Production of multiquark hadrons in high energy multiproduction processes

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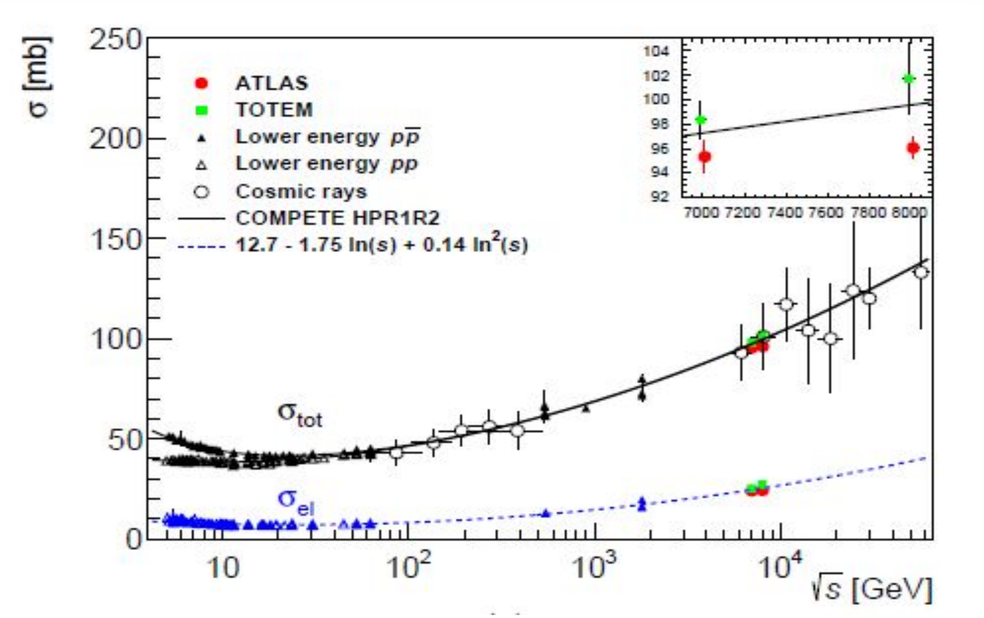
- Based on our serial works on multiquark hadron production, colour connection, and their relation with hadronization mechanism in high energy multiproduction processes, e,g.,
- *Hidden-heavy Pentaquark productin at e^+e^- colliders*, to be submitted//*Exotic Hadron Bound State Production at Hadronic Colliders*, arXiv:1610.04411//*New $B_s\pi^\pm$ and $D_s\pi^\pm$ states in high energy multiproduction process*, P.R.D94 (2016) no.1, 014023 //*Studying color connection effects of $e^+e^- \to c\bar{c}c\bar{c} \to \Xi_{cc}+X$ $e^+e^- \to c\bar{c}c\bar{c} \to \Xi_{cc}+X$ 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 $Q\bar{Q}Q'\bar{Q}'$ system and doubly heavy baryon production in e^+e^- e^+e^- annihilation*, P.L.B727 (2013) 468-473//*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'15(colour connection),'11(unitarity and exotic) ......
- In Collabration among the particle theory group of Shandong University

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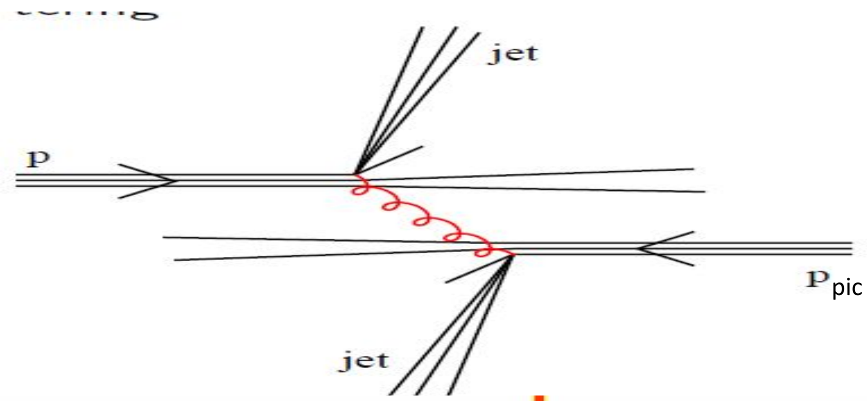
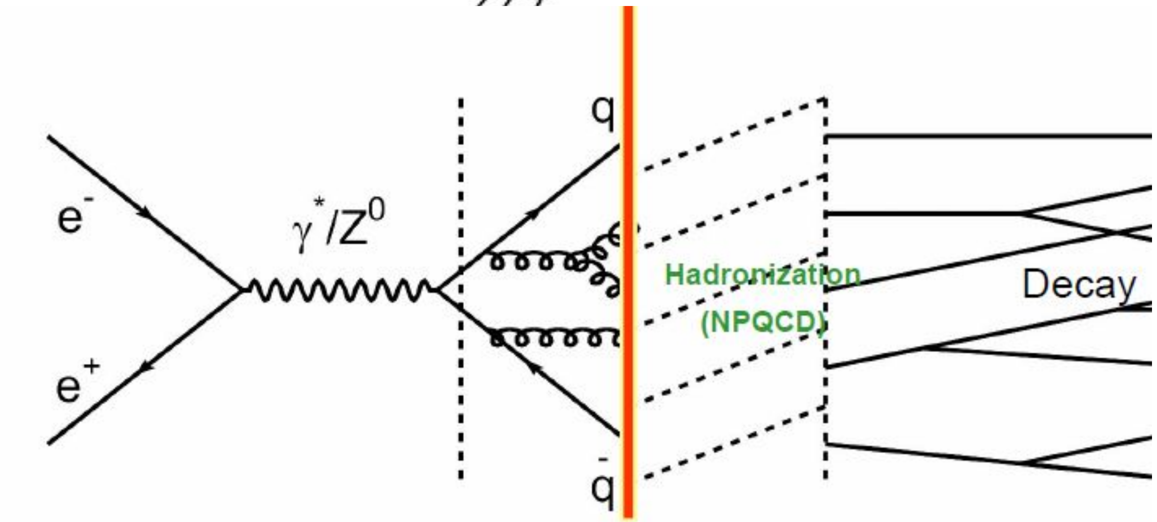
Local parton-hadron duality (number of 'clusters')
Definition of jet (parton level)
Quark and gluon are the basic degrees of freedom--but confined



pic from G Salam



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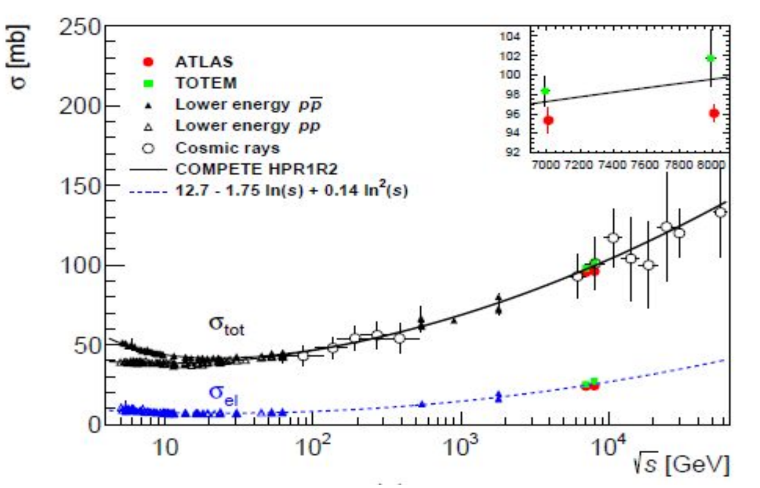

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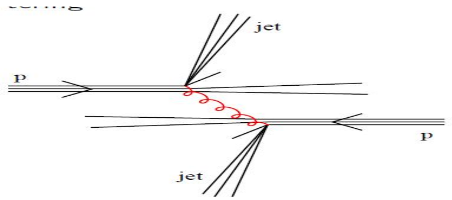
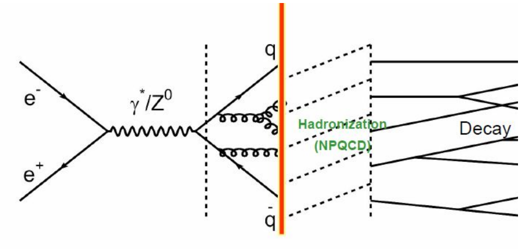




We not doubt/query on QCD,
just confused by how QCD works for soft interactions (HE/LE)
We not doubt/query on existence of quarks,
just confused on how they combine to be a hadron
We not doubt/query on colour confinement,
just confused by how colour is confined

QCD=
'UTOPIA'

Multiquark hadrons in Multiproduction 'combines' the above questions together

1611.02454

Multiquark hadrons in Multiproduction 'combines' the above questions together

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

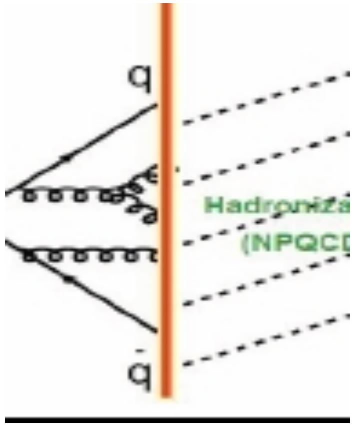
- **Complexity of the colour structure of the multiquark hadrons**

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

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

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

- **--->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

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

- 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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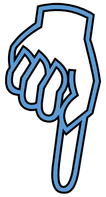

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- 'Reversal employ… uent quark model, where all the quark states a… ses of the *same* Hilbert space of states/static ->
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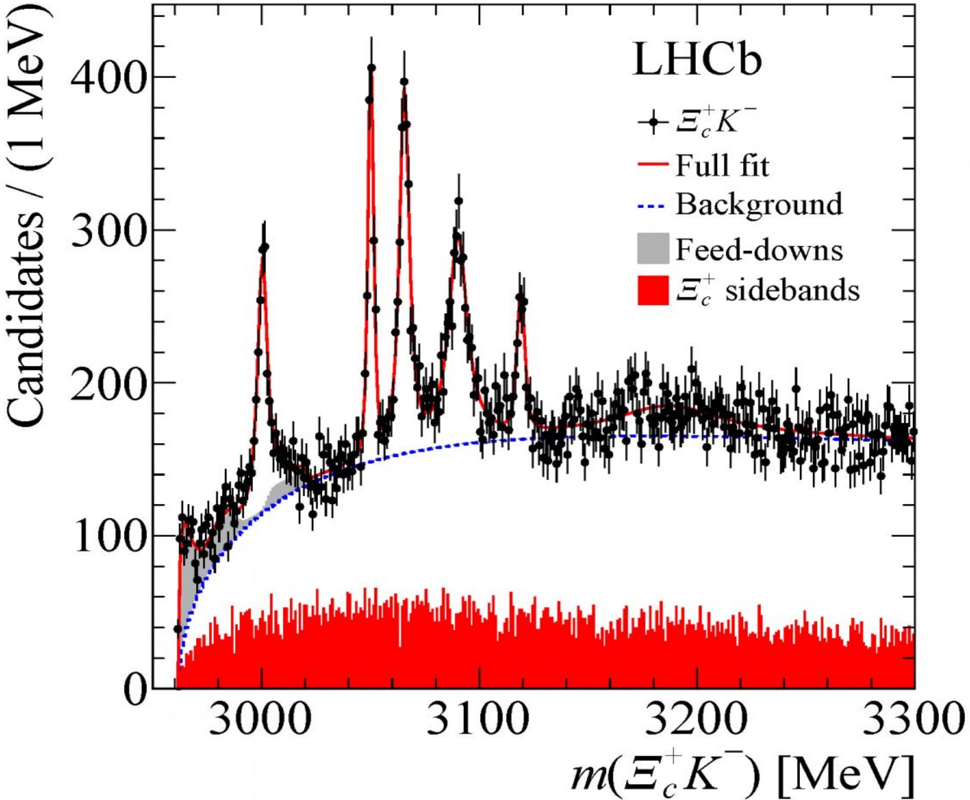


From CERN webpage,
Ω c(3000)0, Ω c(3050)0, Ω c(3066)0, Ω c(3090)0 and Ω c(3119)

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

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

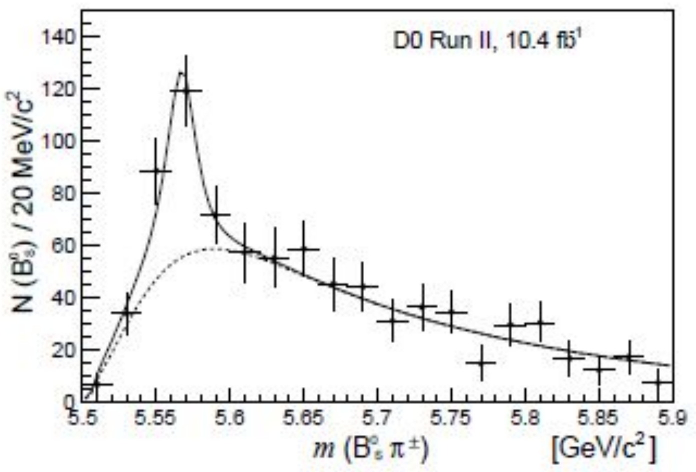
$$\bar{q}_1\bar{q}_2q_3\bar{q}_4q_5q_6$$

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

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

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

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

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

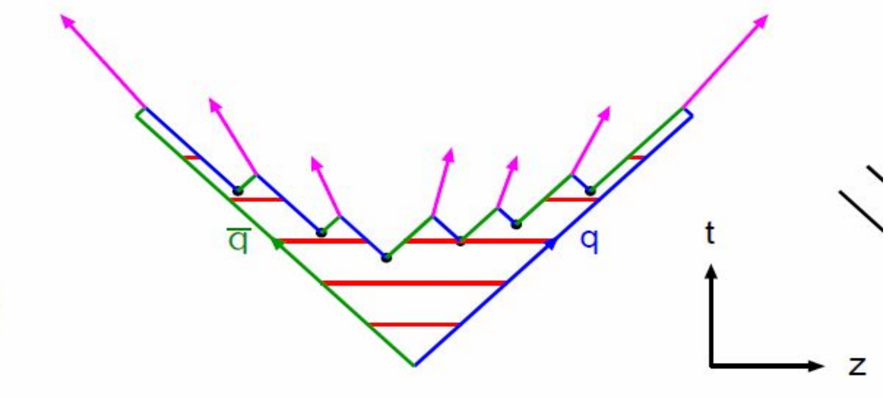
$$\rho^{max}_{combination} = \frac{P_X}{P_{Bs}} \sim 5\%. \qquad (7)$$

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

string model

$d = m_{\perp q}/\kappa$

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



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, . . .

$\Rightarrow$ “moderate” predictivity (many parameters!)

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

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

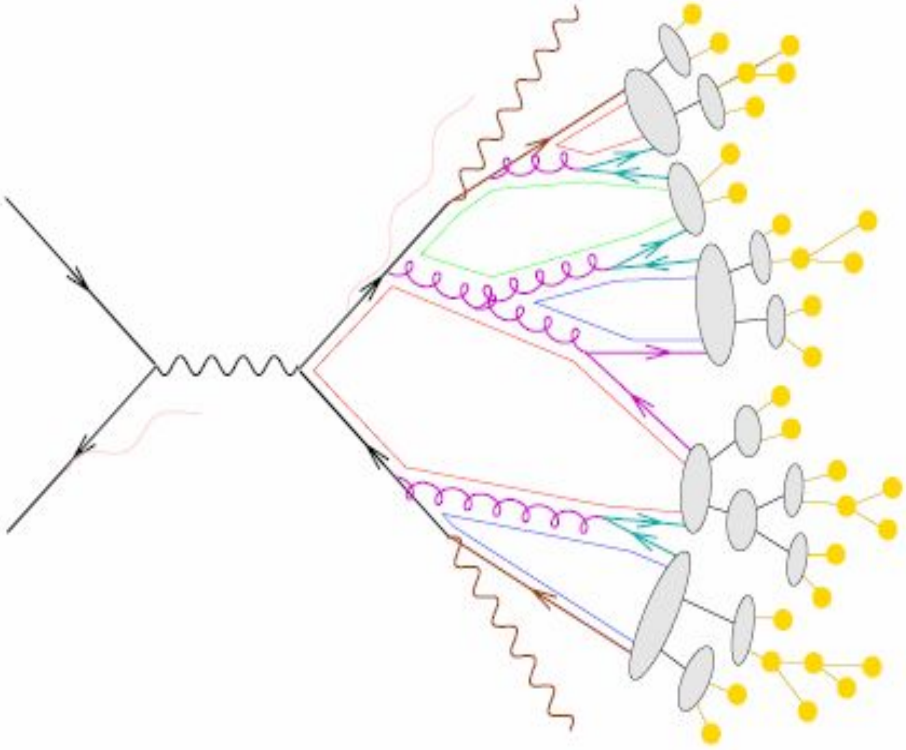
Here $D_1 = 1 + 1 + \lambda + \lambda/2 + \lambda/2 + \lambda^2/2$, and $D_2 = 1 + 1 + \lambda + \lambda/2 + \lambda/2 + \lambda/2 + \lambda^2/2 + \lambda^2/2 + \lambda^3/2$.

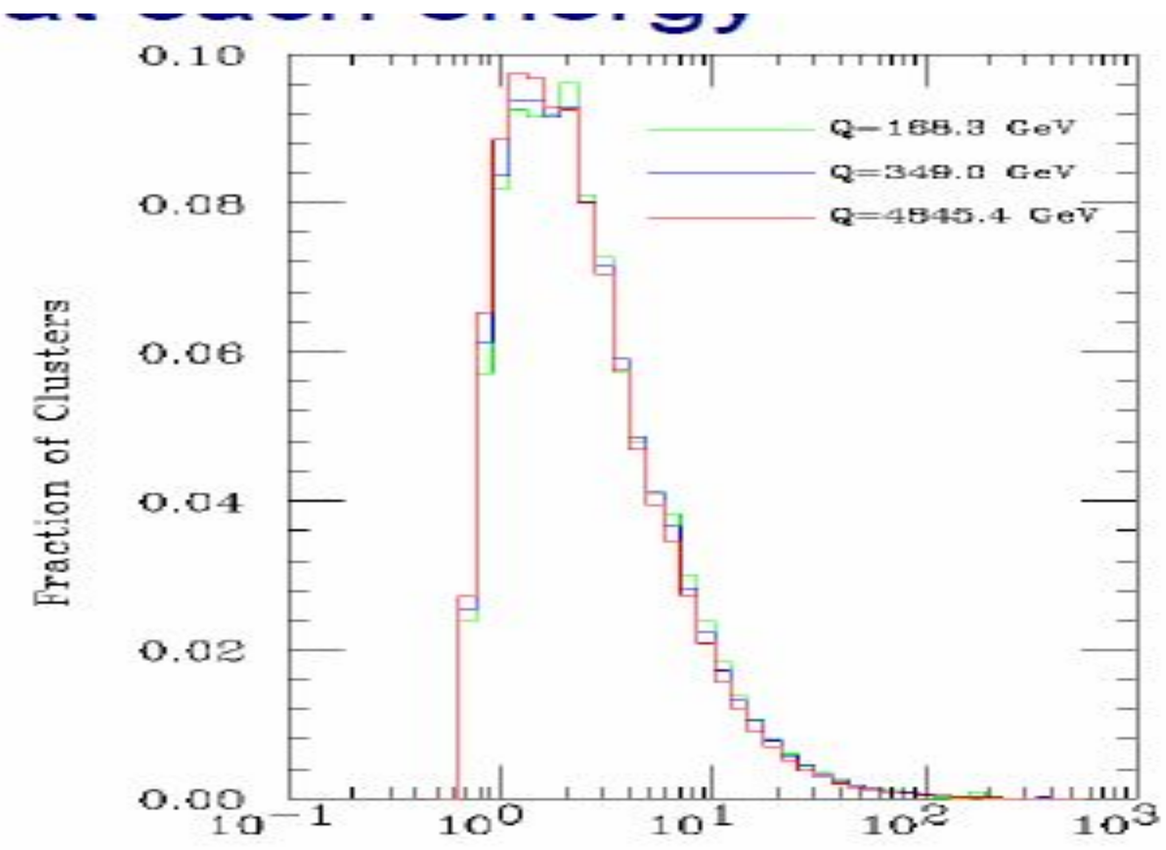
$$P_{Bs} = \frac{1 + 1 + \lambda}{D_1} \times \frac{\lambda}{D_2}; \tag{3}$$

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

cluster model/ cluster mass widely distributed

X(5568)





Sjostrand

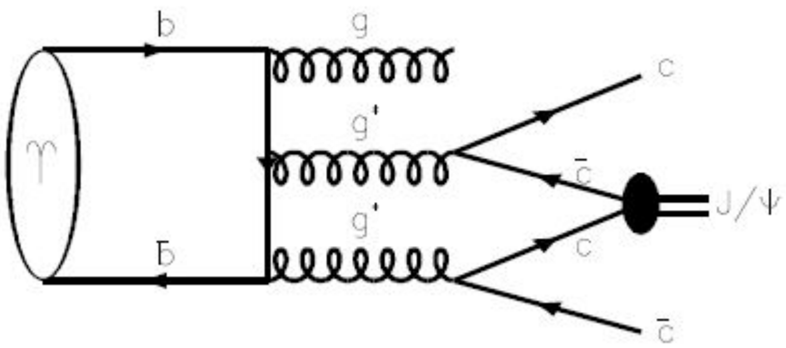
Seymour

An interesting 'mini' multiproduction evidence

1605.00990 **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.

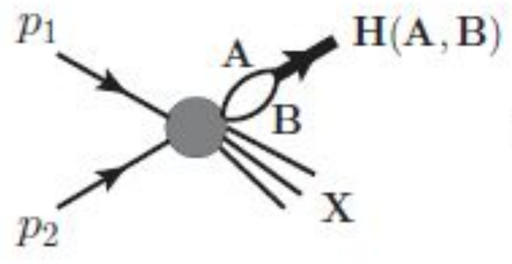
State	N_{fit}	N_{up}	$\varepsilon(\%)$	$\sigma_{\text{syst}}(\%)$	$\Sigma(\sigma)$	$\mathcal{B}_R^{\text{prod}}$
$X(3872) \to \pi^+\pi^- J/\psi$	4.8±15.4	31.4	3.26	18.7	0.3	$< 9.5 \times 10^{-6}$
$Y(4260) \to \pi^+\pi^- J/\psi$	−31.1±88.9	134.6	3.50	35.6	–	$< 3.8 \times 10^{-5}$
$Y(4260) \to \pi^+\pi^- \psi(2S)$	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	–	$< 5.7 \times 10^{-6}$



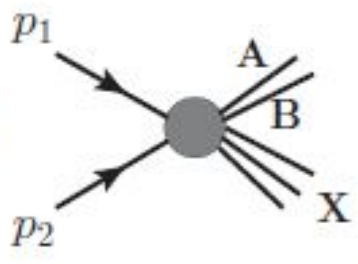
To parameterize the production of X(5568)(as hadron (BK)/ cluster(bsbar udbar) molecule) and how to do calculation

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

and prepare for the case of production



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



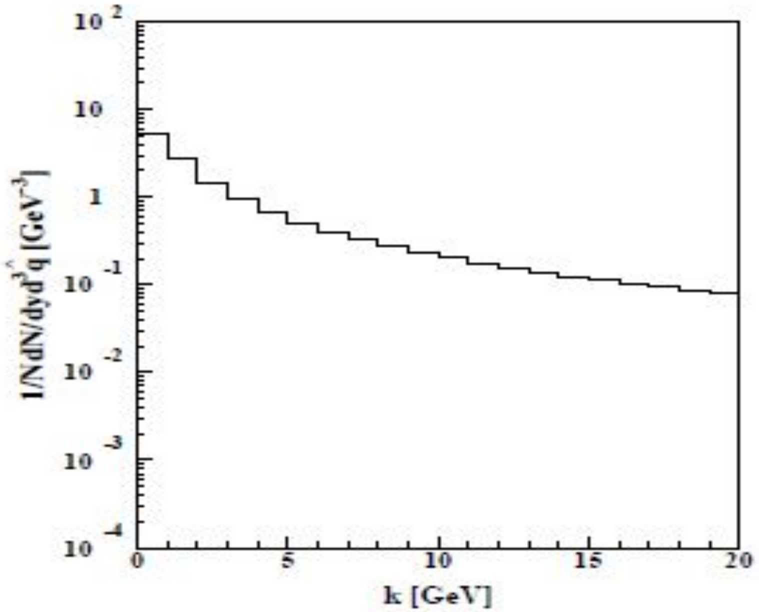
Expand the amplitude around k=0

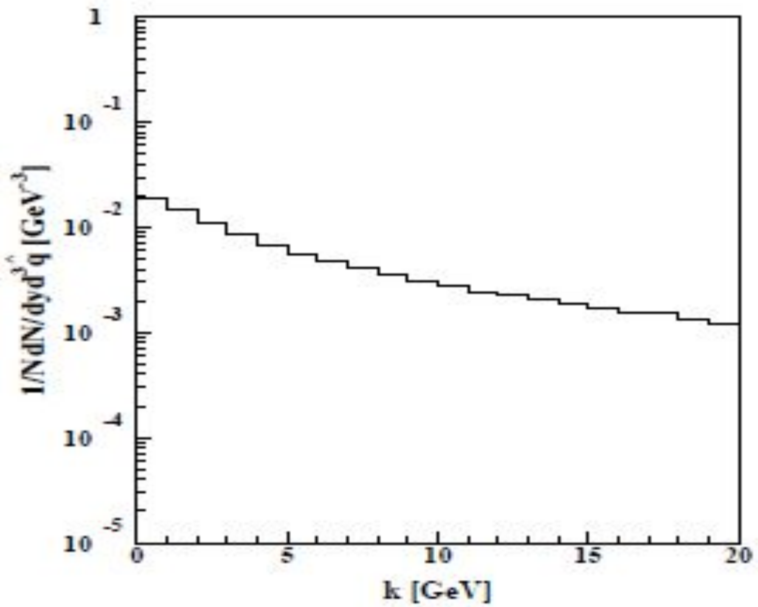
fitting data to get the wave function at origin, can be used every where... factorization

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

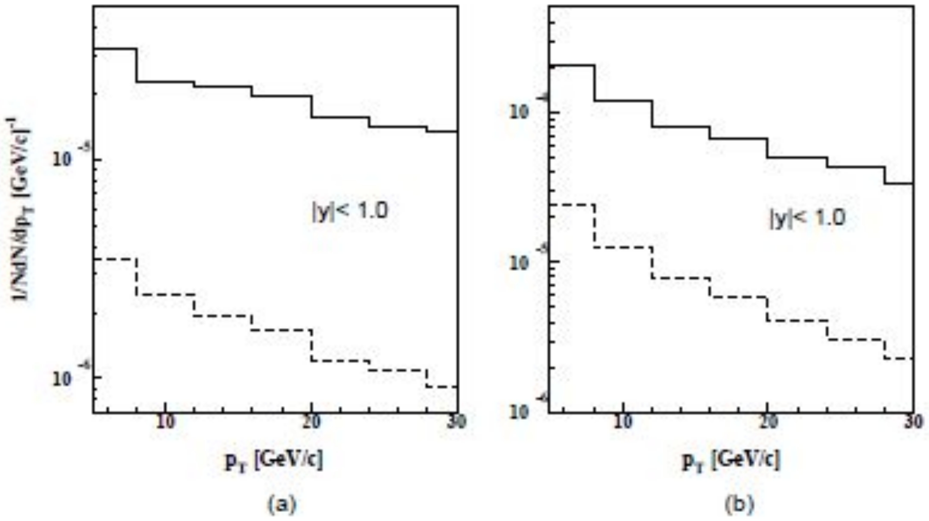
- It may be process dependent--final state interaction...
- need more study, not only angle, rapidity, but 3D correaltion

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





Escape from curse of unitarity, and useful for exp.



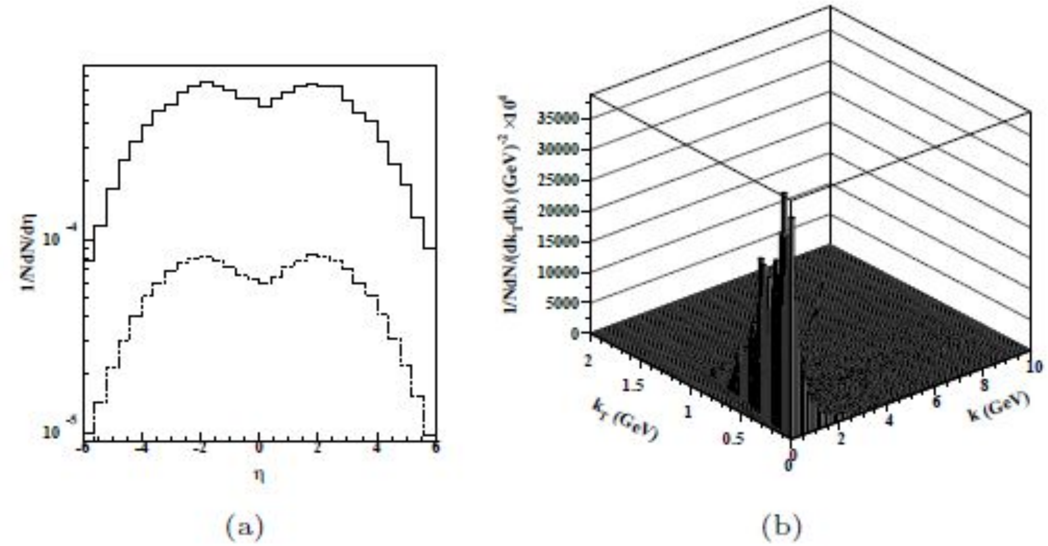


FIG. 2: (a) Pseudo-rapidity distributions. The dashed line

Summary

- 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)

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沧海桑田

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X(3872), f0(980)

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