New insights into the hadron production mechanism in pp and p-Pb collisions at LHC

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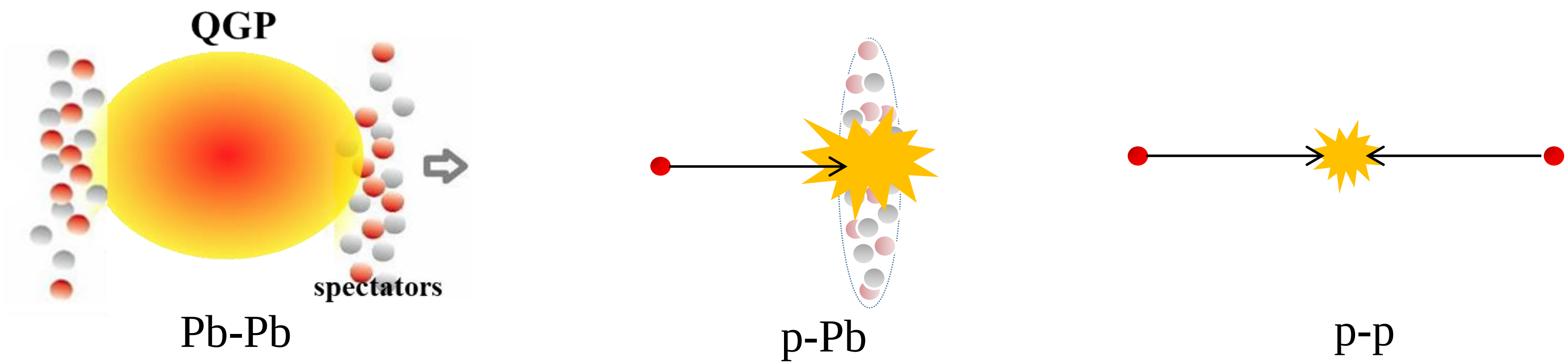
Outline

1. **Motivation**
2. **Our finding in small-system pp and p-Pb collisions at LHC**
3. **Summary**

Motivation



Is Quark Gluon Plasma (QGP) also formed in pp and p-Pb collisions at LHC?

Recently, striking features observed by ALICE and CMS collaborations for high multiplicity events in pp and p-Pb collisions at LHC, e.g,

long range angular correlations (ridge), CMS JHEP1009(2010), CMS PLB718(2013),742(2015)

flow-like patterns, NPA932(14), CMS PLB742(2015),765(2017)

enhanced strangeness ALICE Nature Phys.13(2017)

……

Theoretical explanations focus on the creation of mini-QGP or phase transition, color re-connection or string overlap at hadronization

What can we learn from the data of hadronic p_T spectra and yields ?

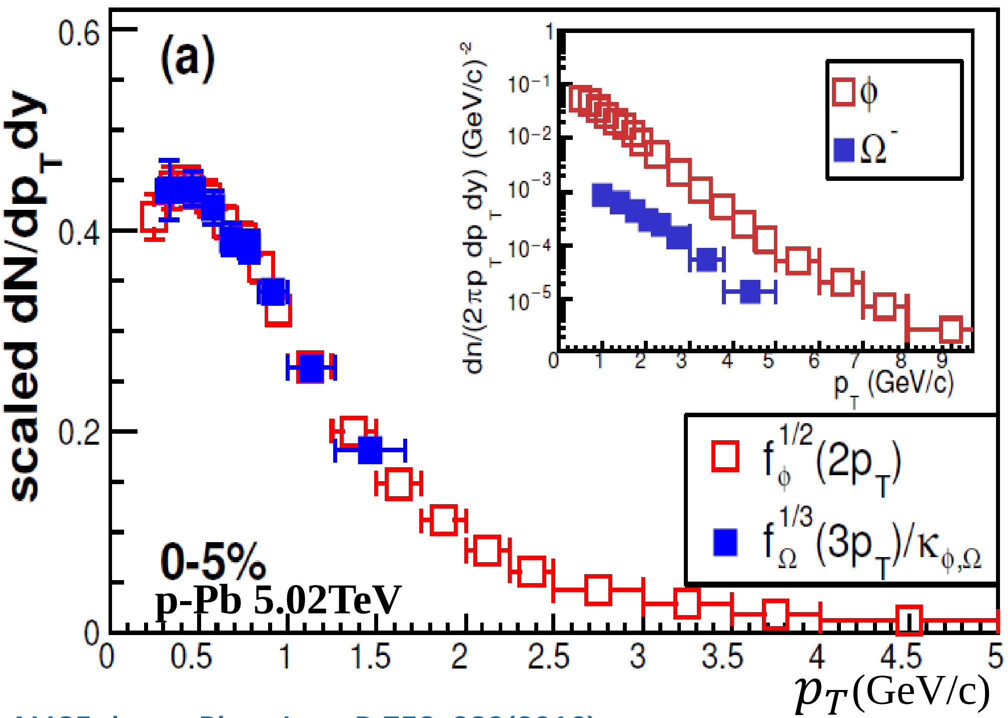
Quark number scaling of hadronic p_T spectra in p-Pb collisions at 5.02 TeV

Song,Gou,Shao,Liang, Phys.Lett. B774(2017),516

By looking at the midrapidity data on p_T spectra of $\Omega(sss)$ and $\phi(s\bar{s})$

(i) divide p_{T_h} by quark number, i.e. $p_{T_h}/3$ for Ω, $p_{T_h}/2$ for ϕ,

(ii) compare the inverse quark number power of $\frac{dN}{dp_T}$, i.e. $\left(\frac{dN_\Omega}{dp_T}\right)^{1/3}$ and $\left(\frac{dN_\phi}{dp_T}\right)^{1/2}$



ALICE data： Phys. Lett. B 758, 389(2016).
Eur. Phys. J. C76, 245 (2016)

More precisely, $f_h(p_T) = dN_h/dp_T dy$

$$f_\Omega^{\frac{1}{3}}(3p_T) = \kappa_{\phi,\Omega} f_\phi^{\frac{1}{2}}(2p_T)$$

in other words,

$$f_\Omega(3p_T) = \kappa_\Omega f_s^3(p_T)$$

$$f_\phi(2p_T) = \kappa_\phi f_s^2(p_T)$$

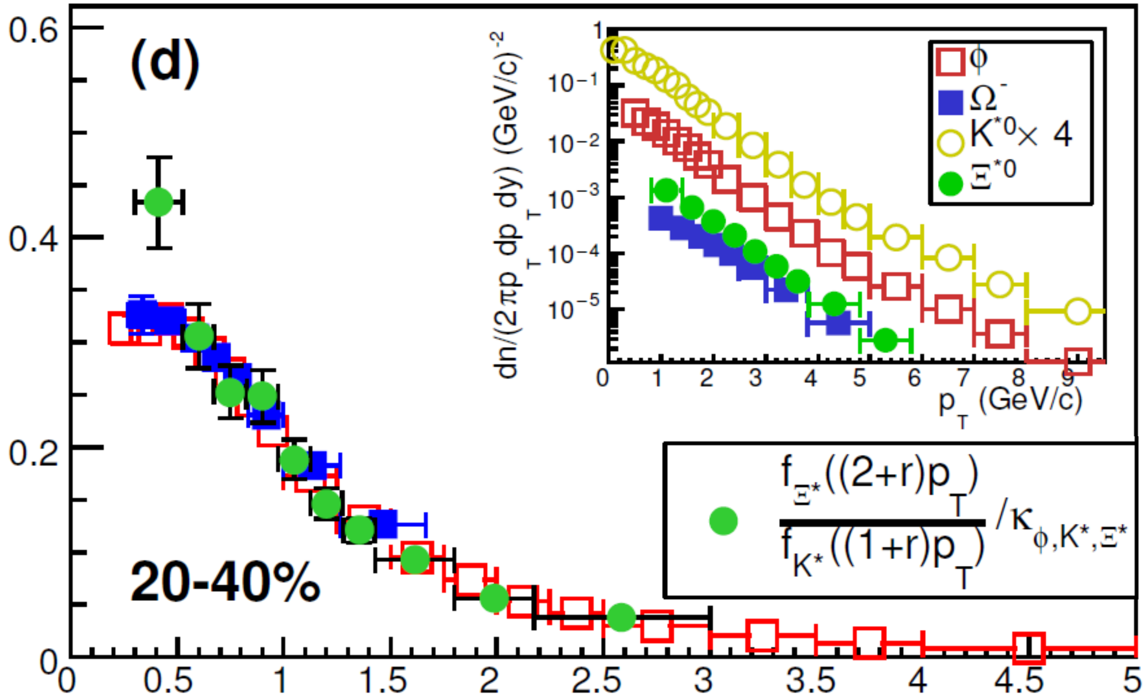
where κ is independent of p_T

Quark number scaling of hadronic p_T spectra in p-Pb collisions at 5.02 TeV

For $\Xi^{*0}(uss)$ and $K^{*0}(d\bar{s})$, we also find

$$\frac{f_{\Xi^{*0}}((2+r)p_T)}{f_{K^{*0}}((1+r)p_T)} = \kappa_{K^*,\Xi^*} f_s(p_T) = \kappa_{\phi,K^*,\Xi^*} f_\phi^{1/2}(p_T)$$

where $r \approx 2/3$



p_T(GeV/c)

ALICE data, Eur. Phys. J. C77, 389(2017)

Quark Combination Mechanism

Start from general formula

$$f_{B_j}(p_B) = \int dp_1 dp_2 dp_3 \;\; R_{B_j}(p_1,p_2,p_3;p_B) \;\; f_{q_1 q_2 q_3}(p_1,p_2,p_3)$$
$$f_{M_j}(p_M) = \int dp_1 dp_2 \;\; R_{M_j}(p_1,p_2;p_M) \;\; f_{q_1 \bar{q}_2}(p_1,p_2)$$

Assume independent distribution of (anti-)quarks

$$f_{q_1 q_2 q_3}(p_1,p_2,p_3) = f_{q_1}(p_1) f_{q_2}(p_2) f_{q_3}(p_3)$$
$$f_{q_1 \bar{q}_2}(p_1,p_2) = f_{q_1}(p_1) f_{\bar{q}_2}(p_2)$$

Suppose the combination takes place mainly for quark and/or antiquark that takes a given fraction of momentum of the hadron,

$$R_{B_j}(p_1,p_2,p_3;p_B) = \kappa_{B_j} \prod_{i=1}^{3} \delta(p_i - x_i p_B)$$
$$R_{M_j}(p_1,p_2;p_M) = \kappa_{M_j} \prod_{i=1}^{2} \delta(p_i - x_i p_M)$$

We obtain

$$f_{B_j}(p_B) = \kappa_{B_j} f_{q_1}(x_1 p_B) f_{q_2}(x_2 p_B) f_{q_3}(x_3 p_B)$$
$$f_{M_j}(p_M) = \kappa_{M_j} f_{q_1}(x_1 p_M) f_{\bar{q}_2}(x_2 p_M)$$

which directly leads to

$$f_\Omega(3p_T) = \kappa_\Omega f_s^3(p_T)$$
$$f_\phi(2p_T) = \kappa_\phi f_s^2(p_T)$$

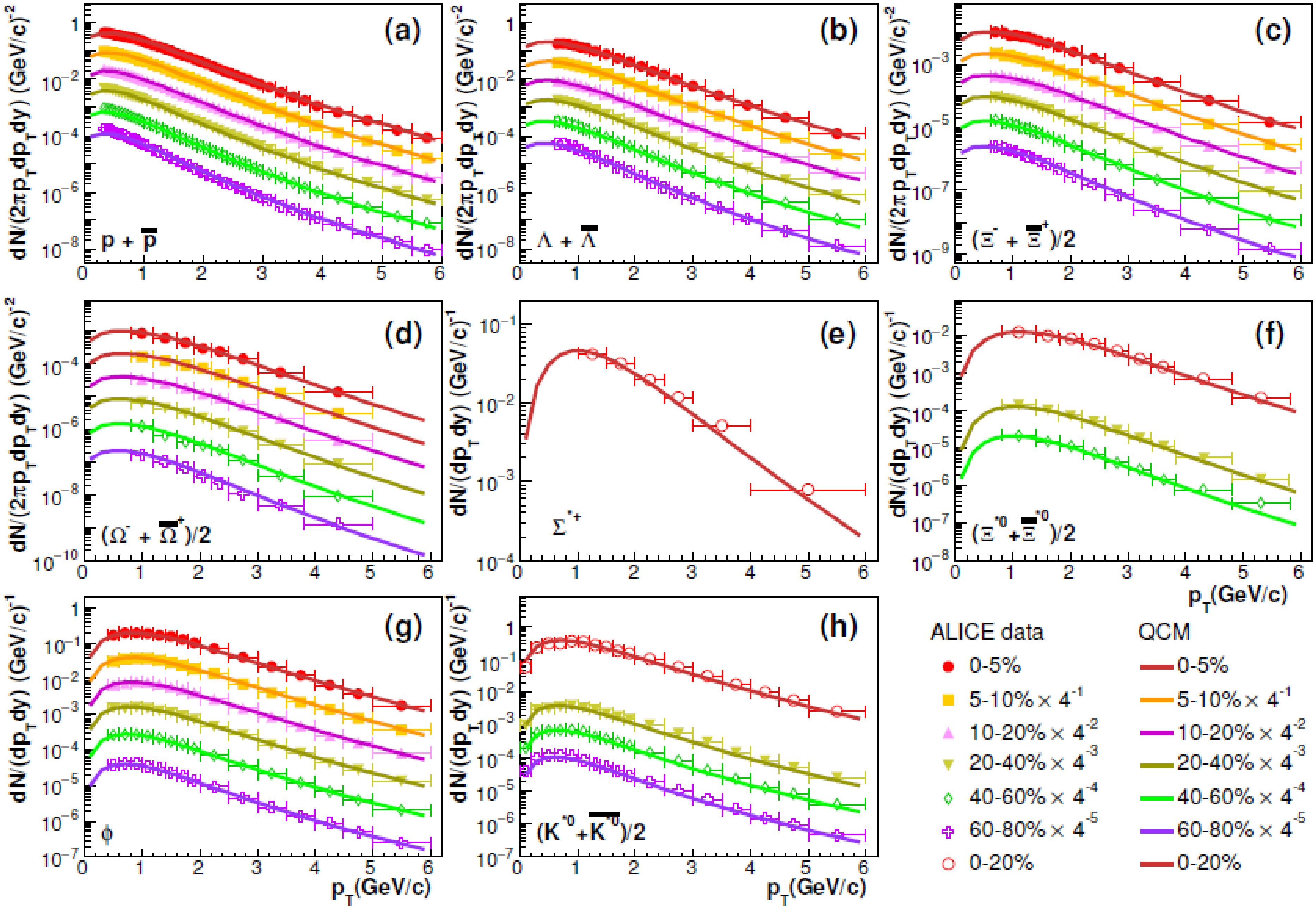
$$\Rightarrow \quad f_\Omega^{\frac{1}{3}}(3p_T) = \kappa_{\phi,\Omega} f_\phi^{\frac{1}{2}}(2p_T)$$

For combination of u(d) and s quark(s), equal velocity implies $x_i = m_i / \sum_j m_j$,
denote $\frac{x_u}{x_s} = \frac{m_u}{m_s} = r$

$$f_{\Xi^{*0}}\big((2+r)p_T\big) = \kappa_{\Xi^{*0}}\, f_s^2(p_T) f_u(r\, p_T)$$
$$f_{K^{*0}}\big((1+r)p_T\big) = \kappa_{K^{*0}}\, f_s(p_T) f_{\bar{d}}(r\, p_T)$$

$$\Rightarrow \quad \frac{f_{\Xi^{*0}}\big((2+r)p_T\big)}{f_{K^{*0}}\big((1+r)p_T\big)} = \kappa_{\phi,K^*,\Xi^*} f_\phi^{\frac{1}{2}}(2p_T)$$

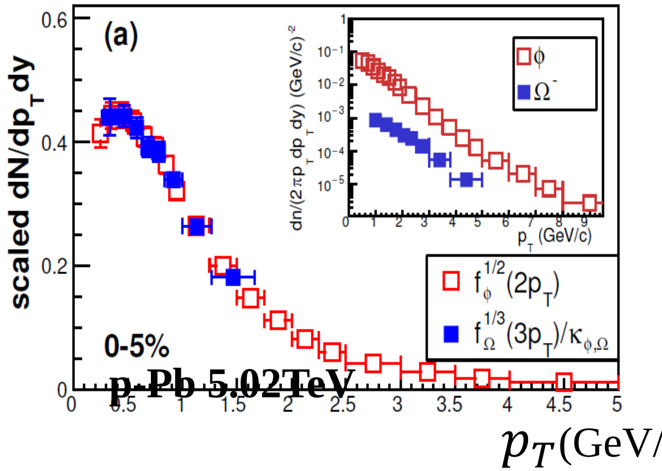
$r \approx 2/3$ if we take $m_s = 500$ MeV and $m_u = m_d = 330$ MeV.


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
p + p̄
Λ + Λ̄
(Ξ⁻ + Ξ̄⁺)/2
(Ω⁻ + Ω̄⁺)/2
Σ*+
(Ξ*0 + Ξ̄*0)/2
φ
(K*0 + K̄*0)/2
p_T(GeV/c)
ALICE data
QCM
0-5%
5-10% × 4^-1
10-20% × 4^-2
20-40% × 4^-3
40-60% × 4^-4
60-80% × 4^-5
0-20%

Song,Gou,Shao,Liang, Phys.Lett. B774(2017),516

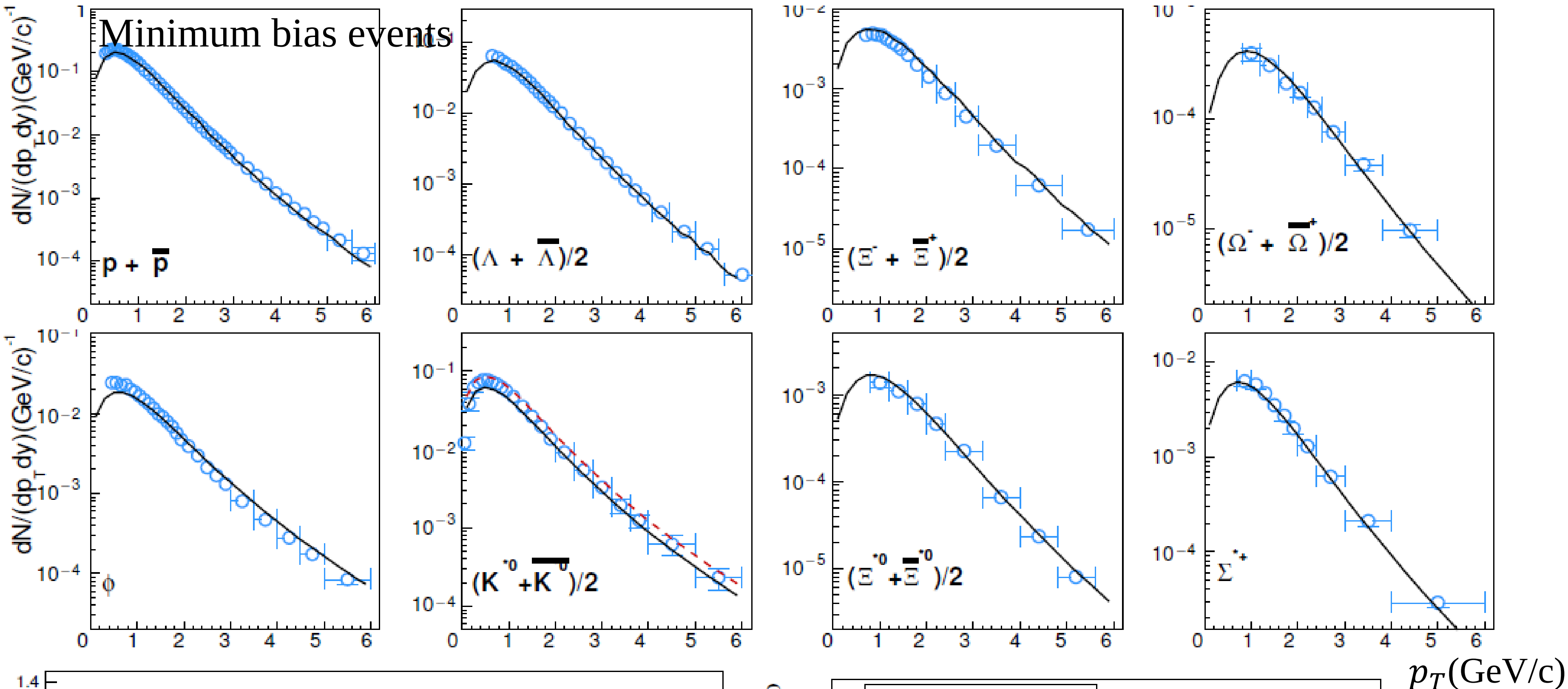
Interesting findings

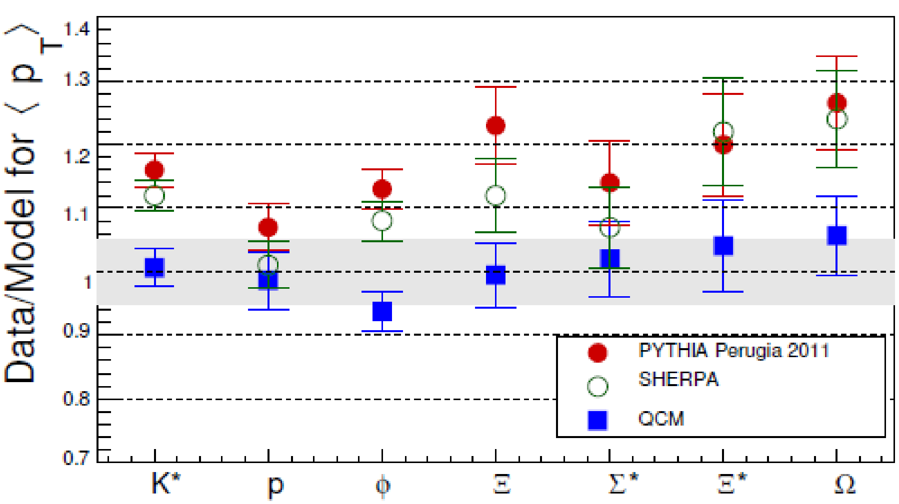
- the observed scaling property is a direct consequence of quark combination mechanism of hadronization
- It is a strong indication of the existence of the underlying source with constituent quark degree of freedom (CQdof) for the production of hadrons in p-Pb collisions at such high energies.

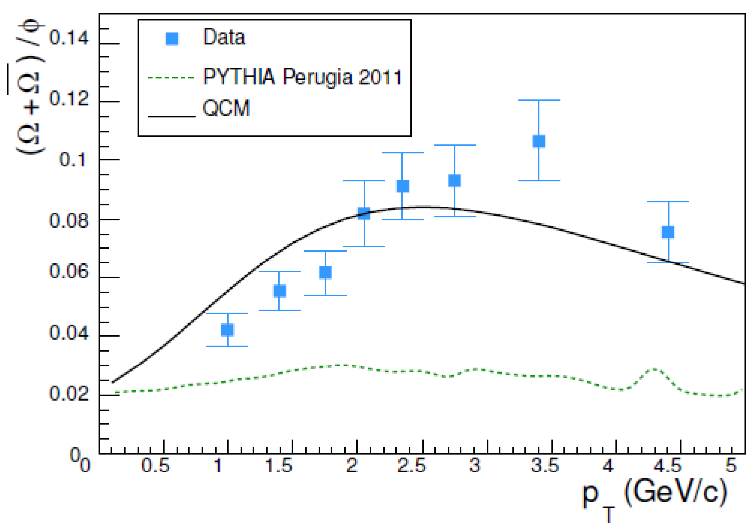


results in pp collisions at 7 TeV

Gou,Shao,Song…,PRD96(2017), 094010







Rewrite the spectrum

$$f_{M_j}(p_M) = N_{M_j} f_{M_j}^{(n)}(p_M)$$
$$f_{B_j}(p_B) = N_{B_j} f_{B_j}^{(n)}(p_B)$$

with normalized distribution $\int dp\, f^{(n)}(p) = 1$,

$$f_{M_j}^{(n)}(p_M) = A_{M_j} f_{q_1}^{(n)}(x_1 p_M) f_{\bar{q}_2}^{(n)}(x_2 p_M)$$
$$f_{B_j}^{(n)}(p_B) = A_{B_j} f_{q_1}^{(n)}(x_1 p_B) f_{q_2}^{(n)}(x_2 p_B) f_{q_3}^{(n)}(x_3 p_B)$$

, and yield

$$N_{M_j} = N_{q_1 \bar{q}_2} \frac{\kappa_{M_j}}{A_{M_j}} = N_{q_1 \bar{q}_2} \; P_{q_1 \bar{q}_2 \to M_j}$$
$$N_{B_j} = N_{q_1 q_2 q_3} \frac{\kappa_{M_j}}{A_{M_j}} = N_{q_1 q_2 q_3} P_{q_1 q_2 q_3 \to B_j}$$

$P_{q_1 \bar{q}_2 \to M_j}$ and $P_{q_1 q_2 q_3 \to B_j}$ are momentum-integrated combination probabilities

adopt flavor-blind approximation

$$P_{q_1 \bar{q}_2 \to M_j} = C_{M_j} \frac{\bar{N}_M}{N_{q\bar{q}}}$$
$$P_{q_1 q_2 q_3 \to B_j} = C_{B_j} \frac{\bar{N}_B}{N_{qqq}}$$

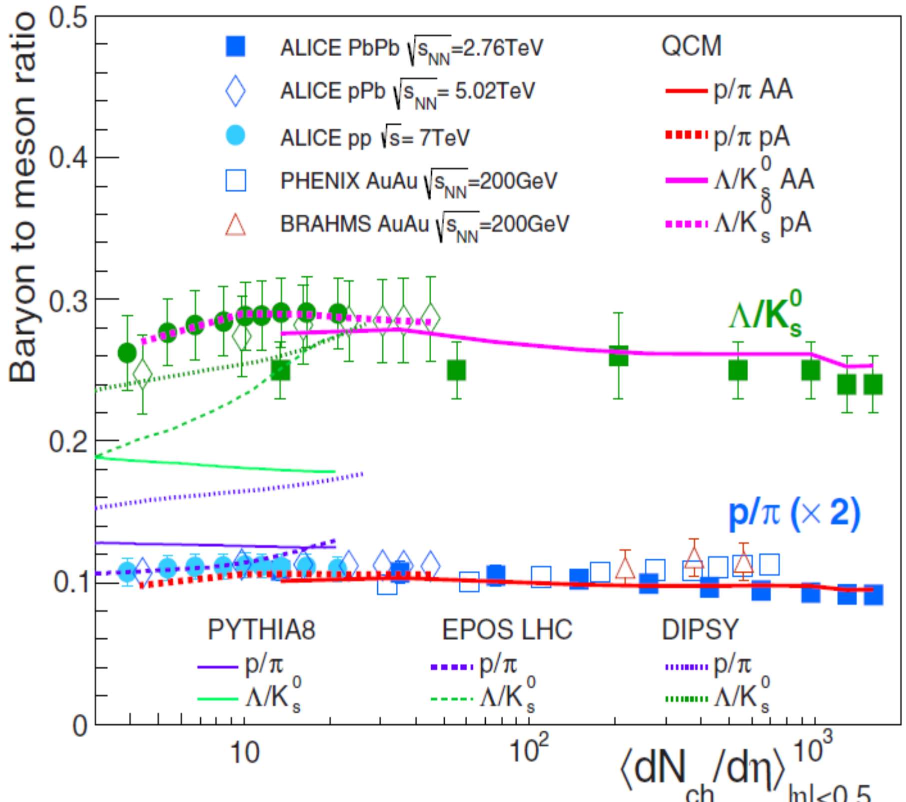
C_{M_j} and C_{B_j} select the different spin states for the same flavor combination

$$C_{M_j} = \begin{cases} \dfrac{1}{1 + R_{V/P}} & for\ J^P = 0^- \ mesons \\ \dfrac{R_{V/P}}{1 + R_{V/P}} & for\ J^P = 1^- \ mesons \end{cases}$$
$$C_{B_j} = \begin{cases} \frac{R_{O/D}}{1+R_{O/D}} & for\ J^P = (1/2)^+ baryons \\ \frac{1}{1+R_{O/D}} & for\ J^P = (3/2)^+ baryons \end{cases}$$

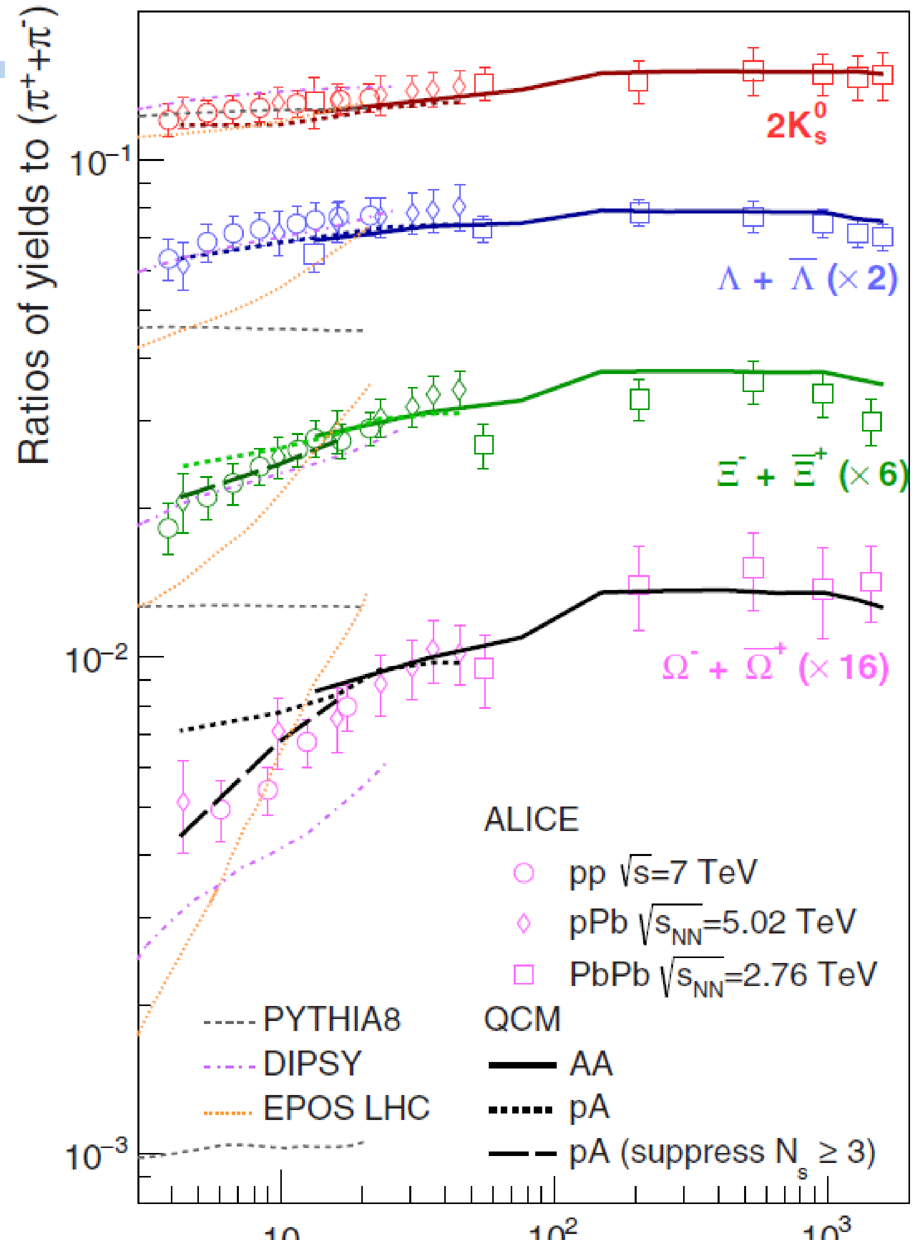
Parameters $R_{V/P} = 0.45$ $R_{O/D} = 2$

Shao,Song, et al, Phys.Rev.C95(2017) ,064911

p_T-integrated Yields of hadrons in pp, p-Pb and Pb-Pb collisions at LHC



Baryon/Meson yield ratios

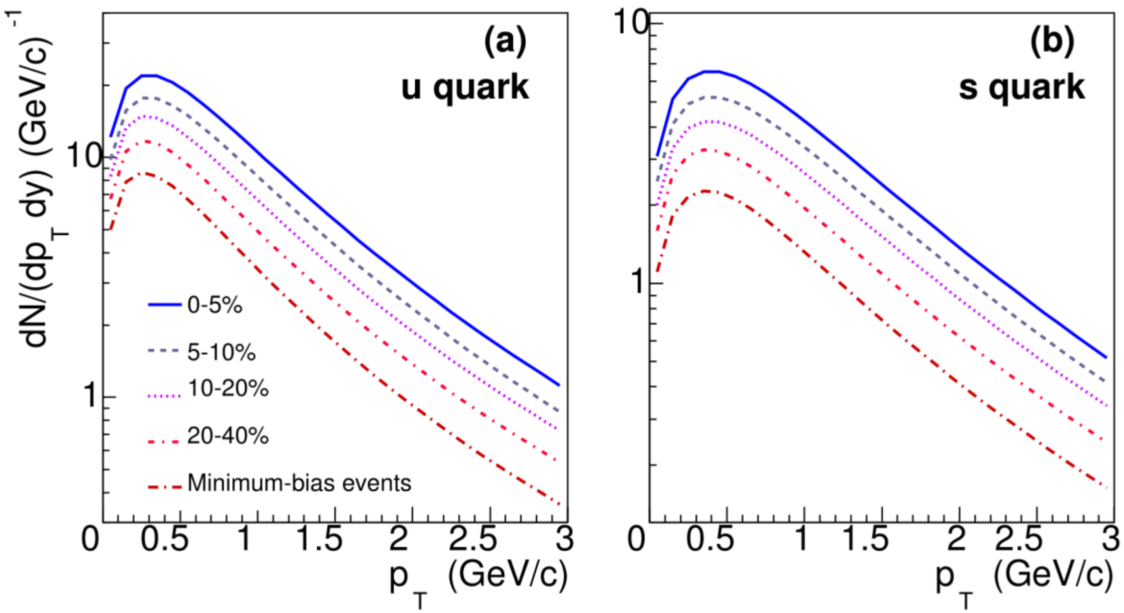


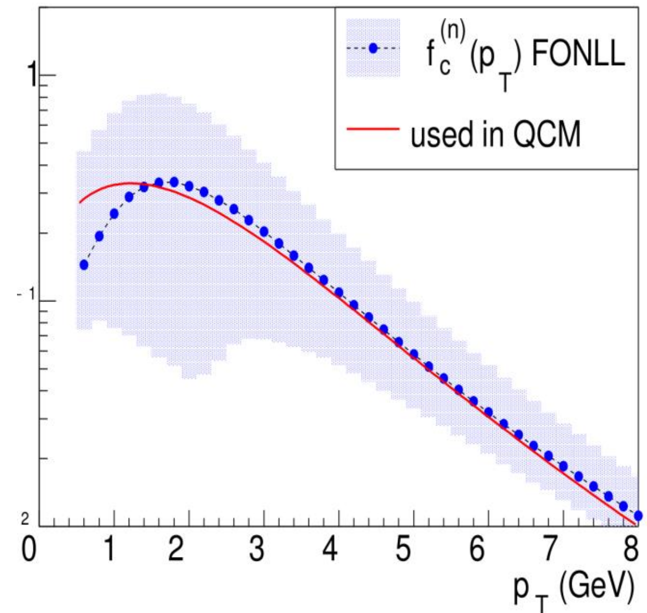
Hierarchy in yields among K, Λ, Ξ and Ω

Production of single-charm hadrons in p-Pb collisions at 5.02 TeV, soon appears in arxiv

Equal-velocity combination of charm quark and light-flavor (anti)quarks

Quark spectra at hadronization





got from light-flavor hadrons

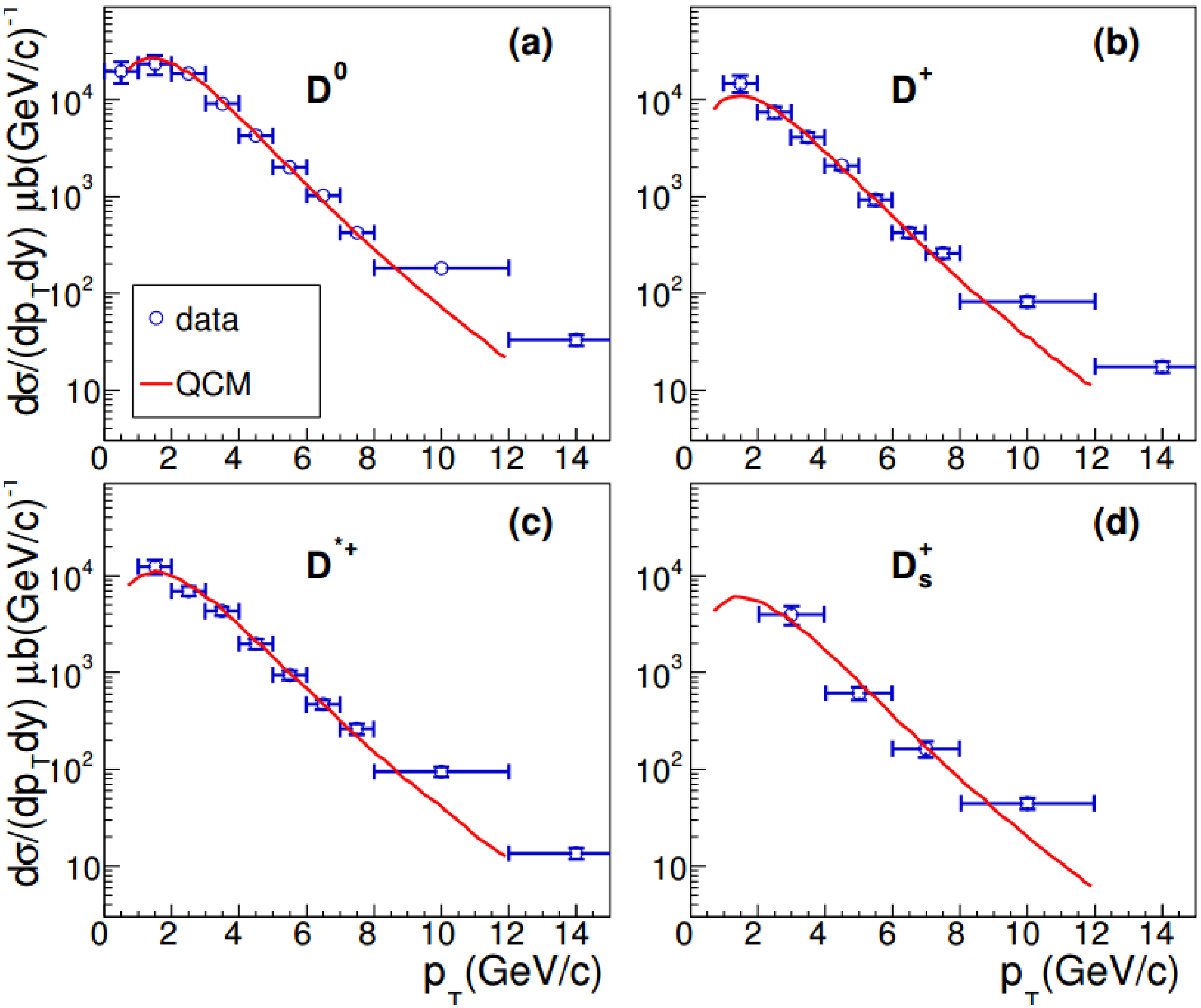
consistent with pQCD calculations

Parameters in the model:

$R_{V/P} = 1.5 \quad R_{S3/S1} = 1.5$ thermal weights

D mesons of $p_T \lesssim 8$ GeV,

= c quark of $p_{T,c} \lesssim 6$ + l quark of $p_{T,l} \lesssim 2$ GeV



Summary

We show that

- Experimental data for p_T spectra of identified hadrons in pp and p-Pb collisions at LHC energies can be well understood by the quark combination mechanism

This indicates that

- the existence of the underlying source with constituent quark degree of freedom (CQdof) for the production of hadrons in small parton system created in pp and p-Pb collisions at LHC energies.

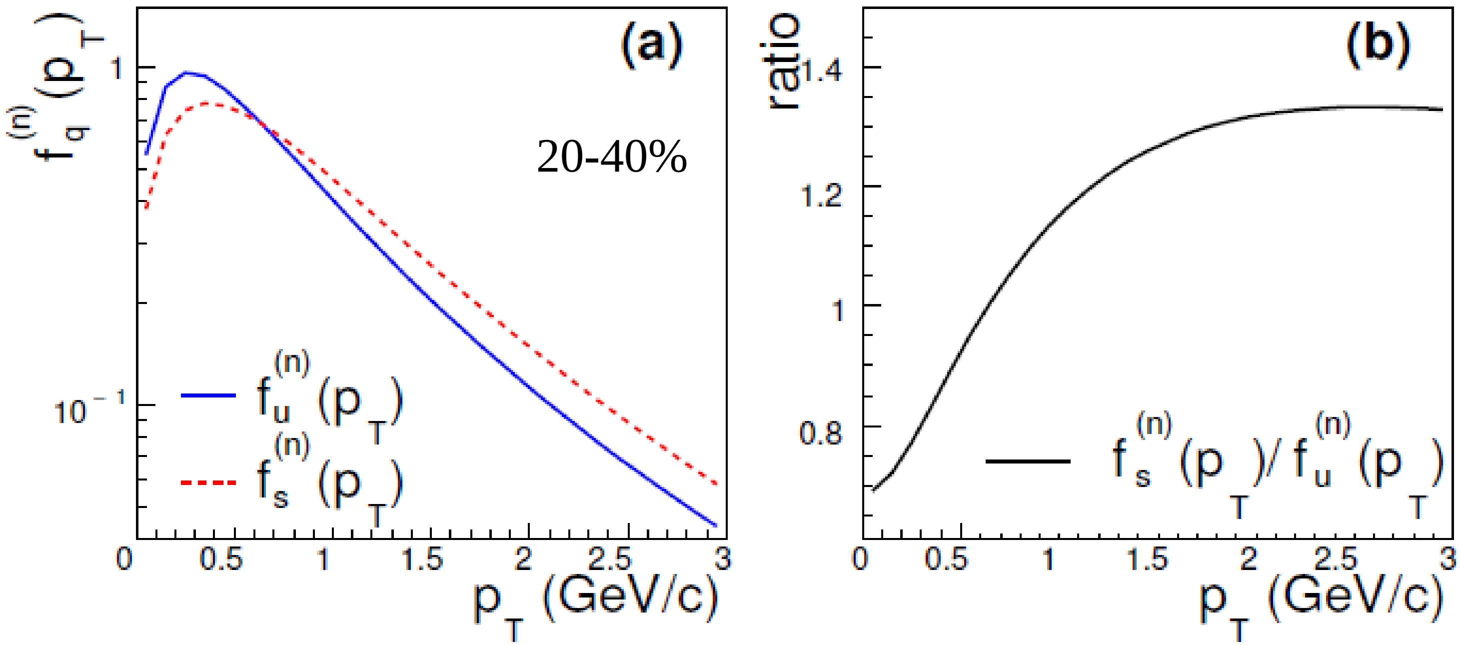
The possible signature of the formation of mini-QGP like matter!

More studies are necessary!

Thanks !

Extraction of quark p_T spectra from the data

$$f_q^{(n)}(p_T) = \mathcal{N}_q \sqrt{p_T} \left[1 + \frac{1}{n_q c_q} \left(\sqrt{p_T^2 + m_q^2} - m_q \right) \right]^{-n_q}$$



similar to AA collisions at RHIC and LHC energies!

J.H. Chen, et al, PRC78,034907(08); RQ Wang, Shao, Song, PRC91,014909(15); Shao, Song, et al, PRC80,014909(09);

$\boldsymbol{\kappa_{M_i}}$ and $\boldsymbol{\kappa_{B_i}}$ can be well determined in QCM with a few parameters

$$\kappa_{B_i} \approx A_{q_1,q_2,q_3} C_{B_i} N_{iter} / 15 \langle N_q \rangle^2$$

$$\kappa_{M_i} \approx 4 A_{q_1,\bar{q}_2} C_{M_i} / 5 \langle N_q \rangle$$

where $\langle N_q \rangle$ is total quark number. C_{B_i} and C_{M_i} are determined by parameters $R_{D/O}$ and $R_{V/P}$.

$\mathcal{N}_{q_1,q_2,q_3}$ and $\mathcal{N}_{q_1,\bar{q}_2}$ are determined by quark p_T spectrum

$$A_{q_1,q_2,q_3} \int dp_T \prod_{i=1}^{3} f_{q_i}^{(n)}(x_i p_T) = 1$$

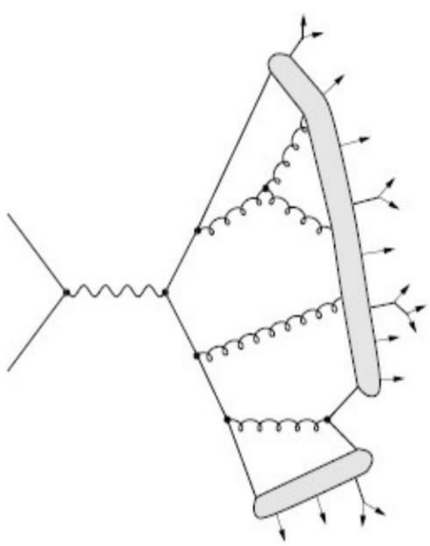
$$A_{q_1,\bar{q}_2} \int dp_T f_{q_1}^{(n)}(x_1 p_T) f_{\bar{q}_2}^{(n)}(x_2 p_T) = 1$$

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

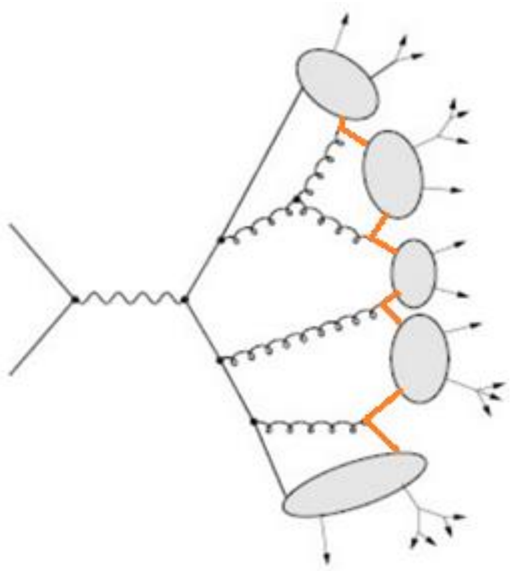
- **Non-perturbative QCD process**
- **Phenomenological schemes are then used to model the hadronization process**

Early-years studies suggest :

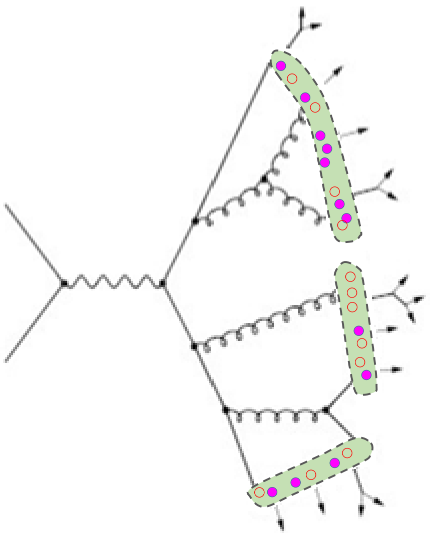
(1) string fragmentation



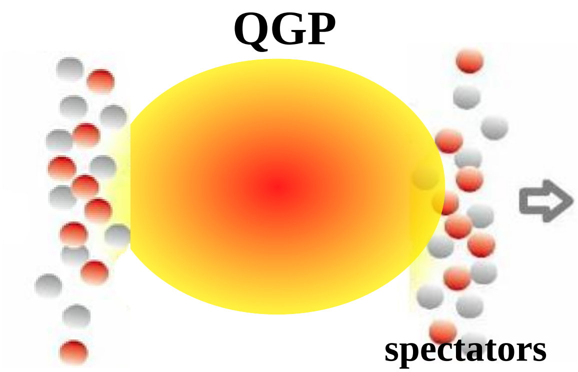
(2) cluster fragmentation



(3) quark combination



Quark Gluon Plasma in relativistic heavy ion collisions

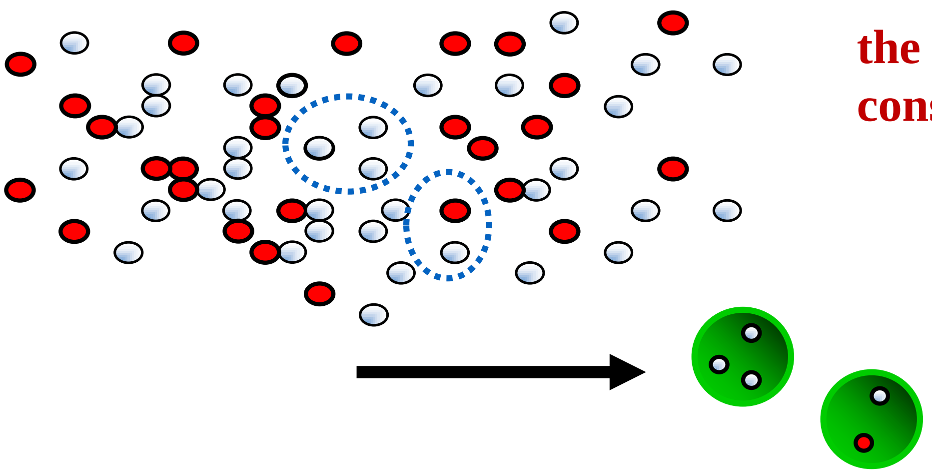


Partons in final state :

Soft, p ~ 1GeV

Large number $\gtrsim 10^3$

Quark combination mechanism(QCM) at hadronization

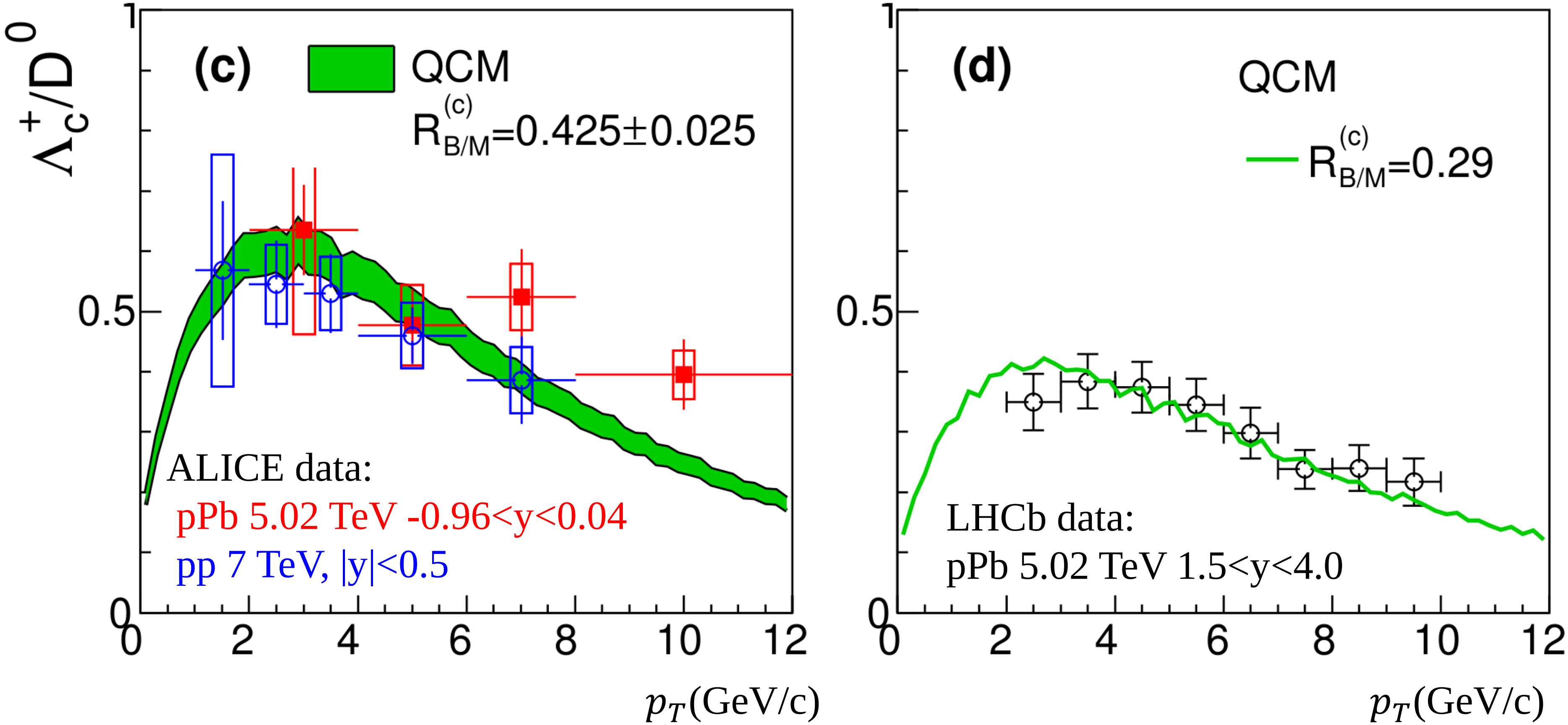


the effective degrees of freedom: constituent quarks and antiquarks

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



$R^{(c)}_{B/M} = \frac{N_{B_c}}{N_{M_c}}$ global formation competition between baryon and meson

Light-flavor extrapolation $R^{(c)}_{B/M} \approx 0.26$

Scaling property at different charged-particle multiplicity $\frac{dN_{ch}}{d\eta}$