Cold QCD Highlights for a 2nd Detector

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EIC User Group Meeting 2022
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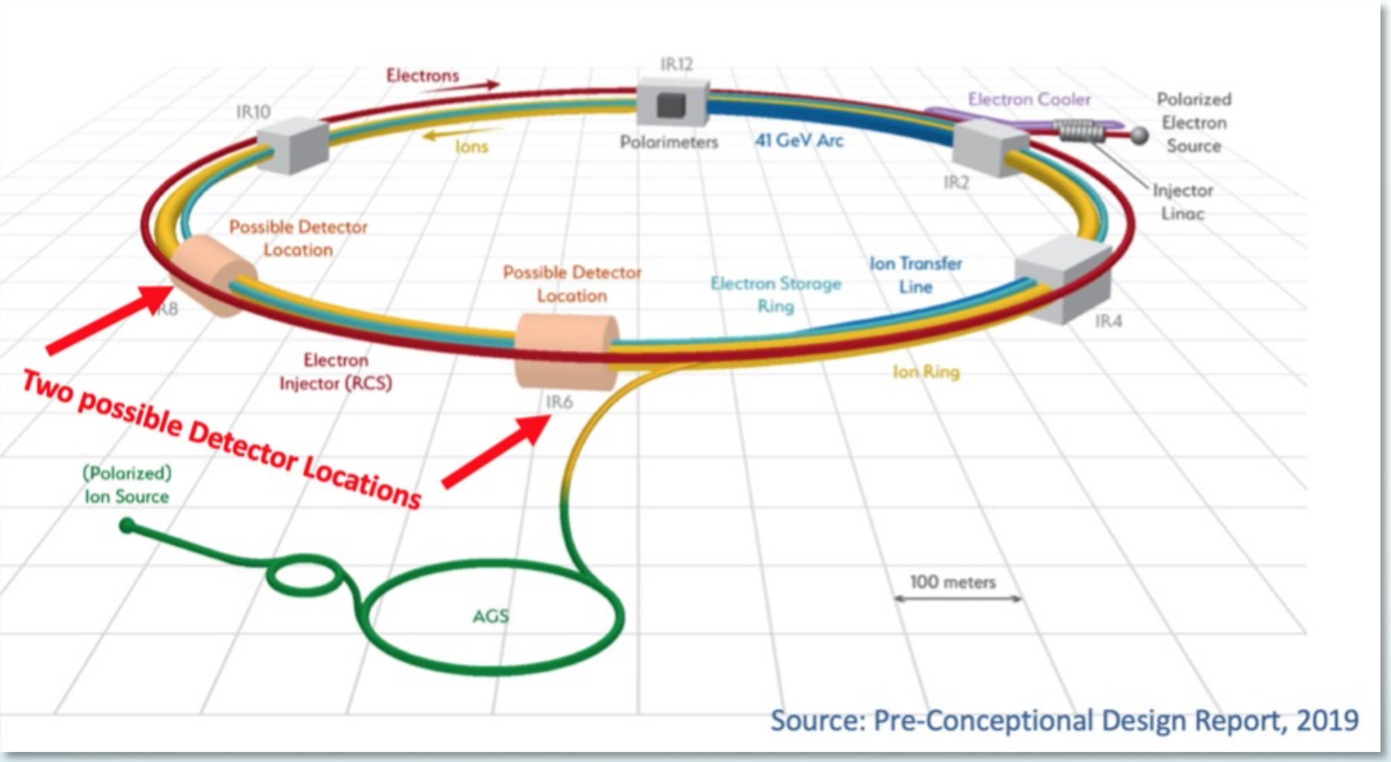
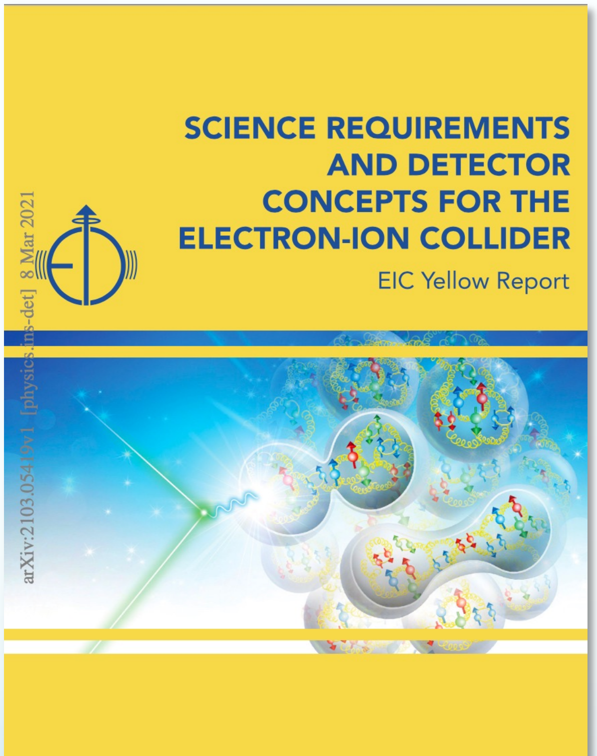
Goal or question

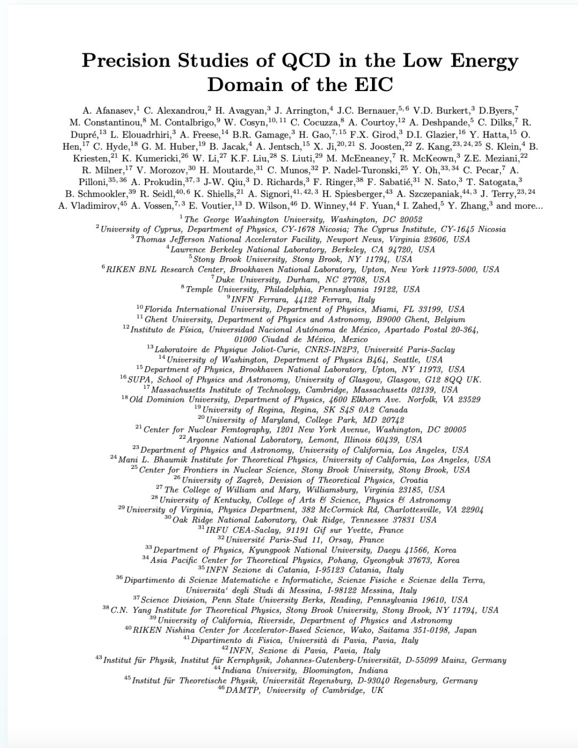
- With Detector I at IP6 as the default, what are the physics opportunities for Detector II at IP8?



References

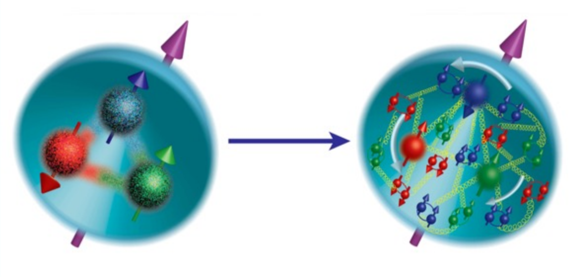
- Shamelessly use figures/plots from these references



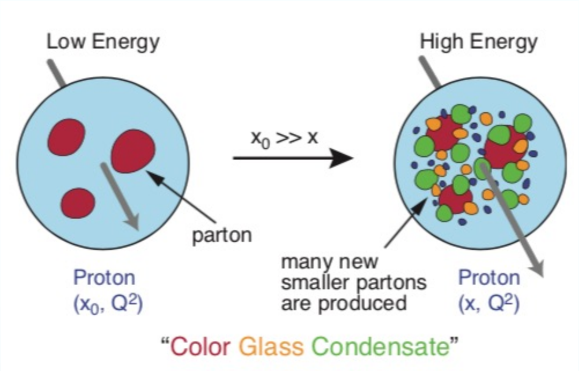


EIC Scientific Pillars

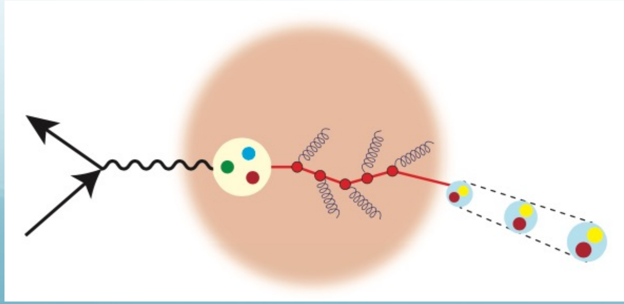
- Quantum Imaging of protons and nuclei



- A new form of matter - color glass condensate

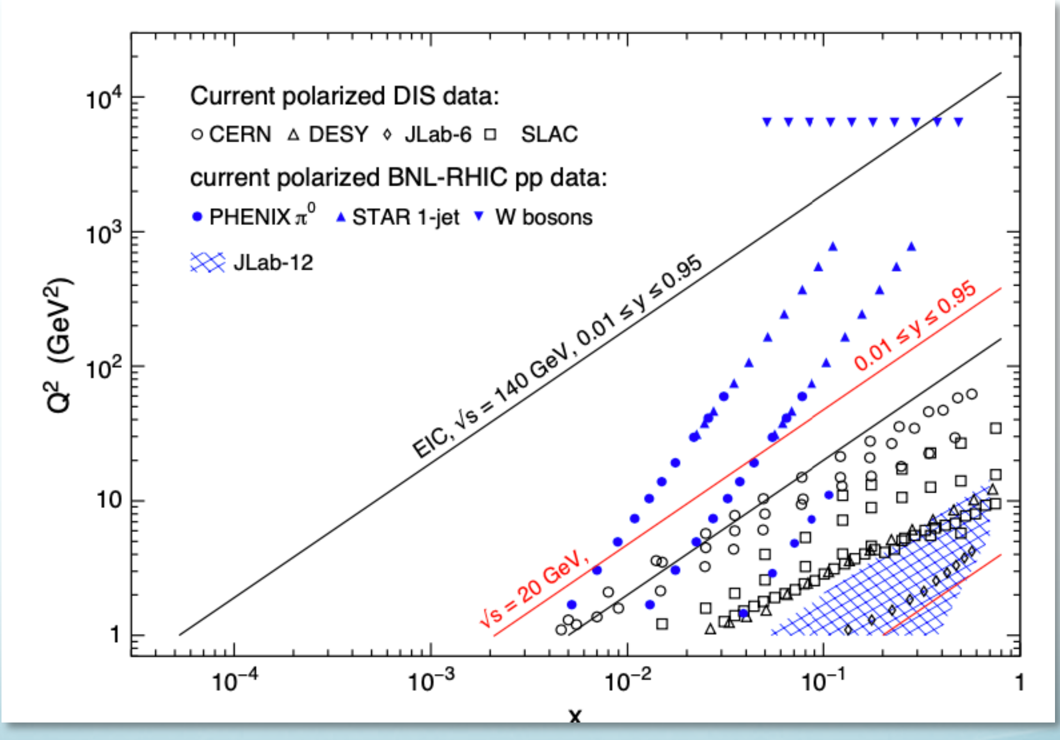


- Particle propagation in cold nuclear matter



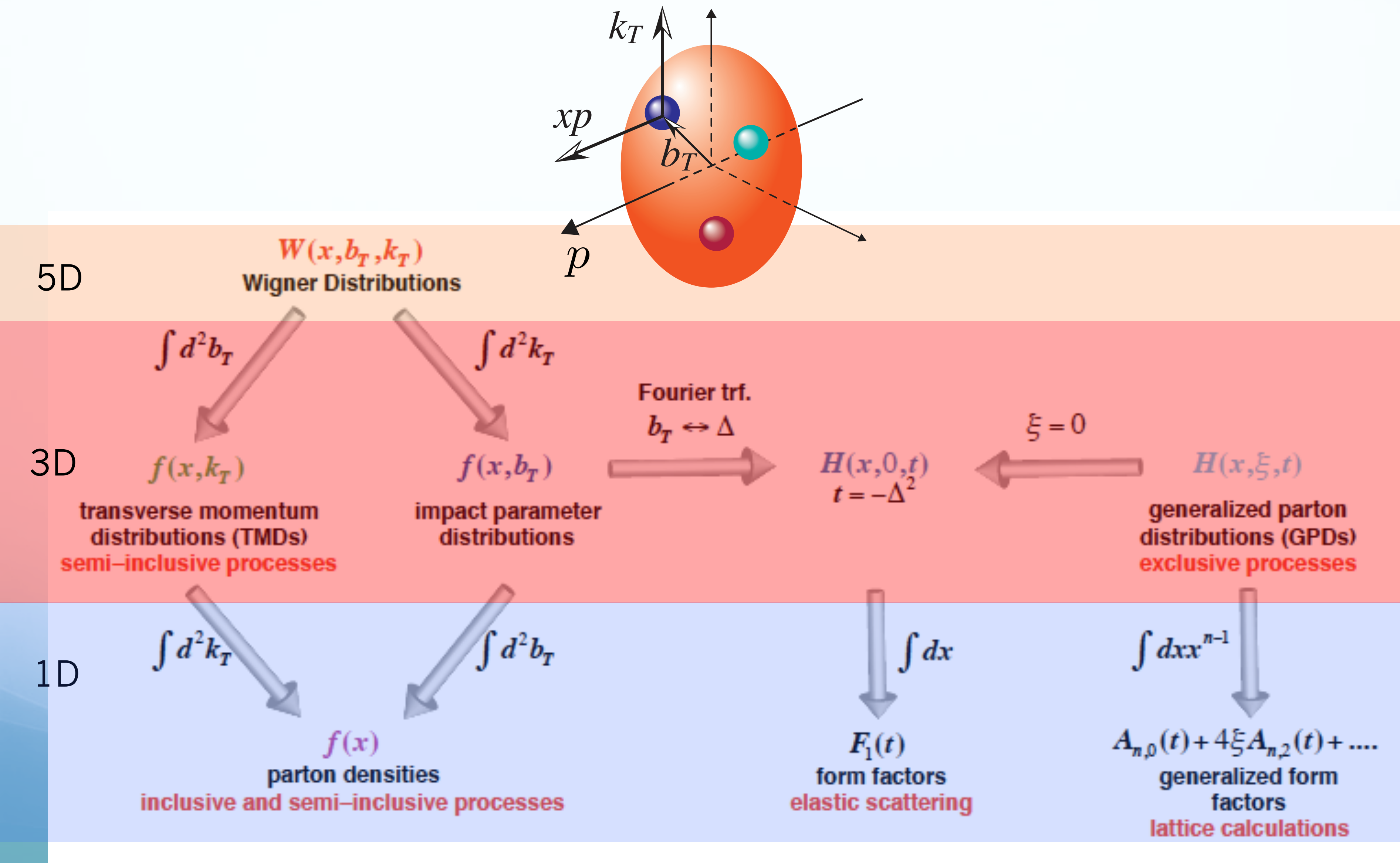
Kinematics coverage

- Examine the science requiring high luminosity at low to medium center of mass energies (20 to 60 GeV)
  - Complimentary to high CM energy (140 GeV): constraints at high x and relatively smaller Q
  - Such a region is also essential for EIC scientific goals



Quantum imaging

- Wigner distributions: a quantum version of phase-space distribution



GPDs

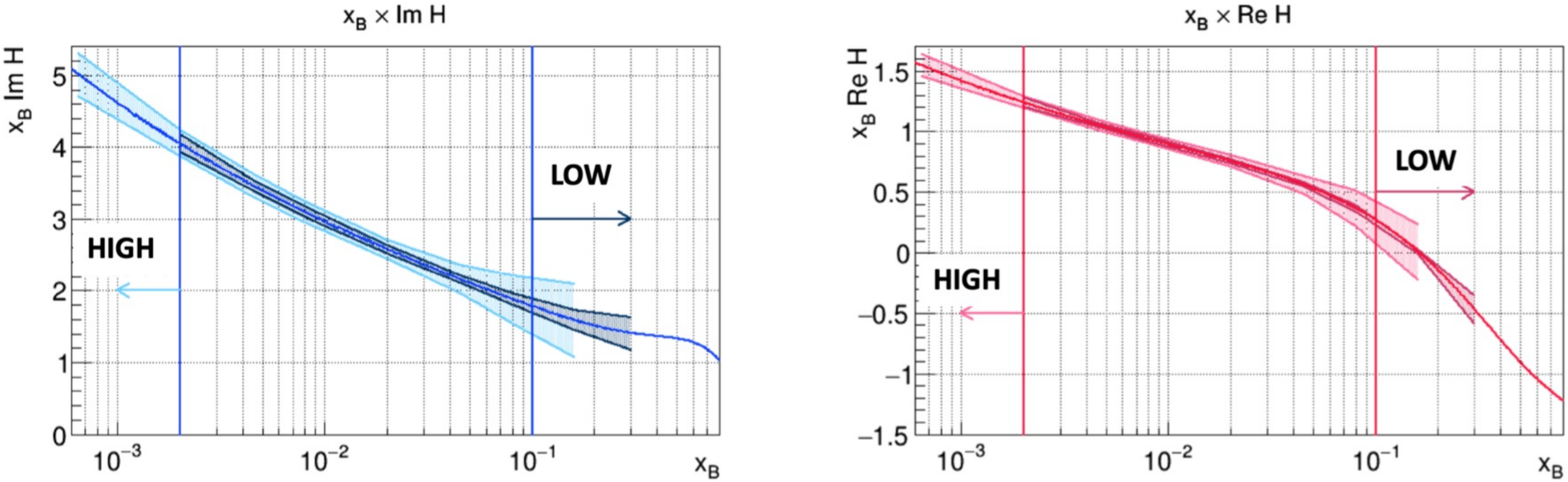


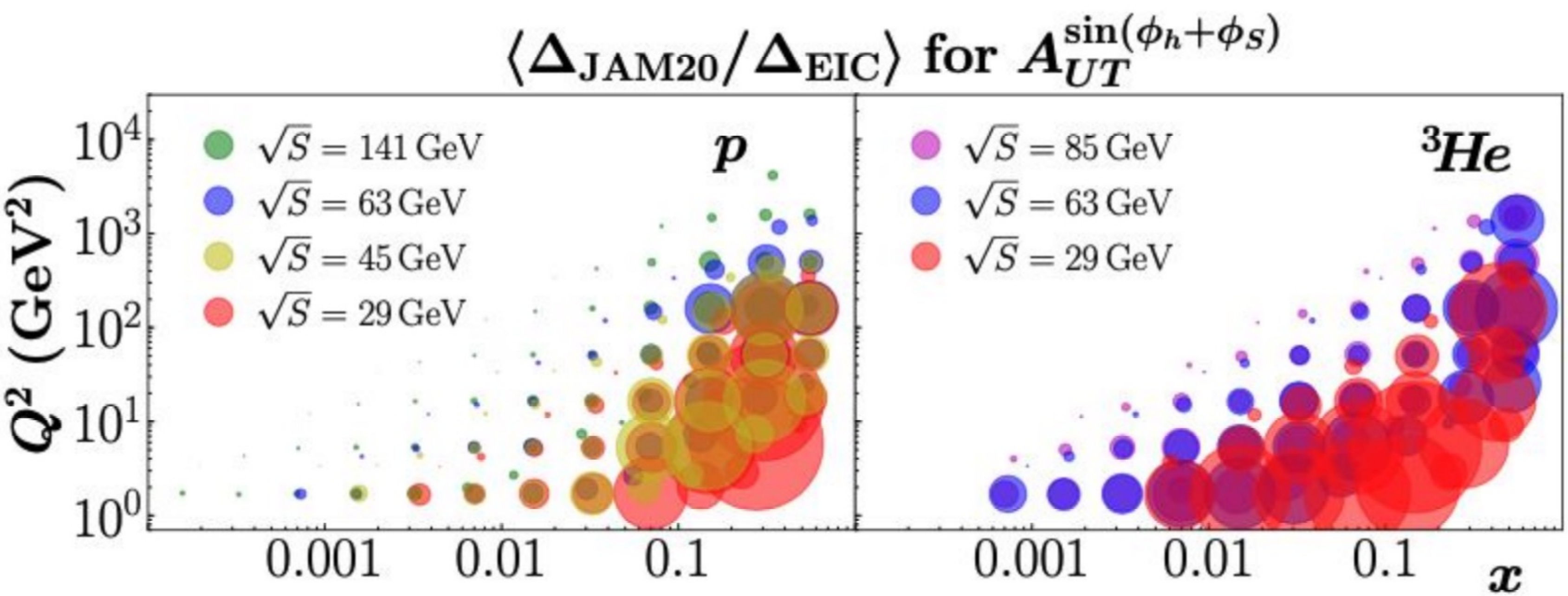
FIG. 8. Compton form factors Im$\mathcal{H}$ and Re$\mathcal{H}$ extracted at local x_B values from simulated DVCS events at different CM beam energies, $\sqrt{s} = 28$ GeV (LOW) and $\sqrt{s} = 140$ GeV (HIGH). The dark shaded bands represent the reach and the uncertainties at the lower CM-energy. The lighter shaded bands represent the higher CM-energy. The x_B regions labeled LOW can only be covered at the low CM-energy with reasonable uncertainties. The x_B region labeled HIGH can only be reached with the high CM-energy. The widths of the bands indicate the estimated uncertainties due to overall reconstruction effects, statistics and systematic uncertainties. For each of the two CM-energies a combined integrated luminosity of 200 fb^{-1} equally split between longitudinally polarized and transversely polarized proton runs is assumed. At $x_B > 0.1$ smaller uncertainties can be achieved at the low CM-energy, which provides overlapping x_B kinematics with the JLab 12 GeV experiments (not shown). The region $x_B < 2 \times 10^{-3}$ can only be reached at the high CM-energy.

TMDs: Collins effect

Impact of EIC (from YR)

https://arxiv.org/abs/2101.06200

Gamberg, Kang, Pitonyak, Prokudin, NS, Seidl



High-x region provides significant constraints

TMDs: Sivers effect

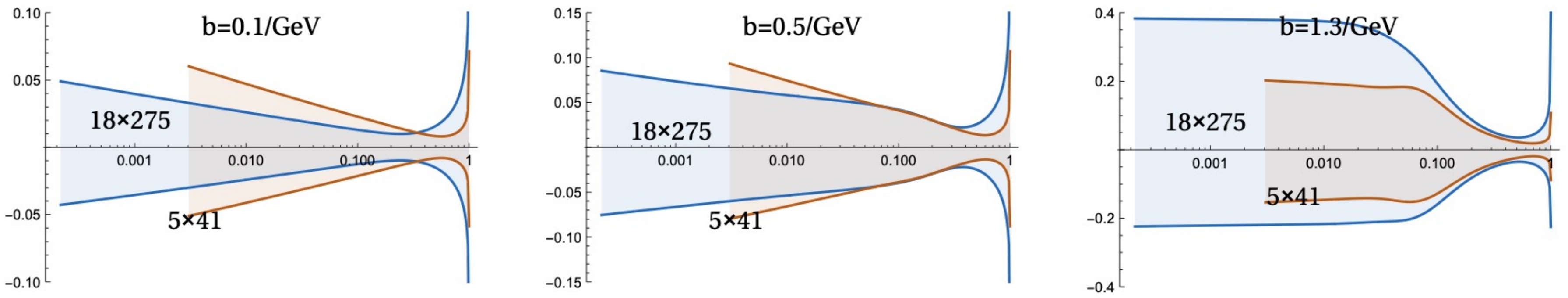


FIG. 22. Comparison of relative uncertainty bands for unpolarized u-quark TMD PDFs at different values of b as a function of x. Lighter blue band is the impact of 18×275 data, light brown band is the impact of 5×41 EIC pseudo data. The dataset used for these projections is the same as used for the Yellow Report [8]. In particular all energy options use the same integrated luminosity.

TMD evolution

- Just like collinear PDFs, TMDs also depend on the scale of the probe = evolution

Collinear PDFs

$F(x, Q)$

- ✓ DGLAP evolution
- ✓ Resum $\left[\alpha_s \ln(Q^2/\mu^2)\right]^n$
- ✓ Kernel: purely perturbative

TMDs

$F(x, k_\perp; Q)$

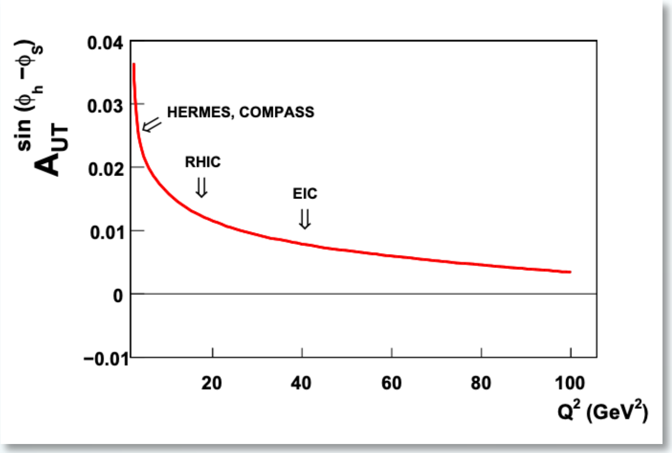
- ✓ Collins-Soper/rapidity evolution equation
- ✓ Resum $\left[\alpha_s \ln^2(Q^2/k_\perp^2)\right]^n$
- ✓ Kernel: can be non-perturbative when $k_\perp \sim \Lambda_{\rm QCD}$

$$F(x, Q_i)$$
$$\downarrow$$
$$R^{\rm coll}(x, Q_i, Q_f)$$
$$\downarrow$$
$$F(x, Q_f)$$

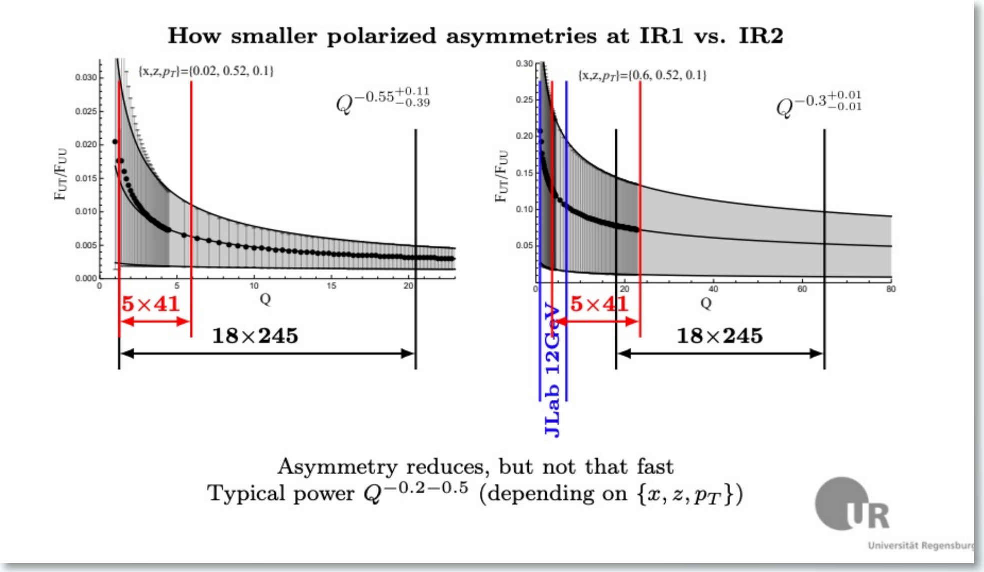
$$F(x, k_\perp, Q_i)$$
$$\downarrow$$
$$R^{\rm TMD}(x, k_\perp, Q_i, Q_f)$$
$$\downarrow$$
$$F(x, k_\perp, Q_f)$$

TMD evolution: low vs high Q

- On one hand, we need large enough Q to make sure TMD factorization work, need both small Q and large Q data to better constrain the TMD evolution



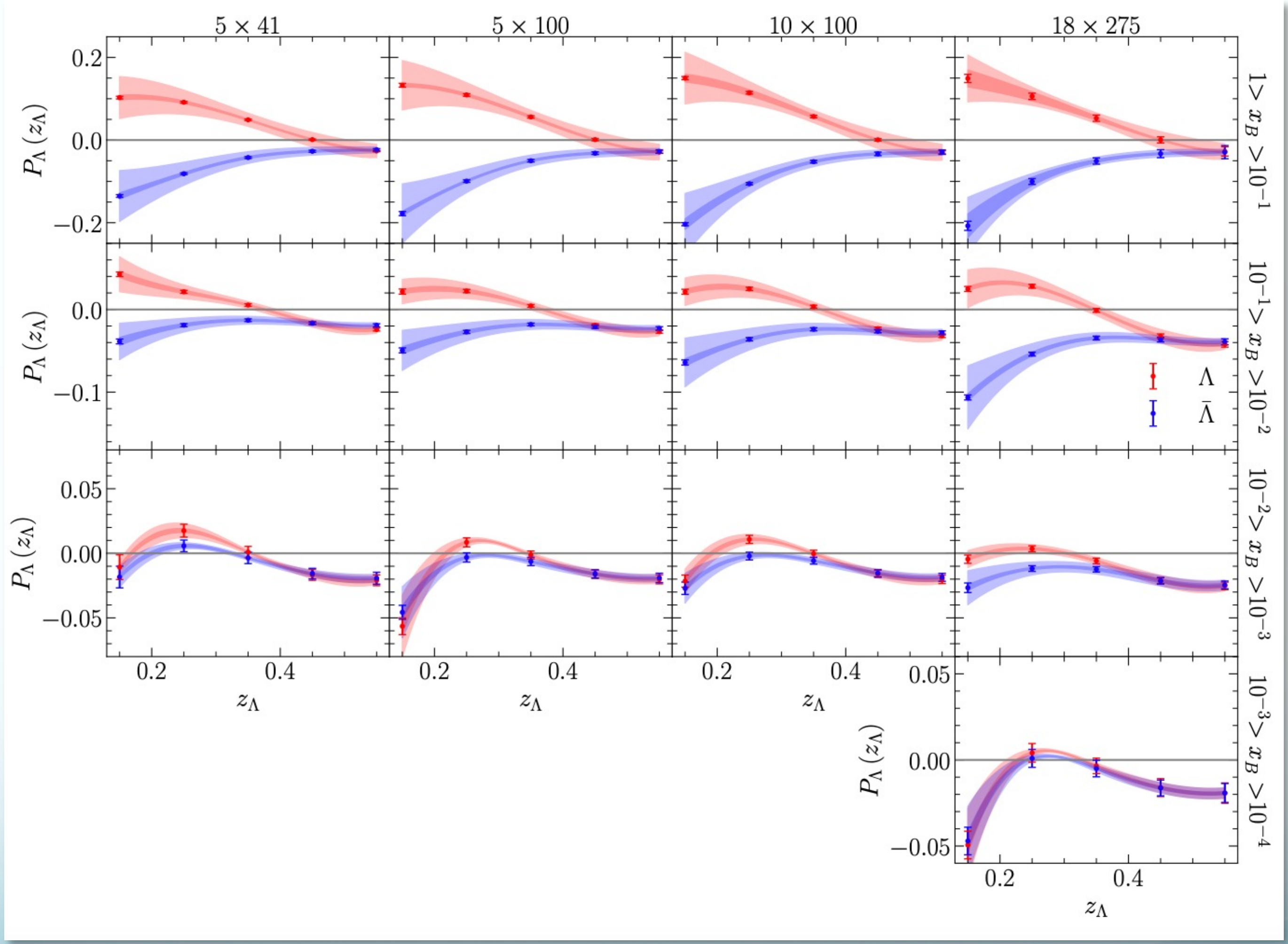
Aybat, Prokudin, Rogers, PRL 2012



A. Vladimirov, 2021

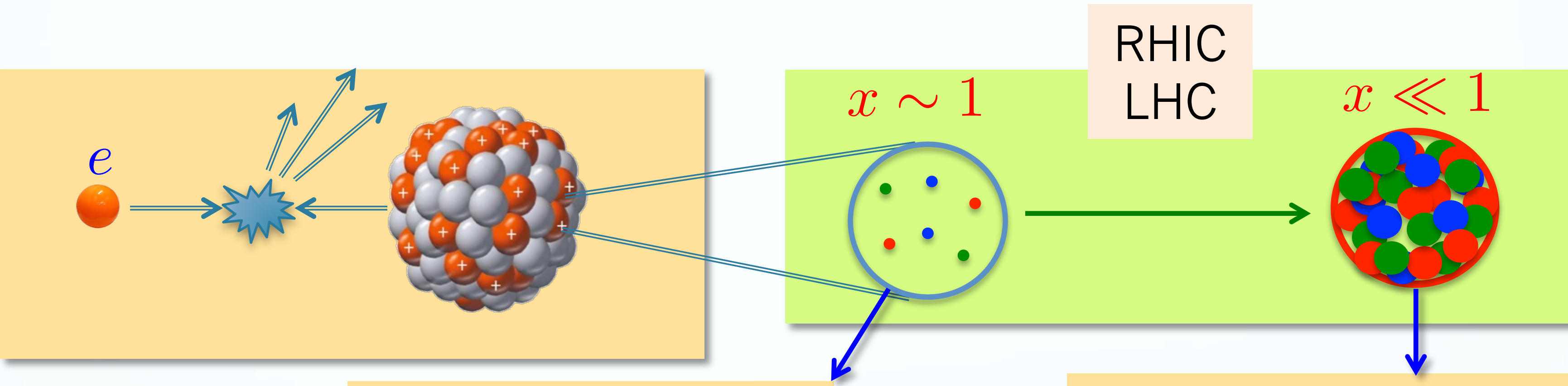
Another example

- Lambda polarization in SIDIS



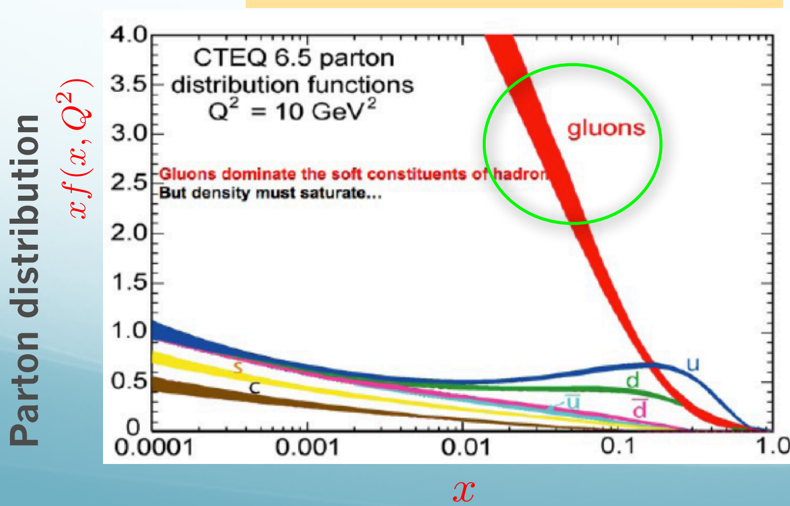
Kang, Terry, Vossen, Xu, Zhang, 2108.05383, PRD 22

Color Glass Condensate



- A dilute system
- Probes interact independently

- A dense system
- Probes interact coherently

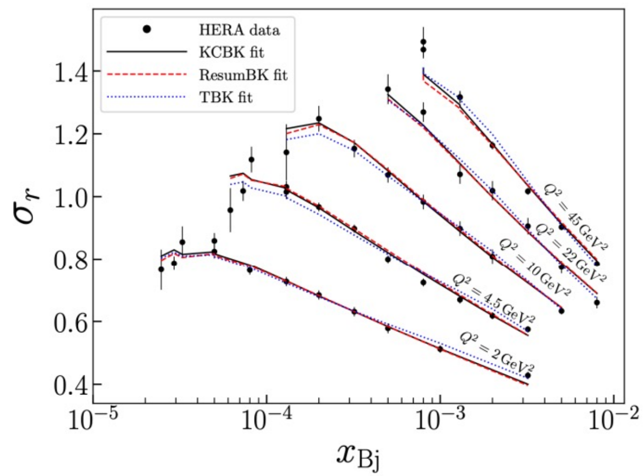


Rapid recent progress in the field

Uplifting saturation physics to NLO

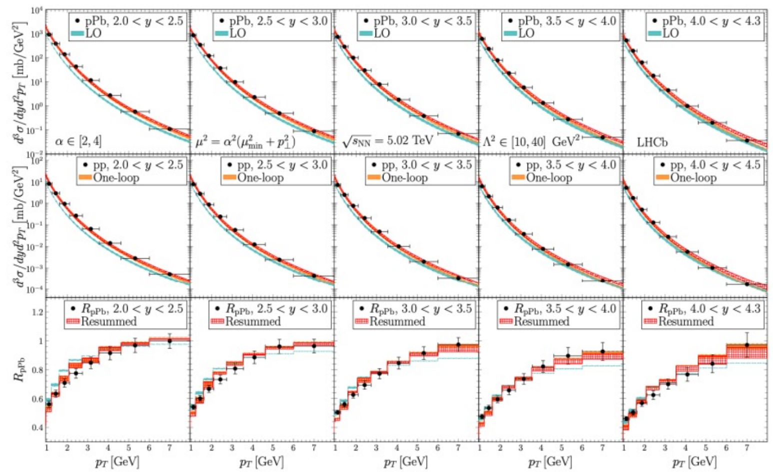
Recent developments

DIS structure functions



Beuf, Lappi, Hänninen, Mäntysaari (2020)

Hadron production in pp (pA)



Shi, Wang, Wei, Xiao (2021)

Many recent developments pushing saturations physics to NLO

Diffractive structure functions

Massive structure functions

Exclusive vector meson production in DIS

Jyväskylä group (Lappi et al, 2020-2022)

Dijet production in DIS *Caucal, FS, Venugopalan (2021)*

Jet production in pA *Liu, Xie, Kang, Liu (2022)*

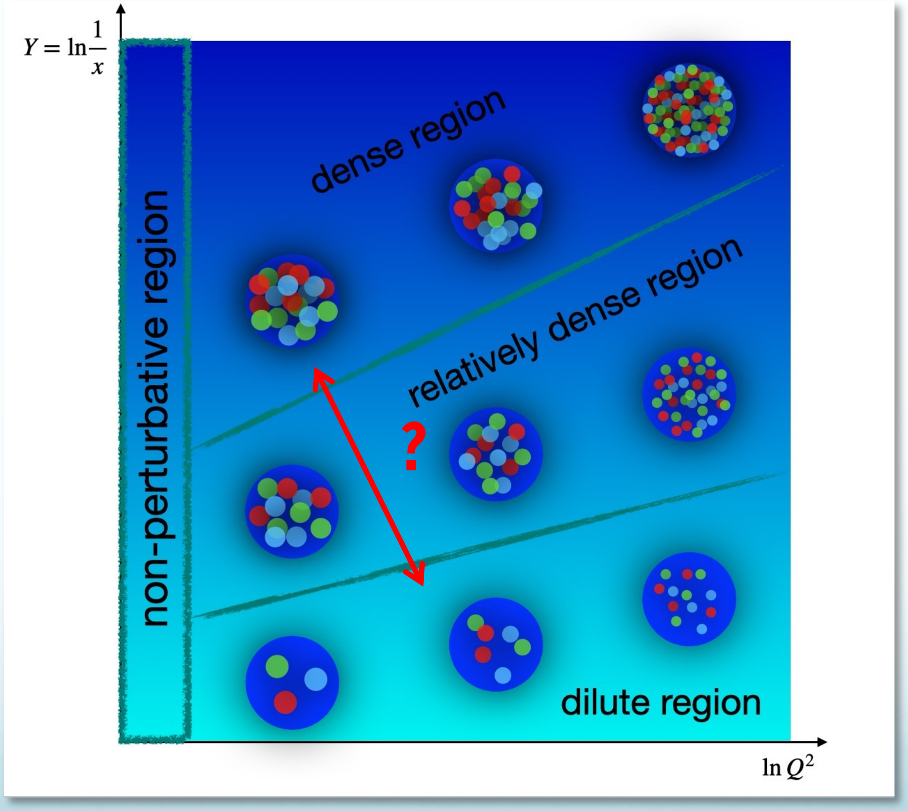
Dijet production in photo-production *Taels et al (2022)*

Dihadron production in DIS *Bergabo, Jalilian-Marian(2022)*

Courtesy of Farid Salazar, 2022

Key questions

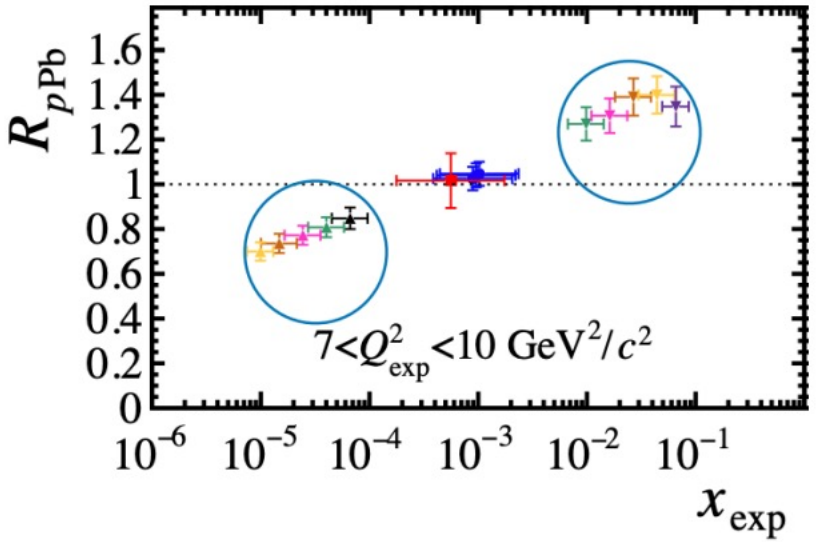
- Where and how does the transition from a dilute parton system to a saturated gluon-dominated state occur?
- What are the properties of such a dense gluon regime?



Different physics at different regions??

- Enhancement at large x and suppression at small x?

Nuclear modification of charged particle production

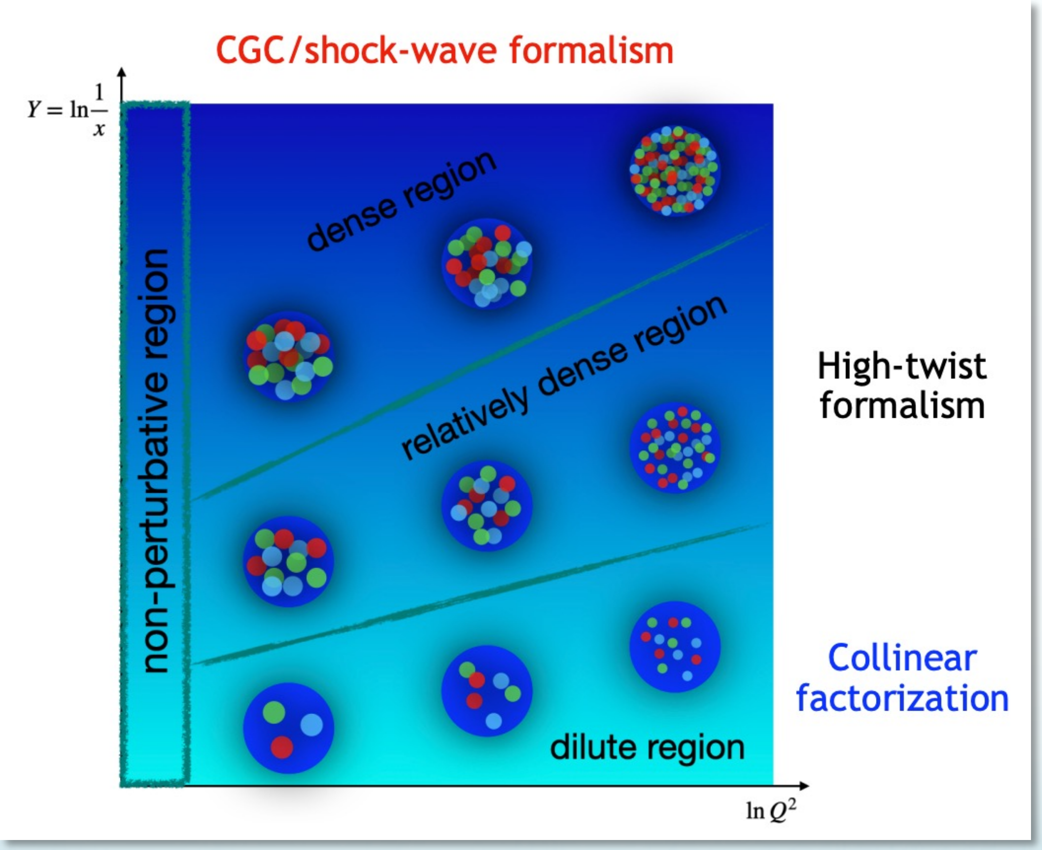


Enhancement (backward region) vs suppression (forward region)

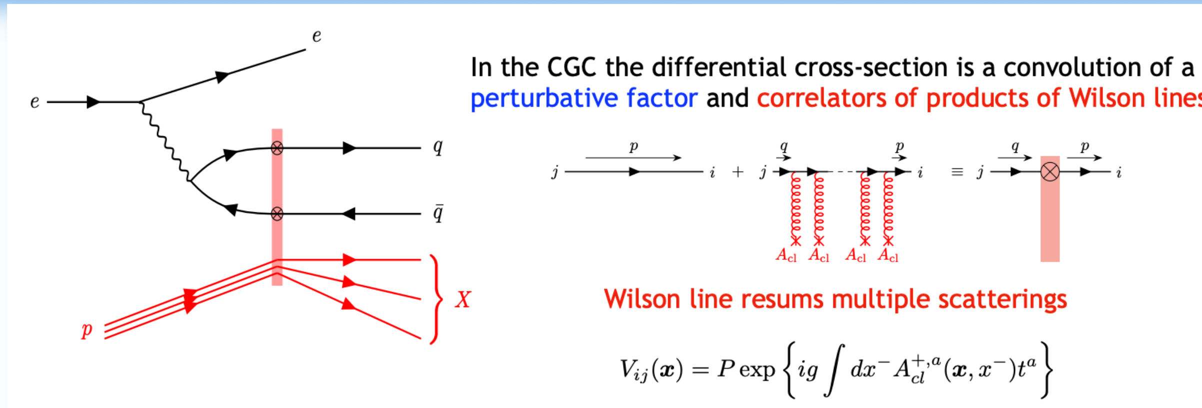
LHCb Collaboration. Phys. Rev. Lett. 128, 142004

Current theory

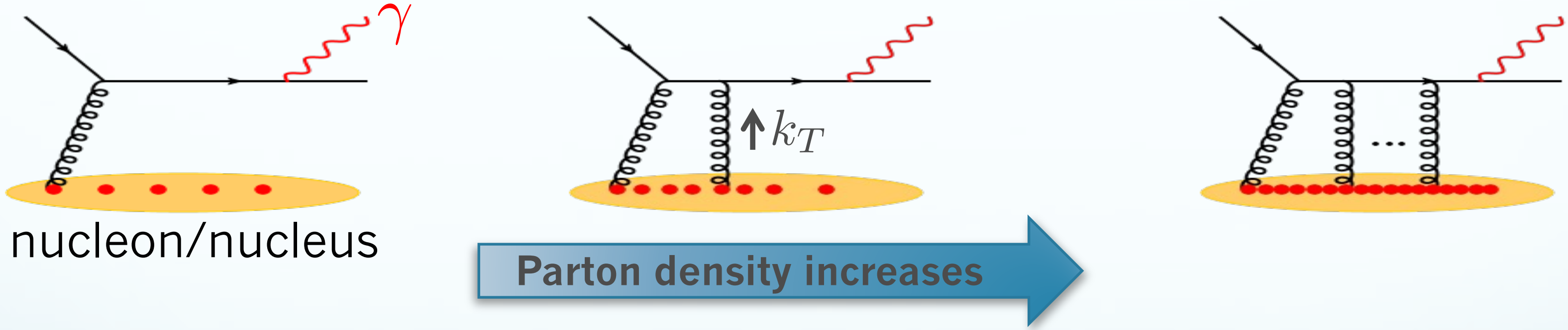
- Connection among them? How to unified the formalisms?



Transition



- Understand how physics evolves

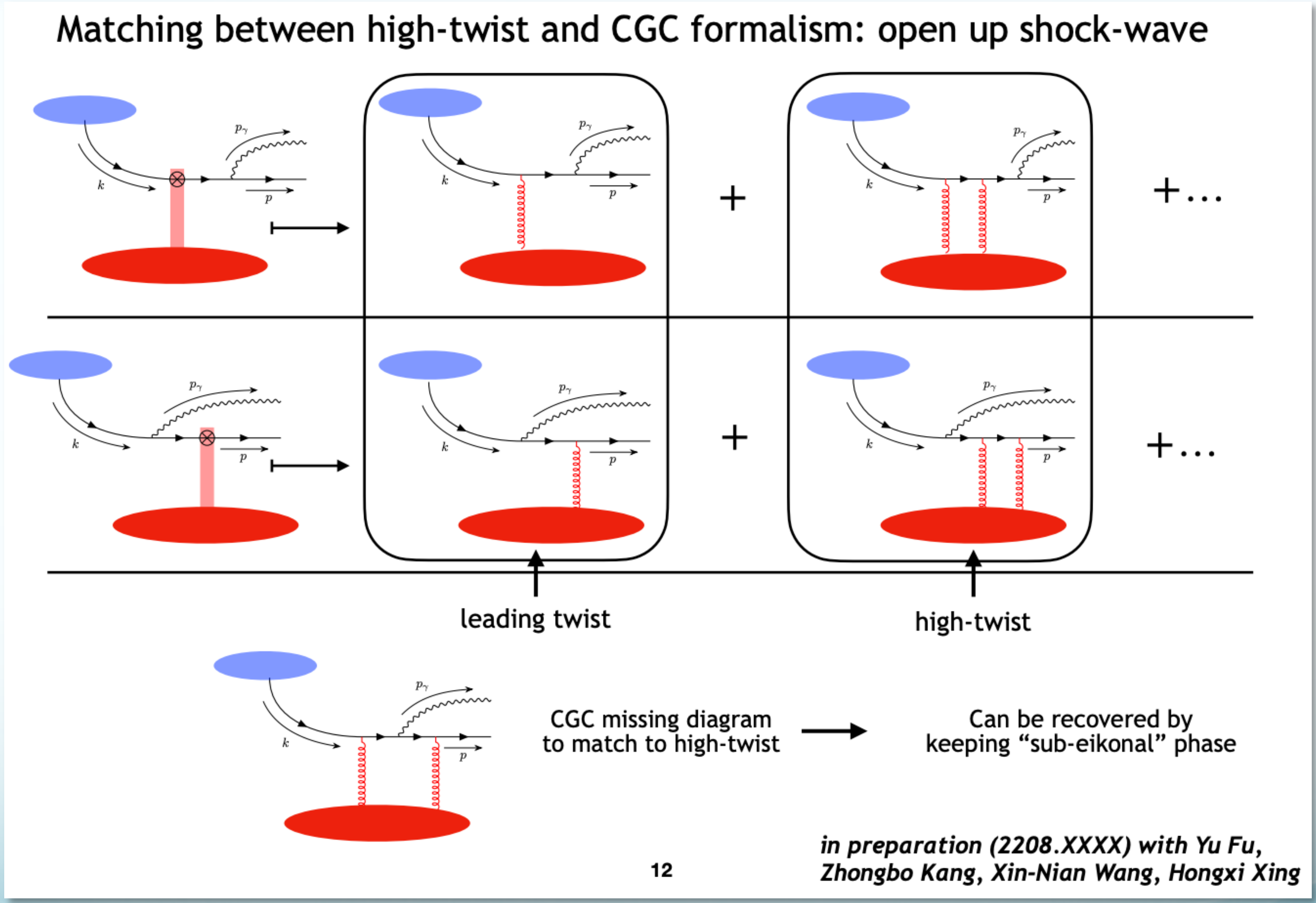


- Multiple scattering expansion formalism for incoherent interaction

$$\sigma \sim \sigma_0\left[1 + C_1\frac{\langle k_T^2\rangle}{Q^2} + C_2\left(\frac{\langle k_T^2\rangle}{Q^2}\right)^2 + \cdots\right]$$

single scattering + double scattering +...

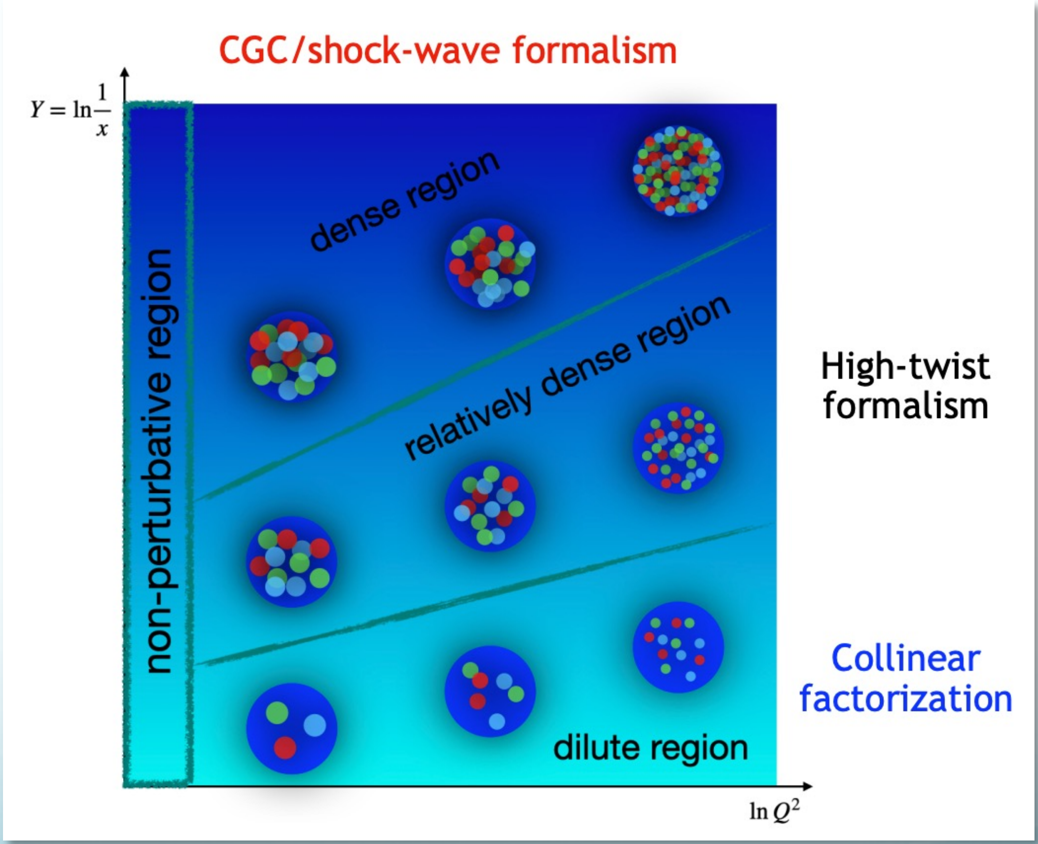
A unified framework for dilute-dense dynamics



Courtesy of Farid Salazar, 2022

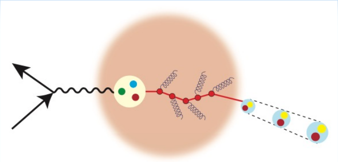
Come back: the main point

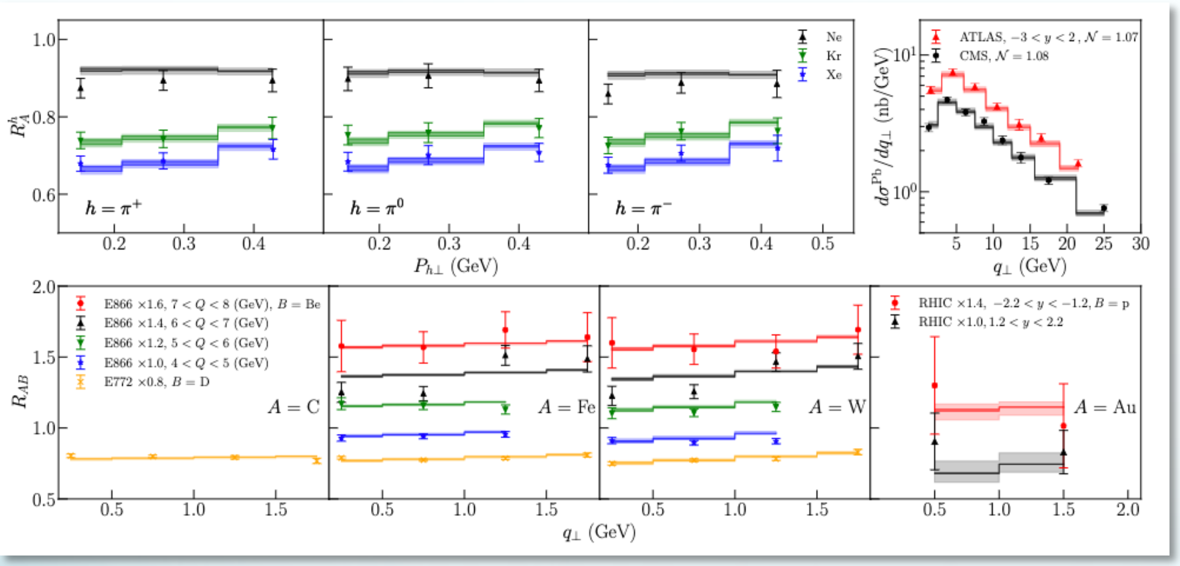
- In order to unambiguously identify the gluon saturation region, one needs both low x (dense) and high x (transition) regions
  - Detector II would perfectly serve such a purpose

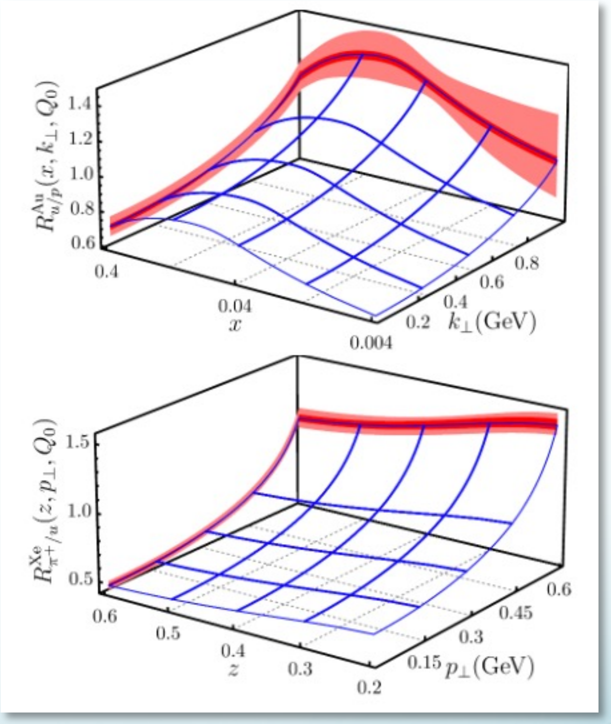


Hadron propagation in nuclei

- Nuclear TMD PDFs and TMD FFs
  - Similar to nuclear collinear PDFs idea (EKS98, EPPS16, etc)
  - Use the same TMD factorization for hadron production in e+A, except replacing with nuclear TMDs [via broadening parameters]







$$\frac{d\sigma}{dx_B dQ^2 dz_h d^2P_{hT}} \propto \int d^2k_T d^2q_T f_q(x_B, k_T) D(z_h, q_T) \delta^2(z_h k_T + q_T - P_{hT})$$

Alrashed, Anderle, Kang, Terry, Xing, 2021

Nuclear modification is larger at smaller Q

- Predictions at different Q and x

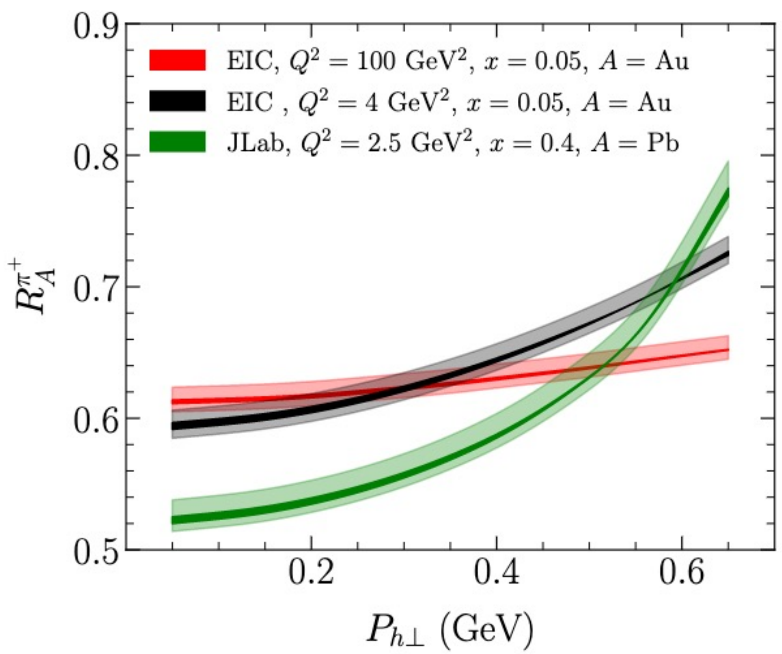


FIG. 4. Prediction for SIDIS π^+ production at the future EIC and JLab at $z = 0.4$. The light and dark bands are the same as in Fig. 2.

EW/BSM physics

- Weak mixing angle
  - Data point of different CM energies can be combined, or the Q2-dependence of the EW parameter can be explored

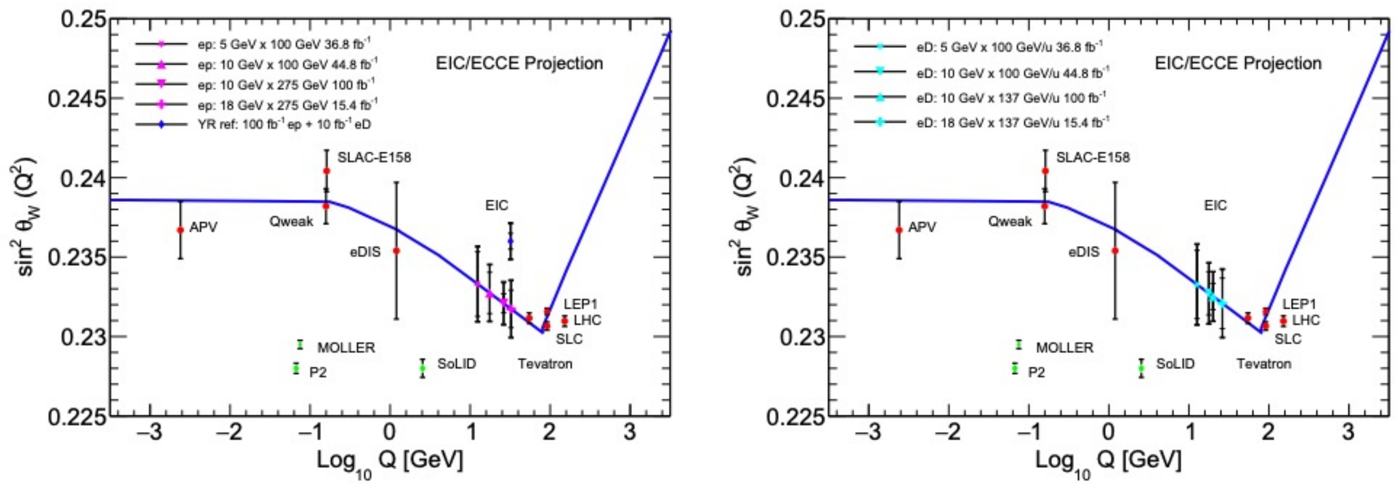
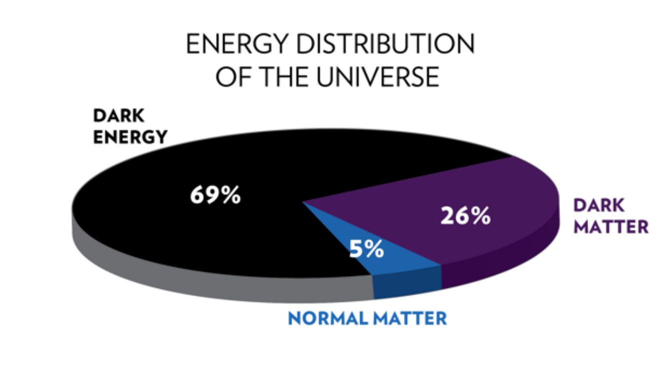


FIG. 3. From [4]: Projected results for $\sin^2\theta_W$ using *ep* (left, solid magenta markers) and *eD* (right, solid cyan markers) collision data and the nominal annual luminosity given in Table 10.1 of the Yellow Report [3], along with existing world data (red solid circles). Data points for Tevatron and LHC are shifted horizontally for clarity. Result from combining 100 fb^{-1} *ep* 18 × 275 GeV and 10 fb^{-1} *eD* 18 × 137 GeV is also shown and is called the "YR reference point" (blue diamond). The PDF uncertainty is from CT18NLO. The electron beam polarization is assumed to be 80% with a relative 1% uncertainty. The inner error bars show the combined uncertainty from statistical and 1% uncorrelated background effect; the median error bars show the experimental uncertainty that includes statistical, 1% uncorrelated background, and 1% electron polarimetry. The outer-most error bars (which almost coincide with the median error bars) include all the above and the PDF uncertainty evaluated using the CT18NLO sets. Results evaluated with the MMHT2014 and NNPDF31NLO sets are similar. Also shown are the expected precision from P2 [11], MOLLER [12] and SoLID [13] PVDIS [14, 15], respectively. The script used to produce this plot was inherited from [16], and the scale dependence of the weak mixing angle expected in the SM (blue curve) is defined in the modified minimal subtraction scheme ($\overline{\text{MS}}$ scheme) [17].

Dark matter at EIC

- Dark matter exist (observed via gravity)



- How to look for dark matter

1608.08632

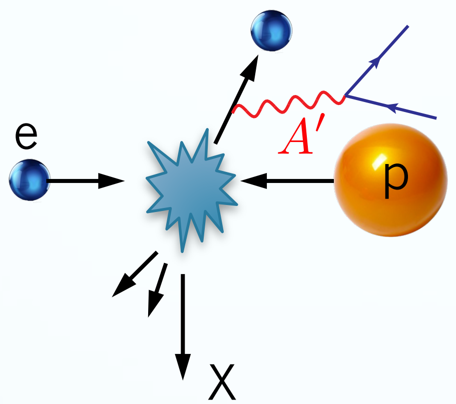
Dark sectors typically include one or more mediator particles coupled to the SM via a *portal*. The portal relevant for dark sector-SM interactions depends on the mediator spin and parity: it can be a scalar ϕ, a pseudoscalar a, a fermion N, or a vector A'. The gauge and Lorentz symmetries of the SM greatly restrict the ways in which the mediator can couple to the SM. The dominant interactions between the SM and these mediators are therefore the following SM gauge singlet operators:

$$\mathcal{L} \supset \begin{cases} -\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}\,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H\,, & \text{Higgs portal} \\ y_n L H N\,, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}\,, & \text{axion portal.} \end{cases} \tag{1}$$

Dark photon

Dark photon search

- Dark photon at EIC



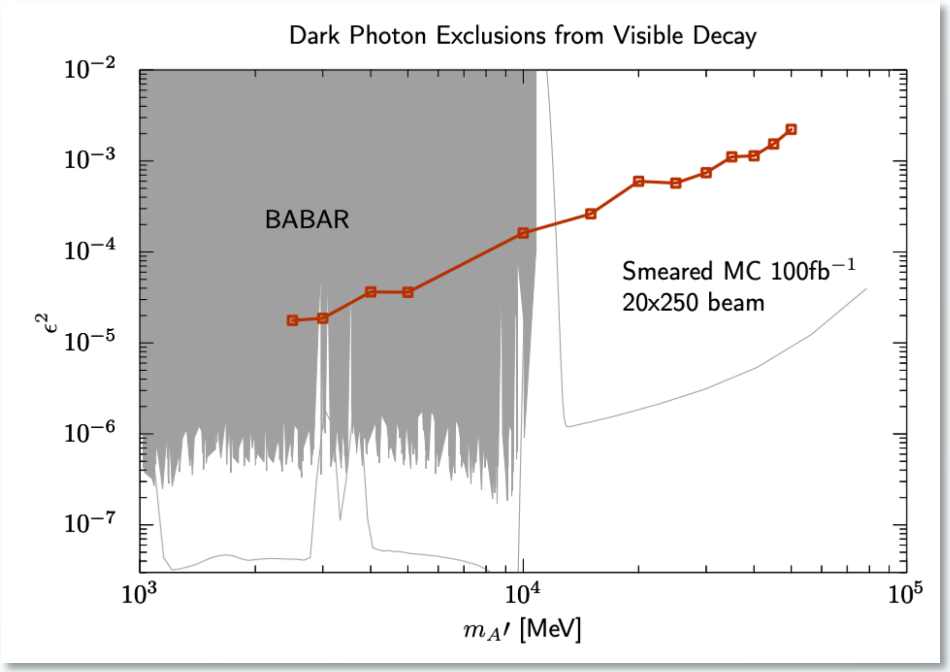


FIG. 10. Dark photon mass and coupling strength for a benchmark $ep \to epA' \to epee^+$ search. The solid red line reflects the curve above which a dark photon could be excluded at 2σ with 100 fb^{-1} of data. Performance is shown without cuts to enhance signal, and without hadronic background contributions. Effects due to structures in the branching ratio are not represented, but will follow similar structures in existing measurements. The solid gray area represents the region excluded by BABAR's existing search, while the thin gray lines represent projections for Belle II (leptonic, left) and LHCb (hadronic, right) regions excluded through existing leptonic searches. Further details are in the text.

Conclusions

- There is absolutely no doubt that a second detector can offer additional/complimentary physics opportunities [along three major EIC science thrusts + also EW/BSM physics]
  - Quantum imaging
  - Color Glass Condensate
  - Cold nuclear matter effect
  - EW/BSM physics
- Thank everyone for all the efforts from various white papers

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Thank you!