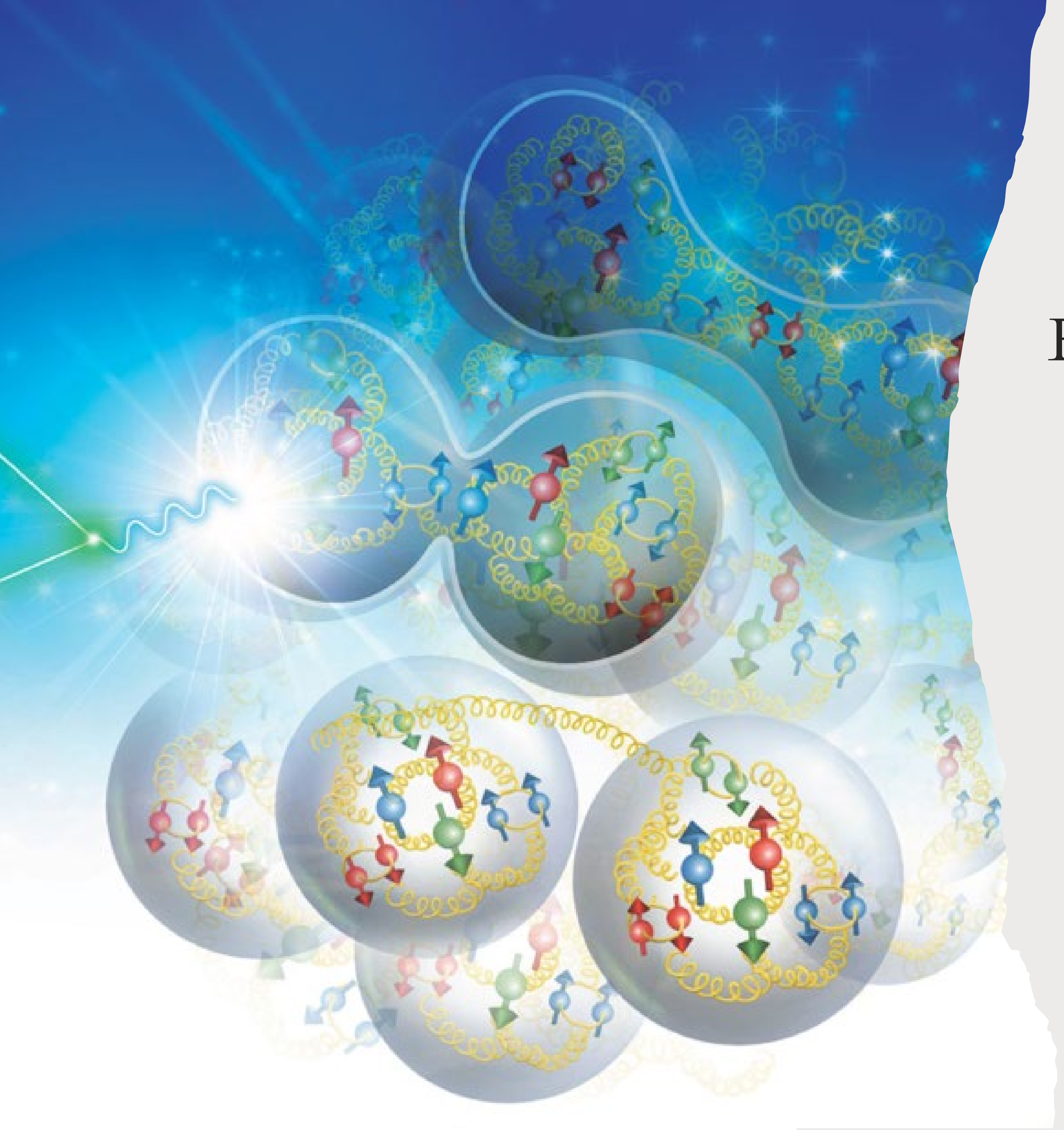


EPIC DEVELOPMENTS, CONNECTIONS AND PERSPECTIVES ON HEAVY ION PHYSICS

Olga Evdokimov (UIC)

for the ePIC collaboration

SCIENTIFIC CASE FOR THE EIC

- EIC: long time in the making and planning
- EIC potential and prospects are discussed in the US Long Rage Planning from 2002
- EIC is a key element of the Long-Range Plan of 2015
- NAS assessment: "The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely."
- Long-Rang Plan of 2023 recommends EIC as the highest priority for facility construction

EIC SCIENCE PILLARS

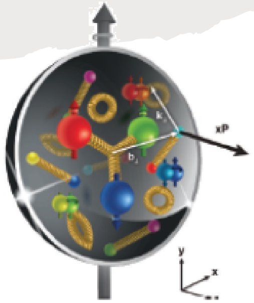
SPIN is one of the fundamental properties of matter.
All elementary particles, but the Higgs carry spin.
Spin cannot be explained by a static picture of the proton
It is the interplay between the intrinsic properties and interactions of quarks and gluons

The EIC will unravel the different contribution from the quarks, gluons and orbital angular momentum.

Does the mass of visible matter emerge from quark-gluon interactions?

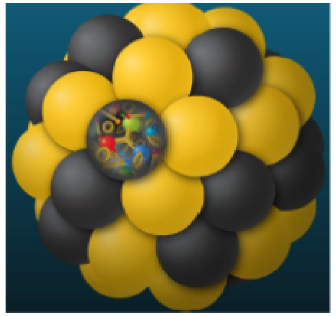
Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

proton
determine an important term contributing to the proton mass, the so-called "QCD trace anomaly

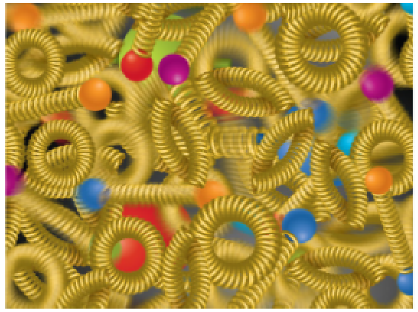


How are the quarks gluon distributed in space and momentum inside the nucleon & nuclei?

nucleon properties emerge from them and their interactions?
How can we understand their dynamical origin in QCD?
What is the relation to Confinement



Is the structure of a free and bound nucleon the same?
How do quarks and gluons, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?



How many gluons can fit in a proton?
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?
What happens to the gluon density in nuclei? Does it saturate at high energy?

gluon splitting
?
=
gluon recombination

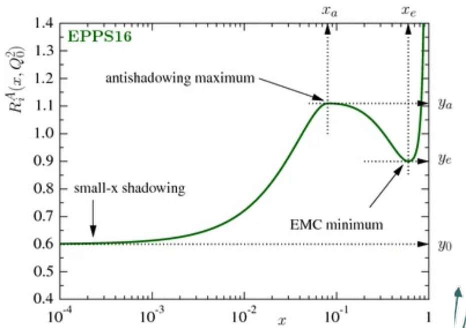
Composition from E. Aschenauer at 2024 EICUG meeting

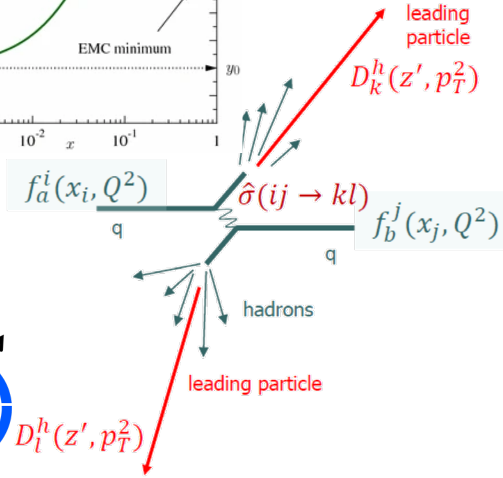
$AA \rightarrow (pA, ep) \rightarrow eA$: COMMON PURSUITS

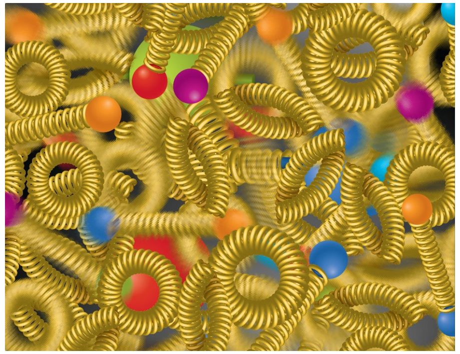
Parton Distributions/Initial State	↔ Gluon Saturation ↔	Hadronization/Fragmentation

Differences in PDF for bound and free nucleons;

Details of shadowing, anti-shadowing, EMC regimes







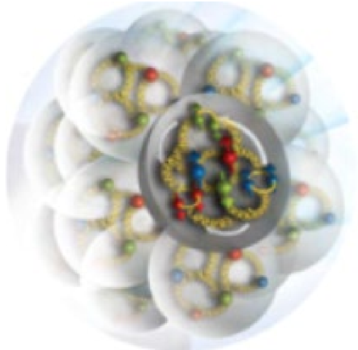
Does gluon density saturate? When?

Does it lead to a gluonic matter with universal properties in all nuclei? (even in proton?)

Effects of a dense nuclear environment on partonic interactions / correlations

Final state effects: partonic interactions with nuclear medium

Emergence of confined hadronic states from quarks and gluons

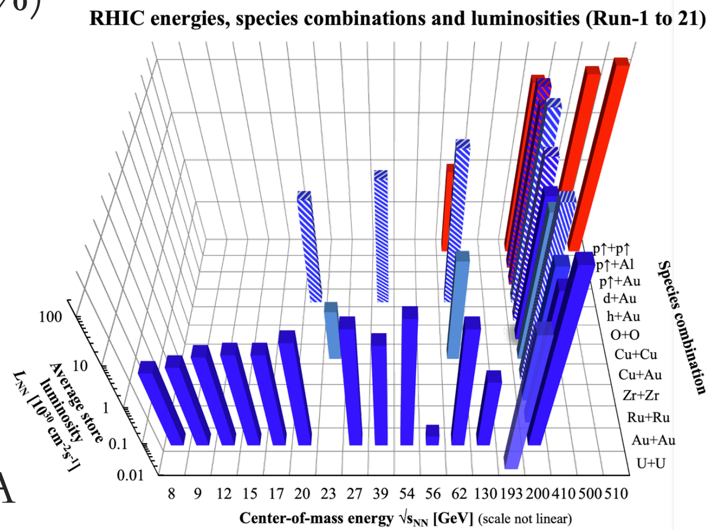


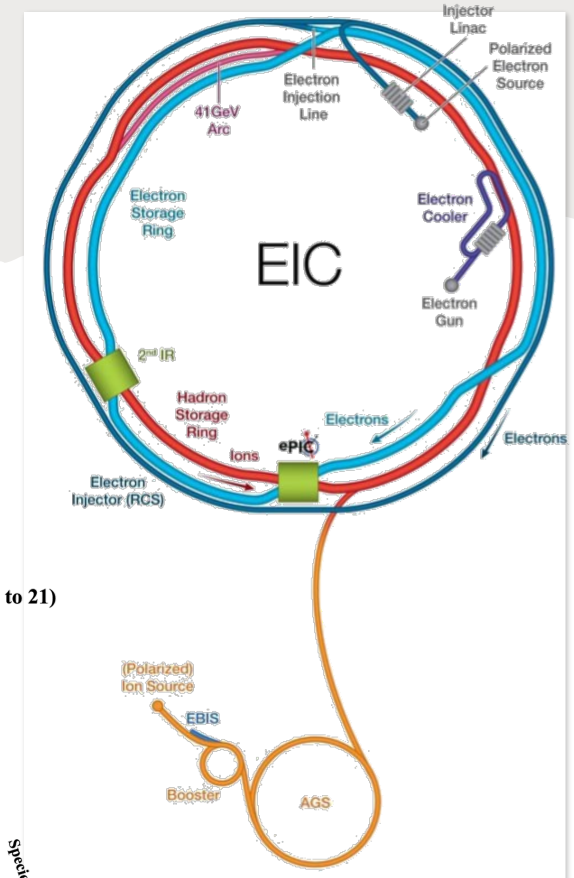
Quark-gluon interactions ↔ confinement and nuclear binding

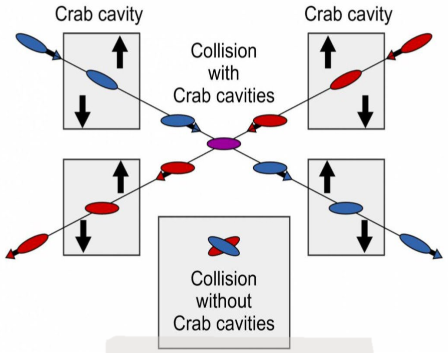
Factorization and universality tests

EIC MACHINE DESIGN & REQUIREMENTS

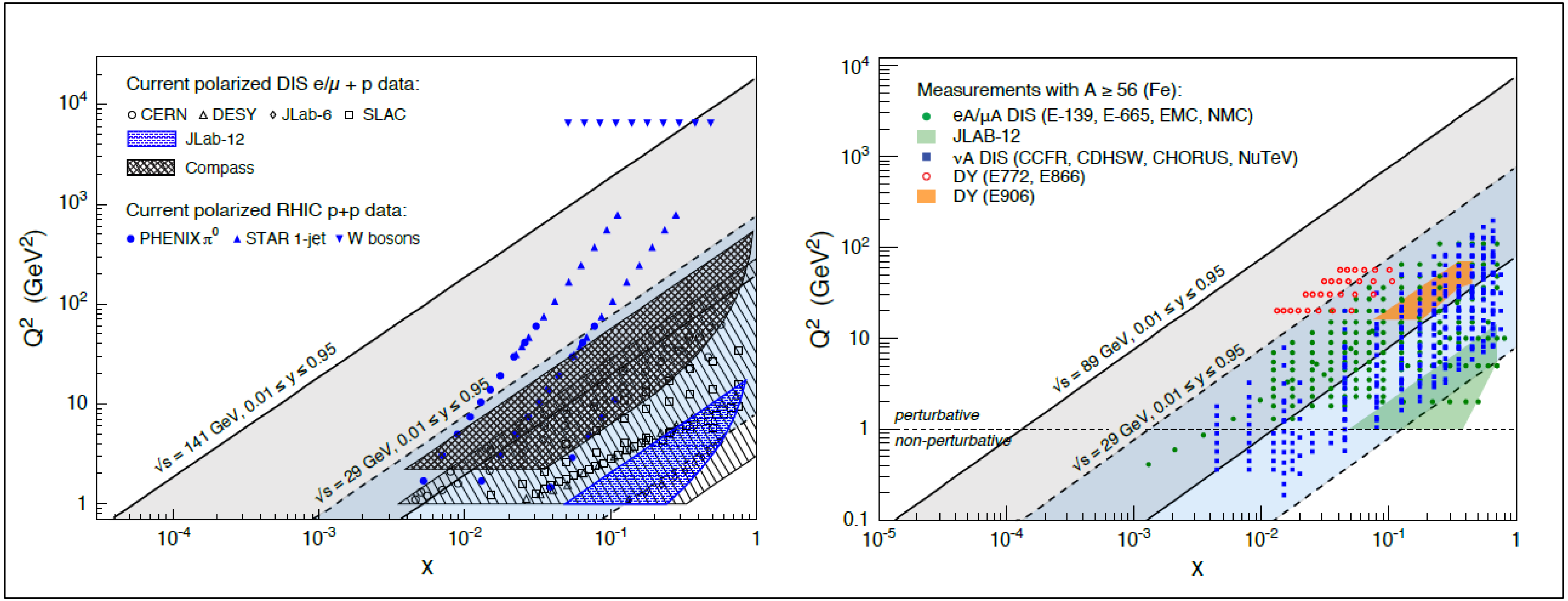
- EIC science drives the requirements and machine design:
  - High luminosity (10^{33}– $10^{34}\ cm^{-1}s^{-1}$)
  - High polarization for electrons / light ions (70%)
  - Wide range of $\sqrt{s_{ep}}$ (20 – 140 GeV)
  - Variety of ion species (p to U)
- Repurposing the existing RHIC collider:
  - Hadron ring with 2 IRs exists and operational
  - Adding electron ring with beams 5 - 18 GeV
- What is new/different:
  - $\times$ 100 – 1000 luminosity increase over HERA
  - polarization for electrons, protons, light nuclei
  - 25 mrad crossing angle with crab cavities







EIC KINEMATIC REACH

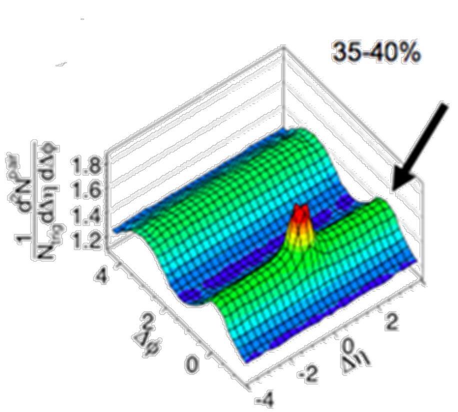


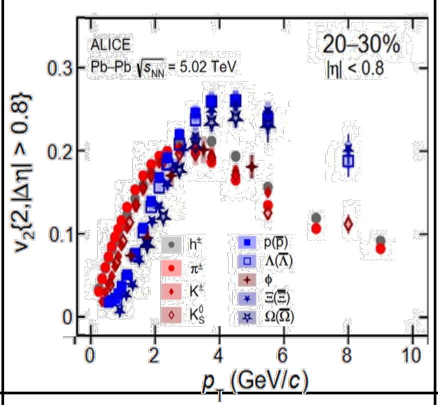
Polarized ep Polarized eA

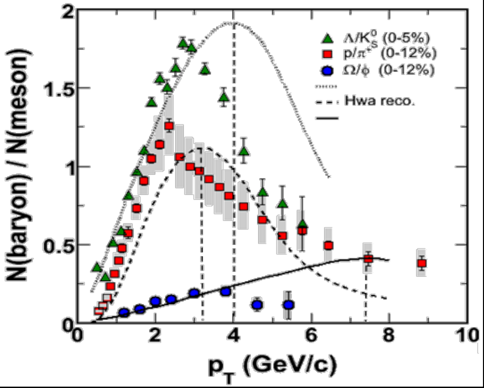
- Extension of existing polarized beam measurements:

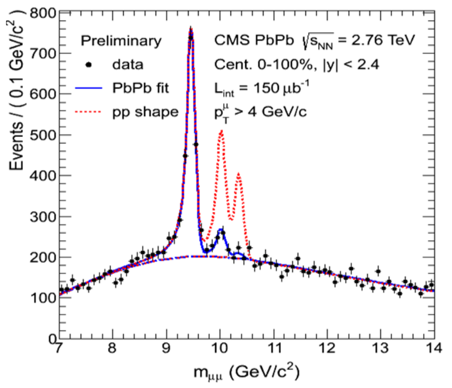
$\times$ 100 in x at a fixed Q^2 and by $\times$ 100 in Q^2 at a fixed x

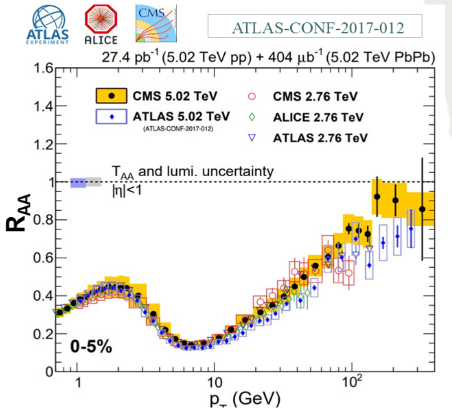
(SELECTED) QGP PILLARS







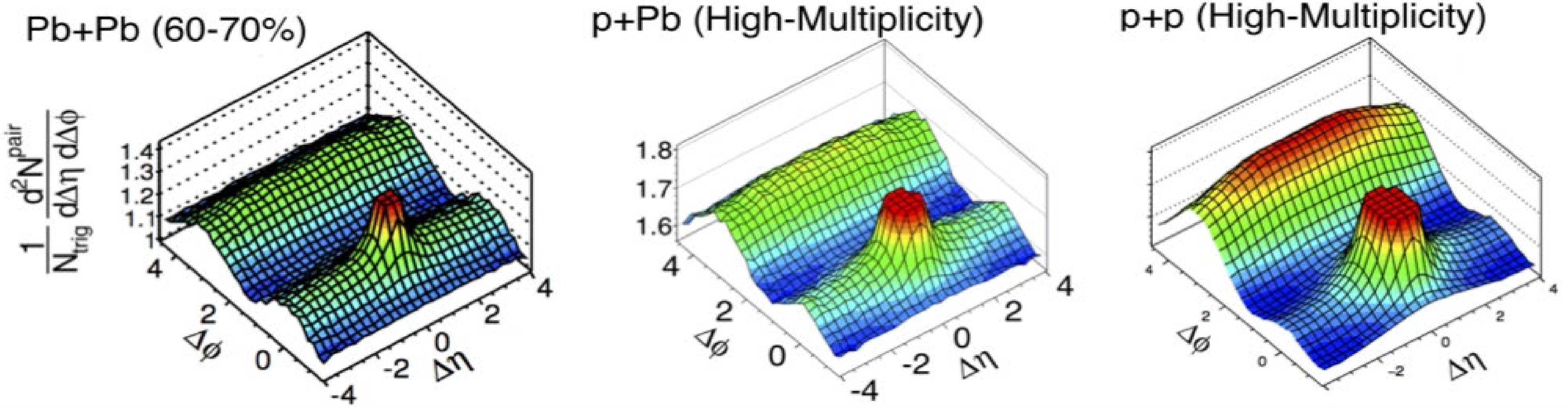




Collectivity	nCQ Scaling	*Baryon/Meson*	*Quarkonia Melting*	Jet Quenching
Hierarchy of flow correlations described by hydrodynamics; finite estimates of η/s, close to quantum limit	Across energies and ion species Baryon/meson grouping Hadronization via recombination	QGP hadronization: parton recombination? Interplay with / modification of FF?	Color screening Hierarchy of suppressions consistent with expectations from binding energies QGP thermometer	Many manifestations: nuclear modification, energy rebalance / redistribution in dijets, JS, JFF, …

Exploring synergies of the AA/pA and eA/ep programs…

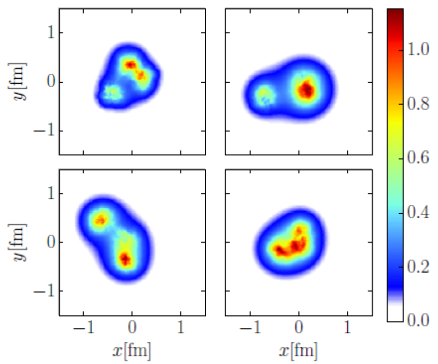
COLLECTIVE PHENOMENA IN SMALL SYSTEMS



- Long range correlations: everywhere! AA, pA, high multiplicity pp
  NOT reproduced in any established MC generators!

- Understanding of proton structure is critical for reproducing the signals

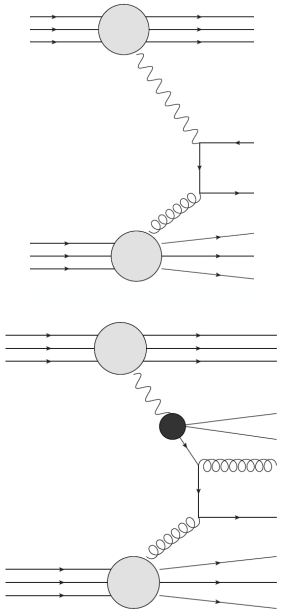
PRD 94(2016)034042

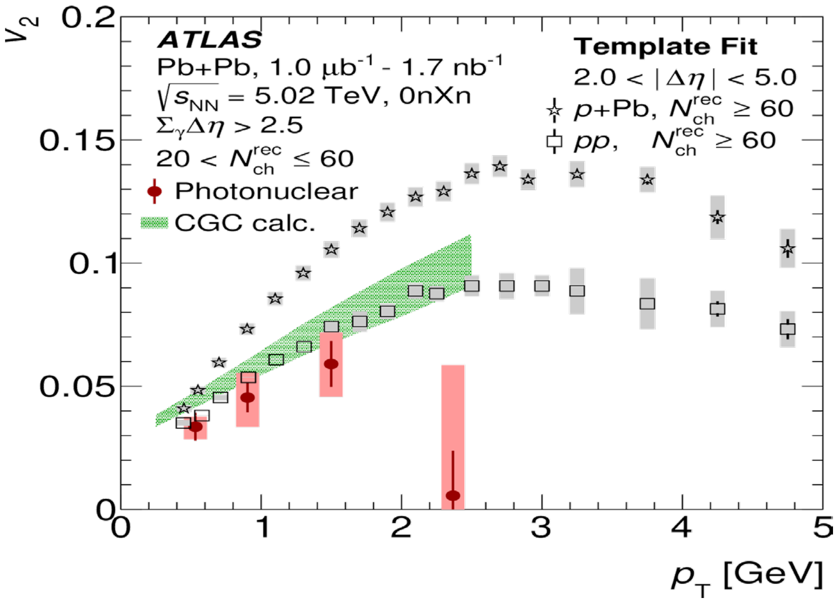


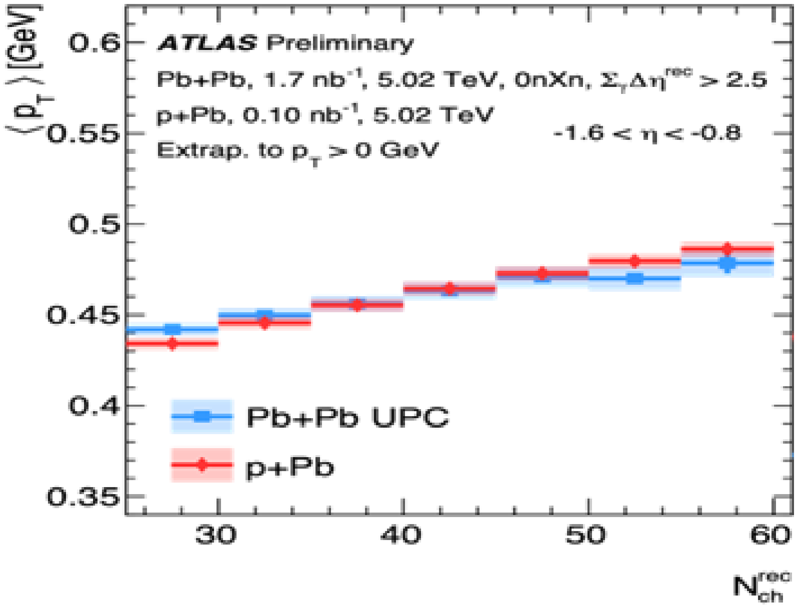
proton density
x ~ 10^{-3}

COLLECTIVE PHENOMENA IN SMALL SYSTEMS

- Flow in ever-smaller systems: changing the probe





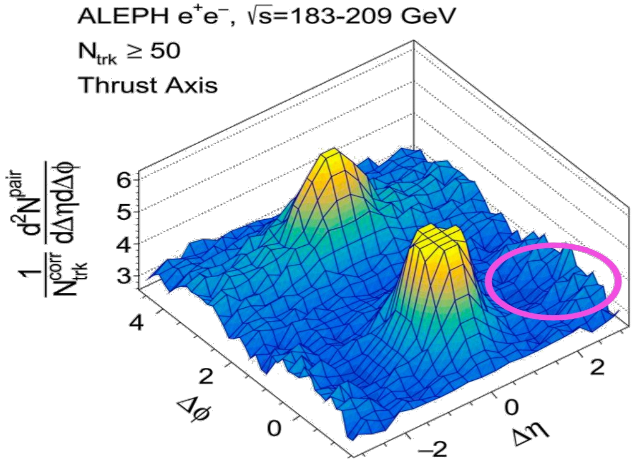


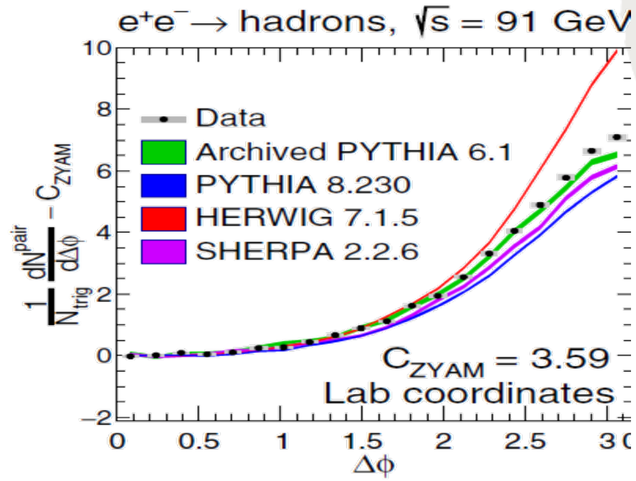
- ATLAS: non-zero v_2 in γPb collisions
- Consequence of **ρ**Pb interactions? CGC?

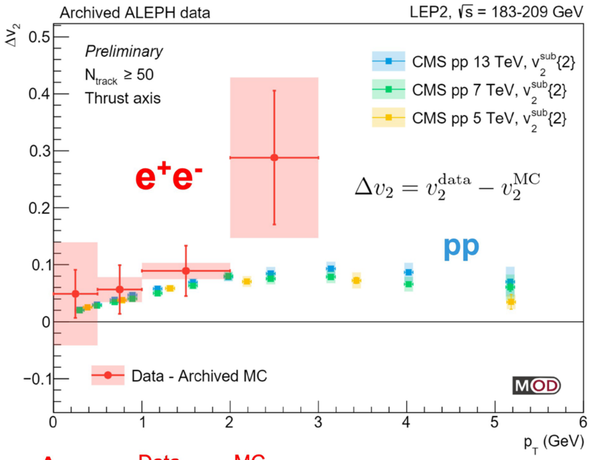
- ATLAS UPC data from 5.02 TeV PbPb events: $\langle p_T \rangle$ increase at backward pseudorapidity
- Match pPb measurements for the same multiplicities
- Radial flow?

WHAT'S TOO SMALL FOR COLLECTIVE PHENOMENA?

- ZEUS ep JHEP04(2020)070
  No ridges at high multiplicity, described by MC
- ALEPH: minimum bias e^+e^- PRL123(2020)212002
  No ridges, described by MC







- $\Delta v_2 = v_2^{Data} - v_2^{MC}$

- ALEPH: high-multiplicity e^+e^- enriched with $e^+e^- \rightarrow W^+W^-$ (a two-string system)
  Ridge structure similar to that of high multiplicity pp events!
- **EIC Impacts: HIN** (QGP formation in small systems, initial state,...)

pA TO eA: INITIAL STATE

- Nature of initial state?

  High density of low-x gluons

  QGP droplet? Saturated CGC state?

- Nuclear Parton Distribution Functions

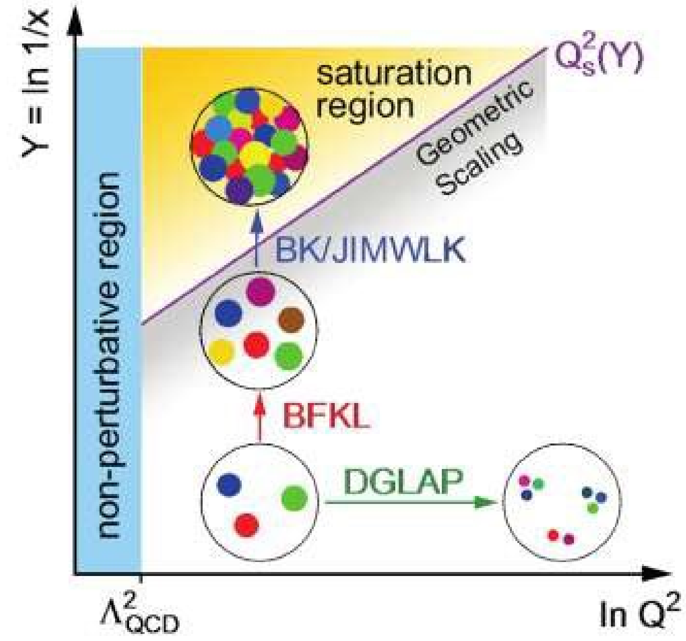
  PDF for bound and free nucleons are different:

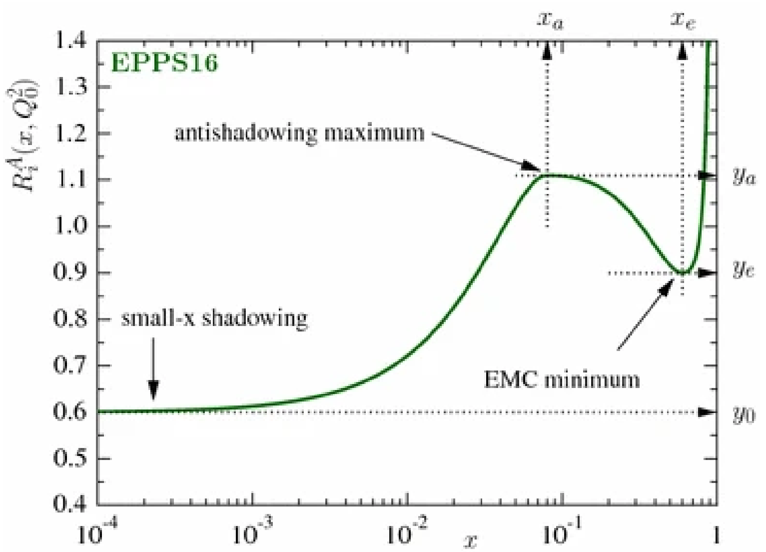
  Shadowing, Anti-shadowing, EMC effects

  Large theory uncertainties

- Energy Loss

  Initial vs. Final state

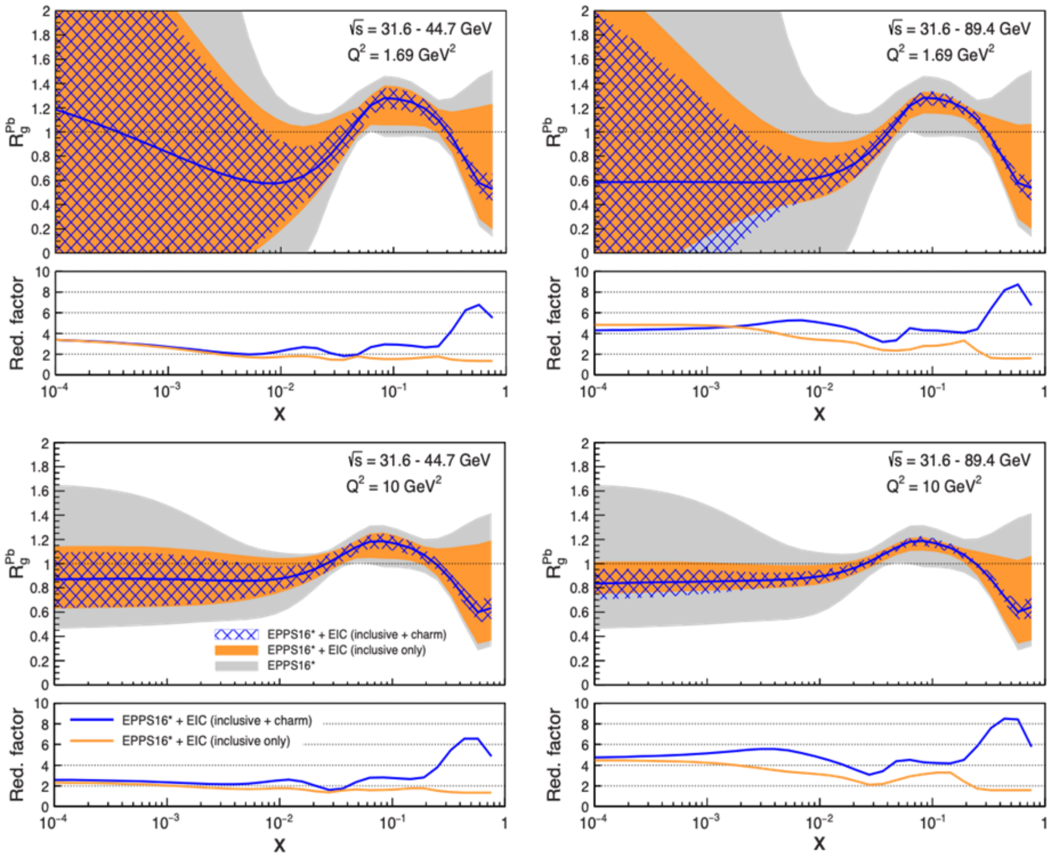




pA TO eA: NUCLEAR PDF EFFECTS

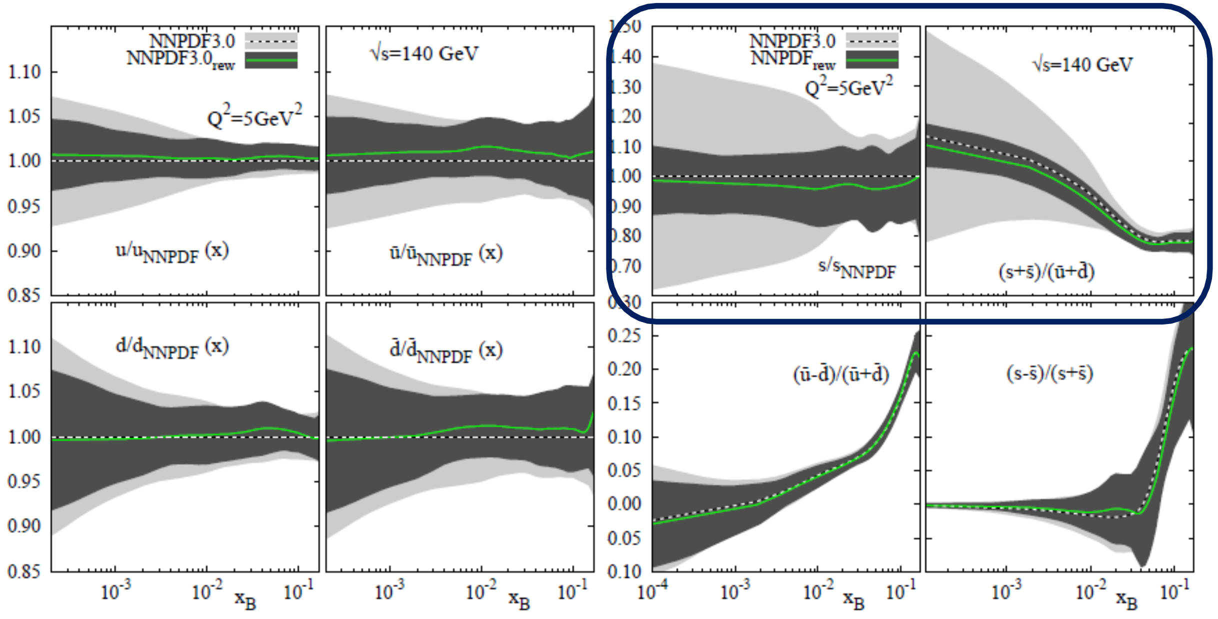
- Projected precision of EIC measurements allows for substantial reduction of nPDF uncertainties
- Will have no potential complications of disentangling initial and final state effects
- **EIC Impacts: HIN** (initial state; jet quenching baseline, low-x regime relevant for gluon saturation,…)
- For best precision – charm identification
- In the meantime: RHIC and LHC pA data!

arXiv:1708.01527



EIC: FREE NUCLEON PDFs

- For completeness, expected impact on the unpolarized sea quark PDFs from EIC SIDIS measurements for identified pions and kaons
- Moderate impact on up, down, anti-up and anti-down
- Major improvement for strange PDFs, especially at low x, and s/light
- Requires good handling of PID



EIC Yellow Report NPA (2022) 122447

OLGA EVDOKIMOV (UIC)

AUGUST 22, 2024

ep, eA: TACKLING HADRONIZATION

RHIC and LHC results:

- Strangeness:

  multiplicity dependent enhancements in pp of similar levels as in pA and peripheral AA

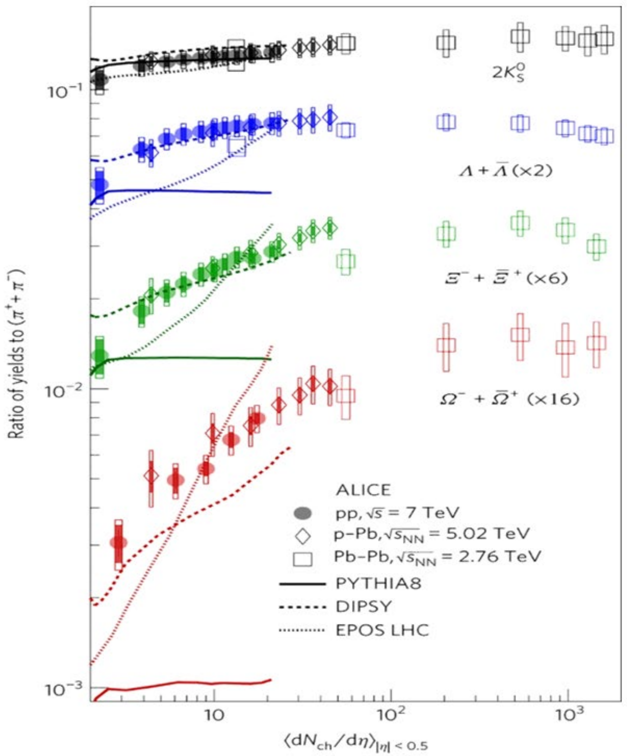
- Charm sector:

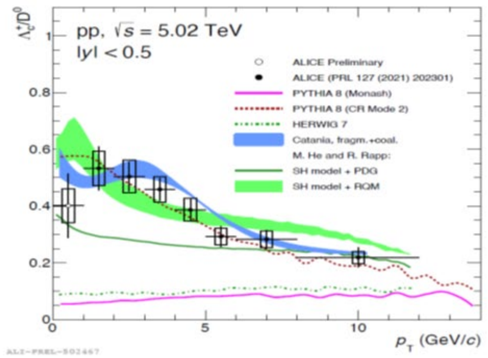
  Λ_c/D^0: enhancements over e^+e^- for pp and AA

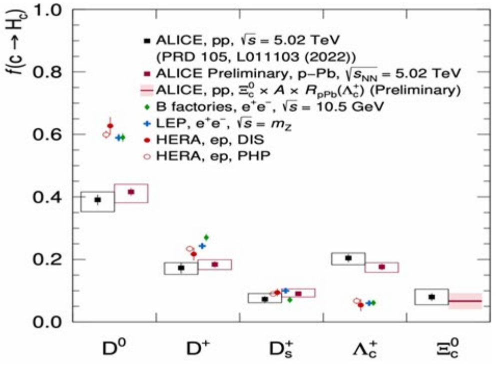
  Changes in charm-fragmentation fractions?

- **EIC Impacts: HIN, HEP, Hadronic physics** (understanding of hadronization)

LHC







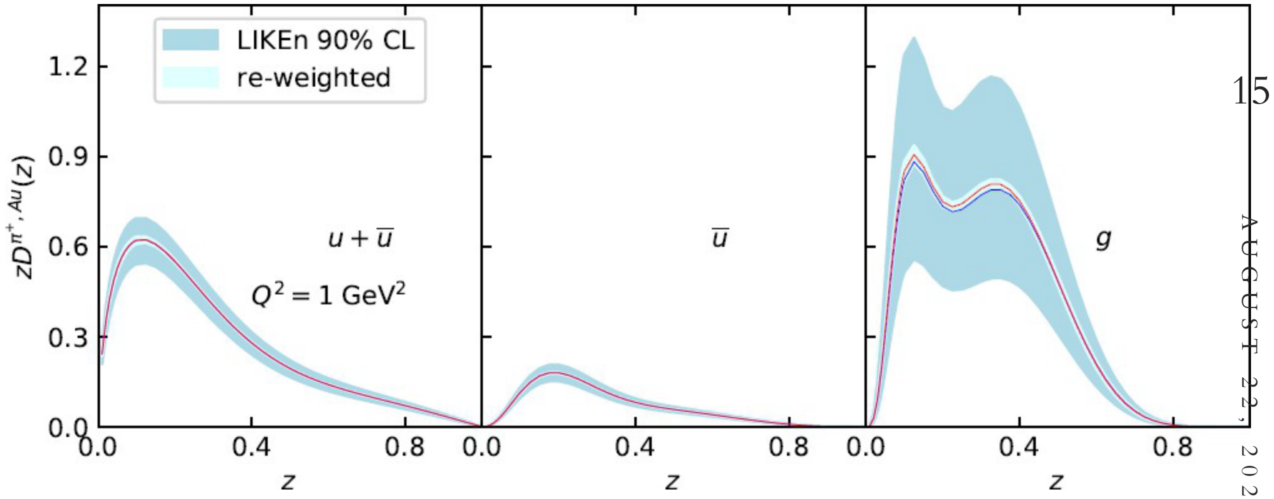
EIC eA: FRAGMENTATION FUNCTIONS

- In collisions involving nuclei, final state observables depend on nPDFs AND nFF
- Multiplicity dependent modifications were first observed by HERMES

- SIDIS is the cleanest tool for precision measurements of nFF with flavor separation (and quark/antiquark)
- High precision EIC data should allow full mapping of fragmentation

- **EIC impact: HIN, HEP, Hadronic physics** (understanding of hadronization)

Projected impact of EIC data in nFFs



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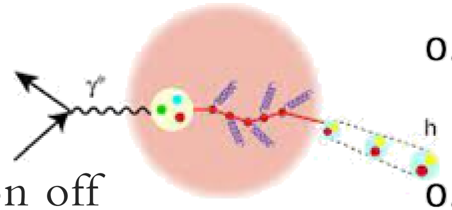
HADRONIZATION IN NUCLEI

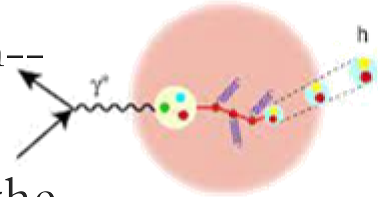
- Competing physics explanations for observed dependences that cannot be resolved with light hadron measurements:
- Energy loss

  hadronization outside the medium gluon radiation off struck quark

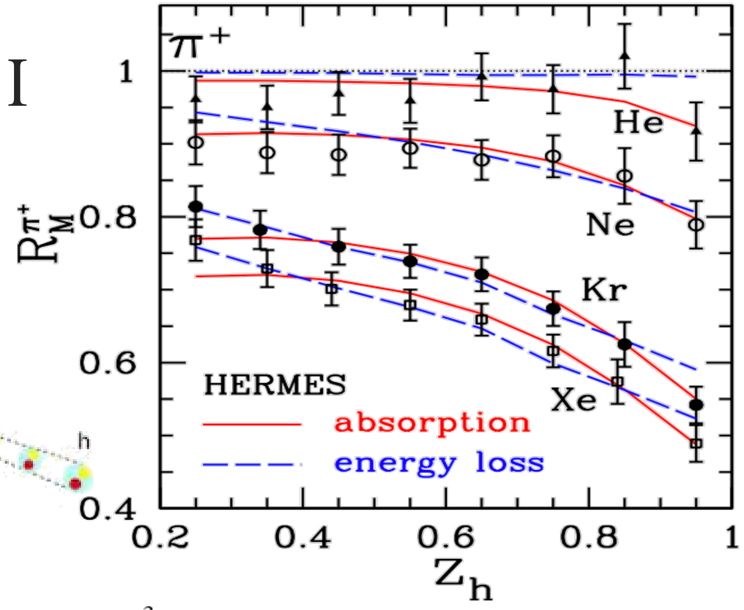


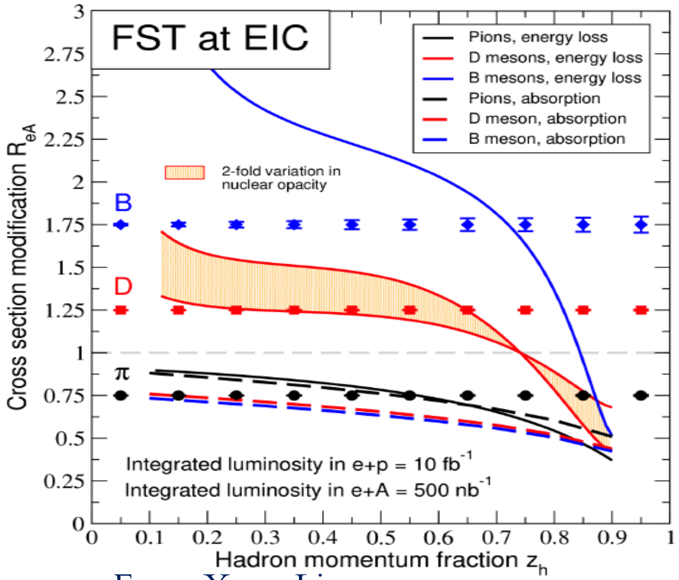
- Prehadron absorption

  color neutralization inside the medium prehadron–-nucleon scatterings



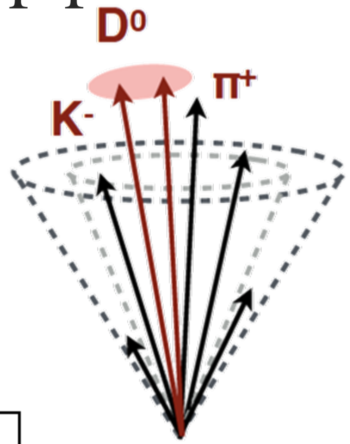
- Heavy flavor R_{eA} could provide a handle on the two
- **EIC Impacts:** differentiating between E-loss absorption models; CNM transport properties





From Xuan Li

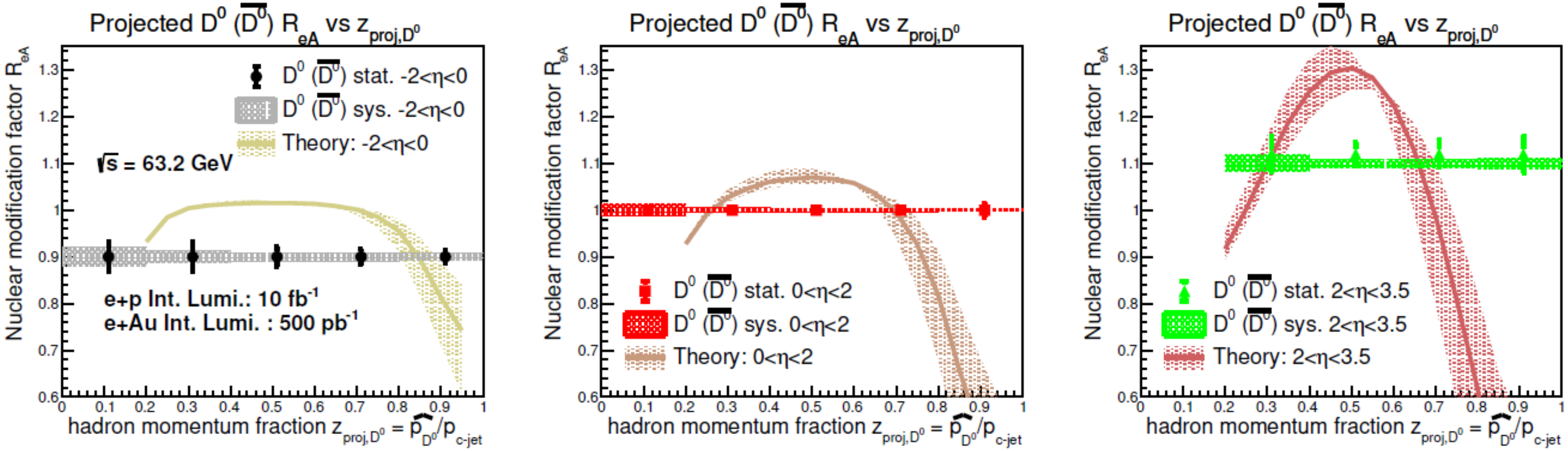
EIC eA: FLAVOR DEPENDENCE OF FF



- In-jet hadron PID provides access to flavor dependent fragmentation functions

  Projections of R_{eA} uncertainties for in-jet D^0 @ 10 fb^{-1} **ep**, 500 pb^{-1} **eAu**

  Theory: NLO calculations with partonic energy loss



Theory: PLB 827 (2022) 137007

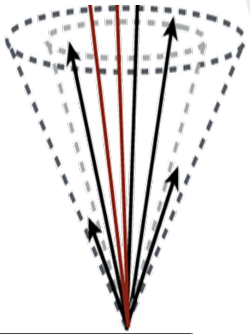
From Xuan Li arXiv: 2311.10875

Expected precision and wide rapidity coverage should ensure sufficient discriminating power for medium effect predictions for heavy flavor productions

JET OBSERVABLES FOR HADRONIZATION STUDIES

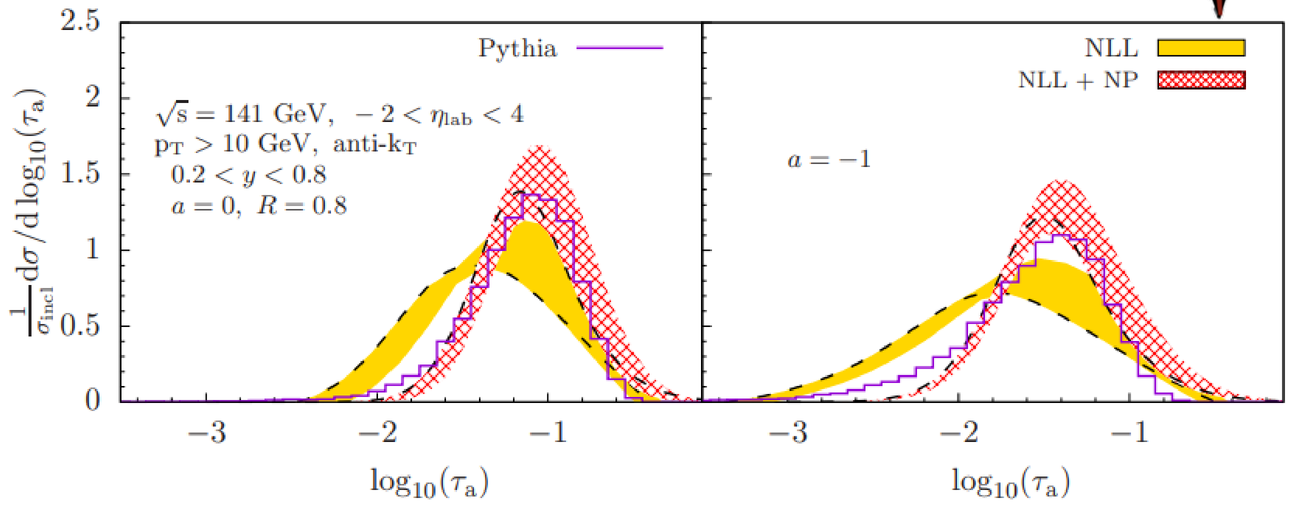
- HEP/HIN collaborations lead to active development of jet substructure observables for nuclear collisions
- Jet substructure techniques are used to study parton radiation patterns in pp, pA, AA.

  Soft drop grooming → vary impact of nonperturbative effects
- EIC: theoretically clean DIS environment



Example: jet angularity

$$\tau_a = \frac{1}{p_T} \sum_{i \in J} p_{Ti} \Delta R_{iJ}^{2-a}$$



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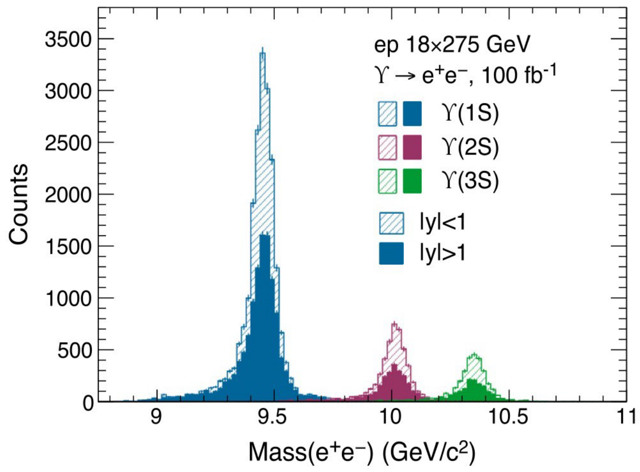
QUARKONIA AND EXOTICA

- Multiple production mechanisms for quarkonia in ep and eA
- Photo- and electro-production of quarkonia → probe gluon densities and transverse positions

  (Old) resolution example: Upsilon reconstruction example in mid- and forward rapidities for exclusive events

NIM A 1046 (2023) 167606

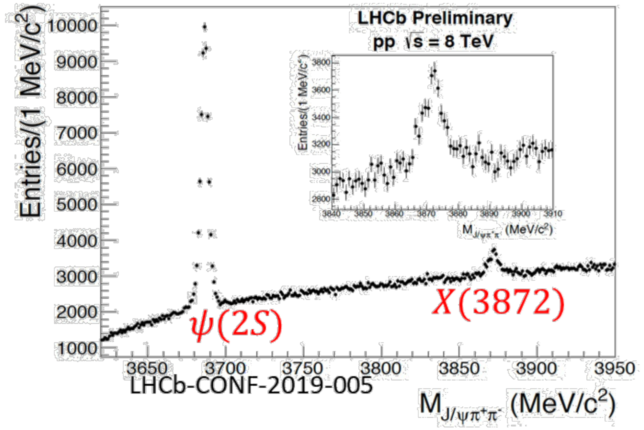


- Exotic state structure studies at the EIC
- Example: X(3872) – compact tetraquark vs. hadronic molecule?

  Similar studies attempted at LHC with hot QCD matter

  Can use CNM as a fine(r) filter for deciphering quark and molecular states

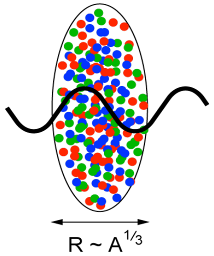
$\psi(2S)$ and exotic X(3872) via $J/\psi\pi\pi$



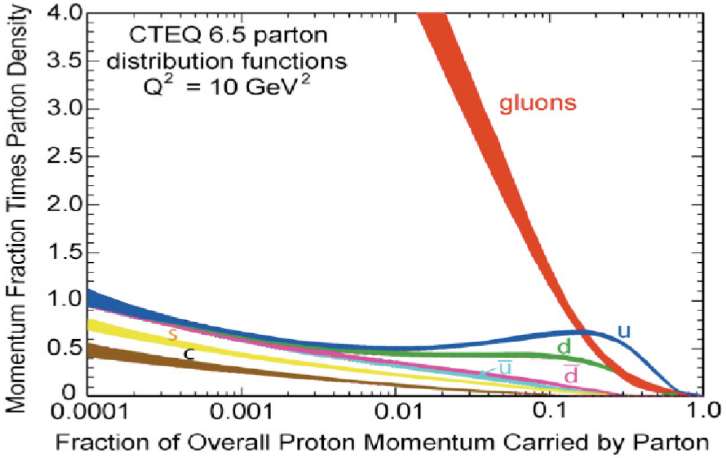
Matt Durham EIC @ Snowmass

EIC eA: GLUON SATURATION

- Could the gluon density G(x, Q^2) continuously grow?
- Non-Linear Evolution idea: recombination compensates gluon splitting
  New evolution equations
  Saturation of gluon densities characterized by scale $Q_s(x)$
- Saturation → Color-Glass-Condensate?
- Experimentally, nucleus serves as Q_s amplifier



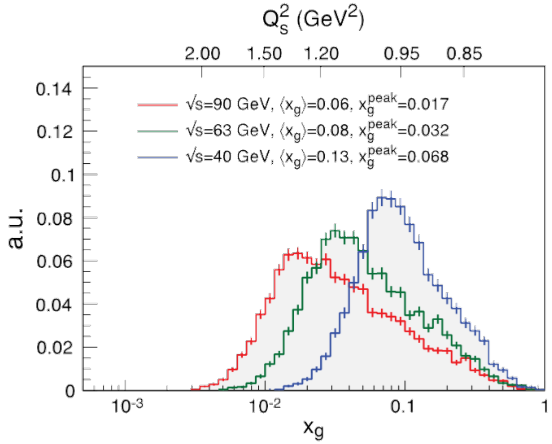
$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$



- Di-hadron correlations are sensitive to the transverse momentum dependence of the gluon distribution and gluon correlations (also: diffraction cross-sections, structure functions at low-x)

* Some interesting recent results from RHIC and LHC

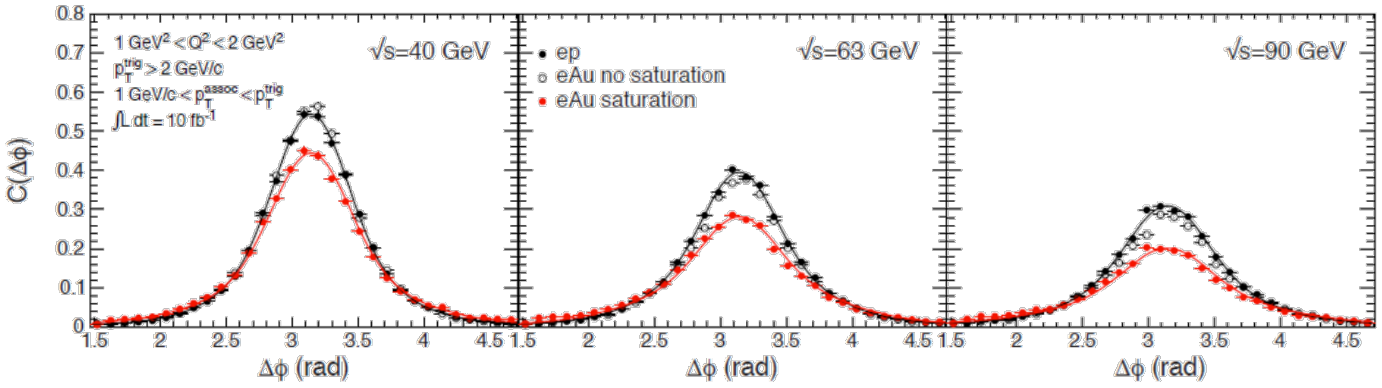
EIC eA: GLUON SATURATION

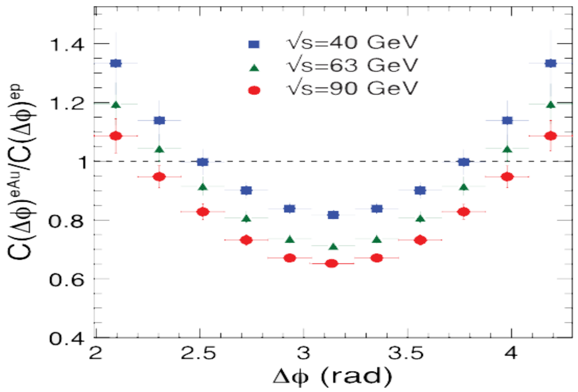


- Range of energies and ion species: EIC could map the transition between the linear to non-linear QCD regime

- EIC will allow studying the evolution of Q_s with x

2→2 vs. 2→many





- **Impacts: HIN** (initial state), CGC discovery?,

EPIC DETECTOR IN THE WORKS

- Tracking:

  New 1.7T solenoid

  Si MAPS Tracker   MPGDs (μRWELL/ μMegas)

- PID:

  Backward pfRICH   Barrel hpDIRC

  Forward dRICH   AC-LGAD TOF(Barrel & Forward)

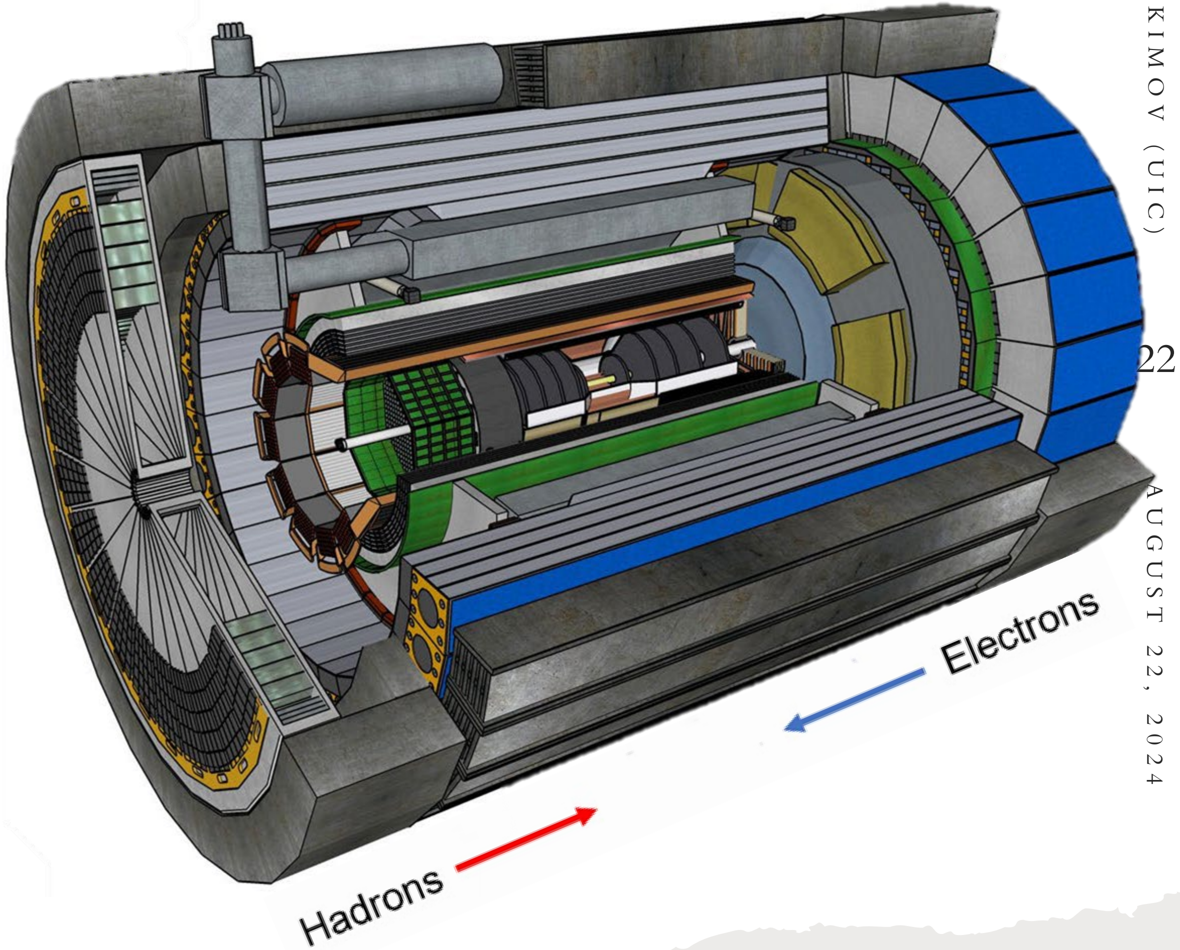
- Calorimetry:

  Backward: PbWO4 EMCal + Steel/Scint HCal

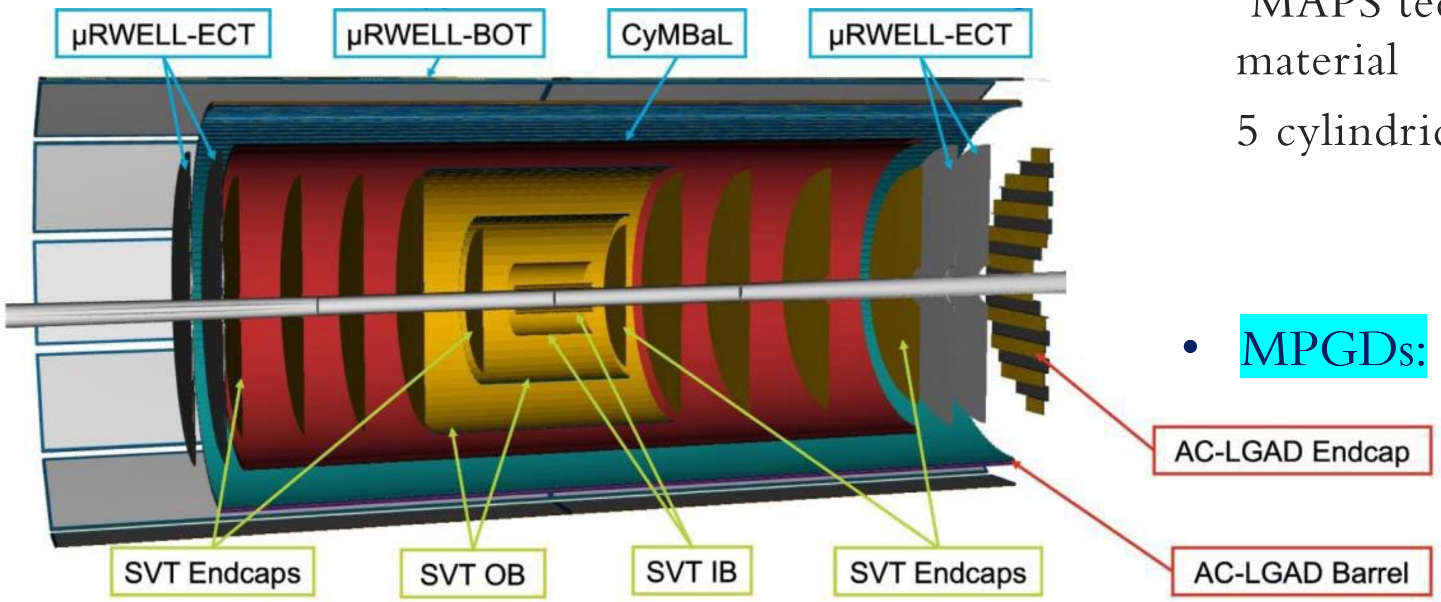
  Barrel Sampling/Imaging EMCal + Hcal (sPHENIX)

  Forward: Finely segmented EMCal +HCal

- (and a suite of far forward/backward detectors, see Spencer's talk)



EPIC TRACKING



- Silicon Vertex Tracker (SVT):

  MAPS technology: <20μm spatial resolution, low material

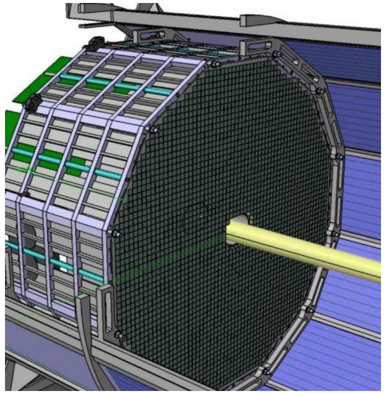
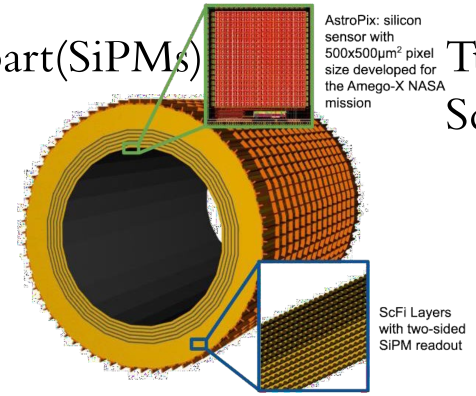
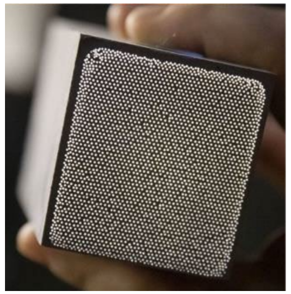
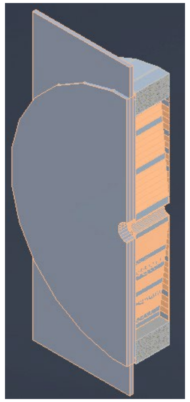
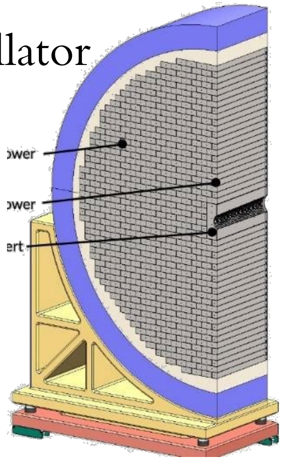
  5 cylindrical layers, 5 forward/backward disks

- MPGDs: 10 ns time/150μm spatial resolution

  2 GEM-μRwell endcaps,
  Cylindrical Micromegas barrel,
  Outer GEM-μRwell planar layer

AC-LGAD TOF: PID and tracking:
~30 ps time/ 30 μm spatial resolution

EPIC CALORIMETRY

	Backward	Barrel	Forward
EMCal	$PbWO_4$ crystals SiPM readout 	Pb/SciFi sampling part(SiPMs) 6 Imaging layers: Pb/SciFi with ASTROPIX 	Tungsten-powder SciFi 
HCal	Steel + Scintillator SiPM-on-tile 	Steel + Scintillator sPHENIX (reuse) 	Steel + Scintillator SiPM-on-tile 

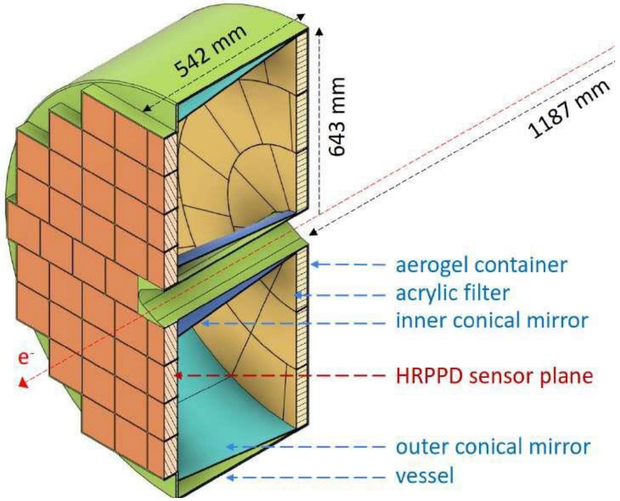
PARTICLE IDENTIFICATION

Backward	Barrel	Forward

Backward

pfRICH

Proximity focusing aerogel RICH

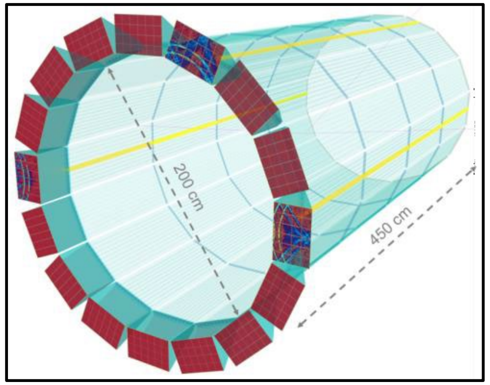


Barrel

High Performance ***DIRC***

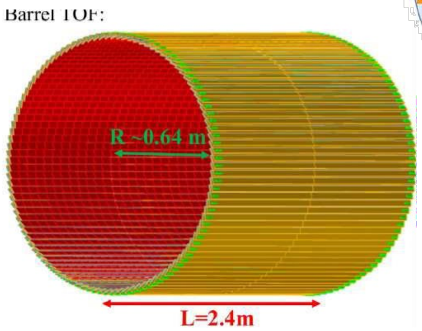
Quartz bar radiator (BABAR bars reuse)

Light detection: MCP-PMTs



AC-LGAD TOF

Strips



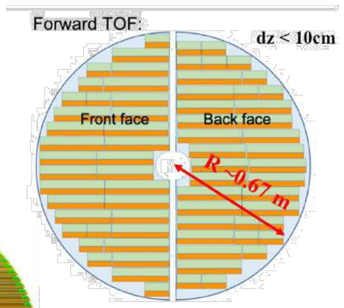
Forward

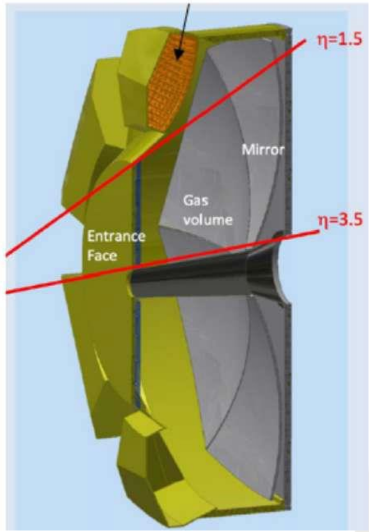
mRICH

Dual Radiator RICH:

Aerogel and C2F6 gas

Light detection: MCP-PMTs





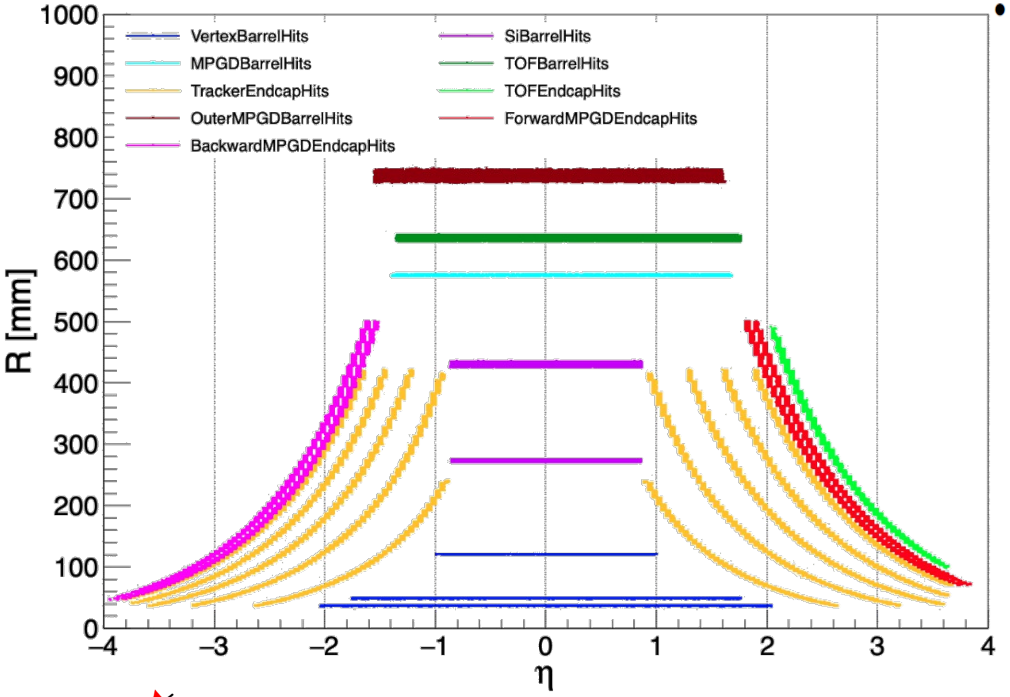
AC-LGAD TOF

Pixels

EPIC TRACKING IN THE WORKS

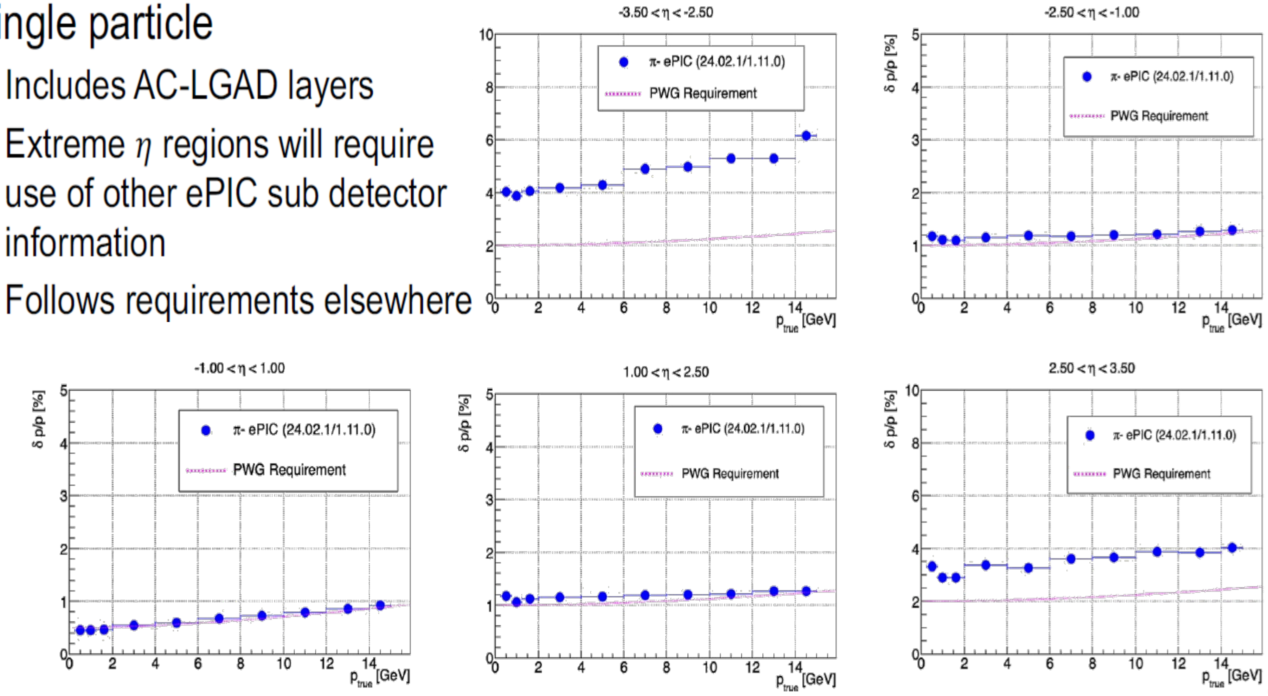
- Examples of performance plots (work in progress)

Tracking coverage:



Momentum resolution:

- Single particle
  - Includes AC-LGAD layers
  - Extreme η regions will require use of other ePIC sub detector information
  - Follows requirements elsewhere

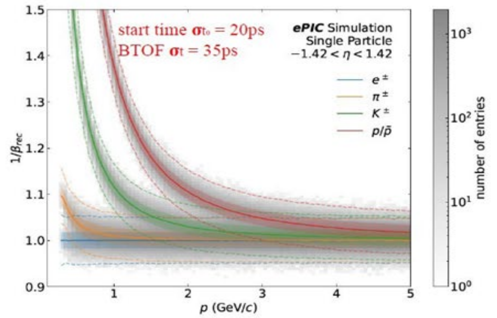


From Silvia Dalla Torre

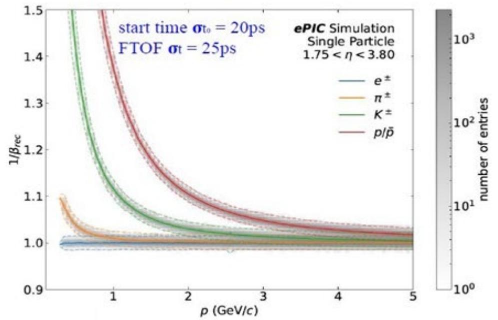
PARTICLE IDENTIFICATION IN EPIC

CURRENT PID PERFORMANCE EXAMPLES

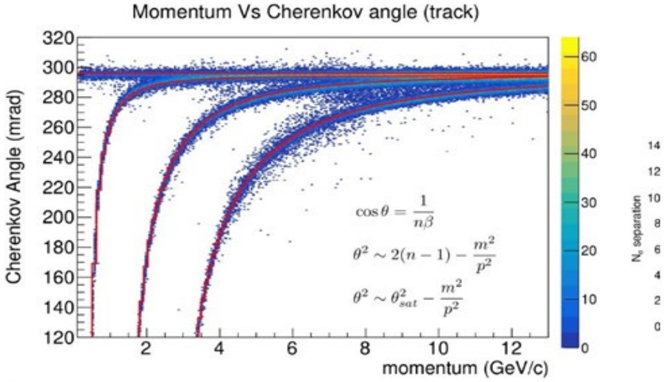
- BTOF with timing resolution of 35 ps can provide 3σ π/K separation upto ~1.3 GeV/c



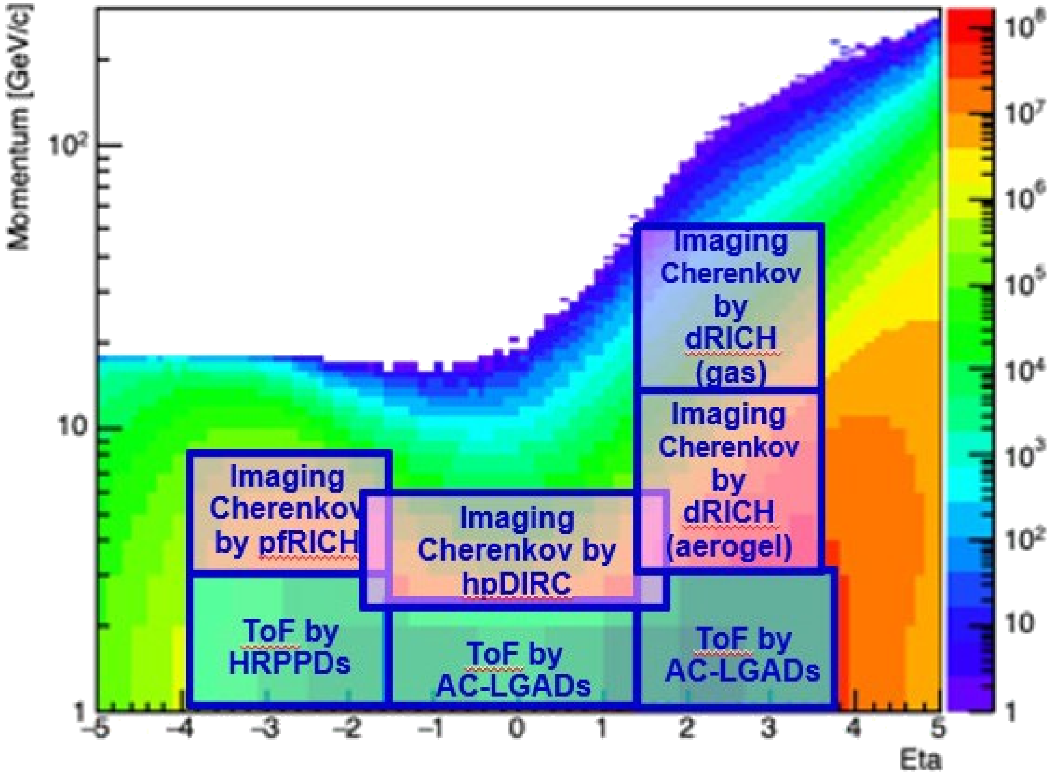
- FTOF with timing resolution of 25 ps can provide 3σ π/K separation upto ~2.4 GeV/c



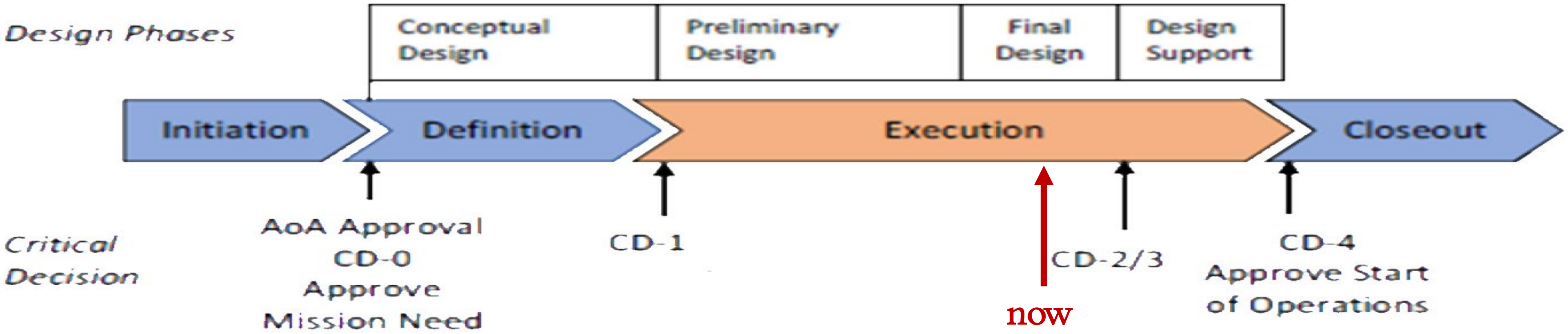
Cherenkov imaging PID in backward endcap: ***(pfRICH)***



PARTICLE IDENTIFICATION WITH EXPECTED PERFORMANCE OF 3σ SEPARATION FOR π/K



EIC PROJECT TIMELINE



Price tag:

EIC accelerator: $1.3B
ePIC detector: $300M
Other costs:
Management: $200M
Infrastructure: $250M
Pre-ops: $50M
Contingency…

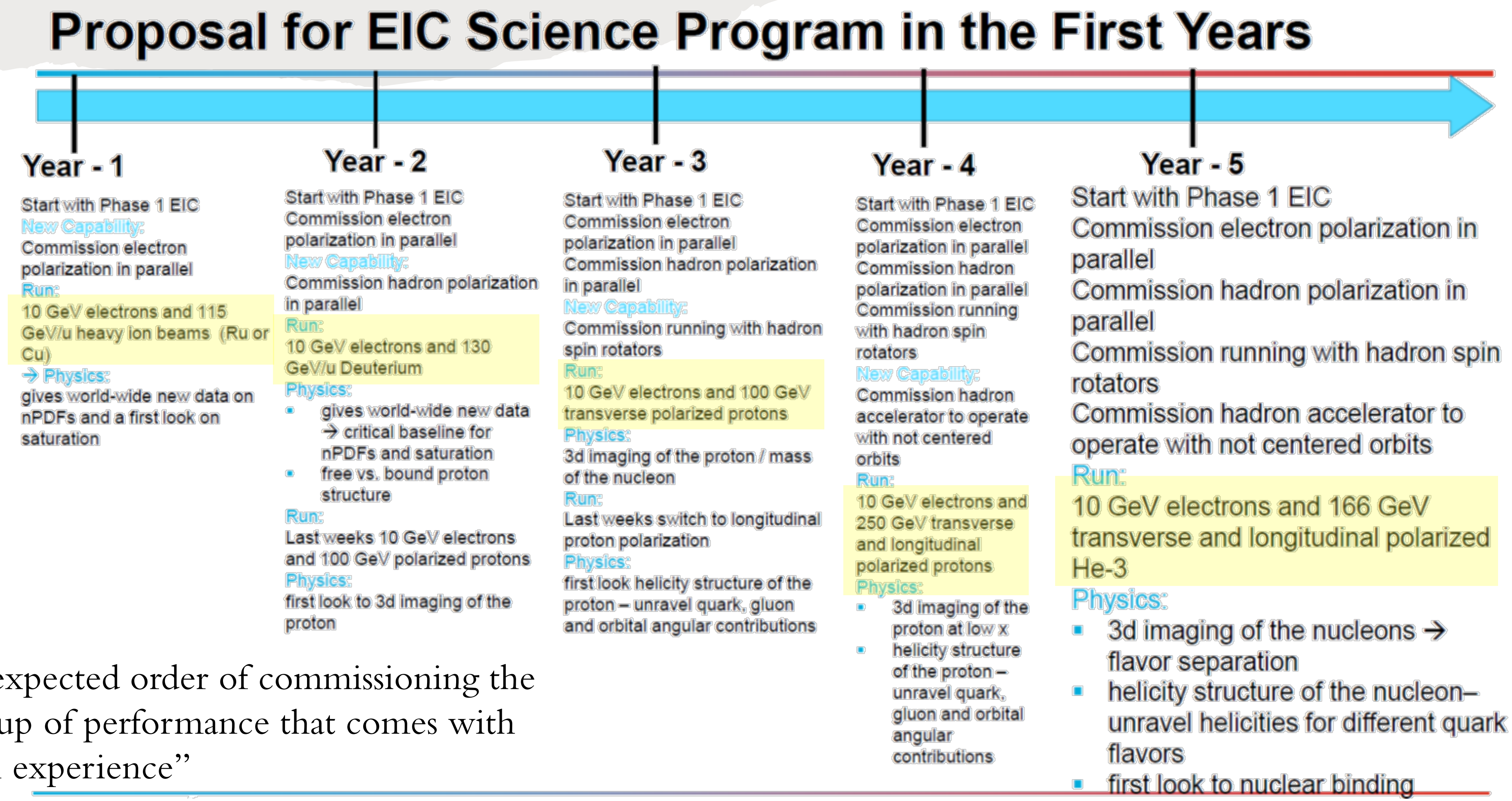
- CD-0 ("Mission Need") Approved Jan 2019
- CD-1 (Alternative Selection /Cost Range) Approved Jul 2021
- CD-3a (Long Lead Procurement) Approved Mar 2024

- CD-3b (Long Lead Procurement) March 2025 (expected)

- CD-2 (Performance Baseline)/CD-3 (Start of Construction) End of 2025 (expected)

- CD-4 (Project completion/start of operations) 2034?

FOOD FOR THOUGHT



- "Alignment with expected order of commissioning the collider and ramp up of performance that comes with gain of operational experience"

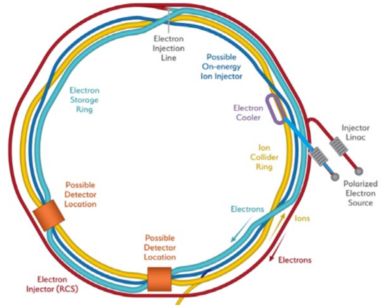
From E. Aschenauer at 2024 EICUG/ePIC meeting

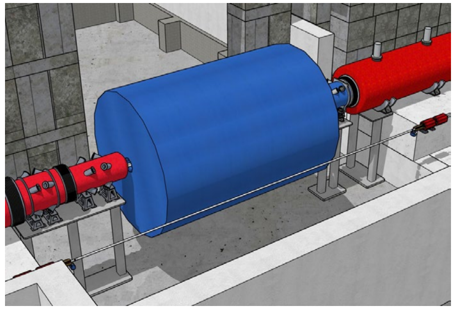
SUMMARY AND OUTLOOK

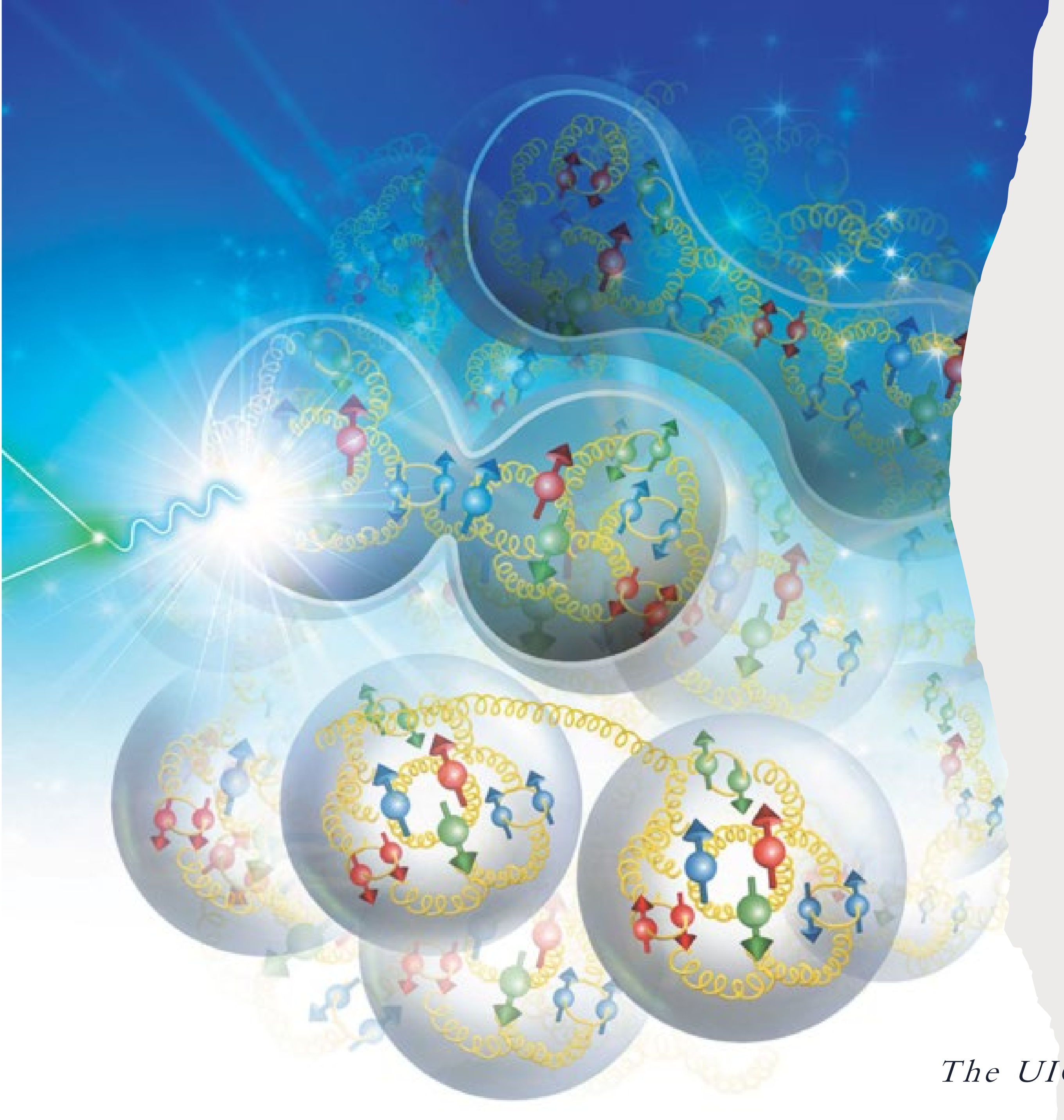
- The EIC is moving ahead, endorsed as the highest priority new construction facility. The machine design encompasses high luminosity, high polarization for electron and light hadron beams, a wide range of energies and ion species.

- The design of the ePIC detector is in advanced stages – expect many physics performance plots updated with full reconstruction chain in the coming months.

- Understanding of nuclear effects in QCD requires joint efforts of HIN and DIS communities to tackle the open questions regarding the nature of initial state in high density limits, emergence of confinement and hadronization, limits of factorization and universality, etc.





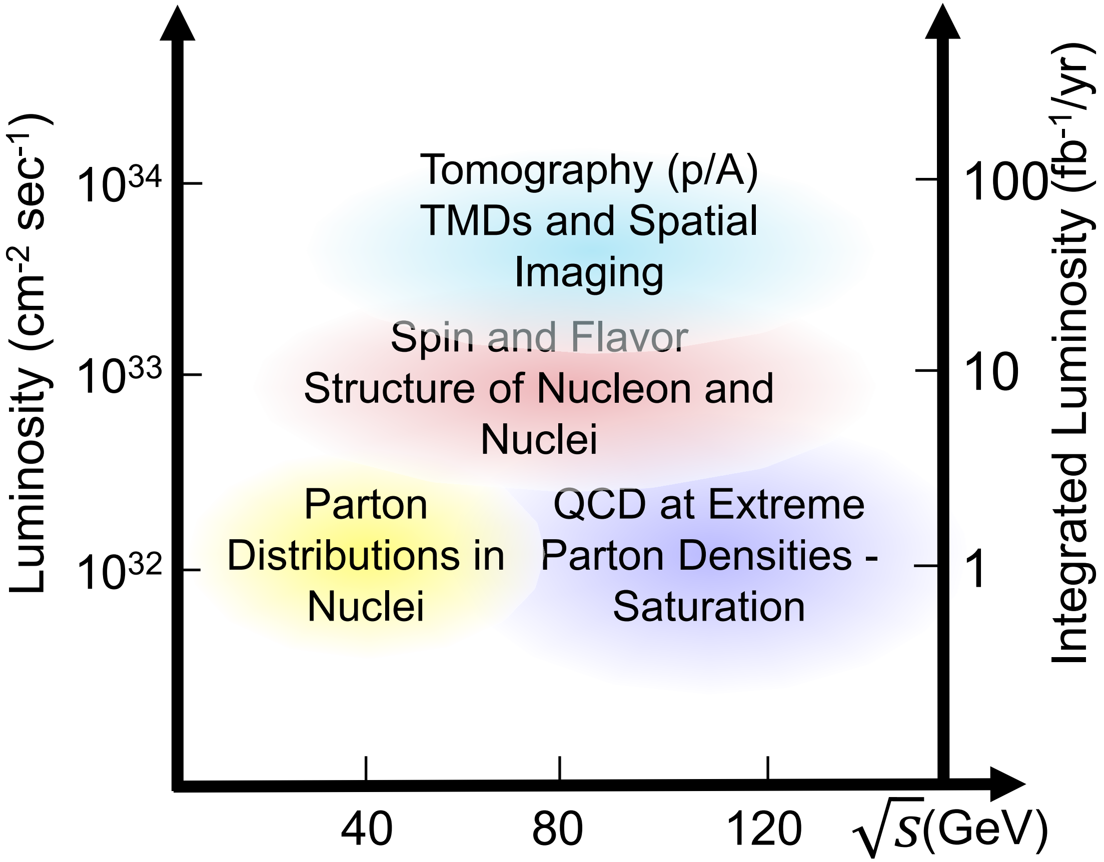


THANK YOU!

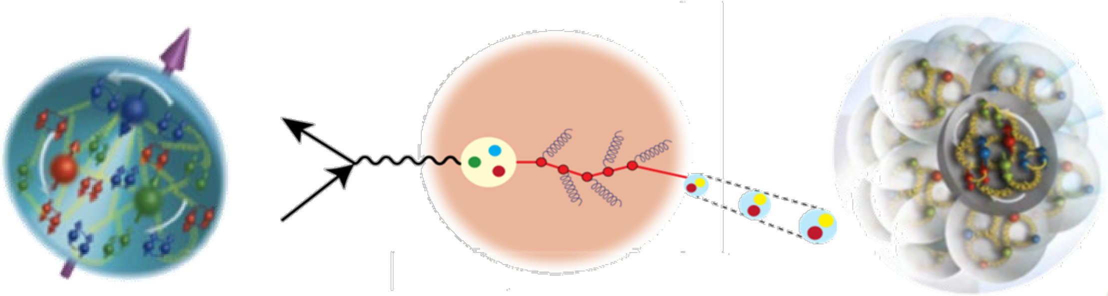
The UIC HENP Group's work is supported by US DOE-NP

BONUS SLIDES

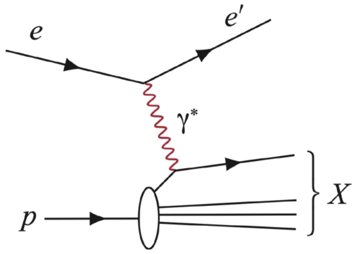
EIC – A NEW QCD LABORATORY



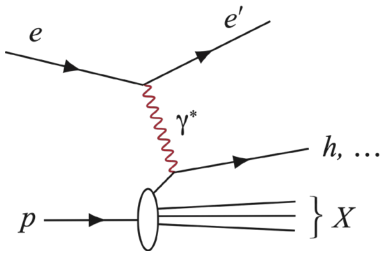
- A new premier facility to study the structure and dynamics of the visible matter
- Major physics goals:
  - Understanding the properties of hadrons (mass, spin)
  - Complete (3D) imaging of hadrons (PDF, TMD, GPD)
  - Properties of QCD nuclear matter at high parton densities
  - Emergence of hadrons
    Hadronization, universality tests



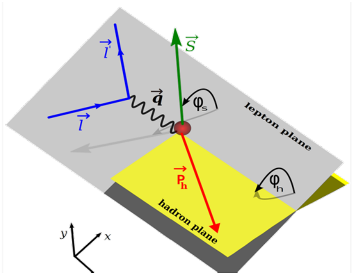
PHYSICS DRIVEN DETECTOR DESIGN

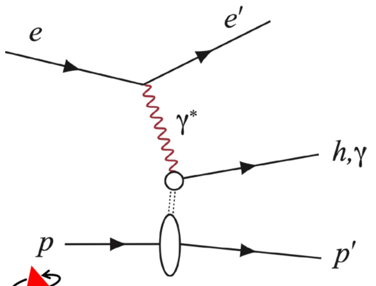


Inclusive DIS



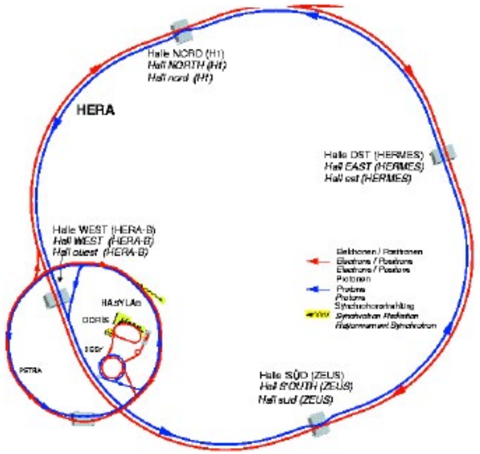
Semi-Inclusive DIS

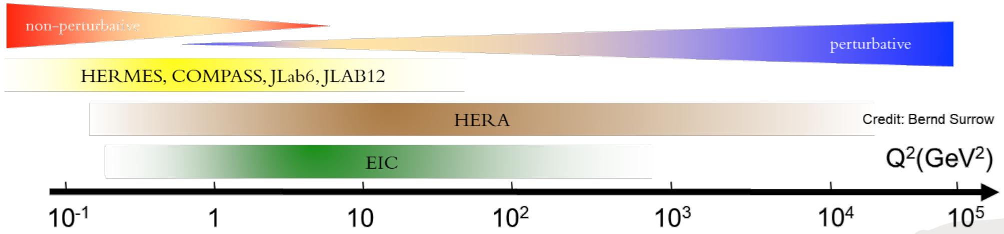




Deeply-Virtual Compton Scattering

- Inclusive: Unpolarized fi(x,Q^2) and helicity distribution Δfi(x,Q2) functions through unpolarized and polarized structure function measurements (F_2, F_L, g_1)
  - Define kinematics (x, y, Q^2) through electron (e-ID and E' + θ resolutions are critical) / hadron final state or combination of both depending on kinematic x-Q^2 region
- SIDIS: Flavor tagging through hadron identification studying FF / TMD's
  - (Transverse momentum, k_T, dependence) requiring azimuthal asymmetry measurement - Full azimuthal acceptance. Heavy flavor (*c*, *b*): Excellent secondary vertex reconstruction
- Exclusive: Tagging of final state proton using Roman pot system studying GPD's (Impact parameter, b_T, dependence) using DVCS and VM production
- eA: Impact parameter determination / Neutron tagging (ZDC)





EIC VS. HERA

- HERA: the first electron-proton collider (1992-2007)
- Energies:

  e^-, e^+: 27.5 GeV, p: 820 (920)GeV, $\sqrt{s} \sim 320\ GeV$
- Polarization available for e beam

- Two collider-mode experiments: H1, ZEUS

  total luminosity: $1\ fb^{-1}$
- Two fixed-target experiments: HERMES, HERA-B
- Enormous success, many break-throughs/new physics*

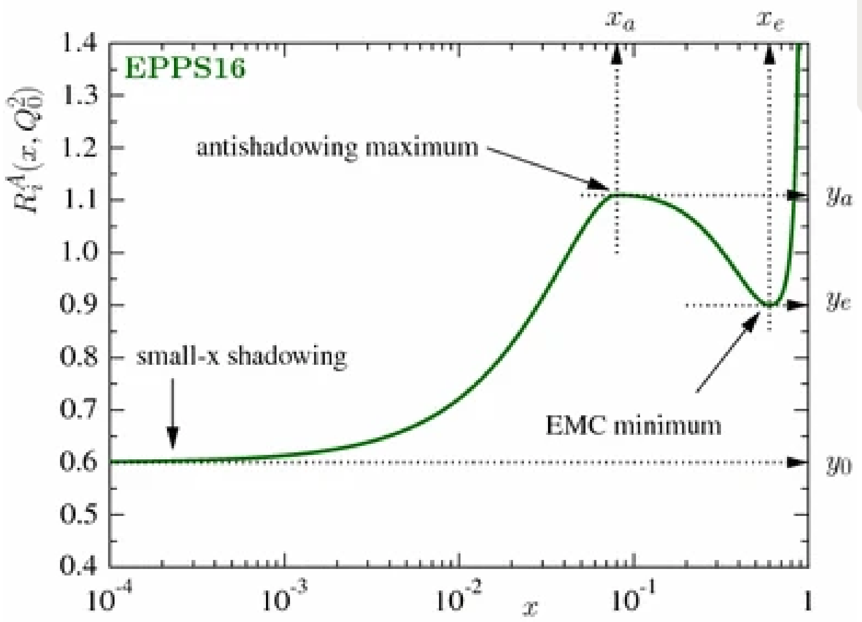
* *Many important measurements also from other programs: COMPASS, JLab6, JLAB12*

eA: NUCLEAR PDF EFFECTS

- "Why QGP aficionados should care:"

Parton distribution functions for bound nucleons are different than that of a free proton, they are connected as (EPPS16, *EPJ C77(2017) 163*):

$$f^i_{p/A}(x_i, Q^2) = R^i_A(x_i, Q^2) f^i_p(x_i, Q^2)$$



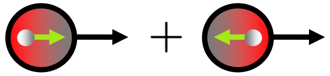
- Nuclear PDF effects are critical to properly map QGP properties → inclusive DIS in eA collisions

$$\frac{d^2\sigma^{eA\to eX}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2)\right]$$

Measurements of the structure functions and their evolution at EIC will allow precise extraction of nPDFs together with extending F_2 and F_L into low-x regime relevant for gluon saturation

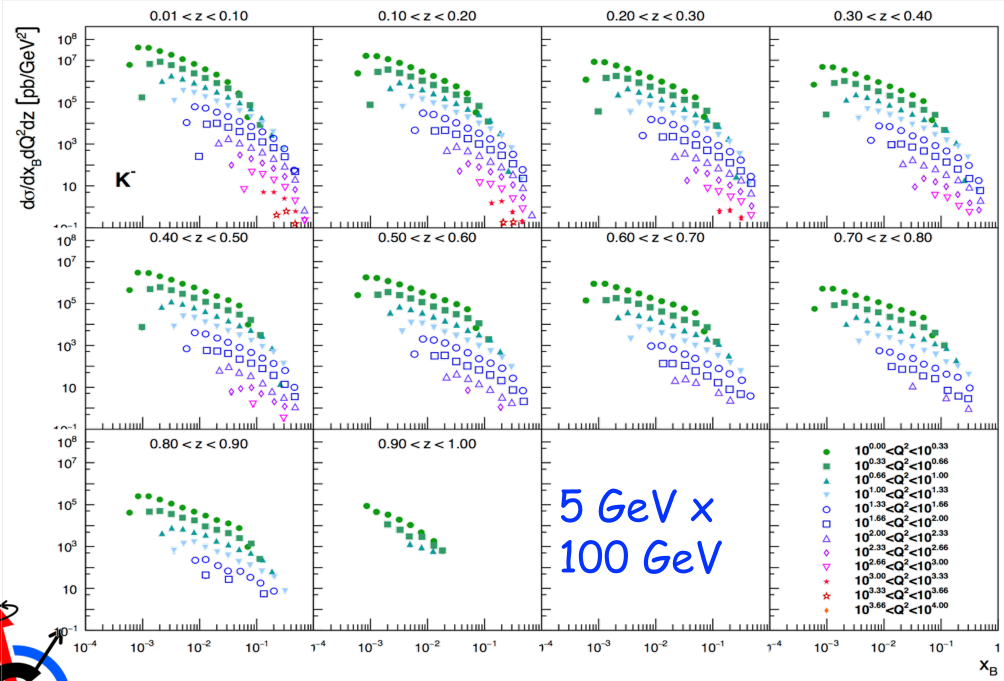
ePIC

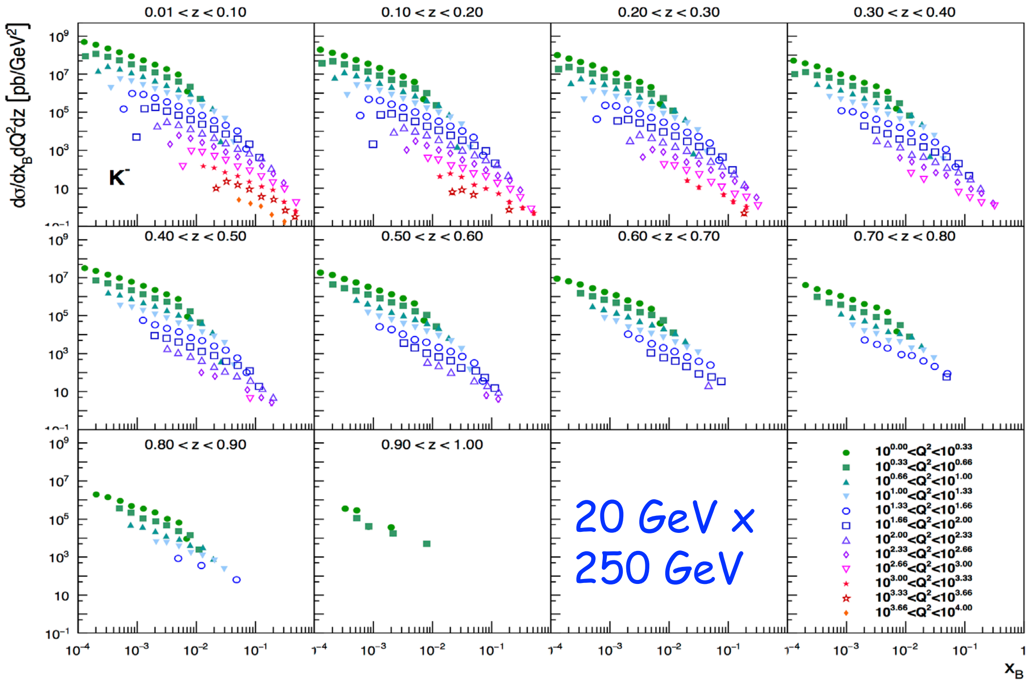
PARTON DISTRIBUTION FUNCTIONS

- Unpolarized PDF: $f(x) =$ 

  $f^{+}(x) + f^{-}(x)$

- EIC SIDIS: Sea quark PDFs extraction: detailed z,x,Q^2 measurements





PRD 99(9) (2019) 094004

UNDERSTANDING HADRONIZATION

- Baryon-to-meson ratios are sensitive to hadronization
- Enhancements are seen in light and strange sectors at RHIC and LHC

Charm sector: Λ_c/D^0

High p_T: similar AA to pp ratios, enhancement at mid-p_T

- Most striking feature: enhancement over e^+e^-
- Charm-fragmentation fractions appear non universal