Quark-Gluon Plasma and Relativistic Heavy-Ion Collisions

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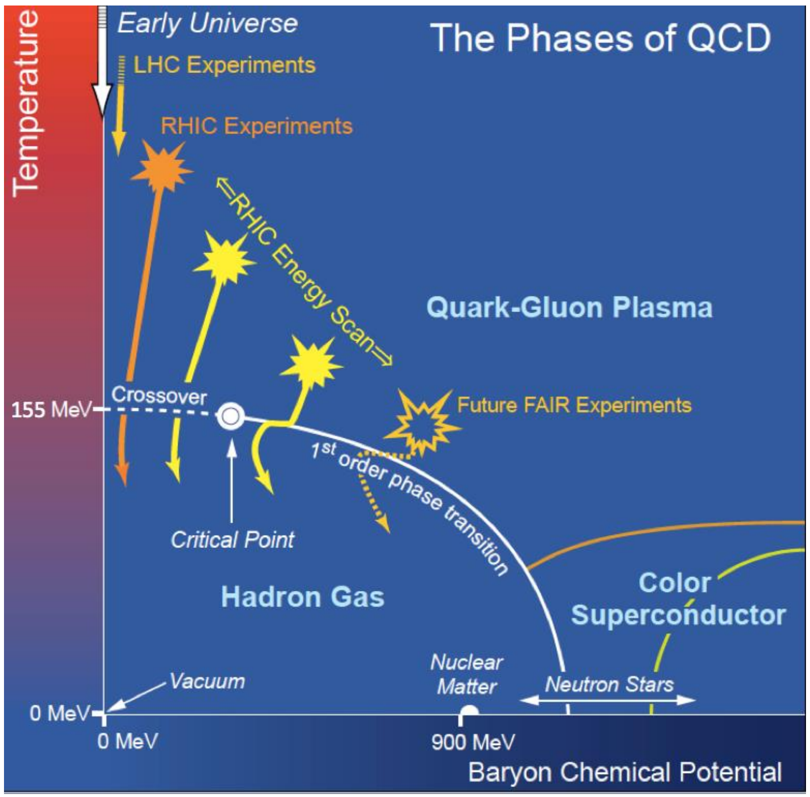
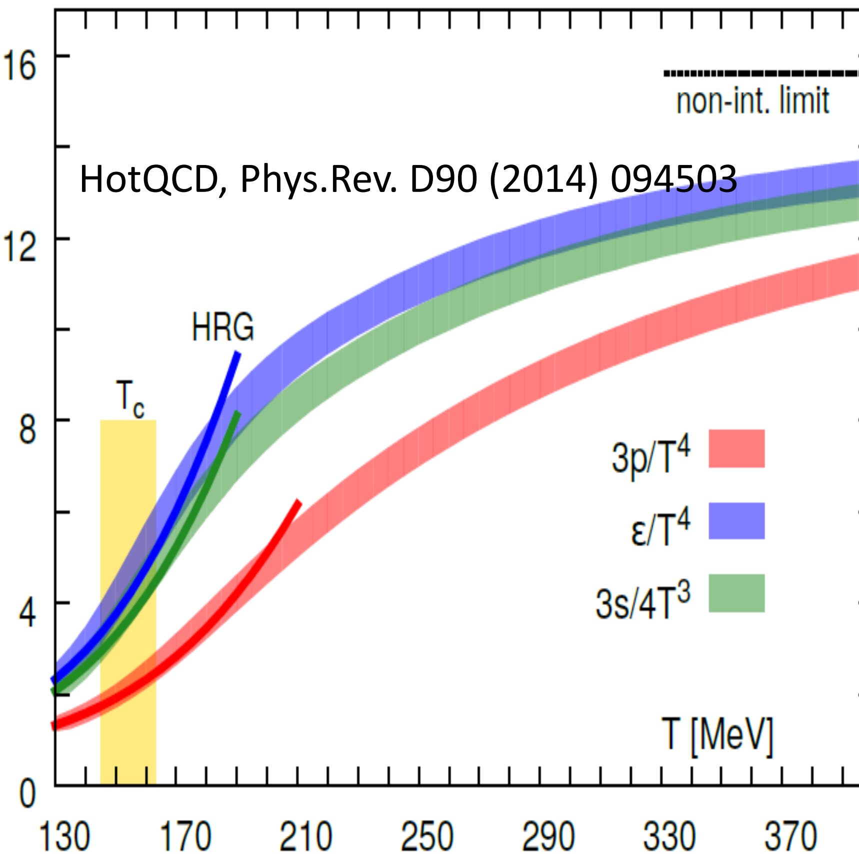
Strong-interaction QCD matter

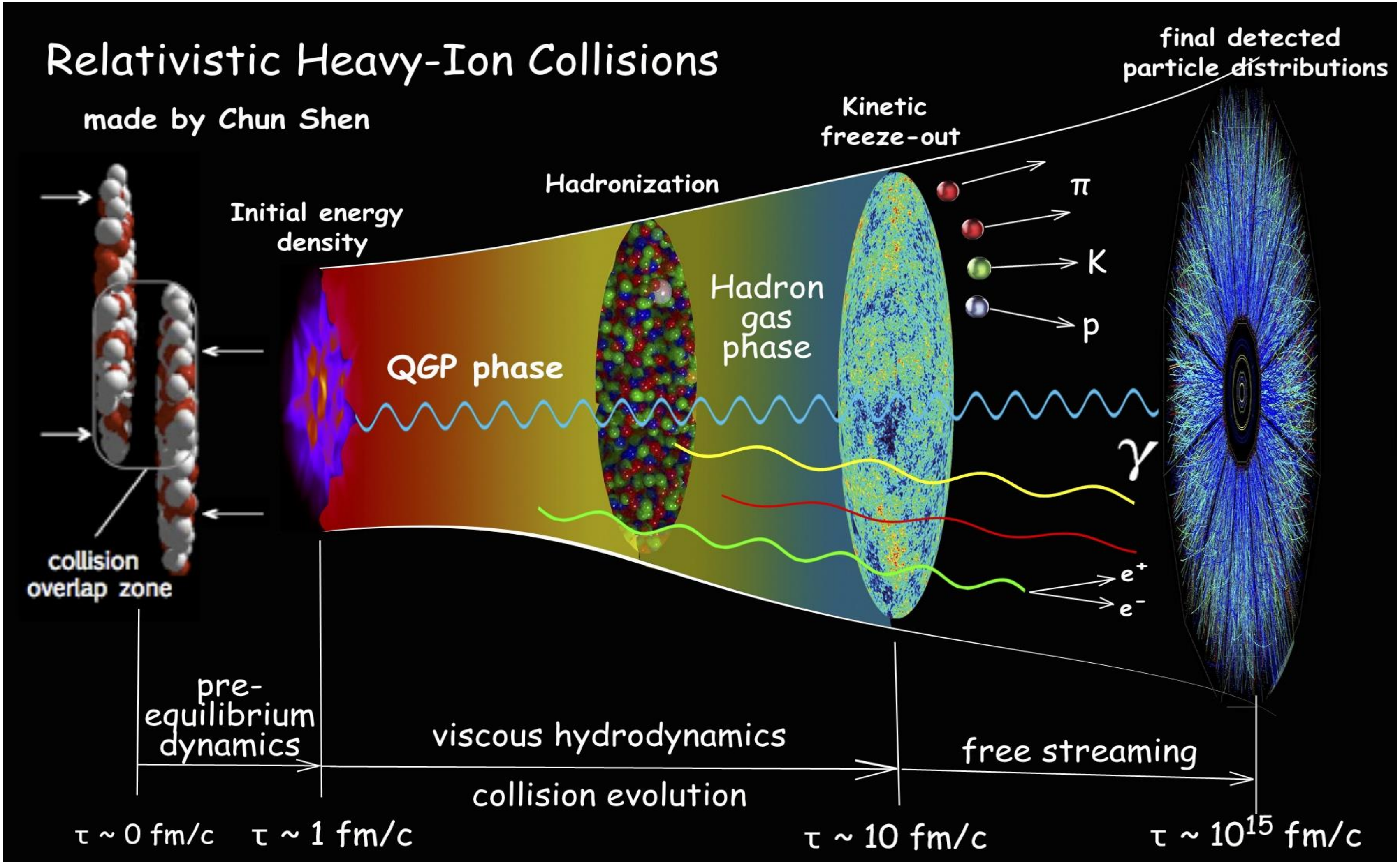
How does QCD behave at finite (extreme) temperatures and densities?





More info. on phases of QCD, see talks by Y.-X. Liu, H.-T. Ding, Y. Yin, X.-F. Luo, J. Xu, etc.

“Standard Model” of RHIC & LHC heavy-ion collisions (Little Bangs)



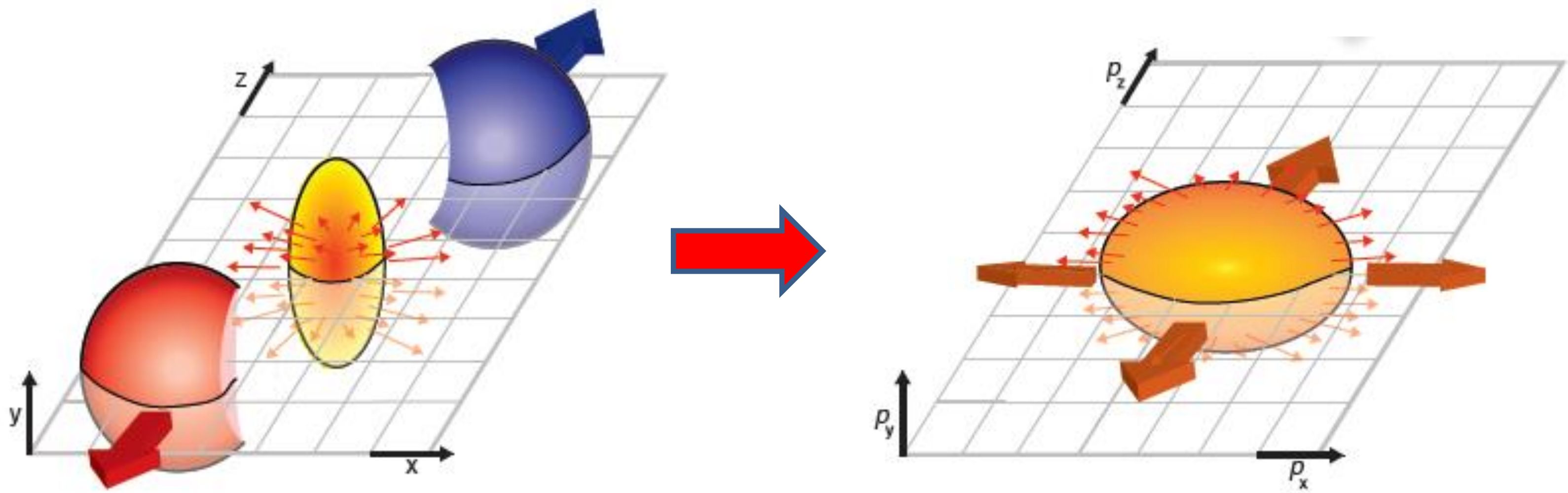
Outline

- **Soft Probes:**
  - **Particle yields & spectra, collective flow, fluctuations & correlations,** chiral/magnetic/vortical effect (see Xuguang Huang & Shi Pu's talks), search for critical end point and RHIC beam energy scan (see Yi Yin, Xiaofeng Luo & Shisu Shu's talks), …
- **Hard Probes:**
  - **Jets & high p_T hadrons, heavy quarks,** quarkonia & electromagnetic probes (see Zebo Tang & Chi Yang's talks), …
- **Small Systems**
  - (See Zhengyu Chen's talk for more info.)
- **Summary**

Soft Probes

Anisotropic collective flows

- **The interaction among QGP constituents translates initial state geometric anisotropy to final state momentum anisotropy.**



$$\frac{dN}{p_T dp_T dy d\phi} = \frac{dN}{2\pi p_T dp_T dy}\left(1 + \sum_n 2v_n(p_T, y)\cos\{n[\phi - \Psi_n(p_T, y)]\}\right)$$

- **Relativistic hydrodynamics has been very successful in describing medium evolution and collective flows. => strongly-coupled QGP**

Relativistic hydrodynamics

- **Energy-momentum conservation:**

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = \varepsilon U^\mu U^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

- **Equations of motion (Israel-Stewart viscous hydrodynamics):**

$$\dot{\varepsilon} = -(\varepsilon + P + \Pi)\theta + \pi^{\mu\nu}\sigma_{\mu\nu}$$

$$(\varepsilon + P + \Pi)\dot{U}^\alpha = \nabla^\alpha(P + \Pi) + \dot{U}_\mu \pi^{\mu\nu} - \Delta^\alpha_\nu \nabla_\mu \pi^{\mu\nu}$$

$$\dot{\Pi} = -\frac{1}{\tau_\Pi}\left[\Pi + \zeta\theta + \Pi\zeta T \partial_\alpha\left(\frac{\tau_\Pi}{2\zeta T}U^\alpha\right)\right]$$

$$\Delta^{\mu\nu}_{\alpha\beta}\dot{\pi}^{\alpha\beta} = -\frac{1}{\tau_\pi}\left[\pi - 2\eta\sigma^{\mu\nu} + \pi^{\mu\nu}\eta T \partial_\alpha\left(\frac{\tau_\pi}{2\eta T}U^\alpha\right)\right]$$

- **Equation of state:** $P = P(\varepsilon)$
- **Hadron spectra from Cooper-Fry formula:**

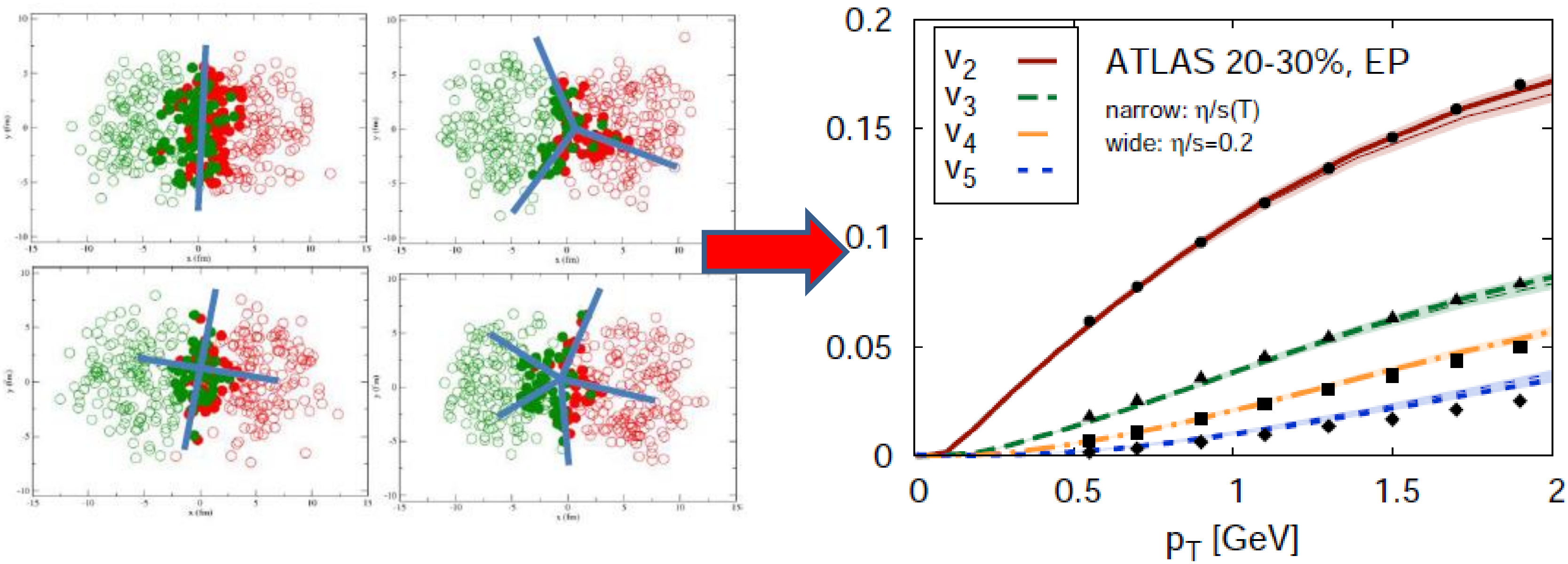
$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\int p \cdot d^3\sigma f(p \cdot U, T)$$

- **Hadron rescattering and decay**

0902.3663; 1301.2826; 1301.5893; 1311.1849; 1401.0079; 1712.03282; 1712.05815; etc

Initial-state fluctuations and final-state flows

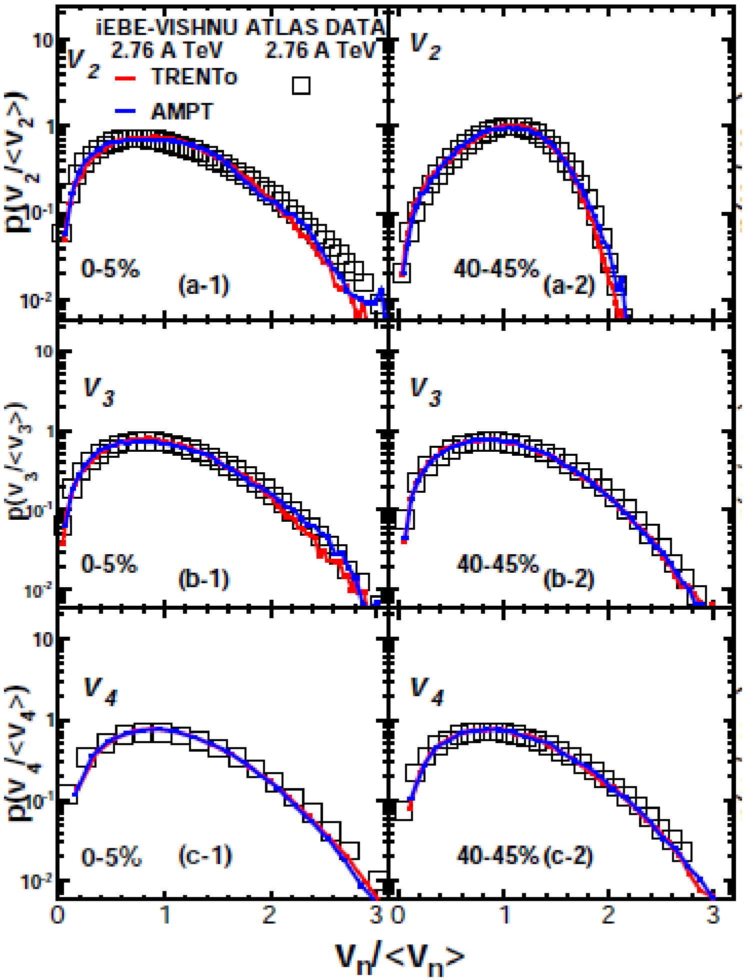
- **Event-by-event initial state density and geometry fluctuations play an important role in understanding final state anisotropic flows.**

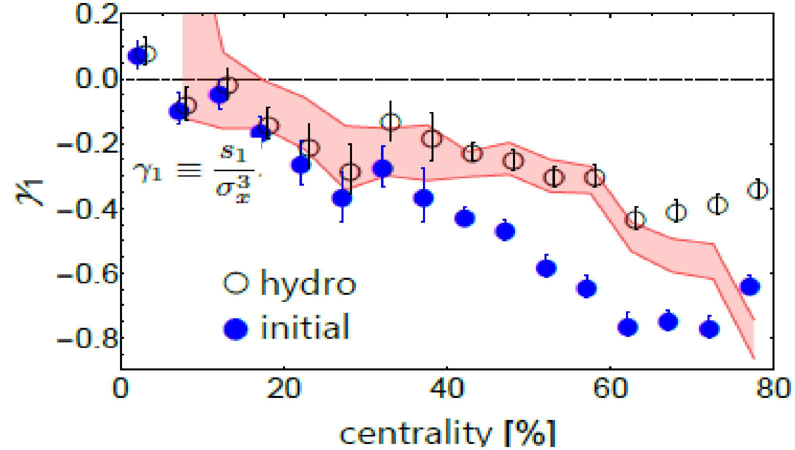


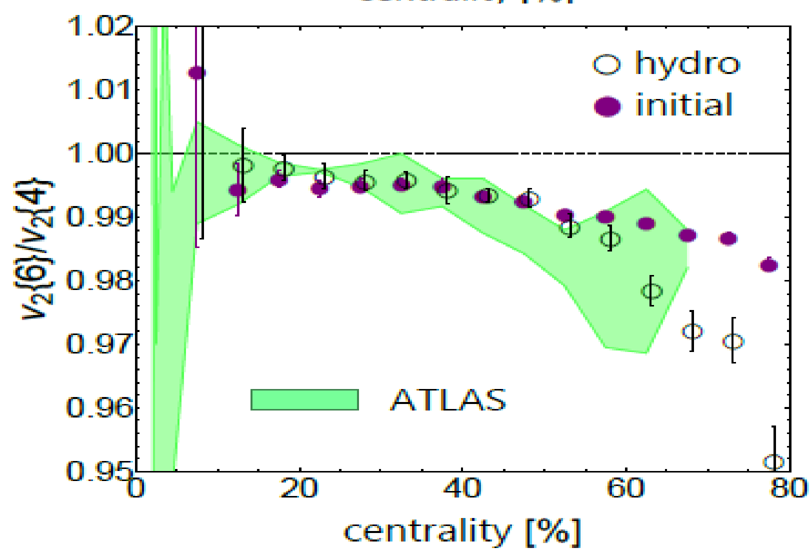
- **Flow observables: high-order v_n, EBE v_n fluctuations, v_n/Φ_n correlations, symmetric cumulants, non-linear response, longitudinal decorrelations, etc.**

Alver and Roland, PRC 2010; GYQ, Petersen, Bass, Muller, PRC 2010; Staig, Shuryak, PRC 2011; Teaney, Yan, PRC 2011; Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 2012; etc.

EBE v_n distributions and fluctuations

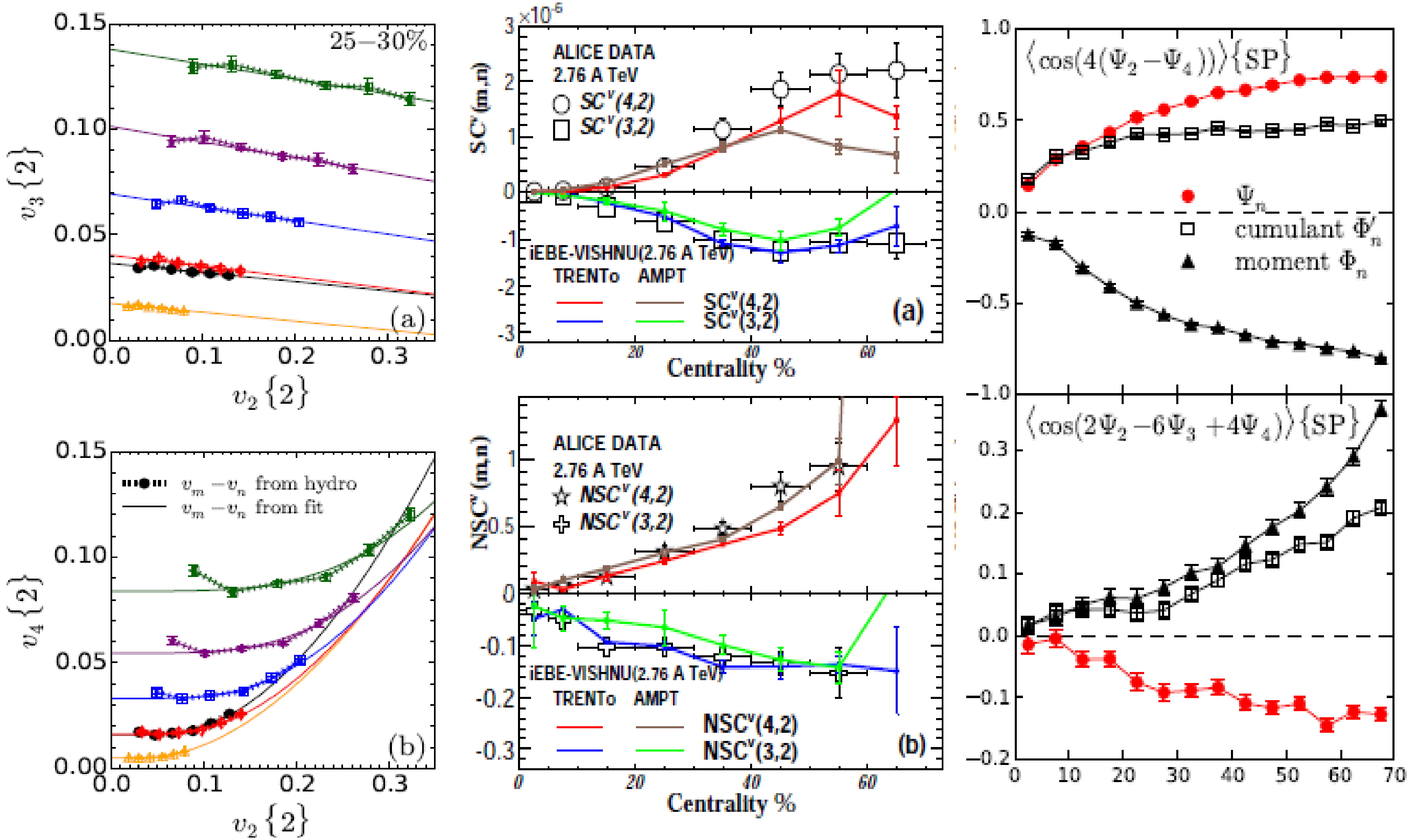






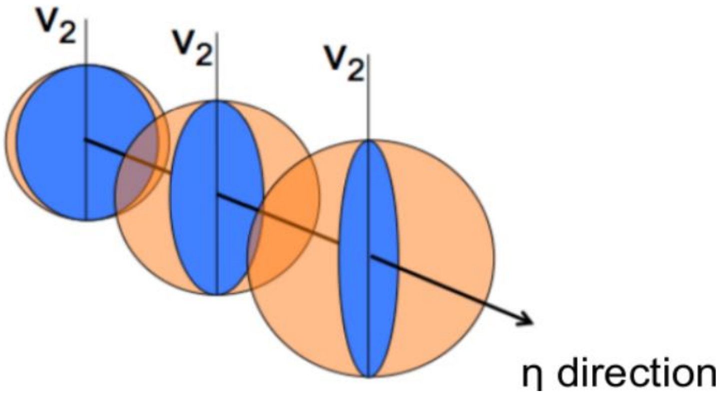
Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 2012; Renk, Niemi, PRC, 2014; Fu, PRC 2015; Zhao, Xu, Song, EPJC 2017; Giacalone, Yan, Noronha-Hostler, Ollitrault, PRC 2017; etc.

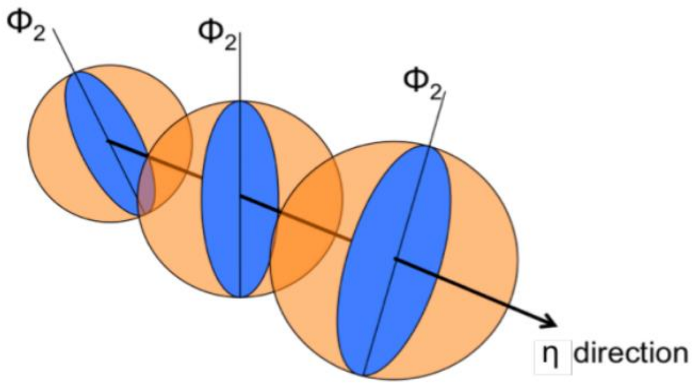
Correlations of flow magnitudes & angles



Bhalerao,Luzum, Ollitrault, PRC 2011; GYQ, Muller, PRC 2012; Jia, Mohapatra, EPJC 2013; Qiu, Heinz, PRC 2013; Qian, Heinz, He, Huo, PRC 2017, Zhao, Xu, Song, EPJC 2017; etc.

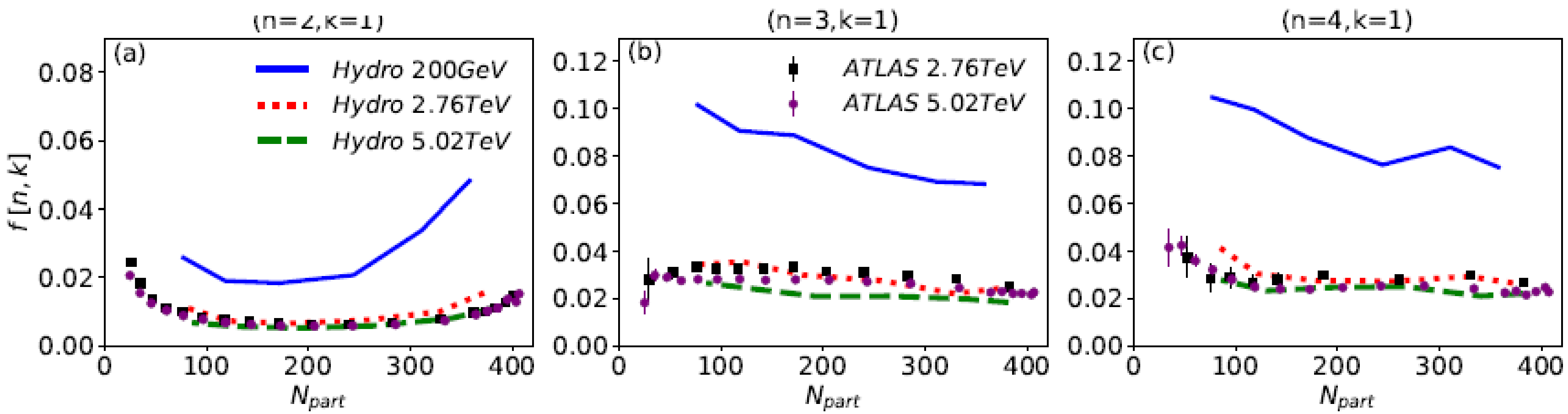
Longitudinal fluctuations and decorrelations





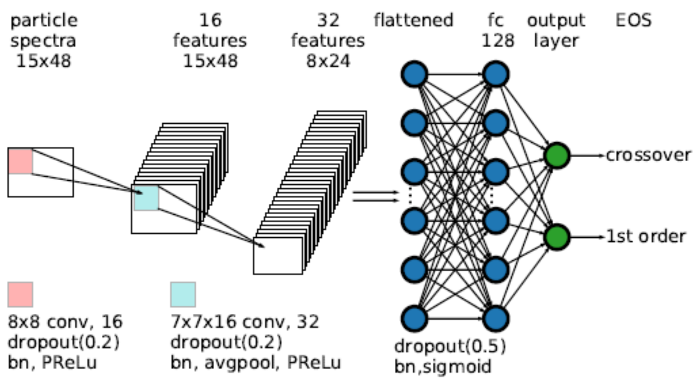
$$r[n,k](\eta) = \frac{\langle \mathrm{Q}_n^k(-\eta)\mathrm{Q}_n^{*k}(\eta_\mathrm{r})\rangle}{\langle \mathrm{Q}_n^k(\eta)\mathrm{Q}_n^{*k}(\eta_\mathrm{r})\rangle}$$

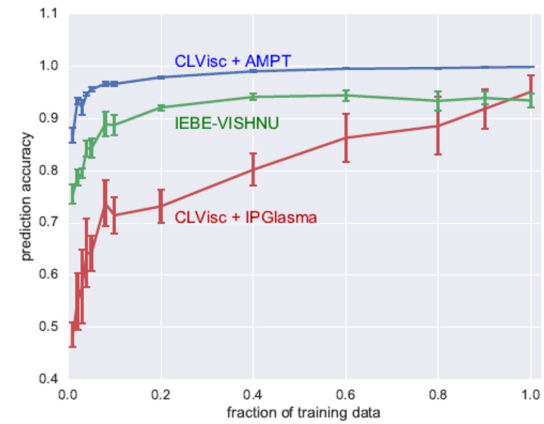
$$r[n,k](\eta) \approx 1 - 2f[n,k]\eta$$

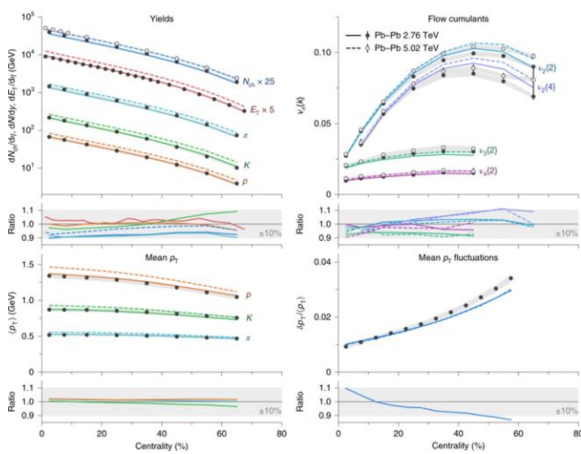


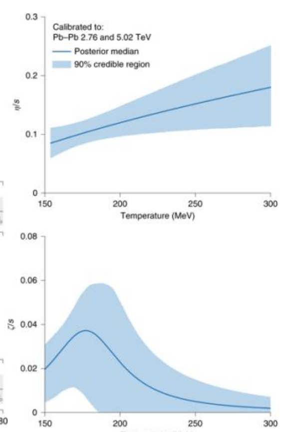
Petersen, Bhattacharya, Bass, Greiner, PRC 2011; Xiao, Liu, Wang, PRC 2013; Pang, GYQ, Roy, Wang, Ma, PRC 2015; Wu, Pang, GYQ, Wang, PRC 2018; etc.

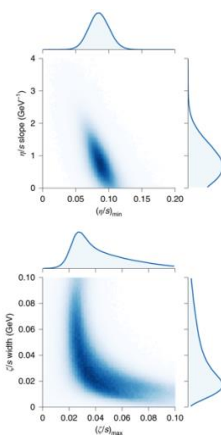
Deep learning & statistical analysis

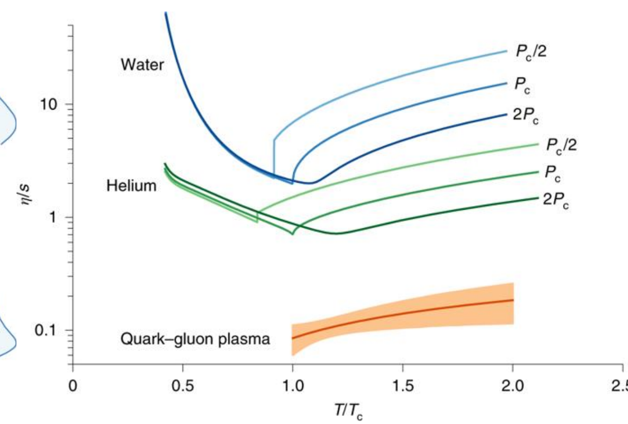










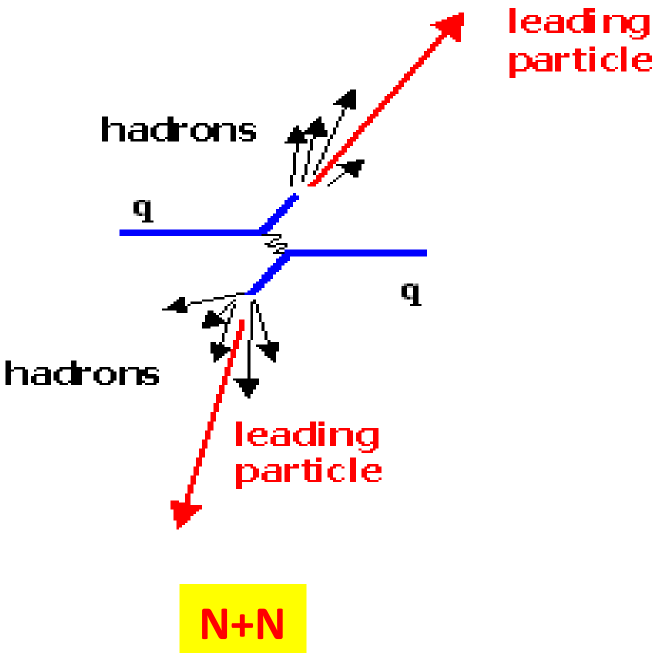


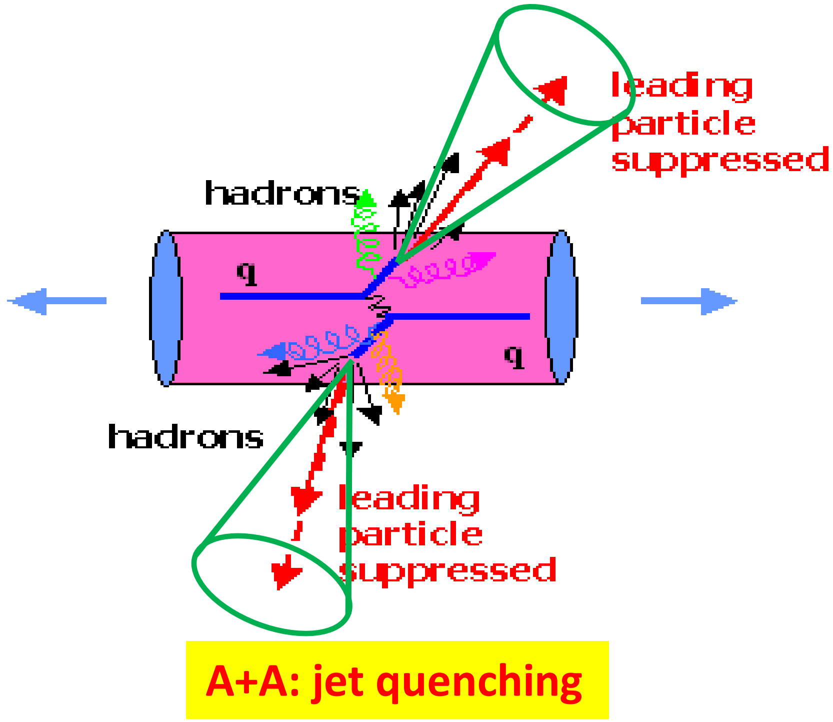
Very powerful tools for connecting final state observables with the QGP properties.

Pang, Zhou, Su, Petersen, Stocker, Wang, Naure Commun. 2018;
Bernhard, Moreland, Bass, Nature Physics 2019

Hard Probes

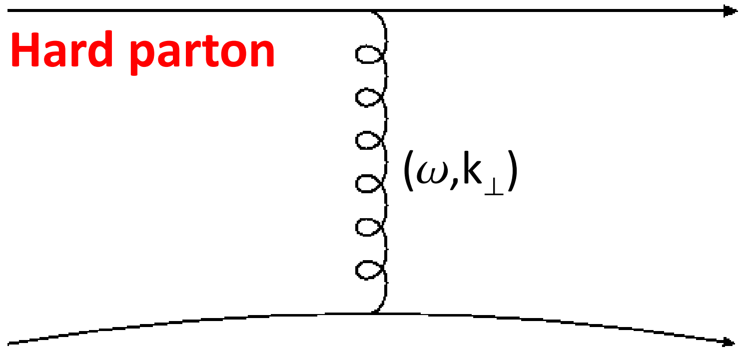
Jet quenching



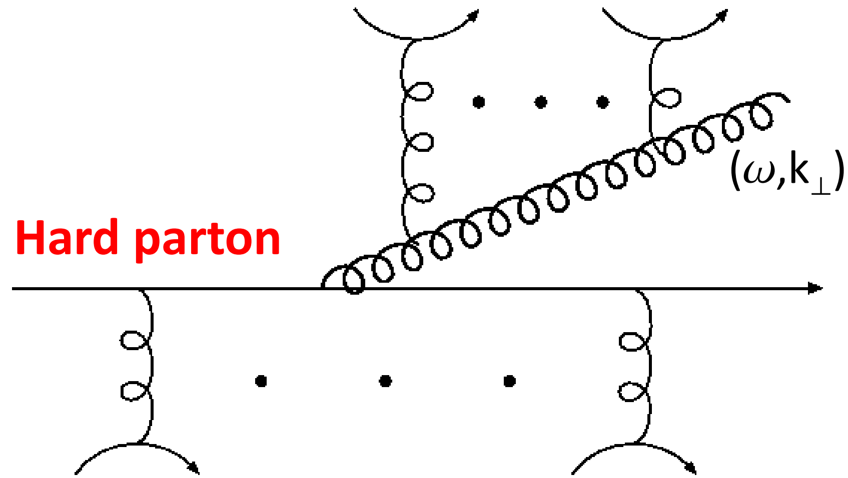


- **Jets and jet-medium interaction (jet quenching) provide valuable tools to probe hot & dense QGP in heavy-ion collisions (at RHIC & LHC):**
- **(1) jet energy loss (2) jet deflection and broadening (3) modification of jet structure/substructure (4) jet-induced medium excitation**

Elastic and inelastic interactions



Elastic (collisional)



Inelastic (radiative)

$$\frac{d\Gamma_{coll}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

$$\frac{d\Gamma_{rad}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

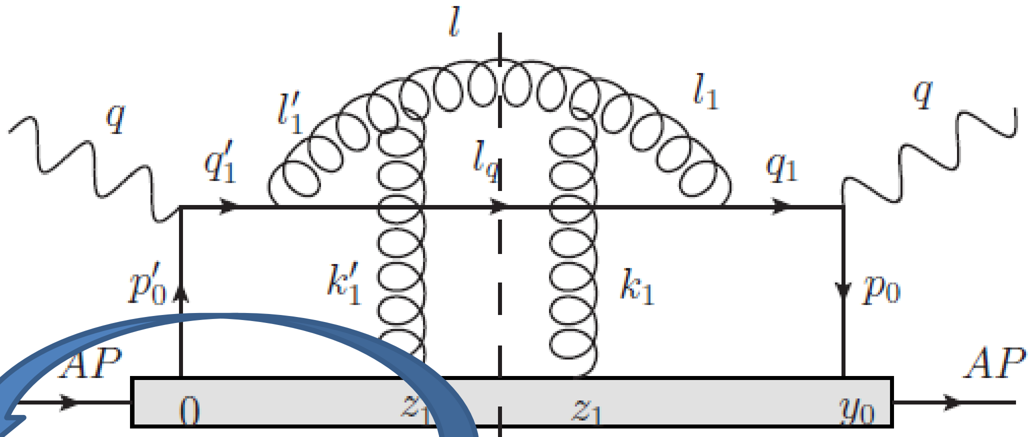
Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic, 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008; …

BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe (& Caron-Huot, Gale)
GLV: Gyulassy-Levai-Vitev (& Djordjevic, Heinz)
HT: Wang-Guo (& Zhang, Wang, Majumder)

Recent developments

- **Include next-to-eikonal corrections within the path integral formalism**
  - Apolinario, Armesto, Milhano, Salgado, JHEP 2015
- **Reinvestigate the GLV formalism by relaxing soft gluon emission approximation**
  - Blagojevic, Djordjevic, Djordjevic, PRC 2018; Sievert, Vitev, PRD 2018
- **Go beyond multiple soft scattering approximation in the BDMPS-Z formalism**
  - Mehtar-Tani, JEHP 2019; Blok, Tywoniuk, EPJC 2019
- **Generalize the HT formalism by going beyond collinear rescattering expansion & soft gluon emission approximation**
  - Zhang, Hou, GYQ, PRC 2018; PRC 2019 arXiv:1804.00470; Zhang, GYQ, Wang, PRD in press
- **Investigate the interference between sequential gluon emissions**
  - Casalderrey-Solana, Pablos, Tywoniuk, JHEP 2016; Arnold, Chang, Iqbal, JHEP 2015; JHEP 2016

Medium-induced inelastic (radiative) process



Zhang, Hou, GYQ, PRC 2018 & PRC 2019; Zhang, GYQ, Wang, PRD in press

+ other 20 diagrams

$$\frac{dN_g^{med}}{dy\,d^2\mathbf{l}_\perp} = \frac{\alpha_s}{2\pi^2}P(y)\int dZ_1^-\int\frac{dk^-d^2\mathbf{k}_{1\perp}}{(2\pi)^3}\mathcal{D}(k_1^-,\mathbf{k}_{1\perp})$$

$$\times\left\{\left[2-2\cos\left(\frac{y(1-y)}{(y-\lambda_1^-)\,(1+\lambda_1^--y)}\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+(y-\lambda_1^-)^2M^2}{l_\perp^2+y^2M^2}\frac{Z_1^-}{\tilde{\tau}^-_{\rm form}}\right)\right]\right.$$

$$C_A\left[\frac{1+(1+\lambda_1^--y)^2}{1+(1-y)^2}\left(\frac{y-\frac{\lambda_1^-}{2}}{y-\lambda_1^-}\right)^2\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+\frac{(y-\lambda_1^-)^4M^2}{1+(1+\lambda_1^--y)^2}}{\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+(y-\lambda_1^-)^2M^2\right]^2}\right.$$

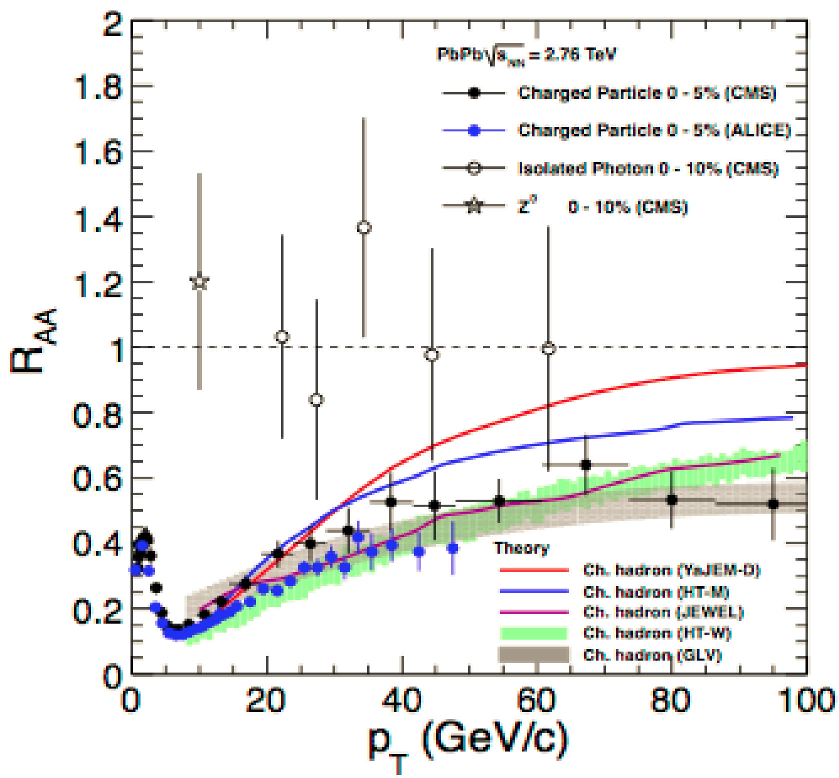
$$-\frac{1+(1+\lambda_1^--y)(1-y)}{2[1+(1-y)^2]}\left(\frac{y-\frac{\lambda_1^-}{2}}{y-\lambda_1^-}\right)\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-\mathbf{k}_{1\perp})+\frac{y^2(y-\lambda_1^-)^2}{1+(1+\lambda_1^--y)(1-y)}M^2}{[l_\perp^2+y^2M^2]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+(y-\lambda_1^-)^2M^2\right]}$$

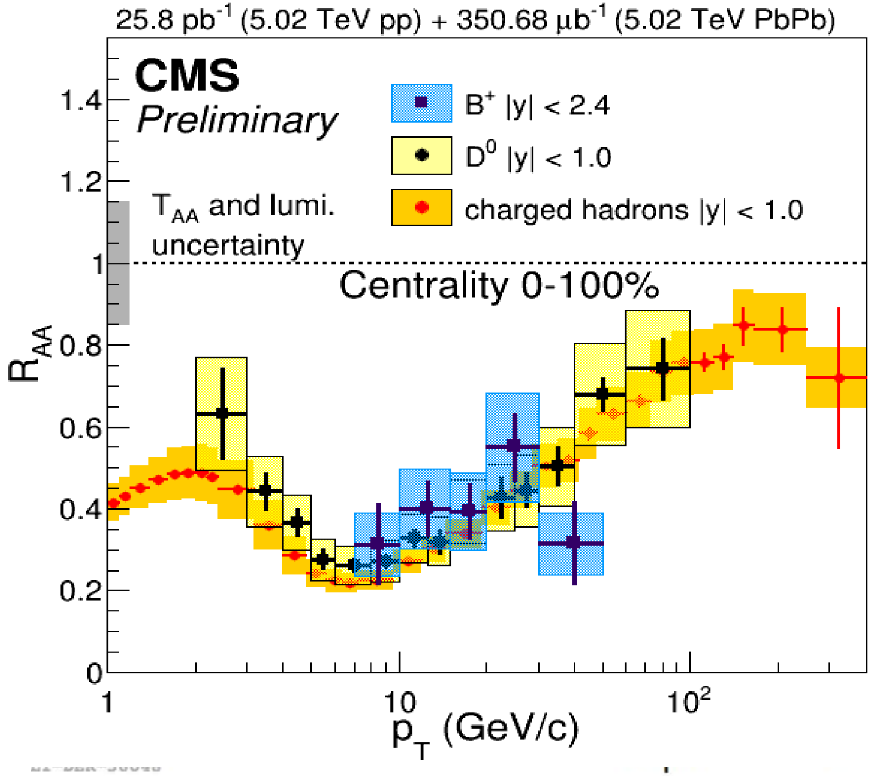
$$\left.\left.-\frac{1+(1+\lambda_1^--y)(1-\frac{y}{1+\lambda_1^-})}{2[1+(1-y)^2]}\left(\frac{y-\frac{\lambda_1^-}{2}}{y-\lambda_1^-}\right)\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})\cdot\left(\mathbf{l}_\perp-\frac{y}{1+\lambda_1^-}\mathbf{k}_{1\perp}\right)+\frac{\left(\frac{y}{1+\lambda_1^-}\right)^2(y-\lambda_1^-)^2}{1+(1+\lambda_1^--y)(1-\frac{y}{1+\lambda_1^-})}M^2}{\left[\left(\mathbf{l}_\perp-\frac{y}{1+\lambda_1^-}\mathbf{k}_{1\perp}\right)^2+(\frac{y}{1+\lambda_1^-})^2M^2\right]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+(y-\lambda_1^-)^2M^2\right]}\right]+\ldots\ldots\right\}$$

$$\mathcal{D}(k_1^-,\mathbf{k}_{1\perp})=(2\pi)^3\frac{dP_{\rm el}}{dk_1^-d^2\mathbf{k}_{1\perp}dZ_1^-}$$

Medium-induced gluon emission beyond collinear expansion & soft emission limit with transverse & longitudinal scatterings for massive/massless quarks

Nuclear modifications of large p_T hadrons





$$R_{AA} = \frac{1}{N_{\mathrm{coll}}} \frac{dN^{AA} / d^2 p_T dy}{dN^{pp} / d^2 p_T dy}$$

Color & flavor dependences of parton energy loss: $\Delta E_g > \Delta E_{uds} > \Delta E_c > \Delta E_b$?

Linearized Boltzmann Transport (LBT) Model

- **Boltzmann equation:** $p_1 \cdot \partial f_1(x_1, p_1) = E_1 C[f_1]$
- **Elastic collisions:**

$$\Gamma_{12\to34} = \frac{\gamma_2}{2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \times f_2(\vec{p}_2) \left[1 \pm f_3(\vec{p}_1 - \vec{k})\right] \left[1 \pm f_4(\vec{p}_2 + \vec{k})\right] \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) |\mathcal{M}_{12\to34}|^2$$

$$P_{el} = 1 - e^{-\Gamma_{el}\Delta t}$$

Matrix elements taken from LO pQCD

- **Inelastic collisions:**

$$\langle N_g \rangle = \Gamma_g \Delta t = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

$$P_{inel} = 1 - e^{-\langle N_g \rangle}$$

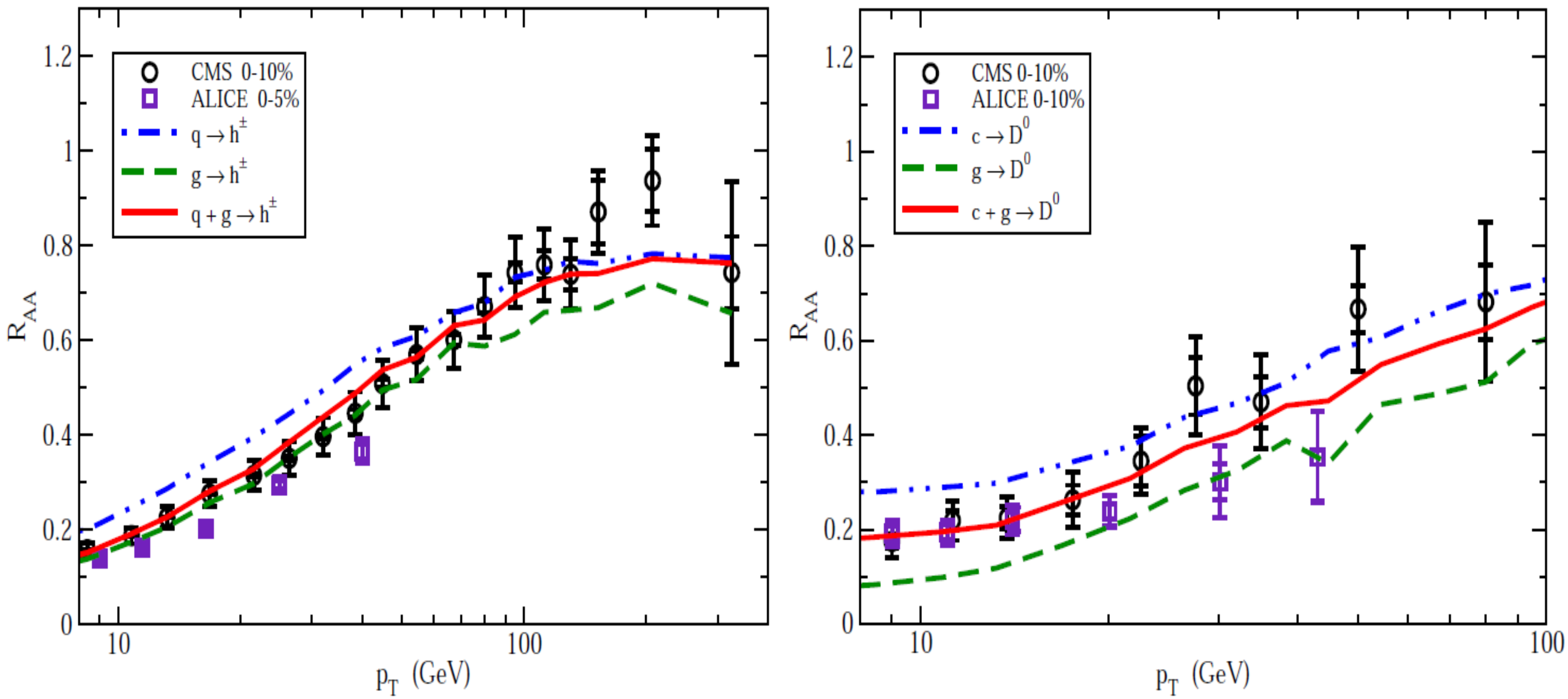
Radiation spectra taken from Guo, Wang PRL 2000; Zhang, Wang, Wang 2004

- **Elastic + Inelastic:**

$$P_{tot} = 1 - e^{-\Gamma_{tot}\Delta t} = P_{el} + P_{inel} - P_{el}P_{inel}$$

He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016, PLB 2018; etc.

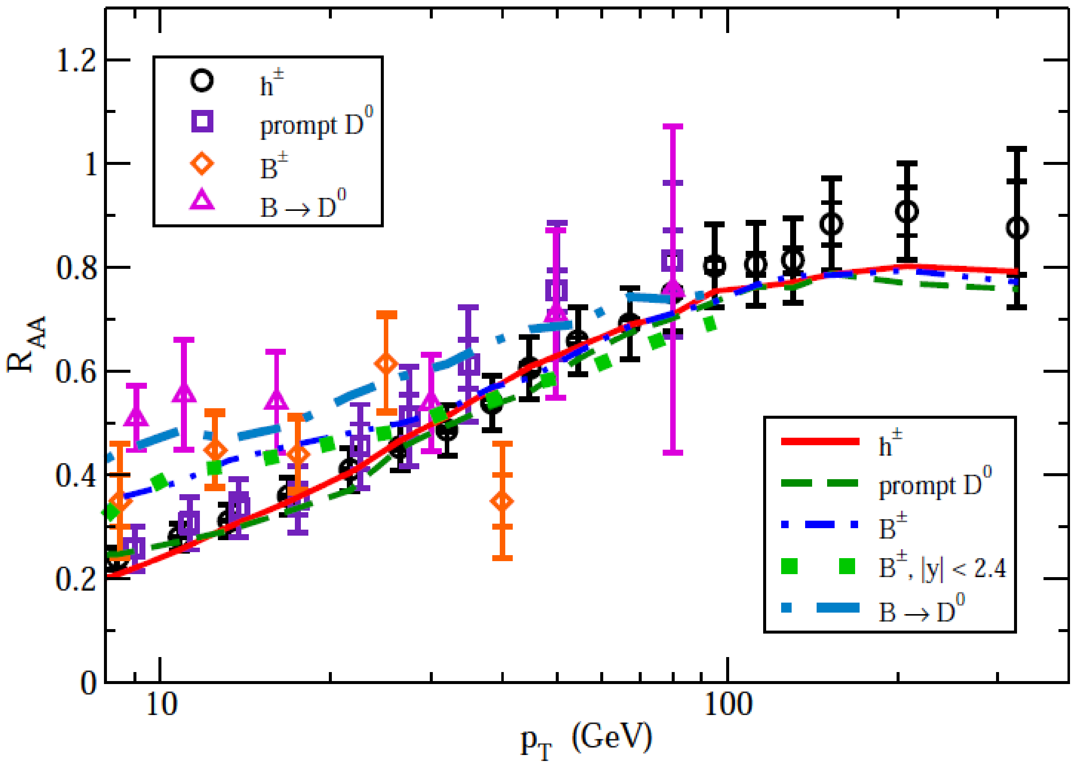
Charged hadron & D meson R_{AA}



- **A state-of-art jet quenching framework (NLO-pQCD + LBT + Hydrodynamics)**
- **Quark-initiated hadrons have less quenching effects than gluon-initiated hadrons.**
- **Combining both quark and gluon contributions, we obtain a nice description of charged hadron & D meson R_{AA} over a wide range of p_T.**

Xing, Cao, Qin, Xing, arXiv:1906.00413

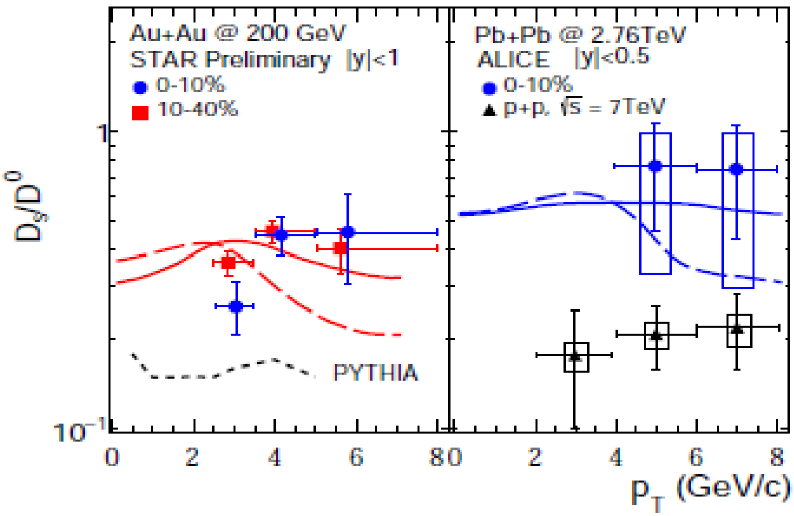
Flavor hierarchy of jet quenching

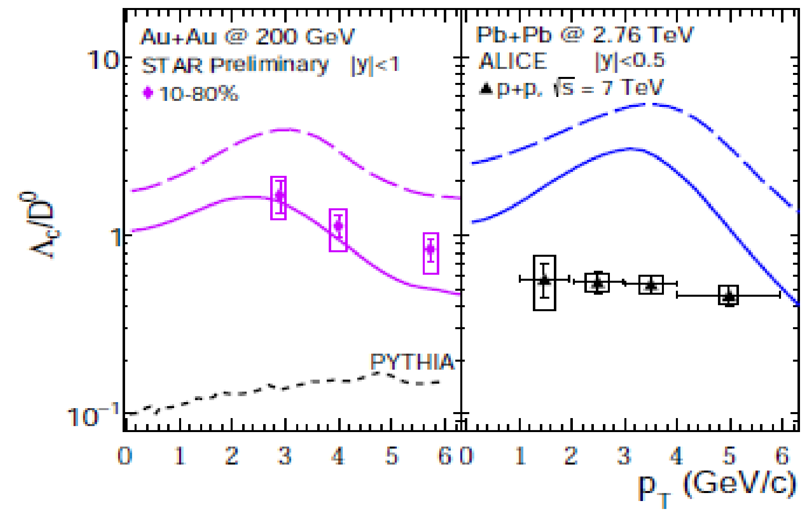


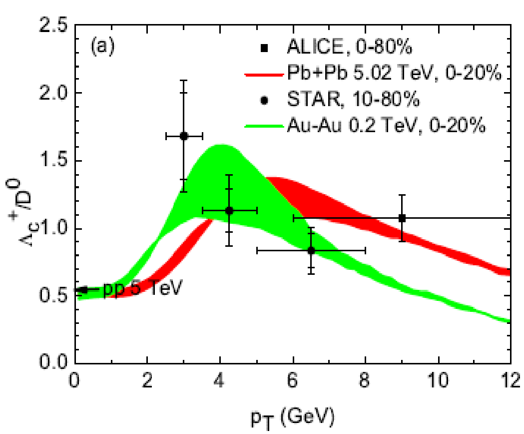
- A state-of-art jet quenching framework (NLO-pQCD + LBT + Hydrodynamics)
- At p_T > 30-40 GeV, B mesons will also exhibit similar suppression effects to charged hadrons and D mesons, which can be tested by future measurements.

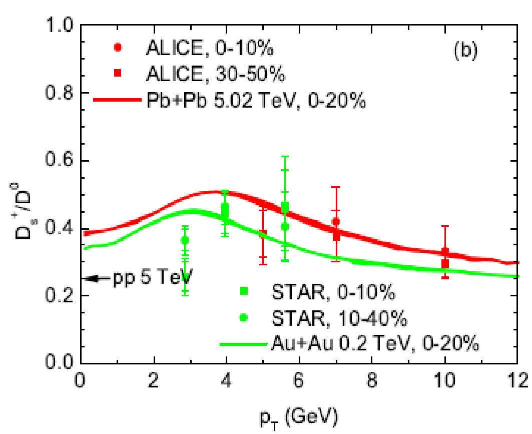
Xing, Cao, Qin, Xing, arXiv:1906.00413

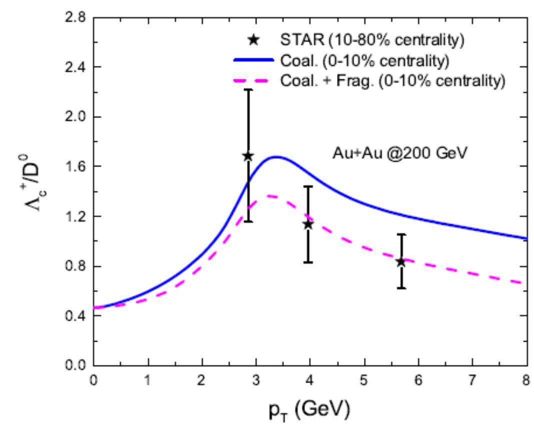
Heavy quark hadronization





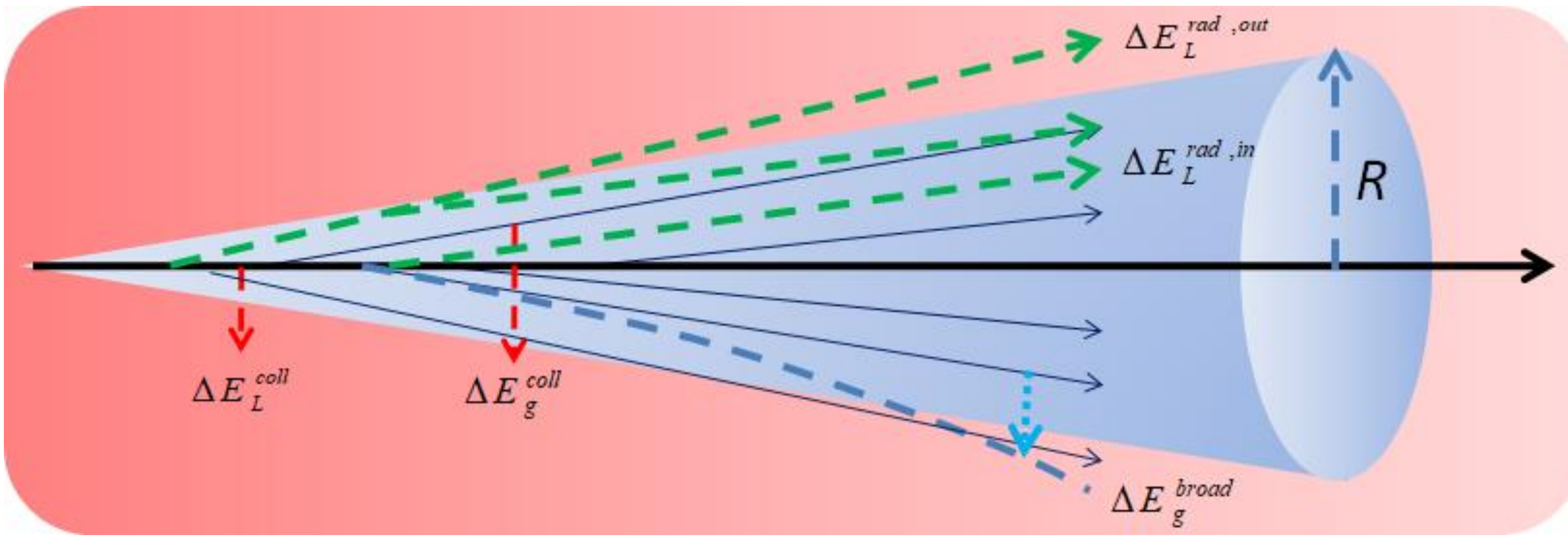






Zhao, Shi, Xu, Zhuang, arXiv:1805.10858; He, Ralf, arXiv:1905.09216; Cho, Sun, Ko, Oh, arXiv:1905.09774; etc.

Full jet evolution & energy loss in medium



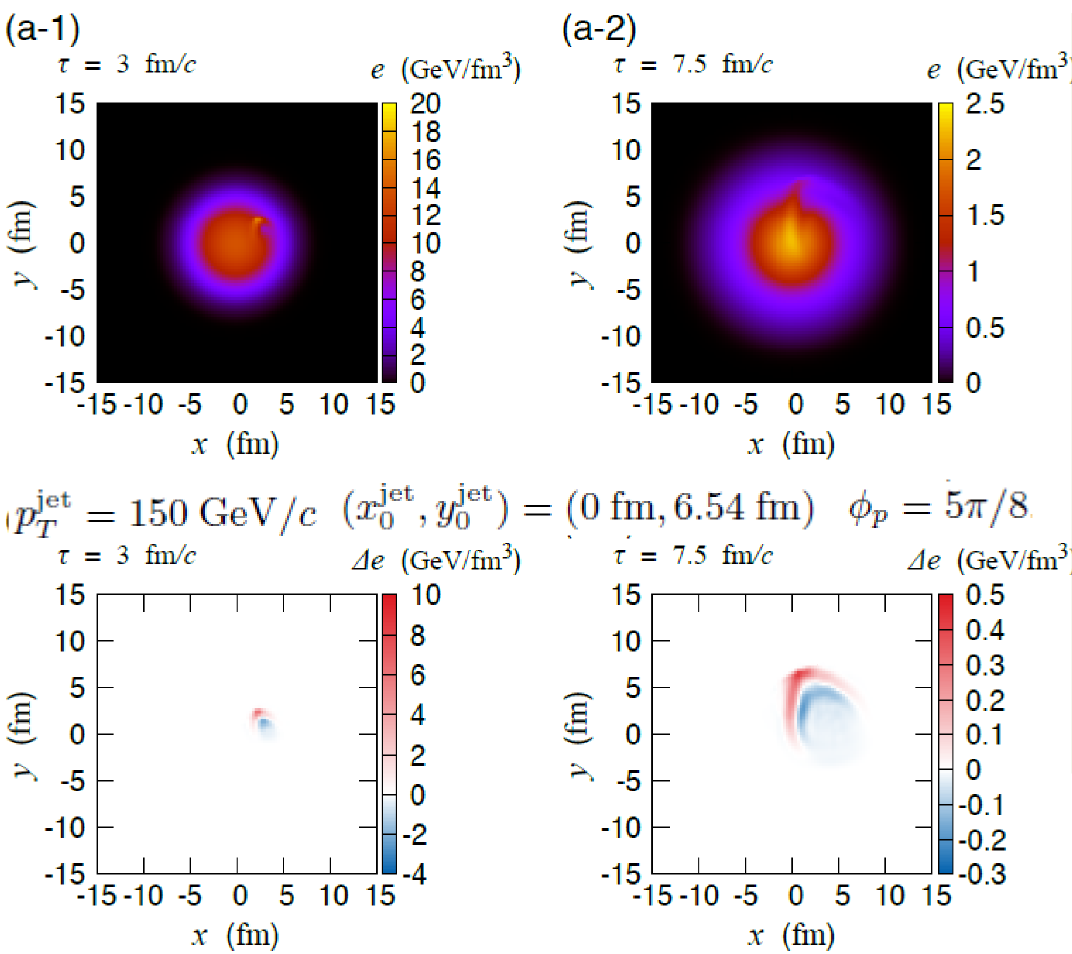
$$E_{jet} = E_{in} + E_{lost} = E_{in} + E_{rad,out} + E_{kick,out} + (E_{th} - E_{th,in})$$

Vitev, Zhang, PRL 2010; GYQ, Muller, PRL, 2011; Casalderrey-Solana, Milhano, Wiedemann, JPG 2011; Young, Schenke, Jeon, Gale, PRC, 2011; Dai, Vitev, Zhang, PRL 2013; Wang, Zhu, PRL 2013; Blaizot, Iancu, Mehtar-Tani, PRL 2013; etc.

Jet evolution & medium response

$$\frac{df(\vec{p},t)}{dt} = C_{coll.E.loss}[f] + C_{coll.broad}[f] + C_{rad}[f]$$

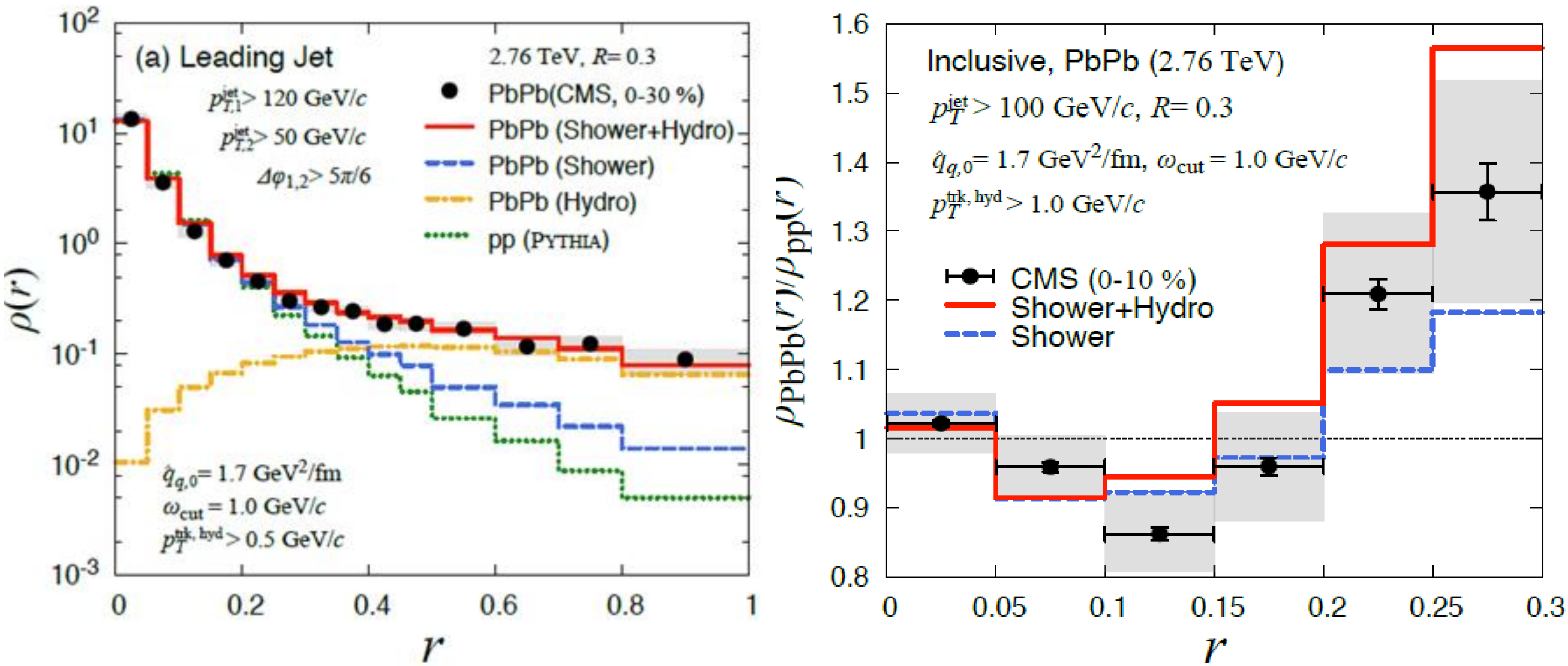
$$\partial_\mu T^{\mu\nu}_{\rm QGP}(x) = J^\nu(x) = -\partial_\mu T^{\mu\nu}_{\rm jet}(x) = -\frac{dP^\nu_{\rm jet}}{dt d^3x} = -\sum_j \int \frac{d^3k_j}{\omega_j} k_j^\nu k_j^\mu \partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)$$



- V-shaped wave fronts are induced by the jet, and develop with time
- The wave fronts carry the energy & momentum, propagates outward & lowers energy density behind the jet
- Jet-induced flow and the radial flow of the medium are pushed and distorted by each other

Chang, GYQ, PRC 2016
Tachibana, Chang, GYQ, PRC 2017
Chang, Tachibana, GYQ, 1906.09562

Effect of jet-induced flow on jet shape



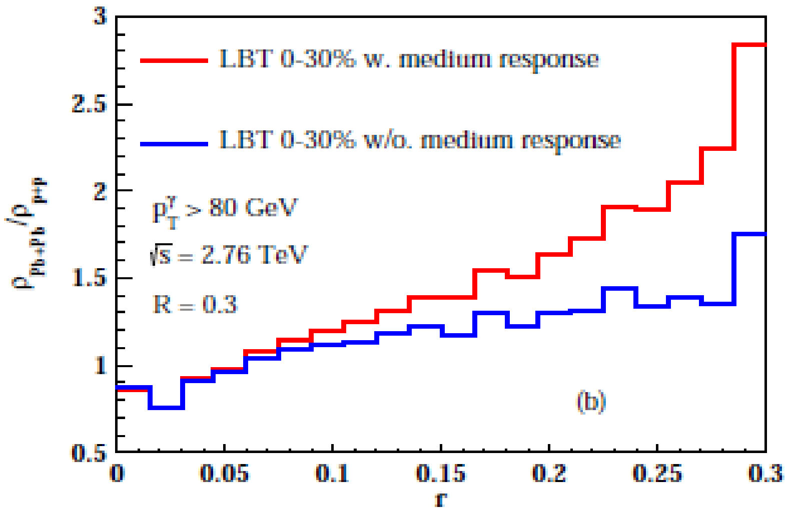
The inclusion of jet-induced medium flow does not modify jet shape at small r, but significantly enhance jet broadening effect at large r (r > 0.2-0.25).

The contribution from the hydro part is quite flat and finally dominates over the shower part in the region from r = 0.4-0.5.

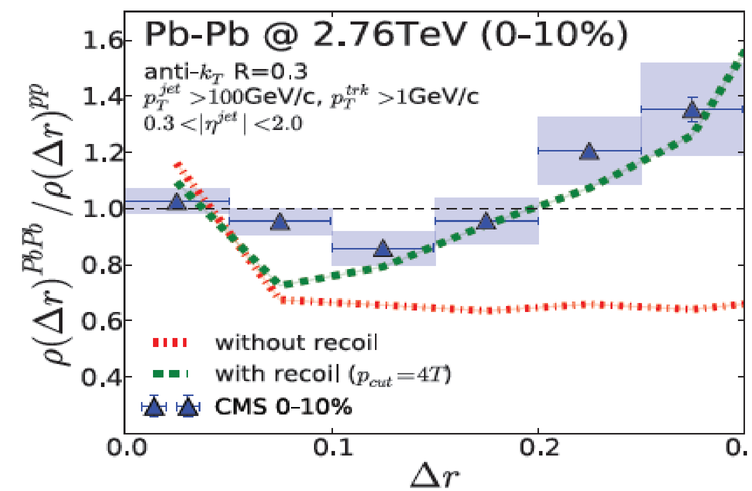
Signal of jet-induced medium excitation in full jet shape at large r.

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, 1906.09562

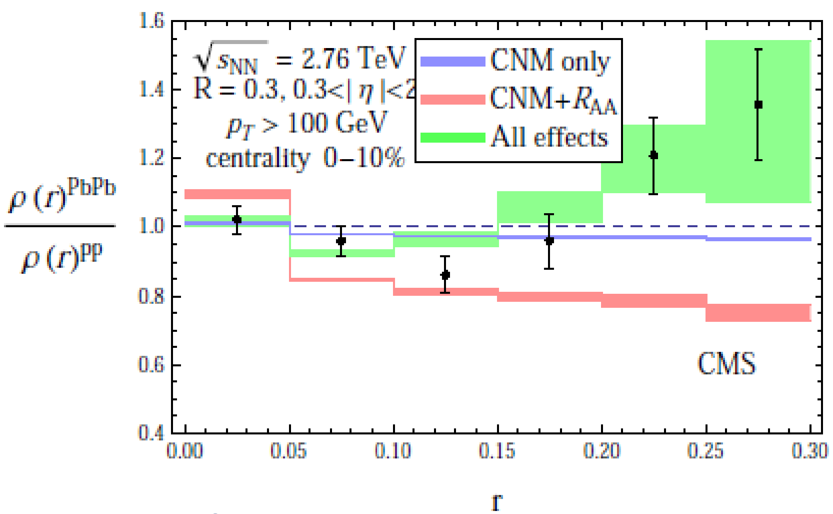
Effect of jet-induced flow on jet shape



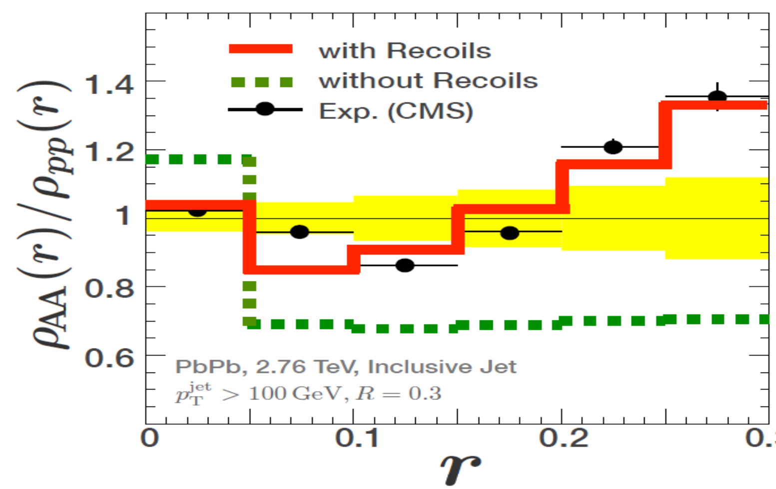
Luo, Cao, He, Wang, PLB 2018



C. Park, S. Jeon, C. Gale, 2018

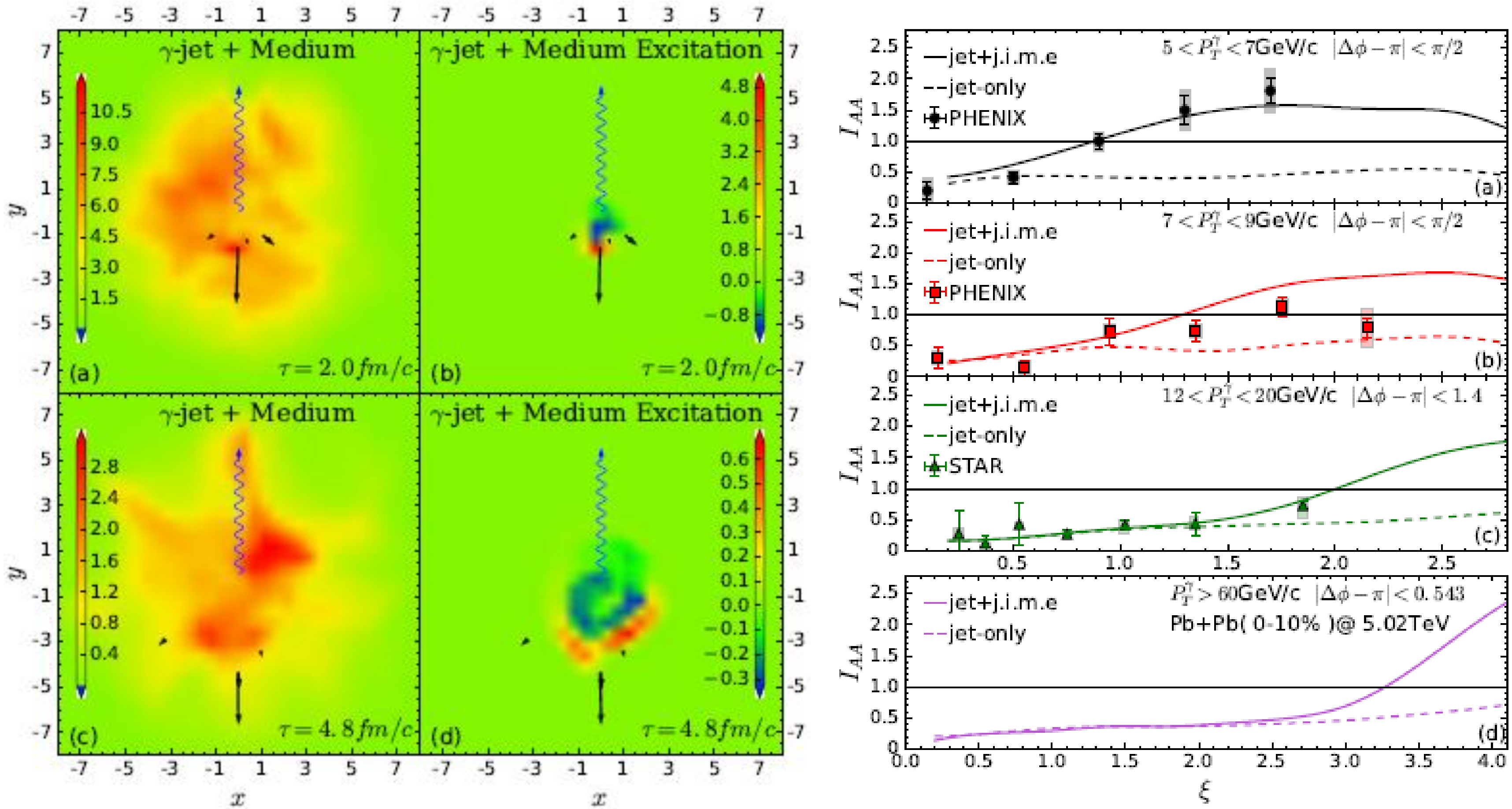


Chien, Vitev, JHEP 2016



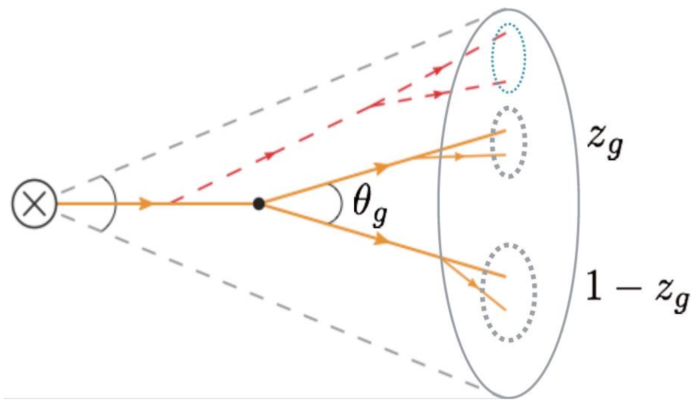
Elayavalli, Zapp, JHEP 2017

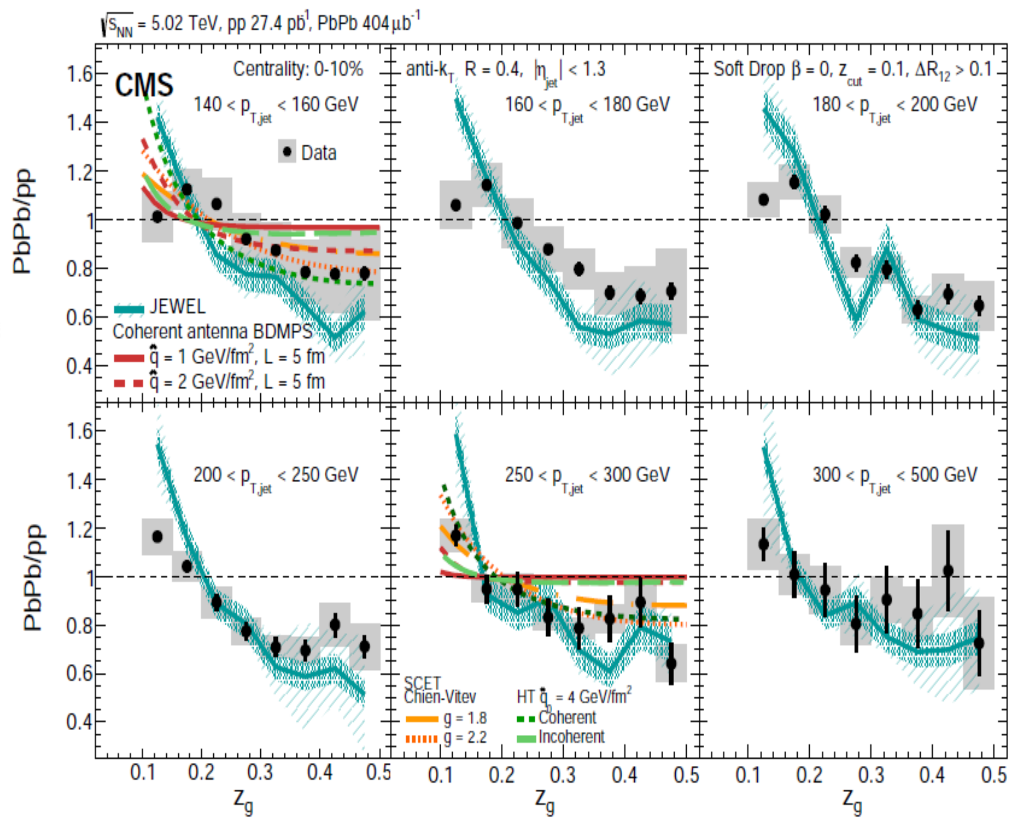
Effect of jet-induced flow in γ-hadron correlations



Chen, Cao, Luo, Pang, Wang, PLB 2018

Jet substructure via soft-drop grooming

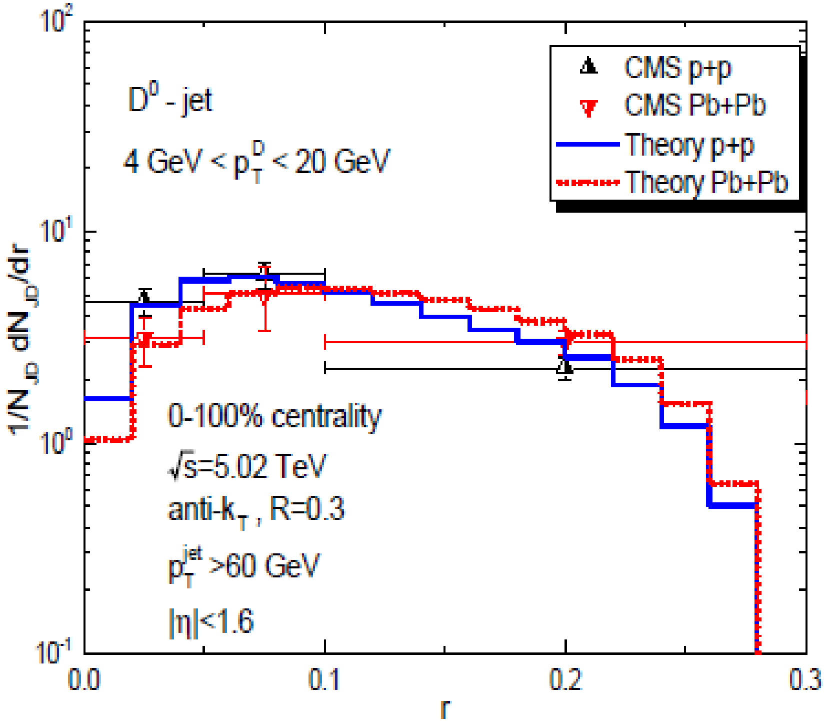


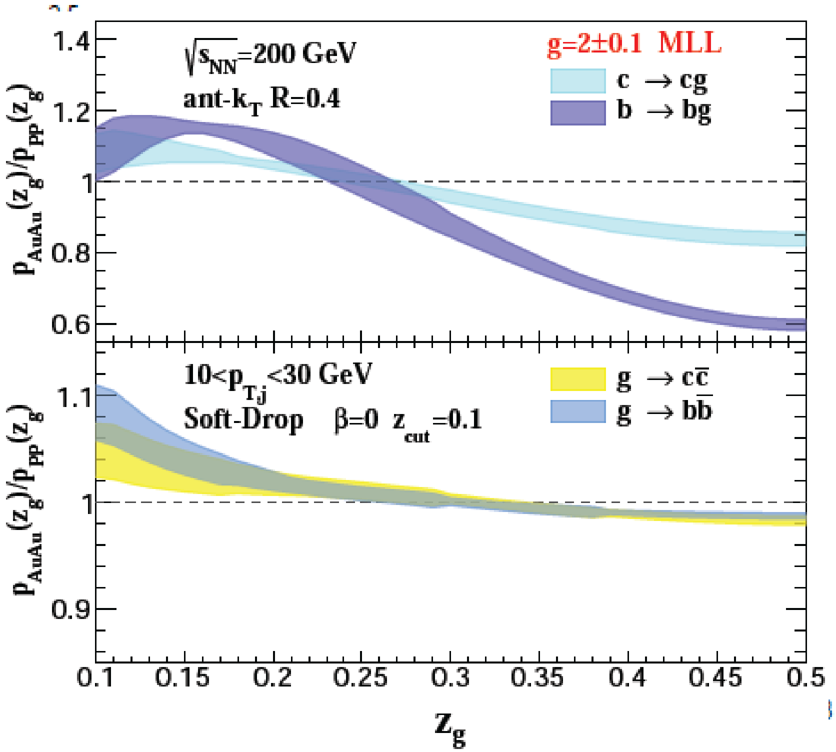


- **Recursively remove soft wide angle radiation from a jet**
- **Recluster anti-k_T jet with Cambridge/Aachen (C/A) algorithm, then de-cluster the angular-ordered C/A tree by dropping soft branches**

Butterworth, Davison, Rubin,Salam, PRL (2008); Larkoski, Marzani, Soyez, Thaler, JHEP (2014); Larkoski, Marzani, Thaler, PRD (2015)
Chien, Vitev, PRL 2017; Mehtar-Tani, Tywoniuk, JHEP 2017; Chang, Cao, GYQ, PLB 2018; etc.

Heavy quark jet (structure/substructure)





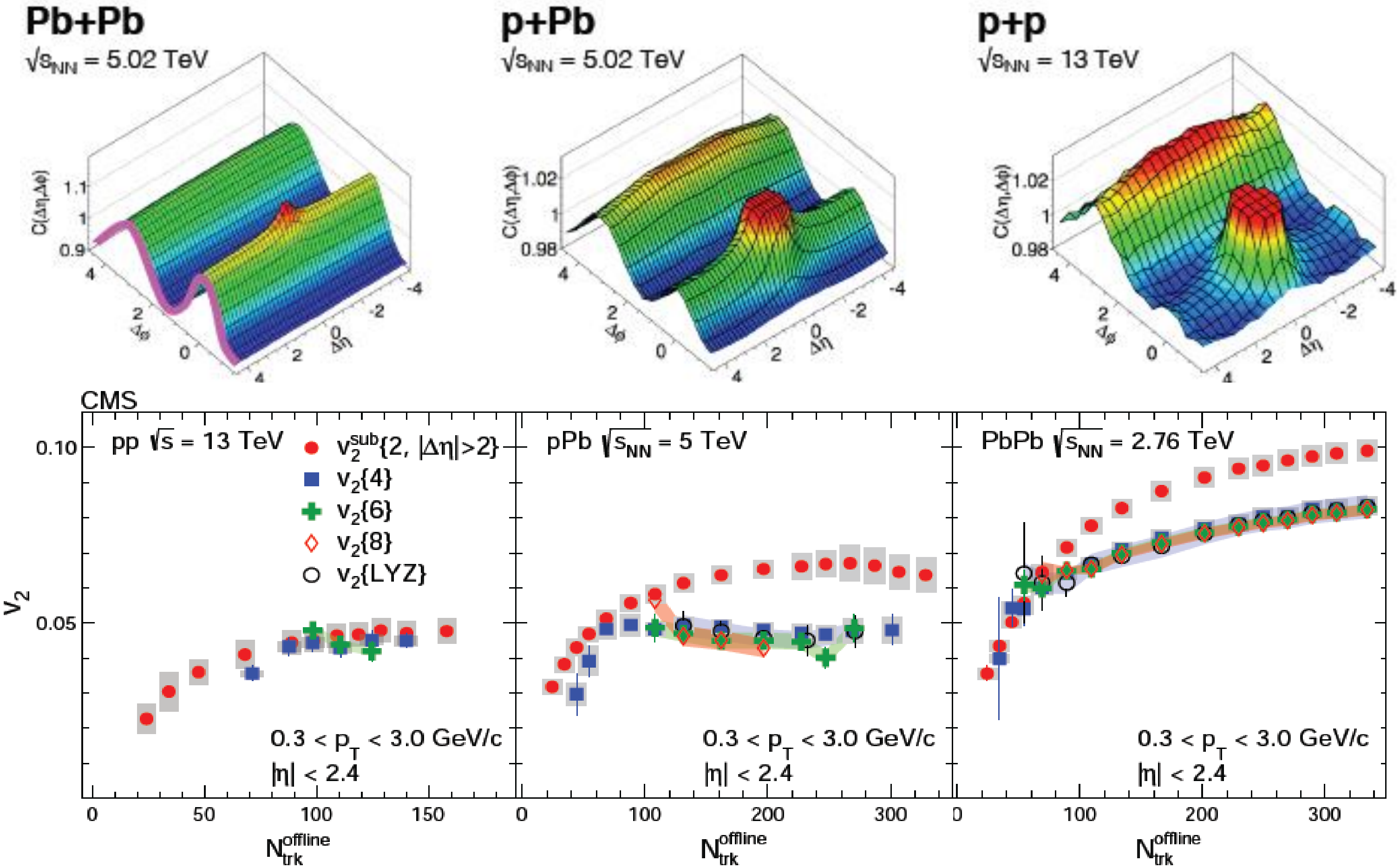
- The radial distribution of D mesons in jets shifts to the larger radius can be explained by the diffusion of charm quarks in jets inside the QGP medium
- The substructure of heavy flavor jets and its medium modification are different from that of light flavor jets

Wang, Dai, Zhang, Wang, EPJC 2019; Li, Vitev, PLB 2019

Small systems

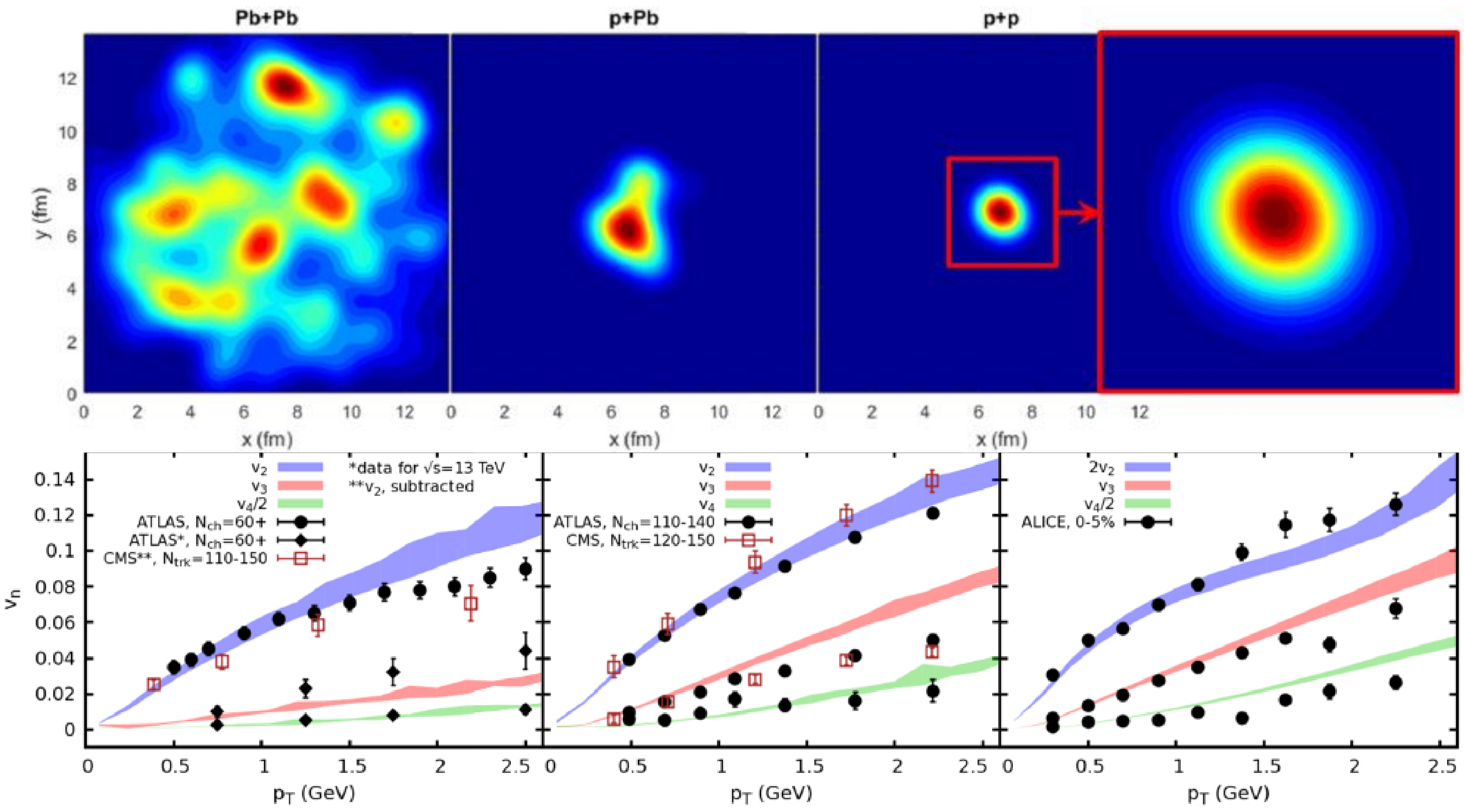
Flow in small collision systems

- **Plenty of evidences for strong collectivity in small collision systems**



What is the dynamical origin of the observed collectivity?

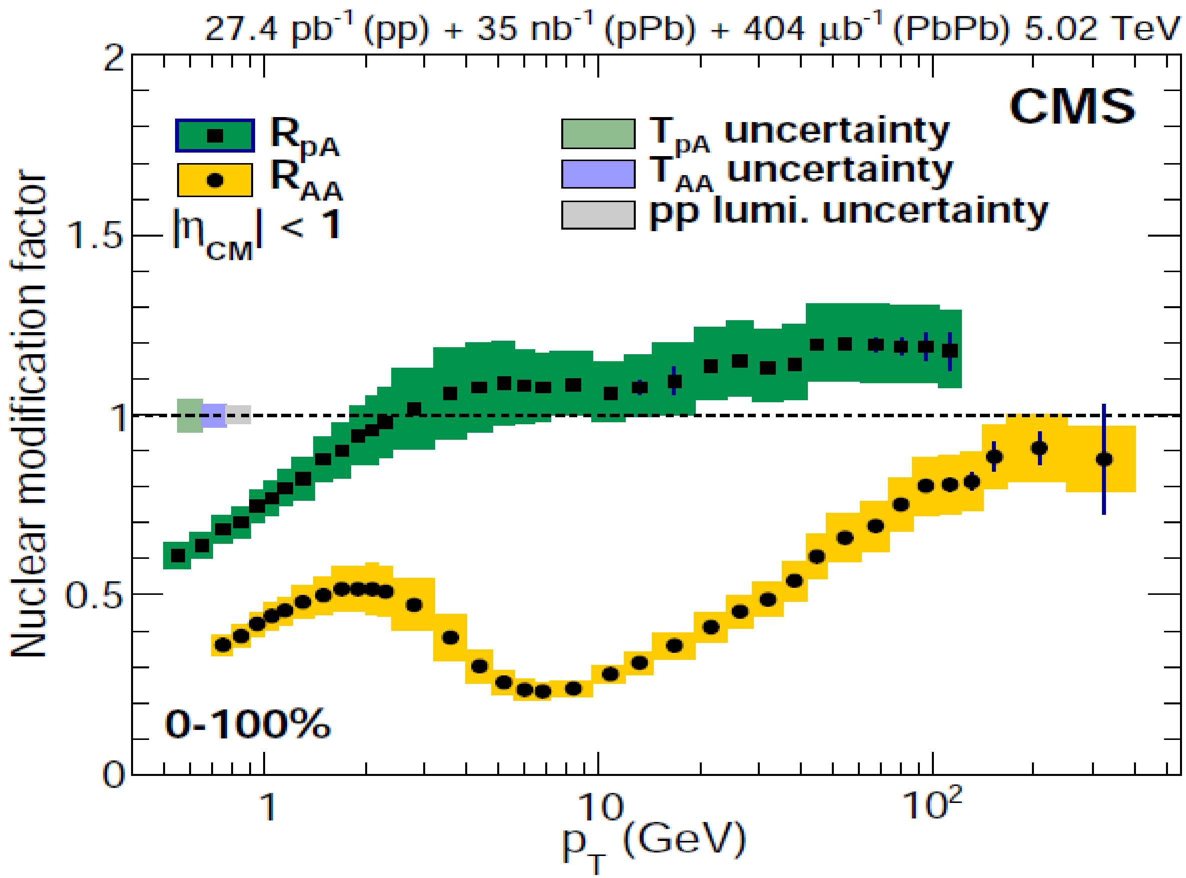
Final state effect?



- **The flow harmonics can be viewed as the final-state effect due to hydrodynamic evolution of small collisional systems with certain amount of initial anisotropy.**

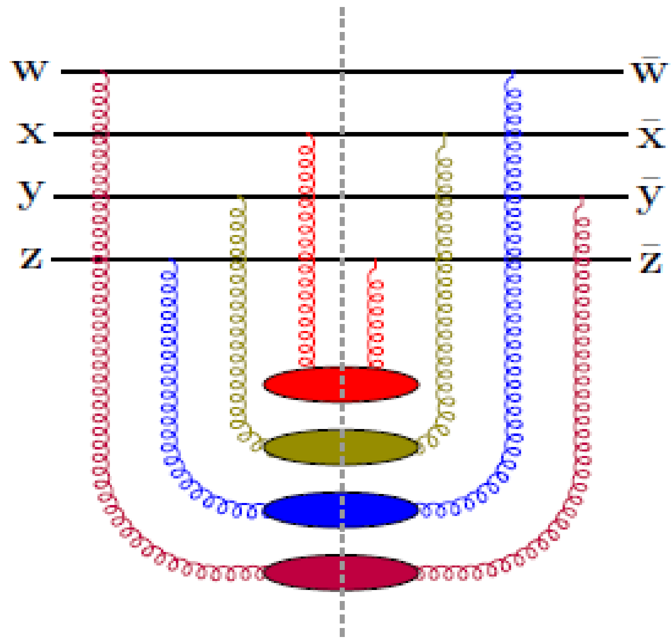
Bozek, Broniowski, Torrieri, PRL 2013; Bzdak, Schenke, Tribedy, Venugopalan, PRC 2013; GYQ, Muller, PRC 2014; Bzdak, Ma, PRL 2014; Weller, Romatschke, PLB 2017; zhao, zhou, xu, deng, song, PLB 2018; etc.

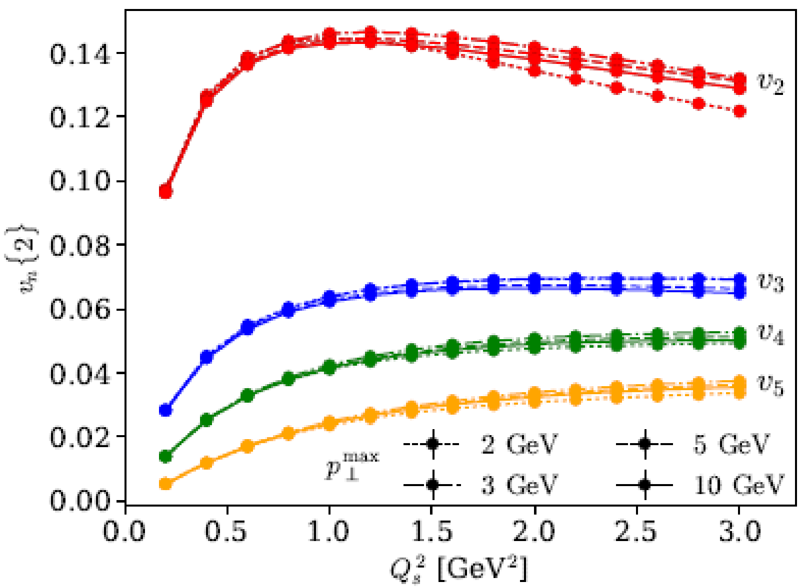
Signature in hard probes?



- **Up to now, there is no jet quenching observed in pA collisions**

Or initial state effect?



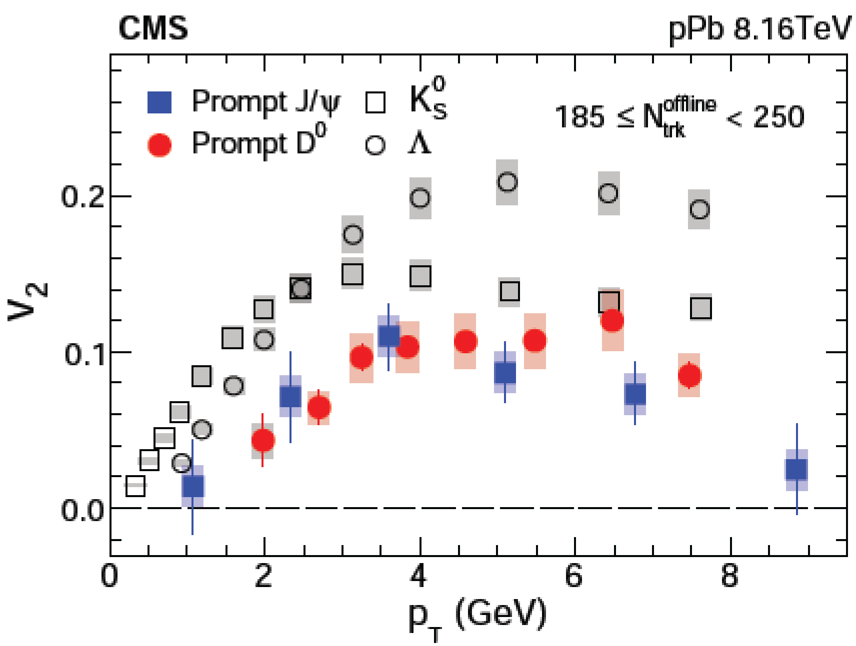


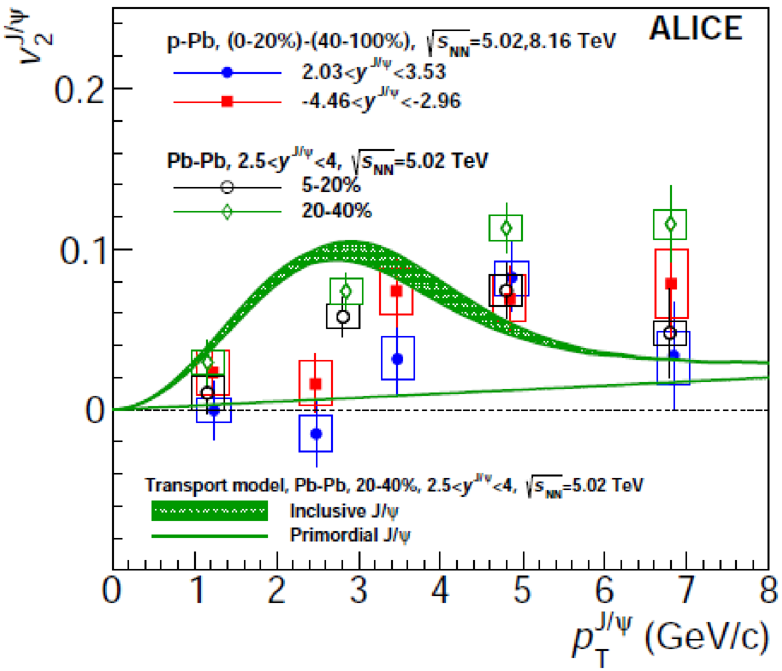
- **In color glass condensate (CGC) dilute-dense factorization framework or the saturation formalism, interactions between partons originated from the projectile proton and dense gluons inside the target nucleus can provide significant amount of collectivity (correlations) among partons.**

Dusling, Mace, Venugopalan, PRL (2018), 1705.00745; PRD (2018), 1706.06260; etc.

Flow of heavy hadrons in small systems

- **Charm hadrons also have sizable collectivity in small collision systems.**



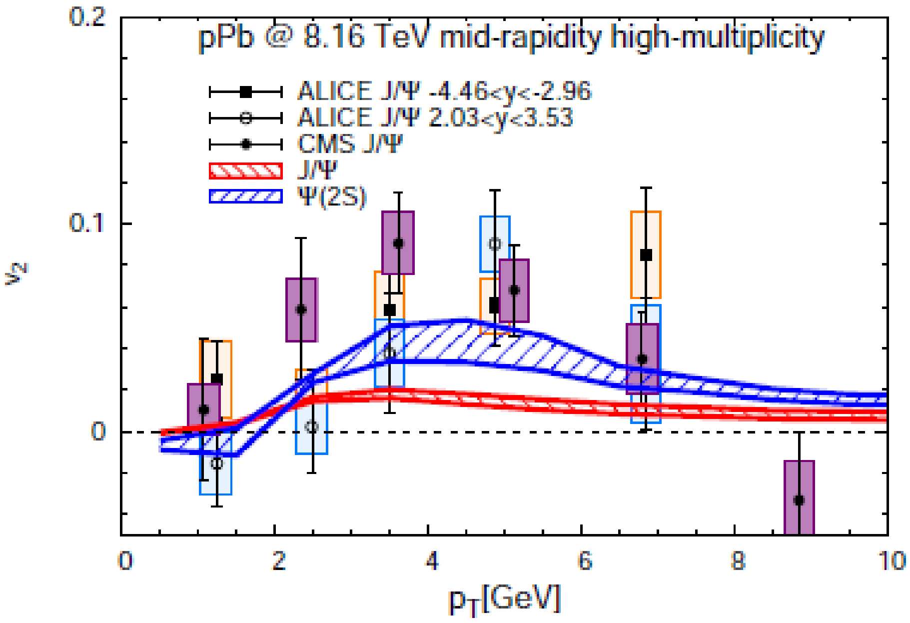


- **Large values of elliptic flow v_2 for J/ψ mesons and for D^0 mesons in pPb collisions at the LHC, although they are slightly less than the v_2 values of light hadrons**

Initial or final state effect?

J/Ψ v_2 from final state interaction

- **It is difficult for hydrodynamics to generate large collectivity for heavy mesons, since heavy quark in general does not flow as much as the light quark or gluon due to the large quark mass.**

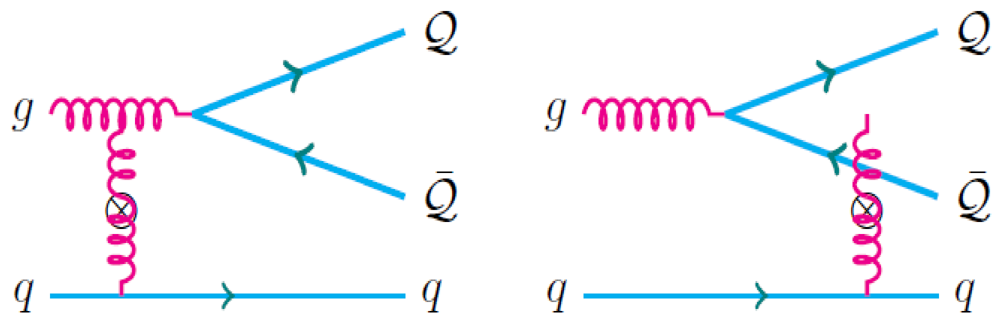


- **The final state interactions can only provide a small fraction of the observed v_2 for J/Ψ mesons**

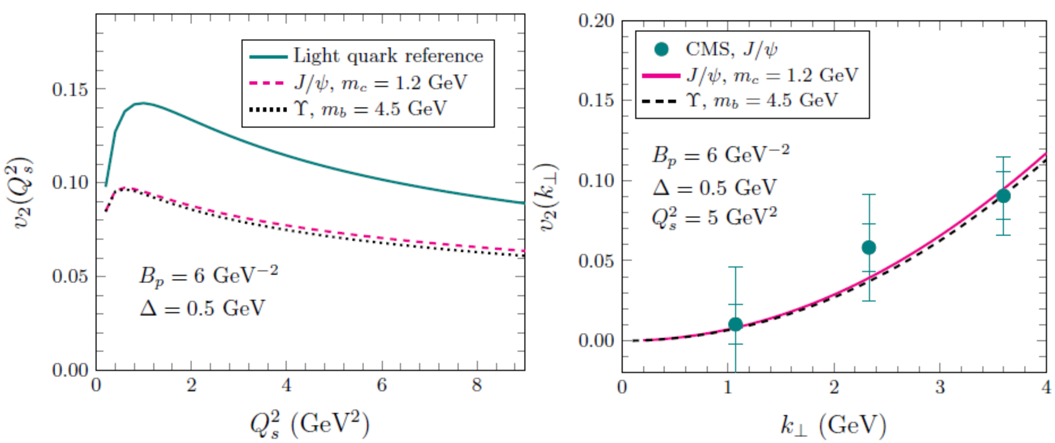
Du, Rapp, JHEP 1903 (2019) 015

J/Ψ v_2 from initial state correlations

- **J/Ψ production together with a reference light quark (which fragments into light hadrons)**
- **Based on the dilute-dense factorization in color glass condensate (CGC) and the color evaporation model (CEM)**
- **J/Ψ v_2 can be generated from the interaction between partons from the proton projectile and dense gluons in the nuclear target**
- **Little mass dependence implies that ϒ should have a similar v_2, which can be tested in future.**



$$v_2[J/\Psi] = V_{2\Delta}[J/\Psi, \mathrm{ref}] \,/\, v_2[\mathrm{ref}]$$



Zhang, Marquet, GYQ, Wei, Xiao, PRL 2019

Summary

- **Soft probes**
  - Explore the bulk properties of the QGP at higher precision with various observables (spectra, flow, fluctuations, correlations, etc.) for different collision energies and system sizes (centralities) using advanced statistical tools

- **Hard probes**
  - Characterize the properties and microscopic structures of the QCD matter via heavy and light flavor jet and jet structure/substructure observables

- **Small systems**
  - Understand the dynamical origins of the collectivity and correlations of heavy and light particles observed in pp, pA and AA collisions