高能重离子碰撞物理和核子结构理论研究进展综述
Theory Overview of High Energy Heavy Ion Physics and Nucleon Structure[1]

肖博文
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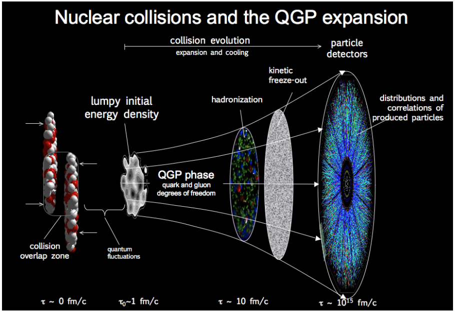
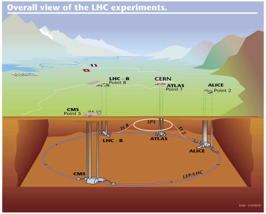
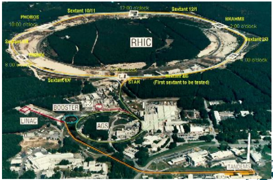
[1]感谢高建华，庞龙刚，秦广友，王新年，袁烽和周剑等同事为此报告所提供的建议和帮助

Heavy Ion Collisions

Relativistic heavy-ion collision experiments at RHIC and LHC open an unprecedented window for studying strongly interacting nuclear matter under extremely hot and dense conditions.





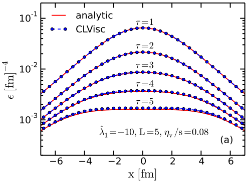


- Soft physics: QCD phase diagram, Hydrodynamics (macroscopic), transport theory (microscopic) $\cdots$;
- Hard Probes: Jet quenching, dijets, $\cdots$;
- Initial States: Small-x gluon distributions, gluon saturation in heavy nuclei, $\cdots$;
- Chiral effects.

CLVisc: CCNU + LBNL (3+1)D viscous hydrodynamics

$$\nabla_\mu T^{\mu\nu} = 0, \quad \text{with} \quad T^{\mu\nu} = \epsilon u^\mu u^\nu - P(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}.$$

$$\pi^{\mu\nu} = \eta_v \sigma^{\mu\nu} - \tau_\pi \left[\Delta^\mu_\alpha \Delta^\nu_\beta u^\lambda \nabla_\lambda \pi^{\alpha\beta} + \frac{4}{3}\pi^{\mu\nu}\vartheta\right] - \lambda_1 \pi^{\langle\mu}_{\lambda}\pi^{\nu\rangle\lambda} - \lambda_2 \pi^{\langle\mu}_{\lambda}\Omega^{\nu\rangle\lambda} - \lambda_3 \Omega^{\langle\mu}_{\lambda}\Omega^{\nu\rangle\lambda}$$

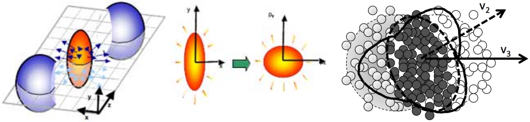


ε: energy density, p: pressure, u^μ: fluid four-velocity and $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$: projection operator which is orthogonal to the fluid velocity, $\pi^{\mu\nu}$: shear stress tensor, $\Omega^{\mu\nu}$: vorticity.

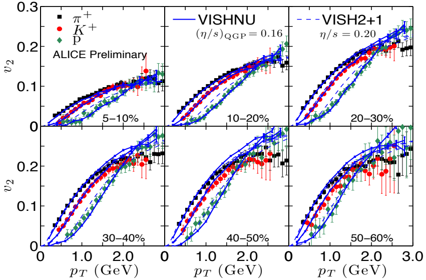
- Parallelized on GPU to solve the 2nd order relativistic hydrodynamics.
- Match perfectly with the conformal exact solution assuming conformal symmetry.
- Efficient to simulate actual event-by-event relativistic heavy ion collisions. 60x faster.
- Publicly available: https://gitlab.com/snowhitiger/PyVisc.
- L.-G. Pang, H. Petersen, X.-N.Wang, arXiv:1805.03762, accepted by PRC; L.-G. Pang, Y. Hatta, X.-N.Wang and B.-W.Xiao, PRD91 (2015) no.7, 074027; L.-G. Pang, Q. Wang, X.-N. Wang, PRC86 (2012) 024911.
- New development: HuiChao Song *et al* arXiv:1801.03334: Applications of deep learning to relativistic hydrodynamics.

Relativistic Hydrodynamics

Anisotropic flow of particles in terms of Fourier expansions



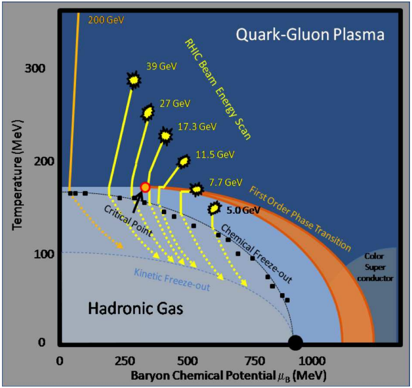
$$E\frac{dN}{d^3p} = \frac{1}{2\pi}\frac{dN}{p_\perp dp_\perp dy}\left[1 + 2\sum_{n}^{\infty} v_n \cos n(\phi - \psi_{RP})\right].$$



- Viscous hydrodynamics correctly yields elliptic flow v_2 and higher harmonics for pion, kaon and proton in the soft momentum region.
- [Huichao Song, Shen, Heinz, 2011 (VISHNU)]
- [Shen et al., PRC84 (2011) 044903 (VISH2+1)]

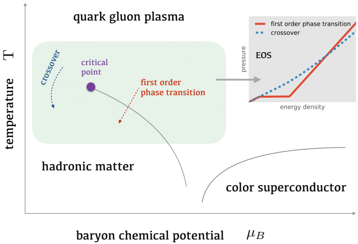
QCD phase diagram

RHIC Beam Energy Scan Program: study of phase diagram and search for the critical point in QCD.

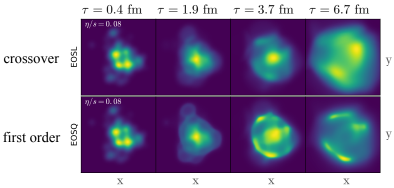


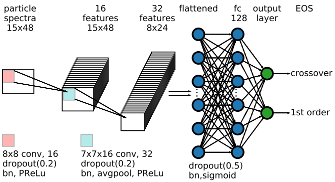
[S. Gupta, X. Luo, B. Mohanty, H. Ritter, N. Xu, Science **332**, 1525 (2011).]

- The transition between QGP and hadronic states is conjectured to be a crossover at small density (small μ), and first order at moderate density (moderate μ).
- Similarly, water at high pressure and high temperature, the transition between gas-liquid becomes crossover with smooth thermodynamic quantities.



Equation-of-state-meter using deep learning

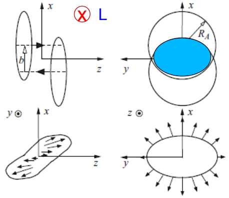


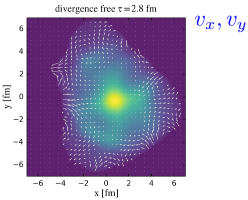


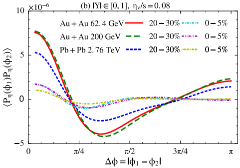
- Given equation-of-state, CLVisc simulations of heavy ion collisions can produce momentum distribution of final state hadrons; It is difficult to determine the QCD EoS and phase transition type from QGP to hadronic matter.
- Deep learning is used to classify crossover and 1st order phase transition in the QCD EoS with 95% prediction accuracy, given the final spectra (simulation data).
- The study demonstrated that a traceable encoder of the QCD phase structure survives the dynamical evolution and exists in the final snapshot of heavy ion collisions, one can decode these information from the highly complex output using machine learning.

[L.-G. Pang, K. Zhou, N. Su, H. Petersen, H. Stocker, X.-N. Wang, Nature Commun. 9 (2018) no.1, 210]

Vortical fluid in quark gluon plasma and Λ polarization







- The most vortical fluid: $\omega \sim 9 \times 10^{21} s^{-1}$ [STAR collaboration, Nature **548**, 62 (2017)].
- Correlation between polarization of Λ hyperon and global orbital angular momentum. [Z.t. Liang and X.n. Wang, PRL 94,102301(2005), Q. Wang, Quark Matter 2017 plenary talk];
- CLVisc reveals vortex pairs in transverse plane and vortex rings along the beam direction in E-B-E simulations of heavy ion collisions.
- The longitudinal polarizations are coupled to collision geometry, which is shown in the Λ spin-spin correlation.

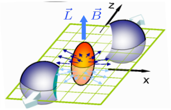
[R.-H. Fang, L.-G. Pang, Q. Wang, X.-N. Wang, PRC94 (2016) no.2, 024904; L.-G. Pang, H. Petersen, Q. Wang and X.-N. Wang, PRL 117 (2016) no.19, 192301; H. Li, L.-G. Pang, Q. Wang and X.-L. Xia, PRC96 (2017) no.5, 054908.]

Progress in Quantum Transport Theory

Non-equilibrium effects: pre-equilibrium, system evolving …

+

Quantum effects: Global polarization, CME, CVE …



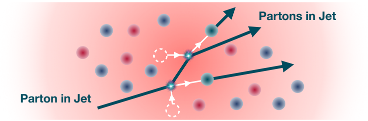
- QTT can describe global polarization, Chiral Magnetic effct, Chiral Vortical effect in a covariant and consistent way.
- [J. H. Gao, S. Pu, Q. Wang, Phys. Rev. D96 (2017) no.1, 016002;J. H. Gao, Q. Wang, Phys. Lett. B749 (2015) 542-546.]
- Simplified QTT: have reduced 16 Wigner functions and 32 Wigner equations to 1 distribution function and 1 Boltzmann-like equation (background field approximation and chiral limit).
- [J. H. Gao, Z. T. Liang, Q. Wang, X. N. Wang, arXiv:1802.06216.]

QGP medium modification of jets

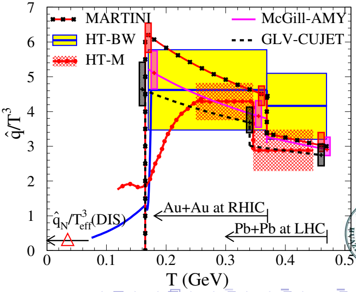
Jet and QGP medium interactions are characterized by the momentum broadening and energy loss:

$$\hat{q} \equiv \frac{\text{Momentum transfer squared}}{\text{Length}} \quad , \quad -\frac{dE}{dx} = \frac{\alpha_s N_c}{4}\hat{q}L.$$

- $\hat{q}$ and $\frac{dE}{dx}$ are two sides of the same coin.
- Reflect the strength of the medium response to traversing jets.
- $\hat{q}$ from JET collaboration[Phys.Rev. C90 (2014) no.1, 014909]:

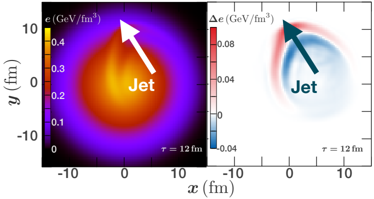


$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \;\; \text{at} \;\; \begin{matrix} \text{T=370 MeV,} \\ \text{T=470 MeV,} \end{matrix}$$

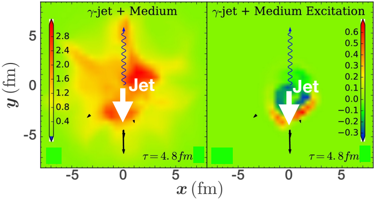


Medium response due to jet propogation

[Y. Tachibana, N.B. Chang, G.Y. Qin, Phys.Rev. C95 (2017) no.4, 044909]



[W. Chen, S. Cao, T. Luo, L. G. Pang and X. N. Wang, Phys.Lett. B777 (2018) 86-90]



Hydrodynamic equation with source term

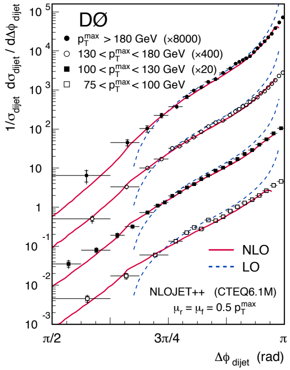
$$\partial_\mu T^{\mu\nu}_{\text{fluid}} = J^{\nu}_{\text{jet}}(x)$$

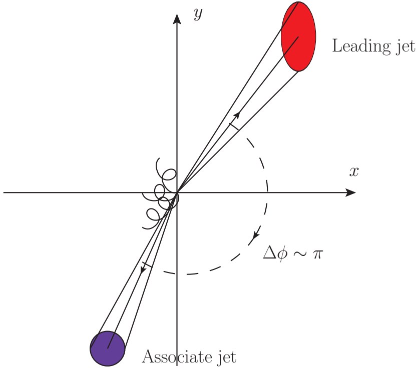
Energy-momentum tensor of the QGP fluid

Energy and momentum deposited from the jet

- Take into account the redistribution of jet energy and momentum in medium.
- Full picture of jet quenching phenomenon.
- Coupled Linearized-Boltzmann Transport and hydrodynamics model includes medium response and recoil.

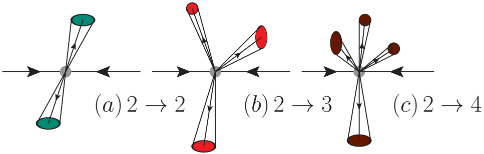
Dijet angular correlation in pp collisions





- Dijet azimuthal angular correlation has been measured at Tevatron and the LHC.
- Well-described by pQCD at NLO [Nagy, 02] except in the back-to-back region.

Perturbative expansions in dijet productions



Correlations:

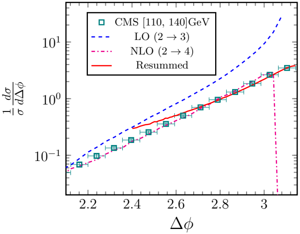
- $2 \to 2$: 0th order
- $2 \to 3$: leading order
- $2 \to 4$: next-to-leading order

$$\sigma_0 \sum_{i=0}^{\infty} \alpha_s^i \left(L^i + C^{(i)}\right) \quad \text{ideal QCD expansion}$$

$\sigma_0 \sum_{i=0}^{n-1} \alpha_s^i L^i$	$\sigma_0 \sum_{i=0}^{n-1} \alpha_s^i C^{(i)}$ $\Leftarrow$ pQCD
$\sigma_0 \sum_{i=n}^{\infty} \alpha_s^i L^i$	$\sigma_0 \sum_{i=n}^{\infty} \alpha_s^i C^{(i)}$

$\Uparrow$ resummation

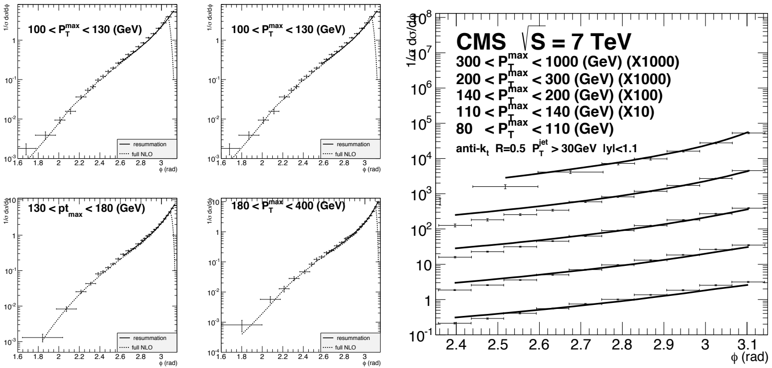
↖ negligible



- pQCD expansion eventually breaks down in the back-to-back region.
- Appearance of large logarithms such as $L \sim \ln^2 \frac{P_\perp^2}{q_\perp^2}$ with $P_\perp \gg q_\perp$.
- Momentum imbalance $\vec{q}_\perp \equiv \vec{p}_{1\perp} + \vec{p}_{2\perp}$, jet momenta $P_\perp \sim p_{1\perp} \sim p_{2\perp}$.

From pQCD to Sudakov resummation: paradigm shift

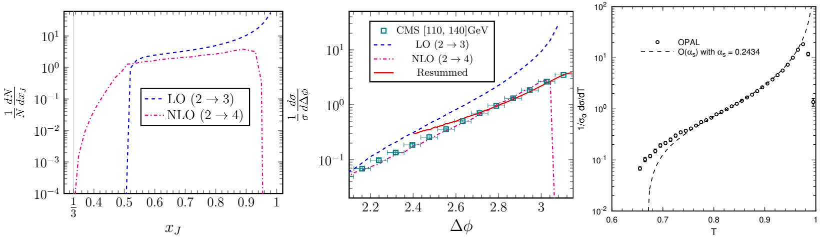
[P. Sun, C. P. Yuan and F. Yuan, Phys. Rev. Lett. **113**, 232001 (2014), PRD, 2015]



- pQCD framework can describe the large angle region.
- Sudakov resummation is essential to understand the data near $\phi \sim \pi$.
- QCD theoretical framework to resum soft gluons in dijet processes at NLL.

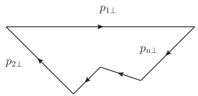
Dijet asymmetry at the LHC

Fully corrected dijet asymmetry $x_J \equiv \frac{p_{2\perp}}{p_{1\perp}}$ data measured by ATLAS.



Two interesting features in pQCD calculation for x_J distributions

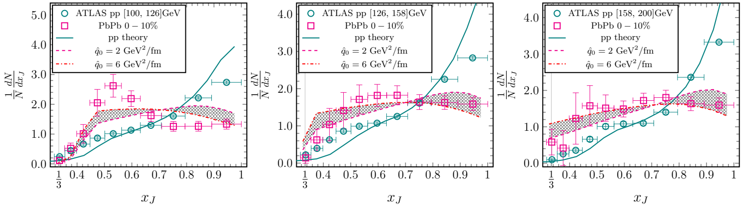
- pQCD $2 \to n$ process is bounded from below $x_J \geq \frac{1}{n-1}$ (Similar to thrust in e^+e^-).



$$\Rightarrow \qquad (n-1)p_{2\perp} \geq p_{1\perp}$$

- pQCD expansion fails to converge around $x_J \sim 1$ due to back-to-back dijet configurations. (Similar to angular correlation)

Dijets asymmetry as a probe of QGP

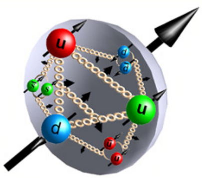


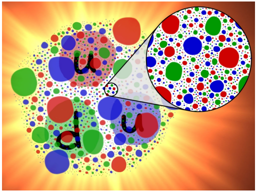
New methods to directly probe transport coefficient $\hat{q}$: [Chen, Qin, Wei, Xiao and Zhang, PLB, 18]

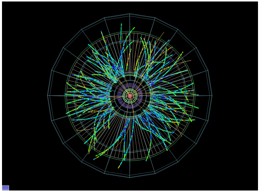
- NLO pQCD + Sudakov Resummation + $2+1D$ viscous hydrodynamics + Jet energy loss.
- Dijet asymmetries in *PbPb* gives $\hat{q} \sim 2-6\mathrm{GeV}^2/\mathrm{fm}$ at the LHC.
- Calculation in medium is embedded in OSU $2+1$ d viscous hydro. [Z. Qiu, C. Shen, and U. Hein, 11]

Ultimate goals in the physics research of hadronic structure

A famous proverb in English language: "One Picture Worth Ten Thousand Words" which is labeled a Chinese proverb.

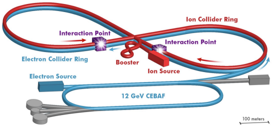


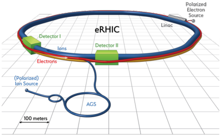


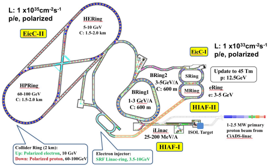


- Depict the kaleidoscopic multi-dimensional landscape of the internal structure of hadrons including nucleons and nuclei.
- Spin structure of the nucleon. Where does the proton spin come from?
- Understand the important role of gluons in nucleons.
- EIC machine is like a kaleidoscopic tube (color and dynamics) and a stereoscopic "camera" (multiple-dimensional) with extremely high resolution.

Electron Ion Collider



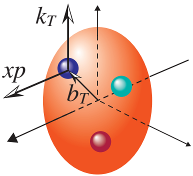


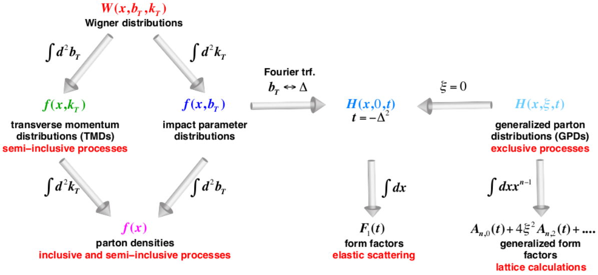


- Two proposed realization of EIC in US:
  JLEIC (Jefferson Lab) and eRHIC (Brookhaven).
- JLEIC: $\sqrt{s} = 20 \to 65 - 140\,\text{GeV}$ (Magnet technology choice).
- eRHIC: Up to $\sqrt{s} = 140\,\text{GeV}$.
- EIC in China (EicC-I) $\sqrt{s} = 12 \to 30\,\text{GeV}$.
- Polarized electron and light-ion beams.
- High-luminosity and high-precision.

3D Tomography of Proton

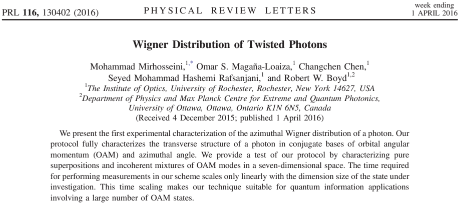
Wigner distributions ingeniously encode all quantum information of how partons are distributed inside hadrons. [Ji, 03; Belitsky, Ji, Yuan, 03]





- Small-x gluon distributions $\Leftrightarrow$ gluon Wigner distributions? [Ji, 03]

Can we measure Wigner distributions?



PRL **116,** 130402 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

Wigner Distribution of Twisted Photons

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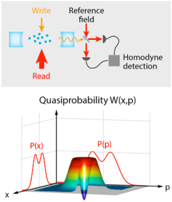
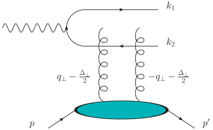
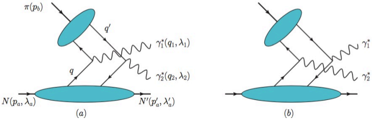
(Received 4 December 2015; published 1 April 2016)

We present the first experimental characterization of the azimuthal Wigner distribution of a photon. Our protocol fully characterizes the transverse structure of a photon in conjugate bases of orbital angular momentum (OAM) and azimuthal angle. We provide a test of our protocol by characterizing pure superpositions and incoherent mixtures of OAM modes in a seven-dimensional space. The time required for performing measurements in our scheme scales only linearly with the dimension size of the state under investigation. This time scaling makes our technique suitable for quantum information applications involving a large number of OAM states.



- Yes, we can! [Y. Hatta, B. Xiao, F. Yuan, Phys. Rev. Lett. **116**, 202301 (2016)]
- Quark GTMD in the double DY process: [S. Bhatttacharya,A. Metz, Jian Zhou, 17]



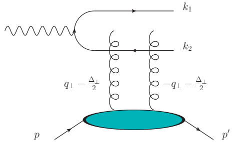


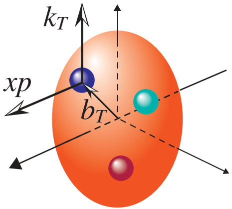
- Elliptic Wigner distribution: correlation between $b_\perp$ ($\Delta_\perp$) and $q_\perp$. [Jian Zhou, 17]

$$F_x(q_\perp, \Delta_\perp) = F_0(|q_\perp|, |\Delta_\perp|) + 2\cos 2(\phi_{q_\perp} - \phi_{\Delta_\perp}) F_\epsilon(|q_\perp|, |\Delta_\perp|) + \cdots$$

Hunting the Gluon OAM at an EIC

Directly probing the gluon OAM at an EIC. [Ji, Yuan, Zhao, Phys. Rev. Lett. **118**, 192004 (2017); Hatta, Nakagawa, Xiao, Yuan, Zhao, PRD 17]





Wigner distribution and OAM
[Ji, Xiong, Yuan, 12; Hatta, 11; Lorce, Pasquini,11]

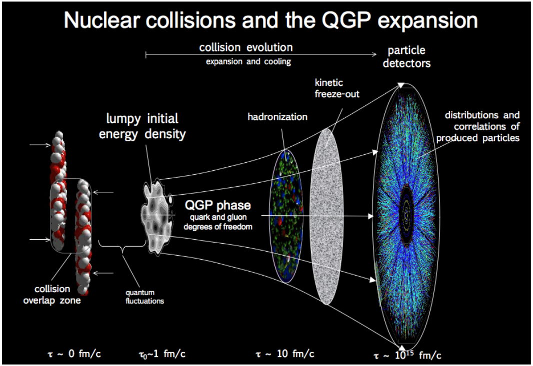
$$L_g = \int dx d^2 b_\perp d^2 k_\perp W_g(x, b_\perp, k_\perp)(b_\perp \times k_\perp).$$

- The single spin asymmetry of this process is sensitive to L_g.
- First measurement of the gluon OAM in the proton spin sum rule!

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g.$$

- Quark OAM seems to be more difficult to probe directly. Interesting development: [Bhatttacharya, Metz, Zhou, 17; Engelhardt, 17]

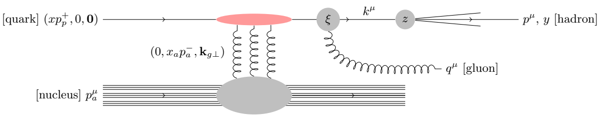
Summary



- Flows and hydrodynamics.
- Study of QCD phase diagram.
- Jet quenching phenomenon.
- Nucleon Structure, gluon saturation and low-x physics.
- Apology: there are many other interesting topics, such as thermalization, J/Ψ production, chiral effects, etc, that I do not have time to cover.

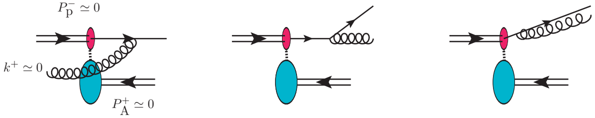
Forward rapidity single hadron productions in pA collisions

Dilute-Dense factorizations: large x proton as dilute probe:



$$x_p = \frac{k_\perp}{\sqrt{s}} e^{+y} \sim 1 \quad \text{dilute}$$
$$x_A = \frac{k_\perp}{\sqrt{s}} e^{-y} \ll 1 \quad \text{dense}$$

- LO [Dumitru, Jalilian-Marian, 02]: probing $xG_{\rm DP}(x, k_\perp)$ at small-x.
- NLO Complete NLO: [Chirilli, Xiao and Yuan, 12].

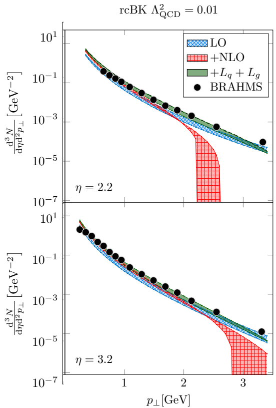


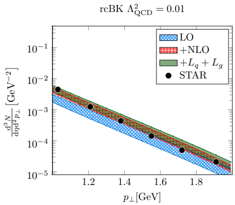
Rapidity Divergence   Collinear Divergence (P)   Collinear Divergence (F)

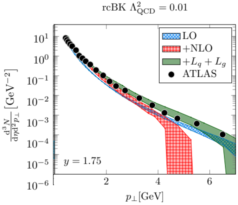
- Numerical implementations: Saturation physics at One Loop Order (SOLO). [Stasto, Xiao, Zaslavsky, 13]

Numerical implementation of the NLO result

SOLO results [Stasto, Xiao, Zaslavsky, Phys. Rev. Lett. **112**, 012302 (2014); Watanabe, Xiao, Yuan, Zaslavsky, PRD 15]



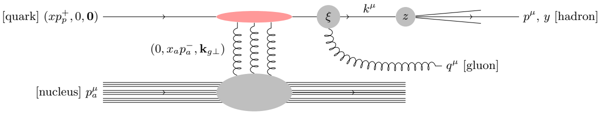




- Agree with RHIC and LHC data in low $p_\perp$ region, where pQCD does not apply.
- SOLO (1.0 and 2.0) break down in the large $p_\perp$ region. [Altinoluk, Armesto, Beuf, Kovner and Lublinsky, 14; Ducloue, Lappi and Zhu, 16, 17; Iancu, Mueller and Triantafyllopoulos, 16]
- Another idea: threshold resummation! The resummation of plus-functions or $\bar{\alpha}_s \ln(1 - x_p) < 0$.

Threshold resummation in the saturation formalism

Dilute-Dense factorizations: large x proton or γ^* $\rightarrow$ as dilute probe:



$$x_p = \frac{k_\perp}{\sqrt{s}} e^{+y} \sim 1 \quad \text{dilute}$$

$$x_A = \frac{k_\perp}{\sqrt{s}} e^{-y} \ll 1 \quad \text{dense}$$

- Threshold resummation is the resummation of plus-functions. In single forward hadron production, [F. Yuan, B. Xiao,1806.03522 and work in preparation]

$$\int_{x_p}^{1} \frac{d\xi}{(1-\xi)_+} f(\xi) \sim f(1)\ln(1-x_p)$$

- It is also the resummation of logarithm $\bar{\alpha}_s \ln(1-x_p) < 0$. For example: let $X = \bar{\alpha}_s \ln(1-x_p)$, $e^X = 1 + X + \frac{1}{2}X^2 + \cdots$
- Mellin transform is the technique used to perform resummation.

$$\int_0^1 d\tau \tau^{N-1} \int_\tau^1 \frac{d\xi}{\xi} \mathcal{P}(\xi) q\left(\frac{\tau}{\xi}, \mu\right) = P_N q_N,$$

- Interesting connection with renormalization group equation (RGE) formalism ([Neubert et al, 06]) and N-space formalism ([Catani et al]).