Hydrodynamics and Jet Quenching in Small Systems

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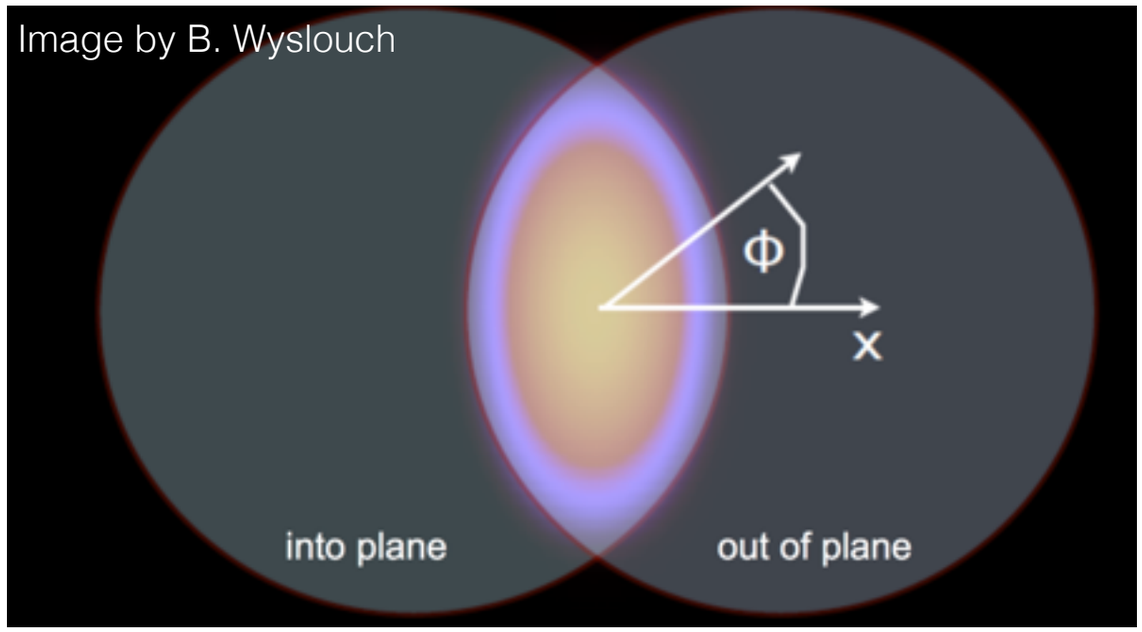
Outline

- Introduction
- Hydrodynamic behaviour in small systems
- Sign of jet quenching in small systems
- Conclusion

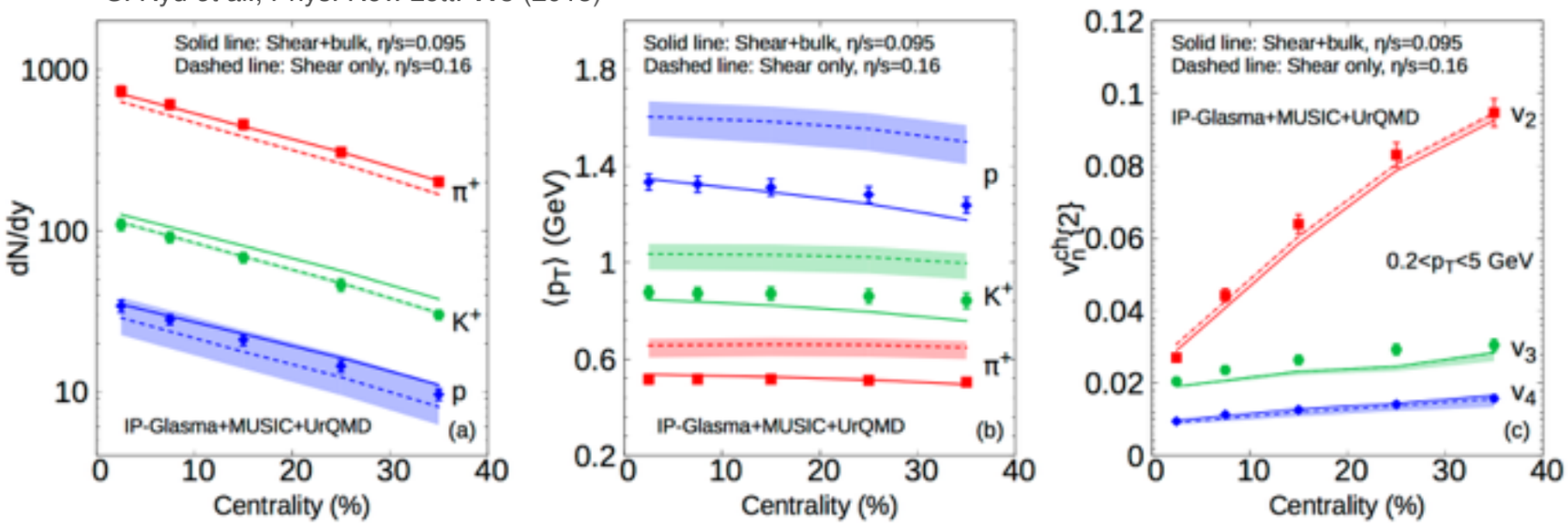
Collectivity in heavy ion collisions



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi)]\right)$$

- Pressure gradients leads to anisotropic flow
- Fourier coefficient corresponding to harmonic flows

S. Ryu *et al.*, Phys. Rev. Lett. **115** (2015)

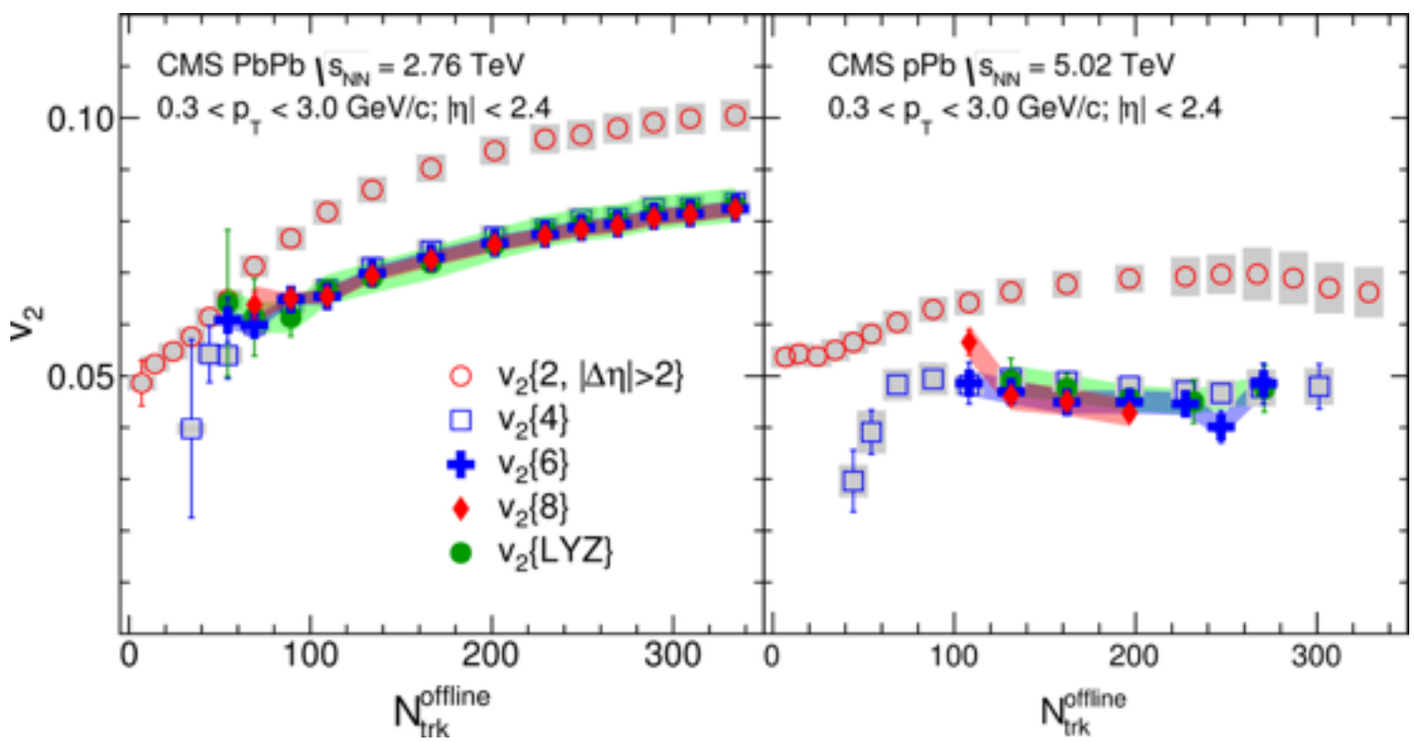


Pb-Pb at 2.76TeV ALICE

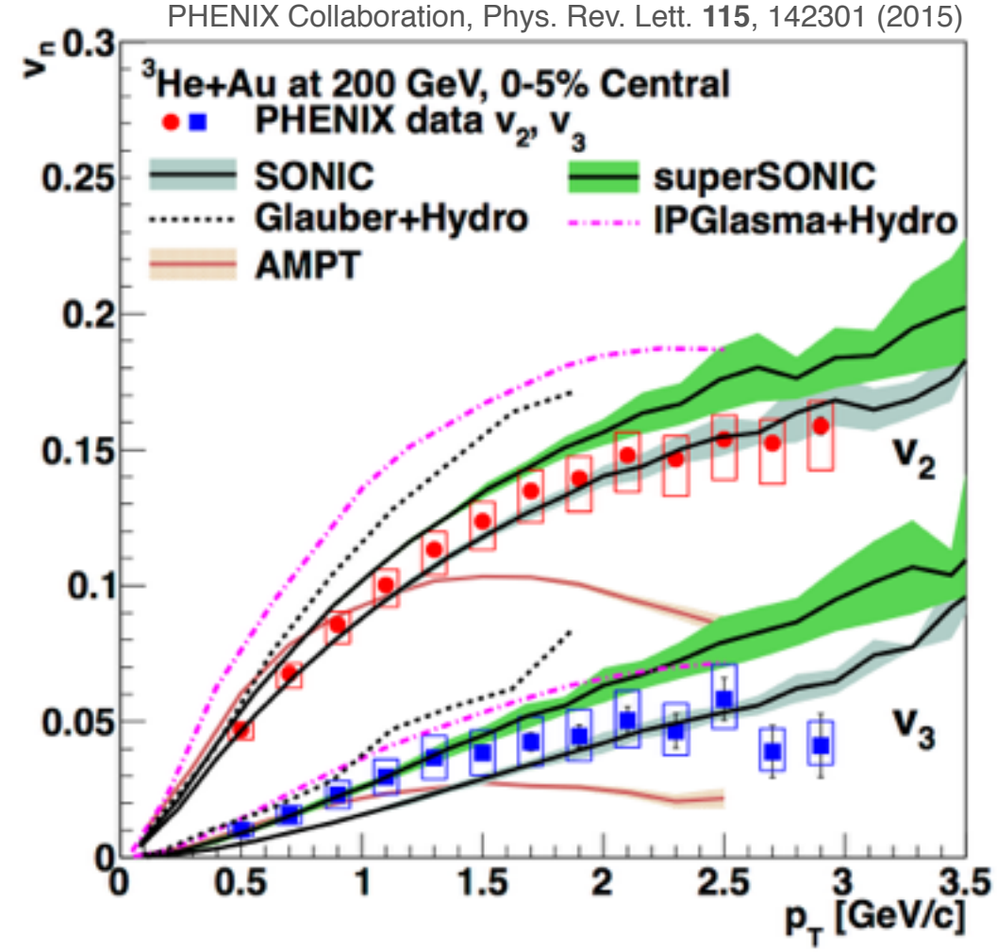
- Collective behavior was observed in AA collisions
- From this, strongly coupled medium was suggested

Collective motion in small systems

CMS Collaboration, Phys. Rev. Lett. **115**, 012301 (2015)



PHENIX Collaboration, Phys. Rev. Lett. **115**, 142301 (2015)



Pb-Pb/p-Pb CMS

^{3}He-Au at 200GeV PHENIX

- Again, collectivity was measured in central small collisions
- Hydrodynamics simulations can qualitatively describe the measurements

Probes for QGP

- Great progress : Clue of QGP in large systems,
  possibly QGP in small systems
- Rare probes can provide supplementary information on the QCD matter

A. Electromagnetic probes - photons

Enhancement of direct photons at low p_T can be observed from a thermalized medium

C. Shen, J.-F. Paquet, G. S. Denicol, S. Jeon and C. Gale, Phys. Rev. Lett. 116, 072301 (2016)

B. Hard probes - jets

Color opacity of a strongly coupled medium leads to jet quenching

C. Shen, C. Park, J. F. Paquet, G. S. Denicol, S. Jeon and C. Gale arXiv:1601.03070 [hep-ph]

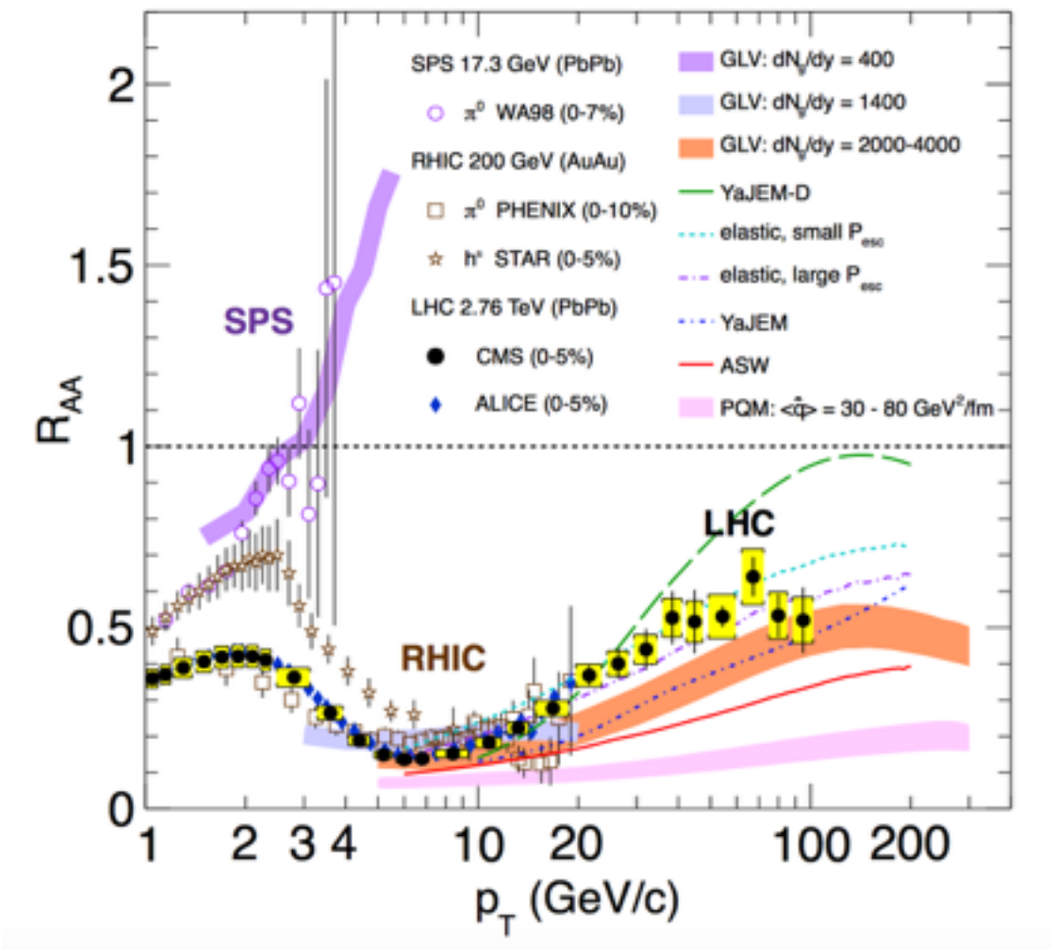
C. Heavy quarks

suppression of quarkonia yield due to the color screening effect of QGP

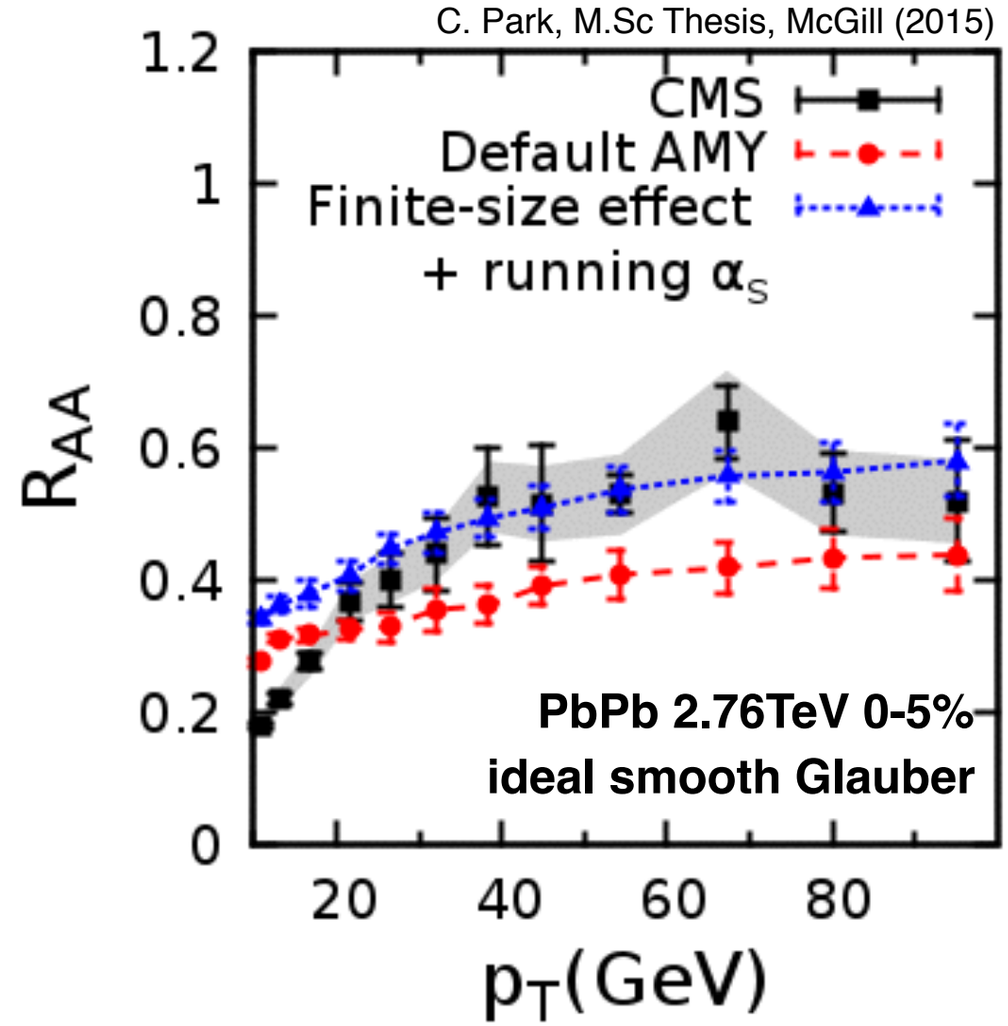
F. Karsch, M. T. Mehr, H. Satz, Zeitschrift für Physik C Particles and Fields (1988)

Hard probe - Jet quenching

CMS Collaboration, Eur. Phys. J. **C72**, 1945 (2012)

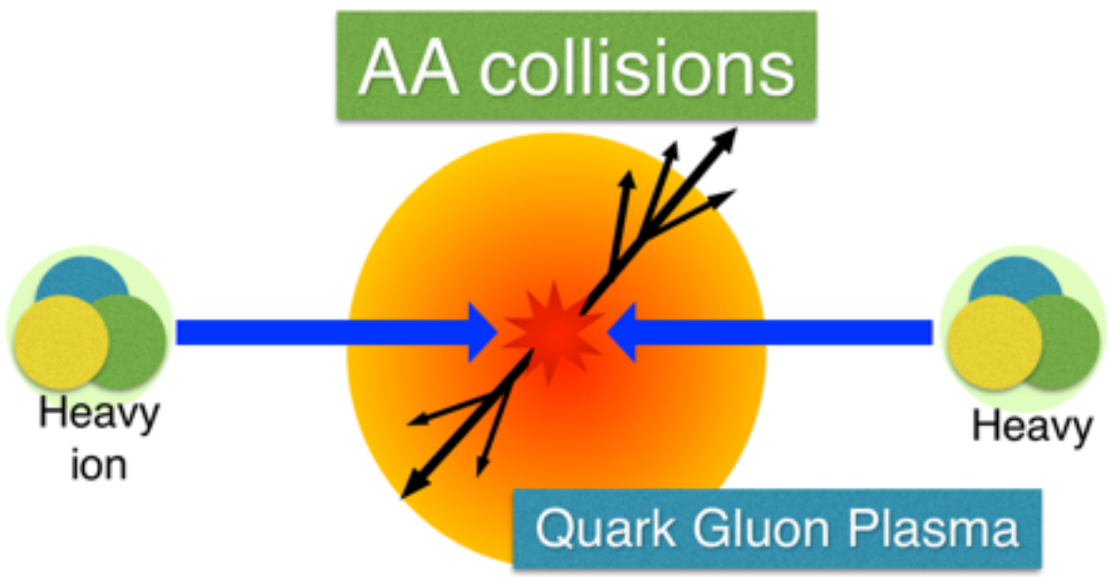


C. Park, M.Sc Thesis, McGill (2015)



- Strong suppression in the broad p_T range
  : Interactions with the QCD matter
- Theories of energy loss support the presence of QGP

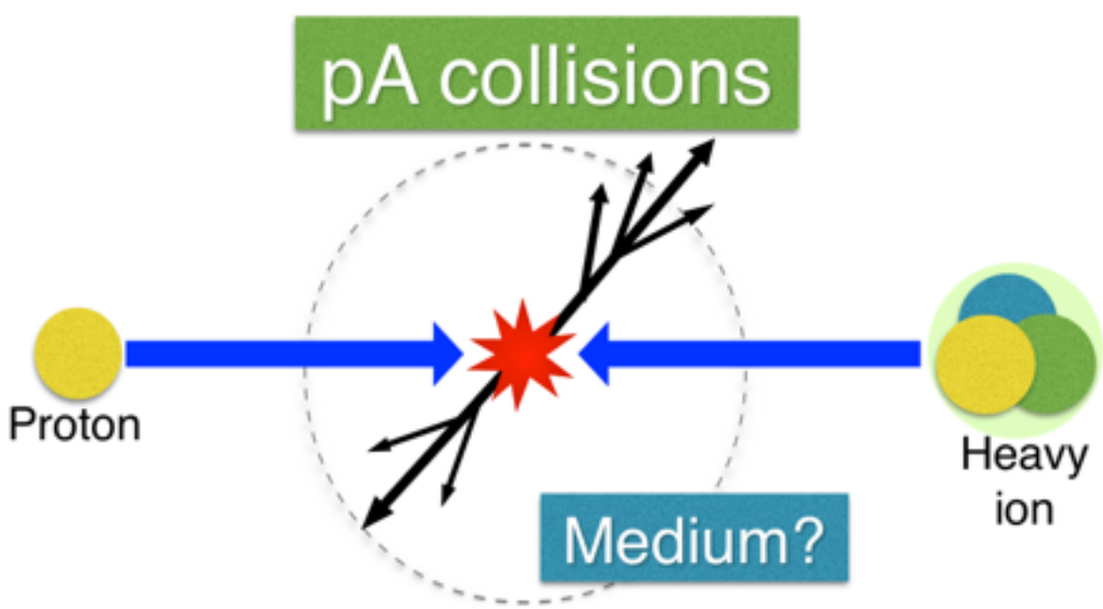
Creation of QGP in high energy collisions?



What we have found :

- Collectivity - sign of strongly coupled QCD medium
- Jet quenching due to the medium interactions

QGP was created in AA collisions!



- Collectivity as well (central) **QGP?**

Medium evolution for small systems

- **iEBE-VISHNU**

  C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass, U. Heinz [arxiv:1409.8164]

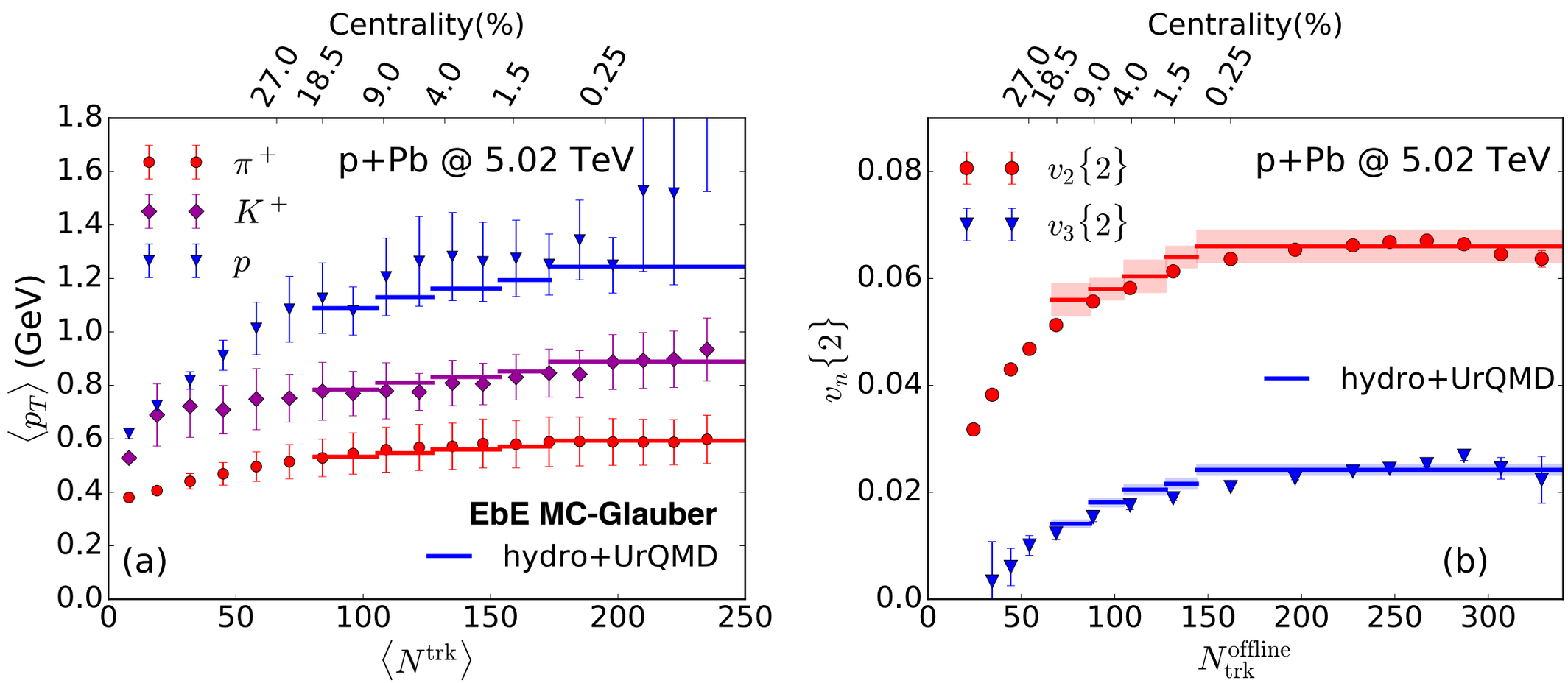
  - 2+1D Viscous Israel-Stewart Hydrodynamics
  - Hadronic cascade afterburner
  - MC-Glauber initial conditions

- **MUSIC**

  B. Schenke, S. Jeon, C. Gale, Phys. Rev. **C82**, 014903 (2009)

  - 3+1D version of Hydrodynamics
  - Study non-trivial longitudinal dynamics

Collectivity in small systems

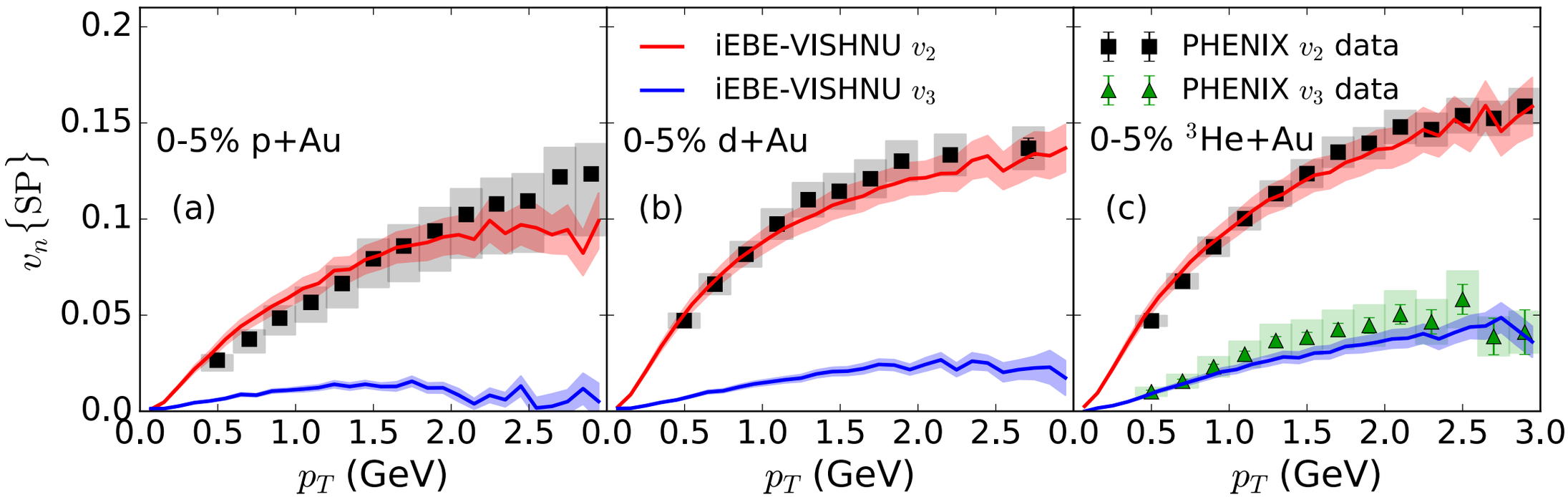


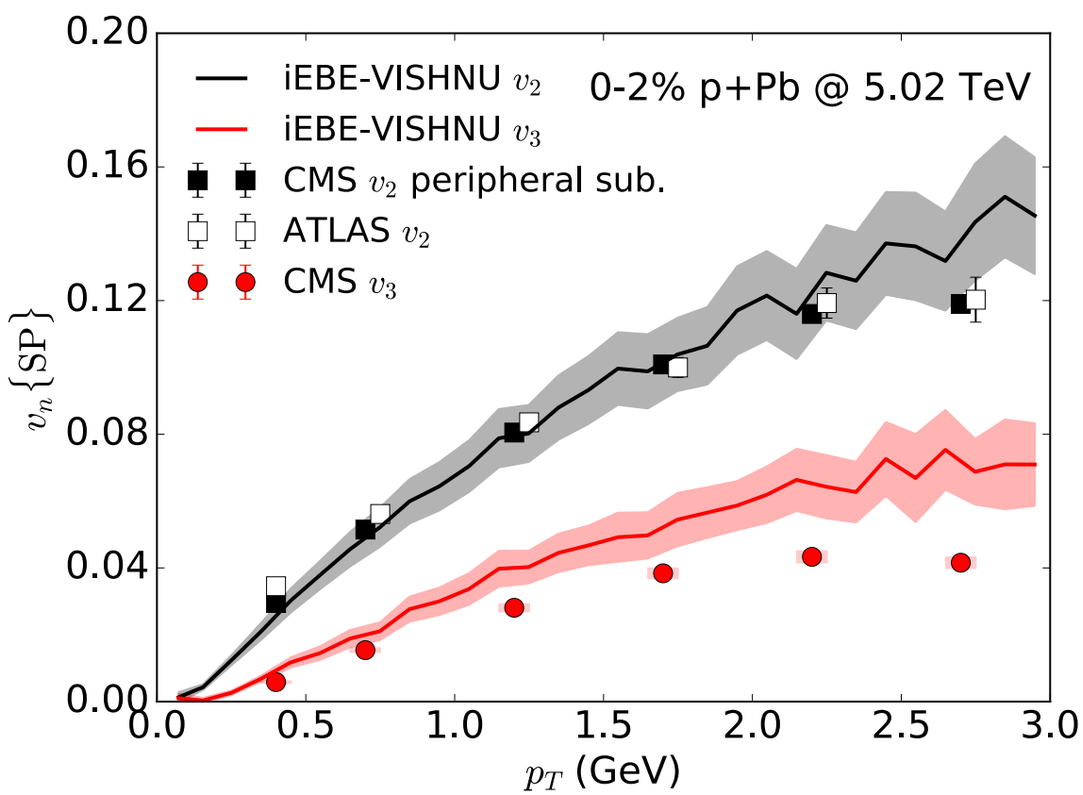
C. Shen, *et al*. [preliminary]

- Hydrodynamics describes the collective behaviour in small collision systems well

p_T differential anisotropic flows

C. Shen, *et al.* [preliminary]

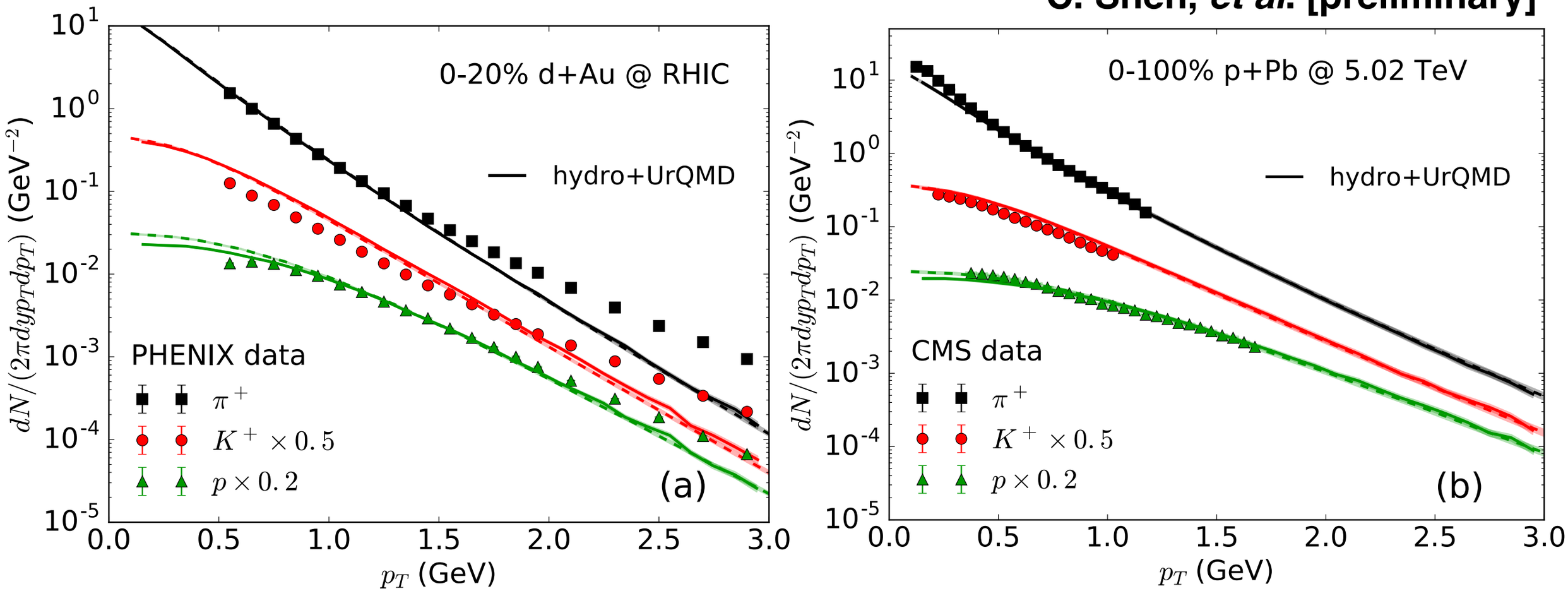




- Hydro simulations give fair agreement with anisotropic flows from both RHIC and LHC

Identified hadron spectra

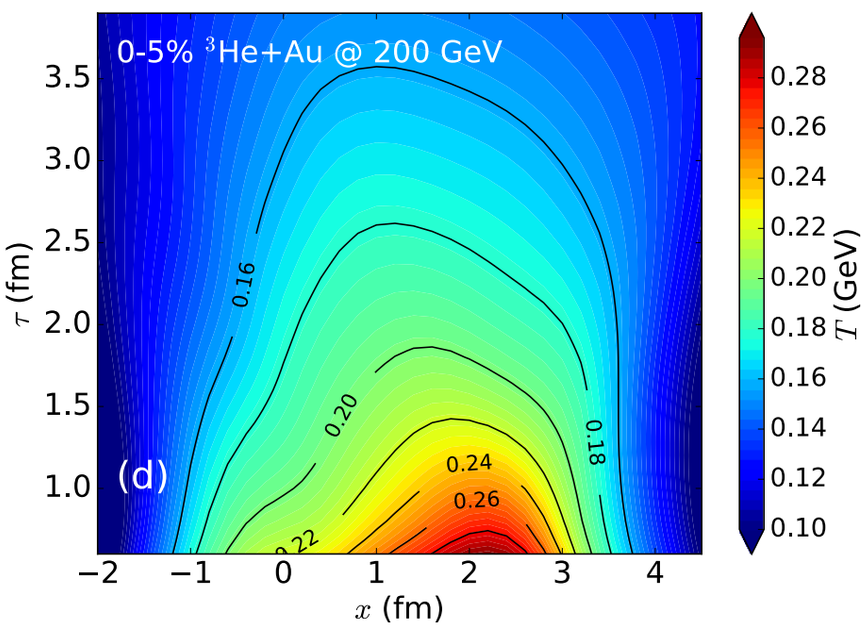
C. Shen, *et al.* [preliminary]



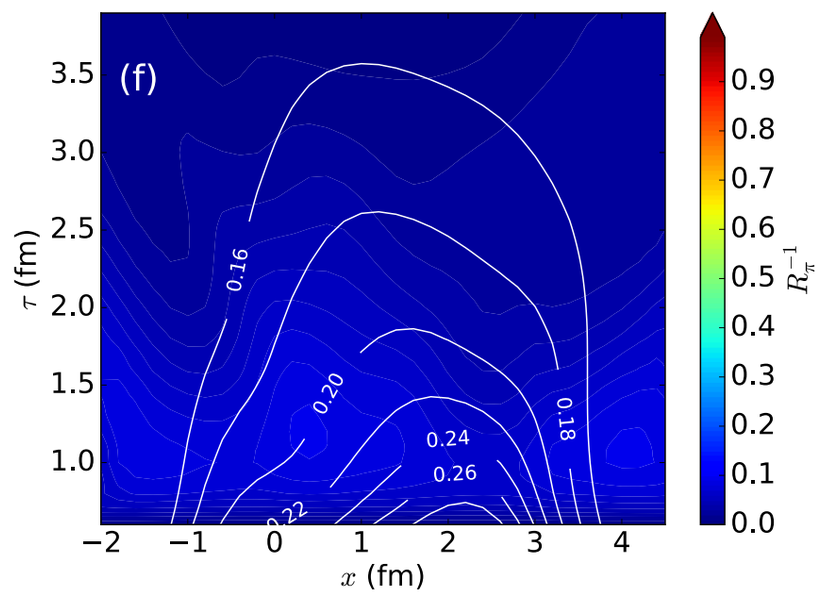
- Hydrodynamics gives good descriptions below 1.5GeV
- Deviation is observed at higher p_T at RHIC energy
  need an additional source from jet shower

Validity of hydrodynamics

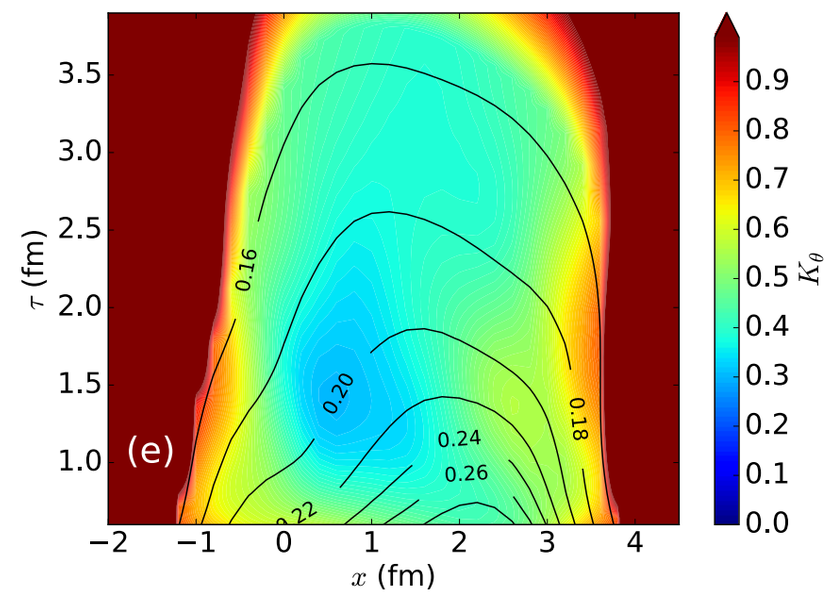
Temperature



Inverse Reynolds number



Knudsen number

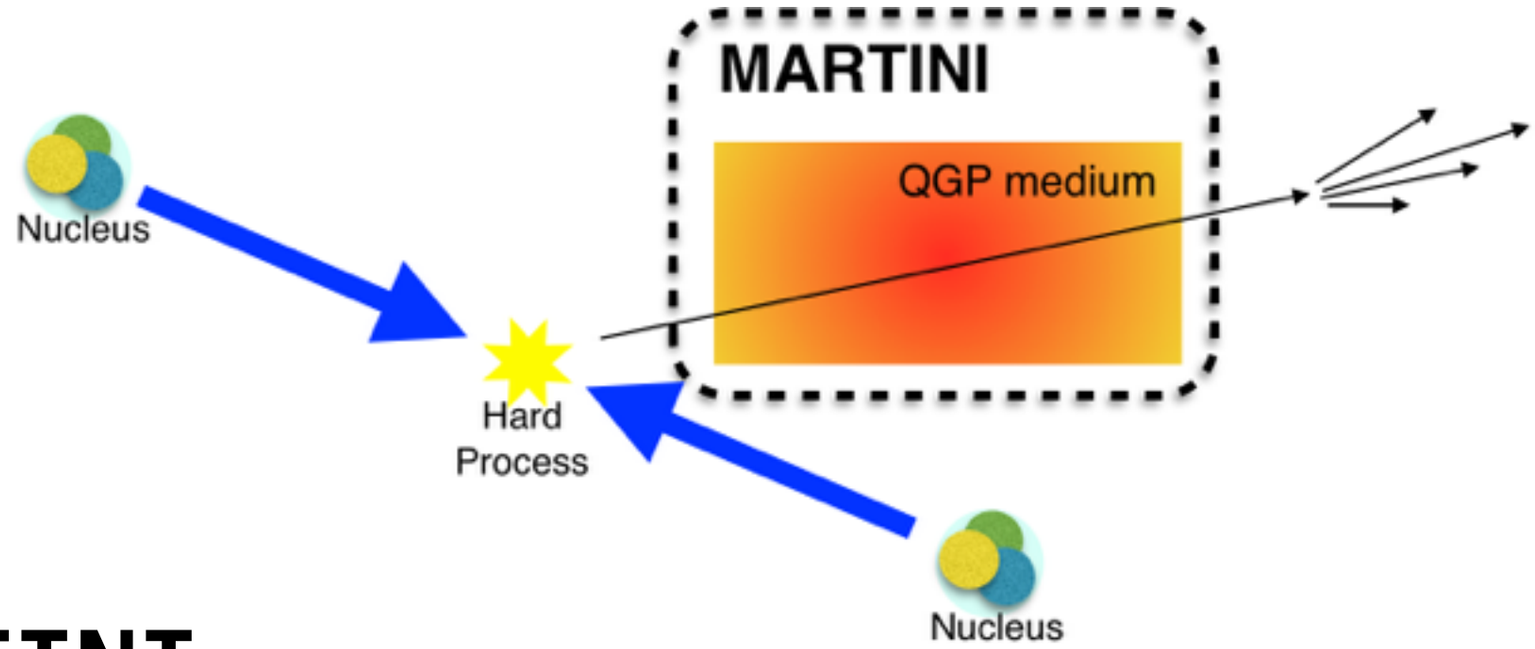


C. Shen [preliminary]

$$Rn^{-1} = \frac{\sqrt{\pi^{\mu\nu}\pi_{\mu\nu}}}{e + \mathcal{P}} \qquad Kn = \frac{l_{micro}}{L_{macro}} = \tau_\pi \theta$$

- $Rn^{-1} < 0.3$, $Kn < 0.6$
- Fairly valid in small collision systems

Tool for jet interactions

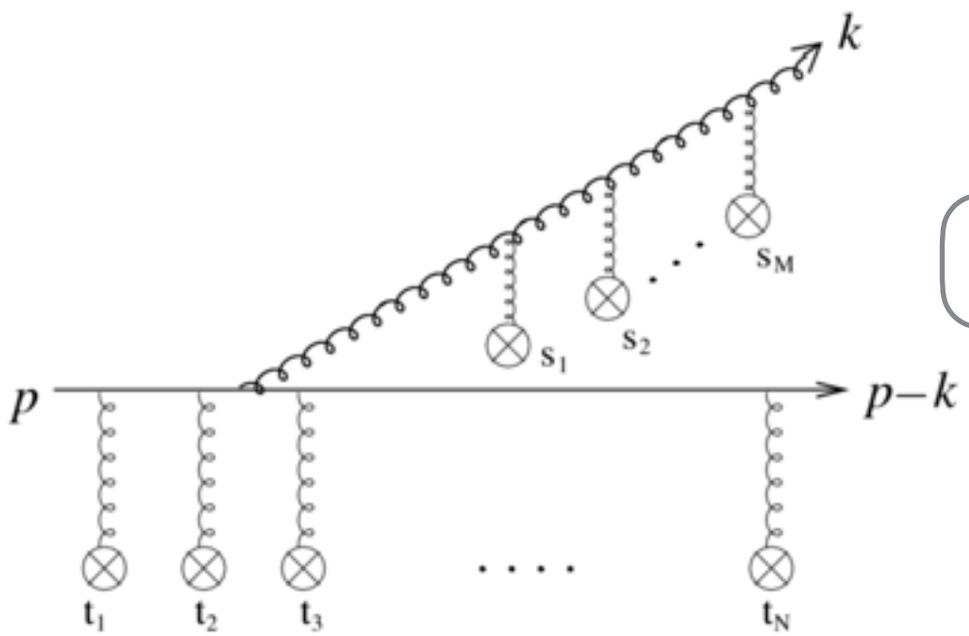


- **MARTINI**

  B. Schenke, S. Jeon, C. Gale, Phys. Rev. **C80**, 054913 (2009)

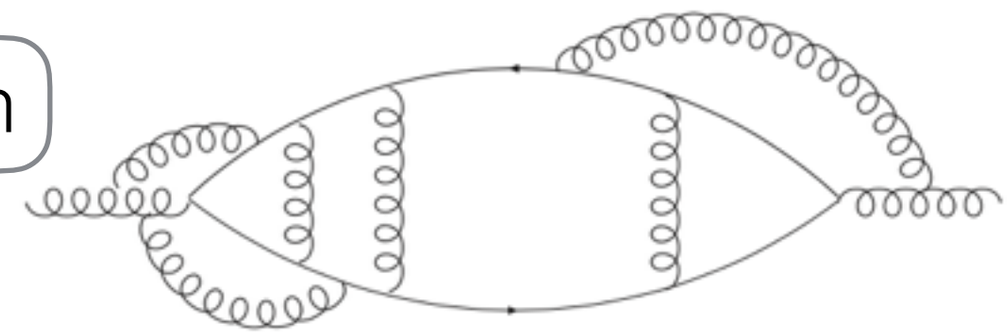
  - Event generator for hard jets in heavy ion collisions
  - Based on PYTHIA 8.2
  - AMY(Arnold-Moore-Yaffe) radiation scheme as well as collisional processes

AMY in MARTINI



summation

S. Jeon, Nuclear Physics A vol. 830 (1) p. 107c-114c



bremsstrahlung + medium interaction

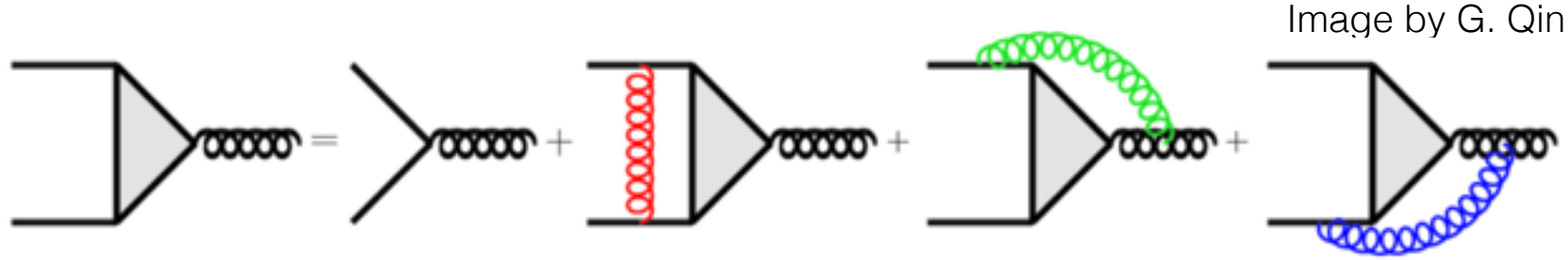
Gluon self energy

Task : To sum over all possible diagrams and square

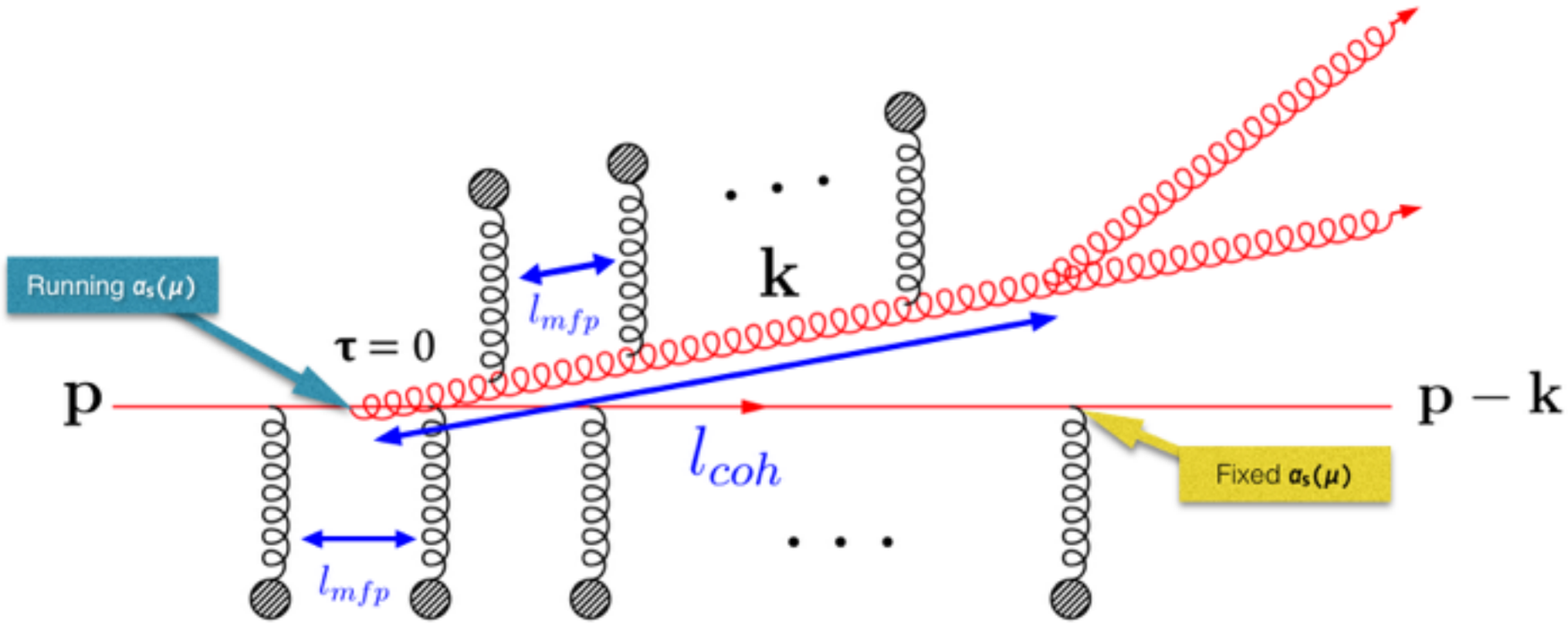
How to do?

Schwinger-Dyson type equation

Image by G. Qin



New developments in MARTINI



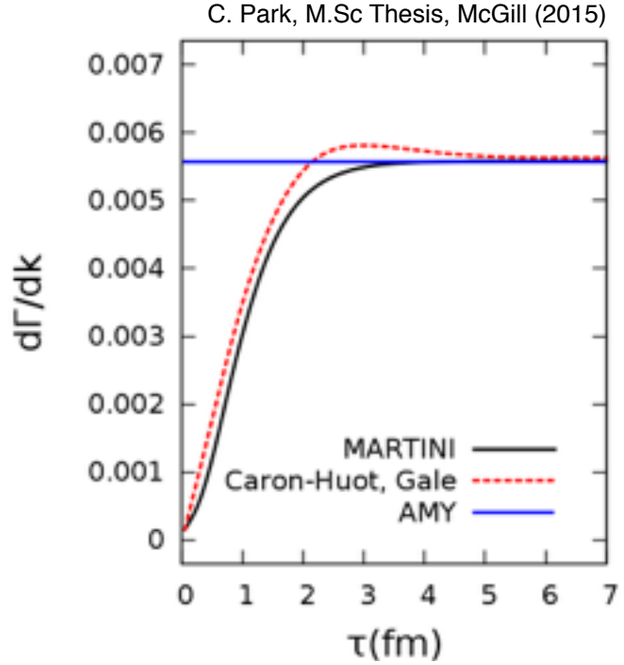
S. Caron-Huot and C. Gale, Phys. Rev. **C82**, 064902 (2010)

Path length dependent radiation

$$l_{\rm mfp} \sim \frac{1}{g^2 T}$$

$$l_{coh} \sim k/k_\perp^2$$

C. Park, M.Sc Thesis, McGill (2015)



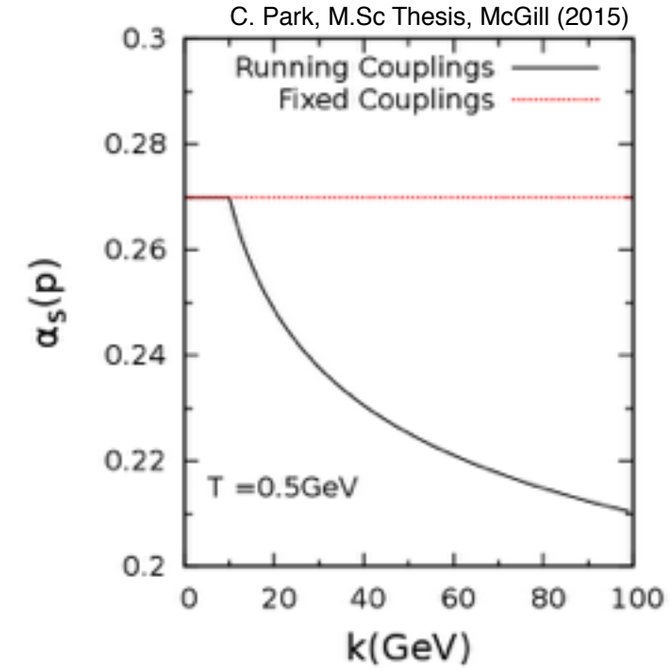
C. Young, B. Schenke, S. Jeon, and C. Gale, Nucl. Phys. **A910-911**, 494 (2013)

Running coupling constant

- Splitting vertex only

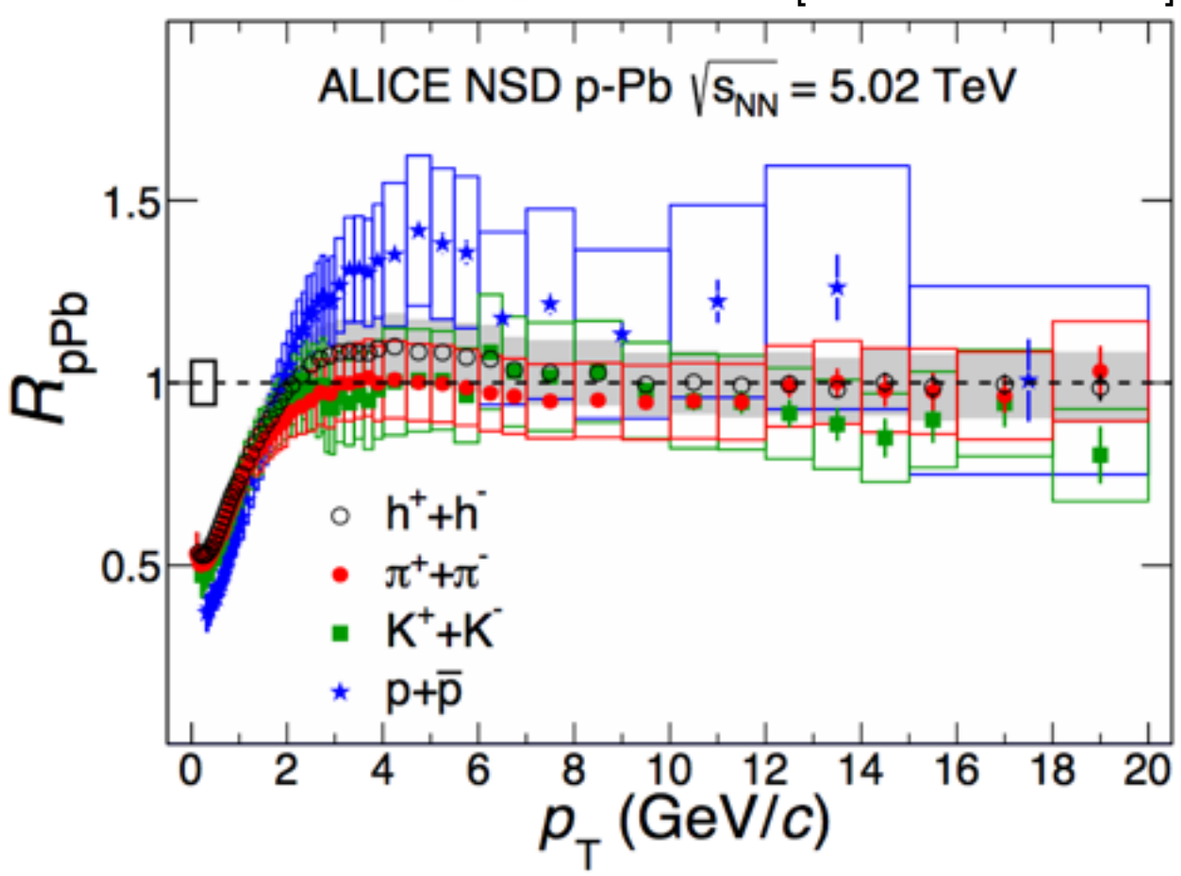
$$\langle |k_\perp| \rangle = (\hat{q}k)^{\frac{1}{4}}$$

C. Park, M.Sc Thesis, McGill (2015)

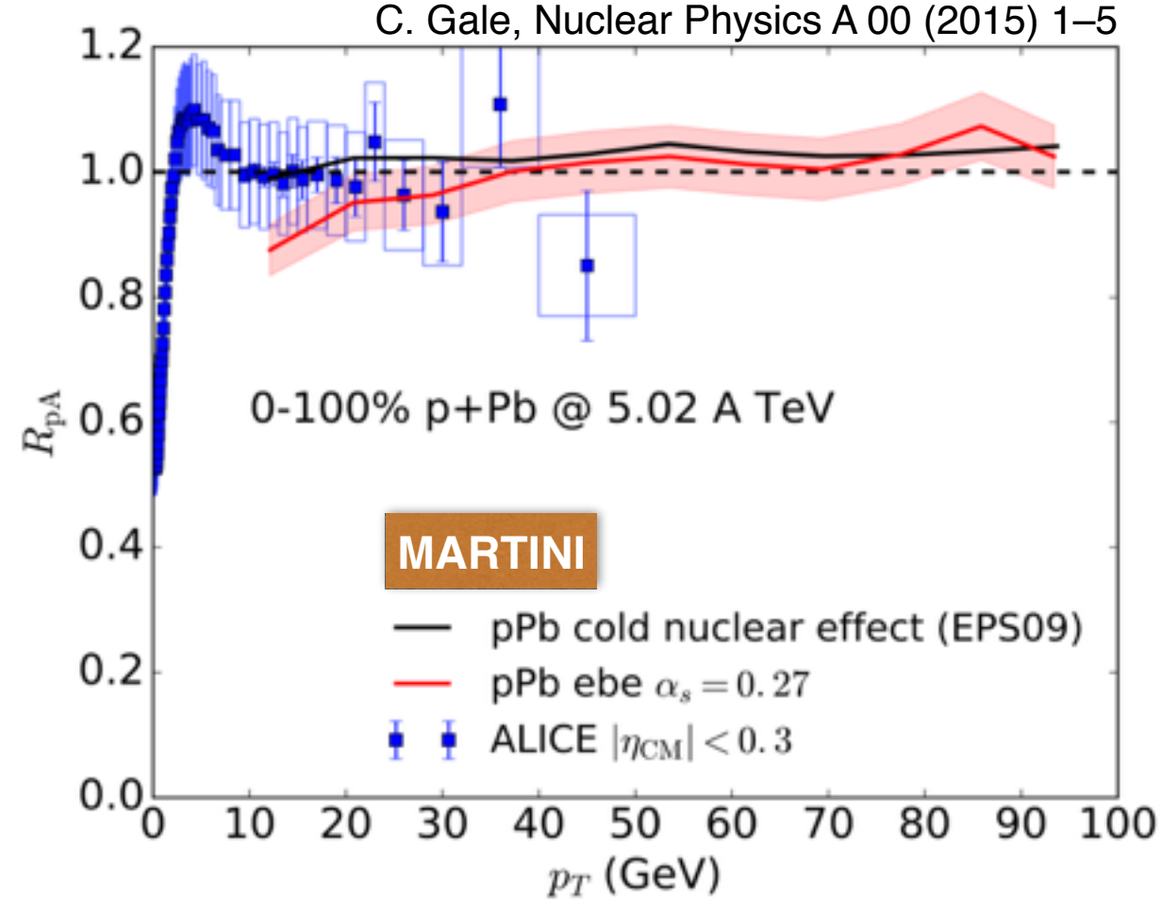


Minimum bias in small systems

ALICE Collaboration [arXiv:1601.03658v1]

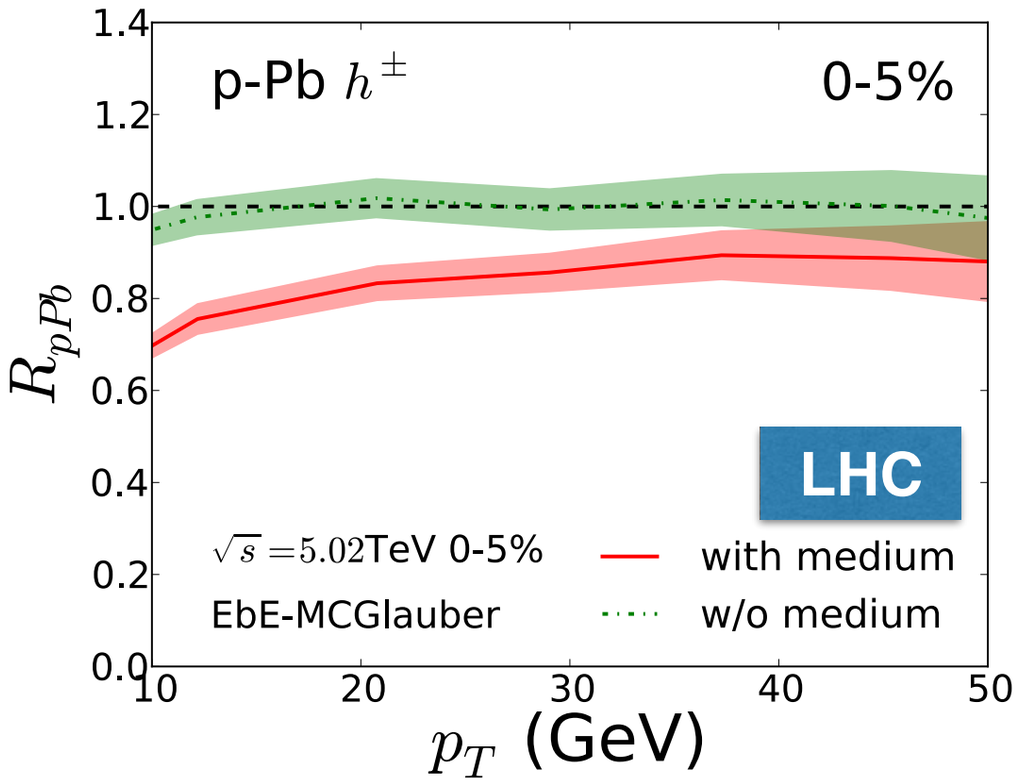


C. Gale, Nuclear Physics A 00 (2015) 1–5

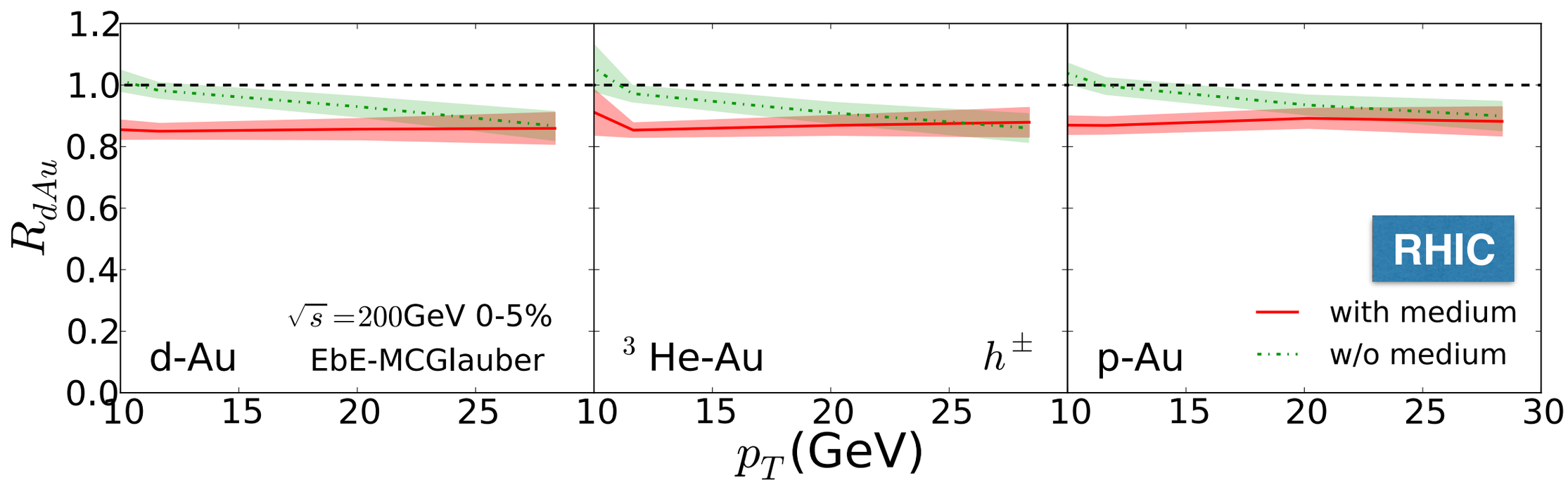


- ALICE measurement : close to or above unity at p_T > 2GeV
- In MB, energy loss doesn't show up

Central collision results



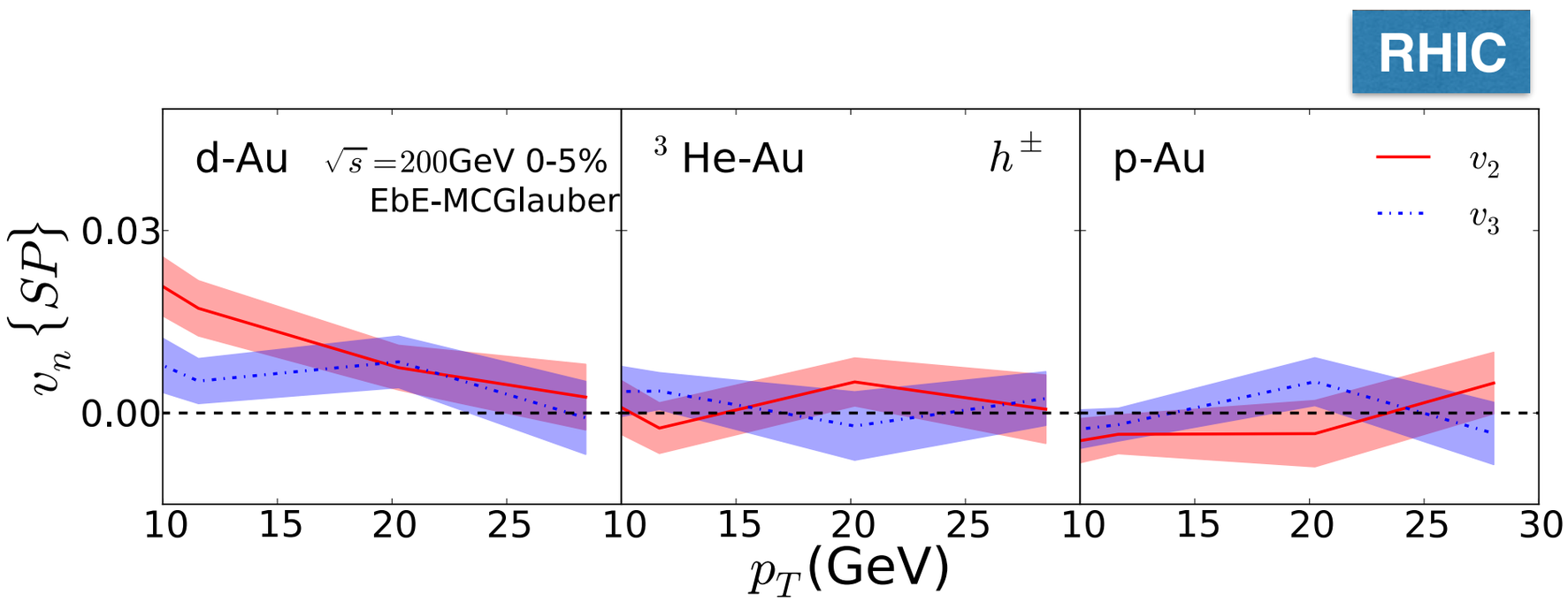
- Central collisions : visible energy loss for p_T ~10-20 Gev
- Possible signature of QGP in small systems is predicted

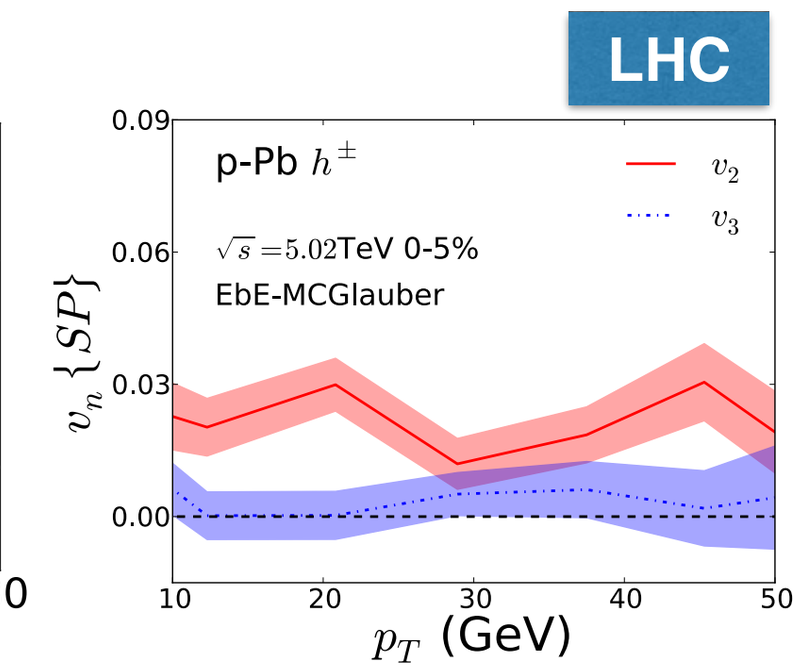


Charged hadron v_n at high p_T

Scalar product method A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C **58**, 1671

reference flow : v_n integrated from 0.3 to 3 GeV





- Prediction : v_2 ~ 2% in central d-Au, p-Pb collisions
- v_3 almost vanishes (back-to-back jets dominate)

Conclusion

- Hard QCD jets can probe the medium created in large systems as well as in small systems
- We estimated jet energy loss in small systems with calibrated hydrodynamic medium (RpA~0.8)
- We found finite v_2 in central d-Au/p-Pb, v_3 close to zero
- Future work : interplay between soft and hard particles in the hadronic phase; Study the rapidity dependence/ correlations of the jet observables with full 3+1D hydrodynamic simulations (MUSIC)

Backup

AMY integral equation

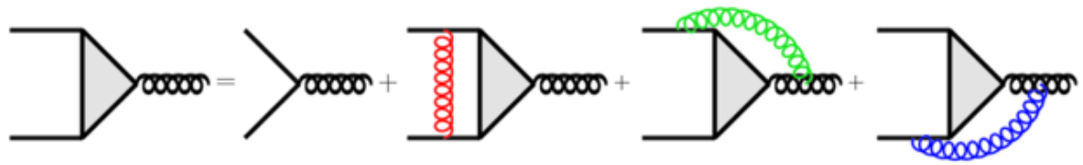


Image by G. Qin

Integral equation

$$2\mathbf{h} = i\delta E(\mathbf{h},p,k)\mathbf{F}(\mathbf{h}) + g_s^2 \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2} C(\mathbf{q}_\perp)\Big\{(C_s - C_A/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h} - k\mathbf{q}_\perp)] + (C_A/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h} + P\mathbf{q}_\perp) + (C_s - C_A/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h} - (p-k)\mathbf{q}_\perp)]\Big\}$$

Differential rate to exchange q⊥

$$C(\mathbf{q}_\perp) = \frac{m_D^2}{\mathbf{q}_\perp^2(\mathbf{q}_\perp^2 + m_D^2)}, \quad m_D^2 = \frac{g_s^2 T^2}{6}(2N_c + N_f).$$

Energy difference **δ**E

$$\delta E(\mathbf{h},p,k) = \frac{\mathbf{h}^2}{2pk(p-k)} + \frac{m_k^2}{2k} + \frac{m_{p-k}^2}{2(p-k)} - \frac{m_p^2}{2p}$$

AMY radiative rate

$$\frac{d\Gamma(p,k)}{dk} = \frac{C_s g_s^2}{16\pi p^7} \frac{1}{1 \pm e^{-k/T}} \frac{1}{1 \pm e^{-(p-k)/T}} \times \begin{Bmatrix} \frac{1+(1-x)^2}{x^3(1-x)^2} & q \to qg \\ N_f \frac{x^2+(1-x)^2}{x^2(1-x)^2} & g \to qq \\ \frac{1+x^4+(1-x)^4}{x^3(1-x)^3} & g \to gg \end{Bmatrix}$$

$$\times \int \frac{d^2\mathbf{h}}{(2\pi)^2} 2\mathbf{h} \cdot \mathrm{Re}\ \mathbf{F}(\mathbf{h},p,k),$$

Collisional process

All the possible 2-2 scattering diagrams

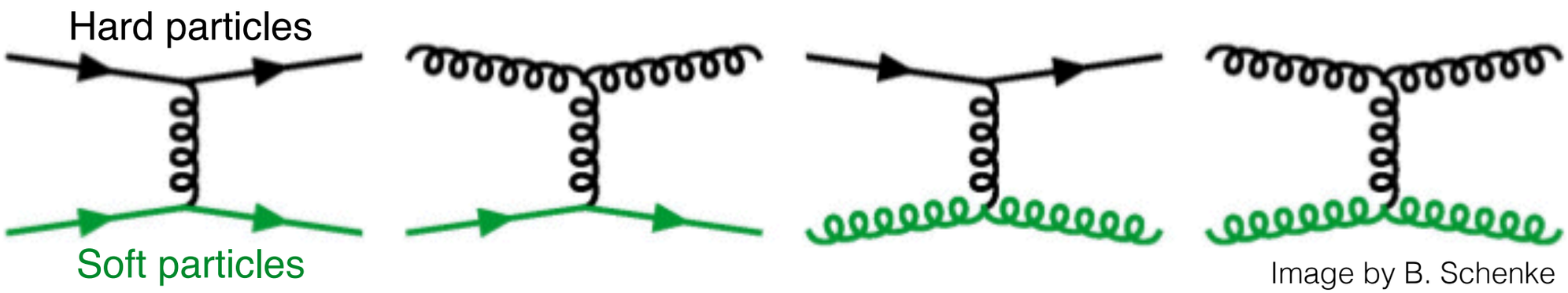


Image by B. Schenke

2-2 scattering rate

$$\frac{d\Gamma_{\rm el}}{d\omega}(E,\omega,T) = d_k \int_{kk'} \frac{2\pi}{4pp'}\delta(p-p'-\omega)\delta(k'-k-\omega) \times |\mathcal{M}|^2 f(k,T)(1 \pm f(k',T)),$$

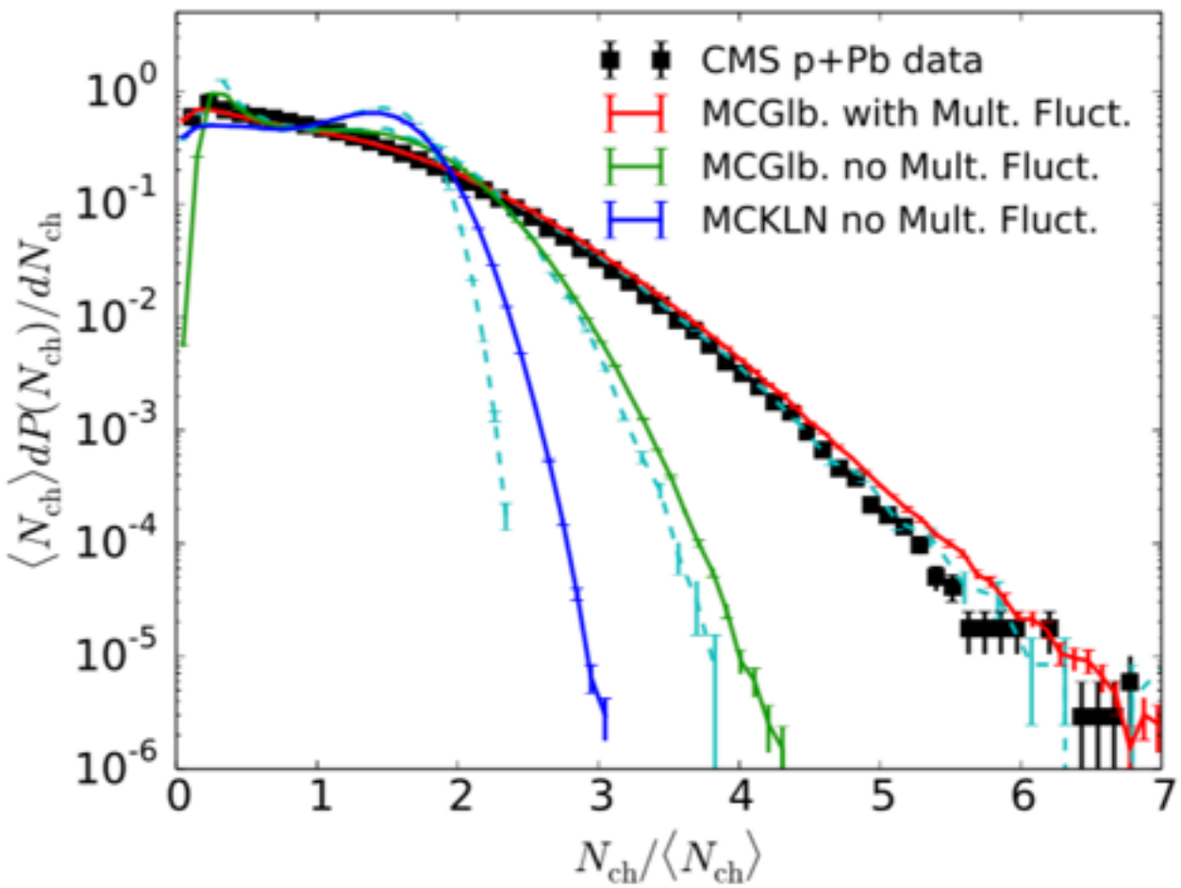
Matrix elements

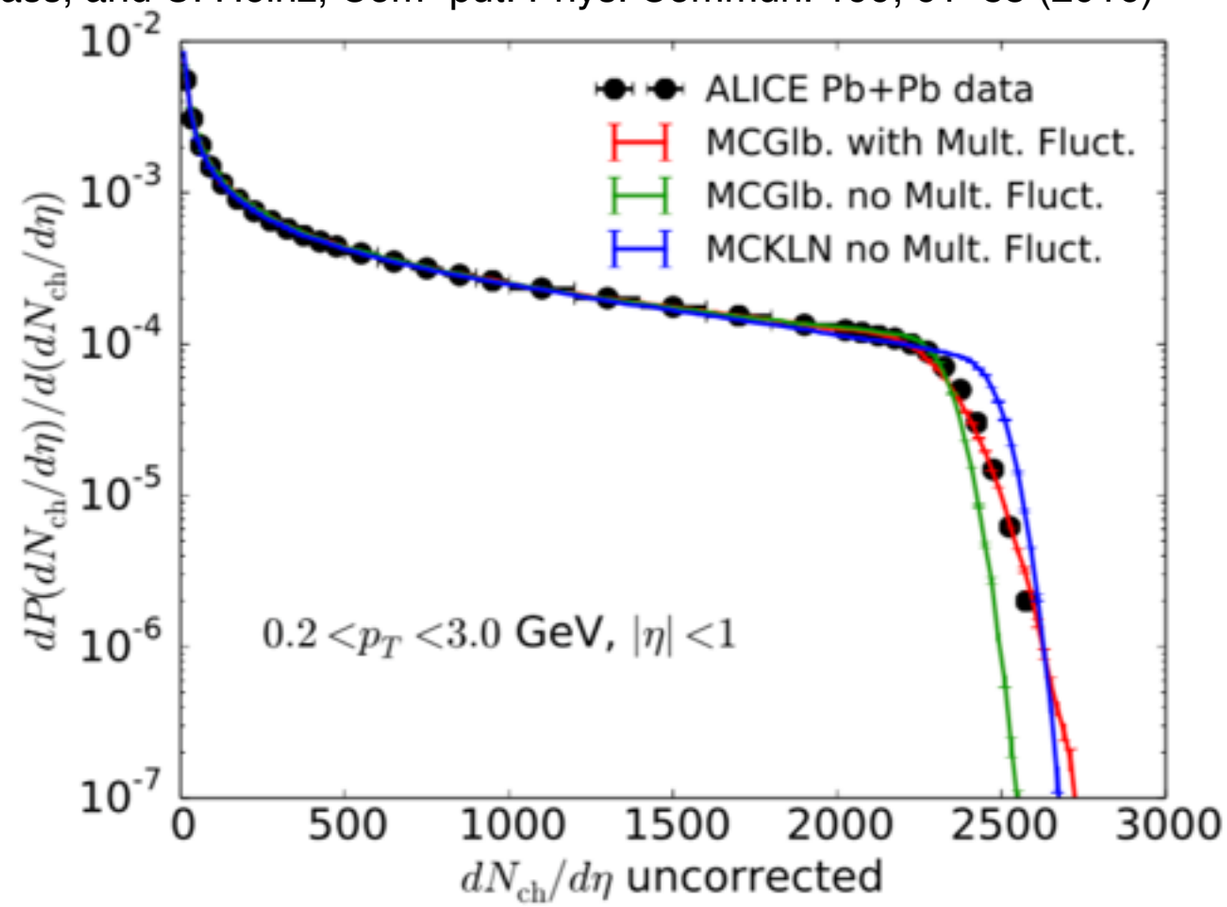
$$|\mathcal{M}|^2_{qq} = \frac{4}{9}g^4\frac{s^2+u^2}{t^2}, \qquad |\mathcal{M}|^2_{qg} = 2g^4\left(1-\frac{su}{t^2}\right),$$

$$|\mathcal{M}|^2_{gq} = 2g^4\left(1-\frac{su}{t^2}\right), \qquad |\mathcal{M}|^2_{gg} = \frac{9}{2}g^4\left(\frac{17}{8}-\frac{su}{t^2}\right)$$

MC-Glauber Initial condition

C. Shen, Z. Qiu, H. Song, J. Bernhard, S Bass, and U. Heinz, Com- put. Phys. Commun. 199, 61–85 (2016)

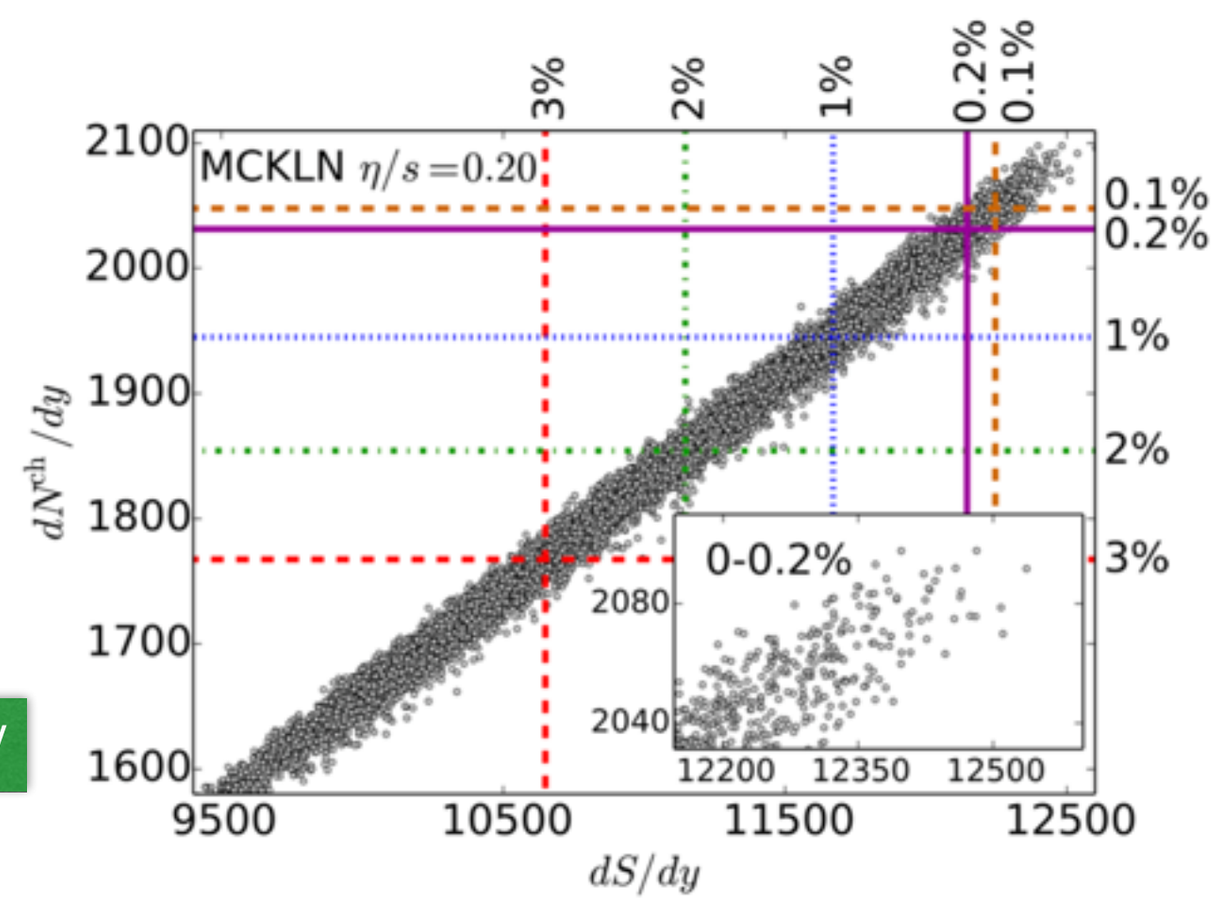




Centrality determination

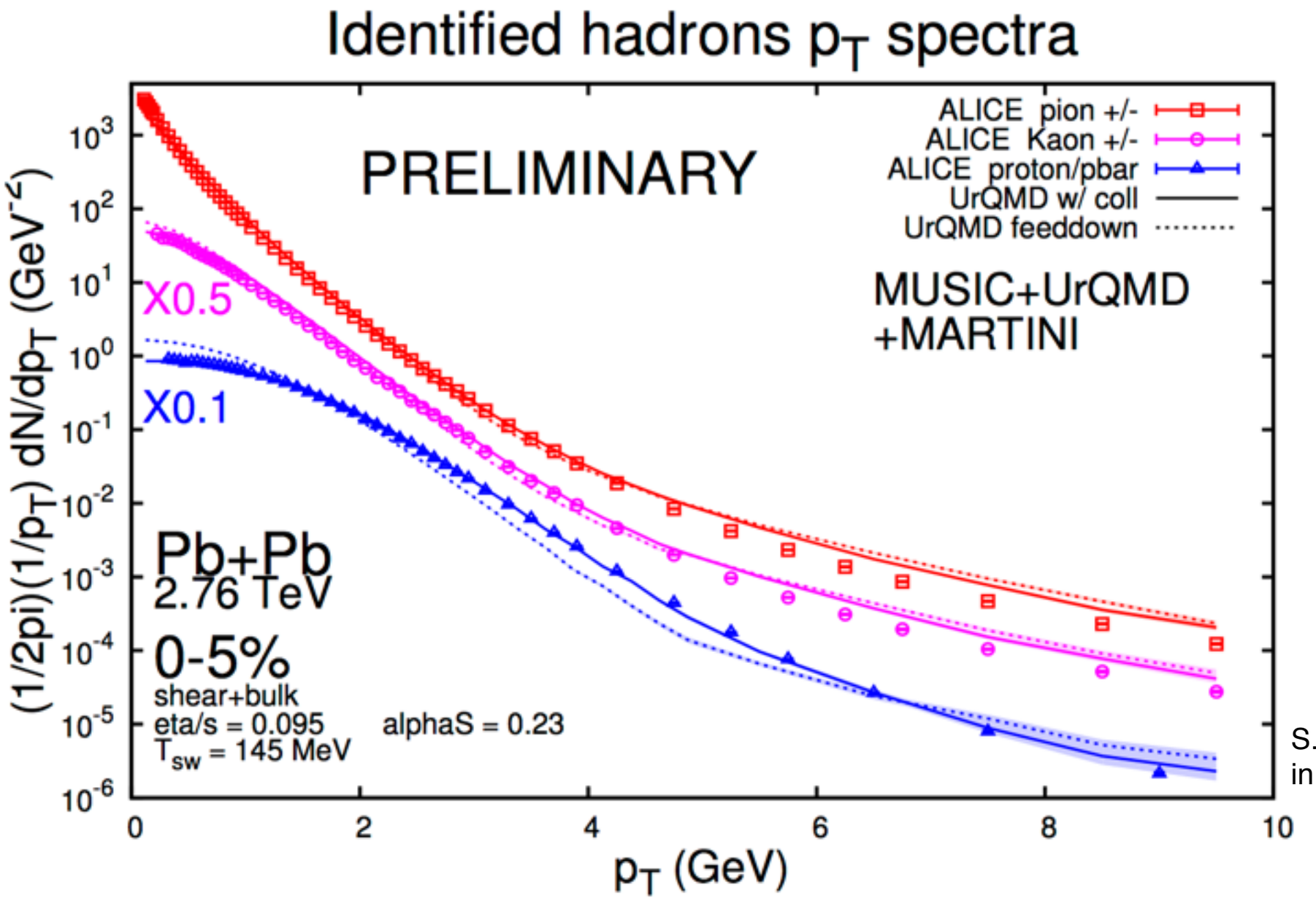
- We need initial state quantity for estimation
  (e.g. N_{coll}, N_{part}, b, total initial entropy dS/dy)
- dS/dy is highly correlated with final state multiplicity dN^{ch}/dy.
- Using dS/dy is a good estimation

Pb-Pb at 2.76TeV



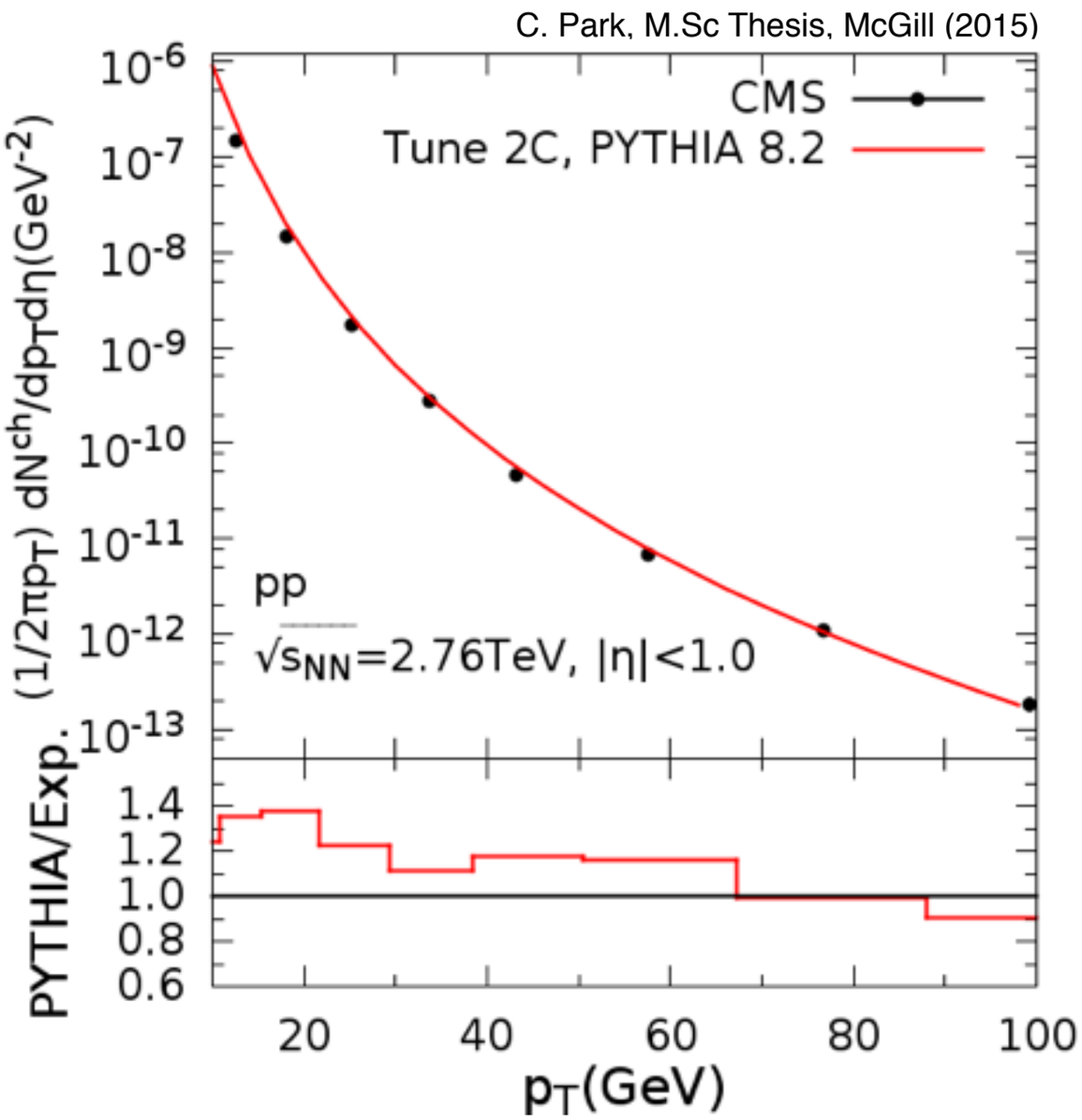
C. Shen, Z. Qiu, and U. Heinz, Phys. Rev. **C92**, 014901 (2015)

Jet shower contribution to yield spectra



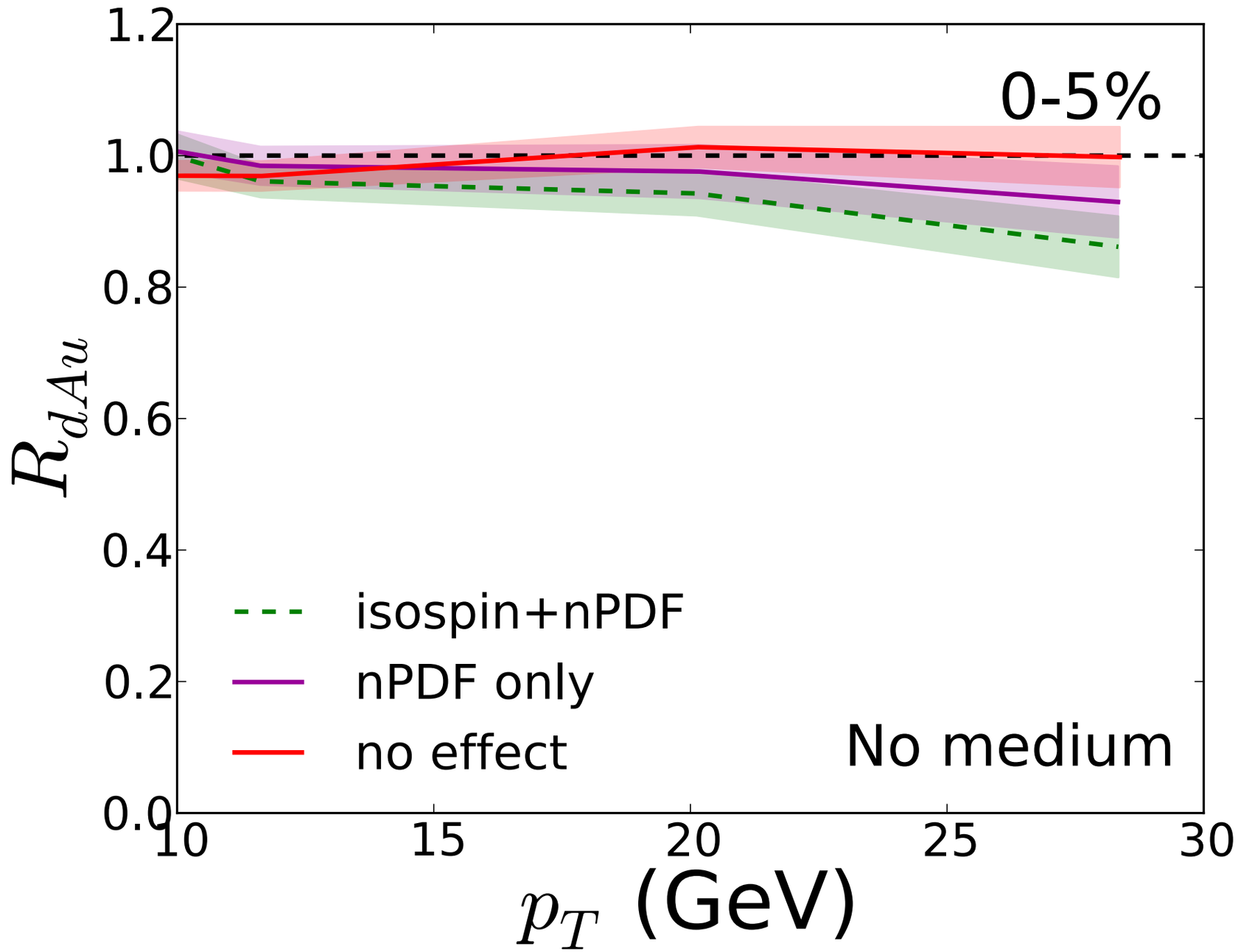
S. Ryu, Poster
in Quark Matter (2015)

Initial parton shower from PYTHIA

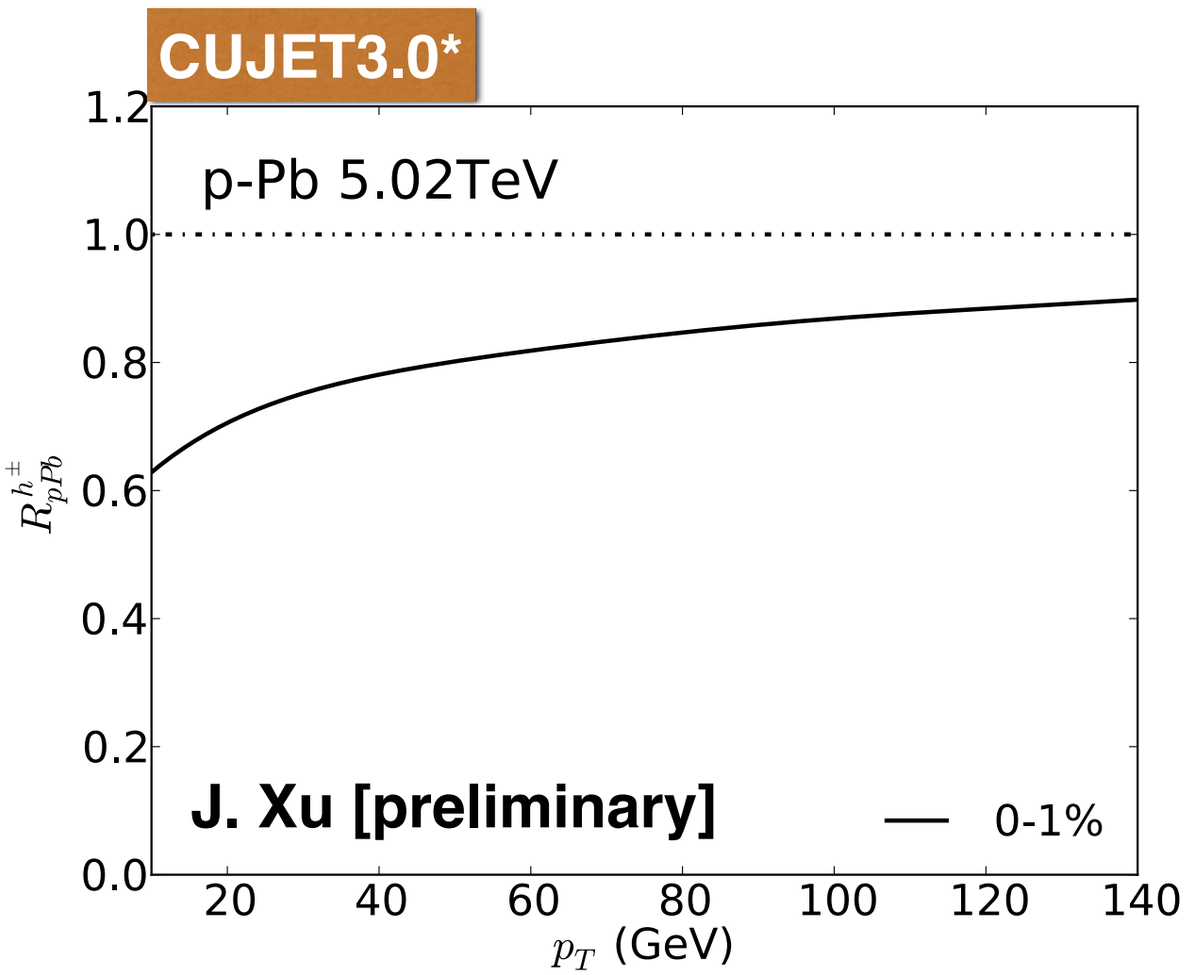


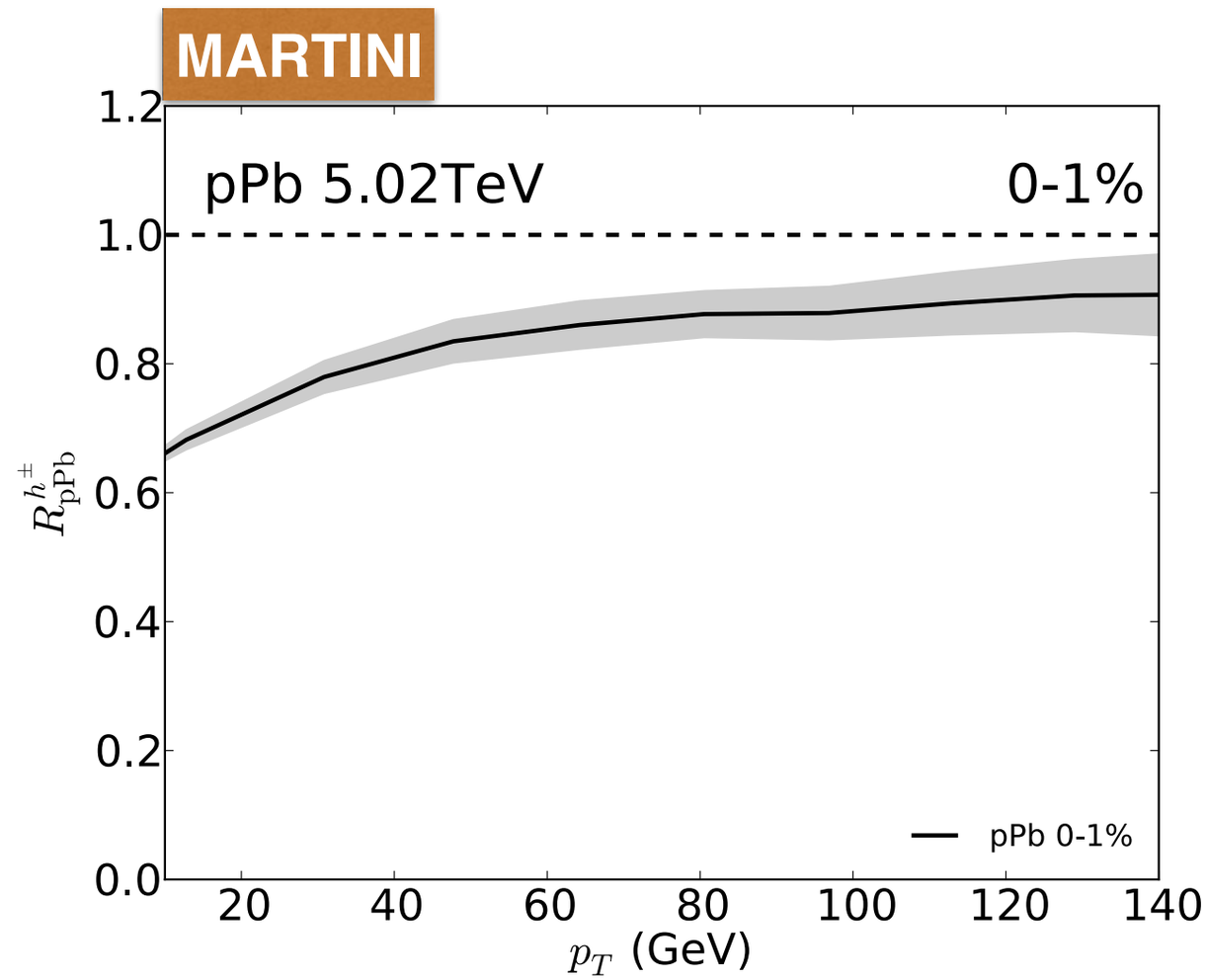
- pQCD shows good agreement with data (ratio < 1.4)
- Switching point from pQCD to soft QCD at ~ 10GeV
- Reliable above 10GeV

Isospin / nPDF effects



Comparison to CUJET3.0





- Exactly same hydro (smooth)
- Different energy loss schemes, PDFs.

*Xu, Liao, Gyulassy, (1) Chin. Phys. Lett. 32, 092501 (2015) [arXiv:1411.3673]; (2) JHEP 1602 (2016) 169 [arXiv:1508.00552]; (3) In final preparation