Hadron/Nuclear structure theory aspects

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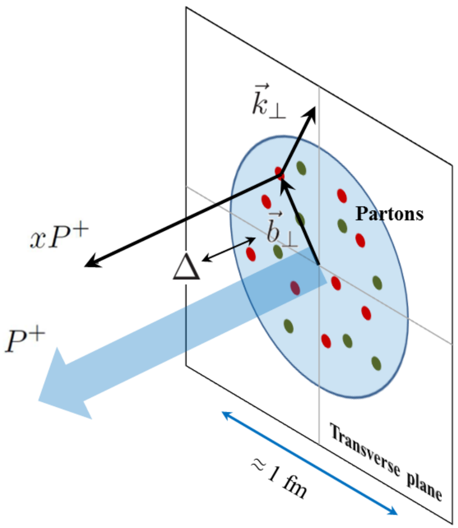
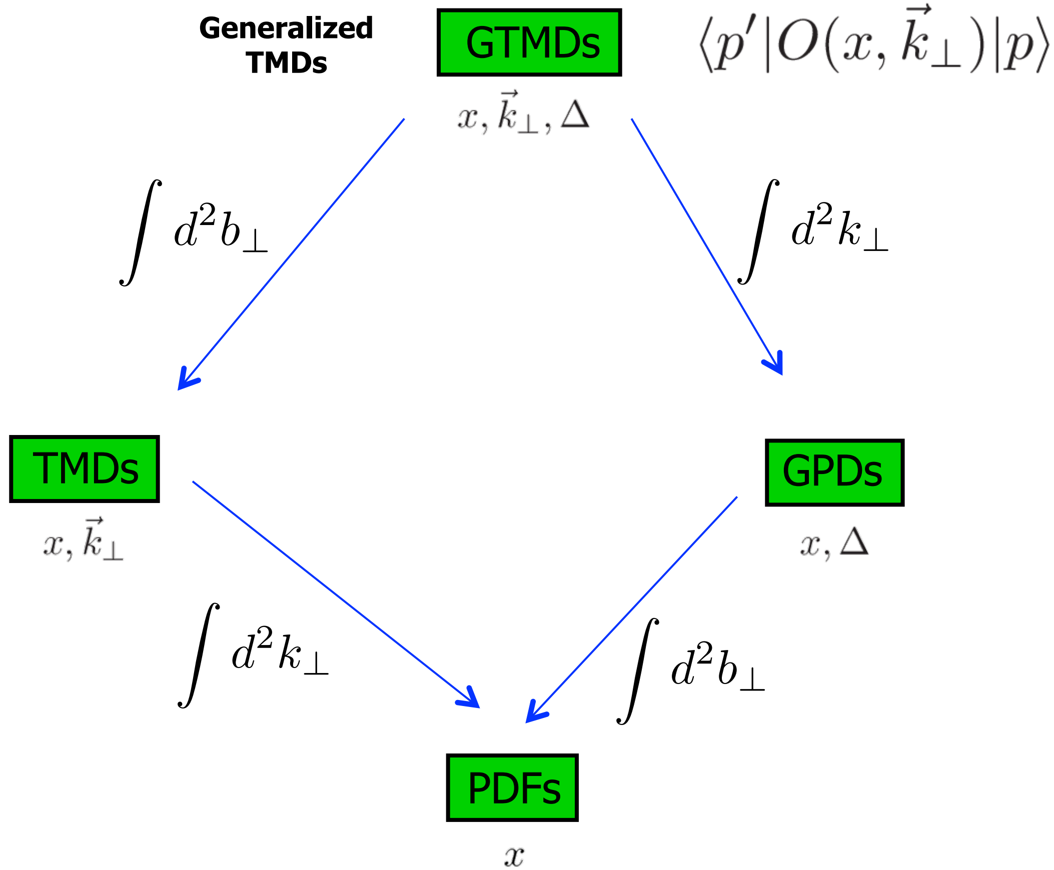
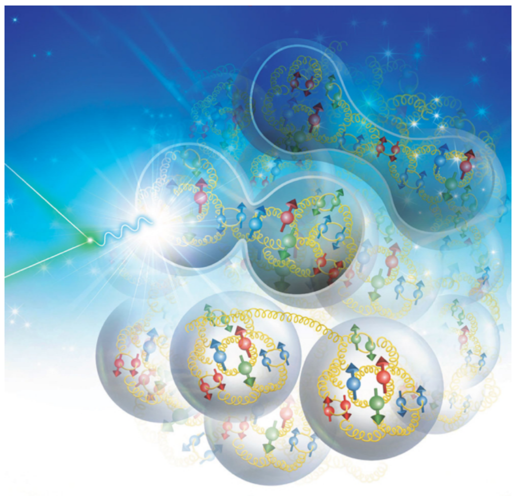
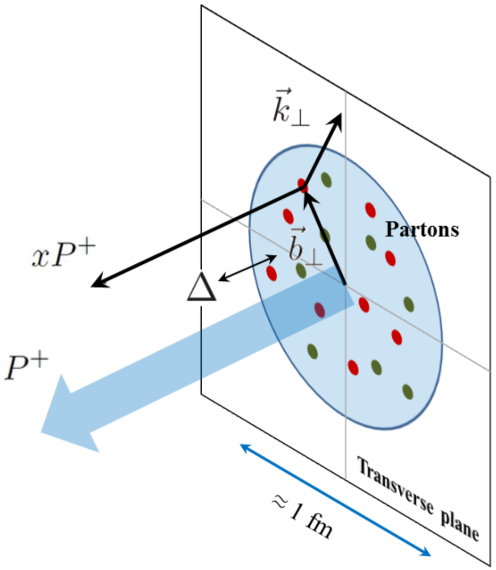

$\vec{k}_\perp$
xP^+
$\vec{b}_\perp$
Δ
Partons
P^+
≈ 1 fm
Transverse plane


Generalized TMDs
GTMDs
$\langle p' | O(x, \vec{k}_\perp) | p \rangle$
$x, \vec{k}_\perp, \Delta$
$\int d^2 b_\perp$
$\int d^2 k_\perp$
TMDs
$x, \vec{k}_\perp$
GPDs
x, Δ
$\int d^2 k_\perp$
$\int d^2 b_\perp$
PDFs
x



0+1d: PDFs, NPDFs and beyond

$$\int d^2b_\perp \int d^2k_\perp$$



Collinear factorization

in standard pQCD calculations, the incoming parton transverse momenta are set to zero in the matrix element and are integrated over in the parton densities

$$d\sigma_{AB\to X} = \sum_{ij} \int dx_1 dx_2 \, \underbrace{f_{i/A}(x_1,\mu^2) f_{j/B}(x_2,\mu'^2)}_{k_T \text{ integrated quantities}} \, d\hat{\sigma}_{ij\to X} + \mathcal{O}\left(\Lambda_{QCD}^2/M^2\right)$$

$d\hat{\sigma}_{ij\to X}$: the incoming partons are taken collinear to the projectile hadrons

M: some hard scale

in general for a hard process, this approximation is accurate

in some cases however, this is not good enough:

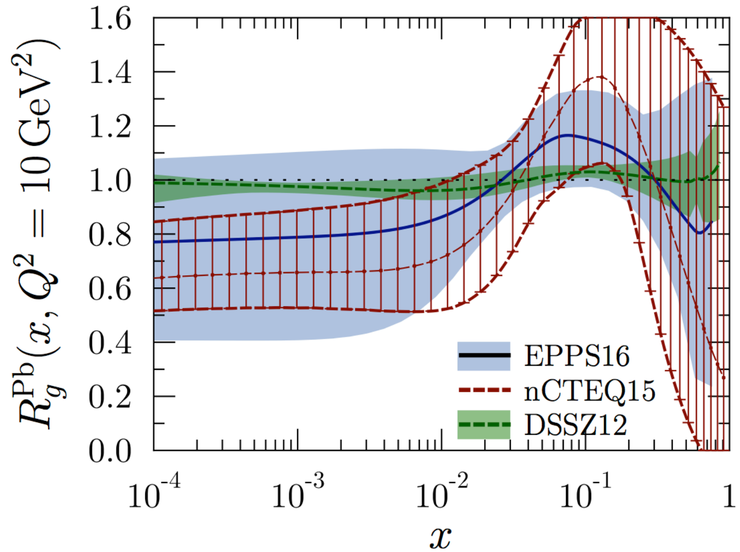
the Λ_{QCD}^2/M^2 power corrections may be enhanced by $A^{1/3}$, $x^{-\lambda}$, $(1-x)^{\alpha}$

most open questions in the field are about going beyond this approximation

Nuclear quarks and gluons

- improvement needed across the board: quark sector, gluon sector, low x, large x

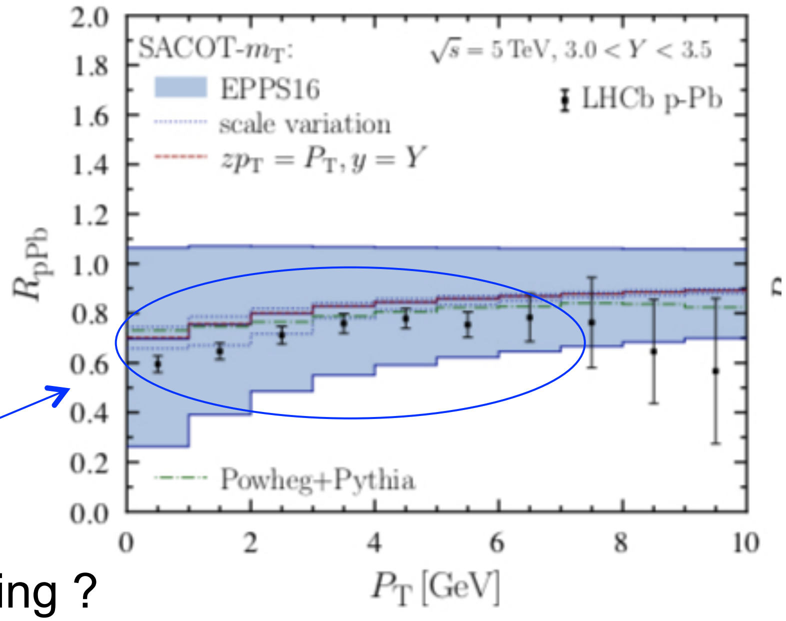
LLR, LPSC



overall, the pA program at the LHC has had a limited impact, collinear factorization calculations still suffer from large uncertainties

as a result, collinear-factorization breaking effects are almost impossible to uncover

e.g. the suppresion of the R_{pA} of D mesons at forward rapidities

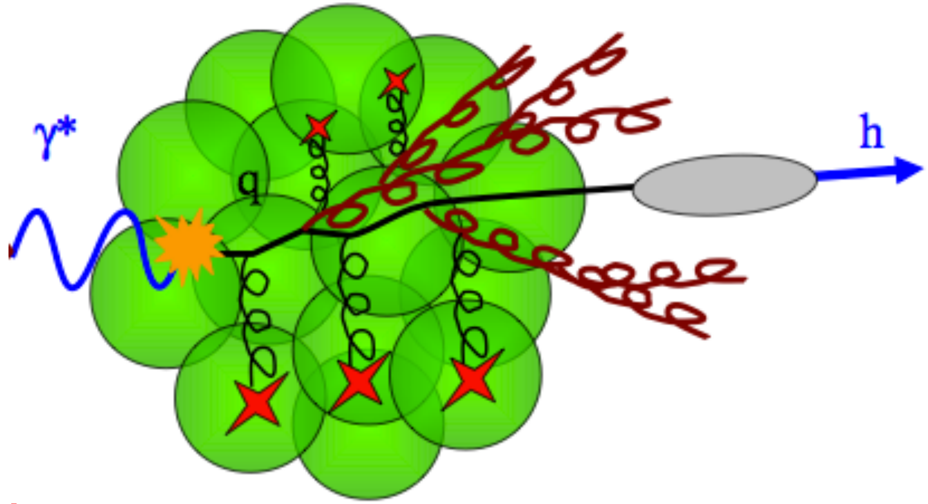


energy loss effects ? saturation effects ? nothing ?

Energy loss in nuclear matter

- hadron/jet production e.g. in DIS

CPHT, IPhT, LLR, Subatech



in-medium parton propagation:
are the energy loss and p_T-broadening of leading partons factorizable ?

in-medium hadronization:
open questions concerning the dynamics of confinement, the stages of hadronization (parton, pre-hadron, hadron) and their time scales

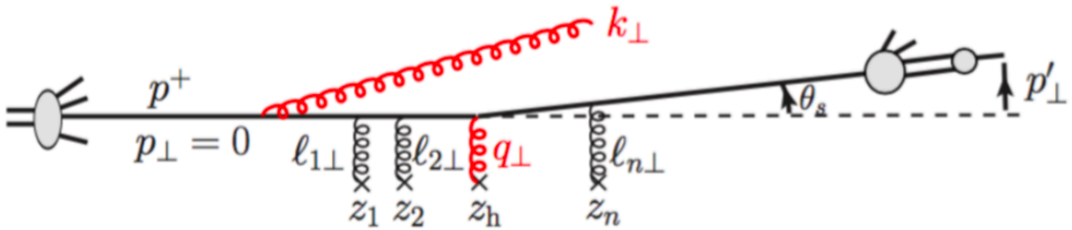
in-medium jet modifications: theory framework, Monte Carlo tools needed

- Exp: EIC + fixed-target experiments

Coherent energy loss

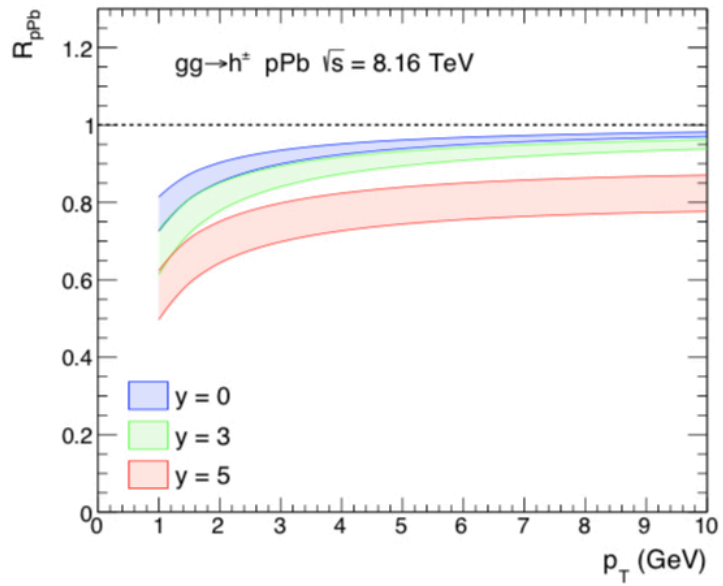
- dominant mechanism when medium interactions occur before and after the hard scattering

LLR, Subatech



next challenges:

- extract A dependence of transport coefficient from data
- work out formalism to allow inclusion of such effects in NPDF fits
- isolate from saturation effects



- Exp: pA program @ LHCb and fixed-target experiments

Parton saturation

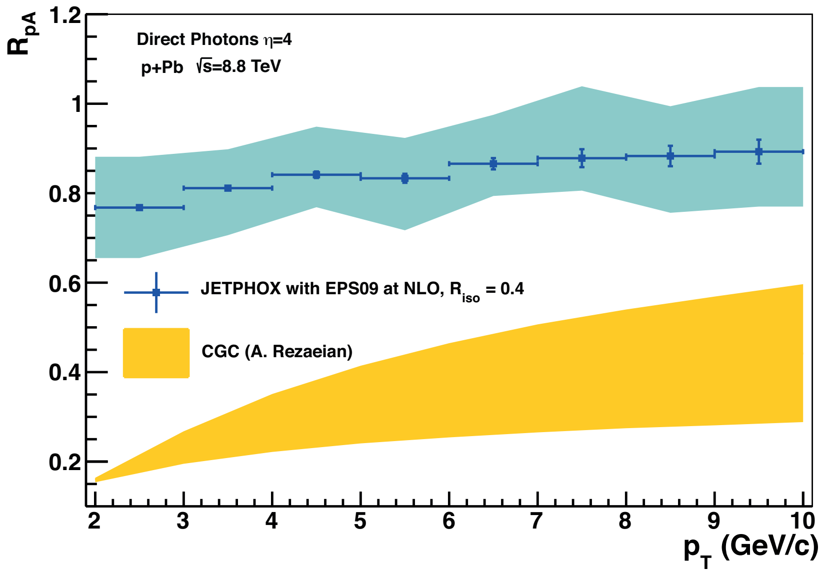
- forward rapidities probe small values of x, possibly non-linear QCD evolution

theoretical efforts for the next decade: NLO calculations

CPHT, IJCLab, IPhT

- long-standing problem: finding a golden channel

promising candidate: isolated photons at forward rapidities



- smallest possible *x* reach:
  no mass, no fragmentation

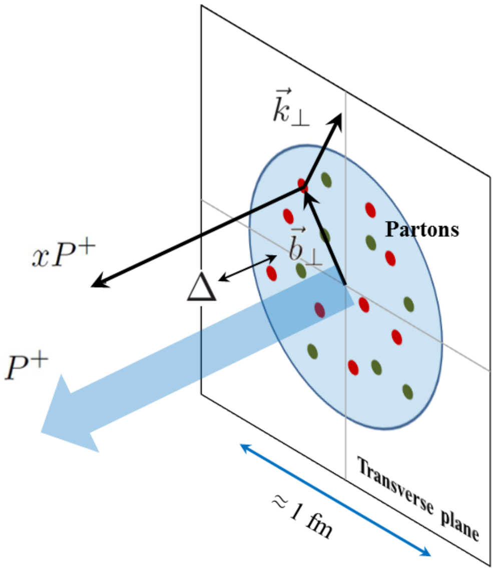
- no cold matter final-state effects (E-loss, …)

- no isospin effects in p+Pb vs p+p (contrary to d+Au vs p+p at RHIC)

- Exp: FOCAL, LHCb, EIC

0+3d: TMDs

$$\int d^2 b_\perp$$



TMD factorization

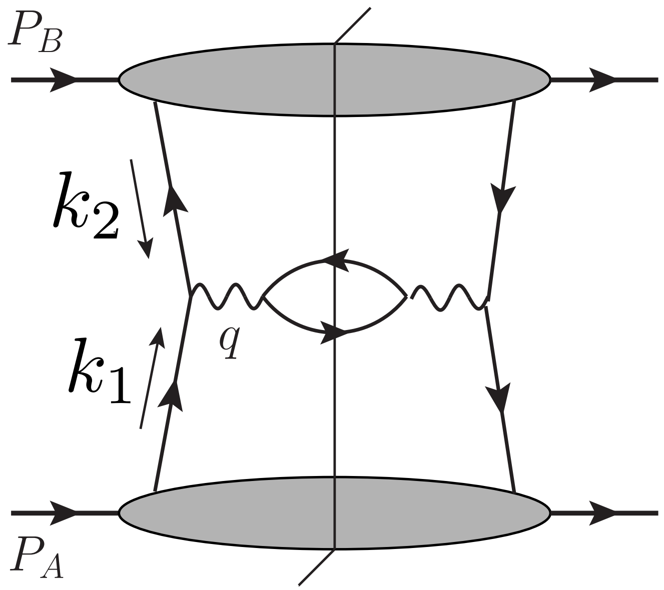
this is a more advanced QCD factorization framework
which can be usesul and sometimes is even necessary

the transverse momentum of the di-jet system q_T is the sum of the transverse momenta of the incoming partons

$$d\hat{\sigma} \propto \delta(k_{1t} + k_{2t} - q_T)$$

so in collinear factorization

$$d\sigma^{AB\to J_1 J_2 X} \propto \delta(q_T) + \mathcal{O}(\alpha_s)$$



naively, TMD factorization is

$$d\sigma^{AB\to J_1 J_2 X} = \sum_{i,j} \int dx_1 dx_2 d^2k_{1t} d^2k_{2t}\ f_{i/A}(x_1, k_{1t}) f_{j/B}(x_2, k_{2t})\ d\hat{\sigma}^{ij\to J_1 J_2}$$

but unfortunately, this is not so simple

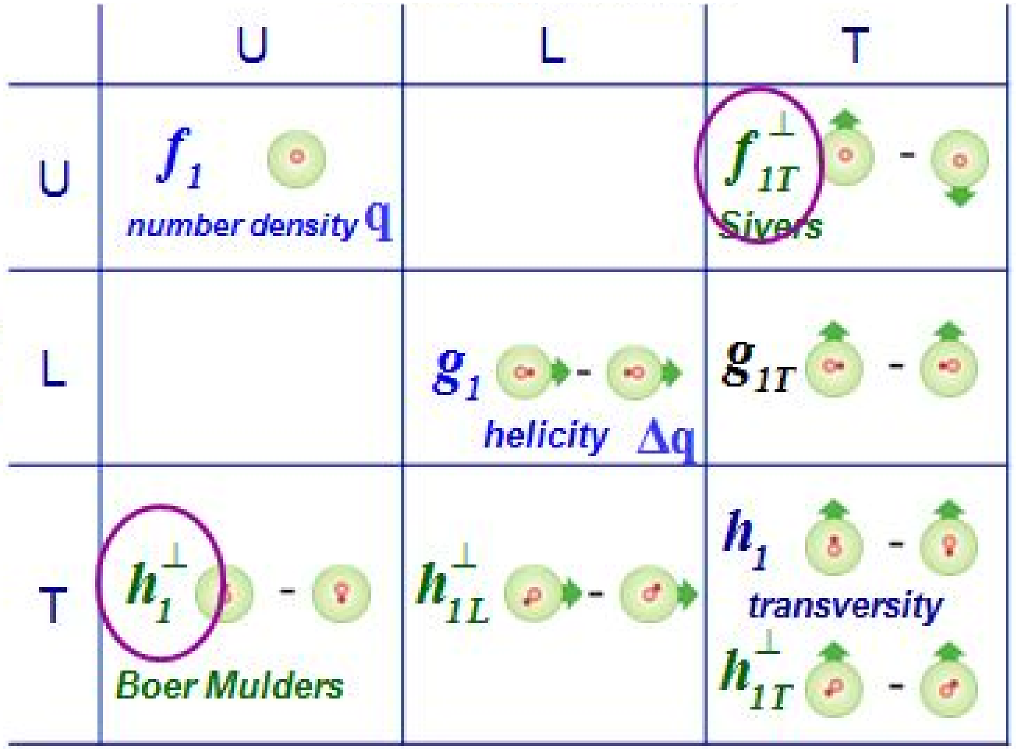
Spin physics

TMDs are crucial to describe hard processes in polarized collisions
(e.g. Drell-Yan and semi-inclusive DIS)

8 leading-twist TMDs

nucleon polarization

quark polarization



Sivers function

correlation between transverse spin of the nucleon and transverse momentum of the quark

Boer-Mulders function

correlation between transverse spin and transverse momentum of the quark in unpolarized nucleon

upcoming challenges: quark TMD extractions @ NLO, the gluon sector, nuclear TMDs

- Exp: EIC + fixed-target experiments

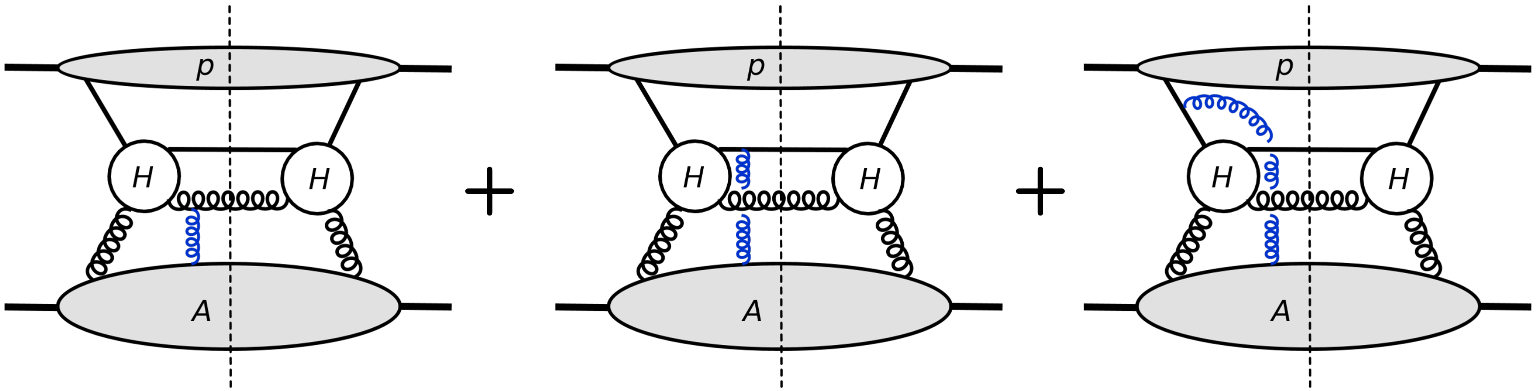
CPHT, IJCLab

TMD gluon distributions

- the naive operator definition is not gauge-invariant

$$\mathcal{F}_{g/A}(x_2, k_t) \stackrel{\text{naive}}{=} 2\int \frac{d\xi^+ d^2\boldsymbol{\xi}_t}{(2\pi)^3 p_A^-} e^{ix_2 p_A^- \xi^+ - ik_t\cdot\boldsymbol{\xi}_t} \left\langle A\right| \mathrm{Tr}\left[F^{i-}\left(\xi^+, \boldsymbol{\xi}_t\right) F^{i-}(0)\right]\left|A\right\rangle$$

- a theoretically consistent definition requires to include more diagrams



+ similar diagrams with $2, 3, \ldots$ gluon exchanges

They all contribute at leading power and need to be resummed.

this is done by including gauge links in the operator definition

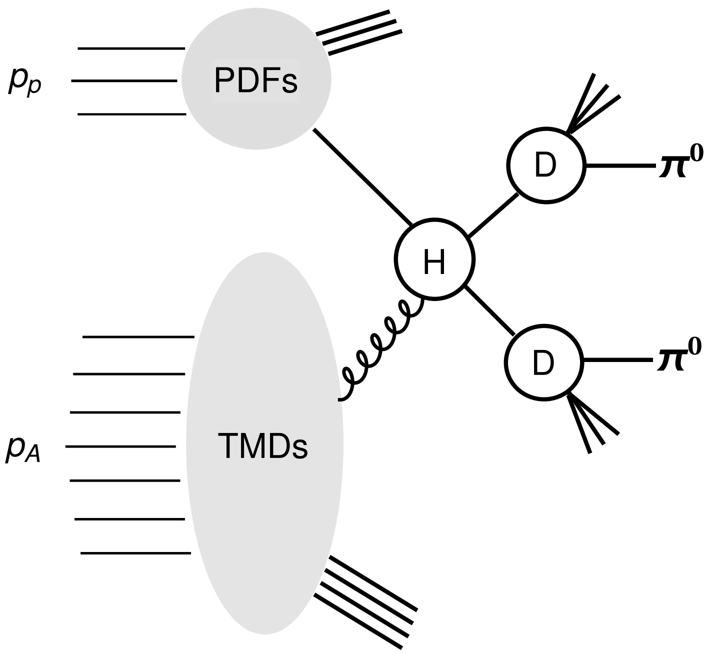
Process-dependent TMDs

- the proper operator definition(s)

some gauge link $\mathcal{P}\exp\left[-ig\int_{\alpha}^{\beta} d\eta^{\mu} A^{a}(\eta) T^{a}\right]$

$$\mathcal{F}_{g/A}(x_2, k_t) = 2\int \frac{d\xi^+ d^2\boldsymbol{\xi}_t}{(2\pi)^3 p_A^-} e^{ix_2 p_A^- \xi^+ - ik_t\cdot\boldsymbol{\xi}_t} \langle A|\mathrm{Tr}\left[F^{i-}\left(\xi^+,\boldsymbol{\xi}_t\right) U_{[\xi,0]} F^{i-}(0)\right]|A\rangle$$

  - $U_{[\alpha,\beta]}$ renders gluon distribution gauge invariant



- TMDs on both sides: no factorization (expect DY: no color in the final state)

- a single TMD involved: factorization OK

however, the precise structure of the gauge link is process-dependent:

it is determined by the color structure of the hard process H

Process-dependent TMDs

- the proper operator definition(s)

some gauge link $\mathcal{P}\exp\left[-ig\int_\alpha^\beta d\eta^\mu A^a(\eta)T^a\right]$

$$\mathcal{F}_{g/A}(x_2,k_t) = 2\int\frac{d\xi^+ d^2\boldsymbol{\xi}_t}{(2\pi)^3 p_A^-} e^{ix_2 p_A^- \xi^+ - ik_t\cdot\boldsymbol{\xi}_t} \langle A|\mathrm{Tr}\left[F^{i-}\left(\xi^+,\boldsymbol{\xi}_t\right) U_{[\xi,0]} F^{i-}(0)\right]|A\rangle$$

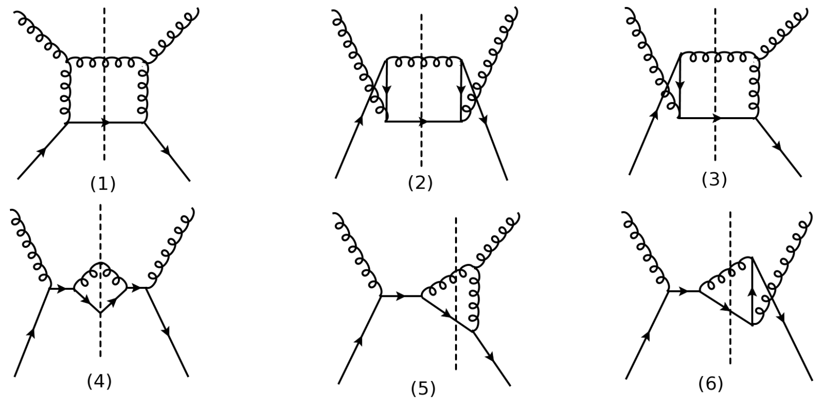
  - $U_{[\alpha,\beta]}$ renders gluon distribution gauge invariant

- in general, several gluon distributions are needed already for a single process

example for the $qg \to qg$ channel

each diagram generates a different gluon distribution

loss of universality



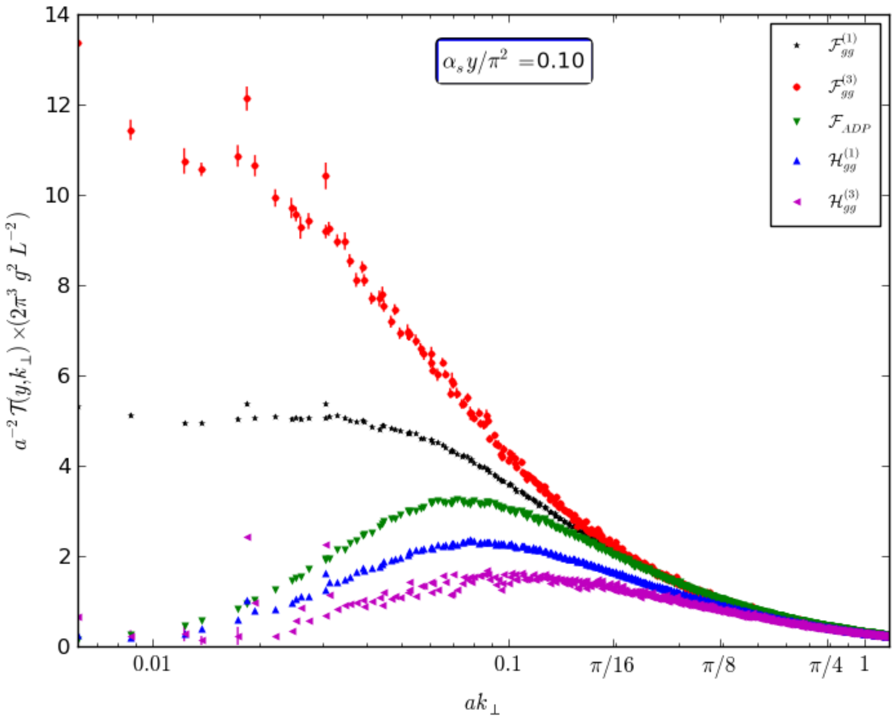
main problem: quantify the magnitude of factorization-breaking terms

- Exp: pp (pA) program @ LHCb, fixed-target experiments, EIC

TMD non-universality at small-x

at small-x, the momentum scale at which non-universalities occur ($k_t \sim Q_S$) becomes perturbative, and thus these can be dealt with

CPHT, IPhT

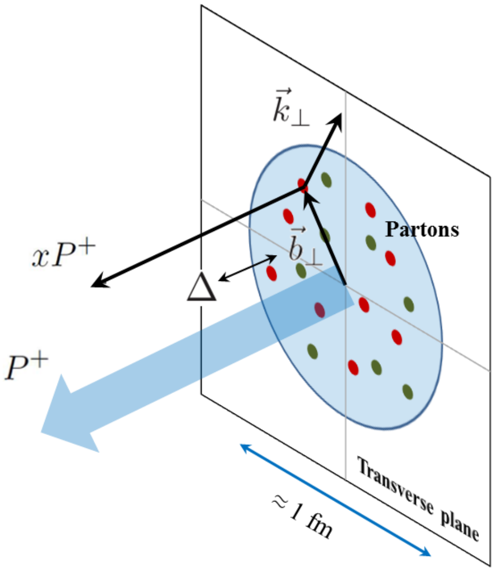


next task: what about at intermediate x (where most experimental coverage lies)

- Exp: pp (pA) program @ LHCb, fixed-target experiments, EIC

2+1d: GPDs

$$\int d^2 k_\perp$$



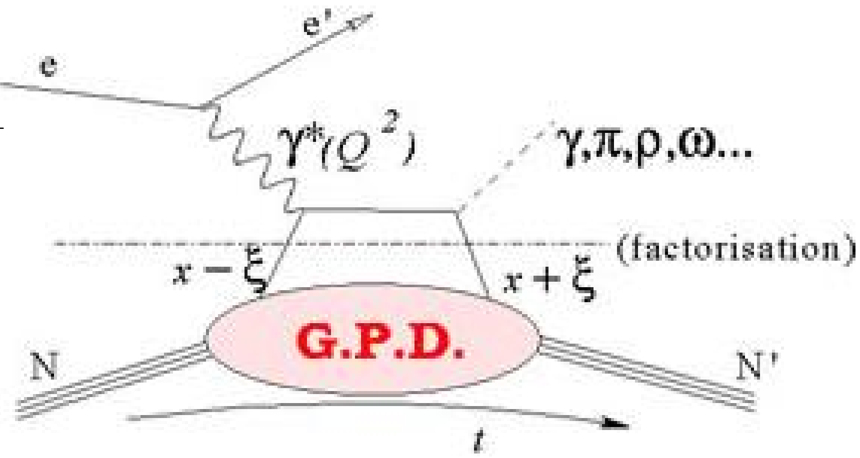
GPDs and transverse imaging

- accessible in exclusive processes

CPHT, IJCLab, IRFU

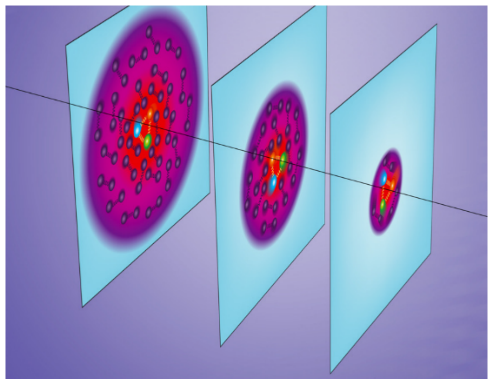
FTs of impact-parameter dependent pdfs

$$q(x, \mathbf{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} H(x, \xi = 0, -\mathbf{\Delta}_\perp^2)\, e^{-i\mathbf{b}_\perp \cdot \mathbf{\Delta}_\perp}$$



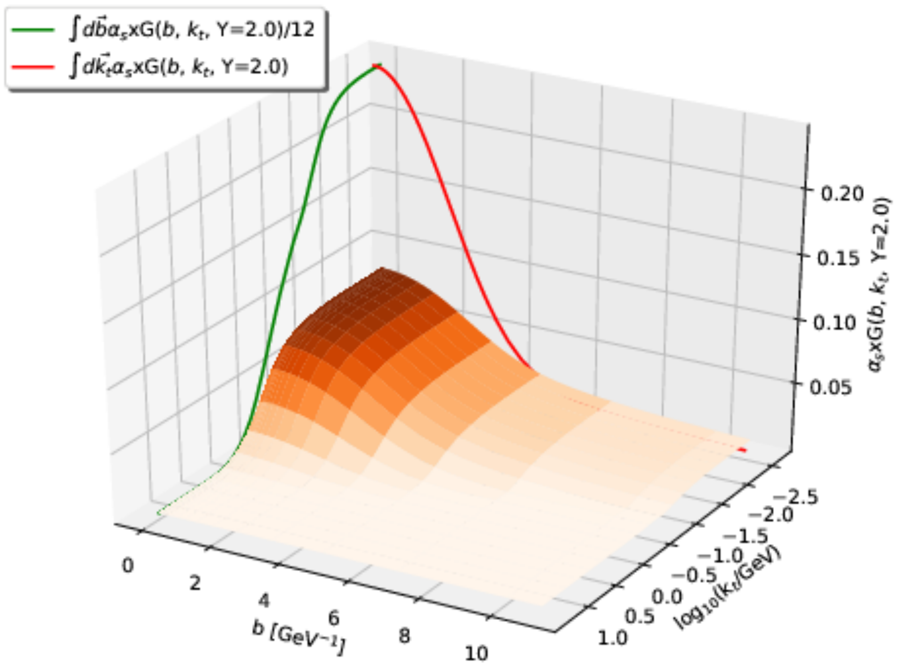
- open questions:

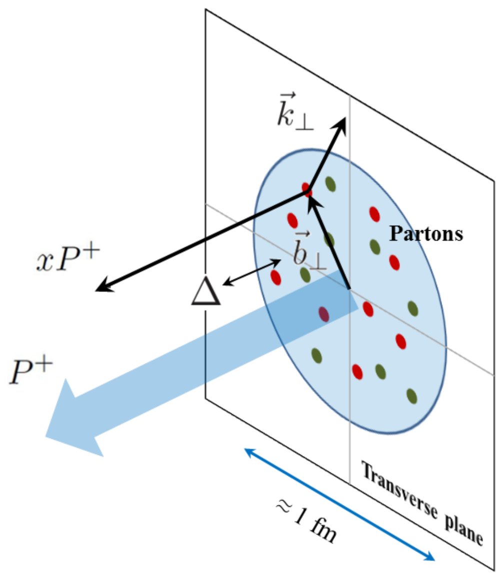
- NLO and power corrections
- access transversity GPDs
- small-x: extend CGC theory to deal with non-forward matrix elements
- nuclear GPDs



- Exp: JLab + EIC

2+3d: Wigner functions





- Exp: EIC

CPHT

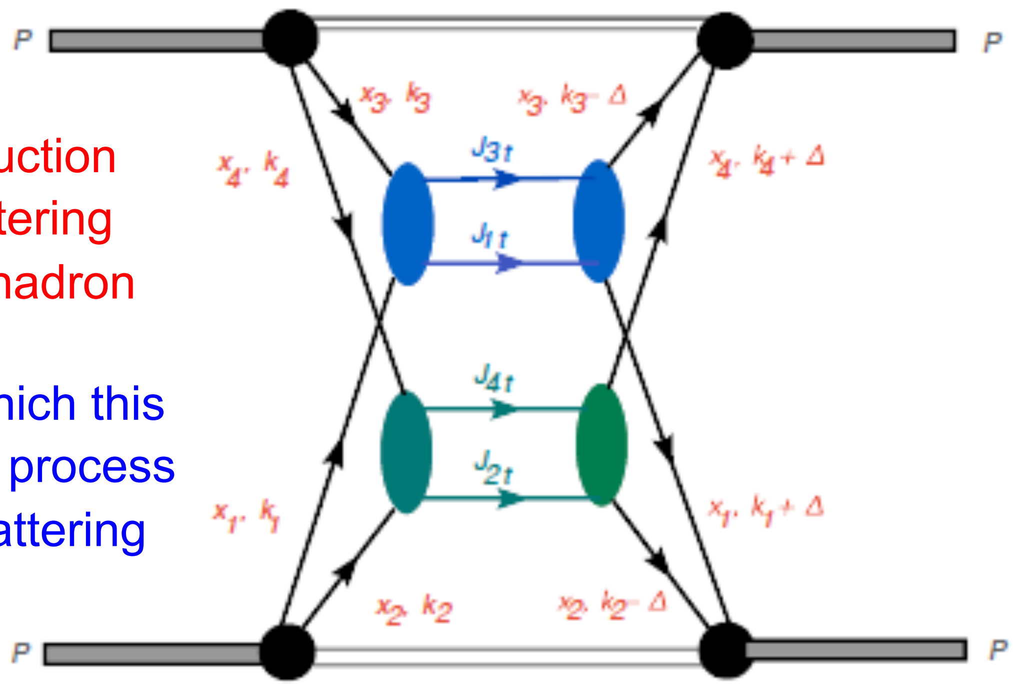
Multiple parton interactions

keeping track of both partonic transverse momentum and position is crucial to describe multiple partonic interactions

IJCLab

consider for instance: 4-jet production coming from a double hard scattering of two partons in each incoming hadron

there is a kinematical domain in which this is as important as the leading-twist process of 4-jet production in one hard scattering



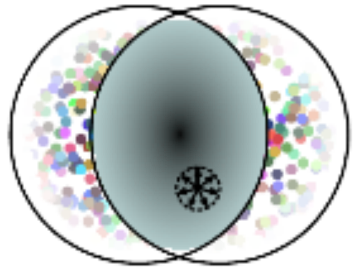
with two partons coming from each hadron, the transverse momentum Δ can be non zero

- Exp: small-systems

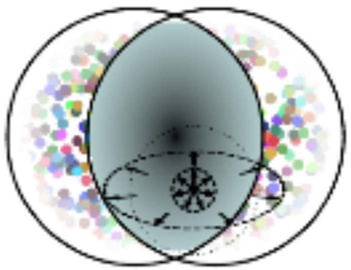
Role of hadron structure in small systems: initial-state-only paradigm

Collective behavior in HIC

- general paradigm:

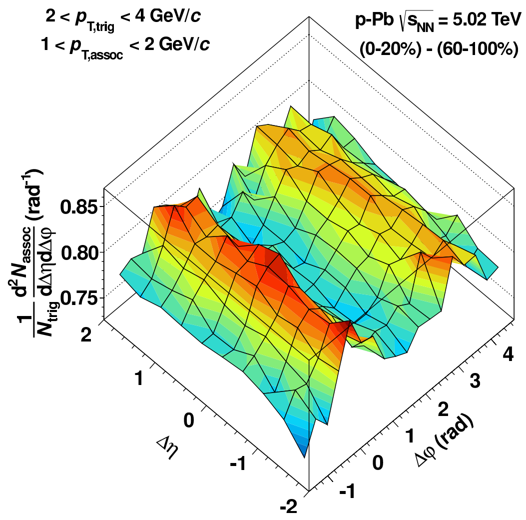


the initial momentum distribution is isotropic



strong interactions induce pressure gradients
the expansion turns the space anisotropy
into a momentum anisotropy

- in the absence of flow:



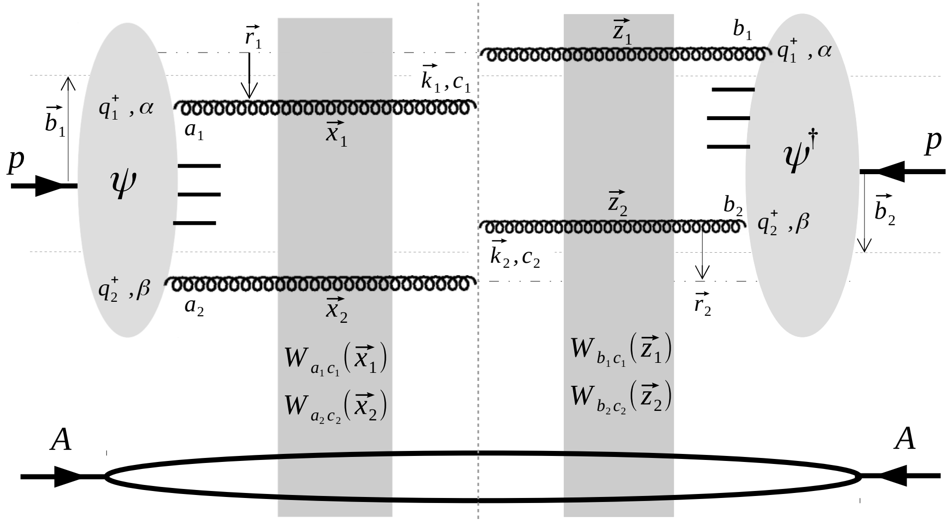
one becomes sensitive to the initial momentum
anisotropies which are small but non zero

if this is what happens in small-systems,
then hadron structure plays a crucial role

Double Wigner distribution

- first-principle, initial-state only approach: CPHT

anisotropies can be generate during the interaction (under control) or come from pre-existing correlation in the wave function (ignored so far)



most generally, 2-particle correlations involve a double Wigner distribution

- challenges ahead:

unravel momentum/position correlation in hadron structure, possible connections with geometry ("event planes"), identify origin of odd harmonics

- Exp: EIC + small-systems

Role of hadron structure in small systems: IS+hydro paradigm

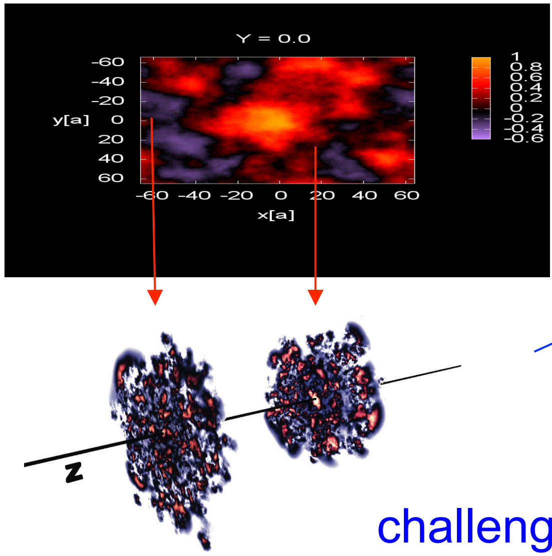
CGC + hydro

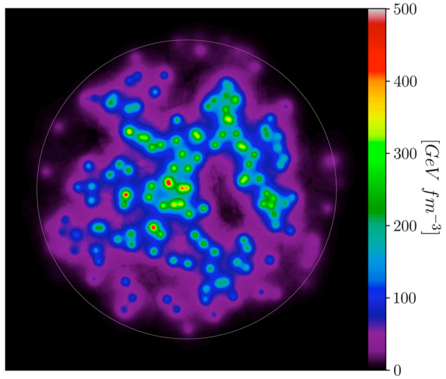
- if in the presence of flow, the initial momentum correlations are lost

instead, those created by the fluid behavior reflect the initial spatial distribution and fluctuations of the QCD matter

the Glauber model is not enough to describe the nature and dynamics of the pre-hydro fluctuations, QCD cannot be ignored

- Glasma+hydro approach successful in the context of HIC





initial overlap

CPHT, IPhT

→ hydro

requires precise knowledge of initial geometry

challenge for theory: bring two distinct exp. communities closer

- Exp: small-systems, Jlab, QGP

Conclusions

- activities in hadron/nuclear structure theory are very diverse

  - PDFs, TMDs, GDPs for protons and nuclei
  - factorization breaking effects induced by nuclear matter, energy loss, saturation
  - multiple parton interactions, position/momentum correlations
  - others I didn't mention, e.g. lattice QCD, Monte Carlo event generators, quarkonium physics

- all have connections with experimental programs

  - JLab, LHC collider and fixed targets, future EIC

- small systems and EIC:

  - puzzles in small systems provide timely context for the nucleon structure community and the QGP community to get closer
  - this is important in preparation for the EIC, the next high-energy nuclear physics collider
  - theorists happy to help initiate first links