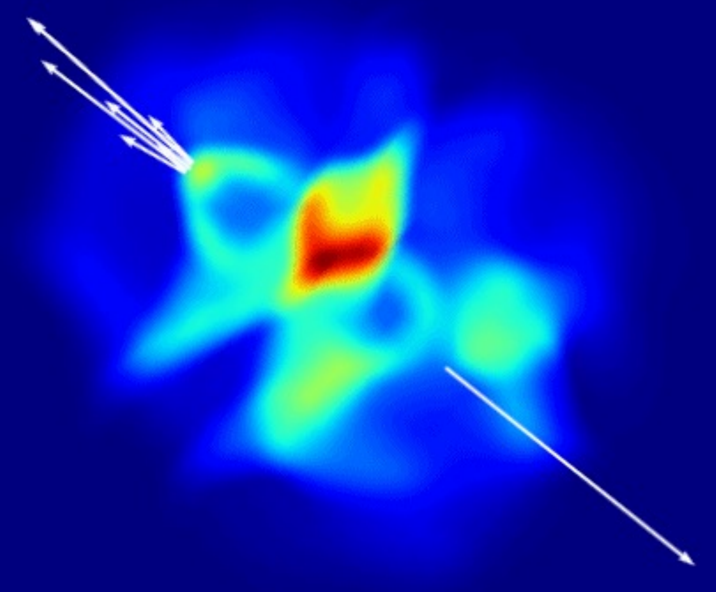


Heavy-ion Physics 1

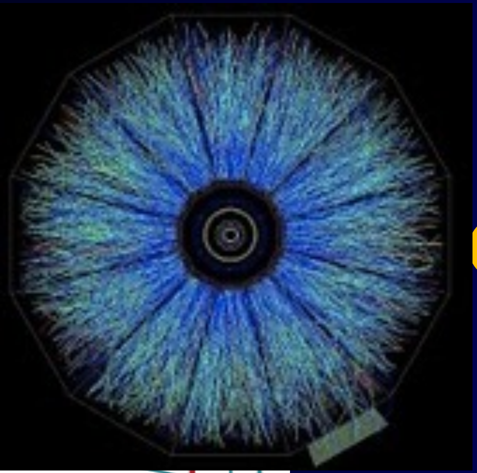
Xin-Nian Wang
Lawrence Berkeley National Laboratory

Forms of matter

火 水 土

(gas) (liquid) (solid)

Bose-Einstein condensate, fermionic condensate, superfluids, supersolids, paramagnetic, ferromagnetic, liquid crystals, …



Quantum Chromodynamics & Quark-Gluon Plasma

QCD QGP

Pre-QCD era: quark model, parton model and “jet”

Gell-Mann

- Discovery of a zoo of hadrons: mesons, baryons and excited states:
  Leading to quark model (1968) by Gell-Mann and Zweig

Feynman

- Observation of Bjorken scaling of cross sections of deeply inelastic scattering:
  Leading to the parton model (1969) of hadrons by Feynman
- Production of energetic hadrons in high-energy collisions:
  Uncorrelated jet model for hadron production: De Groot and Ruijgrok (1971)

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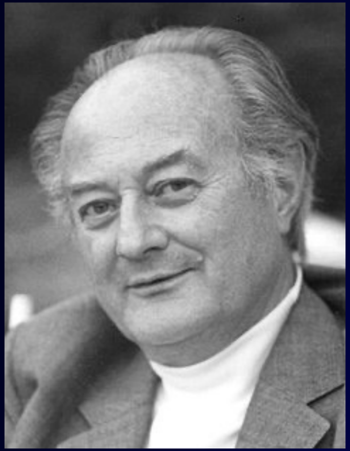
Hagedorn limiting temperature

Increasing number of hadron production (and decays) in high-energy collisions



Hagedorn statistic boost trap model (1968):

$$\rho(m,V_0)=\delta(m-m_0)+\sum_N \frac{1}{N!}\left[\frac{V_0}{(2\pi)^3}\right]^N \int \prod_{i=1}^{N}\left[dm_i\rho(m_i)d^3p_i\right]\delta^4(\sum_i p_i - p)$$

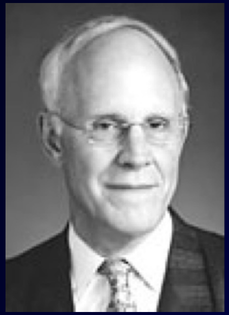
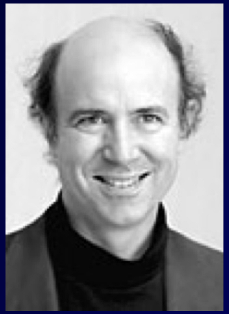
With the solution: $\rho(m,V_0)=\mathrm{const.}m^{-3}e^{m/T_H}$

Partition function of the Hagedorn (hadron) resonance gas (HRG) model:

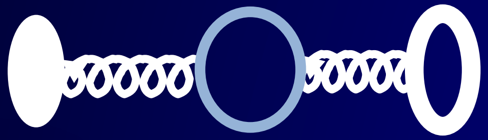
$$\ln \mathcal{Z}(T,V)=\frac{VT}{2\pi^2}\int dm m^2\rho(m)K_2(m/T)\approx V\left[\frac{T}{2\pi}\right]^{3/2}\int dm m^{-3/2}e^{-m\left[\frac{1}{T}-\frac{1}{T_H}\right]}\to\infty \quad \text{when} \quad T>T_H$$

Asymptotic freedom & confinement in QCD

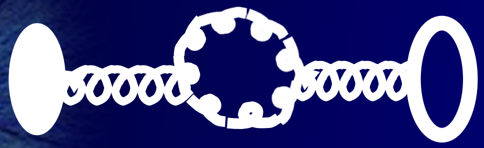
Gross & Wilczek; Politzer (1973)


$$\alpha_s(Q^2) = \frac{4\pi/(11 - 2n_f/3)}{\ln(Q^2/\Lambda^2_{\mathrm{QCD}})}$$

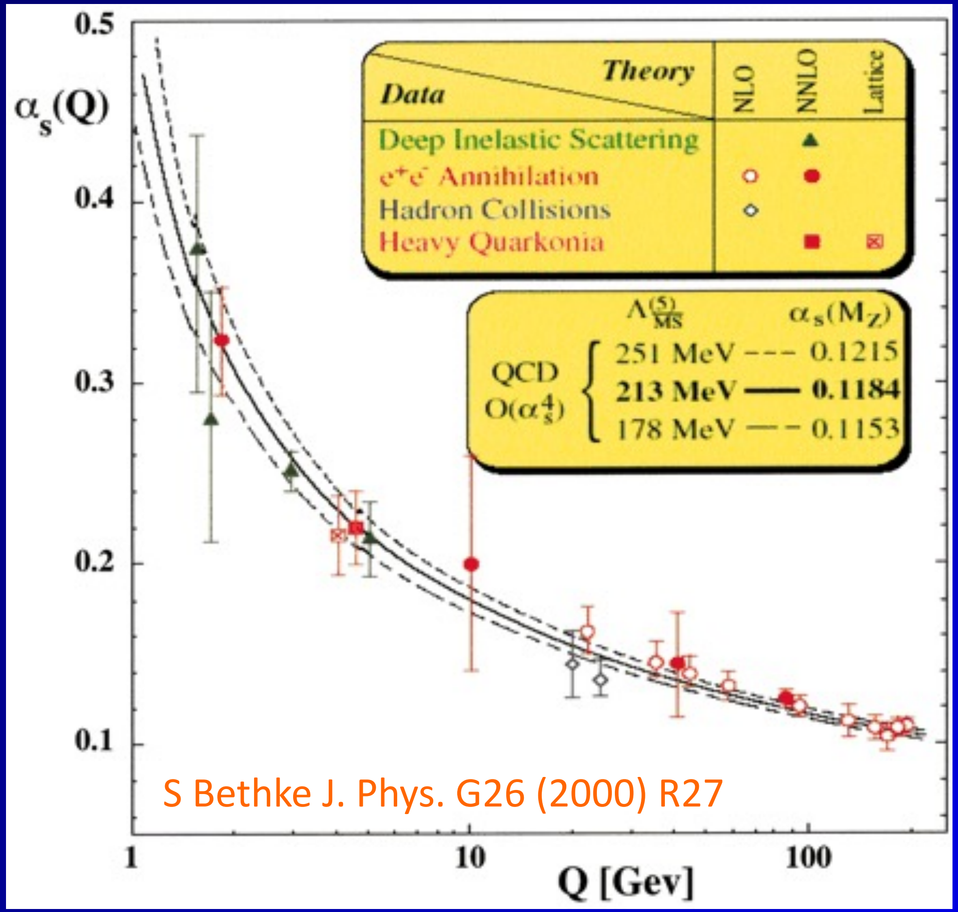


screening



anti-screening

← Confinement



S Bethke J. Phys. G26 (2000) R27

Asymptotically free →

QCD: Theory for strong interaction

$$L_{QCD} = \sum_{f=1}^{n_f} \bar{\psi}\gamma_\mu (i\partial^\mu - g A_a^\mu \frac{\lambda_a}{2} - m)\psi - \frac{1}{4}\sum_a F_a^{\mu\nu} F_{a,\mu\nu}$$

- SU(3) gauge symmetry (non-Abelian)
  - Asymptotic freedom at short distance
  - Confinement at long distance

$$\alpha_s(Q^2) = \frac{4\pi/(11 - 2n_f/3)}{\ln(Q^2/\Lambda^2_{\rm QCD})}$$

- Chiral symmetry and its spontaneous breaking
  - Goldstone boson and chiral condensate

$$\langle \bar{\psi}\psi \rangle \neq 0$$

- Scale and $U_A(1)$ anomaly

$$\langle F^{\mu\nu} F_{\mu\nu} \rangle \neq 0$$

- ….

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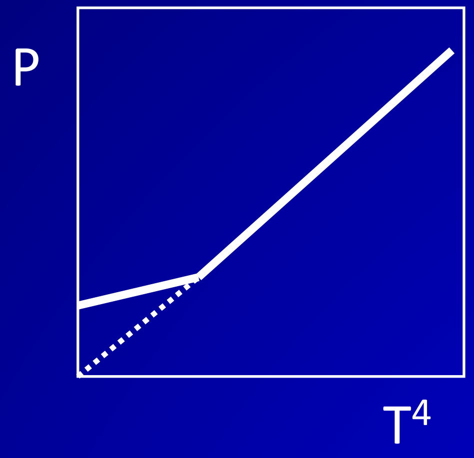
Quark-gluon plasma in a MIT bag model

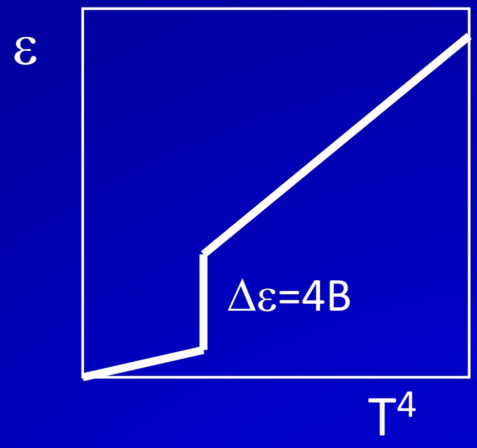
J Collins and M. Perry (1975) G. Baym and S Chin (1976), E. Shuryak (1978)

Ideal QGP: $\epsilon_{q,g} = 6n_f \frac{7\pi^2}{120} T^4 + 16 \frac{\pi^2}{30} T^4$

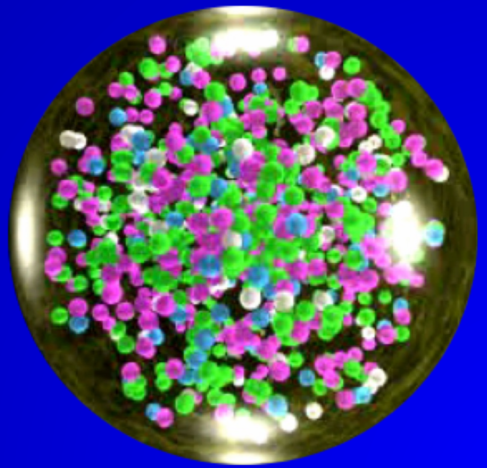
$$\epsilon = \epsilon_{q,g} + B \qquad P = \frac{1}{3}\epsilon_{q,g} - B$$

Massless π gas: $\epsilon_\pi = 3\frac{\pi^2}{30}T^4 \qquad P_\pi = \frac{1}{3}\epsilon_\pi$



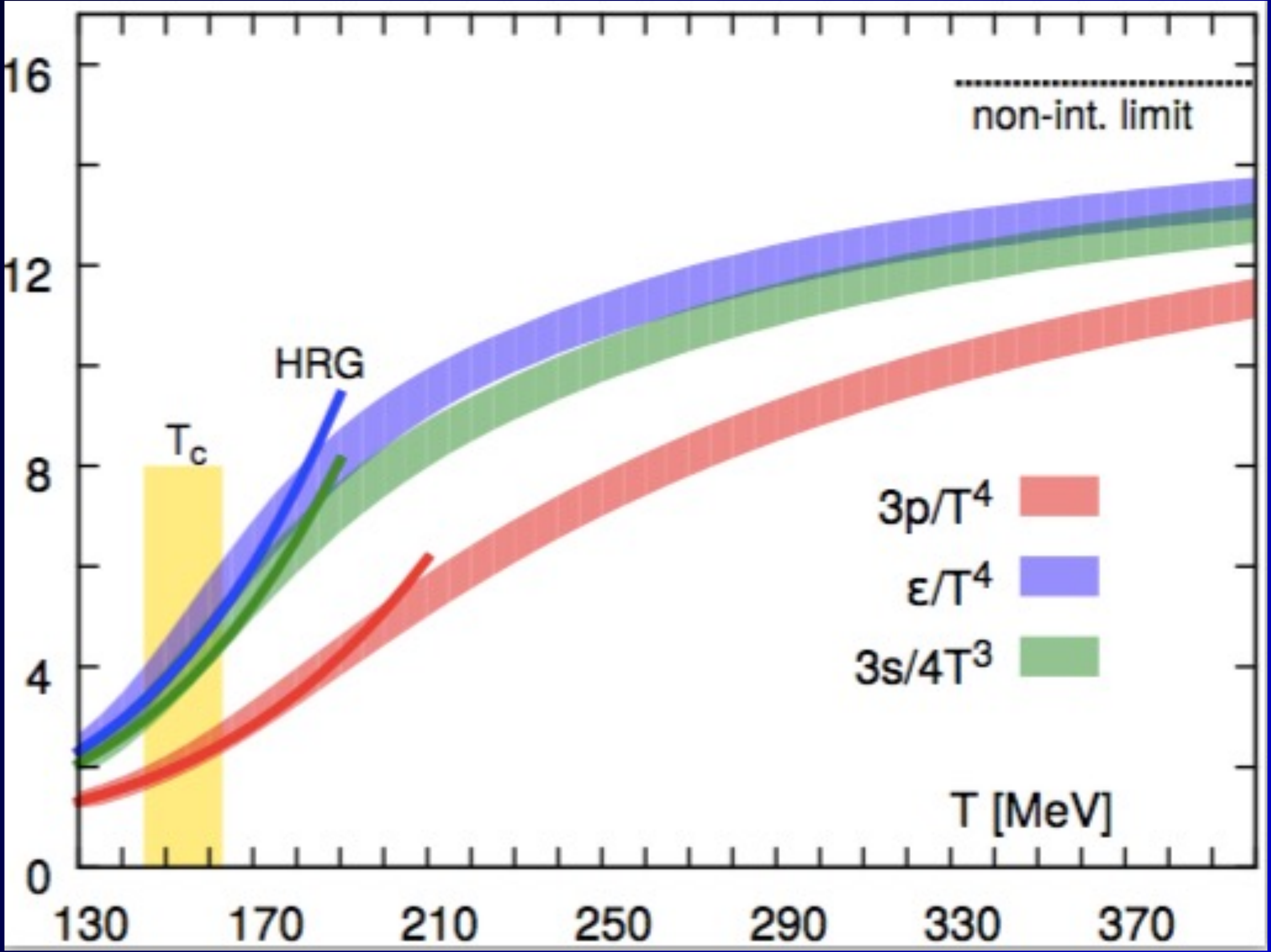


$$P_\pi(T_c) = P_{q+g}(T_c) \quad \Rightarrow \quad T_c \approx 0.72 B^{1/4}$$



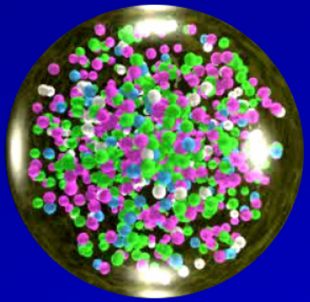
First-order phase transition

Phase transition in QCD



F. Karch et al., 2014

$$\epsilon_{SB} = \left[6 n_f \frac{7\pi^2}{120} + 16 \frac{\pi^2}{30}\right] T^4$$

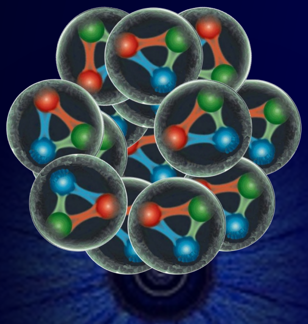


Quark gluon plasma

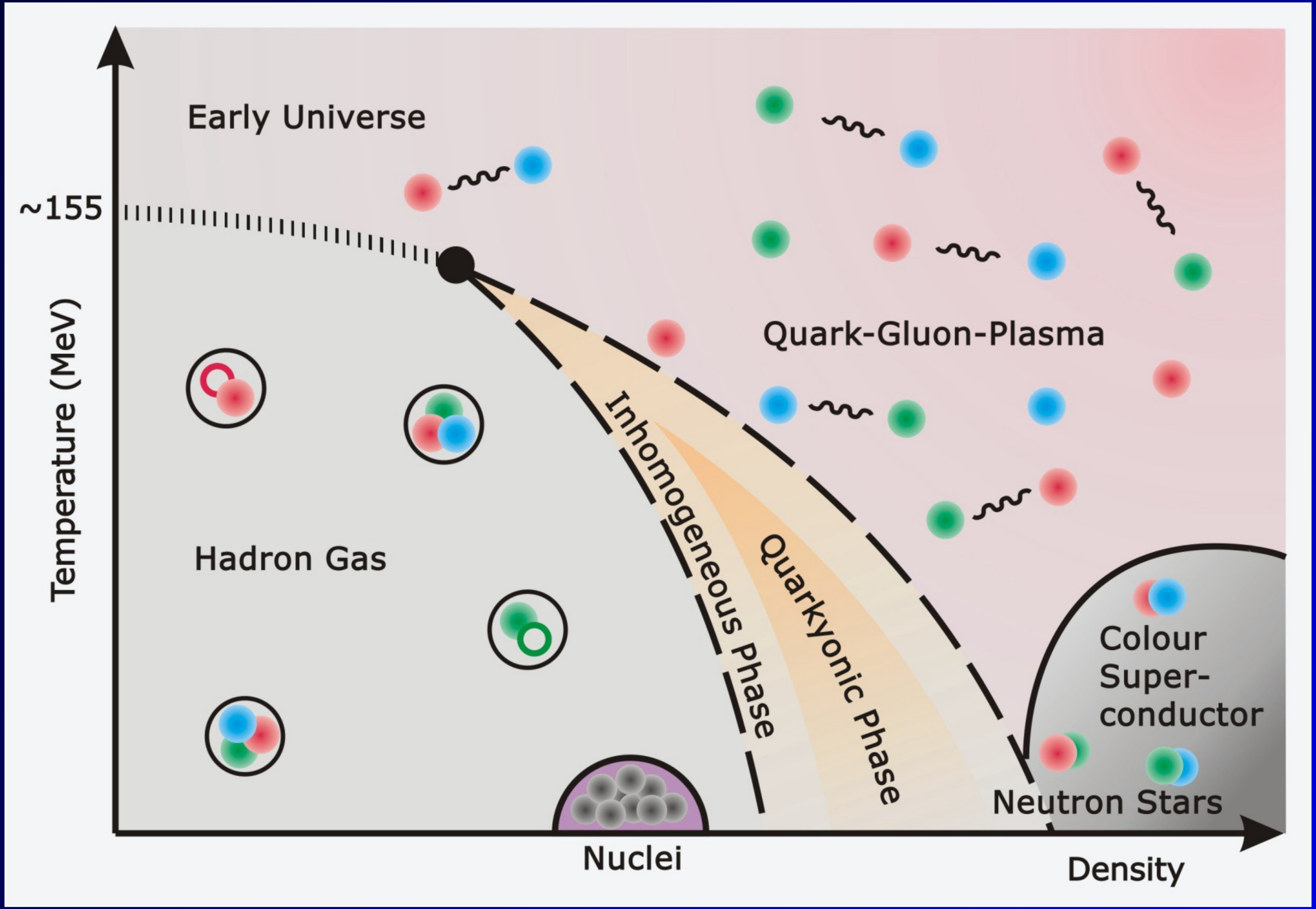
$$\langle \bar{\psi}\psi \rangle \to 0$$

$$\langle \alpha_s F^2 \rangle \to 0$$

Normal nuclear matter

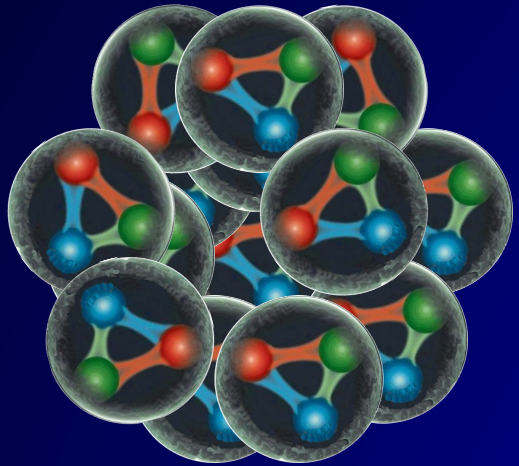


Phase structure of QCD Matter

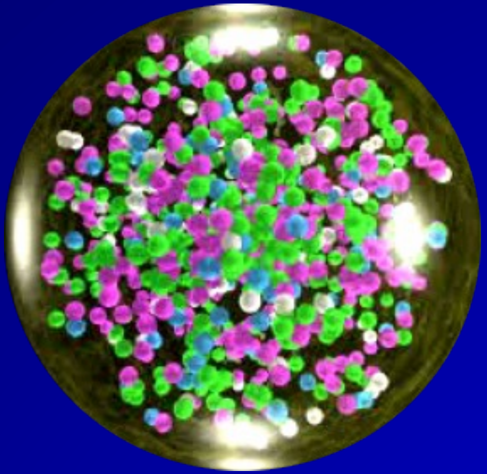


QGP in heavy-ion collisions

confinement



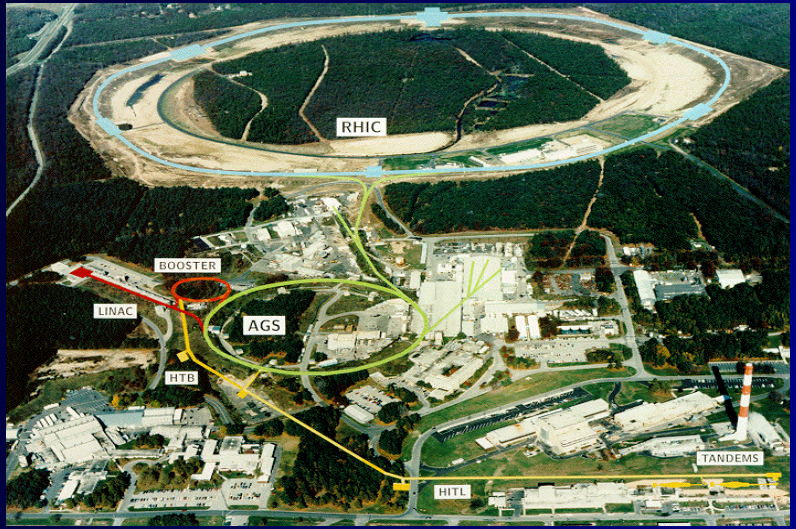
High T, μ



De-confinement

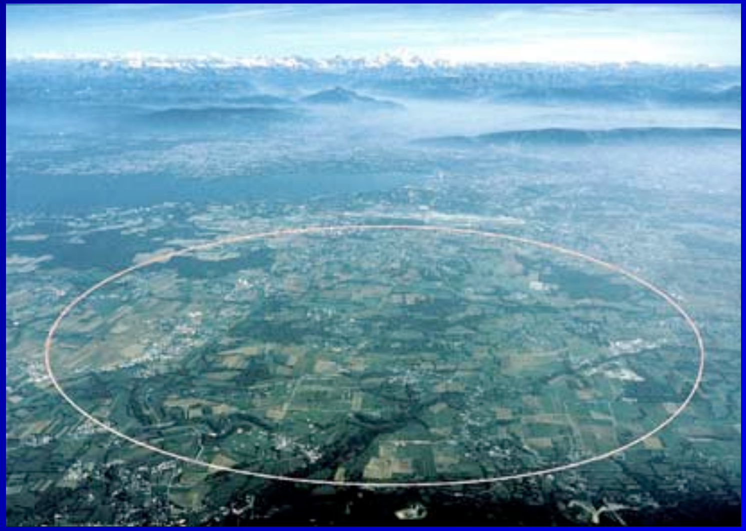
nucleus

quark-gluon plasma (QGP)



RHIC

LHC



10

Properties of QGP in A+A Collisions

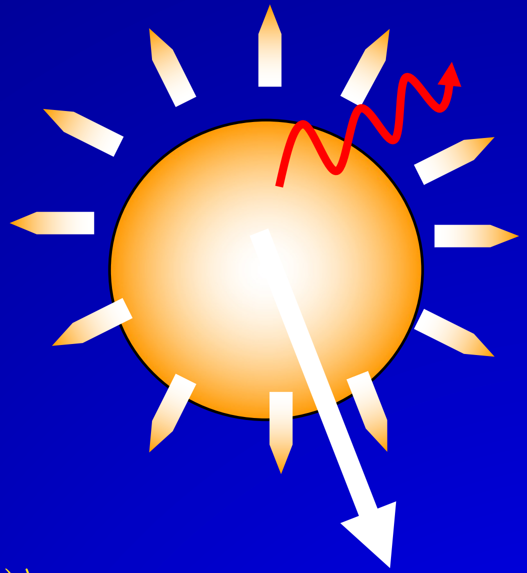
Multi-messenger study of dynamics and properties of QGP

- 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

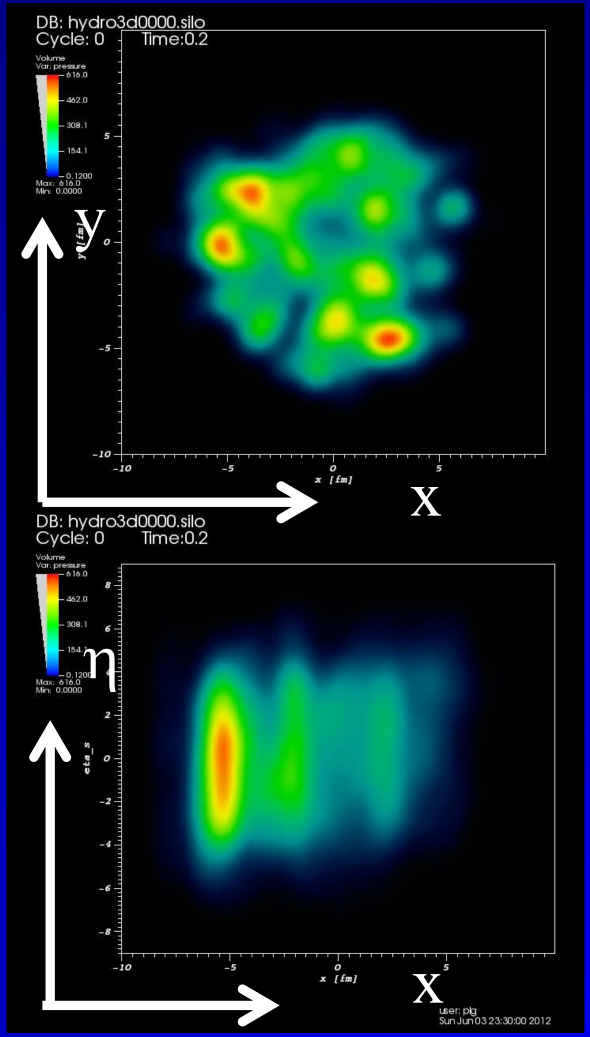
- Hydrodynamics: $$\partial_\mu T^{\mu\nu} = 0$$

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

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

  – a low-momentum effective theory
  – Inputs from first principle QCD (lattice QCD) EoS $p(\varepsilon)$, transport coefficients $\xi(T)$, $\zeta(T)$ (??)
  – Initial condition: parton prod. & thermalization

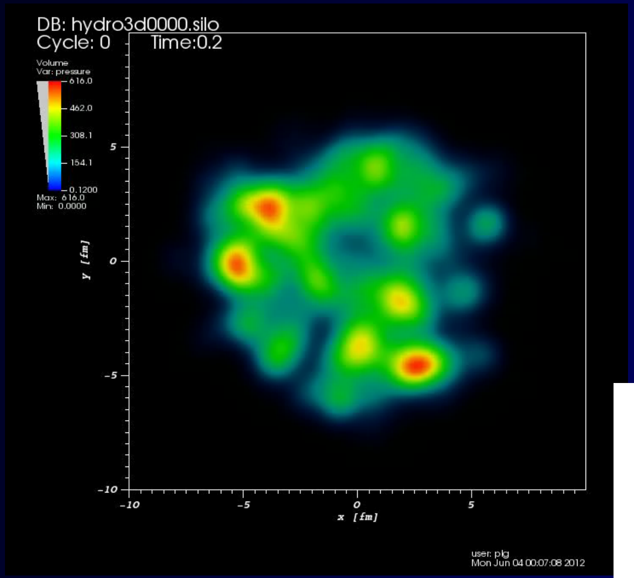
Initial thermalization: hydrodynamic attractors, hydrodynamization, anisotropic hydrodynamics, kinetic theory, etc



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

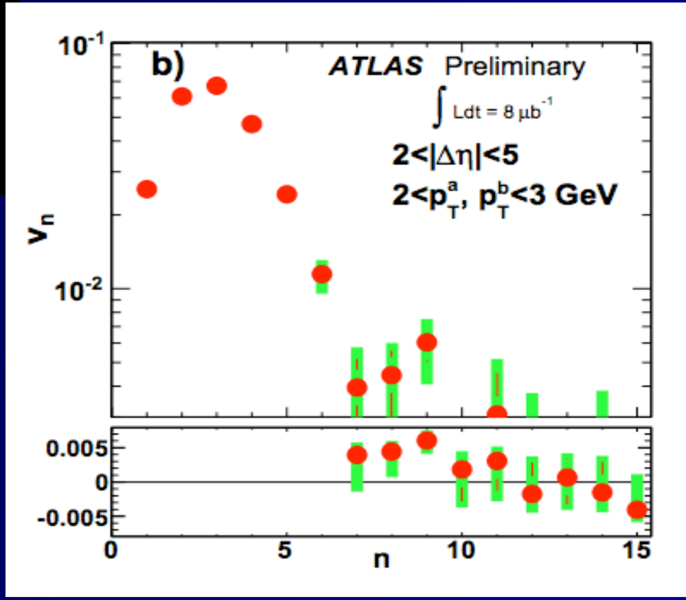
"CMB" of the little bang: Anisotropic flow of QGP

Little Bang



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

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

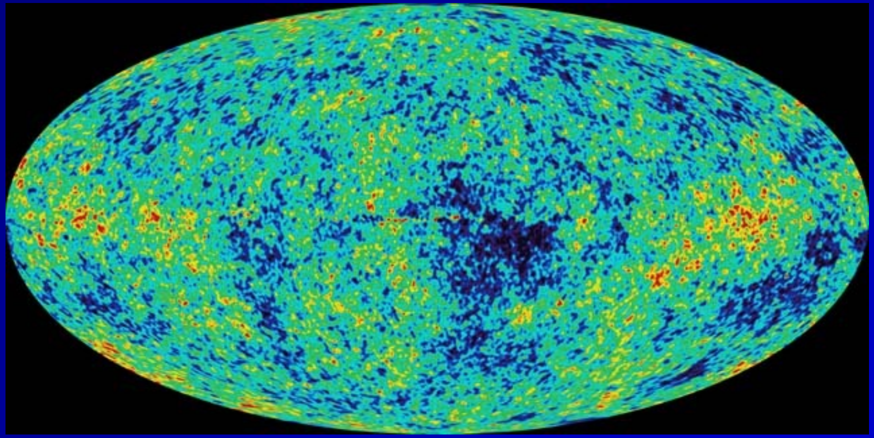


$v_n \sim \kappa\, \varepsilon_n$

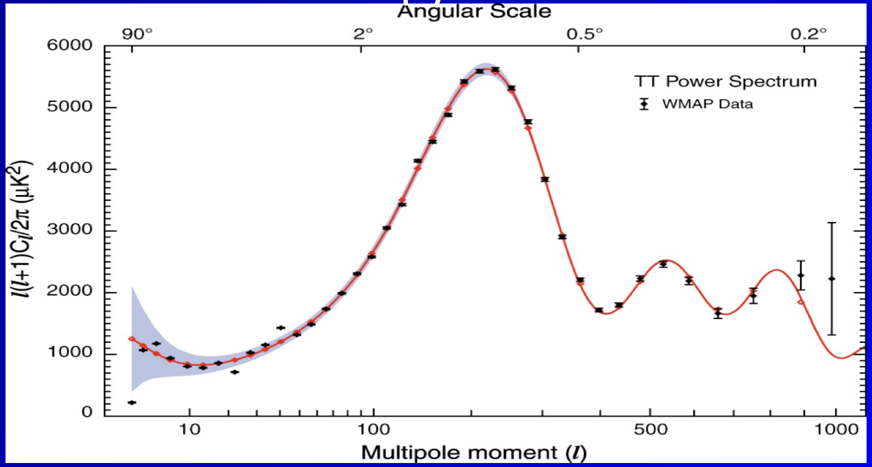
ε_n: Initial geometrical anisotropy

κ: Encodes transport coefficients

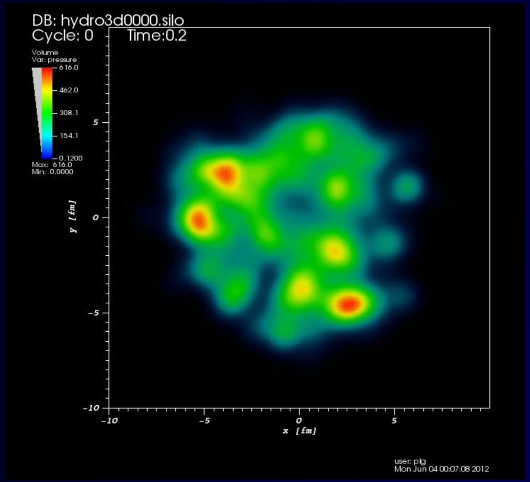
Big Bang



Anisotropy in CMB



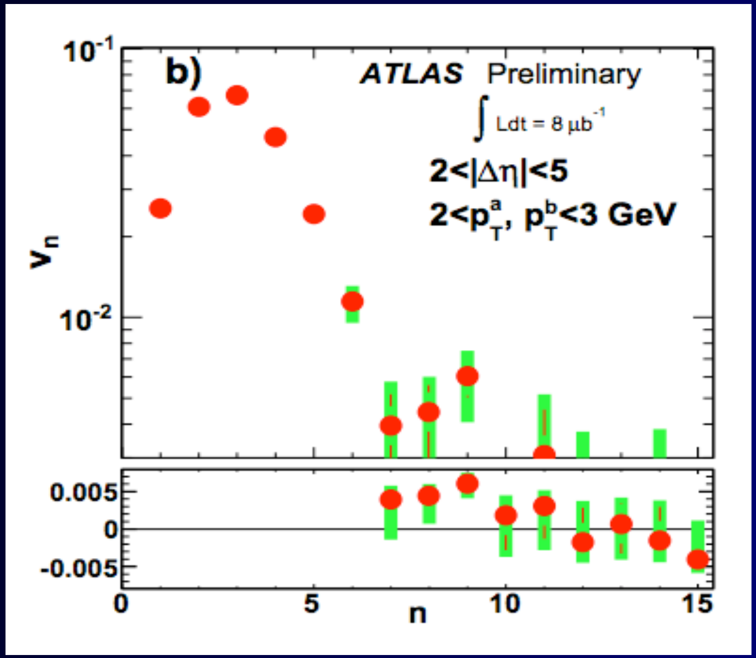
“CMB” of the little bang: Anisotropic flow of QGP

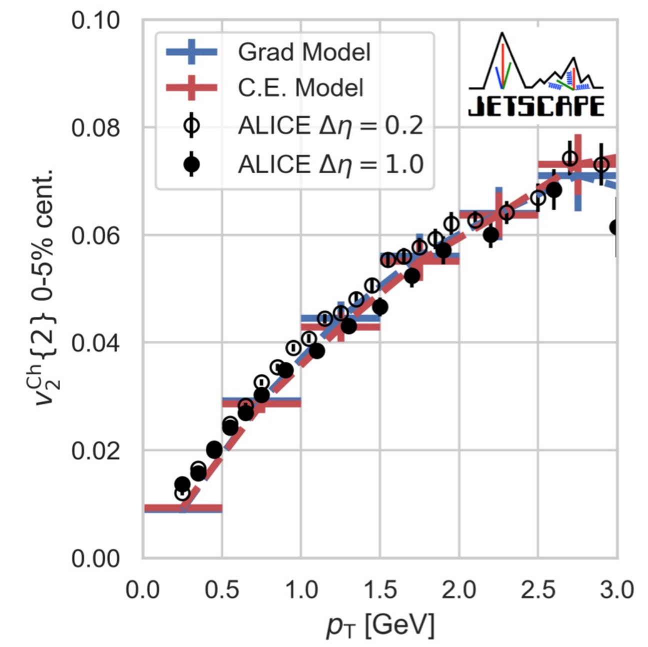


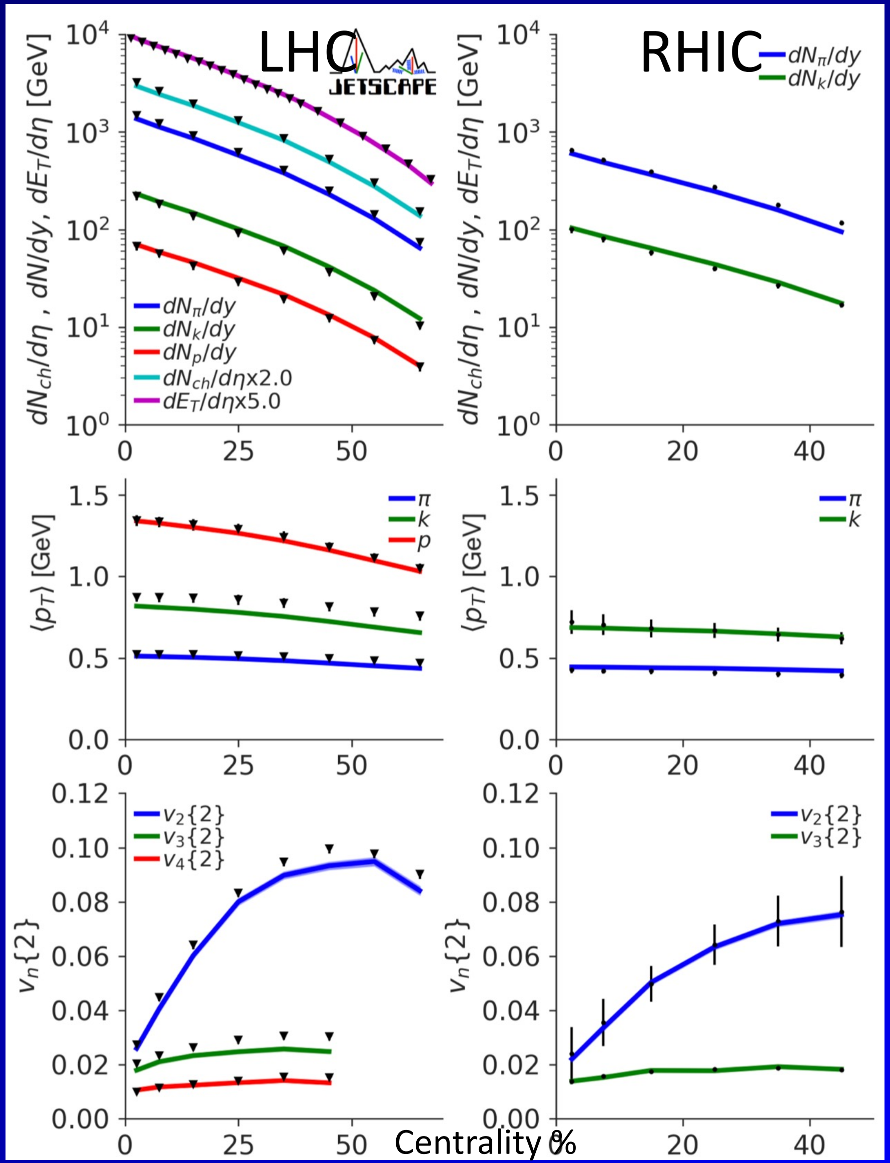
$$f(\phi) = f_0\left[1 + 2\sum_{n=1} v_n \cos n(\phi - \Psi_n)\right]$$

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

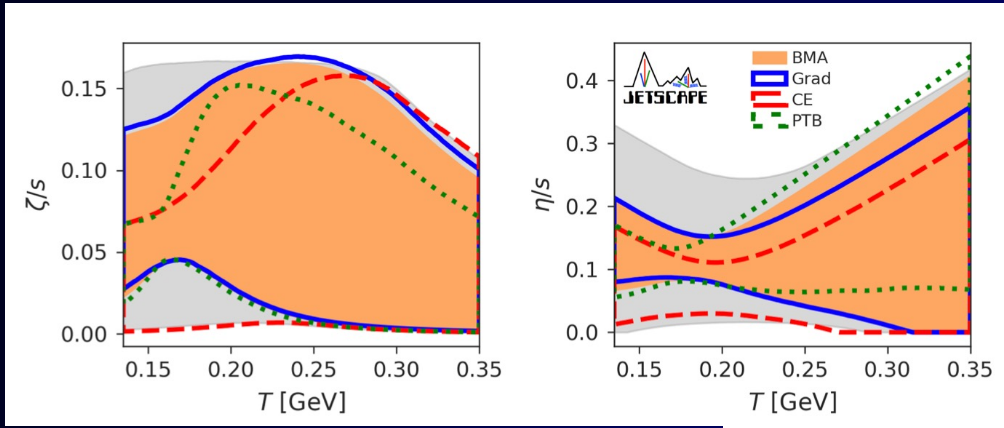
arXiv: 2010.03928



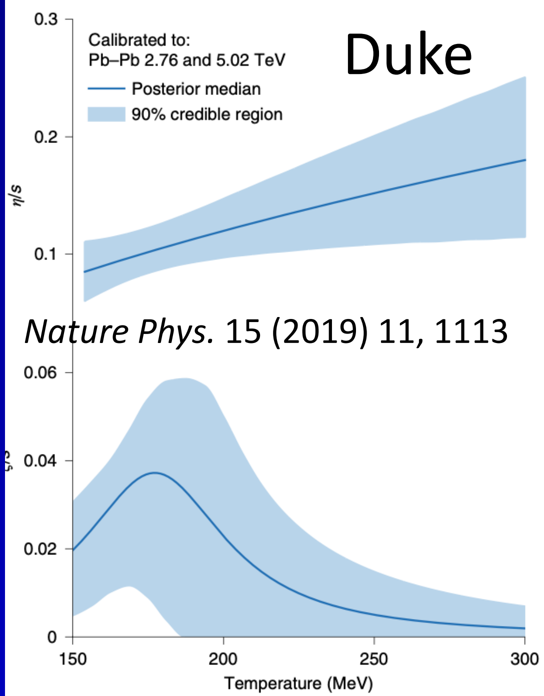




Bayesian inference of transport coefficients

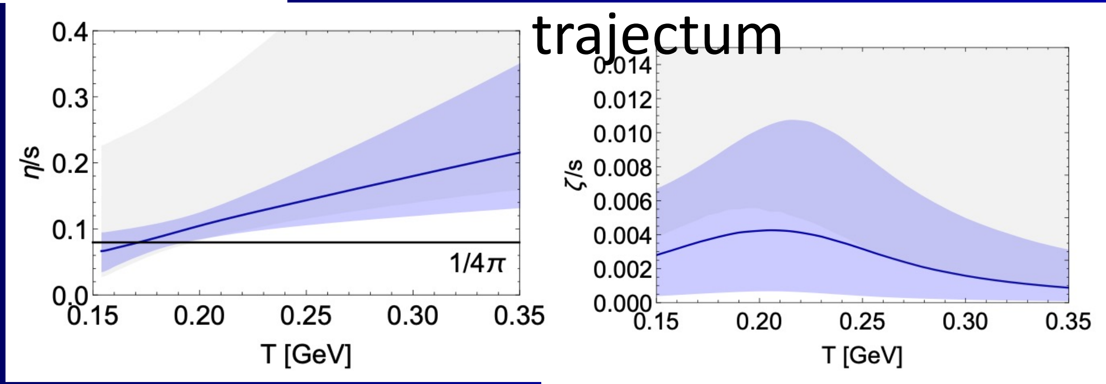


$$\mathcal{P}^{(i)}(\boldsymbol{x}|\mathbf{y}_{\exp}) = \frac{\mathcal{P}^{(i)}(\mathbf{y}_{\exp}|\boldsymbol{x})\mathcal{P}(\boldsymbol{x})}{\mathcal{P}^{(i)}(\mathbf{y}_{\exp})}$$



Nature Phys. 15 (2019) 11, 1113

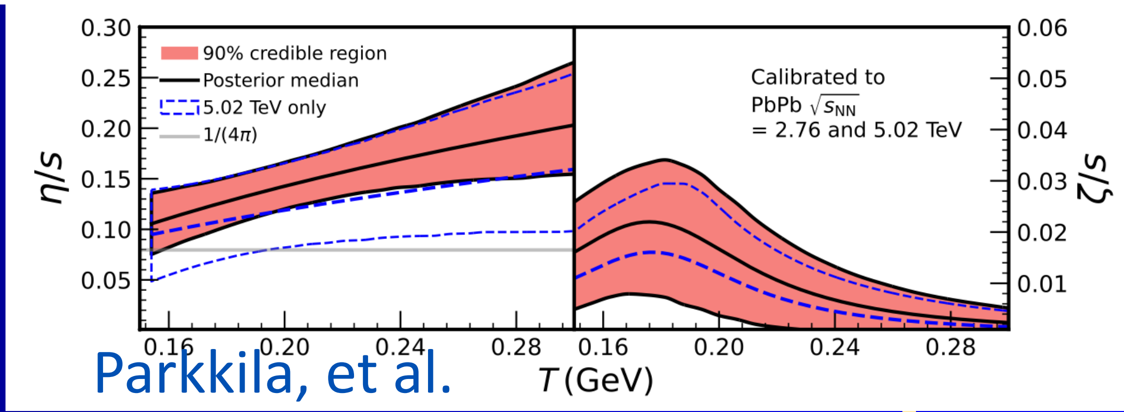
e-Print: 2010.03928
2011.01430



e-Print: 2111.08145

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

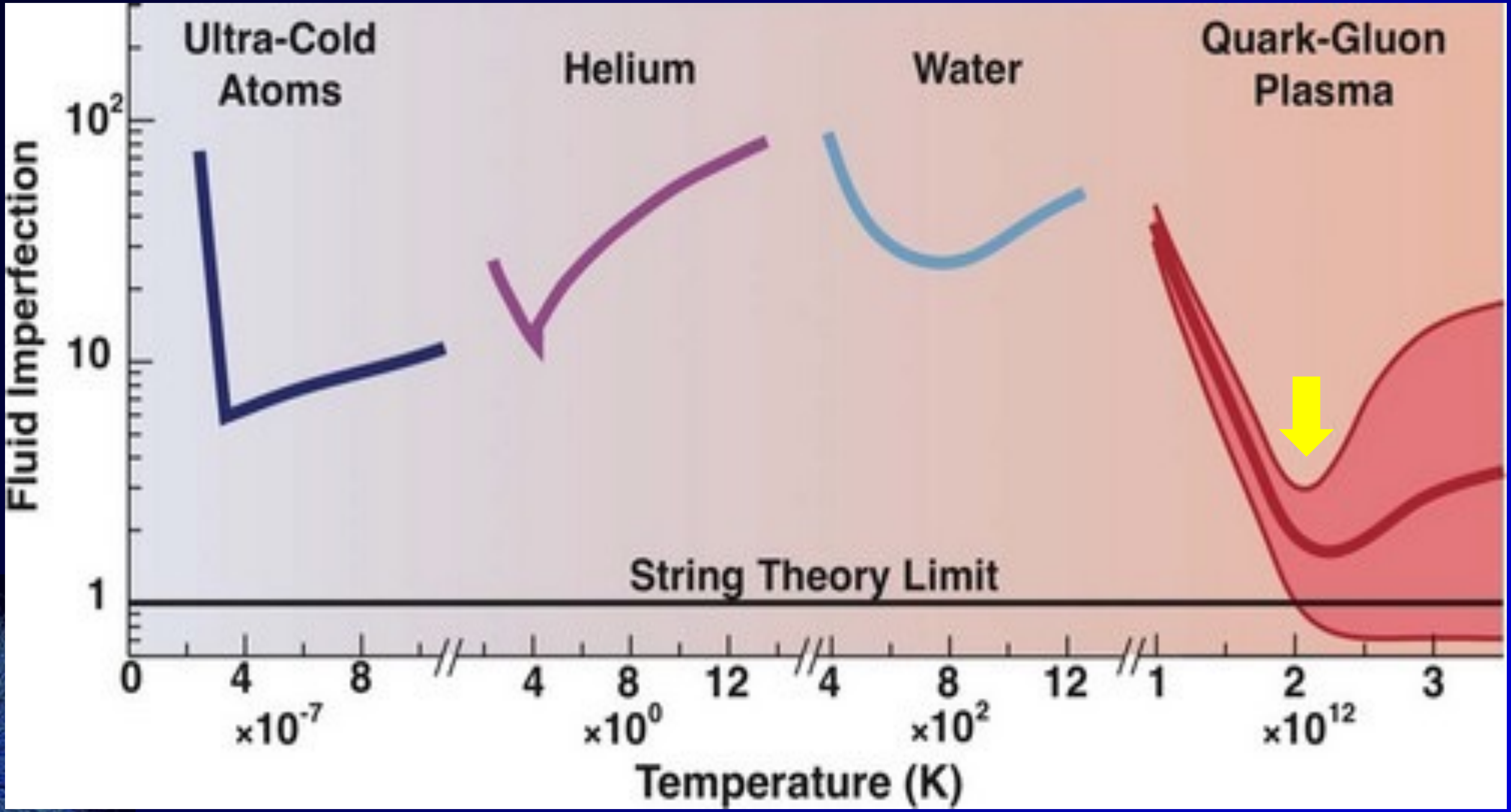
e-Print: 2010.15130; 2010.15134

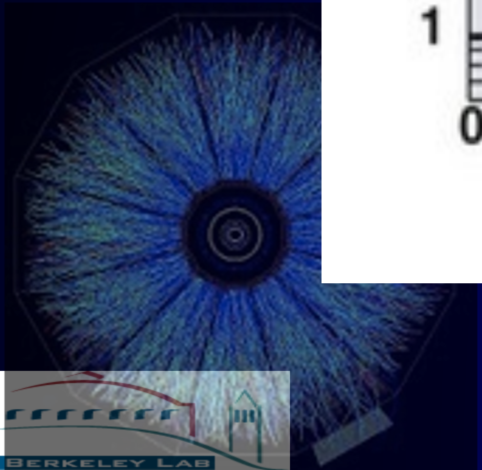


Parkkila, et al.

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

QGP: the most perfect fluid in nature





Separating initial conditions and dynamics

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

Nuclear structure & initial conditions

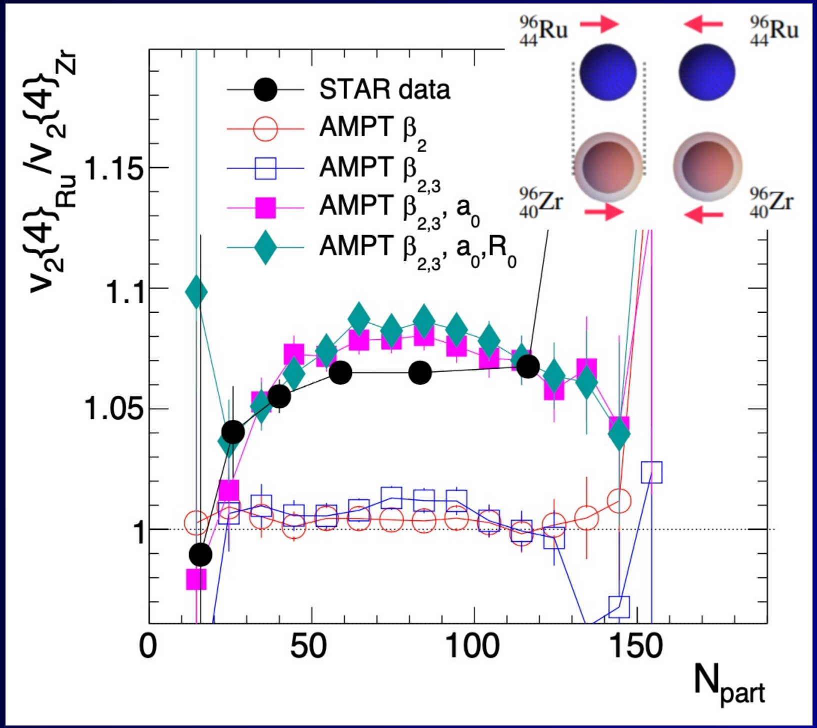
$$\rho(v_n^2, [p_t]) = \frac{\langle \delta v_n^2 \delta[p_t] \rangle}{\sqrt{\langle (\delta v_n^2)^2 \rangle \langle (\delta[p_t])^2 \rangle}}$$

Nuclear deformation

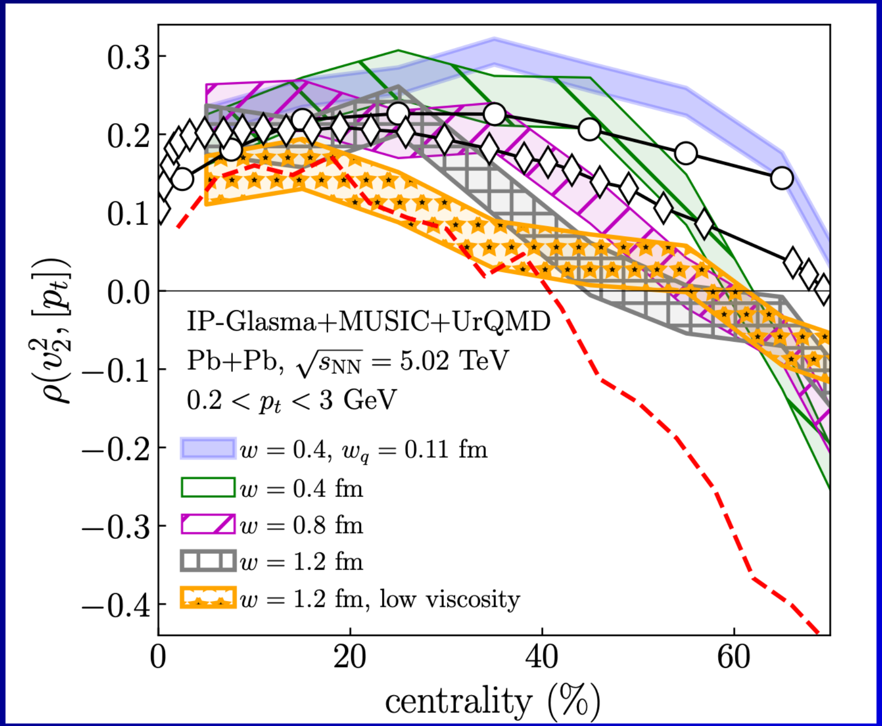
Neutron skin

Triaxility

…



e-Print: 2206.10449



e-Print: 2111.02908

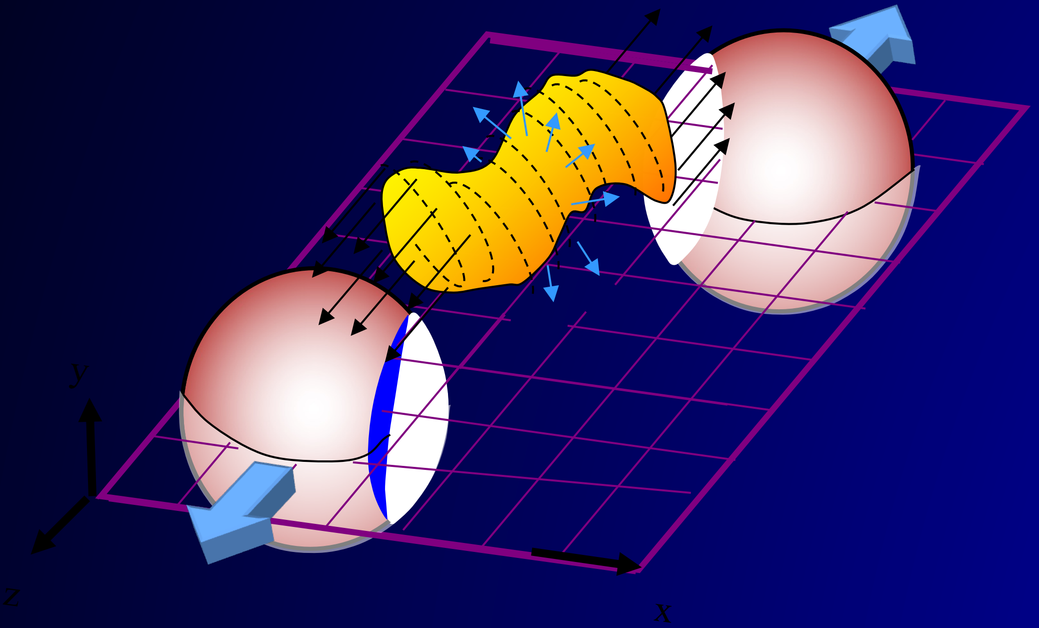
Nucleon size,

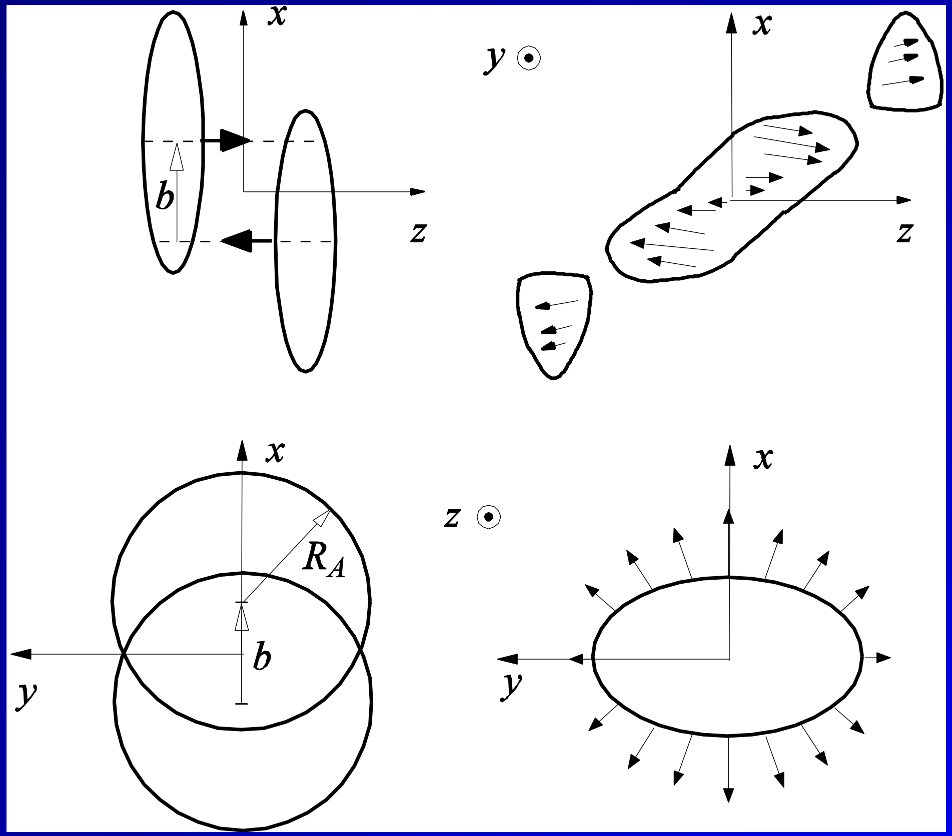
nucleon sub-structure

….

Global Orbital Angular Momentum

High-energy heavy-ion collisions (twisted initial configuration)

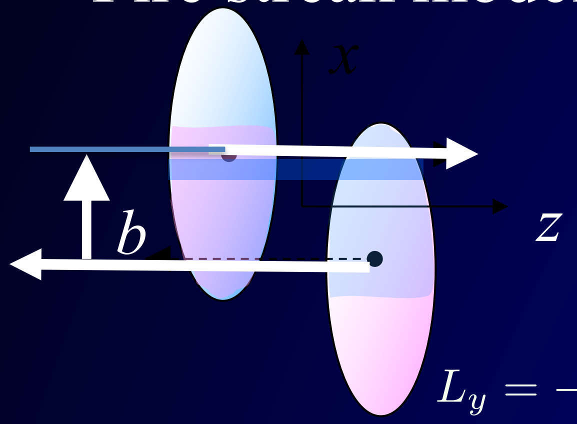




Transverse gradient of fluid velocity & vorticity

Fire streak model

Liang & XNW, PRL 94 (2005) 102301

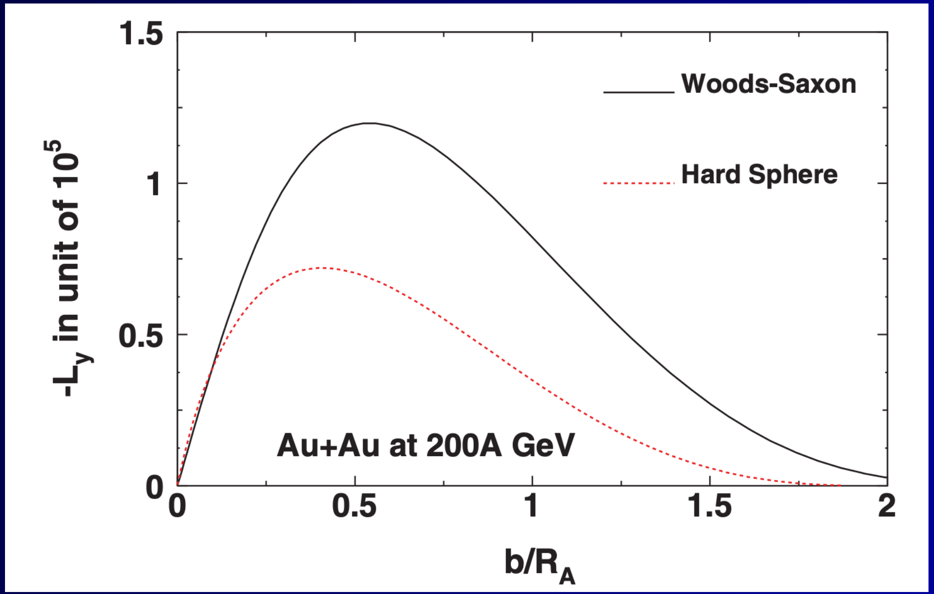


Collective longitudinal momentum per produced parton →

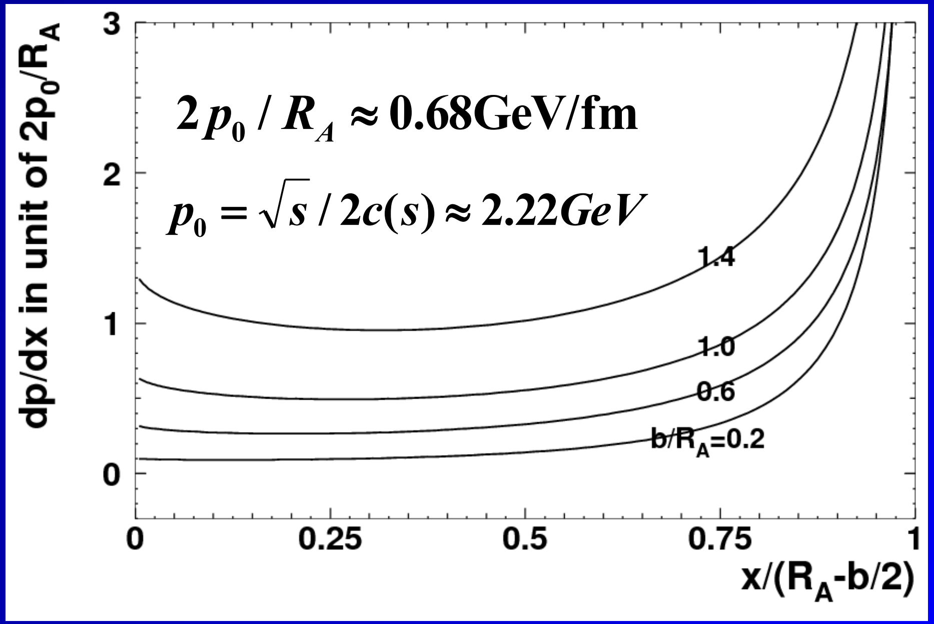
$$p_z(x,b) = \frac{\sqrt{s}}{2} \frac{\frac{dN^P_{part}}{dx} - \frac{dN^T_{part}}{dx}}{c(s)\left(\frac{dN^P_{part}}{dx} + \frac{dN^T_{part}}{dx}\right)}$$

$$L_y = -p_{in} \int x dx \left[\frac{dN^P_{\rm part}}{dx} - \frac{dN^T_{\rm part}}{dx}\right]$$

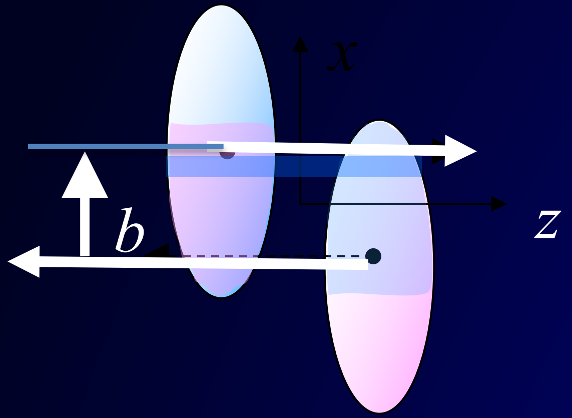
$$\vec{\omega} = \vec{\nabla} \times \vec{v} \sim -\hat{y}\langle \frac{1}{E}\frac{dp_z}{dx}\rangle$$



Total angular momentum carried by QGP



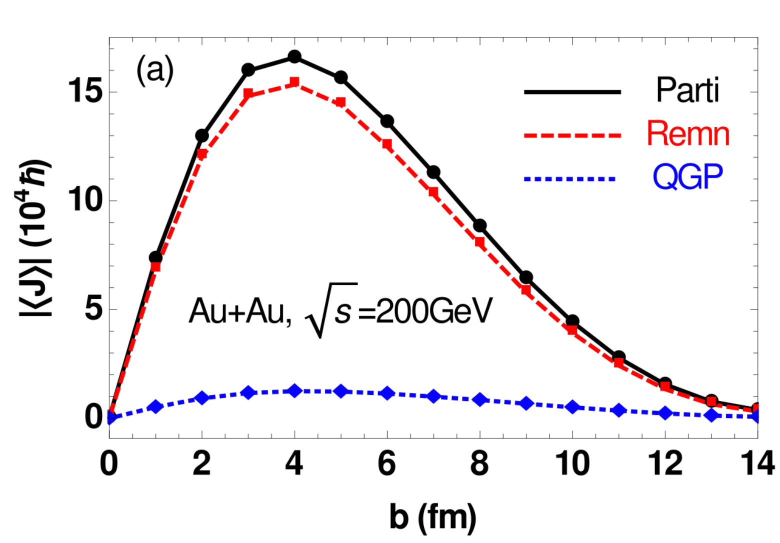
Fluid velocity & vorticity in HIJING

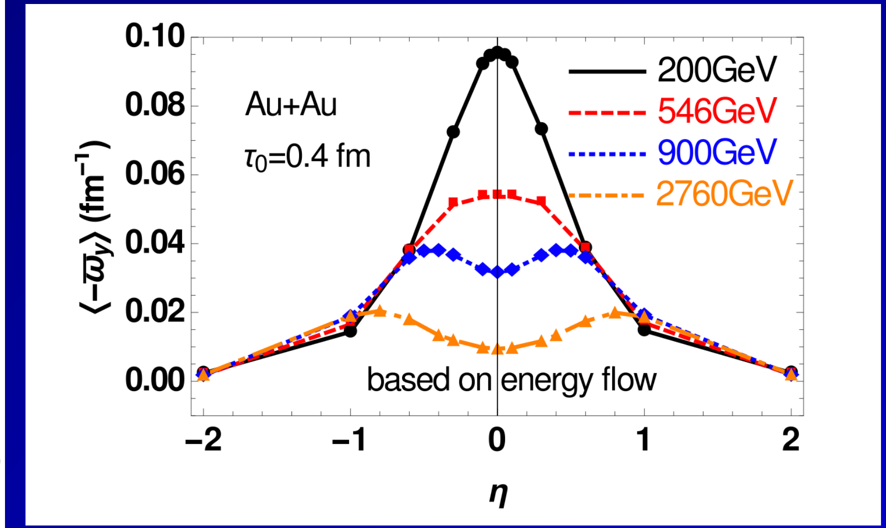


No complete stopping but approximate Bjorken scaling.

Small violation of BJ scaling at → local angular momentum or vorticity

BJ scaling violation and vorticity increase at lower colliding energies

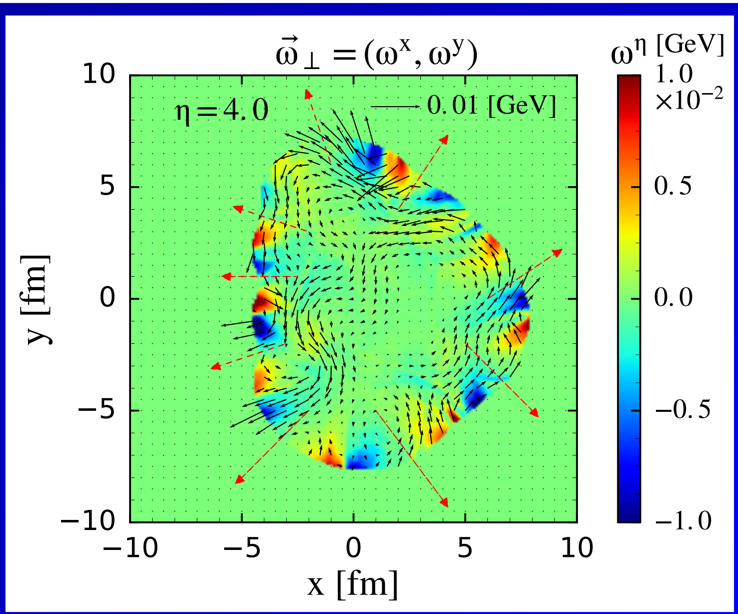




Gao, Chen, Deng, Liang, Q. Wang, XNW, PRC 77 (2008)044902

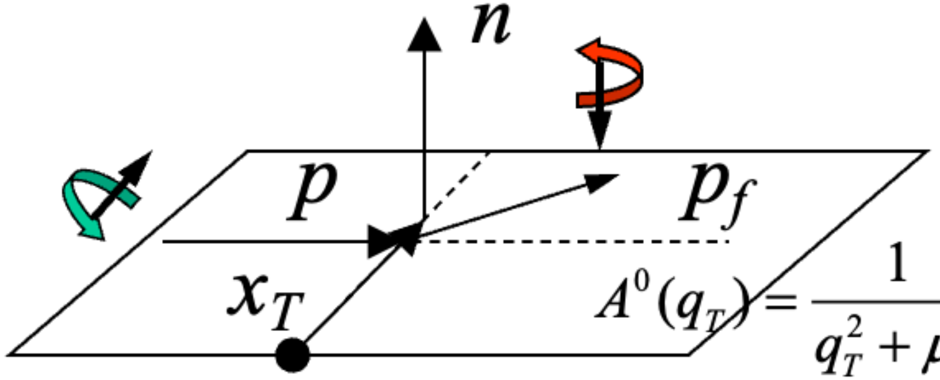
Deng, Huang, *PRC* 93 (2016) 6, 064907

Pang, Petersen, Q. Wang and XNW, *PRL 117* (2016) 19, 192301



Global spin polarization in A+A

Liang & XNW, PRL 94 (2005) 102301



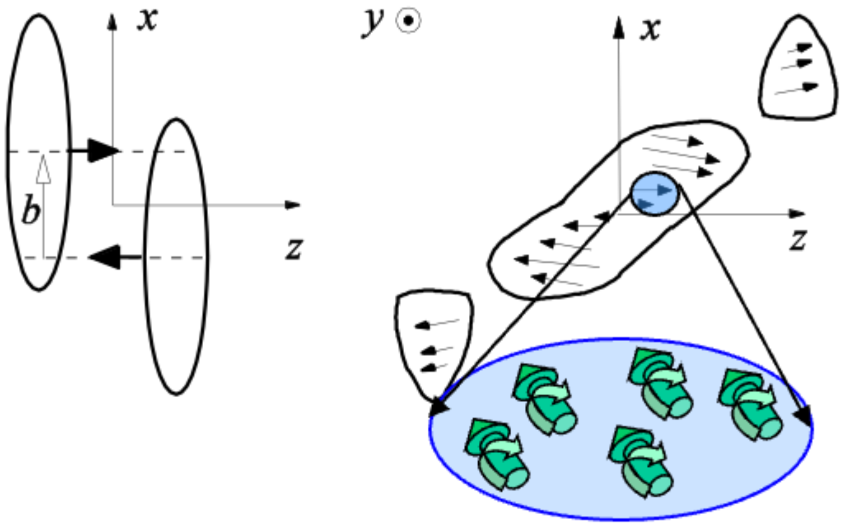
$$A^0(q_T) = \frac{1}{q_T^2 + \mu^2}$$

Static potential model

$$P_q \equiv \frac{\Delta\sigma}{\sigma} = -\pi \frac{\mu p}{4E(E+m_q)}$$

spin-vorticity (orbital) coupling

p: relative momentum of parton scattering with impact parameter b ~ $1/\mu$



nonrelativistic limit: $(m_q \gg p, \mu)$

$$P_q \approx -\pi \frac{\mu p}{4m_q^2} \sim -\omega/m \quad \text{or} -\omega/T$$

Polarization rate: $\Gamma_q = \langle P_q \sigma \rho \rangle \quad \sim \omega \frac{4}{9} \frac{\rho}{\eta}$

Huang, Huovinen & XNW, PRC84 (2011) 054910

Spin polarization in equilibrium

Dirac Eq. $$[\gamma^\mu(i\partial_\mu + e_q A_\mu) - m]\,\psi(x) = 0$$

Pu, Gao, Liang, Wang & XNW, PRL 109 (2012) 232301

Spin: vorticity coupling   Magnetic coupling

$$\delta E_s = \frac{\hbar}{2}\mathbf{n}\cdot\omega + e_q\hbar\frac{\mathbf{n}\cdot\mathbf{B}}{E_p}$$

$$\Pi = \frac{1}{2}\int\frac{d^3p}{(2\pi)^3}\left[f(E_p - \delta E_s) - f(E_p + \delta E_s)\right] \approx \int\frac{d^3p}{(2\pi)^3}\delta E_s\frac{\partial f(E_p)}{\partial E_p}$$

Polarization on the freeze-out surface:

$$\frac{d\Pi^\alpha(p)/d^3p}{d\rho(p)/d^3p} = \frac{\hbar}{4m}\frac{\int d\Sigma_\lambda p^\lambda \tilde{\Omega}^{\alpha\sigma} p_\sigma f_{\rm FD}(x,p)[1 - f_{\rm FD}(x,p)]}{\int d\Sigma_\lambda p^\lambda f_{\rm FD}(x,p)}.$$

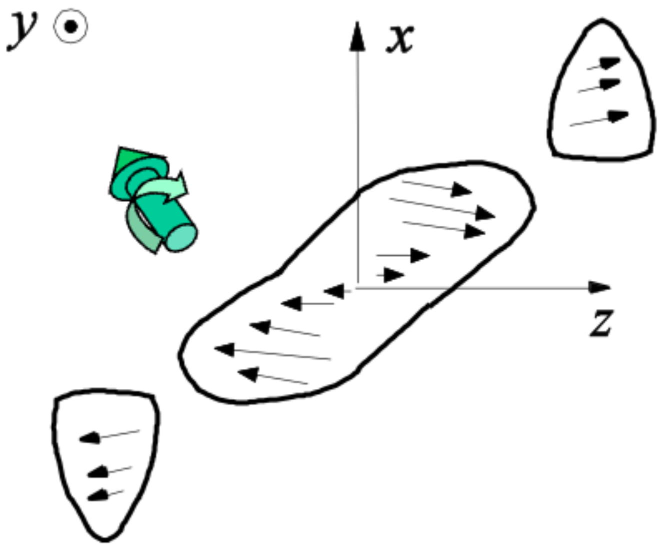
Becattini & Ferroni, EJPC 52 (2007) 597, Betz, Gyulassy & Torrieri, PRC 76 (2007) 044901, Becattini, Piccinini & Rizzo, PRC 77 (2008) 024906, Beccatini, Csernai & Wang, PRC 87 (2013) 034905, Xie, Glastad & Csernai, PRC 92 (2015) 064901, Deng & Huang, arXiv 1603.06117

Consequences in A+A collisions

Globally Polarized thermal, dilepton, J/Ψ, hyperons and vector mesons

Constituent quark model

Liang & XNW, PRL 94 (05) 102301
Liang & XNW, PLB 629(05)20
Gao et al, PRC 77 (08) 044902



$$\rho_{00}^{s=1} \approx \frac{1}{3} - \frac{4}{9} P_q P_{\bar{q}}$$

$$P_\Lambda \approx P_s \qquad P_\Sigma \approx \frac{1}{3}(2P_u + 2P_d - P_s)$$

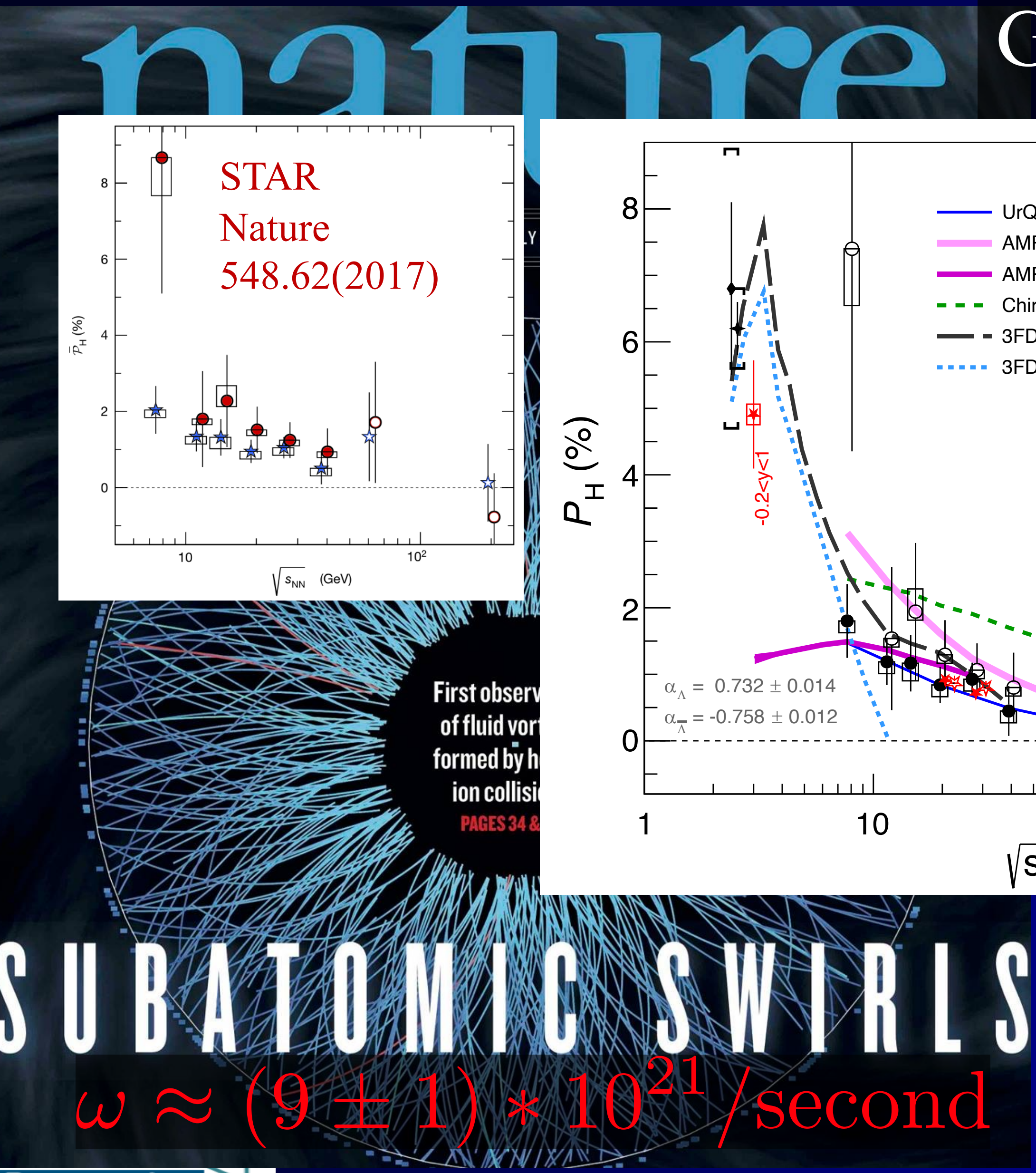
$$P_\Xi \approx \frac{1}{3}(4P_s - P_d) \qquad P_\Omega \approx \frac{3}{5} P_s$$

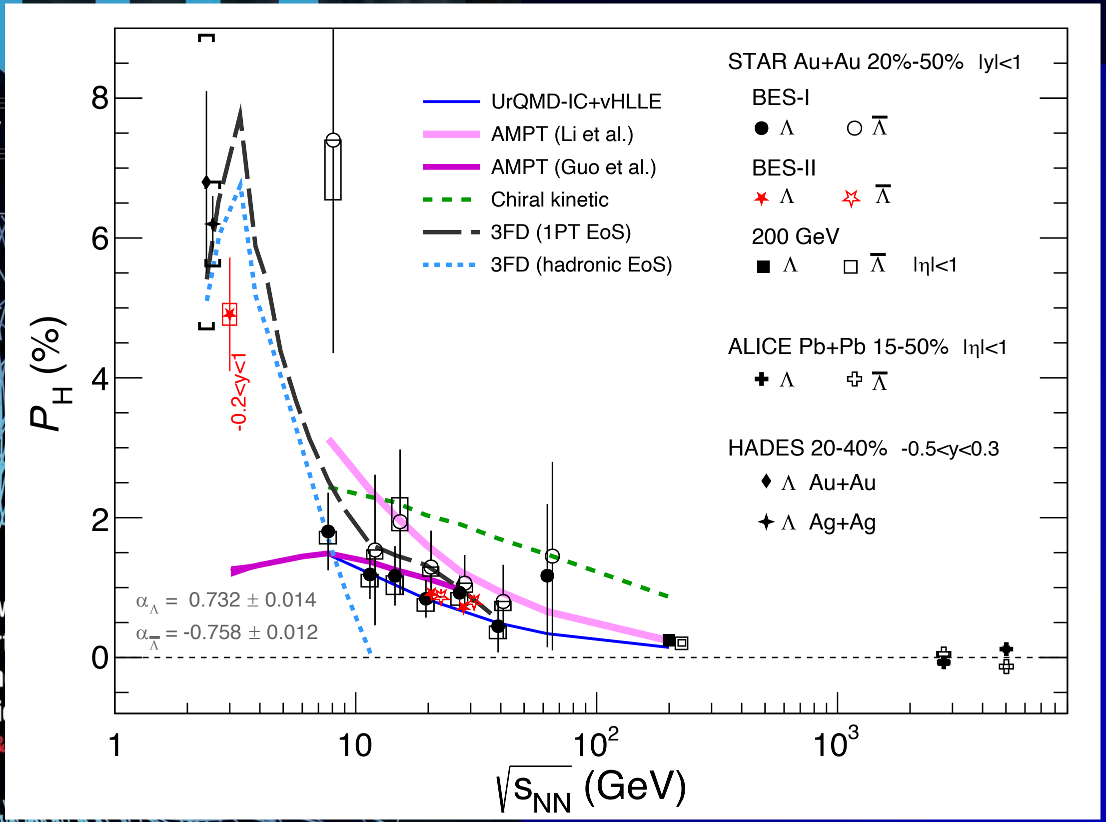
Spin dynamics with quark coalescence model:

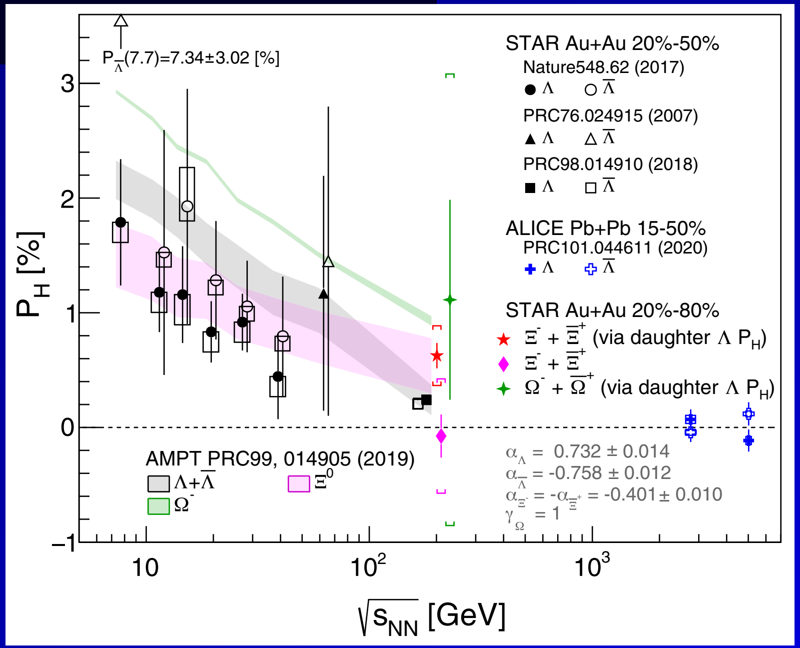
Yang,Fang,Wang & XNW *Phys.Rev.C* 97 (2018) 3, 034917
Sheng, Wang & XNW, *Phys.Rev.D* 102 (2020) 5, 056013

The most vortical fluid in nature

Global hyperon polarization





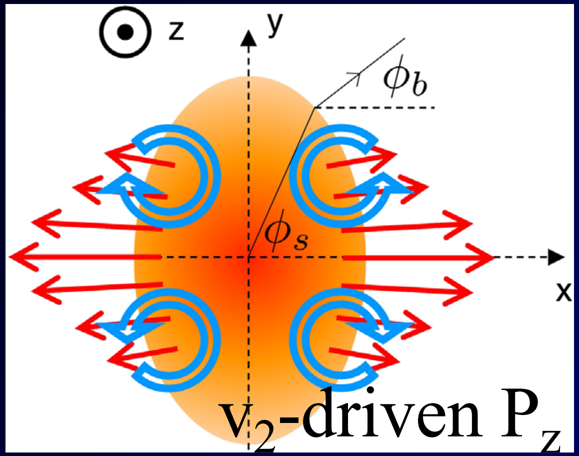


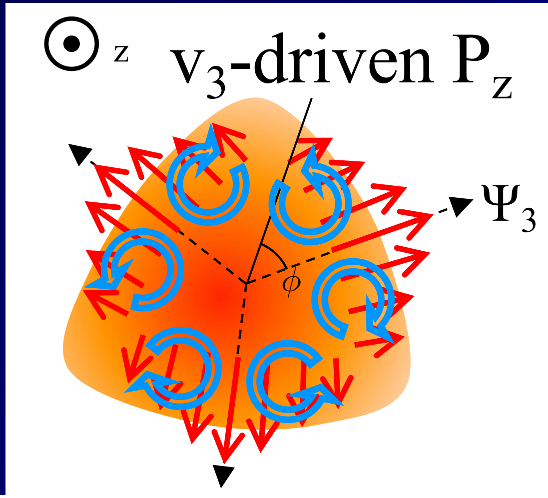
$\omega \approx (9 \pm 1) * 10^{21}$/second

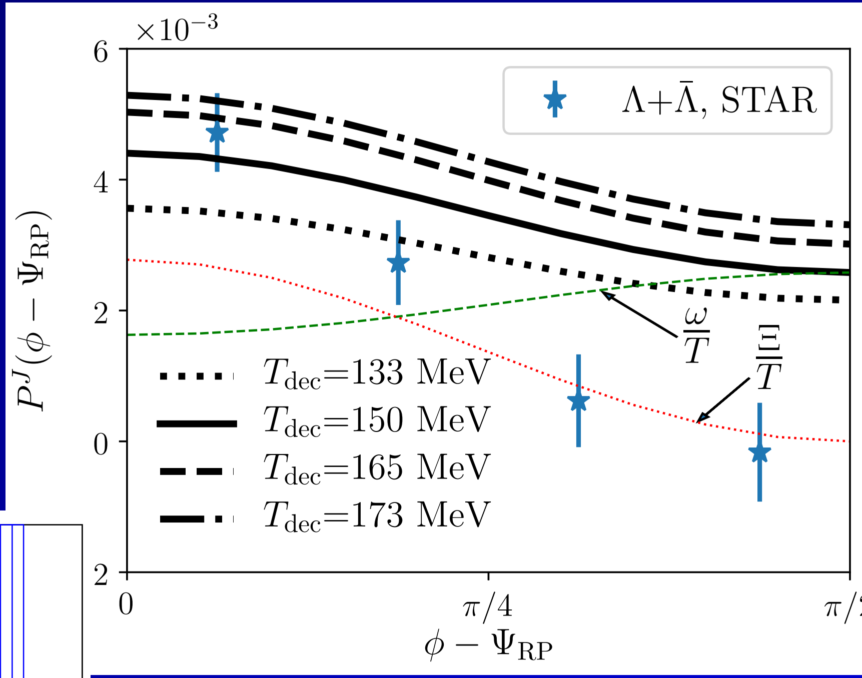
Becattini, Buzzegoli, Niida, Pu, Tang and Wang, arXiv:2402.04540

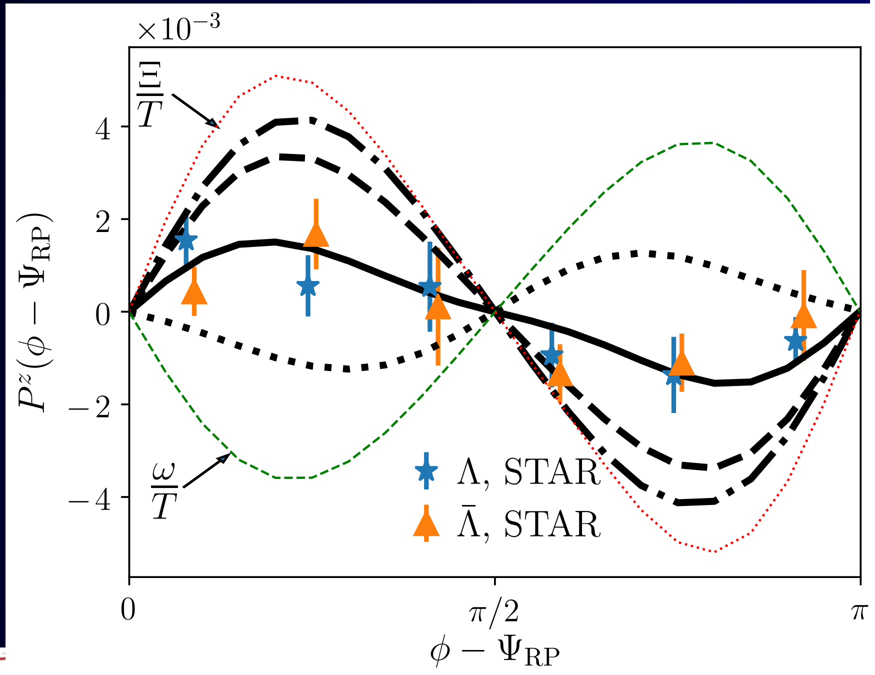
Local spin polarization

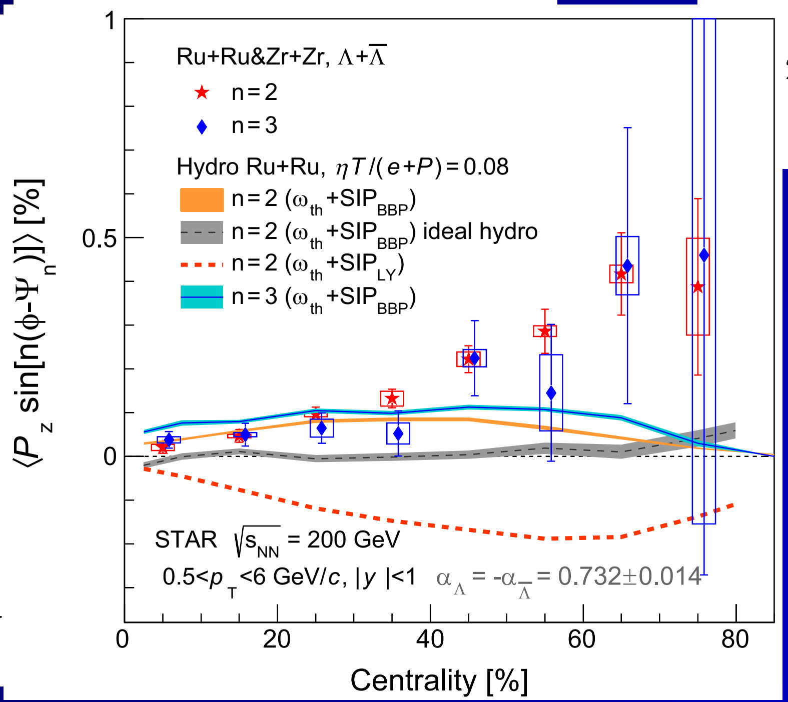
ϕ-dependence of P_T

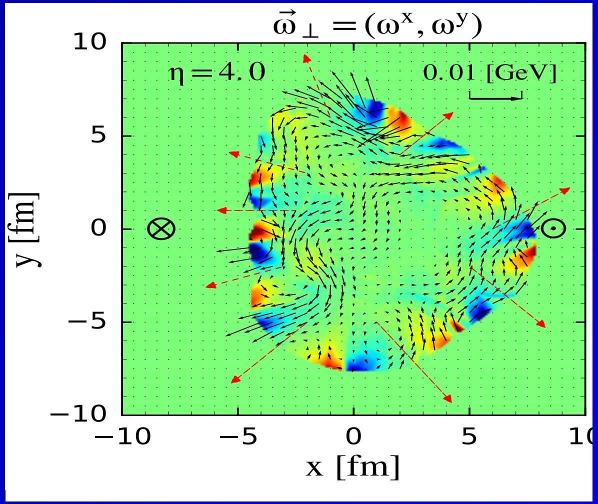












Vector meson spin alignment

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Spin alignment of vector mesons in non-central $A+A$ collisions

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Received 13 December 2004; received in revised form 21 August 2005; accepted 15 September 2005
Available online 3 October 2005

Simple recombination model

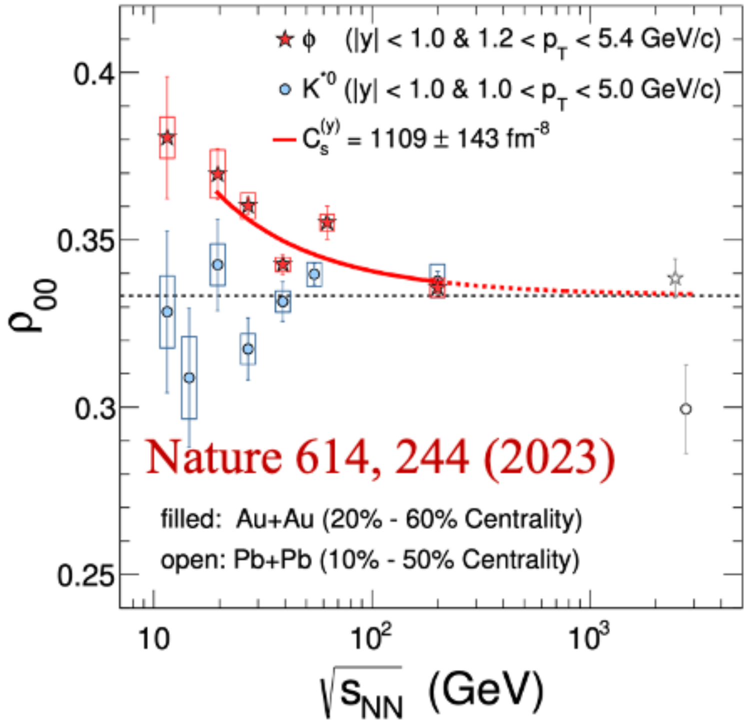
$$\rho_{00} = \frac{1 - P_q P_{\bar{q}}}{3 + P_q P_{\bar{q}}} \leq \frac{1}{3}$$

More sophisticated recombination model

$$\rho^{00} \approx \frac{1}{3} - \frac{4}{9}\langle P_q(\mathbf{x_q}, \mathbf{p}_q) P_{\bar{q}}(\mathbf{x}_{\bar{q}}, \mathbf{p}_{\bar{q}})\rangle$$

Sheng, Wang and XNW, Phys. Rev. D 102, 056013 (2020)

STAR: Large ϕ meson spin alignment



Too big to be explained by vorticity, EM, etc

$$P_{q(\bar{q})} \approx \frac{1}{4m_q}\epsilon^{\mu\nu\rho\sigma}\left[\omega \pm \frac{e_q}{(u\cdot p)T}F_{\rho\sigma}\right]p_\nu$$

Polarization via strong interaction force

Chiral quark model: Manohar and Georgi (1984)

Effective interaction between quarks, gluon and Goldstone boson between Λ_χ and Λ_{QCD}

$$\mathcal{L} = \bar{\psi}\gamma^\mu(iD_\mu + V_\mu + g_A A_\mu \gamma_5)\psi - m\bar{\psi}\psi + \frac{1}{4}f^2 \mathrm{tr}\partial_\mu \Sigma^\dagger \partial^\mu \Sigma - \frac{1}{2}\mathrm{tr}F_{\mu\nu}F^{\mu\nu} + \cdots$$

$$V_\mu = \frac{1}{2}(\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger) \qquad A_\mu = \frac{i}{2}(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger)$$

$$\xi = e^{iM/f} \qquad M = \frac{1}{\sqrt{2}}\begin{bmatrix} \sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{bmatrix}$$

$$P_{q(\bar{q})} \approx \frac{1}{4m_q}\epsilon^{\mu\nu\rho\sigma}\left[\omega \pm \frac{e_q}{(u\cdot p)T}F_{\rho\sigma} \pm \frac{g_V}{(u\cdot p)T}F^V_{\rho\sigma}\right]p_\nu$$

Strong interaction

Polarization via strong interaction force

Spin Boltzmann transport equation with quark coalescence

Sheng, Oliva, Liang, Wang and XNW, PRL 131, 042304 (2023)

$$k \cdot \partial_x f^V_{\lambda_1 \lambda_2}(x, \mathbf{k}) = \frac{1}{8} \left[\epsilon^*_\mu(\lambda_1, \mathbf{k}) \epsilon_\nu(\lambda_2, \mathbf{k}) \mathcal{C}^{\mu\nu}_{\text{coal}}(x, \mathbf{k}) - \mathcal{C}_{\text{diss}}(\mathbf{k}) f^V_{\lambda_1 \lambda_2}(x, \mathbf{k}) \right],$$

$$f^V_{\lambda_1 \lambda_2}(x, \mathbf{k}) \sim \frac{1}{\mathcal{C}_{\text{diss}}(\mathbf{k})} \left[1 - e^{-\mathcal{C}_{\text{diss}}(\mathbf{k}) \Delta t}\right] \epsilon^*_\mu(\lambda_1, \mathbf{k}) \epsilon_\nu(\lambda_2, \mathbf{k}) \mathcal{C}^{\mu\nu}_{\text{coal}}(x, \mathbf{k})$$

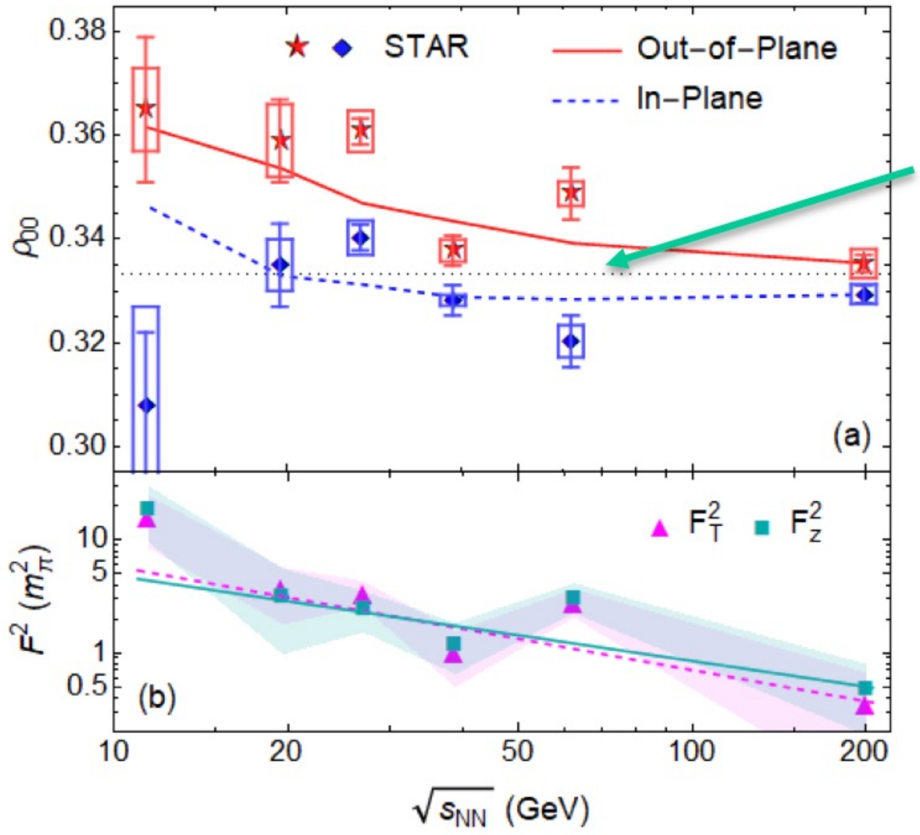
Spin alignment on the hadronization hyper surface

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

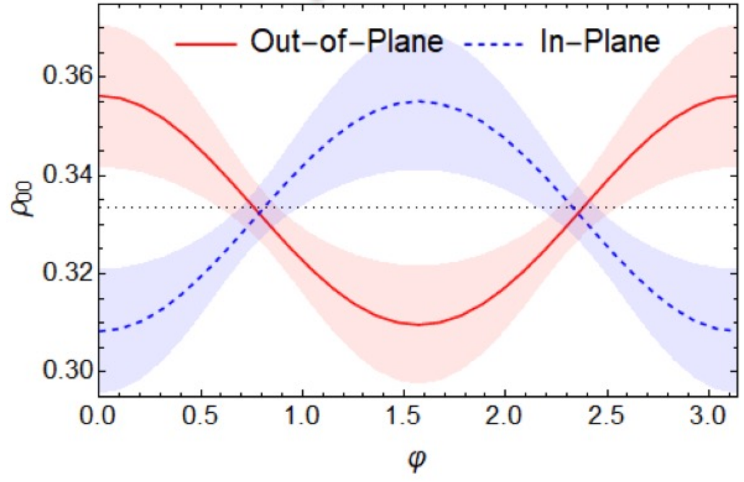
Momentum-dependence

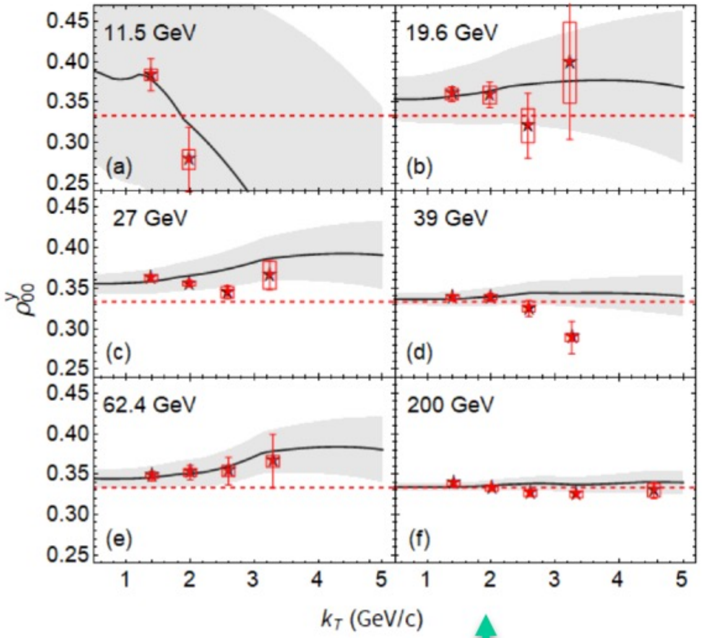
${B^2}_\phi$, ${E^2}_\phi$ rest frame → collisions frame

Barometer of strong force field fluctuations



In and out-plane splitting caused by v2 of the vector meson





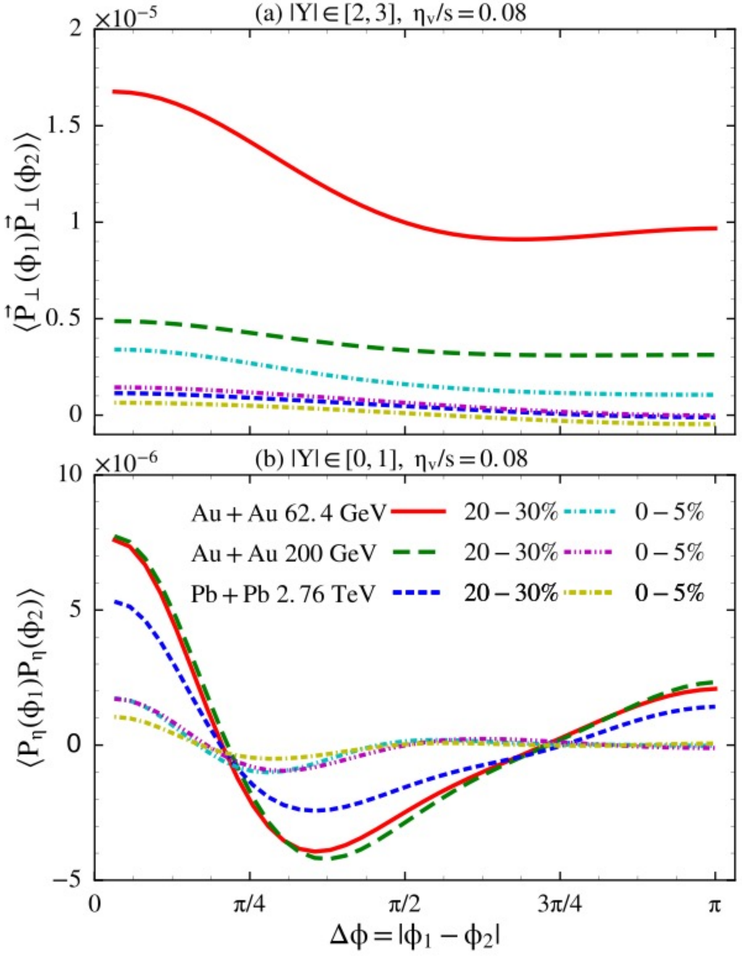
k_T dependence of ρ_{00} dictated by vector meson's spectra

$$\left\langle (g_\phi \mathbf{B}^\phi_{x,y}/T_\mathrm{h})^2 \right\rangle = \left\langle (g_\phi \mathbf{E}^\phi_{x,y}/T_\mathrm{h})^2 \right\rangle \equiv F_T^2$$

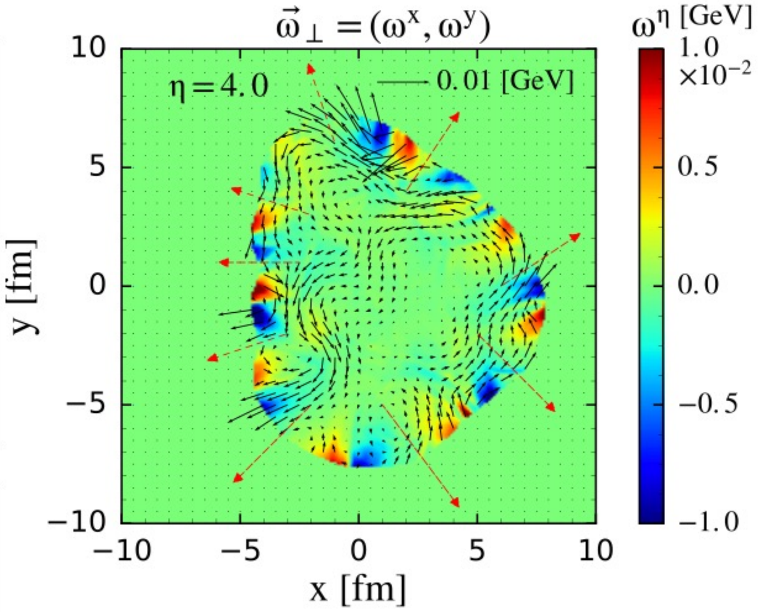
$$\left\langle (g_\phi \mathbf{B}^\phi_{z}/T_\mathrm{h})^2 \right\rangle = \left\langle (g_\phi \mathbf{E}^\phi_{z}/T_\mathrm{h})^2 \right\rangle \equiv F_z^2$$

Sheng, Oliva, Liang, Wang and XNW, PRL 131, 042304 (2023)

Hyperon spin correlations

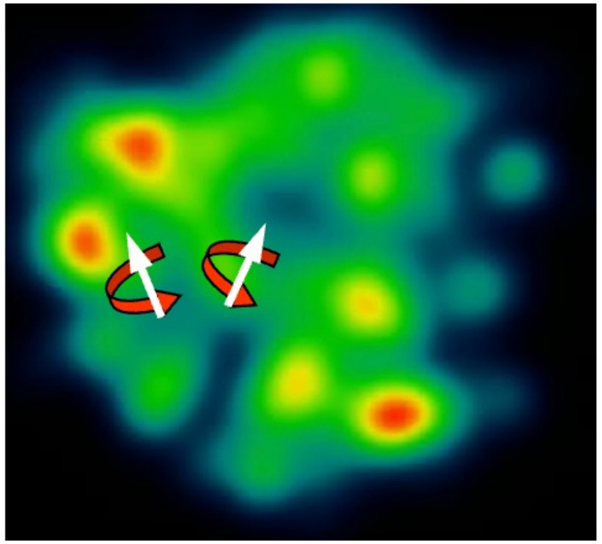


Pang, Petersen, Wang & XNW, PRL 117(2016) 192301



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

Lisa, et al, *PRC* 104 (2021) 1, 011901



strong-field induced hyperon spin correlation

$$c_{\Lambda\Lambda} = P_\Lambda^2 + c_{ss} \qquad c_{\Lambda\bar{\Lambda}} = P_\Lambda^2 - c_{ss}$$

$$P_{q(\bar{q})} \approx \frac{1}{4m_q}\epsilon^{\mu\nu\rho\sigma}\left[\omega \pm \frac{e_q}{(u\cdot p)T}F_{\rho\sigma} \pm \frac{g_V}{(u\cdot p)T}F^V_{\rho\sigma}\right]p_\nu$$

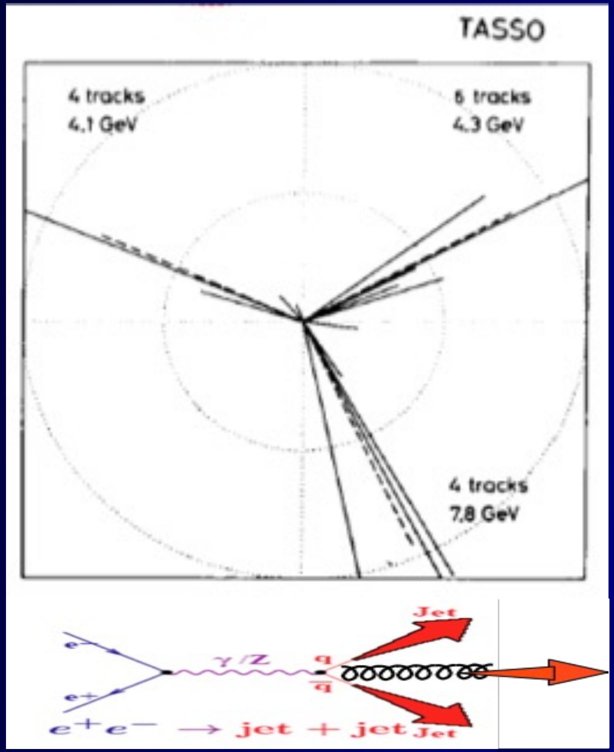
Lv, Yu, Liang, Wang & XNW, e-Print: 2402.13721

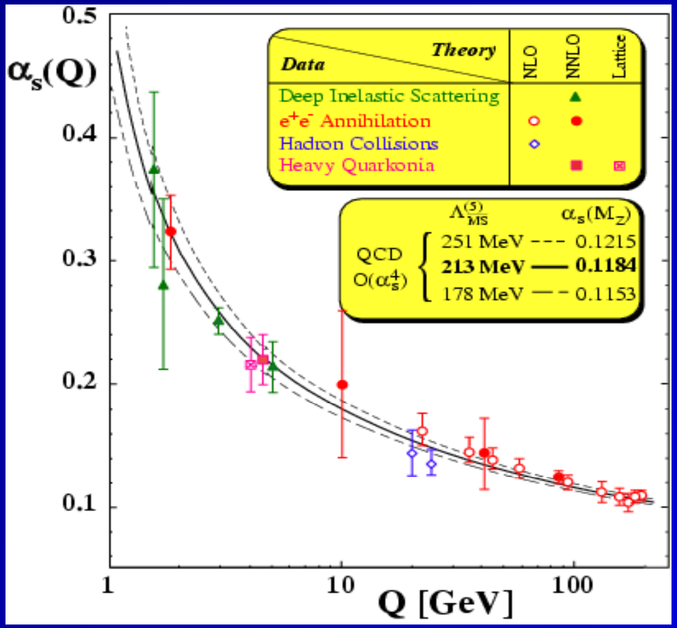
Jet physics in heavy-ion collisions

Jets in high-energy collisions

- Uncorrelated jet model for hadron production: De Groot and Ruijgrok (1971)
- Asymptotic freedom of QCD: Gross & Wilczek, Politzer (1973)
- Partons in QCD: Ellis, Gaillard & Ross (1976), Georgi & Machacek (1977)
- Jets in QCD: Sterman & Weinberg (1977)

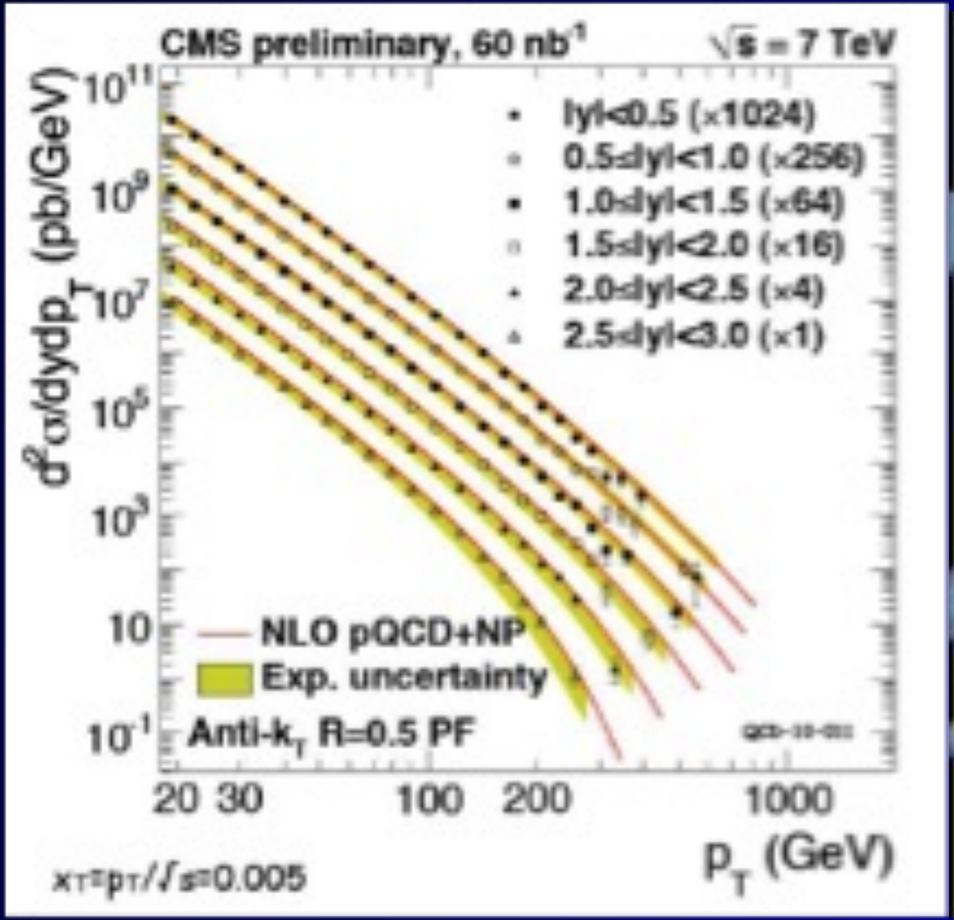
--tools for studying QCD and new discoveries

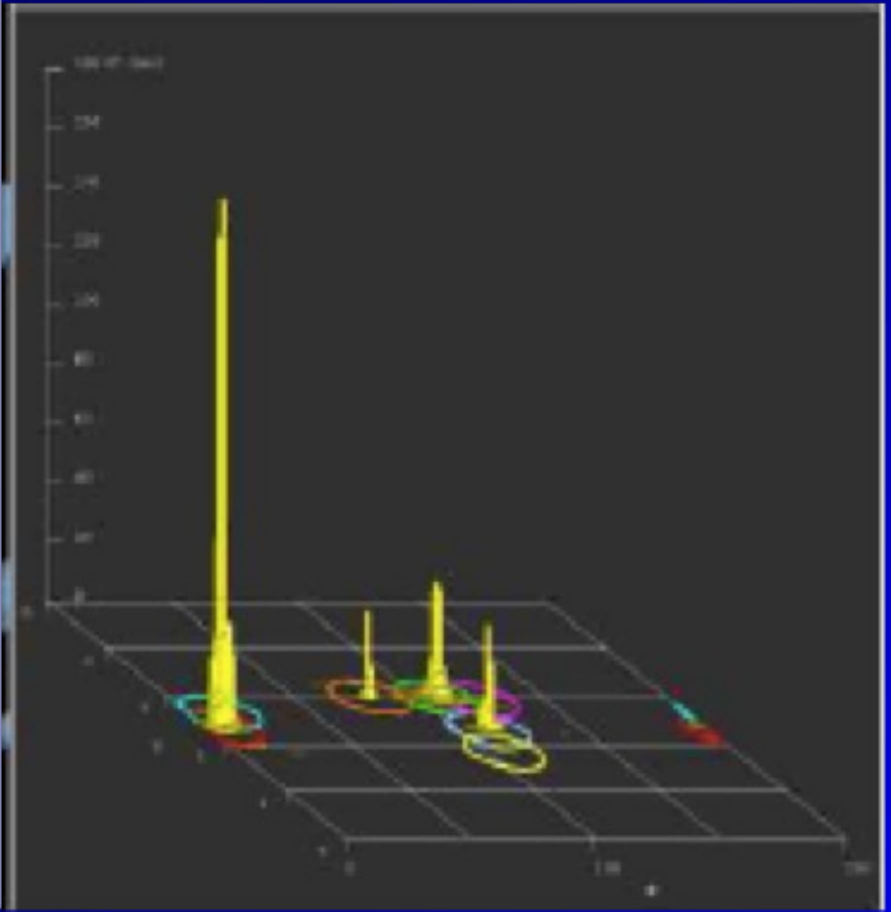




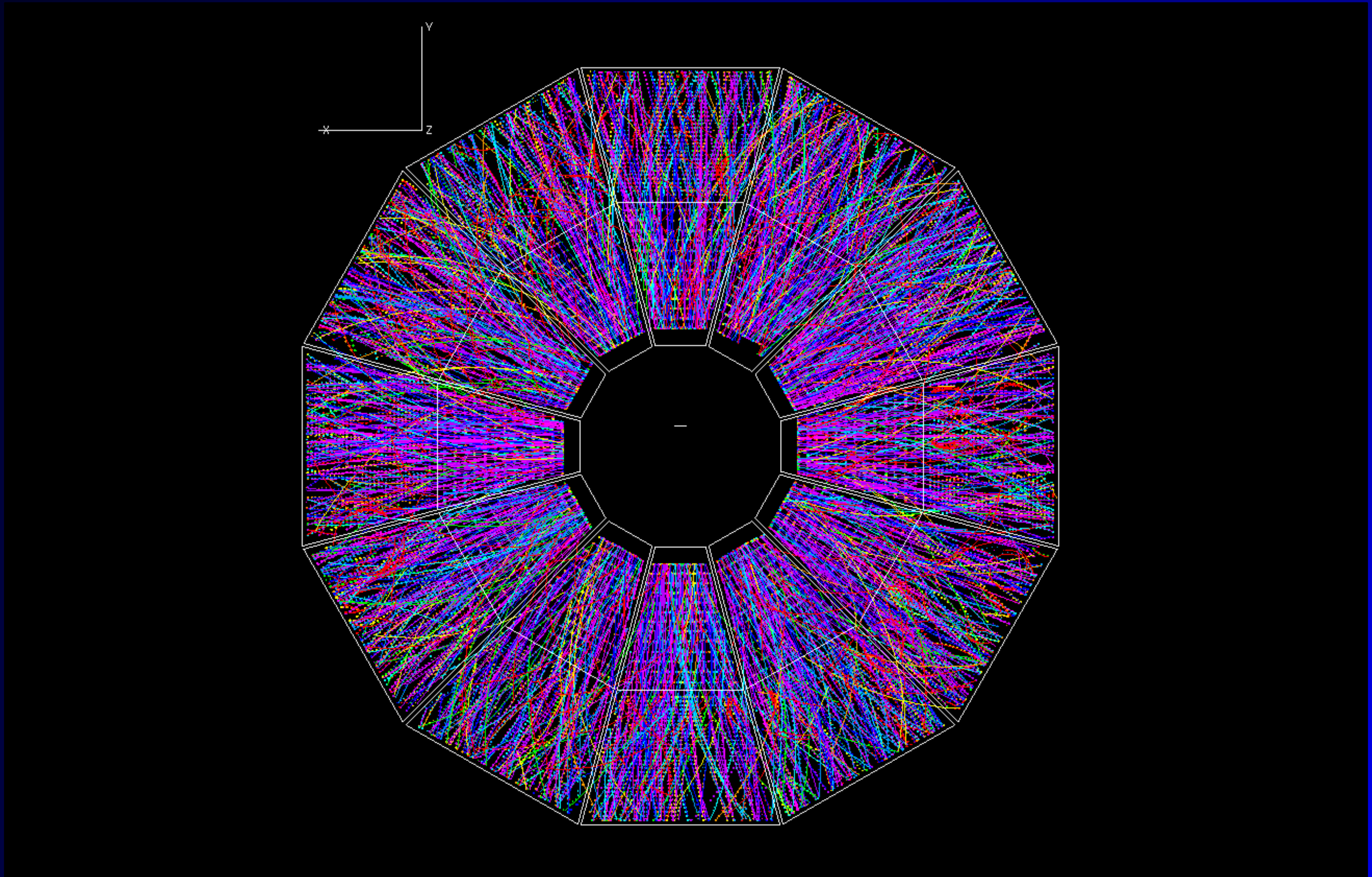
S Bethke J. Phys. G26 (2000) R27

Jets in pp collisions at LHC



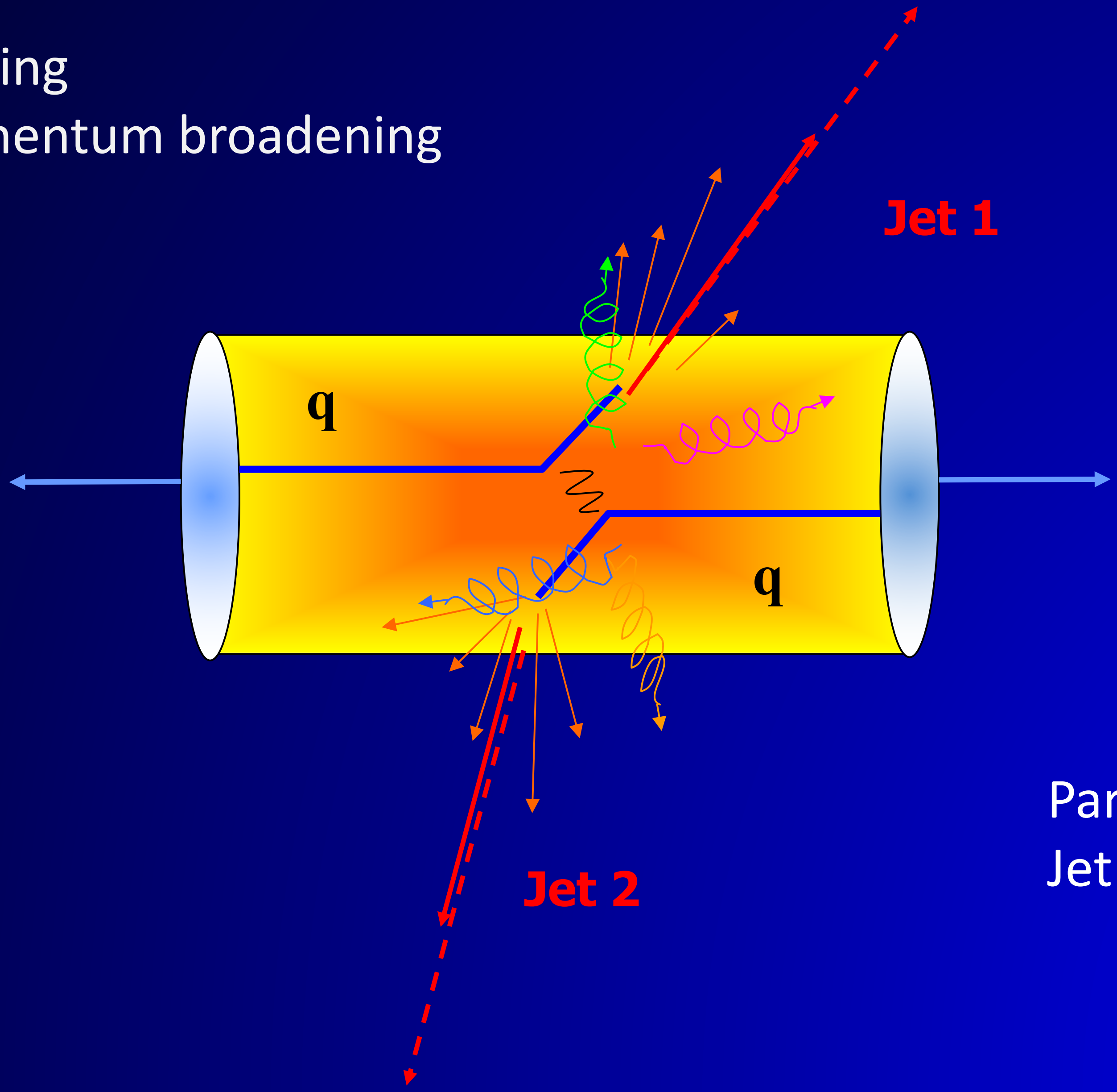


Jets in Heavy-ion Collisions



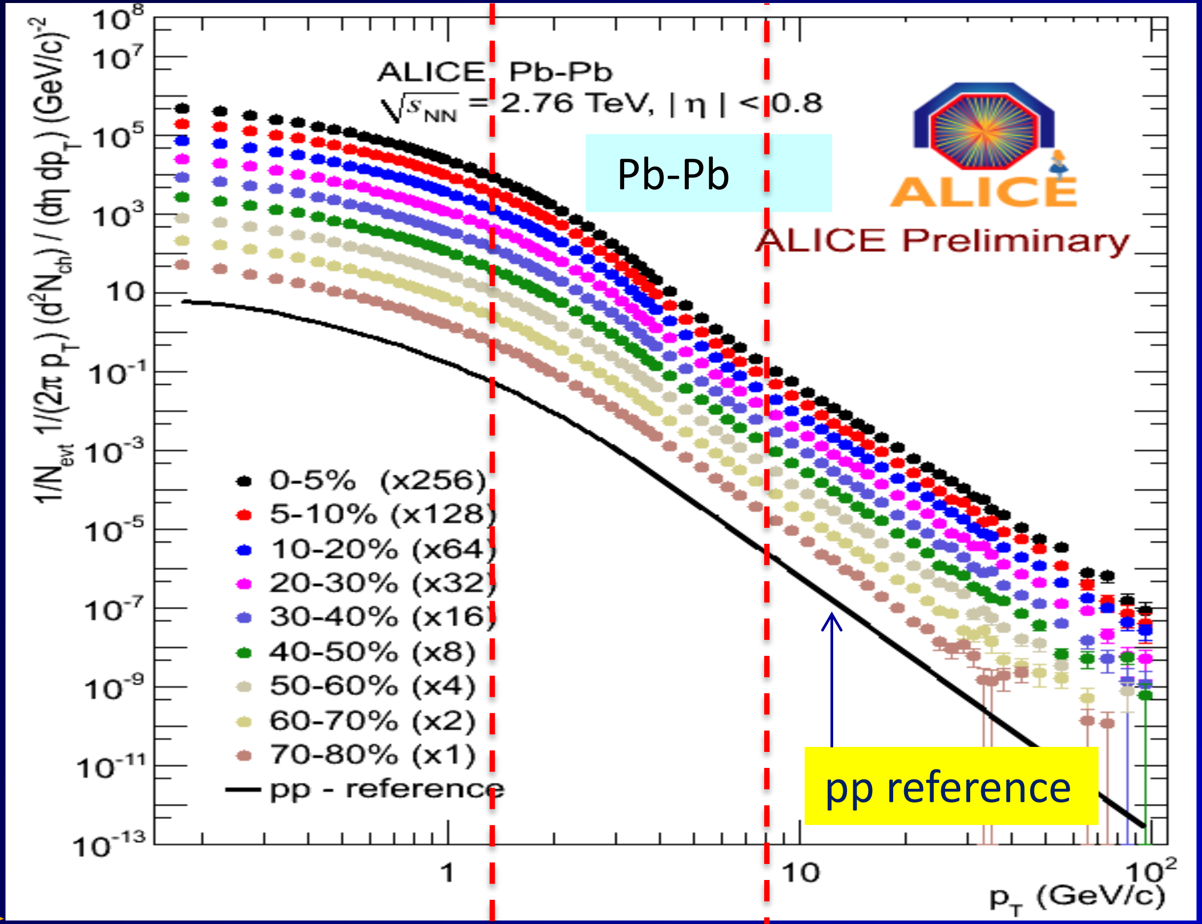
Jets in heavy-ion collisions

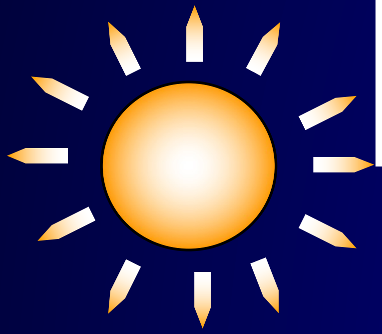
Multiple scattering
Transverse momentum broadening

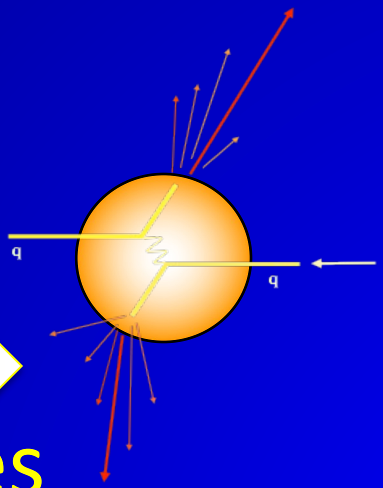


Parton energy loss
Jet suppression

Hard and soft probes



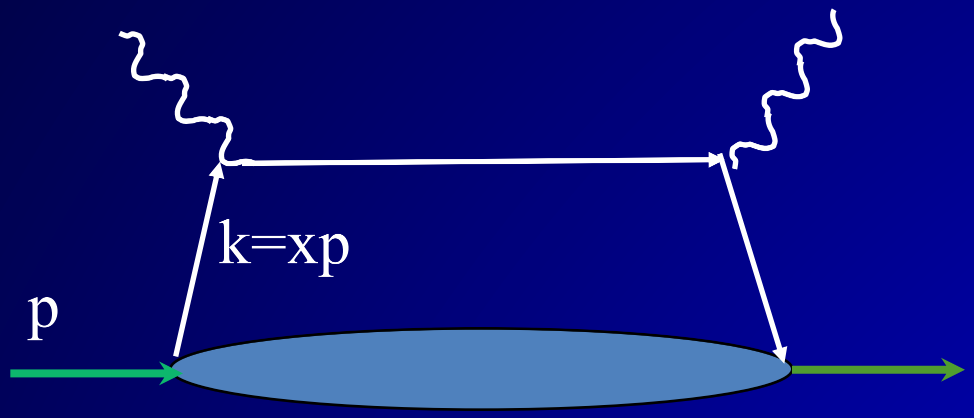




soft probes

hard probes

Deeply Inelastic Scattering

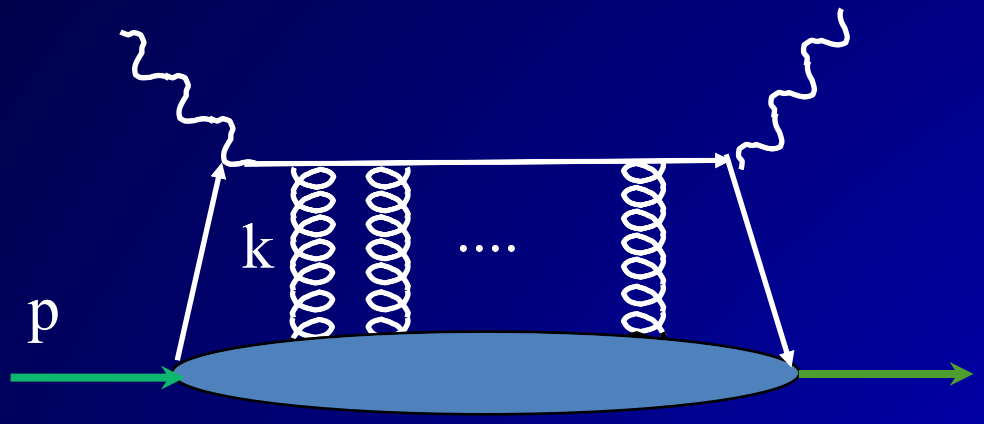


Quark distribution in collinear factorized pQCD parton model:

$$f_A^q(x) = \int \frac{dy^-}{4\pi} e^{ixp^+y^-} \langle A|\bar{\psi}(0)\psi(y)|A\rangle$$

quarks carrying momentum fraction x of the nucleon (nucleus)

Multiple scattering and gauge invariance



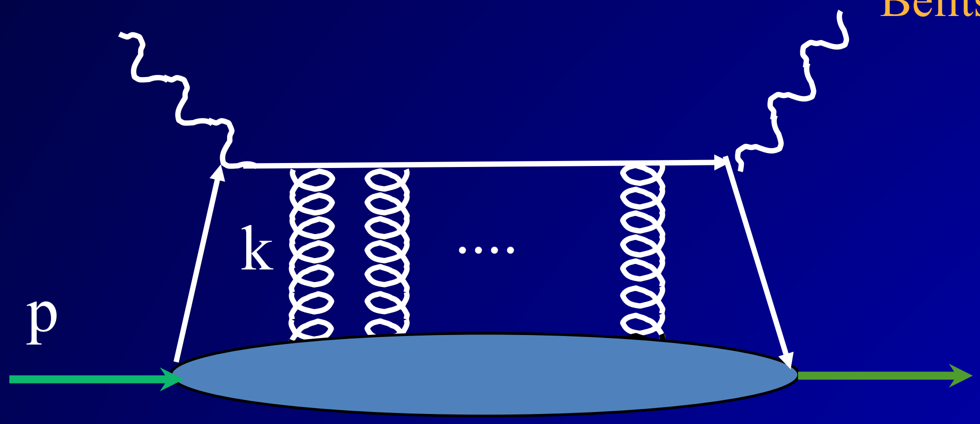
Quark distribution in collinear factorized pQCD parton model:

$$f_A^q(x) = \int \frac{dy^-}{4\pi} e^{ixp^+y^-} \langle A|\bar{\psi}(0)\gamma^+ \mathcal{L}_{\parallel}(0, y^-; \vec{0}_\perp)\psi(y^-)|A\rangle$$

$$\mathcal{L}_{\parallel}(0, y^-; \vec{0}_\perp) = \mathcal{P}\exp\left[ig\int_0^{y^-} d\xi^- A_+(\xi^-, \vec{0}_\perp)\right]$$

TMD parton distribution in DIS

Belitsky, Ji and Yuan (2002)



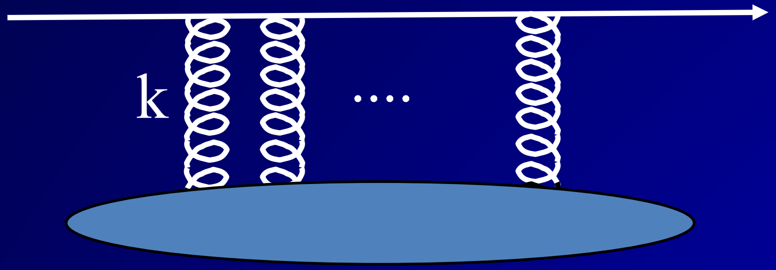
$$f_A^q(x, \vec{k}_\perp) = \int \frac{dy^-}{4\pi} \frac{d^2 y_\perp}{(2\pi)^2} e^{ixp^+ y^- - i\vec{k}_\perp \cdot \vec{y}_\perp} \langle A | \bar{\psi}(0) \gamma^+ \mathcal{L}(0, y) \psi(y) | A \rangle$$

$$\mathcal{L}(0, y) = \mathcal{L}_{\|}^{\dagger}(\infty, 0; \vec{0}_\perp) \mathcal{L}_{\perp}^{\dagger}(\infty; \vec{y}_\perp, \vec{0}_\perp) \mathcal{L}_{\|}(\infty, y^-; \vec{y}_\perp)$$

$$\mathcal{L}_{\|}(-\infty, y^-, \vec{y}_\perp) = \mathcal{P} \exp \left[-ig \int_{y^-}^{-\infty} d\xi^- A_+(\xi^-, \vec{y}_\perp) \right]$$

$$\mathcal{L}_{\perp}(-\infty; \vec{y}_\perp, \vec{0}) = \mathcal{P} \exp \left[-ig \int_{y^-}^{-\infty} d\vec{\xi}_\perp \cdot \vec{A}_\perp(\xi^-, \vec{y}_\perp) \right]$$

Jet Transport in Medium



$$i\vec{\partial}_{y_\perp}\mathcal{L}(0,y) = \mathcal{L}(0,y)\left[i\vec{D}_\perp(y) + g\int_{-\infty}^{y^-} d\xi^- \vec{F}_{+\perp}(\xi^-, y_\perp)\right]$$

Classical Lorentz force

$$\vec{W}_\perp(y^-, \vec{y}_\perp) \equiv i\vec{D}_\perp(y) + g\int_{-\infty}^{y^-} d\xi^- \vec{F}_{+\perp}(\xi^-, y_\perp)$$

Jet Transport Operator

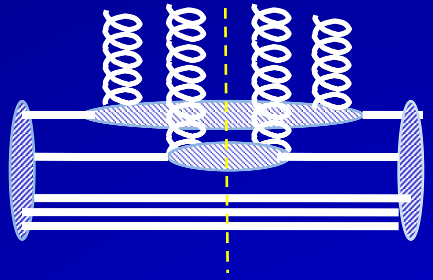
$$f_A^q(x, \vec{k}_\perp) = \int \frac{dy^-}{4\pi} e^{ixp^+y^-} \langle A|\bar{\psi}(0)\gamma^+ \exp[\vec{W}_\perp(y^-)\cdot\vec{\partial}_{k_\perp}]\psi(y^-)|A\rangle \delta^{(2)}(\vec{k}_\perp)$$

Liang, XNW & Zhou （2008）

Momentum Broadening

2-gluon correlation approximation

$$\frac{1}{N_c}\langle\langle \mathrm{Tr}\vec{W}_\perp(y^-)^{2n}\rangle\rangle_A \approx \frac{(2n)!}{2^n n!}\left[\frac{g^2}{2N_c}\frac{-1}{4p^+}\int d\xi_N^- \rho_N^A(\xi_N) d\xi^- \langle N \mid F_{+\sigma}(0)F_+^\sigma(\xi^-) \mid N\rangle\right]^n$$



Dipole approximation

$$\frac{1}{N_c}\langle \mathrm{Tr}\left[\mathcal{L}_\parallel^\dagger(-\infty,\infty;\vec{0}_\perp)\mathcal{L}_\parallel(-\infty,\infty;\vec{y}_\perp)\right]\rangle \approx \exp\left[-\frac{1}{4}\int d\xi_N^- \hat{q}(\xi_N) y_\perp^2)\right]$$

Liang, XNW & Zhou'08
Majumder & Muller'07
Kovner & Wiedemann'01
BDMPS'96

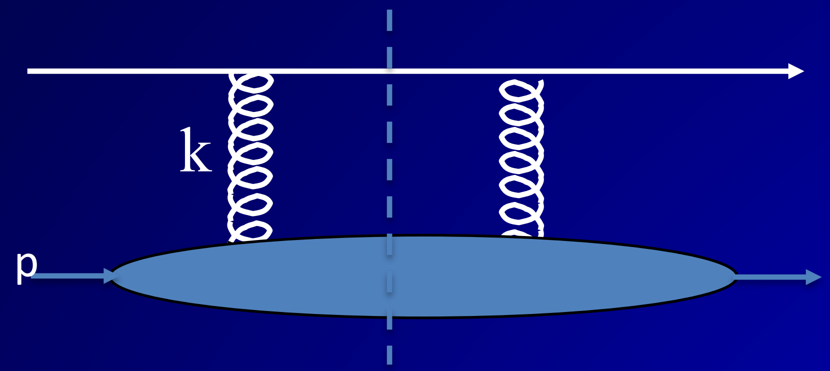
$$f_A^q(x,\vec{k}_\perp) \approx \frac{A}{\pi\Delta}\int d^2q_\perp \exp\left[-\frac{(\vec{k}_\perp-\vec{q}_\perp)^2}{\Delta}\right] f_N^q(x,\vec{q}_\perp)$$

$$\hat{q}(\xi_N) \equiv \frac{4\pi^2\alpha_s C_F}{N_c^2-1}\rho_A(\xi_N) x G_N(x)|_{x\approx 0}$$

$$\Delta = \langle \Delta k_\perp^2\rangle = \int d\xi_N^- \hat{q}(\xi_N)$$

Jet transport parameter

Jet transport coefficient



$$\sigma_R \approx \frac{4\pi\alpha_s C_2(R)}{N_c^2 - 1} \int \frac{d^2k_\perp}{(2\pi)^2} \frac{\phi(0, \vec{k}_\perp)}{k_\perp^2}$$

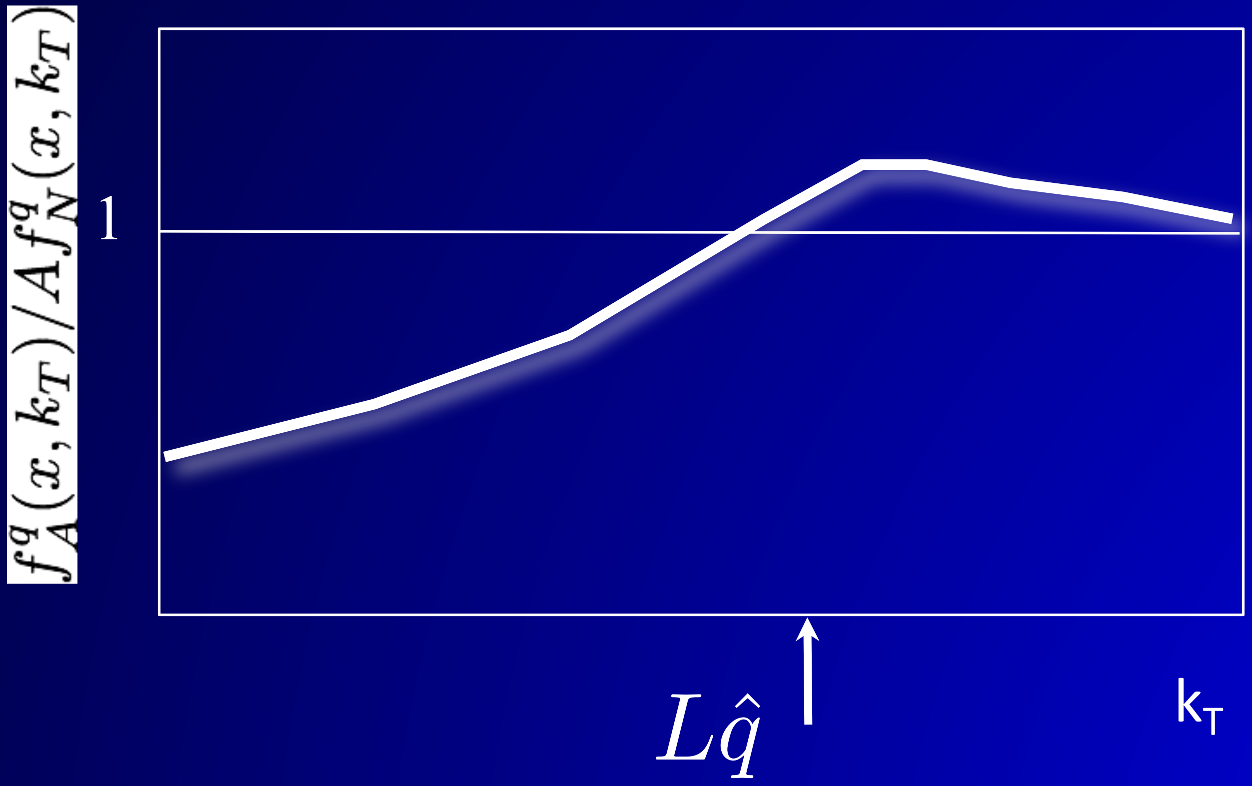
$$\phi(x, \vec{k}_\perp) = \int \frac{dy^-}{2\pi p^+} \int d^2\vec{y}_\perp e^{-ixp^+y^- + i\vec{k}_\perp \cdot \vec{y}_\perp} \langle p | F_\alpha^+(y^-, \vec{y}_\perp) F^{+\alpha}(0) | p \rangle$$

$$\hat{q}_R(y) = \rho(y) \int d^2k_\perp \frac{d\sigma}{d^2k_\perp} k_\perp^2$$

$$= \frac{4\pi\alpha_s C_2(R)}{N_c^2 - 1} \rho(y) \int \frac{d^2k_\perp}{(2\pi)^2} \phi(0, \vec{k}_\perp)$$

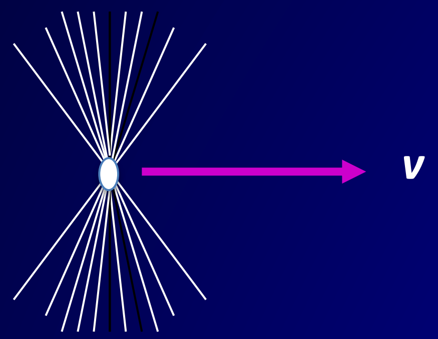
P_T Broadening

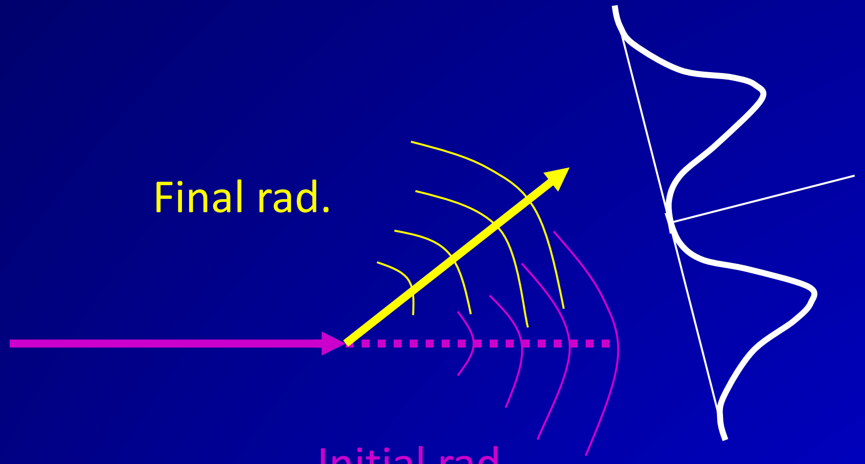
$$f_N^q(x, k_T) \sim 1/(k_T^2 + p_0^2)^\alpha$$



EM Radiation: Single scattering

EM field carried by a fast charge particle before and after scattering





EM Radiation by scattering: Interference between initial and final state radiation

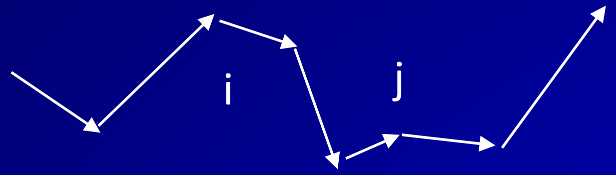
$$\omega \frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2} \left| \frac{\vec{k} \times \vec{v}_i}{\vec{k} \cdot \vec{v}_i - \omega} - \frac{\vec{k} \times \vec{v}_f}{\vec{k} \cdot \vec{v}_f - \omega} \right|^2$$

$$\omega \frac{dI}{d\omega} \approx \frac{2\alpha}{\pi} \left[\ln \frac{2E^2(1 - \vec{v}_i \cdot \vec{v}_f)}{m^2} - 1 \right]$$

Bethe Heitler

EM Radiation: multiple scattering

Classical radiation of a point charge **(Jackson, p671)**



$$\omega \frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2} \left| \sum_i \left(\frac{\vec{k} \times \vec{v}_i}{\vec{k} \cdot \vec{v}_i - \omega} - \frac{\vec{k} \times \vec{v}_{i+1}}{\vec{k} \cdot \vec{v}_{i+1} - \omega} \right) e^{i(\omega t_i - \vec{k} \cdot \vec{r}_i)} \right|^2$$

Lorentz Invariant form:

$$\omega \frac{d^3 I}{d^3 k} = \frac{e^2}{2(2\pi)^3} \sum_\lambda \left| \varepsilon_\lambda(k) \cdot \sum_i J_i(k) e^{ik \cdot x_i} \right|^2$$

$$J_i^\mu(k) = \frac{p_{i-1}}{k \cdot p_{i-1}} - \frac{p_i}{k \cdot p_i}$$

EM current of a charged through a scattering

Two Limits: (In)coherent radiation

$$\exp[ik \cdot (x_i - x_j)] = \exp[i\Delta x_{ij}/\tau_f]$$

Photon formation time:

$$\tau_f = \frac{1}{\omega(1-\cos\theta)} \approx \frac{2}{\omega\theta^2}$$

Coherent Limit: $\tau_f \gg \Delta x_{ij}$ single coherent scattering

$$J\mu(k) = \sum_i \left(\frac{p_{i-1}}{k \cdot p_{i-1}} - \frac{p_i}{k \cdot p_i} \right) e^{ik\cdot x_i} \approx \frac{p_1}{k \cdot p_1} - \frac{p_N}{k \cdot p_N}$$

Incoherent Bethe Heitler Limit: $\tau_f \ll \Delta x_{ij}$

$$\omega \frac{d^3 I}{d^3 k} = \frac{e^2}{4\pi^2} \left[\sum_{i,\lambda} |\varepsilon_\lambda \cdot J_i|^2 + 2Re \sum_{i,\lambda} \sum_{j>i,\lambda'} (\varepsilon_\lambda \cdot J_i)(\varepsilon_{\lambda'} \cdot J_j) e^{ik\cdot(x_i - x_j)} \right]$$

$$\omega \frac{dI}{d\omega} = \frac{L}{\lambda_{mfp}} \left(\omega \frac{dI}{d\omega} \right)_{\mathrm{BH}} \propto N \frac{2\alpha}{\pi}$$

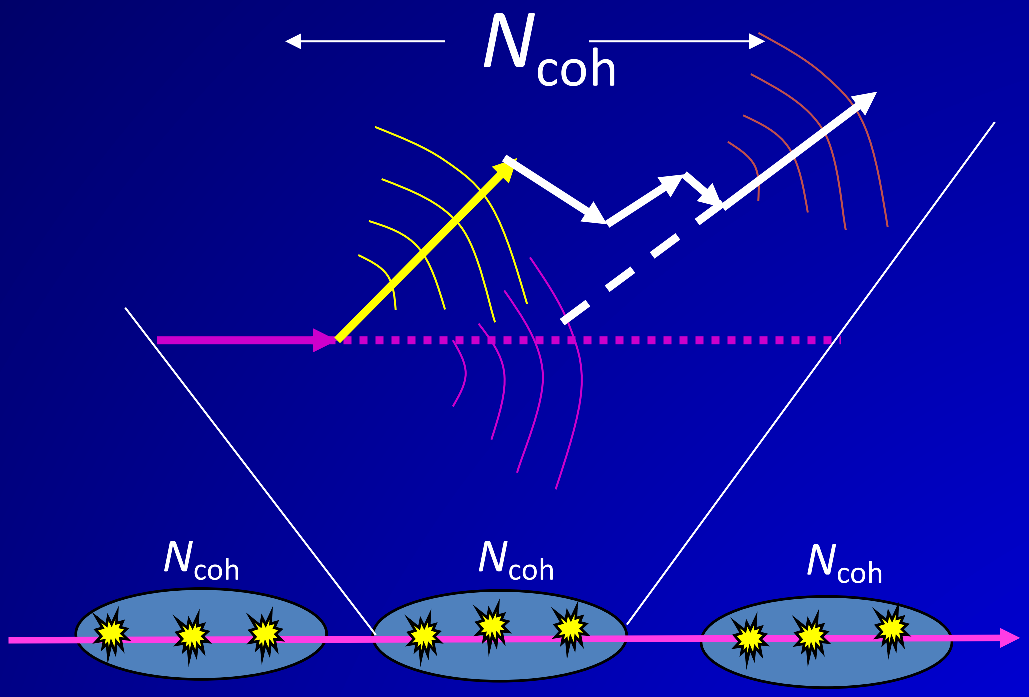
LPM Interference

$$\tau_f = \frac{2}{\omega\theta^2} \qquad \theta^2 = N_{\rm coh}\frac{q_\perp^2}{E^2}$$

$$N_{\rm coh}\lambda \approx \tau_f$$

$$\rightarrow N_{\rm coh} = \frac{2E}{\sqrt{\omega\langle q_\perp^2\rangle\lambda}}$$

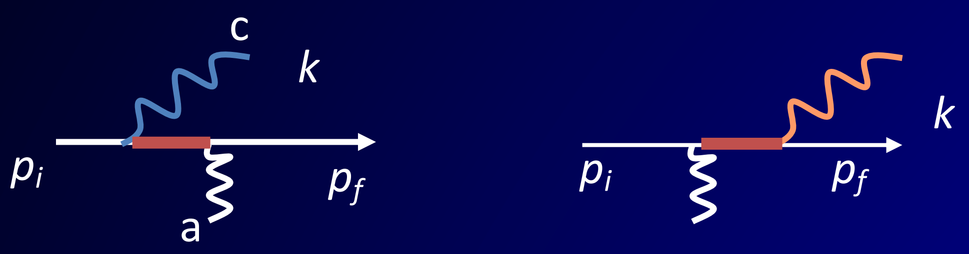
N_{coh} # of scattering for a coherent radiation



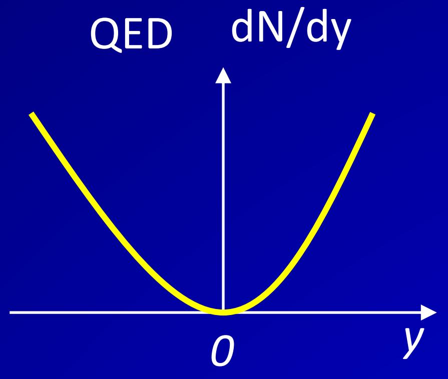
Effective spectra

$$\omega\frac{dI}{d\omega} = \frac{L}{\lambda}\left(\omega\frac{dI}{d\omega}\right)_{\rm BH}\frac{1}{N_{\rm coh}} \propto N\frac{\alpha}{\pi}\sqrt{\frac{\langle q_\perp^2\rangle}{E^2}\lambda\omega}$$

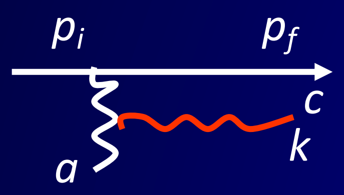
Radiation in QCD: Colors Makes the Difference



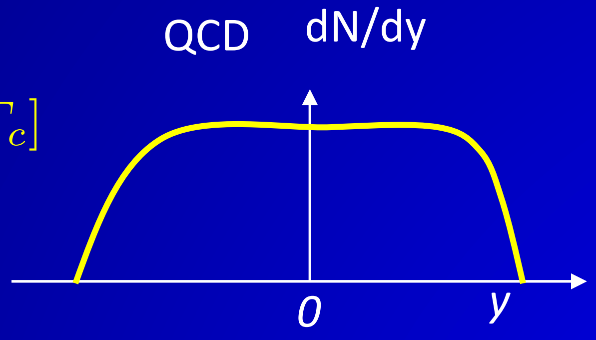
$$R_S^{(1)} \approx ig \frac{2\vec{\epsilon}_\perp \cdot \vec{k}_\perp}{k_\perp^2} [T_a T_c - T_c T_a]$$



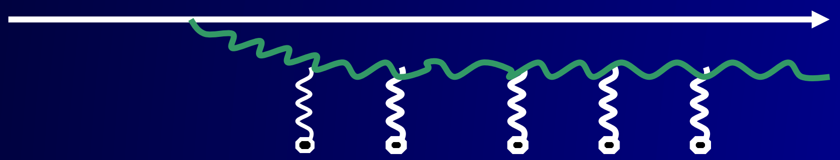
QCD: gluons carry **color**: interference incomplete



$$R_S^{(2)} \approx ig \frac{2\vec{\epsilon}_\perp \cdot (\vec{q}_\perp - \vec{k}_\perp)}{(\vec{q}_\perp - \vec{k}_\perp)^2} [T_a, T_c]$$

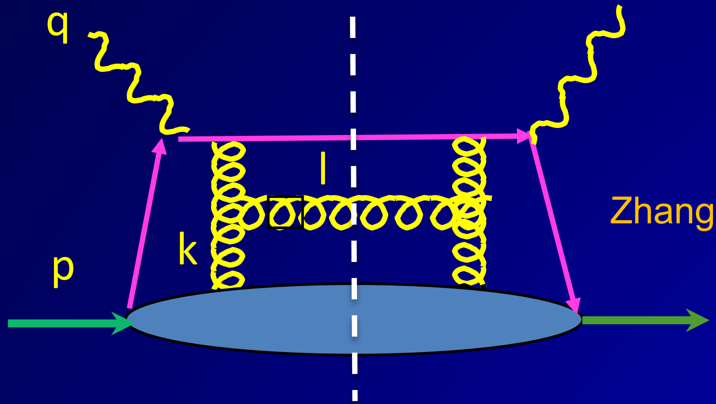


Gluon multiple scattering (BDMP'96)



$$\Delta E = \approx \frac{\alpha_s N_c}{4} \frac{\langle q_\perp^2 \rangle}{\lambda} L^2$$

Parton propagation in QCD medium



Zhang, Qin and XNW arXiv:1905.12699

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

medium TMD gluon distr.

$$\mathcal{N}_g^{static+soft} = \int \frac{d\varphi}{2\pi} \frac{2\vec{k}_\perp \cdot \vec{l}_\perp}{(\vec{l}_\perp - \vec{k}_\perp)^2} \left(1 - \cos\left[\frac{(\vec{l}_\perp - \vec{k}_\perp)^2}{2q^- z(1-z)} y_1^-\right] \right) \rightarrow \text{GLV}$$

τ_f Formation time of the gluon emission y_1^- / τ_f

Parton energy loss and jet transport

$$\frac{dE_{rad}}{dx} \approx E\frac{2C_A\alpha_s}{\pi}\hat{q}(x)\int dz\frac{d\ell_\perp^2}{\ell_\perp^4}zP(z)\sin^2\frac{\ell_\perp^2(x-x_0)}{4z(1-z)E}$$

(High-twist approach)

$$\frac{dE_{el}}{dx} = \int\frac{d^3k}{(2\pi)^3}dq_\perp^2 f(k)\frac{q_\perp^2}{2k}\frac{d\sigma}{dq_\perp^2} \approx \langle\frac{1}{2\omega}\rangle\hat{q}$$

Elastic energy loss

Jet transport coefficient:

$$\hat{q}(y) = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\rho(y)xG(x)|_{x\approx 0} = \frac{\langle q_\perp^2\rangle}{\lambda}$$

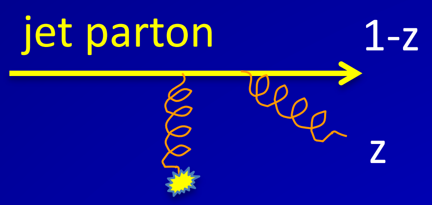
pQCD (BDMPS'96)
AdS/CFT (Liu,Rajagopal &Wideman'06)
lattice QCD (Majumder'12)

Extract jet transport coefficient from parton energy loss

Jet tomography via leading hadrons

Energy loss distribution or medium induced splitting function

$$\Delta\widetilde{P}_{a\to ag}(z) \approx \frac{2C_A\alpha_s}{\pi}\int dx\hat{q}(x)\int\frac{d\ell_\perp^2}{\ell_\perp^4}P(z)\sin^2\frac{\ell_\perp^2(x-x_0)}{4z(1-z)E}$$



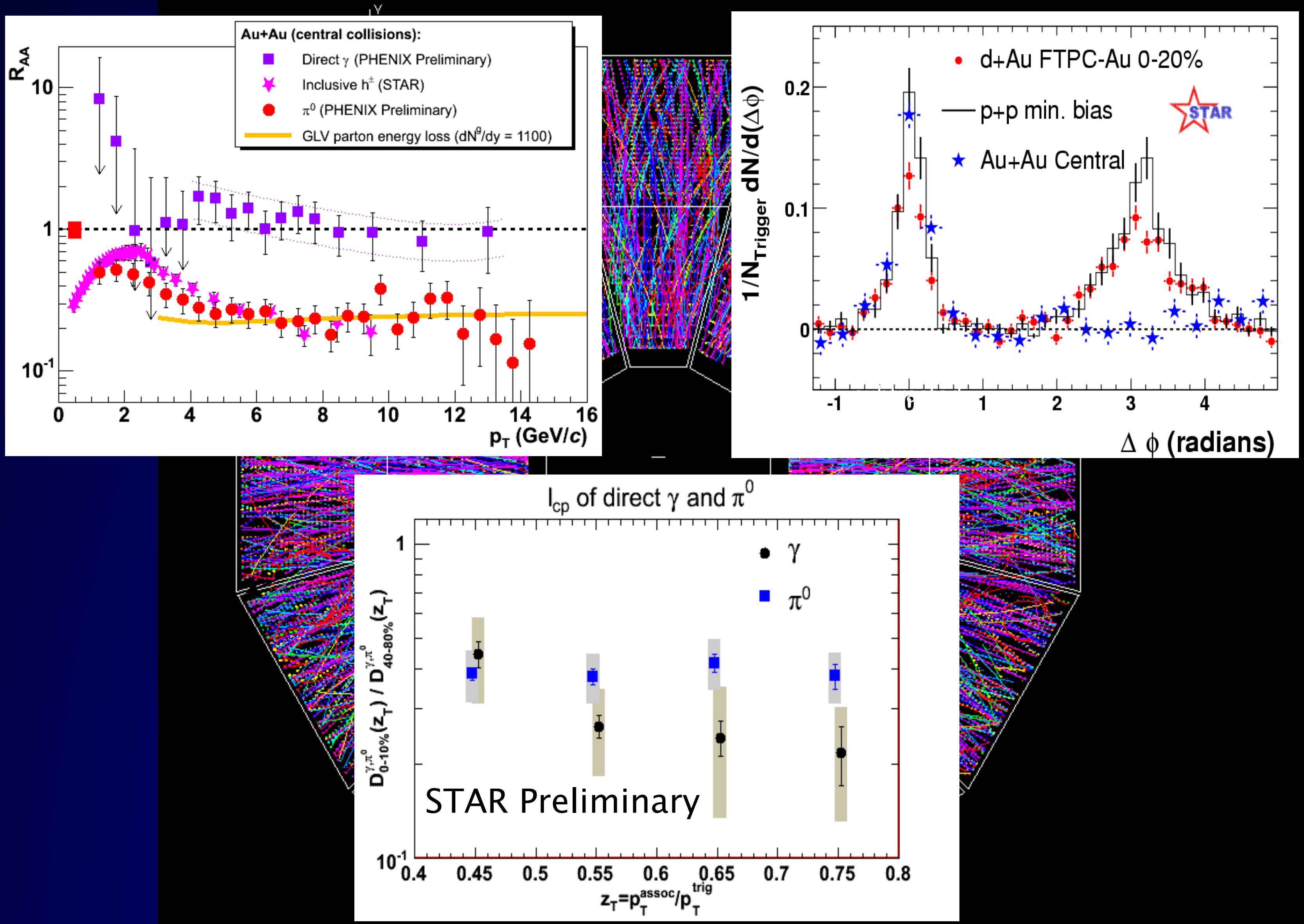
Modified frag function & hadron spectra:

$$\widetilde{D}_{c/h}(z_h) \approx [P_{a\to ag}(z) + \Delta\widetilde{P}_{a\to ag}(z)] \otimes D_{a/h}(z_h)$$

$$d\sigma_h = \sum_{a,b,c} f_a \otimes f_b \otimes d\sigma_{ab\to c+X} \otimes \widetilde{D}_{c/h}$$

Parton energy loss leads to suppression of leading hadrons

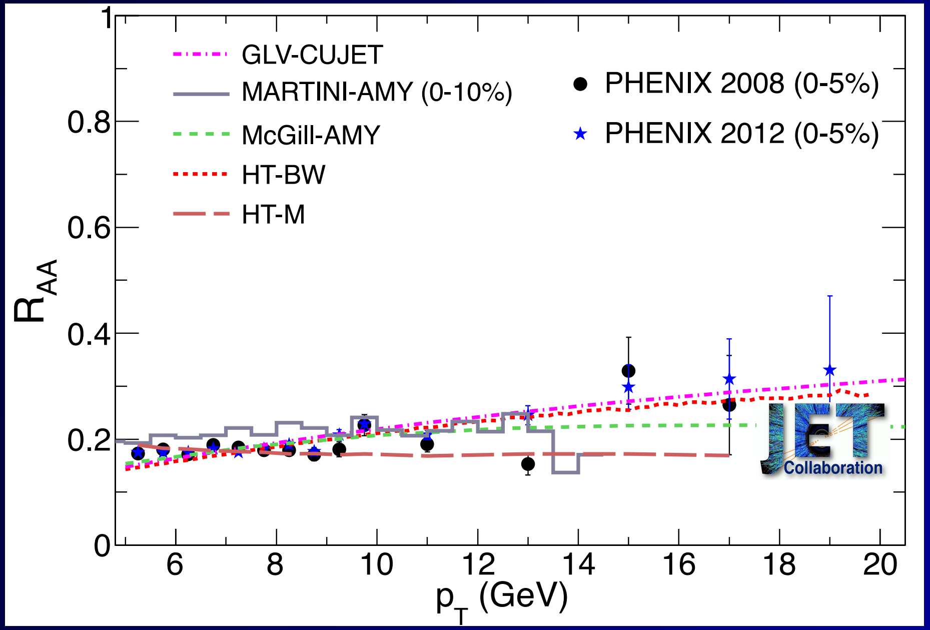
Jet Quenching phenomena at RHIC



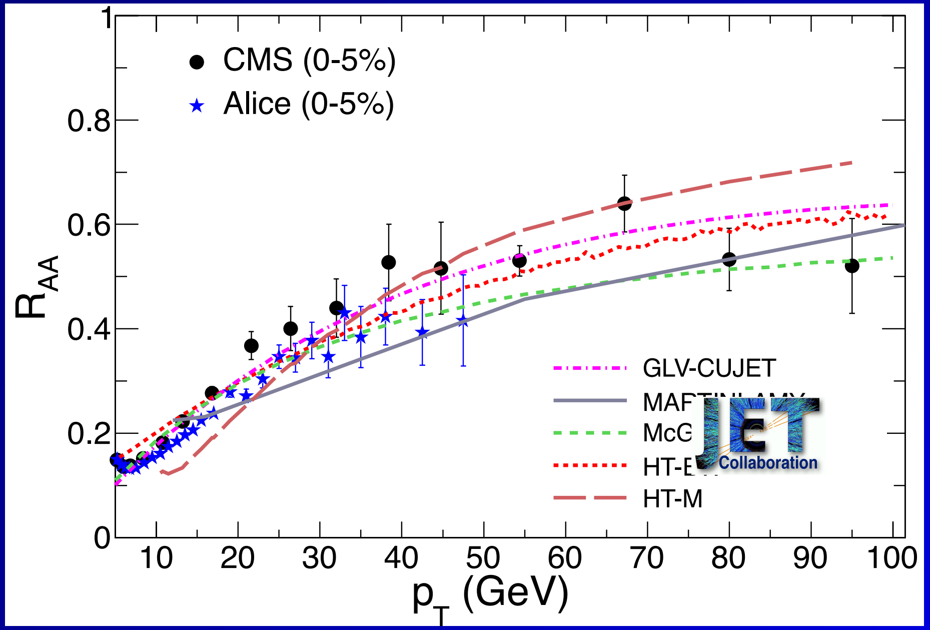
Jet quenching phenomenology

Suppression of single hadron spectra at RHIC and LHC

Best χ^2 fits with different model calculations :



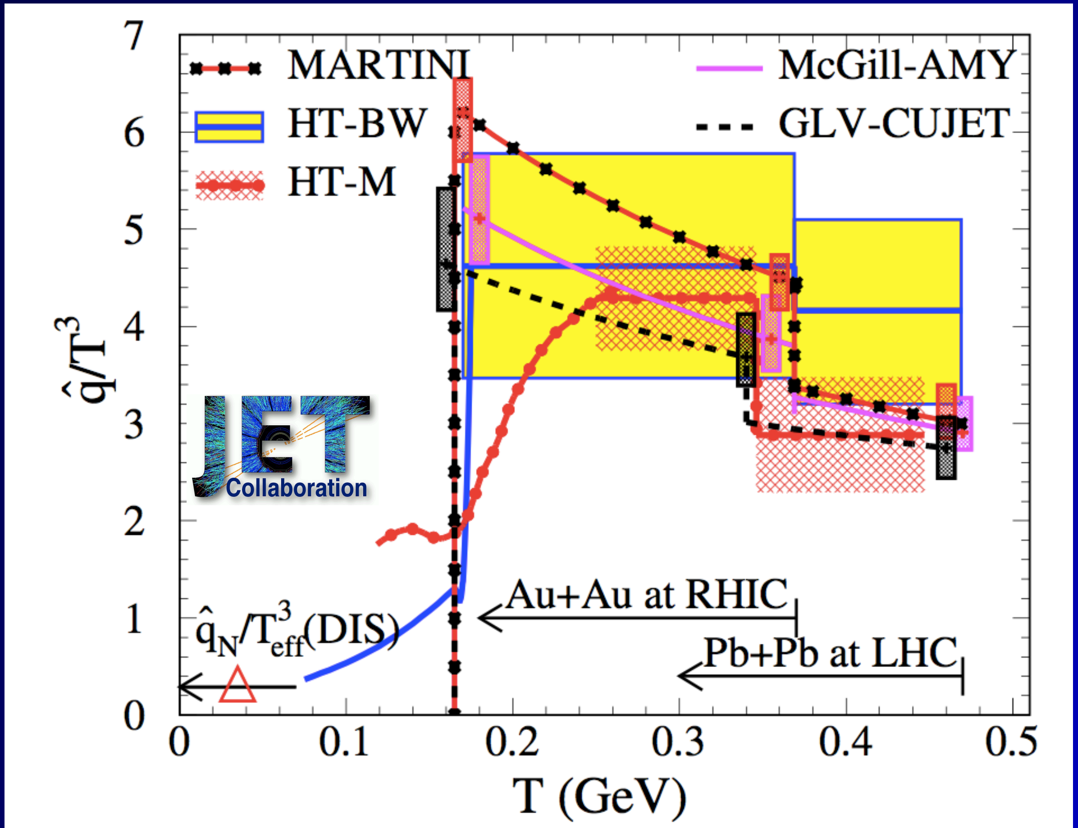
RHIC



LHC

Jet transport coefficient

JET Collaboration: arXiv:1312.5003



BDMPS'96

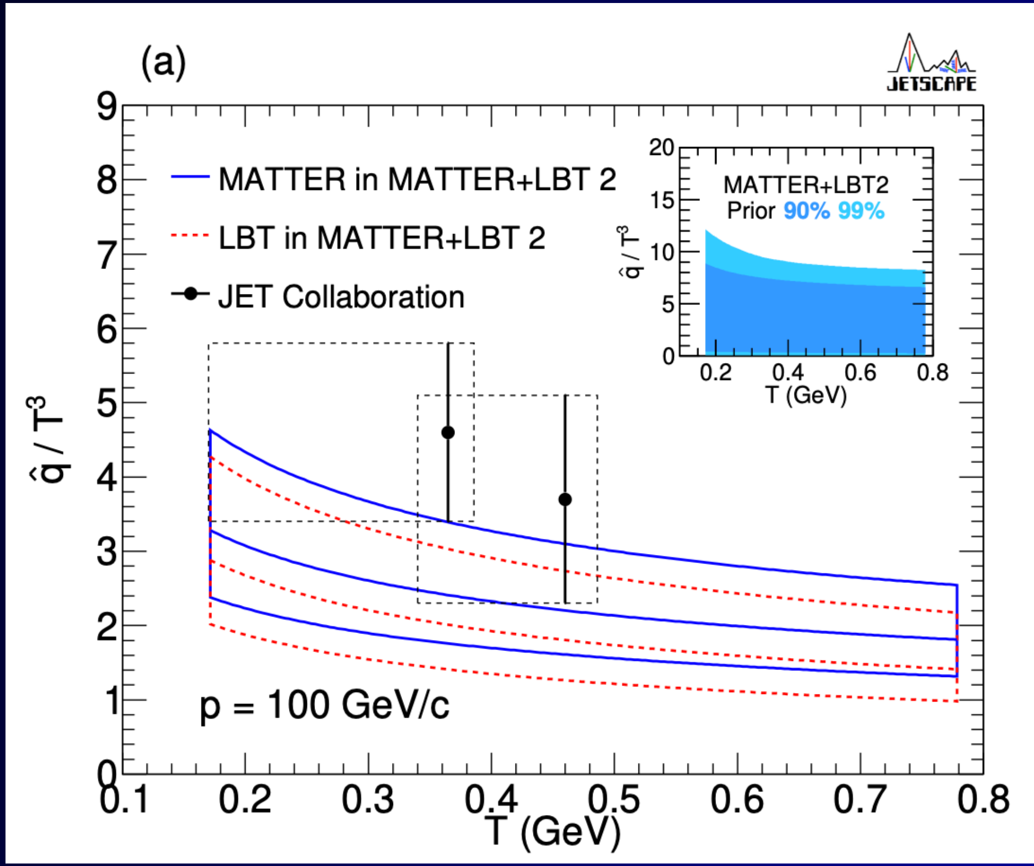
$$\Delta E \approx \frac{\alpha_s N_c}{4}\hat{q}L^2$$

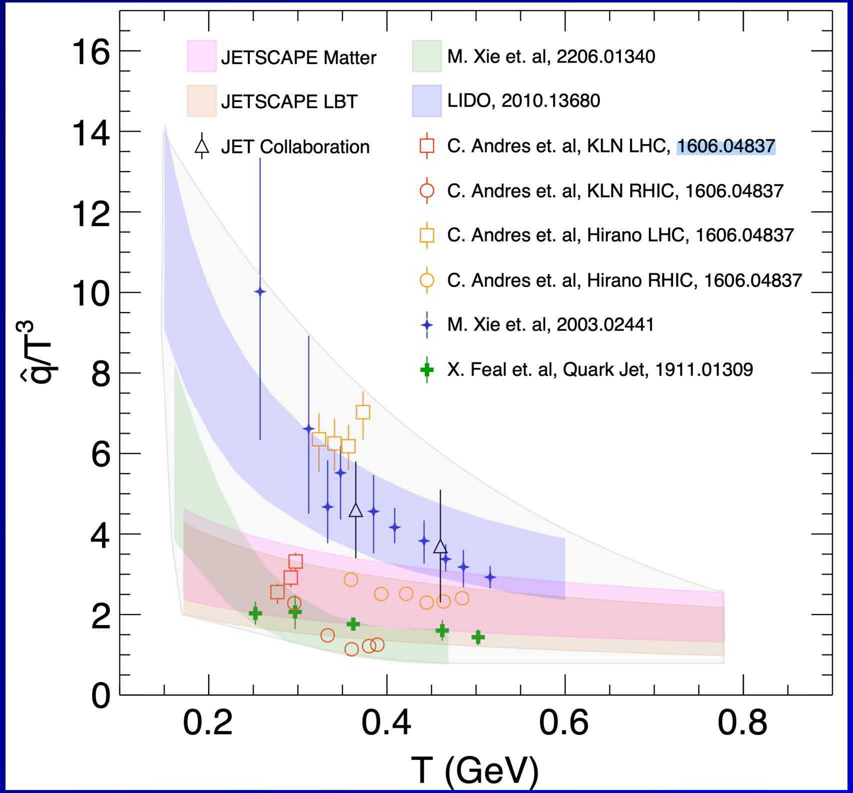
$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \text{ at } \begin{array}{l} \mathrm{T{=}370\ MeV}, \\ \mathrm{T{=}470\ MeV}, \end{array}$$

RHIC
LHC

Jet transport coefficient

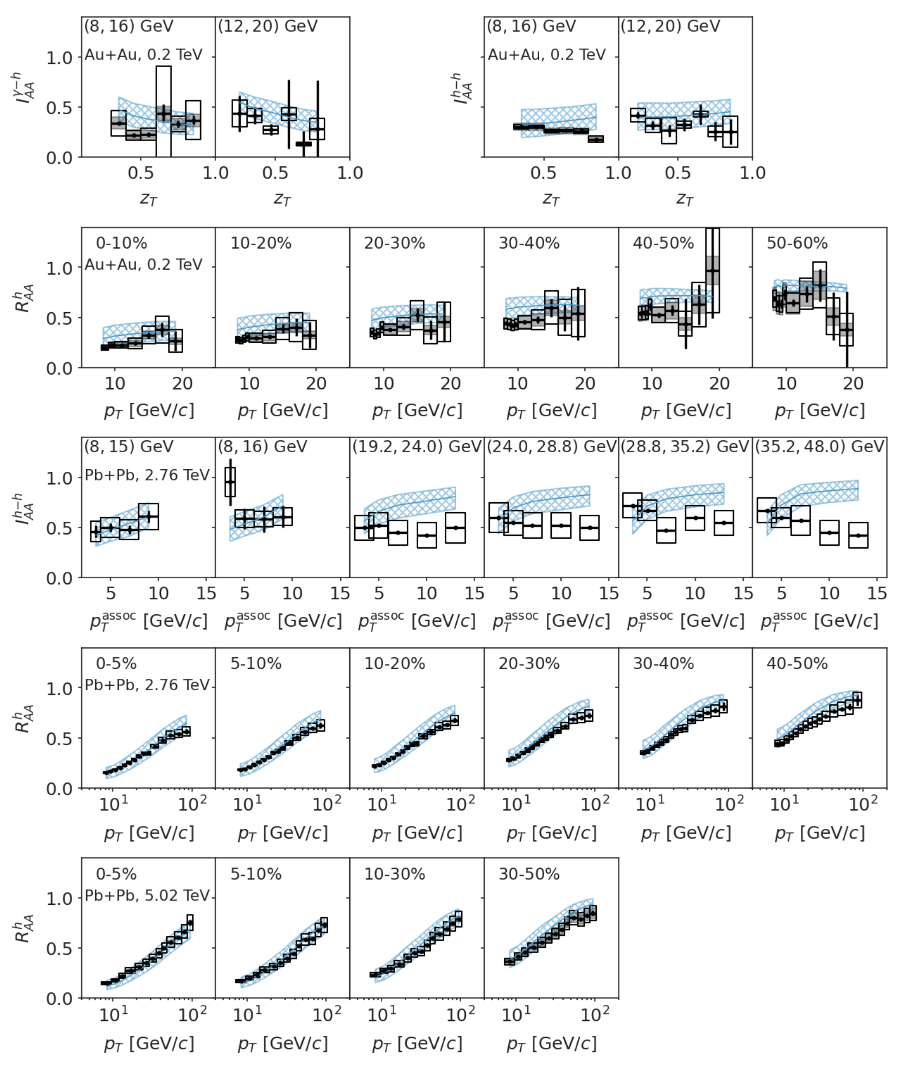
Bayesian parameter estimation





S. Cao et al. [JETSCAPE], Phys. Rev. C 104, no.2, 024905 (2021)

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

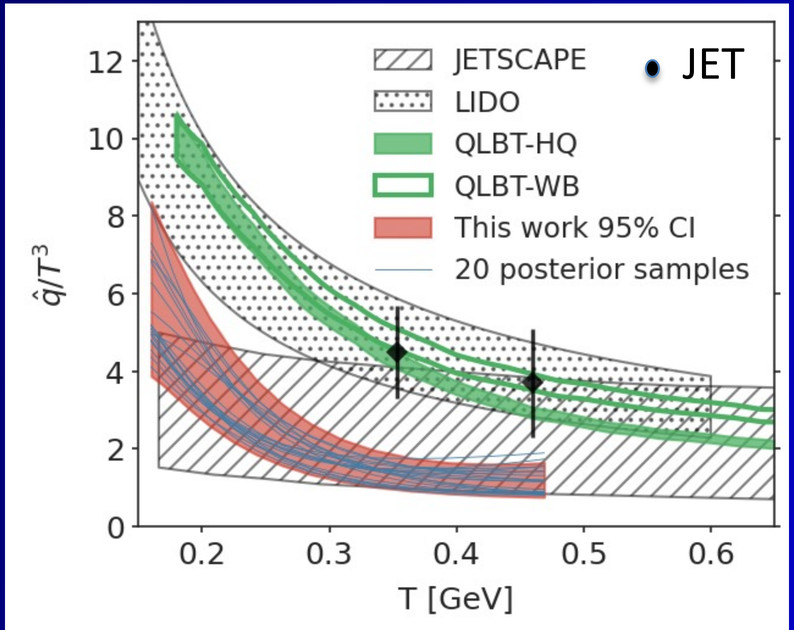
IF Bayesian e-Print: 2206.01340

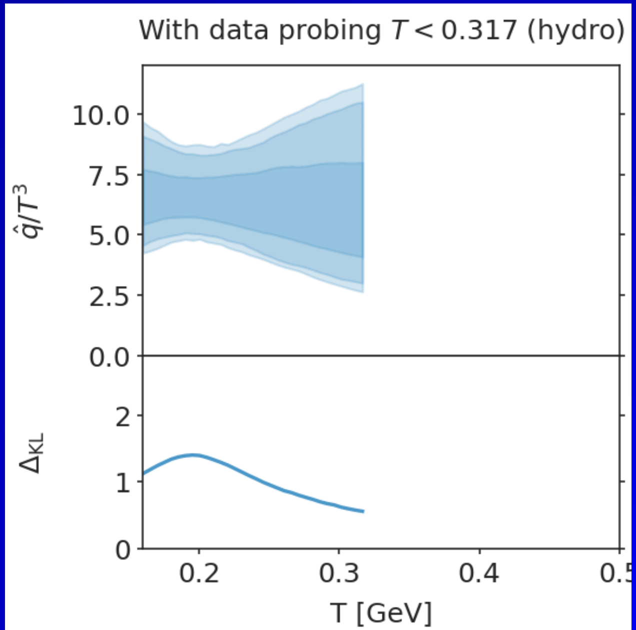
Strong T-dependence

Weak E-dependence

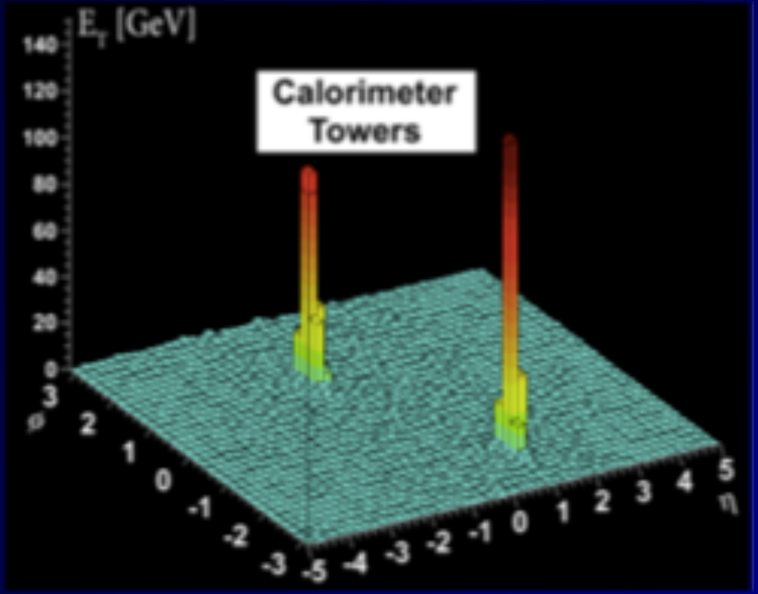
Information-Field approach to priors is free of long-range correlation

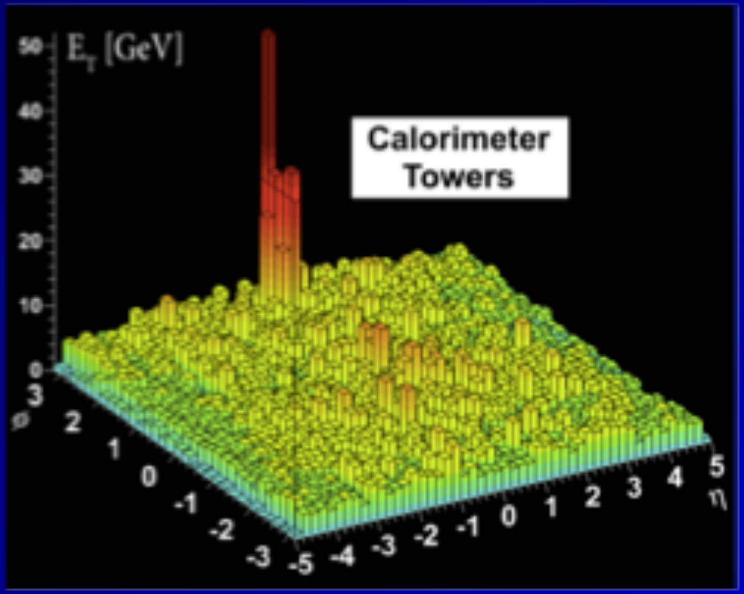
Xie, Ke, Zhang & XNW, PRC 108, L011901 (2023)





Jet energy and background subtraction





Jet energy as defined in the jet reconstruction algorithm

Uncorrelated background should be subtracted

Jet-induced medium response is correlated with jet: not background

Some of the energy lost by leading partons remain inside jet-cone

Monte Carlo Simulations of Jet Quenching

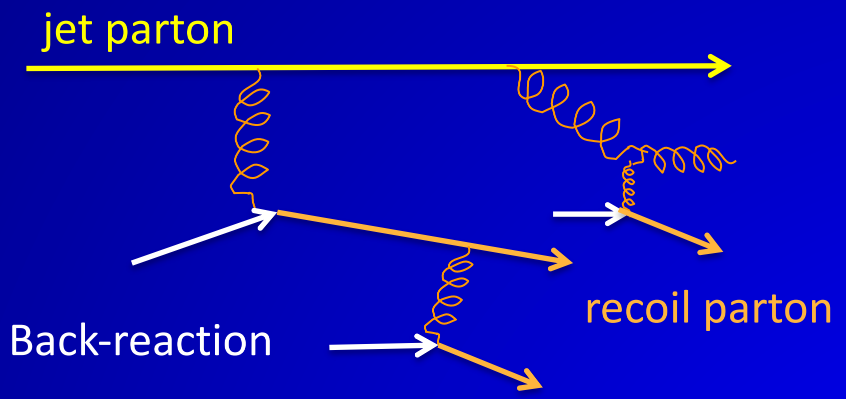
- LBT: Linear Boltzmann Transport model
  - CCNU +LBNL
- JEWEL: Jet Evolution with Energy Loss
  - K. Zapp at al @CERN
- LIDO: LInearized Diffusion plus boltzmann partonic transport mOdel
  - Weiyao Ke et al @ Duke
- JETSCAPE: MATTER + LBT
  - JETSCAPE Collaboration

LBT: Linear Boltzmann Transport

$$p_1 \cdot \partial f_1 = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4)|M_{12\to34}|^2 (2\pi)^4 \delta^4(\sum_i p_i) + \text{inelastic}$$

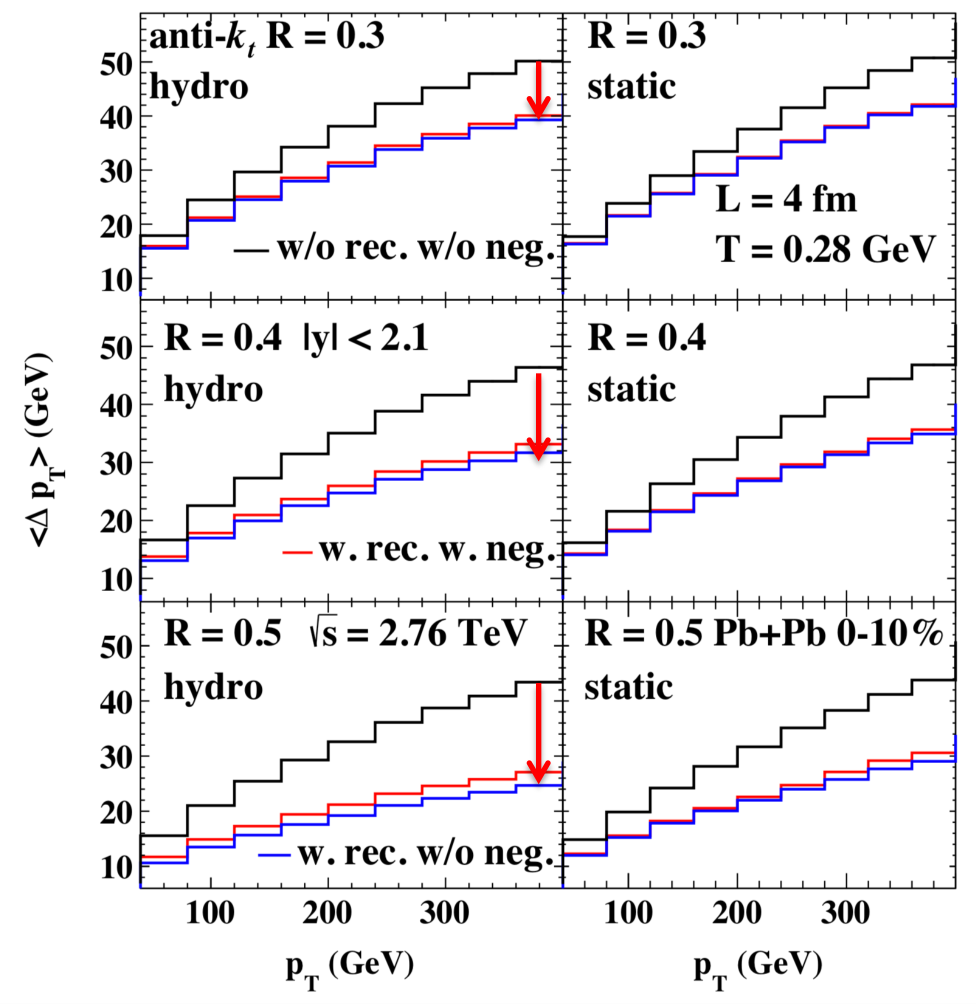
Induced radiation
$$\frac{dN_g}{dz d^2k_\perp dt} \approx \frac{2C_A\alpha_s}{\pi k_\perp^4} P(z)\hat{q}(\hat{p}\cdot u)\sin^2\frac{k_\perp^2(t-t_0)}{4z(1-z)E}$$

- pQCD elastic and radiative processes (high-twist)
- Transport of medium recoil partons (and back-reaction)
- CLVisc 3+1D hydro bulk evolution



Li, Liu, Ma, XNW and Zhu, PRL 106（2010）012301
XNW and Zhu, PRL 111 (2013) 062301; He, Luo, XNW & Zhu, PRC91 (2015) 054908;

Medium response reduces jet energy loss



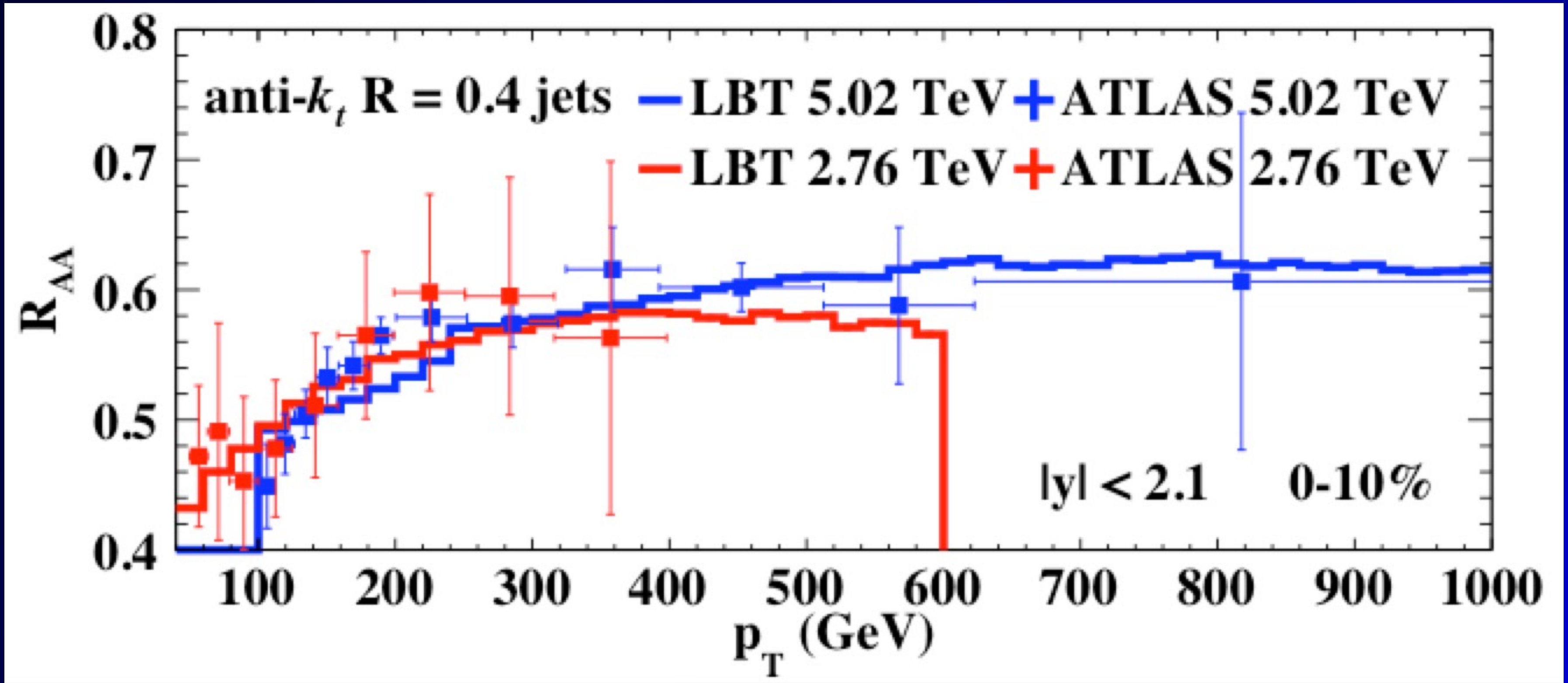
He, Cao, Chen, Luo, Pang & XNW 1809.02525

Recoil partons within the jet cone reduce the net jet energy loss –change pt dependence

Diffusion wake (backreaction) reduces the thermal background, if taken into account, increase the net jet Energy loss with given cone-size

Depend on jet cone-size R
Sensitive to radial flow

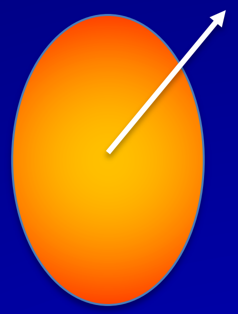
Energy and pT dependence



He, Cao, Chen, Luo, Pang & XNW 1809.02525

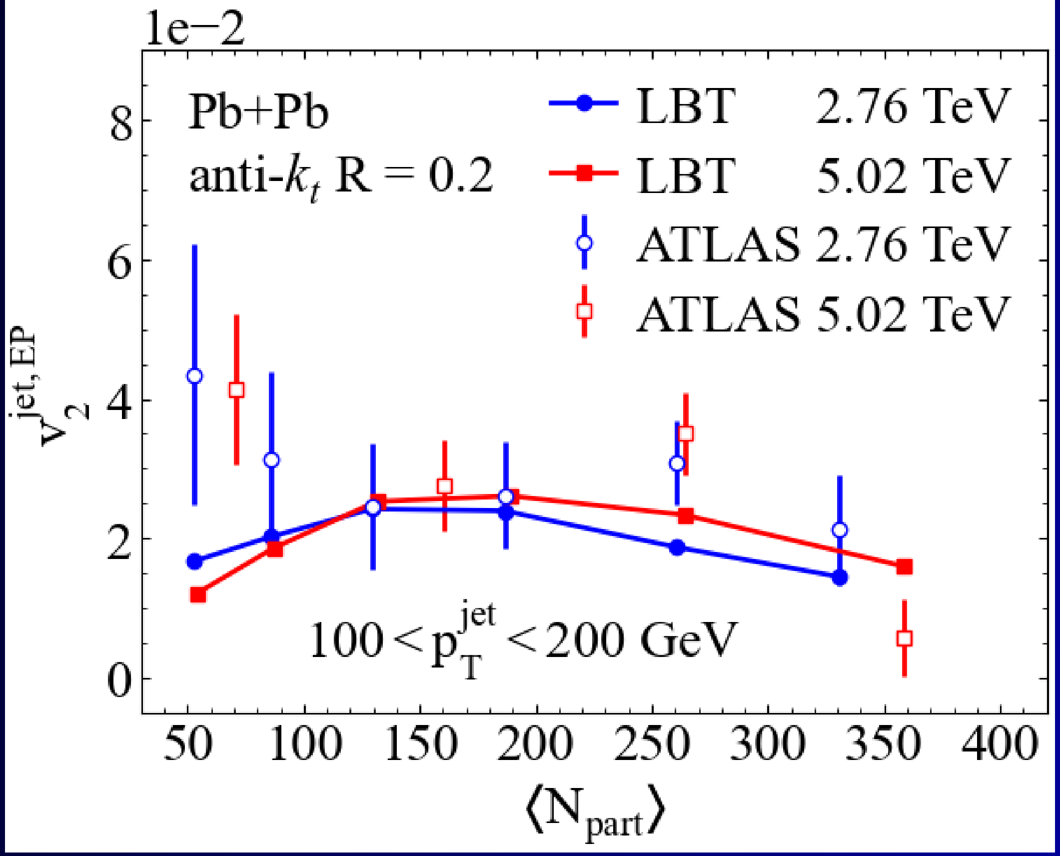
Weak pT dependence: initial jet spectra and pT dependence of energy loss ΔE
Week energy dependence: increase of jet energy loss and the slope of initial spectra

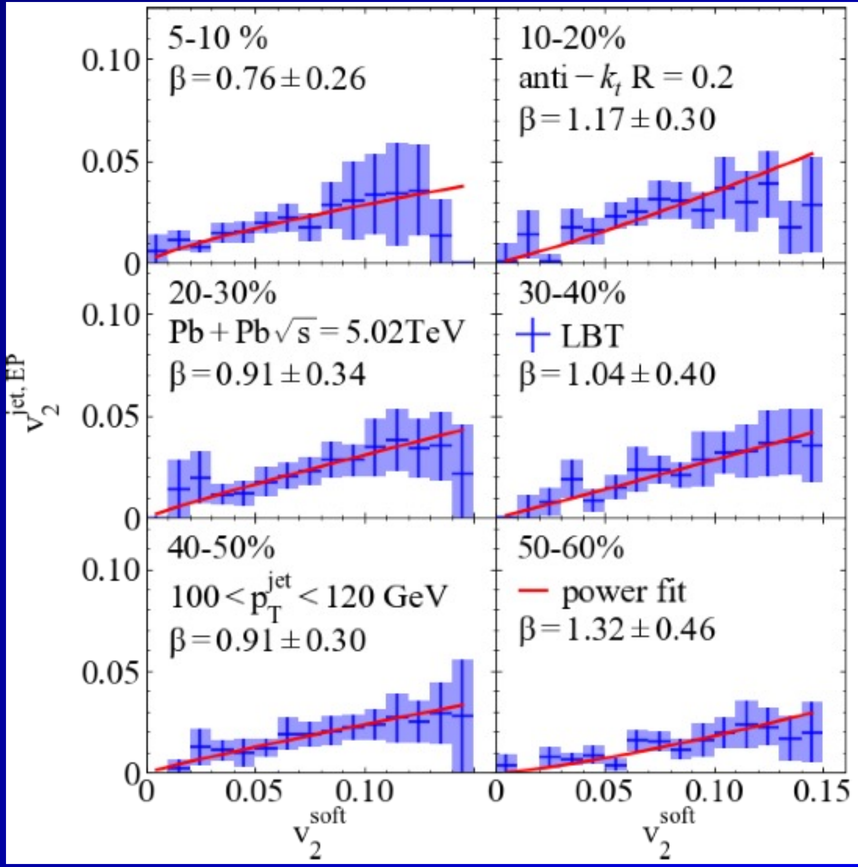
Jet anisotropy v_n



$$\frac{dN_{\rm jet}}{d\phi} = a[1 + 2v_2^{\rm jet}\cos(2(\phi_{\rm jet} - \Psi)) + \cdots]$$

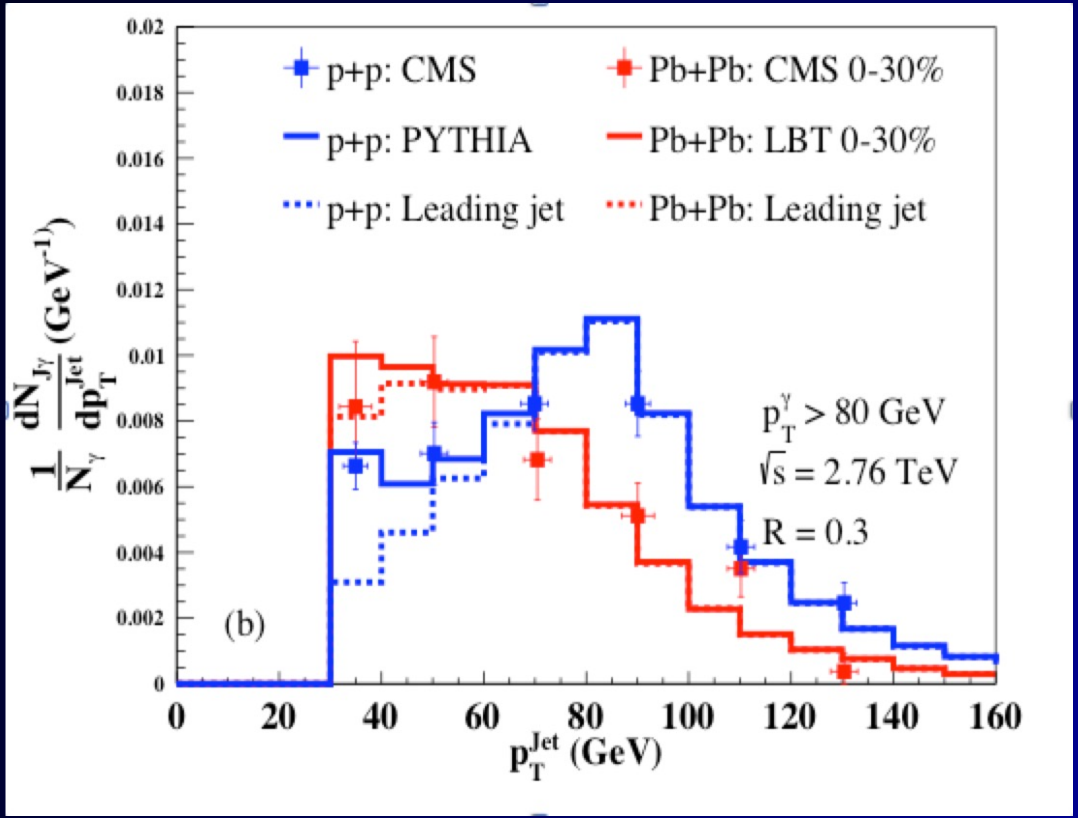
Hard-soft correlation



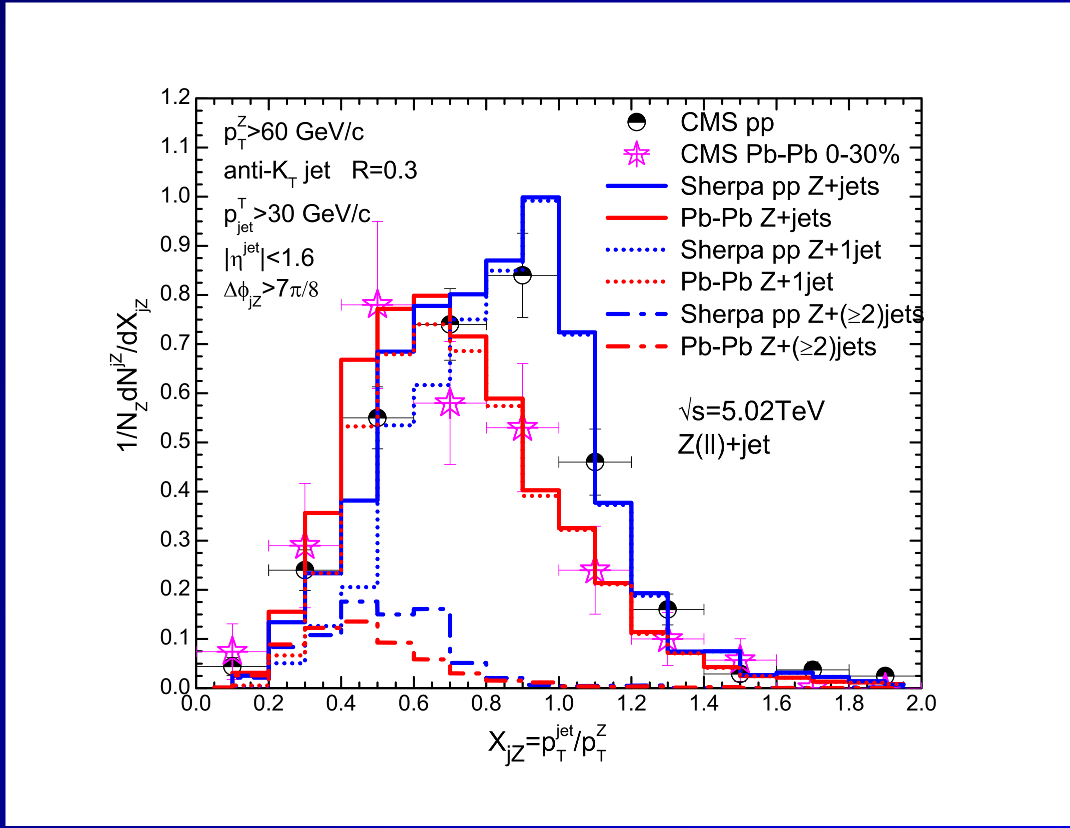


Yayun He et al, 2201.08408

Jet energy loss and γ(Z^0)-jet asymmetry



Luo, Cao, He & XNW, PLB782(18)707



Zhang, Luo, XNW, Zhang, arXiv:1804.11041

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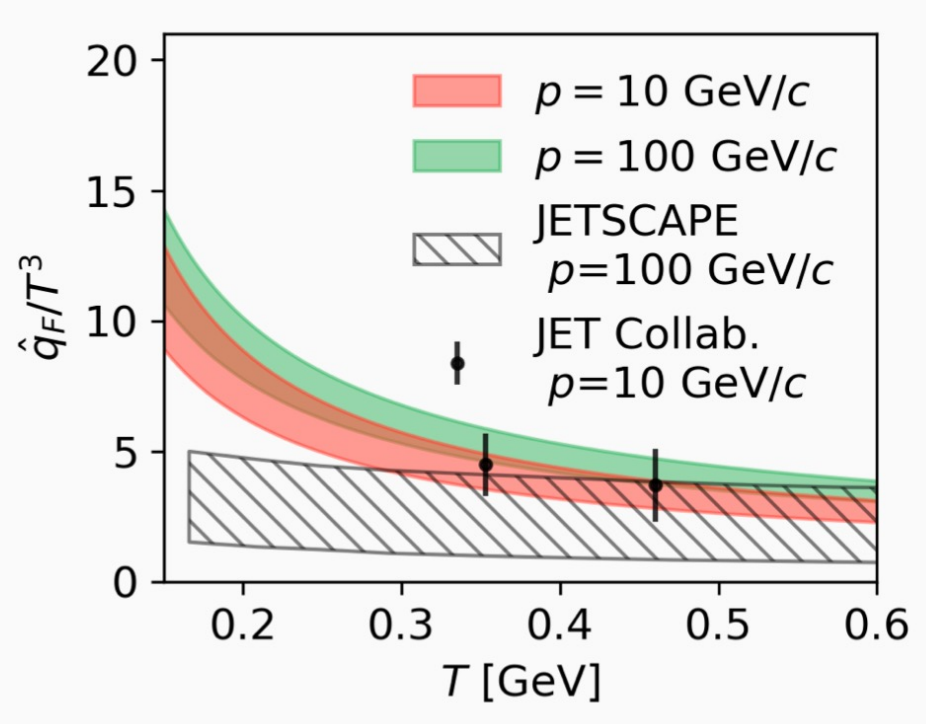
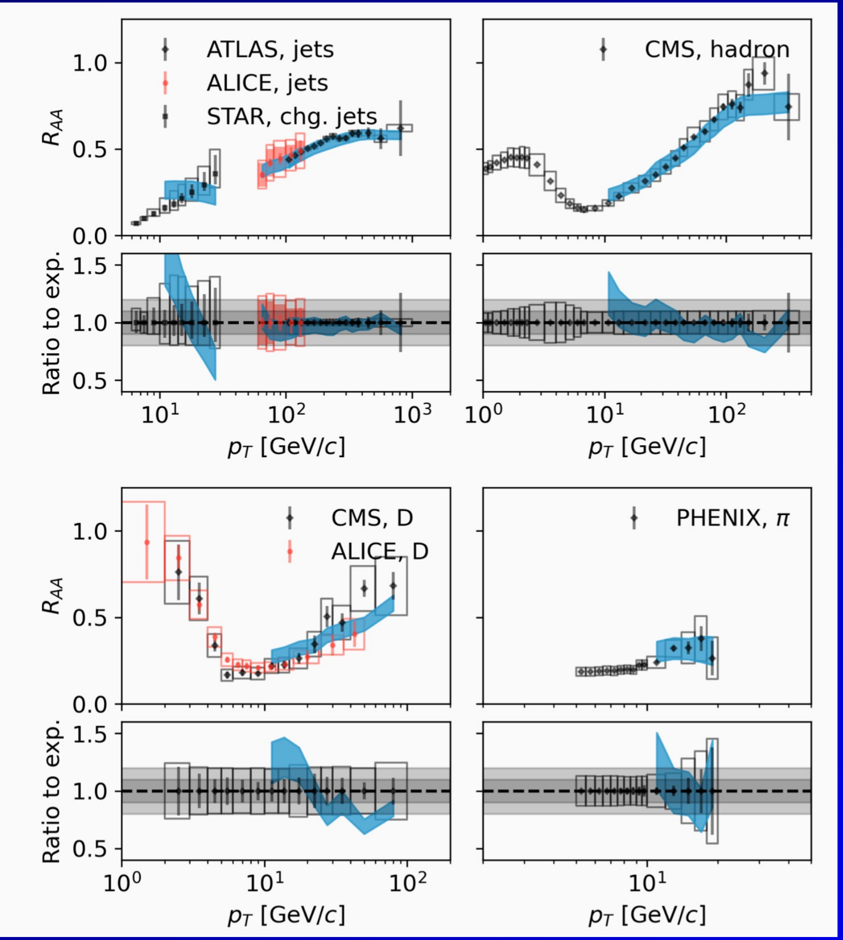
Hadron + Jet constraints on qhat

Weiyao Ke & XNW, JHEP 05, 041(2021)





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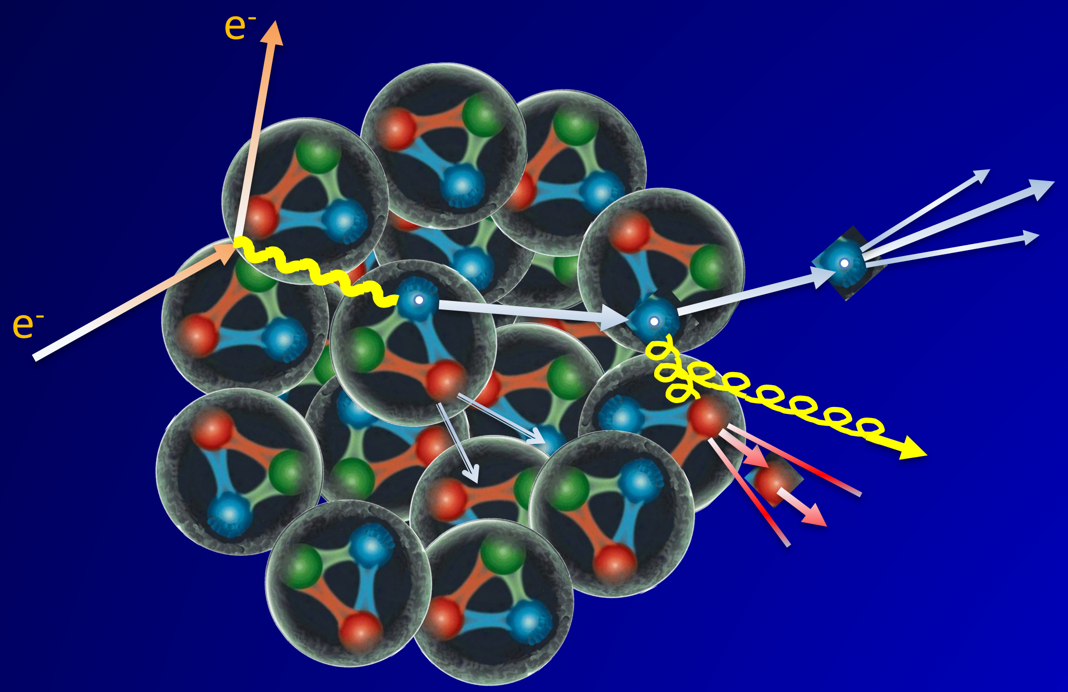
Parton propagation inside nuclei in DIS



Multiple scattering, p_T broadening, parton energy loss, hadronization, hadronic interaction in nuclei

Gluon Saturation and qhat in cold nuclei

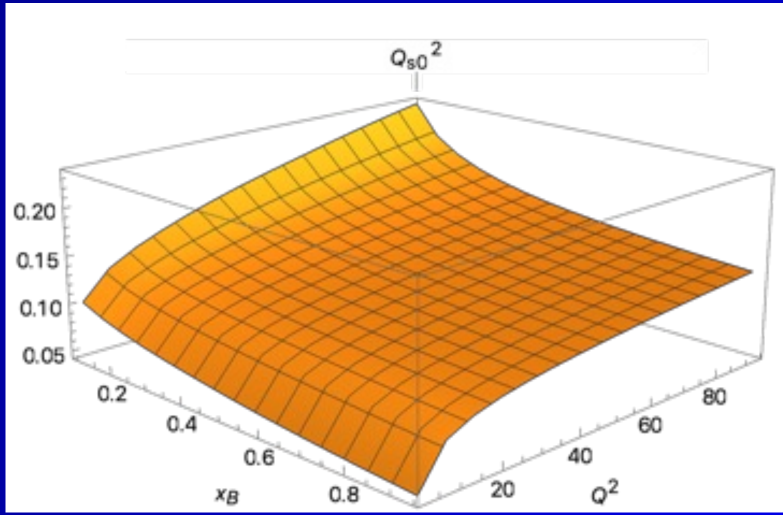
$$\phi(x_G, k_\perp, \mu^2) = \begin{cases} \phi^0(\frac{Q_s^2}{Q^2} x_B, Q_s, \mu^2)|_{\mu^2=Q_s^2}, k_\perp < Q_s; \\ \phi^0(x_G, k_\perp, \mu^2)|_{\mu^2=k_\perp^2}, \quad k_\perp > Q_s, \end{cases}$$

$$x_G = \frac{k_\perp^2}{2p^+q^-} = \frac{k_\perp^2}{Q^2} x_B$$

$$Q_s^2(x_B, Q^2, b_\perp) = \frac{4\pi^2 C_A}{N_c^2 - 1} t_A(b_\perp) \int \frac{d^2 k_\perp}{(2\pi)^2} \alpha_s(\mu) \phi(x_G, k_\perp, \mu^2),$$

$$Q_s^2(x_B, Q^2, b_\perp) \equiv \int dy^- \hat{q}_A(y^-)$$

$$\approx Q_{s0}^2(x_B, Q^2) A^{1/3} \sqrt{1 - \frac{b_\perp^2}{R_A^2}}$$



Yuanyuan Zhang & XNW 2104.04520

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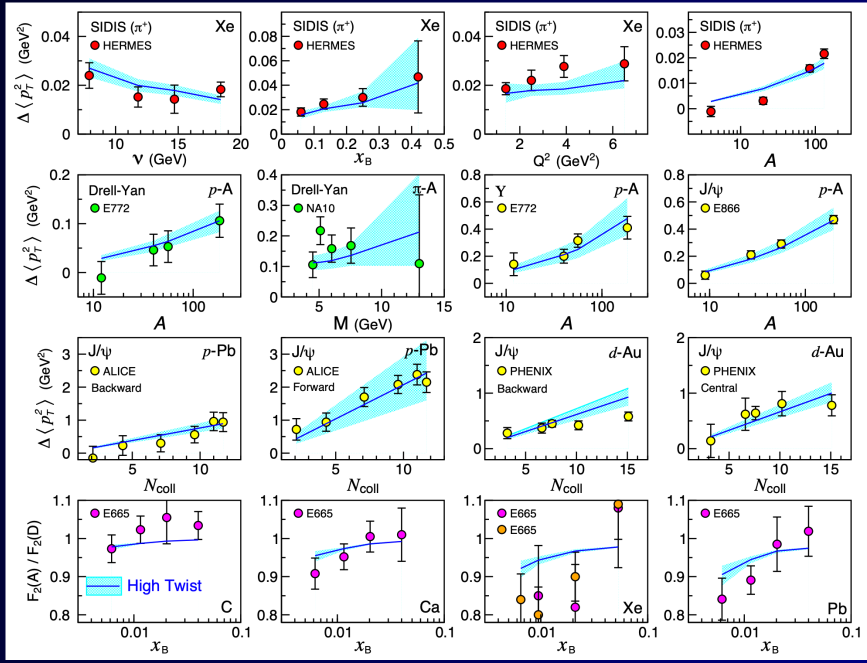
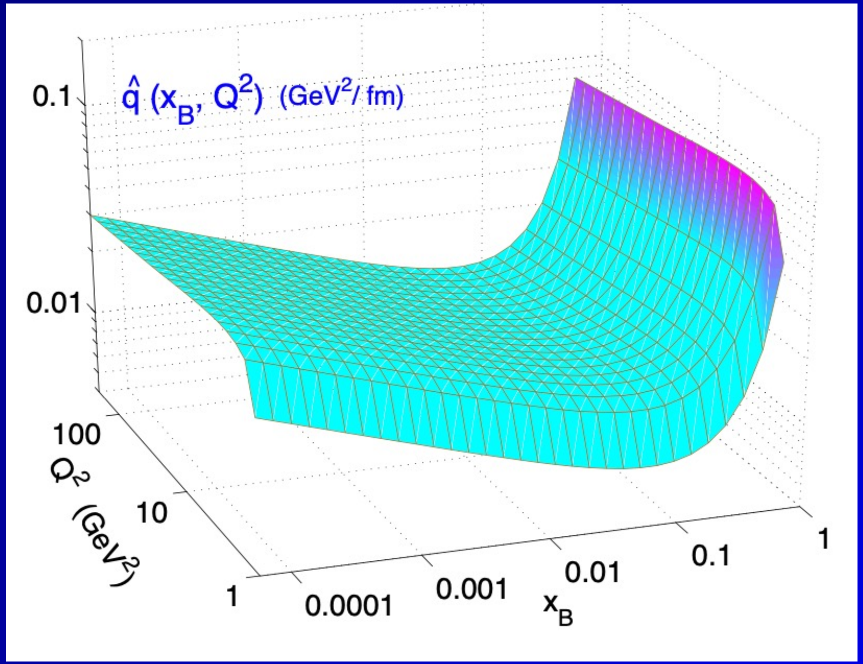
Jet transport coefficient in nuclei

A global extraction of the jet transport coefficient in nuclei

$$\hat{q}_0 \approx 0.02\ \ \mathrm{GeV}^2/\mathrm{fm}$$



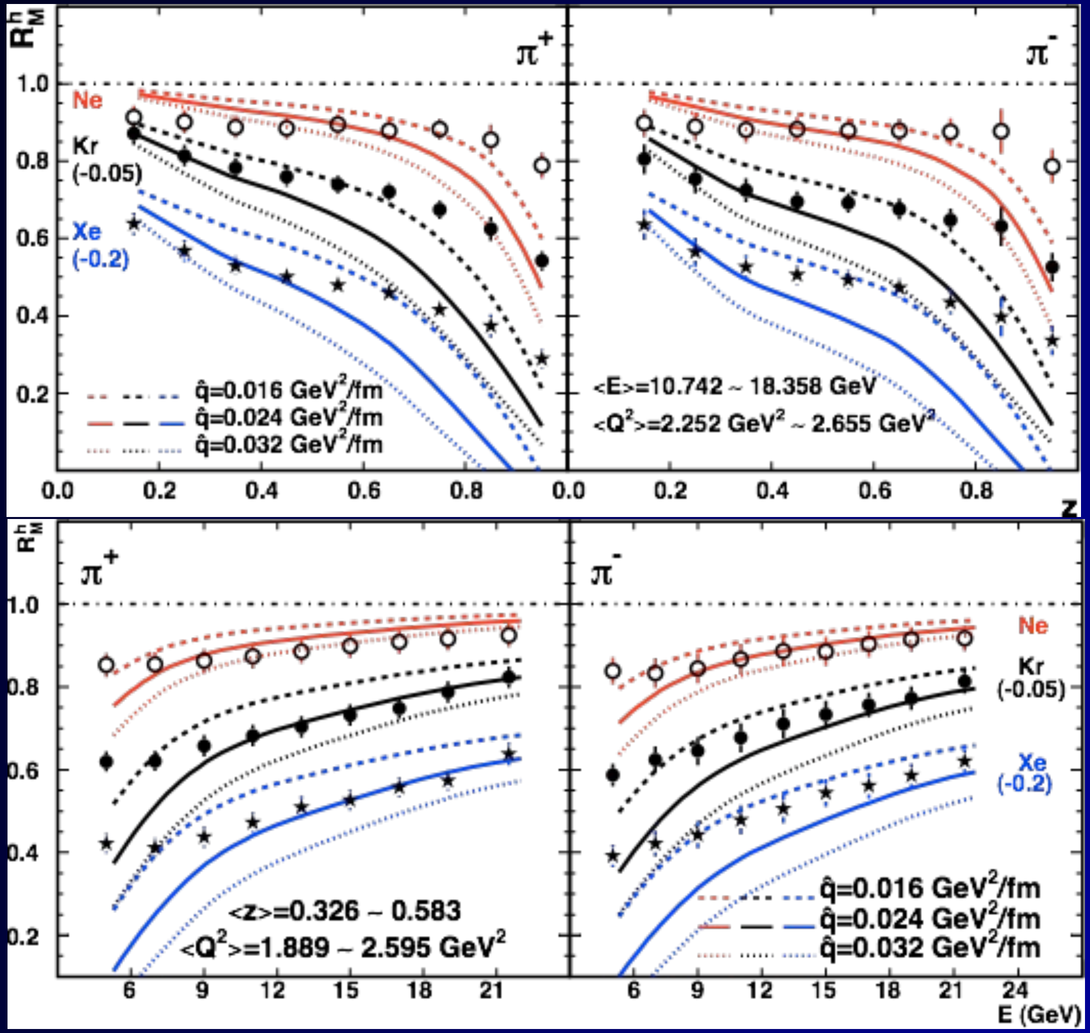


Data on: DIS, SIDIS(π), Drell-Yan, J/ψ (pA), Υ (pA)

Ru, Kang, Wang, Xing & Zhang *PRD* 103 (2021) 3, L031901

Jet quenching in DIS of large nuclei

$R = \frac{N_h^{eA}}{N_h^{eD}}$



Multiple gluon emission: modified DGLAP

$$\frac{\partial \tilde{D}_q^h(z_h,Q^2)}{\partial \ln Q^2}=\frac{\alpha_s(Q^2)}{2\pi}\int_{z_h}^1\frac{dz}{z}\left[\tilde{\gamma}_{q\to qg}(z,Q^2)\tilde{D}_q^h(\frac{z_h}{z},Q^2)+\cdots\right]$$

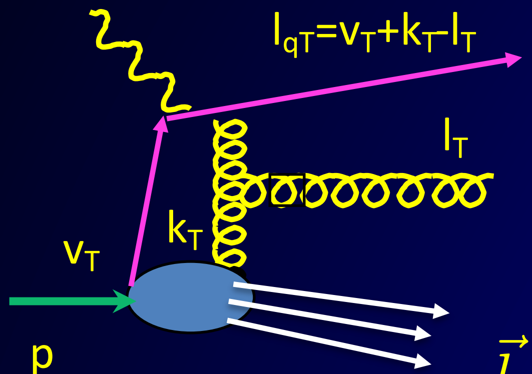
$$\tilde{\gamma}_{a\to bc}(z,Q^2)=\gamma_{a\to bc}(z)+\Delta\gamma_{a\to bc}(z,Q^2),$$

$$\Delta\gamma_{q\to qg}(z,\ell_T^2)=\frac{1}{\ell_T^2+\mu_D^2}\left[C_A\frac{(1-z)(1+(1-z)^2)}{z}+C_F z(1+(1-z)^2)\right]\int dy^-\hat{q}(y^-)4\sin^2(x_L p^+ y^-/2)$$

$$\hat{q}_{\rm HT}\approx 0.02\ \ {\rm GeV}^2/{\rm fm}$$

Deng & XNW, *PRC* 81 (2010) 024902
Chang, Deng & XNW *PRC* 89 (2014) 3, 034911
Chang, Deng & XNW, *PRC* 92 (2015) 5, 055207

Nuclear modification of dijets at EIC

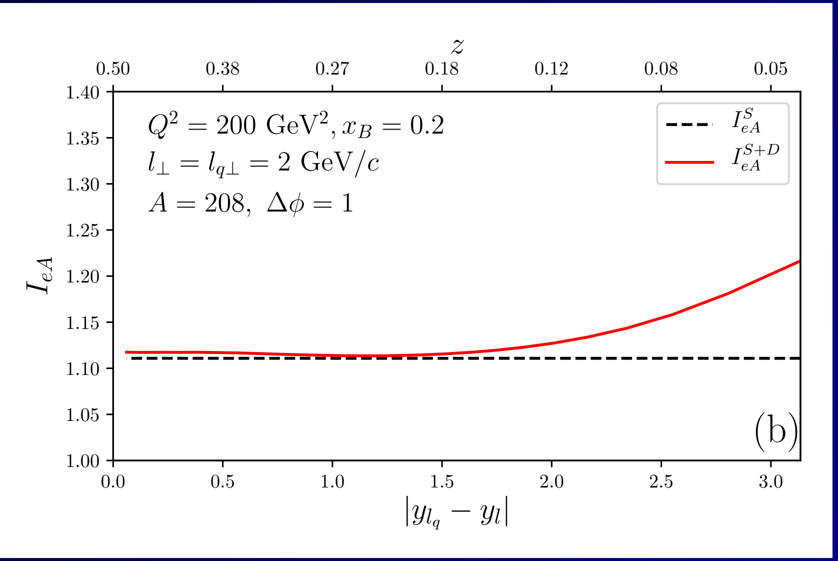


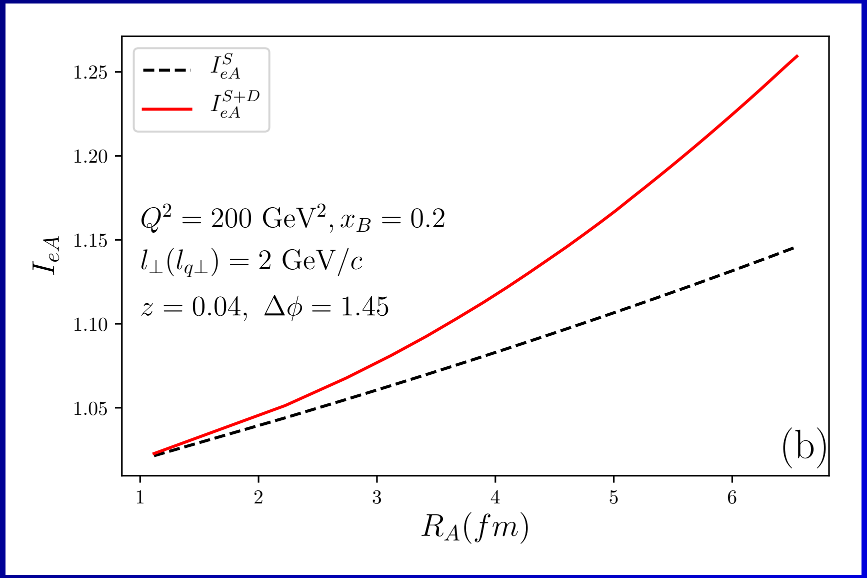
$$\frac{d\hat{\sigma}_D}{dx_B dQ^2 dz d^2l_\perp d^2l_{q\perp}} = \sigma_0 \frac{1+z^2}{1-z}\frac{\alpha_s^2}{N_c}\int dy_1^- \rho(y_1^-, \vec{y}_{N\perp})$$

$$\otimes \int d^2\vec{v}_\perp \int \frac{d^2\vec{k}_\perp}{(2\pi)^2} f_q^A(x_B,\vec{v}_\perp)\frac{\phi(0,\vec{k}_\perp)}{k_\perp^2}\mathcal{N}_g(\vec{l}_\perp,\vec{l}_{q\perp},\vec{k}_\perp,\vec{v}_\perp)$$

$$\vec{l}_\perp + \vec{l}_{q\perp} = \vec{k}_\perp + \vec{v}_\perp$$

Yuanyuan Zhang & XNW 2104.04520





Large rapidity gap δy → small formation time τ_f

LPM → $\sigma_D \sim A^{5/3}$ $\sigma_S \sim A^{4/3}$

eHIJING: electron Heavy Ion Jet Interaction Generator

- Pythia for γ^*+N → jet shower processes
- Simple model for saturation in gluon TMD distribution
- Elastic scattering with TMD distr.

$$\alpha_s \phi_g(x_g, k_\perp^2, Q^2) = \frac{(1-x_g)^p x_g^\lambda}{q_\perp^2 + Q_s^2},$$

Kharzeev & Levin PLB 523 79-87]

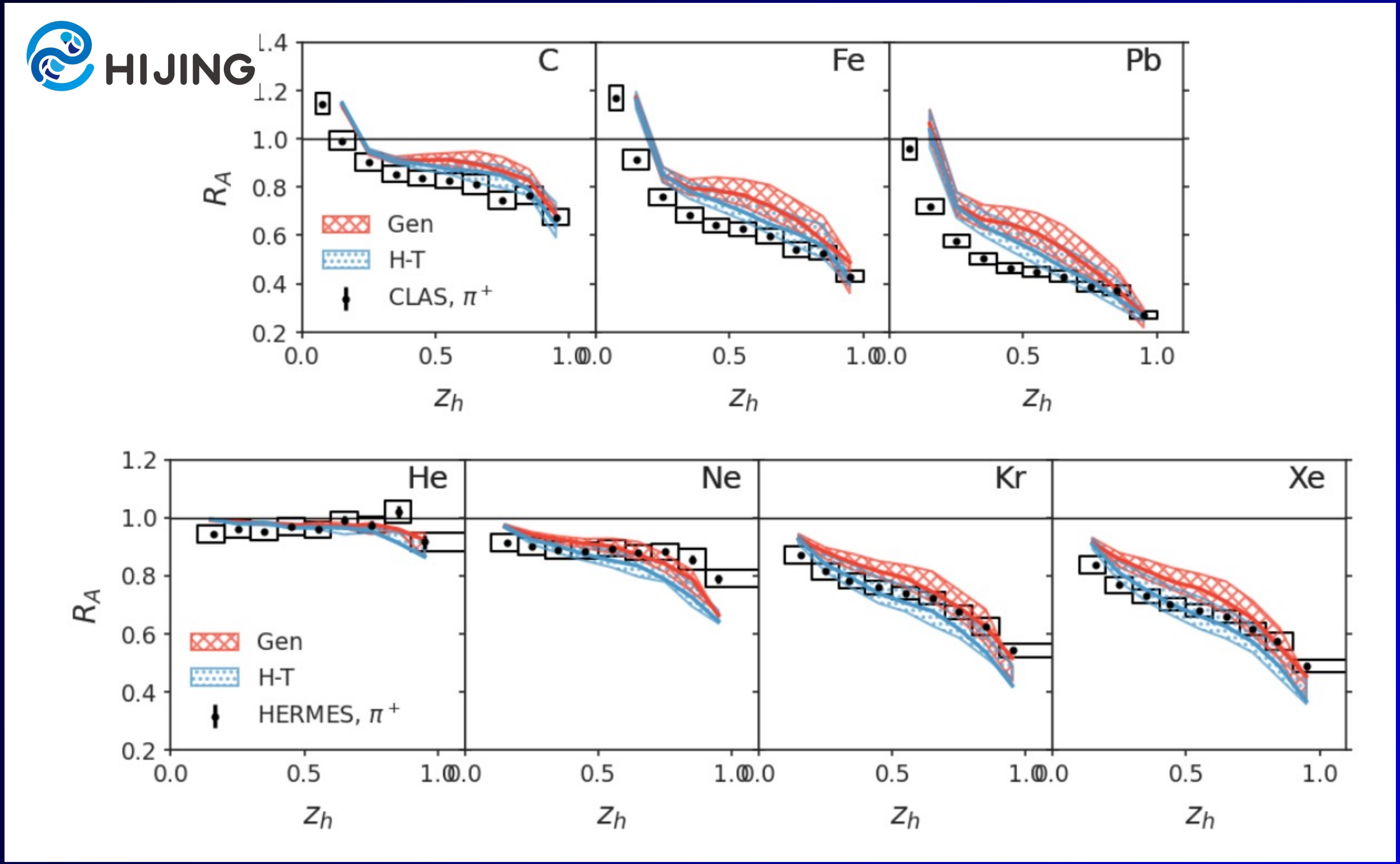
- Induced gluon emission

$$\frac{dN_g}{dz dl_\perp^2} = \frac{P_{qq}^0(z)}{l_\perp^2}\left\{1 + \tilde{T}_A \int_0^L dt^+ \int \frac{d^2k_\perp}{\pi} \frac{\alpha_s \phi_g(x_g, k_\perp^2)}{k_\perp^2} \frac{2\vec{k}_\perp \cdot \vec{l}_\perp}{(\vec{l}_\perp - \vec{k}_\perp)^2}\left[1 - \cos\frac{t^+}{\tau_f}\right]\right\}$$

- Multi-scale evolution for multiple gluon emission
  – Q^2, Q_s^2, μ_0^2
- String hadronization

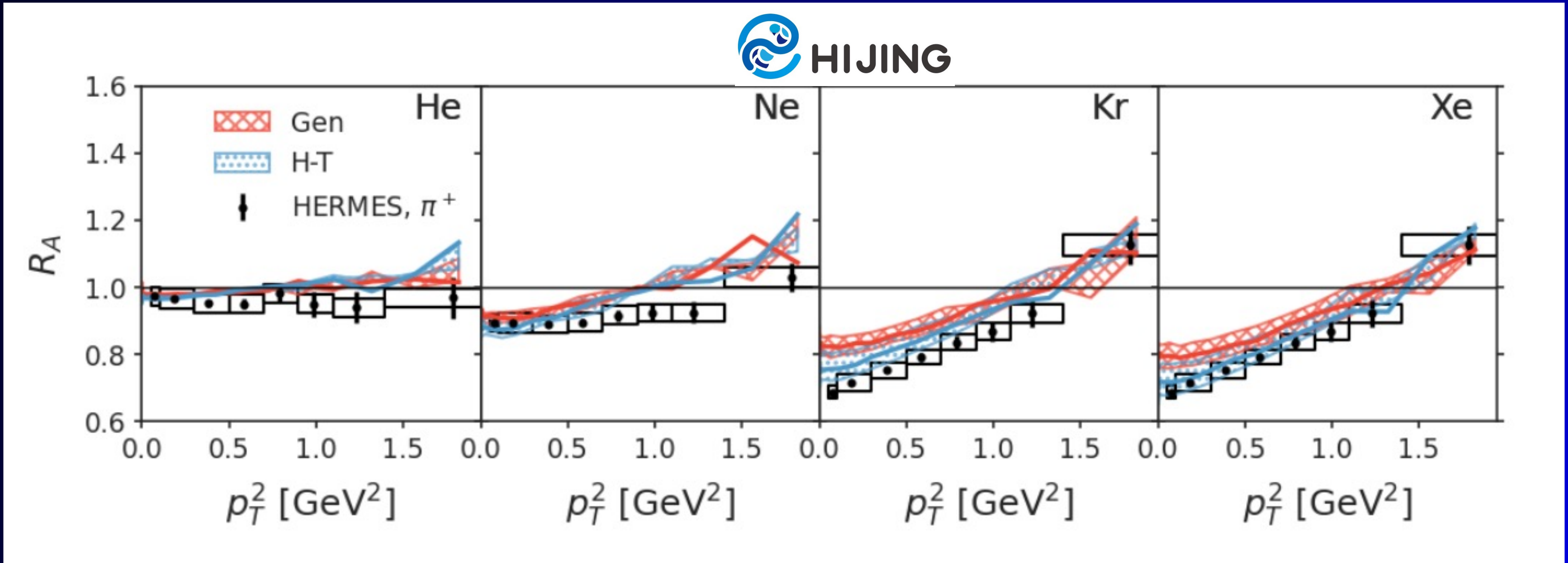
Weiyao Ke, et al to be published soon

Suppression of single hadron spectra



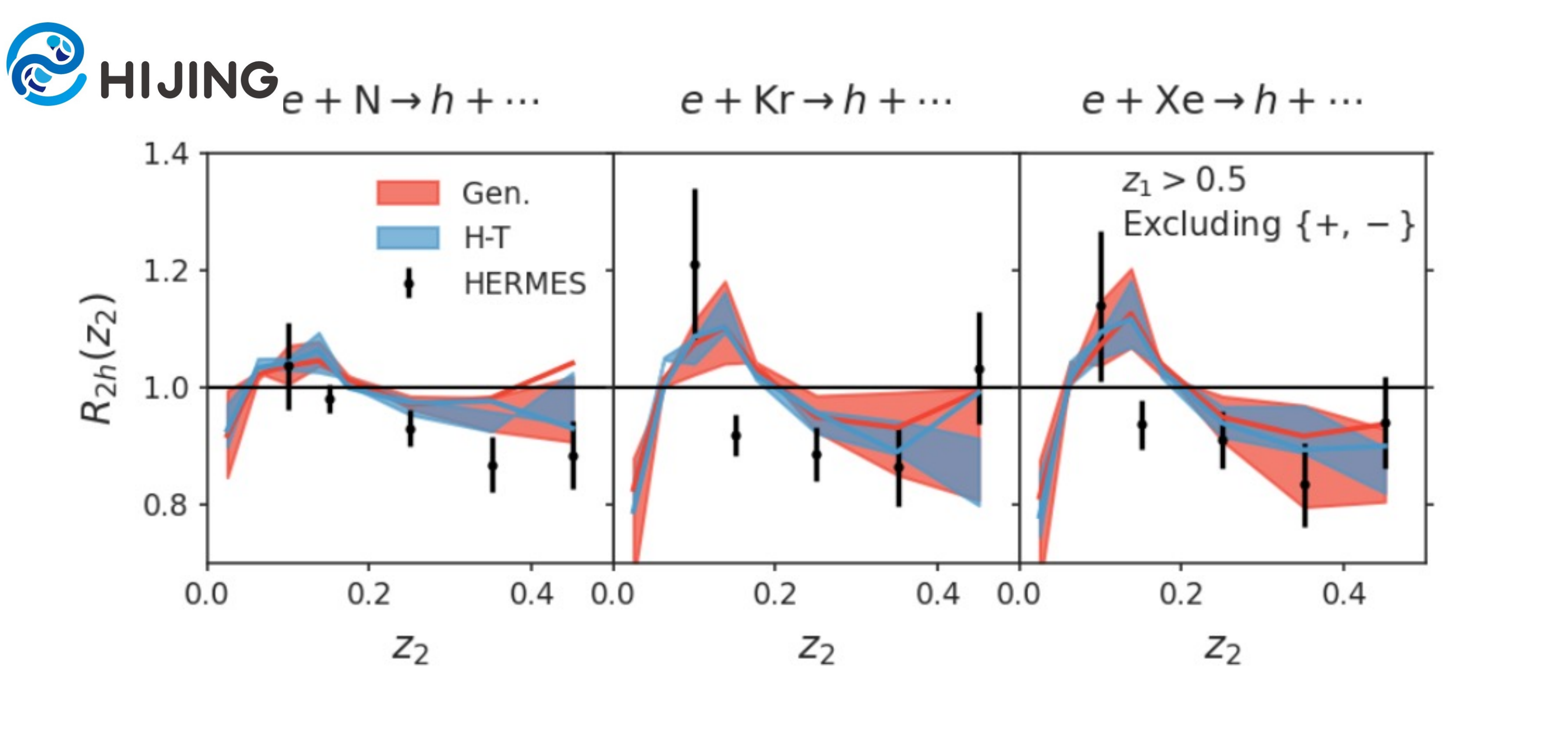
Effect of hadron absorption in CLAS?

Transverse momentum broadening



modification of p_T spectra due to suppression of low p_T hadrons due to parton energy loss + p_T broadening

Modification of dihadron correlation



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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

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