Hadron production in pp and pPb collisions at LHC energies

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outline

1. **Hadronization && phenomenological models**
2. **Quark Number Scaling (QNS) property in production of light-flavor hadrons**
3. **EVC mechanism of constituent quarks**
4. **Systematic explanation of p_T spectra of light-flavor hadrons**
5. **EVC explanation of v_2 of hadrons**
6. **EVC mechanism of charm hadron production**
7. **Understand parton system before hadronization**
8. **Summary**

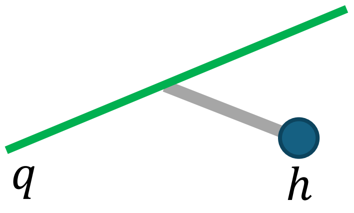
1. Hadronization

- **the process of the formation of hadrons out of final-state quarks and/or gluons produced in high energy reactions**
- **Non-perturbative QCD process**
- **Currently modeled and/or parameterized in phenomenological methods.**

Two pictures:

Fragmentation

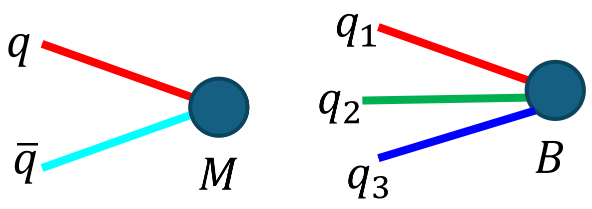
String fragmentation,
cluster fragmentation,
etc.



Probability $D_{q\to h}(z)$

Combination

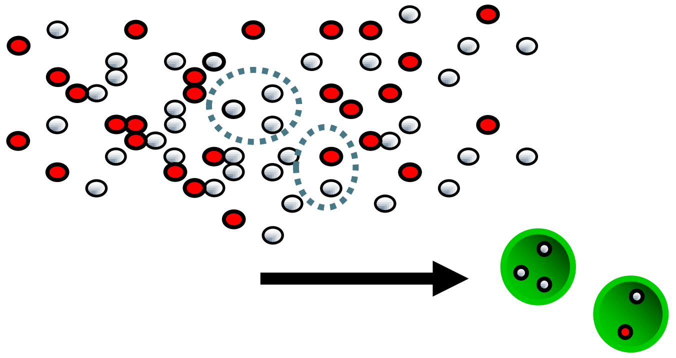
quark (re-)combination,
parton coalescence,
etc.



Combination models on market

- **quark recombination model**
  R. J. Fries, B. Muller, C. Nonaka, S. A. Bass,
  e.g., Phys. Rev. C **68**, 044902 (2003)
- **parton coalescence model**
  V. Greco, C. M. Ko, P. Lévai, L.W. Chen, et al.
  e.g., Phys. Rev. C **68**, 034904 (2003)
- **quark recombination model**
  R. C. Hwa and C. B. Yang, e.g, Phys. Rev. C **70**, 024904 (2004)
- **resonance recombination model**
  L. Ravagli, R. Rapp, e.g., Phys.Lett. B 655,126 (2007)
  M. He, R.J. Fries, R. Rapp, e.g., Phys.Rev.C 82, 034907 (2010)
- **quark combination model (Shandong Group)**
  Q.B.Xie, F.L.Shao, et al., e.g., Phys. Rev. C71,044903 (2005)
  phenomenological combine rule
- **transport model**
  P.F.Zhuang, et al, e.g., Phys. Rev. C76, 014907(2009)
- **quark molecular dynamics model**
  M. Hofmann et al, e.g., Nucl. Phys. B 478,161(2000)
- **variational model**
  A.Alala, etal, e.g., Phys. Rev. C77,044901(2009)

….



which kind of quarks?

how to combine?

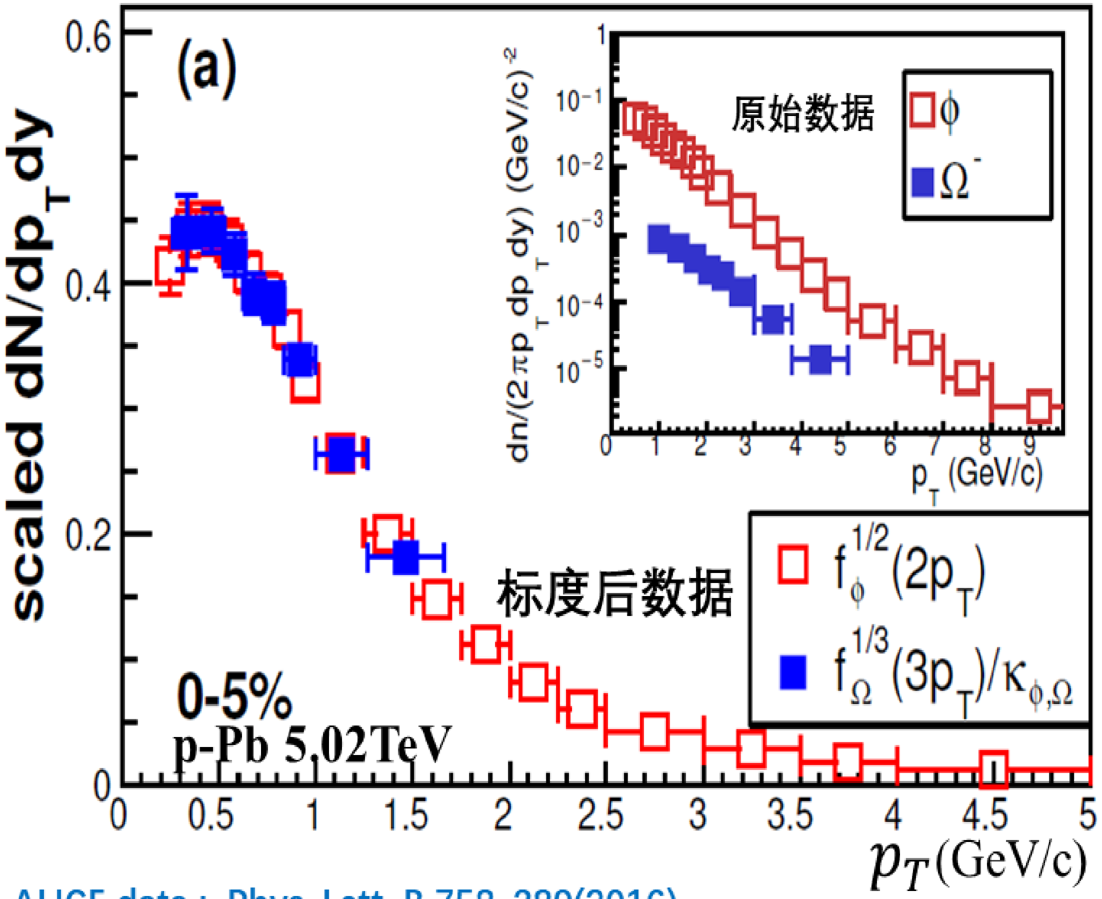
how to test in experiments?

2.

Quark Number Scaling (QNS) property in p_T spectra of hadrons in pp and p-Pb collisions at LHC

Refs:

- Jun Song, Hai-hong Li, and Feng-lan Shao, Phys. Rev. D105, 074027 (2022).
- Hai-hong Li, Feng-lan Shao, and Jun Song, Chin. Phys. C 45, 113105 (2021).
- Jian-wei Zhang, Hai-hong Li, Feng-lan Shao, and Jun Song, Chin.Phys. C44, 014101(2020).
- Jun Song, Xing-rui Gou, Feng-lan Shao, Zuo-tang Liang, Phys. Lett. B774, 516(2017).
- Xing-rui Gou, Feng-lan Shao, Rui-qin Wang, Hai-hong Li, Jun Song, Phys. Rev. D96,094010(2017).



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

QNS formula

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

another form

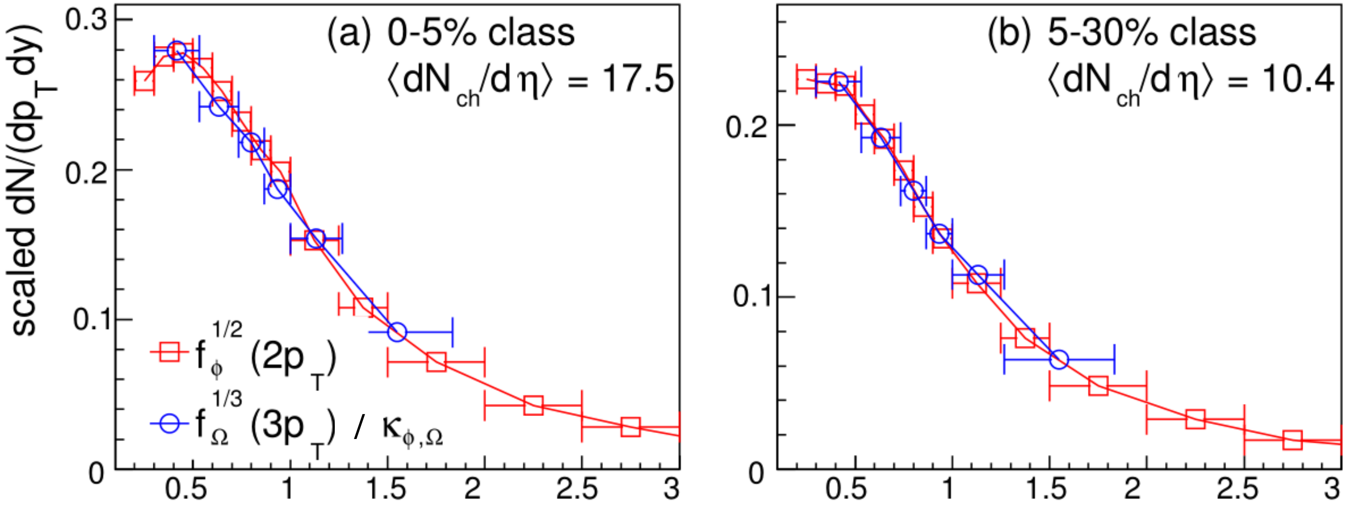
$$f_\Omega(3p_T) = \kappa_\Omega f_s^3(p_T)$$

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

$$f(p_T) \equiv dN_h/dp_T dy$$

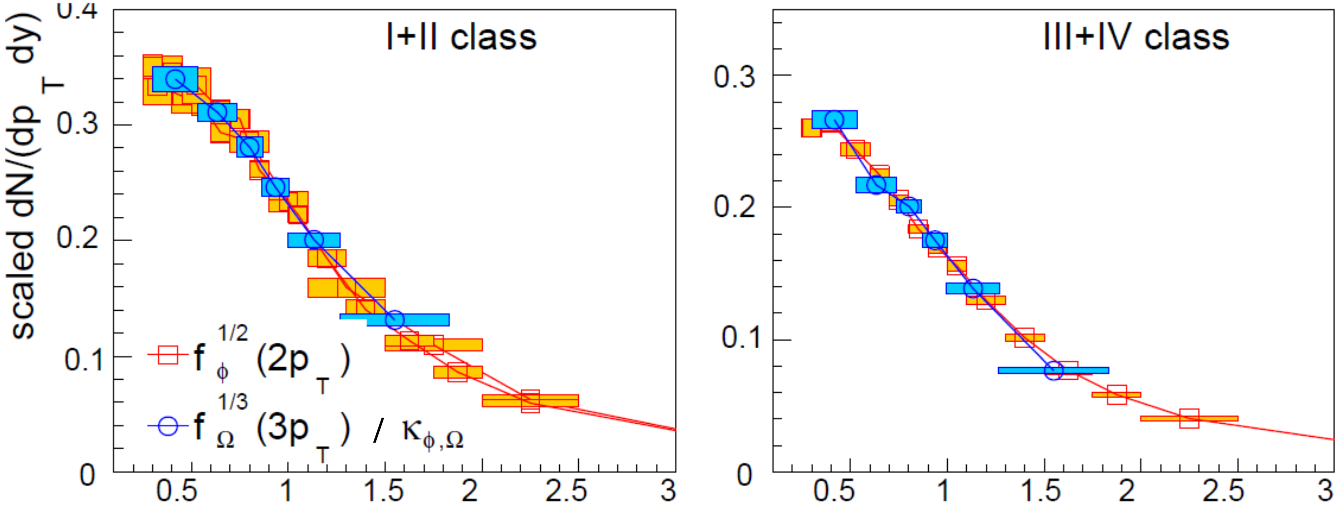
κ_ϕ, κ_Ω, $\kappa_{\phi,\Omega}$ are independent of p_T

Gou,Shao,Song…, Phy.Rev.D96, 094010(2017)



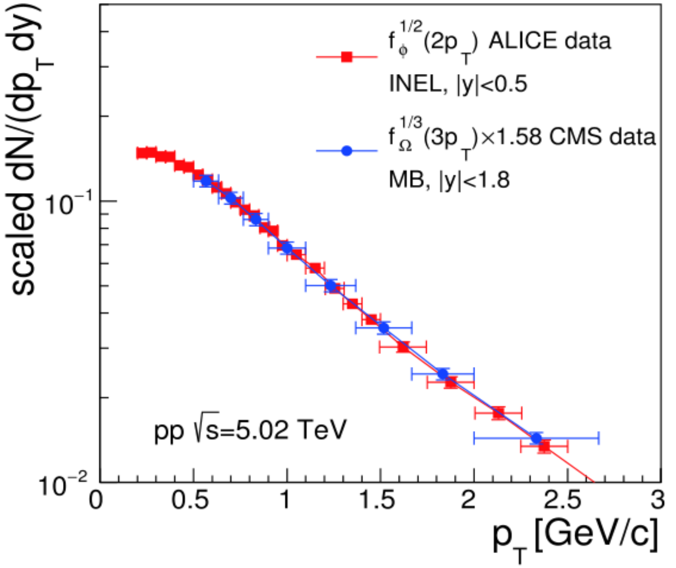
pp at $\sqrt{s}$ =7TeV

Zhang,Shao,Song, Chin.Phys. C44, 014101(2020)



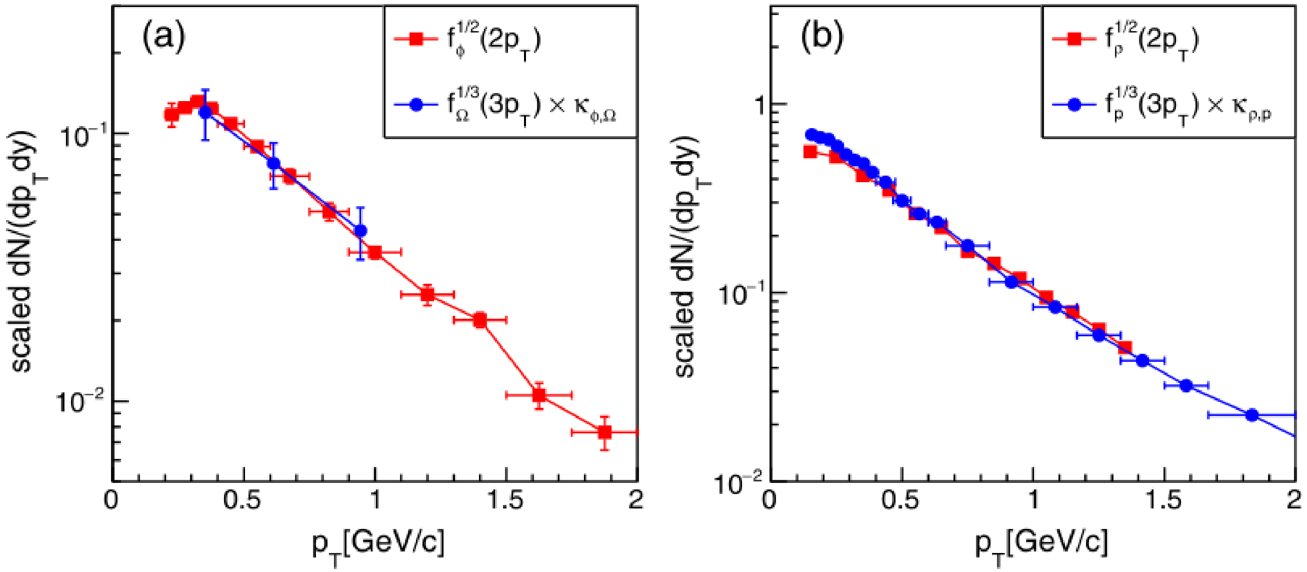
pp at $\sqrt{s}$ =13TeV

Li, Shao, Song, Chin. Phys. C 45, 113105 (2021)



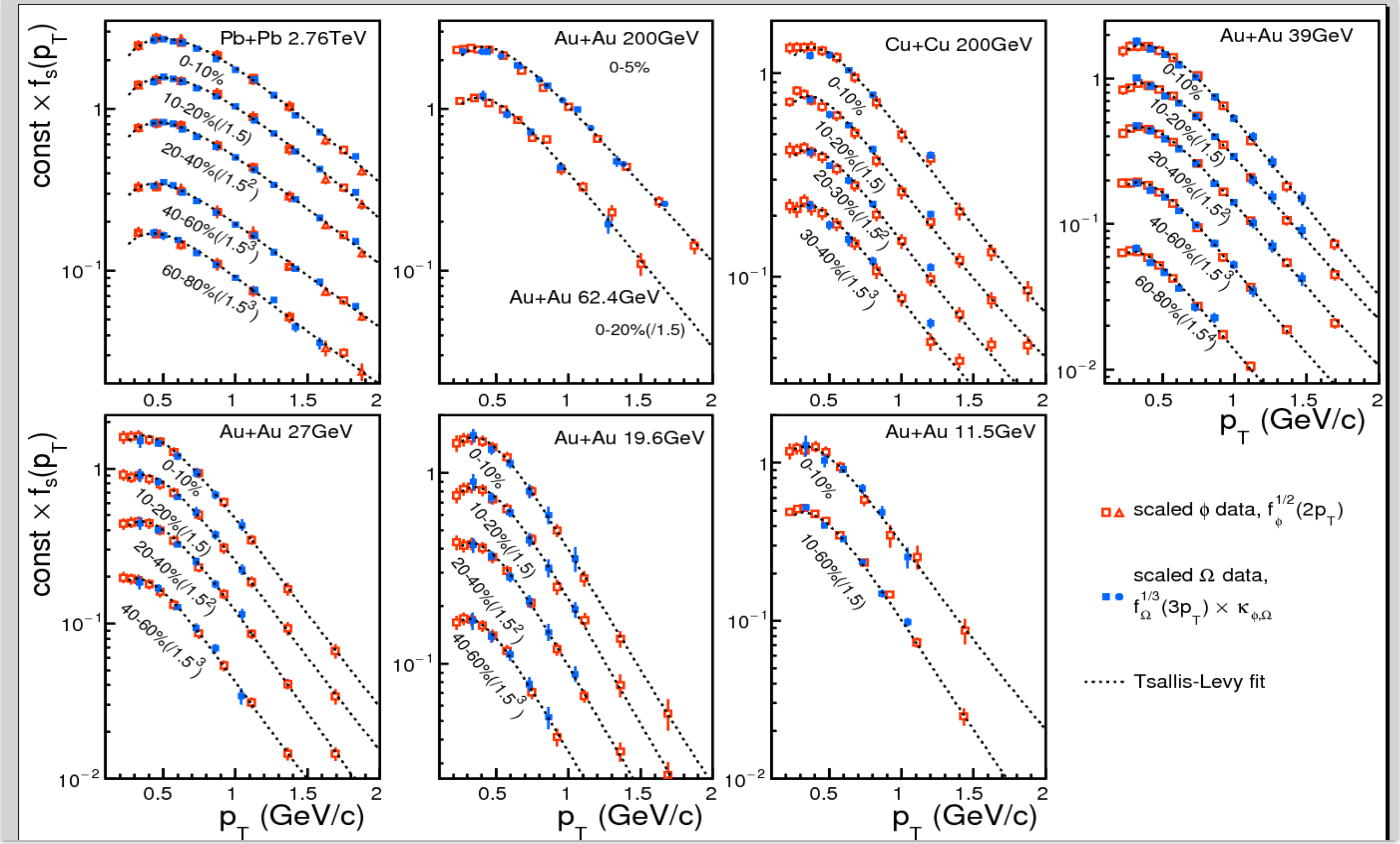
pp at $\sqrt{s}$ =5.02TeV

Song, Li, Shao, PRD105, 074027 (2022)



pp at $\sqrt{s}$ =200 GeV

QNS in heavy-ion collisions



3.

Equal-Velocity Combination (EVC) of constituent quarks and antiquarks at hadronization

Refs:

- Jun Song, Xing-rui Gou, Feng-lan Shao, Zuo-tang Liang, Phys. Lett. B774, 516(2017).
- Xing-rui Gou, Feng-lan Shao, Rui-qin Wang, Hai-hong Li, Jun Song, Phys. Rev. D96,094010(2017).
- Jun Song, Hai-hong Li, and Feng-lan Shao, Eur. Phys. J. C 78:344 (2018).
- Hai-hong Li, Feng-lan Shao, and Jun Song, Phys. Rev. C 97, 064915 (2018).

Start from general formula in momentum space

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

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

Assume independent distribution of (anti-)quarks

$$f_{q_1 q_2 q_3}(p_1, p_2, p_3) = f_{q_1}(p_1) f_{q_2}(p_2) f_{q_3}(p_3)$$

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

equal velocity combination (EVC) approximation

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

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

Constituent quark model of hadron

momentum fraction

meson $x_{1,2} = \frac{m_{1,2}}{m_1 + m_2}$, baryon $x_{1,2,3} = \frac{m_{1,2,3}}{m_1 + m_2 + m_3}$

$m_s = 500$ MeV, $m_u = m_d = 330$ MeV.

We obtain

$$f_{B_j}(p_B) = \kappa_{B_j} f_{q_1}(x_1 p_B) f_{q_2}(x_2 p_B) f_{q_3}(x_3 p_B)$$

$$f_{M_j}(p_M) = \kappa_{M_j} f_{q_1}(x_1 p_M) f_{\bar{q}_2}(x_2 p_M)$$

The combination of $\boldsymbol{s}$ and $\boldsymbol{\bar{s}}$

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

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

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

$f_s(p_T) = f_{\bar{s}}(p_T)$ is taken at LHC

The combination of $\boldsymbol{u(d)}$ and $\boldsymbol{s}$, denote $\boldsymbol{\frac{x_u}{x_s} = \frac{m_u}{m_s} = r}$

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

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

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

Consider stochastic combination and flavor-blind of strong interaction

$$\frac{\kappa_{M_j}}{A_{M_j}} = C_{M_j} P_{q\bar{q}\to M}$$
$$\frac{\kappa_{B_j}}{A_{B_j}} = C_{B_j} N_{iter} P_{qqq\to B}$$

$A_{B_j} = 1/\int dp_T \prod_{i=1}^{3} f_{q_i}^{(n)}(x_i p_T)$, $A_{M_j} = 1/\int dp_T f_{q_1}^{(n)}(x_1 p_T) f_{\bar{q}_2}^{(n)}(x_2 p_T)$ are normalization coefficients of jointed quark distributions.

$P_{q\bar{q}\to M} \approx \frac{2}{x(1-z^2)}\left[1 - z\frac{(1+z)^a+(1+z)^a}{(1+z)^a-(1+z)^a}\right]$, averaged probability of $q\bar{q} \to M$

$P_{qqq\to B} \approx \frac{8}{3x^2(1+z)^3}\frac{(1+z)^a}{(1+z)^a-(1+z)^a}$, averaged probability of $qqq \to B$

Song,Shao, PRC 88, 027901(2013)

N_{iter}=1,3,6 for three identical, two identical and three different flavors

$x = N_q + N_{\bar{q}}$, $z = (N_q - N_{\bar{q}})/x$, $a = 1 + \frac{1}{3}\left(\overline{N}_M/\overline{N}_B\right)_{z=0} \approx 4.86 \pm 0.1$ for light-flavor sector

N_q number of all quarks; $N_{\bar{q}}$ that of all antiquarks

C_{M_j} and C_{B_j} are fine-tune parameters

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

$R_{V/P} \approx 0.5$
$R_{O/D} \approx 2.0$

Include decay contributions

$$f_{h_j}^{(final)}(p) = f_{h_j}(p) + \sum_{i \neq j} \int dp' f_{h_i}(p') D_{ij}(p', p)$$

decay function $D_{ij}(p', p)$ is determined by the decay kinematics and decay branch ratios in PDG

Model inputs: $\boldsymbol{f_{q_i}(p)}$ **which are fixed by experimental data**

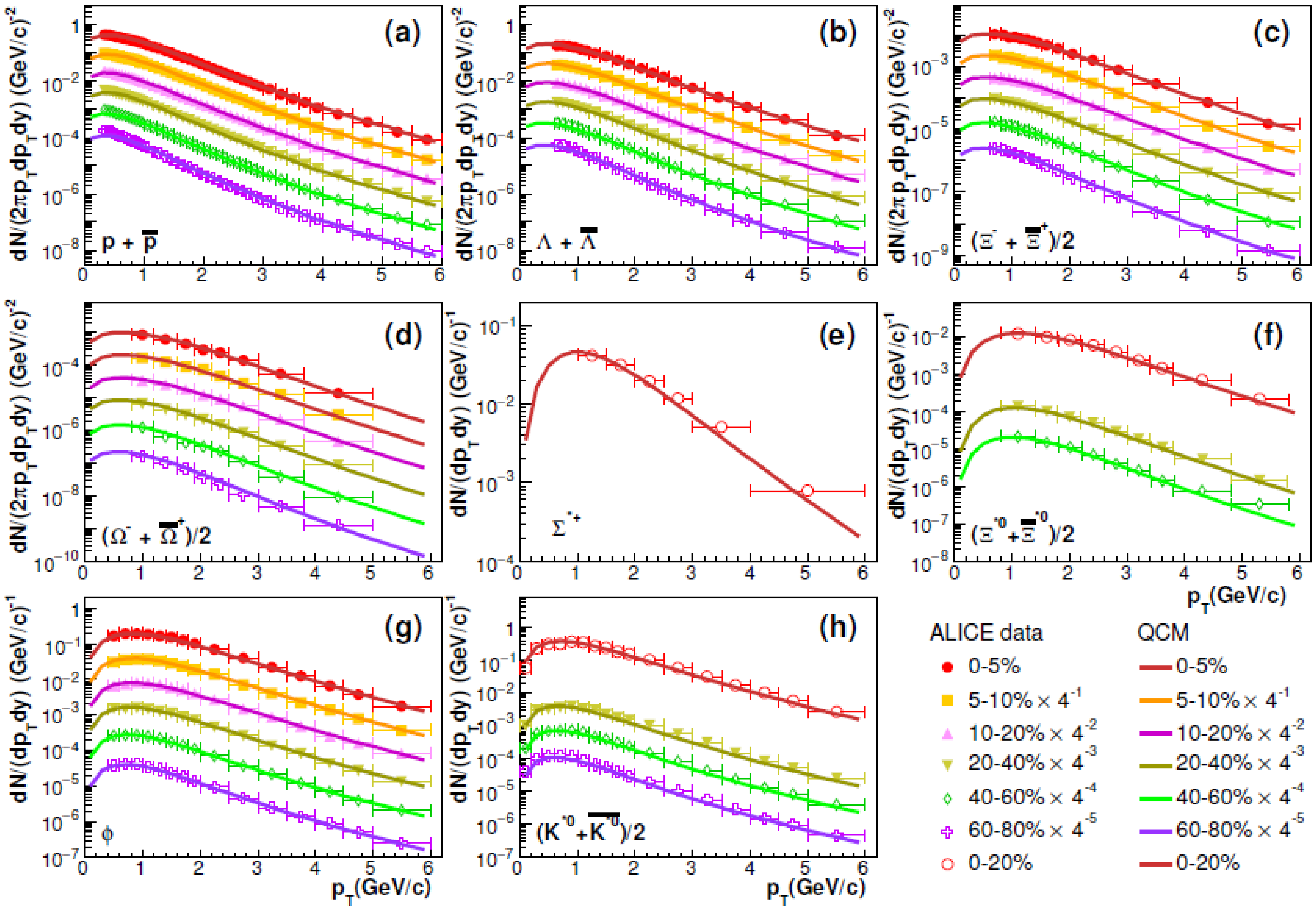
4.

Systematic explanation of p_T spectra of light-flavor hadrons

Refs:

- Jun Song, Hai-hong Li, and Feng-lan Shao, Phys. Rev. D105, 074027 (2022).
- Yan-ting Feng, Jun Song, and Feng-lan Shao, Phys. Rev. C106, 034910 (2022).
- Hai-hong Li, Feng-lan Shao, and Jun Song, Chin. Phys. C 45, 113105 (2021).
- Jian-wei Zhang, Hai-hong Li, Feng-lan Shao, and Jun Song, Chin.Phys. C44, 014101(2020).
- Jun Song, Xing-rui Gou, Feng-lan Shao, Zuo-tang Liang, Phys. Lett. B774, 516(2017).
- Xing-rui Gou, Feng-lan Shao, Rui-qin Wang, Hai-hong Li, Jun Song, Phys. Rev. D96,094010(2017).

p-Pb collisions at 5.02 TeV

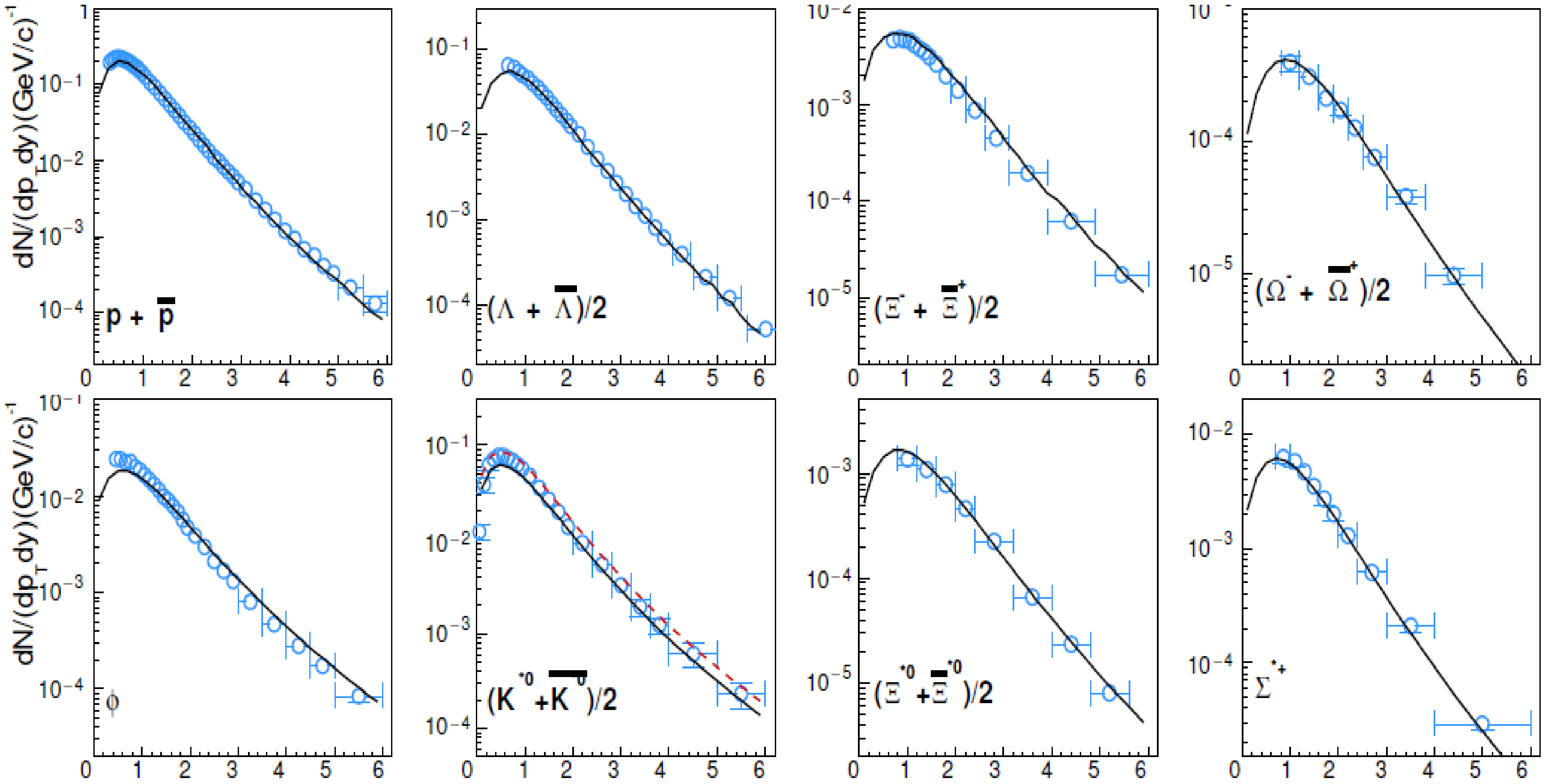


Two inputs:

$$f_u(p_T) = f_d(p_T) = f_{\bar{u}}(p_T) = f_{\bar{d}}(p_T)$$

$$f_s(p_T) = f_{\bar{s}}(p_T)$$

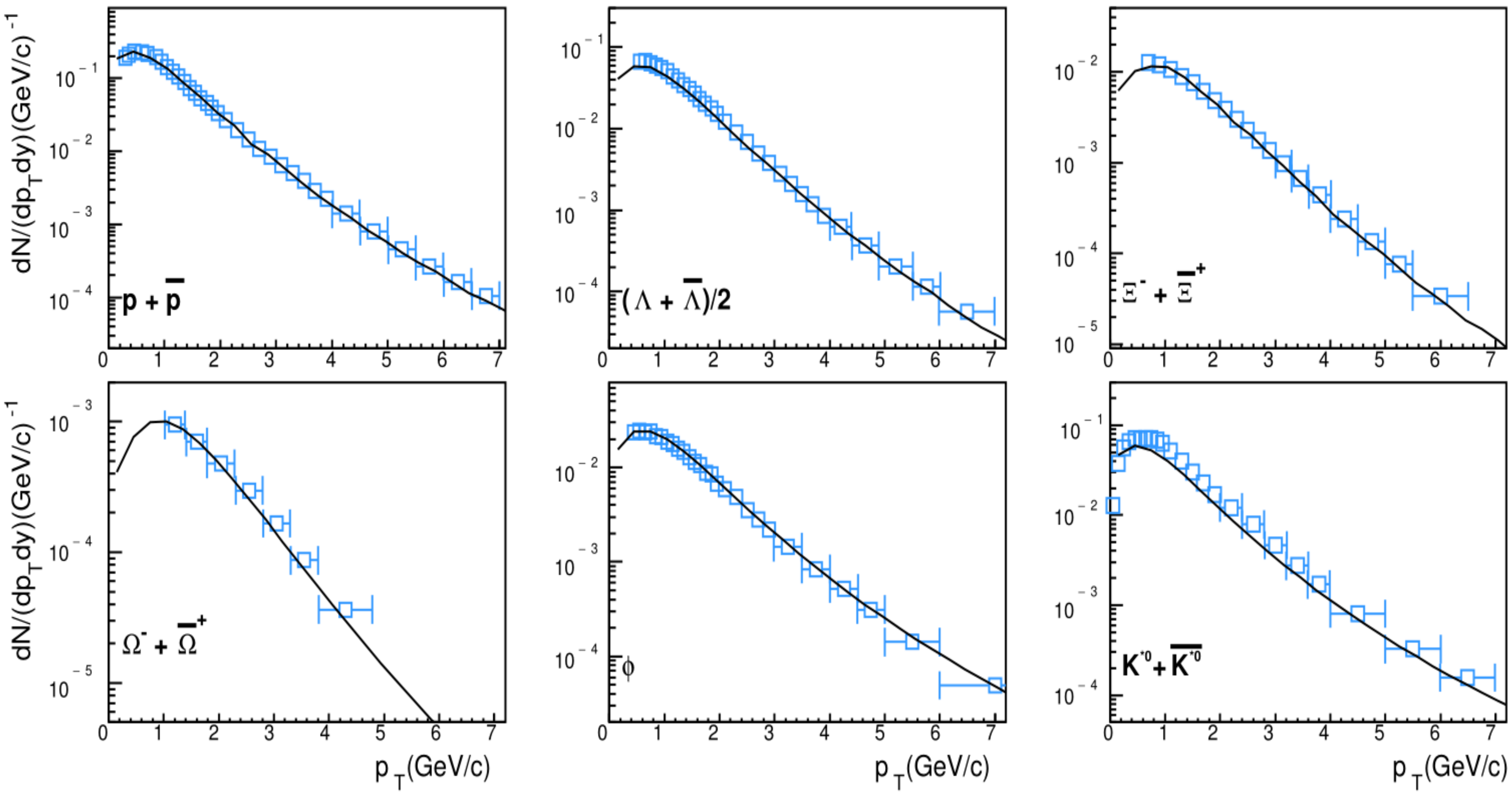
pp collisions at 7 TeV



Minimum bias events

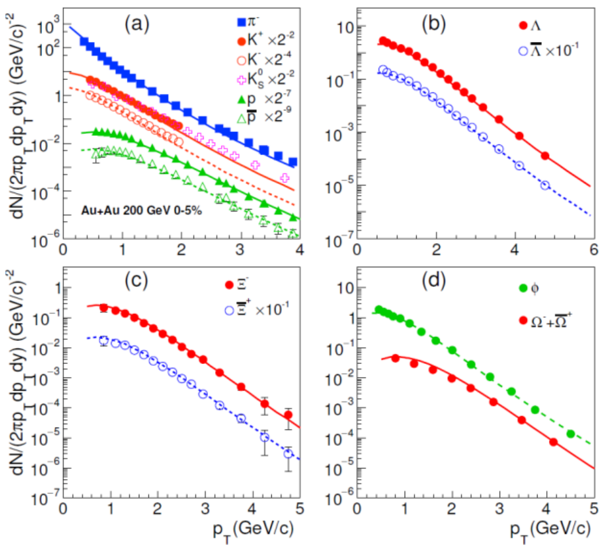
p_T(GeV/c)

pp collisions at 13 TeV

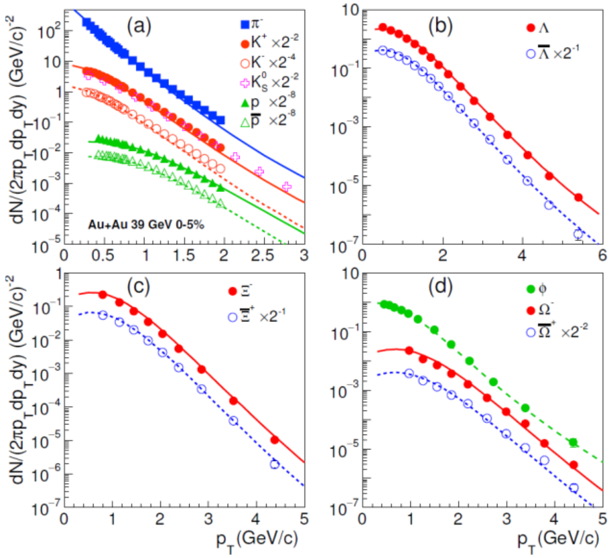


p_T spectra at STAR BES energies

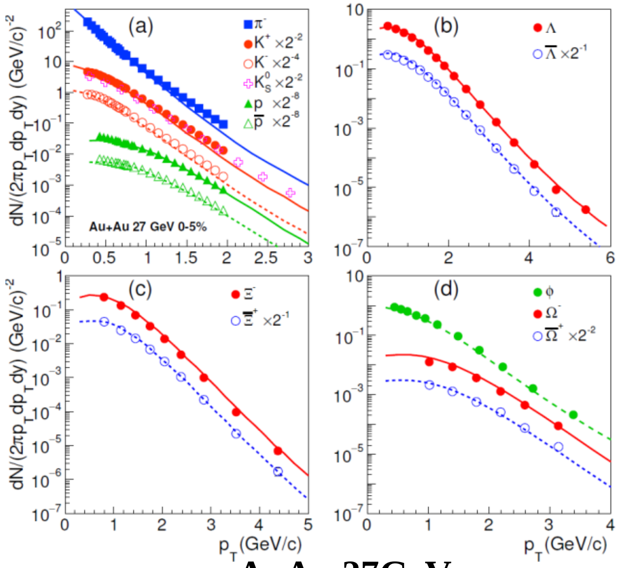
Song, Shao, et al., Phy.Rev.C103, 034907 (2021)



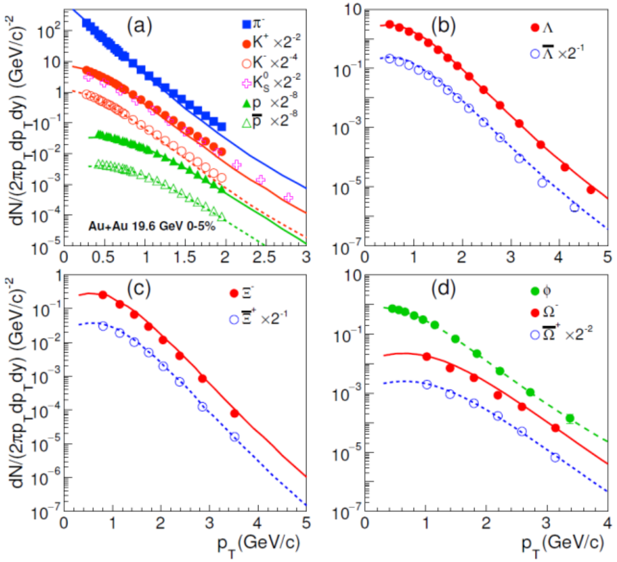
AuAu 200GeV



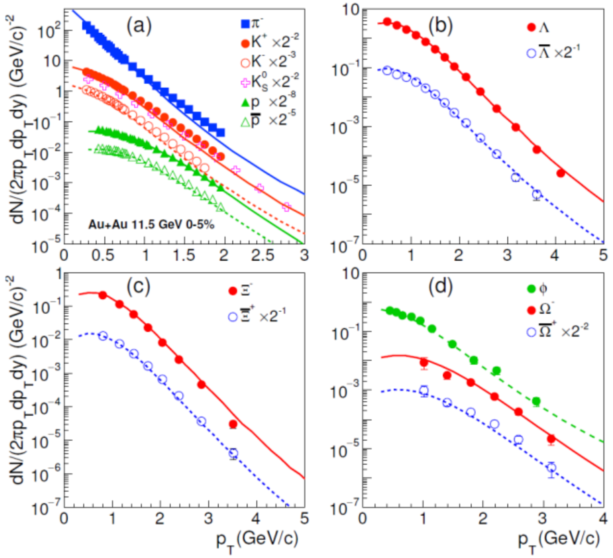
AuAu 39GeV



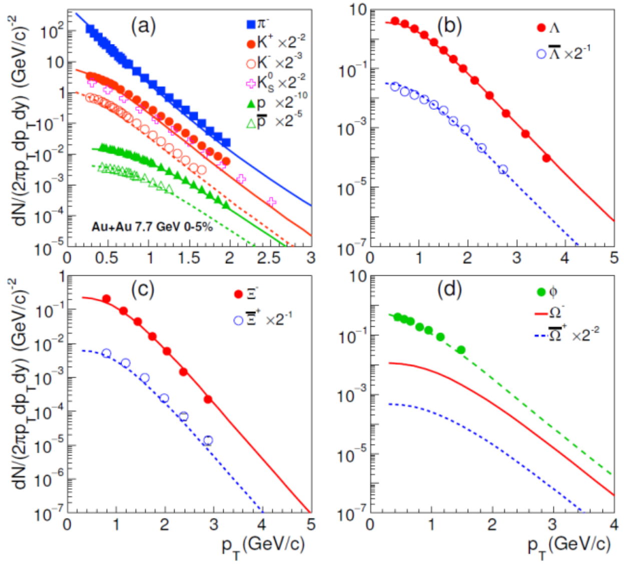
AuAu 27GeV



AuAu 19.6GeV



AuAu 11.5GeV

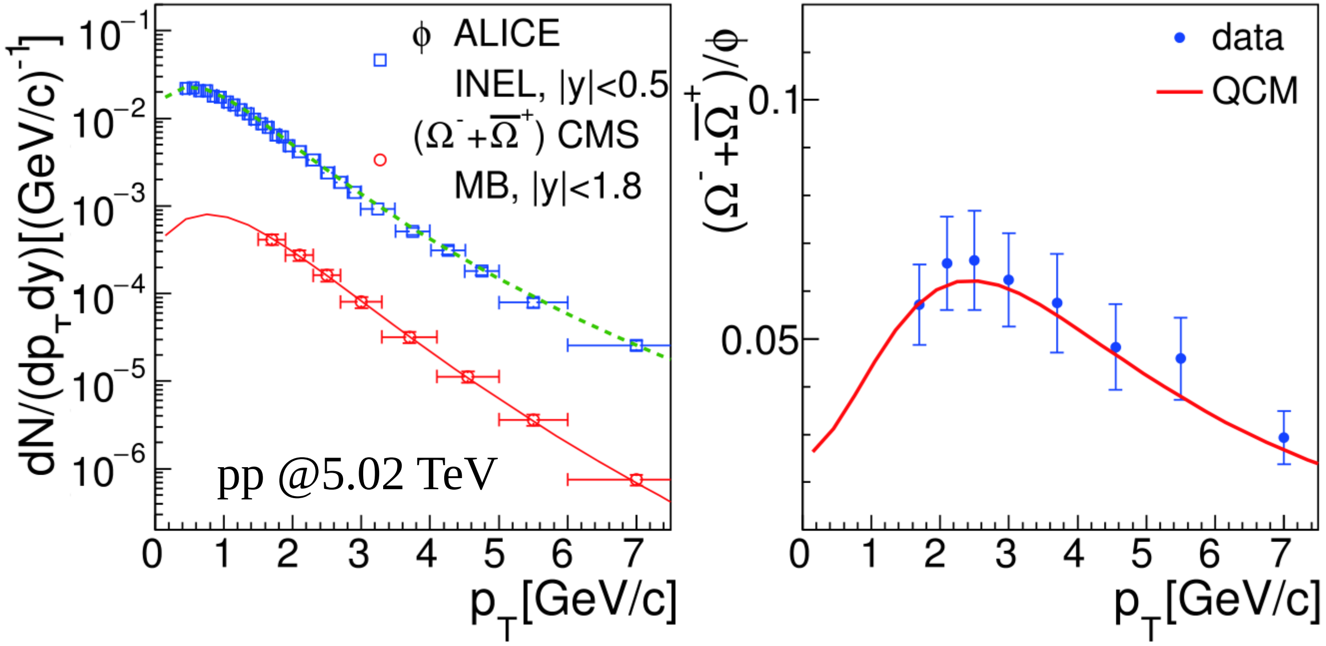


AuAu 7.7GeV

Three inputs $f_u(p_T) \approx f_d(p_T)$, $f_{\bar{u}}(p_T) \approx f_{\bar{d}}(p_T)$, $f_s(p_T) \approx f_{\bar{s}}(p_T)$ at each energy.

Analytical aspect of EVC :

Ω/ϕ ratio as the function of p_T



$$f_s(p_{T_s}) \sim \begin{cases} p_T \exp\left[-\frac{\sqrt{p_T^2+m^2}}{T}\right] & p_{T_s} \lesssim 1.0\frac{GeV}{c} \\ \left(1+\frac{p_T}{p_{T_0}}\right)^{-n} & p_{T_s} \gtrsim 1.0\frac{GeV}{c} \end{cases}$$

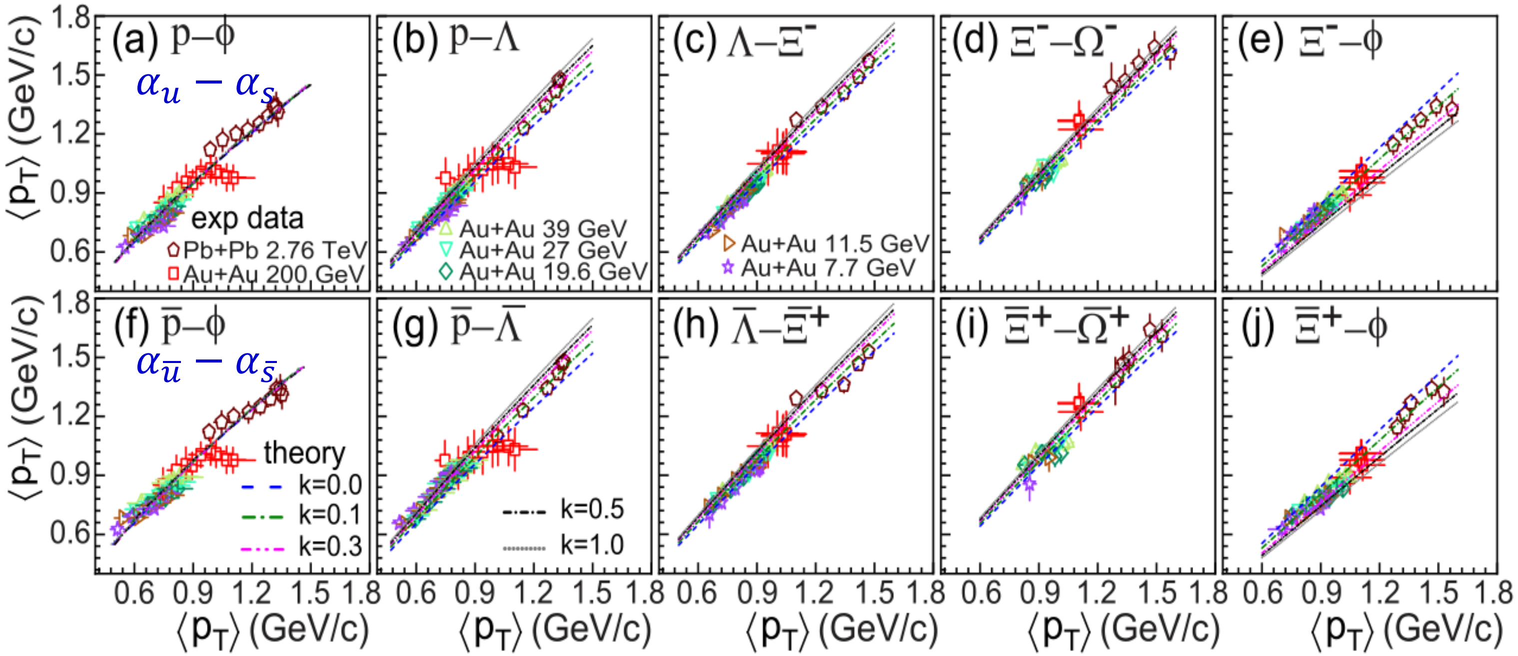
$$[\ln f_s(\xi)]'' \sim \begin{cases} <0 & p_{T_s} \lesssim 1.0 GeV/c \\ >0 & p_{T_s} \gtrsim 1.0 GeV/c \end{cases}$$

$$\left[\ln\frac{\Omega}{\phi}(p_T)\right]' \sim \begin{cases} >0 & p_T \lesssim 2.5 GeV/c \\ <0 & p_T \gtrsim 2.5 GeV/c \end{cases}$$

$$\left[\boldsymbol{ln}\frac{\boldsymbol{\Omega}}{\boldsymbol{\phi}}(\boldsymbol{p_T})\right]' = -\frac{\mathbf{1}}{\mathbf{6}}[\ln \boldsymbol{f_s}(\boldsymbol{\xi})]'' \qquad \frac{p_T}{3} < \xi < \frac{p_T}{2}$$

Analytical aspect of EVC :

$\langle p_T \rangle$ correlation between two hadrons



Quark thermal distribution :

$$f_{q_i}(p_T) = N p_T^k e^{-\sqrt{p_T^2 + m_i^2}/T_i}$$

$$\langle p_T \rangle_M = \left(m_{q_1} + m_{\bar{q}_2}\right) \sqrt{\frac{2}{\alpha_M}} \frac{\Gamma(k+1)}{\Gamma(k+\frac{1}{2})} \frac{K_{k+\frac{3}{2}}(\alpha_M)}{K_{k+1}(\alpha_M)}$$

$$\langle p_T \rangle_B = \left(m_{q_1} + m_{q_2} + m_{q_3}\right) \sqrt{\frac{2}{\alpha_B}} \frac{\Gamma(\frac{3k}{2}+1)}{\Gamma(\frac{3k}{2}+\frac{1}{2})} \frac{K_{\frac{3k}{2}+\frac{3}{2}}(\alpha_B)}{K_{\frac{3k}{2}+1}(\alpha_B)}$$

$$\alpha_M = \frac{m_{q_1}}{T_1} + \frac{m_{\bar{q}_2}}{T_2} = \alpha_{q_1} + \alpha_{\bar{q}_2}$$

$$\alpha_B = \alpha_{q_1} + \alpha_{q_2} + \alpha_{q_3}$$

5.

EVC explanation of v_2 of hadrons

Refs:

- Jun Song, Hai-hong Li, and Feng-lan Shao, Eur. Phys. J. C (2021) 81:5

Hadron v_2 as functions of quark v_2

$$v_{2,M_i}(p_T) = v_{2,q_1}(x_1 p_T) + v_{2,\bar{q}_2}(x_2 p_T),$$
$$v_{2,B_i}(p_T) = v_{2,q_1}(x_1 p_T) + v_{2,q_2}(x_2 p_T) + v_{2,q_3}(x_3 p_T).$$

$$v_{2,\Omega}(p_T) = 3v_{2,s}(p_T/3),$$
$$v_{2,p}(p_T) = 3v_{2,u}(p_T/3),$$
$$v_{2,\phi}(p_T) = v_{2,s}(p_T/2) + v_{2,\bar{s}}(p_T/2),$$
$$v_{2,\Lambda}(p_T) = 2v_{2,u}\left(\frac{1}{2+r}p_T\right) + v_{2,s}\left(\frac{r}{2+r}p_T\right),$$
$$v_{2,\Xi}(p_T) = v_{2,u}\left(\frac{1}{1+2r}p_T\right) + 2v_{2,s}\left(\frac{r}{1+2r}p_T\right)$$

$$r = \frac{x_s}{x_u} = \frac{m_s}{m_u}$$

quark v_2 in terms of hadron v_2

$$v_{2,u}(p_T) = \frac{1}{3} v_{2,p}(3p_T),$$

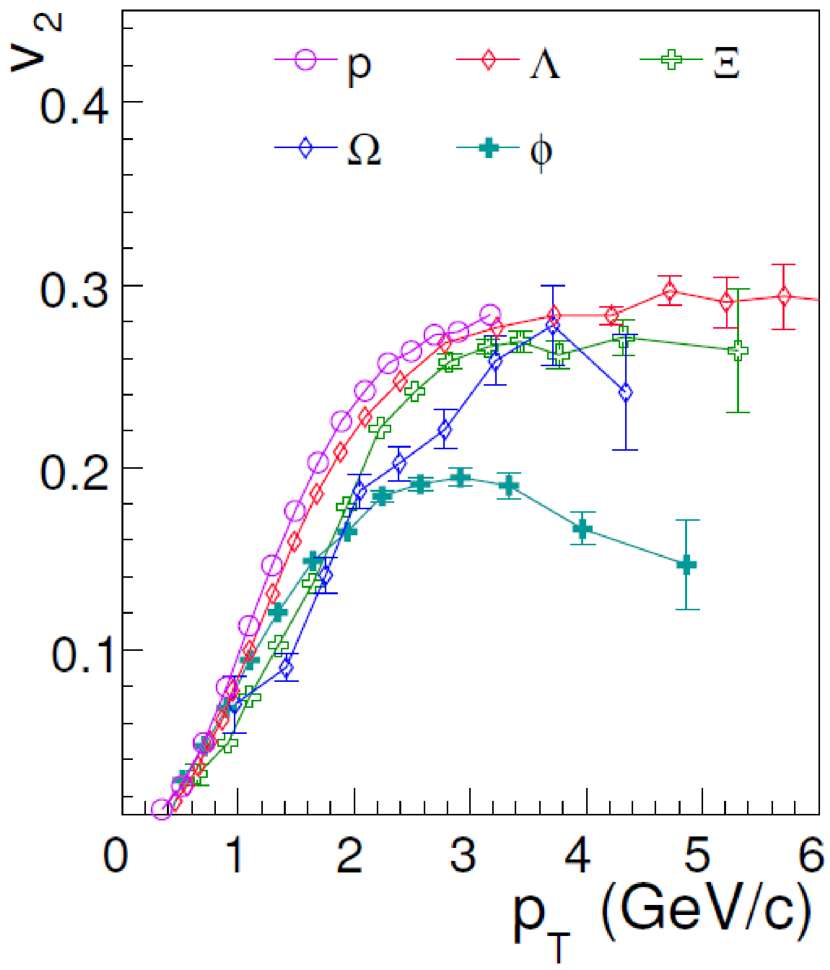
$$v_{2,u}(p_T) = \frac{1}{3}\left[2v_{2,\Lambda}((2+r)p_T) - v_{2,\Xi}((1+2r)p_T)\right],$$

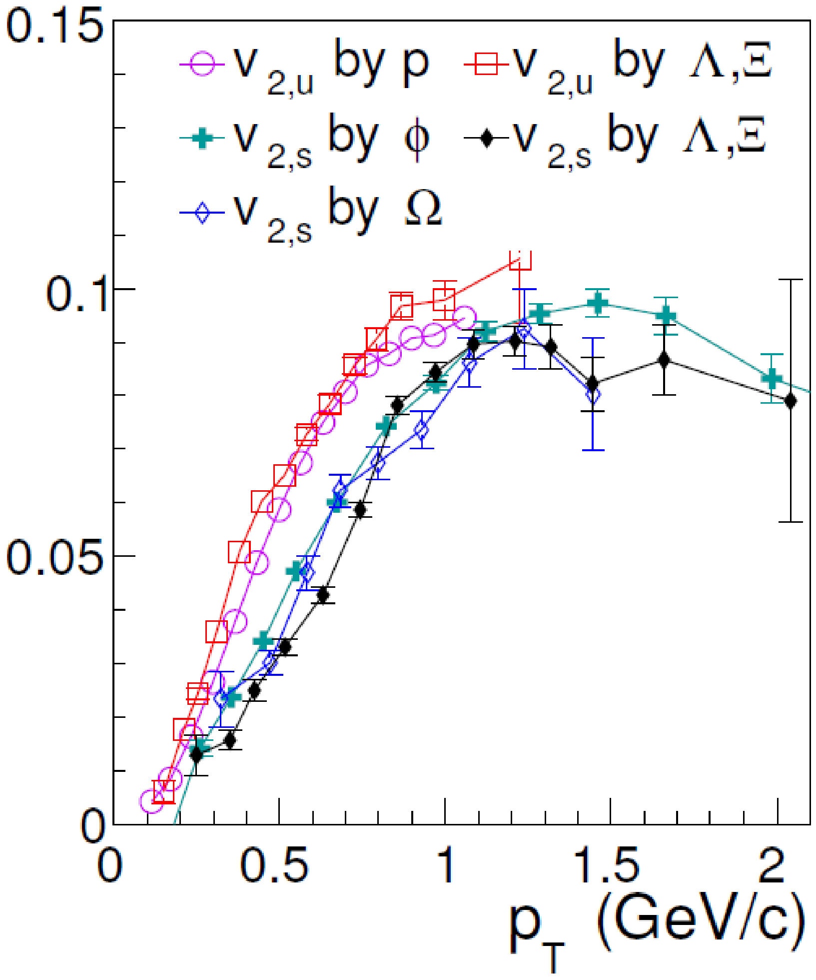
$$v_{2,s}(p_T) = \frac{1}{3} v_{2,\Omega}(3p_T),$$

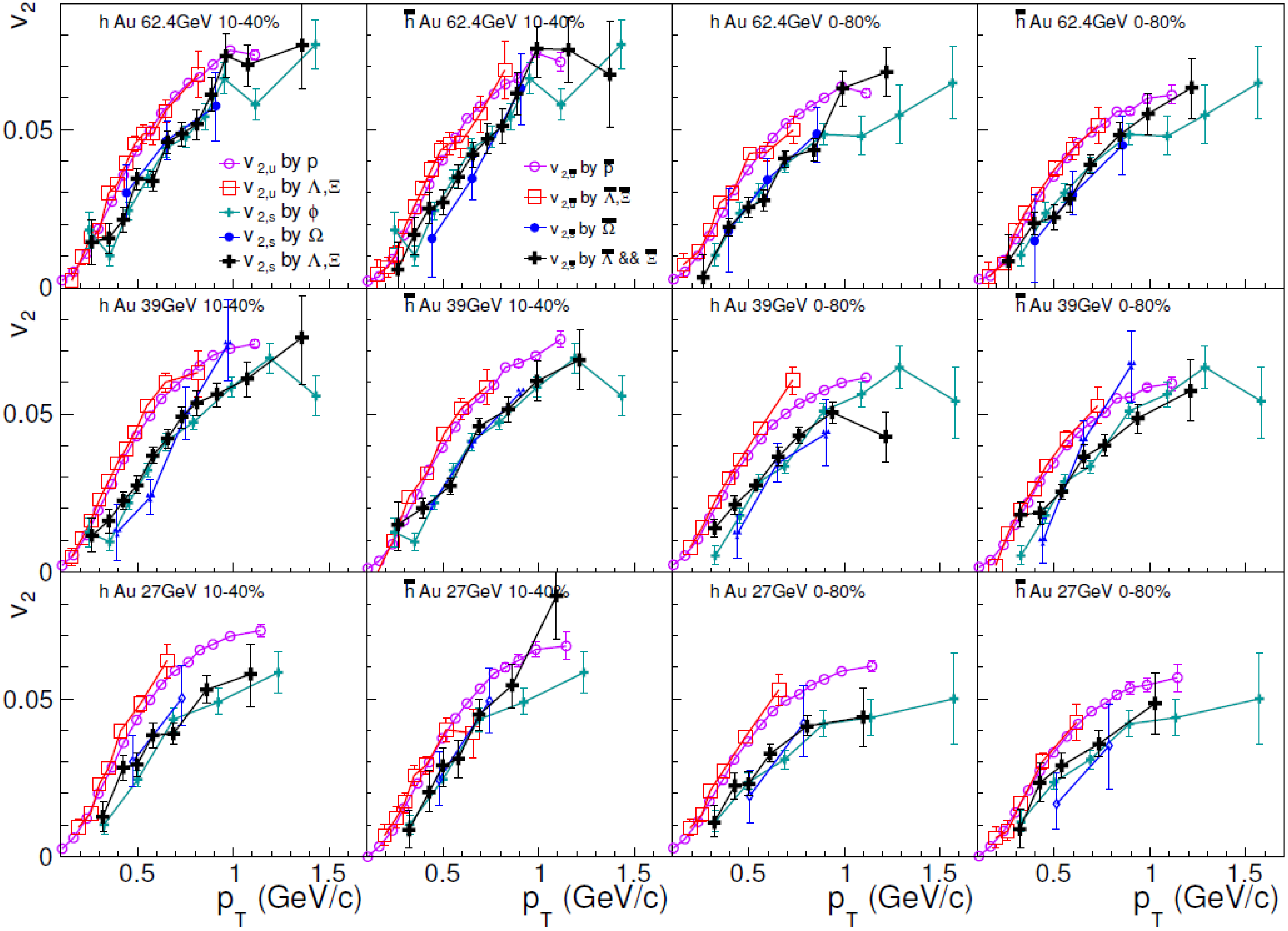
$$v_{2,s}(p_T) = \frac{1}{2} v_{2,\phi}(2p_T),$$

$$v_{2,s}(p_T) = \frac{1}{3}\left[2v_{2,\Xi}\left(\frac{1+2r}{r}p_T\right) - v_{2,\Lambda}\left(\frac{2+r}{r}p_T\right)\right].$$

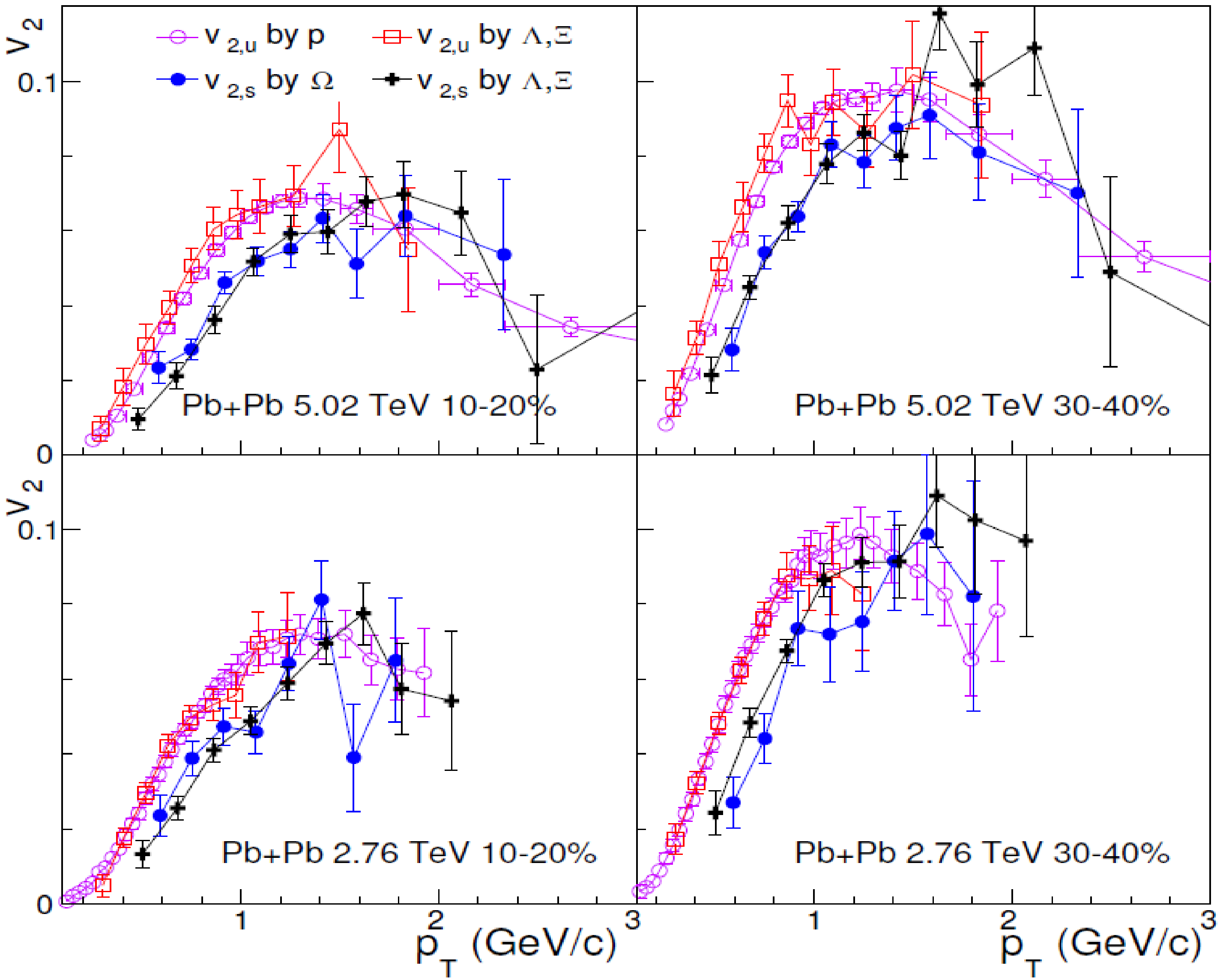
AuAu 200 GeV for 30-80% centrality







h Au 62.4GeV 10-40%
h̄ Au 62.4GeV 10-40%
h Au 62.4GeV 0-80%
h̄ Au 62.4GeV 0-80%
h Au 39GeV 10-40%
h̄ Au 39GeV 10-40%
h Au 39GeV 0-80%
h̄ Au 39GeV 0-80%
h Au 27GeV 10-40%
h̄ Au 27GeV 10-40%
h Au 27GeV 0-80%
h̄ Au 27GeV 0-80%
$v_{2,u}$ by p
$v_{2,u}$ by Λ,Ξ
$v_{2,s}$ by φ
$v_{2,s}$ by Ω
$v_{2,s}$ by Λ,Ξ
$v_{2,\bar{u}}$ by $\bar{p}$
$v_{2,\bar{u}}$ by $\bar{\Lambda},\bar{\Xi}$
$v_{2,\bar{s}}$ by $\bar{\Omega}$
$v_{2,\bar{s}}$ by $\bar{\Lambda}$ && $\bar{\Xi}$
v_2
0.05
0
0.5
1
1.5
p_T (GeV/c)



v_2
0.1
0
$v_{2,u}$ by p
$v_{2,u}$ by Λ,Ξ
$v_{2,s}$ by Ω
$v_{2,s}$ by Λ,Ξ
Pb+Pb 5.02 TeV 10-20%
Pb+Pb 5.02 TeV 30-40%
Pb+Pb 2.76 TeV 10-20%
Pb+Pb 2.76 TeV 30-40%
1
2
3
p_T (GeV/c)

6.

EVC mechanism of charm hadron production

Refs:

- Jun Song, Hai-hong Li, and Feng-lan Shao, Eur. Phys. J. C 83:852(2023).
- Jun Song, Hai-hong Li, and Feng-lan Shao, Phys. Rev. D105, 074027 (2022).
- Hai-hong Li, Feng-lan Shao, and Jun Song, Chin. Phys. C 45, 113105 (2021).
- Jun Song, Hai-hong Li, and Feng-lan Shao, Eur. Phys. J. C 78:344 (2018).
- Hai-hong Li, Feng-lan Shao, and Jun Song, Phys. Rev. C 97, 064915 (2018).

p_T spectra of single-charmed hadrons in EVC

$$f_D(p_T) = \kappa_D f_c\left(\frac{r_{cu}}{1+r_{cu}}p_T\right) f_{\bar{u}}\left(\frac{1}{1+r_{cu}}p_T\right)$$

$$f_{D_s}(p_T) = \kappa_{D_s} f_c\left(\frac{r_{cs}}{1+r_{cs}}p_T\right) f_{\bar{s}}\left(\frac{1}{1+r_{cs}}p_T\right)$$

$$f_{\Lambda_c}(p_T) = \kappa_{\Lambda_c} f_c\left(\frac{r_{cu}}{2+r_{cu}}p_T\right) f_u^2\left(\frac{1}{1+r_{cu}}p_T\right)$$

0.75-0.85 0.15-0.25

$$r_{cu} = \frac{m_c}{m_u}$$

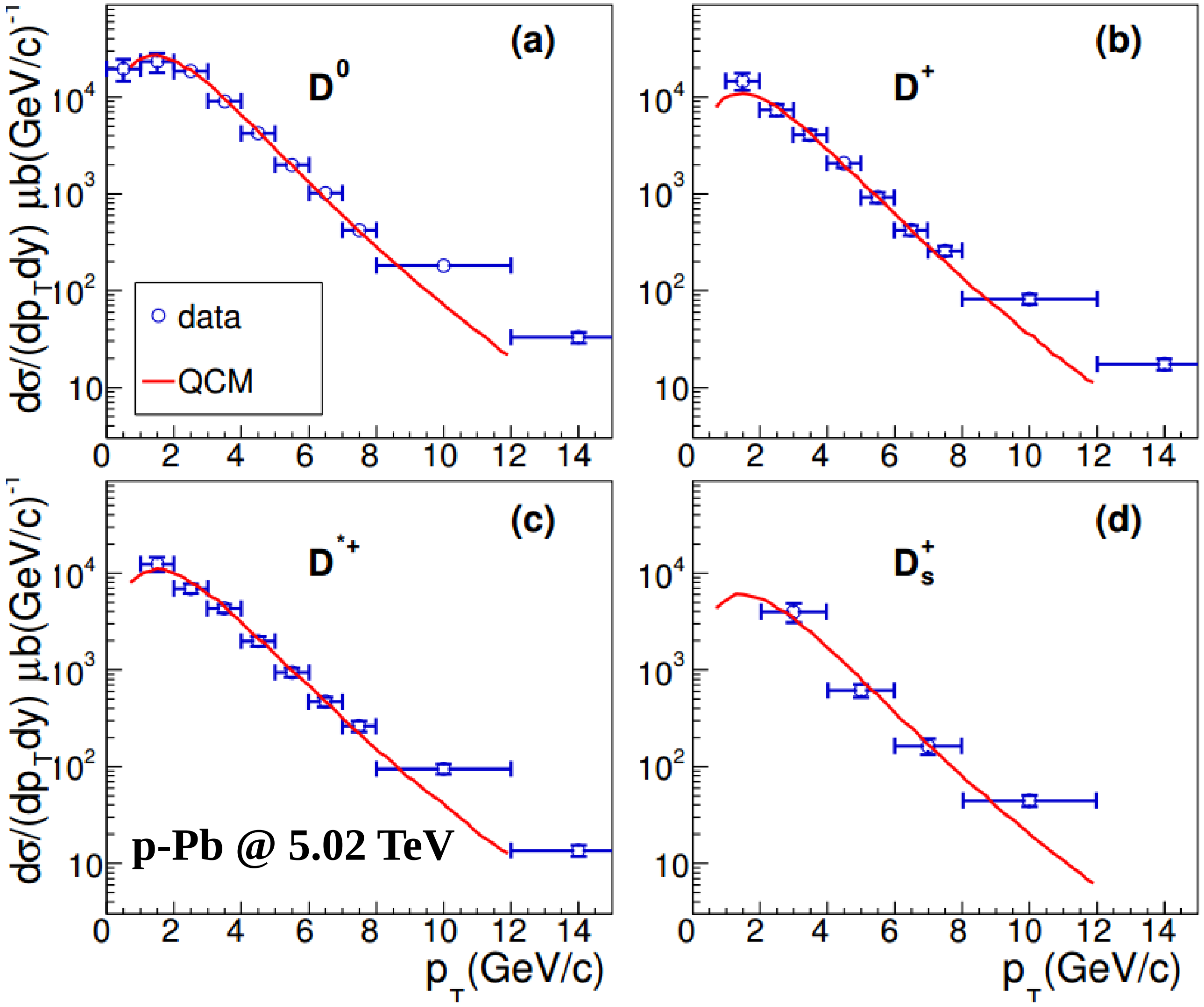
$$r_{cs} = \frac{m_c}{m_s}$$

$$m_c = 1.5\ \text{GeV}$$

charm hadrons of $p_T \lesssim 10$ GeV/c :

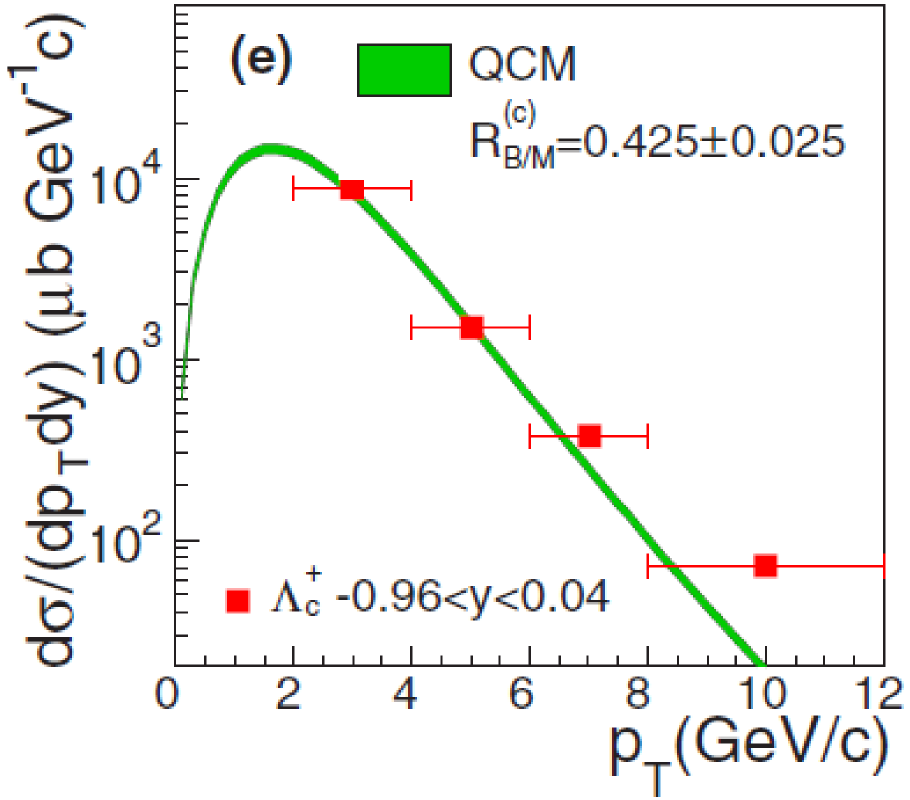
***c* quark of $p_{T,c} \lesssim 8$ + *l* quark of $p_{T,l} \lesssim 2$ GeV/c**

p_T spectra of D mesons

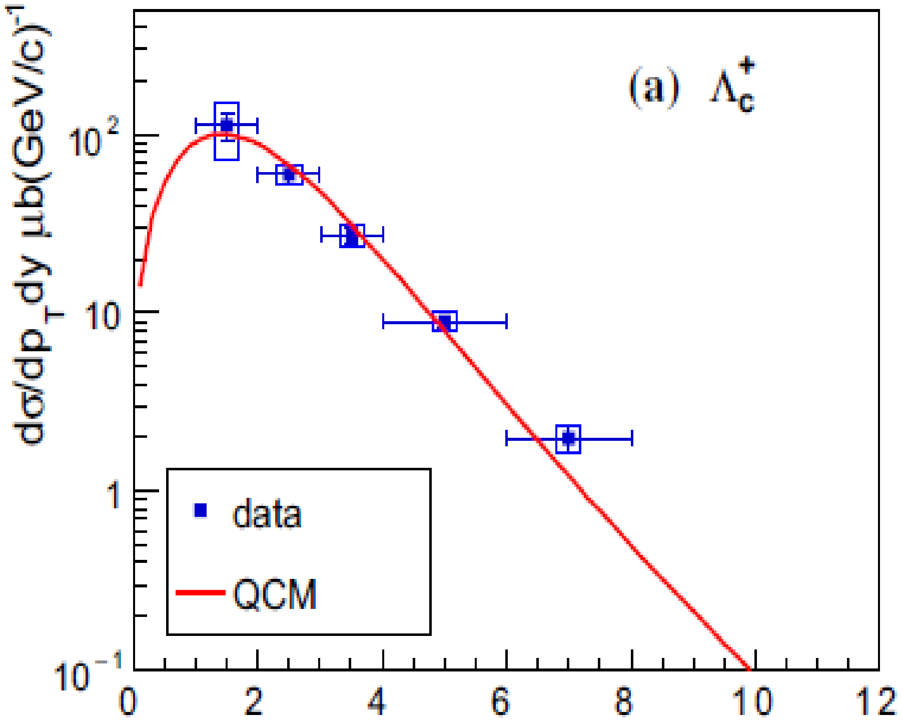


Song, Li, Shao, Eur.Phys.J. C 78:344 (2018)
Li, Shao,Song, Phy.Rev.C97, 064915 (2018)

p_T spectrum of Λ_c^+

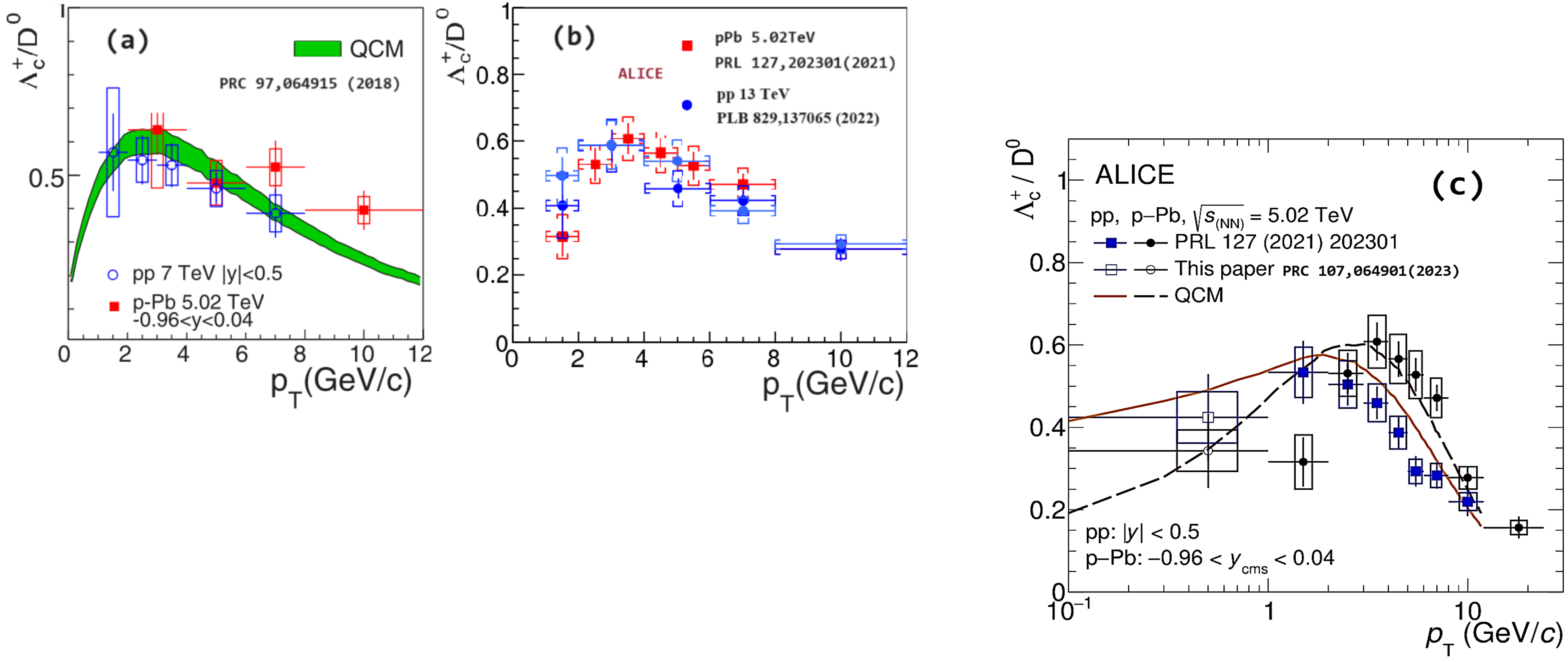


pPb @ 5.02 TeV



pp @ 7 TeV

Non-monotonical p_T dependence of charmed Baryon/Meson ratio

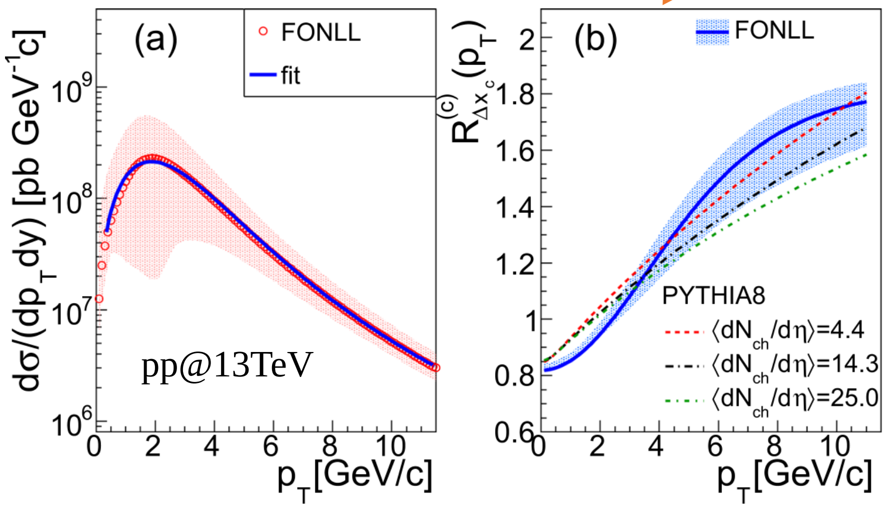


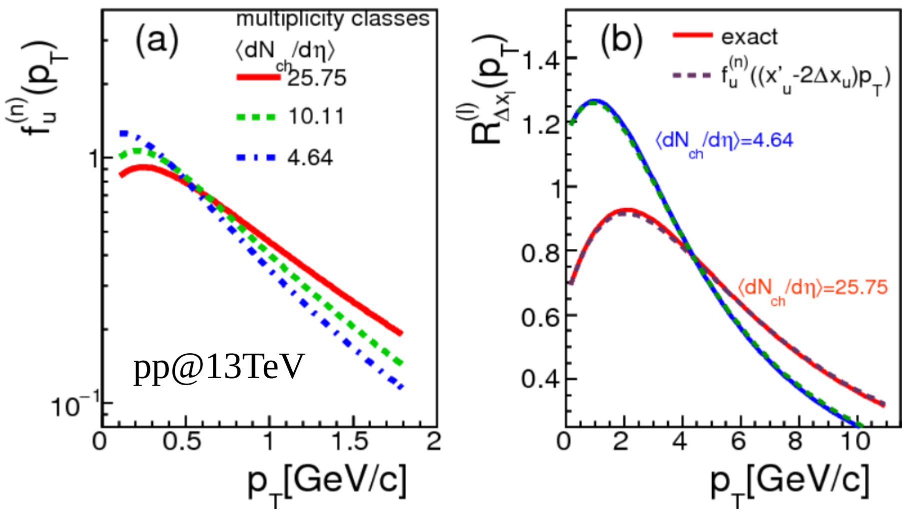
Origin of p_T dependence for Λ_c^+/D^0 ratio

$$\frac{f_{\Lambda_c}(p_T)}{f_{D^0}(p_T)} = R^{(N_{q_i})}\left[\frac{A_{\Lambda_c}}{A_{D^0}} R^{(c)}_{\Delta x_c}(p_T) R^{(l)}_{\Delta x_l}(p_T) R^{(cl)}_{\rm corr}(p_T)\right]$$

charm

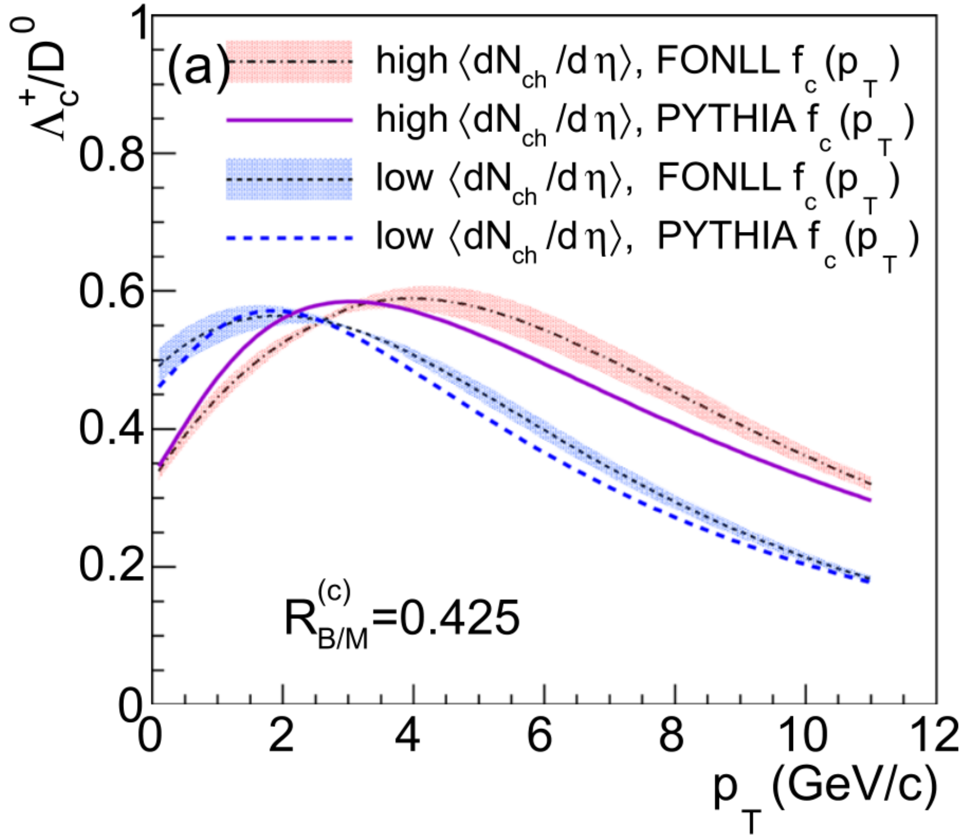
light-flavor





Influence of

the shape of quark distribution

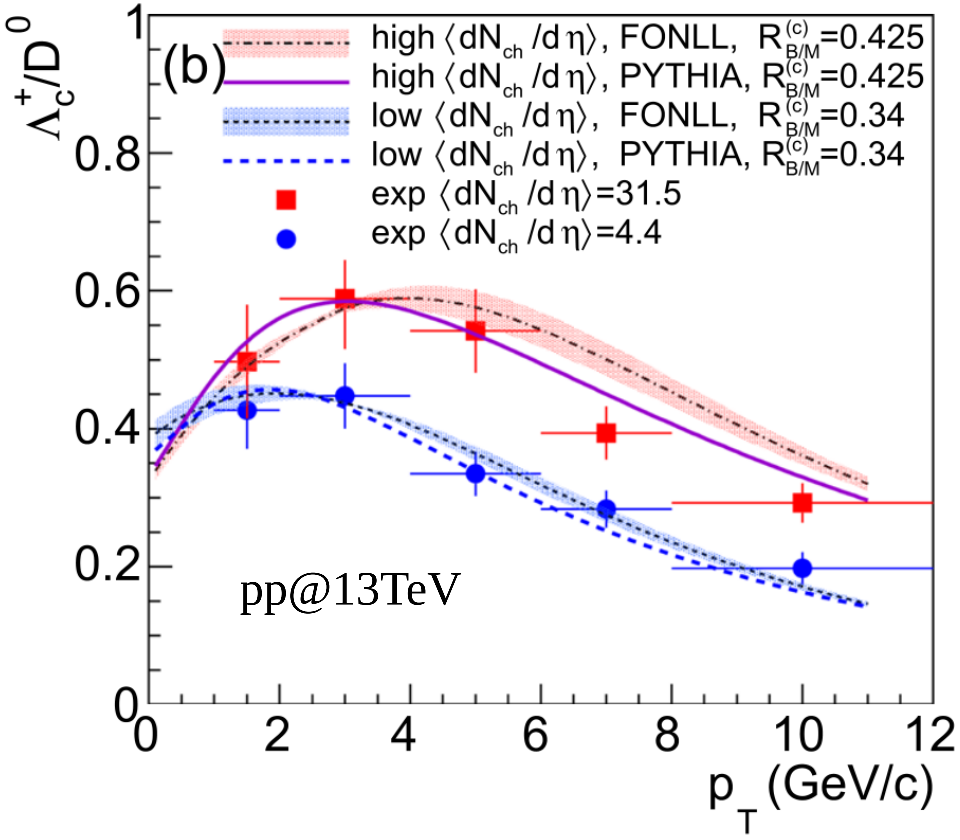


Influence of

the shape of quark distribution

&

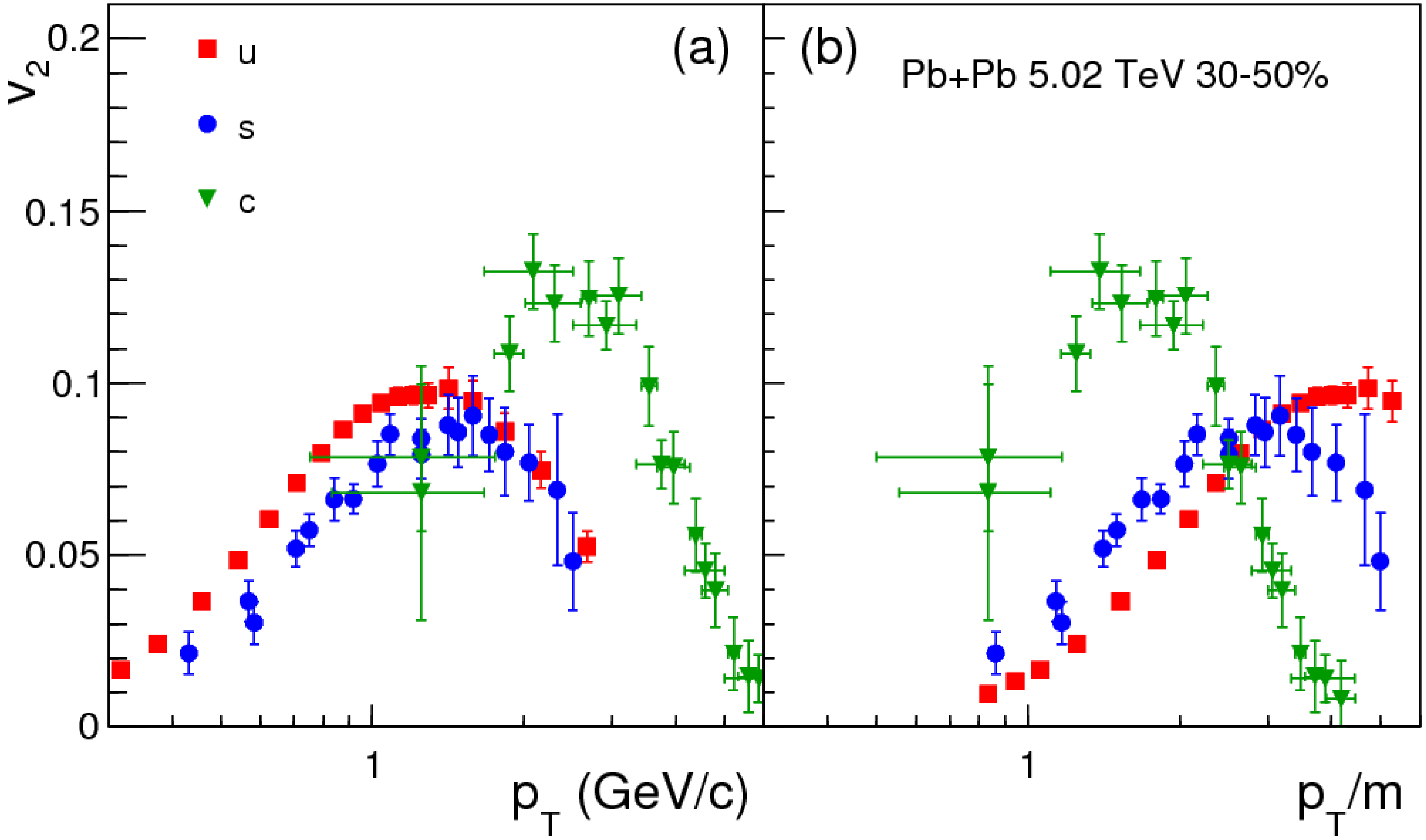
baryon/meson production competition



7.

understand parton system before hadronization

Compare v_2 of up, strange and charm quarks



Effects of hadronization

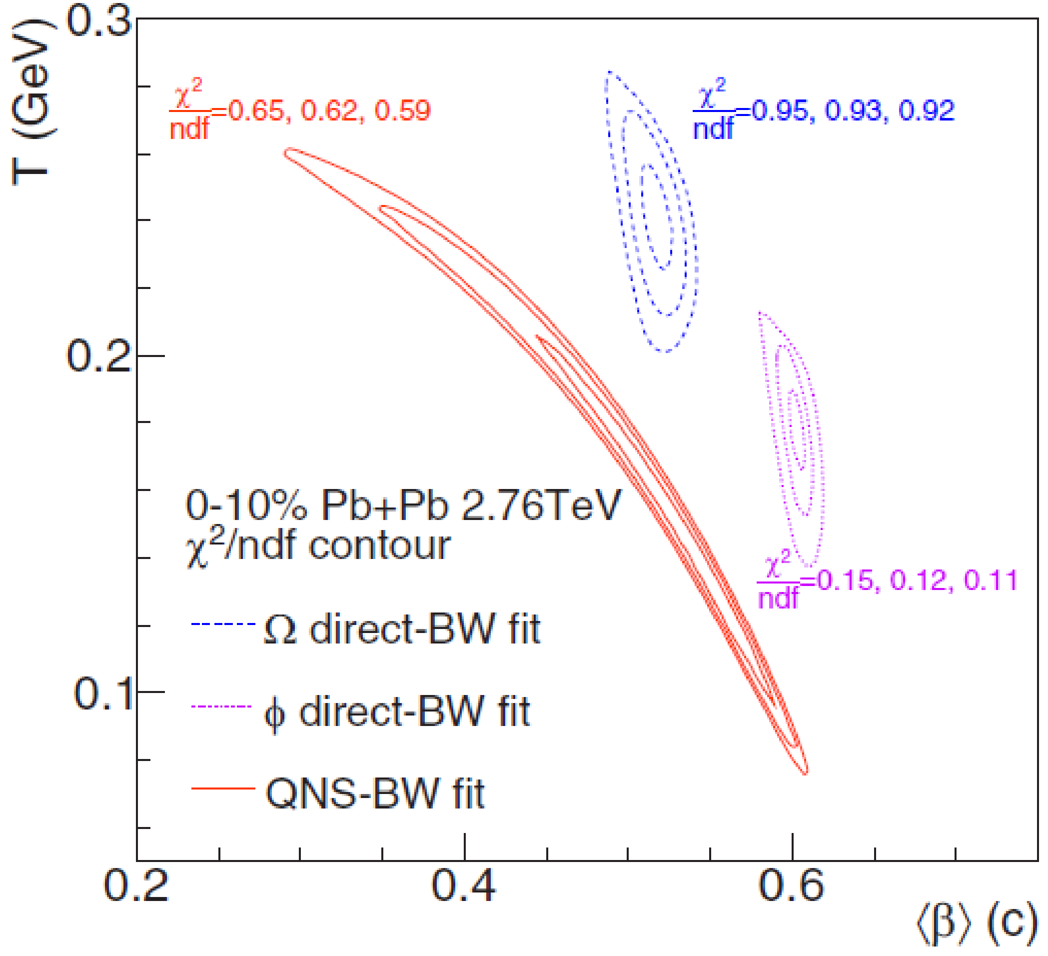


FIG. 4. Contour plot of blast-wave model fit of data of the p_T spectra of Ω and ϕ in central (0–10%) Pb + Pb collisions at $\sqrt{s_{NN}} =$ 2.76 TeV [3,4].

Summary

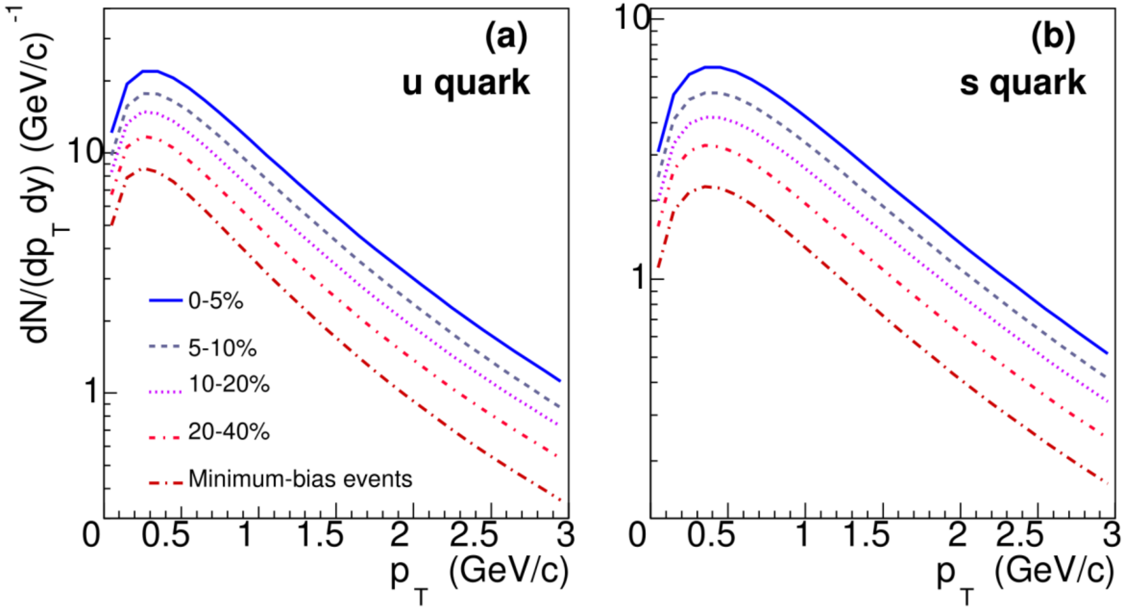
EVC is an effective mechanism

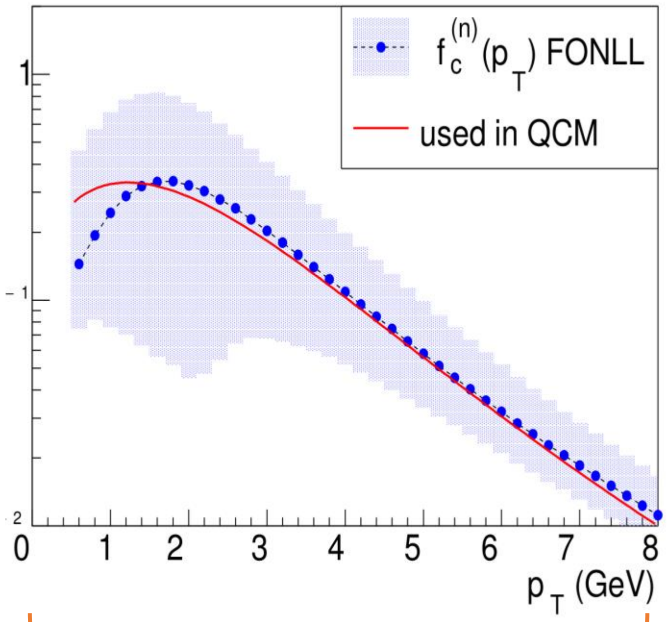
- ✓ quark number scaling for hadronic p_T spectra.
- ✓ self-consistent description for p_T spectra of light-flavor hadrons as well as single-charmed hadrons in pp and pPb collisions at LHC energies.
- ✓ v_2 of hadrons in heavy-ion collisions.
- ✓ energy-scan test of hadronic p_T spectra in Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV.

Thanks for your attention!

Quark spectra at hadronization are known.

e.g., in p-Pb collisions at 5.02 TeV

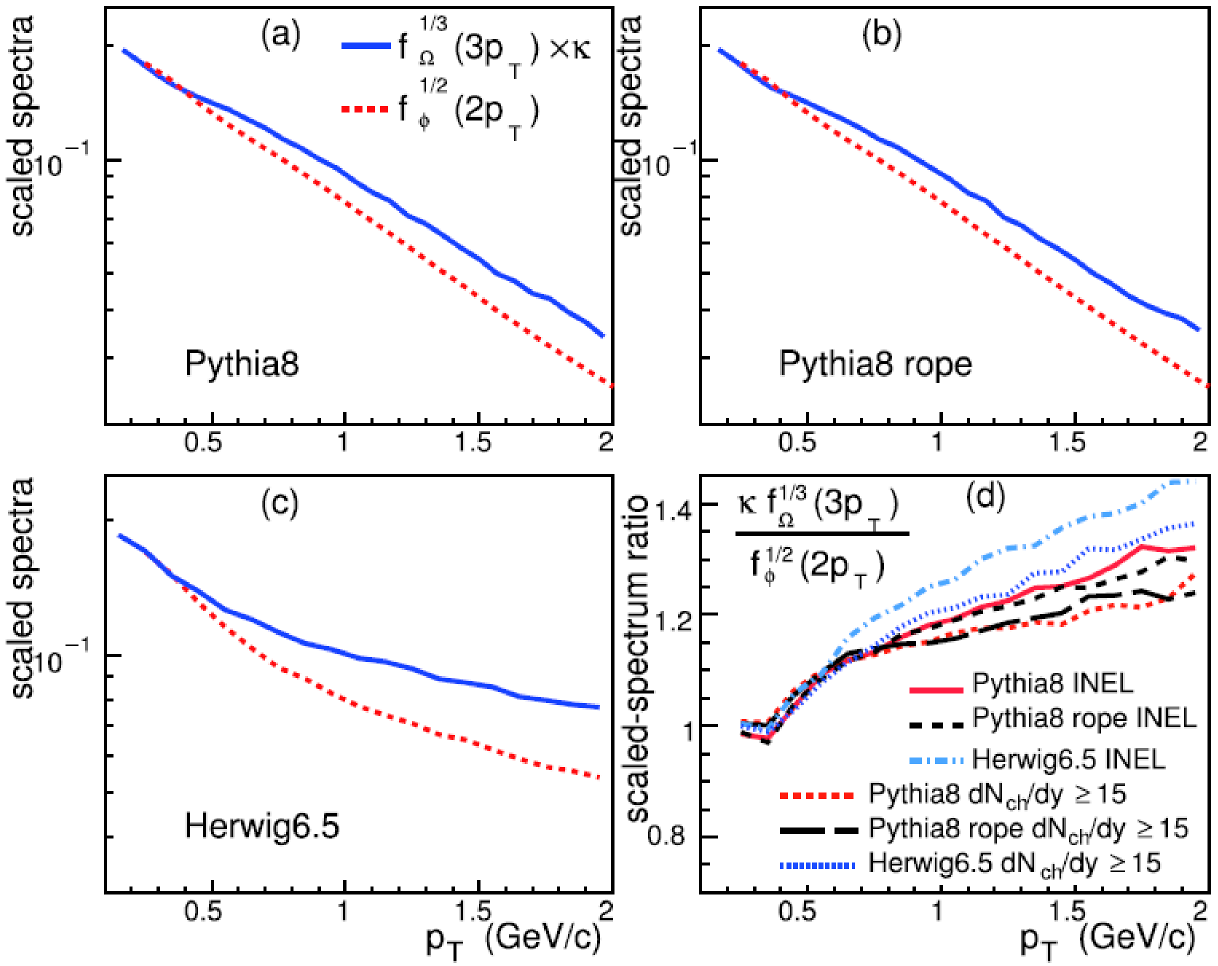




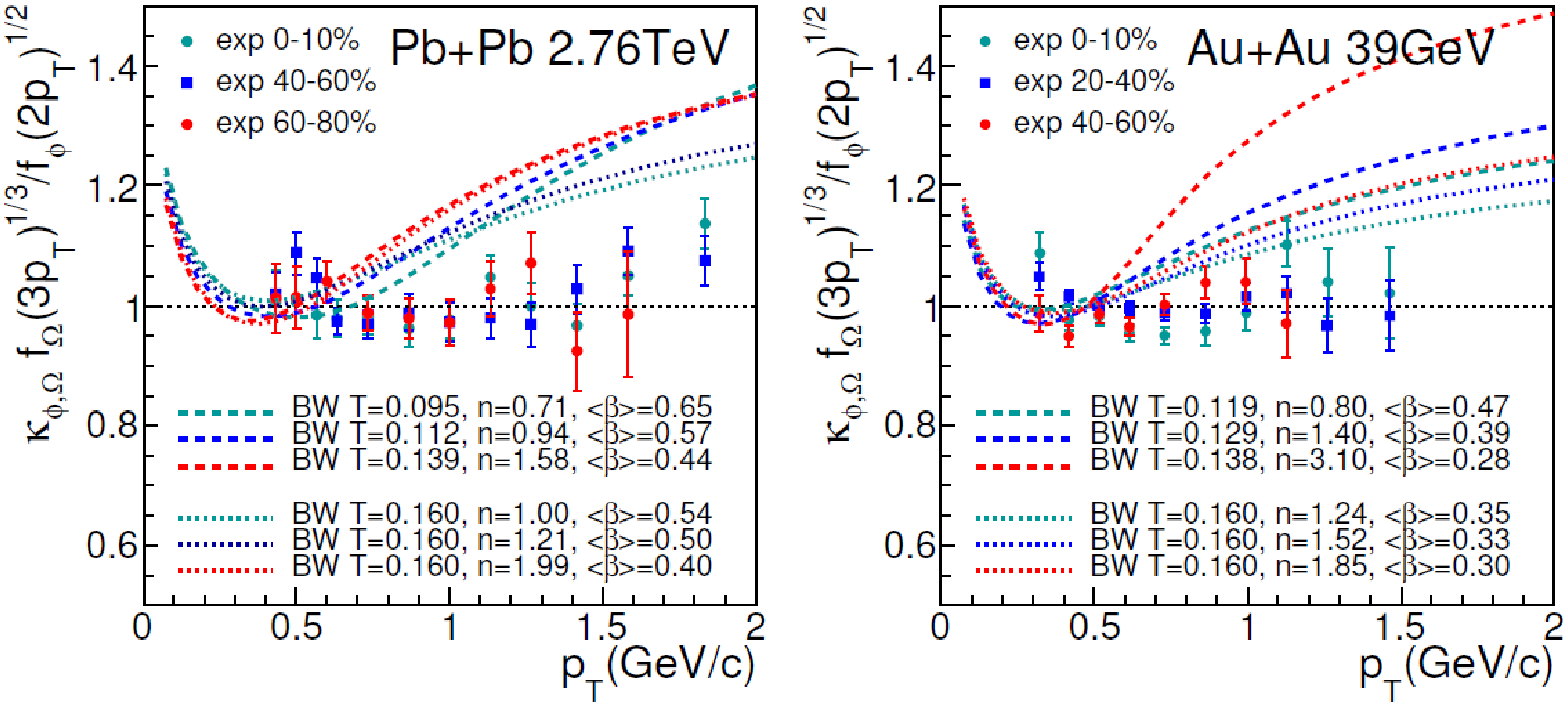
obtained from light-flavor hadrons

consistent with pQCD calculations

QNS in PYTHIA & HERWIG



QNS in Blast-wave model



QNS in other (re-)combination/coalescence models