Strategy for hadron spectroscopy

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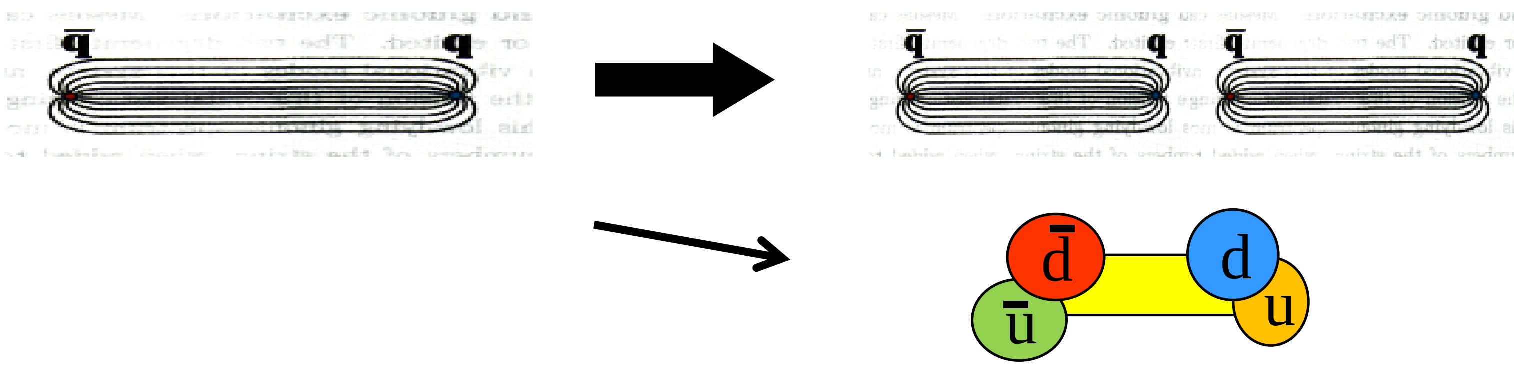
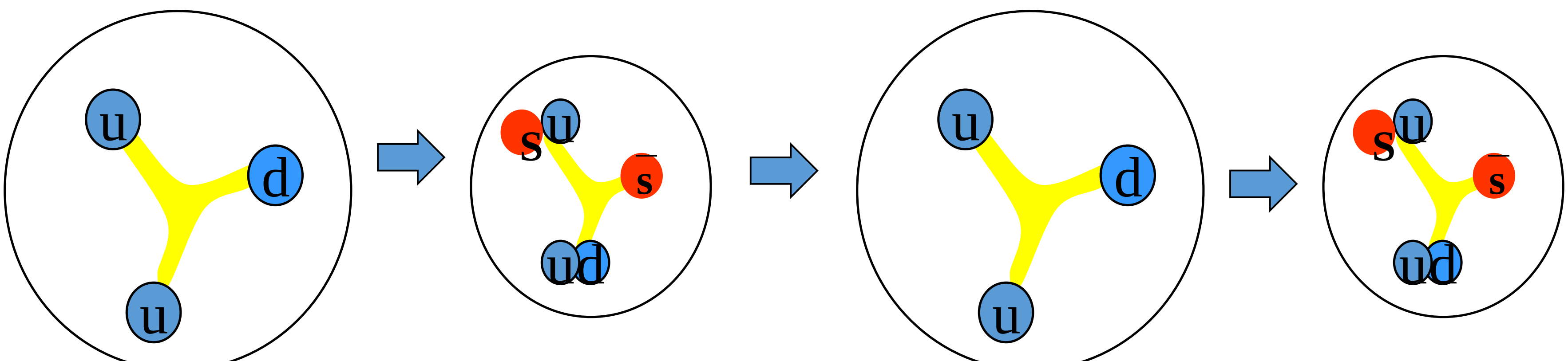
Prepared for the Changsha Workshop, Nov. 4-9 2018

1. Key problem in hadron spectroscopy:

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

crucial for quark confinement & hadron structure



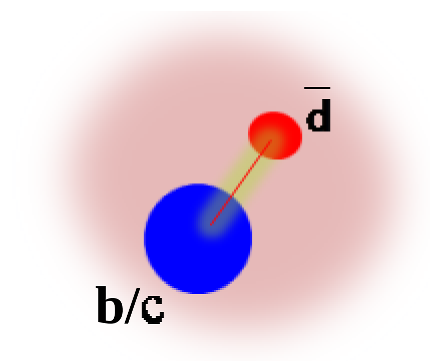


2. my favorite strategy for hadron spectroscopy:

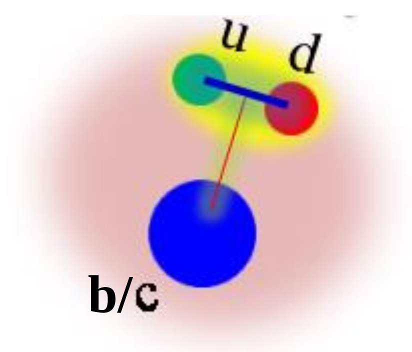
$\bar{c}cuud$ & $\bar{c}cuds$ → sss - $\bar{q}qsss$ → cqq - $\bar{q}qcqq$
→ hyperons → light baryons

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

s → c → b



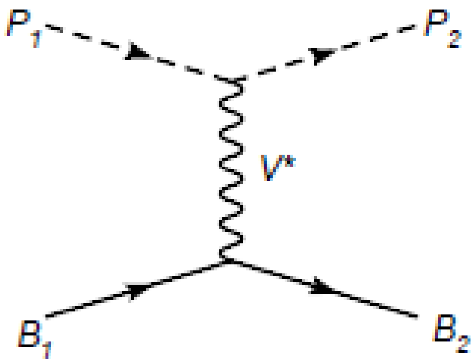
charm & beauty meson



charm & beauty baryon

3. Predictions of pentaquark states with hidden charm

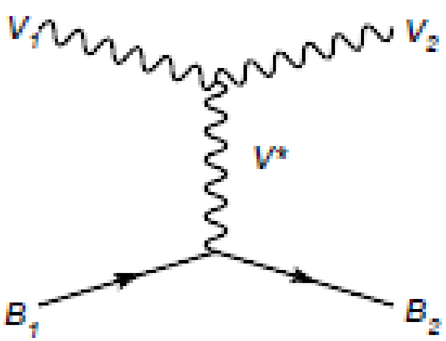
[1] J.J.Wu, R.Molina, E.Oset, B.S.Zou, "Prediction of narrow N* and Λ* resonances with hidden charm above 4 GeV", PRL105 (2010) 232001; "Dynamically generated N* and Λ* resonances in the hidden charm sector around 4.3 GeV," PRC84 (2011) 015202



$$\mathcal{L}_{VVV} = ig\langle V^\mu [V^\nu, \partial_\mu V_\nu]\rangle$$
$$\mathcal{L}_{PPV} = -ig\langle V^\mu [P, \partial_\mu P]\rangle$$
$$\mathcal{L}_{BBV} = g(\langle \bar{B}\gamma_\mu [V^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle)$$

$$V_{ab(P_1 B_1 \to P_2 B_2)} = \frac{C_{ab}}{4f^2}(E_{P_1} + E_{P_2}),$$

$$V_{ab(V_1 B_1 \to V_2 B_2)} = \frac{C_{ab}}{4f^2}(E_{V_1} + E_{V_2})\vec{\epsilon}_1 \cdot \vec{\epsilon}_2,$$



$$T = [1 - VG]^{-1} V \qquad T_{ab} = \frac{g_a g_b}{\sqrt{s} - z_R}$$

$K\Sigma$, Kp → $\bar{D}^{(*)}\Sigma_c$, $\bar{D}_s^{(*)}\Lambda_c$ bound states

	(I,S)	z_R (MeV)	g_a			J^P
N*	$(1/2,0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$		$1/2^-$
		4269	2.85	0		
Λ*	$(0,-1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi'_c$	
		4213	1.37	3.25	0	
		4403	0	0	2.64	

TABLE III: Pole positions z_R and coupling constants g_a for the states from $PB \to PB$.

	(I,S)	z_R (MeV)	g_a			J^P
N*	$(1/2,0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$		$1/2^-$, $3/2^-$
		4418	2.75	0		
Λ*	$(0,-1)$		$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi'_c$	
		4370	1.23	3.14	0	
		4550	0	0	2.53	

TABLE IV: Pole position and coupling constants for the bound states from $VB \to VB$.

	(I,S)	M	Γ	Γ_i						J^P
N*	$(1/2,0)$			πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$	
		4261	56.9	3.8	8.1	3.9	17.0		23.4	$1/2^-$
	$(0,-1)$			$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$	
Λ*		4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8	
		4394	43.3	0	10.6	7.1	3.3	5.8	16.3	

TABLE V: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $PB \to PB$, with units in MeV.

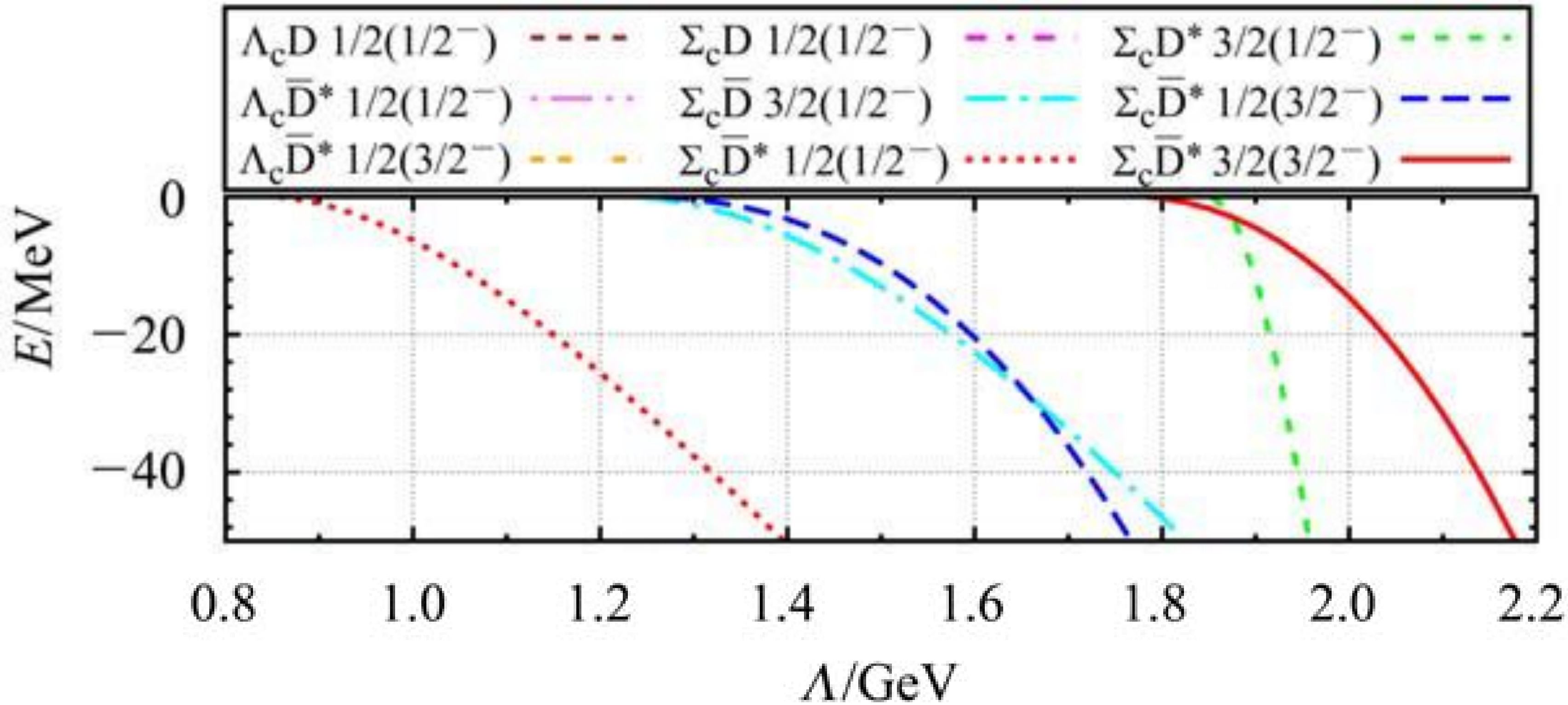
	(I,S)	M	Γ	Γ_i						J^P
N*	$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$	
		4412	47.3	3.2	10.4	13.7			19.2	$1/2^-$, $3/2^-$
	$(0,-1)$			$\bar{K}^*N$	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$	
Λ*		4368	28.0	13.9	3.1	0.3	4.0	1.8	5.4	
		4544	36.6	0	8.8	9.1	0	5.0	13.8	

TABLE VI: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $VB \to VB$ with units in MeV.

[2] Z.C.Yang, Z.F.Sun, J.He, X.Liu, S.L.Zhu, "The possible hidden-charm molecular baryons composed of anti-charmed meson and charmed baryon,'' Chin. Phys. C36 (2012) 6

Schoedinger Equation method with π, η, ρ, ω, σ exchanges:

$\bar{D}^*\Sigma_c$ ($3/2^-$) N* state -- 4360 ~ 4460 MeV



[3] C.W.Xiao, J.Nieves, E.Oset, “Combining heavy quark spin and local hidden gauge symmetries in the dynamical generation of hidden charm baryons”, PRD 88 (2013) 056012

3 $J^P = 3/2^-$ P_c^+ states : $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ states

TABLE II. The coupling constants to various channels for certain poles in the $J = 3/2$, $I = 1/2$ sector.

$4334.45 + i19.41$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$1.31 - i0.18$	$0.16 - i0.23$	$0.20 - i0.48$	$2.97 - i0.36$	$0.24 - i0.76$
$\|g_i\|$	1.32	0.28	0.52	2.99	0.80
$4417.04 + i4.11$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.53 - i0.07$	$0.08 - i0.07$	$2.81 - i0.07$	$0.12 - i0.10$	$0.11 - i0.51$
$\|g_i\|$	0.53	0.11	2.81	0.16	0.52
$4481.04 + i17.38$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$1.05 + i0.10$	$0.18 - i0.09$	$0.12 - i0.10$	$0.22 - i0.05$	$2.84 - i0.34$
$\|g_i\|$	1.05	0.20	0.16	0.22	2.86

a $J^P = 5/2^-$ P_c^+ state : $\bar{D}^*\Sigma_c^*$ bound states at 4487 MeV

[4] 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	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^-$	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	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^+$	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	

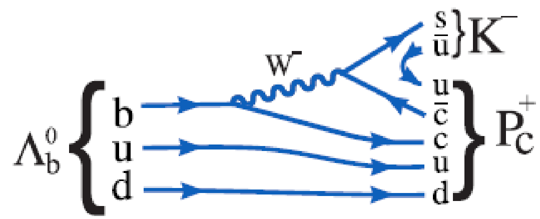
$M(5/2^+) - M(3/2^-)$: 130 ~300 MeV

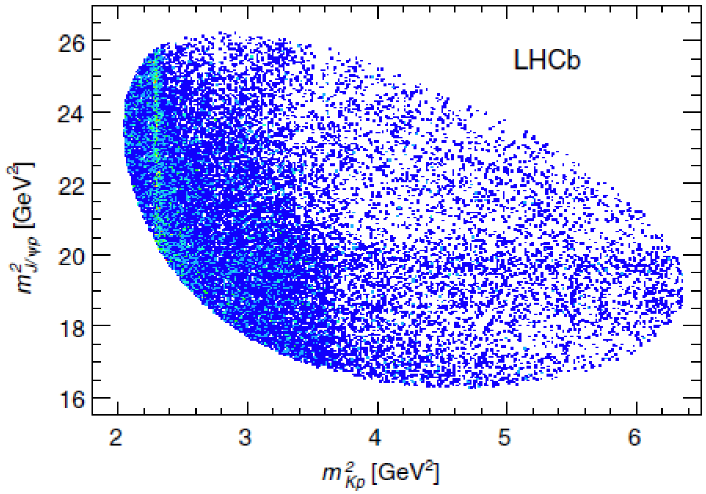
Observation of P_c states

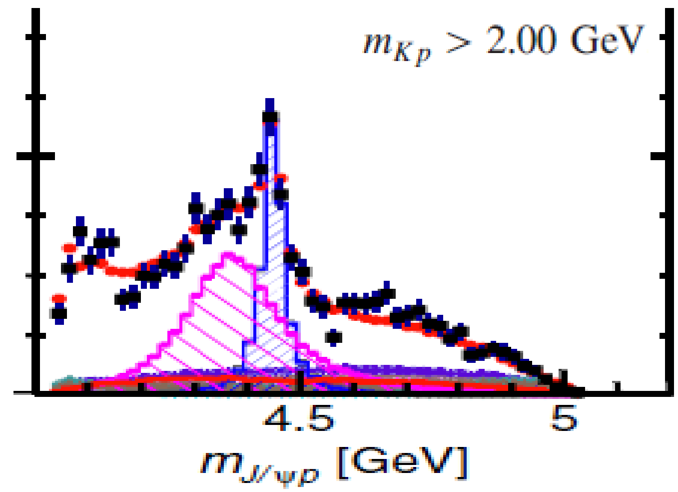
LHCb, Phys.Rev.Lett. 115 (2015) 072001 :

Observation of two N* from $\Lambda_b^0 \to J/\psi K^- p$

631 cites - the top cited paper on HS since 2010







1) 4380±8±29 MeV , 205±18±86 MeV, $P_c^+(4380)$

2) 4450±2±3 MeV , 39±5±19 MeV, $P_c^+(4450)$

The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

Progress on P_c states after LHCb observation

Thresholds $\bar{D}\Sigma_c^*$ **(4383MeV),** $\bar{D}^*\Sigma_c$ **(4460MeV),** $p\chi_{c1}$ **(4449MeV)**

1) $\bar{D}\Sigma_c^*$ **,** $\bar{D}^*\Sigma_c$ **,** $\bar{D}^*\Sigma_c^*$ **molecular states**

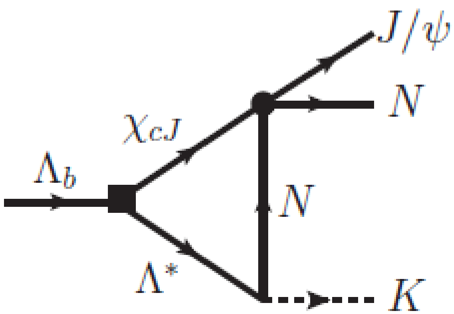
R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;
H.X.Chen, W.Chen, X.Liu, T.G.Steele, S.L.Zhu, PRL115 (2015)172001
L.Roca, J.Nieves, E.Oset, PRD92 (2015) 094003;
J.He, PLB 753 (2016)547 ;

2) diquark *cu* & triquark $\bar{c}(ud)$ **states**

L.Maiani, A.D.Polosa, V. Riquer, PLB749 (2015) 289;
R.Lebed, PLB749 (2015) 454;
G.N.Li, M.He, X.G.He, JHEP 1512 (2015) 128;
R.Zhu, C.F.Qiao, PLB756 (2016) 259;

3) Kinematic triangle-singularity

F.K.Guo, Ulf-G.Meißner, W.Wang, Z.Yang, PRD92 (2015) 071502
X.H.Liu, Q.Wang, Q.Zhao, PLB757 (2016) 231



For comprehensive reviews, cf.:

H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1
F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou, RMP 90 (2018)015004

$\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ bound states

[1] R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;

$P_c^+(4380)$ -- $\bar{D}^*\Sigma_c$ $3/2^-$; $P_c^+(4450)$ -- $\bar{D}^*\Sigma_c^*$ $5/2^-$

[2] Y.Yamaguchi, E. Santopinto, PRD96 (2017) 014018

$P_c^+(4380)$ -- $\bar{D}^{(*)}\Sigma_c^{(*)}$ - $\bar{D}^{(*)}\Lambda_c$ $3/2^+$; $P_c^+(4450)$ -- $\bar{D}^{(*)}\Sigma_c^{(*)}$ - $\bar{D}^{(*)}\Lambda_c$ $5/2^-$

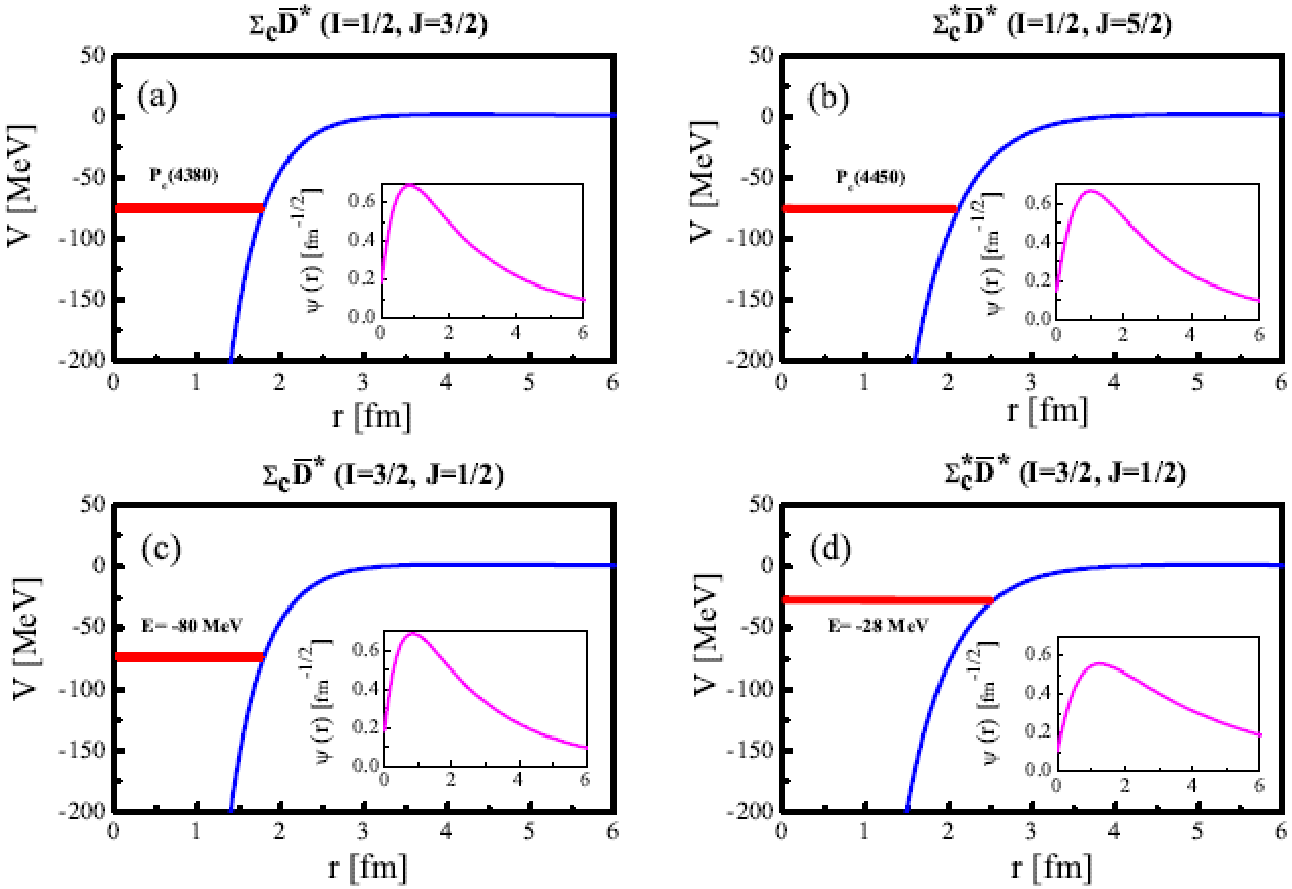
[3] J.He, PLB 753 (2016)547 ; PRD95 (2017)074004
Y.H.Lin, C.W.Shen, F.K.Guo, B.S.Zou, PRD95(2017)114017

$P_c^+(4380)$ -- $\bar{D}\Sigma_c^*$/ $\bar{D}^*\Sigma_c$ $3/2^-$; $P_c^+(4450)$ -- $\bar{D}^*\Sigma_c$ $5/2^+$

→ Different predictions to be checked !

[1] R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002

OPE: Prediction of I=3/2 pentaquarks !



[2] Y.Yamaguchi, E. Santopinto, PRD96 (2017) 014018

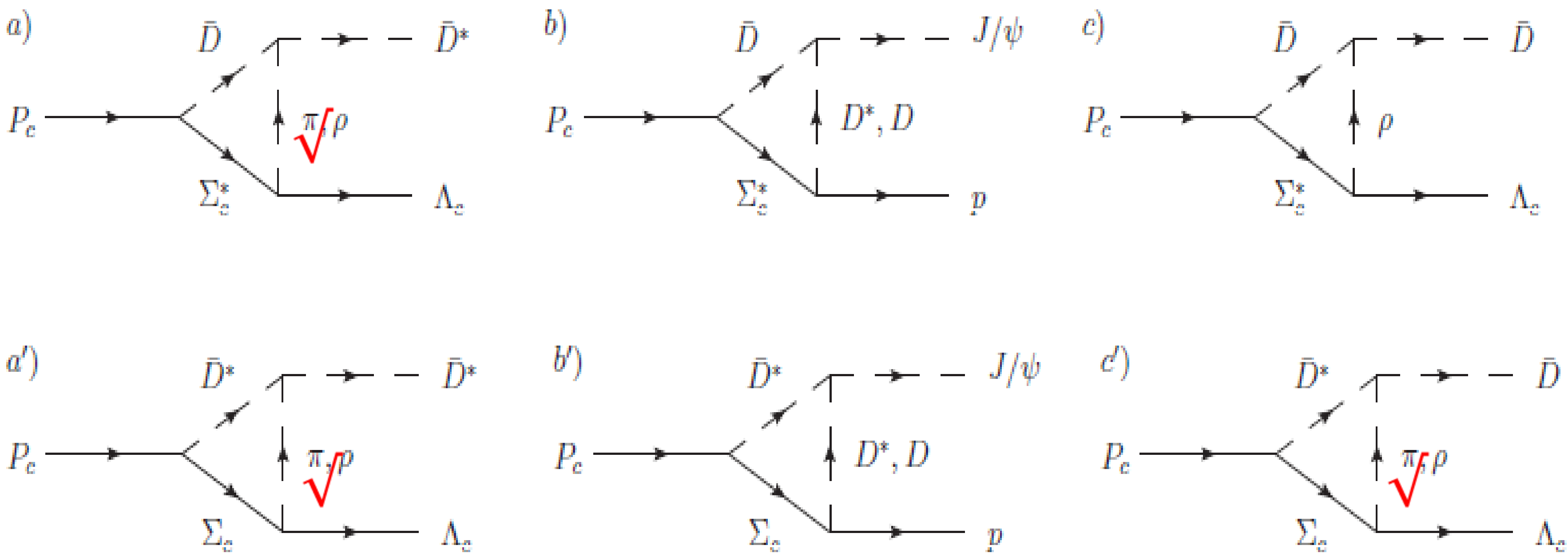
Prediction of a few more J=3/2 pentaquarks !

Λ [MeV]	1300	1400	1500	1600
$J^P = 3/2^-$	$4236.9 - i0.8$	4136.0	4006.3	3848.2
	$4381.3 - i11.4$	$4307.9 - i18.8$	$4242.6 - i1.4$	4150.1
	$4368.5 - i64.9$	$4348.7 - i21.1$	$4312.7 - i16.0$	$4261.0 - i7.0$
$J^P = 3/2^+$	$4223.0 - i97.9$	$4206.7 - i41.2$	$4169.3 - i5.3$	4104.2
	$4363.3 - i57.0$	$4339.7 - i26.8$	$4311.8 - i6.6$	$4268.5 - i1.3$
$J^P = 5/2^-$	—	$4428.6 - i89.1$	$4391.7 - i88.8$	$4338.2 - i56.2$
$J^P = 5/2^+$	—	—	$4368.0 - i9.2$	$4305.8 - i1.9$
	—	—	—	—

Problem: much larger width than observed $P_c^+(4450)$
meanwhile too small width for $P_c^+(4380)$

[3] Disentangling $\bar{D}\Sigma_c^*$ / $\bar{D}^*\Sigma_c$ nature of P_c^+ states from their decays

Y.H.Lin, C.W.Shen, F.K.Guo, B.S.Zou, PRD95(2017)114017



One pion exchange is important !

$\bar{D}^{(*)}\Lambda_c$ & $B^{(*)}\Lambda_b$: most favored decay modes of P_c & P_b pentaquarks !

Decay Mode	Widths (MeV) $P_c(4380)$ $\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$P_c(4380)$ $\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$P_c(4450)$ $\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$P_c(4450)$ $\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
$\bar{D}^*\Lambda_c$	131.3	35.3	72.3	20.5
$J/\psi p$	3.8	16.6	16.3	4.0
$\bar{D}\Lambda_c$	1.2	17.0	41.4	18.8
πN	0.06	0.07	0.07	0.2
$\chi_{c0}p$	0.9	0.004	0.02	0.002
$\eta_c p$	0.2	0.09	0.1	0.04
ρN	1.4	0.15	0.14	0.3
ωp	5.3	0.6	0.5	0.3
$\bar{D}\Sigma_c$	0.01	0.1	1.2	0.8
$\bar{D}\Sigma_c^*$	...	...	7.7	1.4
$\bar{D}\Lambda_c\pi$	11.6	...	...	...
Total	144.3	69.9	139.8	46.4

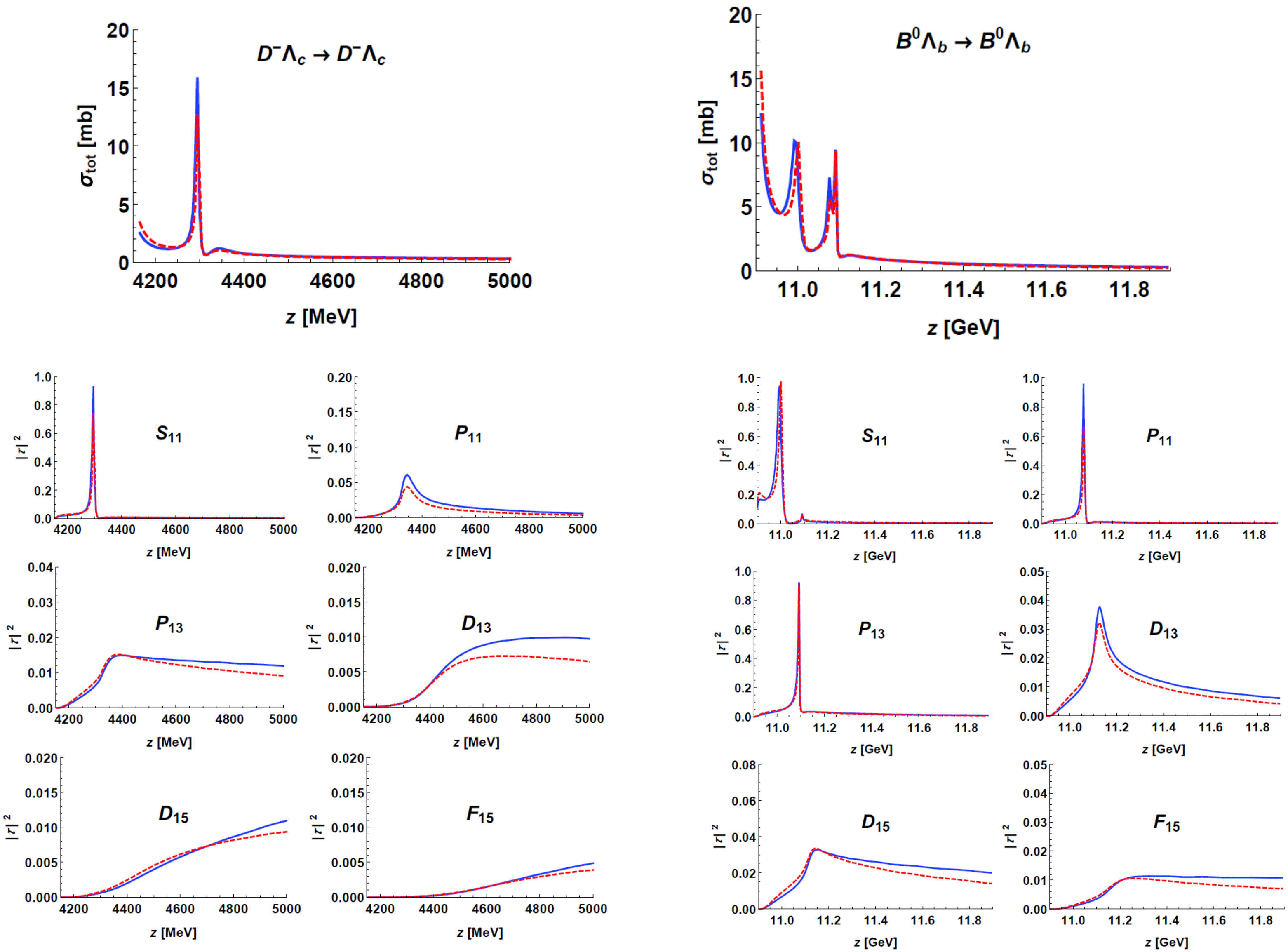
Mode	Widths (MeV) $J^P=3/2^-$ $B\Sigma_b^*$	$J^P=3/2^-$ $B^*\Sigma_b$	$J^P=1/2^-$ $B^*\Sigma_b$
$B^*\Lambda_b$	271.1	19.9	167.0
Υp	0.3	0.04	0.1
ρN	5.5	0.02	0.1
ωp	20.9	0.07	0.4
$B\Lambda_b$	-	7.3	135.9
$B\Sigma_b$	-	-	-
$\eta_b p$	0.02	0.0001	0.0009
$\chi_{b0}p$	1.4	0.0008	0.2
πN	0.7	0.005	0.003
$B\Sigma_b^*$	-	-	-
Total	299.9	27.4	303.8

Y.H.Lin, C.W.Shen, F.K.Guo, B.S.Zou, PRD95(2017)114017
Y.H.Lin, C.W.Shen, B.S.Zou, NPA980(2018)21

γp, πp → $N_{c\bar{c}}$ / $N_{b\bar{b}}$ → $\bar{D}^{(*)}\Lambda_c$ / $B^{(*)}\Lambda_b$: best places to look for them !

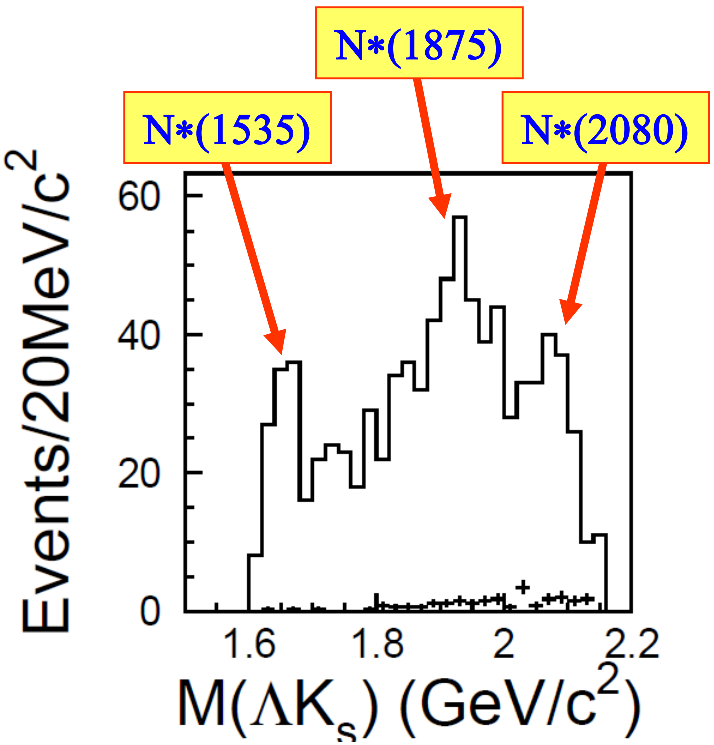
$\bar{D}\Lambda_c-\bar{D}\Sigma_c$ and $B\Lambda_b-B\Sigma_b$ dynamical coupled channel study

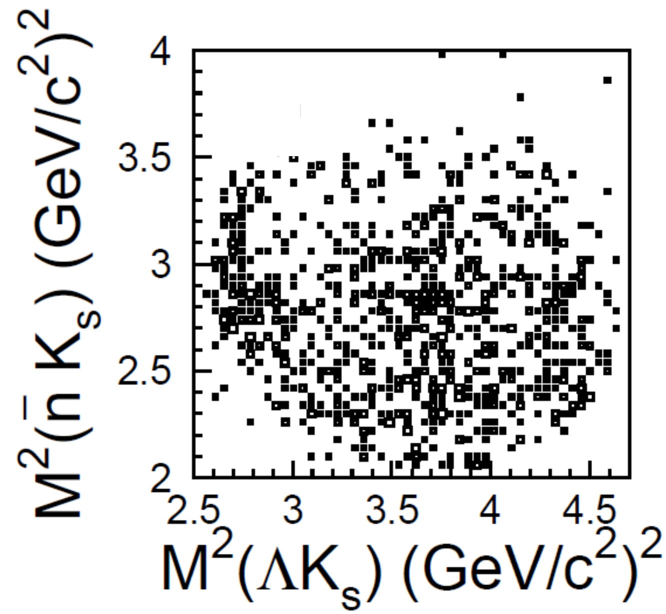
C.W.Shen, Roechen, Meissner, Zou, CPC42(2018) 023106



More pentaquarks with hidden beauty than with hidden charm

$N_{s\bar{s}}$ penta-quarks at BES ?!





$$J/\psi \rightarrow nK_S^0\overline{\Lambda}$$

BESII, Phys. Lett. B659 (2008) 789

$K\Sigma^* \sim 1880$ $K^*\Sigma \sim 2086$

- **New penta-quark spectroscopy provides a new ideal platform for understanding multiquark dynamics**

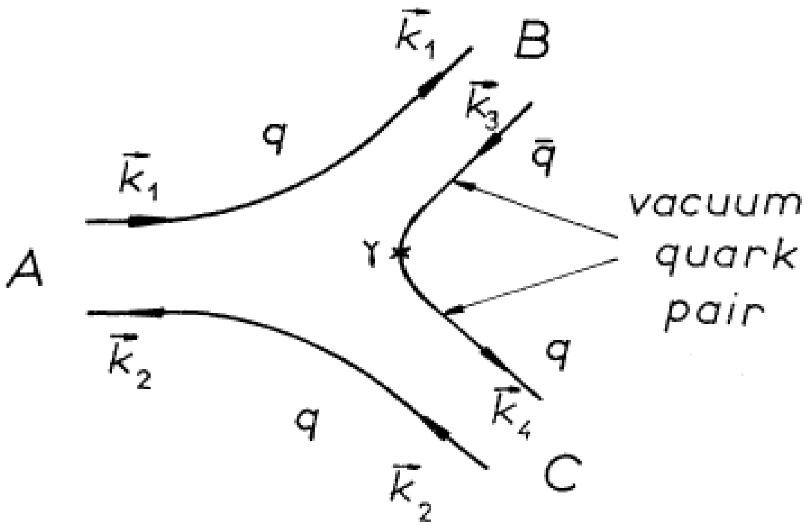
- **Further experimental confirmation and extension for whole penta-quark spectroscopy from γN, πN, KN, $e^+e^- \rightarrow \bar{\Lambda}_b \Lambda_b$, etc.**

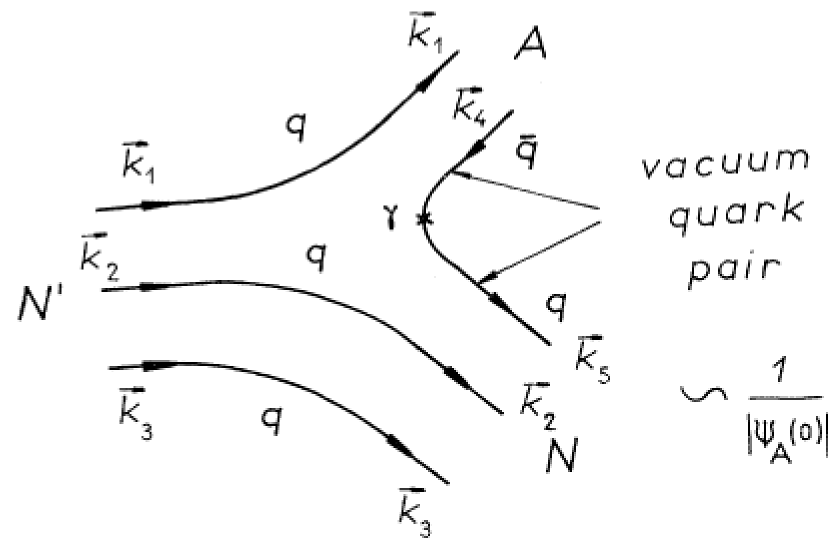
ep/γp@JLab, π10/K10@JPARC, BelleII, BESIII, Eic/EicC, PANDA@FAIR, STCF etc. may play important role here!

4. Mechanisms for $\bar{q}q$ pair production

1) **Perturbative $^3S_1$** **failed for 1^- and 1^+ decays**

2) **Non-perturbative $^3P_0$** **quite successful & popular**





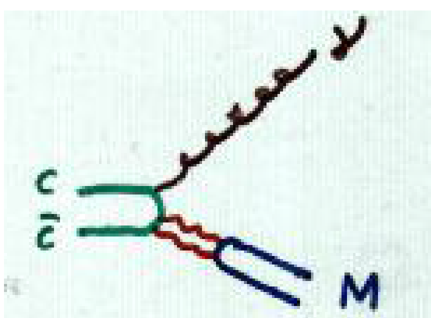
A. Le Yaouanc et al., **Phys.Rev. D8 (1973) 2223**

B. Aubert et al. (BABAR Collaboration), PRD 78 (2008) 112002:

$$\Gamma(\Upsilon(4S)\to\eta\Upsilon(1S))/\Gamma(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)) = 2.41 \pm 0.40_{\text{stat}} \pm 0.12_{\text{syst}}$$

M. Ablikim et al. (BESIII Collaboration), PRD 86 (2012) 071101

$$\Gamma(\psi(4040)\to\eta J/\psi)/\Gamma(\psi(4040)\to\pi^+\pi^- J/\psi) > 2$$

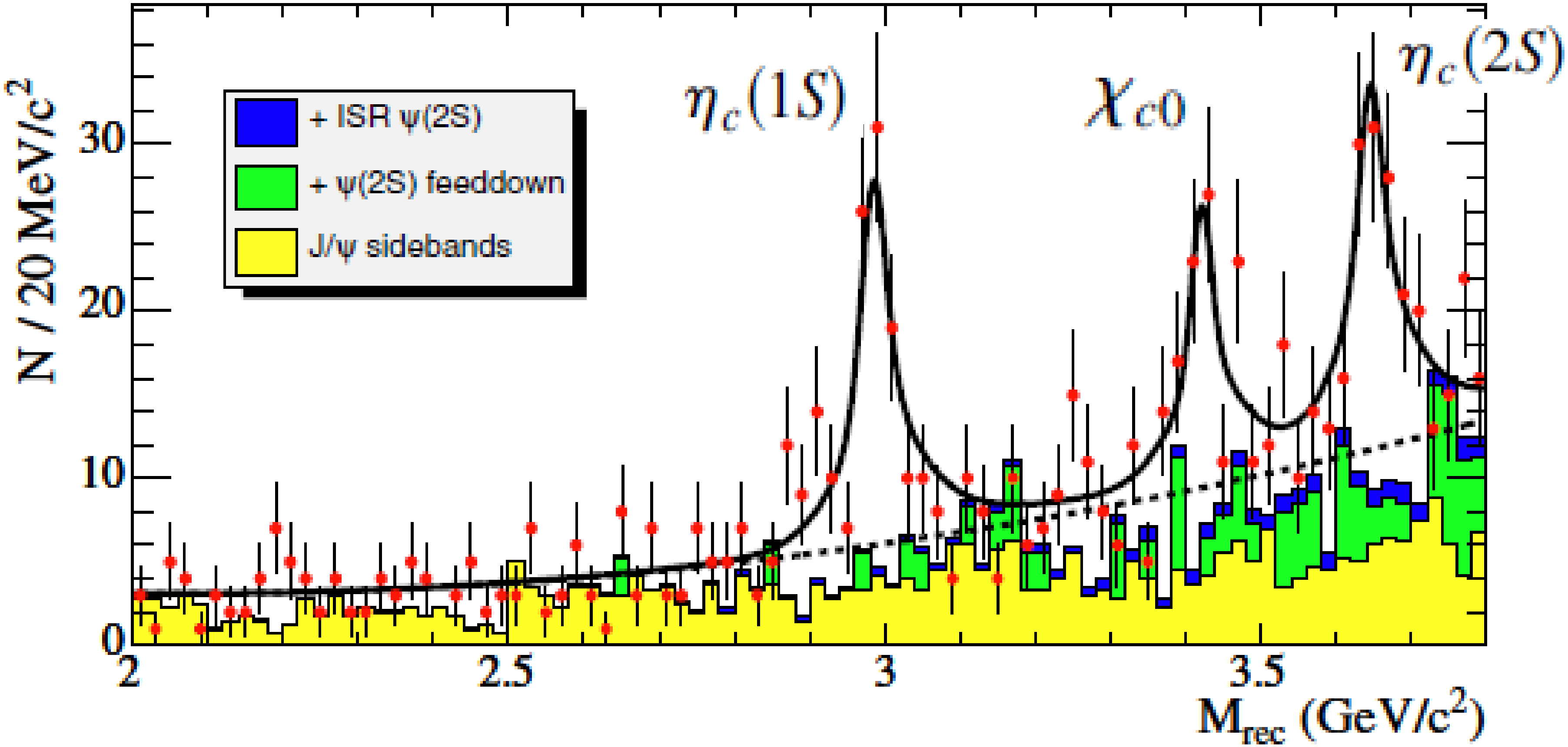


PDG:

$$\Gamma(J/\psi\to\gamma\eta) > \Gamma(J/\psi\to\gamma\sigma)$$

Gluons more favor to produce $\bar{q}q(^1S_0)$ sometimes !

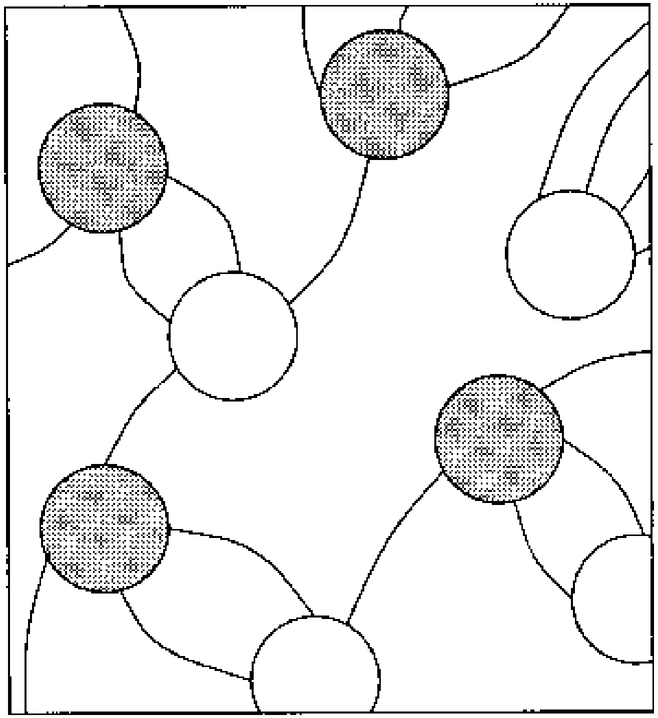
$e^+e^- \rightarrow J/\psi\ c\bar{c}$ **only 0^- and 0^+ $\bar{c}c$ observed !**

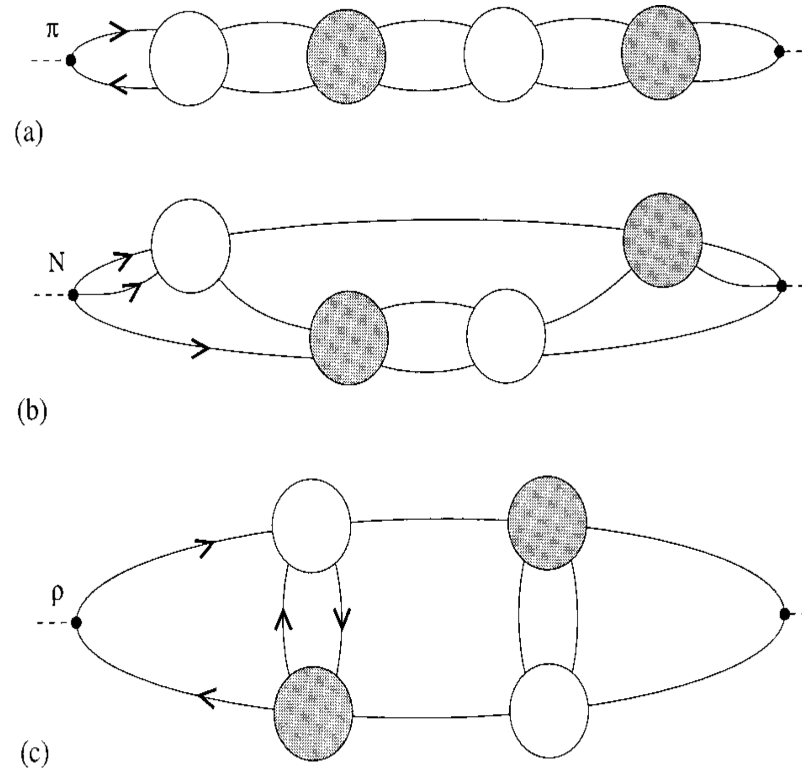


BaBar Collaboration, **Phys.Rev. D72 (2005) 031101**

Phenomenology of instantons in QCD

T. Schafer, E. Shuryak



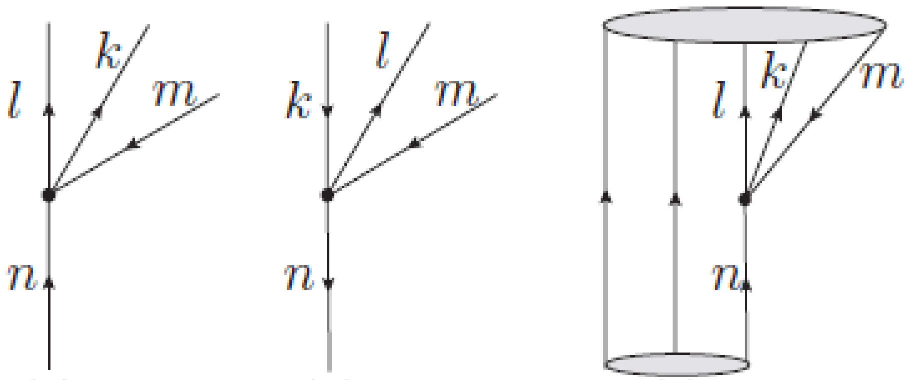


NJL model : **both 0^- & 0^+ important !**

$$\mathcal{L} = i\,\bar{\psi}\partial\!\!\!/\psi + \frac{\lambda}{4}\left[\left(\bar{\psi}\psi\right)\left(\bar{\psi}\psi\right) - \left(\bar{\psi}\gamma^5\psi\right)\left(\bar{\psi}\gamma^5\psi\right)\right] = i\,\bar{\psi}_L\partial\!\!\!/\psi_L + i\,\bar{\psi}_R\partial\!\!\!/\psi_R + \lambda\left(\bar{\psi}_L\psi_R\right)\left(\bar{\psi}_R\psi_L\right).$$

for baryon sss → sss $\bar{q}q$

$$H = \begin{pmatrix} H_3 & V_{\Omega_3 \leftrightarrow \Omega_5} \\ V_{\Omega_3 \leftrightarrow \Omega_5} & H_5 \end{pmatrix}$$



(a) (b) (c)

$$H_N = H_o + H_{hyp} + \sum_{i=1}^{N} m_i$$

$$H_o = \sum_{i=1}^{N} \frac{\vec{p}_i^{\,2}}{2m_i} + \sum_{i<j}^{N} V_{conf}(r_{ij})$$

$$H_{qq}^{NJL} = \sum_{i<j}^{N} \sum_{a=0}^{8} \hat{g}_{ij} \lambda_i^a \lambda_j^a [1 + \frac{1}{4m_i m_j} \hat{\sigma}_i \cdot (\vec{p}_i' - \vec{p}_i) \hat{\sigma}_j \cdot (\vec{p}_j' - \vec{p}_j)]$$

from $$\mathcal{L}_{NJL} = \frac{1}{2} g_s \sum_{a=0}^{8} [(\bar{q}\lambda^a q)^2 + (\bar{q} i \lambda^a \gamma_5 q)^2]$$

Predictions for the lowest Ω* by various models:

$\Omega^*(x/2^-)$ as sss (L=1) : ~ 2020 MeV

Chao, Isgur, Karl, PRD38(1981)155

$\Omega^*(1/2^-)$ as $\bar{K}\Xi$ bound state: ~ 1805 MeV

W.L.Wang, F.Huang, Z.Y.Zhang, F.Liu, JPG35 (2008) 085003

$\Omega^*(x/2^-)$ as $\bar{u}$usss (L=0) : ~ 1820 MeV

Yuan-An-Wei-Zou-Xu, PRC87(2013)025205

$\Omega^*(3/2^-)$ as sss - $\bar{u}$usss mixture : ~ 1780 MeV

by instanton/NJL interaction

An-Metsch-Zou, PRC87(2013) 065207; An-Zou, PRC89 (2014) 055209

K10@JPARC: $K^- p \rightarrow K^+ K^0 \Omega^*$ ⇒ $\Omega^*(1780)$?!

BES3@BEPC2: $e^+ e^- \rightarrow \bar{\Omega}\,\Omega^*$