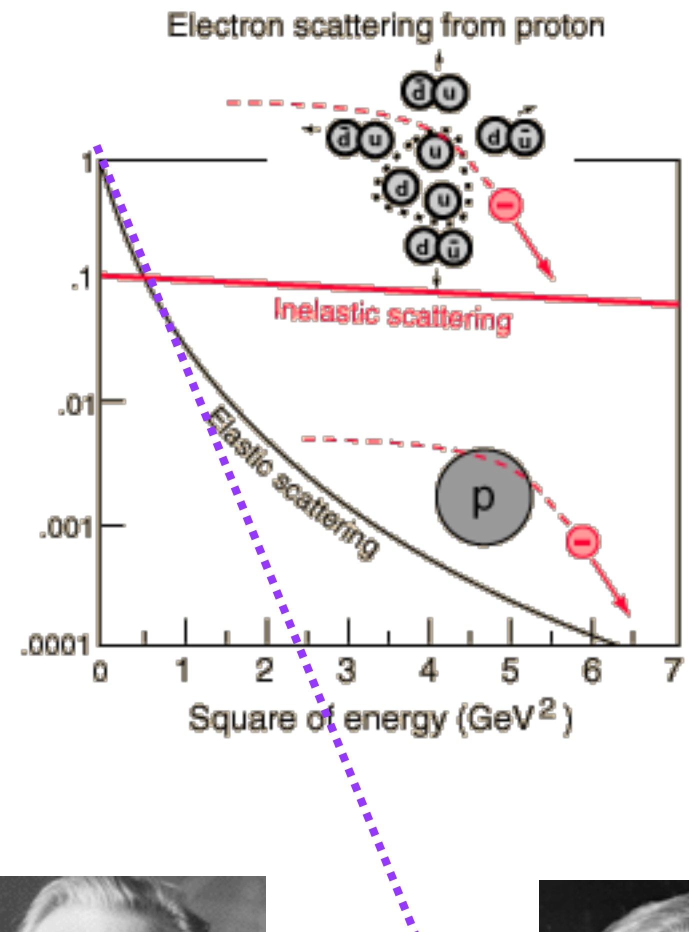
$$e^+e^- \to K\bar{K}J/\psi$$

$$\bar{B}^0 \to J/\psi\pi^0\pi^0$$
$$B^\pm \to J/\psi\pi^\pm\pi^0$$

(if the wavefunction enhanced rescattering diagram contributes)

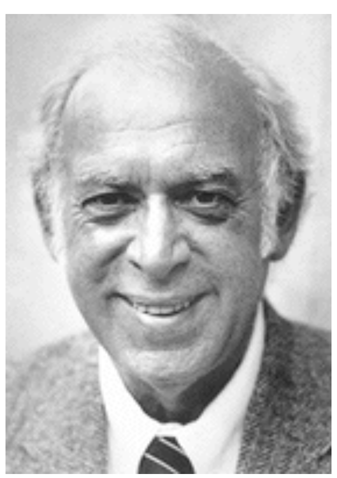
Exploring Quarks

repeat the Rutherford experiment…
expect mushy scattering, find hard kernels instead!

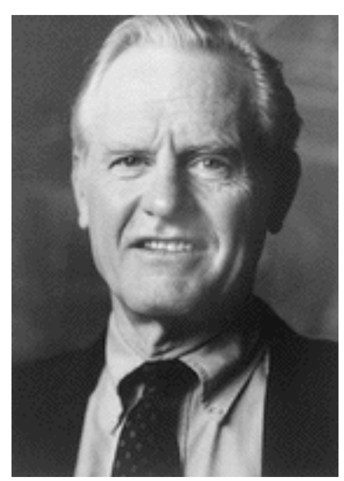


Bj still being nominated for a Nobel Prize, but keeps refusing invitations to give talks in Stockholm!

(source: Kam Seth)



Jerome Friedman
(1930-)



Henry Kendall
(1926-1999)

Richard Taylor
(1929-)

James Bjorken
(1934-)

Exploring Quarks

Leon Lederman et al. Fermilab E288 proposal Feb 1974

A Study of Di-Lepton Production in Proton Collisions at NAL

Lederman et al.

1. Observe and measure the spectrum of virtual photons emitted in p-nucleon collisions via the mass distribution of e^+e^- pairs: $p + p \rightarrow e^+ e^- +$ anything. (1)
   Study characteristics, e.g. parity violation, $p_\perp$ behavior.
2. Search for structures in the above spectrum, publish these and become famous, e.g. $W°$, $B°$.
3. Qualitatively study the mass spectrum of hadron pairs ($\pi\pi$, πp, etc). This is an interesting background for (1). It uses a crude hadron calorimeter, also required for hadron rejection in (1).
4. Check μe universality by looking, in the same arrangement but with the addition of a pion filter, at $\mu^+\mu^-$ pairs.
5. Extend the Experiment #70 study of single leptons in the double arm arrangement, i.e. $W^\pm$ etc. Publish these and become famous.
6. Look at $\pi°\pi°$ pairs by double conversion of $\pi°-\gamma$'s in thin aluminum radiators. This data comes free since one adds 0.1 radiation length to enable an extrapolation to zero target thickness in (1).