Jet Quenching & Collective Flow in Relativistic Nuclear Collisions

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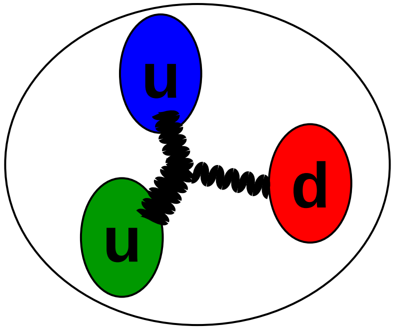
Outline

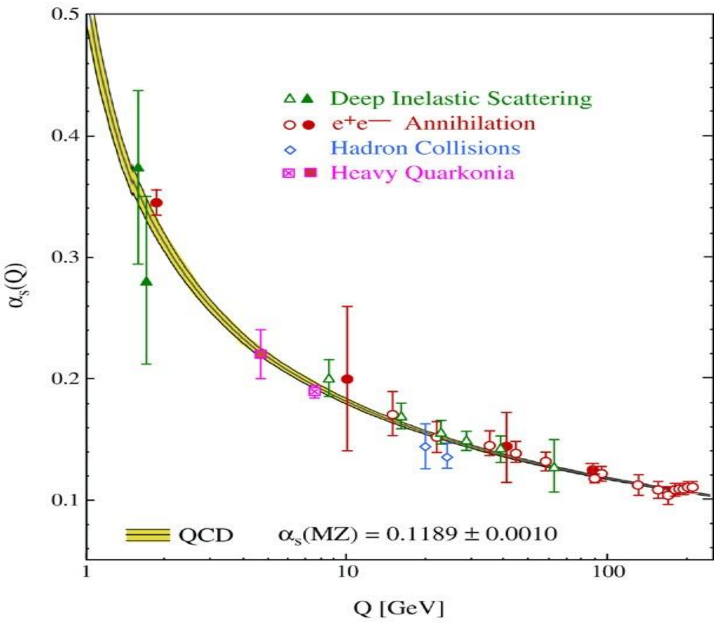
- **Relativistic nuclear collisions**
- **Collective flow, initial state fluctuations, final state correlations**
- **Jet-medium interaction, jet energy loss, heavy quarks**
- **Summary**

QCD and strong interaction

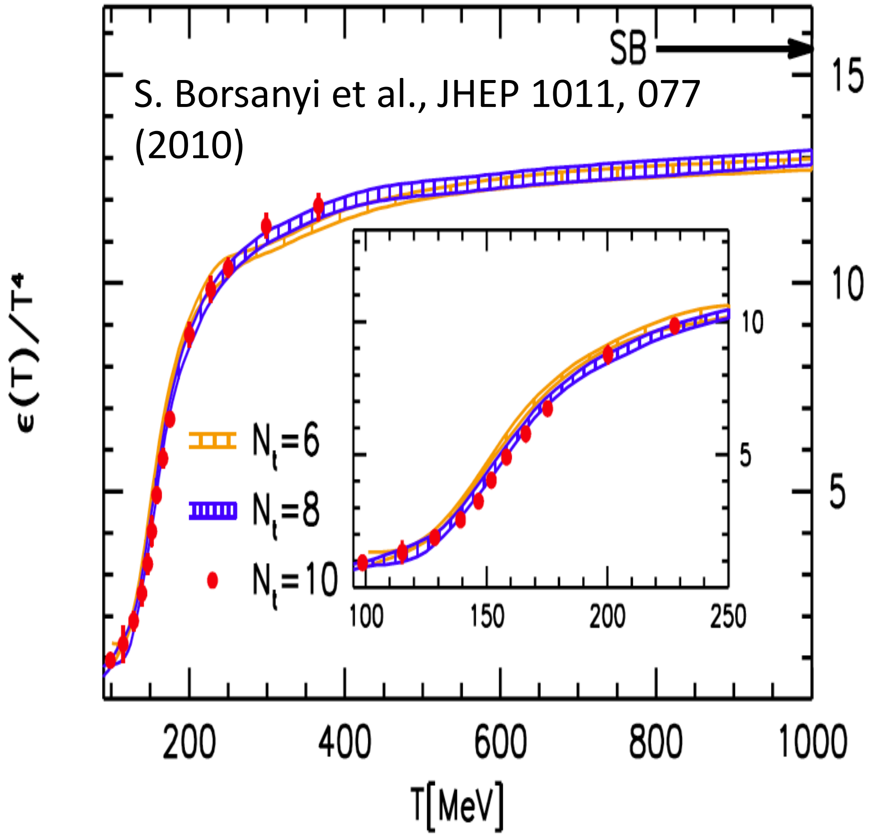
- QCD is an important ingredient of Standard Model and the fundamental quantum field theory of the strong interaction
- Elementary fields: quarks and gluons
- Quarks and gluons carry “color” degrees of freedom
- Color confinement and asymptotic freedom



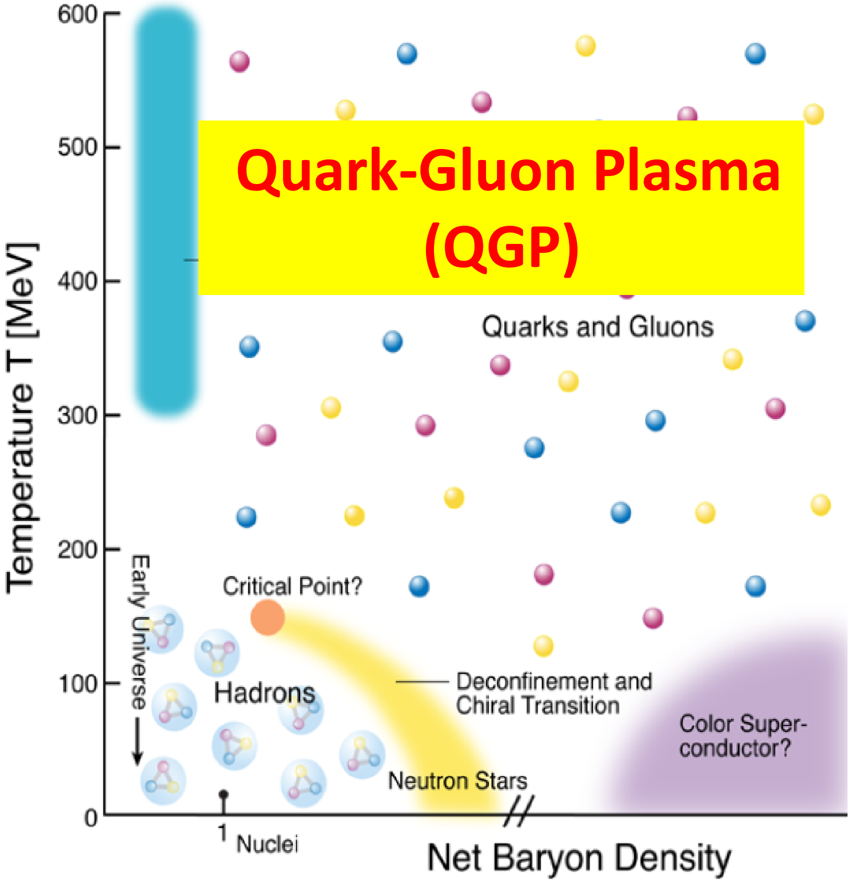
$$\mathcal{L} = \sum_f \overline{\psi}_f (i\gamma^\mu D_\mu - m_f)\psi_f - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$$



Strong-interaction matter



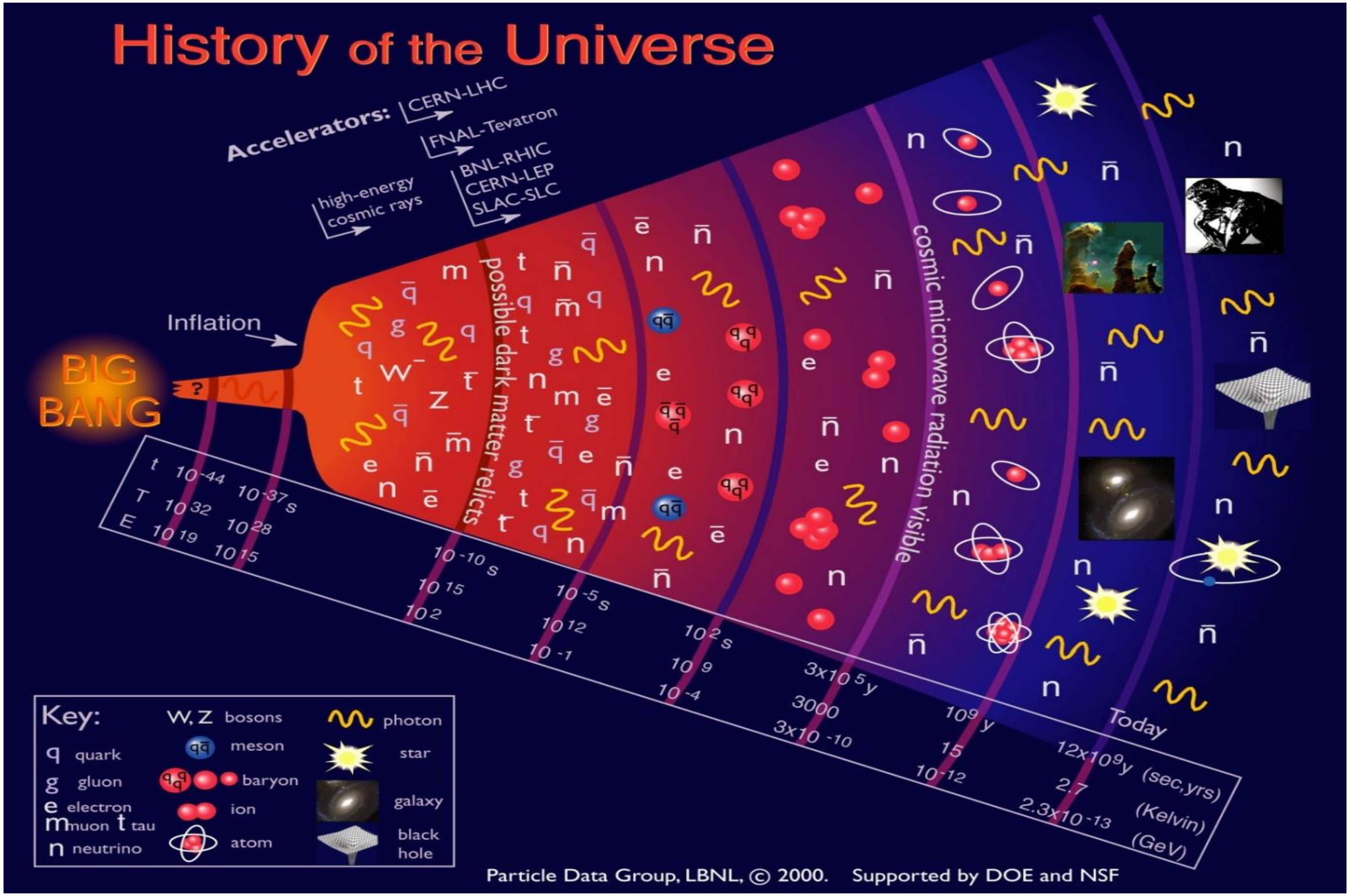
S. Borsanyi et al., JHEP 1011, 077 (2010)



Quark-Gluon Plasma (QGP)

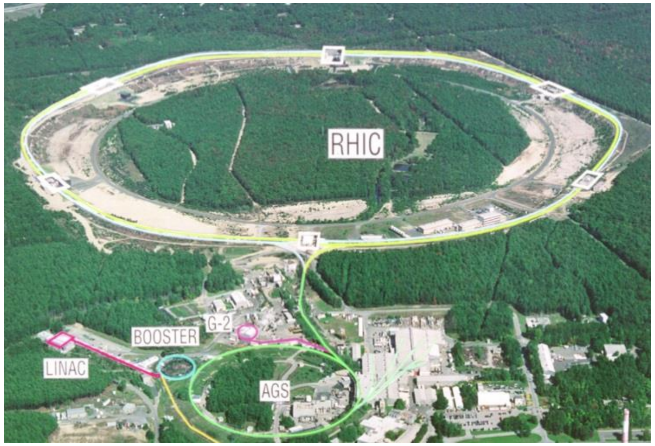
$$Z(\beta) = \mathrm{Tr}\, e^{-\beta H} = \sum_a \int d\phi_a \left\langle \phi_a \middle| e^{-\beta H} \middle| \phi_a \right\rangle = \sum_a \int d\phi_a \left\langle \phi_a \middle| e^{-iHt} \middle| \phi_a \right\rangle$$

QGP and early Universe



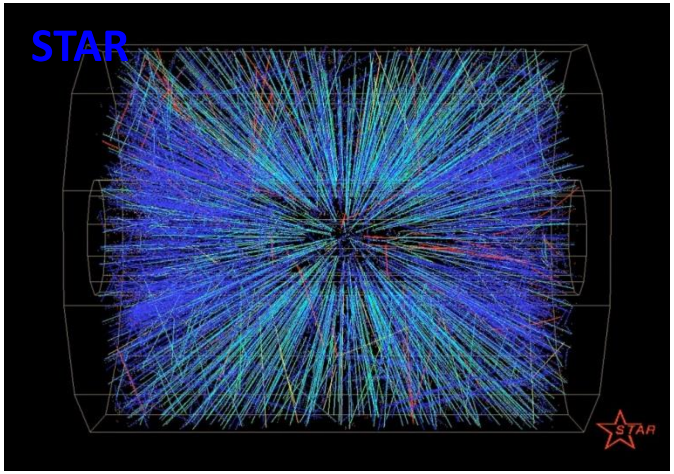
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Relativistic nuclear collisions



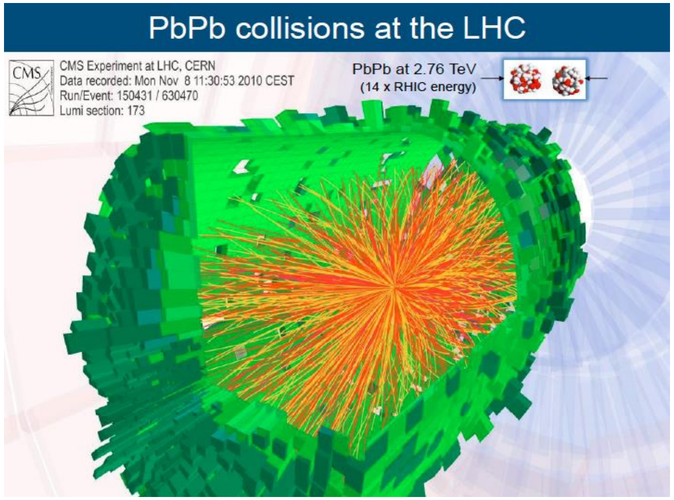
Relativisitic Heavy Ion Collider (RHIC) :

Au-Au, Cu-Cu,U-U @ $\sqrt{s_{NN}}$=10-200GeV

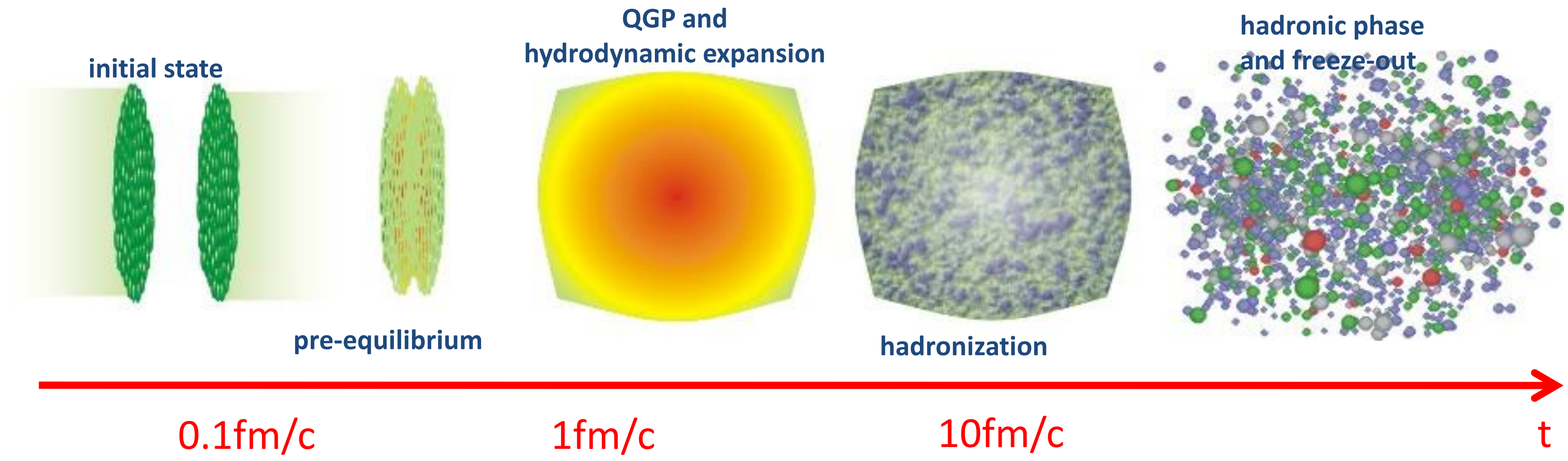


Larger Hadron Collider (LHC):

Pb-Pb @ $\sqrt{s_{NN}}$=2.76TeV/5.5TeV



Evolution of relativistic nuclear collisions



initial state

pre-equilibrium

QGP and
hydrodynamic expansion

hadronization

hadronic phase
and freeze-out

0.1fm/c

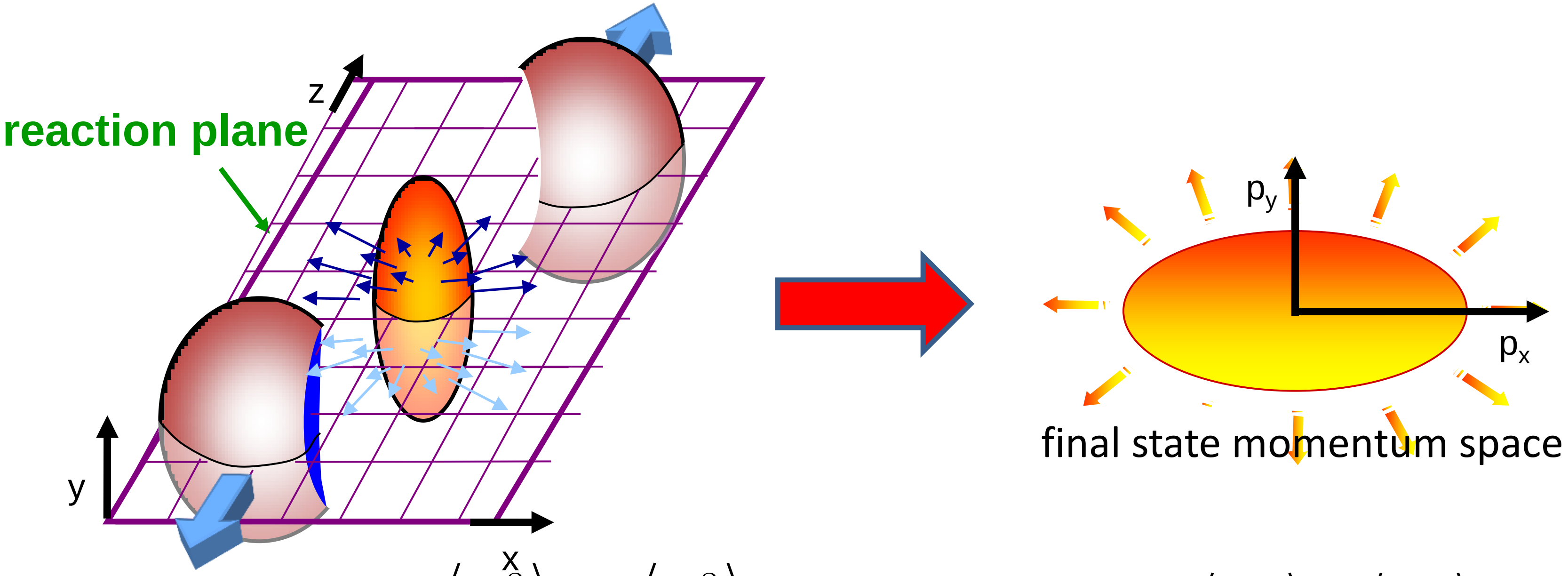
1fm/c

10fm/c

t

Our goals:
To find unambiguous signatures for QGP formation from final state observables by comparing theory/model calculations
To understand the expansion dynamics and extract transport properties of hot/dense matter

Anisotropic collective flow



eccentricity $$\varepsilon_2 = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Elliptic flow $$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

The interaction inside QGP translates initial geometric anisotropy to final state momentum anisotropy

Relativistic hydrodynamics gives nice description of flow

Hydrodynamic simulation

$$\partial_\mu T^{\mu\nu}(x) = 0$$

$$T^{\mu\nu} = \boxed{eu^\mu u^\nu - P(g^{\mu\nu} - u^\mu u^\nu)} + \pi^{\mu\nu} + \ldots$$

- **Ideal hydro**
  - **5 variables (e, P, u_x, u_y, u_z), 4 equations**
  - **Need EoS: e=e(P) to close**
- **Viscous hydro**
  - **5 independent variables in shear tensor** $\mathrm{Tr}\,\pi^{\mu\nu} = 0;\ u_\mu \pi^{\mu\nu} = 0$

$$D\pi^{\mu\nu} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle}\right) - \frac{4}{3}\pi^{\mu\nu}\partial_\alpha u^\alpha$$

- **Particle spectra from Cooper-Fry formula**

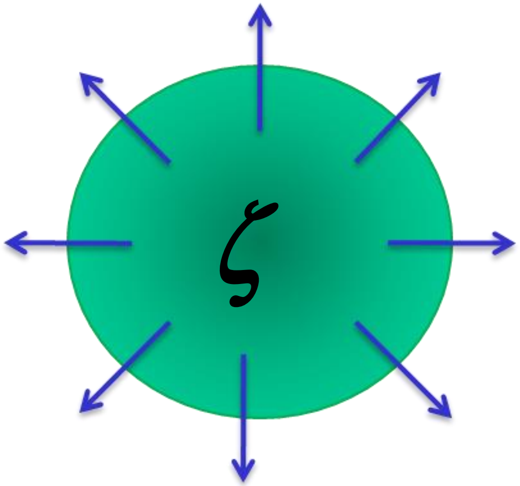
$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\int_{\Sigma=(\tau_f, x, y, \eta_s)} p^\mu d\Sigma_\mu f(p\cdot u, T, \mu)$$

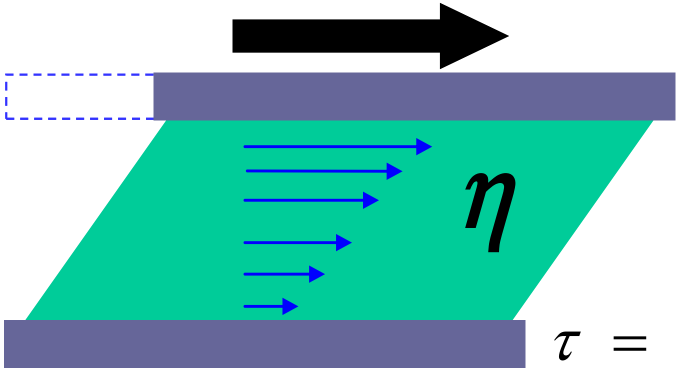
$$f = f_0 + \delta f;\ f_0 = \frac{1}{e^{(p\cdot u - \mu_i)/T_f} \mp 1};\ \delta f = f_0\frac{p_\mu p_\nu \pi^{\mu\nu}}{2T^2(e+P)}$$

- **Hadronic rescattering and decay**

Viscosity

- Bulk viscosity: the resistance to compression/expansion
- Shear viscosity: the resistance to flow



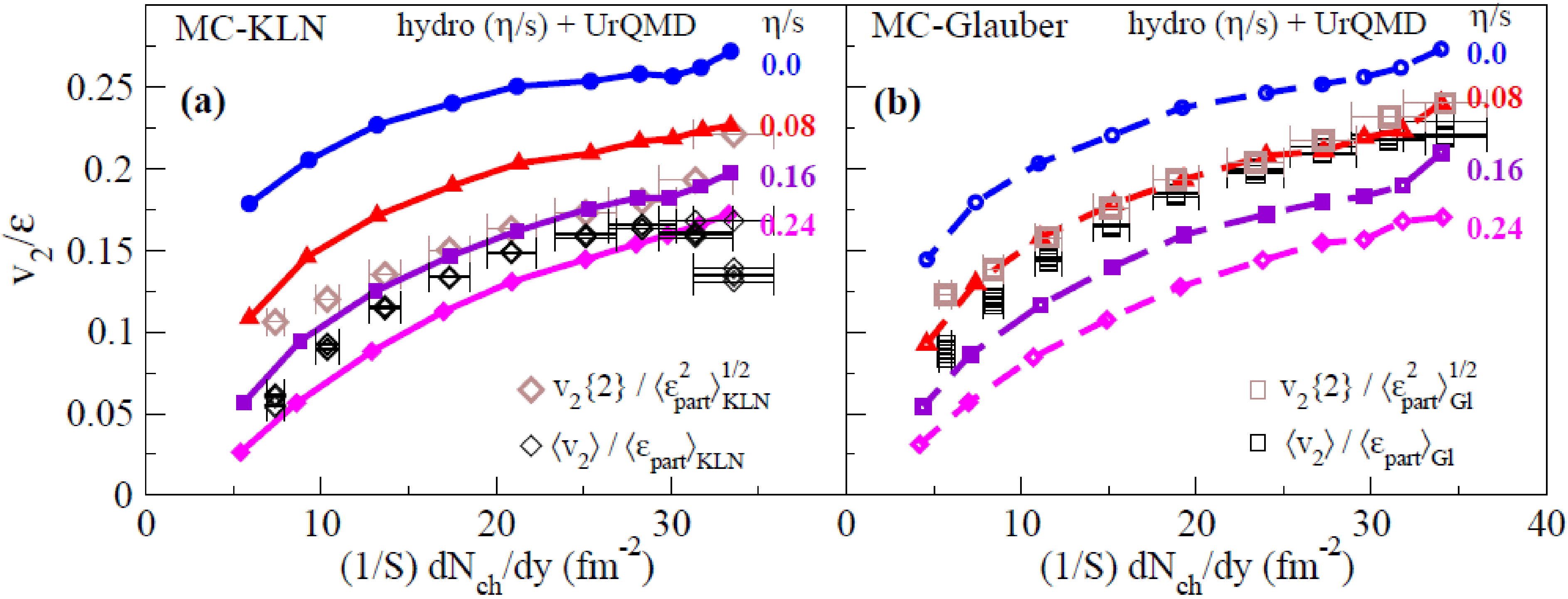


$$\tau = \frac{F}{A} = \eta \frac{\partial u}{\partial y}$$

- Shear viscosity measures the ability of momentum transport between different parts of the system (thus the interaction strength)

$$\eta \approx \tfrac{1}{3} n\bar{p}\lambda_f = \frac{\bar{p}}{3\sigma_{\mathrm{tr}}}$$

Extracting shear viscosity of QGP



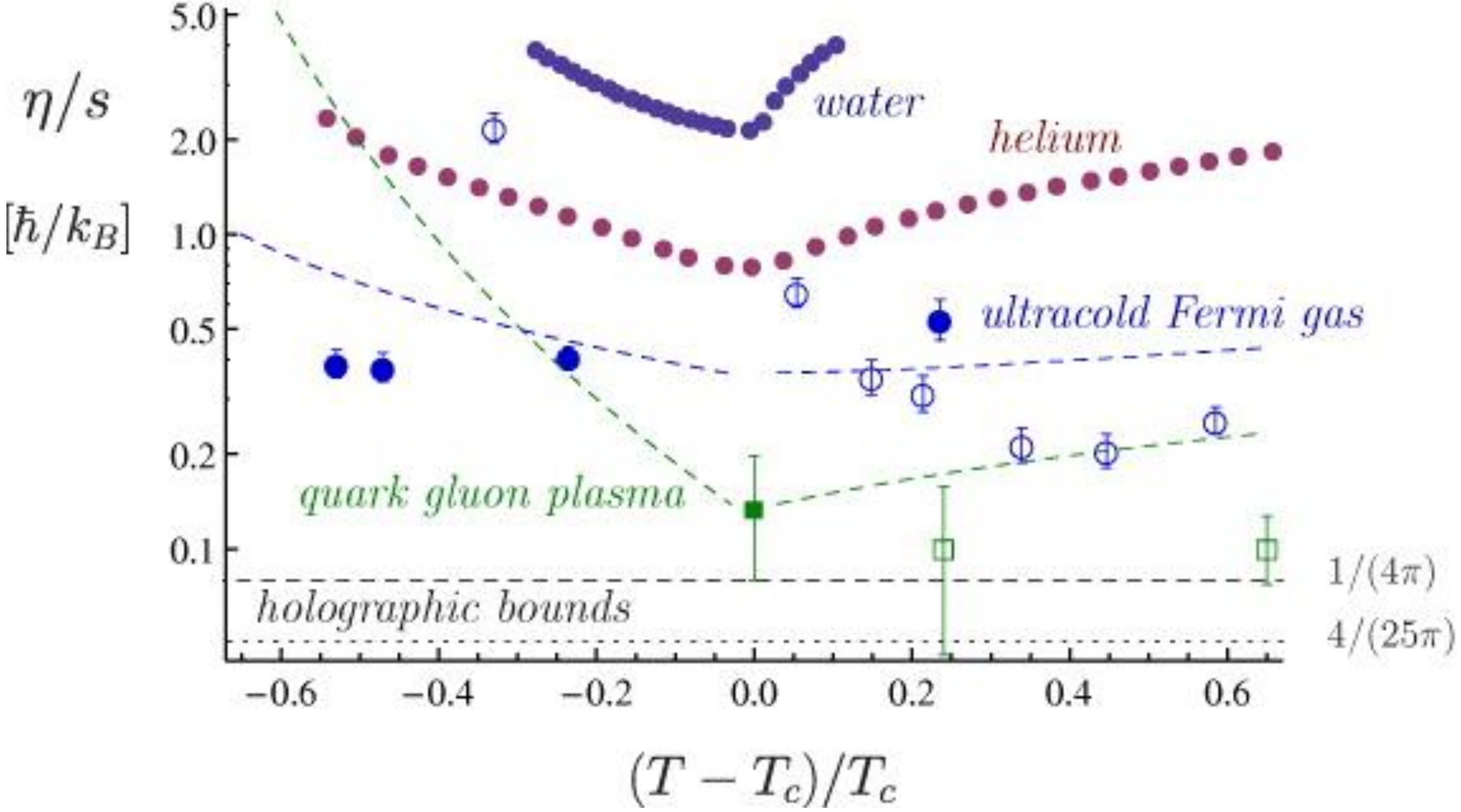
Song, Bass, Heinz, Hirano, Chen, PRL, 2011

This calculation found:

$$\eta / s = (1 - 2.5) / (4\pi)$$

Factor of 2 difference in η/s originates from 20-30% e_2 uncertainty

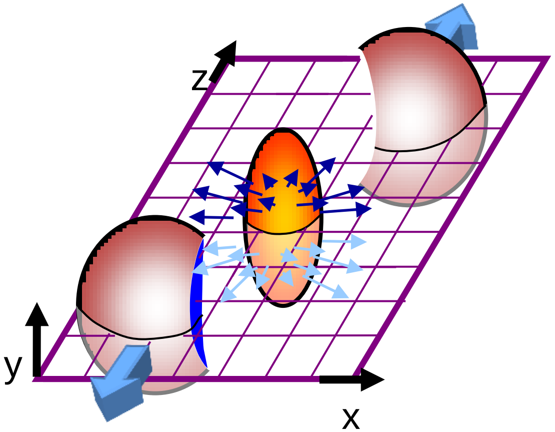
Shear viscosity for other matter



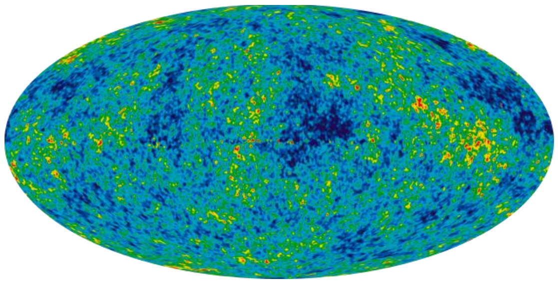
Adams, Carr, Schafer, Steinberg, Thomas, 2012

Initial state fluctuations

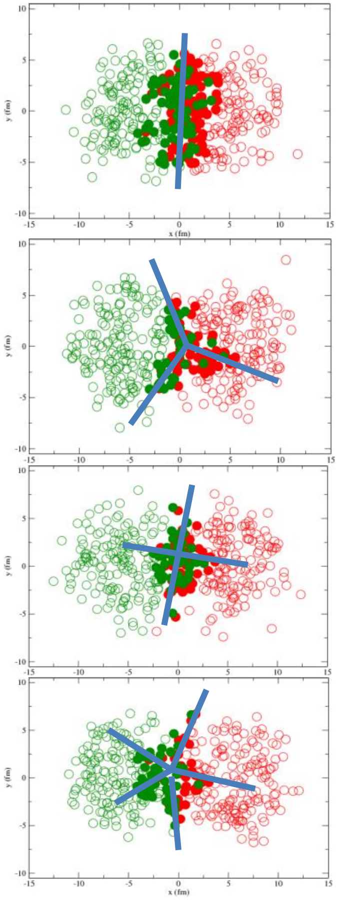
smooth IC



WMAP



lumpy IC

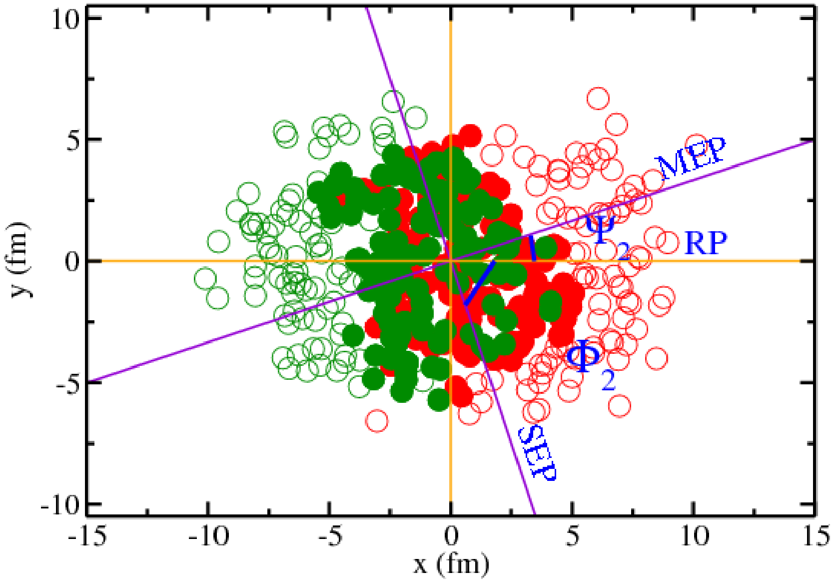


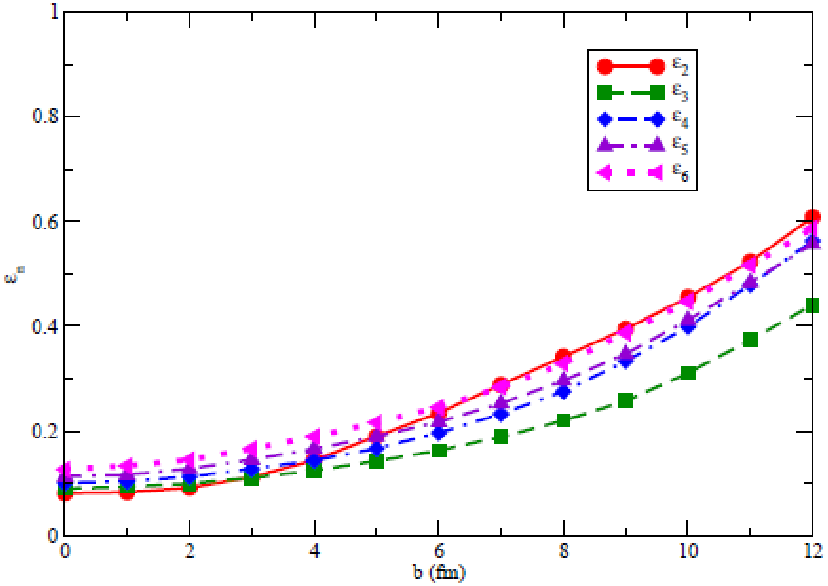
Initial conditions are not smooth, but lumpy, leading to anisotropy and inhomogeneity of QGP

Initial state fluctuations affect the system evolution and manifest in final state flow and correlations

Initial state fluctuations could provide more constraints on transport properties with more observables

Initial geometry



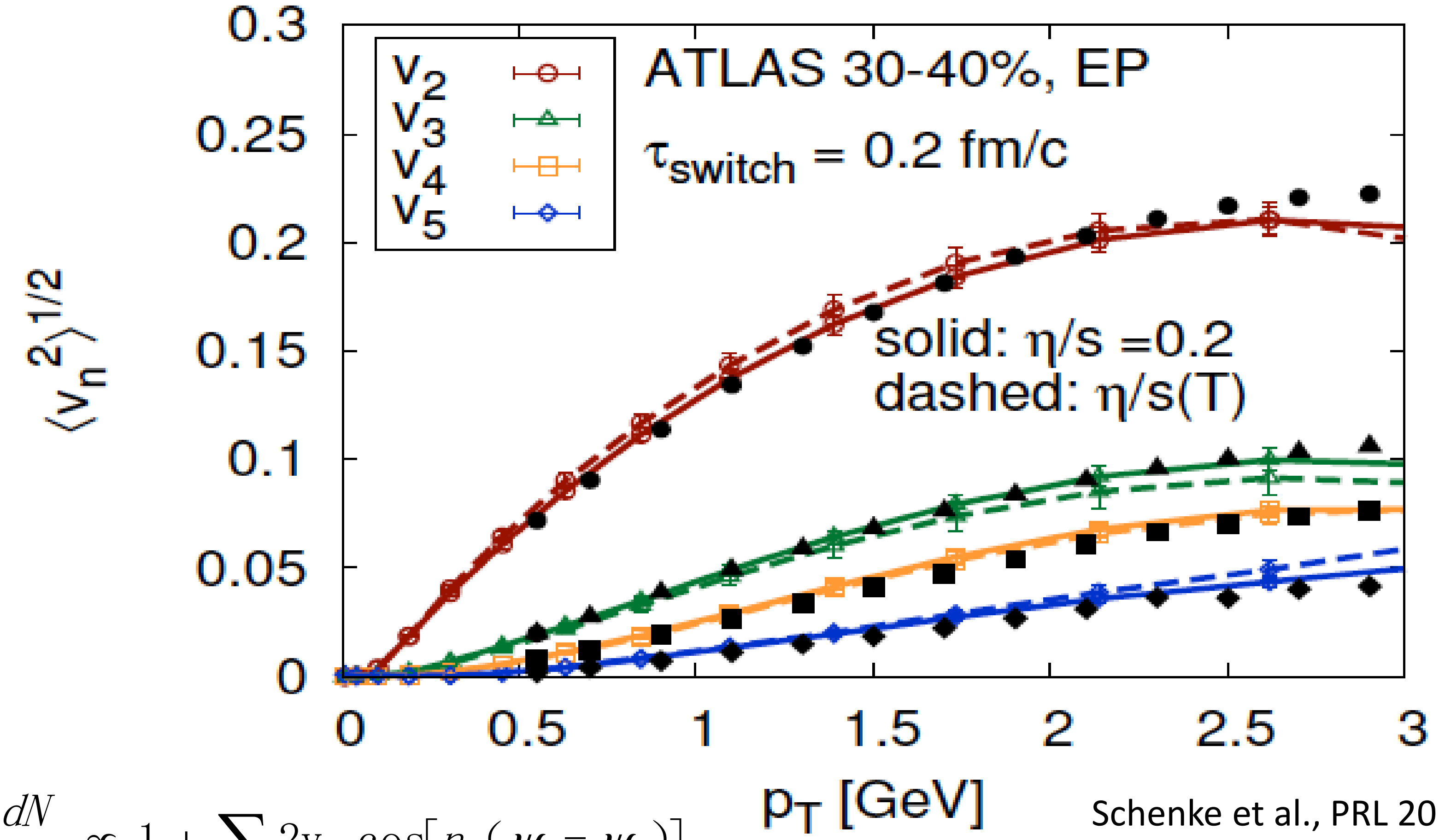


$$\Phi_n = \frac{1}{n}\arctan\frac{\langle r^n \sin(n\phi)\rangle}{\langle r^n \cos(n\phi)\rangle}, \quad \varepsilon_n = \langle r^n \cos[n(\phi - \Phi_n)]\rangle / \langle r^n \rangle$$

Non-zero odd-order eccentricities due to initial state fluctuations

GYQ, Petersen, Bass, Muller, PRC, 2010

Final state anisotropic flow

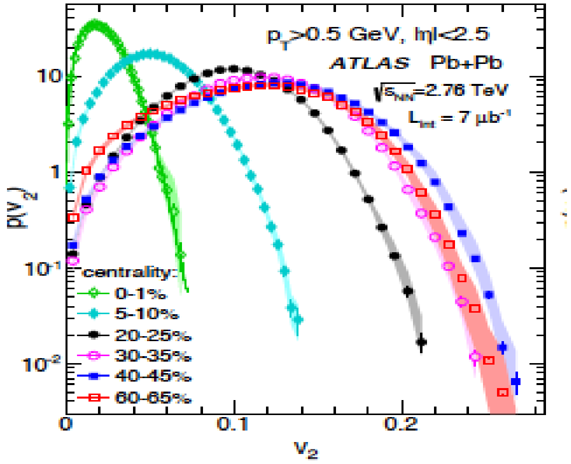


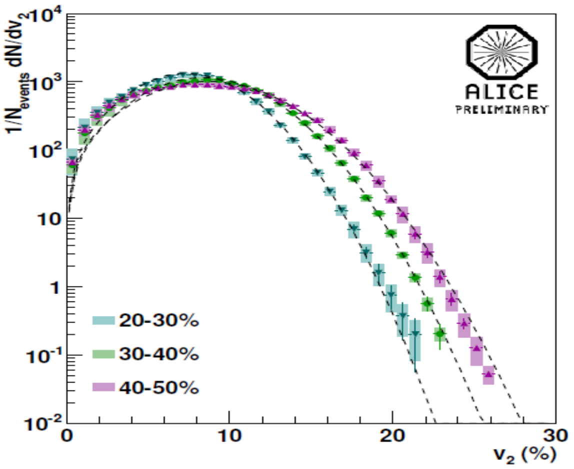
Schenke et al., PRL 2012

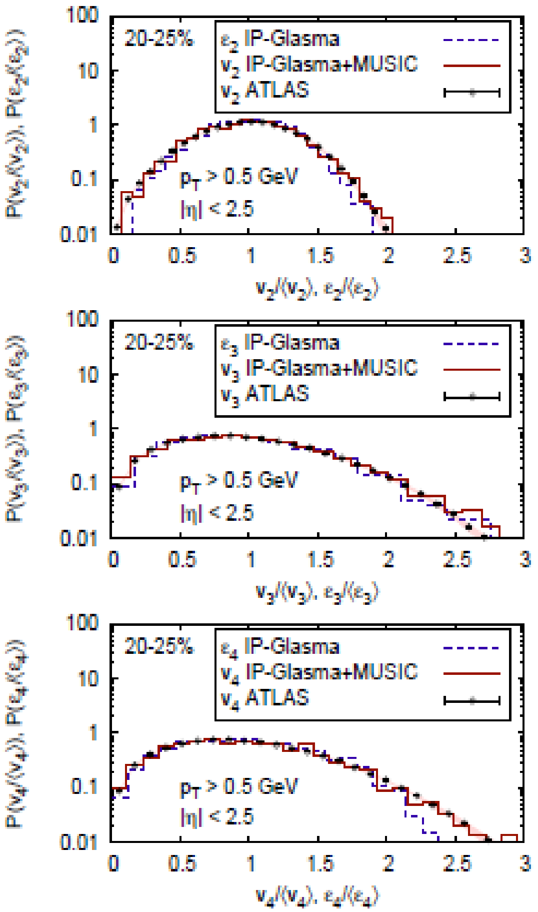
$$\frac{dN}{d\psi} \propto 1 + \sum_n 2v_n \cos[n(\psi - \psi_n)]$$

$$\Psi_n = \frac{1}{n}\arctan\frac{\langle \sin(n\psi_p)\rangle}{\langle \cos(n\psi_p)\rangle}, \quad v_n = \langle \cos[n(\psi_p - \Psi_n)]\rangle$$

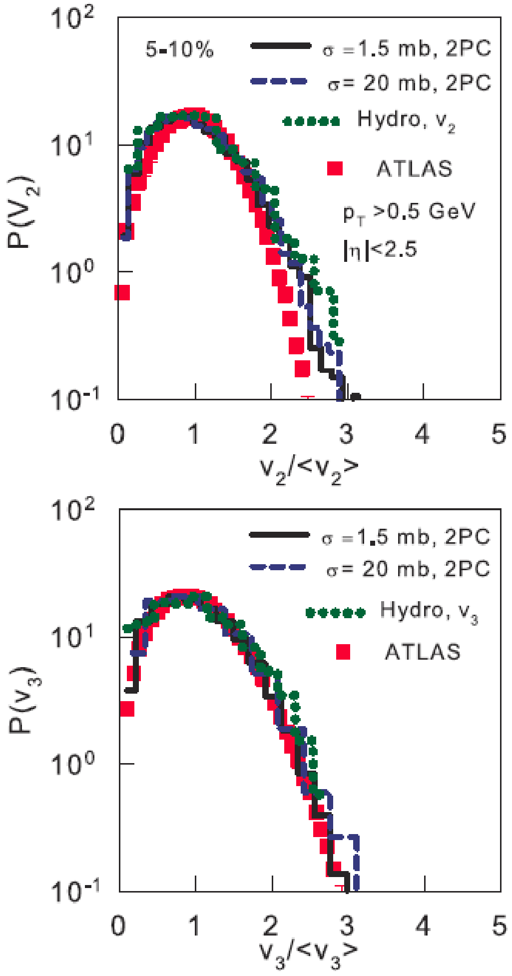
Event-by-event v_n distribution





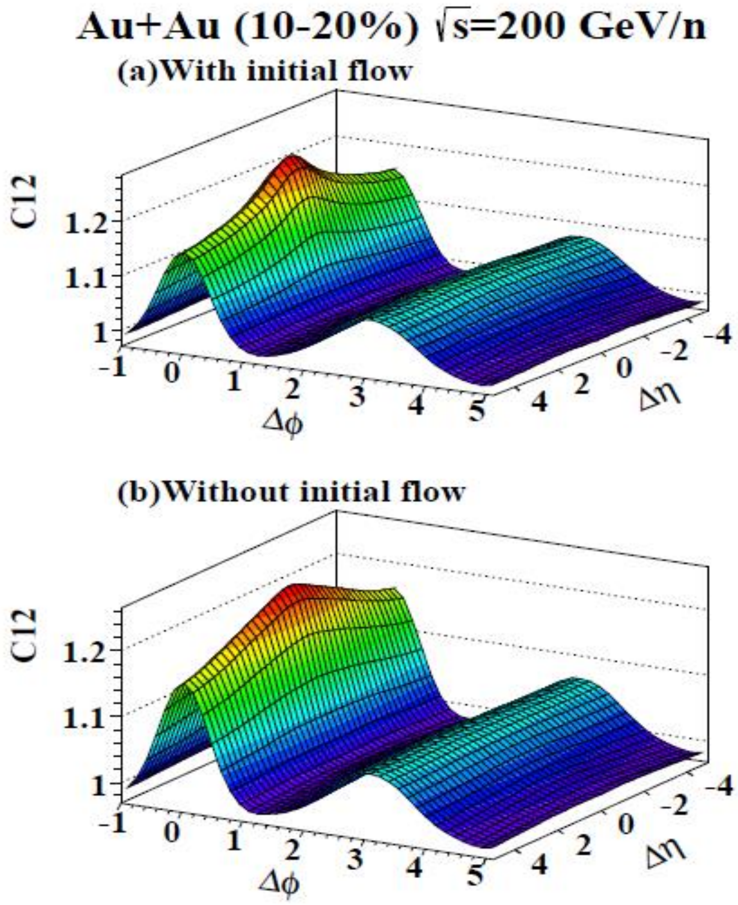


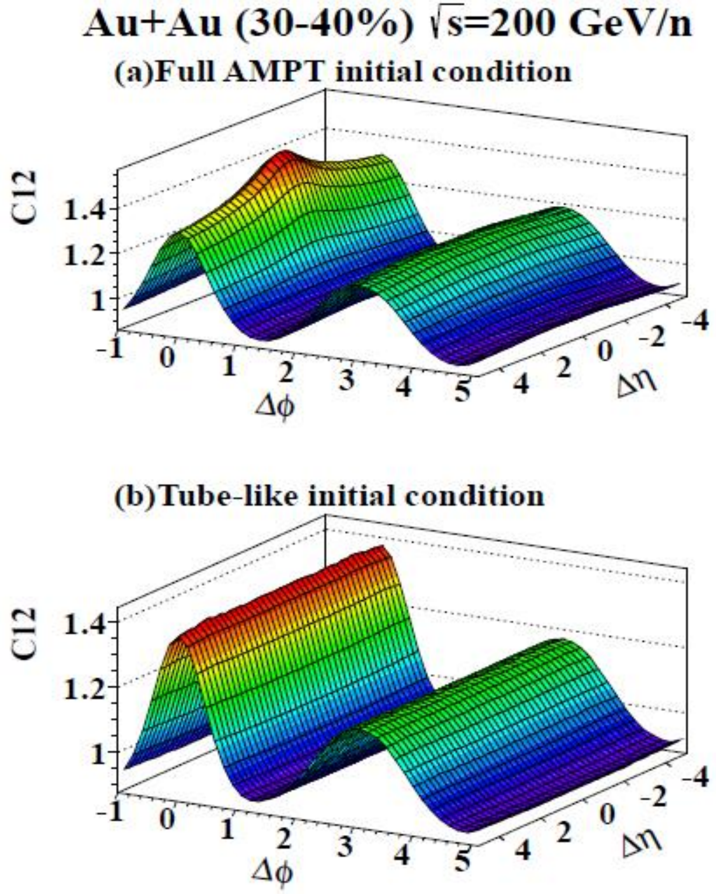
Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 2012



Pang, GYQ, Roy, Wang, in preparation

Dihadron correlations

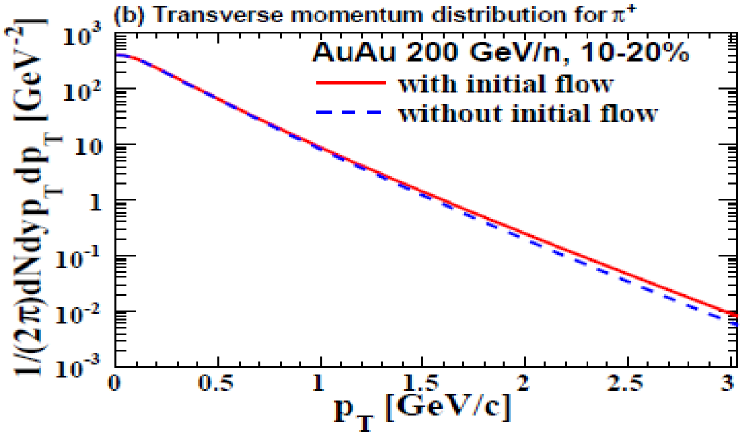


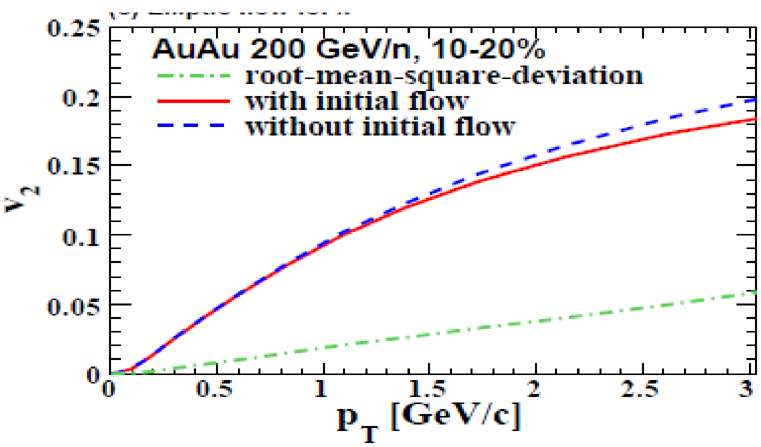


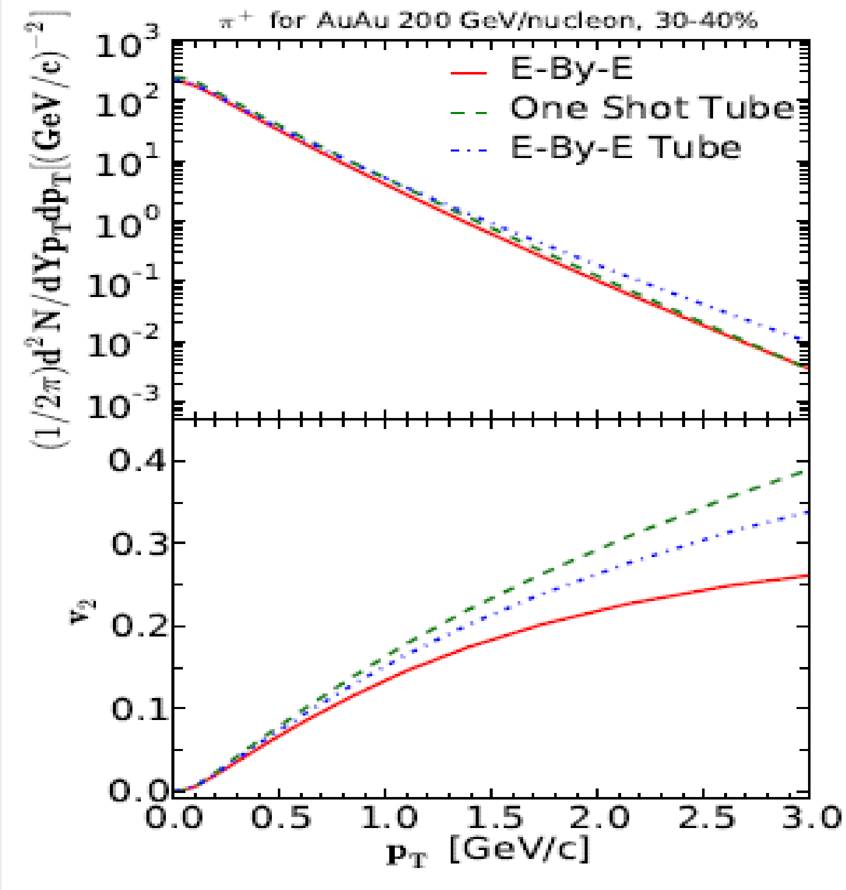
Different IS fluctuations => different FS flow/correlations

Pang, wang, Wang, PRC 2012, 2013

Initial flow and longitudinal fluctuations





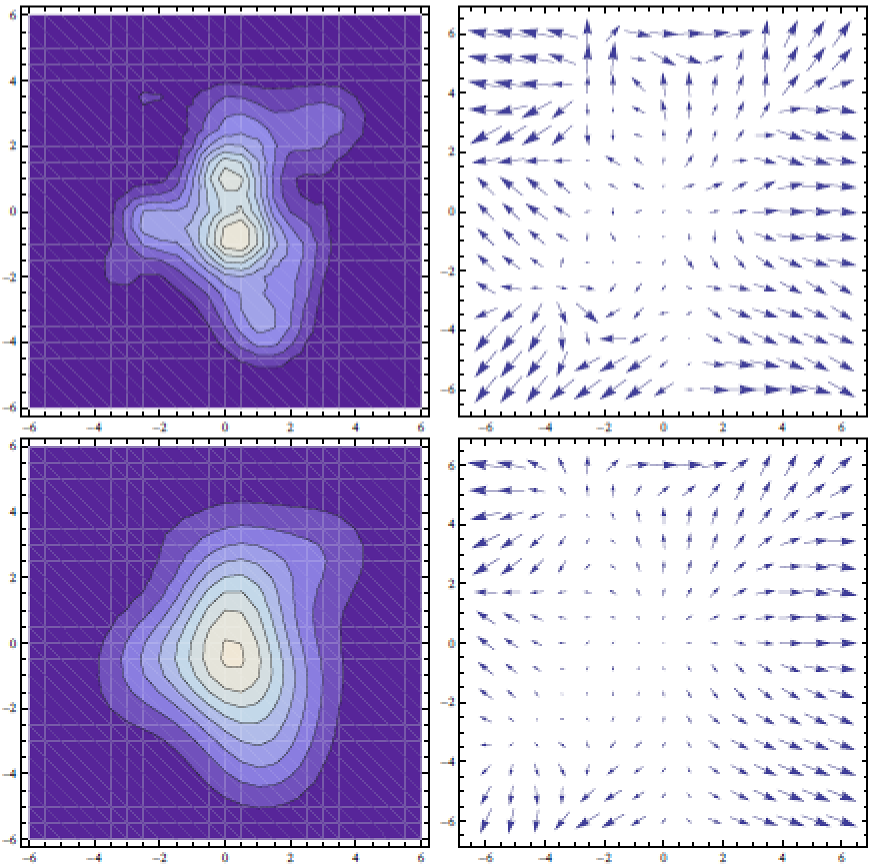


Initial flow fluctuations **harden** p_T spectra and **decrease** elliptic flow

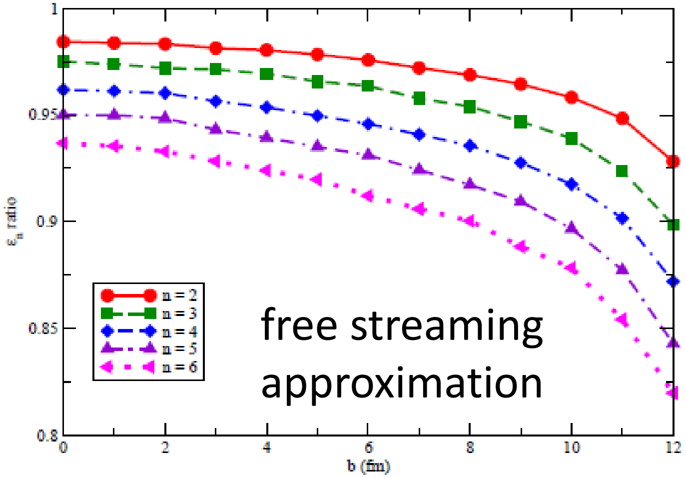
Longitudinal fluctuations **soften** p_T spectra and **decrease** elliptic flow

Pang, wang, Wang, PRC 2012, 2013

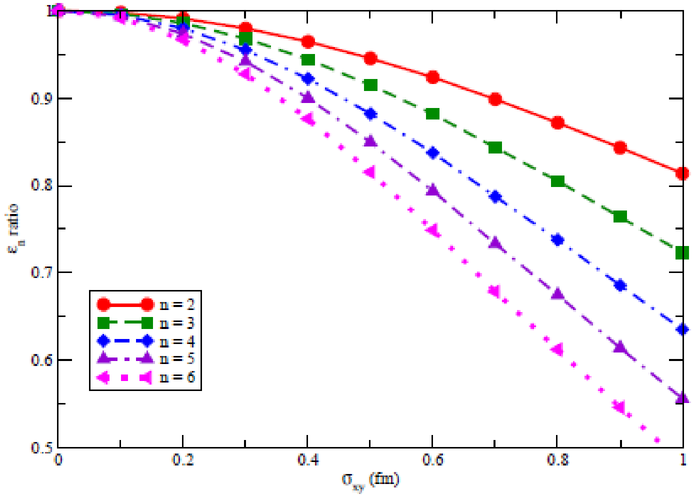
Pre-equilibrium evolution



GYQ, Petersen, Bass, Muller, PRC 2010



free streaming approximation



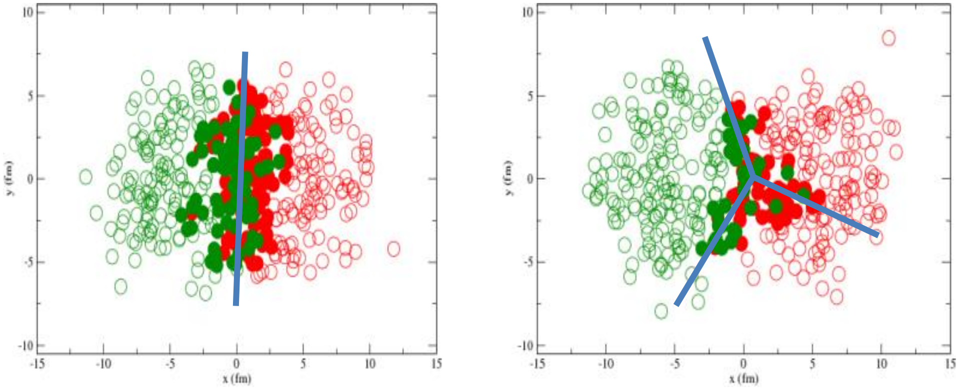
Pre-equilibrium evolution develops radial flow & decreases system anisotropy

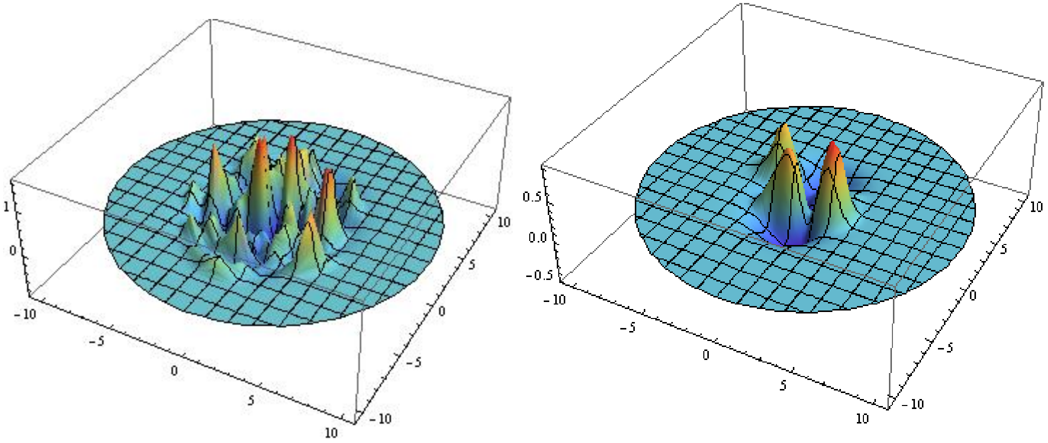
Need A LOT MORE work for detailed thermalization/equilibration mechanisms

About the initial states

- ***Anisotropy***
  - The degree of anisotropy, quantified by harmonic moments: eccentricity, triangularity …

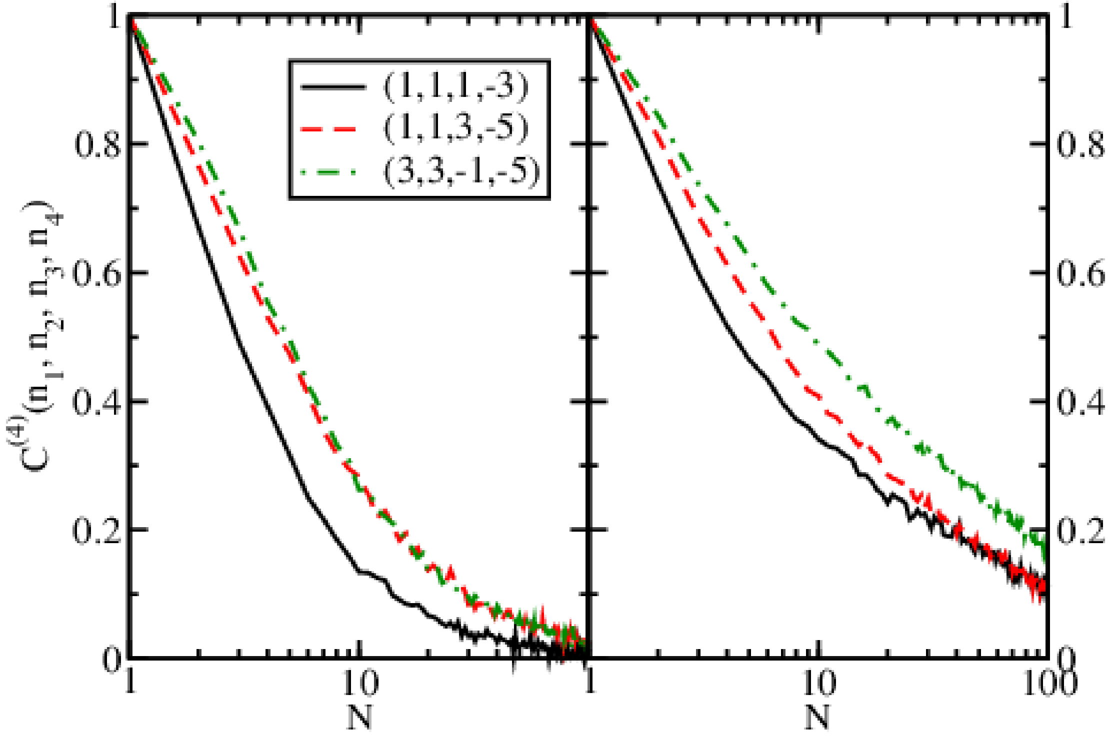
- ***Inhomogeneity***
  - The degree of inhomogeneity: the population of hot/cold spots, their fractions, their magnitudes, their spatial distribution …
  - **Should be encoded by correlations between different orders of harmonic moments**





Initial state event-plane correlations

$$C^{(k)} = \langle \cos[n_1\Phi_{n_1} + n_2\Phi_{n_2} + \cdots + n_k\Phi_{n_k}] \rangle$$

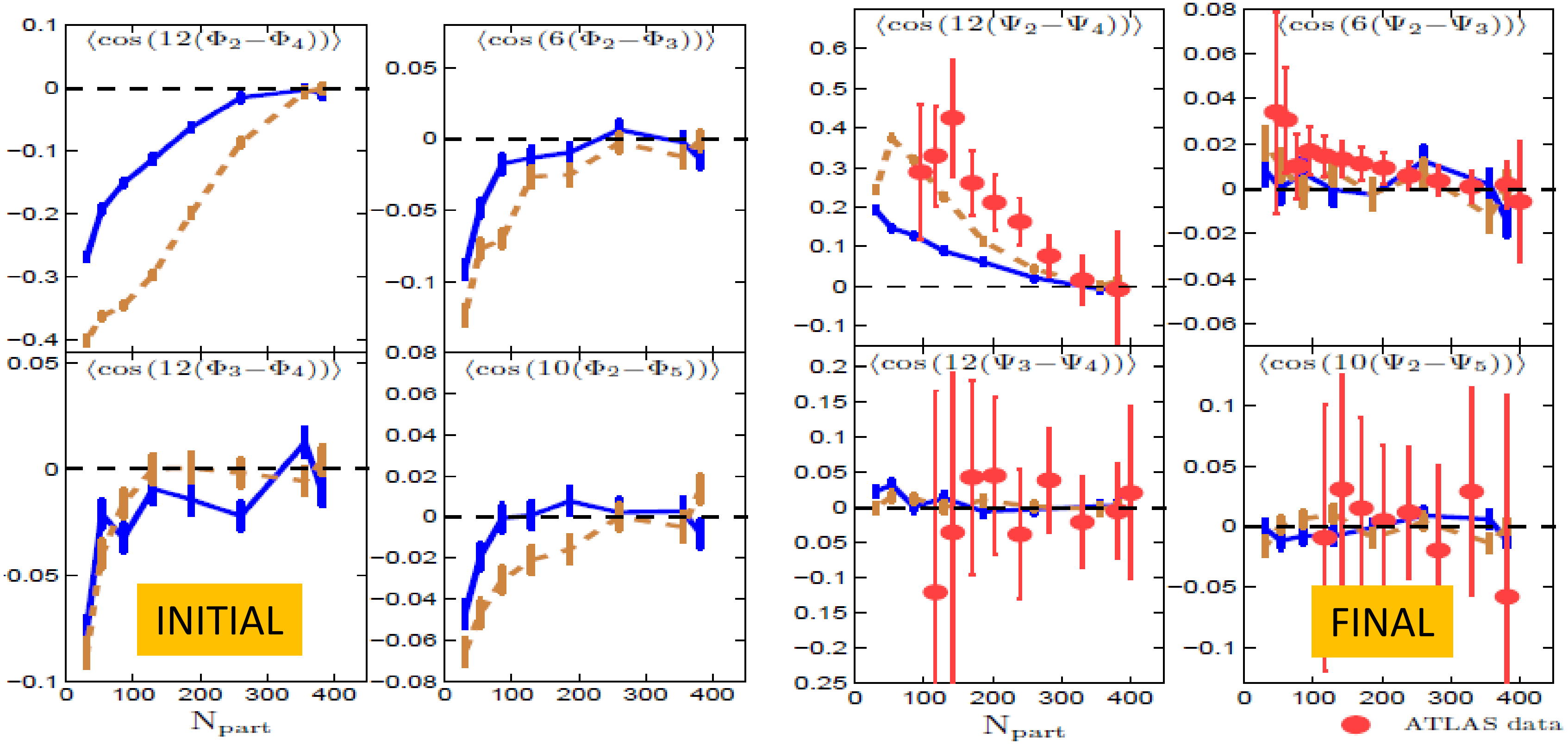


Can we test this in the final state?

Qin, Muller, PRC, 2012

The initial state event-plane correlations are sensitive to the number of local fluctuations (hot and cold spots) of the fireball

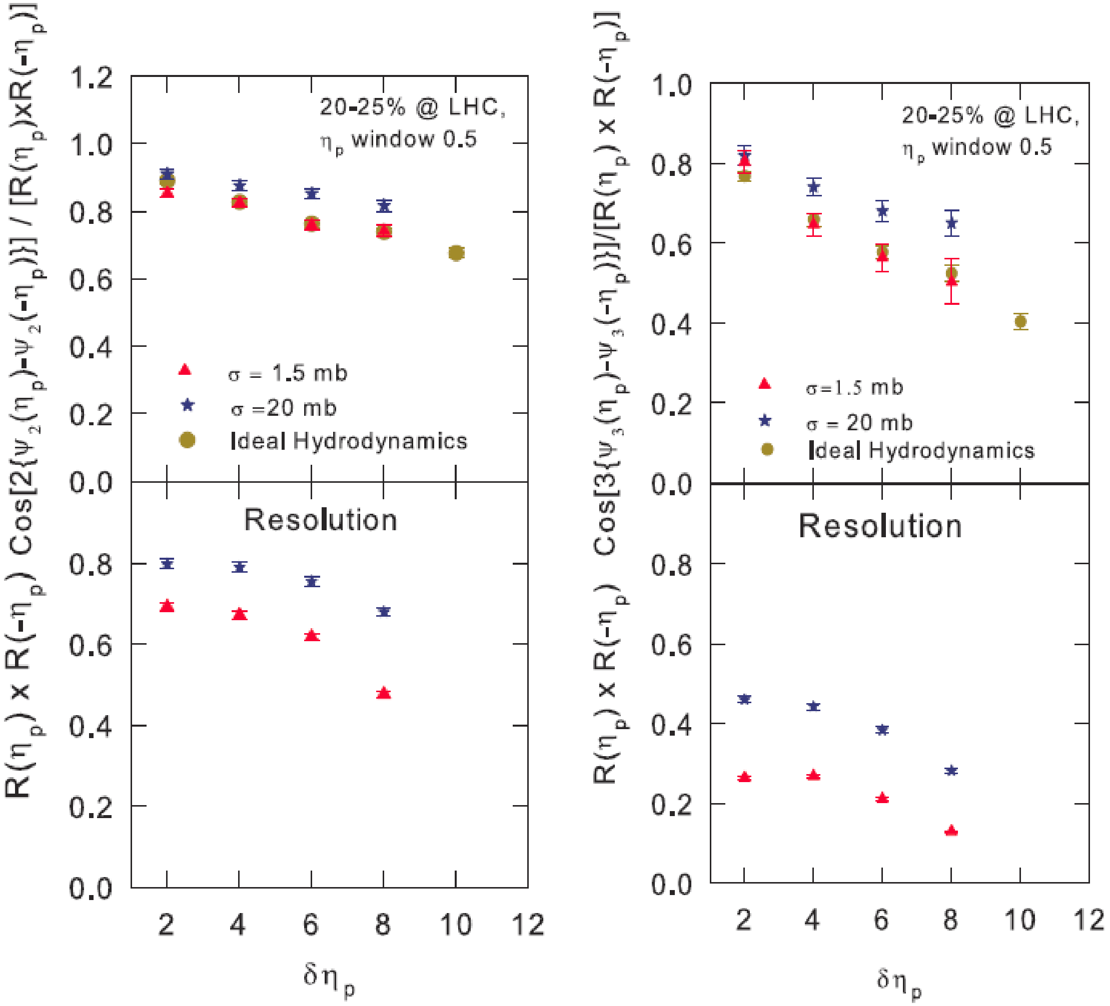
Final state event-plane correlations



Qiu, Heinz, PLB, 2012

The reality is: Non-linear hydrodynamics evolution develops correlations between different order event planes which destroy the original initial state correlations between different order event planes

Same-order event plane correlations

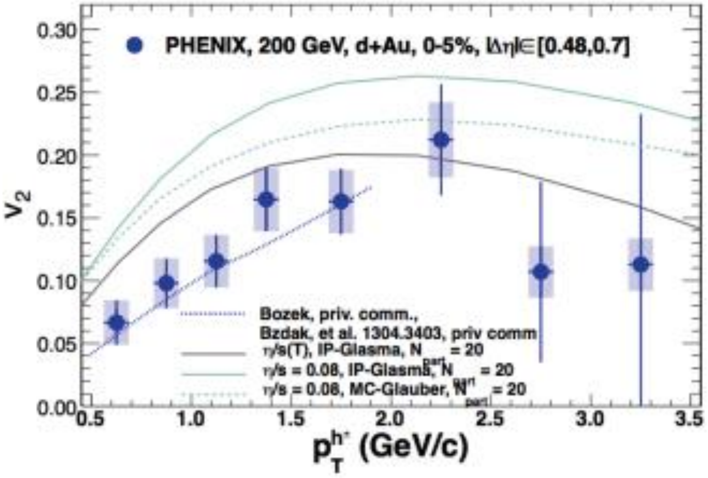


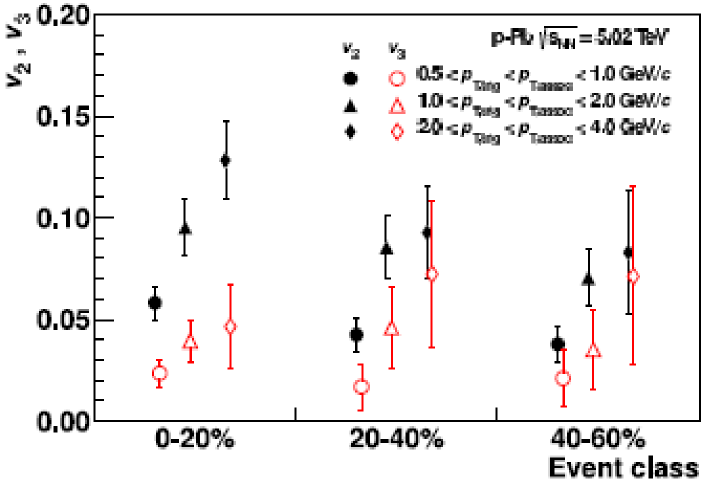
Pang, GYQ, Roy, Wang, in preparation

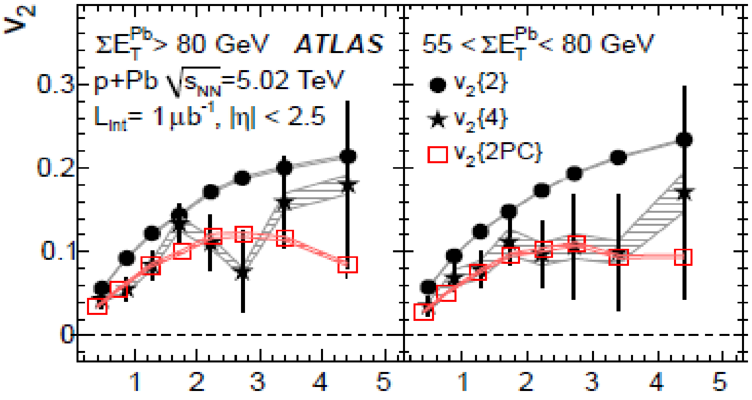
With longitudinal fluctuations, the correlations of same order event planes decreases with increasing pseudo-rapidity gap

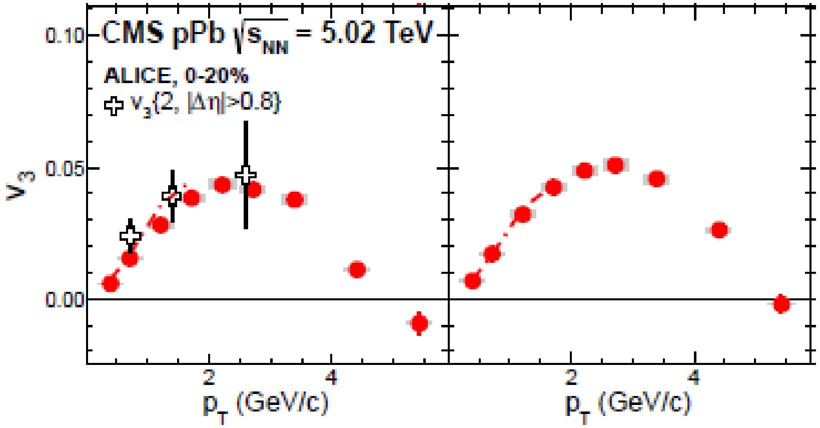
The longitudinal de-correlation of event planes depends on the cross section (shear viscosity)

Flow in smaller p+Pb & d+Au systems?



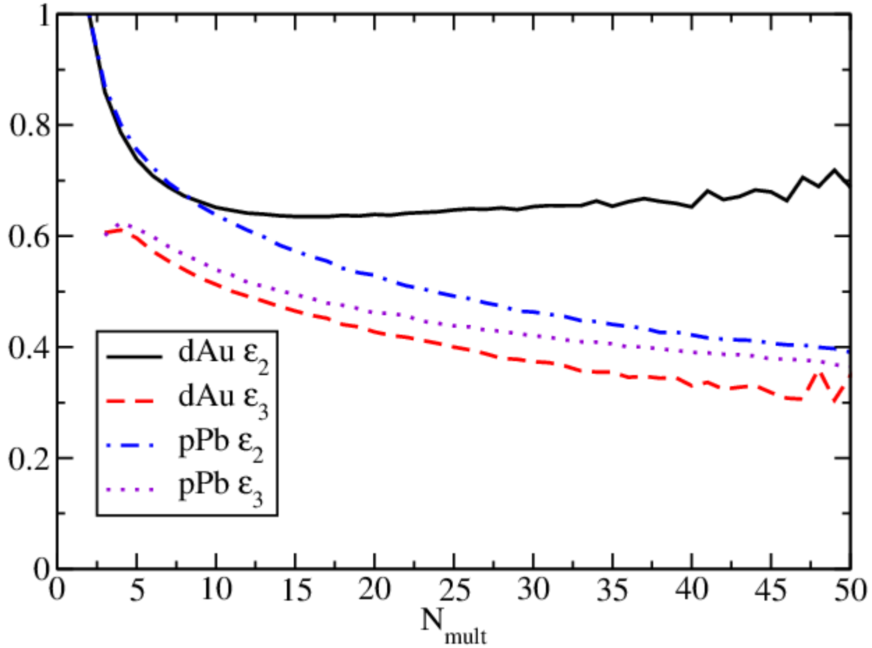


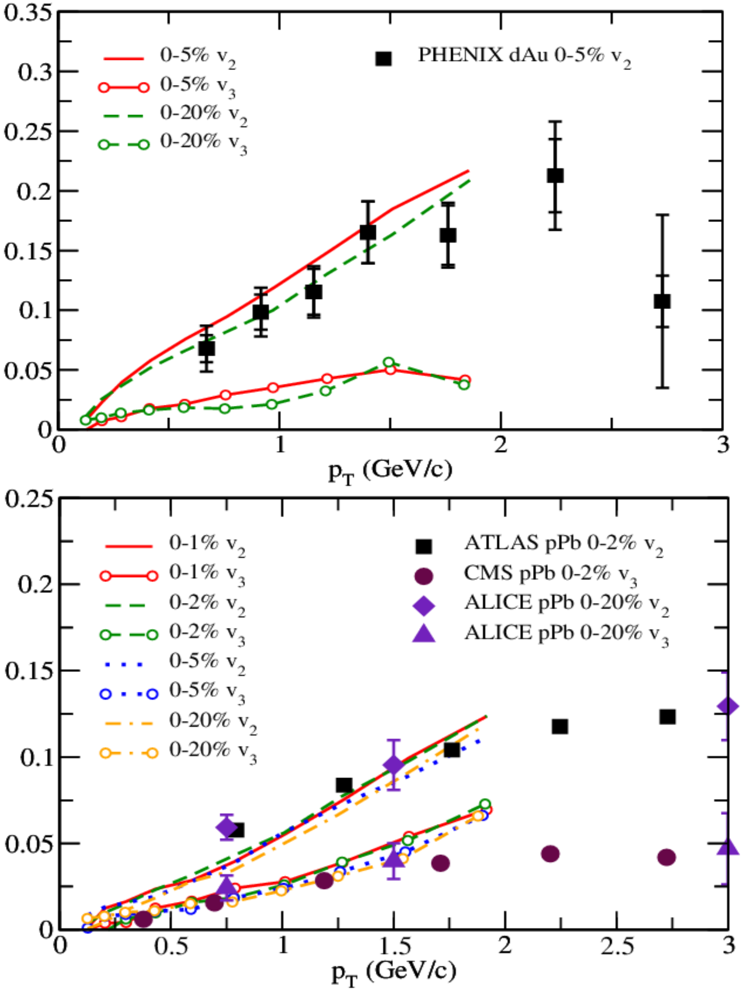




Is it purely an initial state effect or the signature of a mini-QGP?

Results from hydro + IS fluctuations





GYQ, Muller, 2013

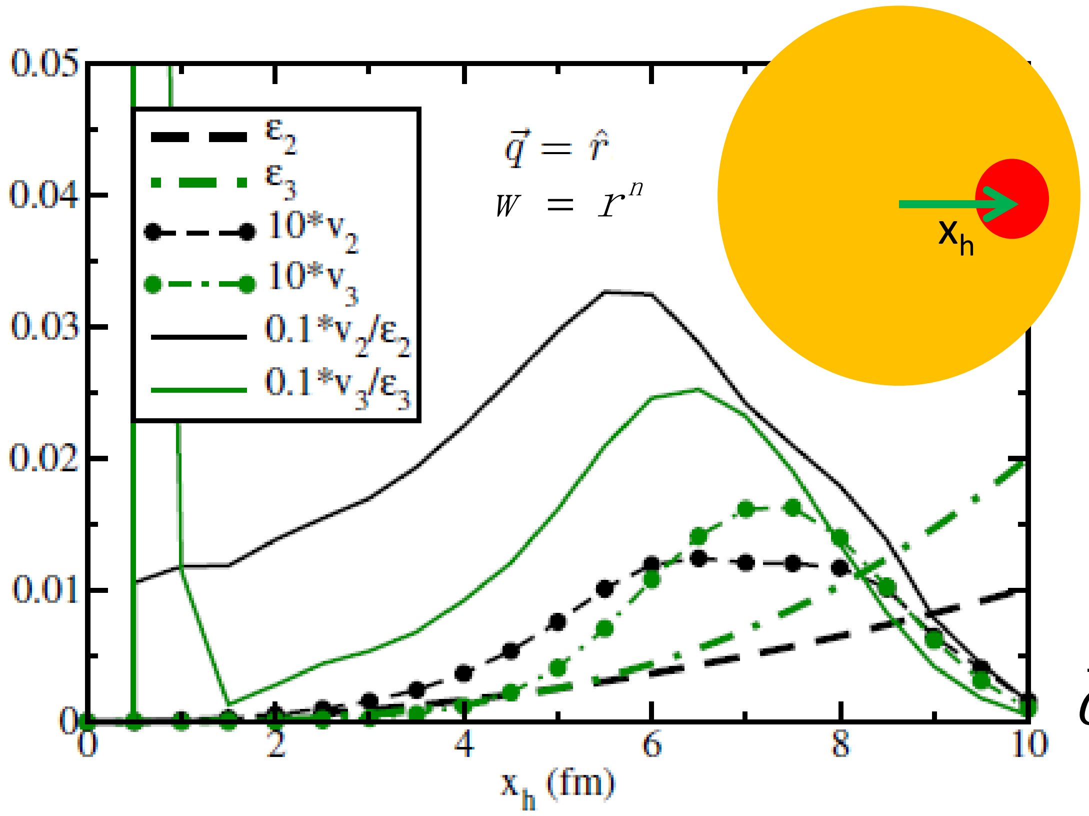
Quite consistent with calculations from hydro + initial state fluctuations

Larger v2 in d-Au than p-Pb collisions

Similar magnitude for v3

No strong centrality dependence

The origin of flow anisotropy?



$$\vec{Q}_n = (Q_{n,x}, Q_{n,y})$$
$$= [\{w\cos(n\phi_q)\}, \{w\sin(n\phi_q)\}]$$

$$\vec{\epsilon}_n = \vec{Q}_n/\{w\} = [\epsilon_{n,x}, \epsilon_{n,y}]$$

$$\epsilon_n = \sqrt{\epsilon_{n,x}^2 + \epsilon_{n,y}^2}$$

$$\Phi_n = \frac{1}{n}\arctan\left(\epsilon_{n,y}/\epsilon_{n,x}\right)$$

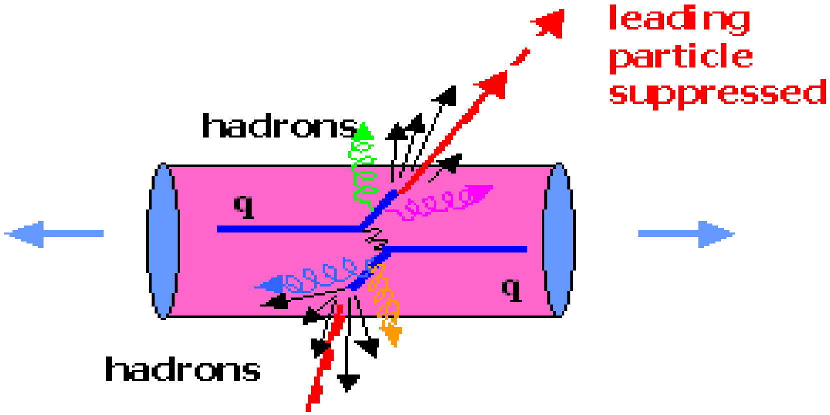
$$\vec{q} = f(\vec{r}, \vec{u}, \ldots)$$

Eccentricity is not the only factor that determines the flow anisotropy

The local density gradients and detailed structures of the system affect the development of the flow

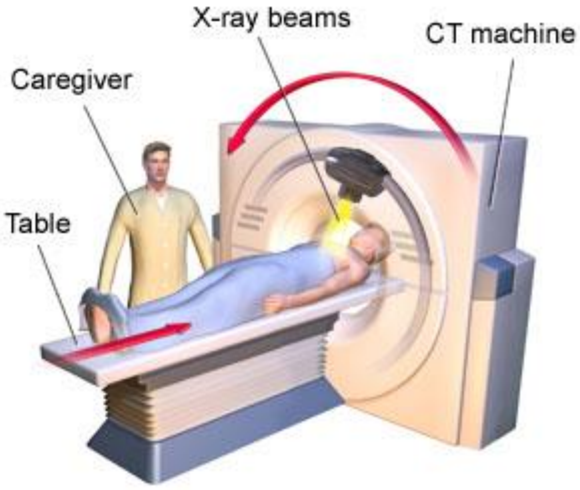
Is it possible to find a new/simple q (measure) for flow anisotropy?

Jet quenching

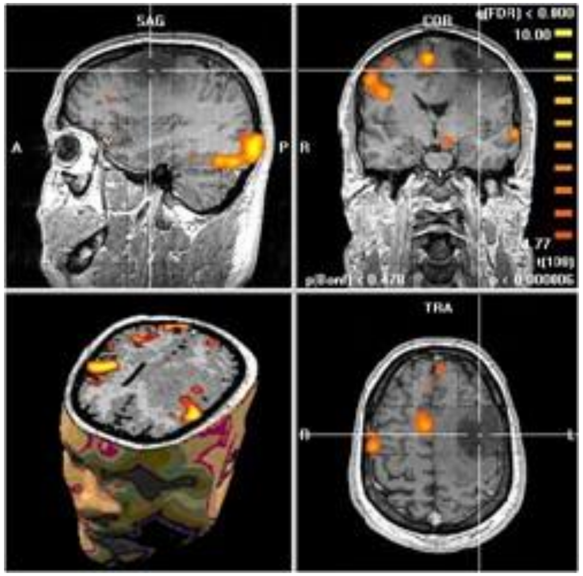


High energy partons produced from initial hard collisions interact with traversed QGP and lose energy in the process

The study of jet modification provides useful tools to probe the properties and internal structure of QGP

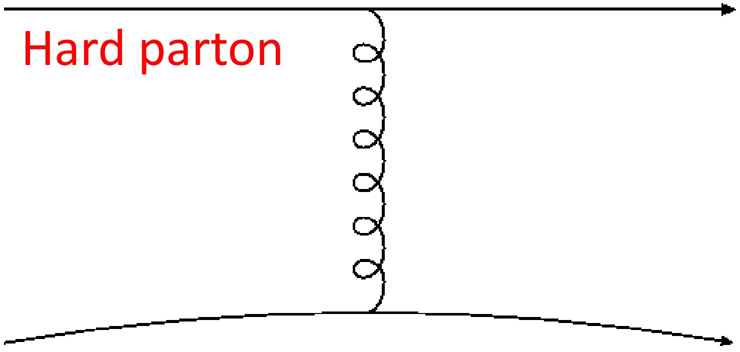


Computerized Axial Tomography Scan

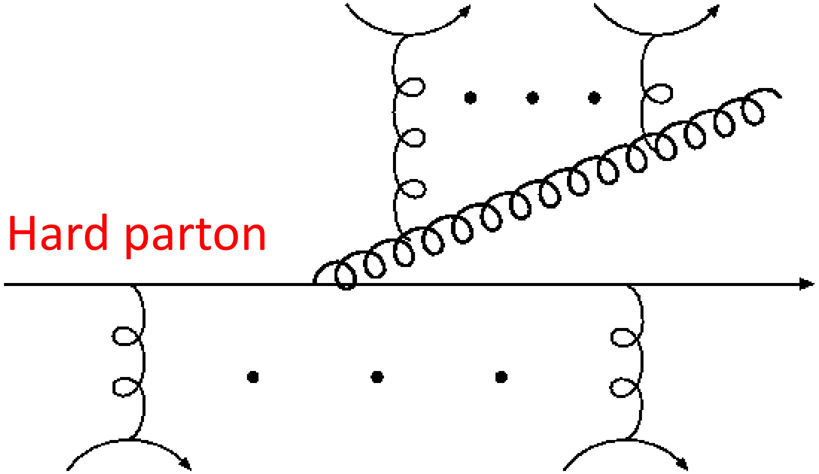


Jet evolution and energy loss in QGP

$$P_{j\to j'}(medium,\ jet)$$

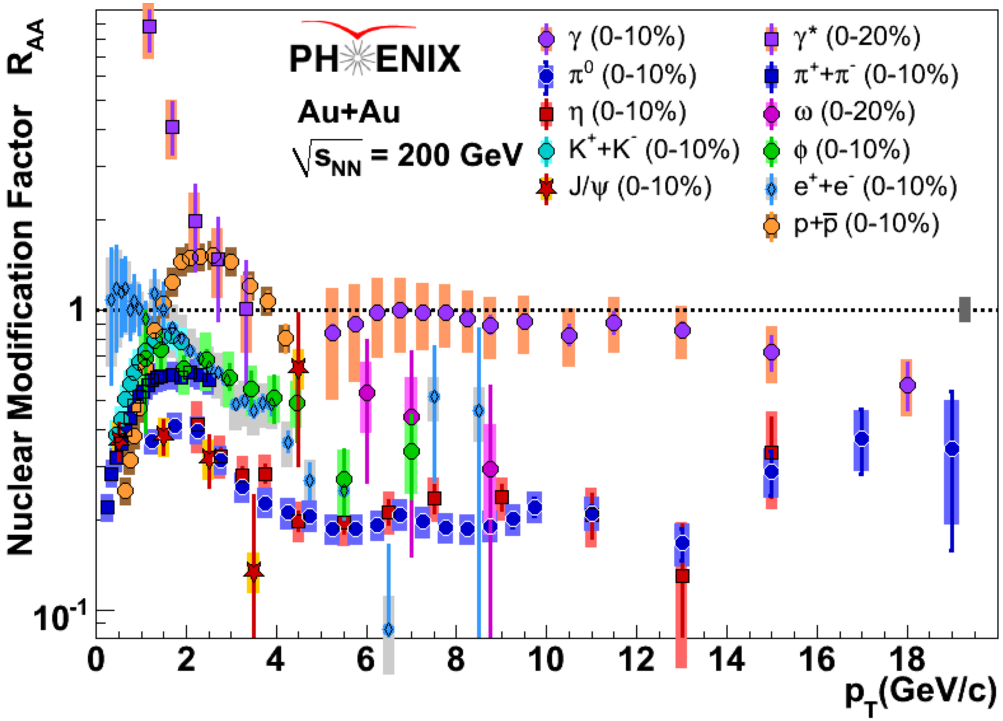


Elastic (collisional)



Inelastic (radiative)

Evidences for jet quenching



$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T dy}{dN_{pp}/dp_T dy}$$

Nuclear modification factor

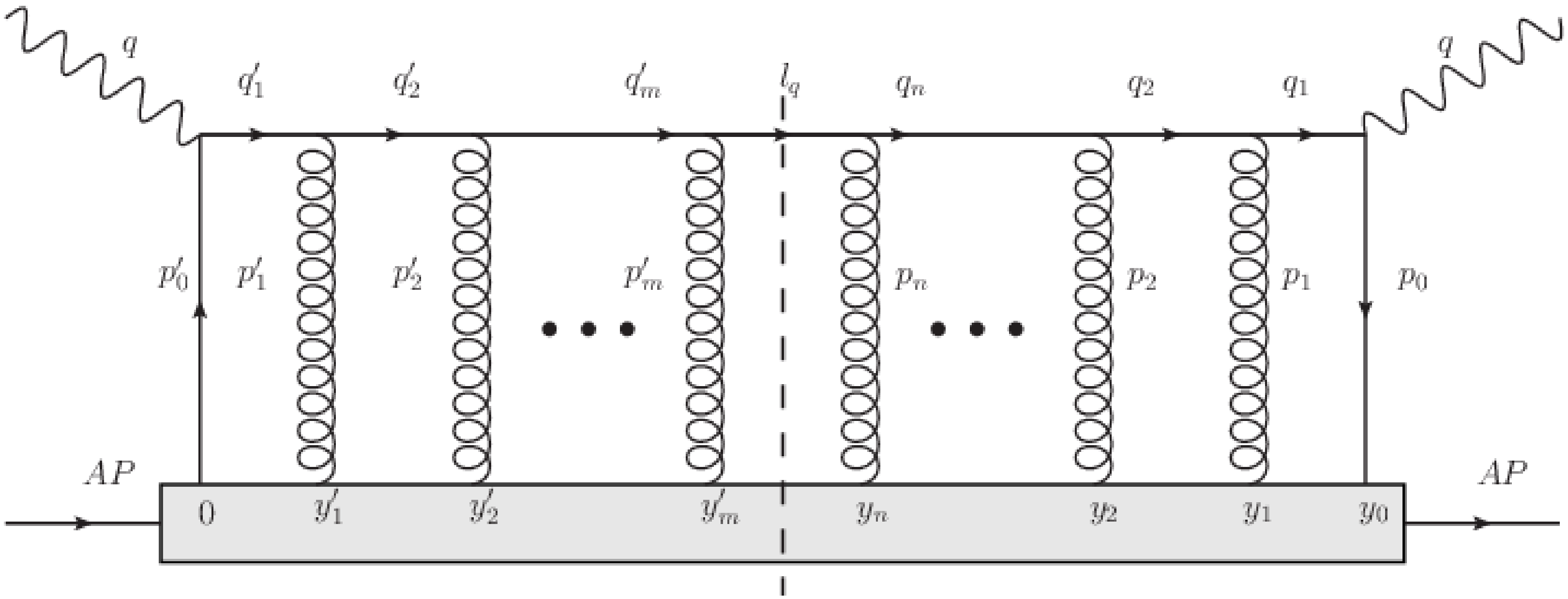
If AA collision is a geometric combination of NN collisions, R_{AA}=1

Photon R_{AA}=1， hadronR_{AA}<1

Due to final state interaction between high energy partons and QGP (i.e., jet energy loss), the production of high p_T hadrons (from the fragmentation of high energy partons) is suppressed

One goal is to quantitative extraction of jet transport coefficients

Jet transport coefficients



$$\frac{\partial \phi}{\partial L^-} = \left[D_{L1} \frac{\partial}{\partial l_q^-} + \frac{1}{2} D_{L2} \frac{\partial^2}{\partial^2 l_q^-} + \frac{1}{2} D_{T2} \nabla^2_{l_{q\perp}} \right] \phi(L^-, l_q^-, \vec{l}_{q\perp})$$

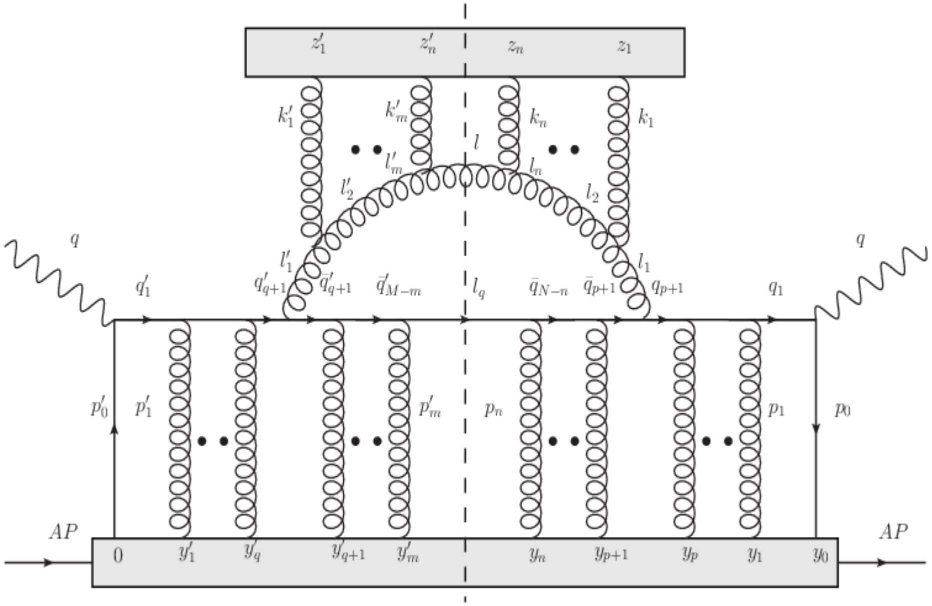
$$\hat{e} = \frac{dE}{dt} = D_{L1}, \hat{e}_2 = \frac{d(\Delta E)^2}{dt} = \frac{D_{L2}}{\sqrt{2}}, \hat{q} = \frac{d(\Delta p_T)^2}{dt} = 2\sqrt{2} D_{T2}$$

GYQ, Majumder, PRC 2013

q=(λ^2, 1, λ)Q, scattered gluons (λ^2, λ, λ)Q

Models for radiative energy loss

BDMPS-Z: Baier, Dokshitzer, Mueller, Peigne, Schiff, Zakharov
ASW: Amesto, Salgado, Wiedemann
AMY: Arnod, Moore, Yaffe
GLV: Gyulassy, Levai, Vitev
Higher Twist (HT): Guo, Wang, Majumder



Modeling the medium

Static scattering centers (BDMPS-Z, GLV, ASW)
HTL perturbative plasma (AMY)
General nuclear medium, soft scatterings (HT)

Resummation schemes

Resume all possible numbers of soft interactions (BDMPS, AMY)
Path integral representation of parton transport(Zakharov, ASW)
Order by order in number of scatterings (GLV)

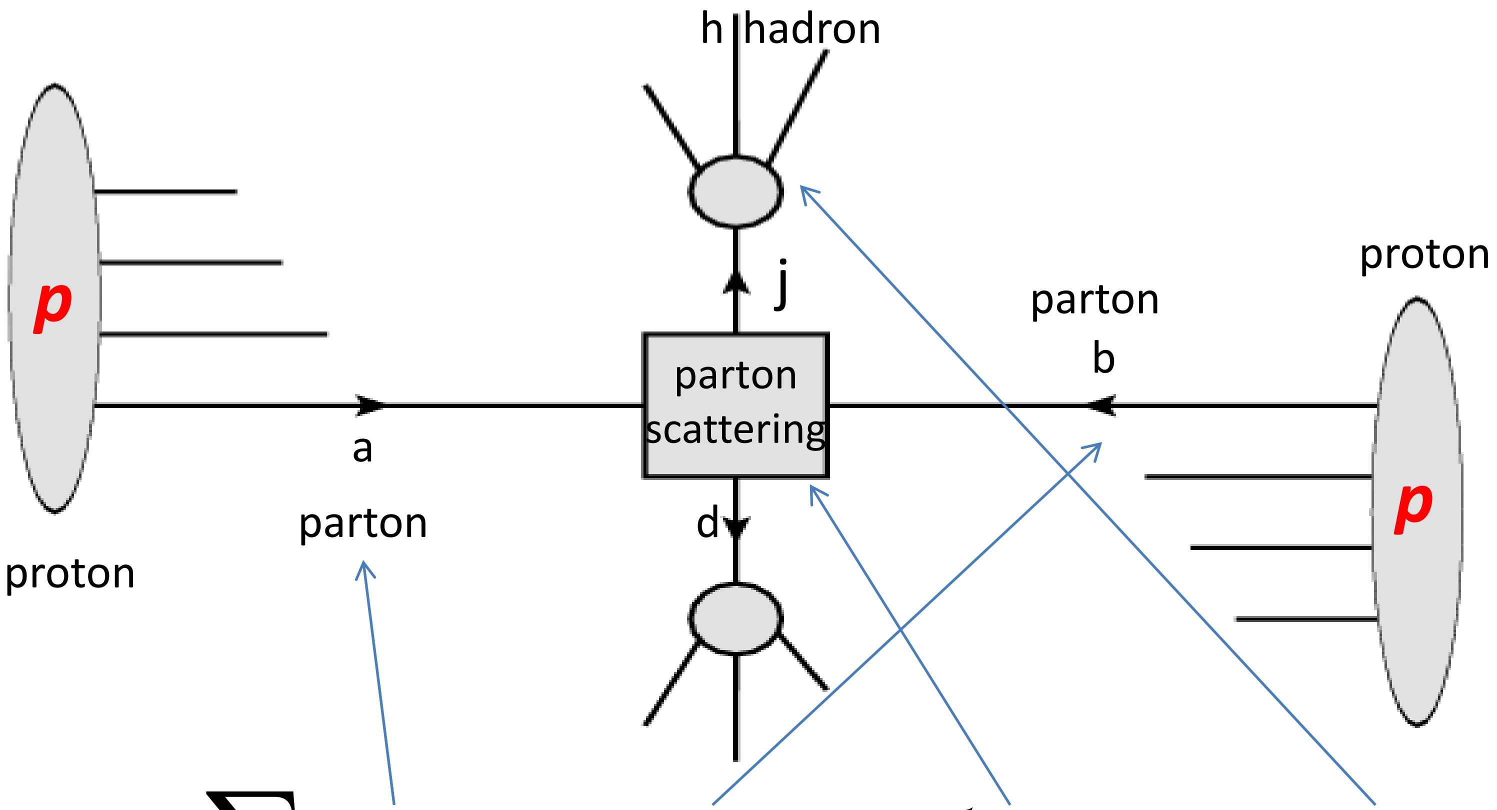
Evolution schemes

Poisson independent emissions (BDMPS, GLV, ASW)
Transport rate equations (AMY)
Modified DGLAP (HT)

$$\frac{dN_g}{d\omega dk_\perp^2 dt} = \frac{2\alpha_s x P(x)\hat{q}(t)}{\pi \omega k_\perp^4} \sin^2\left(\frac{t - t_i}{2t_{form}}\right)$$

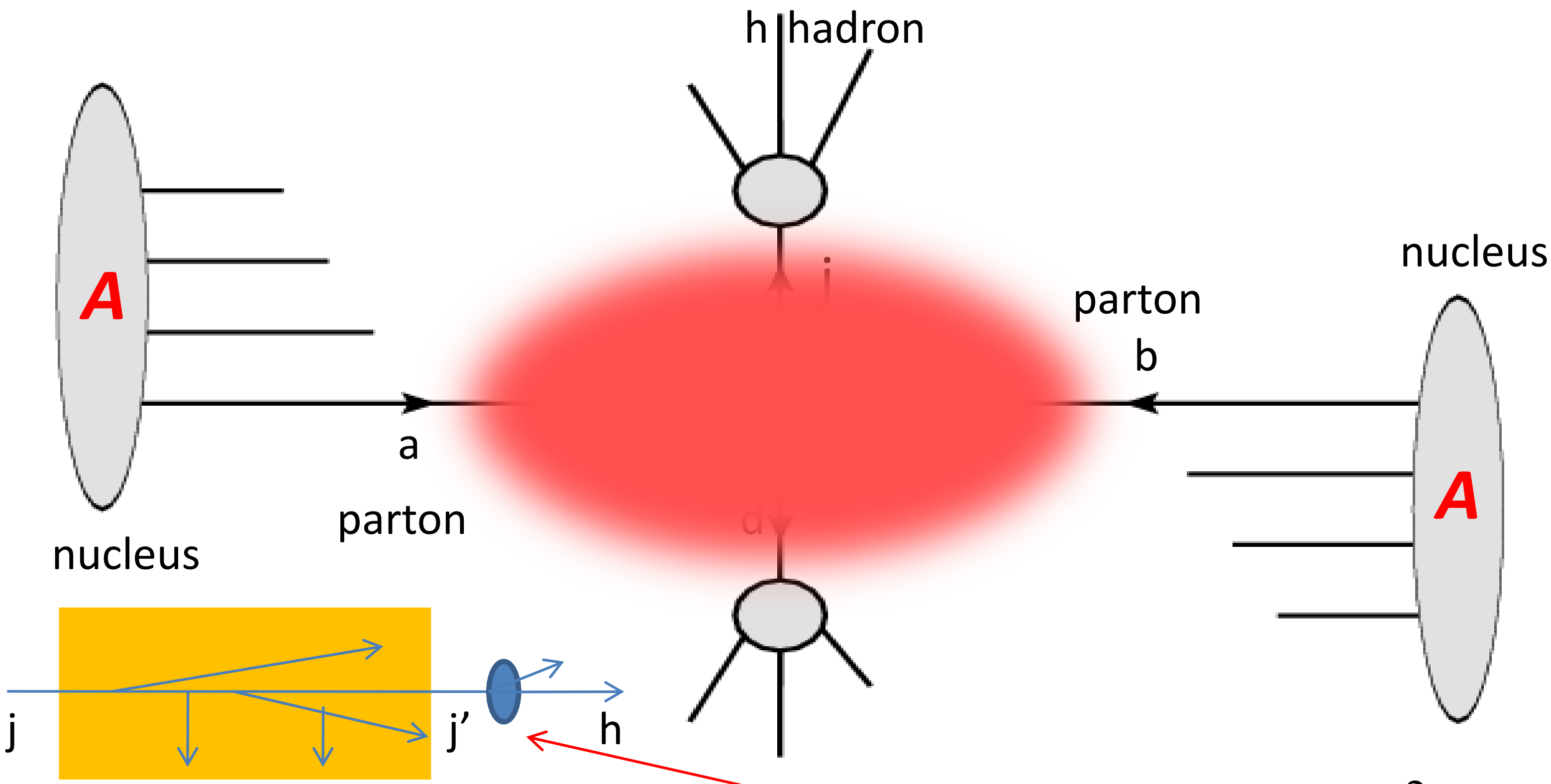
The longitudinal scattering may play a role in medium-induced radiation *(GYQ et al, work in progress)*

General picture of jet quenching study



$$d\sigma_h = \sum_{abjd} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jd} \otimes D_{h/j}$$

General picture of jet quenching study

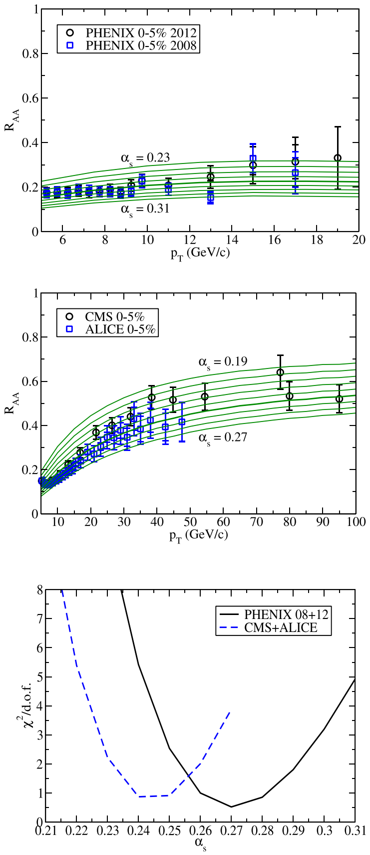


$$d\sigma_h = \sum_{abjd} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jd} \otimes \tilde{D}_{h/j}$$

$$d\sigma_h = \sum_{abjj'd} f_a \otimes f_b \otimes d\sigma_{ab\to jd} \otimes \boxed{P_{j\to j'} \otimes D_{h/j'}}$$

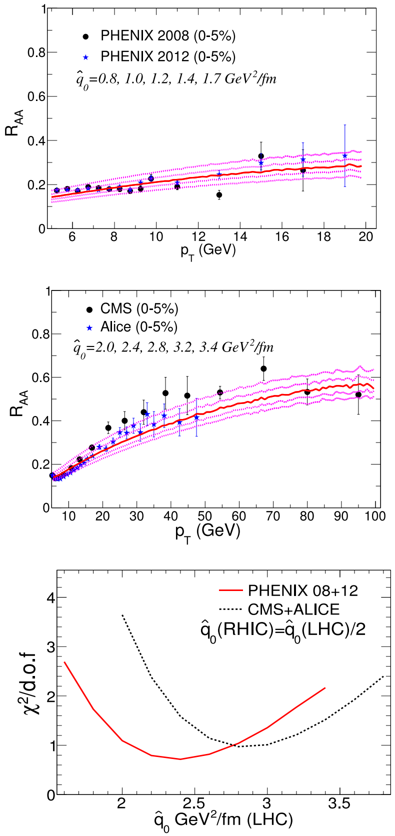
Jet quenching @ RHIC & LHC

McGill-AMY



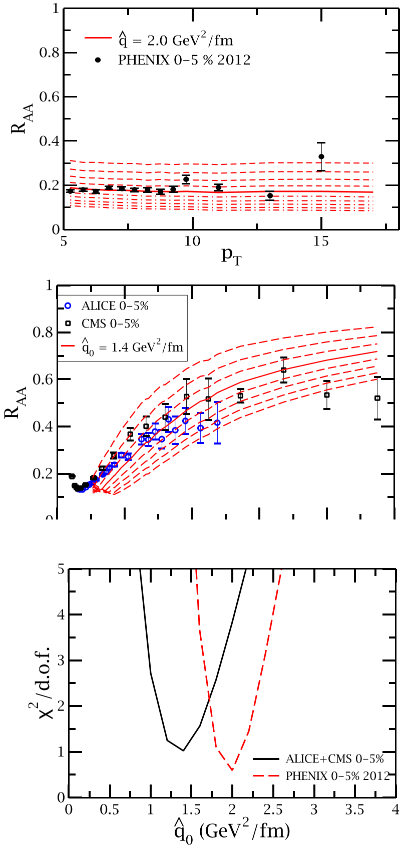
GYQ, et al, PRL 2008

HT-BW



Chen, Hirano, Wang, Wang, Zhang, PRC 2011

HT-M

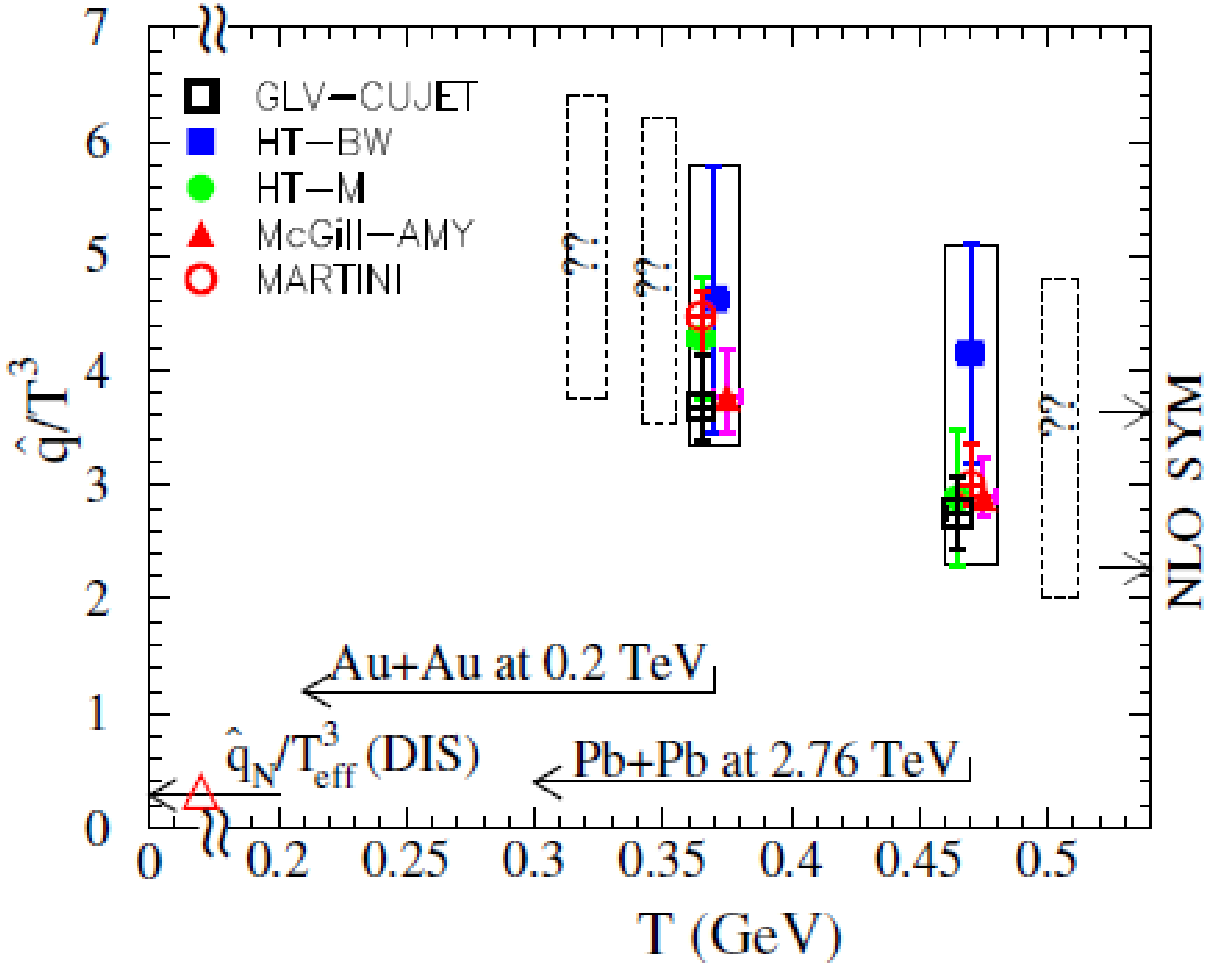


Majumder, Chun, PRL 2012

CUJET and Martini-AMY results not shown here

arXiv:1312.5003 [nucl-th]

Jet transport coefficient



arXiv:1312.5003 [nucl-th]

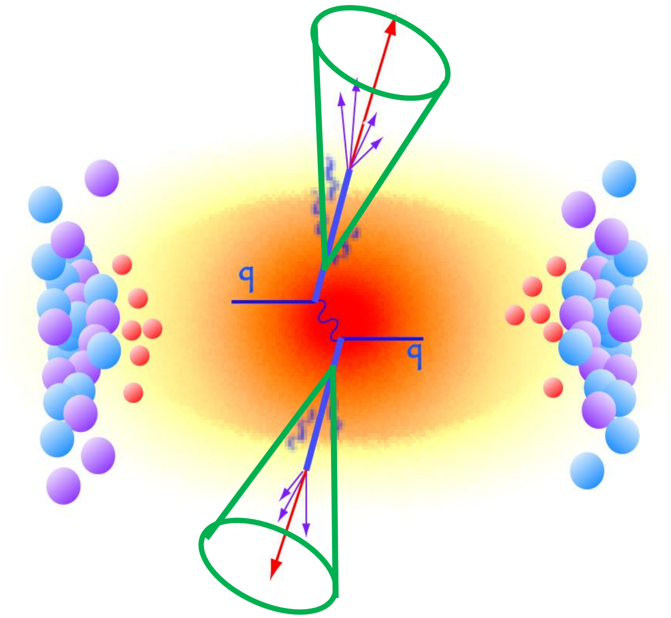
Full jets

Jets: a spray of charged/neutral particles originating from fragmentation of hard-scattered partons

Jet reconstruction: recombining hadron/parton fragments, hoping to get the original parton energy/momentum

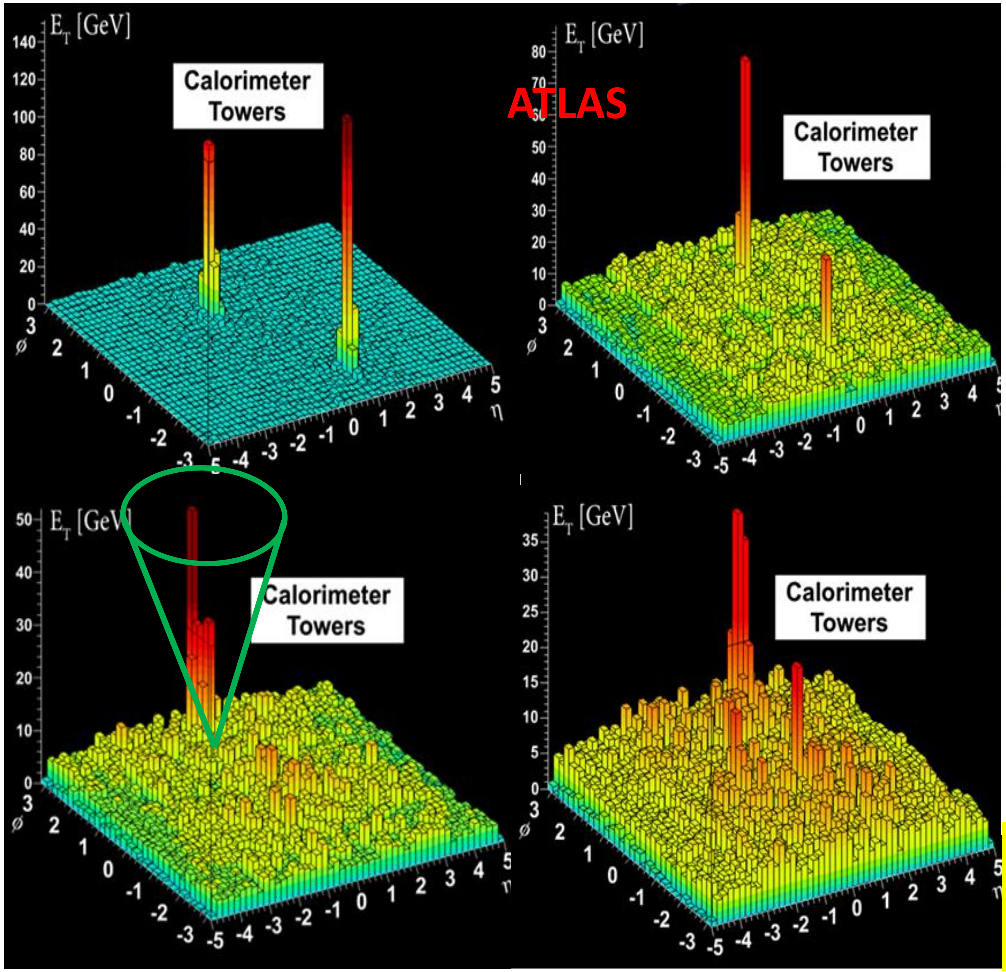
Different algorithms use different criteria to cluster the fragments, and use different sequence for recombination (jet cone size R)

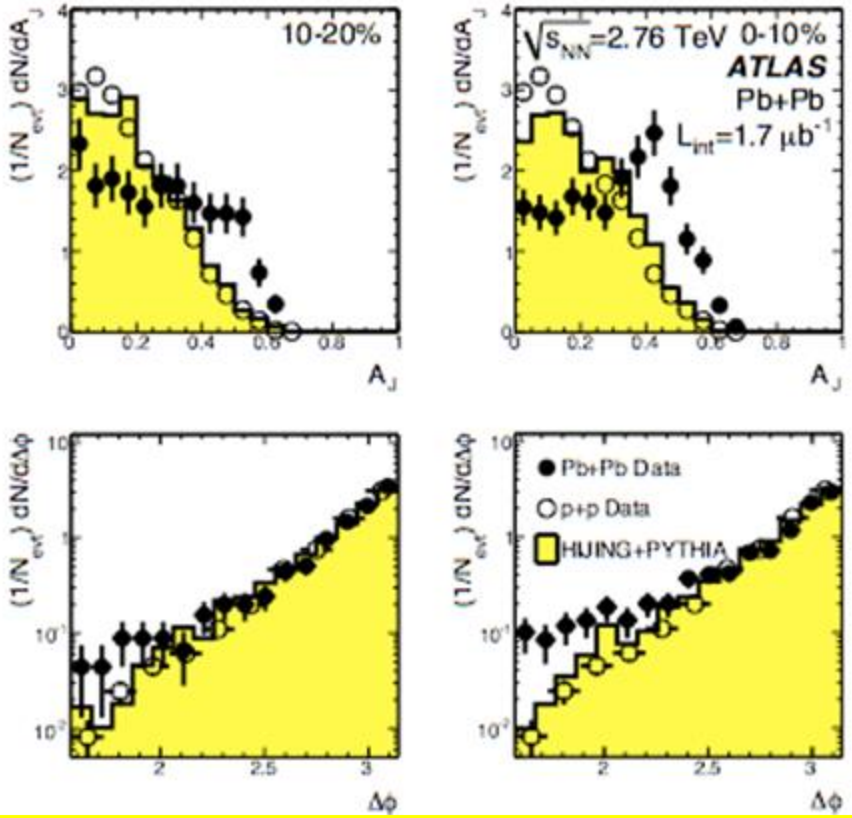
In AA collisions, significant contribution from (hydro) background needs removed



$$R = \sqrt{(\phi - \phi_J)^2 + (\eta - \eta_J)^2}$$

Full jets in HIC

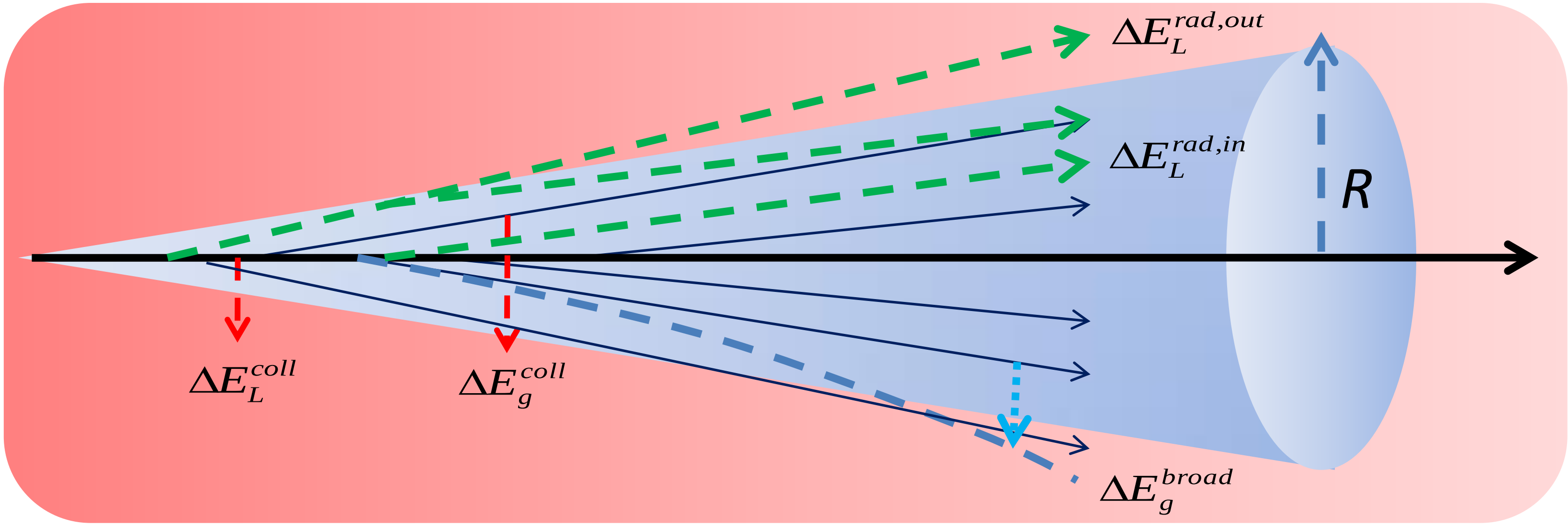




Strong energy imbalance but angular distribution largely unchanged

$$A_J = \frac{E_{J,1} - E_{J,2}}{E_{J,1} + E_{J,2}}$$

Jet shower evolution in medium



Leading parton:

Transfers energy to medium by elastic collisions

Medium-induced gluon radiation (inside and outside jet cone)

Radiated gluons (vacuum & medium-induced):

Transfer energy to medium by elastic collisions

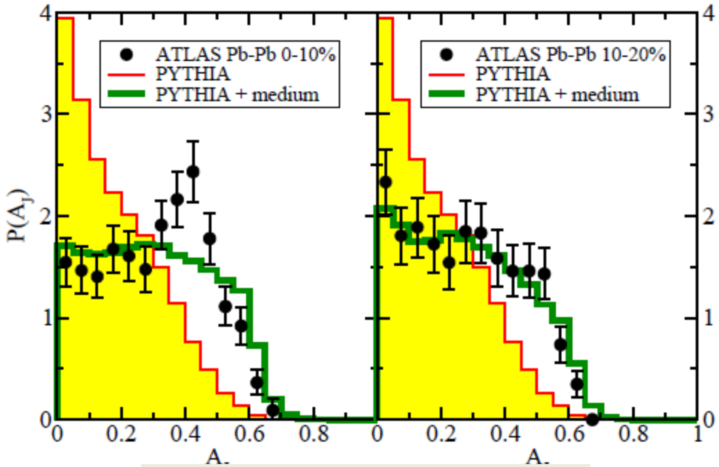
Be kicked out of the jet cone by multiple scatterings after emission

$$E_L(t) = E_L(t_i) - \int \hat{e}_L dt - \int \omega d\omega dk_\perp^2 dt \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

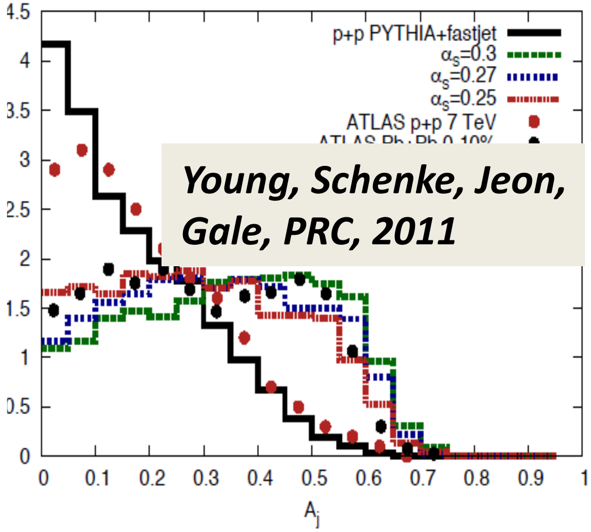
$$\frac{df_g(\omega,k_\perp^2,t)}{dt} = \hat{e}\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_g + \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

GYQ, Muller, PRL, 2011

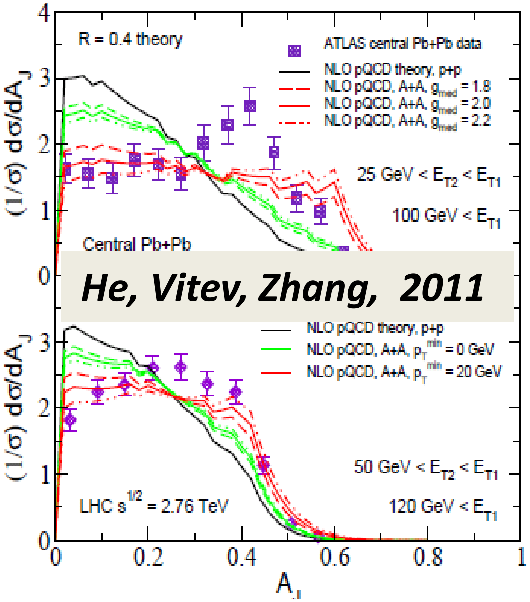
Theory postdictions for dijet asymmetry



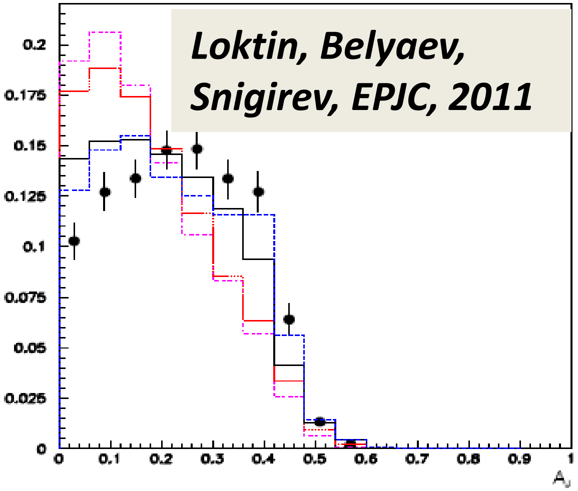
GYQ, Muller, PRL, 2011



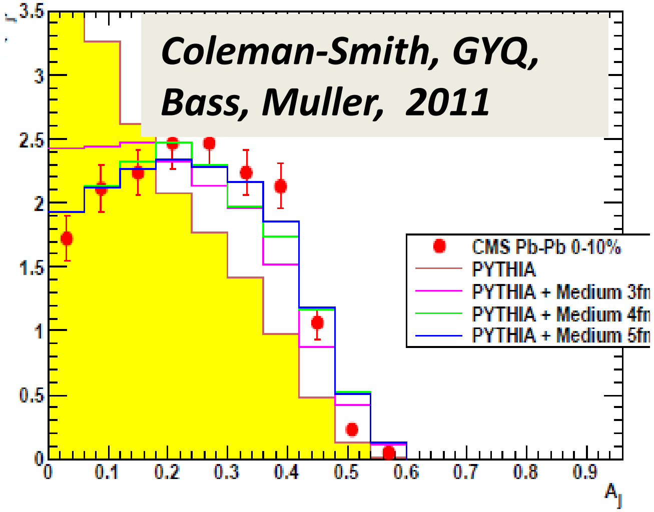
Young, Schenke, Jeon, Gale, PRC, 2011



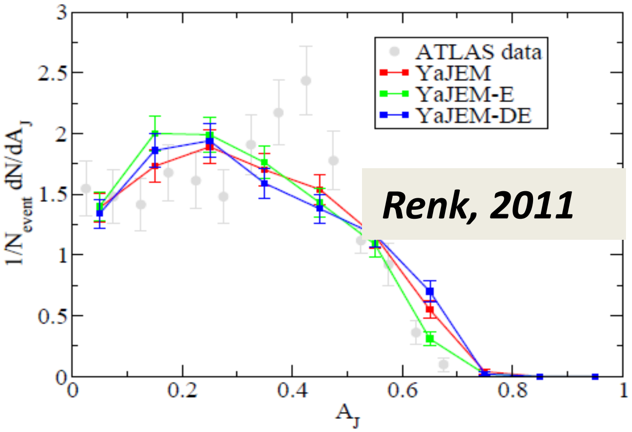
He, Vitev, Zhang, 2011



Loktin, Belyaev, Snigirev, EPJC, 2011

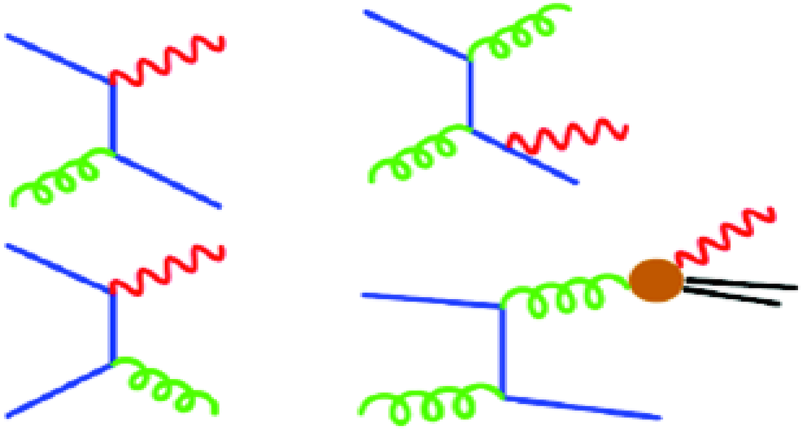


Coleman-Smith, GYQ, Bass, Muller, 2011



Renk, 2011

Photon tagged full jets

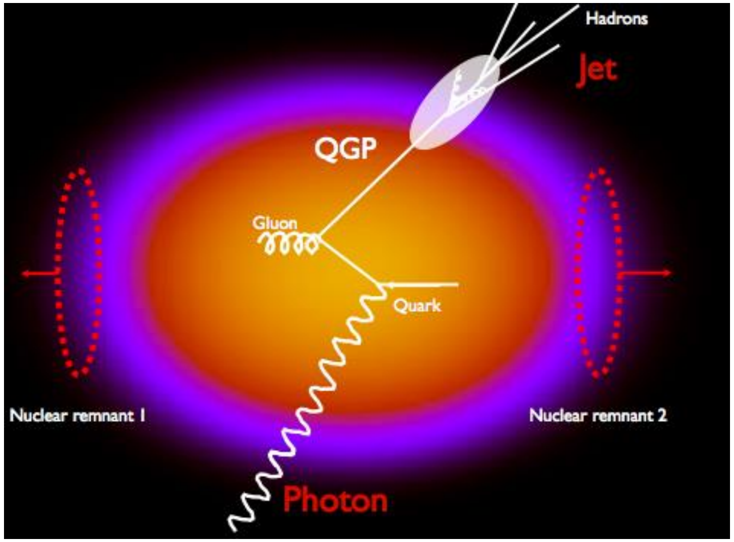


Photons experience no final state interaction once produced from early hard collisions

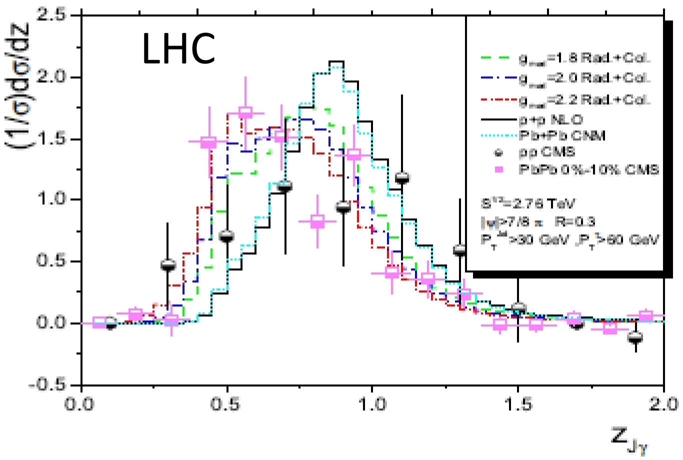
Provide better control of the initial jet information (e.g., p_T, direction)

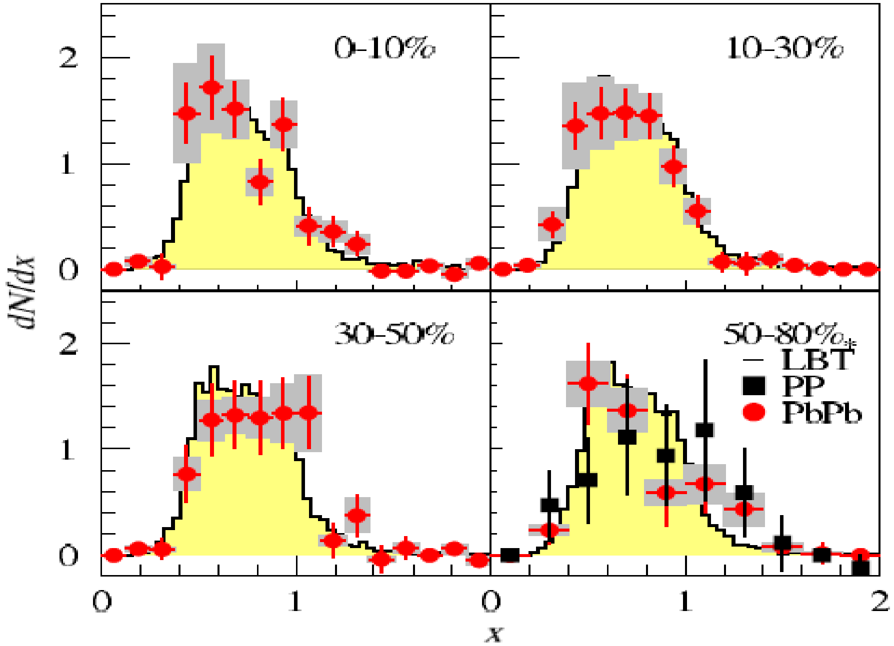
Provide a good tool for the tomographic study of QGP

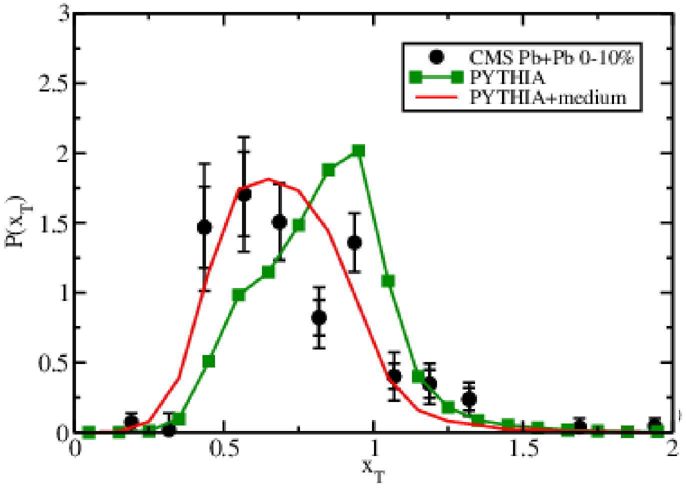
Haven been regarded as "golden" channel for studying jet-medium interaction



Medium modification of γ-full jet







The distribution shifts towards smaller $x_J = p_T^{\gamma}/p_T^{Jet}$

More quenching for more central collisions

Dai, Vitev, Zhang, PRL 2013; Wang, Zhu, PRL 2013; Qin, arxiv:1210.6610

Tomography of QGP

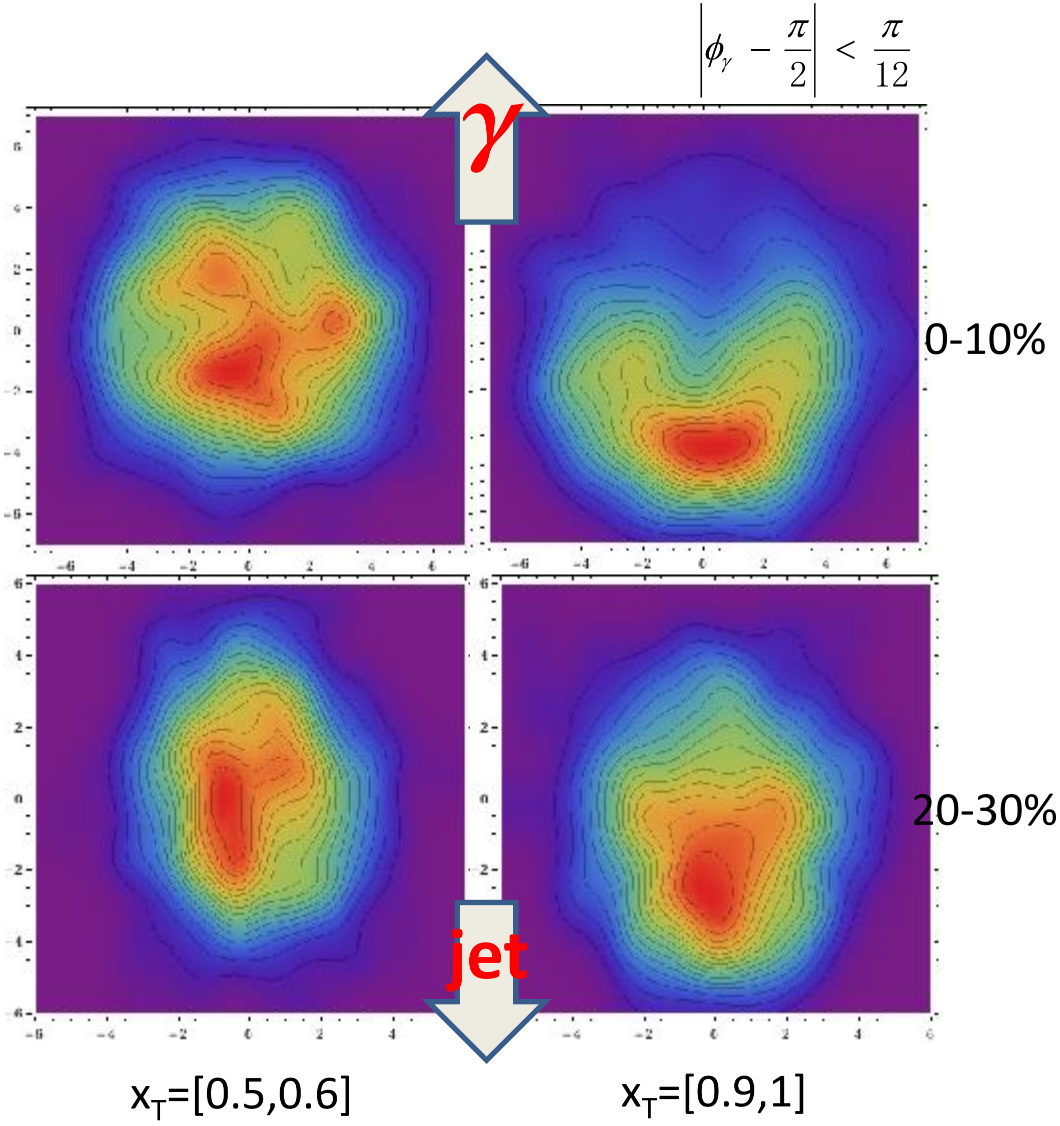
Larger x_T jets are more produced at the surface of the medium

Smaller x_T jets have traveled large distance of medium

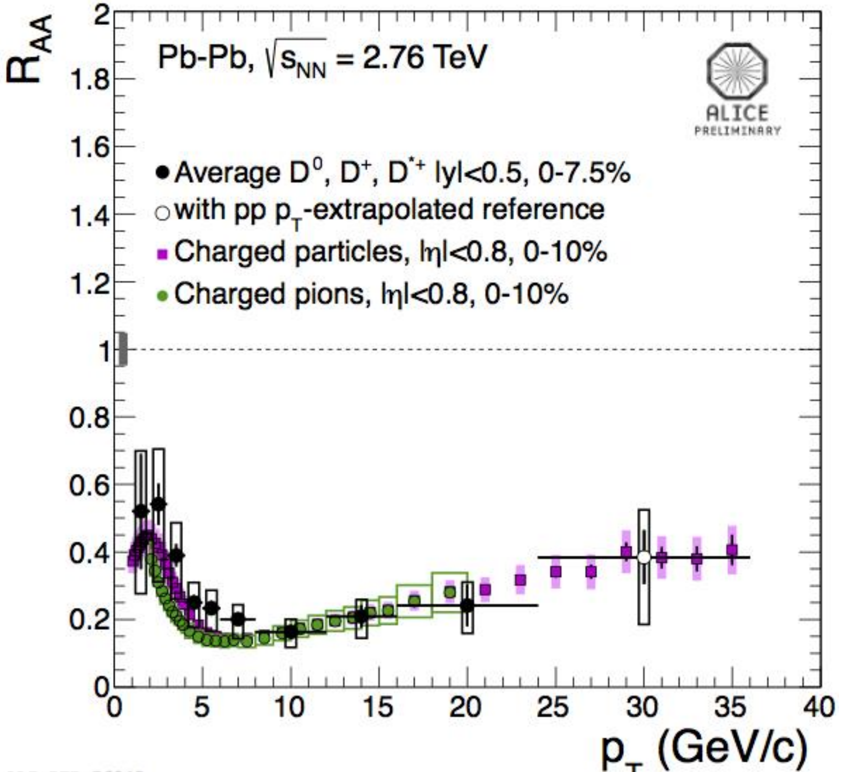
Different average x_J probe different path lengths

Combined with different directions, probe different areas of the collision zone

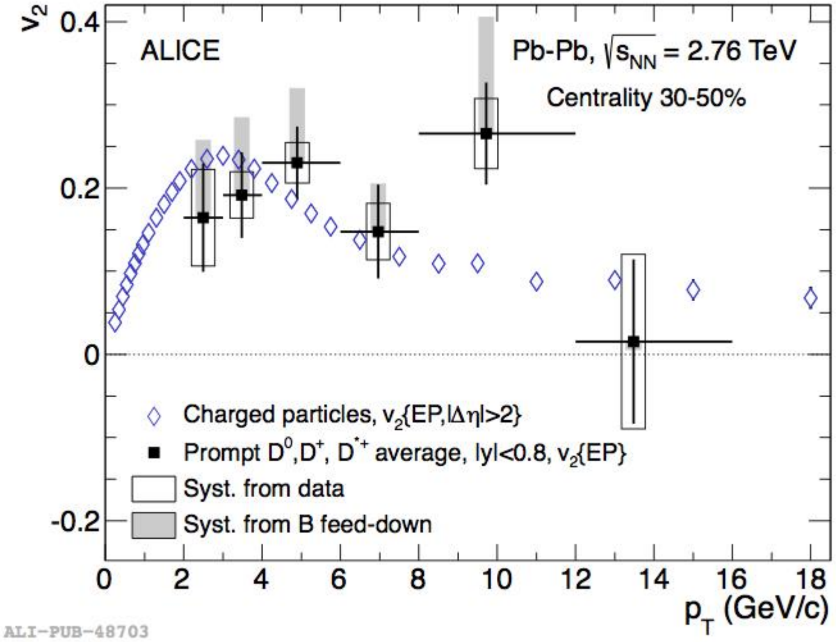
Qin, arxiv:1210.6610



Nuclear modification of heavy flavors



ALI-DER-56048

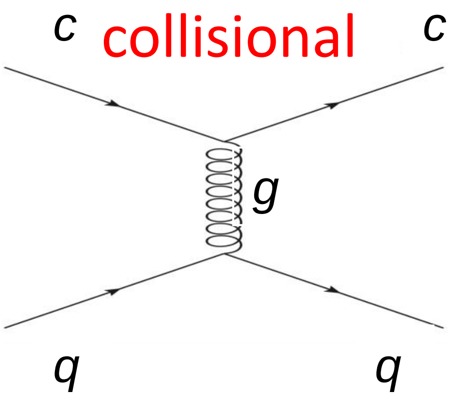


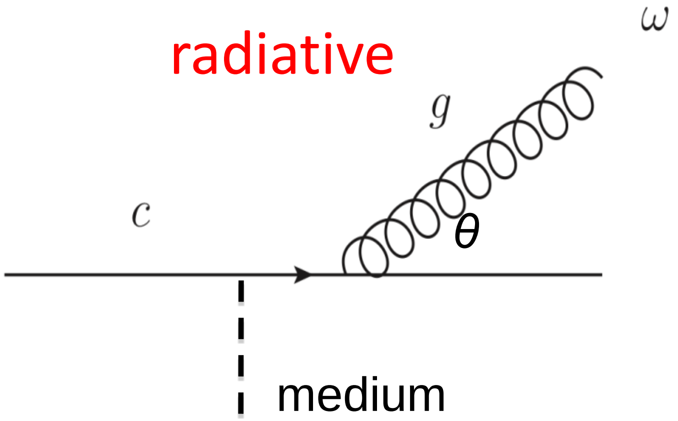
ALI-PUB-48703

Due to finite masses, heavy quarks are expected to lose less energy in QGP medium

Large suppression and flow for heavy flavor mesons have been observed, comparable to light hadrons!

Heavy quark energy loss


collisional


radiative

Gluon radiation is suppressed compared to light flavors (dead cone effect)
Many earlier studies only consider collisional energy loss

One method is to use Langevin equation to describe heavy quark (Brown) motion in medium

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi}$$

$$\langle \xi^i(t)\xi^j(t')\rangle = \kappa\delta^{ij}\delta(t-t') \qquad D = \frac{T}{M\eta_D(0)} = \frac{2T^2}{\kappa}$$

Add gluon radiation

Radiation of gluon gives additional drag force to the propagating heavy quarks

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g \qquad \vec{f}_g = -\frac{d\vec{p}_g}{dt}$$

Cao, GYQ, Bass, PRC 2013

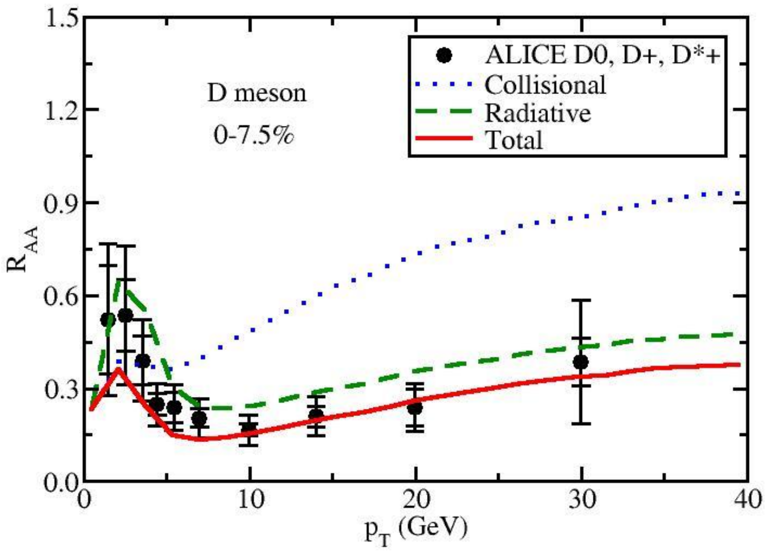
The momentum distribution of radiated gluons may be taken from (any) jet energy loss calculation; here we use Higher-Twist results

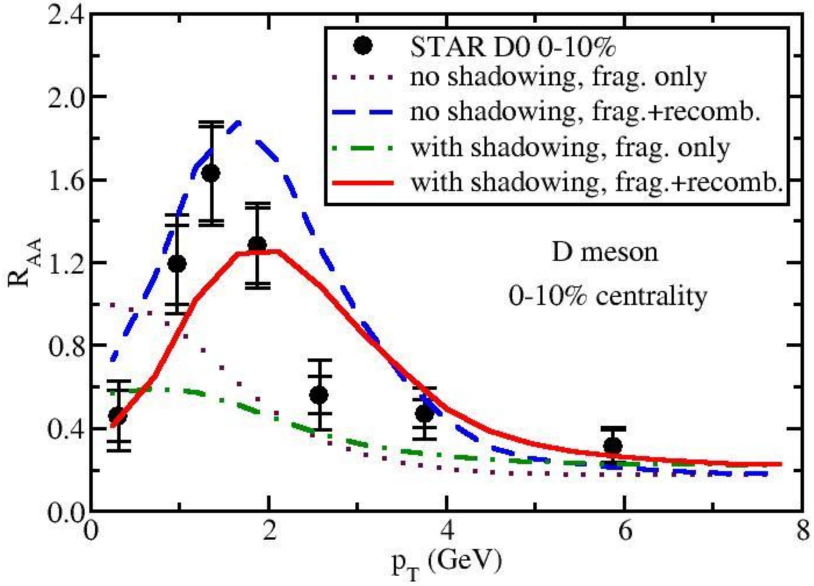
$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s(k_\perp)}{\pi} P(x) \frac{\hat{q}}{k_\perp^4} \sin^2\left(\frac{t-t_i}{2\tau_f}\right) \left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^4$$

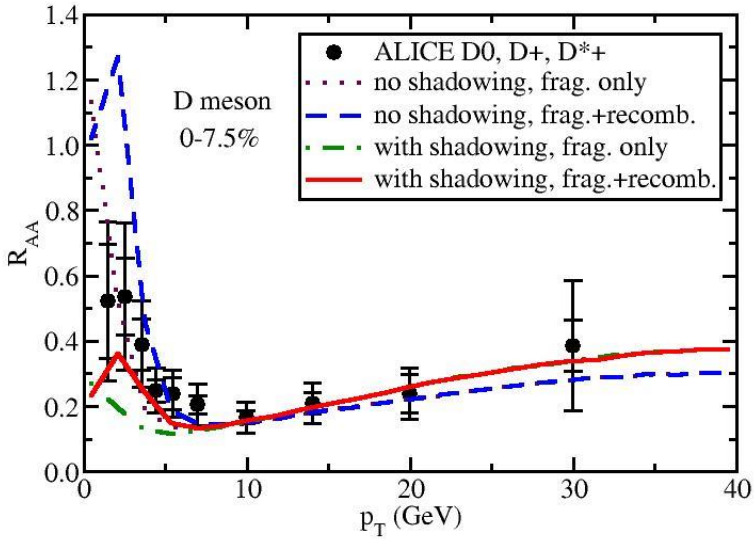
Guo, Wang, *PRL 85, 3591*; Majumder, *PRD 85, 014023*; Zhang, Wang ,Wang, *PRL 93, 072301*.

$$\hat{q} = 2\kappa C_A / C_F \qquad \eta_D(p) = \frac{\kappa}{2TE}$$

Nuclear modification of D mesons







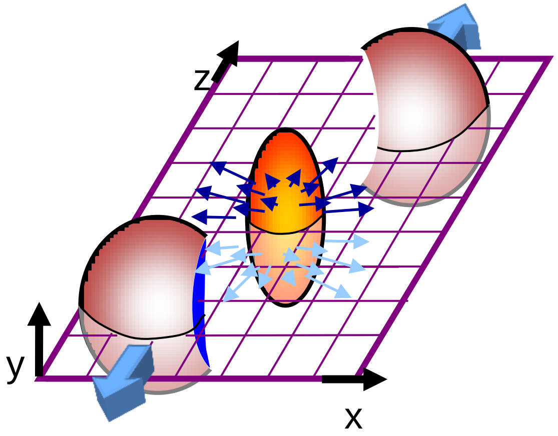
Collisional dominates low p_T, radiative dominates high p_T.

Shadowing effect reduces R_{AA} significantly at low p_T.

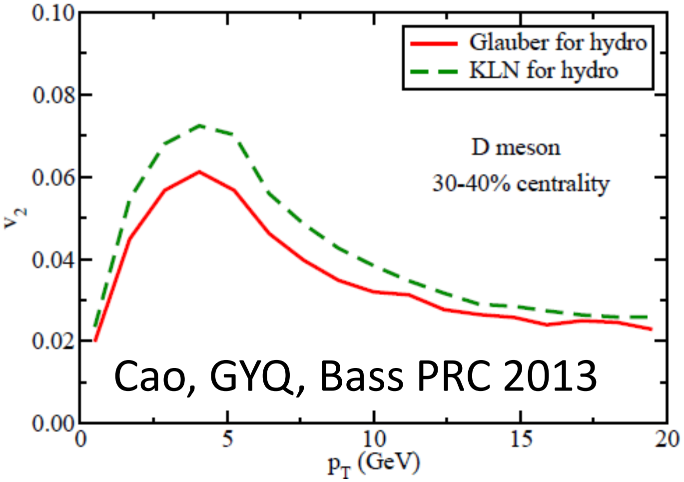
Recombination mechanism raises R_{AA} at intermediate p_T, and has more significant contribution to R_{AA} at RHIC energy

Cao, GYQ, Bass, PRC 2013

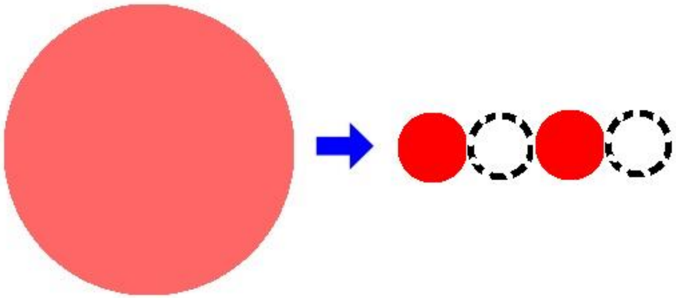
Probing initial state by hard probes



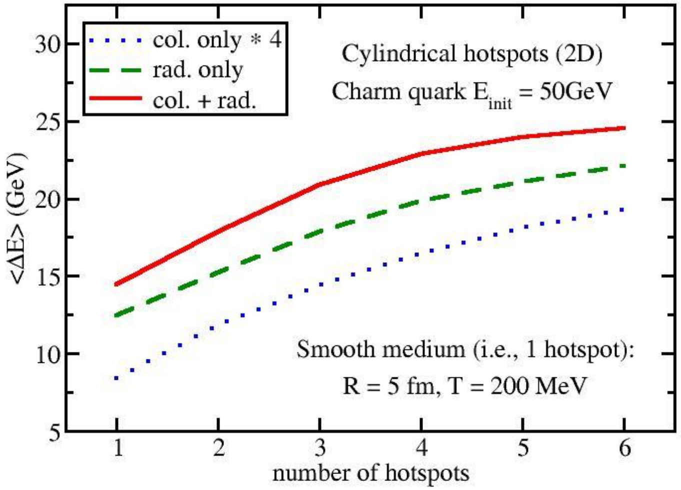
anisotropy



Cao, GYQ, Bass PRC 2013

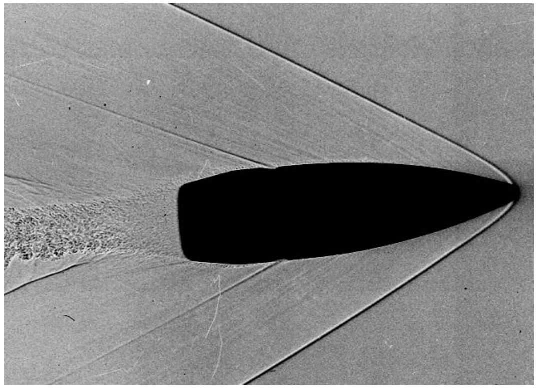


inhomogeneity



more realistic simulation in progress

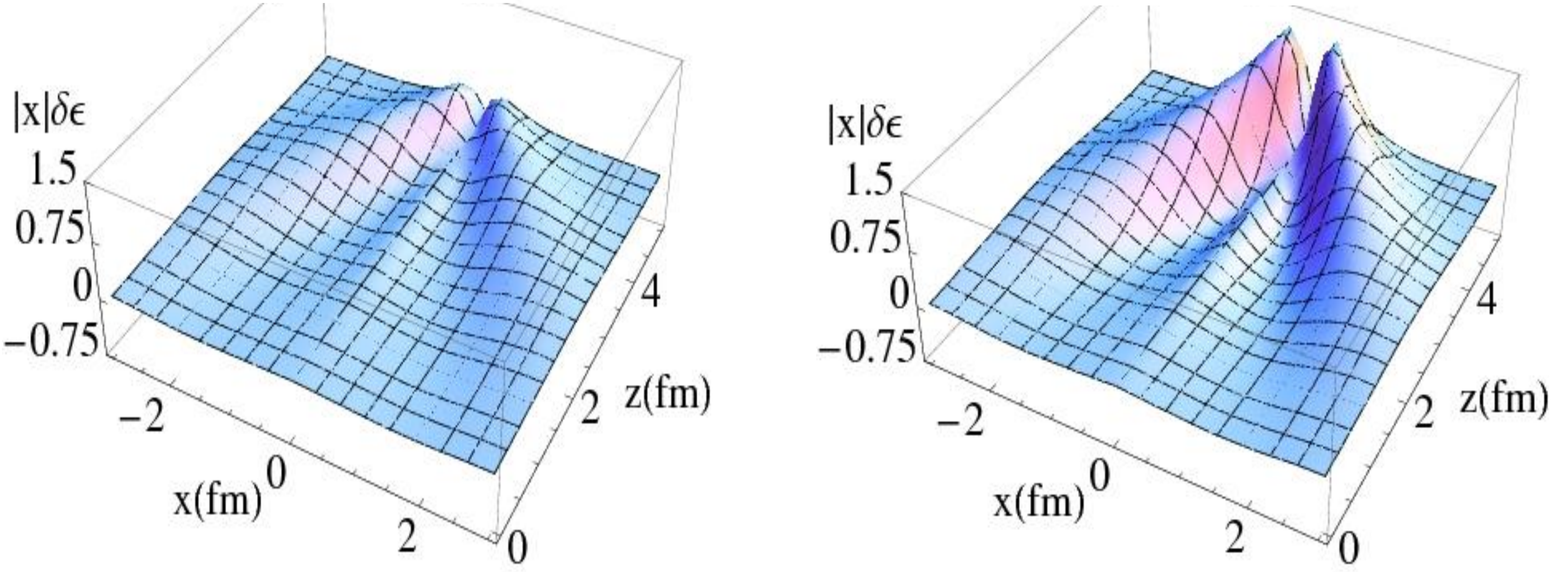
Medium excitation by jets



Mach cone formation at $v_{source} > v_{medium}$

The propagation of high energy partons through QGP will excite Mach cone

Complication: QGP is dynamically evolving, and we need simulate both jet energy loss and QGP evolution at the same time



only leading parton

full jet shower

GYQ, Majumder, Song, Heinz, PRL 2009

Summary

- **Hydrodynamics has been very successful in describing space-time evolution of QGP and explaining collective phenomena in relativistic nuclear collisions**

- **Initial state fluctuations manifest in the final state collective flow and correlations**

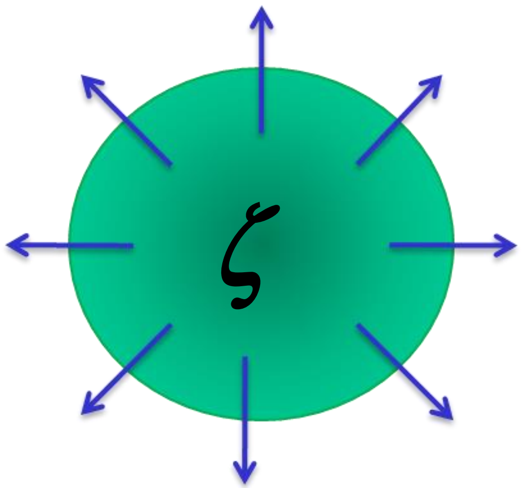
- **Flow in small p+Pb & d+Au systems probably needs new ideas**

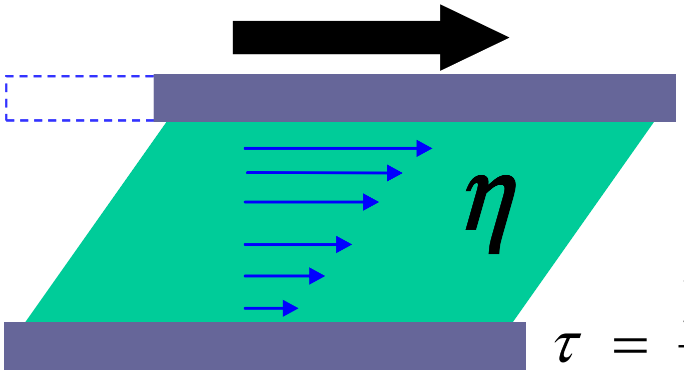
- **Jets/hard probes are useful tools for studying QGP (and initial states)**

- ***Full jet observables and correlation measurements may provide more detailed information about jet-medium interaction***

Viscosity

- Bulk viscosity: the resistance to compression/expansion
- Shear viscosity: the resistance to flow





$$\tau = \frac{F}{A} = \eta \frac{\partial u}{\partial y}$$

- Shear viscosity measures the ability of momentum transport between different parts of the system (thus the interaction strength)

$$\eta \approx \frac{1}{3} n\bar{p}\lambda_f = \frac{\bar{p}}{3\sigma_{tr}}$$

Shear viscosity

Use Kubo method to extract transport coefficients in terms of the correlation functions in the stress-energy tensor for the system

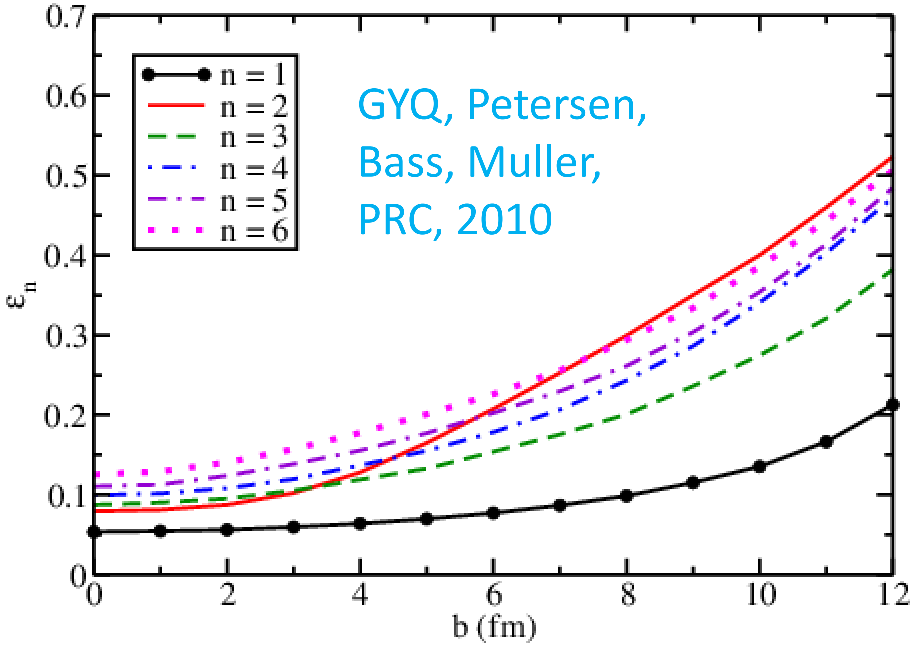
$$\eta_s = \frac{1}{T}\int d^3r \int dt \langle T^{xy}(\vec{0},0)\, T^{xy}(\vec{r},t)\rangle$$

Use relaxation time approximation for Boltzmann equation to obtain the shear viscosity (for a+b->c+d)

$$\eta_s = \frac{1}{15T}\int_0^\infty \frac{d^3p_a}{(2\pi)^3}\,\frac{|p_a|^4}{E_a^2}\,\frac{1}{w_a(E_a)} f_a^{eq}$$

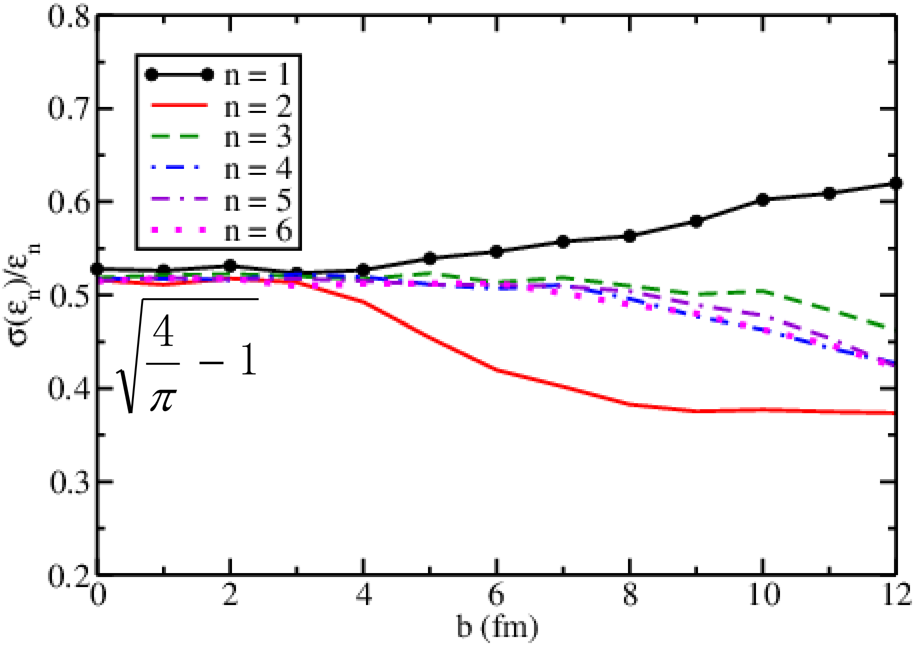
$$w_a(E_a) = \int_0^\infty \frac{d^3p_b}{(2\pi)^3}\,\frac{\sqrt{s(s-4m^2}}{2E_a 2E_b} f_b^{eq}\,\sigma_T$$

Anisotropy of fluctuating initial states



GYQ, Petersen, Bass, Muller, PRC, 2010

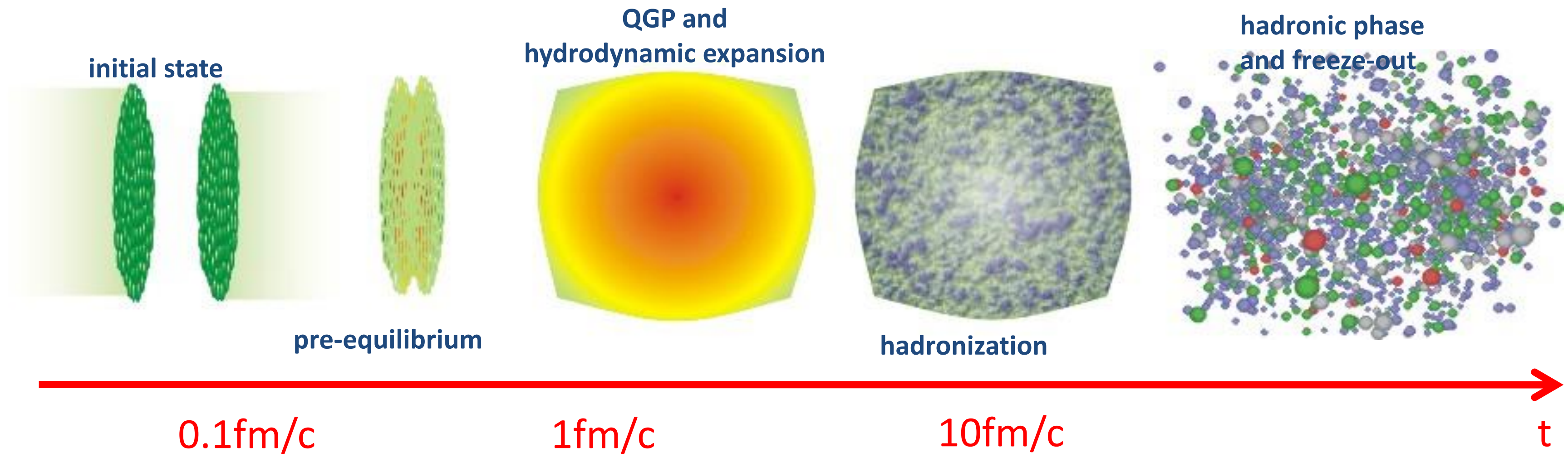
In central collisions, finite anisotropy purely due to fluctuations; same distribution for all ϵ_n (χ distribution)



With increasing b, ϵ_n increase

Largest b dependence for ϵ_2 due to geometry (also seen in the fluctuations)

From initial state to final flow/correlations

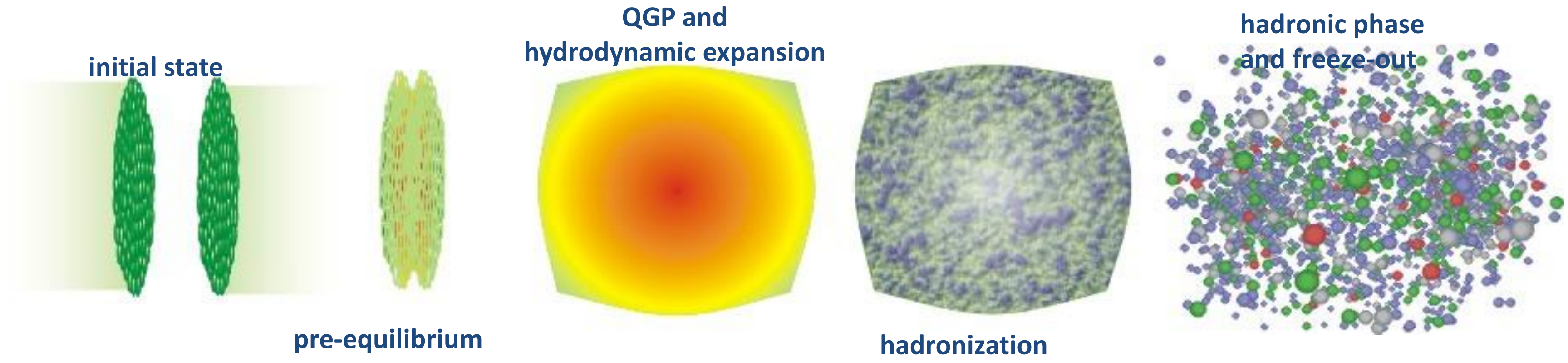


Initial conditions remain to be one of the largest uncertainties in extracting QGP transport properties

Little knowledge about pre-equilibrium evolution and thermalization mechanisms; need a lot more work

Different IS fluctuations => different FS flow/correlations

From initial state to final flow/correlations



- **Initial conditions**
  - **Fluctuations, geometry, asymmetry, anisotropy, inhomogeneity, etc**
- **Pre-equilibrium evolution and thermalization**
- **Hydrodynamic evolution**
- **Hadronization**
- **Hadronic rescattering and freeze-out**
- **Analyze anisotropic flow and correlations for final state momentum distributions**
- ***Initial conditions remain to be one of the largest uncertainties in extracting QGP transport properties***

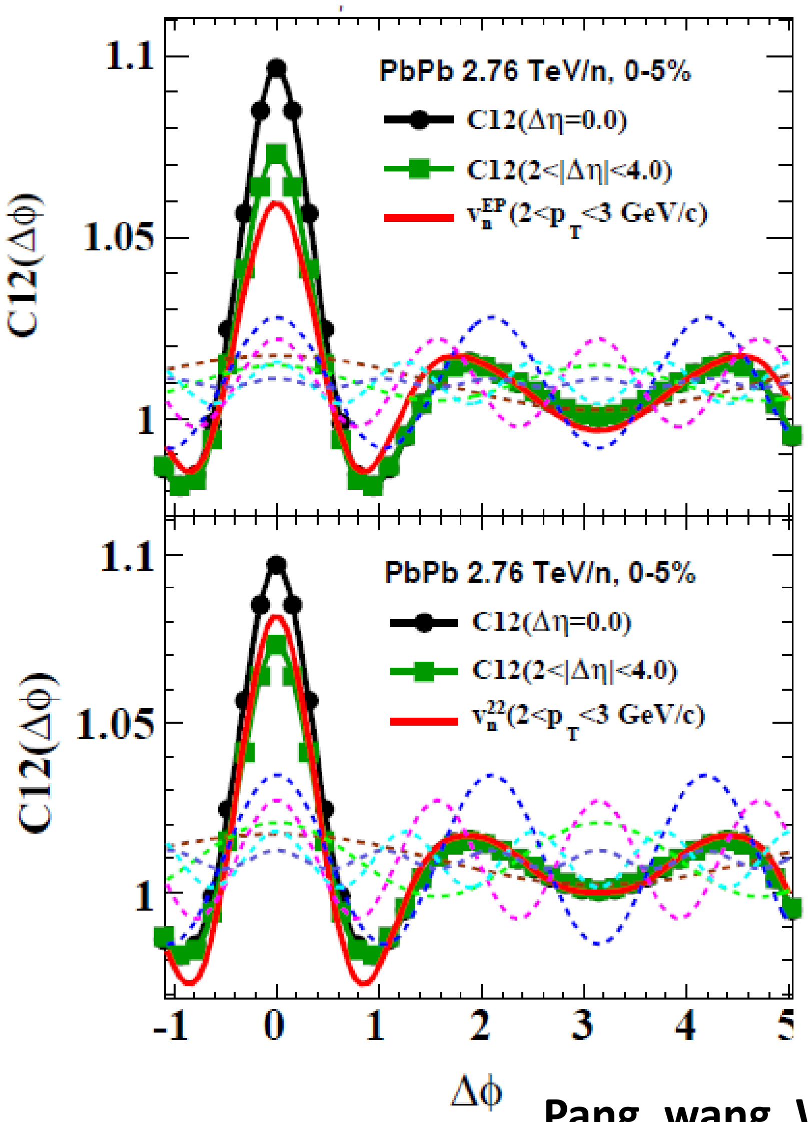
Different IS fluctuations => different FS flow/correlations

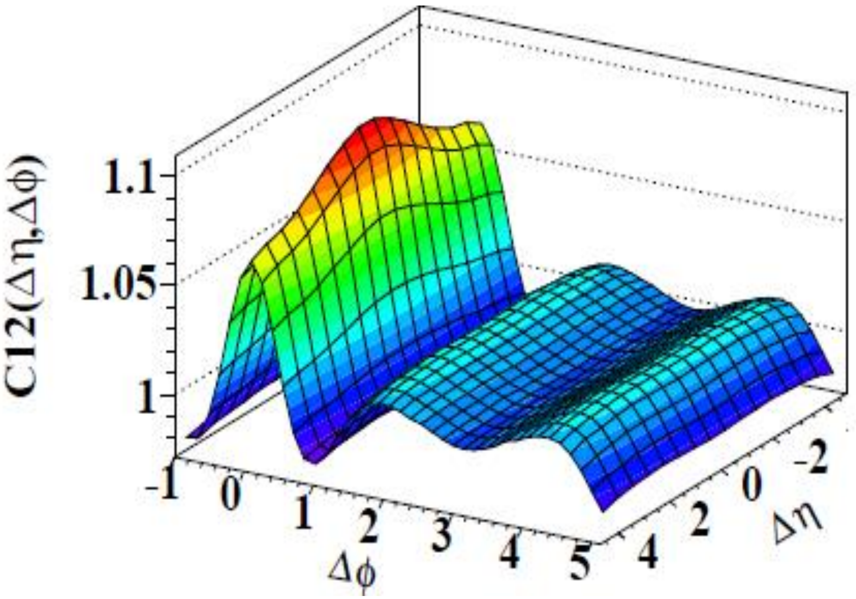
Various initial condition models

- **Fluctuations of nucleon positions: MC Glauber, MC KLN-CGC**
- **Fluctuations of color charges inside nucleons: IP-Glasma**
  - Schenke, Tribedy, Venugopalan, PRL 2012; Muller, Schafer, PRD 2012
- **Fluctuations of multiplicity: modified MC Glauber & KLN-CGC**
  - GYQ, Petersen, Bass, Muller, PRC 2010; Dumitru, Nara, PRC 2012
- **Pre-equilibrium evolution and initial flow: modified MC Glauber, URQDM, HIJING, AMPT, EPOS/NEXUS, etc**
  - GYQ, Petersen, Bass, Muller, PRC 2010, Petersen, Bleicher, PRC 2010; Pang, Wang, Wang, PRC 2012; Gardim et al, PRL 2012, Werner et al, PRC 2012

Different initial state fluctuations => different final states

Separate different contribution



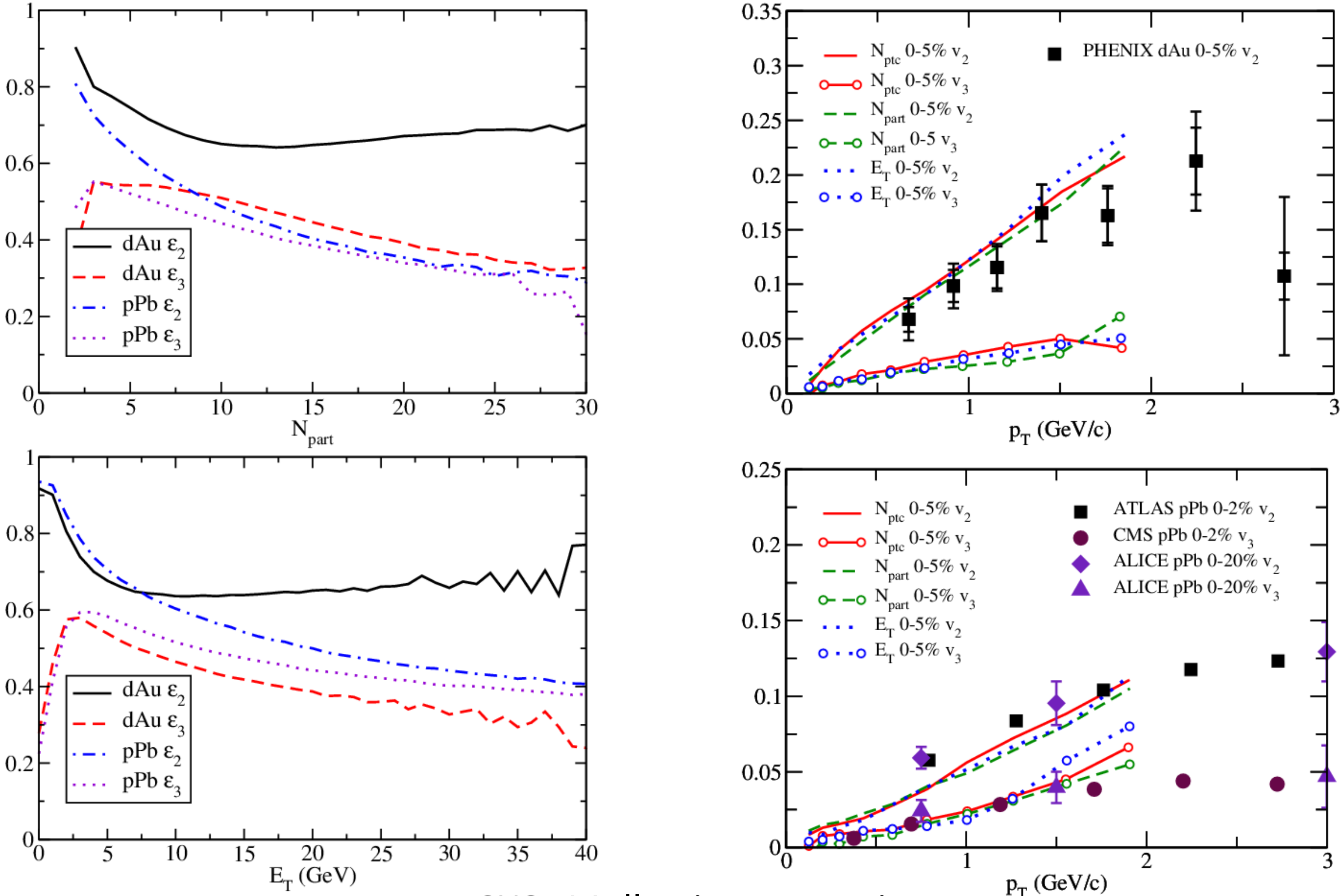


Away-side: short and long range correlations are consistent with the flow contribution, little contribution from mini-jets

Near side: The excess of long range correlations over flow contribution comes from mini-jets

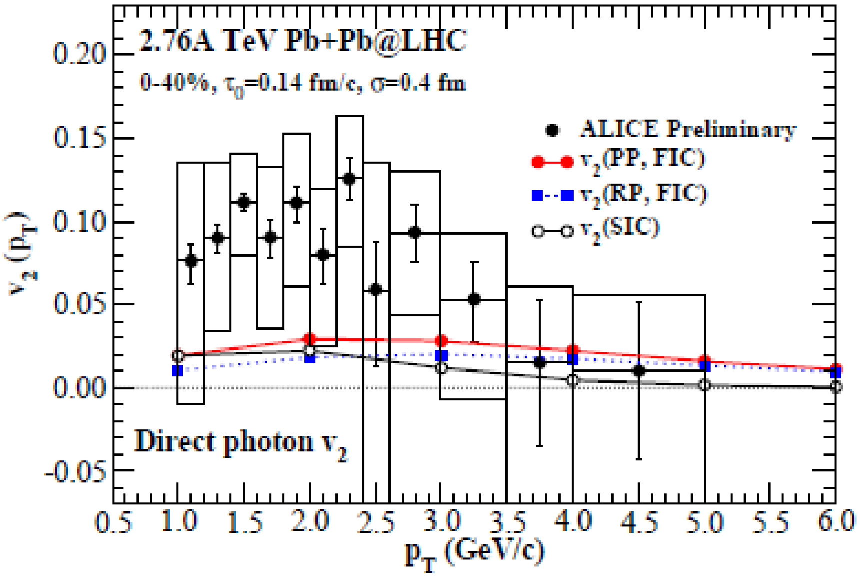
Pang, wang, Wang, 2013

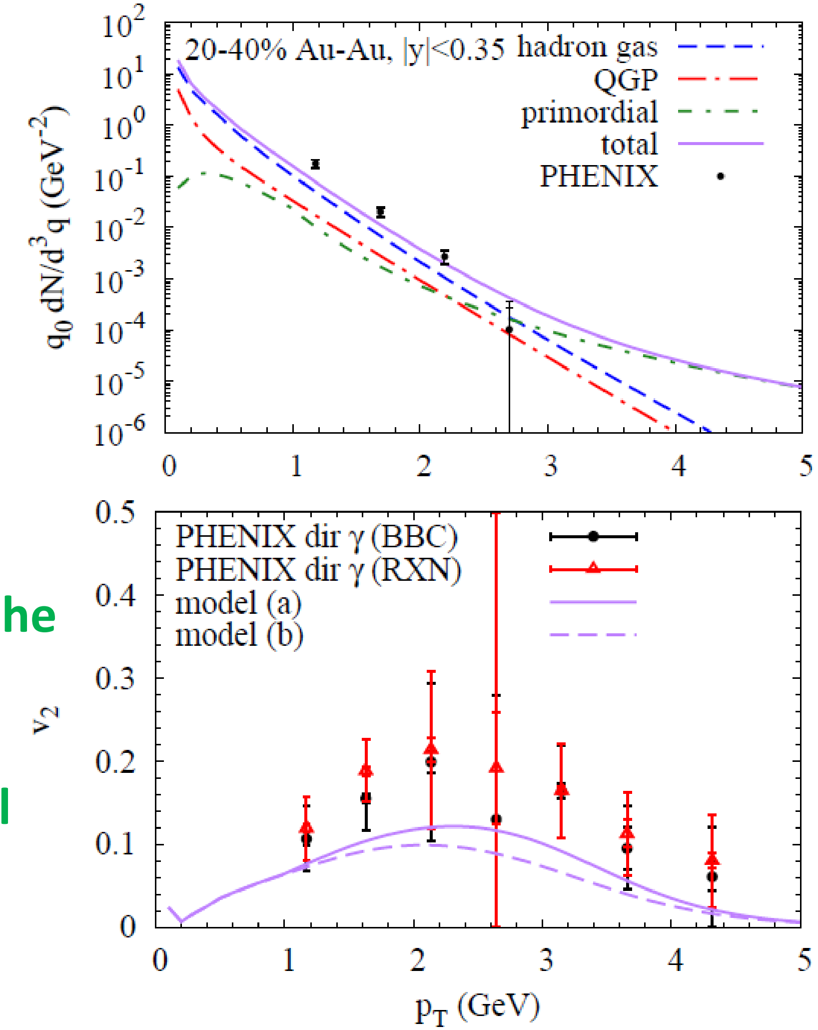
Different centrality determination



GYQ, Muller, in preparation

Flow for thermal photons





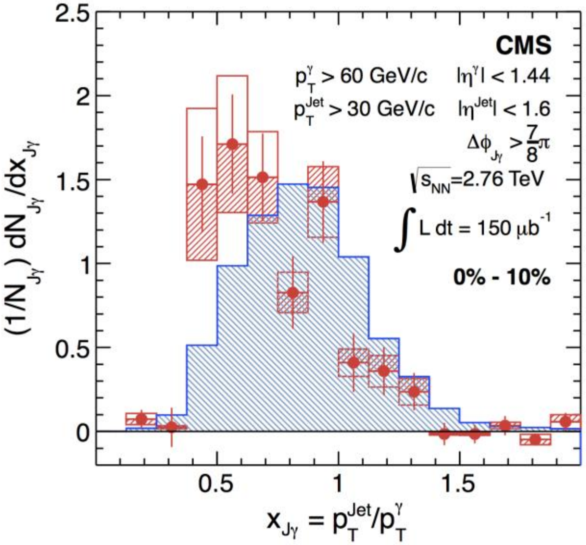
Van Hees, Rapp, Gale, PRC 2012

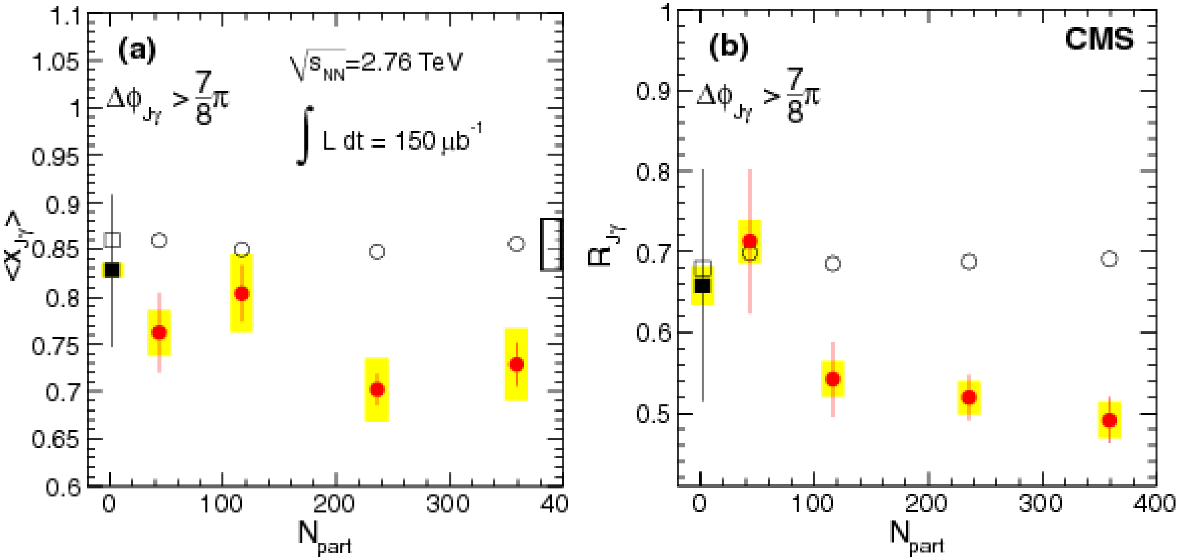
Photon v2 is expected to be smaller than the hadron v2

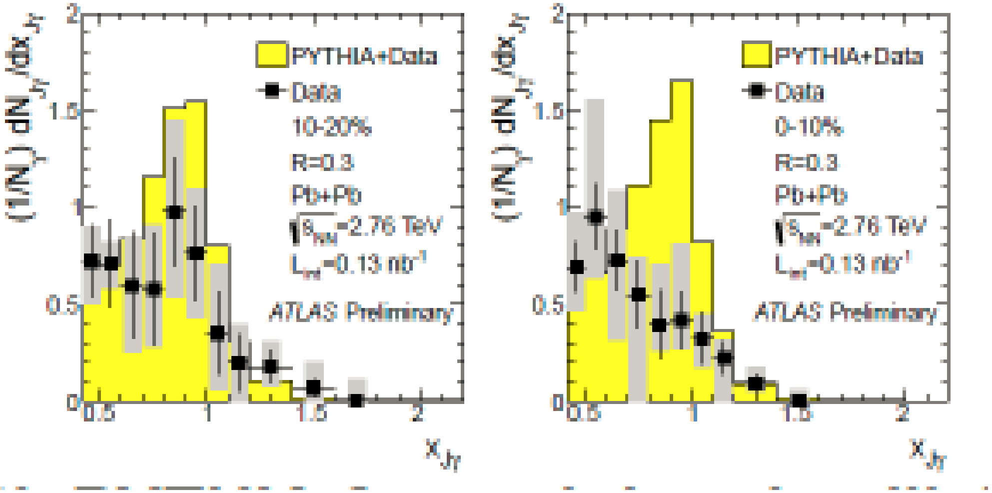
The inclusion of E-b-E fluctuations & viscosity cannot increase to observed level

The best description used strong initial expansion and large photon production rates in the hadronic phase

γ-full jet correlations





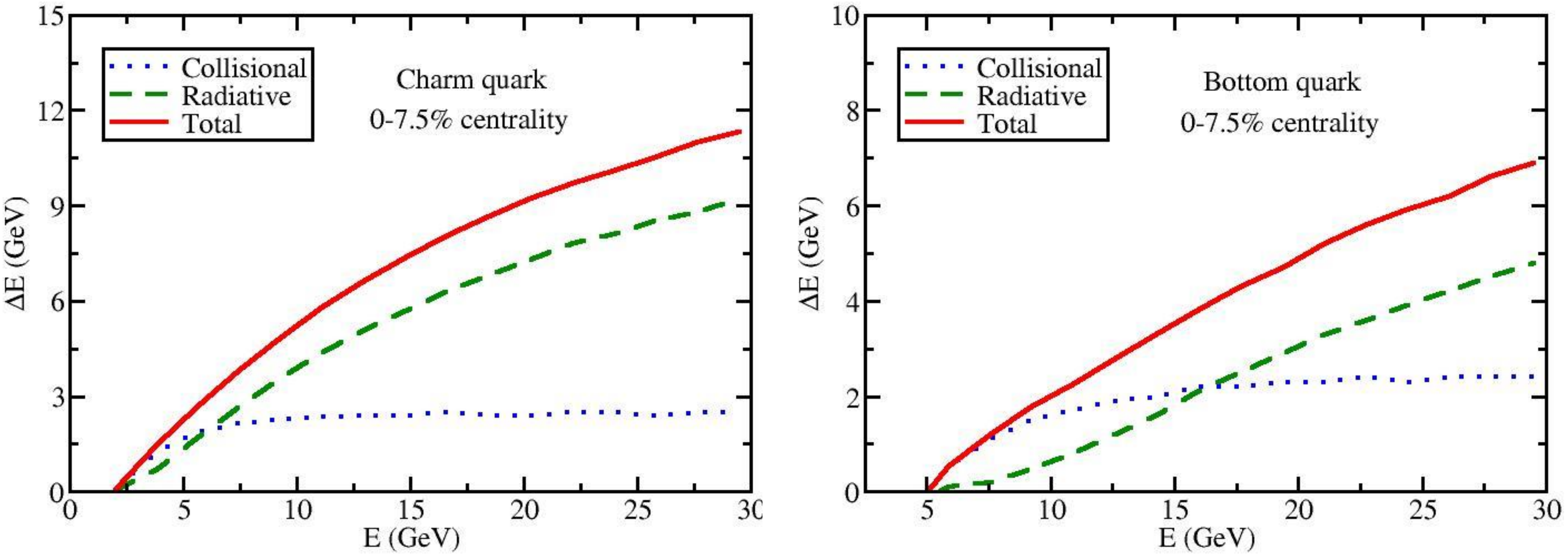


The distribution shifts towards smaller x_J

More quenching for more central collisions

Missing pair probability (the integral is smaller for ATLAS)

Radiative vs collisional energy loss

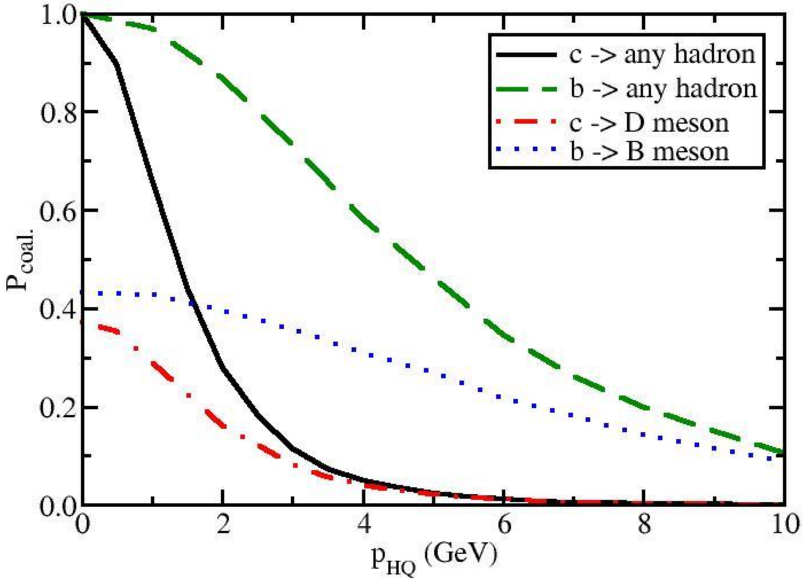


Collisional E-loss dominates low energy region, while radiative dominates high energy region (Crossing point: 6 GeV for *c* and 16 GeV for *b* quark)

Collisional E-loss alone may work well at RHIC but is insufficient at the LHC

Cao, GYQ, Bass, PRC 2013

Heavy quark hadronization: frag. vs rec.

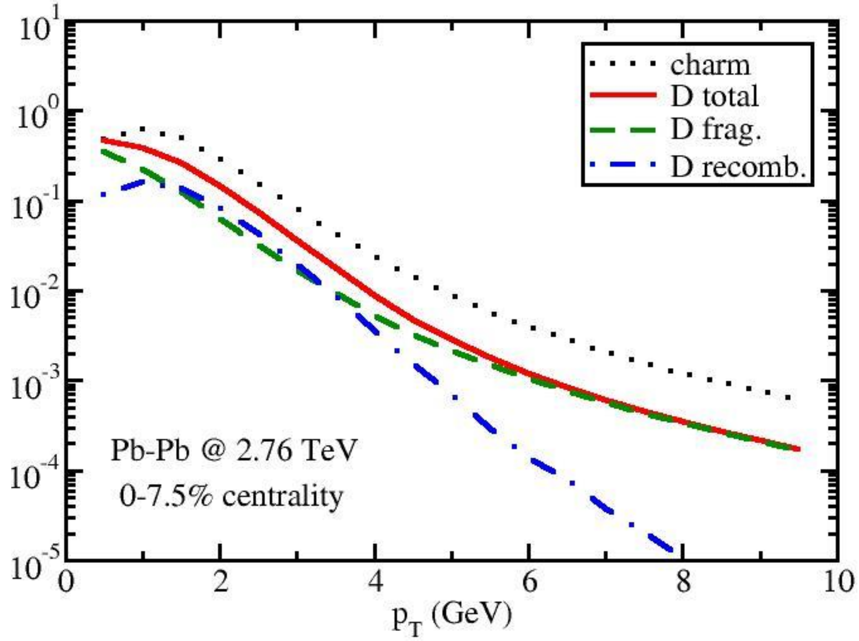


$$f_M^W(\vec{r},\vec{q}) \equiv N g_M \int d^3r' e^{-i\vec{q}\cdot\vec{r}'} \phi_M(\vec{r}+\frac{\vec{r}'}{2})\phi_M^*(\vec{r}-\frac{\vec{r}'}{2})$$

Use f^W to calculate $P_{coal.}(p_{HQ})$ for all channels: D/B Λ Σ Ξ Ω

Normalization: $P_{coal.}(p_{HQ}=0)=1$

Use Monte-Carlo to determine the hadronization of each HQ: frag. or recomb.? recomb. to D/B or a baryon?



Fragmentation dominates D meson production at high p_T.

Recombination significantly enhances the D meson spectrum at intermediate p_T. f

Cao, GYQ, Bass, PRC 2013

The Sudden Recombination Model

Two-particle recombination:

$$\frac{dN_M}{d^3p_M} = \int d^3p_1 d^3p_2 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2} f_M^W(\vec{p}_1,\vec{p}_2)\delta(\vec{p}_M-\vec{p}_1-\vec{p}_2)$$

$\frac{dN_i}{d^3p_i}$ Distribution of the *i* th kind of particle

Light quark: fermi-dirac distri. in the l.r.f of the hydro cell

Heavy quark: the distribution at T_c after Langevin evolution

$f_M^W(\vec{p}_1,\vec{p}_2)$ Probability for two particles to recombine

$$f_M^W(\vec{r},\vec{q}) \equiv N g_M \int d^3r' e^{-i\vec{q}\cdot\vec{r}'}\phi_M(\vec{r}+\frac{\vec{r}'}{2})\phi_M^*(\vec{r}-\frac{\vec{r}'}{2})$$

$$\vec{r} = \vec{r}'_1 - \vec{r}'_2$$

$$\vec{q} = \frac{1}{E'_1+E'_2}(E'_2\vec{p}'_1 - E'_1\vec{p}'_2)$$

➡ Variables on the R.H.S. are defined in the c.m. frame of the two-particle system.

The Sudden Recombination Model

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N: normalization factor

g_M: statistics factor

e.g. D ground state: 1/(2*3*2*3)=1/36 – spin and color

D*: 3/(2*3*2*3)=1/12 – spin of D* is 1

Φ_M: meson wave function – approximated by S.H.O.

Integrating over the position space leads to

$$f_M^W(q^2) = N g_M \frac{(2\sqrt{\pi}\sigma)^3}{V} e^{-q^2\sigma^2} \qquad \sigma = 1/\sqrt{\mu\omega}$$

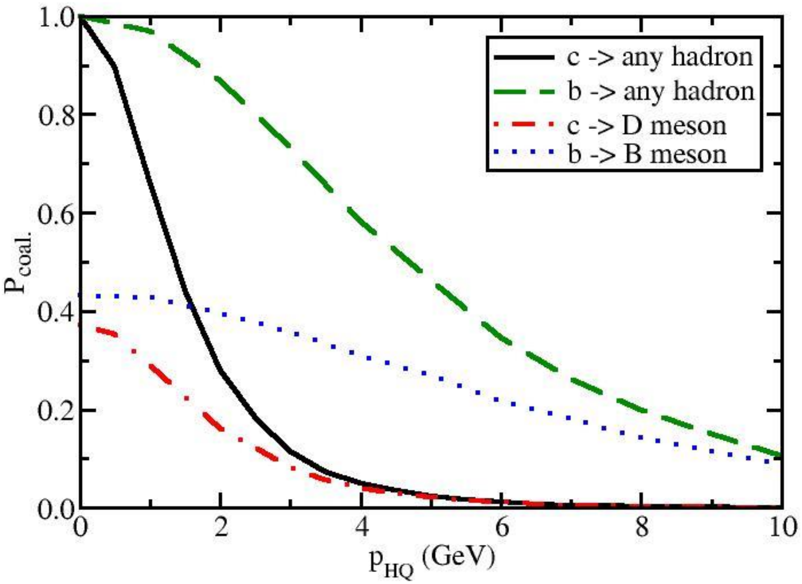
μ: reduced mass of the 2-particle system

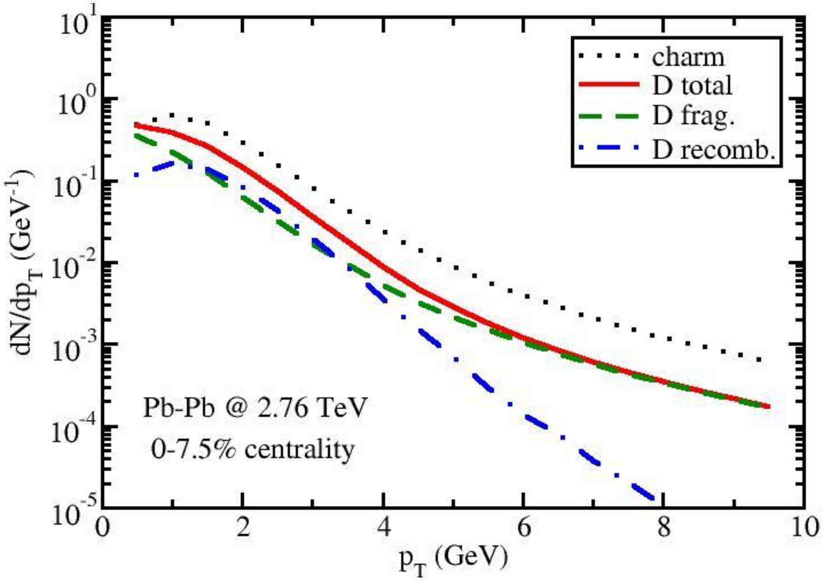
ω: S.H.O frequency – calculated by meson radius

0.106 GeV for *c*, and 0.059 GeV for *b*

Can be generalized to 3-particle recombination (baryon)

The Hybrid Coal. + Frag. Model





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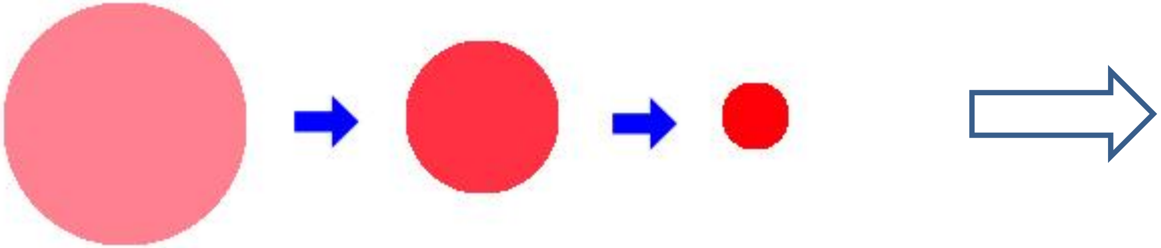
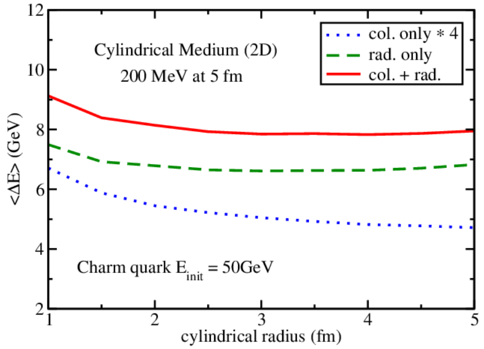
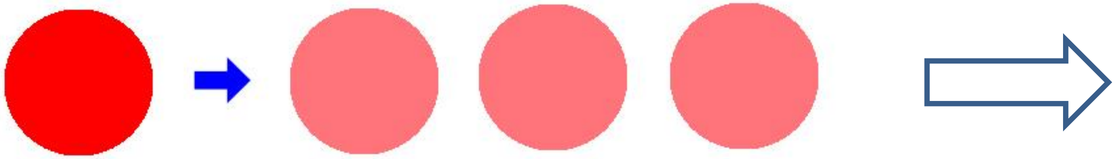
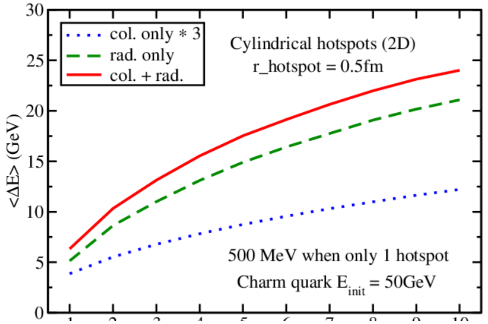
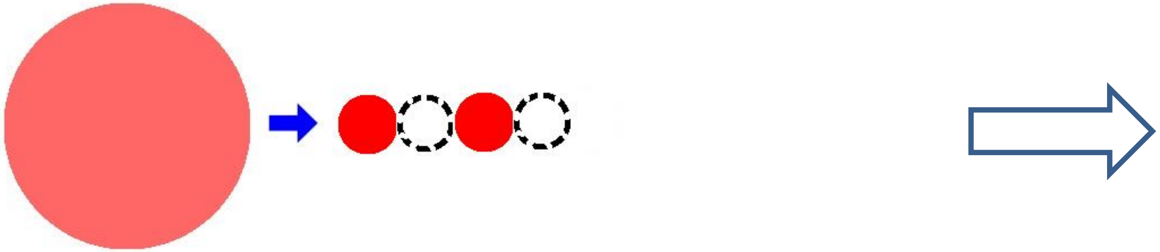
Inhomogeneity

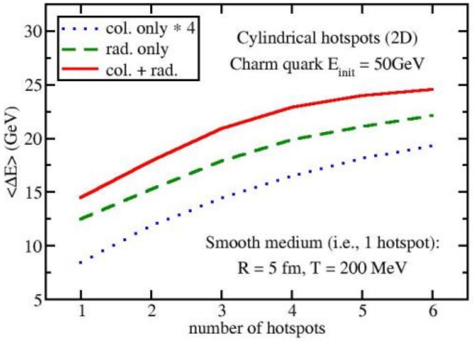






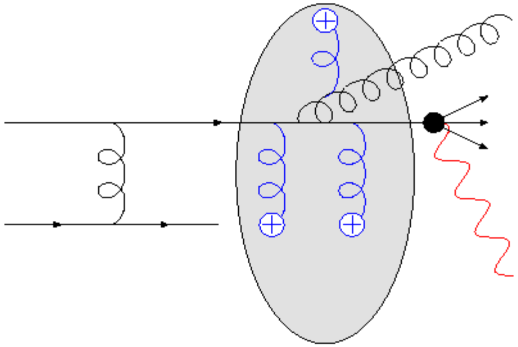




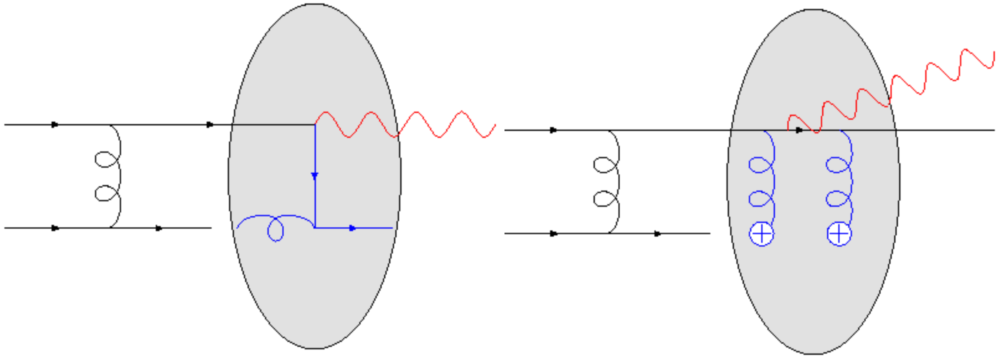


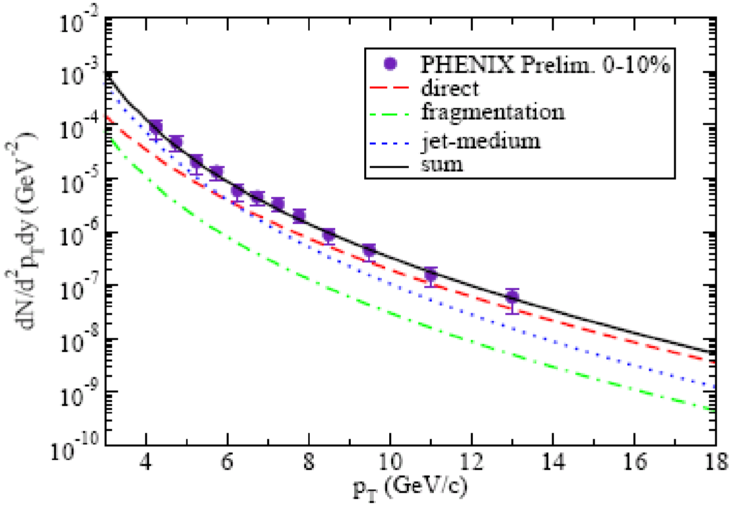
Photon production

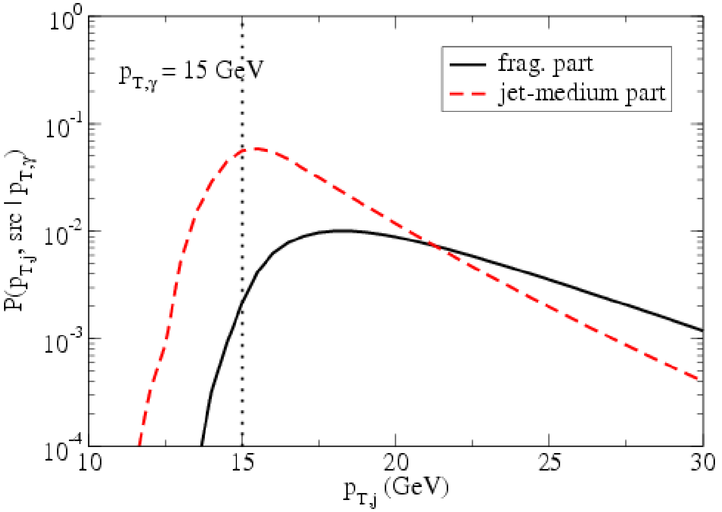
- *Sizable contribution from jet-medium photons at intermediate p_T*
- *Different photon-trigged jets have different distribution and shapes*



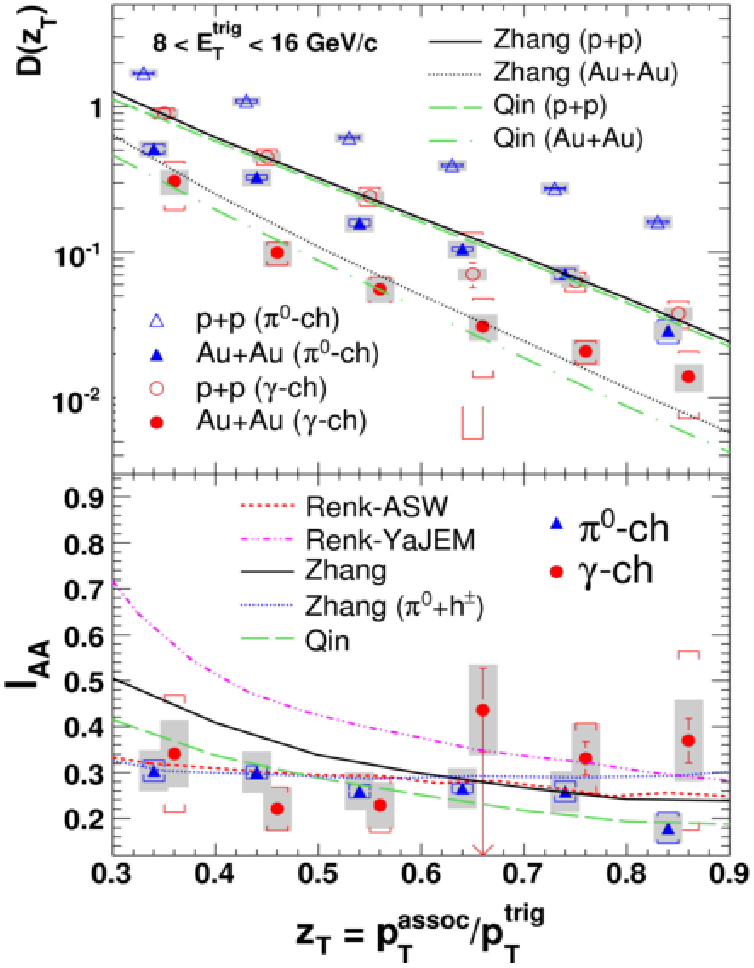
GYQ, Ruppert, Gale, Jeon, Moore, PRC, EPJC, 2009



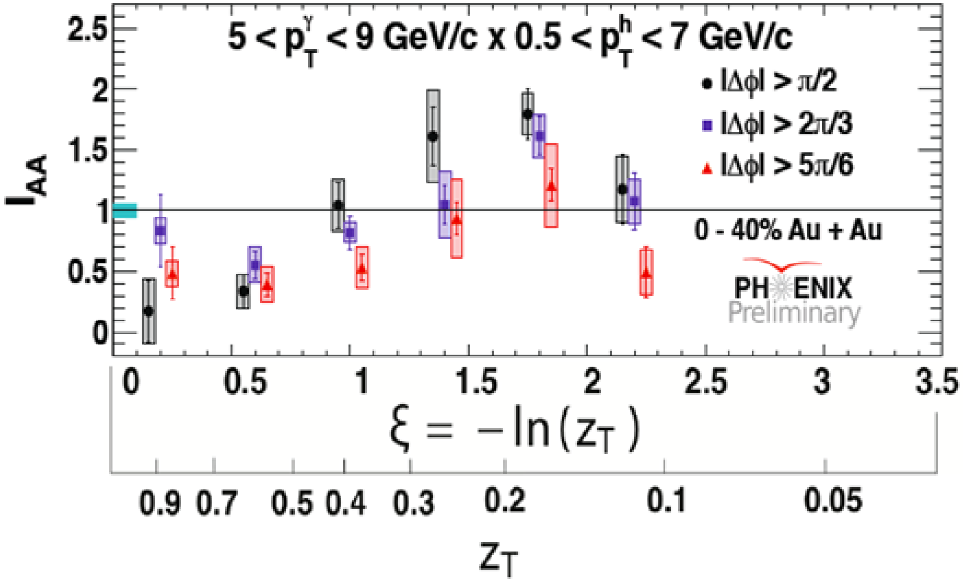




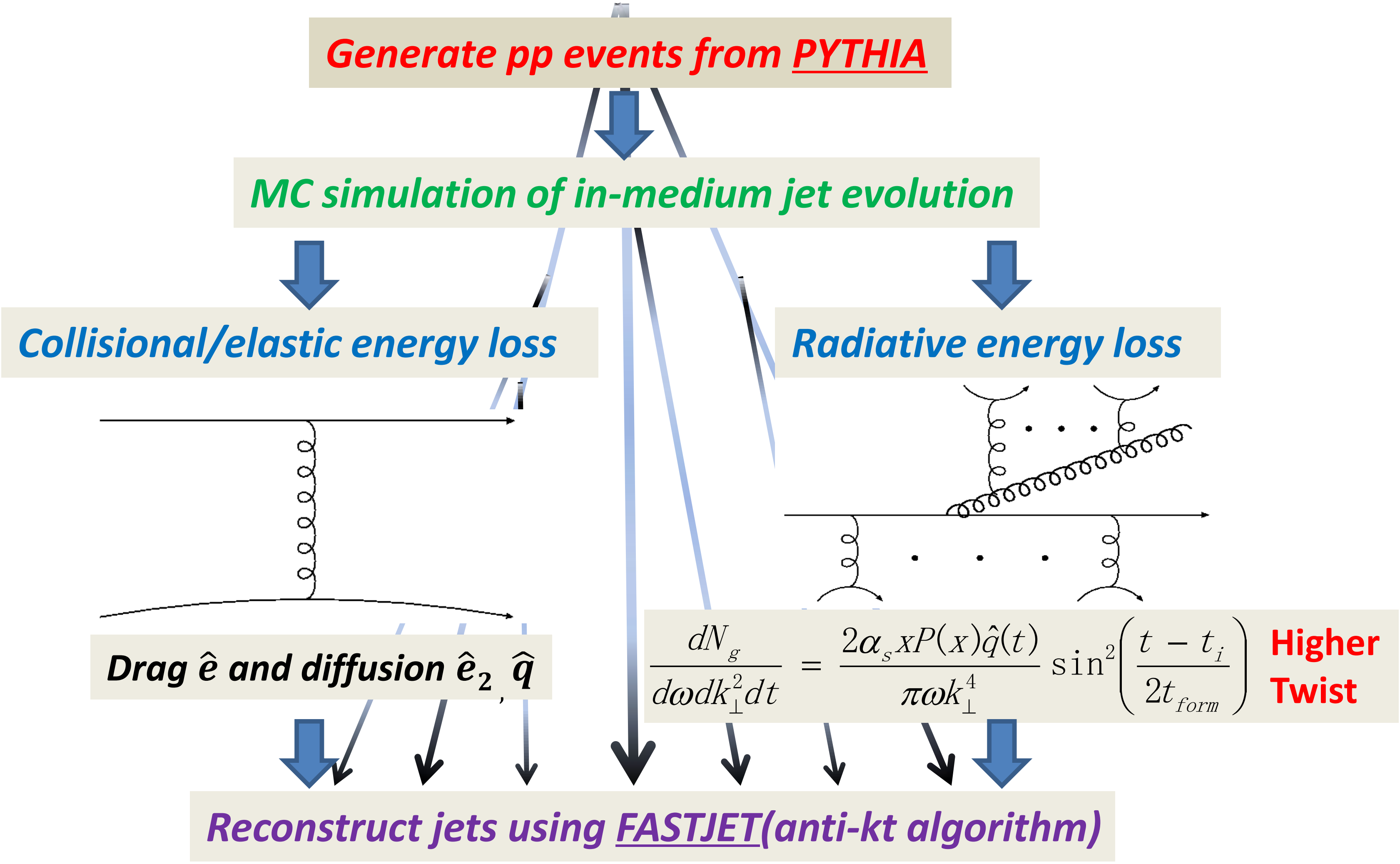
Photon-hadron correlations



- *Photon-triggered FF is an approx. of medium-modified FF*
- *Suppression at high z_T and enhancement at low z_T*
- *Consistent with the picture of jet energy loss and redistribution of lost energy from jet*



Simulating in-medium jet evolution



Generate pp events from PYTHIA

MC simulation of in-medium jet evolution

Collisional/elastic energy loss

Radiative energy loss

Drag $\hat{e}$ and diffusion $\hat{e}_2$, $\hat{q}$

$$\frac{dN_g}{d\omega dk_\perp^2 dt} = \frac{2\alpha_s x P(x)\hat{q}(t)}{\pi\omega k_\perp^4}\sin^2\left(\frac{t - t_i}{2t_{form}}\right)$$

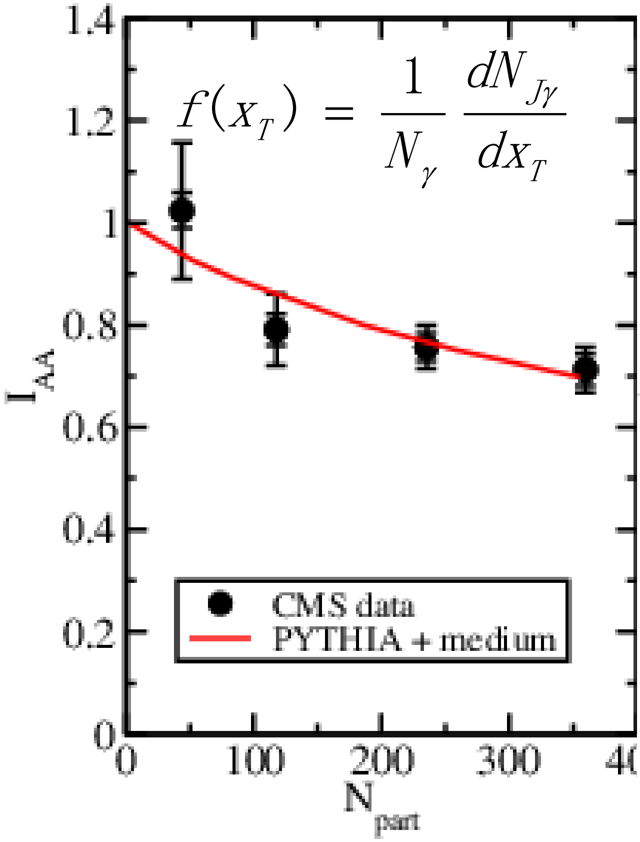
Higher Twist

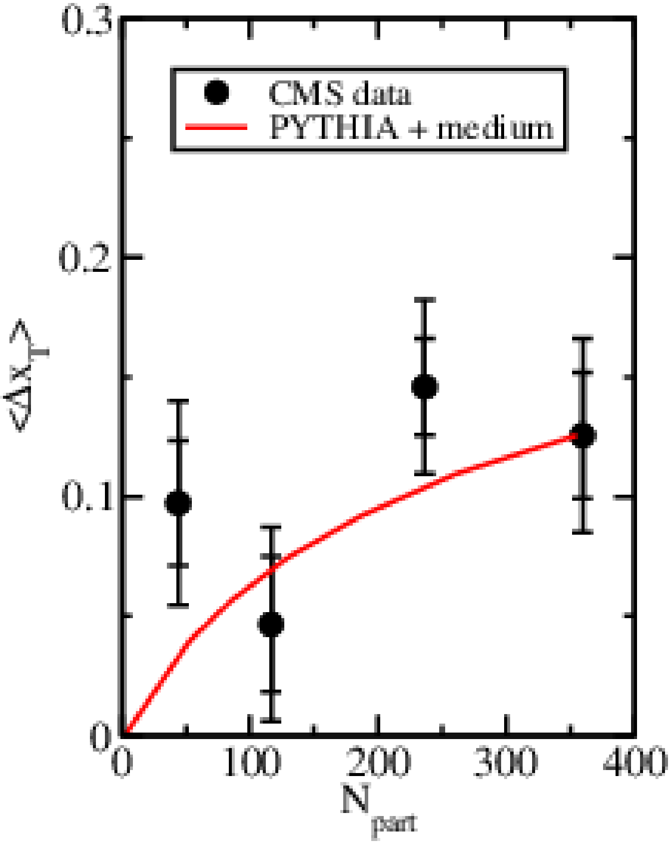
Reconstruct jets using FASTJET(anti-kt algorithm)

Medium modification of γ-jet

- Fit one data point I_{AA} = 0.7 in 0-10% PbPb collisions

- Larger medium modification on tagged jets for more central collisions (smaller yield & large energy loss)





$$I_{AA} = f_{AA}(x_T) \,/\, f_{pp}(x_T) \qquad \langle \Delta x_T \rangle = \langle x_T \rangle_{pp} - \langle x_T \rangle_{AA}$$

$$\hat{q} \approx 2\hat{e}_2 \approx 4T\hat{e} \propto T^3$$

Modification for different x_T jets

- **Combined with the distribution of tagged jet distribution $f(x_T)$**
- **Stronger suppression and centrality dependence for larger x_T jets**
- **Less suppression (or enhancement) for smaller x_T jets**