High Temperature QCD Theory

Xin-Nian Wang (LBNL)

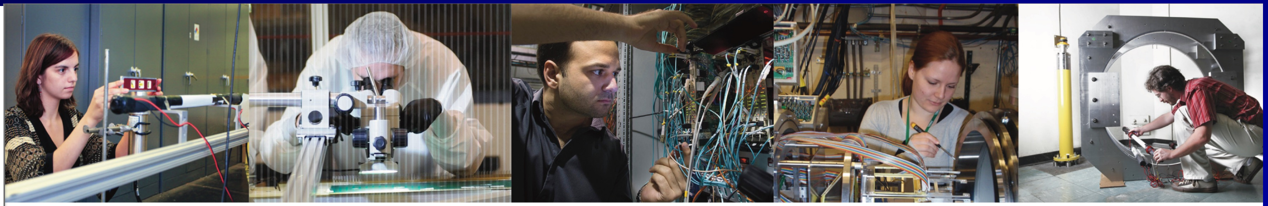
input from your colleagues

"Getting ~~an education from MIT~~ is like taking a drink from a fire hose"
---- Jerome Wiesner (former MIT president)

RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- *With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.*
- *Expeditiously completing the Facility for Rare Isotope Beams (FRIB) construction is essential. Initiating its scientific program will revolutionize our understanding of nuclei and their role in the cosmos.*
- *The targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model must be sustained.*
- *The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.*



The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

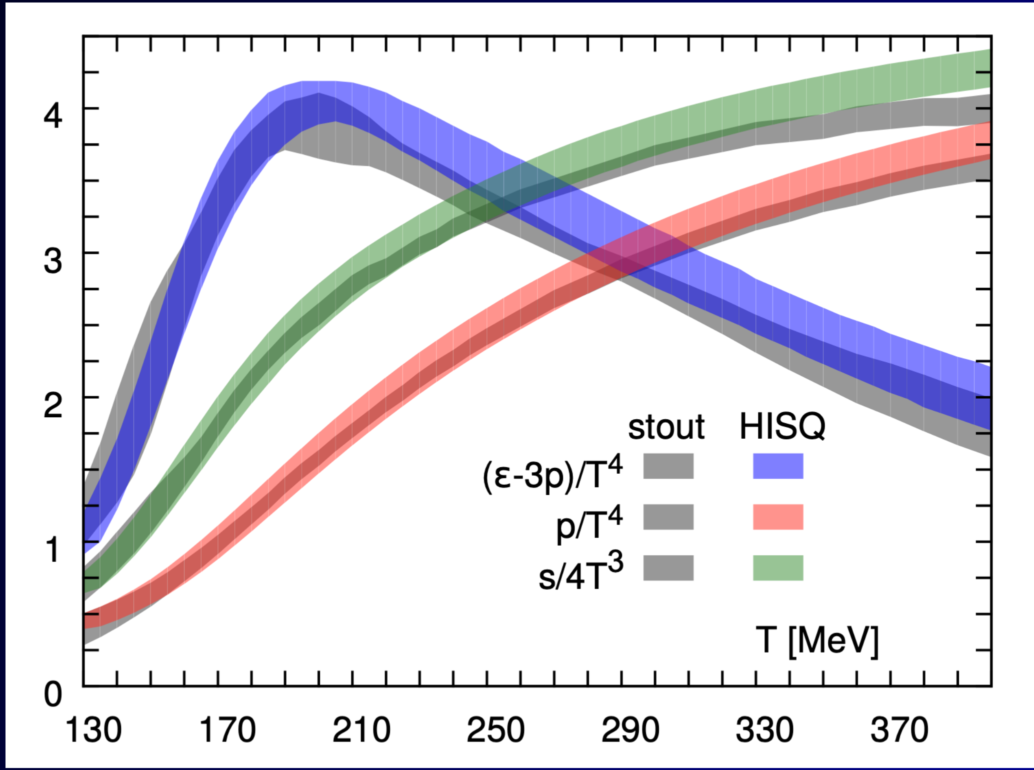
- Characterization of liquid QGP,
- Mapping the phase diagram of QCD
- Hard microscopy of QGP to see how quarks and gluons conspire to make a liquid-like medium.

Outlines

- Soft probes of QGP
- Spin dynamics in heavy-ion collisions
- Hard and EM probes of QGP
- Interplay between soft and hard probes: medium response
- Summary and prospective

Phases and properties of QCD matter

Nf=2+1, physical pion mass continuum extrapolated



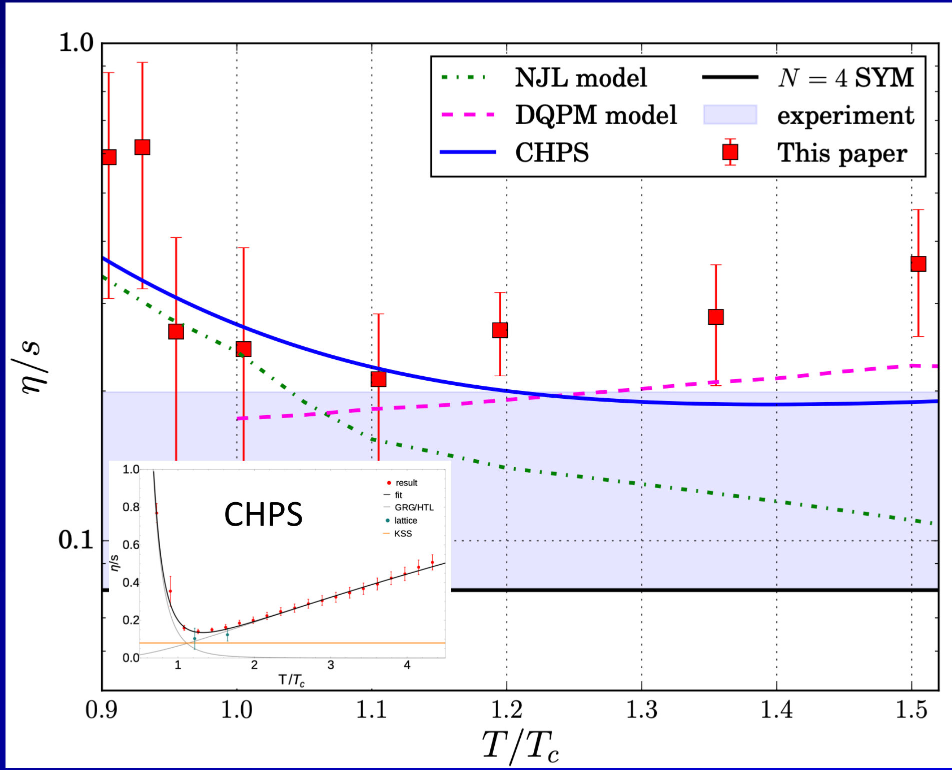
HotQCD:e-Print:1407.6387; Wup-Bud: e-Print: 1309.5258

Chiral crossover T_c=156.5 (1.5) MeV with physical pion mass

HotQCD: e-Print: 1812.08235; Wup-Bud: e-Print: 2002.02821

See talk by Petreczky

Shear viscocity of hot QCD matter



glue-matter lattice QCD e-Print: 1701.02266

CHPS: MEM FRG spectral e-Print: 1411.7986

NJL model e-Print:1305.7180

DQPM transport model e-Print: 1605.02371

Properties of QGP in A+A Collisions

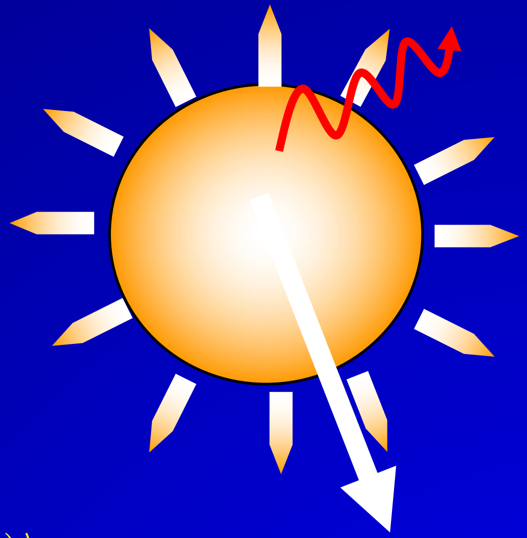
Multi-messenger study of dynamics and properties of QGP

- Soft probes: collective flow - bulk properties, EoS, transport properties, initial conditions

$$T_{\mu\nu}(x) : T(x), u(x)$$

$$T_{\mu\nu} \Longleftrightarrow \epsilon, P, s, c_s^2 = \partial p/\partial\epsilon$$

$$\eta = \lim_{\omega\to 0} \frac{1}{2\omega} \int dtdx e^{i\omega t} \langle [T_{xy}(0), T_{xy}(x)] \rangle$$



- EM Probes: EM emission – Temperature, EM response, medium modification of resonances

$$W_{\mu\nu}(q) = \int \frac{d^4x}{4\pi} e^{iq\cdot x} \langle j_\mu(0) j_\nu(x) \rangle$$

- Hard probes: Jet quenching, heavy quarks– Jet transport coefficients, diffusion constant

$$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int \frac{dy^-}{\pi} \langle F^{\sigma +}(0) F_\sigma^{\ +}(y) \rangle$$

Collective flow of QGP

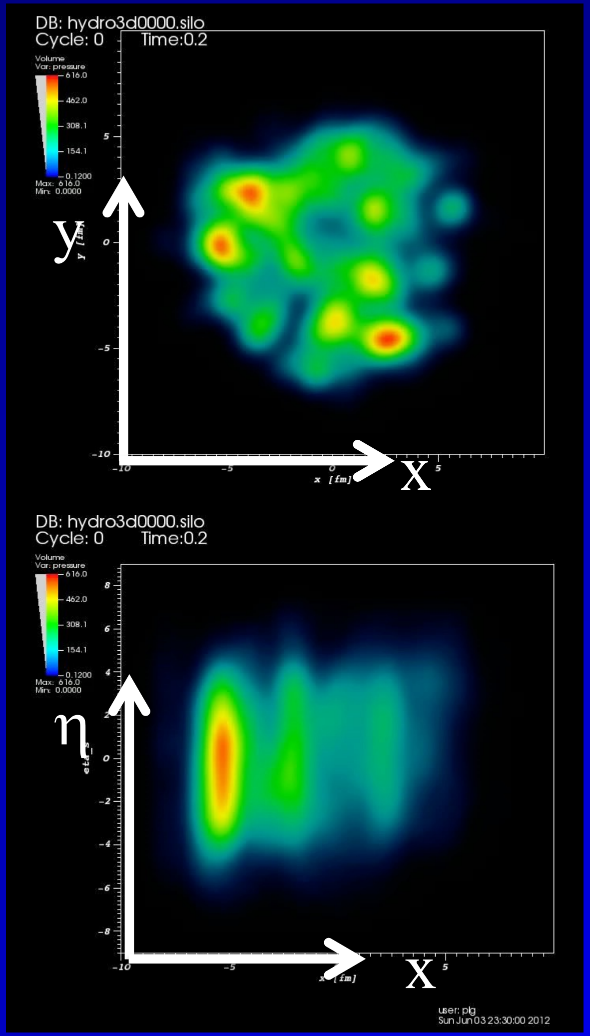
- Hydrodynamics: $\partial_\mu T^{\mu\nu} = 0$

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Delta T^{\mu\nu}$$

$$\Delta T^{\mu\nu} = \eta(\Delta^\mu u^\nu + \Delta^\nu u^\mu) + (\frac{2}{3}\eta - \zeta)H^{\mu\nu}\partial_\rho u^\rho$$

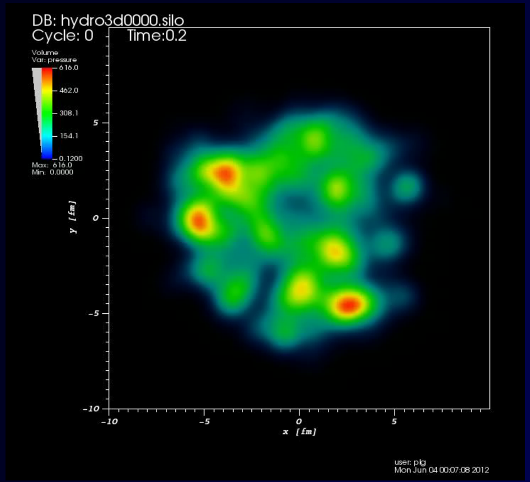
  – a low-momentum effective theory
  – Inputs from first principle QCD (lattice QCD) EoS p(ε), transport coefficients ξ(T), ζ(T) (??)
  – Initial condition: parton prod. & thermalization

Initial thermalization: hydrodynamic attractors, hydrodynamization, anisotropic hydrodynamics, kinetic theory, etc



(3+1)D viscous hydro (CLVisc) with AMPT initial condition (LG Pang 2018)

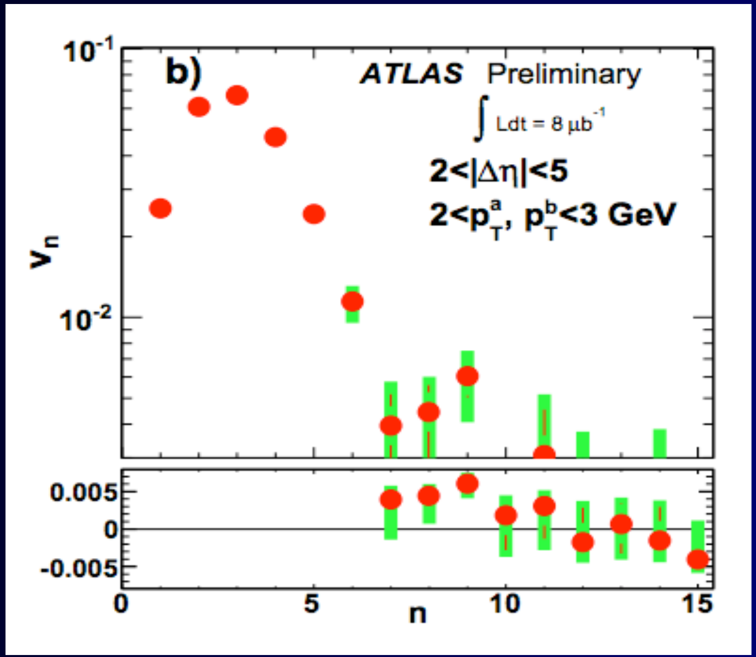
“CMB” of the little bang: Anisotropic flow of QGP

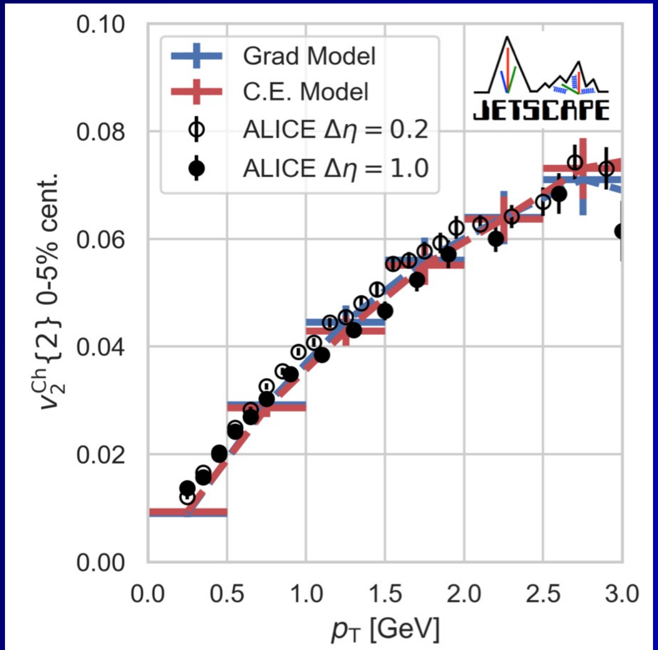


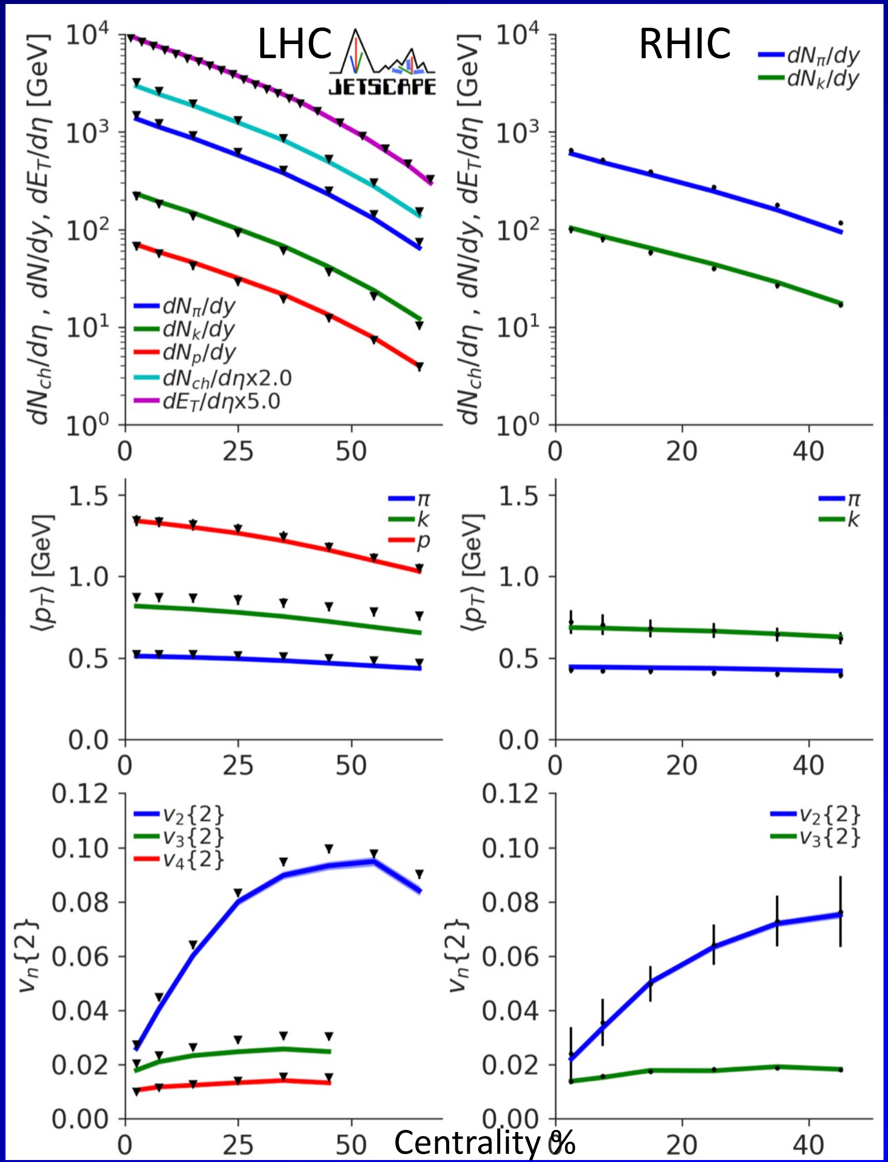
$$f(\phi) = f_0 \left[1 + 2\sum_{n=1} v_n \cos n(\phi - \Psi_n)\right]$$

$$\Psi_n = \frac{1}{n} \arctan \frac{\langle p_T \sin(n\phi)\rangle}{\langle p_T \cos(n\phi)\rangle}$$

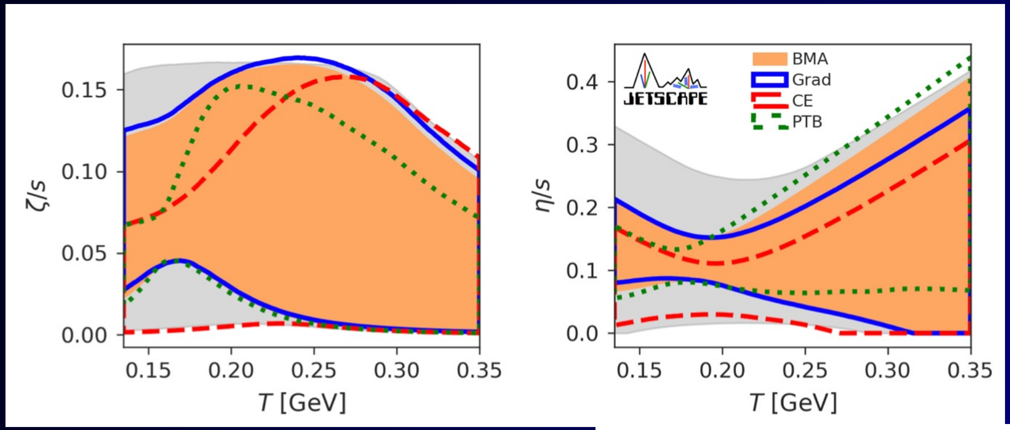
arXiv: 2010.03928



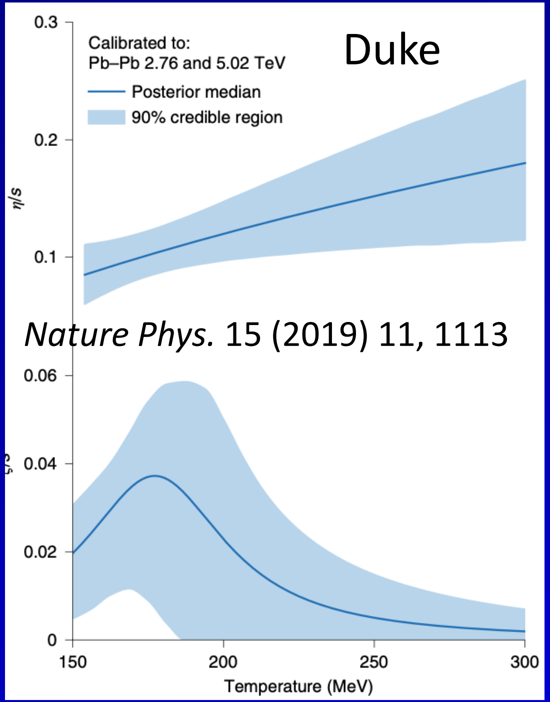




Bayesian inference of transport coefficients

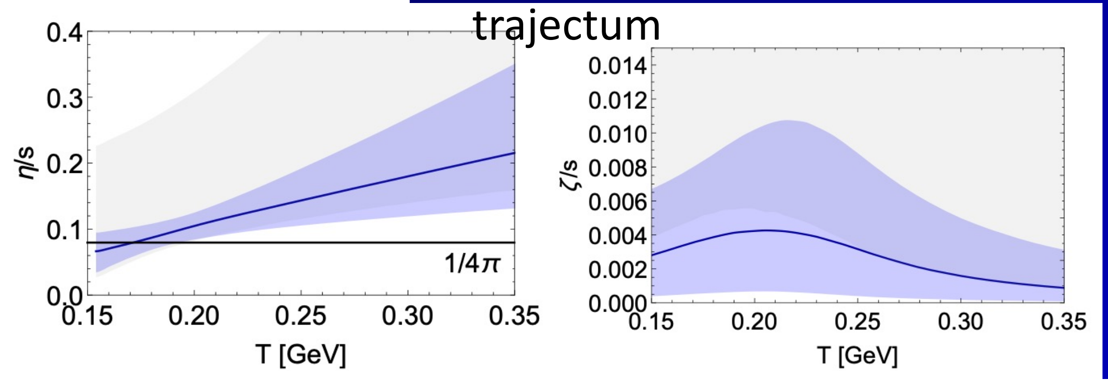


$$\mathcal{P}^{(i)}(\boldsymbol{x}|\mathbf{y}_{\rm exp}) = \frac{\mathcal{P}^{(i)}(\mathbf{y}_{\rm exp}|\boldsymbol{x})\mathcal{P}(\boldsymbol{x})}{\mathcal{P}^{(i)}(\mathbf{y}_{\rm exp})}$$



Nature Phys. 15 (2019) 11, 1113

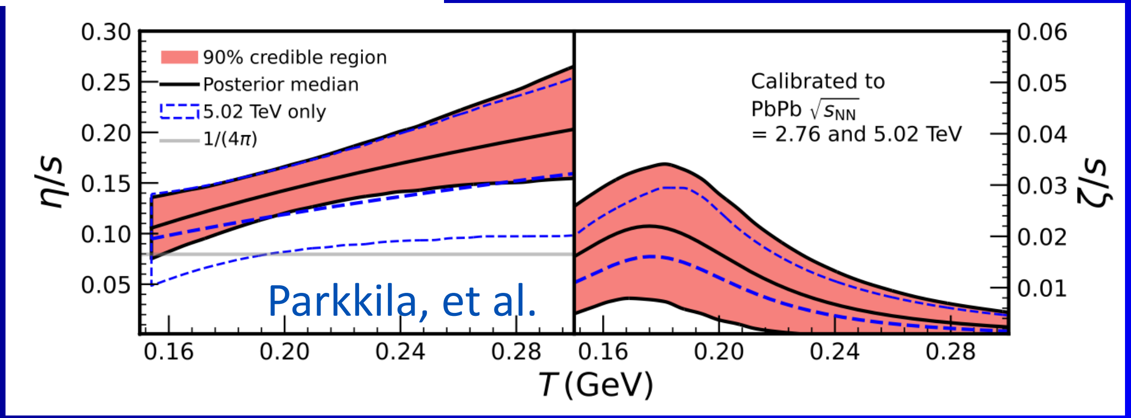
e-Print: 2010.03928
2011.01430



2+1D viscous hydro
Trento initial condition
Hadr transpt: SMASH, UrQMD

e-Print: 2111.08145

e-Print: 2010.15130; 2010.15134



Uncertainties:
modeling of initial condition (short distance correlation, early non-equilibrium evolution), transition to hadron transport (resonances) etc.

See talks by Paquet & Chen

Separating initial conditions and dynamics

Pearson correlation coefficient **e-Print:1601.04513**

$$\rho(v_n^2, [p_t]) = \frac{\langle \delta v_n^2 \delta[p_t] \rangle}{\sqrt{\langle (\delta v_n^2)^2 \rangle \langle (\delta[p_t])^2 \rangle}}$$

See talk by Jia

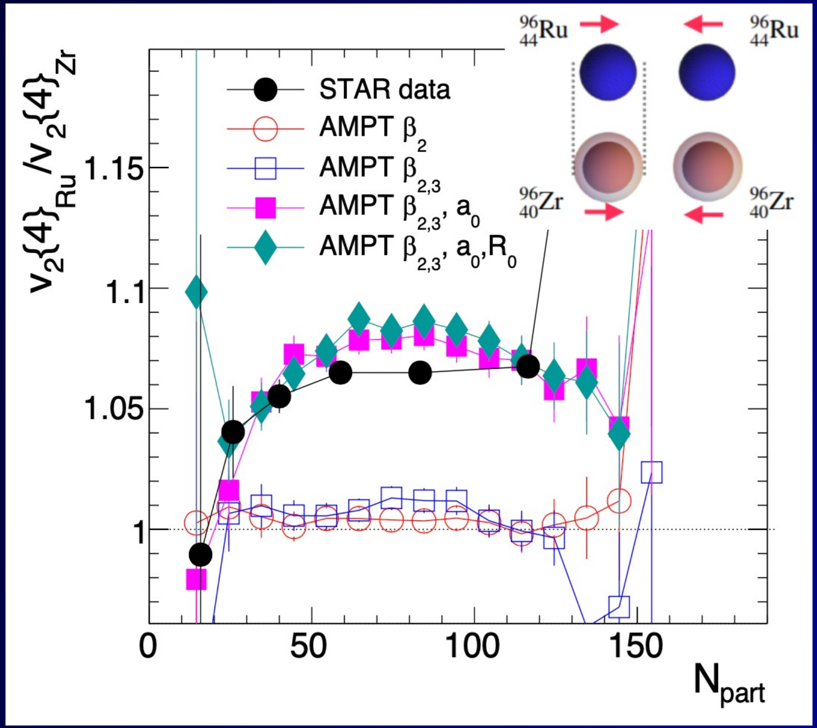
Nuclear structure & initial conditions

Nuclear deformation,

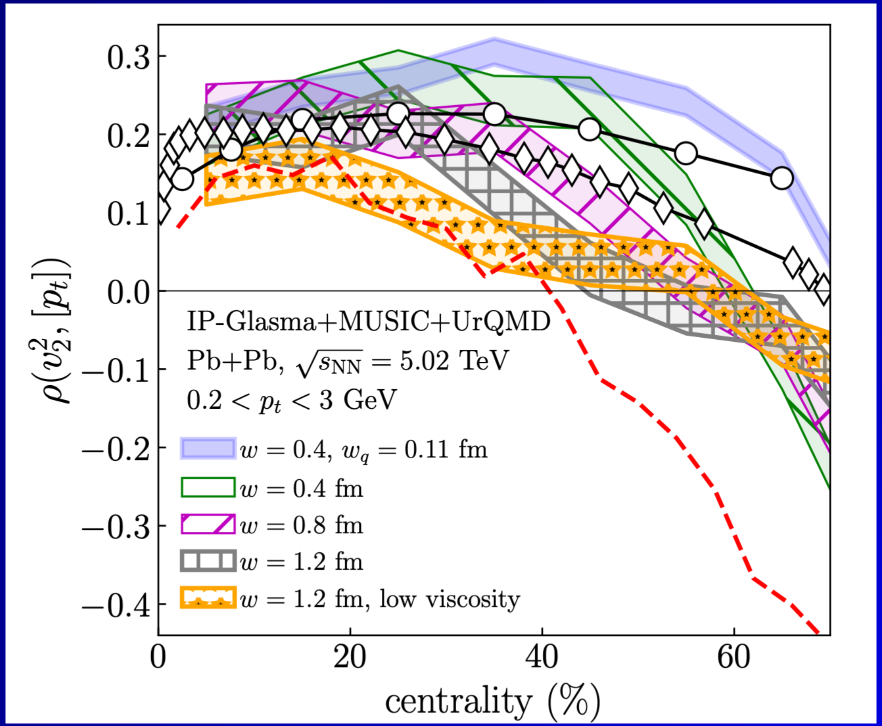
Neutron skin,

Triaxility

...



e-Print: 2206.10449



e-Print: 2111.02908

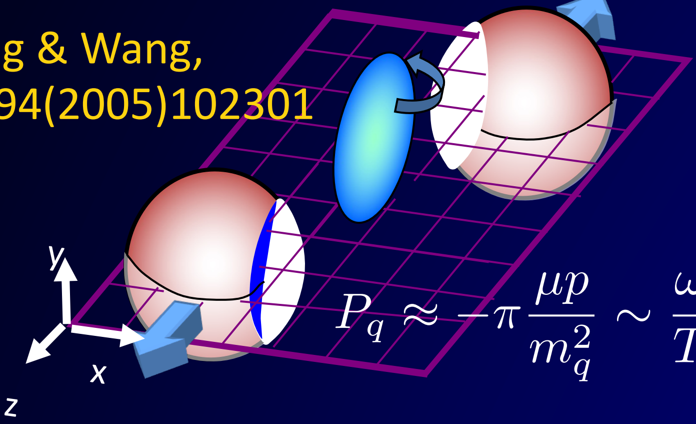
Nucleon size,

nucleon sub-structure

....

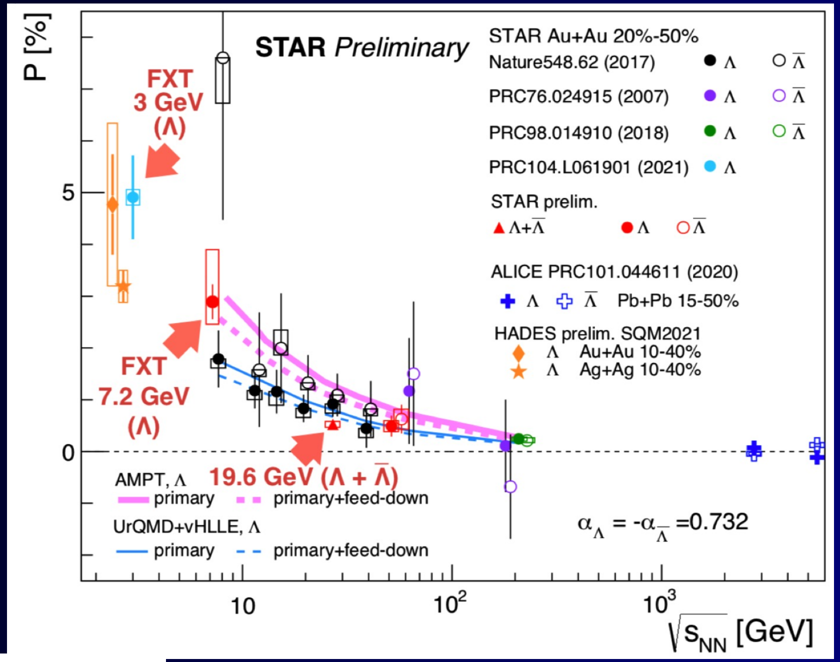
Spin dynamics in heavy-ion collisions

Liang & Wang, PRL94(2005)102301

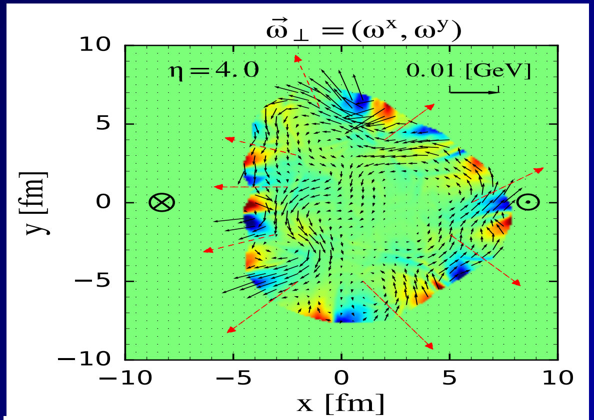


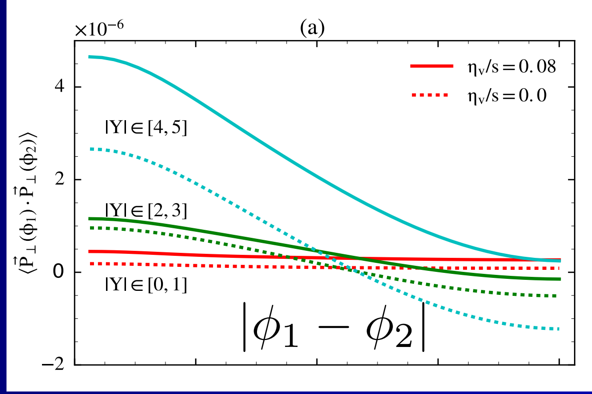
$$P_q \approx -\pi \frac{\mu p}{m_q^2} \sim \frac{\omega}{T}$$

Sarkar, QM23



Smoke ring structure



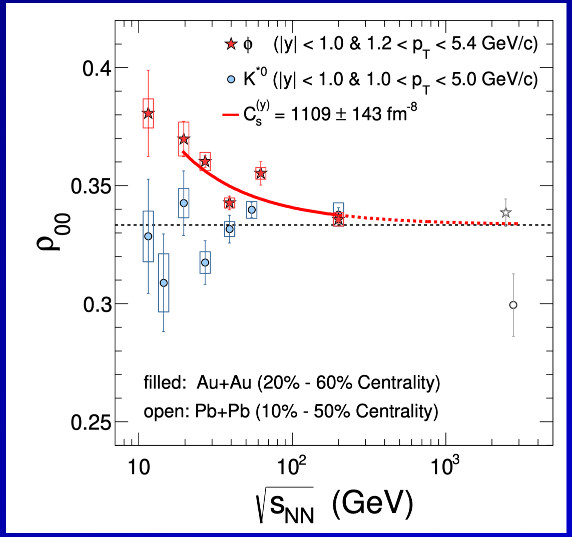


e-Print: 1605.04024

$$\mathcal{R} = \langle \frac{\vec{\omega} \cdot (\hat{t} \times \vec{v})}{|\hat{t} \times v|} \rangle$$

e-Print: 2102.11919

Vector meson spin alignment



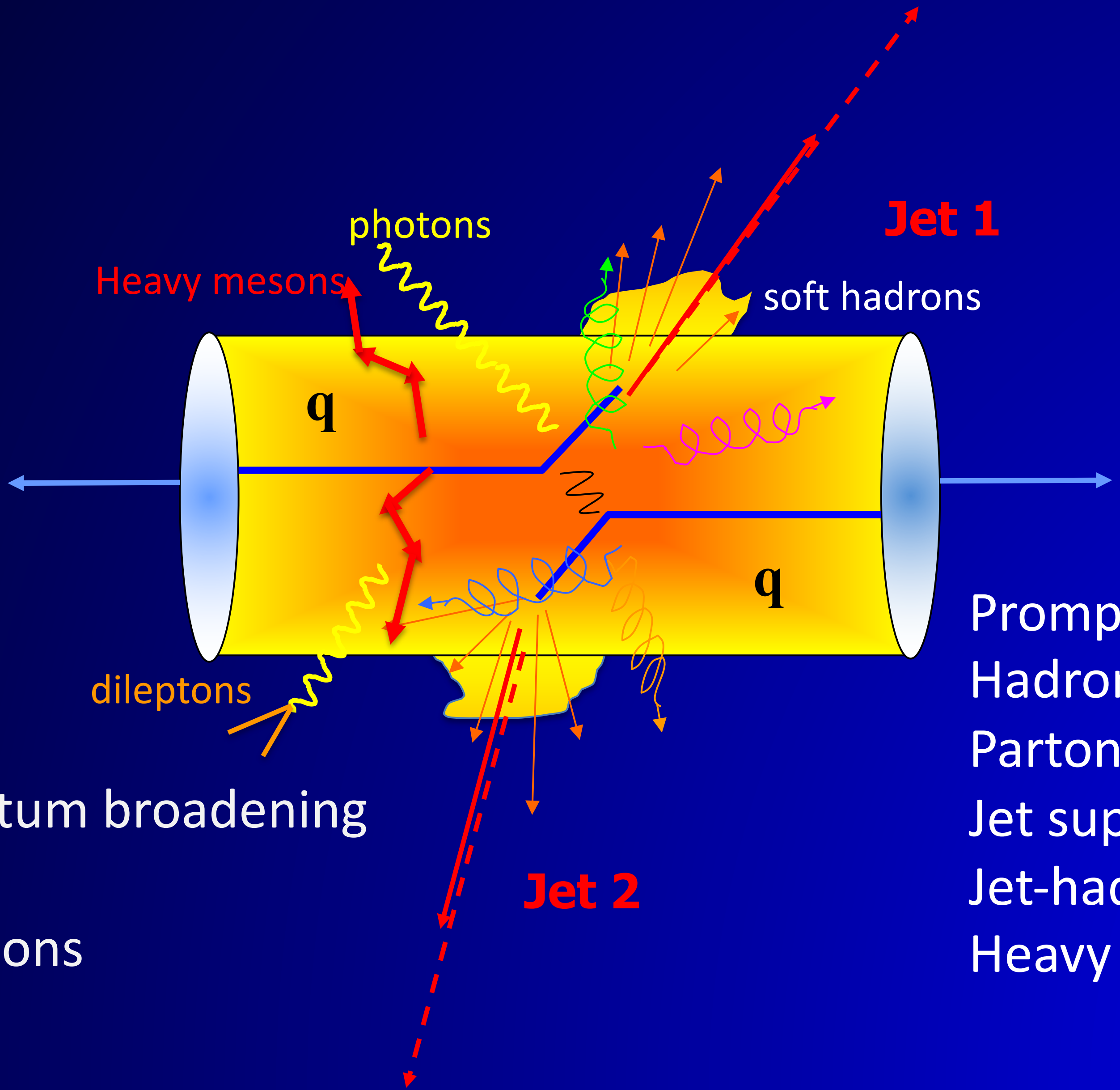
e-Print: 2204.02302

$$\rho_{00} \approx \frac{1}{3} + \frac{g_\phi^2}{m_\phi^2 T_{\rm eff}^2}(C_1 B^2 \phi + C_2 E_\phi^2)$$

e-Print: 2205.15689

- Shear induced spin polarization
- Spin transport theory
- Spin hydrodynamics
- CME (a few percent level signal)

Hard and EM probes in heavy-ion collisions

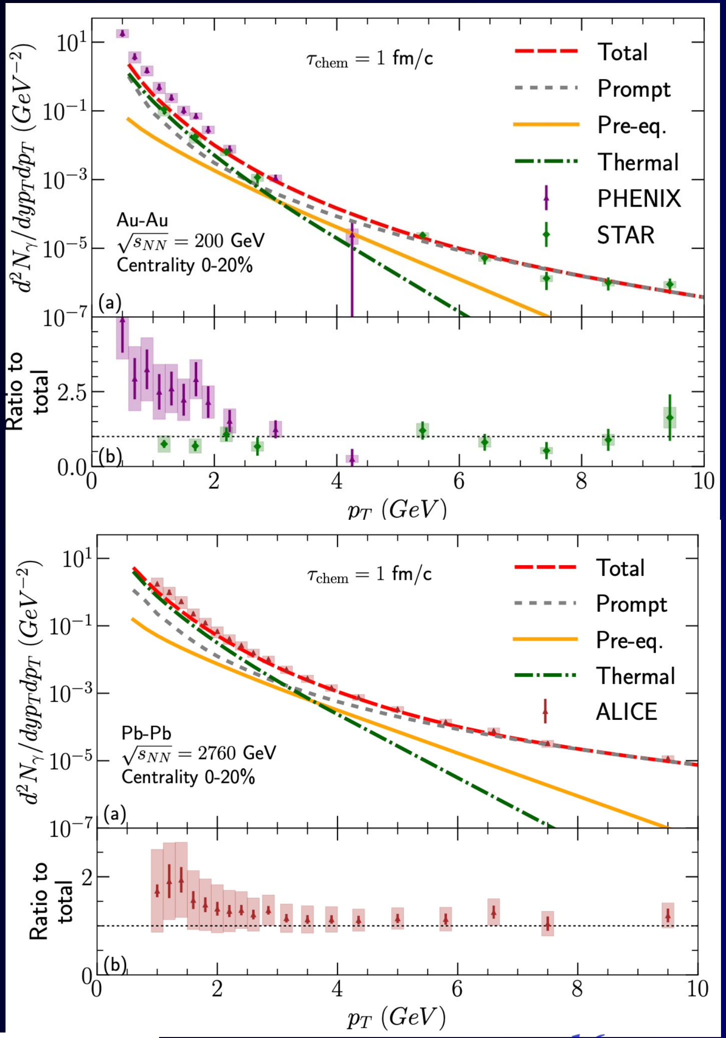


EM response
Multiple scattering
Transverse momentum broadening
Medium response
Heavy quark diffusions

Prompt γ emission
Hadron properties in medium
Parton energy loss
Jet suppression
Jet-hadron correlation
Heavy meson modification

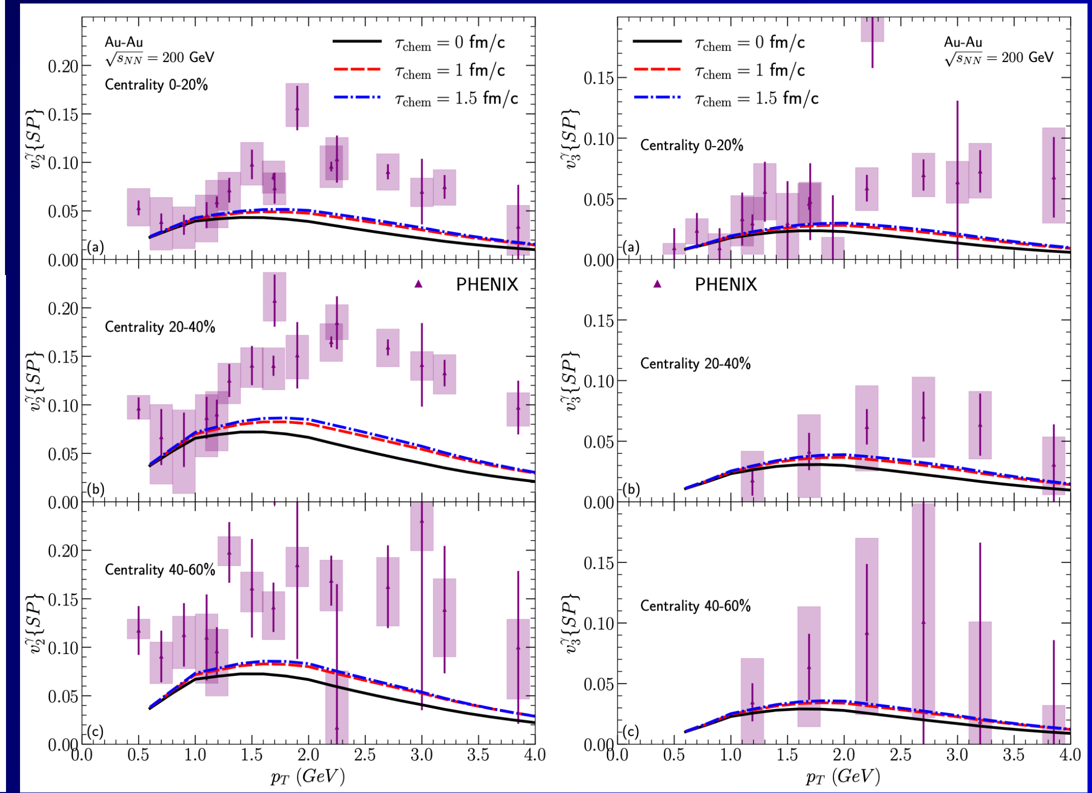
EM emissions from the evolving QGP

e-Print: 2106.11216   2008.02902



Sources:
Direction production: nPPF
Thermal production QGP: hydro evolution
Thermal production HG: hadron properties

Pre-eq contribution:
Sensitive to pre-eq dynamics, medium transport properties



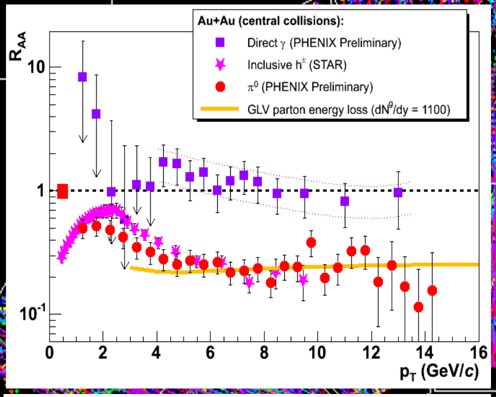
Jet-medium interaction → 10%
e-Print: 2207.12513

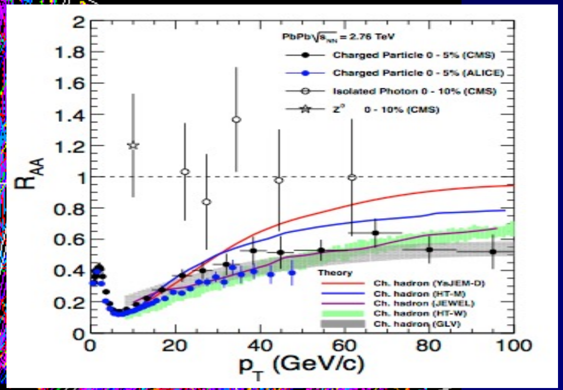
Out-eq contribution:
hadronic transport

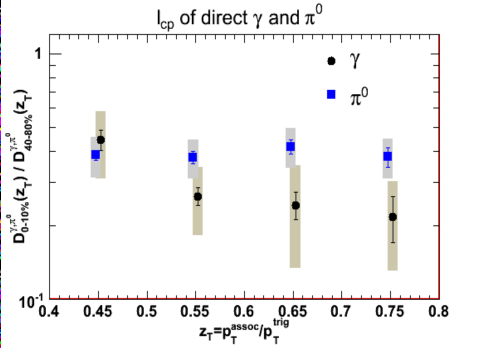
e-Print: 2111.13603

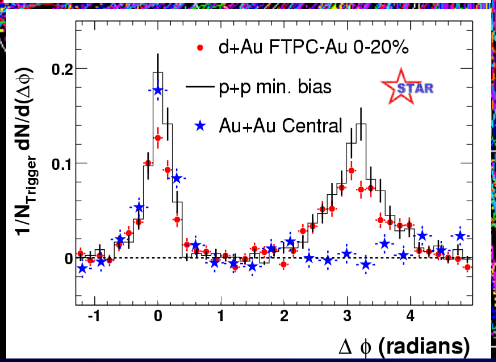
Bayesian analysis including photons and dileptons!

Jet Quenching at RHIC & LHC





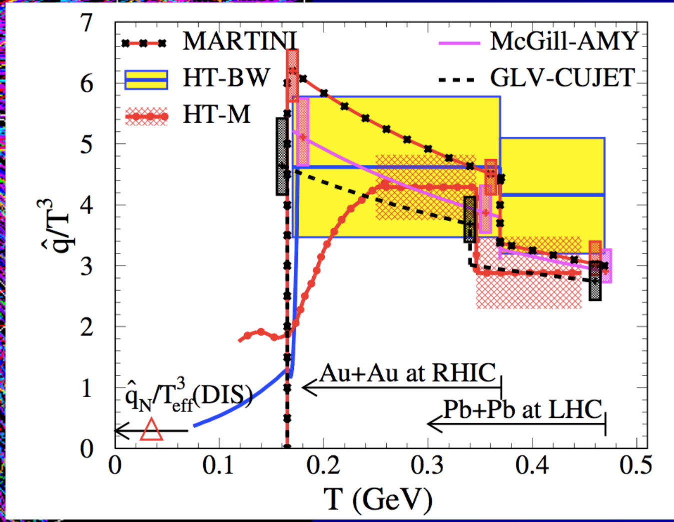


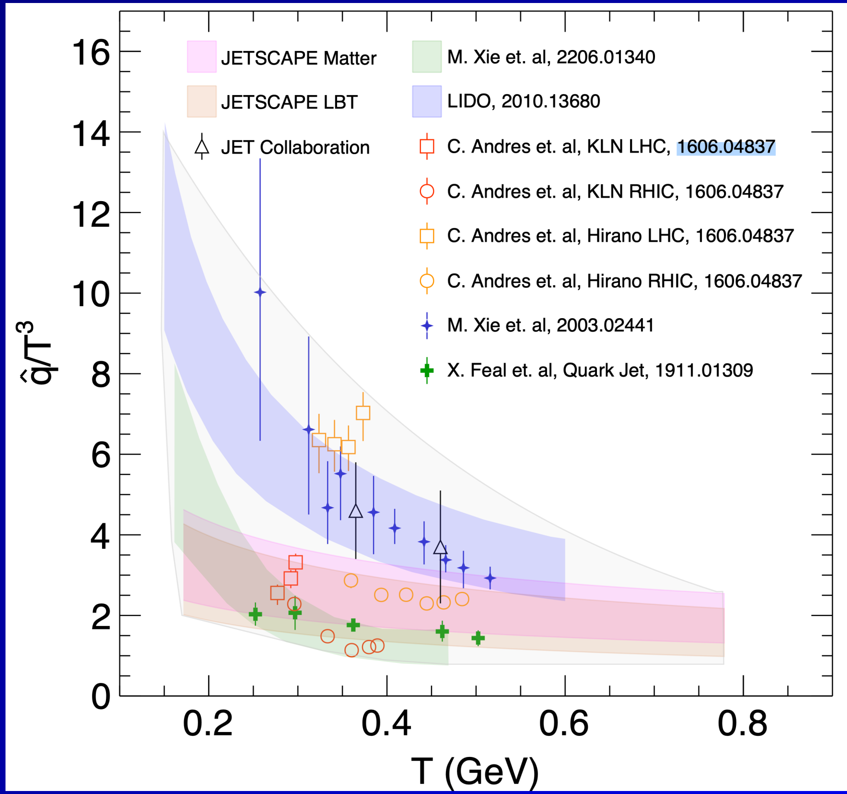


BDMPS’96

$$\Delta E \approx \frac{\alpha_s N_c}{4}\hat{q}L^2$$

JET Collaboration: e-Print: 1312.5003

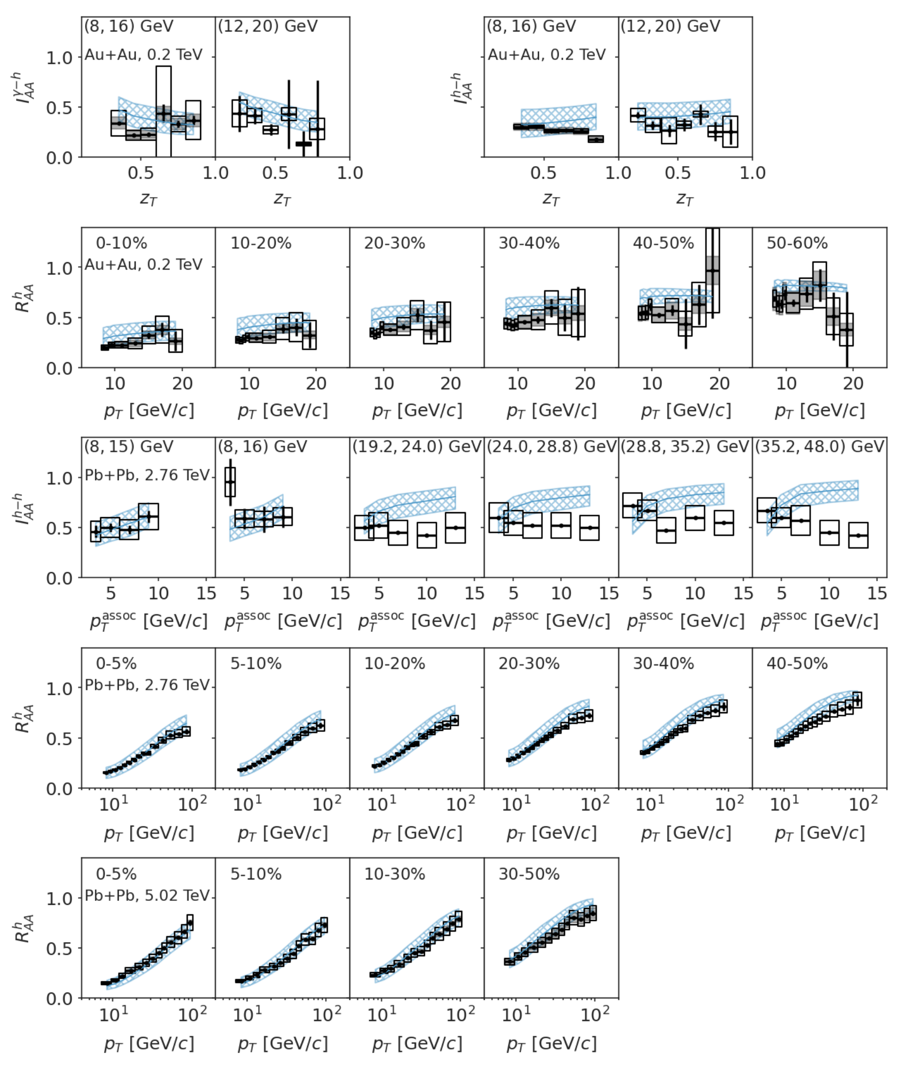




$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm at } \begin{matrix} T{=}370 \text{ MeV}, \\ T{=}470 \text{ MeV}, \end{matrix}$$

e-Print: 2203.16352

Bayesian inference of jet transport coefficient



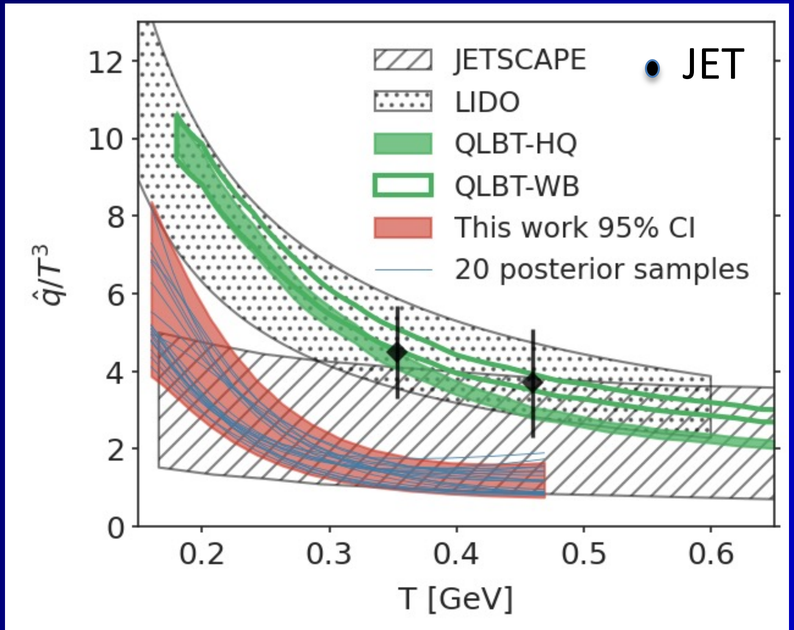
e-Print: 2208.14419

LIDO e-Print: 2010.13680

JETSCAPE e-Print: 2102.11337

QLBT: e-Print: 2107.11713

IF Bayesian e-Print: 2206.01340



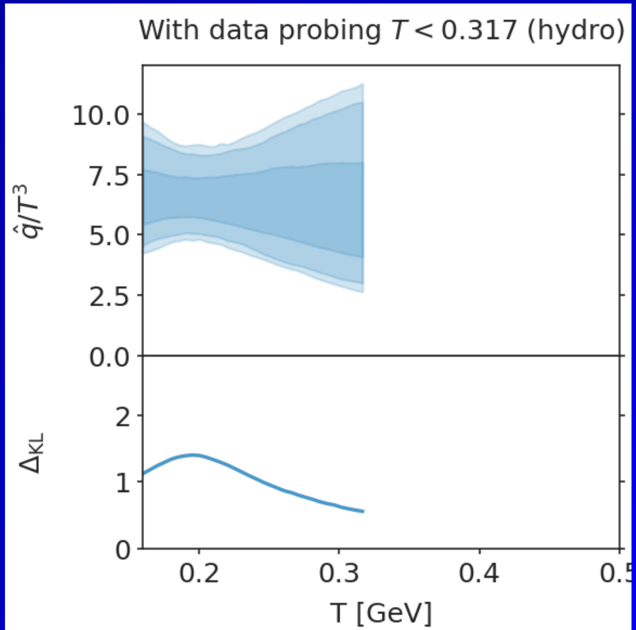
See talk by Yi Chen

Strong T-dependence

Weak E-dependence

Information-Field approach to priors is free of long-range correlation

e-Print: 2208.14419



Heavy quark transport coefficient

e-Print: 2107.11713

Heavy quark transport dynamics:

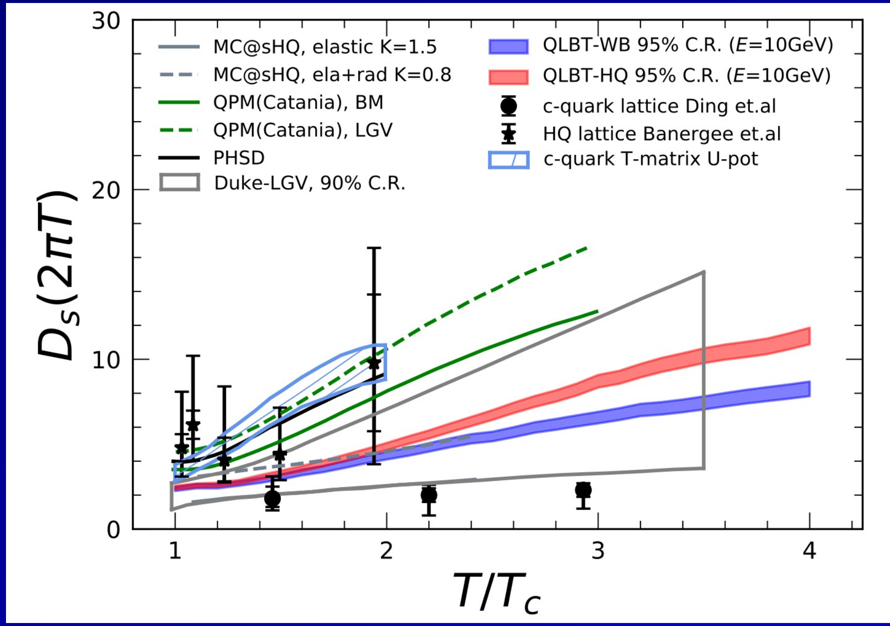
Elastic vs inelastic processes, quasi-particle

Bulk matter evolution: flow and initial conditions

Hadronization: coalescence

Heavy meson transport in QGP and hadronic matter

High pt contributions from gluon fragmentation



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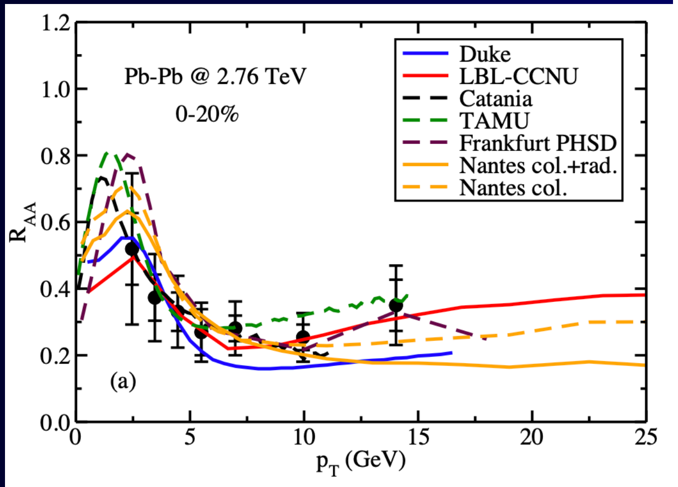
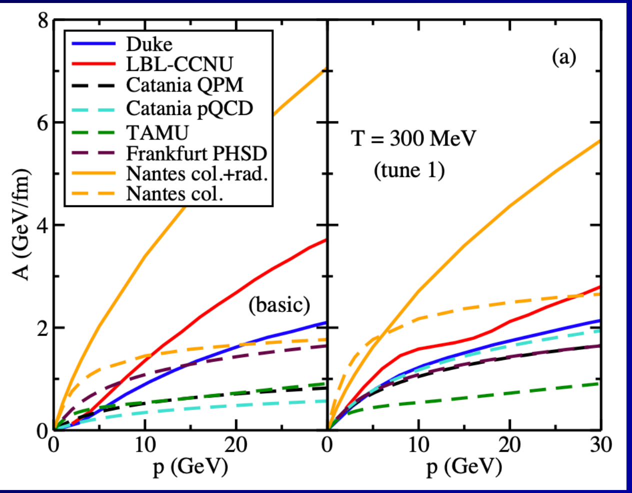
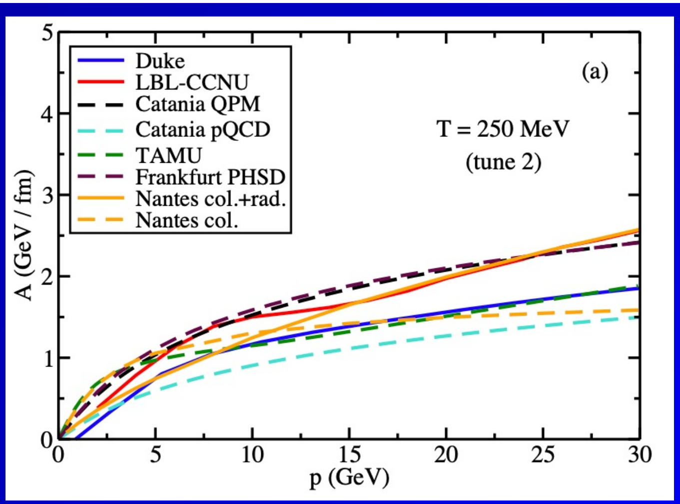
e-Print: 1809.07894





Common bulk medium



Parton energy loss and broadening

- Improved opacity expansion

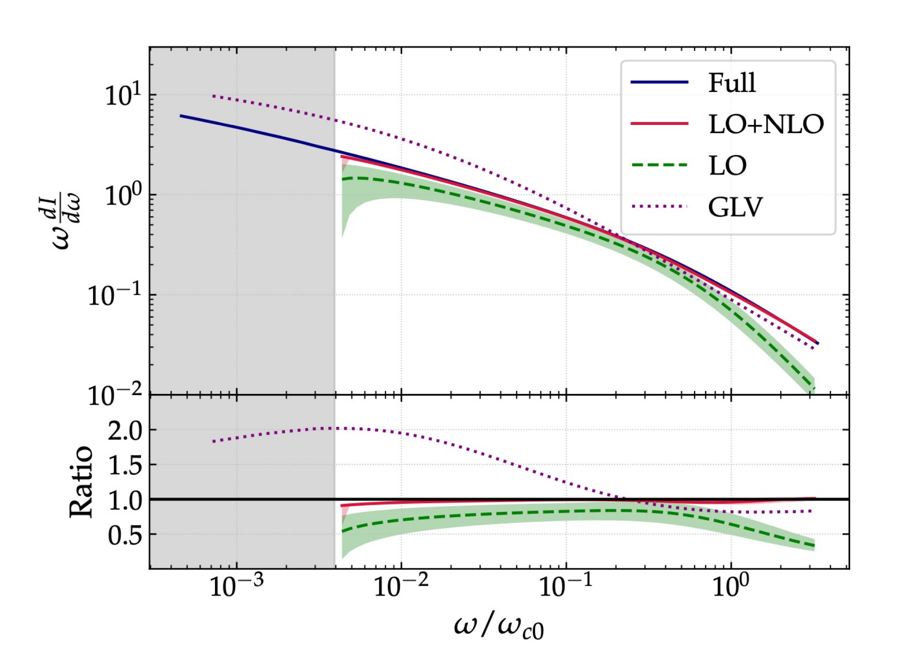
  e-Prints: 2009.13667, 1903.00506, 1910.02032

- Overlapping formation times

  e-Print: 2111.05348

- Resummation of multiple emissions

  e-Prints: 2011.06522, 2002.01517



- Corrections due to flow and density gradient (beyond eikonal)
  - Gradient tomography

  e-Prints: 2202.08847; 2204.05323

- Non-local quantum correction

  e-Prints: 2109.12041, 2203.09407

see talk by Majumder

$$Q_s^2 \simeq \langle k_\perp^2 \rangle_{\text{median}} \propto L^{1+2\sqrt{\bar{\alpha}}}$$

Jets and their substructures

- Space-time structure of medium-induce gluon emission, color-(in)coherence
  - VLE before formation time +MIE(no coherence)+VE
  - Multi-stage & muti-scale jet in-medium evolution

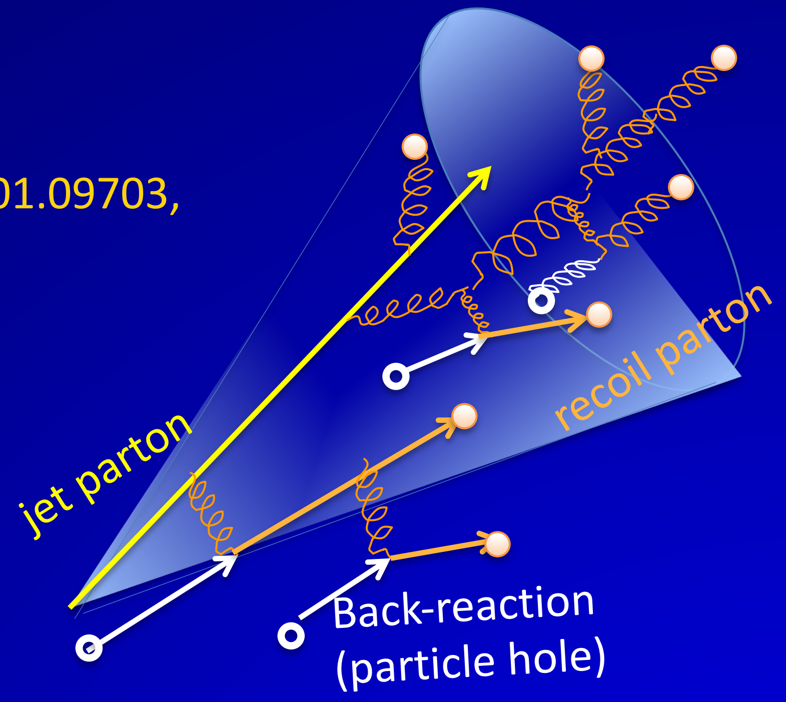
e-Prints: 1301.6102, 1801.09703, 1907.04866

- Inclusion of medium response
  - LBT, JEWEL, MATTER+LBT …

e-Print: 1503.03313, 0804.3568, 1705.00050

- Hadronization & recombination
  - Resolving RAA and jet v2 puzzle

e-Print: 2103.14657

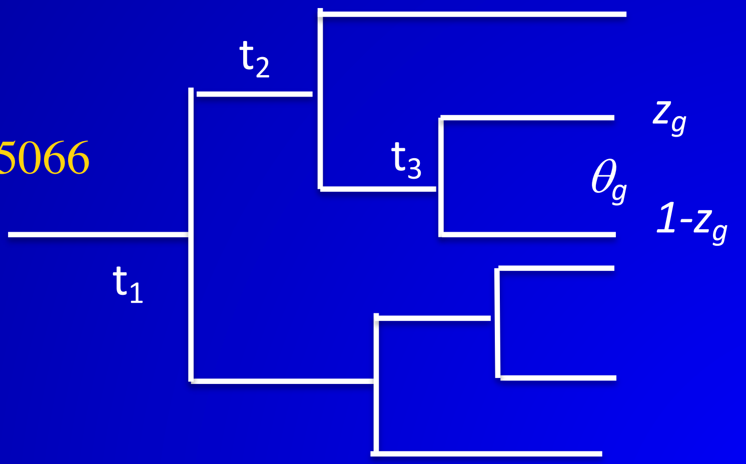


- Jet substructure and grooming & clustering
  - soft drop grooming: reducing non perturbative effect
  - Clustering: perturbative splitting

e-Prints: 1402.2657, 1502.01719, 1704.05066

  - proxy of formation time $\tau_f \approx \frac{1}{E z_g (1 - z_g)\theta_g^2}$ e-Print: 2012.02199

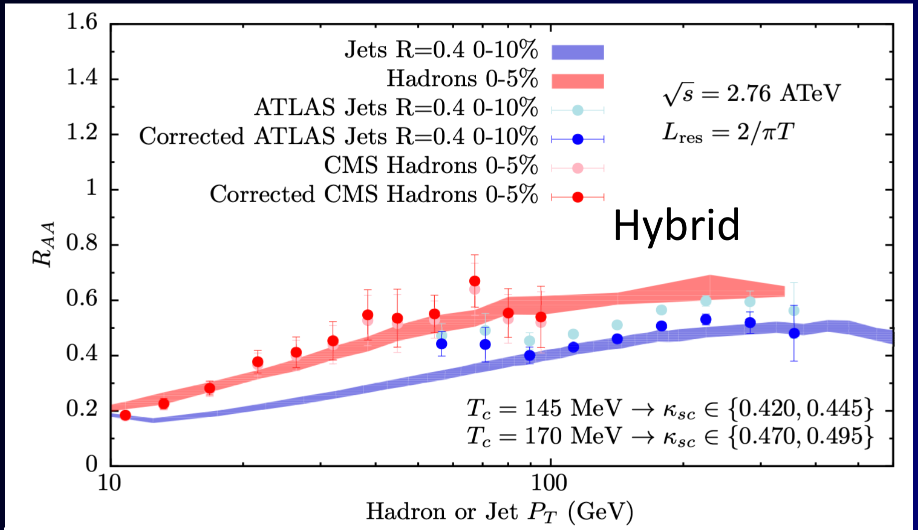
see talk by Majumder

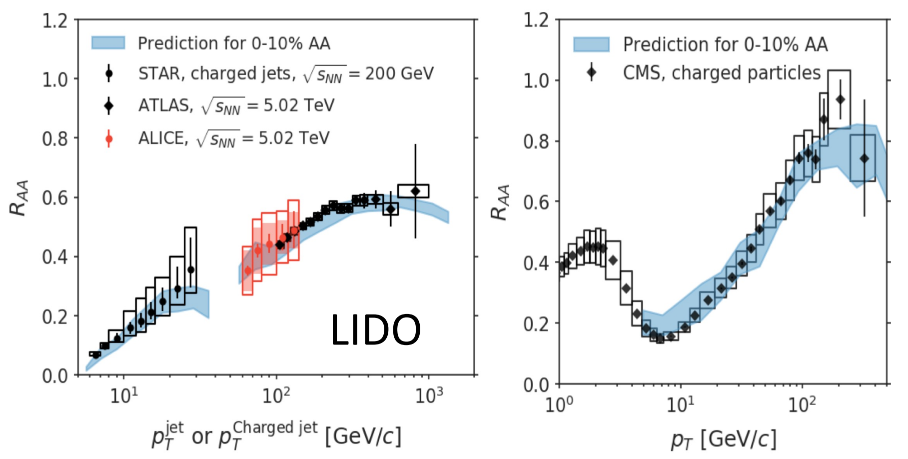


Jet suppression & medium response

Suppression of single jets and charged hadrons

e-Print:1808.07386

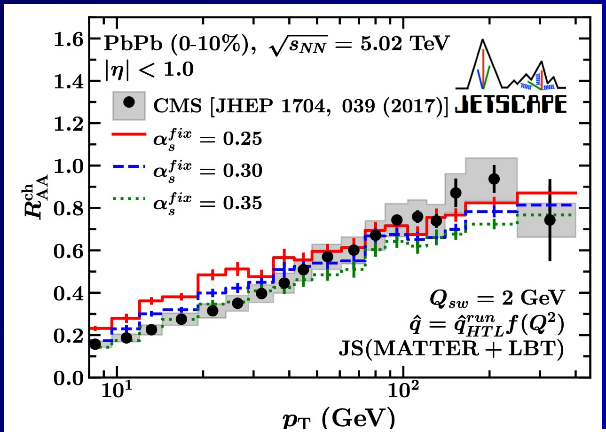


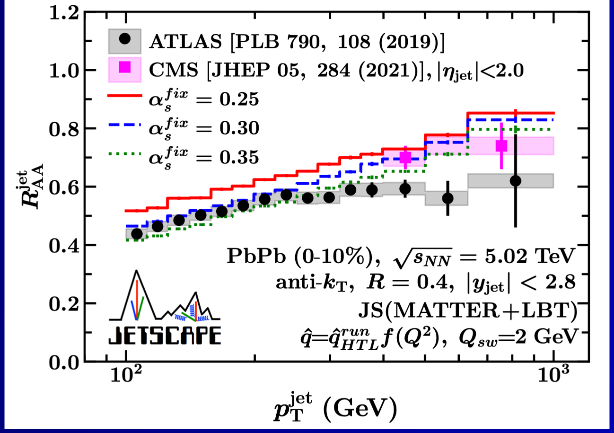


e-Print: 2010.13680

Inclusion of medium response necessary!

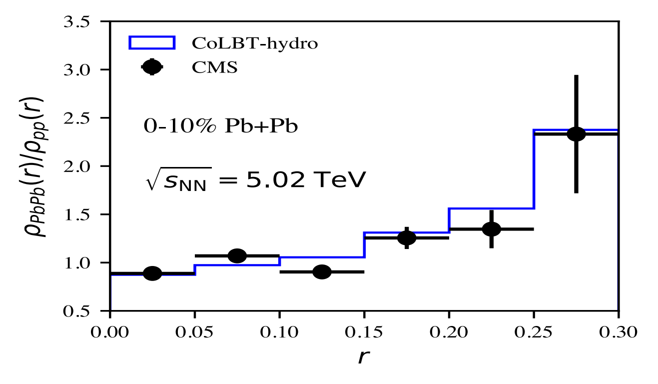
e-Print:2204.01163

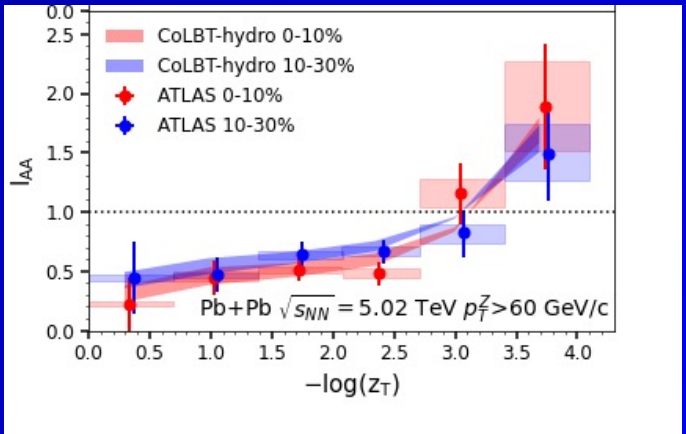




MATTER + LBT

Modification of jet shape and fragmentation function





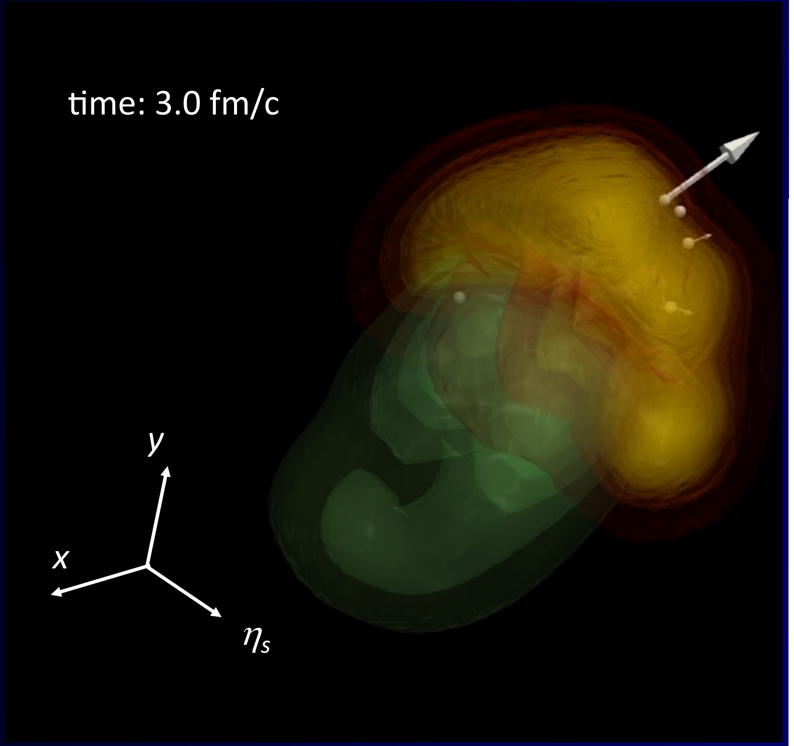
e-Print: 2101.05422

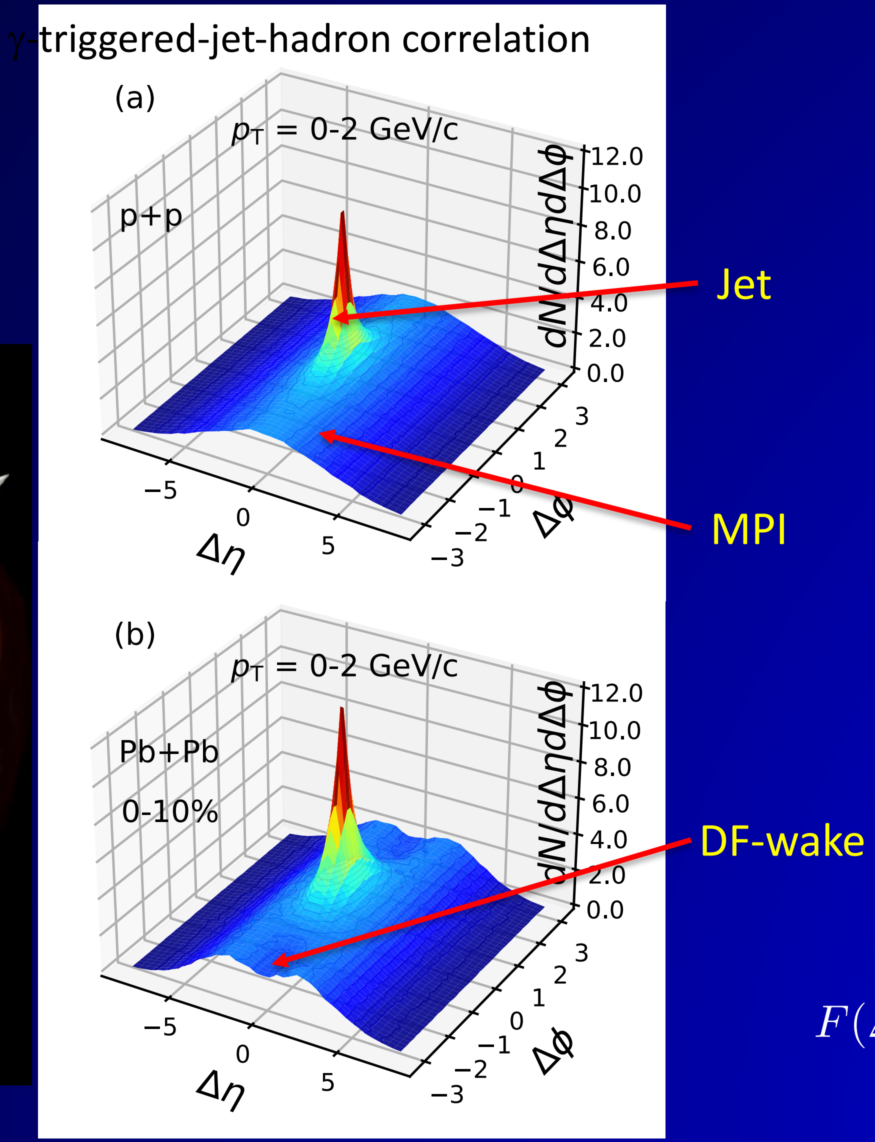
CoLBT

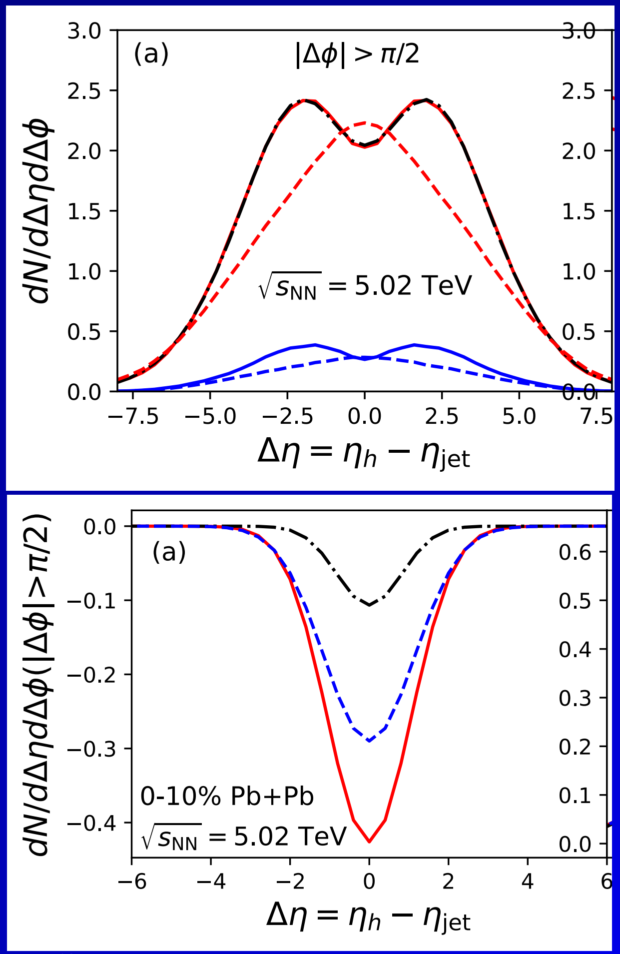
Search for jet-induced diffusion wake

Diffusion (DF) wake leads to depletion of soft hadron yield in the back of jet direction

e-Print: 2203.03683







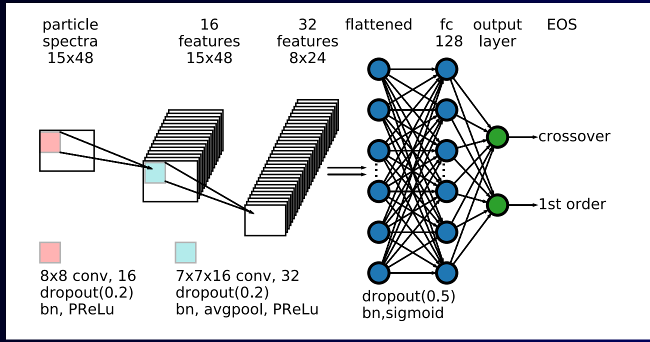
$$F(\Delta\eta) = \int_{\eta_{j1}}^{\eta_{j2}} d\eta_j F_3(\eta_j)(F_2(\Delta\eta, \eta_j) + F_1(\Delta\eta)),$$

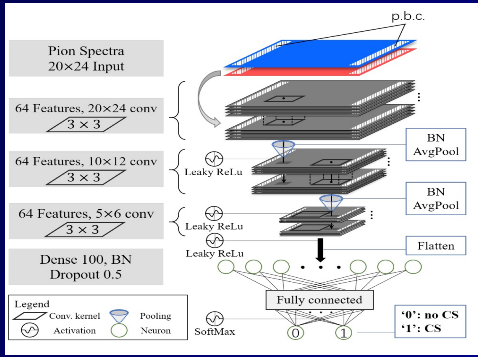
Jet-distr (F_3) MPI (F_2) DF-wake (F_1)

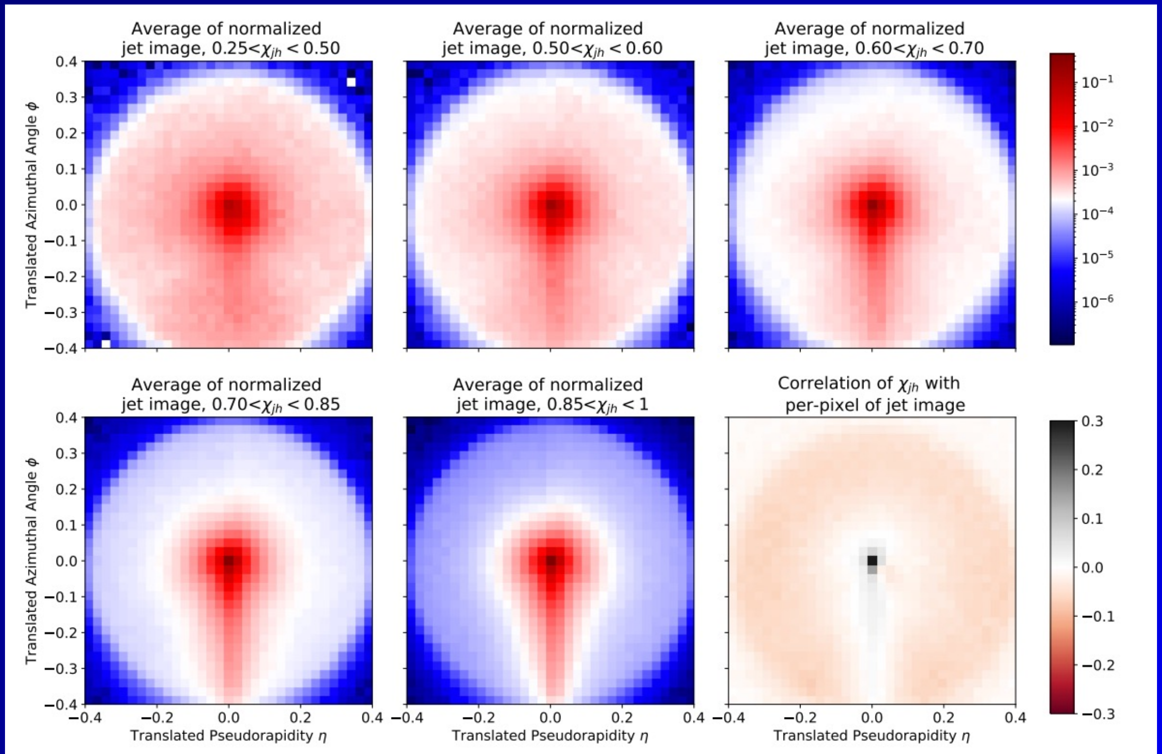
AI/ML in Heavy-ion physics

DCNN (Deep convolutional neural network)

Jet-tomographer

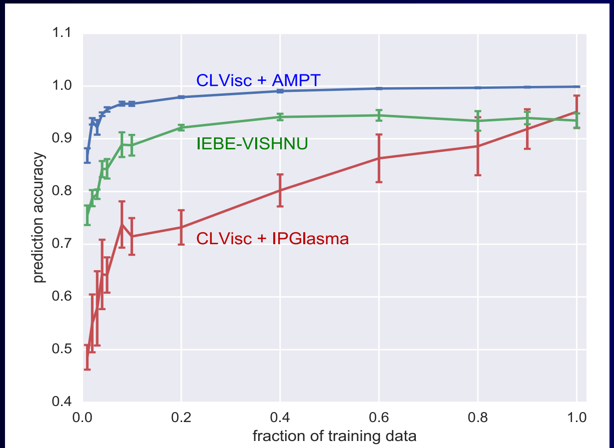


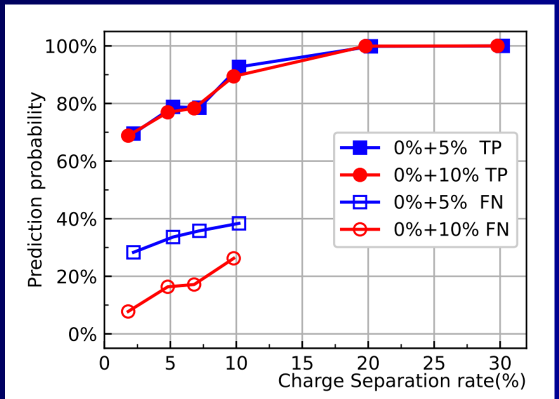




EoS-meter

CME-meter





Use jet imagine to predict jet energy loss & initial prod point

e-Print: 1612.04262

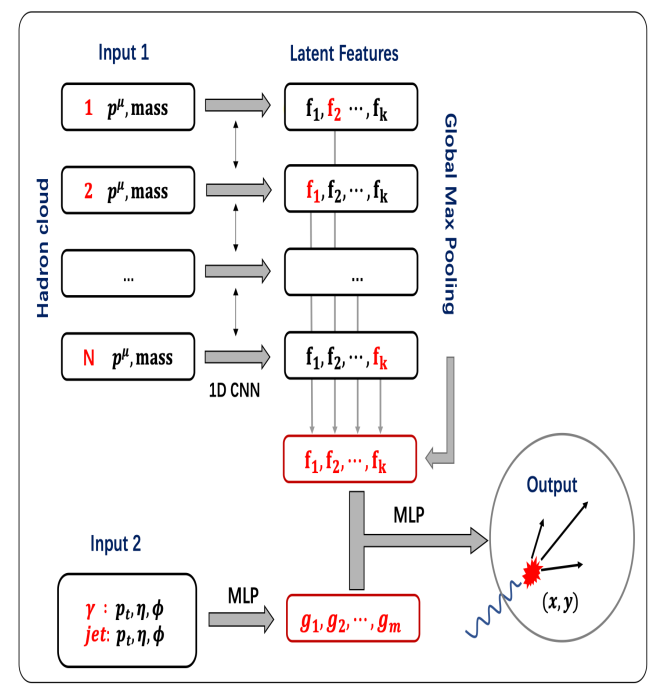
e-Print: 2105.13761

e-Print: 2106.11271, 2012.07797

BERKELEY LAB

Deep learning assisted jet tomography

PCN (point cloud network)



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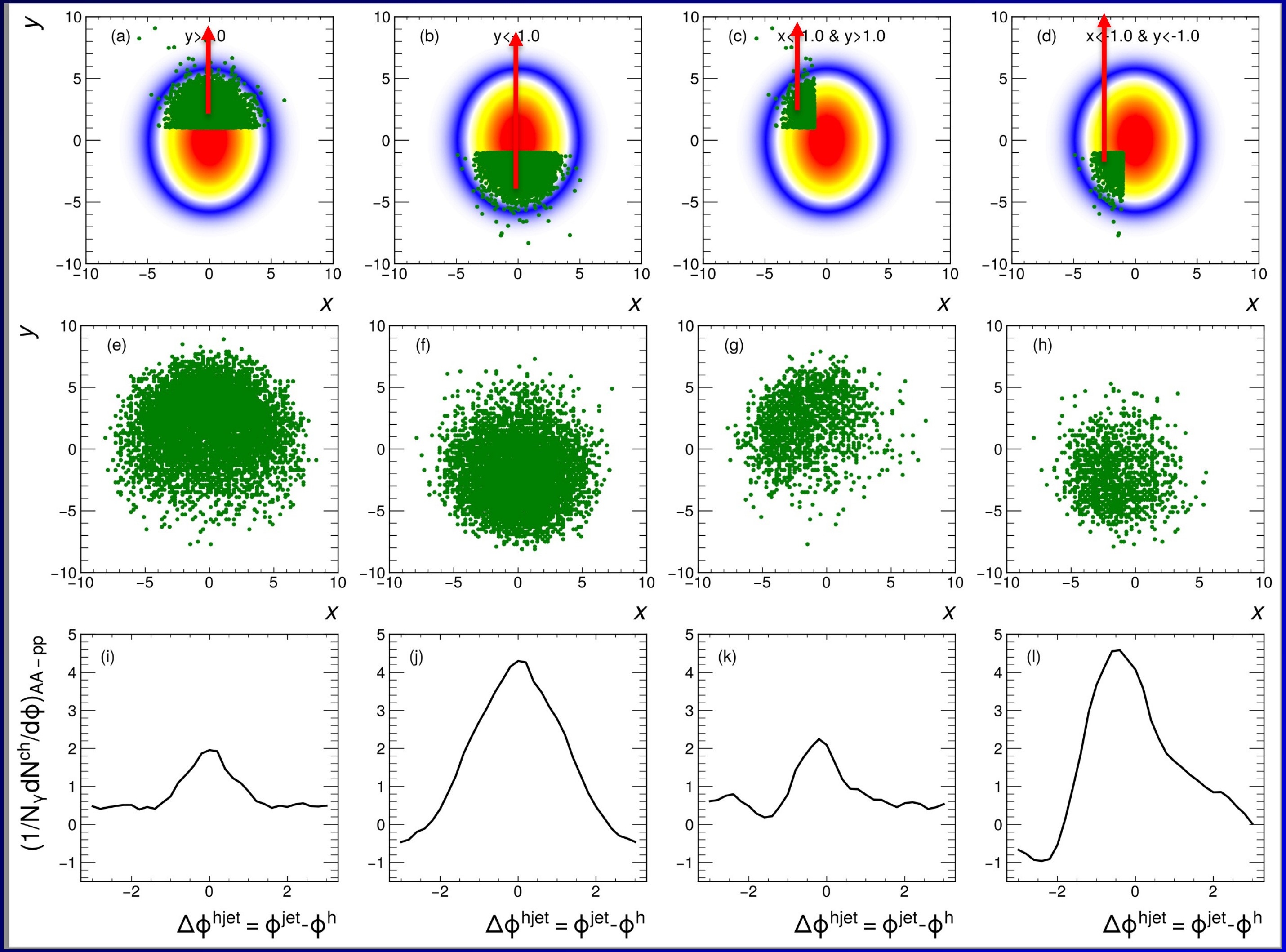
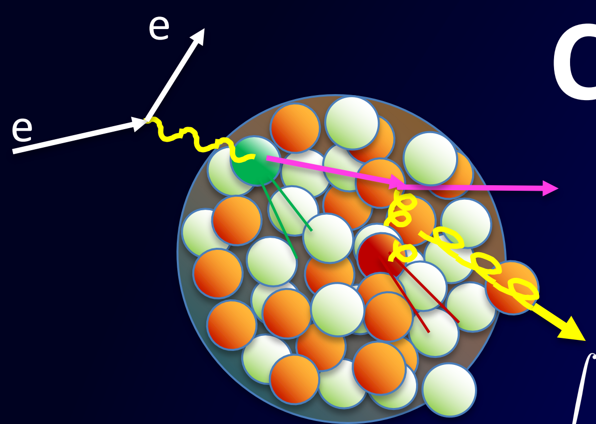


DL network selection

Actual distribution

γ-soft hadron correlation

Connection to physics at EIC

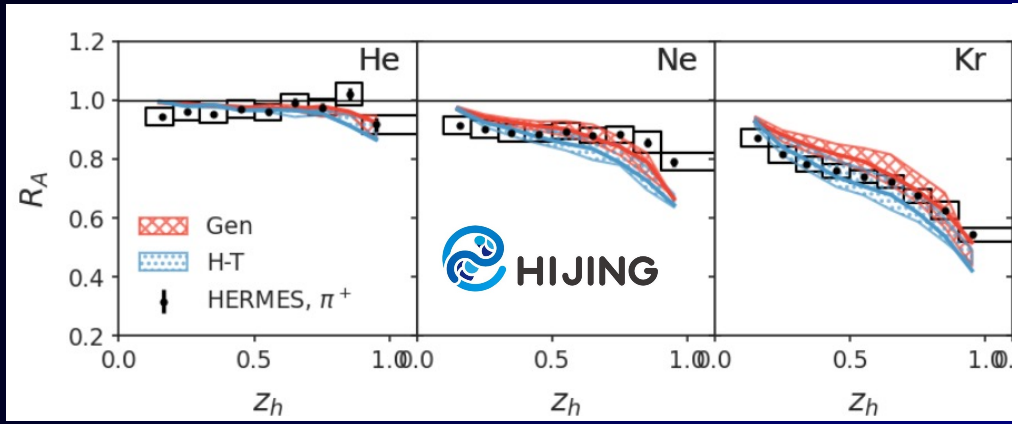


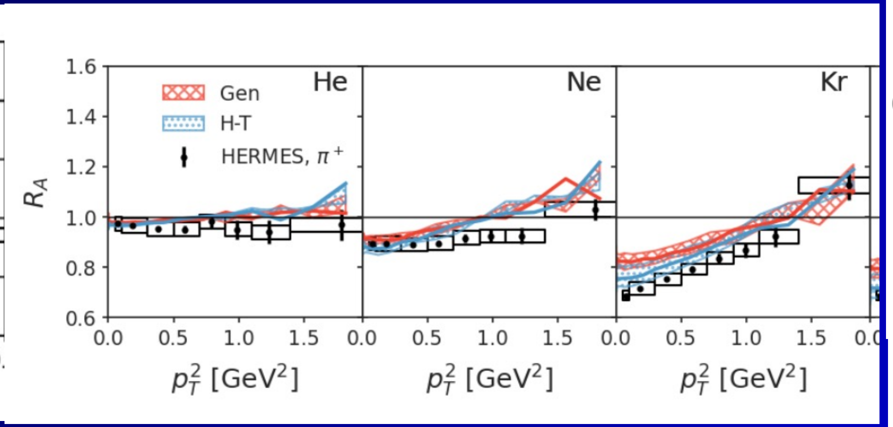
TMD gluon distr.

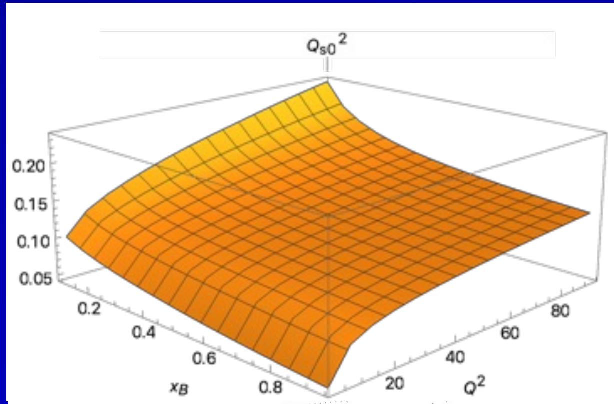
$$\frac{dN_g}{dl_\perp^2\, dz} = \int_{y^-}^{\infty} dy_1^- \left[\rho_A(y_1^-, \vec{y}_\perp)\frac{2\pi\alpha_s}{N_c}\pi \int \frac{dk_\perp^2}{(2\pi)^2}\frac{\phi_N(0,\vec{k}_\perp)}{k_\perp^2}\right]\pi\frac{\alpha_s}{2\pi}P_{qg}(z)\frac{C_A}{l_\perp^2}\mathcal{N}_g(\vec{l}_\perp,\vec{k}_\perp)$$

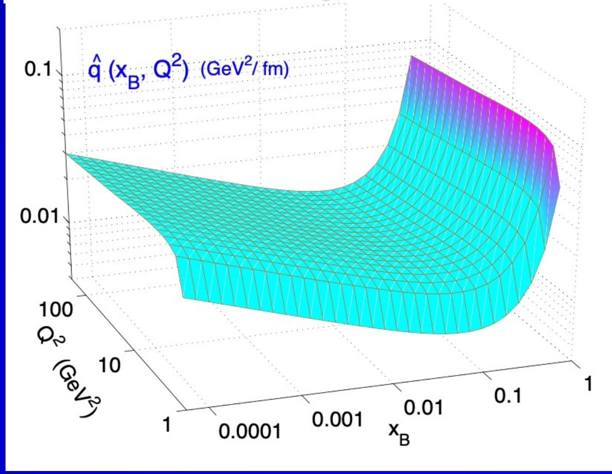
$$\int dy^- \hat{q}_A(y^-) \equiv Q_s^2(x_B, Q^2, b_\perp) = \frac{4\pi^2 C_A}{N_c^2-1}t_A(b_\perp)\int\frac{d^2k_\perp}{(2\pi)^2}\alpha_s(\mu)\phi(x_G, k_\perp, \mu^2) \approx Q_{s0}^2(x_B, Q^2)A^{1/3}\sqrt{1-\frac{b_\perp^2}{R_A^2}}$$

gluon saturation scale









Parton energy loss in cold nuclear medium, saturation scale in jet-nucleon interaction

Hadronization mechanism   Jet modifications   See talk by Vitev

Connection to small systems of strongly interaction matter: initial conditions

Collection phenomena in EIC (flow?)

e-Print: 2104.04520

1907.11808

Summary

- Precision quantification of QGP properties and initial conditions
  - Transport properties, initial conditions (nucleon structure): multi-correlation observbales
  - Jet transport coefficient: precision jet substructure, high precision di(γ/Z^0)-hadron correlation (high Lum LHC, RHIC: sPHENIX, STAR)
  - Jet-induced medium response; improved & refined jet tomography
- Spin dynamics: broaden the study of spin polarization (alignment): a window to emerging properties of QGP
- Theoretical advancement: precision calculations (NLO, resummation, gradient corrections etc), initial thermalization
- AI/ML tools essential for precision quantification of QGP properties: demand for computing resources; implementations in data analyeses

Theory support

Theory alliances, topical collaborations
& base program (especially universities & labs without a major facility)

Theoretical nuclear physics is essential for establishing new scientific directions, and meeting the challenges and realizing the full scientific potential of current and future experiments. We recommend increased investment in the base program and expansion of topical programs in nuclear theory.

Jet structure and Medium response