Probing the partonic degree of freedom in high multiplicity p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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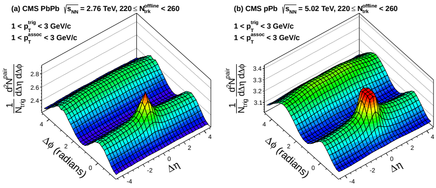
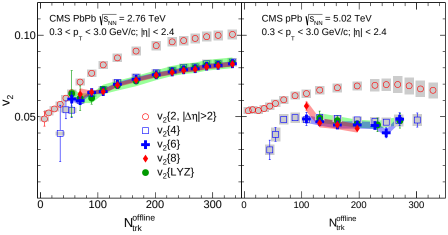
(New Development of Hydrodynamics, Fudan University)
based on: **W. Zhao**, C.M. Ko, Y.X. Liu, G.Y. Qin and H. Song, 1911.xxxx.

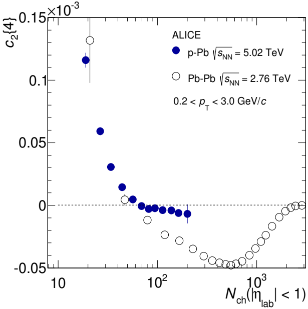
"collectivity" features in p-Pb system

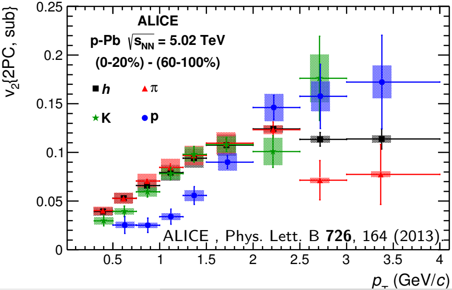


CMS, Phys. Lett. B **724**, 213 (2013).



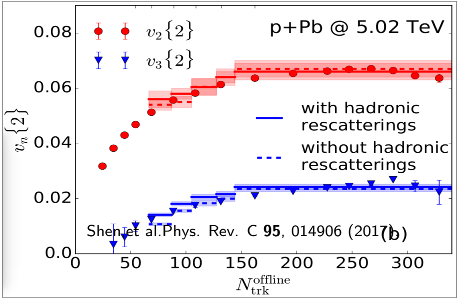
- Strong signals for collectivity in p-Pb.



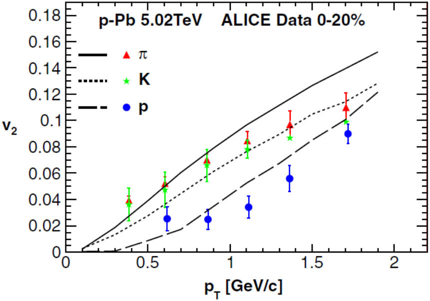


ALICE , Phys. Lett. B **726**, 164 (2013).

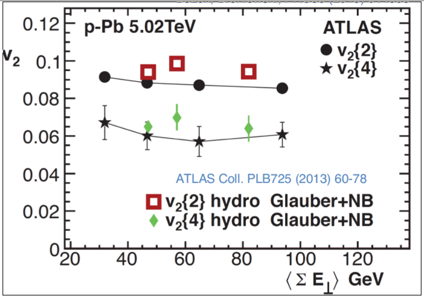
Collective flow? Hydrodynamcis simulations in p-Pb



Shen et al.Phys. Rev. C **95**, 014906 (2017)



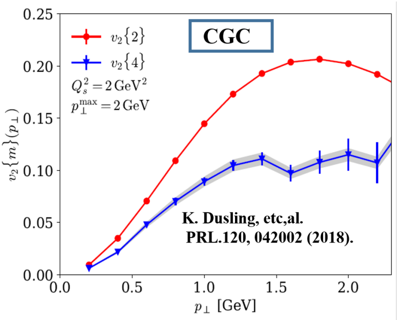
Bozek, et al.Phys. Rev. Lett. **111**, 172303 (2013).



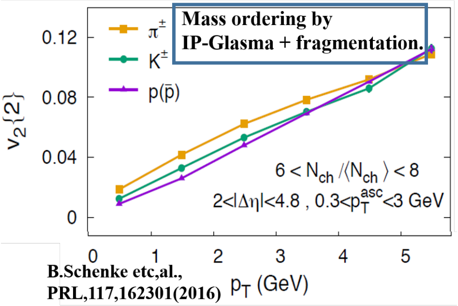
ATLAS Coll. PLB725 (2013) 60-78

- Hydrodynamics can well reproduce the 2- and 4-pariticle correlations and mass ordering in p-Pb system.

Initial states correlations in small system



K. Dusling, etc,al. PRL.120, 042002 (2018).



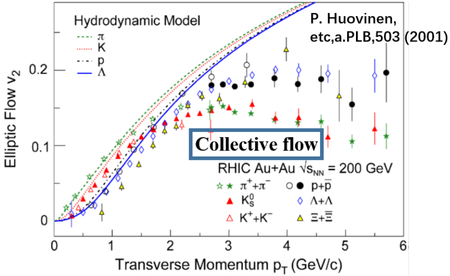
Mass ordering by IP-Glasma + fragmentation.

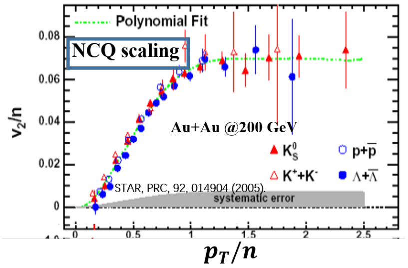
B.Schenke etc,al., PRL,117,162301(2016)

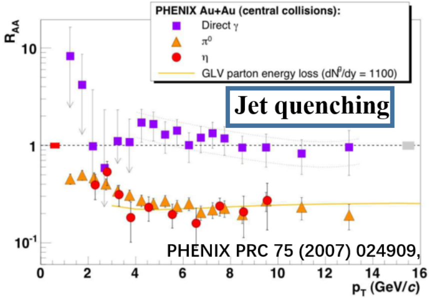
- Based on initial state correlations, CGC or IP-Glasma model also describe many collective features, such as multiparticle correlations and mass ordering in small system.

Is QGP formed in small system?

Reminder: QGP discovery in heavy-ion collisions







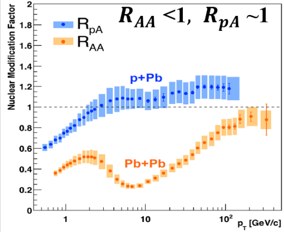
- It has been announced that QGP has been found at RHIC in heavy-ion collisions.

Related signatures in small system

Collective flow: Hydrodynamics or CGC initial states correlations?

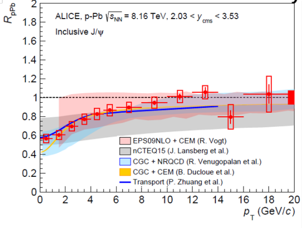
Hard probes: no longer leave obvious hints of formation of QGP.

Light flavour

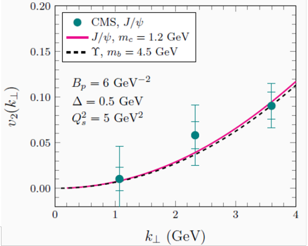


J.L.Nagle, eta,al. Ann.Rev. Nucl. Part. Sci 68,211 (2018)

Heavy flavour



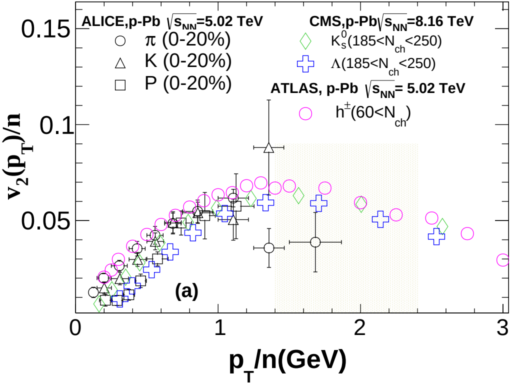
ALICE, JHEP 1807, 160 (2018)



C. Zhang,eta,al. PRL. 122,172302 (2019).

- R_{pA} of light hadrons and heavy flavour is consistent with one and compatible with cold nuclear effect.
- $v_2(p_T)$ of heavy quark is also compatible with the CGC model calculations.

NCQ scaling in small system

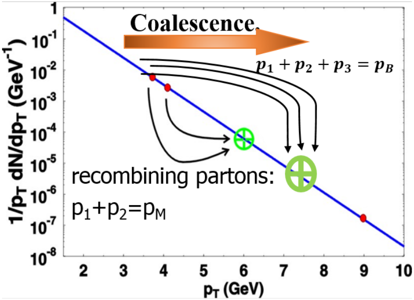


- Observe the approximately NCQ scaling at intermediate p_T in high multiplicity events of p-Pb collision in data.
- NCQ scaling is a important signal to probe the partonic degree of freedom in small system.

ALICE data: PLB,726, 164 (2013). CMS data: PRL, 121, 082301 (2018). ATLAS data: PRC, 96, 024908 (2017).

Coalescence model and NCQ scaling

Quark calescence process

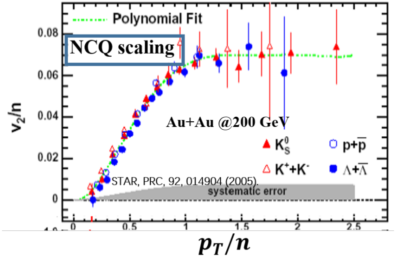


- Coalescence:
  - Occurs in an instant, quark are already there and close in phase space.
  - The parton spectrum is shifted to higher p_T in the hadron spectrum, $p_h = np_T$(n=2,3).
  - Partonic hydro behavior shifted to higher p_T in hadrons.

Naïve coalescence and NCQ scaling

- If narrow wave function in momentum space:$\sim \delta(p_h - \sum_i p_{tI})$ and quark exhibits the same elliptic flow:
- quark's elliptic flow:$f_a(\mathbf{p}_T) = \bar{f}_a(p_T)\,(1 + 2v_{2,q}(p_T)\cos 2\phi)$
- the meson's elliptic flow:$v_2^M(p_T) = \frac{2v_{2,q}(p_T/2)}{1+2v_{2,q}^2(p_T/2)} \sim 2v_{2,q}(p_T/2)$
- the baryon's elliptic flow:$v_2^B(p_T) = \frac{3v_{2,q}(p_T/3)}{1+6v_{2,q}^2(p_T/3)} \sim 3v_{2,q}(p_T/3)$

STAR PRC.72 (2005) 014904



- NCQ scaling is a important signal of deconfinement of quark and gluons in system.

D. Molnar and S. A. Voloshin, Phys. Rev. Lett. **91**, 092301 (2003).

Probe the partonic degree of freedom in high multiplicity p+Pb collisions

Coalescence model

Mesons and baryons' momentum distributions by recombining of quarks:

$$\begin{aligned}\frac{dN_M}{d^3\mathbf{P}_M} &= g_M \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_q(\mathbf{x}_1,\mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2,\mathbf{p}_2)\\ &\quad \times W_M(\mathbf{y},\mathbf{k})\delta^{(3)}(\mathbf{P}_M-\mathbf{p}_1-\mathbf{p}_2)\,, \end{aligned} \tag{1}$$

and

$$\begin{aligned}\frac{dN_B}{d^3\mathbf{P}_B} &= g_B \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1,\mathbf{p}_1)\\ &\quad \times f_{q_2}(\mathbf{x}_2,\mathbf{p}_2) f_{q_3}(\mathbf{x}_3,\mathbf{p}_3) W_B(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2)\\ &\quad \times \delta^{(3)}(\mathbf{P}_B-\mathbf{p}_1-\mathbf{p}_2-\mathbf{p}_3)\,, \end{aligned} \tag{2}$$

$g_{B(M)}$ is the statistic factor, $f_{q,\bar{q}}(\mathbf{x}_1,\mathbf{p}_1)$ is the phase-space distribution of (anti)quarks, normalized as $\int d^3\mathbf{x} d^3\mathbf{p} f_{q,\bar{q}}(\mathbf{x},\mathbf{p}) = N_{q,\bar{q}}$, $W_{M(B)}$ is the winger function of meson(baryon).

V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003).

Framework of `Hydro-Coal-Frag`

-- **Thermal hadrons**: generated by hydro. with Cooper-Frye.

Meson: $P_T < 2P_1$; baryon: $P_T < 3P_1$.

-- **Coalescence hadrons**: generated by quark coalescences, including thermal-thermal, thermal-hard and hard-hard coalescence.

***a*. *Thermal partons* generated by hydro with $P_T > P_1$.**

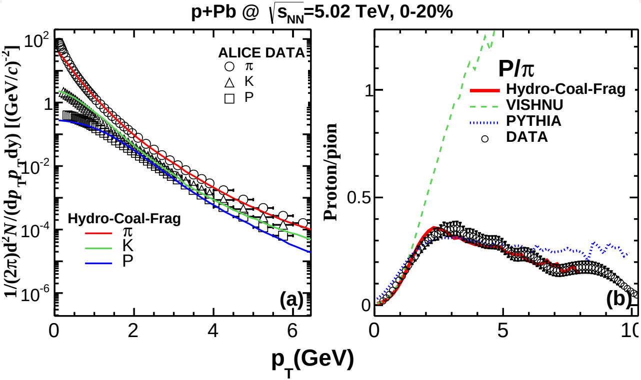
***b*. *Hard partons* generated by PYTHIA8, then suffered with energy loss by LBT with α=0.15. Get the hard parton with $P_T > P_2$.**

-- **Fragmentation process: the remnant hard quarks feed to fragmentation .**

-- **All hadrons feed to the UrQMD model.**

NOTE: the main two parameters, $p_{T1} = 1.6GeV$ and $p_{T2} = 2.6GeV$ are fixed by spectra of pions, kaons and protons at intermediate p_T. The parameters of hydro and `LBT` are fixed by other places already.

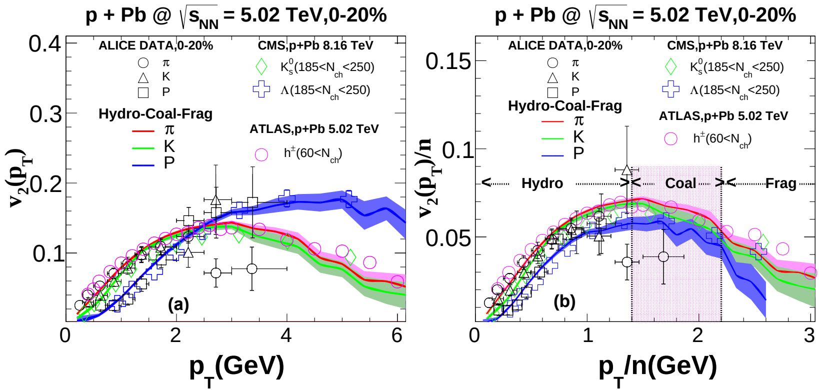
Spectra of π, K, P and P/π



- Our combined model, `Hydro-Coal-Frag`, gives a nice description of spectra of pion, kaon and proton as well as the P/π over p_T from 0 to 6 GeV.

W. Zhao, C.M.Ko, Y.X.Liu, G,Y.Qin and H. Song, 1911.xxxx.

$v_2(p_T)$ and NCQ scaling

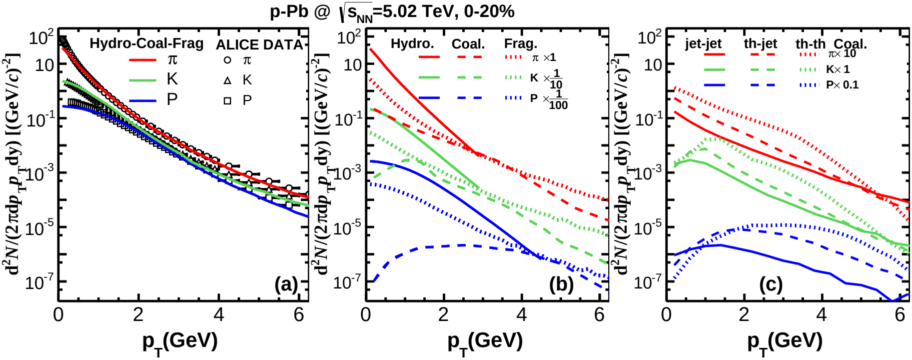


- `Hydro-Coal-Frag` model gives a nice description of $v_2(p_T)$ of pion, kaon and proton over p_T from 0 to 6 GeV.
- At intermediate p_T, `Hydro-Coal-Frag` model can get the approximately NCQ scaling at data shown.

W. Zhao, C.M.Ko, Y.X.Liu, G,Y.Qin and H. Song, 1911.xxxx.

The importance of quark coalescence process in p-Pb system

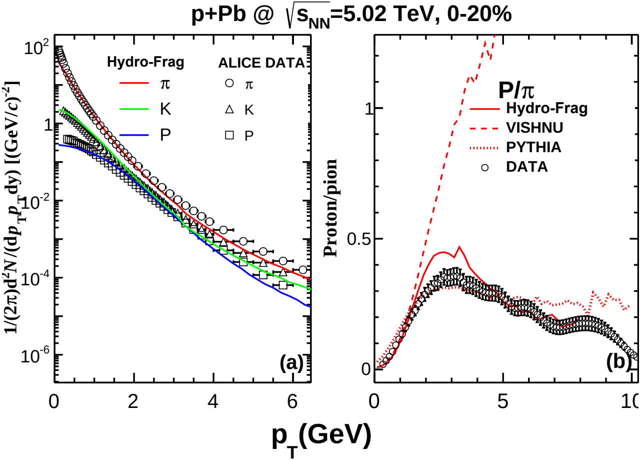
Hydro. Coalescence and fragmentation contributions



- Low p_T: hydrodynamics dominates.
- Intermediate p_T: coalescence and fragmentation.
- High p_T : Fragmentation dominates.
- Coalescence hadrons: Thermal-thermal coalescence dominates.

W. Zhao, C.M.Ko, Y.X.Liu, G,Y.Qin and H. Song, 1911.xxxx.

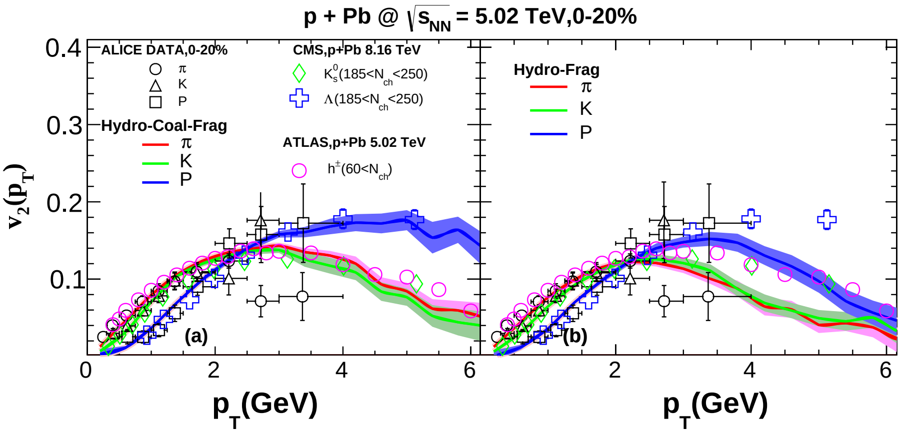
spectra of Hydro-Frag



- Hydro-Frag underestimates the spectra at intermediate p_T.
- Hydro-Frag also fail to reproduce the P/π.

W. Zhao, C.M.Ko, Y.X.Liu, G,Y.Qin and H. Song, 1911.xxxx.

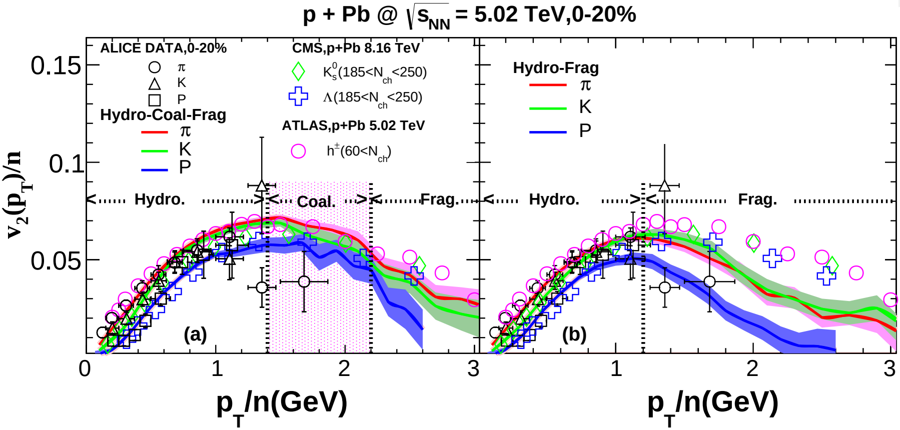
$v_2(p_T)$ of `Hydro-Coal-Frag`, and `Hydro-Frag`



- Without coalescence, `Hydro-Frag` greatly underestimates the $v_2(p_T)$ at intermediate p_T.

W. Zhao, C.M.Ko, Y.X.Liu, G,Y.Qin and H. Song, 1911.xxxx.

NCQ scaling of `Hydro-Coal-Frag`, and `Hydro-Frag`



- Without coalescence, `Hydro-Frag` will greatly violate the NCQ scaling at intermediate p_T, with the deviation of NCQ scaling at the level of ±50% .

W. Zhao, C.M.Ko, Y.X.Liu, G,Y.Qin and H. Song, 1911.xxxx.

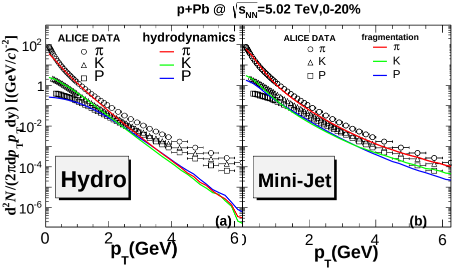
Summary

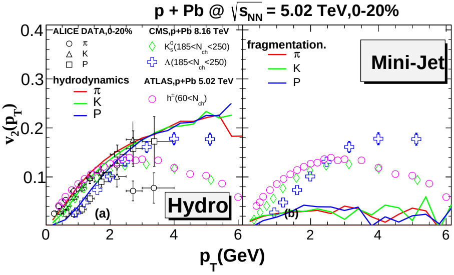
- NCQ scaling is a very important signal to probe the partonic degree of freedom in small system.
- Our model, `Hydro-Coal-Frag`, that combines `Hydro.`, `Coal.` and `Frag.` together can well describe the spectra, $v_2(p_T)$ and the approximately NCQ scaling at intermediate p_T.
- Quark coalescence is necessary in high multiplicity p+Pb collisions. Without quark coalescence, it would not only underestimate the magnitude of $v_2(p_T)/n$ but also greatly violate the NCQ scaling behavior at intermediate p_T.
- This implies the possible formation of QGP in high multiplicity p-Pb collisions at LHC.

Thanks

Back up

Further explore p-Pb system by hydro or min-jet





- Hydrodynamics works at low p_T, but fails at intermediate and high p_T.
- Mini-jet can't generate enough flow at low and intermediate p_T.
- At intermediate p_T: one need to combine soft and hard parts.

Wigner function for excited states

To guarantee positive value of Wigner function for stable Monto Carlo sampling, the Wigner function replaced by the overlap of hadron Wigner function W_M with parton's Wigner function, $W_{q,\bar{q}}$:

$$\begin{aligned} \overline{W}_M(\mathbf{y},\mathbf{k}) &= \int d^3\mathbf{x}_1' d^3\mathbf{k}_1' d^3\mathbf{x}_2' d^3\mathbf{k}_2' \\ &\times W_q(\mathbf{x}_1',\mathbf{k}_1') W_{\bar{q}}(\mathbf{x}_2',\mathbf{k}_2') W_M(\mathbf{y}',\mathbf{k}'). \end{aligned} \tag{3}$$

Using harmonic oscillator for wave functions of excited stated of hadrons,

$$\phi_n(x) = \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} \frac{1}{\sqrt{2^n n!}} H_n(\xi) e^{-\xi^2/2}, \tag{4}$$

$\xi = \sqrt{\frac{m\omega}{\hbar}}x$, $H_n(\xi)$ are Hermite polynomials, ω is the oscillator frequency.

K. C. Han, R. J. Fries and C. M. Ko, Phys. Rev. C **93**, no. 4, 045207 (2016).

The quark wave function to be Gaussian wave packet, the wigner function of a meson in n-th excited state is

$$\overline{W}_{M,n}(\mathbf{y},\mathbf{k}) = \frac{v^n}{n!}e^{-v}. \tag{5}$$

with

$$v = \frac{1}{2}\left(\frac{\mathbf{y}^2}{\sigma_M^2} + \mathbf{k}^2\sigma_M^2\right). \tag{6}$$

Similarly, the Gaussian smeared Wigner function for baryon is:

$$\overline{W}_{B,n_1,n_2}(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2) = \frac{v_1^{n_1}}{n_1!}e^{-v_1}\cdot\frac{v_2^{n_2}}{n_2!}e^{-v_2}, \tag{7}$$

with

$$v_i = \frac{1}{2}\left(\frac{\mathbf{y}_i^2}{\sigma_{Bi}^2} + \mathbf{k}_i^2\sigma_{B_i^2}\right), \quad i = 1, 2. \tag{8}$$

K. C. Han, R. J. Fries and C. M. Ko, Phys. Rev. C **93**, no. 4, 045207 (2016).

Decay of excited states

Excited states decay into multiple pions in the case of light quark mesons, to kaon and pion in the case of light and strange mesons, to (anti)nucleon and pion in the case of light flavor (anti)baryons, and to Λ and pion in the case of strangeness ± 1 baryons. For decays into multiple pions, the relative probabilities are determined through the available phase space:

$$P_l(M) \sim \left[\frac{1}{6\pi^2}\left(\frac{M}{m_\pi}\right)^3\right]^l \frac{(4l-4)!(2l-1)}{(2l-1)!^2(3l-4)!}\,. \tag{9}$$

Here l is the number of pions, M is the mass of the excited state, or the invariant mass of the light quark-antiquark pair.

Excited states decay into kaon or Λ in a similar way.

K. C. Han, R. J. Fries and C. M. Ko, Phys. Rev. C **93**, no. 4, 045207 (2016).