New insights of soft hadron production in pp and p-Pb collisions at LHC

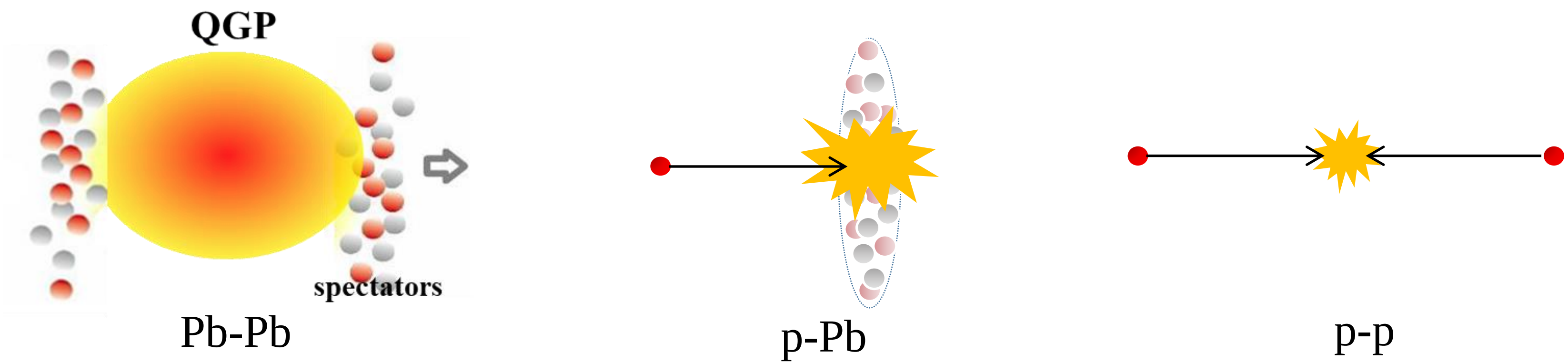
Jun Song （宋军） Jining University (Qufu, Shandong)

Collaborators : Feng-lan Shao, Zuo-tang Liang, Xing-rui Gou, Hai-hong Li,*et al*

Outline

1. **Motivation**
2. **Quark number scaling property for hadron p_T spectra**
3. **Quark combination mechanism in pp and p-Pb collisions at LHC**
4. **Summary**

Motivation



Recently, striking features observed by ALICE, CMS, LHCb 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)
- **enhanced baryon/meson ratios,**

  ……

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

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

Our studies suggest the change of hadronization mechanism from fragmentation to quark combination !

Quark number scaling of hadronic p_T spectra

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

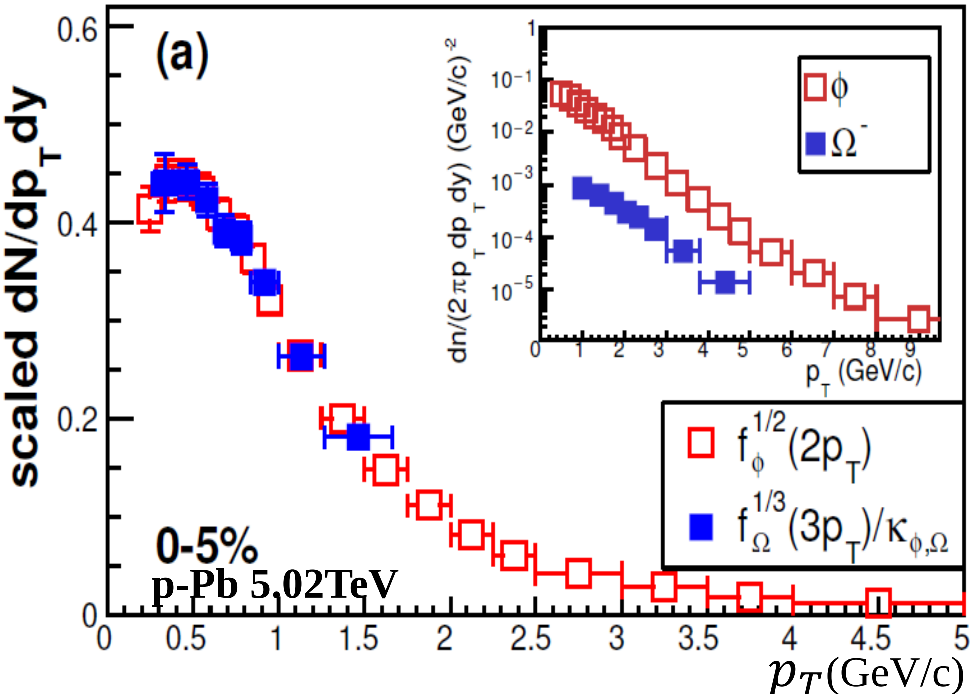
Manipulate data of p_T spectra of $\Omega(sss)$ and $\phi(s\bar{s})$ in p-Pb collisions at 5.02 TeV

(1) divide p_T bin by quark number, $p_{T_\Omega}/3$, $p_{T_\phi}/2$,

(2) take the inverse quark number power of density dN_h/dp_Tdy,
i.e. $dN_\Omega^{1/3}/dp_Tdy$ and $dN_\phi^{1/2}/dp_Tdy$

(3) divide Ω data by a constant to keep the same magnitude with that of ϕ

$f(p_T) \equiv dN_h/dp_Tdy$



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

mathematic relation

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

in other words,

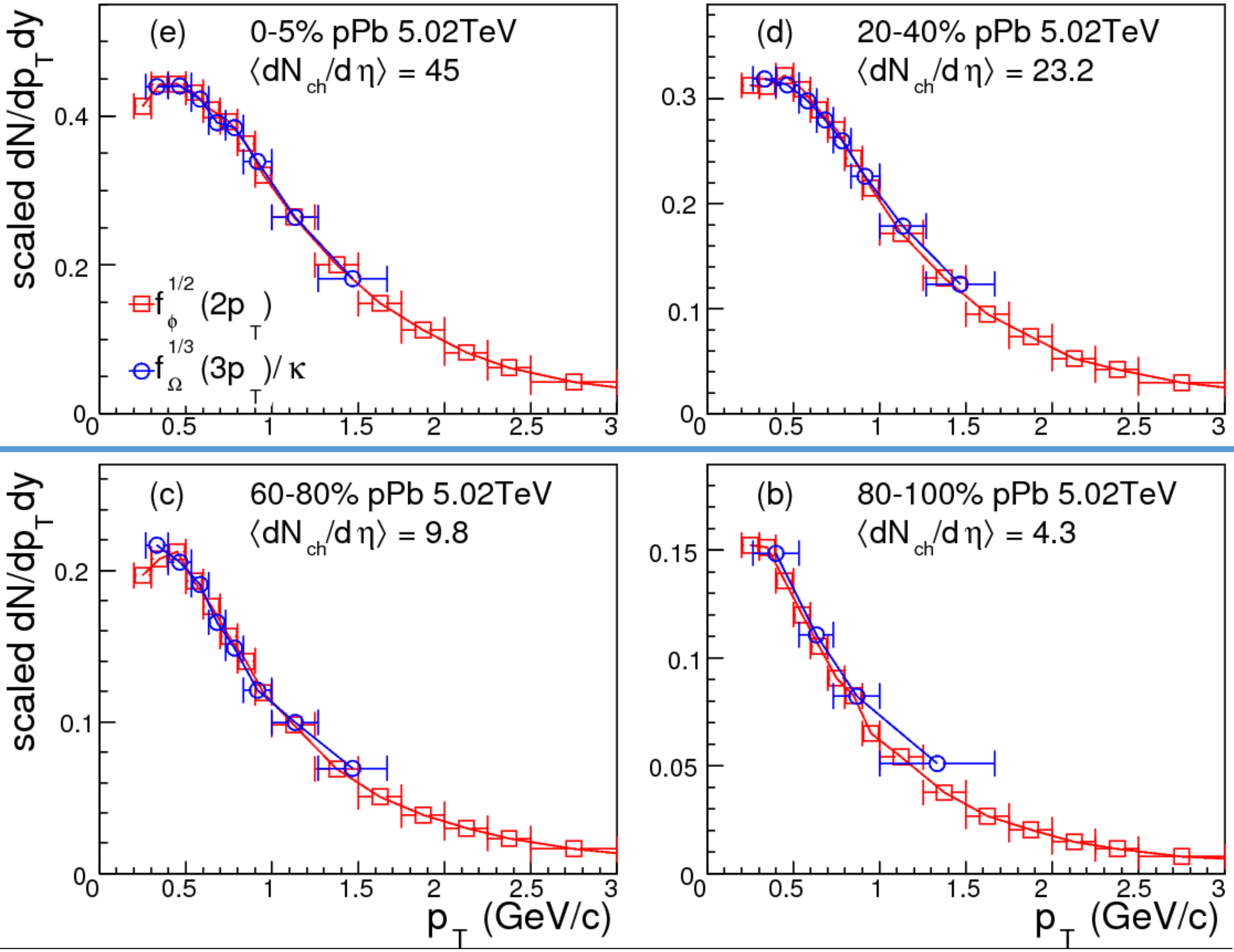
$$f_\Omega(3p_T) = \kappa_\Omega f_s^3(p_T)$$

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

where κ is independent of p_T

Scaling property in different multiplicity classes

in p-Pb collisions at 5 TeV



high multiplicity events
QNS holds well

small multiplicity events
QNS is broken

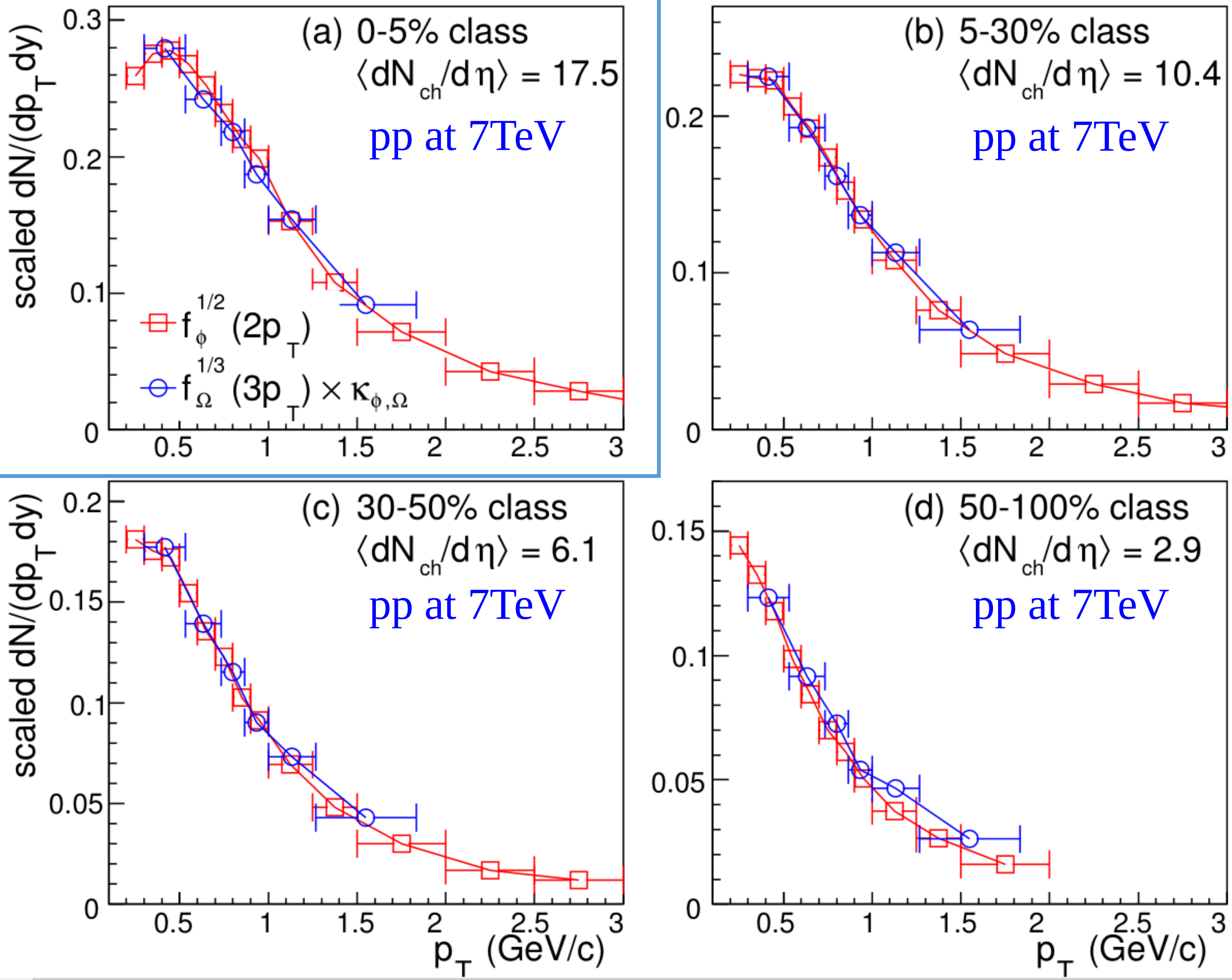
Scaling property at different multiplicity classes

Scaling property in different multiplicity classes

in pp collisions at 7 TeV

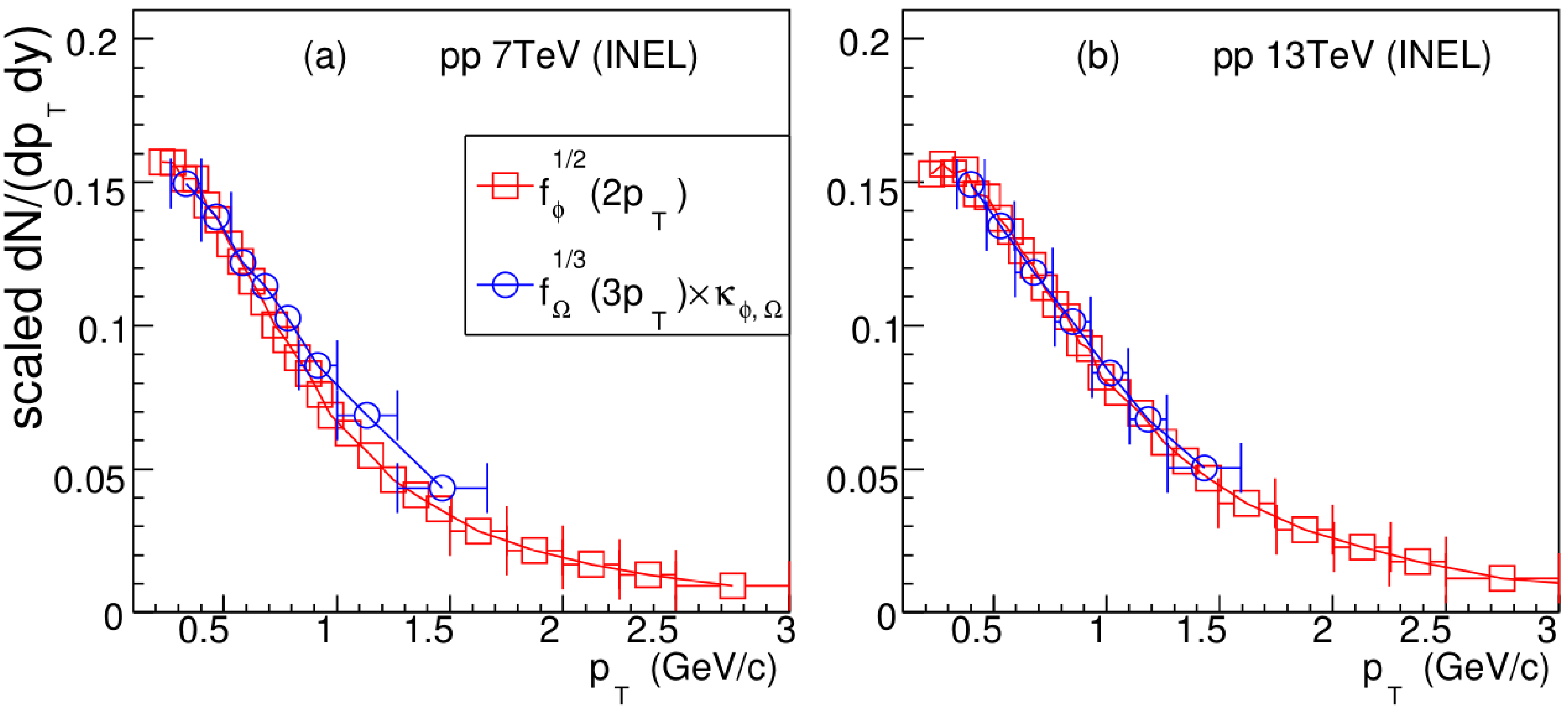
high multiplicity events
QNS holds well

small multiplicity events
QNS is broken



Scaling property in *pp* collisions

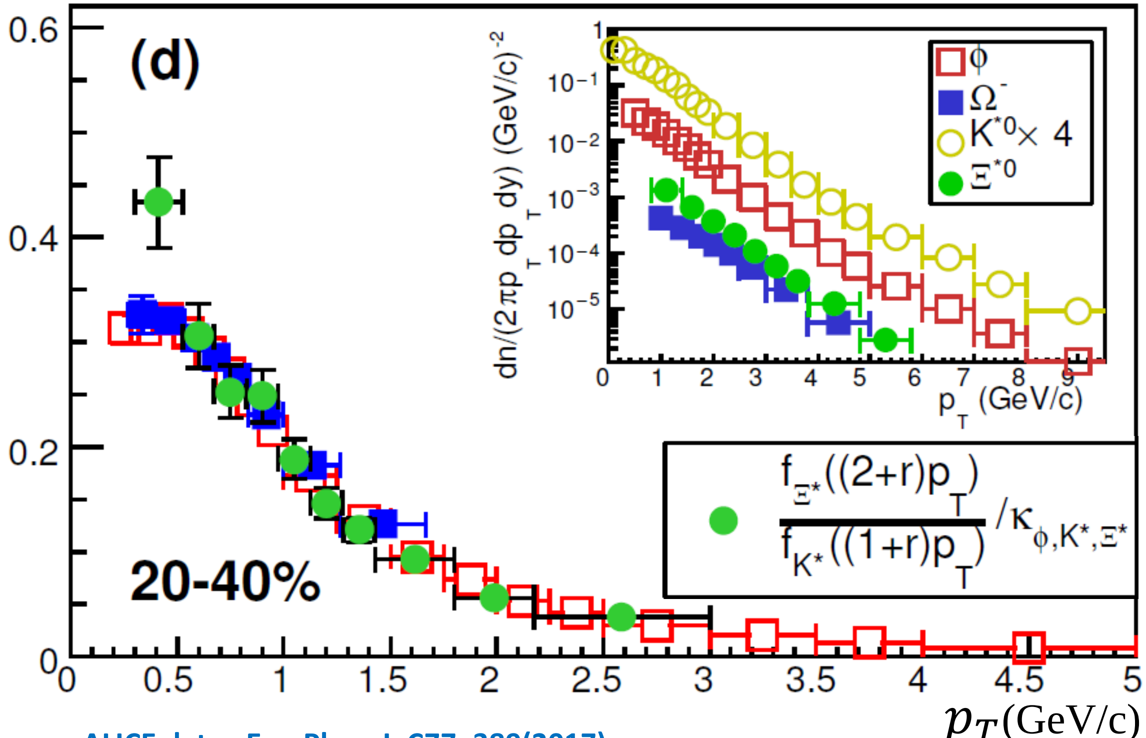
at different collision energies



Scaling property between $\Xi^{*0}(uss)$ and $K^{*0}(d\bar{s})$

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

where $r \approx 2/3$



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

Quark number scaling property exhibited is a clear signal of quark combination hadronization for small parton system created in pp and p-Pb collisions at LHC energies

Start from general formula

$$f_{B_j}(p_B) = \int dp_1 dp_2 dp_3\ R_{B_j}(p_1,p_2,p_3;p_B)\ f_{q_1q_2q_3}(p_1,p_2,p_3)$$
$$f_{M_j}(p_M) = \int dp_1 dp_2\ R_{M_j}(p_1,p_2;p_M)\ f_{q_1\bar{q}_2}(p_1,p_2)$$

Assume independent distribution of (anti-)quarks

$$f_{q_1q_2q_3}(p_1,p_2,p_3) = f_{q_1}(p_1)f_{q_2}(p_2)f_{q_3}(p_3)$$
$$f_{q_1\bar{q}_2}(p_1,p_2) = f_{q_1}(p_1)f_{\bar{q}_2}(p_2)$$

Adopt the co-moving combination

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

equal velocity combination

$\boldsymbol{x_i = m_i/\sum_j m_j,}$

$m_s = 500$ MeV

$m_u = m_d = 330$ MeV.

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

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

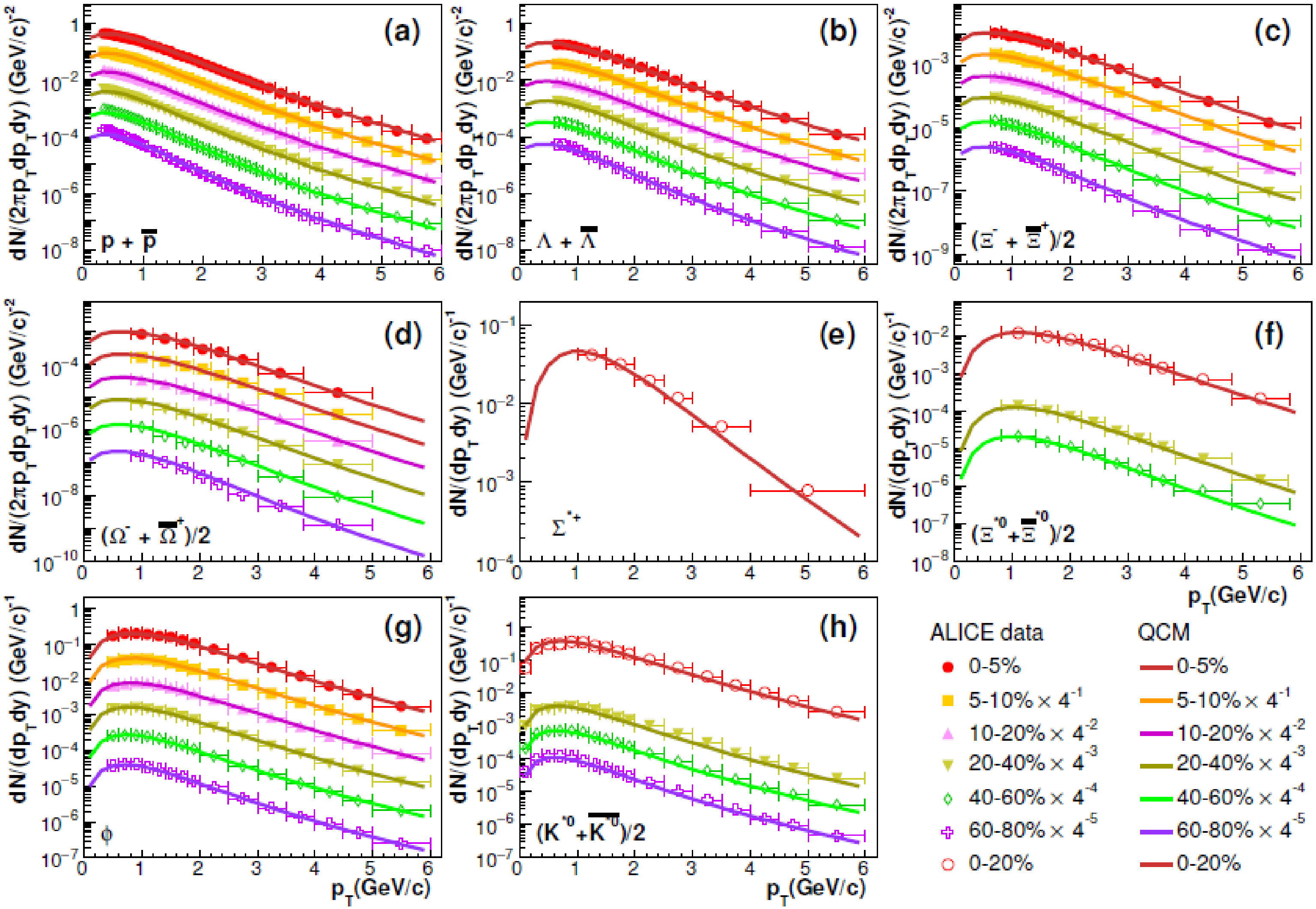
C_{M_j} and C_{B_j} select the different spin states for the same flavor combination

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

Parameters $R_{V/P} = 0.45$ $R_{O/D} = 2.0$

QCM in p-Pb collisions at 5.02 TeV

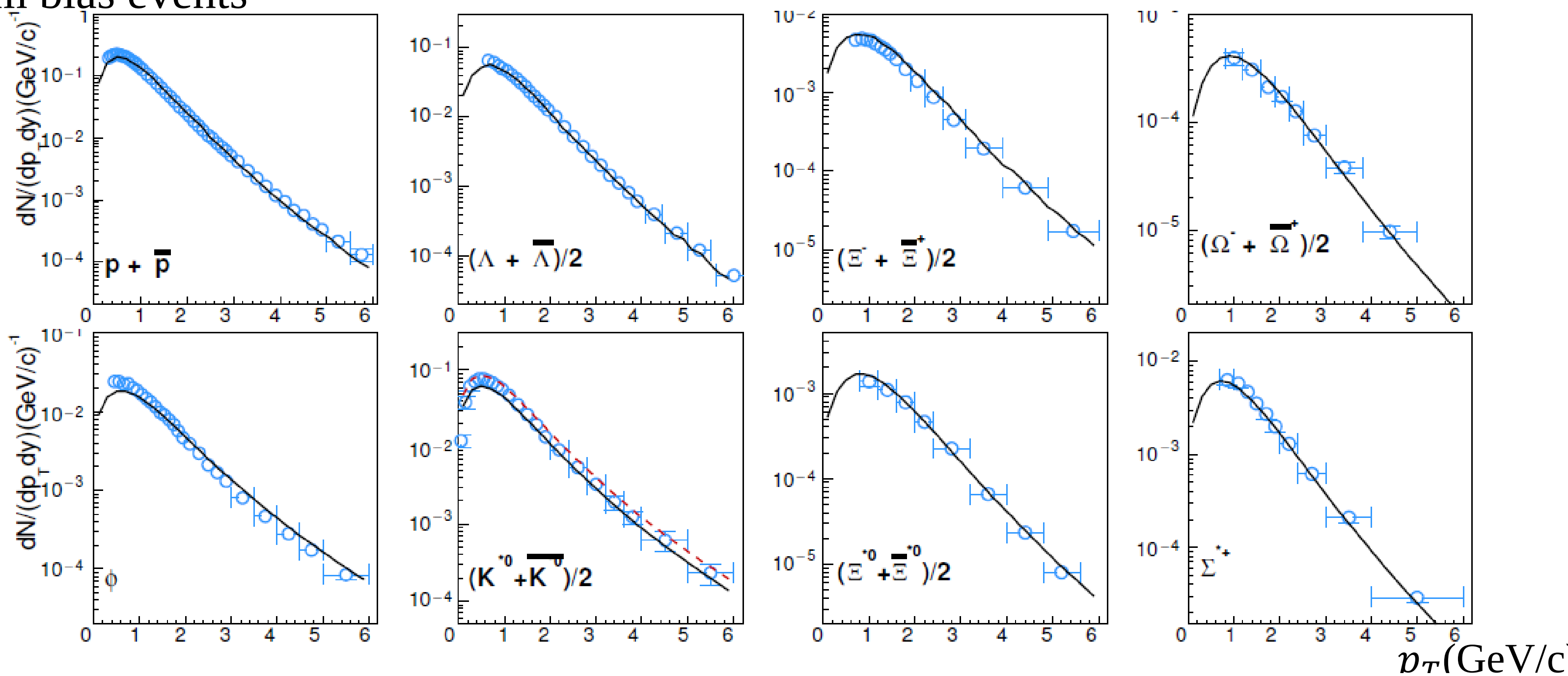
Song,Gou,Shao,Liang, Phys.Lett. B774(2017),516

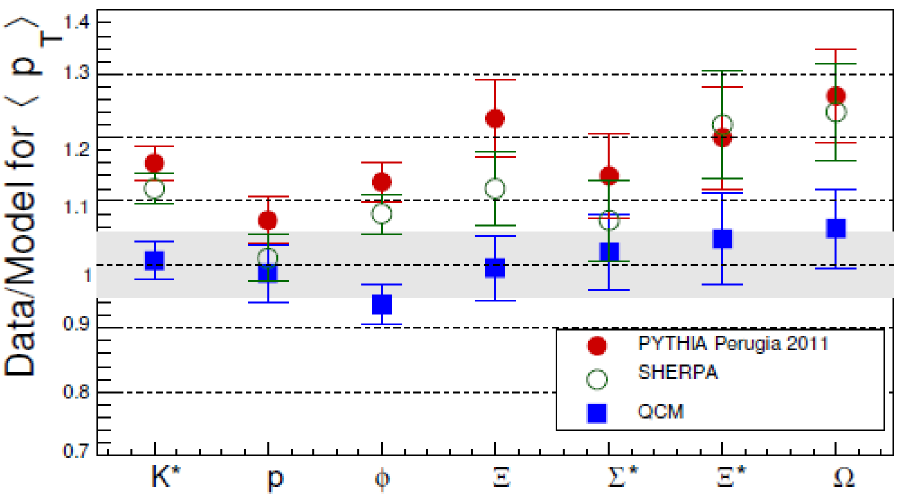


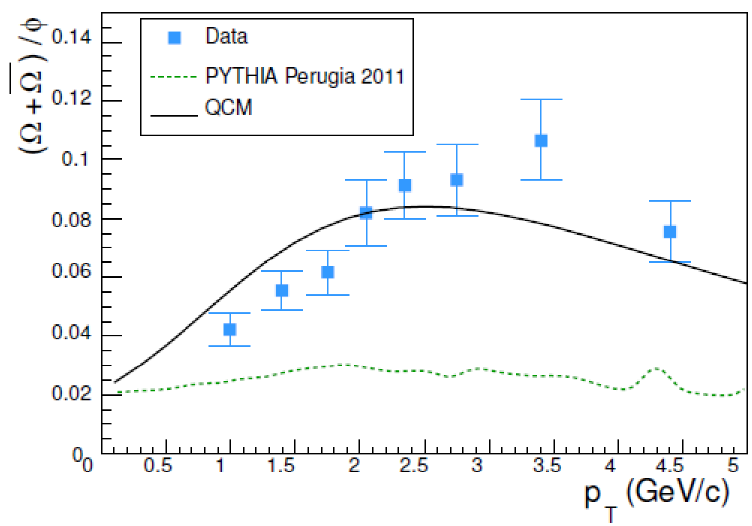
QCM in pp collisions at 7 TeV

Gou,Shao,Song…,PRD96(2017), 094010

Minimum bias events

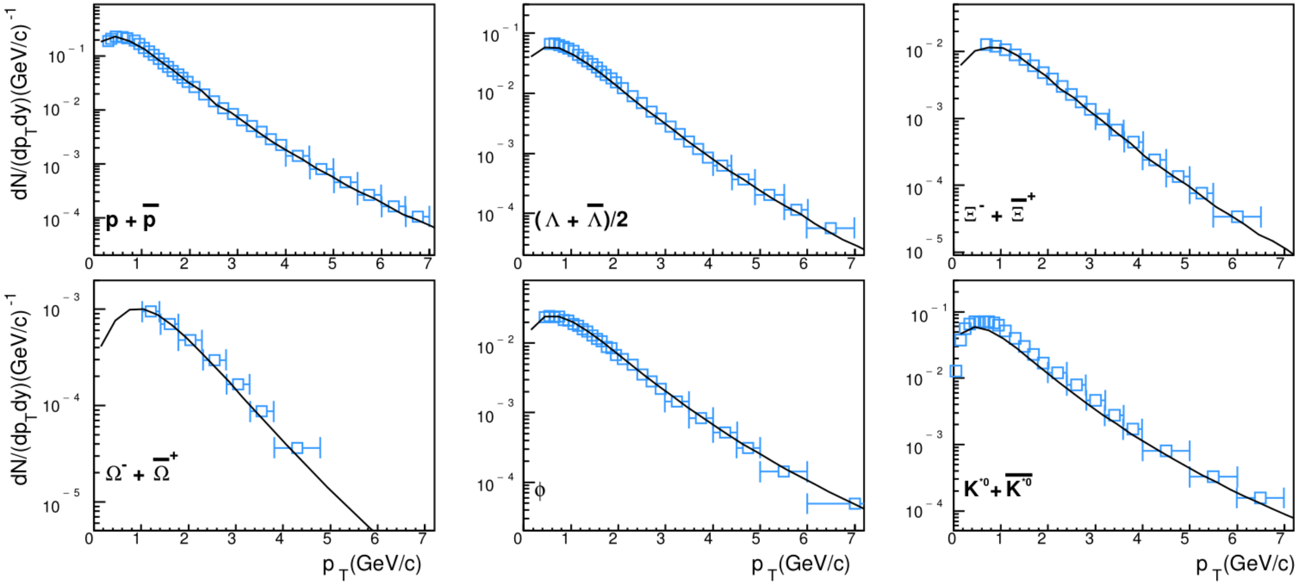


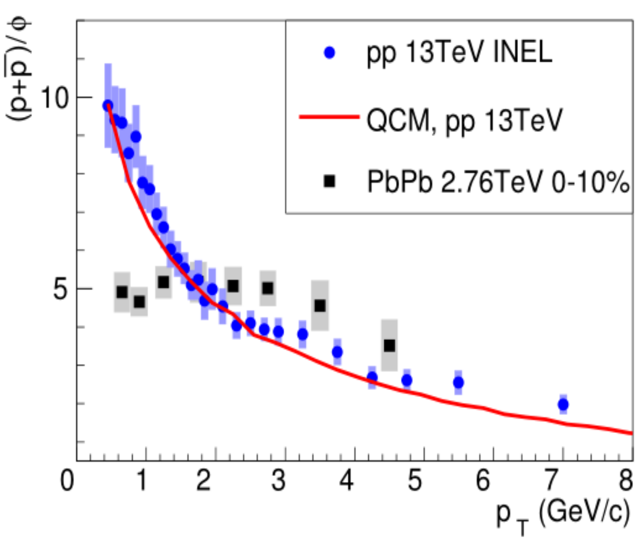


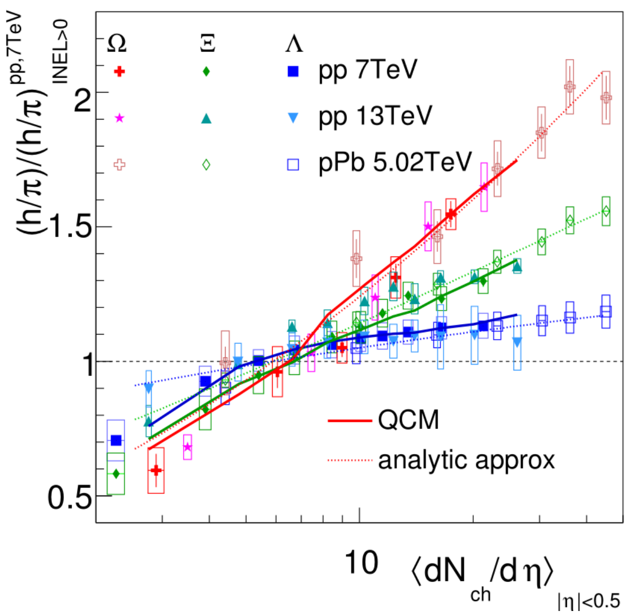


QCM in pp collisions at 13 TeV

Zhang,Shao,Song,arXiv:1811.00975





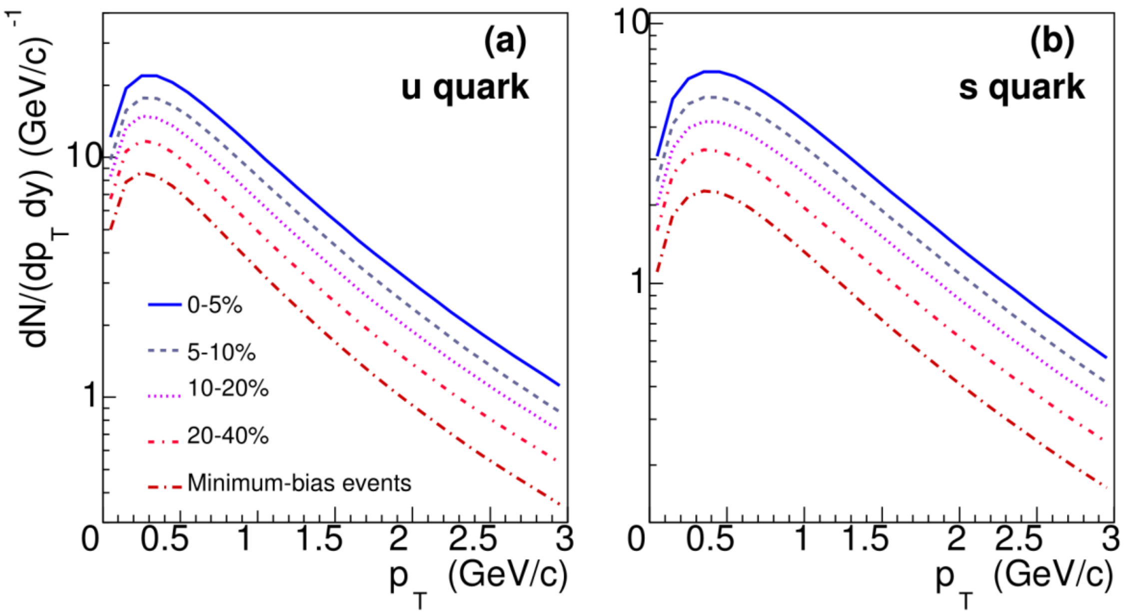


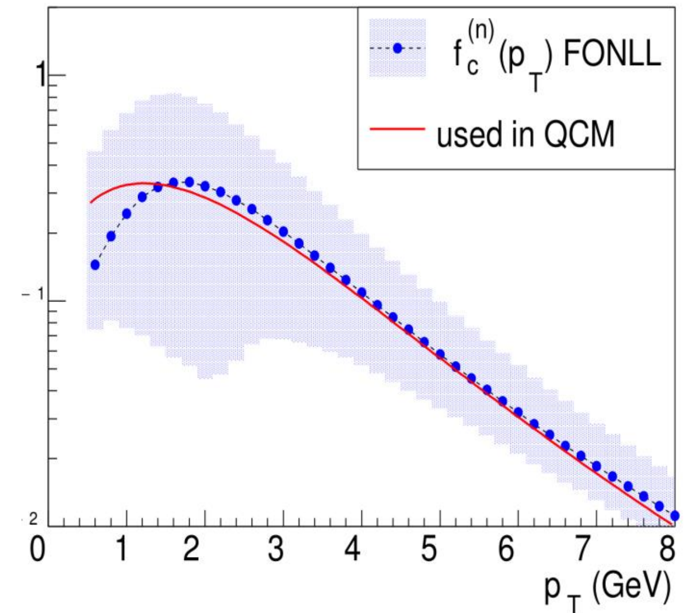
Production of single-charm hadrons in pp and p-Pb collisions at LHC

Song, Li, Shao, Eur.Phys.J. C78 (2018) 344
Li, Shao,Song, PRC97(2018), 064915

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

Quark spectra at hadronization





got from light-flavor hadrons

consistent with pQCD calculations

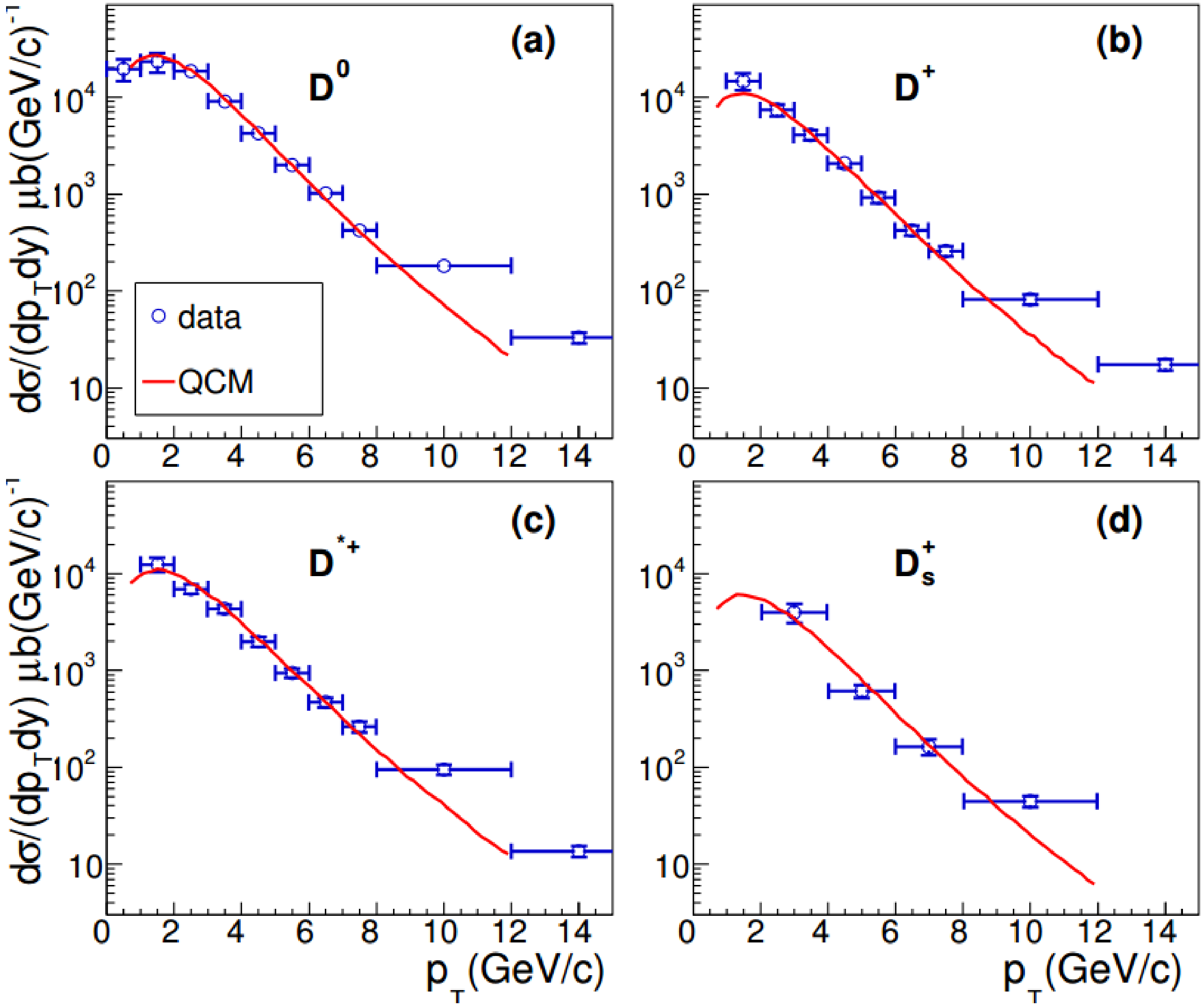
Parameters in the model:

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

Song, Li, Shao, Eur.Phys.J. C78 (2018) 344
Li, Shao,Song, PRC97(2018), 064915

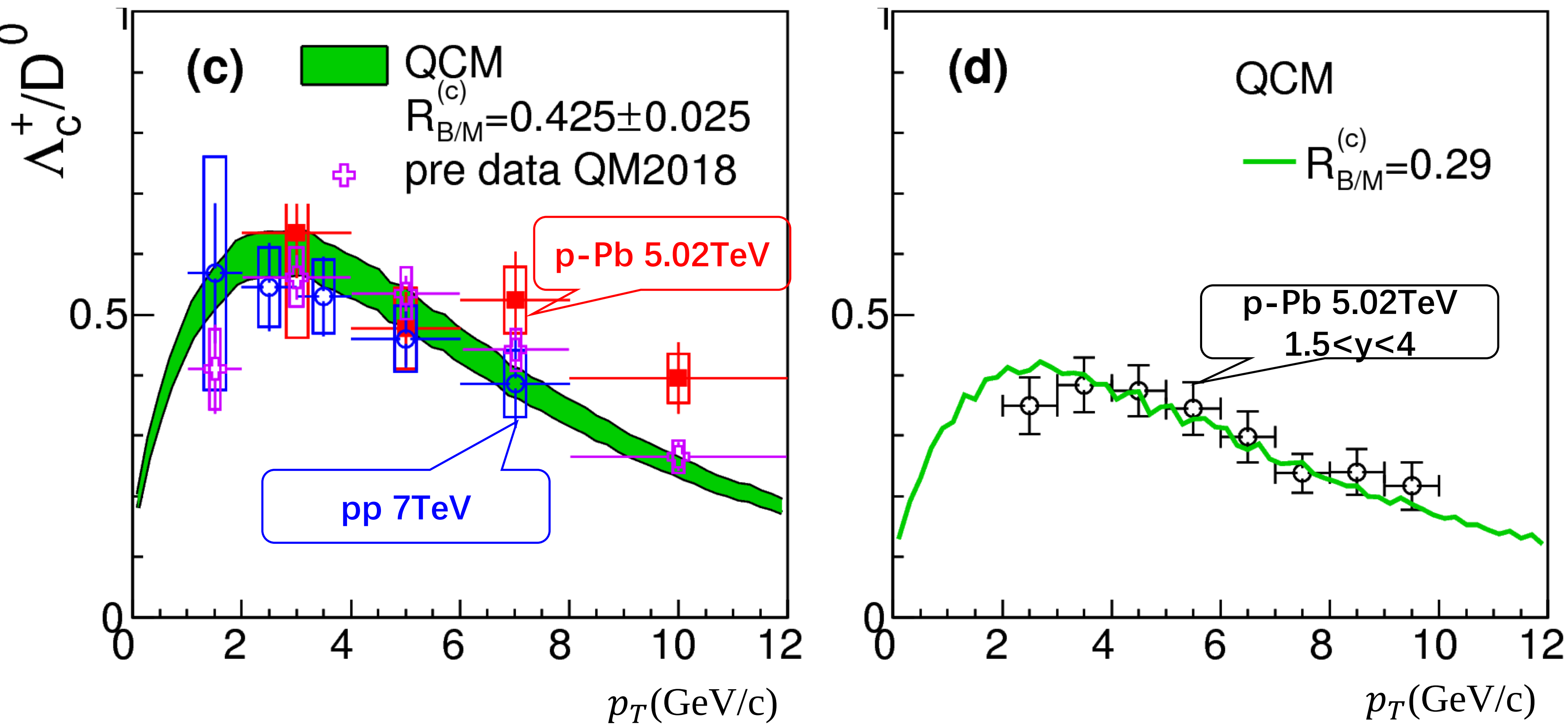
D mesons of $p_T \lesssim 8$ GeV,

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



Song, Li, Shao, Eur.Phys.J. C78 (2018) 344
Li, Shao,Song, PRC97(2018), 064915

p_T dependence of charmed Baryon/Meson ratio



Summary

We show that in pp and p-Pb collisions at LHC energies

① data for p_T spectra Ω and ϕ exhibit the constituent quark number scaling property,

② Equal velocity combination of light-flavor quarks successfully explain p_T spectra of light-flavor hadrons

③ Equal velocity combination of charm quark and light-flavor quark successfully explain data of D mesons and Λ_c baryon,

- **clear signals of quark combination mechanism at hadronization**

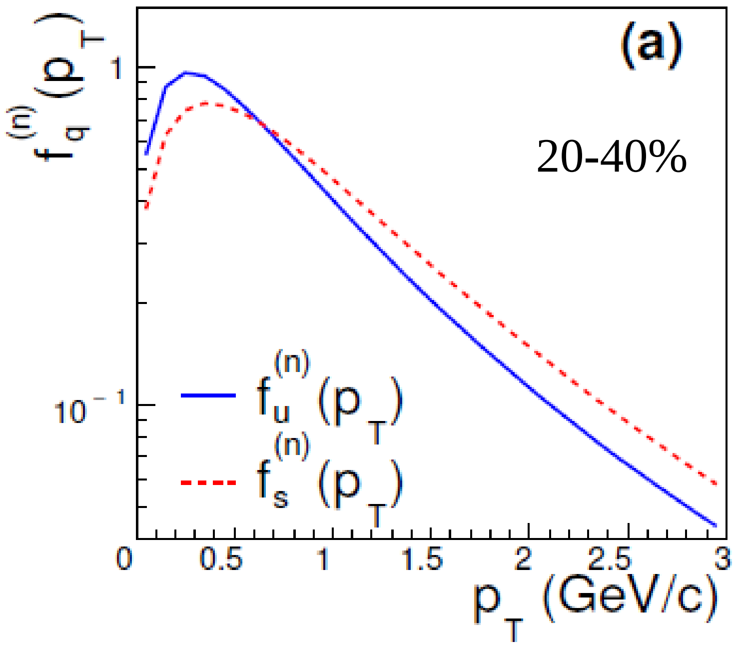
Our results further suggest that

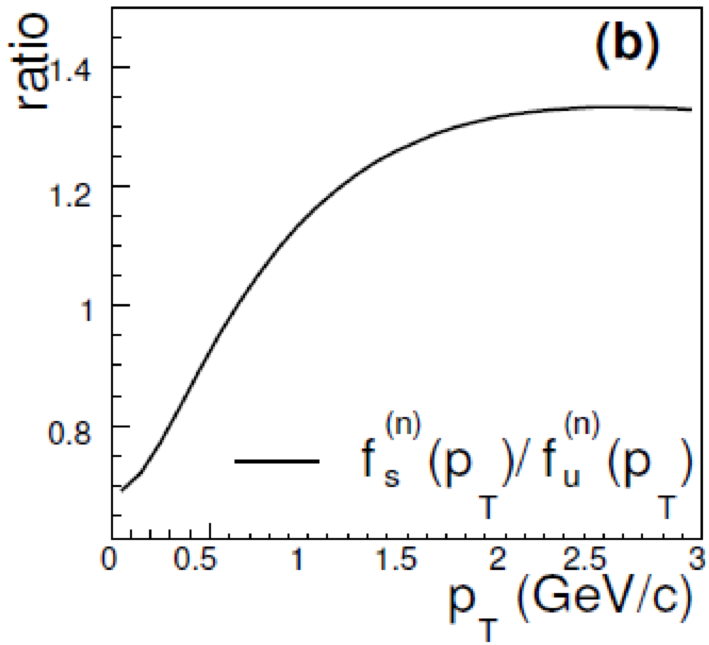
- constituent quark degrees of freedom (CQdof) play important role in the production of hadrons in small quark/parton systems created in pp and p-Pb collisions at LHC.
- It should be incorporated in developing more sophisticated hadronization model

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

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

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

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

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

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

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 $\boldsymbol{x_i = m_i/\sum_j m_j}$,
denote $\boldsymbol{\frac{x_u}{x_s} = \frac{m_u}{m_s} = r}$

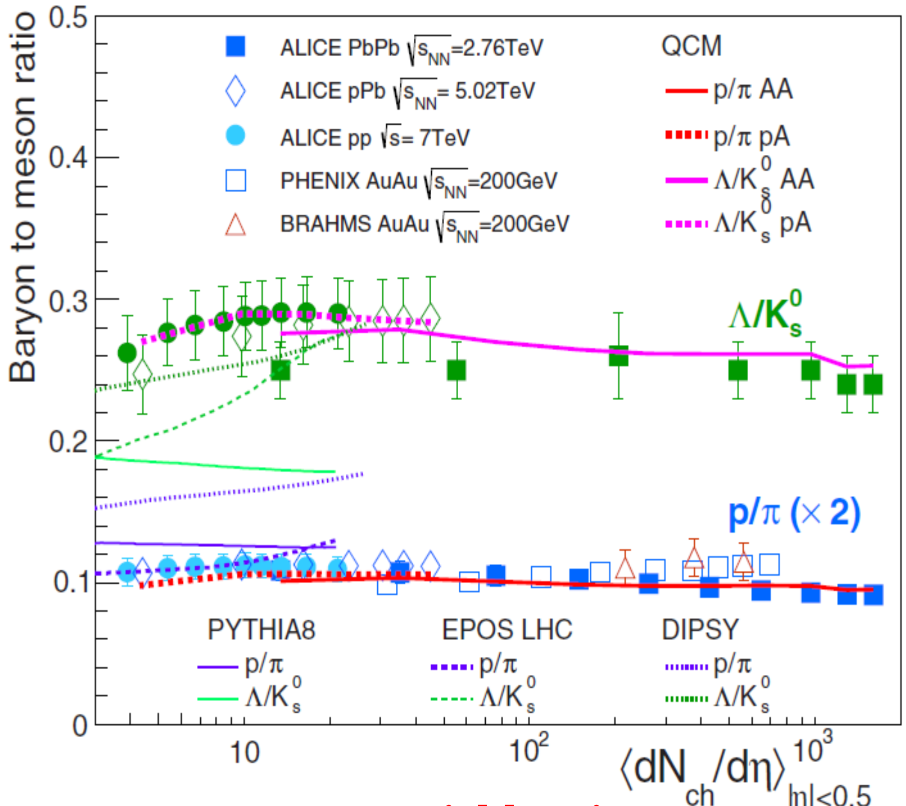
$$f_{\Xi^{*0}}\big((2+r)p_T\big) = \kappa_{\Xi^{*0}}\, f_s^2(p_T) f_u(r\, p_T)$$
$$f_{K^{*0}}\big((1+r)p_T\big) = \kappa_{K^{*0}}\, f_s(p_T) f_{\bar{d}}(r\, p_T)$$

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

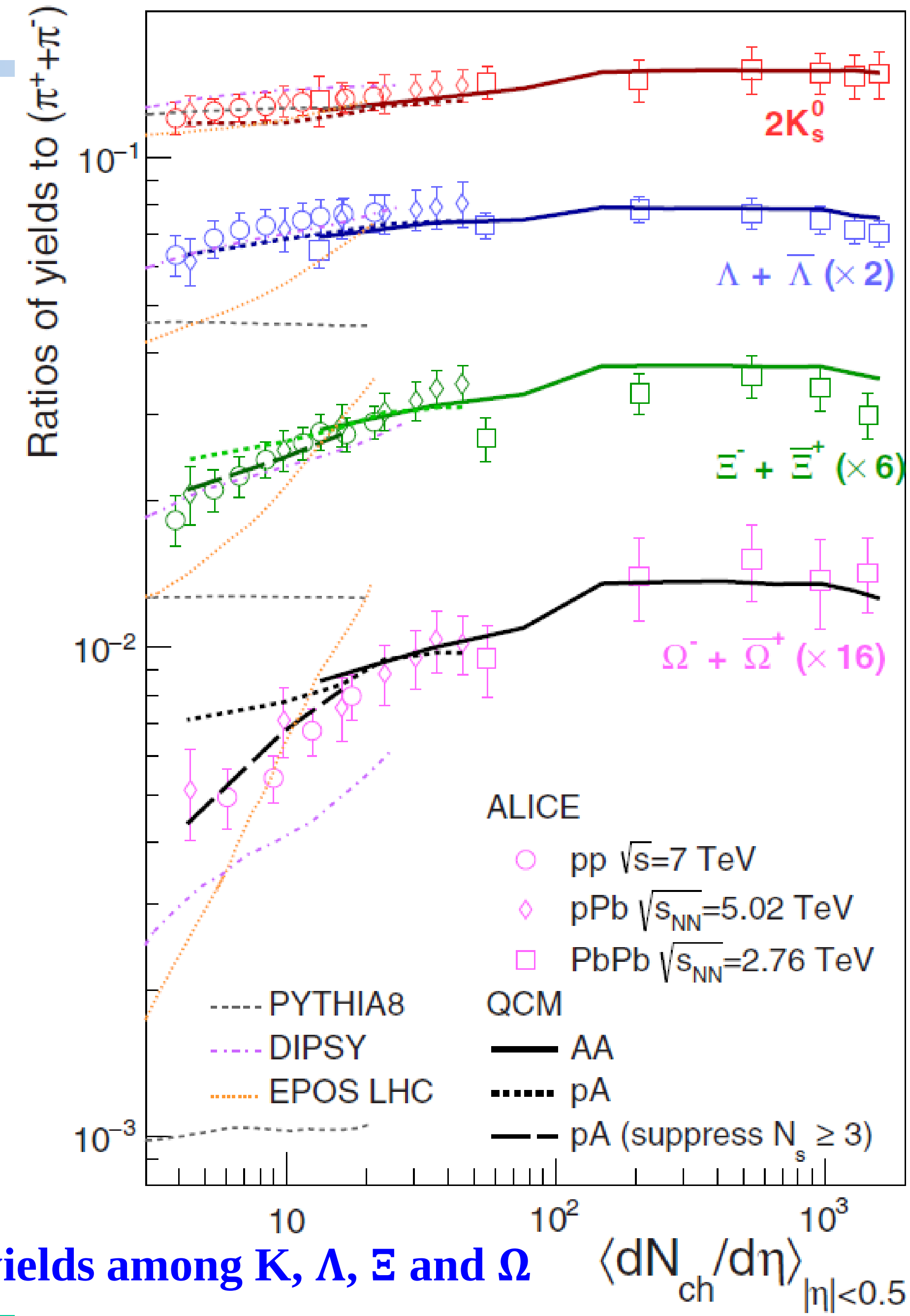
$r \approx 2/3$ if we take $m_s = 500 - 550$ MeV and $m_u = m_d = 330$ MeV.

SFL,SJ, 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