Phenomenological study of hadron correlation and fluctuation in relativistic heavy ion collisions

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Outline

1. **Hadronization phenomenology in relativistic heavy ion collisions**
2. **Correlation and fluctuation of identified hadrons**
3. **Summary**

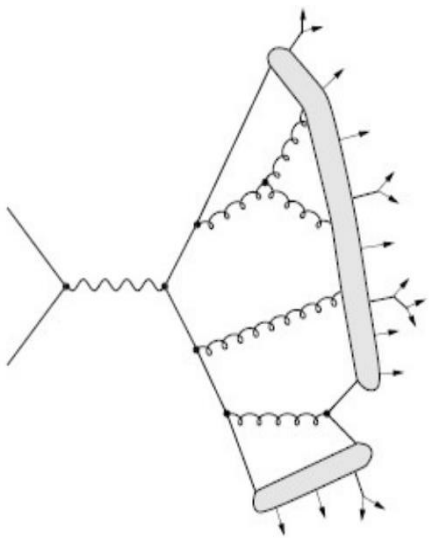
1. Hadronization phenomenology

Hadronization is the process of the formation of hadrons out of final-state quarks and/or gluons produced in high energy reactions

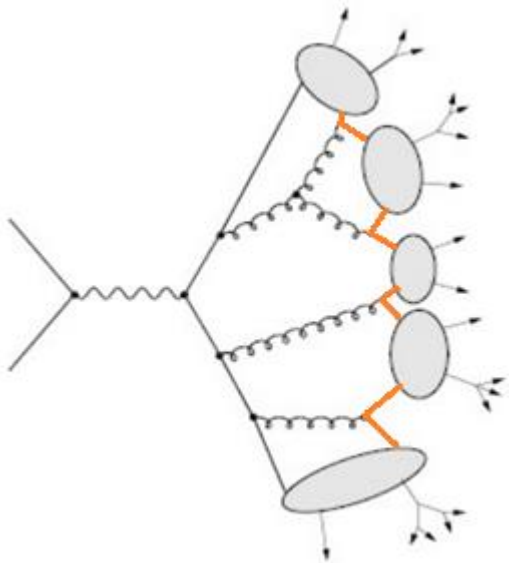
- **Non-perturbative QCD process**
- **Phenomenological schemes are then used to model the hadronization process**

Survived models in e^+e^-, *pp* collisions,

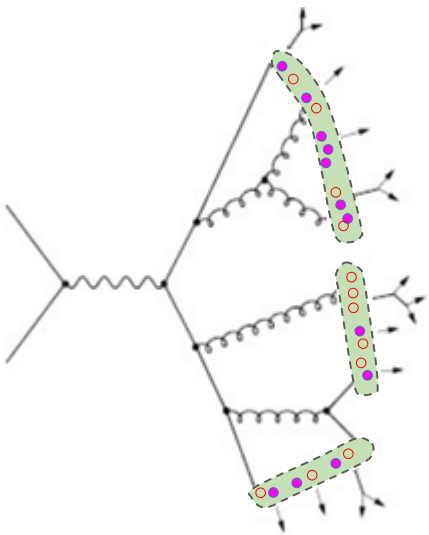
(1) string fragmentation



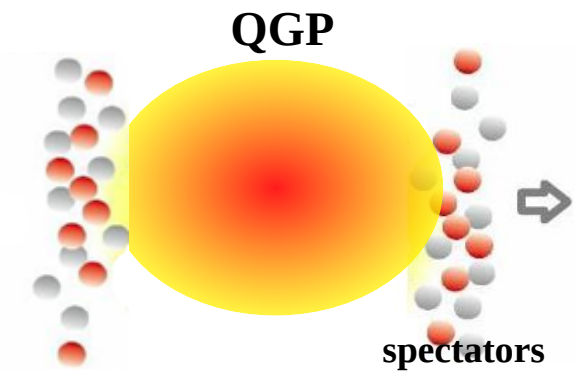
(2) cluster fragmentation



(3) quark combination



Quark Gluon Plasma in relativistic heavy ion collisions



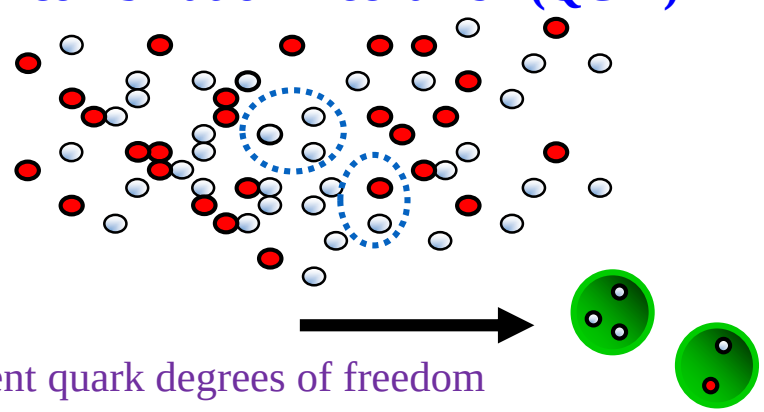
Partons in final state :

Soft, p ~ 1GeV

Large number $\gtrsim 10^3$

Hadron formation via combination of quarks and antiquarks neighboring in phase space

Quark combination mechanism(QCM)



constituent quark degrees of freedom
gluon is replaced by a pair of quarks

Combination probability :

(a) sudden approximation

$$|< q\bar{q}; p_q, p_{\bar{q}} | M; p_M >|^2$$

$$|< q_1 q_2 q_3; p_{q_1}, p_{q_2}, p_3 | B; p_B >|^2$$

(b) non-sudden approximation

various phenomenological combination criteria

Quark combination mechanism of hadron production

for QGP hadronization

Quark recombination model

Oregon group, R. C. Hwa and C. B. Yang

see e.g., Phys. Rev. C **70**, 024904 (2004)

Duke group, R. J. Fries, B. Muller, C. Nonaka, S. A. Bass

see, e.g., Phys. Rev. C **68**, 044902 (2003)

at RHIC,LHC

Parton coalescence model

V. Greco, C. M. Ko, P. Lévai, L.W. Chen

see, e.g., Phys. Rev. C **68**, 034904 (2003)

SDQCM : Quark **C**ombination **M**odel (Shandong Group)

Q. B. Xie, F. L. Shao

see, e.g., Phys. Rev. C **71**, 044903 (2005); **75,** 034904 (2007)

ALCOR : *Al*gebra *co*alescence *r*ehadronization model

J. zimányi, T. S. Biró, T. Csörgő, P. Lévai

see, e.g., Phys. Lett. B **347**, 6 (1995)

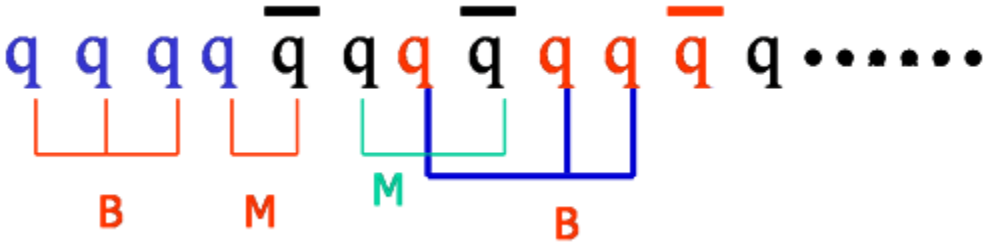
Other combination-like models based on transport, variation, statistic method, etc

(See, e.g., Miao&Gao&Zhuang, PRC 76, 014907(2007); W.Cassing, PRC78,034919; A.Alala,PRC77,044901; R.Abir,PRC80,051903)

SDQCM

Quark distribution $f_q(y,p_T)$ → sort in phase-space, e.g. in rapidity (1 dimension) → Combination rule：

The smaller the difference in rapidity for two(three) quarks, the longer is the interaction time. So there is enough time for a $q\bar{q}(qqq)$ to be in a color singlet and form a meson(baryon).



$SU_f(3)$ →

$$M(q\bar{q}) \qquad P_{M_i} = C_{M_i} \frac{N_{q_1\bar{q}_2}}{N_{q\bar{q}}}$$

$$B(qqq) \qquad P_{B_i} = C_{B_i} \frac{N_{q_1q_2q_3}}{N_{qqq}}$$

→ decay → final hadron

More discussion of combination dynamics are found in PRC71,044903 (05);80,014909(09),85,054906(12);88,027901;91,014909(15)

Recent works (~10 related papers since 2012)

(1) Yield ratios & p_T ratios

(2) Correlations of conservative charges

(a) baryon-strangeness correlation,

(b) balance function of electric charge

(3) Dynamical correlations and fluctuations

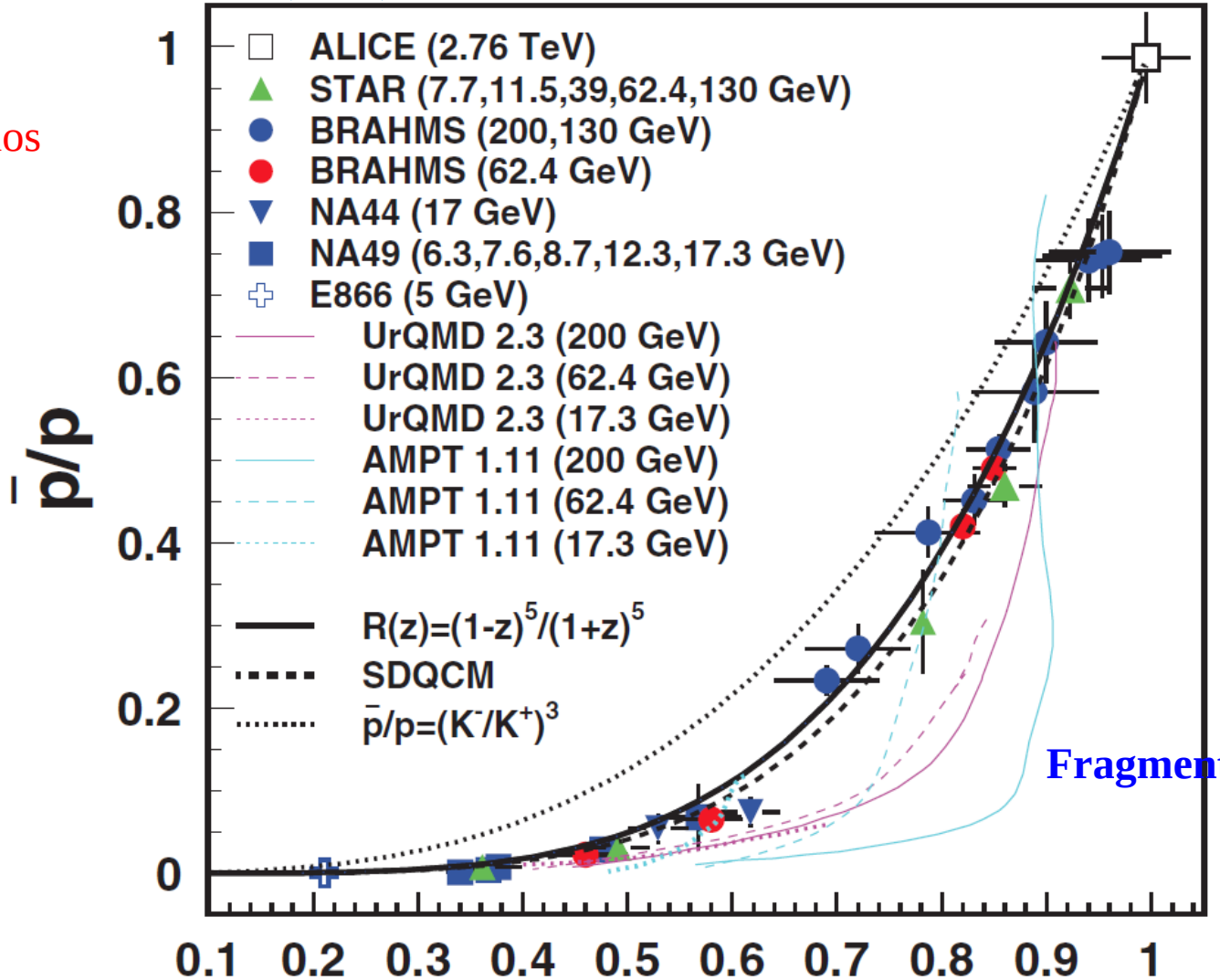
(a) a new balance function of identified hadrons in rapidity ,

(b) multiplicity fluctuations and correlations of identified baryons.

(1) Yield ratios & p_T ratios

JS&FLS, PRC88,027901(2013)

Yield ratios

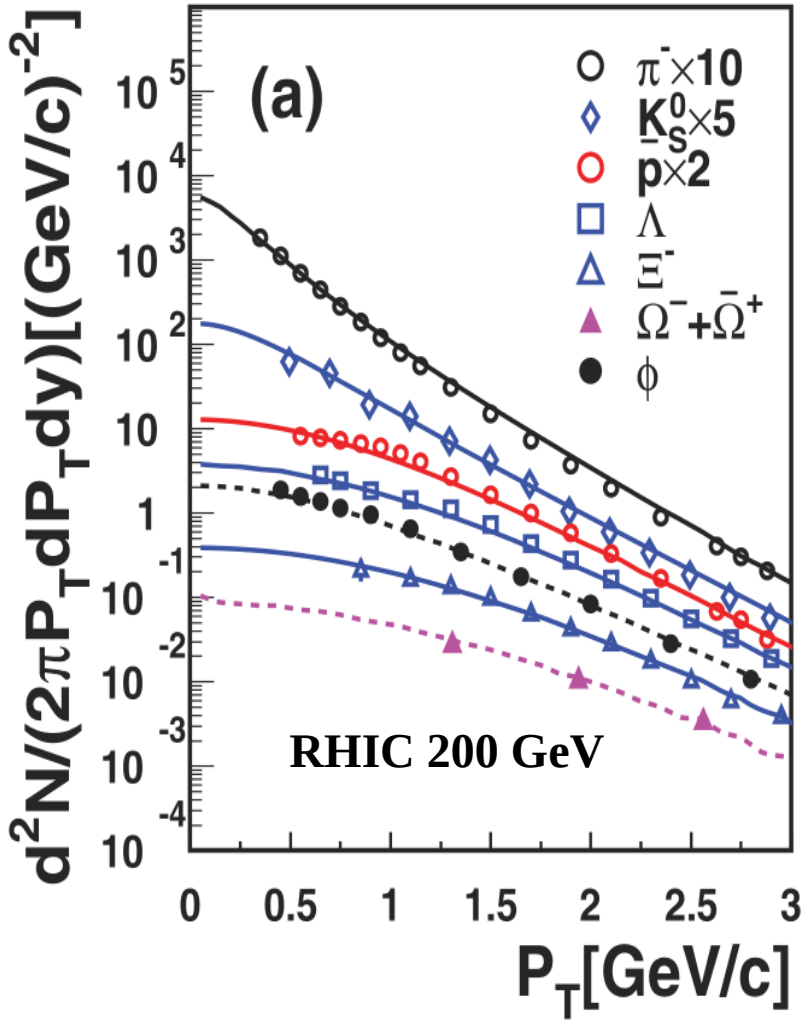


Fragmentation fails!

$K^-/K^+ = N_{\bar{q}} / N_q$

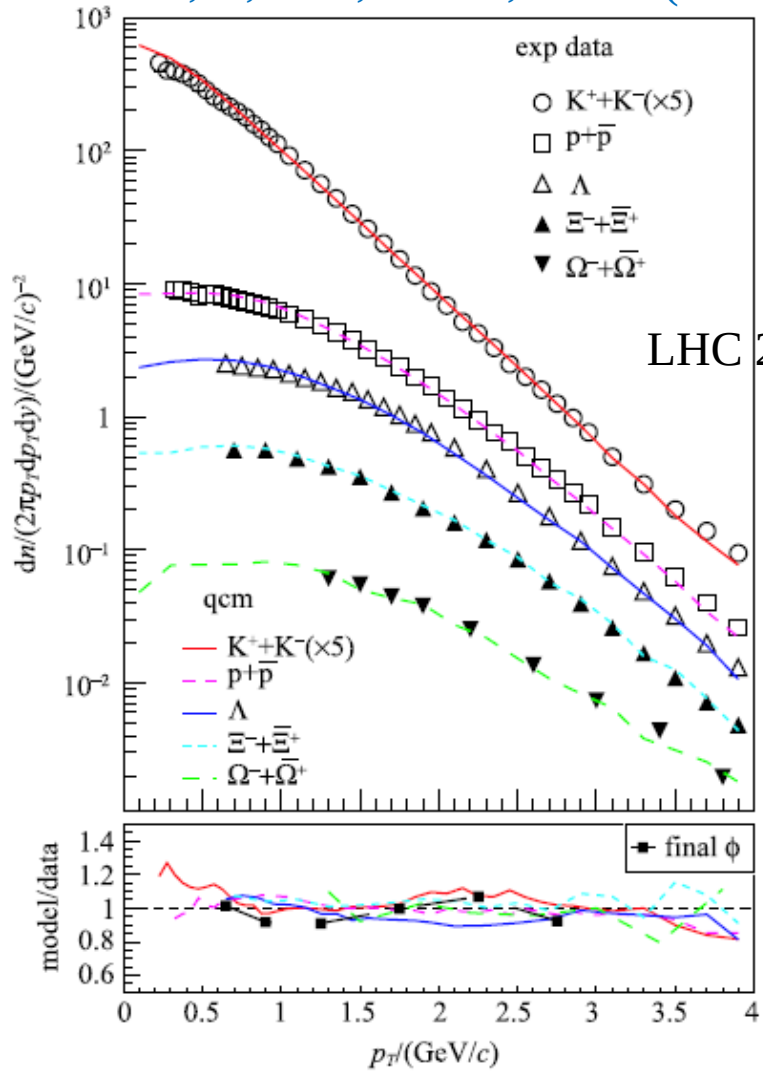
(1) Yield ratios & p_T ratios

ZK&SJ&SFL, PRC86,014606(2012)



WRQ,SJ,SFL,PRC91, 014909(2015)

SFL,SJ,ZMS,CPC41,014101(2017)

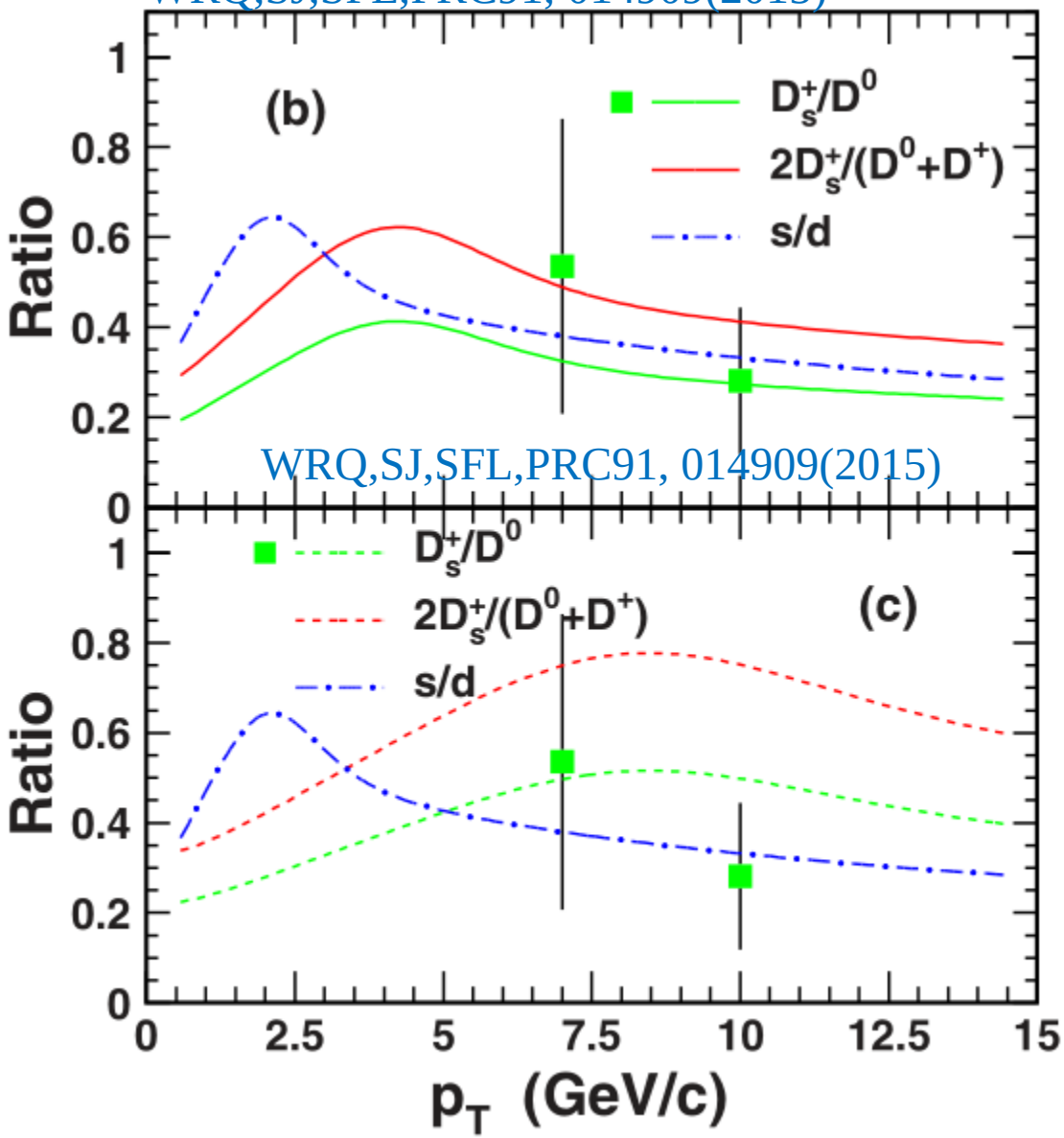


LHC 2.76TeV

Input $f_q(p_T)$,$f_s(p_T)$

(1) Yield ratios & p_T ratios

WRQ,SJ,SFL,PRC91, 014909(2015)



p_T ratios of D_s/D_0

$$R(\mathbf{p}) = \frac{f_{Ds}(\mathbf{p})}{f_{D_0}(\mathbf{p})} \sim \frac{f_{\bar{s}}(\mathbf{p}_{\bar{s}})}{f_{\bar{u}}(\mathbf{p}_{\bar{u}})}$$

$$\sim \lambda_s(\mathbf{p}_q) \sim \lambda_s(a\,\mathbf{p})$$

equal p_T combination, a ~ 0.5,

ratio peak ~ 4 GeV

equal velocity combination, a ~ 0.25,

ratio peak ~ 8 GeV

SFL,SJ, WRQ PRC 92, 044913(2015)

Baryon-strangeness correlation

$$C_{BS} = -3\frac{\langle B\cdot S\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle} = -3\frac{\langle B\cdot S\rangle}{\langle S^2\rangle}$$

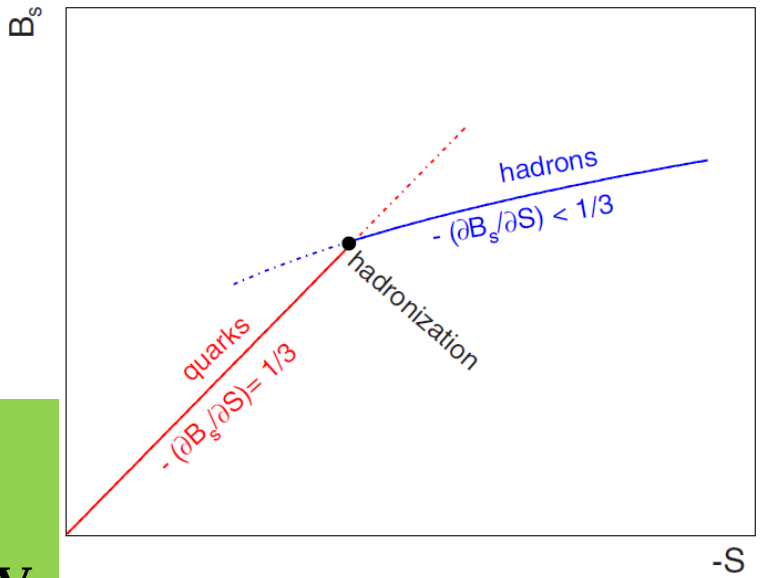
apply $\langle S\rangle = 0$ in AA collisions

In free quark system, $C_{BS}^{(q)} = 1$, In hadron system with small μ_B, $C_{BS}^{(h)} < 1$

In our model,

$$C_{BS}^{(h)} = -3\frac{\langle \delta B^{(h)} \delta S^{(h)}\rangle}{\langle \delta S^{(h)2}\rangle} \approx -3\frac{\partial B_s^{(h)}}{\partial S^{(h)}}\Big|_{\langle N_h\rangle}$$

where $B_s^{(h)}$ is the baryon number carried by strange baryons



$C_{BS}^{(h)}$=0.78 at $\mu_B = 0$,

corresponding to LQCD calculations at 162MeV.

(2) Charge correlations

SJ,SFL,LZT,PRC86,064903(2012)

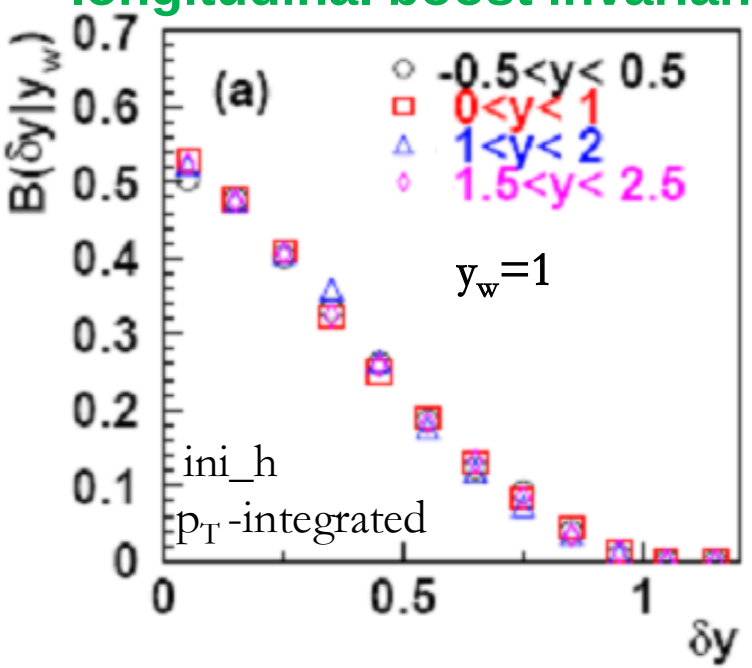
electric charge balance function

$$B(\delta y|Y_{\rm w}) = \frac{1}{2}\left[\frac{\langle n_{+-}(\delta y)\rangle - \langle n_{++}(\delta y)\rangle}{\langle n_{+}\rangle} + \frac{\langle n_{-+}(\delta y)\rangle - \langle n_{--}(\delta y)\rangle}{\langle n_{-}\rangle}\right]$$

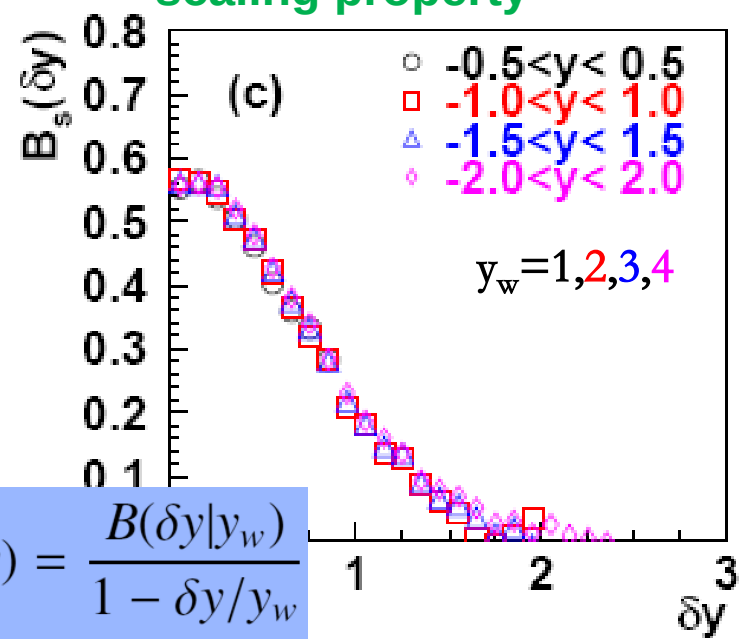
in the selected rapidity window Y_w, describing the probability of charge balance in δy interval

reproduce the observation of

longitudinal boost invariance



scaling property



$$B_s(\delta y) = \frac{B(\delta y|y_w)}{1-\delta y/y_w}$$

SJ, SFL, PRC91, 054906 (2015)

A new correlation function for identified hadrons

design for LHC

$$G_{\alpha\beta}(y_1, y_2) = \frac{\left\langle [n_\alpha(y_1) - n_{\bar{\alpha}}(y_1)][n_\beta(y_2) - n_{\bar{\beta}}(y_2)] \right\rangle}{\langle n_\alpha(y_1)\rangle\langle n_\beta(y_2)\rangle}$$

In QCM, we have

$$G_{\alpha\beta}(\Delta y) = \sum_{f_1, f_2 = u,d,s} Q_{\alpha,f_1} Q_{\beta,f_2} G_{f_1 f_2}(\Delta y)$$

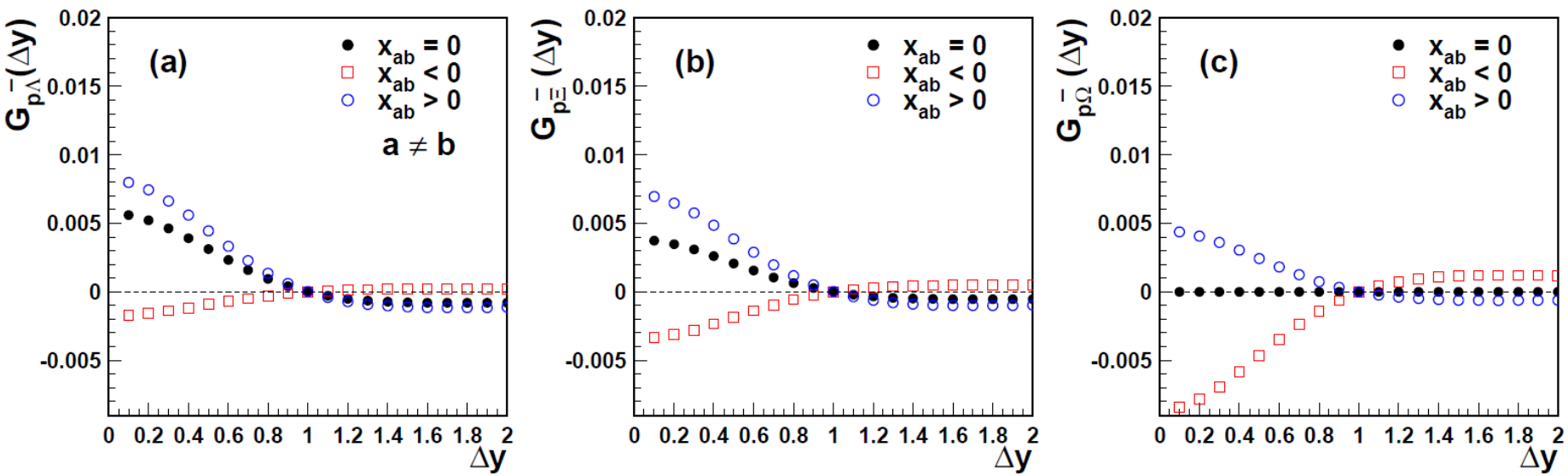
Flavor correlations of quarks !

where $Q_{\alpha,f1}$ denotes the number of net-f_1 in hadron α

(2) Charge correlations

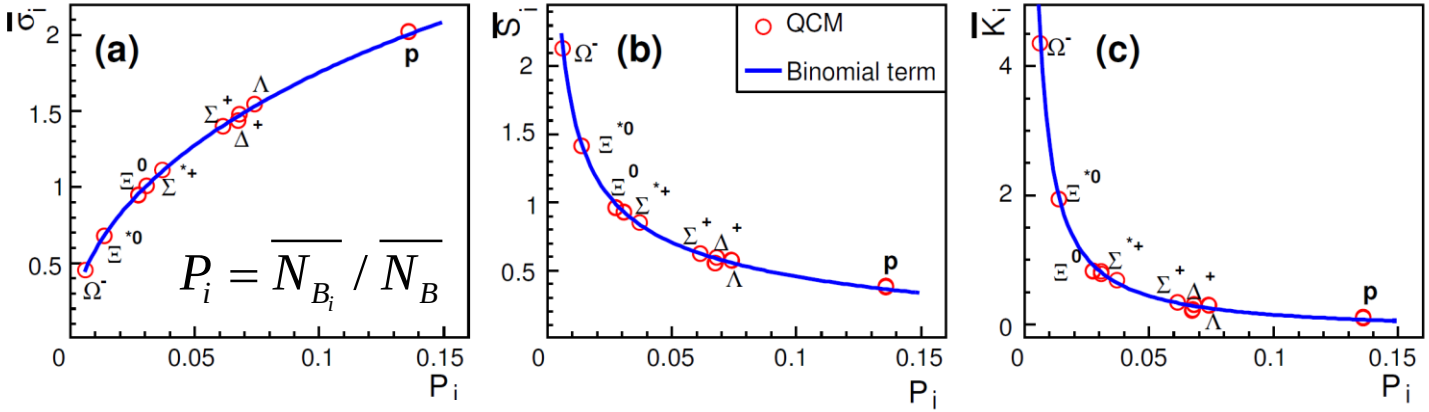
TABLE I: $G_{\alpha\beta}(\Delta y)$ of directly-produced hadrons after hadronization in terms of $G_{ab}(\Delta y)$ of the quark system before hadronization.

$G_{\alpha\beta}$	π^+	p	K^+	Λ	Ξ^0	Ω^-
π^-	$-2G_{uu}+2G_{ud}$					
$\bar{p}$	$-G_{uu}+G_{ud}$	$-5G_{uu}-4G_{ud}$			*transpose symmetric*	
K^-	$-G_{uu}+G_{ud}$	$-2G_{uu}-G_{ud}+3G_{us}$	$-G_{uu}+2G_{us}-G_{ss}$			
$\bar{\Lambda}$	0	$-3G_{uu}-3G_{ud}-3G_{us}$	$-G_{uu}-G_{ud}+G_{us}+G_{ss}$	$-2G_{uu}-2G_{ud}-4G_{us}-G_{ss}$		
$\bar{\Xi}^0$	$-G_{uu}+G_{ud}$	$-2G_{uu}-G_{ud}-6G_{us}$	$-G_{uu}-G_{us}+2G_{ss}$	$-G_{uu}-G_{ud}-5G_{us}-2G_{ss}$	$-G_{uu}-4G_{us}-4G_{ss}$	
$\bar{\Omega}^+$	0	$-9G_{us}$	$-3G_{us}+3G_{ss}$	$-6G_{us}-3G_{ss}$	$-3G_{us}-6G_{ss}$	$-9G_{ss}$

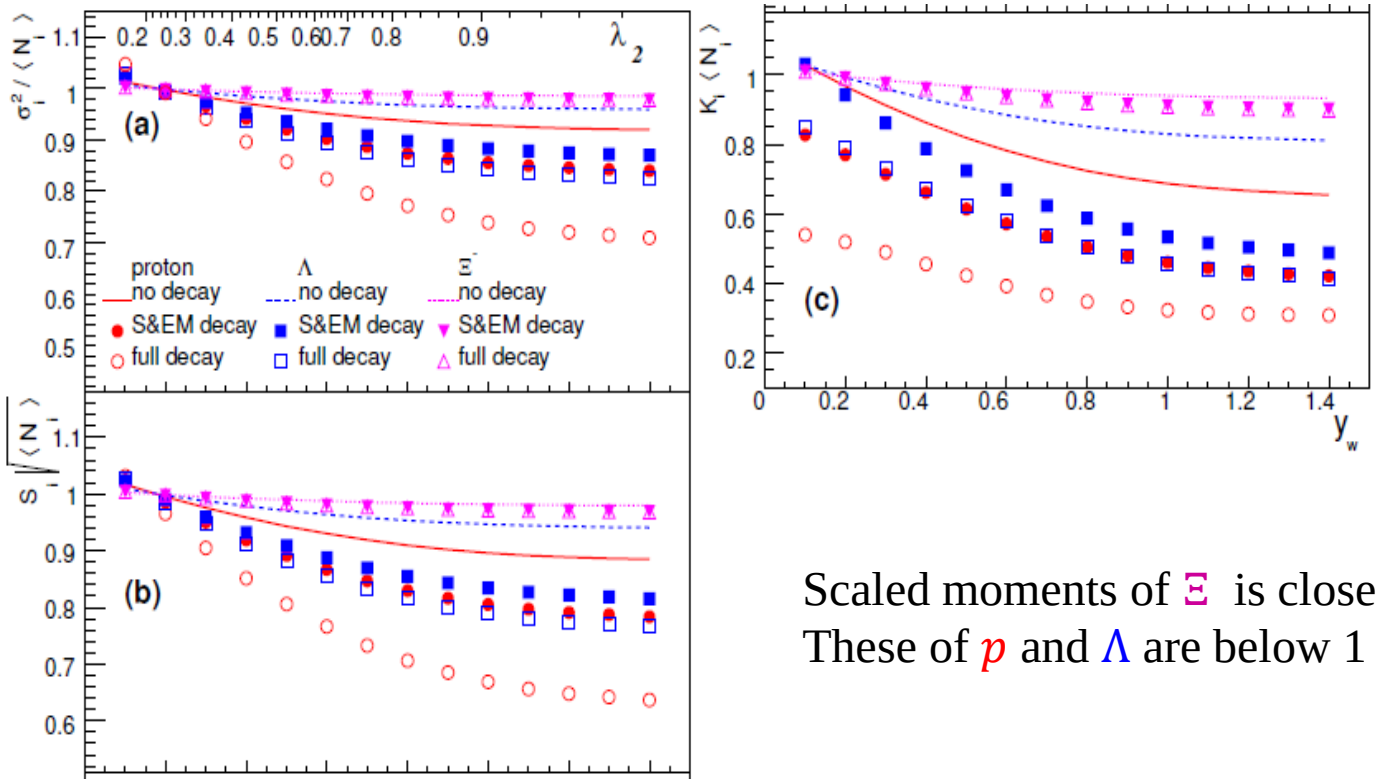


Test three different charge correlation scenario of quark system

(3) multiplicity fluctuations and correlations of identified baryons, SJ, *et al*, arXiv:1609.08013



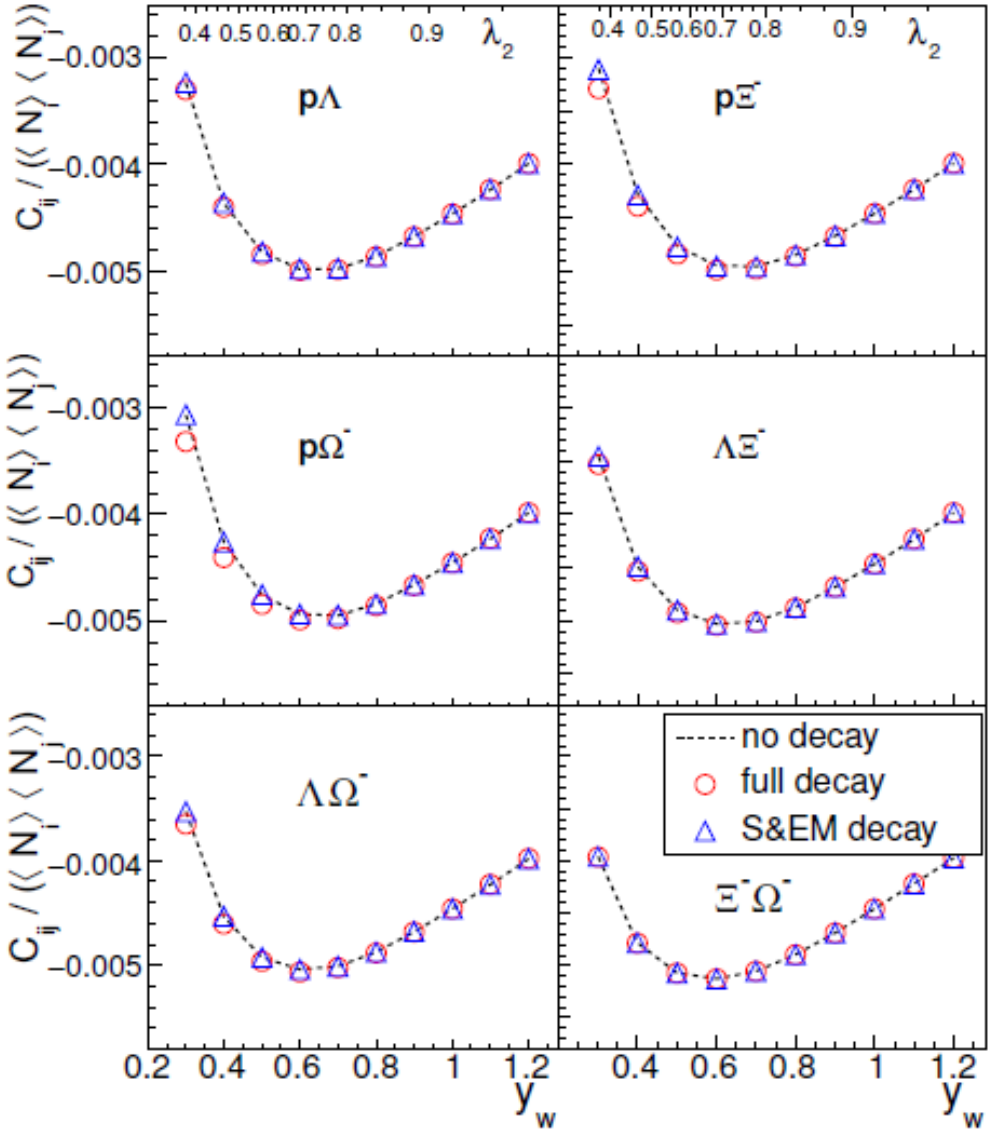
Fluctuations by quark combination process



+ quark fluctuations
+ decay effects

Scaled moments of Ξ is close to 1
These of *p* and Λ are below 1

Two-Baryon correlations

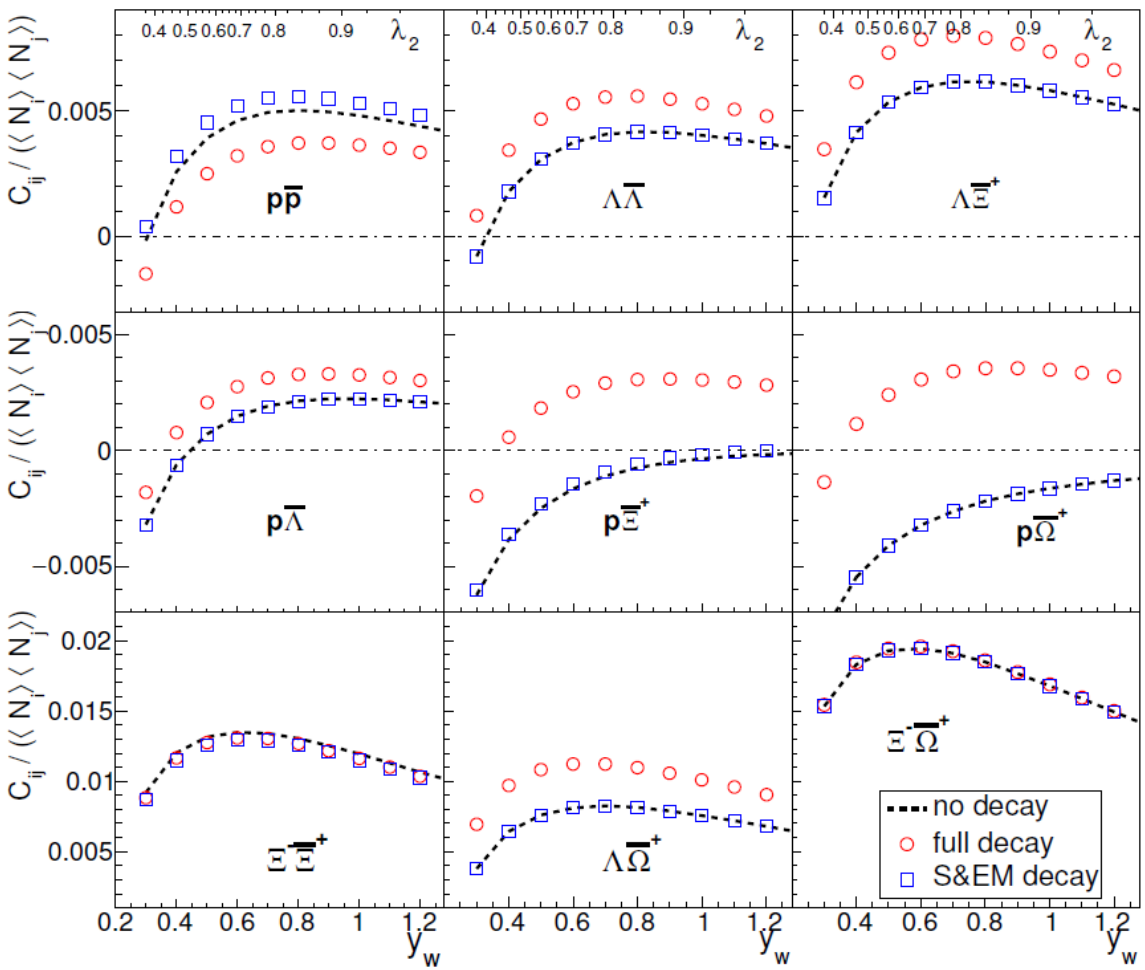


relative correlations $\frac{C_{ij}}{N_i N_j}$

Hardly influenced by decays

Non-monotonic dependence on y_w

Baryon-Antibaryon correlations



Striking properties:

① **Almost same $p\bar{p}$, $p\bar{\Lambda}$, $p\bar{\Xi}$, $p\bar{\Omega}$ with full decays**

② **Negative $p\bar{\Omega}$ correlation with S&EM decays while positive with full decays**

③ **Sign change of $p\bar{\Lambda}$ at moderate y_w**

④ **Non-monotonic dependence on y_w**

……

Summary

QCM can explain many systematics in hadron production in relativistic heavy ion collisions.

A possible hadronization phenomenology

"the effective degrees of freedom at hadronization are massive quarks and antiquarks, and
hadrons are formed by the combination of these quarks and antiquarks according to the valance structures of hadrons".

More investigations, predictions, and experimental data are needed to understand the phenomenology of the hadronization in high energy reactions.