Exotic hadrons and hadron structure

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Outline

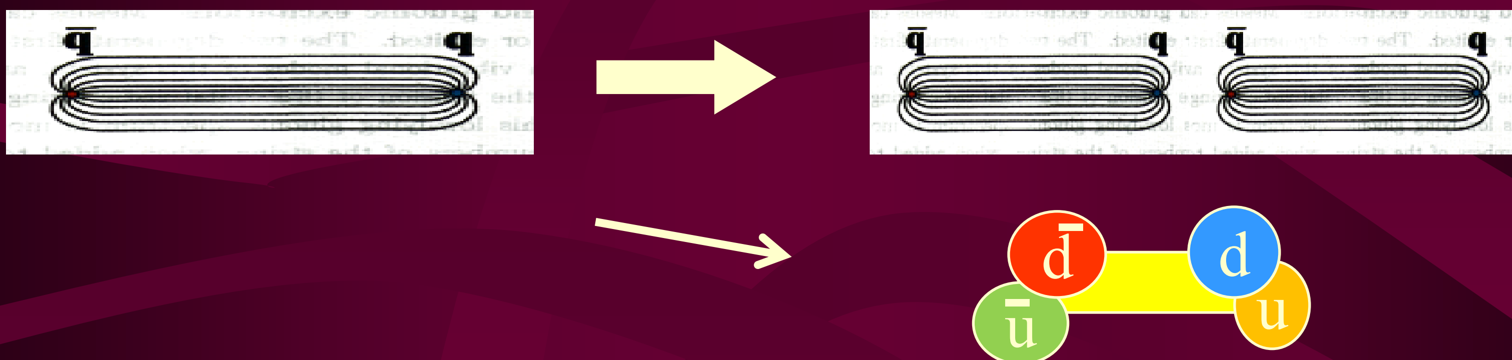
1. **General issues on hadron structure**
2. **Quark-gluon structure of proton**
3. **Exotic hadrons**
4. **Unquenched quark model**
5. **Summary and prospects**

1. General issues on hadron structure:

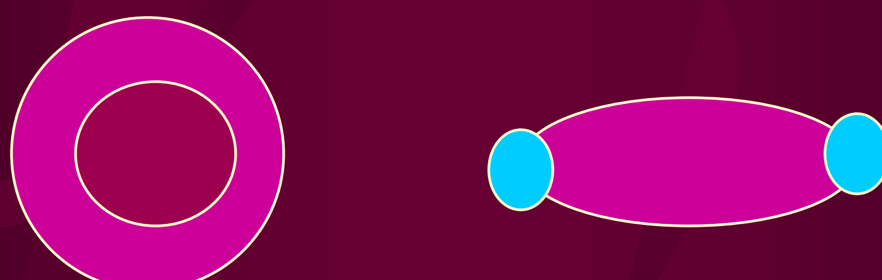
how quarks & gulons contruct hadrons?

Key point for hadron structure & quark confinement

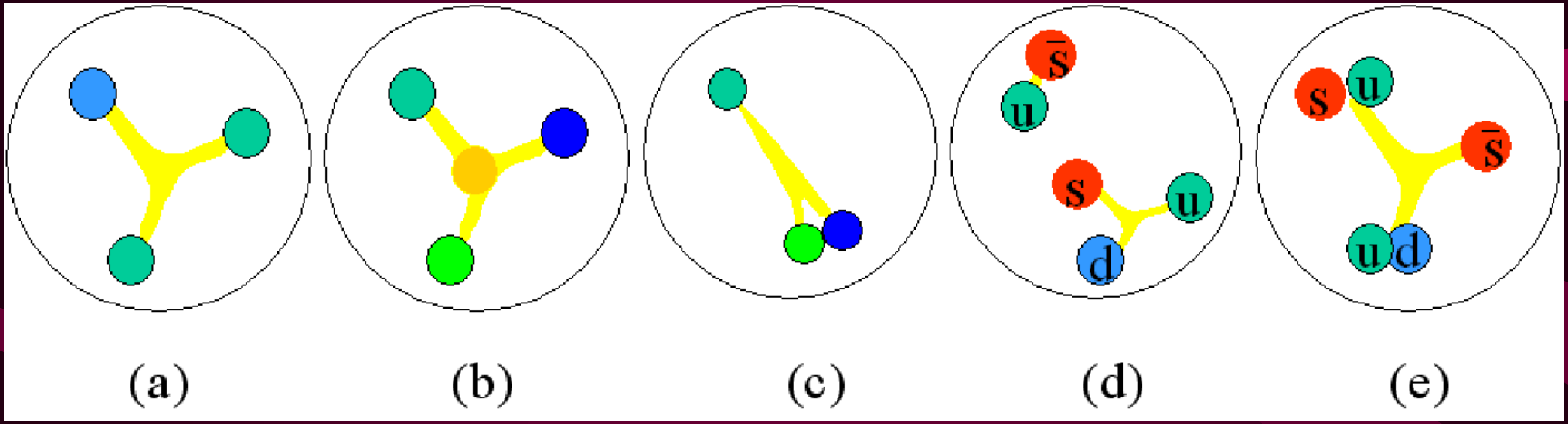
Unquenching dynamics: gluons → $\bar{q}q$



Mesons: $\bar{q}q$, tetraquarks, glueballs, $\bar{q}qg$-hybrids?



How about baryons?



A. qqq　　B. qqqg　　C. q-q^2　　D-E. pentaquarks

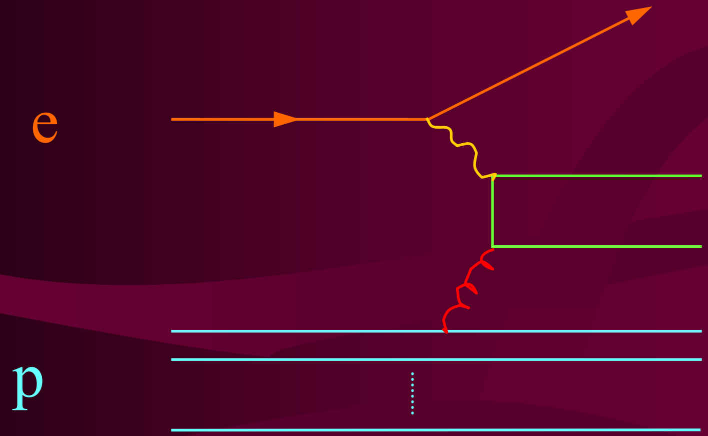
Number of predicted N*： D-E>B>A>C

Number of observed N* <A , "missing" ?

Poor knowledge on baryon spectroscopy
Lack effective reliable theoretical predictions

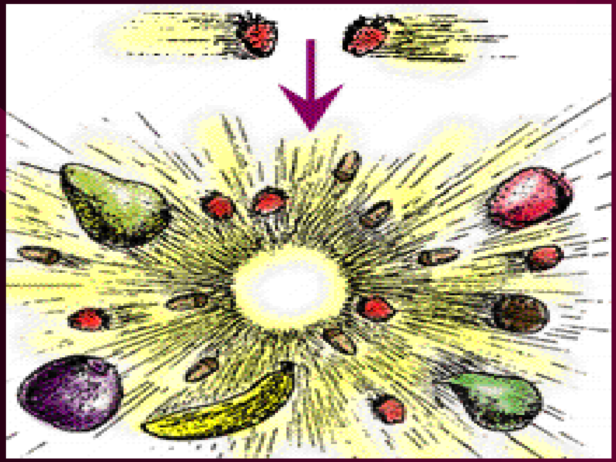
Two major methods for exploring baryon structure

1） lepton-proton scattering → parton distribution of proton



Problem： γ, g, $\bar{q}q$ transition，
intrinsic or extrinsic ?

2） hadrons, leptons, γ collisions → hadron spectroscopy



Atomic spectroscopy → Atomic Quantum Theory

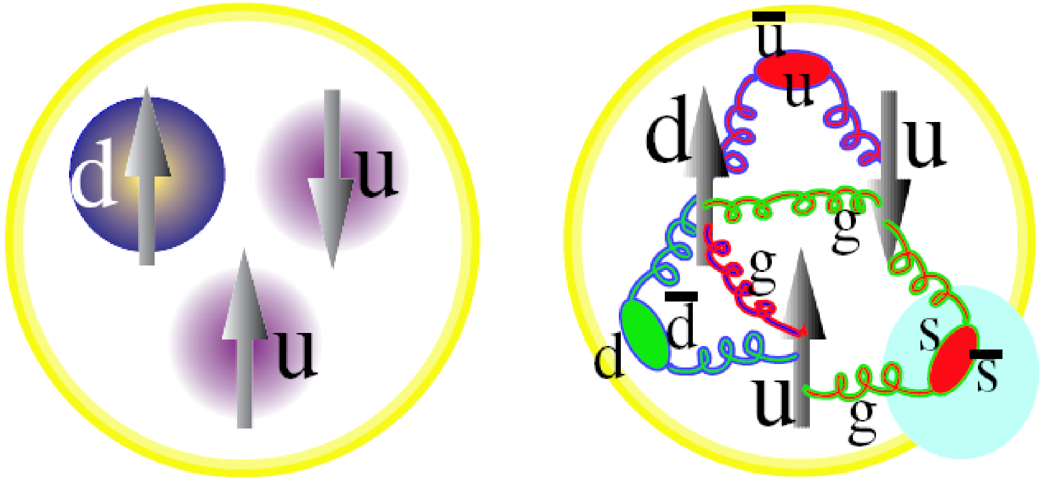
Nuclear spectroscopy → Shell Model &
Collective motion Model

Hadron spectroscopy → ?

2. Quark-gluon structure of proton

Classical picture of the proton

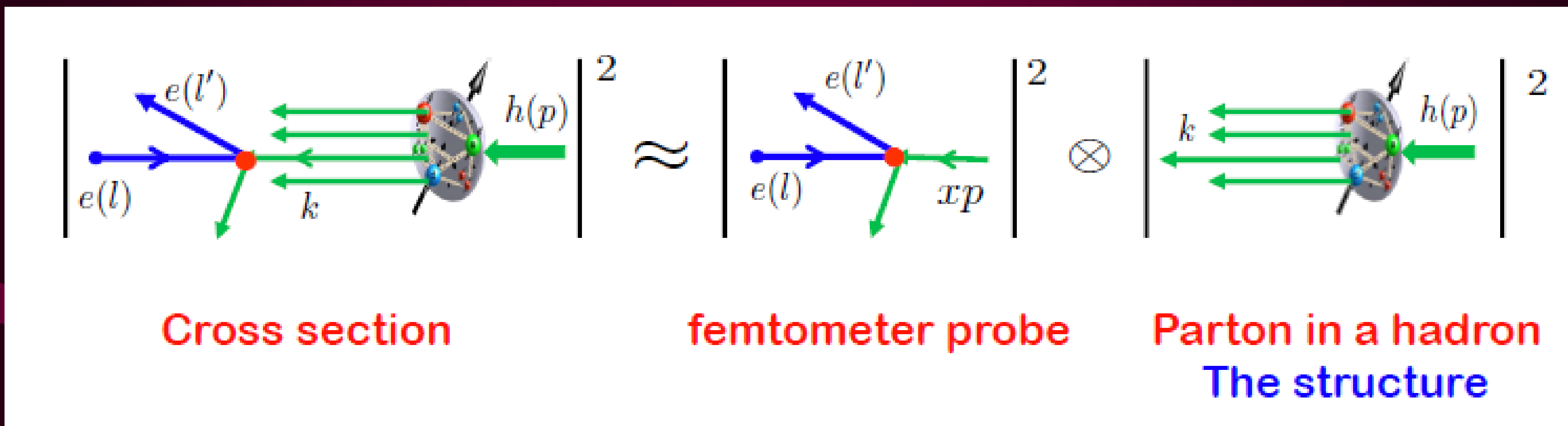
Constituent Quarks	Parton Distributions



($Q^2 = 0$ GeV^2)	($Q^2 > 1$ GeV^2)
baryon octet	structure functions
masses,magn. momenta	momentum, spin

$\bar{u}(x) = \bar{d}(x)$, $\bar{s}(x) = s(x)$

1964-1974 **1974–1992**



QCD factorization → PDF (flavor, spin, momentum) of nucleon

proton spin "crisis" , $\bar{d} - \bar{u} \sim 0.12$, $\bar{s}(x) \neq s(x)$, …

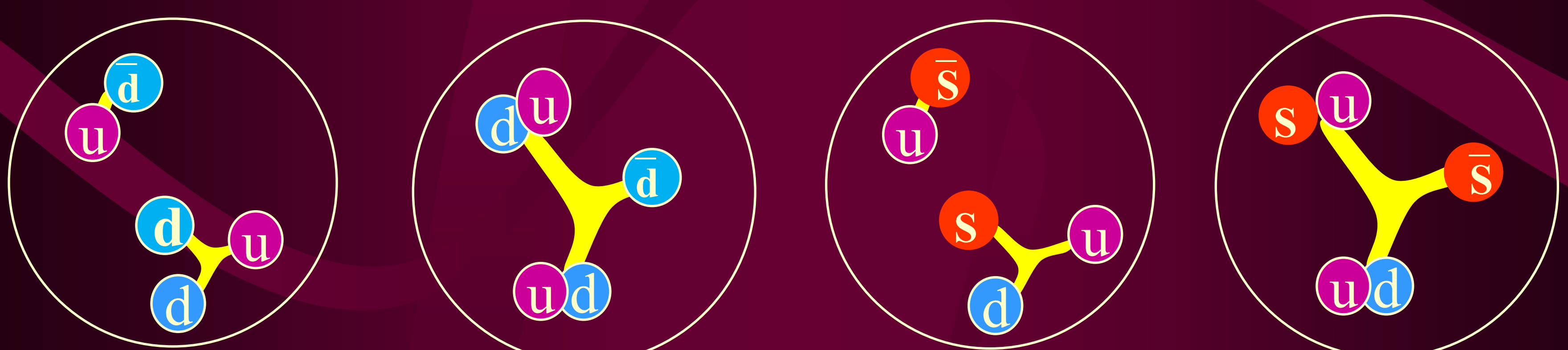
Spin "crisis", $\bar{d} - \bar{u} \sim 0.12$, $\bar{s}(x) \neq s(x)$ puzzles → two possible solutions:

Meson clouds: Thomas, Speth, Weise, Oset, Brodsky, Ma, …

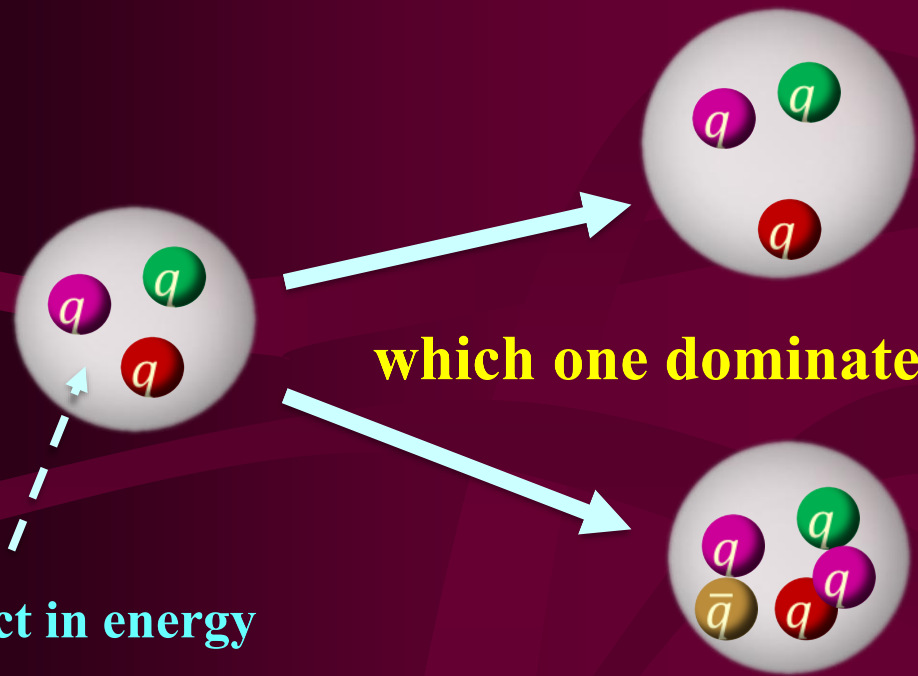
$$| p \rangle \sim | uud \rangle + \varepsilon_1 | n (udd)\, \pi^+ (\bar{d}u) \rangle + \varepsilon_2 | \Delta^{++} (uuu)\, \pi^- (\bar{u}d) \rangle + \varepsilon' | \Lambda (uds)\, K^+ (\bar{s}u) \rangle \ldots$$

diquarks: Riska, Zou, Zhu, …

$$| p \rangle \sim | uud \rangle + \varepsilon_1 | [ud][ud]\, \bar{d} \rangle + \varepsilon' | [ud][us]\, \bar{s} \rangle + \ldots$$



~30% pentaquarks in proton → more in excited baryons !



Classic quark model:
3q excited states

which one dominates?

New view:
Pentaquark excitation
dominates already for ½-

inject in energy

Pentaquark crucial for baryon spectroscopy and structure !

3. Exotic hadrons

Fate of the first pentaquark predicted and observed: $1/2^-$

1959: $\bar{K}N$ molecule predicted by Dalitz-Tuan, PRL2, 425

1961: $\Lambda(1405) \rightarrow \Sigma\pi$ observed by Alston et al., PRL6, 698

1964: Quark model (uds) for $\Lambda(1405)$

1995: $\bar{K}N$ dynamically generated -- Kaiser et al., NPA954, 325

2001: 2 pole structure by $\bar{K}N$-$\Sigma\pi$ -- Oller et al., PLB500, 263

PDG2010: "The clean Λ_c spectrum has in fact been taken to settle the decades-long discussion about the nature of the $\Lambda(1405)$ —true 3-quark state or mere $\bar{K}N$ threshold effect?— unambiguously in favor of the first interpretation."

Fate of the last famous fading pentaquark $\theta^+(1540)$: $1/2^+$

1997: $Z^+(1530)$ predicted by Diakonov et al., ZPA359, 305

2003: $\theta^+(1540) \rightarrow K^+n$ claimed by LEPS, PRL91, 012002

2003: $\bar{s}$ (ud)(ud) for θ(1540) by Jaffe&Wilczek, PRL91, 232003

2003: $\bar{s}$ ud)(ud) for θ(1540) by Karliner&Lipkin, PLB575, 249

2004: supported by 10 expts → θ(1540) well-established by PDG

2004: not supported by BESII, PRD70, 012004

2005: not supported by many high stats experiments

2006: removed from PDG

Note: $\theta^+(1540)$ is not supported by hadronic molecule model & chiral quark model by Huang, Zhang, Yu, Zou, PLB586(2004)69

$1/2^-$ baryon nonet with strangeness

Zou, EPJA 35 (2008) 325

- Mass pattern : quenched or unquenched ?

  uds (L=1) $1/2^-$ ~ $\Lambda^*(1670)$ ~ $[us][ds]\bar{s}$, $K\Xi$ - $\eta\Lambda$

  uud (L=1) $1/2^-$ ~ $N^*(1535)$ ~ $[ud][us]\bar{s}$, $K\Sigma$ - $K\Lambda$-$N\eta$

  uds (L=1) $1/2^-$ ~ $\Lambda^*(1405)$ ~ $[ud][su]\bar{u}$, $\bar{K}N$ - $\pi\Sigma$

  uus (L=1) $1/2^-$ ~ $\Sigma^*(1390)$ ~ $[us][ud]\bar{d}$, $\bar{K}N$ - $\pi\Lambda$

  Zou et al, NPA835 (2010) 199 ; CLAS, PRC87(2013)035206

  BESIII, ArXiv: 2407.12270 [hep-ex]

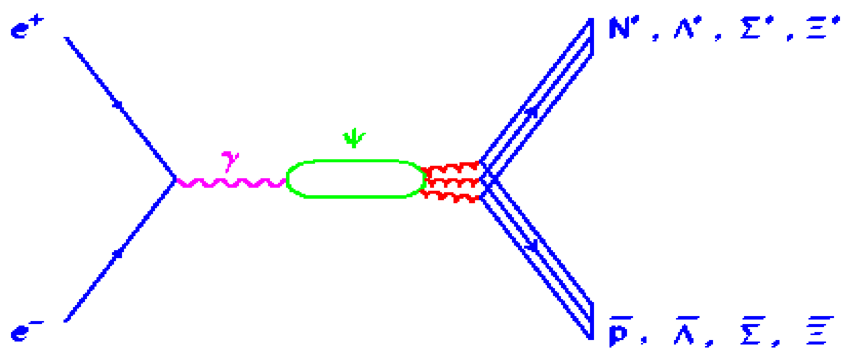
- Strange decays of N*(1535) and Λ*(1670) :

  N*(1535) large couplings $g_{N^*N\eta}$, $g_{N^*K\Lambda}$, $g_{N^*N\eta'}$, $g_{N^*N\phi}$

  Λ*(1670) large coupling $g_{\Lambda^*\Lambda\eta}$

(N*, Λ*, Σ*, Ξ*, Ω*) baryons from ψ decays at BEPC

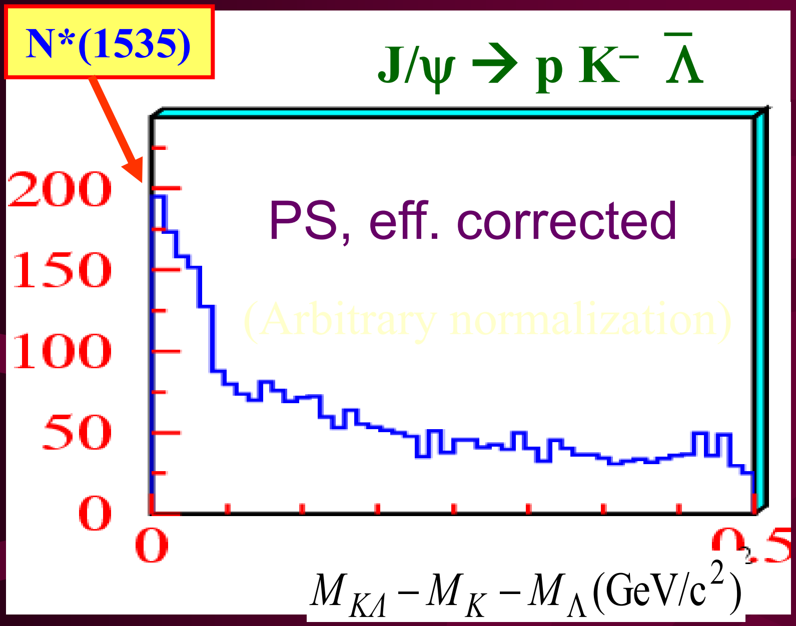
$$\Psi \rightarrow \bar{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*, \Omega^*$$

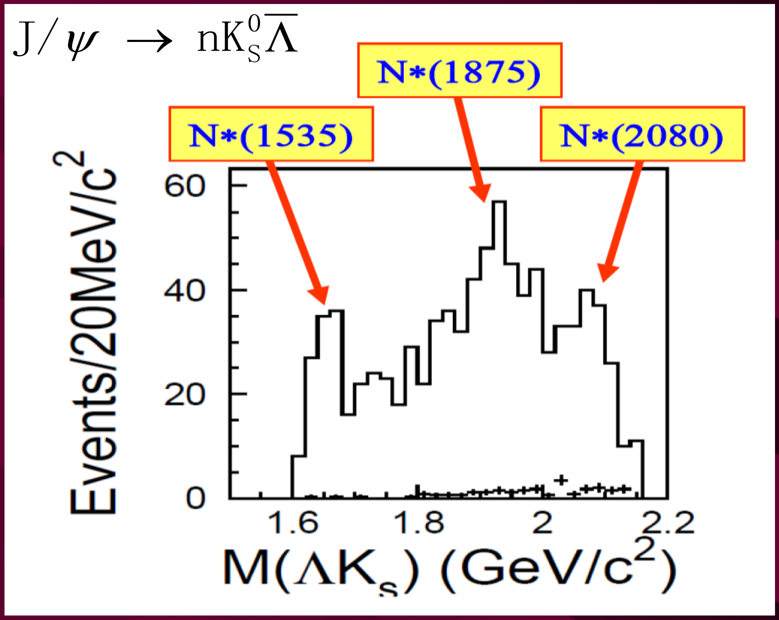


advantages： ideal isospin and low spin filter

comparing to other experiments (ep, γp, πp, Kp)

N* observed in J/ψ → $\bar{\Lambda}$ K N





BESII, IJMPA20 (2005) 1985

BESII, PLB659 (2008) 789

B.C.Liu, B.S.Zou, PRL96 (2006) 042002 : N*(1535) ~ $\bar{s}$suud !

KΣ* ~1880 MeV , K*Σ ~ 2086 MeV !

$\bar{s}suud \rightarrow \bar{c}cuud$

- prediction of three P_c pentaquark states → J/ψ-p :
  1 $D\Sigma_c$ molecule + 2 $D^*\Sigma_c$ molecules

  J.J.Wu, R.Molina, E.Oset, B.S.Zou, PRL 105 (2010) 232001
  W.L.Wang, F.Huang, Z.Y.Zhang, B.S.Zou, PRC 84 (2011) 015203
  J.J.Wu, T.H.Lee, B.S.Zou, PRC 85 (2012) 044002

- 4 more broader P_c states with $\Sigma_c \rightarrow \Sigma_c^*$:
  1 $D\Sigma_c^*$ molecule + 3 $D^*\Sigma_c^*$ molecules

  C.W.Xiao, J.Nieves, E.Oset, PRD 88 (2013) 056012

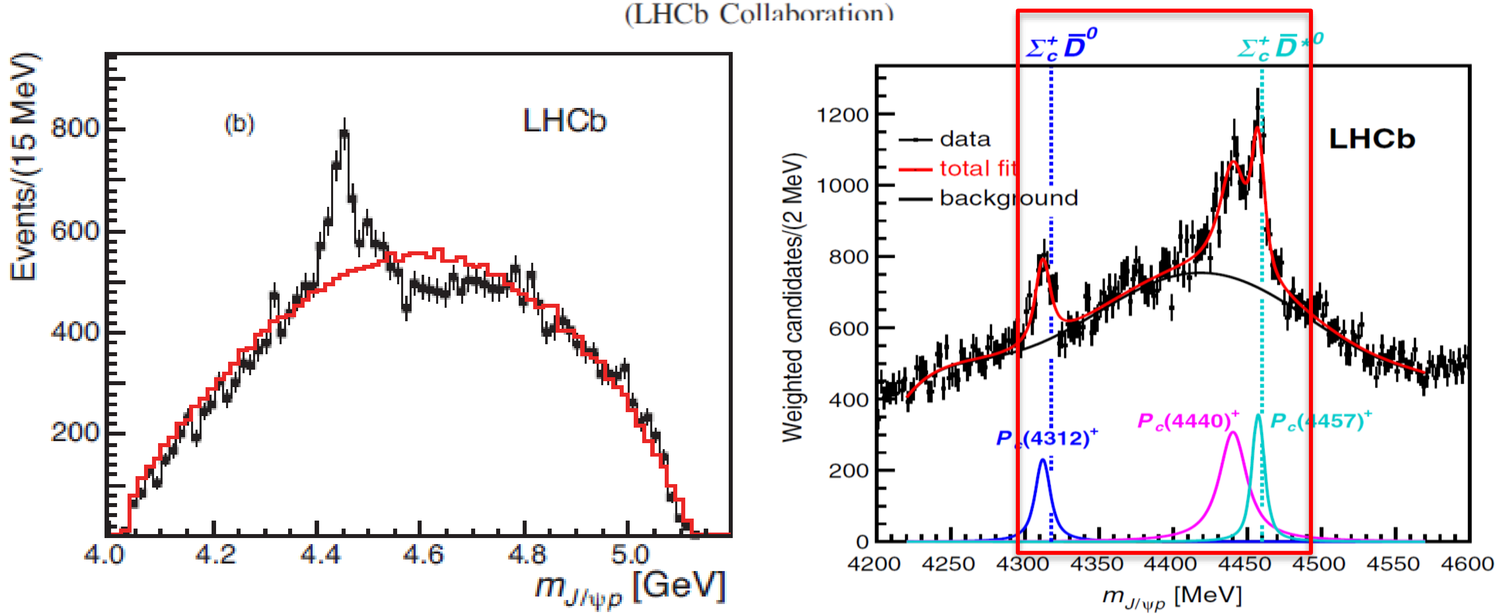
LHCb confirms our prediction of 3 narrow P_c states

Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

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

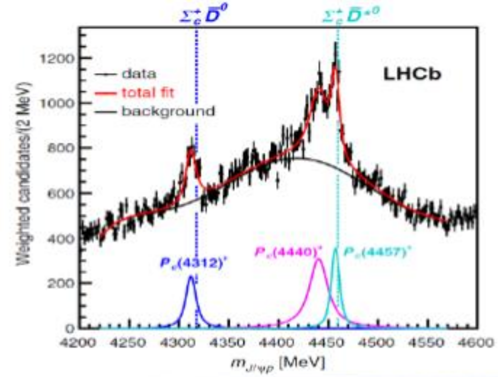
PRL 122 (2019) 222001



A milestone for pentaquark search

P_c states: observation vs predictions

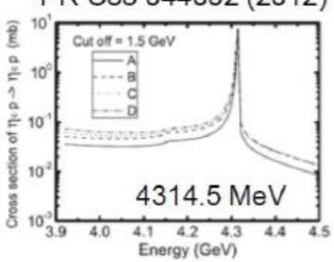
LHCb, PRL122 (2019) 222001



Comparison to numerical predictions

- Many theoretical predictions for $\Sigma_c^+\bar{D}^{(*)0}$ published before 2015, **some in quantitative agreement with the LHCb data**
  - Wu,Molina,Oset,Zou, PRL105, 232001 (2010),
  - **Wang,Huang,Zhang,Zou, PR C84, 015203 (2011),**
  - **Yang,Sun,He,Liu,Zhu, Chin. Phys. C36, 6 (2012),**
  - **Wu,Lee,Zou, PR C85 044002 (2012),**
  - Karliner,Rosner, PRL 115, 122001 (2015)

PR C85 044002 (2012)



ΔE – binding energy

Example:

Nucleon resonances with hidden charm in coupled-channels models

Jia-Jun Wu, T.-S. H. Lee, and B. S. Zou

Phys. Rev. C **85**, 044002 – Published 17 April 2012

arXiv:1202.1036

TABLE III: The pole position $(M - i\Gamma/2)$ and "binding energy" $(\Delta E = E_{thr} - M)$ for different cut-off parameter Λ and spin-parity J^P. The threshold E_{thr} is 4320.79 MeV of $\bar{D}\Sigma_c$ in PB system and 4462.18 MeV of $D^*\Sigma_c$ in VB system. The unit for the listed numbers is MeV.

		PB System		VB System	
$J^P = \frac{1}{2}^-$	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
	650	-	-	-	-
	800	-	-	4462.178 − 0.002i	0.002
	1200	4318.964 − 0.362i	1.826	4459.513 − 0.417i	2.667
	1500	4314.531 − 1.448i	6.259	4454.088 − 1.662i	8.092
	2000	4301.115 − 5.835i	19.68	4438.277 − 7.115i	23.90
$J^P = \frac{3}{2}^-$					
	650	-	-	-	-
	800	-	-	4462.178 − 0.002i	0.002
	1200	-	-	4459.507 − 0.420i	2.673
	1500	-	-	4454.057 − 1.681i	8.123
	2000	-	-	4438.039 − 7.268i	23.14

$\Delta E(4312) = 5.8^{+1.0}_{-6.8}$ MeV

$\Delta E(4457) = 2.5^{+4.3}_{-4.1}$ MeV

$\Delta E(4440) = 19.5^{+4.9}_{-4.3}$ MeV

Λ - cut off on exchanged meson mass.

Multiquark states – crucial for hadron structure !

X(3872)	→	top cited paper for Belle (2003)	2785 cites
Zc(3900)	→	top cited paper for BES (2013)	1207 cites
Pc states	→	top cited paper for LHCb (2015)	1987 cites

H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1:
"The hidden-charm pentaquark and tetraquark states" 1274 cites

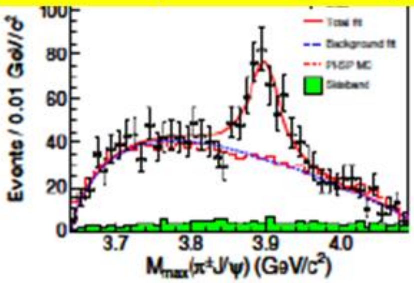
F.K.Guo, C.Hanhart, U.Meißner, Q.Wang, Q.Zhao, B.S.Zou,
Rev.Mod.Phys. 90 (2018)015004: "Hadronic molecules" 1404 cites

N.Brambilla, S.Eidelman, C.Hanhart, A.Nefediev, C.P.Shen,
C.Thomas, A.Vario, C.Z.Yuan, Phys.Rept. 873 (2020) 1:
"The XYZ states: Expt. & theor. status and perspectives" 945 cites

Discovery of Z_c family at BESIII

Zc(3900)⁺

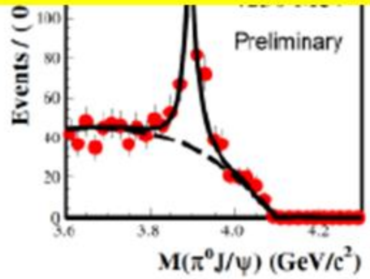
PRL 110, 252001 (2013)



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

Zc(3900)⁰

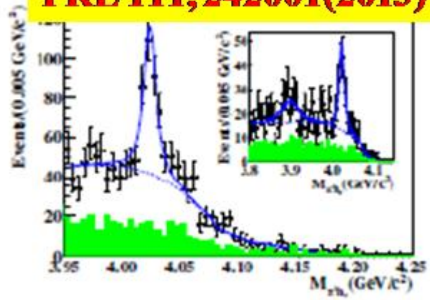
PRL 115, 112003 (2015)



$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$

Zc(4020)⁺

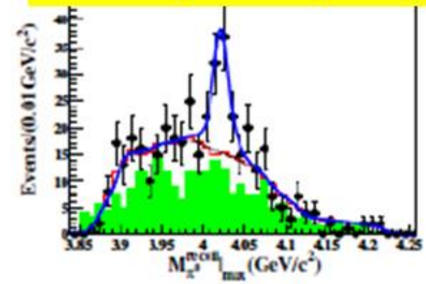
PRL 111, 242001(2013)



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

Zc(4020)⁰

PRL113,212002 (2014)

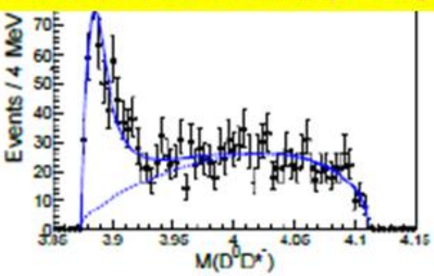


$e^+e^- \rightarrow \pi^0\pi^0 h_c$

Zc(3885)⁺

ST: PRL 112, 022001(2014)

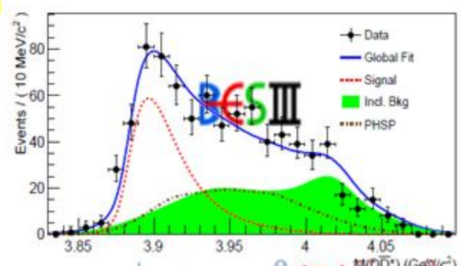
DT: PRD92, 092006 (2015)



$e^+e^- \rightarrow \pi^-(D\bar{D}^*)^+$

Zc(3885)⁰

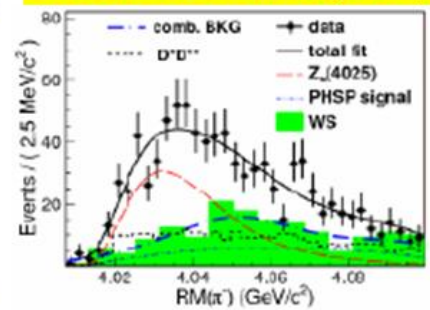
PRL 115, 222002 (2015)



$e^+e^- \rightarrow \pi^0(D^*\bar{D})^0$

Zc(4025)⁺

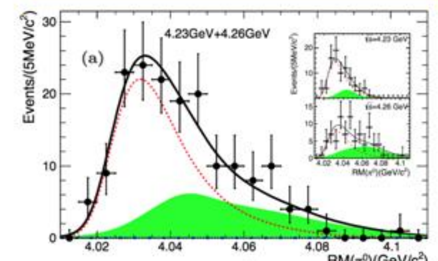
PRL 112, 132001 (2014)



$e^+e^- \rightarrow \pi^-(D^*\bar{D}^*)^+$

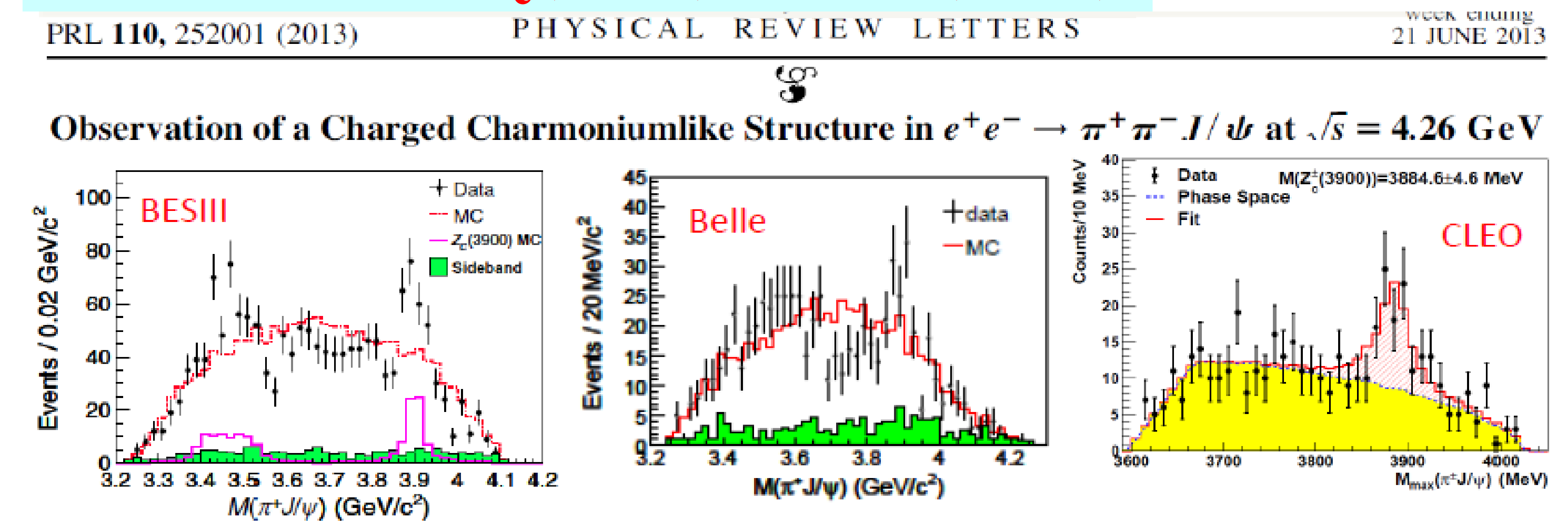
Zc(4025)⁰

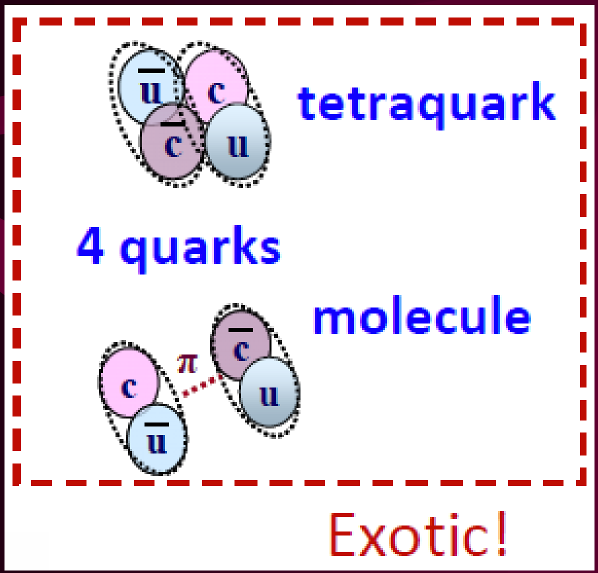
PRL115, 182002 (2015)

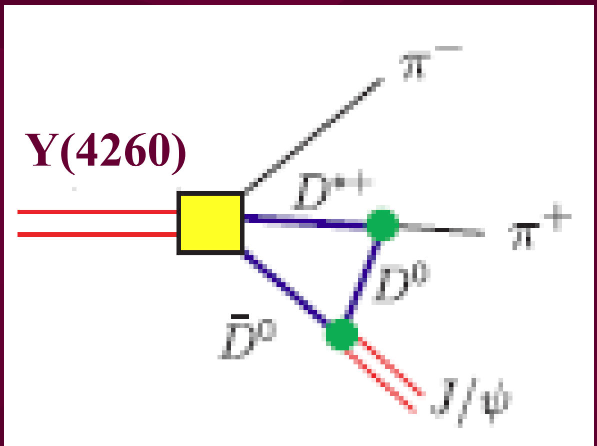


$e^+e^- \rightarrow \pi^0(D^*\bar{D}^*)^0$

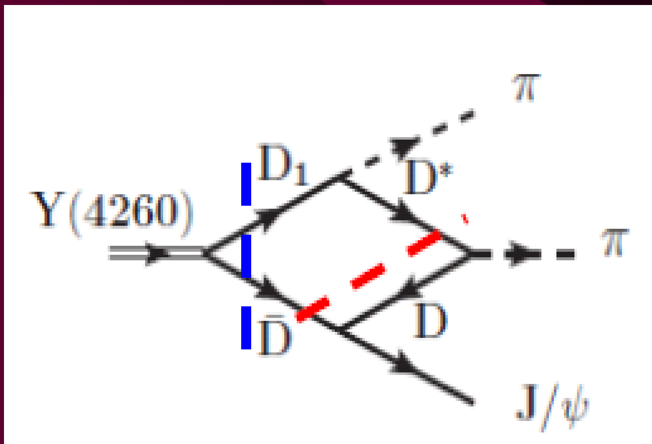
Production of $Z_c(3900)$ with Y(4260)







D.Y.Chen, X.Liu, PRD84(2011)034032



Q.Wang,C.Hanhart,Q.Zhao PRL111(2013)132003

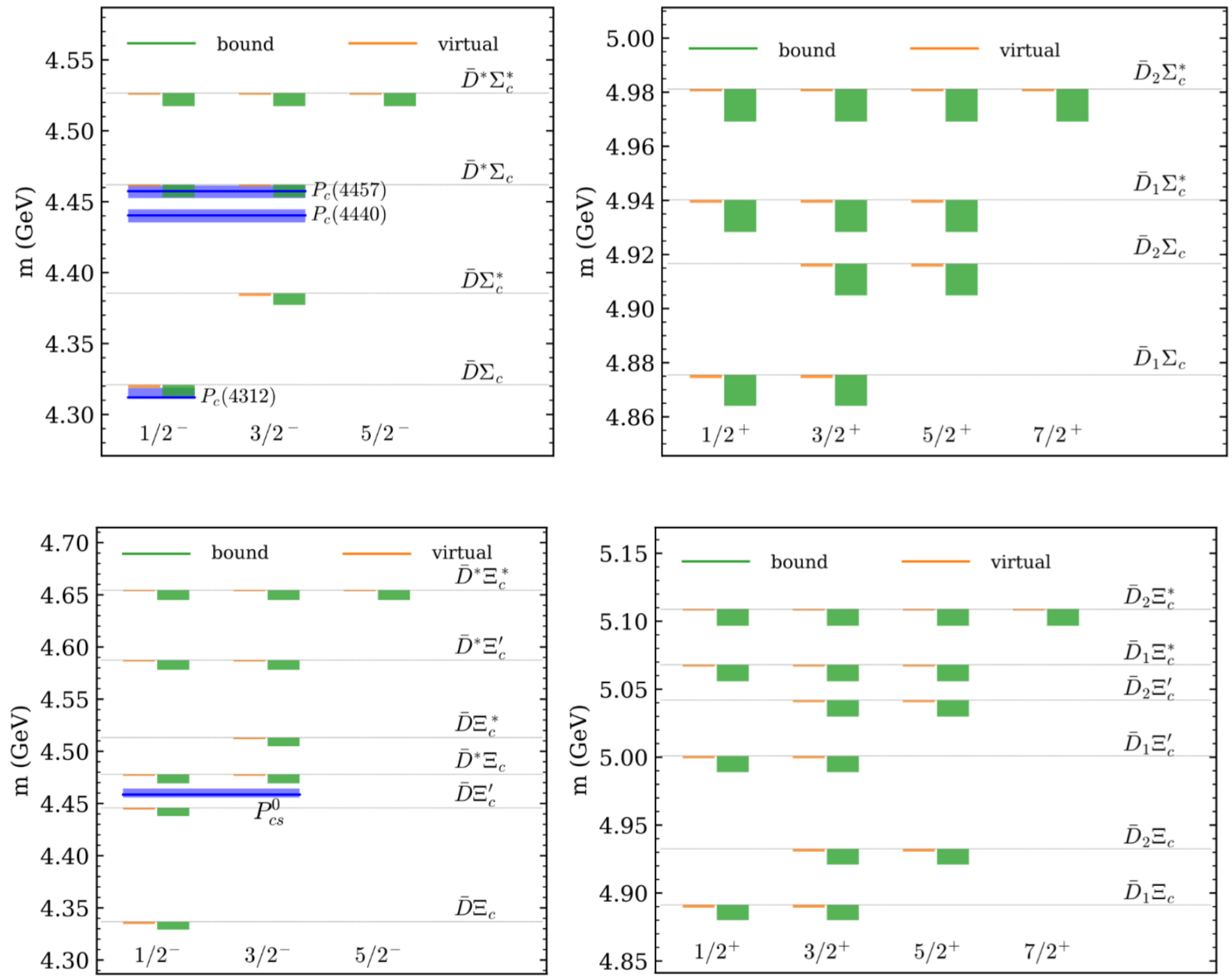
New Particles		relevant thresholds	
$Z_c(3900)$	$\bar{d}u\ \bar{c}c$	$\bar{D}^*D$	3880 MeV
$Z_c(4020)$		$\bar{D}^*D^*$	4020 MeV
$Z_b(10610)$	$\bar{d}u\ \bar{b}b$	$\bar{B}^*B$	10605 MeV
$Z_b(10650)$		$\bar{B}^*B^*$	10650 MeV
$P_c(4312)$	$uud\ \bar{c}c$	$\bar{D}\Sigma_c$	4318 MeV
$P_c(4440)$ & $P_c(4457)$		$\bar{D}^*\Sigma_c$	4459 MeV

Hadron-hadron resonances ?

F.K.Guo, Hanhart, Meissner,Q.Wang,Q.Zhao,Zou, **Rev.Mod.Phys.90 (2018)015004**

A survey of hadronic molecules with hidden charm

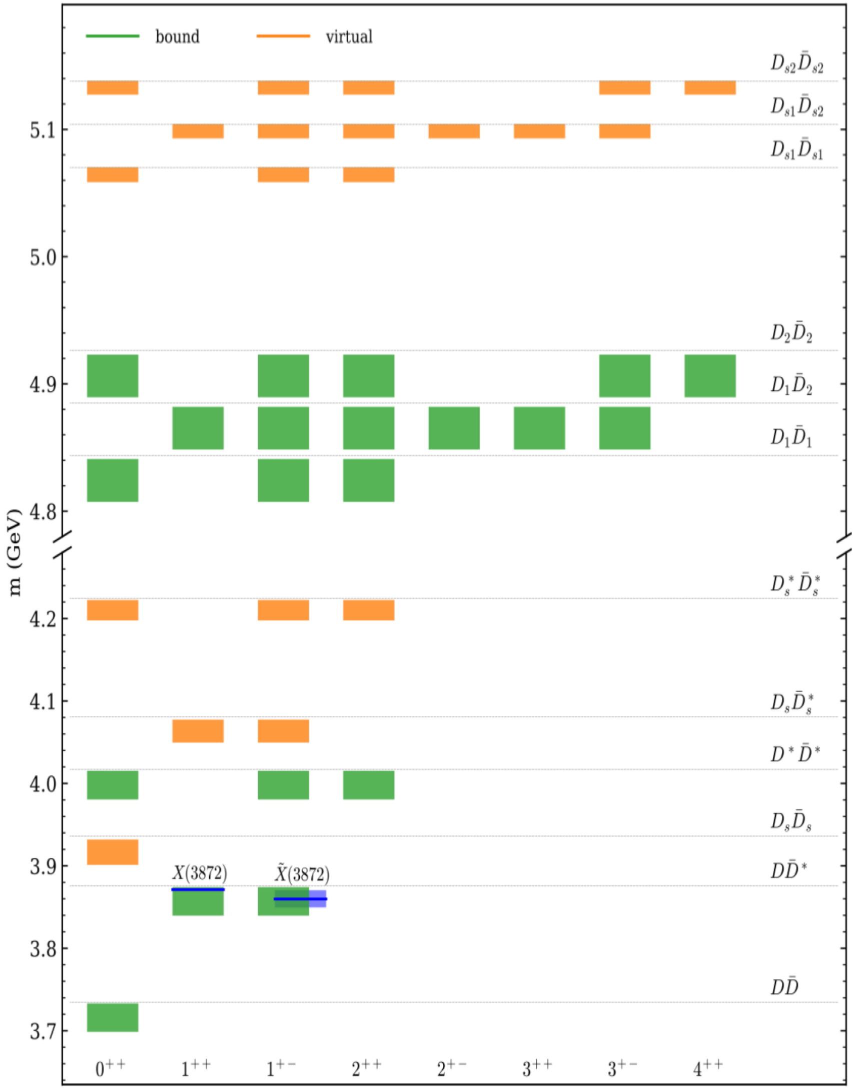
X.K.Dong, F.K.Guo, B.S.Zou Progr. Phys. 41 (2021) 65



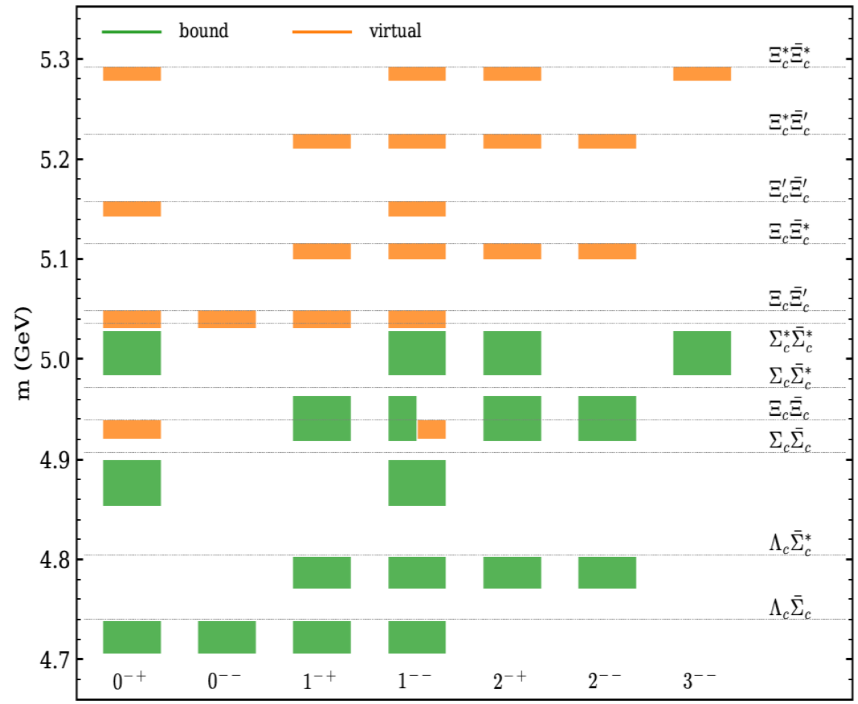
P_c

P_{cs}

Meson-meson molecules (I=0)



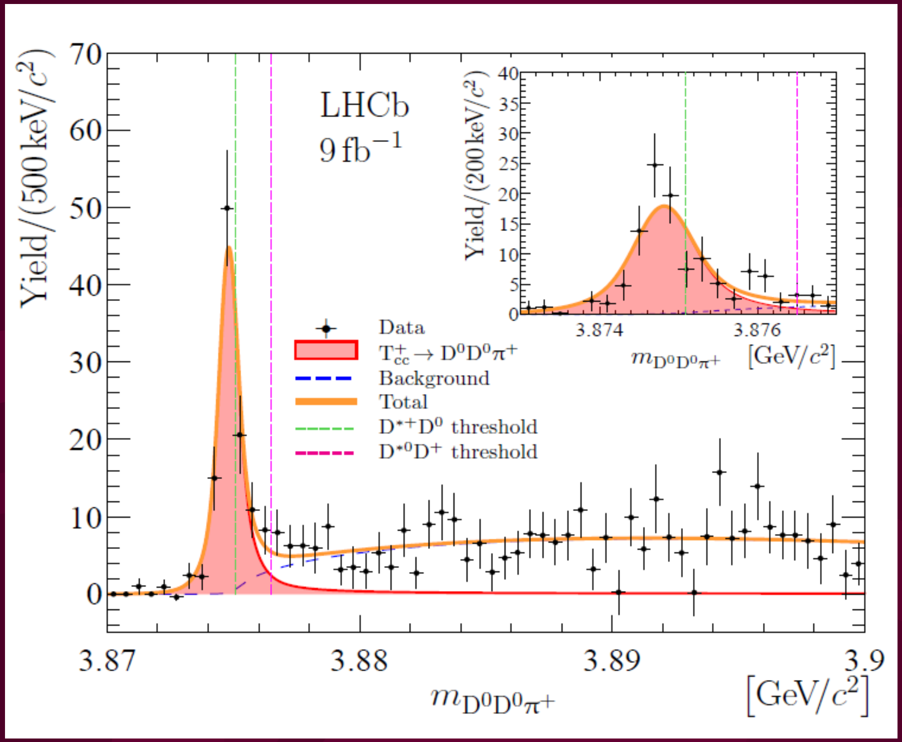
Baryon molecules (I=1) with $\bar{c}c$



- ✓ Isovector interaction between $D^{(*)}\bar{D}^{(*)}$ from light vector exchange vanishes
- ✓ Charmonia exchange could be important here: J/ψ, ψ' exchange
- ✓ $Z_c(3900,4020)$ as $\bar{D}^{(*)}D^*$ virtual states
- ✓ $Z_{cs}(3985)$ as $D_s\bar{D}^*, D\bar{D}_s^*$ virtual state
- ✓ $Z_c(4430)$ as $\bar{D}^*\bar{D}_1^*$virtual states

Observation of T_{cc}^+ by LHCb

Nature Phys. 18 (2022) 7, 751



Consistent with expectation for D*D molecule

X.K.Dong, F.K.Guo, B.S.Zou, Commun.Theor.Phys.73(2021)125201

T.Barnes, N.Black, D.Dean, E.Swanson, Phys.Rev.C60(1999)045202

D.Janc, M.Rosina, Few Body Syst. 35(2004)175

Y.Yang, C.Deng, J.Ping, T.Goldman, Phys.Rev.D80(2009)114023

T.Caramés, A.Valcarce, J.Vijande, Phys.Lett.B699(2011)291

S.Ohkoda, Y.Yamaguchi, S.Yasui, K.Sudoh, A.Hosaka, Phys.Rev.D86(2012)034019

N.Li, Z.F.Sun, X.Liu, S.L.Zhu, Phys.Rev.D88(2013)114008

M.Z.Liu, T.W.Wu, M.P.Valderrama, J.J.Xie, L.S.Geng, Phys.Rev.D99(2019)094018

H.Xu, B.Wang, Z.W.Liu, X.Liu, Phys.Rev.D99(2019)014027

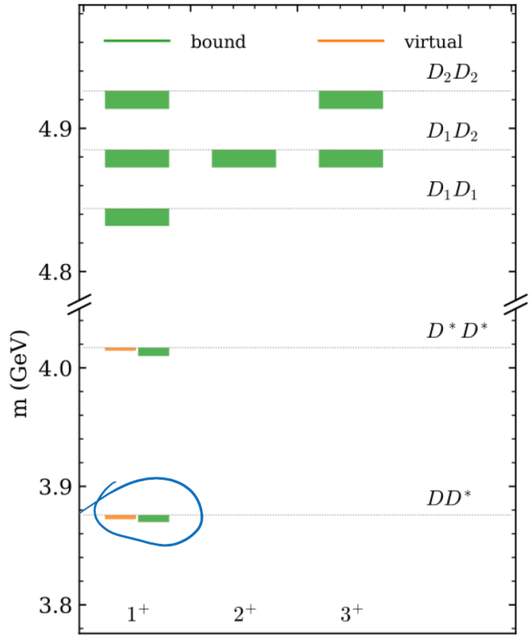
M.Z.Liu, J.J.Xie, L.S.Geng, Phys.Rev.D102(2020)091502

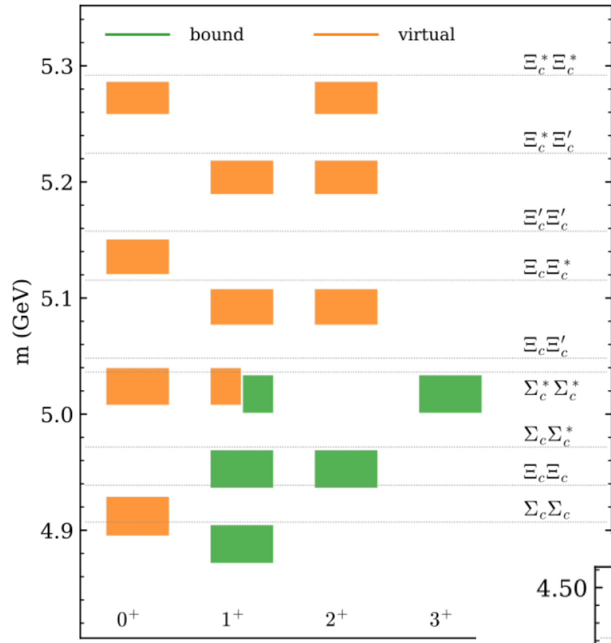
⇓ $V_{\rho,\omega} + V_{\pi} + \dots$

DD*(I=0, J^P =1$^+$) bound state -- T_{cc}^+

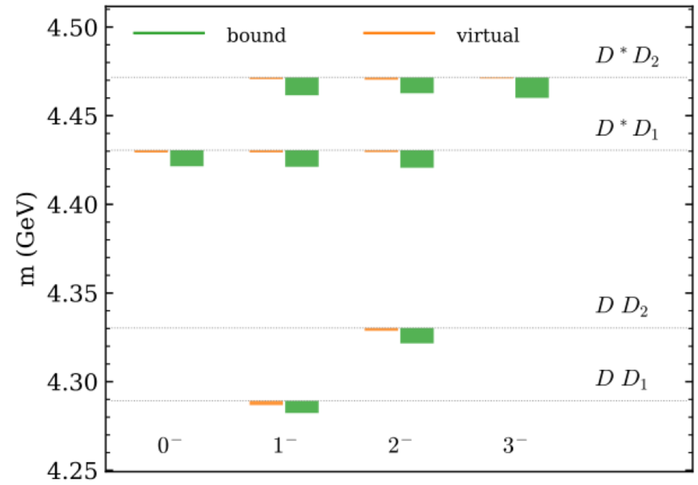
A survey of heavy-heavy hadronic molecules

X.K.Dong, F.K.Guo, B.S.Zou, Commun.Theor.Phys.73(2021)125201





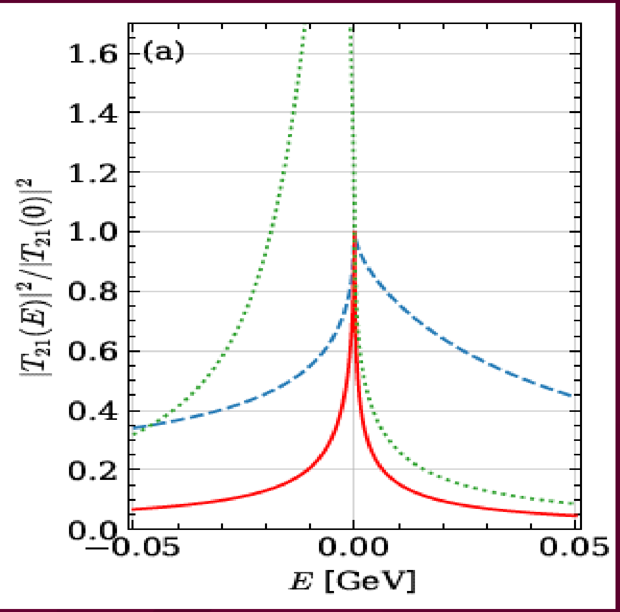
- ✓ Isoscalar $\Sigma_c^{(*)}\Sigma_c^{(*)}$ dibaryons very likely bound



- ✓ T_{cc} as an isoscalar DD^* bound or virtual state, D^*D^* predicted to be similar, with $P = +$
- ✓ Similar in $P = -$ sector

Explaining the many threshold structures in hadron spectrum with heavy quarks

X.K.Dong, F.K.Guo, B.S.Zou, PRL126 (2021) 152001



Prediction of a narrow exotic D^*D_1 molecule with $J^{PC}=0^{--}$

T.Ji, X.K.Dong, F.K.Guo, B.S.Zou, PRL129 (2022) 102002

$e^+e^- \rightarrow \eta\psi_0(4360) \rightarrow \eta\eta\psi$

Hybrid, Glueball or hadronic molecules ?

Observation of $\eta_1(1855)$ with exotic $J^{PC}=1^{-+}$ in $J/\psi \to \gamma\eta\eta'$

BESIII Collaboration, PRL 129 (2022) 192002

Interpretation of the $\eta_1(1855)$ as a $\bar{K}K_1$ (1400)+ c.c. molecule

X.K.Dong, Y.H.Lin, B.S.Zou, SCIENCE CHINA PMA 65 (2022) 261011

M.J.Yan, J.M.Dias, A.Guevara, F.K.Guo, B.S.Zou, Universe 9 (2023) 109

Two dynamical generated a_0 resonances by VV interactions

Z.L.Wang, B.S.Zou, EPJC 82 (2022) 509

$\rho\rho$ / $\rho\omega$ molecules → f_0 (1500) / a_0 (1450)

$\bar{K}^*K^*$(I=0,1) molecules → f_0 (1710) / a_0 (1710)

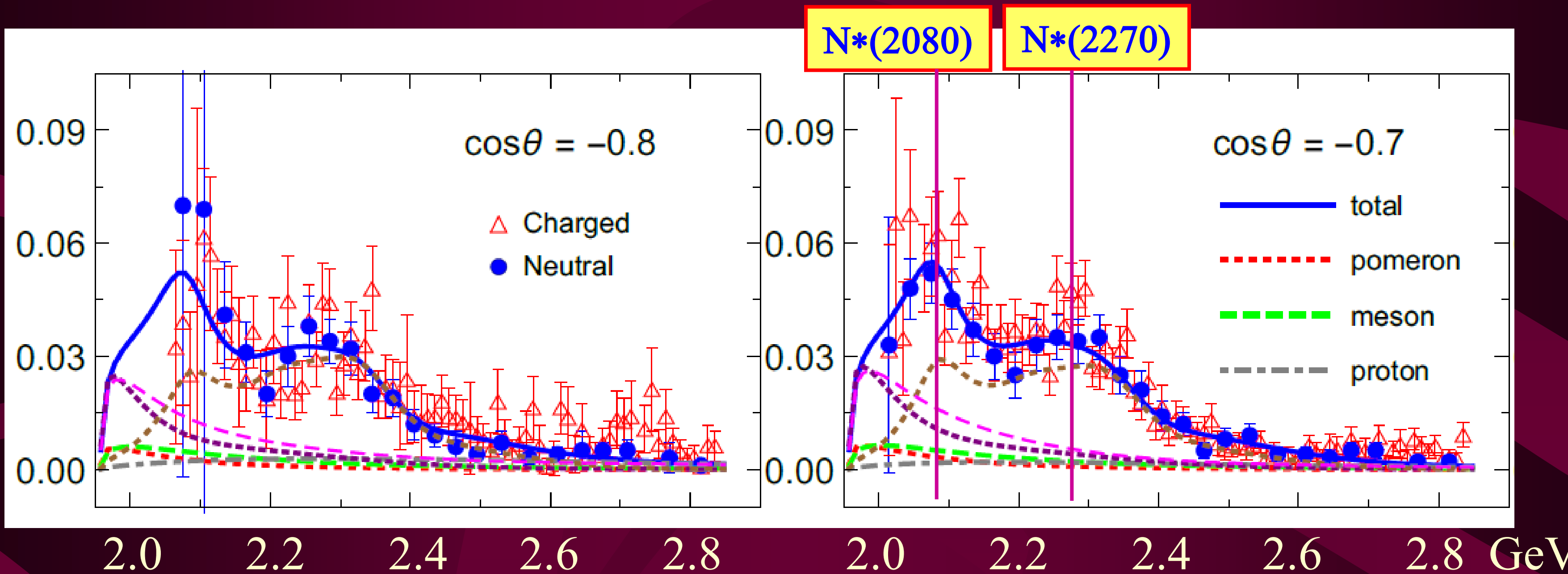
Observation of a_0 (1710) → $K_S^0K^+$ in D_s^+→ $K_S^0K^+\pi^0$ decay

BESIII Collaboration, PRL 129 (2022) 182001

Strange partners of P_c state from γp reactions

$\gamma p \to \phi p$

CLAS, PRC89(2014)019901



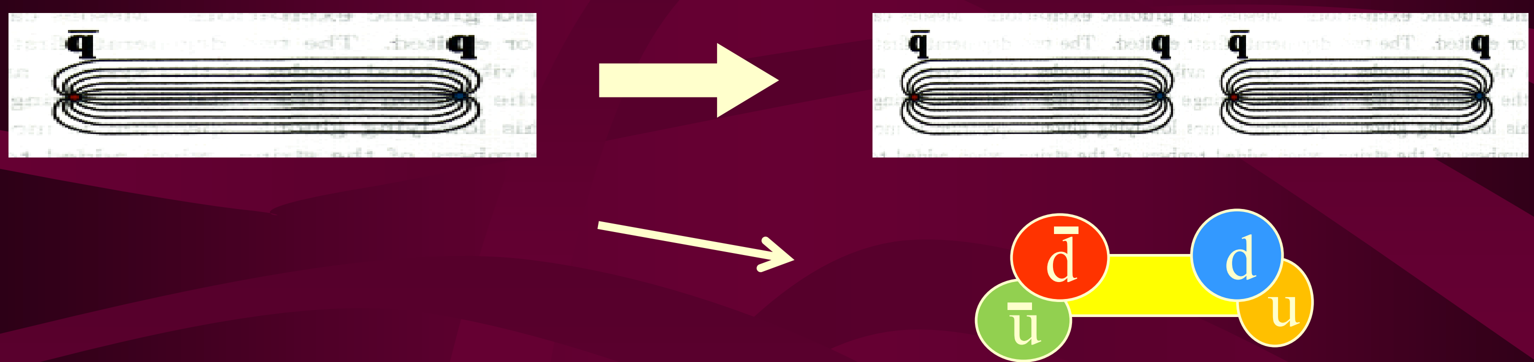
S.M.Wu, F.Wang, B.S.Zou, PRC108 (2023) 045201

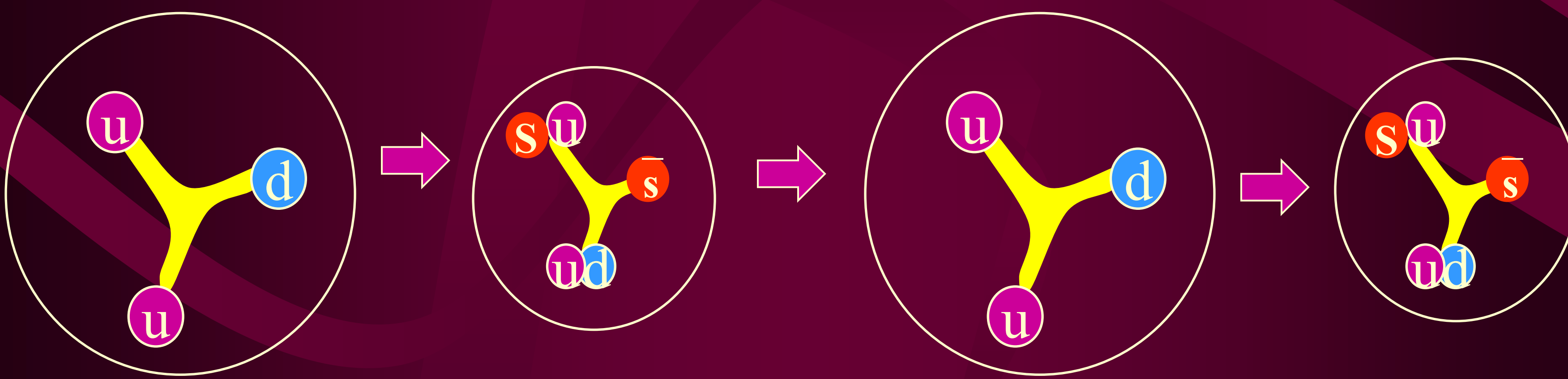
K*Σ ~ 2086 K*Σ* ~ 2280

4. Unquenched quark model

Unquenching dynamics: gluons → $\bar{q}q$

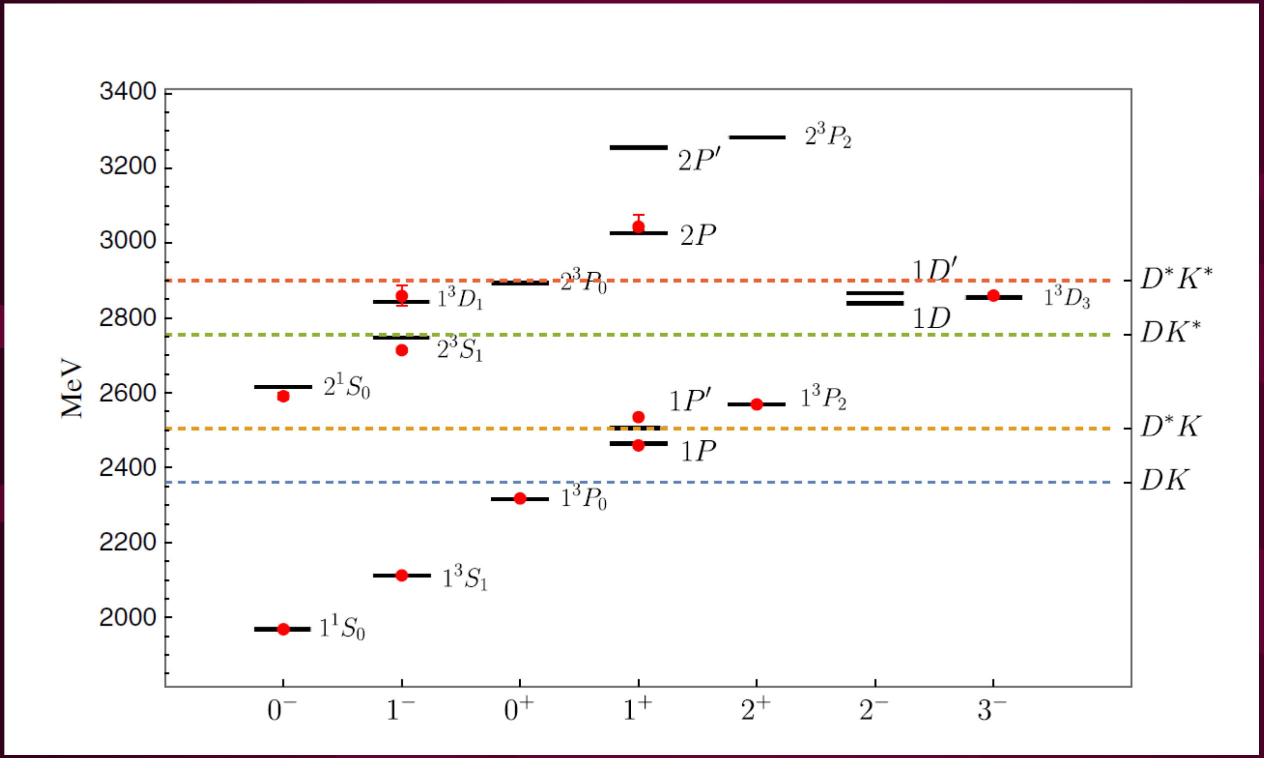
crucial for quark confinement & hadron structure





Unquenched quark model study of the charm-strange meson

W.Hao, Y.Lu, B.S.Zou, PRD106 (2022) 074014



Mass spectrum of Ds mesons

TABLE III. Probabilities (in %) of the coupled channels considered in this work. For the convenience of comparison, values from columns 3 to 12 (various coupled channels) are rescaled by $P_{c\bar{s}}$, such that $P_{c\bar{s}} = 100\%$. e.g., for $D_{s0}^*(2317)$, $P_{c\bar{s}}:P_{DK} = 100:45.5$ "–" means that the corresponding channel is open and its contribution to the wave function normalization is discarded, see the discussion below Eq. (15). $P_{c\bar{s}}$ and P_{molecule} represent the probability of the $c\bar{s}$ and the summation of the probability of all the coupled channels, respectively.

$(n_r+1)^{2S+1}L_J$	State	DK	DK^*	D^*K	D^*K^*	$D_s\eta$	$D_s\eta'$	$D_s\phi$	$D_s^*\eta$	$D_s^*\eta'$	$D_s^*\phi$	P_{molecule}	$P_{c\bar{s}}$
1^1S_0	D_s	0.0	4.3	3.5	8.5	0.0	0.0	1.1	0.7	0.2	2.2	17.0	83.0
1^3S_1	D_s^*	2.5	4.2	3.8	13.9	0.4	0.1	1.0	0.7	0.2	3.5	23.2	76.8
1^3P_0	$D_{s0}^*(2317)$	45.5	0.0	0.0	19.9	1.7	0.2	0.0	0.0	0.0	4.2	40.3	59.7
$1P$	$D_{s1}(2460)$	0.0	8.5	42.8	19.1	0.0	0.0	1.3	1.8	0.3	3.8	43.7	56.3
$1P'$	$D_{s1}(2536)$	–	10.8	–	17.9	–	–	1.7	1.9	0.4	3.4	26.5	73.5
1^3P_2	$D_{s2}^*(2573)$	–	8.5	–	22.8	–	0.2	1.4	1.2	0.3	4.0	27.7	72.3
2^1S_0	$D_{s0}(2590)$	–	20.4	–	26.2	–	–	2.0	4.1	0.4	3.7	36.2	63.8
2^3S_1	$D_{s1}^*(2700)$	–	51.3	–	47.3	–	0.2	1.6	–	0.3	4.7	51.3	48.7
1^3D_1	$D_{s1}^*(2860)$	–	–	–	47.6	–	0.5	0.6	–	0.1	5.8	35.3	64.7
$1D$	–	–	–	–	35.4	–	–	2.0	–	0.4	4.1	29.5	70.5
$1D'$	–	–	–	–	46.9	–	–	2.3	–	0.4	3.9	34.9	65.1
1^3D_3	$D_{s3}^*(2860)$	–	–	–	54.4	–	0.2	1.4	–	0.3	3.8	37.5	62.5
2^3P_0	–	–	–	–	167.5	–	0.6	–	–	–	4.0	63.2	36.8

Note: even for Ds (g.s.) there is 17% tetra-quark components

5. Summary and prospects

- all kinds of observed exotic states fit in hadronic molecule picture well, many more to be observed
- to understand hadron spectrum, quark model needs to be unquenched, with large hadronic molecule components when close to some thresholds
- Further experimental confirmation and extension for whole multiquark spectroscopy are necessary

ep/γp@JLab, π10/K10@JPARC, BelleII, BESIII, Eic/EicC, PANDA@FAIR, STCF etc. may play a important role here!

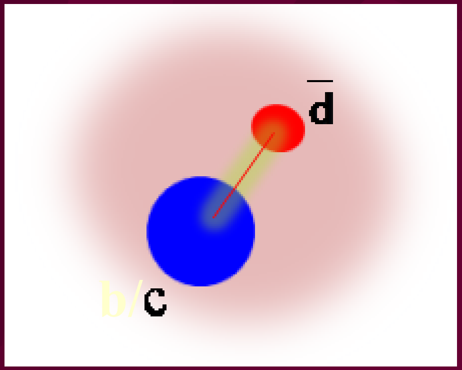
How to proceed ?

- **my favorite strategy for hadron spectroscopy:**

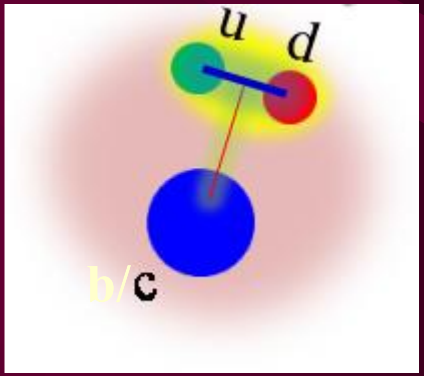
$\bar{c}cuud$ & $\bar{c}cuds$ → sss - $\bar{q}qsss$ → csq - $\bar{q}qcsq$ → cqq - $\bar{q}qcqq$ → hyperons → light baryons

$\bar{c}c$ $\bar{u}d$ & $\bar{c}s$ $\bar{u}d$ → $\bar{c}c$ - $\bar{q}q$ $\bar{c}c$ → $\bar{c}s$ - $\bar{c}s$ $\bar{q}q$ → $\bar{c}q$ - $\bar{c}q$ $\bar{q}q$ → K mesons → light mesons

s → c → b



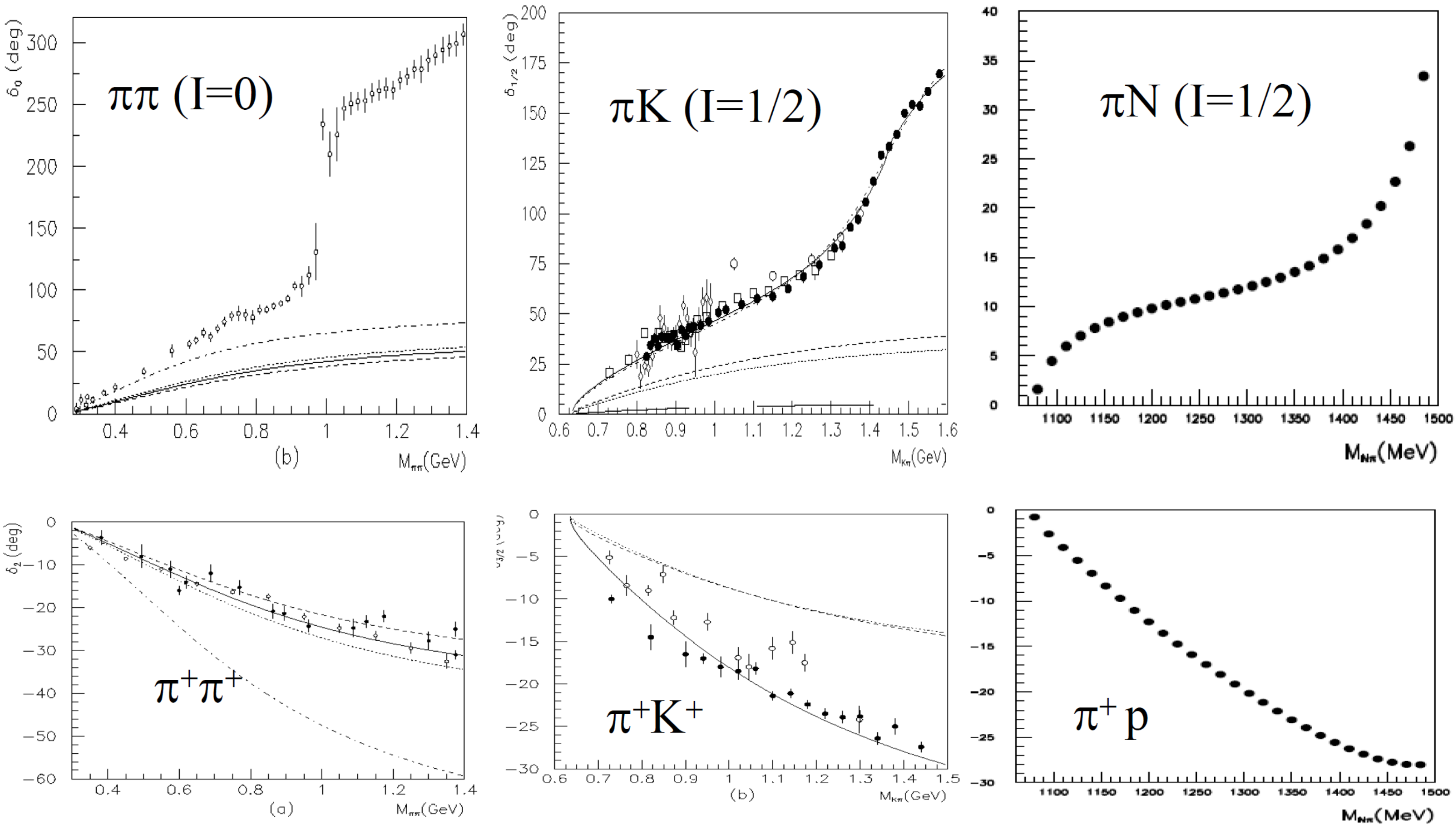
charm & beauty meson



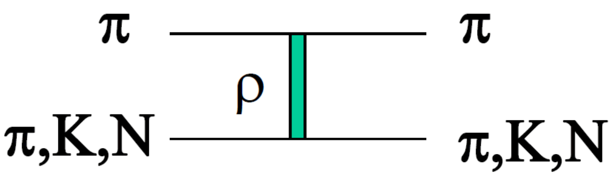
charm & beauty baryon

Thank you for your attention !

Similarity for ππ, πK and πN s-wave scattering → VMD



Important role by t-channel ρ exchange for all these processes



ππ

πK & πN

$K_\rho^{I=0} = -2\, K_\rho^{I=2}$, $K_\rho^{I=1/2} = -2\, K_\rho^{I=3/2}$

D. Lohse, J.W. Durso, K. Holinde, J. Speth, Nucl.Phys.A516, 513 (1990)
B.S.Zou, D.V.Bugg, Phys. Rev. D50, 591 (1994)

U. -G. Meissner, "Low-energy hadron physics from effective chiral Lagrangians with vector mesons", Phys. Rept. 161 (1988) 213

	$\bar{K}N(I=0)$	$\bar{K}N(I=1)$	$KN(I=0)$	$KN(I=1)$
VMD :	$-V_\omega - 3V_\rho$	$-V_\omega + V_\rho$	$V_\omega - 3V_\rho$	$V_\omega + V_\rho$

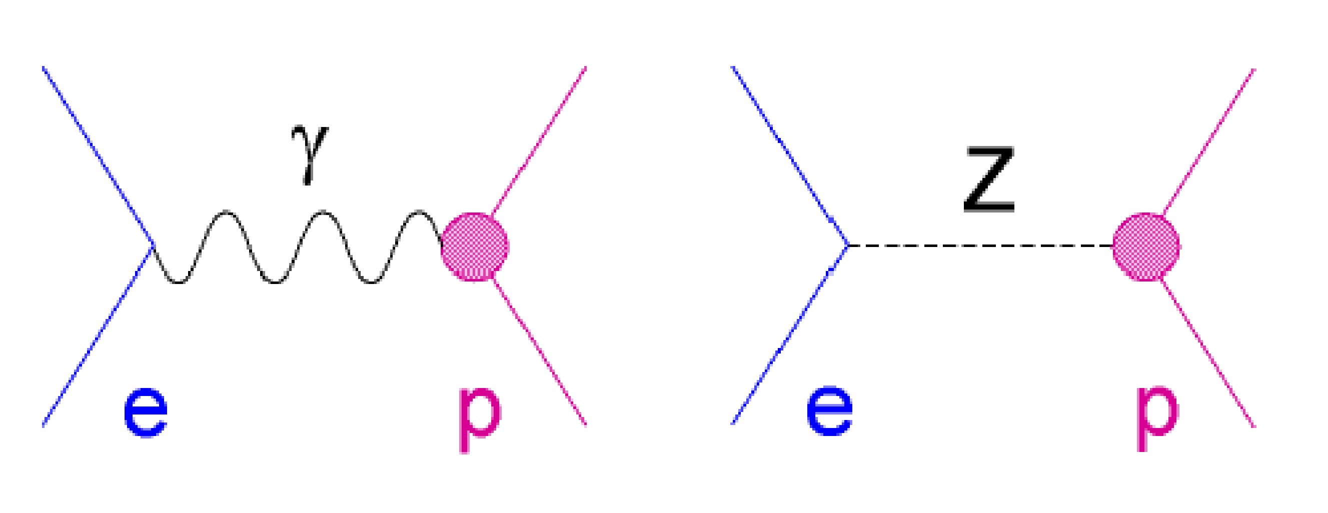
Similarity between $\pi\Sigma$ - $\bar{K}N(I=0)$ and $\pi\pi$ - $\bar{K}K(I=0)$

dipole structure for $\Lambda(1405)$ ← σ - $f_0(980)$

VMD – ChPT unitarized → N*(1535) as $K\Sigma$ bound state

Kaiser et al., PLB362(1995)23

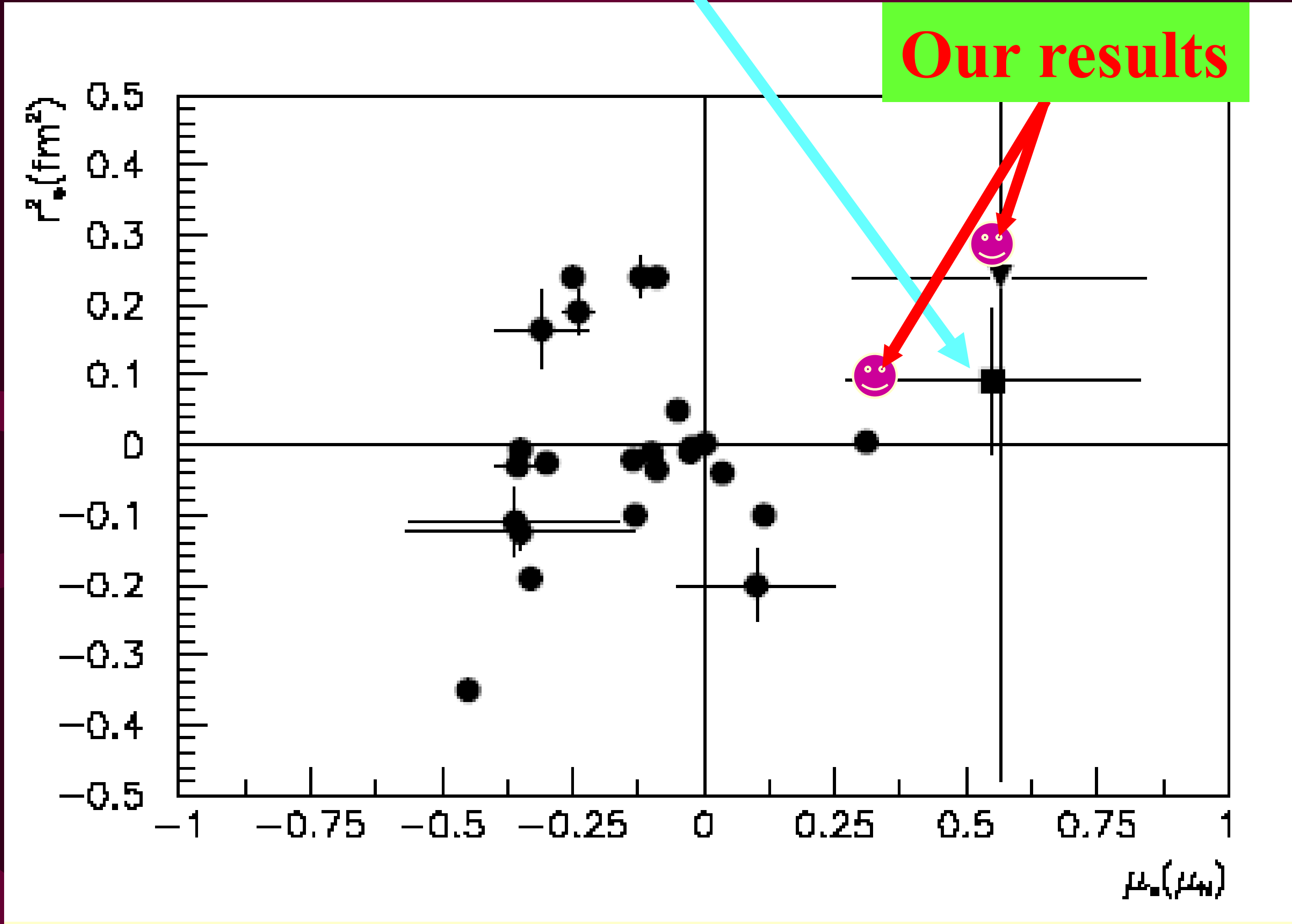
The strange magnetic moment μ_s and radii r_s from parity violating electron scattering



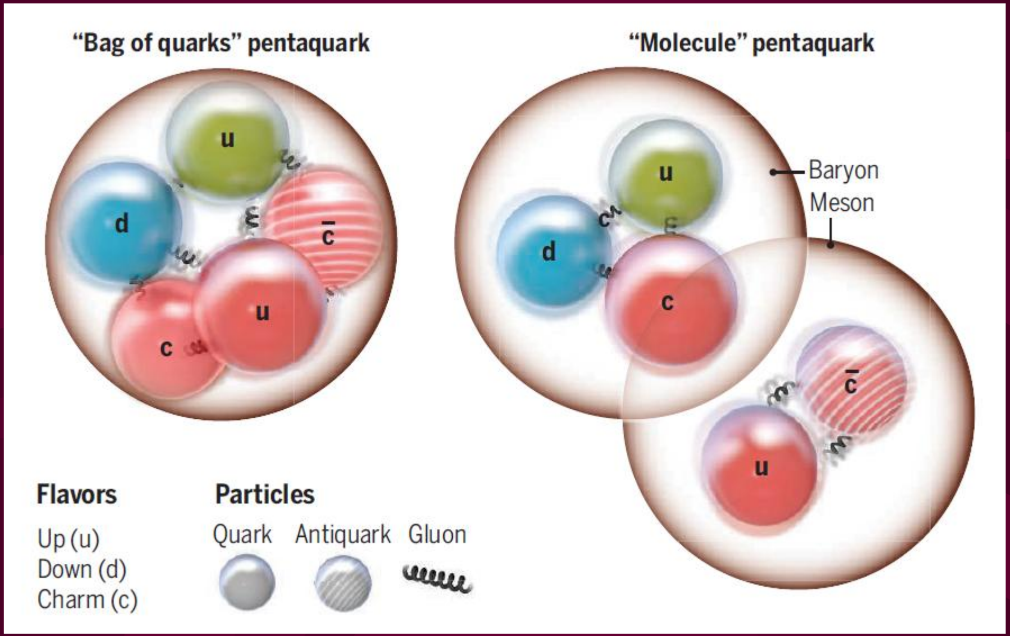
G0,HAPPEX/CEBAF, SAMPLE/MIT-Bates, A4/MAMI

HAPPEX/CEBAF, Phys.Rev.Lett. 96 (2006) 022003
G0/CEBAF, Phys.Rev.Lett. 95 (2005) 092001
A4/MAMI, Phys.Rev.Lett. 94 (2005) 152001
SAMPLE/MIT-Bates: Phys.Lett.B583 (2004) 79

Theory vs experiment for μ_s and r_s



B.S.Zou, D.O.Riska, Phys. Rev. Lett. 95 (2005) 072001
C.S.An,D.O.Riska,B.S.Zou, Phys. Rev. C73 (2006) 035207



“Bag of quarks” pentaquark
“Molecule” pentaquark
u
d
c̄
u
c
u
d
c
c̄
u
Baryon
Meson
Flavors
Up (u)
Down (d)
Charm (c)
Particles
Quark
Antiquark
Gluon

S.G.Yuan, K.W.Wei, J.He, H.S.Xu, B.S.Zou, "Study of $\bar{c}cqqq$ five quark system with three kinds of quark-quark hyperfine interaction," Eur. Phys. J. A48 (2012) 61

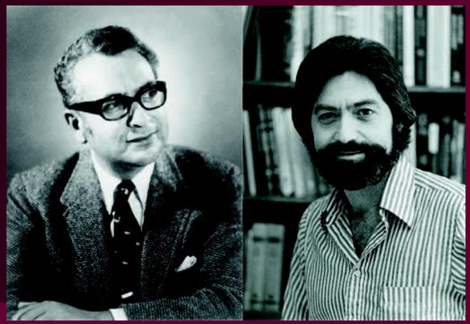
	CM		*FS*		*Inst.*	
J^P	$uds c\bar{c}$	$uud c\bar{c}$	$uds c\bar{c}$	$uud c\bar{c}$	$uds c\bar{c}$	$uud c\bar{c}$
$\frac{1}{2}^-$	4273	4267	4084	3933	4209	4114
$\frac{1}{2}^-$	4377	4363	4154	4013	4216	4131
$\frac{1}{2}^-$	4453	4377	4160	4119	4277	4204
$\frac{1}{2}^-$	4469	4471	4171	4136	4295	4207
$\frac{1}{2}^-$	4494	4541	4253	4156	4360	4272
$\frac{1}{2}^-$	4576		4263		4362	
$\frac{1}{2}^-$	4649		4278		4416	
$\frac{3}{2}^-$	4431	4389	4154	4013	4216	4131
$\frac{3}{2}^-$	4503	4445	4171	4119	4295	4204
$\frac{3}{2}^-$	4549	4476	4263	4136	4362	4272
$\frac{3}{2}^-$	4577	4526	4278	4236	4416	4322
$\frac{3}{2}^-$	4629		4362		4461	
$\frac{5}{2}^-$	4719	4616	4362	4236	4461	4322

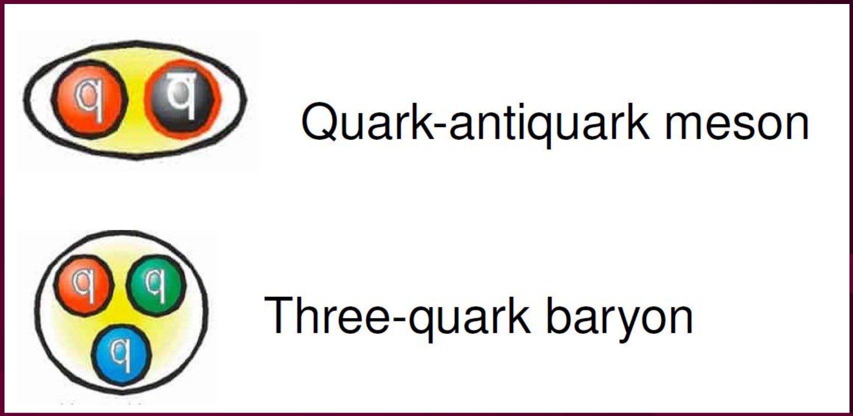
	CM		*FS*		*Inst.*	
J^P	$uds c\bar{c}$	$uud c\bar{c}$	$uds c\bar{c}$	$uud c\bar{c}$	$uds c\bar{c}$	$uud c\bar{c}$
$\frac{1}{2}^+$	4622	4456	4291	4138	4487	4396
$\frac{1}{2}^+$	4636	4480	4297	4140	4501	4426
$\frac{1}{2}^+$	4645	4557	4363	4238	4520	4426
$\frac{1}{2}^+$	4658	4581	4439	4320	4540	4470
$\frac{1}{2}^+$	4690	4593	4439	4367	4557	4482
$\frac{1}{2}^+$	4696	4632	4467	4377	4587	4490
$\frac{1}{2}^+$	4714	4654	4469	4404	4590	4517
$\frac{1}{2}^+$	4728	4676	4486	4489	4614	4518
$\frac{1}{2}^+$	4737	4714	4492	4508	4616	4549
$\frac{1}{2}^+$	4766	4720	4510	4515	4626	4566
$\frac{3}{2}^+$	4623	4457	4291	4138	4487	4396
$\frac{3}{2}^+$	4638	4515	4297	4140	4501	4426
$\frac{3}{2}^+$	4680	4561	4363	4238	4520	4426
$\frac{3}{2}^+$	4692	4582	4439	4320	4540	4470
$\frac{3}{2}^+$	4695	4625	4439	4367	4557	4482
$\frac{5}{2}^+$	4705	4539	4297	4140	4501	4426
$\frac{5}{2}^+$	4719	4649	4439	4320	4540	4470
$\frac{5}{2}^+$	4773	4689	4467	4367	4587	4482
$\frac{5}{2}^+$	4793	4696	4486	4404	4615	4490
$\frac{5}{2}^+$	4821	4710	4492	4515	4632	4517
$\frac{7}{2}^+$	4945	4841	4638	4508	4698	4566
$\frac{7}{2}^+$	4955	4862	4671	4551	4712	4634
$\frac{7}{2}^+$	4974	4919	4705	4587	4765	4669
$\frac{7}{2}^+$	5010		4759		4797	

$M(5/2^+) - M(3/2^-)$: 130 ~300 MeV

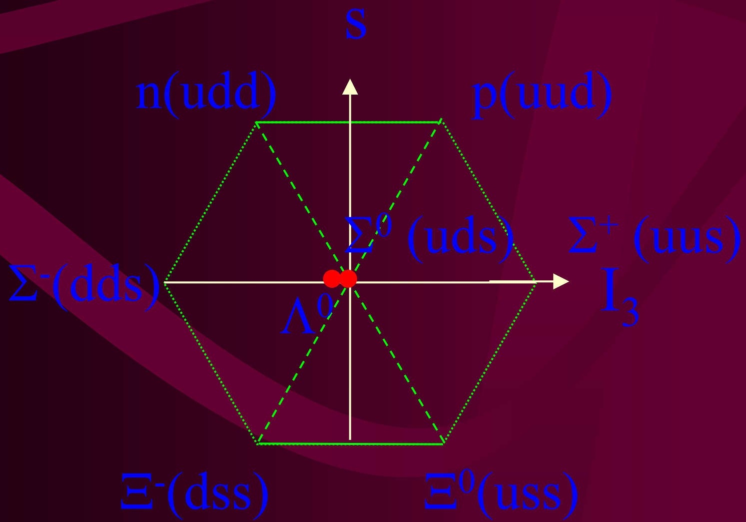
Quenched Quark models

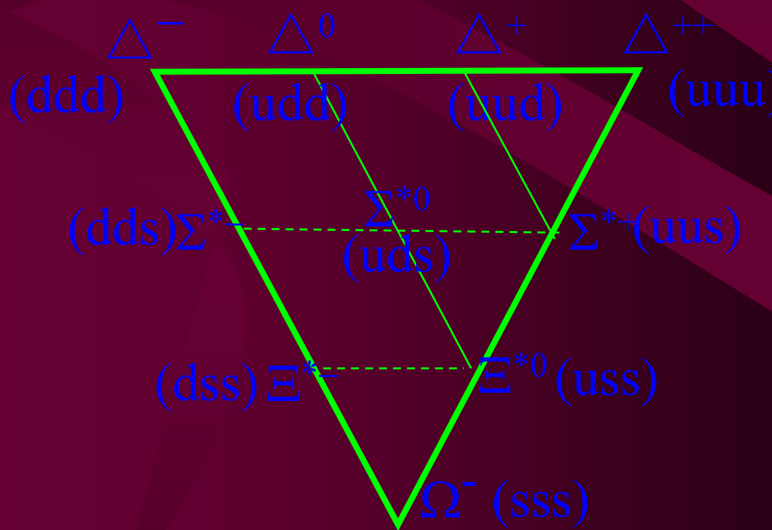
- **1964 – Invention of constituent Quark Model**





Successful for SU(3) mesons and baryons of spatial ground states





● 1974 – Cornell potential for $\bar{c}c$ spectrum

E.Eichten et al., PRL 34 (1975) 369 1281 cites

$$\hat{H}_0 = \frac{p^2}{m_Q} + V_0(r) + V_{\rm SD}(r)$$

$$V_0(r) = \sigma r - \frac{\frac{4}{3}\alpha_s}{r} + C_0 \qquad \text{(Cornell potential)}$$

$$V_{SD}(r) = \underbrace{V_{LS}(r)(\boldsymbol{L}\cdot(\boldsymbol{S}_Q + \boldsymbol{S}_{\bar{Q}}))}_{\text{fine structure}} + \underbrace{V_{SS}(r)(\boldsymbol{S}_Q\cdot\boldsymbol{S}_{\bar{Q}})}_{\text{hyperfine structure}}$$

$$+ \underbrace{V_{ST}(r)\Big((\boldsymbol{S}_Q\cdot\boldsymbol{S}_{\bar{Q}}) - 3(\boldsymbol{S}_Q\cdot\boldsymbol{n})(\boldsymbol{S}_{\bar{Q}}\cdot\boldsymbol{n})\Big)}_{\text{spin tensor force}} \quad \propto \quad \frac{1}{m_Q^2}$$

Extension to light mesons and baryons: surprisingly well !

S. Godfrey, N. Isgur, *PRD* 32 (1985) 189 3221 cites

Mesons in a relativized quark model with chromodynamics

S.Capstick, N. Isgur, *PRD* 34 (1986) 2809 1464 cites

Baryons in a relativized quark model with chromodynamics

1984 – Chiral Quark Model

A. Manohar, H. Georgi, NPB 234 (1984) 189 2314 cites

- quarks with masses generated by SχSB
- pions as Nambu-Goldstone bosons

- K. Shimizu, Phys. Lett. B 148, 418-422 (1984)
  - pseudo-scalar mesons + confining potential (CON)
- I. T. Obukhovsky and A. M. Kusainov, Phys. Lett. B 238, 142-148 (1990).
  - scalar and pseudo-scalar mesons + one-gluon exchange (OGE) + CON
- L. Y. Glozman and D. O. Riska, Phys. Rept. 268, 263-303 (1996); L. Y. Glozman, Nucl. Phys. A 663, 103-112 (2000).
  - pseudo-scalar and vector mesons + CON to study baryon spectrum
- L. R. Dai, Z. Y. Zhang, Y. W. Yu and P. Wang, Nucl. Phys. A 727, 321-332 (2003).
  - scalar, pseudo-scalar, vector mesons + OGE + CON to study phase shift of NN scattering
- J. Vijande, F. Fernandez and A. Valcarce, J. Phys. G 31, 481 (2005); J. Vijande and A. Valcarce, Phys. Lett. B 677, 36-38 (2009); A. Valcarce, H. Garcilazo, F. Fernandez and P. Gonzalez, Rept. Prog. Phys. 68 (2005), 965-1042.
  - scalar, pseudo-scalar mesons + OGE + CON to study meson and baryon spectra.
  - did not include the vector mesons for avoiding the double counting.

slide from Masa Harada

slide from Masa Harada

Problem and Proposal

- A chiral quark model with π and σ provides too much strong attractive force between two quarks which form a good diquark:
  - $M_N^{(exp)} - M_N^{(theo)} = 262\ MeV$
  - $M_{\Lambda_c}^{(exp)} - M_{\Lambda_c}^{(theo)} = 322\ MeV$
  - $M_{\Lambda_b}^{(exp)} - M_{\Lambda_b}^{(theo)} = 359\ MeV$

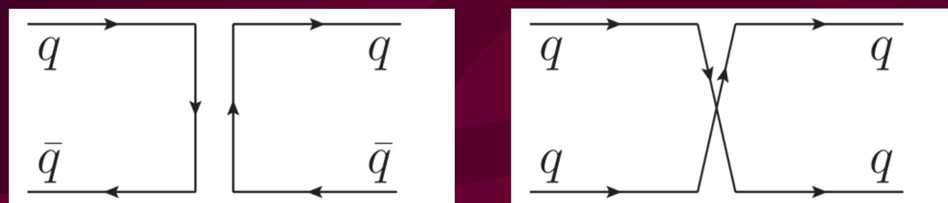
We use best fitted parameters in [J. Vijande, F. Fernandez and A. Valcarce, J. Phys. G 31, 481 (2005)].

- New chiral quark model with vector mesons
  - ρ and ω are included based on the Hidden Local Symmetry(HLS)
  - $m_\rho,\ m_\omega \sim 780\ MeV < \Lambda_\chi$!

● 2023 – Chiral Quark Model with HLS

B.R.He, M.Harada, B.S.Zou, PRD 108 (2023) 054025; EPJC 83 (2023) 1159

HLS - a systematic way to include (π, K, η, η') & $(\rho, K^*, \omega, \phi)$



Meson exchange ~ quark exchange effect

- **Masses of N, Λ_c, Λ_b are fitted well, mainly owing to the effects of ω meson : attractive for $q\bar{q}$ & repulsive for qq**
- **Masses of all observed g.s. hadrons are beautifully fitted, with unobserved ones predicted in agreement with LQCD**
- **T_{cc}-molecule-like structure, T_{bb}-diquark-like structure**