Production of multiquark hadrons in high energy multiproduction processes

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A highlight for the presentation on

'Study hadron property and structure in high energy multiproduction process'

- In high energy scattering, multiproduction process is unique in its relevance to total cross section an in its global property such as rapidity distribution, etc. If there is hard interactions, the jet rate and structure is a good arena of perturbative chromodynamics. However, once any specific hadron is considered, The property and structure of the hadron must make sense while the global and/or perturbative chromodynamics mechanism still can put important constrains.

- The relation of the property and structure of the hadron with its production cross section, distribution etc. is much more complex than its decay process. In one hand there are many difficulties and challenges in calculation; on the other hand, production process provide unique way to study the details of property and structure of the hadron, which is beyond the approach of its decay process.

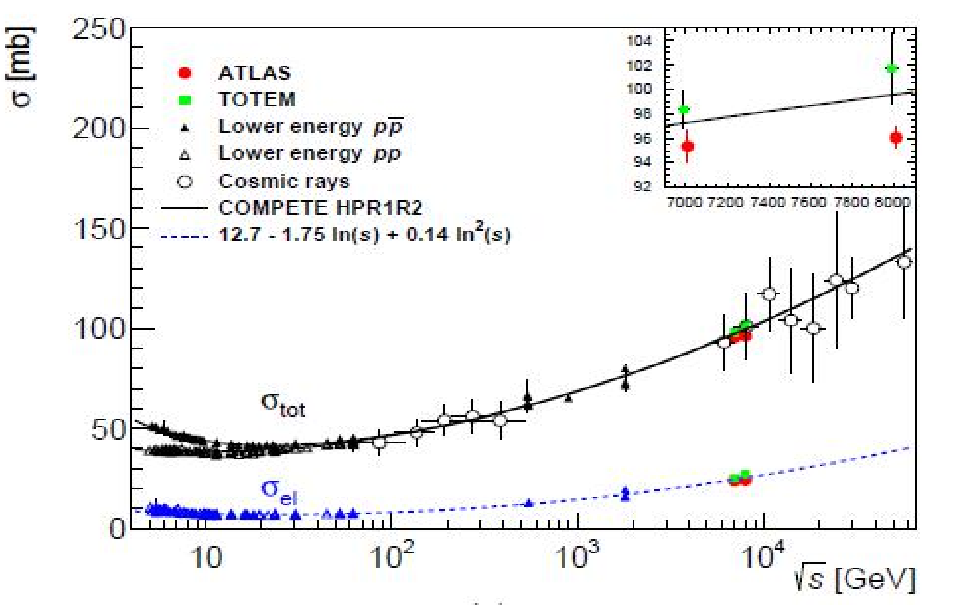
- In this talk I will review our works on such topic in recent years, mainly on the multiquark state (e.g., XYZ particles) production in multiproduction process and the Bethe-Salpeter wave function in exclusive process. For the multiquark state production in multiproduction process, I will emphasize on the unitarity of hadronization process (and relevant models) and discuss why until now, No multiquark states (except the the unclear X(3872)) is observed to produce in multiproduction process. I will also discuss how to calculate hadron molecule production in multiproduction process.

- Some of the Refs.

- 1, Exclusive production ratio of neutral to charged kaon pair in e^+e^- annihilation continuum via a relativistic quark model
- Phys.Rev.C 102 (2020) 1, 015201 • e-Print: 1906.11575 [hep-ph]
- 2, Exotic hadron bound state production at hadron colliders
- Chin.Phys.C 41 (2017) 8, 083106 • e-Print: 1610.04411 [hep-ph]
- 3, New $B_s^0\pi^\pm$ and $D_s^\pm\pi^\pm$ states in high energy multiproduction process
- Phys.Rev.D 94 (2016) 1, 014023 • e-Print: 1603.03250 [hep-ph]
- 4, Unitarity and Entropy Change in Exclusive Quark Combination Models
- e-Print: 1005.4664 [hep-ph]
- 5, Exotic hadron production in quark combination model
- Phys.Rev.C 80 (2009) 035202 • e-Print: 0906.2473 [hep-ph]
- 6, Generalized structure of hadron-quark vertex function in Bethe- Salpeter framework: Applications to leptonic decays of V-mesons
- J.Phys. 32 (2006) 949-961 • e-Print: hep-ph/0512352 [hep-ph]

Multiproduction: in soft interactions vs in a jet

Pionization
Total cross section
Heavy ion complexity
Number and kinds of hadrons
Basic degree of freedom?
Feynman,1969; Cheng & Wu,1971



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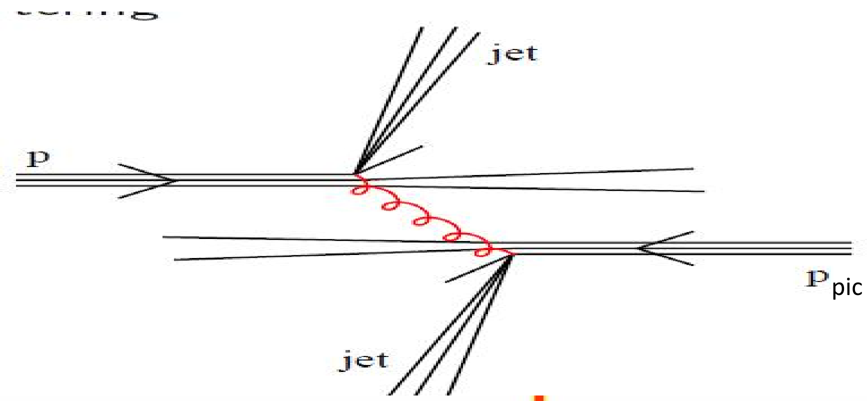
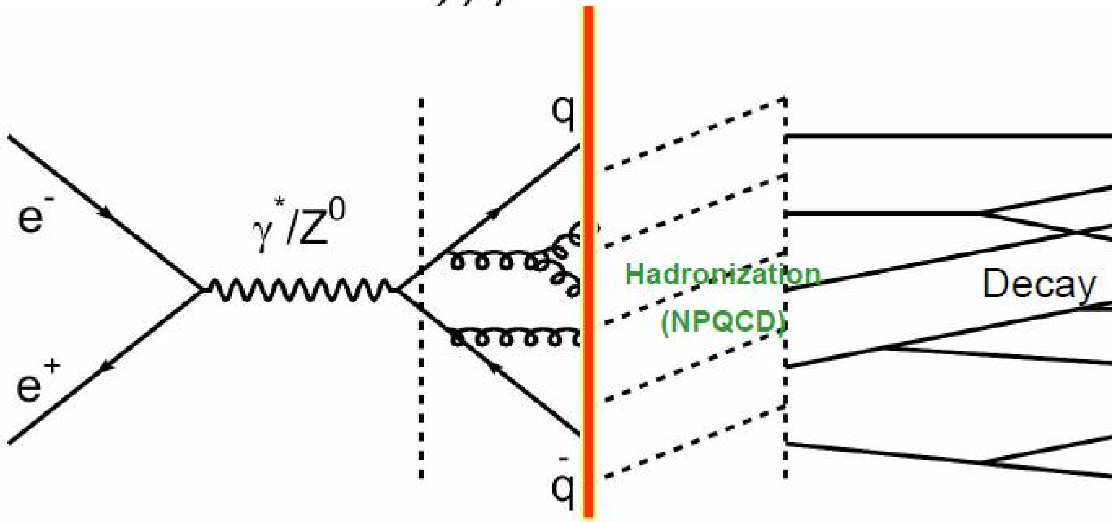
Local parton-hadron duality (number of 'clusters')
Definition of jet (parton level)
Quark and gluon are the basic degrees of freedom--but confined



pic from G Salam



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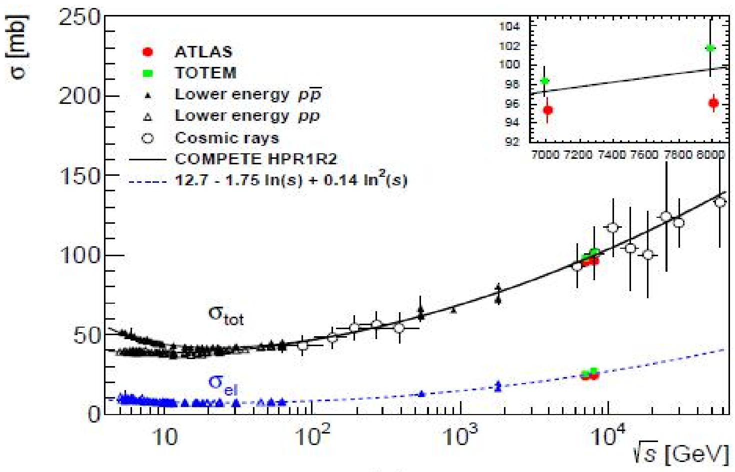

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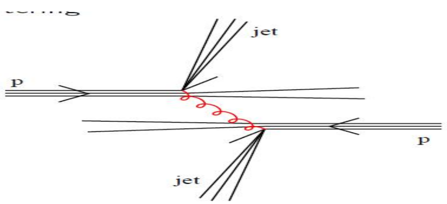

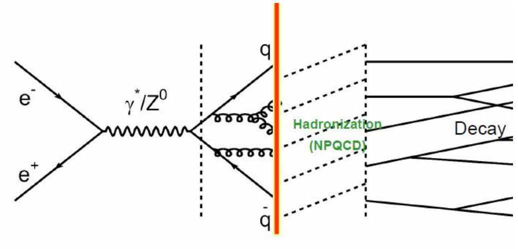

We not doubt/query on QCD,
just confused by how QCD works for soft interactions (HE/LE)
We not doubt/query on existence of quarks,
just confused on how they combine to be a hadron
We not doubt/query on colour confinement,
just confused by how colour is confined

QCD=
'UTOPIA'

Multiquark hadrons in Multiproduction 'combines' the above questions together

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Heavy ior eedom--but

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Basic deg

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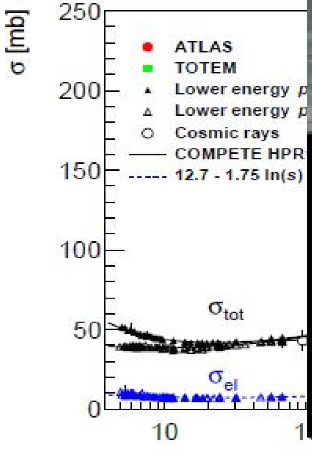

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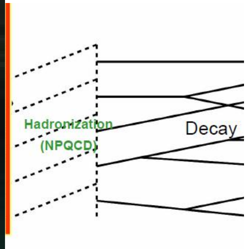

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lron

QCD=

UTOPIA

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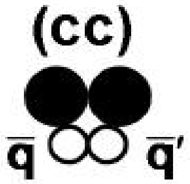
Part I ： Unitarity

Multiquark hadrons in Multiproduction 'combines' the above questions together

Understand these questions: *in* hadron & *during* production (hadronization)

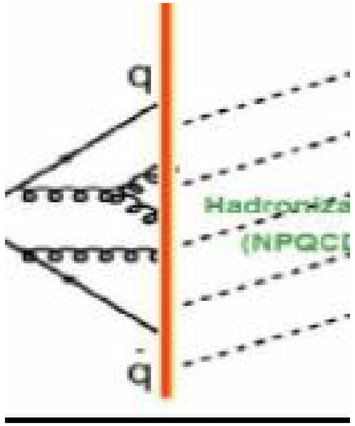
Complexity of the colour structure of the multiquark hadrons



$$(3_1 \otimes 3^*_2) \otimes (3_3 \otimes 3^*_4) = (1_{12} \oplus 8_{12}) \otimes (1_{34} \oplus 8_{34}) = (1_{12} \otimes 1_{34}) \oplus (8_{12} \otimes 8_{34}) \oplus \cdots,$$

$$(3_1 \otimes 3^*_4) \otimes (3_3 \otimes 3^*_2) = (1_{14} \oplus 8_{14}) \otimes (1_{32} \oplus 8_{32}) = (1_{14} \otimes 1_{32}) \oplus (8_{14} \otimes 8_{32}) \oplus \cdots,$$

$$(3_1 \otimes 3_3) \otimes (3^*_2 \otimes 3^*_4) = (3^*_{13} \oplus 6_{13}) \otimes (3_{24} \oplus 6^*_{24}) = (3^*_{13} \otimes 3_{24}) \oplus (6_{13} \otimes 6^*_{24}) \oplus \cdots$$



--->N-body problem? sub-clusters? in hadron as well as in production

Number of quarks(?) in production for a certain collsion energy

--->Number/kinds of hadrons ? (hadronization models)

2-step production **since basic degree of freedom is the quark and gluon**

--->Difficulty of production of multiquark states unitarity

Difficulty of production of multiquark states (unitarity)

ALL quarks go into hadrons (confinement--Tous les hommes sont mortels！ ）

- Formal descriptions: by a unitary time evolution operator

$$\sum_h |<h|U|q>|^2 =<q|U^+U|q>=1. \quad \sum|q><q| = \sum|h><h| = \sum_{h=B,\bar{B},M} |<h|U|q>|^2 \sim 1-\varepsilon, \ \varepsilon \to 0^+$$

- Total probability to become any state of hadron system is 1
- 'Reversal employment' of the Gell-Mann–Zweig constituent quark model, where all the quark states and the hadron states are different bases of the *same* Hilbert space of states/static -> production
- How to take into account these observations? Check in a model, incocnsisitent if P<>1

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From CERN webpage,
Ωc(3000)0, Ωc(3050)0, Ωc(3066)0, Ωc(3090)0 and Ωc(3119)

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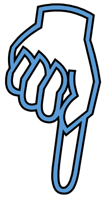

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- 'Reversal employ… …uent quark model, where all the quark states a… …ses of the *same* Hilbert space of states/static -> …
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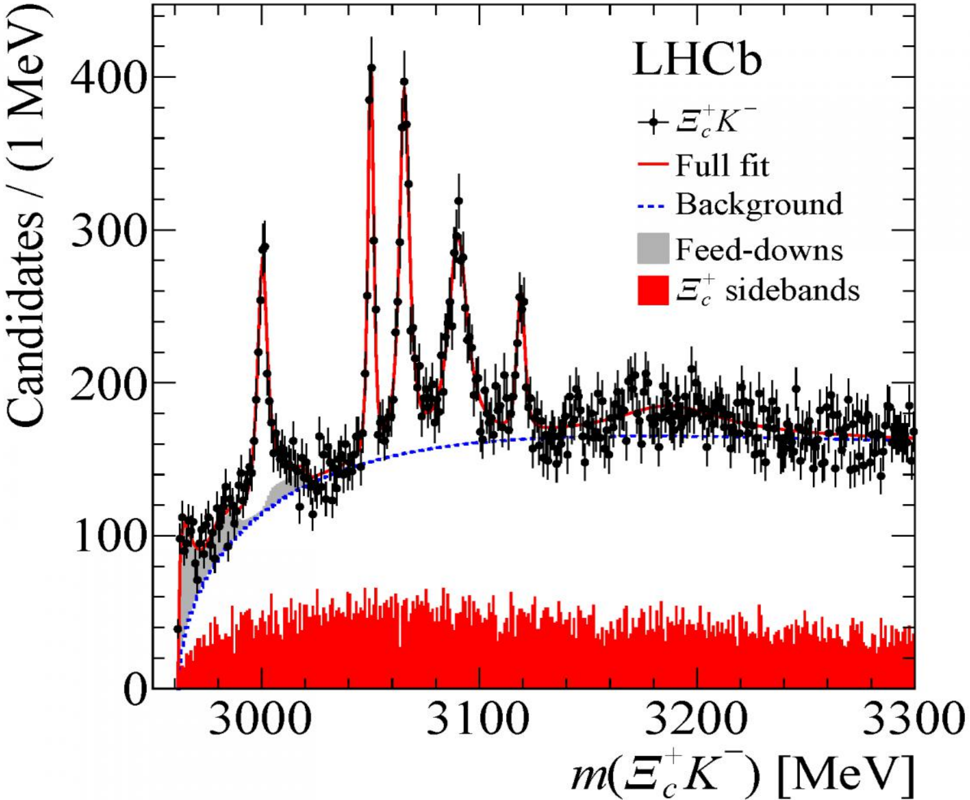

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Quark combination model (e.g., that of sdu)

near rapidity correlation no combination for quarks with interval more than one quark

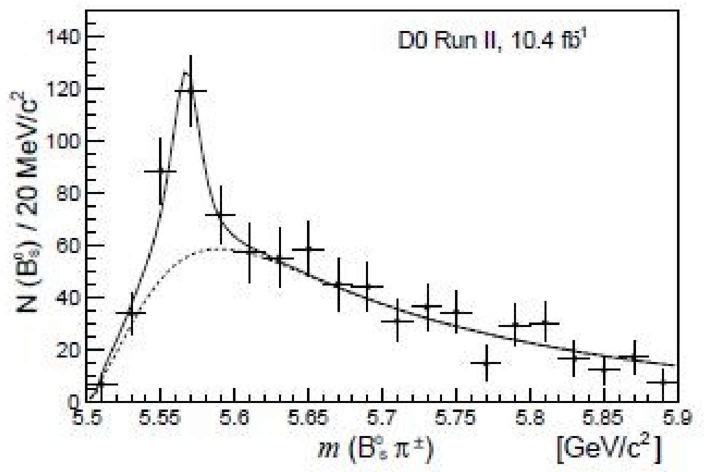
$$\bar{q}_1\bar{q}_2 q_3\bar{q}_4 q_5 q_6$$

$$\bar{q}_1\,\bar{q}_2\, q_3 q_4 q_5 q_6\,\bar{q}_7\, q_8\,\bar{q}_9\, q_{10}\,\bar{q}_{11}\,\bar{q}_{12}\, q_{13} q_{14} q_{15}$$

the combination of number >3: the combination is not free, must be some rules

$$\sum_{h=B,B,M} |<h|U|q>|^2 \sim 1-\varepsilon,\ \varepsilon \to 0^+ \quad \longrightarrow \quad \sum_{allexotic} |<h\,|\,U\,|\,q>|^2 = \varepsilon$$

take the un(?)fortunate D0 X(5568) as an example



four flavours
bottom
large production ratio

first solid evidence of 4-quark state from multiproduction
b s u d

string, cluster, combination.........

combination without the unitary bound

$$P_X = \frac{\lambda}{D}\frac{1}{D}\frac{1}{D} \times 2. \qquad (5)$$

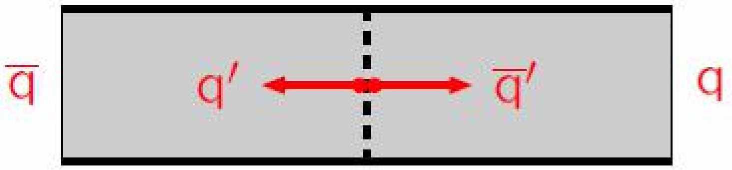
Here $D = 2(1 + 1 + \lambda)$. If we assume that b combines with any other antiquark with probability 1, then

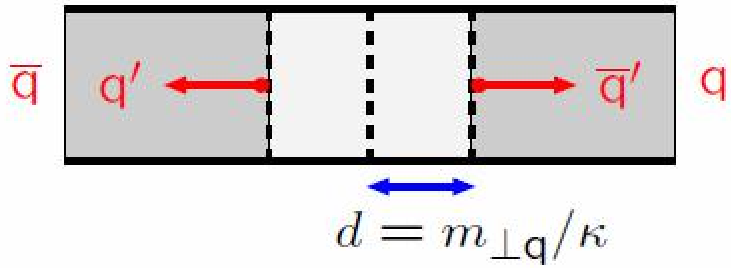
$$P_{Bs} = \frac{\lambda}{(D/2)}, \qquad (6)$$

$$\rho^{max}_{combination} = \frac{P_X}{P_{Bs}} \sim 5\%. \qquad (7)$$

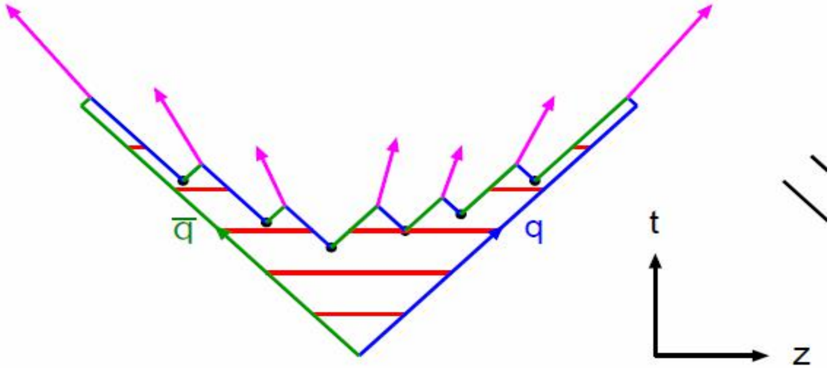
large production rate: exp. rho (wrt Bs)
sim. (7 to 8)% (A.Popov)

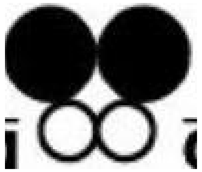
string model





$m_{\perp q'} = 0$ $m_{\perp q'} > 0$





from Sjoestrand

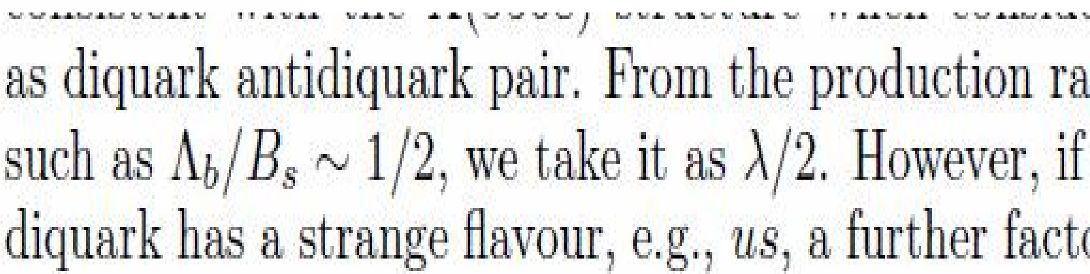
String breaking modelled by tunneling:

$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp q}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp q}^2}{\kappa}\right) \exp\left(-\frac{\pi m_q^2}{\kappa}\right)$$

1) common Gaussian $p_\perp$ spectrum

2) suppression of heavy quarks $u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 :$

3) diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon producti


as diquark antidiquark pair. From the production ra
such as $\Lambda_b/B_s \sim 1/2$, we take it as $\lambda/2$. However, if
diquark has a strange flavour, e.g., us, a further facto

Hadron composition also depends on spin probabilities, hadroni

functions, phase space, more complicated baryon production, . . .

⇒ "moderate" predictivity (many parameters!)

$$
\begin{aligned}
& u : d : s : ud : uu : dd : us : ds : ss \\
= \;& 1 : 1 : \lambda : \tfrac{\lambda}{2} : \tfrac{\lambda}{2} : \tfrac{\lambda}{2} : \tfrac{\lambda^2}{2} : \tfrac{\lambda^2}{2} : \tfrac{\lambda^3}{2}.
\end{aligned}
$$

$$P_X = \frac{2 \times \lambda/2}{D_1} \times \frac{\lambda^2/2}{D_2}. \tag{2}$$

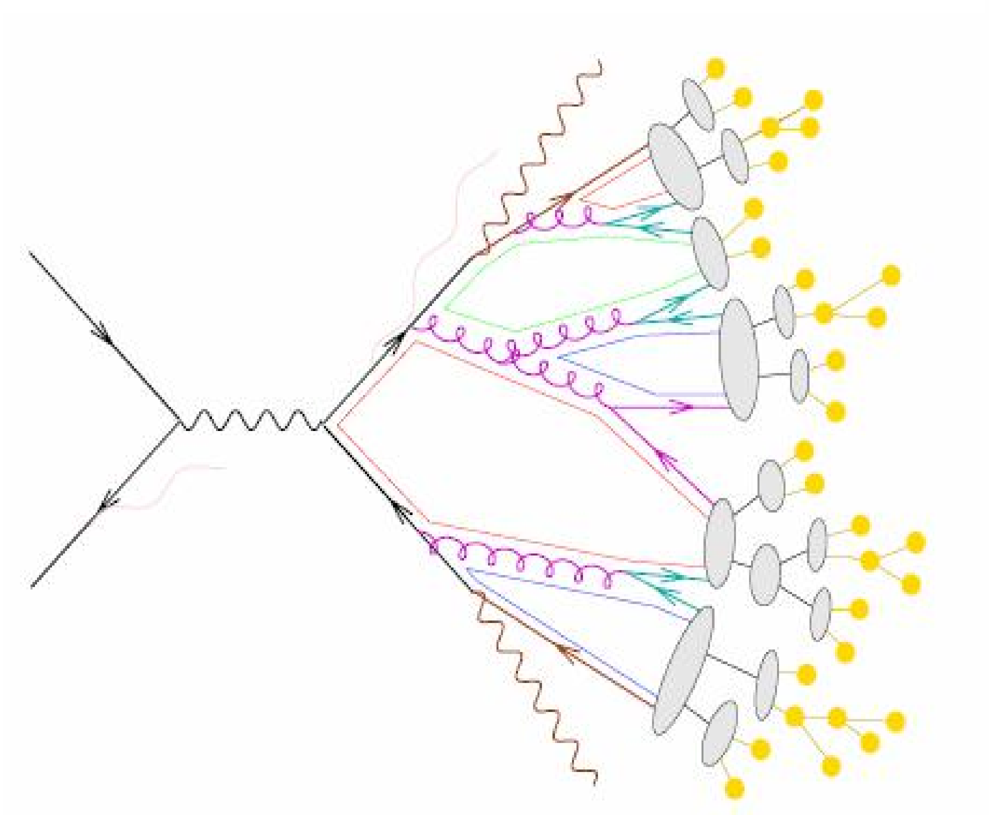
Here $D_1 = 1 + 1 + \lambda + \lambda/2 + \lambda/2 + \lambda^2/2$, and $D_2 = 1 + 1 + \lambda + \lambda/2 + \lambda/2 + \lambda/2 + \lambda^2/2 + \lambda^2/2 + \lambda^3/2$.

$$P_{Bs} = \frac{1 + 1 + \lambda}{D_1} \times \frac{\lambda}{D_2}; \tag{3}$$

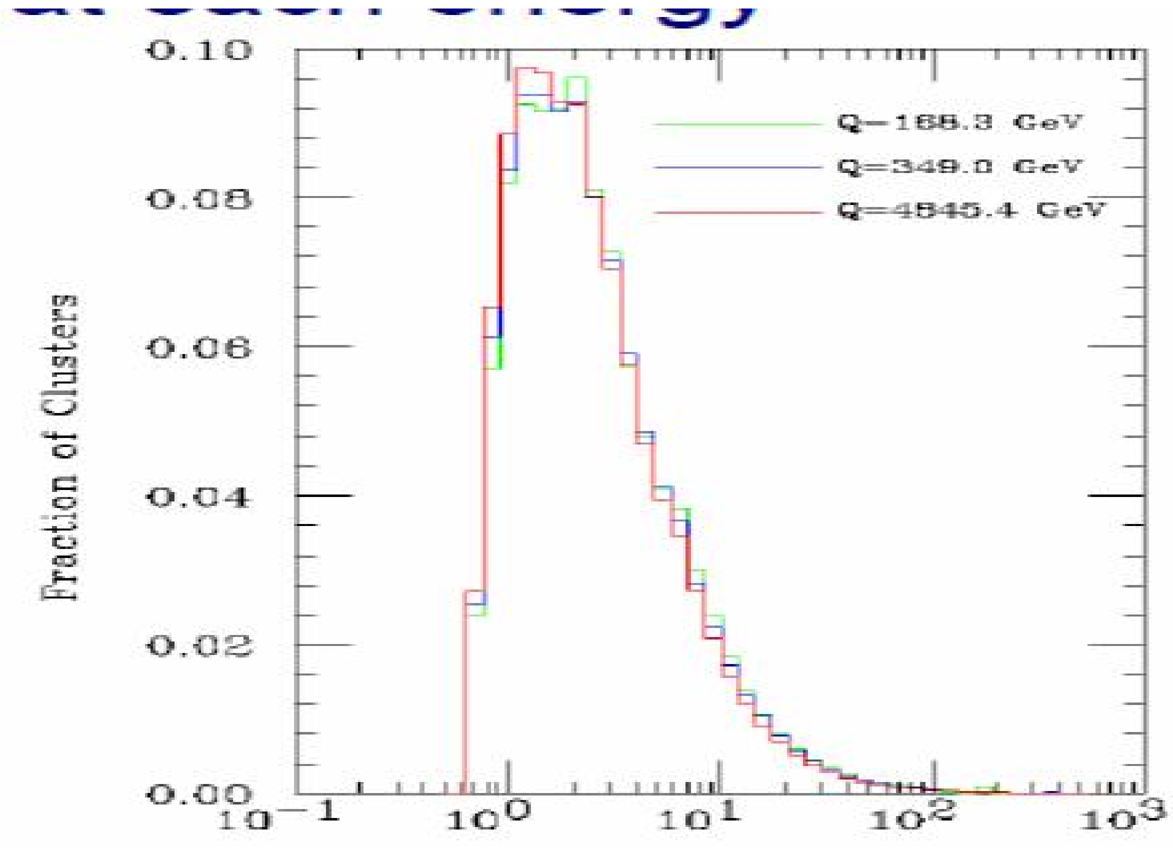
$$\rho_{string} = \frac{P_X}{P_{Bs}} \sim 2\%. \tag{4}$$

cluster model/ cluster mass widely distributed

X(5568)



Sjostrand



Seymour

An interesting 'mini' multiproduction evidence

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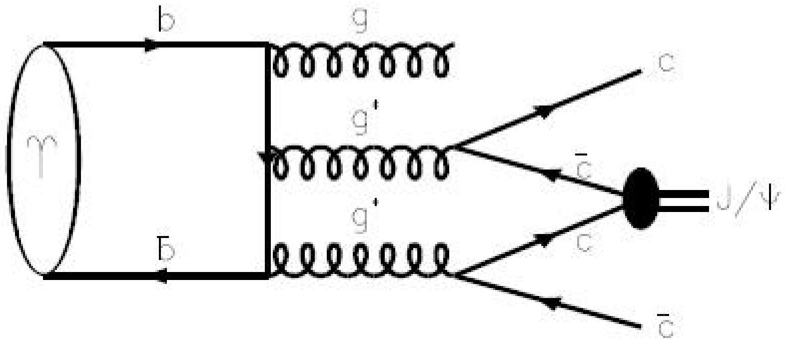
Search for XYZ states in $\Upsilon(1S)$ inclusive decays (The Belle Collaboration)

The branching fractions of the $\Upsilon(1S)$ inclusive decays into final states with a J/ψ or a $\psi(2S)$ are measured with improved precision to be $\mathcal{B}(\Upsilon(1S) \to J/\psi + \text{anything}) = (5.25 \pm 0.13(\text{stat.}) \pm 0.25(\text{syst.})) \times 10^{-4}$ and $\mathcal{B}(\Upsilon(1S) \to \psi(2S) + \text{anything}) = (1.23 \pm 0.17(\text{stat.}) \pm 0.11(\text{syst.})) \times 10^{-4}$. The first search for $\Upsilon(1S)$ decays into XYZ states that decay into a J/ψ or a $\psi(2S)$ plus one or two charged tracks yields no significant signals for XYZ states in any of the examined decay modes, and upper limits on their production rates in $\Upsilon(1S)$ inclusive decays are determined.

State	N_{fit}	N_{up}	$\varepsilon(\%)$	$\sigma_{\text{syst}}(\%)$	$\Sigma(\sigma)$	$\mathcal{B}_R^{\text{prod}}$
$X(3872) \to \pi^+\pi^- J/\psi$	4.8±15.4	31.4	3.26	18.7	0.3	$< 9.5 \times 10^{-6}$
$Y(4260) \to \pi^+\pi^- J/\psi$	−31.1±88.9	134.6	3.50	35.6	–	$< 3.8 \times 10^{-5}$
$Y(4260) \to \pi^+\pi^- \psi(2S)$	6.7±29.4	56.9	0.71	35.0	0.2	$< 7.9 \times 10^{-5}$
$Y(4360) \to \pi^+\pi^- \psi(2S)$	−25.4±30.1	45.6	0.86	50.0	–	$< 5.2 \times 10^{-5}$
$Y(4660) \to \pi^+\pi^- \psi(2S)$	−55.0±26.2	23.1	1.06	40.7	–	$< 2.2 \times 10^{-5}$
$Y(4260) \to K^+K^- J/\psi$	−13.7±10.9	14.5	1.91	45.8	–	$< 7.5 \times 10^{-6}$
$Y(4140) \to \phi J/\psi$	−0.1±1.2	3.6	0.69	11.0	–	$< 5.2 \times 10^{-6}$
$X(4350) \to \phi J/\psi$	2.3±2.5	7.6	0.92	10.4	1.2	$< 8.1 \times 10^{-6}$
$Z_c(3900)^\pm \to \pi^\pm J/\psi$	−26.5±39.1	57.5	4.39	47.3	–	$< 1.3 \times 10^{-5}$
$Z_c(4200)^\pm \to \pi^\pm J/\psi$	−238.6±154.2	235.1	3.87	48.4	–	$< 6.0 \times 10^{-5}$
$Z_c(4430)^\pm \to \pi^\pm J/\psi$	94.2±71.4	195.8	3.97	34.4	1.2	$< 4.9 \times 10^{-5}$
$Z_c(4050)^\pm \to \pi^\pm \psi(2S)$	37.0±47.7	112.7	1.27	46.2	0.4	$< 8.8 \times 10^{-5}$
$Z_c(4430)^\pm \to \pi^\pm \psi(2S)$	23.2±42.4	92.0	1.35	47.1	0.1	$< 6.7 \times 10^{-5}$
$Z_{cs}^\pm \to K^\pm J/\psi$	−22.2±17.4	22.4	3.88	48.7	–	$< 5.7 \times 10^{-6}$



Another interesting evidence

arXiv:1711.01690v1 [hep-ex] 6 Nov 2017

Search for light tetraquark states in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays

S. Jia,[2] C. P. Shen,[2] C. Z. Yuan,[25] I. Adachi,[16,12] J. K. Ahn,[39] H. Aihara,[82] S. Al Said,[76,37] D. M. Asner,[64] H. Atmacan,[72] T. Aushev,[52] R. Ayad,[76] V. Babu,[77] I. Badhrees,[76,36] S. Bahinipati,[20] A. M. Bakich,[75] V. Bansal,[64] P. Behera,[23] M. Berger,[73] V. Bhardwaj,[19] B. Bhuyan,[21] J. Biswal,[32] G. Bonvicini,[87] A. Bozek,[59] M. Bračko,[47,32] T. E. Browder,[15] D. Červenkov,[4] M.-C. Chang,[9] V. Chekelian,[48] A. Chen,[56] B. G. Cheon,[14] K. Chilikin,[43,51] K. Cho,[38] S.-K. Choi,[13] Y. Choi,[74] D. Cinabro,[87] T. Czank,[80] N. Dash,[20] S. Di Carlo,[87] Z. Doležal,[4] D. Dutta,[77] S. Eidelman,[3,62] D. Epifanov,[3,62] J. E. Fast,[64] T. Ferber,[7] B. G. Fulsom,[64] R. Garg,[65] V. Gaur,[86] N. Gabyshev,[3,62] A. Garmash,[3,62] M. Gelb,[34] A. Giri,[22] P. Goldenzweig,[34] O. Grzymkowska,[59] E. Guido,[30] J. Haba,[16,12] T. Hara,[16,12] K. Hayasaka,[61] H. Hayashii,[55] M. T. Hedges,[15] W.-S. Hou,[58] T. Iijima,[54,53] K. Inami,[53] G. Inguglia,[7] A. Ishikawa,[80] R. Itoh,[16,12] M. Iwasaki,[63] Y. Iwasaki,[16] W. W. Jacobs,[24] I. Jaegle,[8] Y. Jin,[82] D. Joffe,[35] K. K. Joo,[5] T. Julius,[49] A. B. Kaliyar,[23] G. Karyan,[7] T. Kawasaki,[61] H. Kichimi,[16] C. Kiesling,[48] D. Y. Kim,[71] H. J. Kim,[41] J. B. Kim,[39] K. T. Kim,[39] S. H. Kim,[14] P. Kodyš,[4] S. Korpar,[47,32] D. Kotchetkov,[15] P. Križan,[44,32] R. Kroeger,[28] P. Krokovny,[3,62] R. Kulasiri,[35] T. Kumita,[84] A. Kuzmin,[3,62] Y.-J. Kwon,[89] J. S. Lange,[10] I. S. Lee,[14] S. C. Lee,[41] L. K. Li,[25] Y. Li,[86] L. Li Gioi,[48] J. Libby,[23] D. Liventsev,[86,16] M. Lubej,[32] T. Luo,[66] M. Masuda,[81] T. Matsuda,[50] D. Matvienko,[3,62] M. Merola,[29] K. Miyabayashi,[55] H. Miyata,[61] R. Mizuk,[43,51,52] H. K. Moon,[39] T. Mori,[53] R. Mussa,[30] M. Nakao,[16,12] T. Nanut,[32] K. J. Nath,[21] Z. Natkaniec,[59] M. Nayak,[87,16] M. Niiyama,[40] N. K. Nisar,[66] S. Nishida,[16,12] S. Ogawa,[79] S. Okuno,[33] S. L. Olsen,[69] H. Ono,[60,61] Y. Onuki,[82] P. Pakhlov,[43,51] G. Pakhlova,[43,52] B. Pal,[6] S. Pardi,[29] C. W. Park,[74] H. Park,[41] S. Paul,[78] I. Pavelkin,[52] R. Pestotnik,[32] L. E. Piilonen,[86] M. Ritter,[45] A. Rostomyan,[7] G. Russo,[29] Y. Sakai,[16,12] M. Salehi,[46,45] S. Sandilya,[6] L. Santelj,[16] T. Sanuki,[80] V. Savinov,[66] O. Schneider,[42] G. Schnell,[1,18] C. Schwanda,[26] Y. Seino,[61] K. Senyo,[88] O. Seon,[53] M. E. Sevior,[49] V. Shebalin,[3,62] T.-A. Shibata,[83] N. Shimizu,[82] J.-G. Shiu,[58] B. Shwartz,[3,62] J. B. Singh,[65] A. Sokolov,[27] E. Solovieva,[43,52] M. Starič,[32] J. Stypula,[59] M. Sumihama,[11] T. Sumiyoshi,[84] M. Takizawa,[70,17,67] U. Tamponi,[30,85] K. Tanida,[31] F. Tenchini,[49] M. Uchida,[83] T. Uglov,[43,52] Y. Unno,[14] S. Uno,[16,12] P. Urquijo,[49] Y. Usov,[3,62] C. Van Hulse,[1] G. Varner,[15] A. Vossen,[24] B. Wang,[6] C. H. Wang,[57] M.-Z. Wang,[58] P. Wang,[25] X. L. Wang,[64,16] M. Watanabe,[61] Y. Watanabe,[33] E. Widmann,[73] E. Won,[39] Y. Yamashita,[60] H. Ye,[7] Y. Yusa,[61] S. Zakharov,[43] Z. P. Zhang,[68] V. Zhilich,[3,62] V. Zhukova,[43,51] V. Zhulanov,[3,62] and A. Zupanc[44,32]

(The Belle Collaboration)

Yonsei University, Seoul 120-749

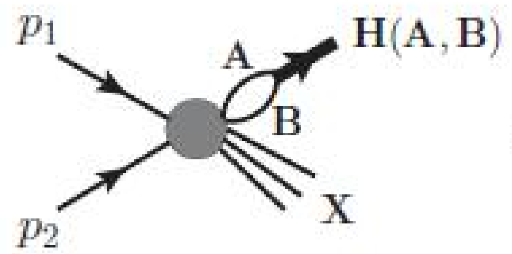
Abstract

We search for the $J^{PC} = 0^{--}$ and 1^{+-} light tetraquark states with masses up to 2.46 GeV/c^2 in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays with data samples of (102 ± 2) million and (158 ± 4) million events, respectively, collected with the Belle detector. No significant signals are observed in any of the studied production modes, and 90% credibility level (C.L.) upper limits on their branching fractions in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays are obtained. The inclusive branching fractions of the $\Upsilon(1S)$ and $\Upsilon(2S)$ decays into final states with

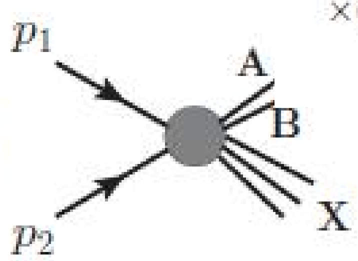
To parameterize the production of X(5568)(as hadron (BK)/ cluster(bsbar udbar) molecule) and how to do calculation

$$\frac{1}{N}\frac{dN}{d^3P_H d^3q}$$
$$\propto \frac{1}{F}\sum\int\prod_{j\neq A,B}\frac{d^3p_j}{(2\pi)^3 2E_j}\overline{|\hat{O}|^2}(p_j, P_H = p_A + p_B, q = p_A - p_B)$$
$$\times(2\pi)^4\delta^{(4)}(P_{intial} - \sum_{j\neq A,B} p_j - p_A - p_B).$$

and prepare for the case of production



$$= \int \frac{d^3k}{(2\pi)^3}\Phi(\vec{k}) \times$$



Expand the amplitude around k=0

FIG. 1: The process $p(p_1)p(p_2) \to A(p_A) + B(p_B) + X \to H(A,B)(P_H) + X$.

fitting data to get the wave function at origin, can be used every where... factorization

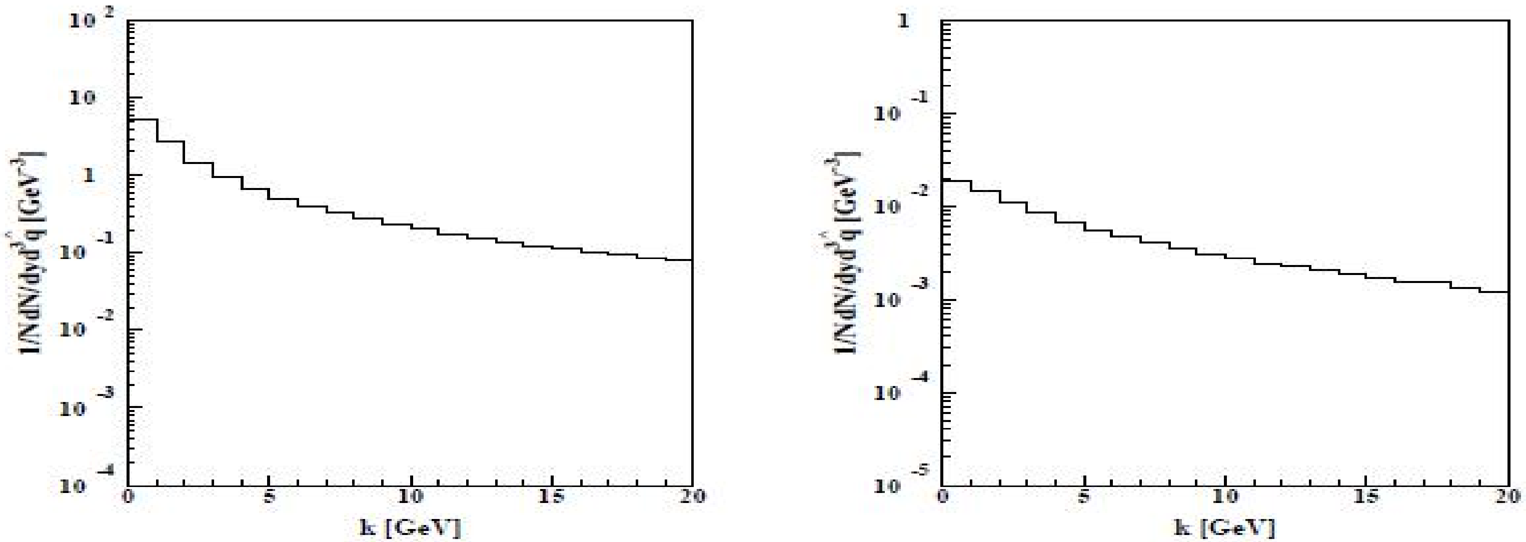
Wei Wang, arXiv:1709.10382, Comment on "Comment on `Note on X(3872) production at hadron colliders and its molecular structure' "
A. Esposito, B. Grinstein, L. Maiani, F. Piccinini, A. Pilloni, A.D. Polosa, V. Riquer,
arXiv:1709.09631 Comment on `Note on X(3872) production at hadron colliders and its molecular structure'
Miguel Albaladejo, Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißner, Juan Nieves, Andreas Nogga, Zhi Yang
arXiv:1709.09101, 'Note on X(3872) production at hadron colliders and its molecular structure'

So we see that the two (or more hadron correlation is very important)

- It may be process dependent--final state interaction...
- need more study, not only angle, rapidity, but 3D correaltion

the amplitude for relative k goes to zero, calculated by event generators with extrapolation

$$\hat{q}=(p_A-p_B)-\frac{(p_A-p_B)\cdot(p_A+p_B)}{(p_A+p_B)^2}(p_A+p_B).$$



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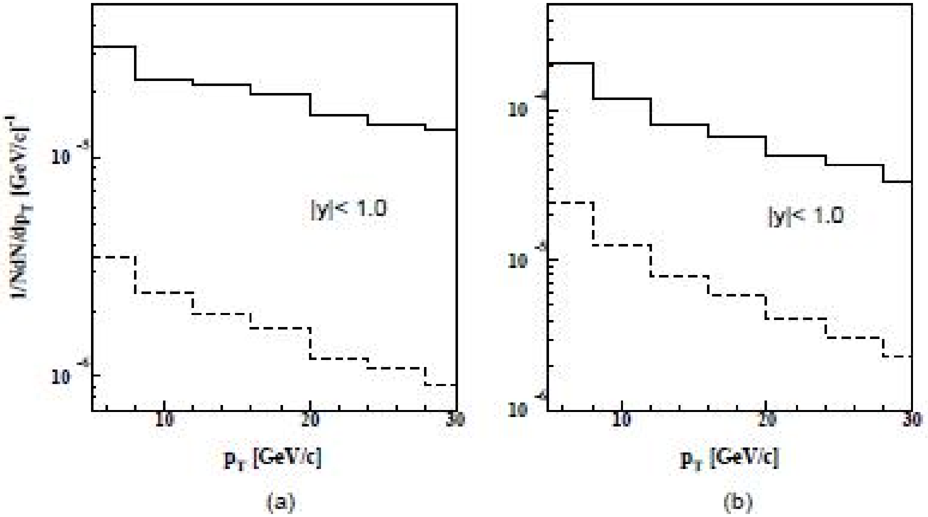
arXiv:1709.09101, 'Note on X(3872) production at hadron colliders and its molecular structure'

(b)

Escape from curse of unitarity, and useful for exp.



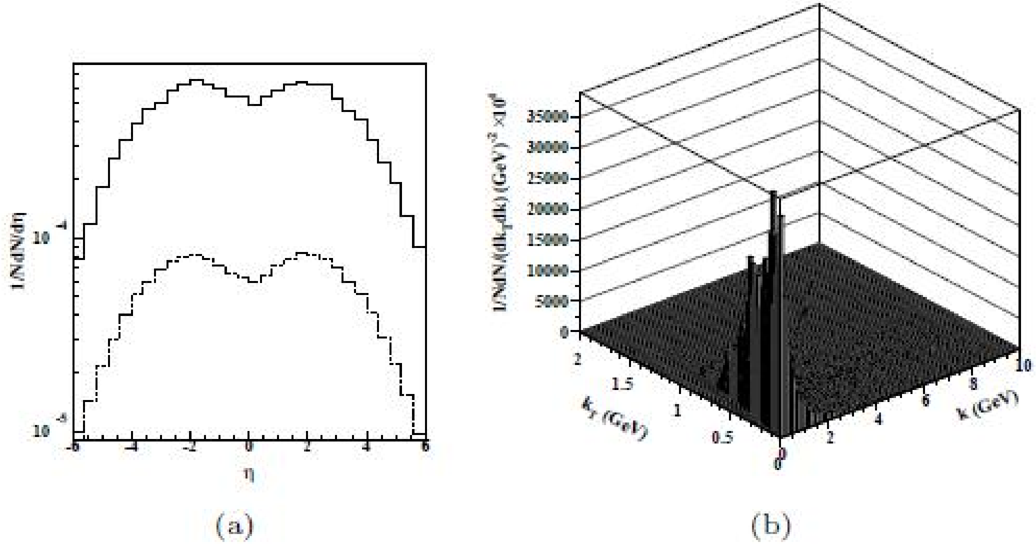
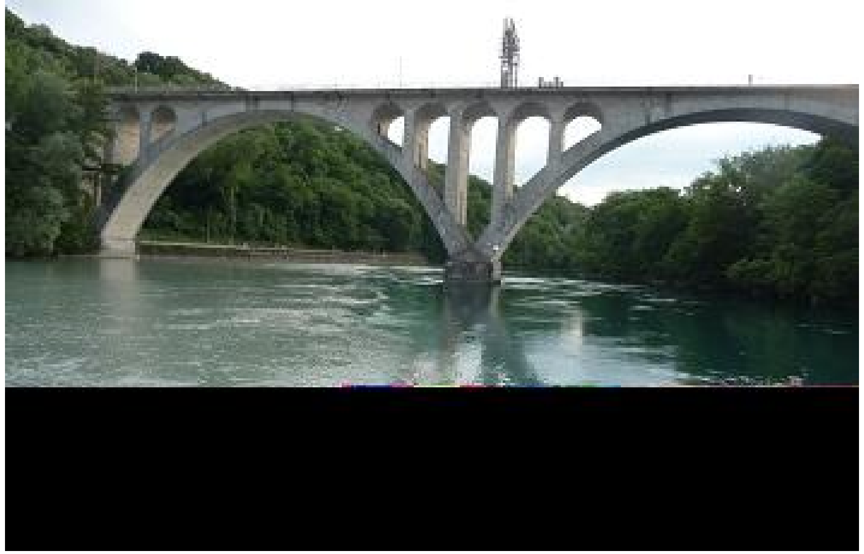


FIG. 2: (a) Pseudo-rapidity distributions. The dashed line

Summary of Part I



- Multiquark hadrons in mutiproduction is la *jonction where* the unsolved problems Soft (high energy as well as low energy) QCD, Bound state problem of QFT, and Confinement emerge
- By applying the quark model in production, unitarity can tell...
- By parameterizing its prodction, for obtaining the hadron (cluster) amplitude, hadron phase space correlation is important...
- Not to forget : yet no multiqaurk hadron confirmed in mutiproduction! what this implies need more study!

X(3872), f0(980)

- Part II ： Preconfinement

‘Local property of high energy mutiproduction’

<u>PRECONFINEMENT AS A PROPERTY OF PERTURBATIVE QCD</u>

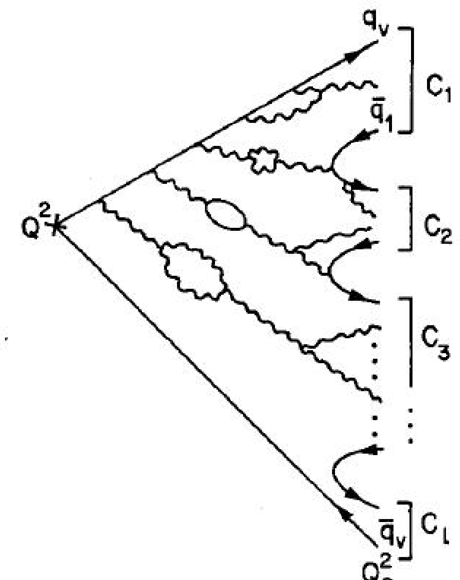
Phys.Lett. 83B:87, 1979

D. Amati and G. Veneziano
CERN -- Geneva

In these previous investigations little, if any, attention was paid to the way in which colour degrees of freedom evolve during the jet development. It is the purpose of this note to argue that quarks and gluons produced in this evolution from Q down to Q_0, become organized in lumps (clusters) of colour singlets with finite (i.e. Q-independent) masses of order Q_0 a phenomenon which we are tempted to call "preconfinement". We can then hope that confinement [occurring in the evolution from Q_0 down to hadron masses $O(m_\pi, m_\rho)$] will convert these singlets of "small" mass into hadrons. If so, there would be no need to invoke any new and incalculable mechanism that involves a large reshuffling of momenta of coloured quanta (as in the standard picture of a parton fragmenting into hadrons).

ges for QCD jets. The perturbative (short time scale) evolution from Q^2 to Q_0^2 already prepares colour singlet states with masses of order Q_0. These can then be converted into hadrons by the non-perturbative (confining) dynamics which can involve only momentum transfers smaller than Q_0 (i.e. a large time scale). The resulting picture looks more like a "fusion" of constituent quanta into hadrons than the commonly adopted fragmentation of single quanta into hadrons. Even if

Combination (Model)



Jet Structure and Infrared Sensitive Quantities in Perturbative QCD
A. Bassetto, M. Ciafaloni, G. Marchesini，Phys.Rept. 100 (1983) 201-272

ges for QCD jets. The perturbative (short time scale) evolution from Q^2 to Q_0^2 already prepares colour singlet states with masses of order Q_0. These can then be converted into hadrons by the non-perturbative (confining) dynamics which can involve only momentum transfers smaller than Q_0 (i.e. a large time scale). The resulting picture looks more like a "fusion" of constituent quanta into hadrons than the commonly adopted fragmentation of single quanta into hadrons. Even if

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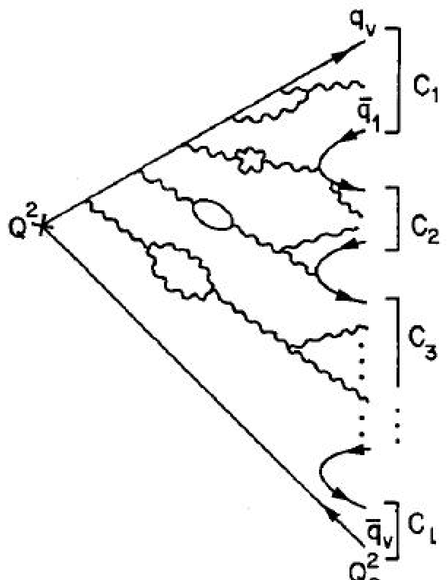


Preconfinement system

- 1, colour strucutre
- 2, baryon number or other U(1) quantum number fluctuations
- 3, what is the relation of this structure and the suppression of exotic hadron production in multiproduction processes.

Thanks for your attention!

Backup:

UNITARITY OF EXCLUSIVE COMBINATION MODELS:

Exotic Hadron Production, Entropy Change & Charmonium Production

LI Shi-Yuan
Shandong University (SDU)

In collaborations with:
HAN Wei, JIN Yi, SHANG Yong-Hui, SHAO Feng-Lan, SI Zong-Guo, YAO Tao, YIN Feng

Based on:
arXiv:1005.4664, P.R.C80:035202,2009, and SDU thesis of Shang and Yin ('09,'10)

Unitarity of exclusive combination model

applying to (massive) constituent quark system in colour-singlet

ALL quarks goes into hadrons (confinement)

- Formal descriptions: by a unitary time evolution operator

$$\sum_h | < h|U|q > |^2 =< q|U^+U|q >= 1. \qquad \sum |q >< q| = \sum |h >< h| = 1$$

- 'Reversal employment' of the Gell-Mann–Zweig constituent quark model, where all the quark states and the hadron states are different bases of the *same* Hilbert space of states
- Total probability to become any state of hadron system is 1
- How to take into account these observations?
- Check in a model, incocnsisitent if P<>1

Quark combination model in SDU

Play with 'Combination rules'

Aware of the simple exp. fact

$$\sum_{h=B,B,M} |<h|U|q>|^2 \sim 1-\varepsilon,\ \ \varepsilon \to 0^+$$

$$\bar{q}_1\bar{q}_2 q_3\bar{q}_4 q_5 q_6$$

$$\bar{q}_1\,\bar{q}_2\,q_3q_4q_5q_6\,\bar{q}_7\,q_8\,\bar{q}_9\,q_{10}\,\bar{q}_{11}\,\bar{q}_{12}\,q_{13}q_{14}q_{15}$$

1. Line up along the rapidity axis
2.combine from one end to the other
3.meson is produced prior than baryon, no combination for quarks with interval more than one q

kill off the combination of number >3, the combination is not free, must be some rules

how to consider the exotic (multi-q)

- experimental fact: $$\sum_{h=B,\bar{B},M} |< h|U|q >|^2 \sim 1-\varepsilon,\ \varepsilon \to 0^+$$
- structure: can be grouped into 'mesons' (anti)baryons
- colour-rearrangement

$$(q_1 q_3)_{\bar{3}} \otimes (\bar{q}_2 \bar{q}_4)_3 \to 1$$
$$(q_1 \bar{q}_2)_{1\ or\ 8} \otimes (q_3 \bar{q}_4)_{1\ or\ 8} \to 1$$
$$\cdots$$

two steps:
1. play with the original one
2. 'use up' some M B Bbar to construct

- gain definition of exotic in a model-denpendne way

$$\frac{E d\sigma^N}{d^3p} = \sum_{N_1 N_2} \int \frac{d^3p_1}{E_1}\frac{d^3p_2}{E_2} \left| < p_1, p_2, N_1, N_2 | p, N > \right|^2 \times \frac{E_1 E_2 d\sigma^{N_1,N_2}}{d^3p_1 d^3p_2}. \quad (5)$$

the hadrons are not confined, rather-->

- a parameter x introduced, restricted by all data available
- what can this `*predicts*':

employ an example $f_0(980)$

All hadrons are not isolated but grouped, according to the colour/flavour symmetry

The exotic also should respect ......

meson pair	$\|<J_1,J_2\|J>\|^2$	$\|<C_1,C_2\|C>\|^2$	$\|<I_1,I_2\|I>\|^2$
ϕ,ω	1/9	1	1
η,η	1	1	4/9
η,η'	1	1	5/9
η',η'	1	1	4/9
K^+,K^-	1	1	1/2
$K^0,\bar{K}^0$	1	1	1/2

	x	$f_0(980)(s\bar{q}\bar{s}q)$	$f_0(980)(s\bar{s})$
(a)	0.60	1.63	0.68
(b)	0.24	0.65	

only $SU_f(2)$ is considered

$$\sum_{h=B,\bar{B},M} |<h|U|q>|^2 \sim 1-\varepsilon,\ \varepsilon \to 0^+$$

$$\sum_{allexotic} |<h|U|q>|^2 = \varepsilon$$

Realized in model

Entropy change, applying to colour singlet *seperated* quark system

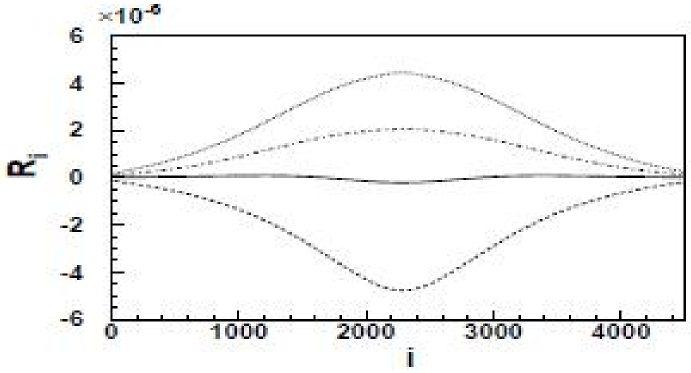
$$S = -tr(\rho \ln \rho)$$

$$\rho(t) = |t, i > P_i < i, t| = U(t,0)|0, i > P_i < i, 0|U^{\dagger}(t,0)$$
$$= U(t,0)\rho(0)U^{\dagger}(t,0).$$

$$\Delta S = \int_A^B \frac{dQ}{T}.$$

$$\Delta S = \sum_i \Delta U_i / T_i.$$

employing the code in computer as a quasi-static process, when N_q is large



$$R_i = 1 - E_{i-1}/E_i$$

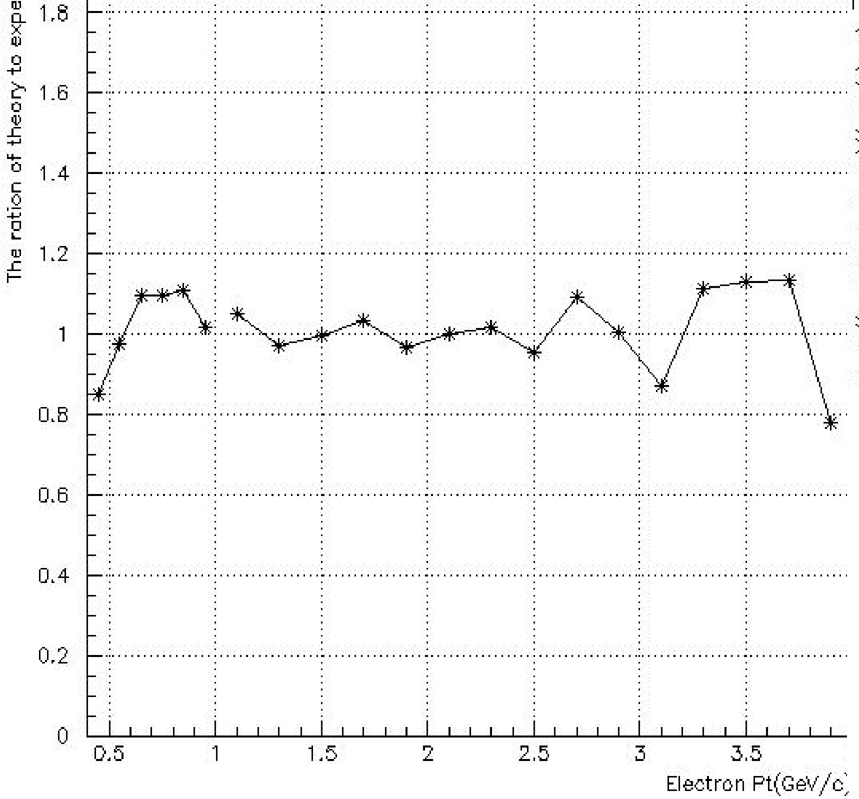
Open charm & charmonium product. mechanism`unification' in combin. model:

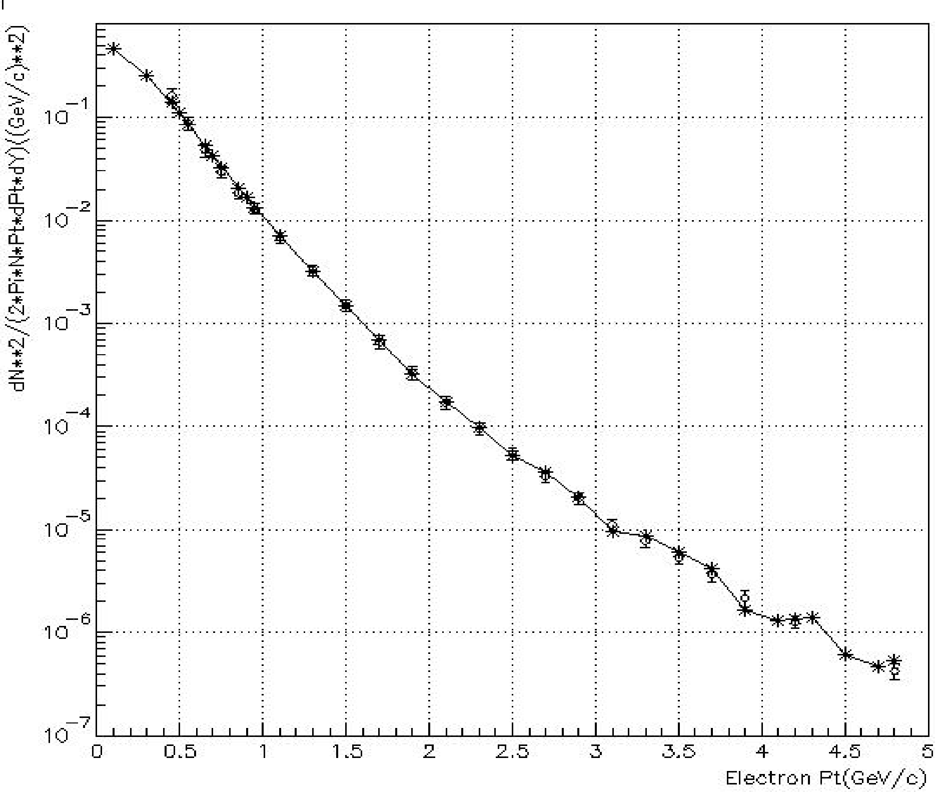
- In above, SUf(3), but heavy quark do not well respect SUf(N) N>3.
- This does not means the hadronization mechanism is differernt, only the unitarity takes a different form.
- With the help of the light quarks, the confiement is achieved but the charm sector is quite the similar as those in EW interactions without confinement:

  the continuous spectrum

  the discrete spectrum

$$\bar{q}_1 \bar{q}_2 c \ q_4 q_5 q_6 \bar{c} q_8 \bar{q}_9 c \bar{c} \bar{q}_{12} \ q_{13} q_{14} q_{15}$$





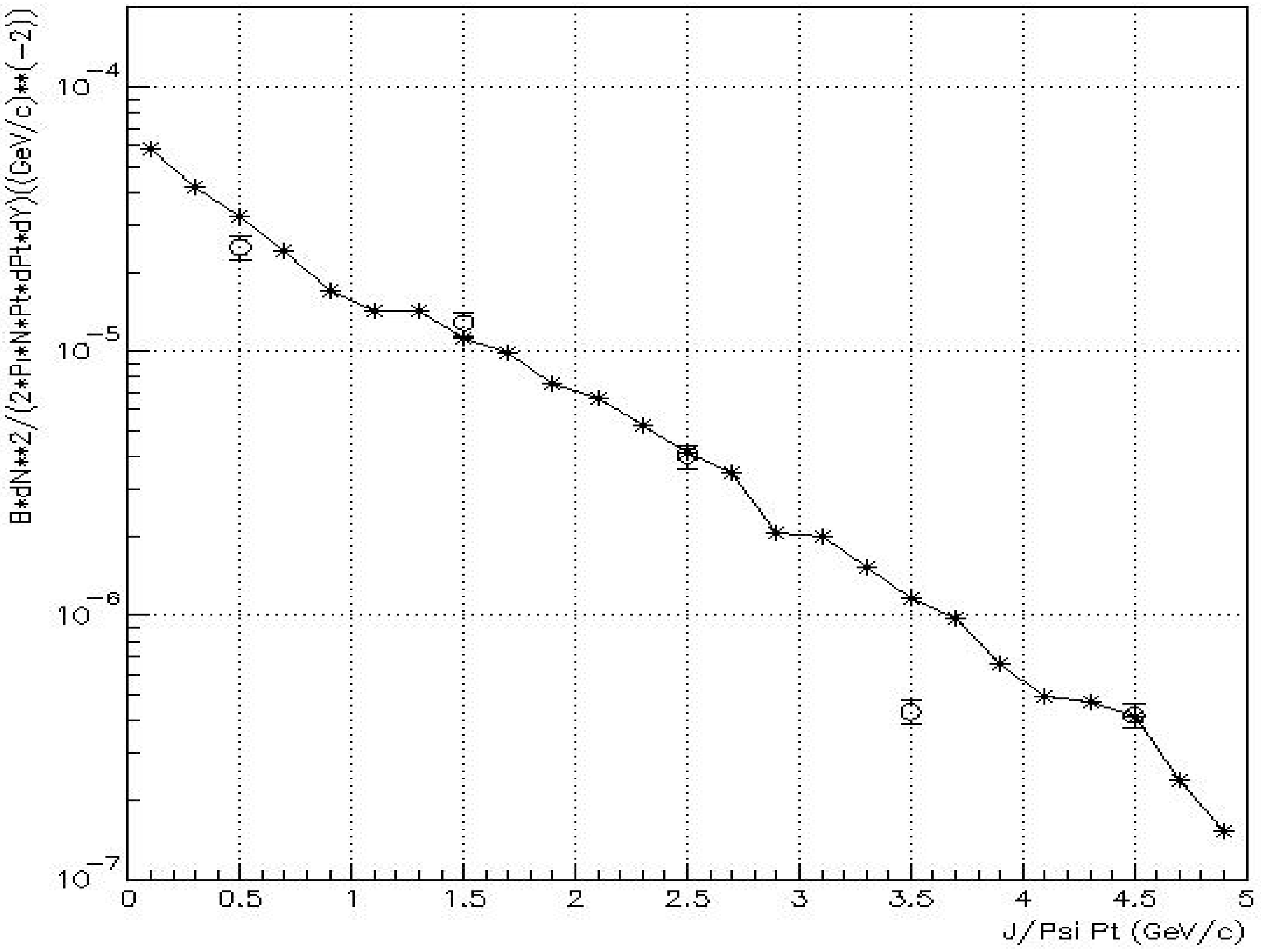
L=0

$$\rho_X = \frac{(2J_X+1)/n_x}{\sum_{L=0}(2J_x+1)+0.25\sum_{L=1}(2J_x+1)}$$

L=1

$$\rho_X = \frac{0.25(2J_X+1)/n_x}{\sum_{L=0}(2J_x+1)+0.25\sum_{L=1}(2J_x+1)}$$

	L	J	n	rw	Br($\rightarrow J/\Psi$)
J/Ψ	0	1	1	1/3	1
η_c	0	0	1	1/9	0
$\Psi(2s)$	0	1	2	1/6	5.74×10^{-1}
$\eta_c(2s)$	0	0	2	1/18	0
χ_{c0}	1	0	1	1/36	1.28×10^{-2}
χ_{c1}	1	1	1	1/12	3.60×10^{-1}
χ_{c2}	1	2	1	5/36	2.0×10^{-1}
h_c	1	1	1	1/12	0


B*dN**2/(2*Pi*N*Pt*dPt*dY)((GeV/c)**(-2))
10^-4
10^-5
10^-6
10^-7
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
J/Psi Pt (GeV/c)

Conclusion

Unitarity
can give strong restriction
helps to understand the entropy
while the charm is in a novel way live with the light in "QGP"...

$$\sum_{allexotic} |< h \,|\, U \,|\, q >|^2 = \varepsilon$$

Even we know the wave function of an isolated hadron, it is not the end of the story to consider exclusive hadronization

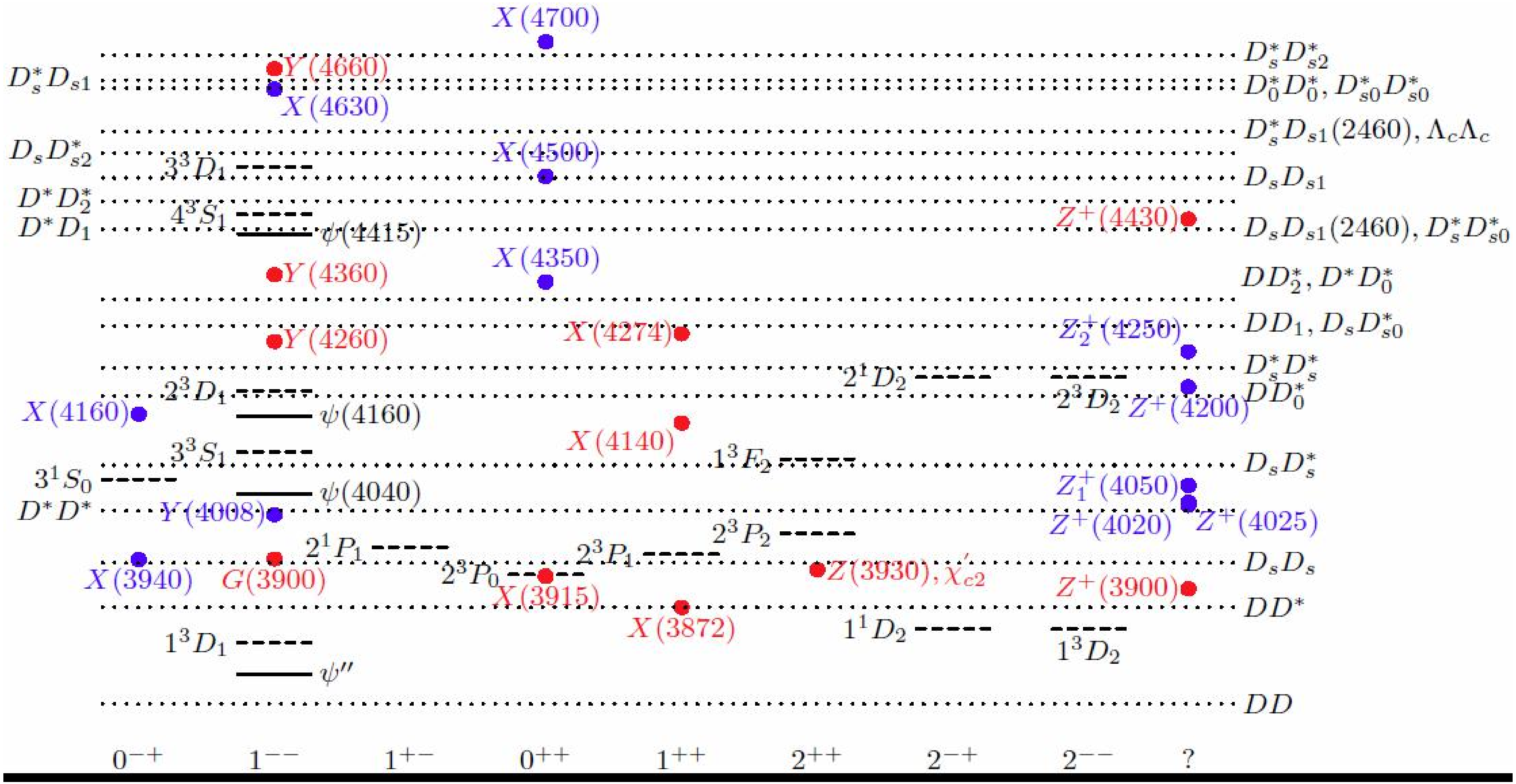
Multiquark state production and hadron correlation in high energy multiproduction processes

LI, Shi-Yuan

Shandong University

Moriond QCD'18

So many…… c-sector/b-sector/light



Maiani, 2017

5. Conclusions

- Data have conclusively shown that there are "structures" beyond (q q-bar) or (qqq) states, but we do not know yet if this is a reflection of known dynamics in a new context (molecules? threshold effects?) or the indication of a new class of quark bound states;

…………………………..

To study exotics in multiproduction process

- Most general hadrons (mesons, baryons) can be produced directly in multiproduction process of high energy collisions
- But cases are not for the exotic hadrons (from decay)

- ?X(5568), ?X(3872), ?light pentaquark
- P.R.D94 (2016) no.1, 014023

- What special property of multiproduction?

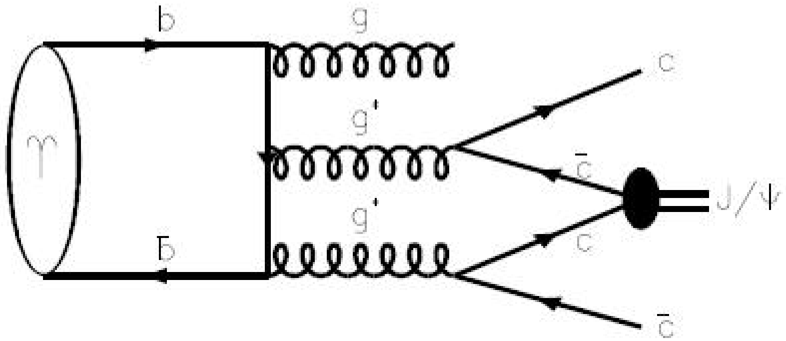
An interesting 'mini' multiproduction evidence

1605.00990

(The Belle Collaboration)

The branching fractions of the $\Upsilon(1S)$ inclusive decays into final states with a J/ψ or a $\psi(2S)$ are measured with improved precision to be $\mathcal{B}(\Upsilon(1S) \to J/\psi + \text{anything}) = (5.25 \pm 0.13(\text{stat.}) \pm 0.25(\text{syst.})) \times 10^{-4}$ and $\mathcal{B}(\Upsilon(1S) \to \psi(2S) + \text{anything}) = (1.23 \pm 0.17(\text{stat.}) \pm 0.11(\text{syst.})) \times 10^{-4}$. The first search for $\Upsilon(1S)$ decays into XYZ states that decay into a J/ψ or a $\psi(2S)$ plus one or two charged tracks yields no significant signals for XYZ states in any of the examined decay modes, and upper limits on their production rates in $\Upsilon(1S)$ inclusive decays are determined.

State	N_{fit}	N_{up}	$\varepsilon(\%)$	$\sigma_{\text{syst}}(\%)$	$\Sigma(\sigma)$	$\mathcal{B}_R^{\text{prod}}$
$X(3872) \to \pi^+\pi^- J/\psi$	4.8±15.4	31.4	3.26	18.7	0.3	$< 9.5 \times 10^{-6}$
$Y(4260) \to \pi^+\pi^- J/\psi$	−31.1±88.9	134.6	3.50	35.6	–	$< 3.8 \times 10^{-5}$
$Y(4260) \to \pi^+\pi^- \psi(2S)$	6.7±29.4	56.9	0.71	35.0	0.2	$< 7.9 \times 10^{-5}$
$Y(4360) \to \pi^+\pi^- \psi(2S)$	−25.4±30.1	45.6	0.86	50.0	–	$< 5.2 \times 10^{-5}$
$Y(4660) \to \pi^+\pi^- \psi(2S)$	−55.0±26.2	23.1	1.06	40.7	–	$< 2.2 \times 10^{-5}$
$Y(4260) \to K^+K^- J/\psi$	−13.7±10.9	14.5	1.91	45.8	–	$< 7.5 \times 10^{-6}$
$Y(4140) \to \phi J/\psi$	−0.1±1.2	3.6	0.69	11.0	–	$< 5.2 \times 10^{-6}$
$X(4350) \to \phi J/\psi$	2.3±2.5	7.6	0.92	10.4	1.2	$< 8.1 \times 10^{-6}$
$Z_c(3900)^\pm \to \pi^\pm J/\psi$	−26.5±39.1	57.5	4.39	47.3	–	$< 1.3 \times 10^{-5}$
$Z_c(4200)^\pm \to \pi^\pm J/\psi$	−238.6±154.2	235.1	3.87	48.4	–	$< 6.0 \times 10^{-5}$
$Z_c(4430)^\pm \to \pi^\pm J/\psi$	94.2±71.4	195.8	3.97	34.4	1.2	$< 4.9 \times 10^{-5}$
$Z_c(4050)^\pm \to \pi^\pm \psi(2S)$	37.0±47.7	112.7	1.27	46.2	0.4	$< 8.8 \times 10^{-5}$
$Z_c(4430)^\pm \to \pi^\pm \psi(2S)$	23.2±42.4	92.0	1.35	47.1	0.1	$< 6.7 \times 10^{-5}$
$Z_{cs}^\pm \to K^\pm J/\psi$	−22.2±17.4	22.4	3.88	48.7	–	$< 5.7 \times 10^{-6}$



Another interesting evidence

Search for light tetraquark states in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays

S. Jia,[2] C. P. Shen,[2] C. Z. Yuan,[25] I. Adachi,[16,12] J. K. Ahn,[39] H. Aihara,[82] S. Al Said,[76,37] D. M. Asner,[64] H. Atmacan,[72] T. Aushev,[52] R. Ayad,[76] V. Babu,[77] I. Badhrees,[76,36] S. Bahinipati,[20] A. M. Bakich,[75] V. Bansal,[64] P. Behera,[23] M. Berger,[73] V. Bhardwaj,[19] B. Bhuyan,[21] J. Biswal,[32] G. Bonvicini,[87] A. Bozek,[59] M. Bračko,[47,32] T. E. Browder,[15]
Yonsei University, Seoul 120-749

Abstract

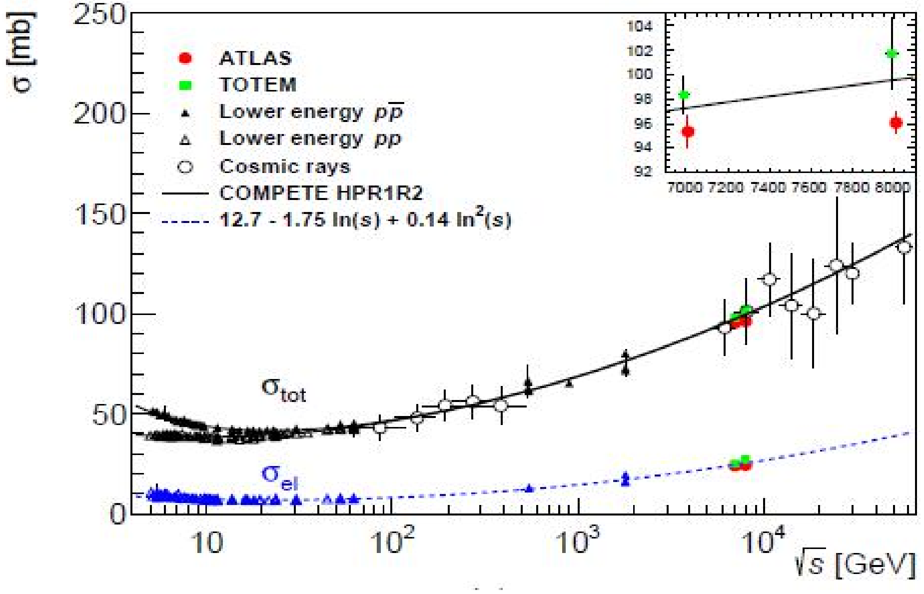
We search for the $J^{PC} = 0^{--}$ and 1^{+-} light tetraquark states with masses up to 2.46 GeV/c^2 in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays with data samples of (102 ± 2) million and (158 ± 4) million events, respectively, collected with the Belle detector. No significant signals are observed in any of the studied production modes, and 90% credibility level (C.L.) upper limits on their branching fractions in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays are obtained. The inclusive branching fractions of the $\Upsilon(1S)$ and $\Upsilon(2S)$ decays into final states with

R. Mussa,[30] M. Nakao,[16,12] T. Nanut,[32] K. J. Nath,[21] Z. Natkaniec,[59] M. Nayak,[87,16] M. Niiyama,[40] N. K. Nisar,[66] S. Nishida,[16,12] S. Ogawa,[79] S. Okuno,[33] S. L. Olsen,[69] H. Ono,[60,61] Y. Onuki,[82] P. Pakhlov,[43,51] G. Pakhlova,[43,52] B. Pal,[6] S. Pardi,[29] C. W. Park,[74] H. Park,[41] S. Paul,[78] I. Pavelkin,[52] R. Pestotnik,[32] L. E. Piilonen,[86] M. Ritter,[45] A. Rostomyan,[7] G. Russo,[29] Y. Sakai,[16,12] M. Salehi,[46,45] S. Sandilya,[6] L. Santelj,[16] T. Sanuki,[80] V. Savinov,[66] O. Schneider,[42] G. Schnell,[1,18] C. Schwanda,[26] Y. Seino,[61] K. Senyo,[88] O. Seon,[53] M. E. Sevior,[49] V. Shebalin,[3,62] T.-A. Shibata,[83] N. Shimizu,[82] J.-G. Shiu,[58] B. Shwartz,[3,62] J. B. Singh,[65] A. Sokolov,[27] E. Solovieva,[43,52] M. Starič,[32] J. Stypula,[59] M. Sumihama,[11] T. Sumiyoshi,[84]

711.01690v1 [hep-ex] 6 Nov 2017

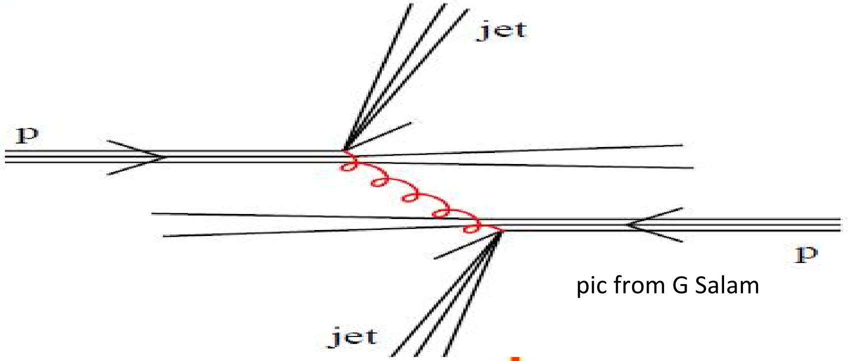
Multiproduction: in soft interactions vs in a jet

Pionization
Total cross section
Heavy ion complexity
Number and kinds of hadrons
Basic degree of freedom?
Feynman,1969; Cheng & Wu,1971



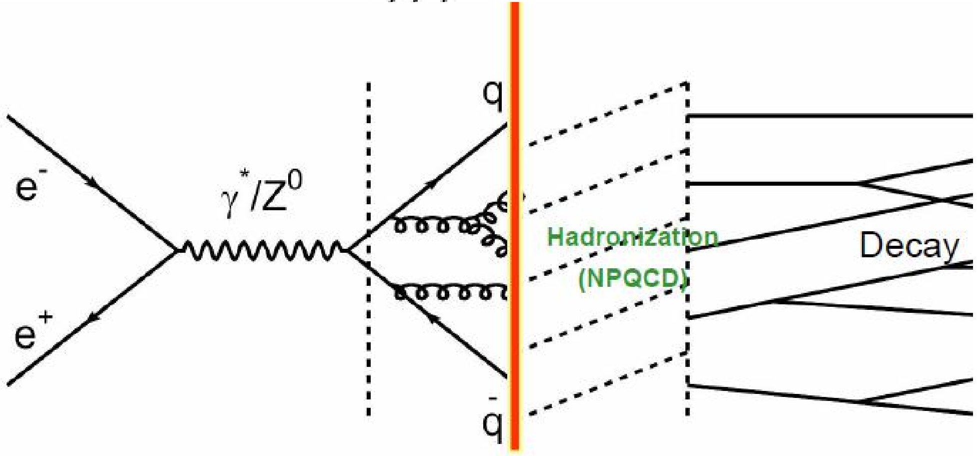
1611.02454

Local parton-hadron duality (number of 'clusters')
Definition of jet (parton level)
Quark and gluon are the basic degrees of freedom--but



how quarks/gluons combined to (what) hadron

how colour is confined



Difficulty of production of multiquark states (*unitarity*)

ALL quarks go into hadrons (confinement--Tous les hommes sont mortels！）

- Formal descriptions: by a unitary time evolution operator

$$\sum_h |<h|U|q>|^2 = <q|U^+U|q> = \sum |q><q| = \sum |h><h| = 1 \qquad \sum_{h=B,\bar{B},M} |<h|U|q>|^2 \sim 1-\varepsilon, \ \varepsilon \to 0^+$$

- Total probability to become any state of hadron system is 1
- 'Reversal employment' of the Gell-Mann–Zweig constituent quark model, where all the quark states and the hadron states are different bases of the *same* Hilbert space of states/static -> production

- Most of the limited space has been occupied by general hadrons, not any more left for the populated exotics---they really of large population even only considering the heavy

- See, Unitarity and Entropy Change in Exclusive Quark Combination Models, arXiv:1005.4664 [hep-ph] ; Exotic hadron production in quark combination model，Phys.Rev. C80 (2009) 035202;talks here at Moriond QCD'11(unitarity and exotic), and some recent ones to repeat this observation

Difficulty of production of multiquark states (colour connection)

- **Complexity of the colour structure of the multiquark hadrons**
- **Eg, qqbar qqbar four quark sysytem**

$$(3_1 \otimes 3_3) \otimes (3^*_2 \otimes 3^*_4) = (3^*_{13} \oplus 6_{13}) \otimes (3_{24} \oplus 6^*_{24}) = (3^*_{13} \otimes 3_{24}) \oplus (6_{13} \otimes 6^*_{24}) \oplus \cdots$$

$$(3_1 \otimes 3^*_2) \otimes (3_3 \otimes 3^*_4) = (1_{12} \oplus 8_{12}) \otimes (1_{34} \oplus 8_{34}) = (1_{12} \otimes 1_{34}) \oplus (8_{12} \otimes 8_{34}) \oplus \cdots,$$

$$(3_1 \otimes 3^*_4) \otimes (3_3 \otimes 3^*_2) = (1_{14} \oplus 8_{14}) \otimes (1_{32} \oplus 8_{32}) = (1_{14} \otimes 1_{32}) \oplus (8_{14} \otimes 8_{32}) \oplus \cdots$$

- **oth in hadron (static properties) as well as in production**

- Colour reconnecion, colour recombination…, total probability again 1
- See, e.g, Studying color connection effects of e+e−→cc¯cc¯→Ξcc+Xe+e−→cc¯cc¯→Ξcc+X process within Quark Combination Model , P.R. D91 (2015) no.11, 114017 ,Search for a doubly charmed hadron at B factories，P.R.D89 (2014) no.9, 094006, Colour connections of four quark QQ¯Q′Q¯′ system and doubly heavy baryon production in e+e- e+e- annihilation，P.L.B727 (2013) 468-473

Direct comparison on ‘fragmentation function’ (N_q→infty)

- To study the fragmentation of ccbar/cc, in ccbar ccbar system: relative rate

Doubly heavy baryon Xi_cc, LHCb, Phys. Rev. Lett. 119, 112001 (2017)

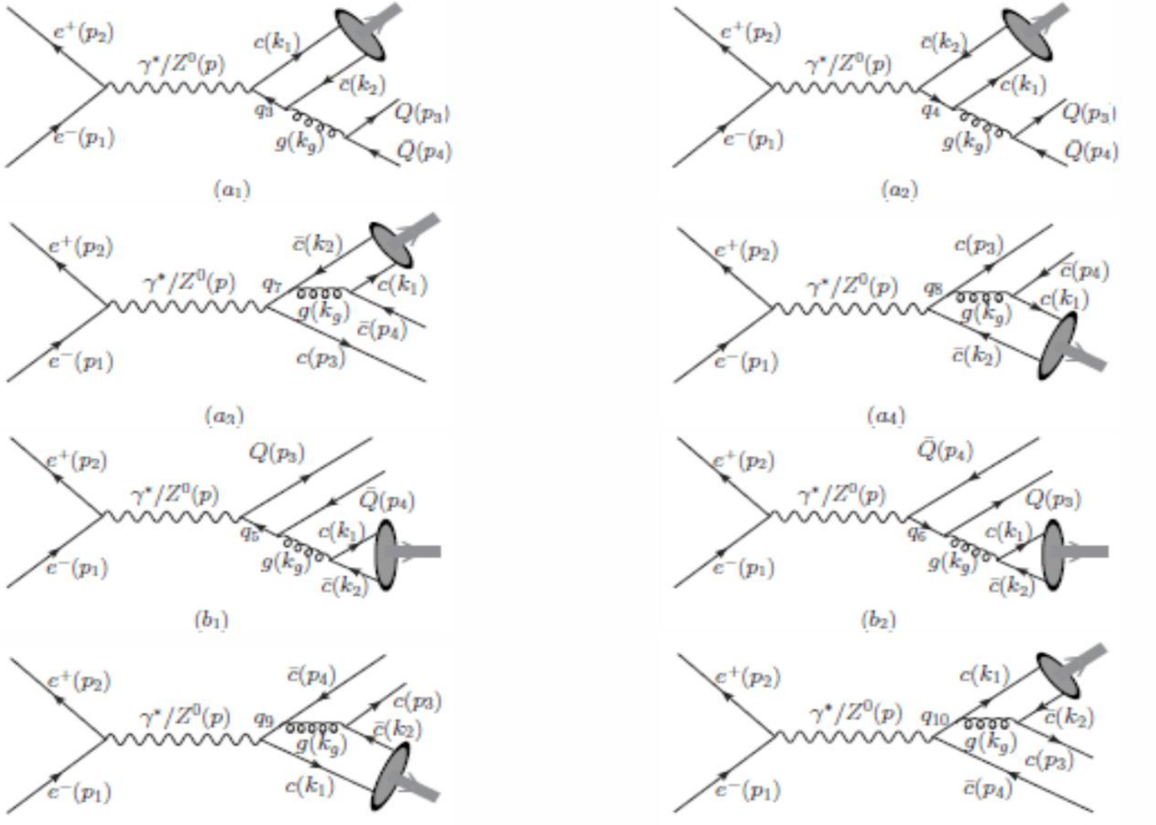
Directly produced so give some confidence on not small probability of the colour connection

$$(3_1\otimes 3_3)\otimes(3_2^*\otimes 3_4^*) = (3_{13}^*\oplus 6_{13})\otimes(3_{24}\oplus 6_{24}^*) = (3_{13}^*\otimes 3_{24})\oplus(6_{13}\otimes 6_{24}^*)\oplus\cdots$$

$$(3_1\otimes 3_2^*)\otimes(3_3\otimes 3_4^*) = (1_{12}\oplus 8_{12})\otimes(1_{34}\oplus 8_{34}) = (1_{12}\otimes 1_{34})\oplus(8_{12}\otimes 8_{34})\oplus\cdots,$$

$$(3_1\otimes 3_4^*)\otimes(3_3\otimes 3_2^*) = (1_{14}\oplus 8_{14})\otimes(1_{32}\oplus 8_{32}) = (1_{14}\otimes 1_{32})\oplus(8_{14}\otimes 8_{32})\oplus\cdots,$$

Colour as well as combination to other 3-quark cluster



Hidden-charm Pentaquark Production at e+e− Colliders
Commun. Theor. Phys. 69 (2018) no.3, 291

Multiquark state and hadron correlation, heavy sector

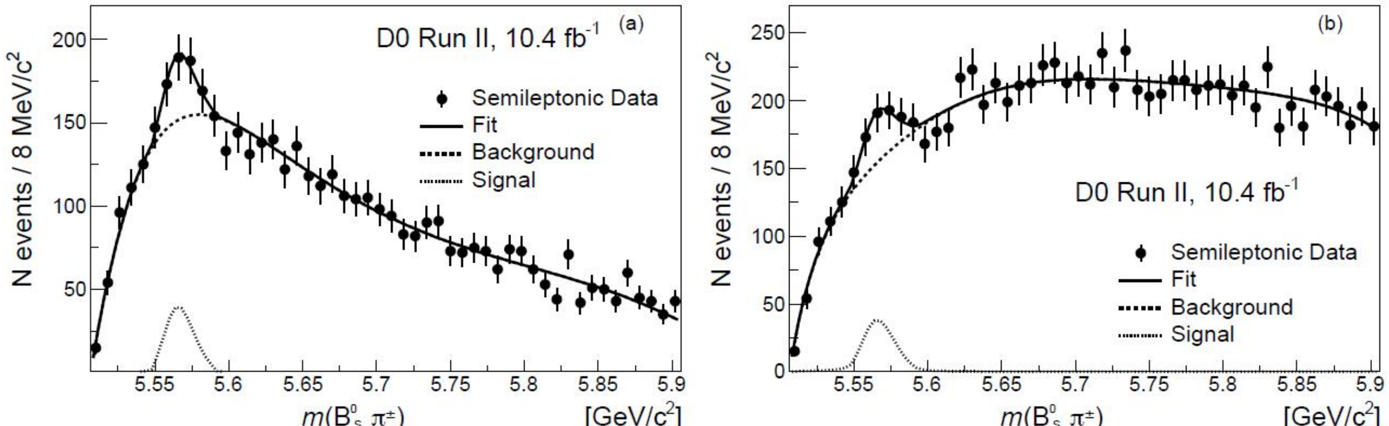
- They are/could be copiously directly produced from the multiproduction process
- X(5568) is now hardly to be confirmed, and its production mechanism must be quite special if exist.
- Correlation to study the event cut, esp. extra ‘cone cut’ by D0
- X(3872) is of no doubt to exist，but large production rate cause debate on its structure.
- We show the correlation is related with calculation of the production in a particular model

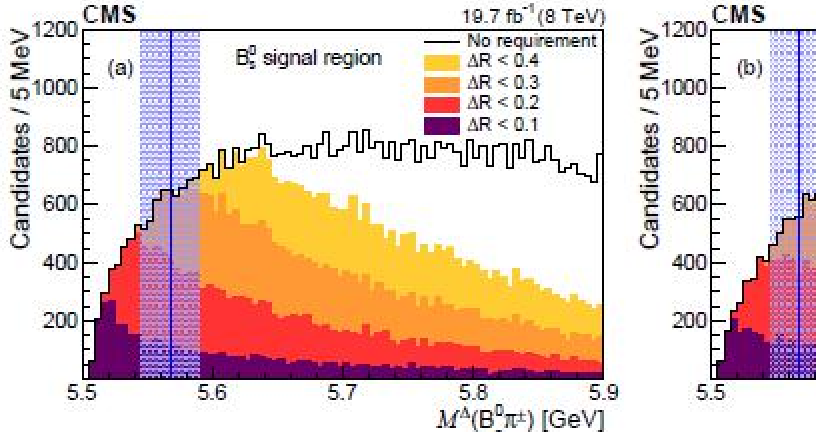
Notre chère X(5568)

- D0 arXiv:1712.10176 [hep-ex] report evidence for a narrow structure, again (1602.07588)
- ATLAS arXiv:1802.01840 [hep-ex] No significant signal was found
- CDF arXiv:1712.09620 [hep-ex] No evidence for this state is found

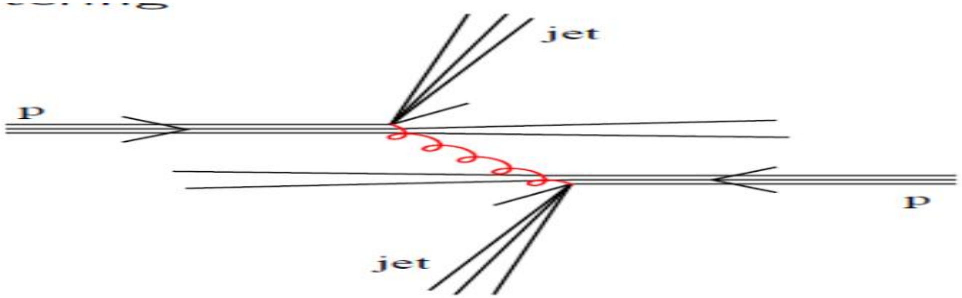
10 o used in this analysis.

re

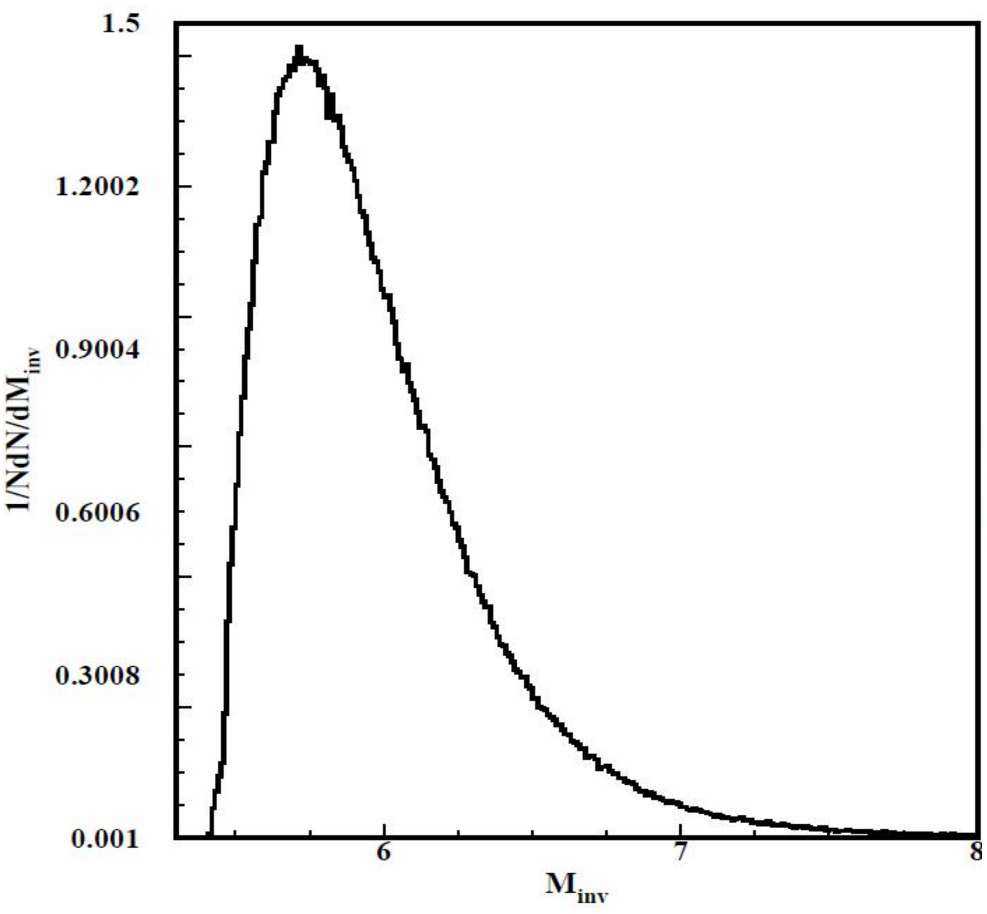


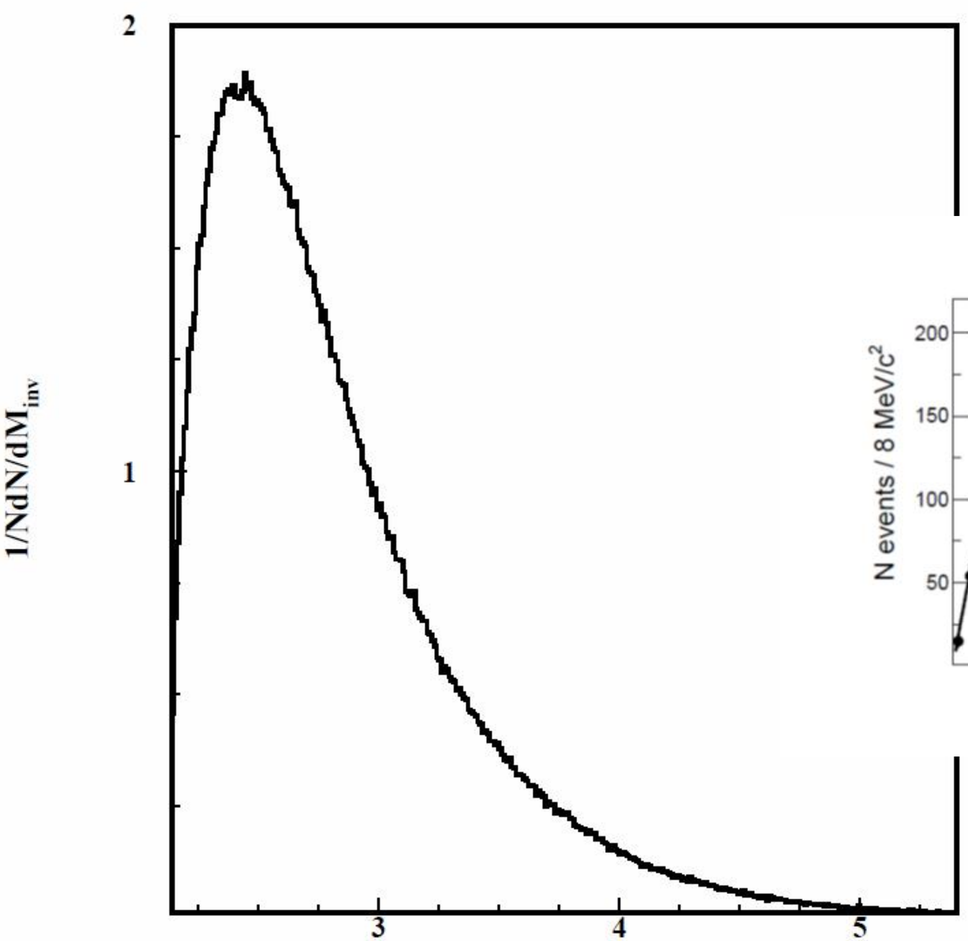


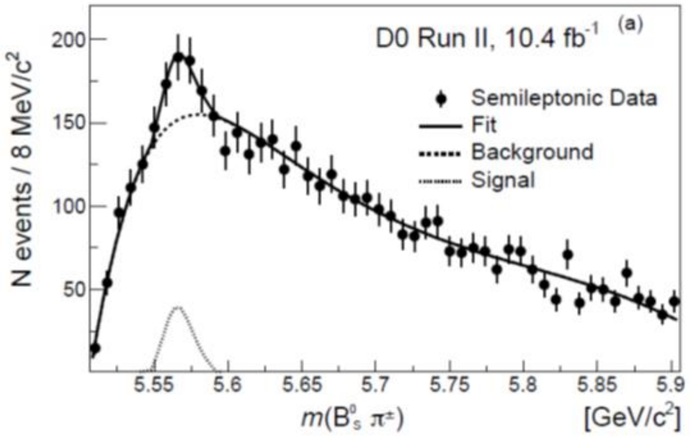
- e+e-



Line shape: peak around threshold, l-Bpi,R-Dpi





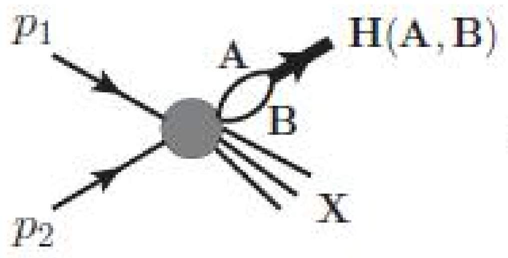


X(3872): DD*bound state?

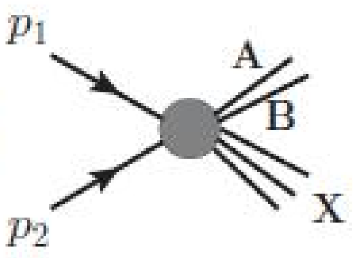
- Can its structure be determined in the production process? At least more information?
- Make a model, then ……
- What about the wave function? What about the amplitude? Factorization--- quest on various scales

To parameterize the production of X(5568)(as hadron (BK)/ cluster(bsbar udbar) molecule) and how to do calculation

and prepare for the case of production



$$= \int \frac{d^3k}{(2\pi)^3} \Phi(\vec{k}) \times$$



$$\Psi(0)$$

FIG. 1: The process $p(p_1)p(p_2) \to A(p_A) + B(p_B) + X \to H(A,B)(P_H) + X$.

$$\frac{1}{N}\frac{dN}{d^3P_H d^3q} \propto \frac{1}{F}\sum_{j\neq A,B}\prod \frac{d^3p_j}{(2\pi)^3 2E_j}\overline{|\hat{O}|^2}(p_j, P_H = p_A + p_B, q = p_A - p_B) \times (2\pi)^4\delta^{(4)}(P_{intial} - \sum_{j\neq A,B} p_j - p_A - p_B).$$

Expand the amplitude around k=0

fitting data to get the wave function at origin, can be used every where… factorization

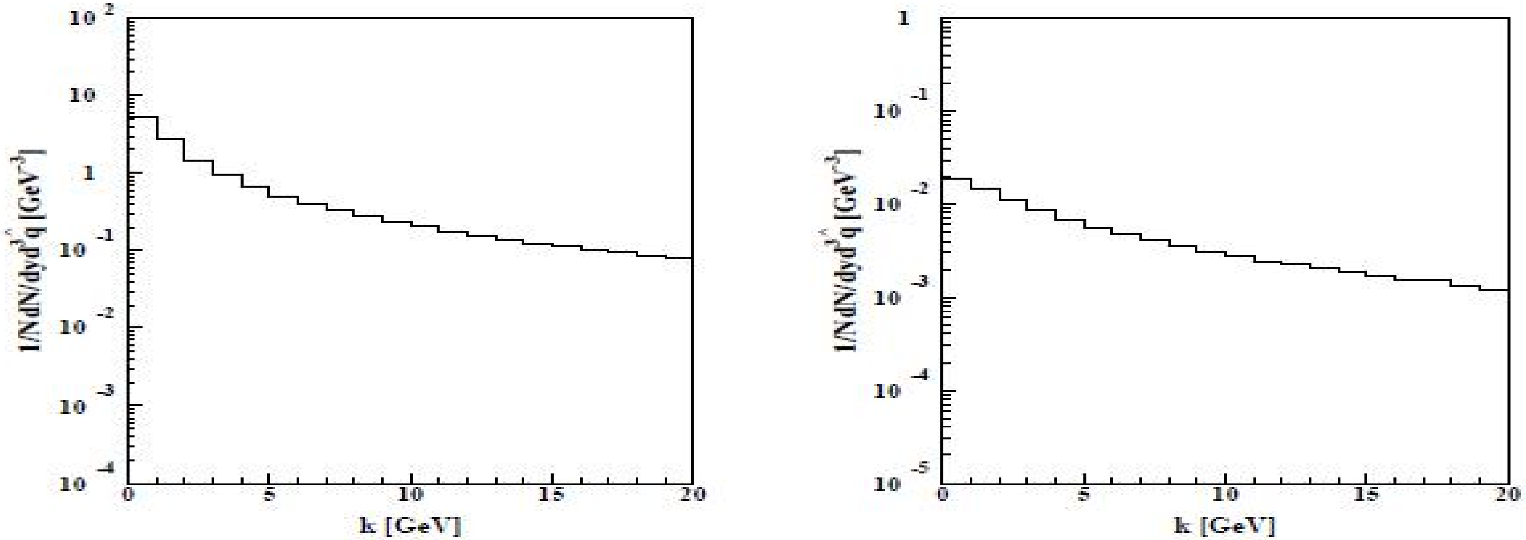
Wei Wang, arXiv:1709.10382, Comment on "Comment on `Note on X(3872) production at hadron colliders and its molecular structure' "
A. Esposito, B. Grinstein, L. Maiani, F. Piccinini, A. Pilloni, A.D. Polosa, V. Riquer,
arXiv:1709.09631 Comment on `Note on X(3872) production at hadron colliders and its molecular structure'
Miguel Albaladejo, Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißner, Juan Nieves, Andreas Nogga, Zhi Yang
arXiv:1709.09101, 'Note on X(3872) production at hadron colliders and its molecular structure'

So we see that the two (or more hadron correlation is very important)

- It may be process dependent--final state interaction...
- need more study, not only angle, rapidity, but 3D correaltion

the amplitude for relative k goes to zero, calculated by event generators with extrapolation

$$\hat{q} = (p_A - p_B) - \frac{(p_A - p_B)\cdot(p_A + p_B)}{(p_A + p_B)^2}(p_A + p_B).$$



(b)

Wei Wang,   arXiv:1709.10382, Comment on "Comment on `Note on X(3872) production at hadron colliders and its molecular structure' "
A. Esposito, B. Grinstein, L. Maiani, F. Piccinini, A. Pilloni, A.D. Polosa, V. Riquer,
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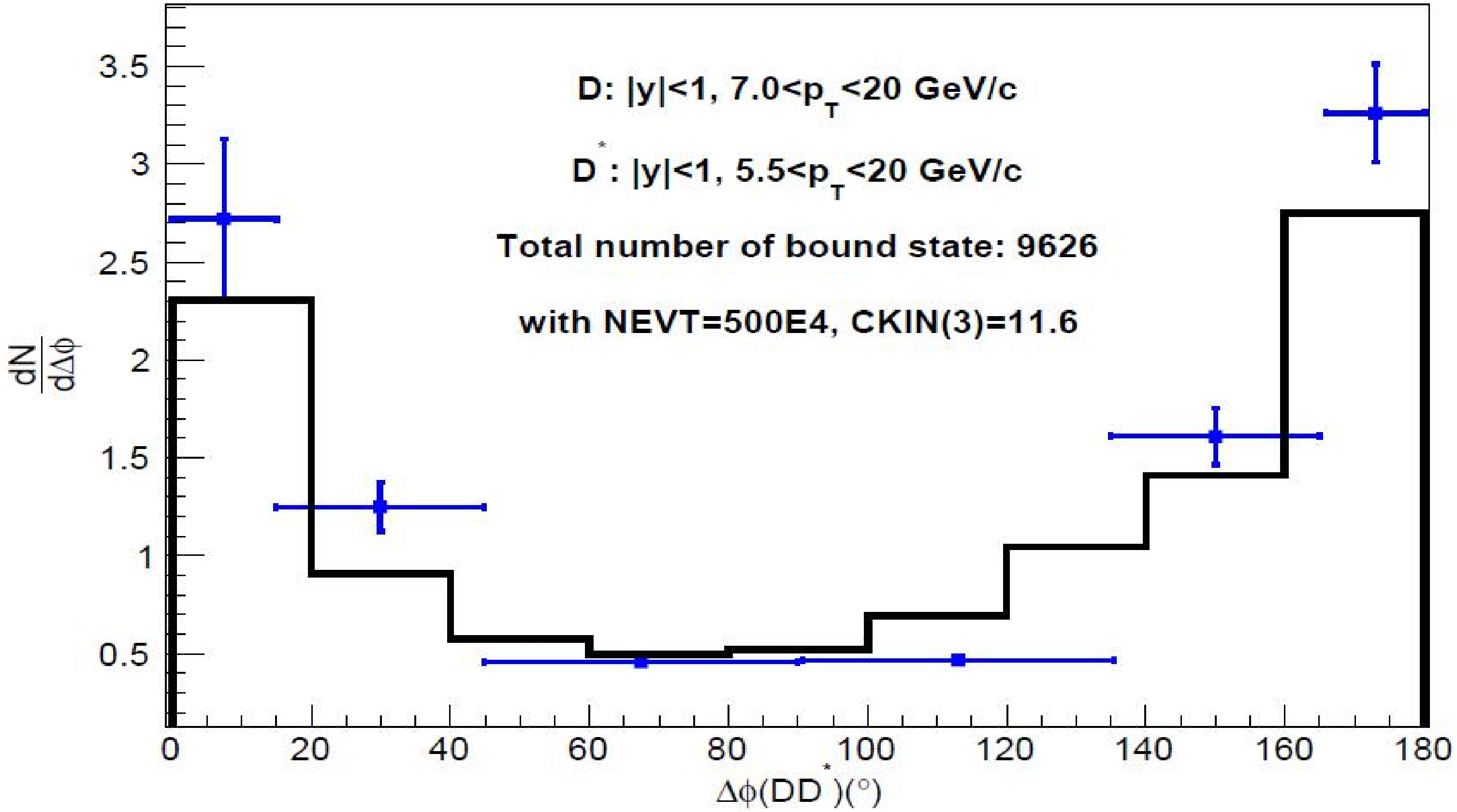
arXiv:1709.09101, 'Note on X(3872) production at hadron colliders and its molecular structure'

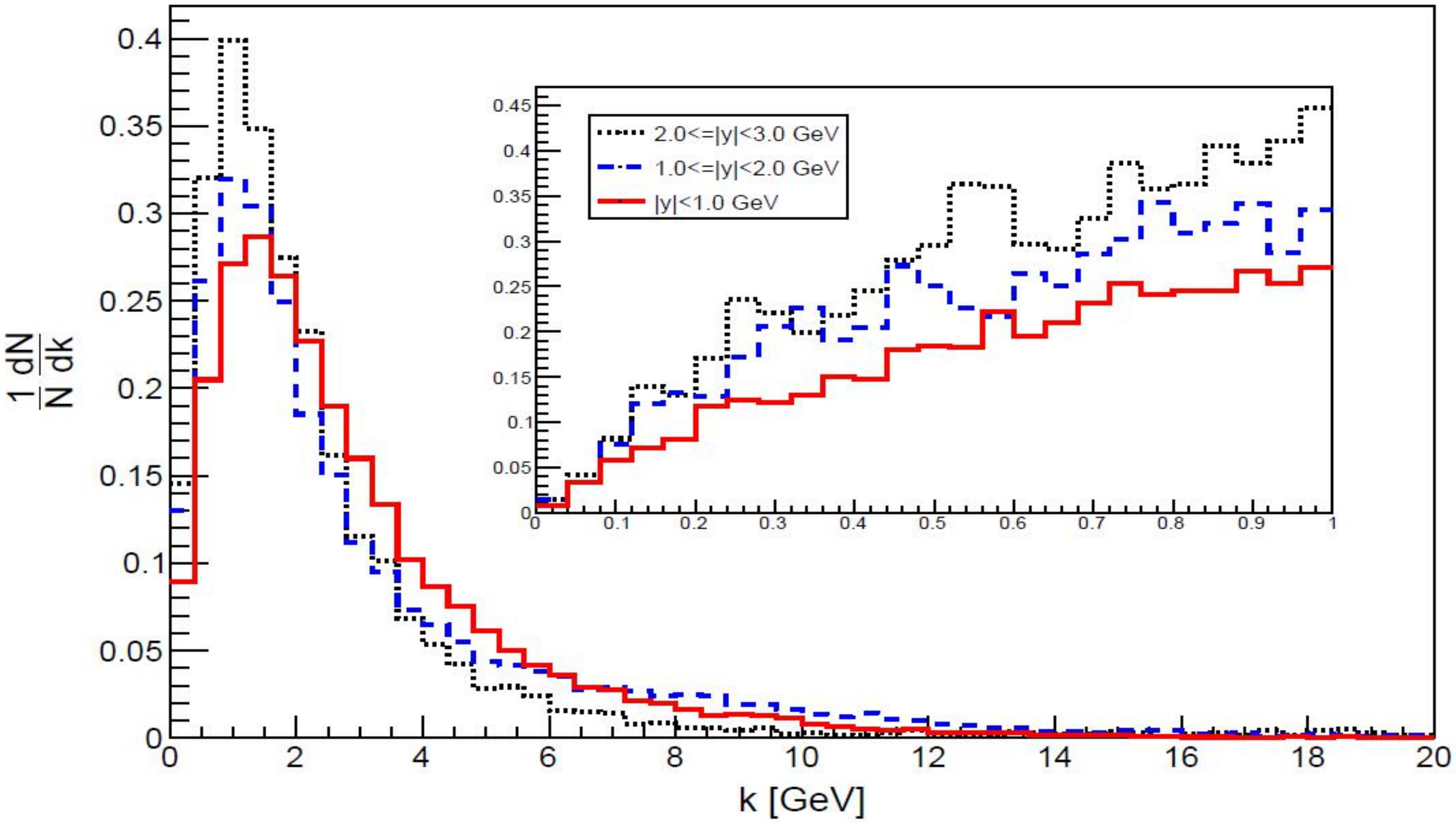
To tune wrt the available data (Pythia…)



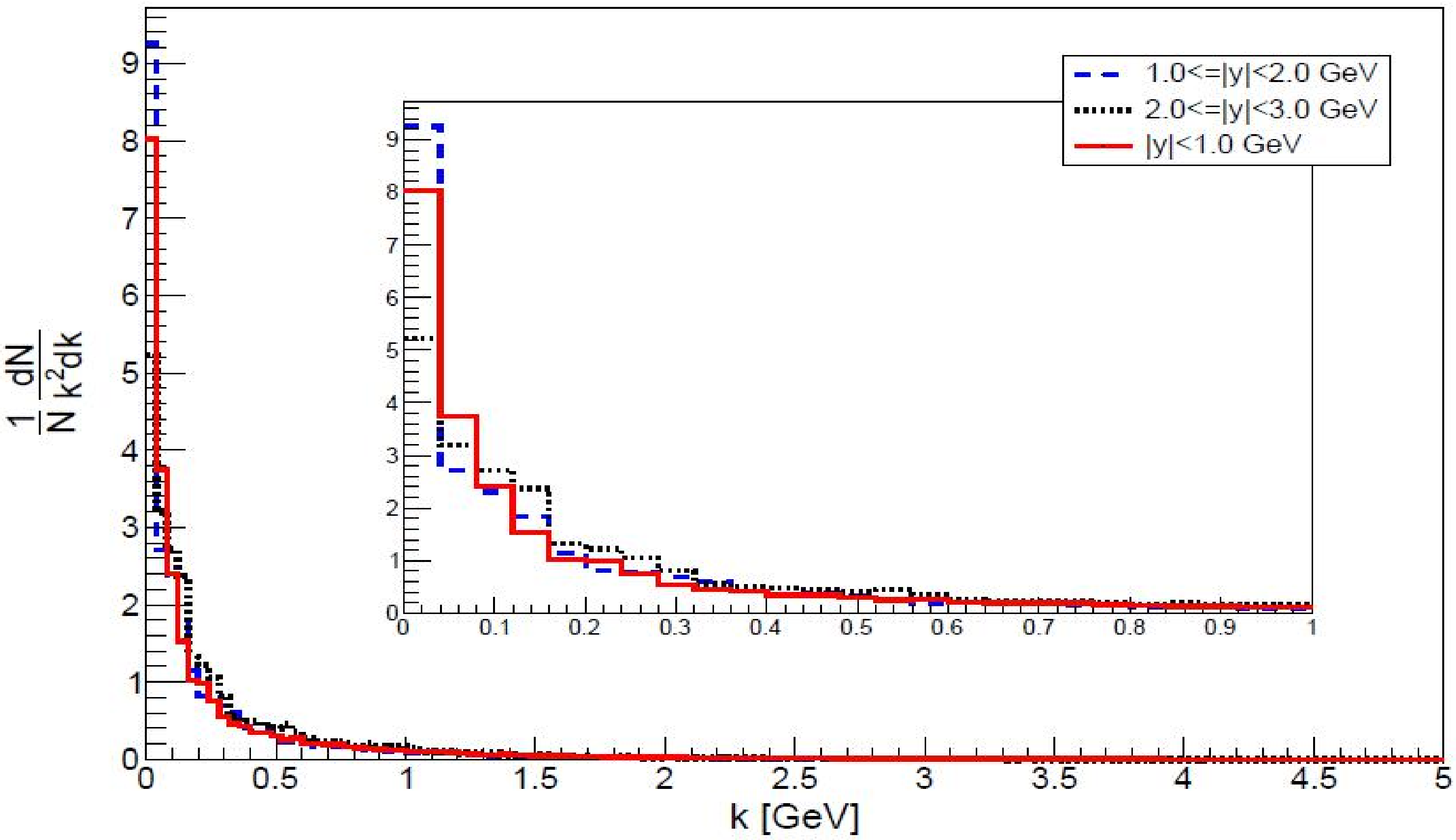
With herwig, see e.g., Bigamini et al, prl 103,162001

CDF, unpublished, https://www-cdf.fnal.gov/physics/new/bottom/060921.blessed-double-charm-corr/

$$\hat{q} = (p_A - p_B) - \frac{(p_A - p_B)\cdot(p_A + p_B)}{(p_A + p_B)^2}(p_A + p_B).$$



$$\hat{q} = (p_A - p_B) - \frac{(p_A - p_B)\cdot(p_A + p_B)}{(p_A + p_B)^2}(p_A + p_B).$$



1, the scale is determined
By the 'interference' between
The hard one and the soft one,
only some 'factorized
formulation/model' can give
precise definition

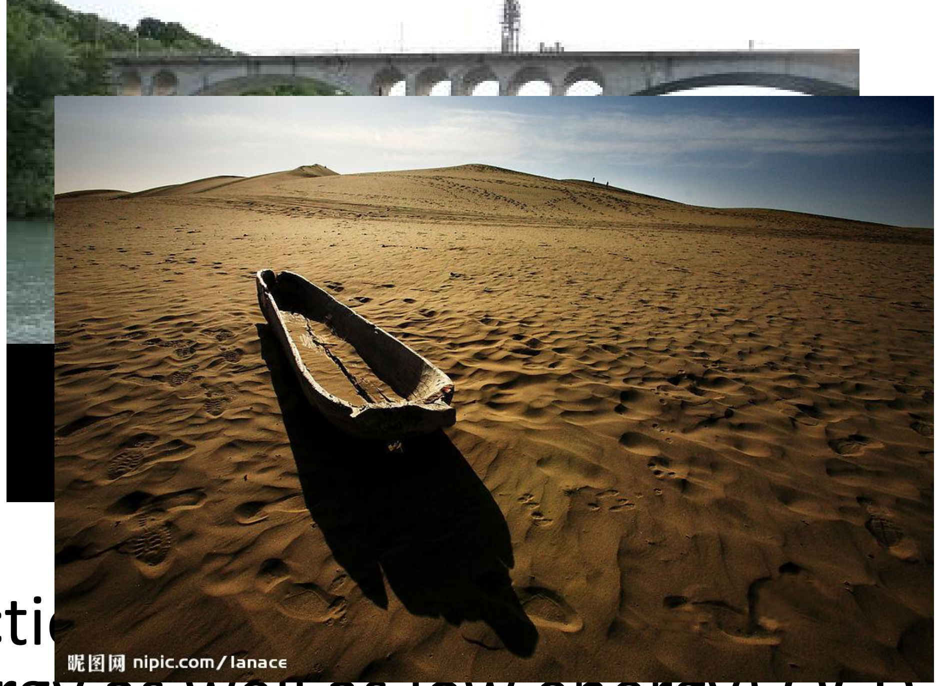
2, simple relativistic effects in
high energy production, again,
some factorization formulation

Summary

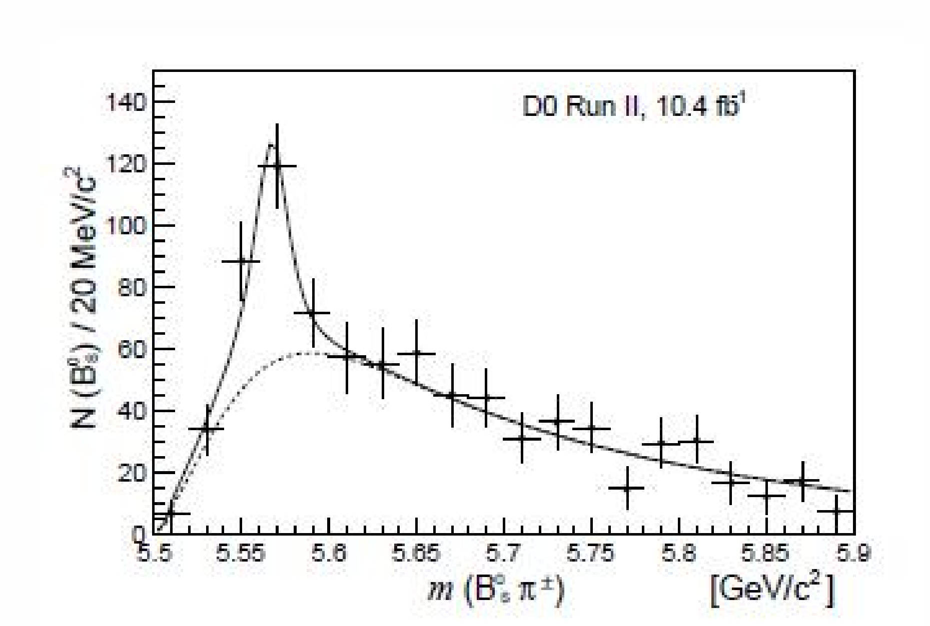
- Study exotics in the multiproduction processes to gain more knowledge about its structure and QCD
- Study the correlations of hadrons in relevant to the multiquark production in the multiproduction processes, e.g.,
- To optimize the event cuts
- To investigate the amplitude needed in the NR calculation
- More…….

Thanks for your attention

Summary



- Multiquark hadrons in mutiproducti



nigh energy as well as low energy) QCD,
FT, and Confinement emerge

沧海桑田

del in production, unitarity can tell...desert?

cti ------->JET n (cluster)
space correlation is important...

iqaurk hadron confirmed in
implies need more study!

X(3872), f0(980)

And good fortune for D0 and for other Collab. to more confirm X(5568)