Physics at the EIC:

How could nuclear physics at the energy frontier profit from electron-Nucleon/Ion collider measurements

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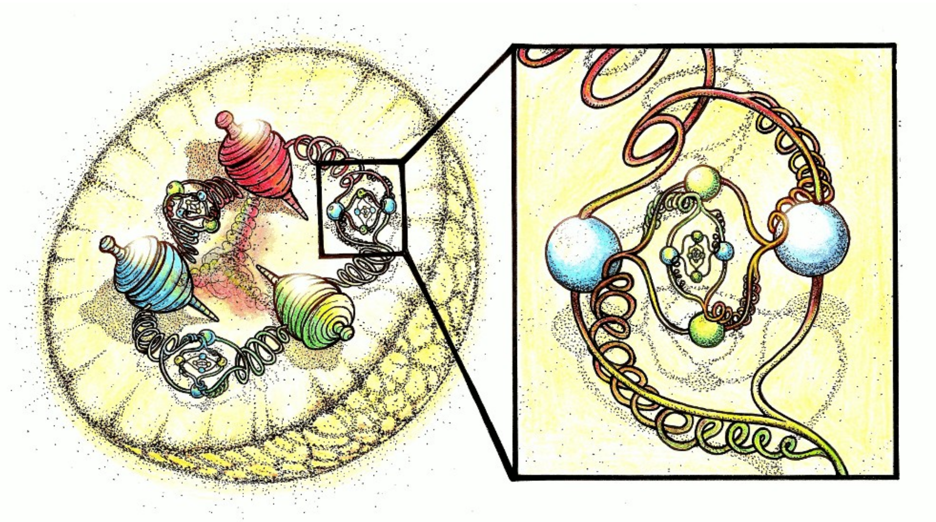
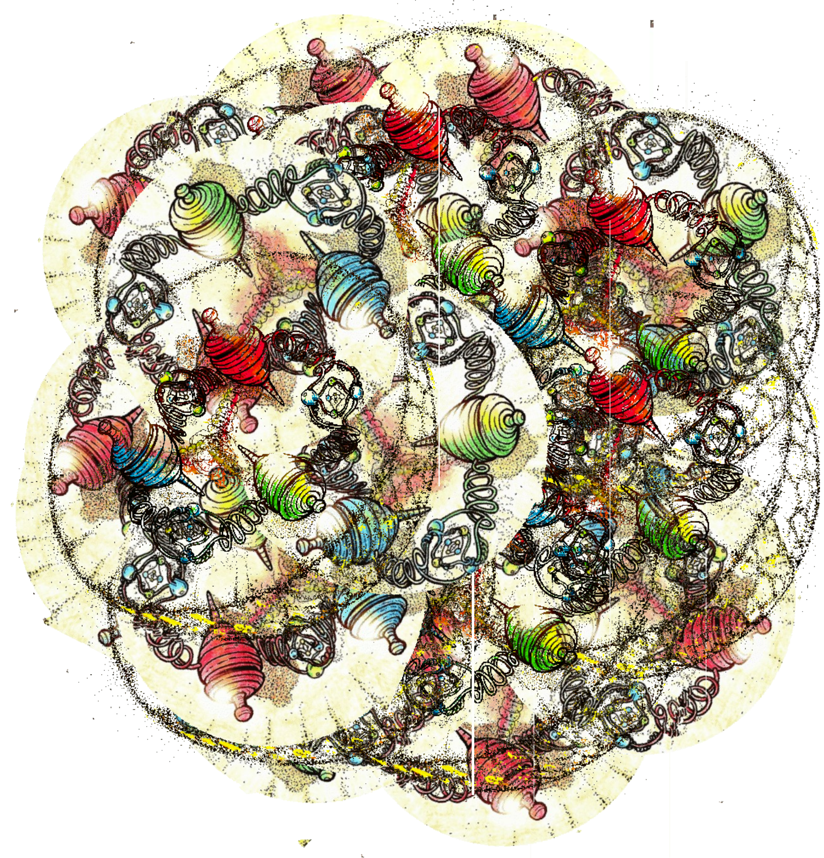
CFNS/IGDORE/IMT-Atlantique

ZIMÁNYI SCHOOL Budapest – December 2018

QCD is expected to describe building blocks of visible matter (nucleons) and their binding in nuclei

Strongly interacting non-abelian gauge theory which has implications far from being fully understood





QCD studies lead to discovery

40 years of continuous discovery
40 years of powerful R&D to help us elucidate it.

Heavy Ion Collisions and the discovery of the formation of a Quark Gluon Plasma:

-Jet production and quenching

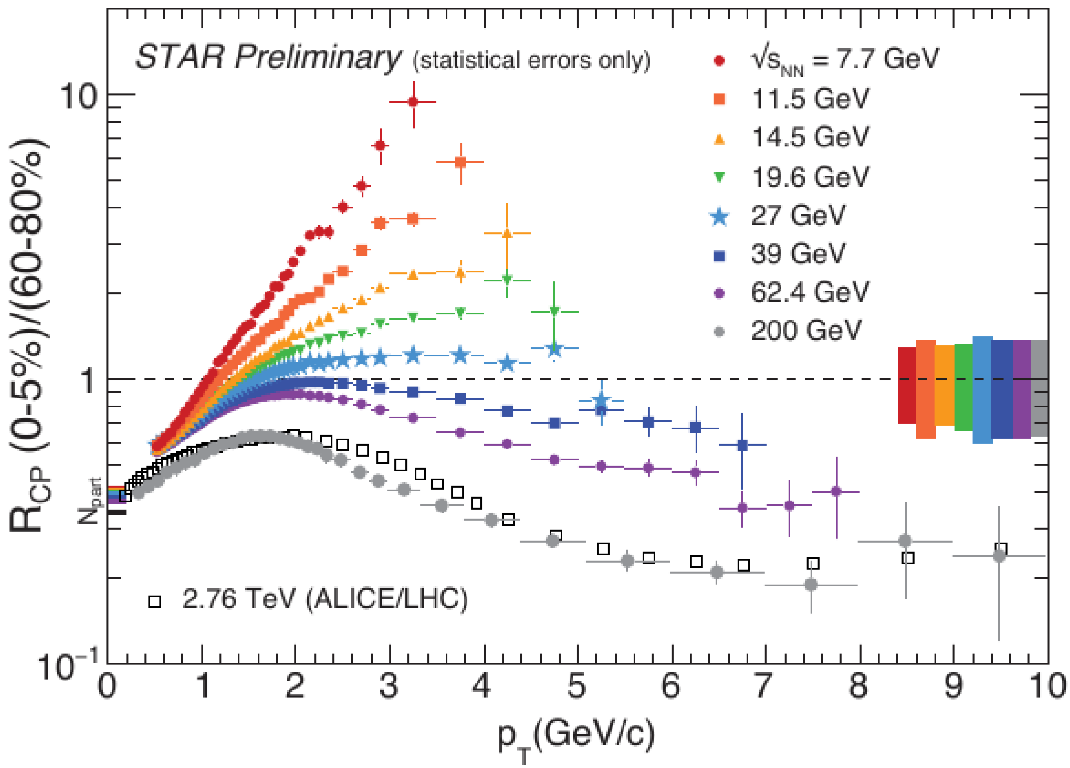
-Viscosity

-Transport properties

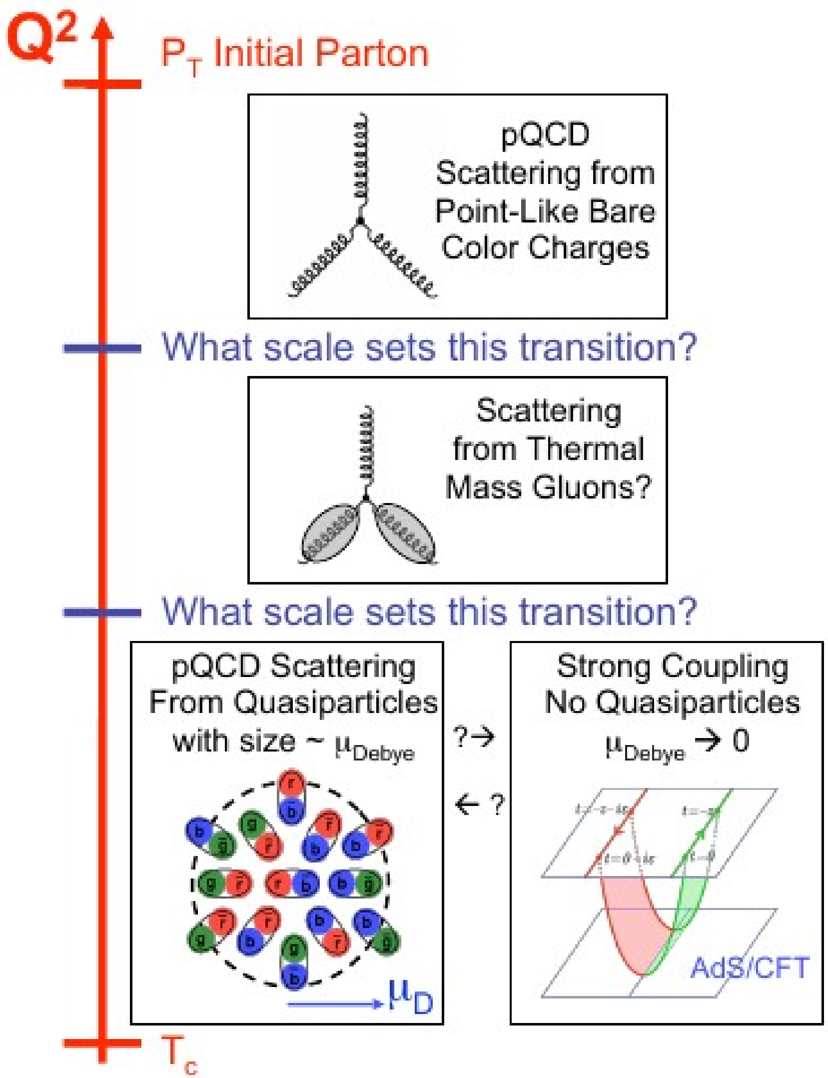
-Collectivity

-Heavy flavor and photon production

-QGP onset



Quark and gluon as quasi particles?



-How do we transition from point like to non-point like physics. How do arrive at a perfect liquid?

-How do color charged-quarks gluons and colorless jets interact with a nuclear medium

-How do the confined hadronic states emerge from these quarks and gluons.

Many open questions we need to address

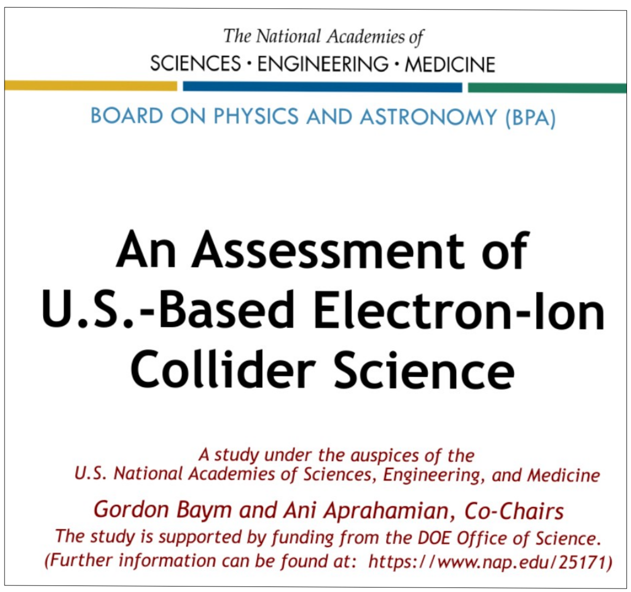
https://arxiv.org/abs/1501.06197 and https://arxiv.org/abs/0903.4379

The EIC Electron Ion Collider

The case for an EIC

NSAC Long Range Plan (2015) - Recommendation III
We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

National Academy of Sciences Report (June 2018):


The National Academies of
SCIENCES · ENGINEERING · MEDICINE
BOARD ON PHYSICS AND ASTRONOMY (BPA)

An Assessment of U.S.-Based Electron-Ion Collider Science

A study under the auspices of the U.S. National Academies of Sciences, Engineering, and Medicine
Gordon Baym and Ani Aprahamian, Co-Chairs
The study is supported by funding from the DOE Office of Science.
(Further information can be found at: https://www.nap.edu/25171)

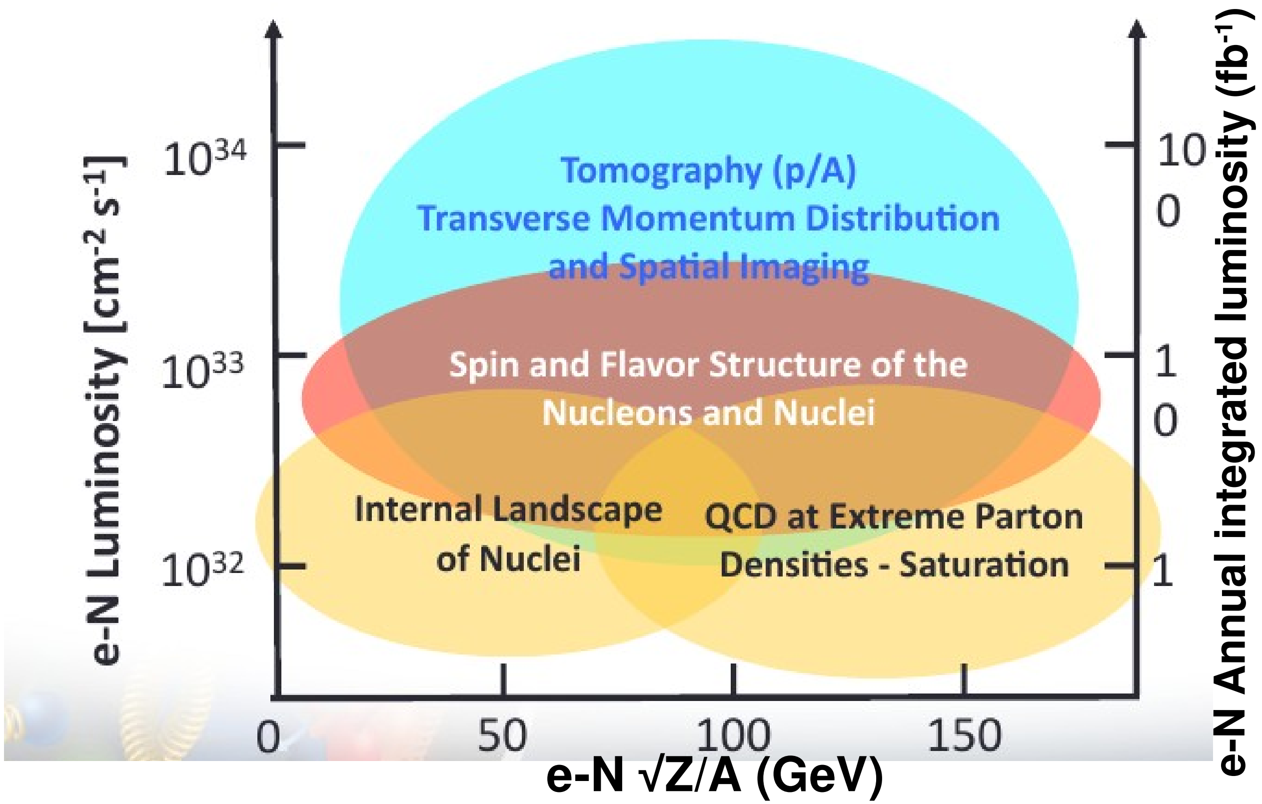
-A unique facility in the world. The science that can be addressed by an EIC is compelling, fundamental, and timely.

-The project is strongly supported by the nuclear physics community. The technological benefits of meeting the accelerator challenges are enormous, both for basic science and for applied areas that use accelerators, including material science and medicine.

https://vimeo.com/282001733

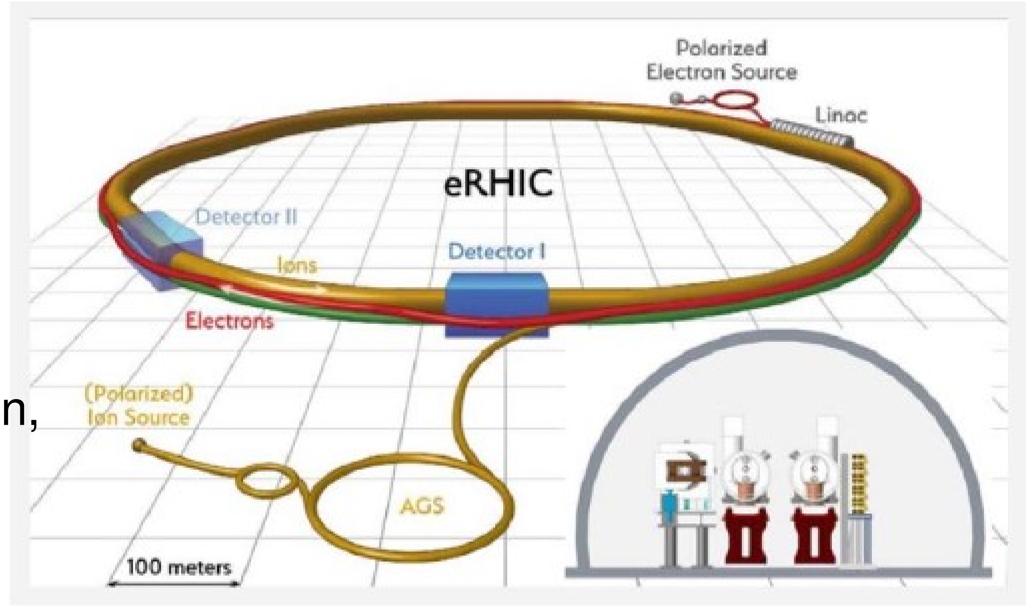
EIC Requirements

- Large luminosity (10^{33} – 10^{34} $cm^{-2}s^{-1}$)
- Center of mass energy range (30–140) GeV
- Hadron and electron beams highly longitudinally spin polarized (~70%)
-Ion beams from D to heaviest stable nuclei
- Large detector acceptance, in particular for small-angle scattered hadrons (optimized high luminosity & high acceptance running modes)



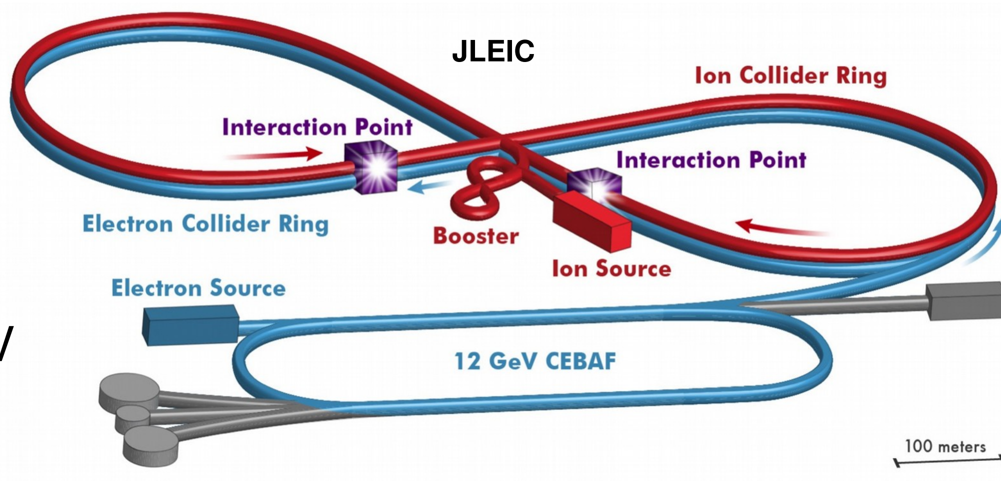
EIC Designs

eRHIC (NY):
Upgrade to RHIC hadron beam
- New electron injector
- 5-18 GeV electron energy,
- Heavy Ions up to 100 GeV/u
- $\sqrt{s}$: 20-140 GeV
- peak L ~ 0.4×10^{34} $cm^{-2}s^{-1}$/A base design, 1.0×10^{34} $cm^{-2}s^{-1}$/A with strong cooling



JLEIC (VA):
- Upgrade to CEBAF 12 GeV electron beam facility
- New hadron injector,
- New figure-8 collider configuration,
- 3-12 GeV electron energy,
- Heavy ions up to 80 GeV/u (upgradable to 160 GeV/u),
- $\sqrt{s}$ 20-100 GeV upgradable to 140 GeV

- average L/run ~10^{34} $cm^{-2}s^{-1}$/A



Physics at the energy frontier

A selection of recent QGP (and nucleon spin physics) results

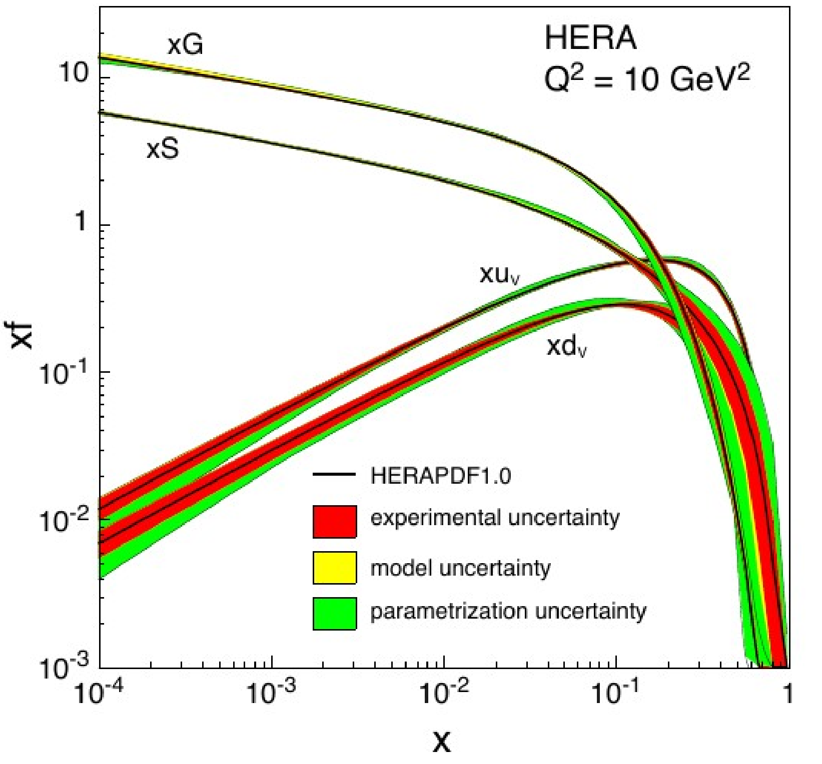
that will need the EIC

1. Hadronization, particle spectra and abundances

2. Collective Expansion

3. Hard Processes

4. Nucleon's spin

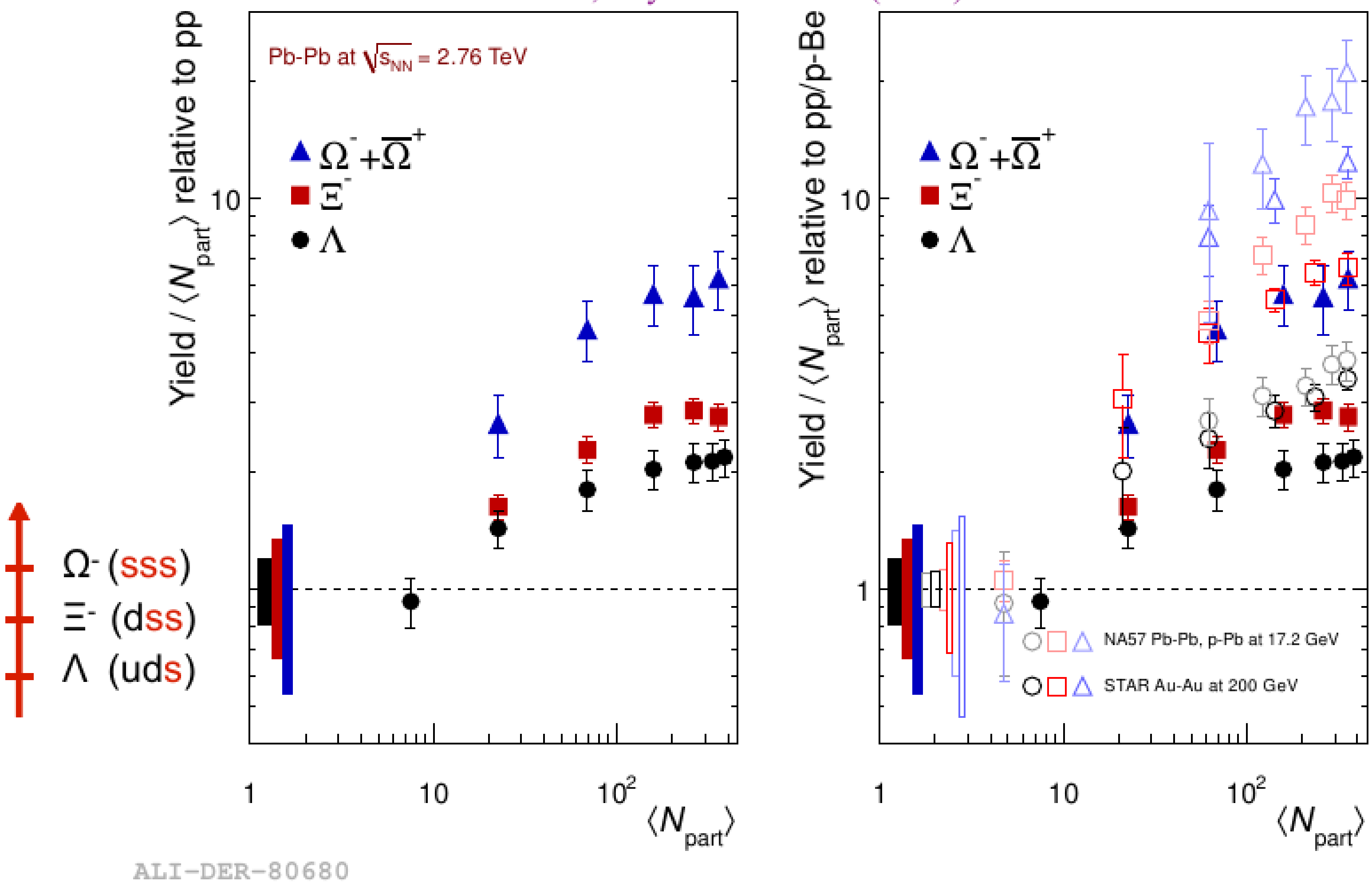


1. Hadronization, particle spectra and abundances

QGP Onset: Strangeness enhancement

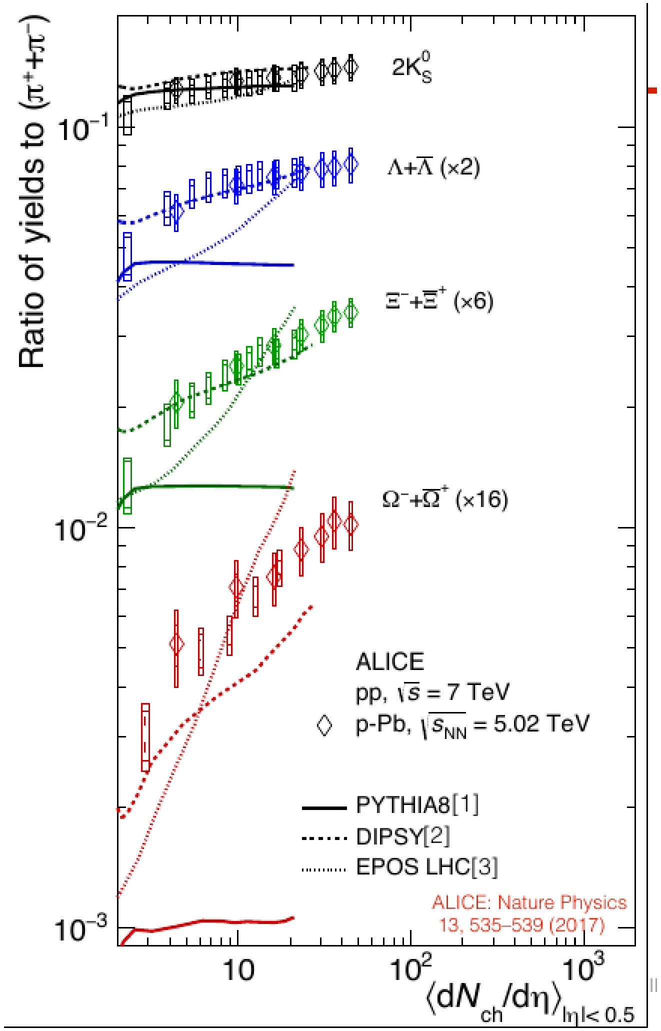
Among the first proposed signatures of the QGP PRL48(1982)1066
Observed in A-A at SPS, RHIC, LHC

ALICE, Phys. Lett. B 728 (2014) 216



QGP Onset: Strangeness enhancement

Enhancement of strange particles with respect to non-strange yield **is also observed** for high multiplicity **pp** and **p-Pb** collisions



-Smooth transition connecting small and larger systems.

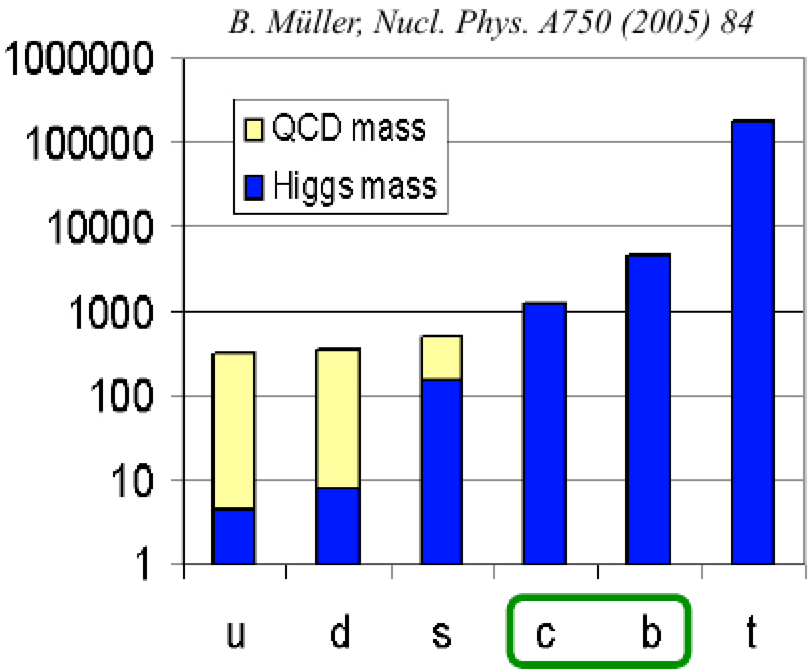
-These measurements may give us insights about the underlying dynamics

-eA can provide a more robust reference.

-More experimental insight is needed to interpret the final state strangeness we are observing in large and small systems

https://arxiv.org/pdf/1305.0609 and https://cds.cern.ch/record/2302756

Heavy flavor vs multiplicity: quarkonia



The contribution of the QCD vacuum condensates to the masses for the three light quark flavours u, d, s considerably exceed the mass believed to be generated by the Higgs field.

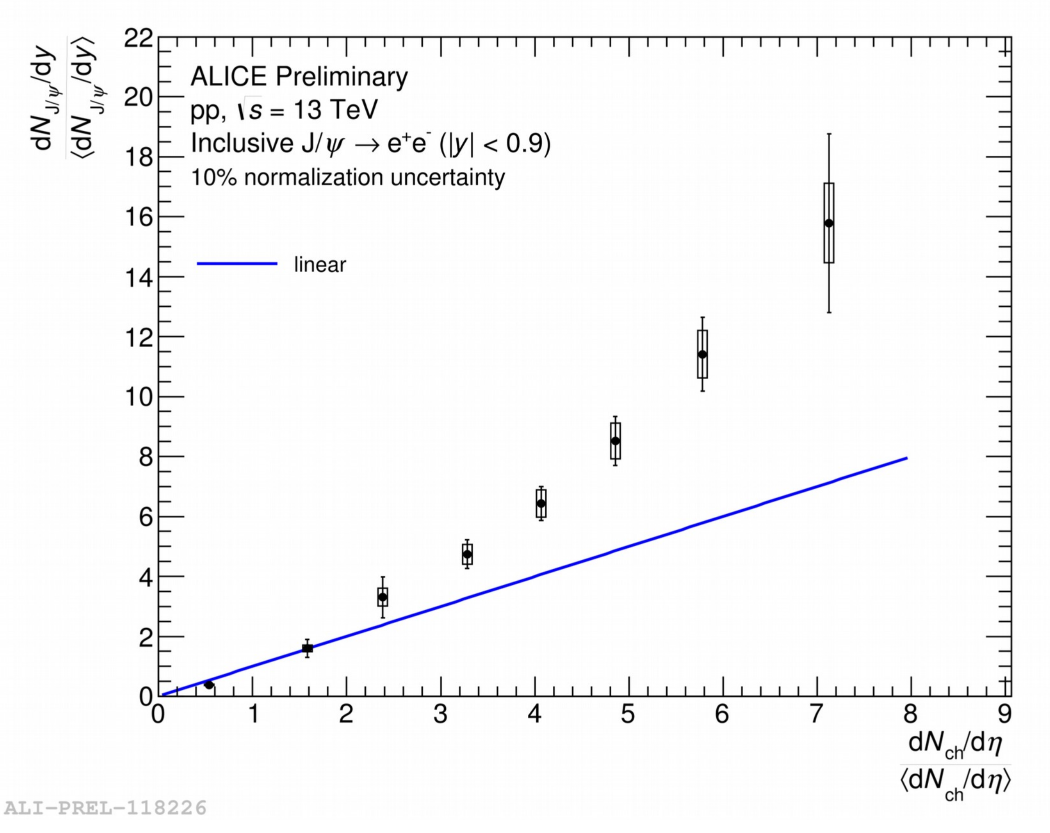
Blue: masses generated by electroweak symmetry breaking (current quark mass)

Yellow: additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses)

- Charm and beauty quark masses are not affected by QCD vacuum (ideal probes to study QGP)
- Charm and beauty quarks provide hard scale for QCD calculations
- **Charmonium production proceeds from hard initial processes and no strong correlations with event activity are expected**

Heavy flavor vs multiplicity: quarkonia

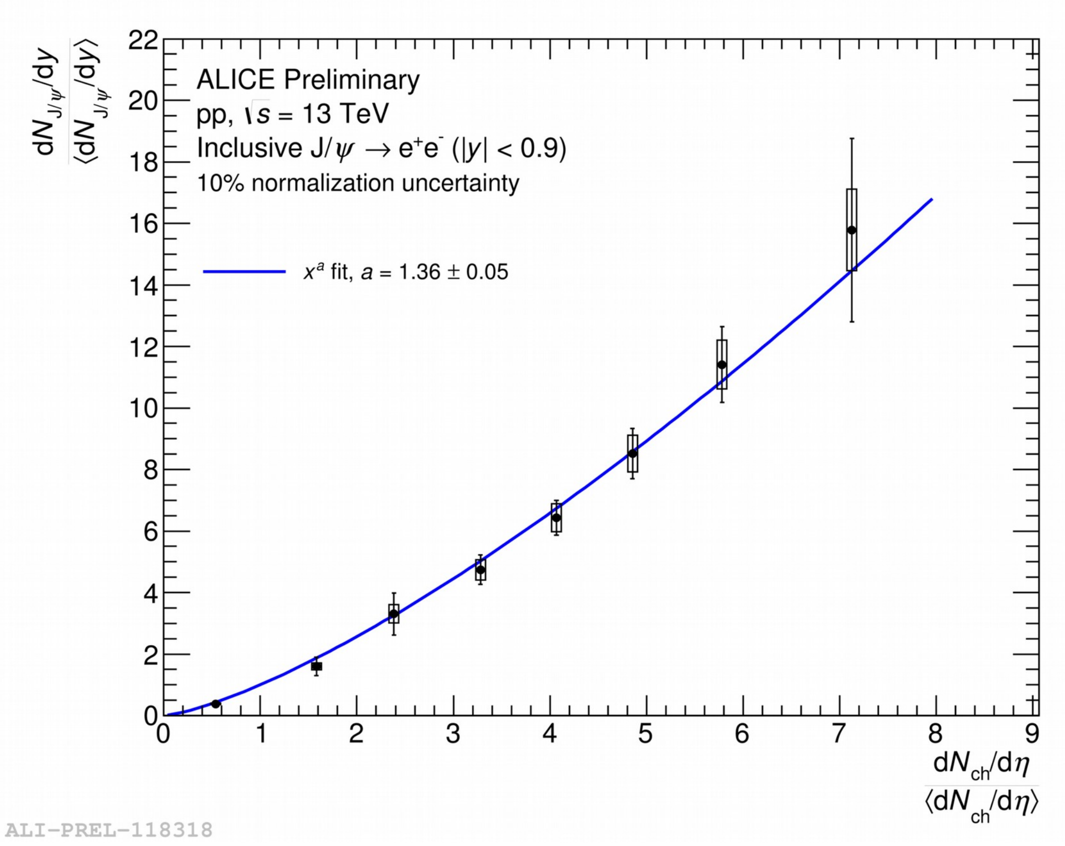
-Charmonium production proceeds from hard initial processes and no strong correlations with event activity are expected



Initial stages 2017 Presentation

Heavy flavor vs multiplicity: quarkonia

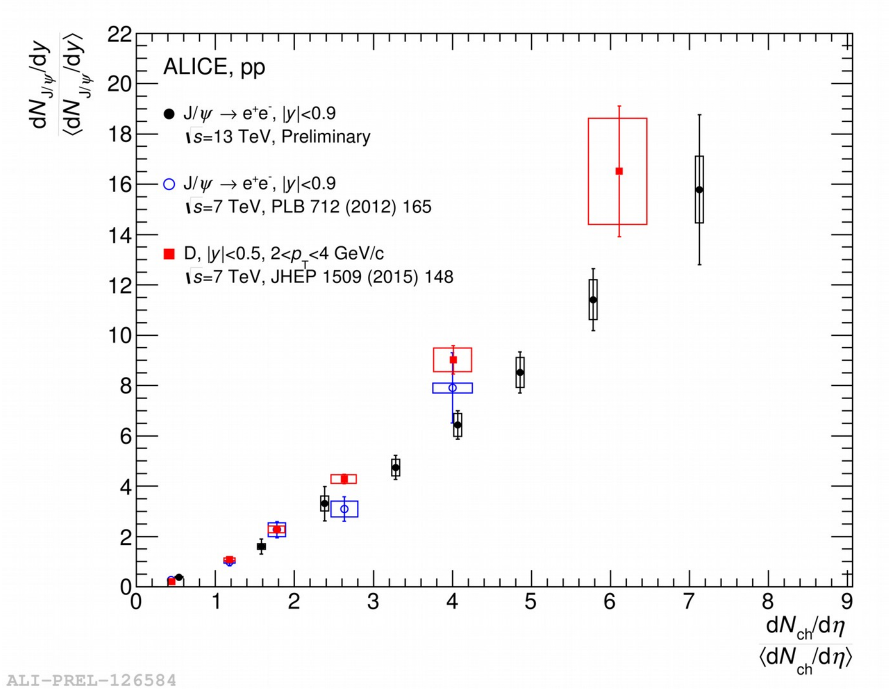
-Charmonium production proceeds from hard initial processes and no strong correlations with event activity are expected



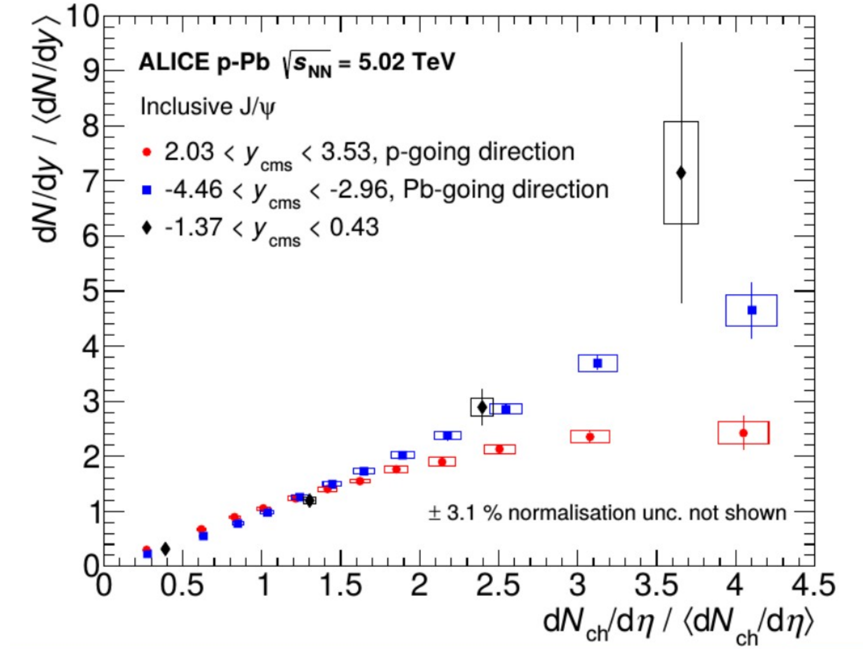
Increase is not linear: highlights importance of other physical processes.

Heavy flavor vs multiplicity

pp collisions



p-Pb Phys.Lett. B776 (2018) 91-104



-Similar effects observed for D’s
-Hadronization doesn’t seem to play a role

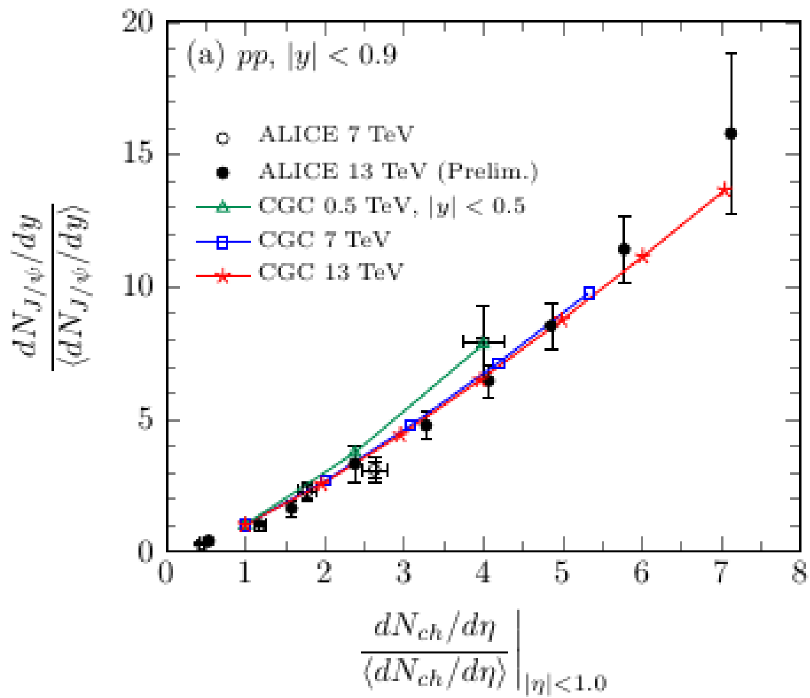
Mid-and backward rapidity (Pb-going):
-Qualitatively similar behavior as in pp collisions

Forward rapidity (p-going): Saturation at high multiplicities?
Bjorken-x range in the domain of shadowing / saturation?

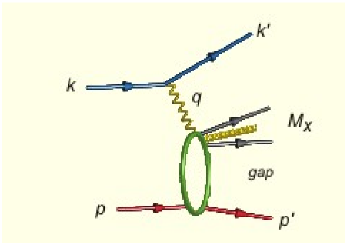
A novel regime of QCD?

Large parton densities
What happens to the gluon density in nuclei? Does it saturate at high energy?
Are we observing a hint of universal properties in all nuclei? (small and large).

https://arxiv.org/abs/1803.11093



-**With the EIC we have enhanced color density with nuclear targets:** access the non-linear evolution in the high gluon density region via nuclear diffraction.



2. Collective Expansion

Hydrodynamical flow

Radial Flow:
Affects shape of low p_T particle spectra

Elliptic Flow:
Sensitive to initial geometry
Requires early thermalization of the medium

Baryon to meson ratio

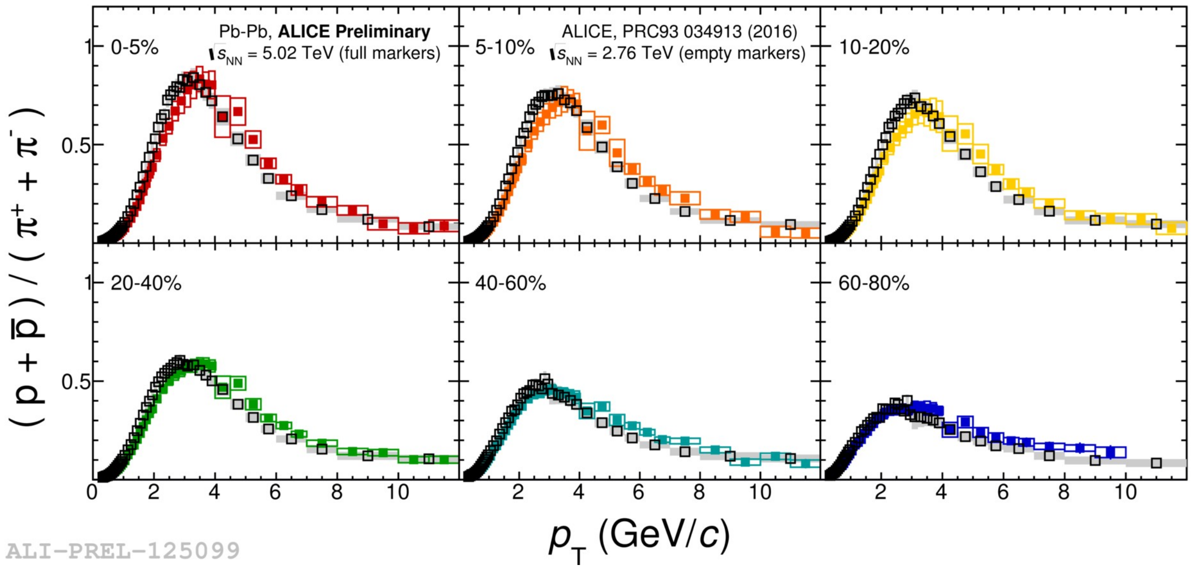
-Pb-Pb no significant energy dependence

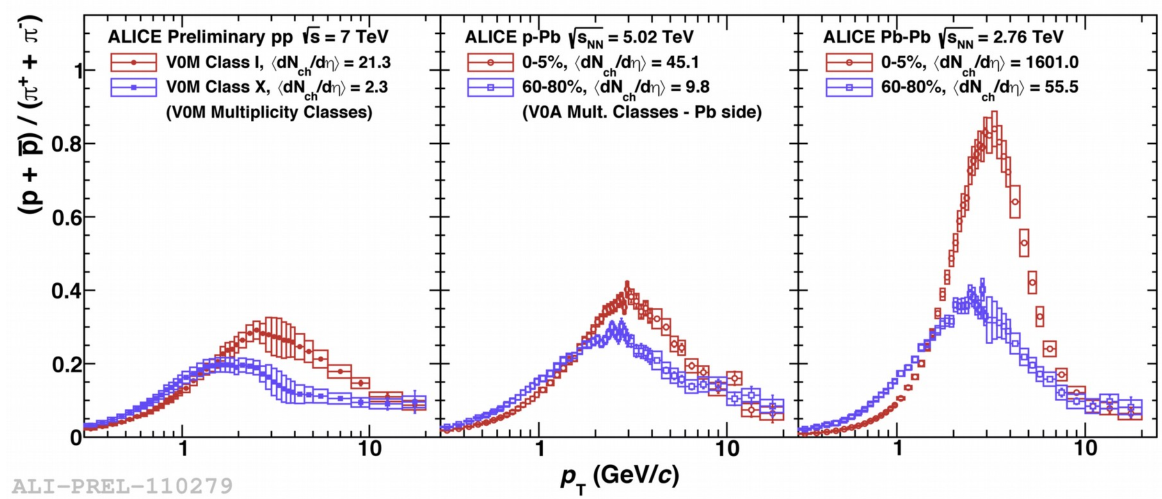
- Radial flow pushes protons to intermediate p_T and depletes low p_T

- Stronger radial flow in central Pb–Pb collisions

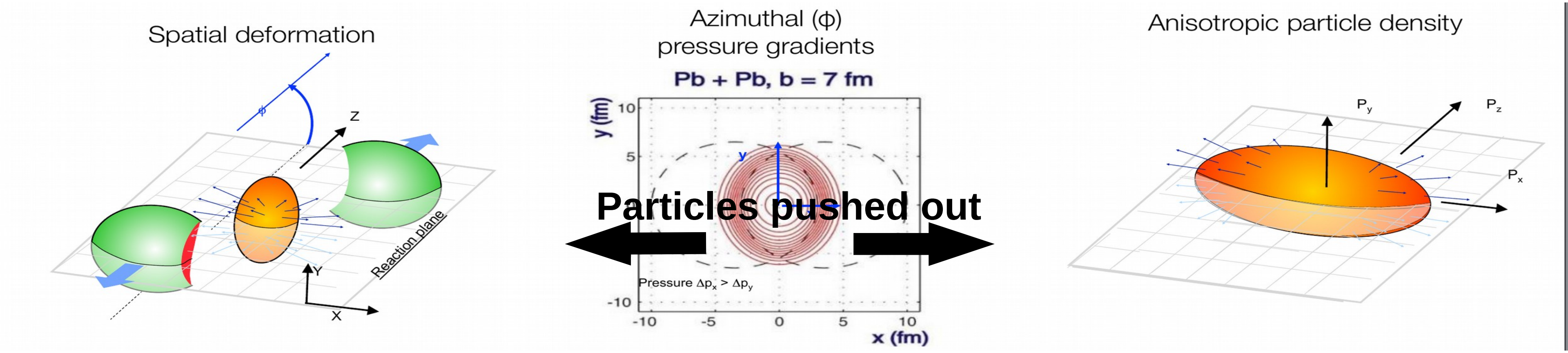
-Low to mid-p_T described by hydrodynamic models

- Similar effects observed in high-multiplicity pp and p–Pb collisions



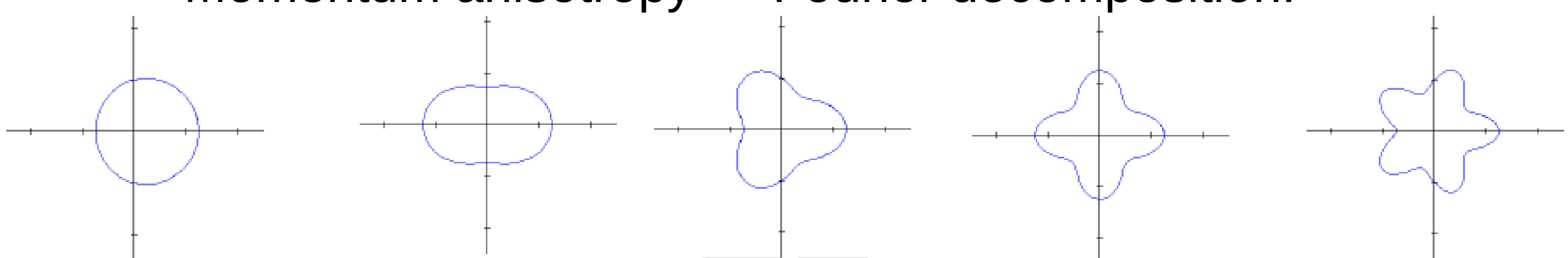


Anisotropic flow



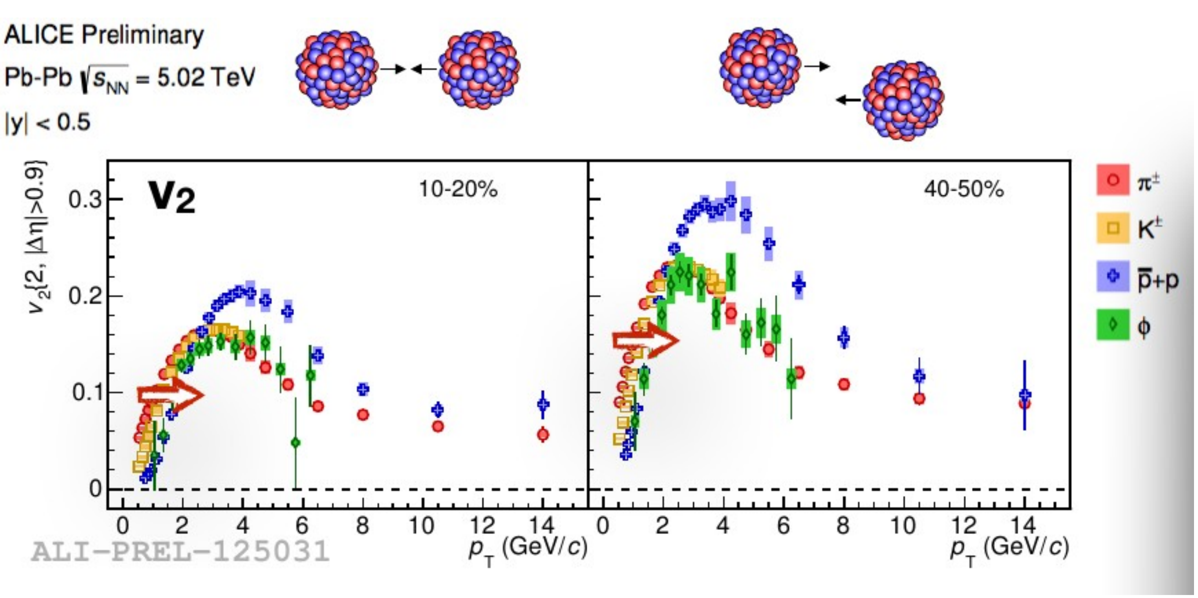
Initial overlap asymmetric → pressure gradients

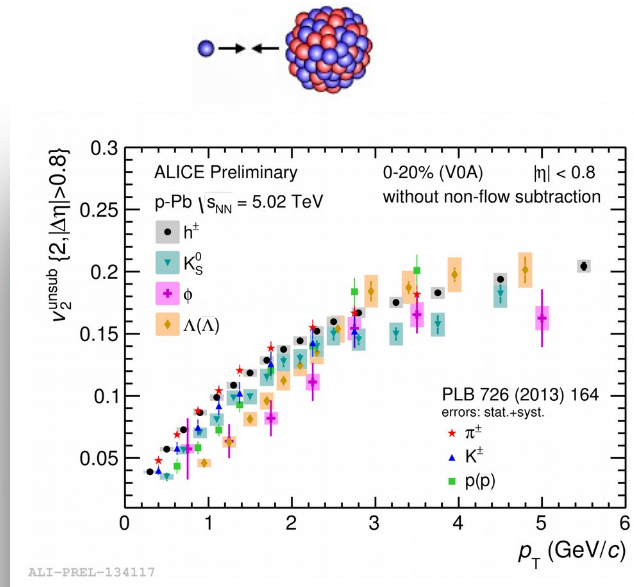
Momentum anisotropy → Fourier decomposition:



$$\frac{d^2N}{dp_T\, d\phi} \approx 1 + 2v_1\cos(d\phi) + 2v_2\cos(2d\phi) + 2v_3\cos(3d\phi) + 2v_4\cos(4d\phi) + 2v_5\cos(5d\phi) + \ldots$$

Light meson flow





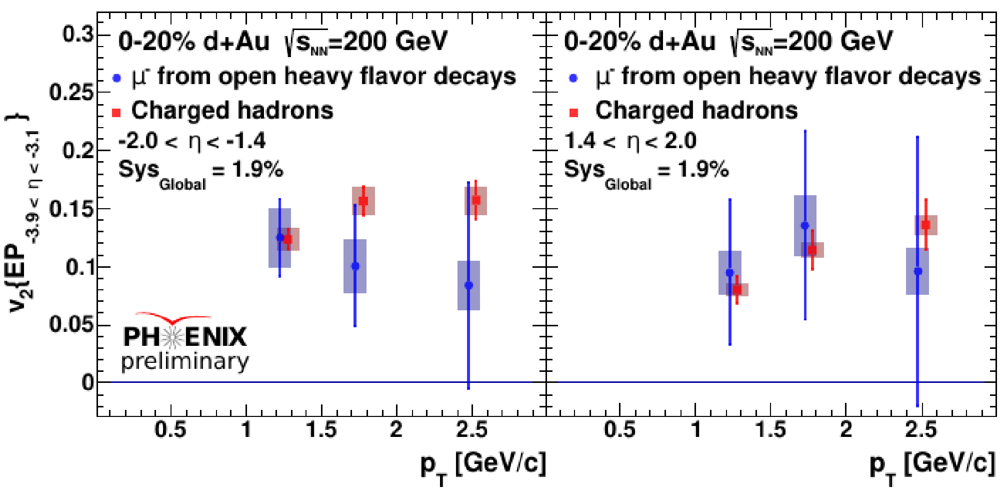
-Low p_T : Mass ordering expected in a collective expansion scenario.

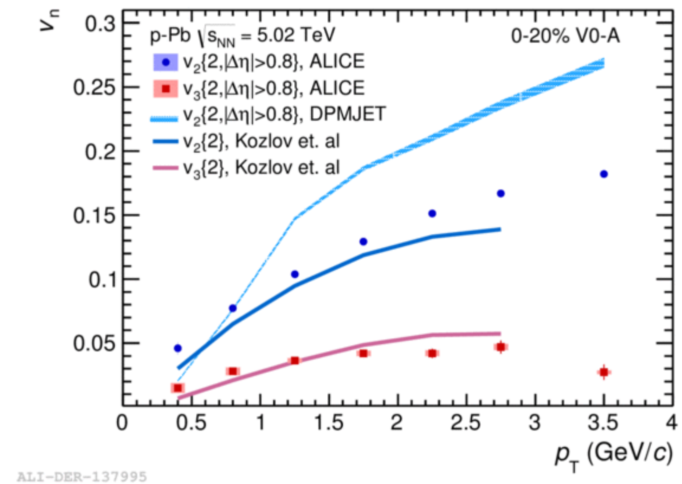
-Low-p_T : v_2 sensitive to hydrodynamic expansion and initial conditions (geometry).

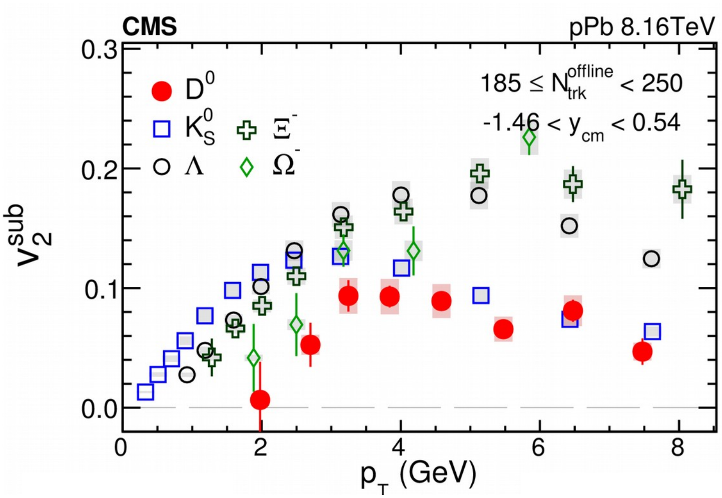
-**Similar results observed in a high multiplicity p-Pb environment.**

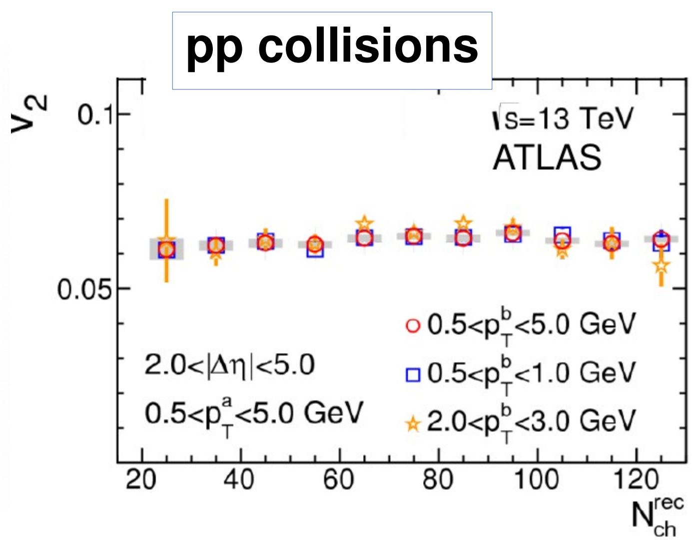
-Effect in these systems may be due **to initial state (saturation?)** or final state effects (expansion and/or thermal equilibrium ?)

Flow in small systems?









$\sqrt{s_{pA}}$=200 GeV PHENIX
QM2018 Talk

$\sqrt{s_{pA}}$=5.02 TeV ALICE
JHEP 09 (2017) 032

$\sqrt{s_{pA}}$=8.16 TeV CMS:
arxiv:1804.09767

$\sqrt{s}$=13 TeV ATLAS:
PRL116, 172301 (2016)

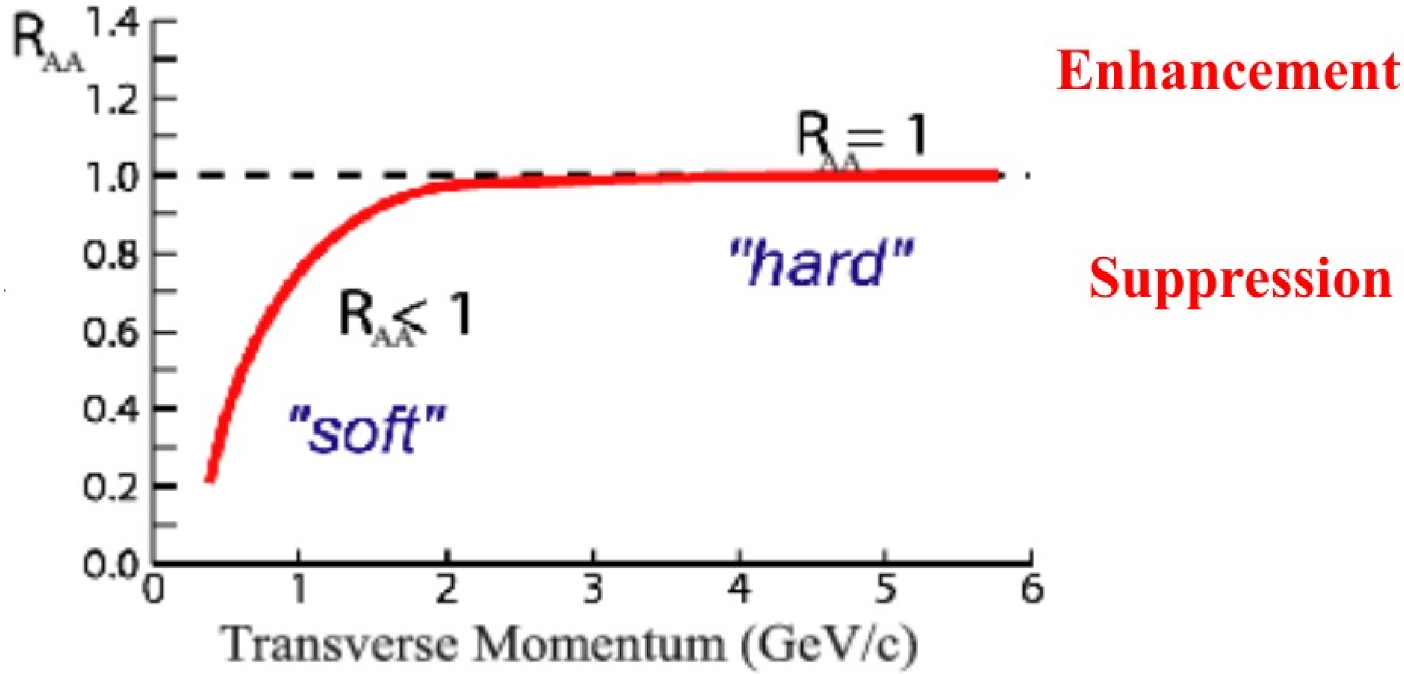
QGP? Saturation? Quantum entanglement?

3. Hard Processes

Nuclear modification factor

Measure spectra of probe and compare to those in pp collisions or A-A collisions

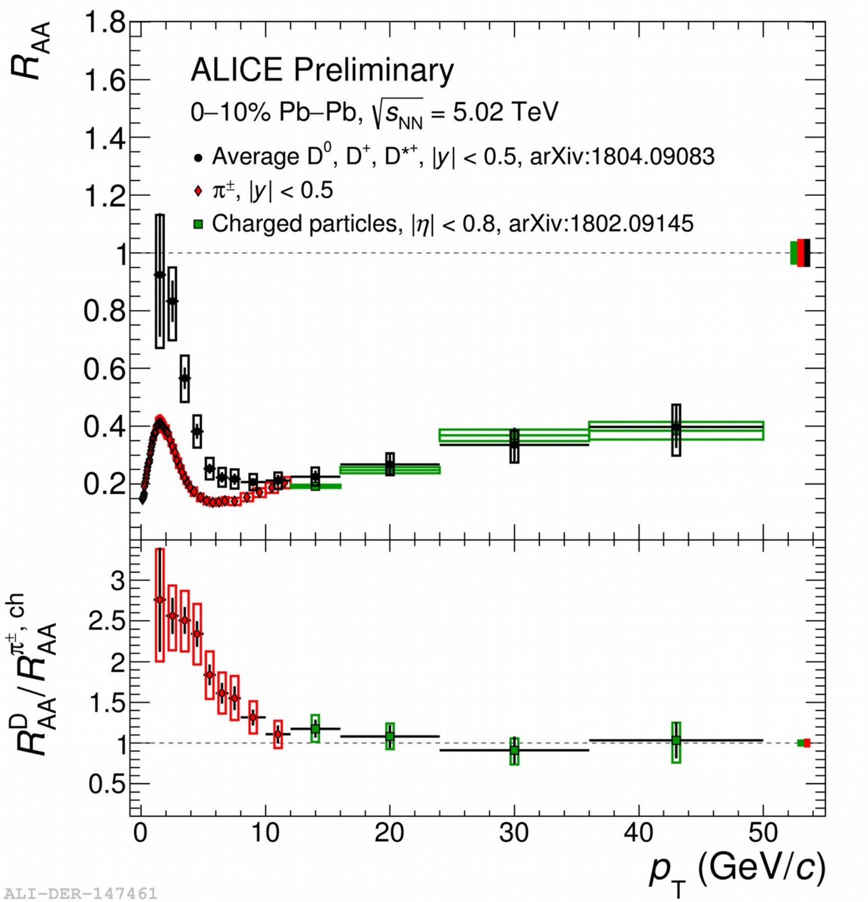
$$R_{\mathrm{AA}} = \frac{\mathrm{AA}}{\text{scaled pp}} = \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}^2 N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

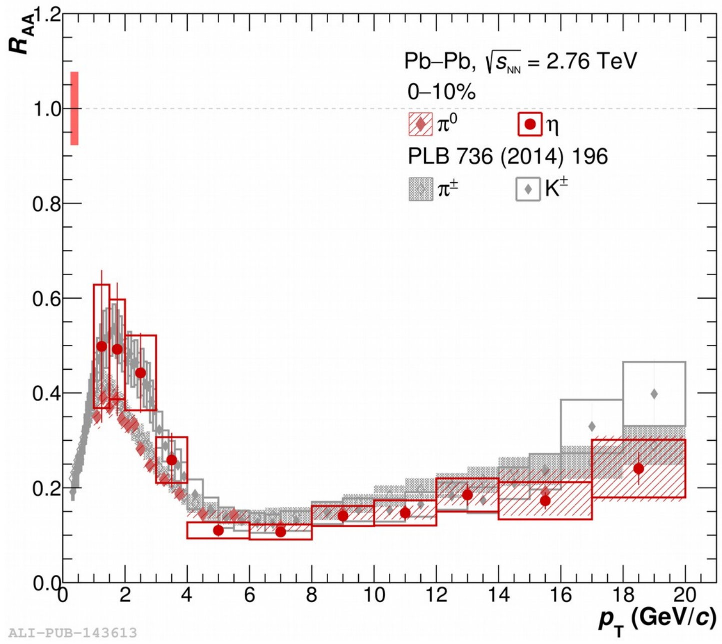


Energy loss in the medium

-High momentum partons lose energy while propagating through the QGP
-Energy loss depends on parton type properties of the medium.
-It can modify color flow

$$R_{AA} = \frac{AA}{\text{scaled pp}} = \frac{d^2N_{AA}/dp_T dy}{\langle N_{coll}\rangle d^2N_{pp}/dp_T dy}$$





Pb-Pb suppression
- Similar to that of pions (at high enough p_T)

-ALICE-PUBLIC-2017-003
-https://arxiv.org/abs/1803.05490

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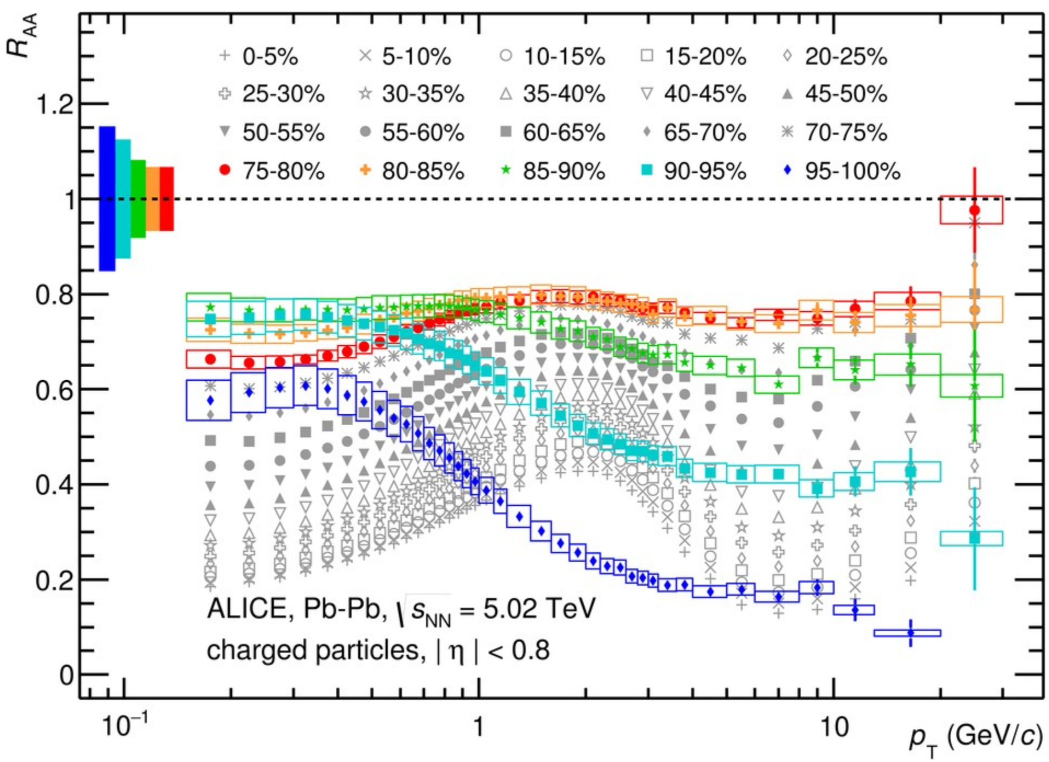
ALICE-PUBLIC-2017-003



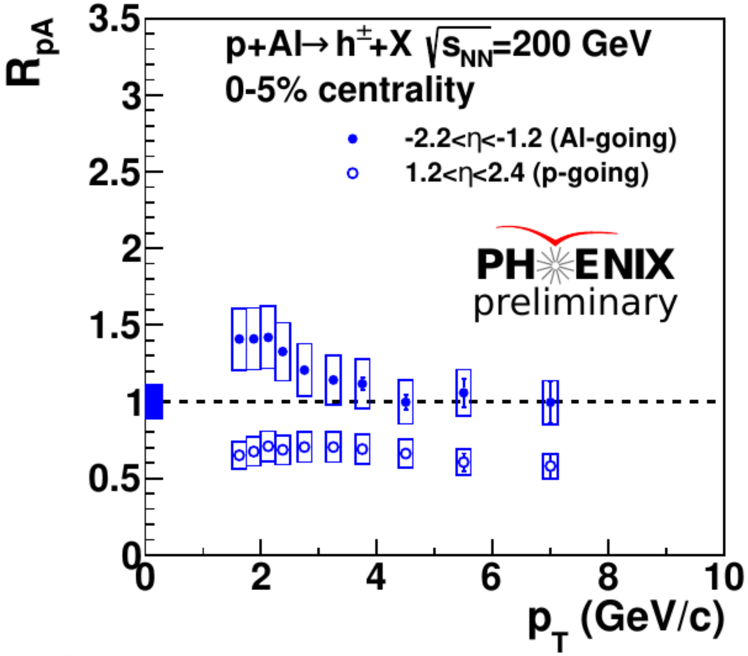
Pb-Pb suppression:
- Increases with centrality

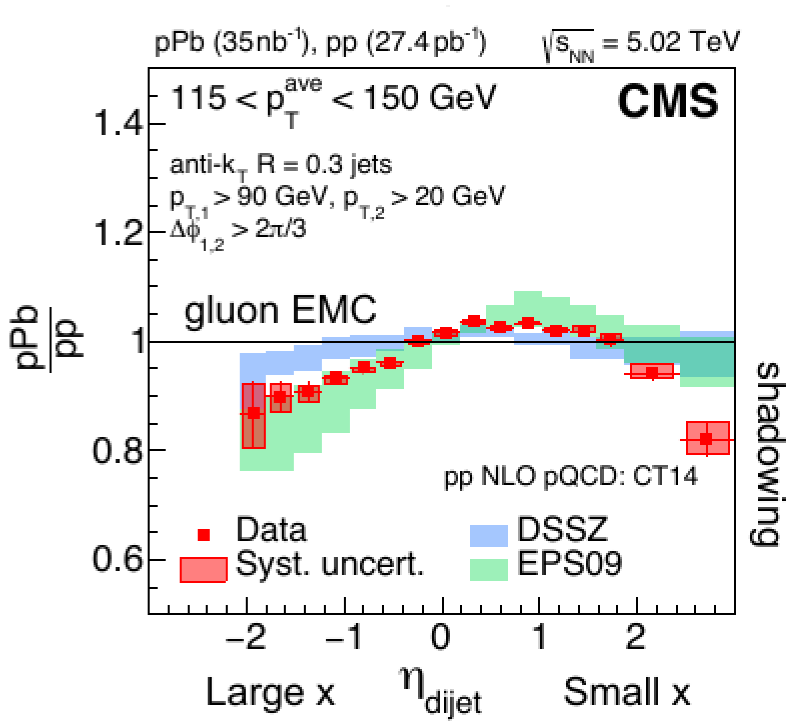
- Not initial state

- Final state effect; due to hot and dense QCD matter

"Unintuitive observation that RAA is below unity in peripheral Pb-Pb, but equal to unity in minimum-bias p-Pb collisions despite similar charged-particle multiplicities".

Energy loss in the medium





PHENIX reports an enhancement observed at backward rapidity in p-Al (and p-Au) collisions.

CMS dijet results support the observation of the gluon's EMC effect as well as quark modification. **Data is more precise than current nPDF' uncertainties**

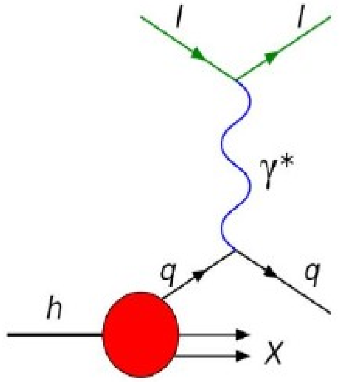
PHENIX: QM2018 J. Bryslawskyj

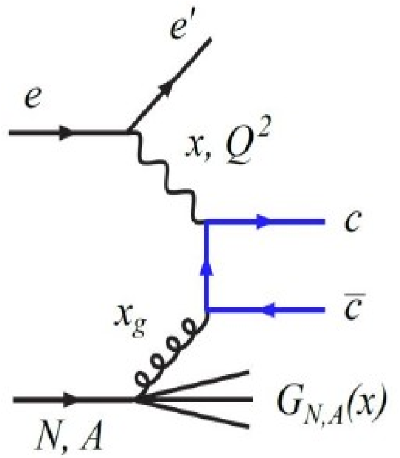
CMS: https://arxiv.org/abs/1805.04736

Impact on nPDF's

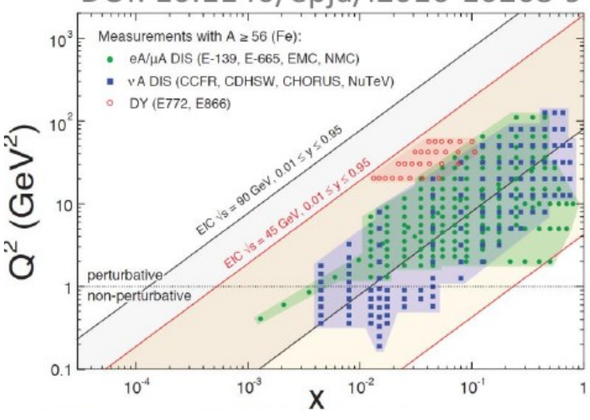
-Electron- Ion collisions will significantly reduced sea/gluon nPDF uncertainties at lower x values ($x \sim 10^{-4}$)

- HF in e+A collision constraints at large-x gluon

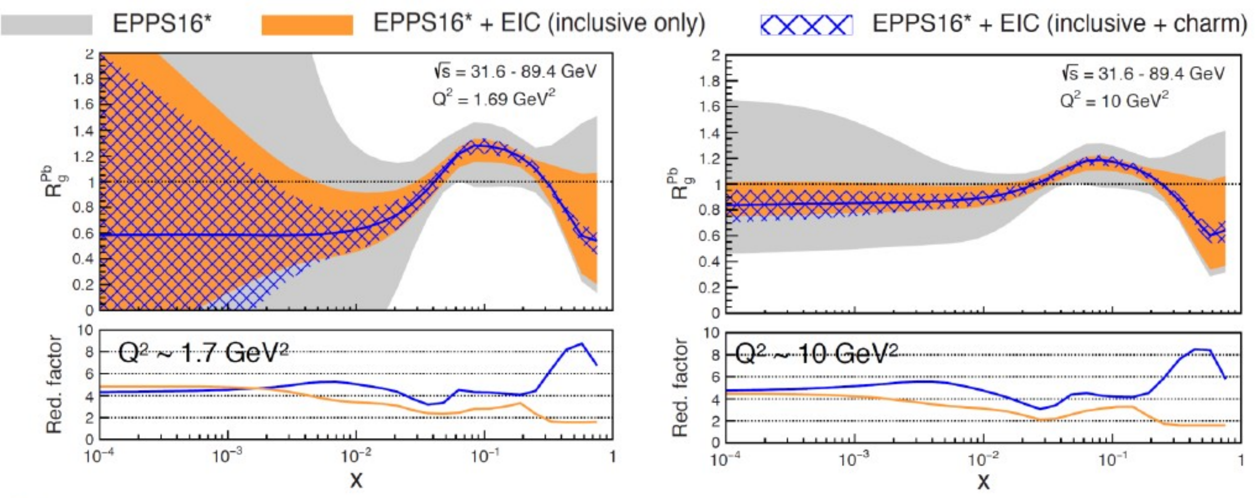




DOI: 10.1140/epja/i2016-16268-9



arXiv:1708.01527



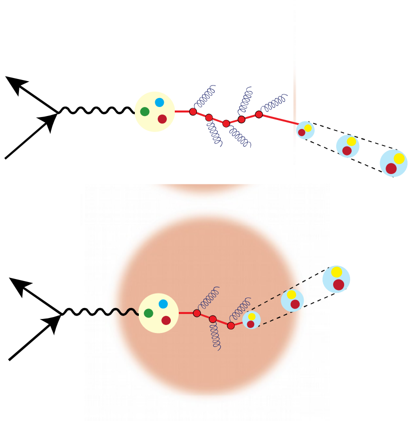
Energy loss in the medium

eA provides a stable nuclear medium (CNM):
-Controlled kinematics of hard scattering

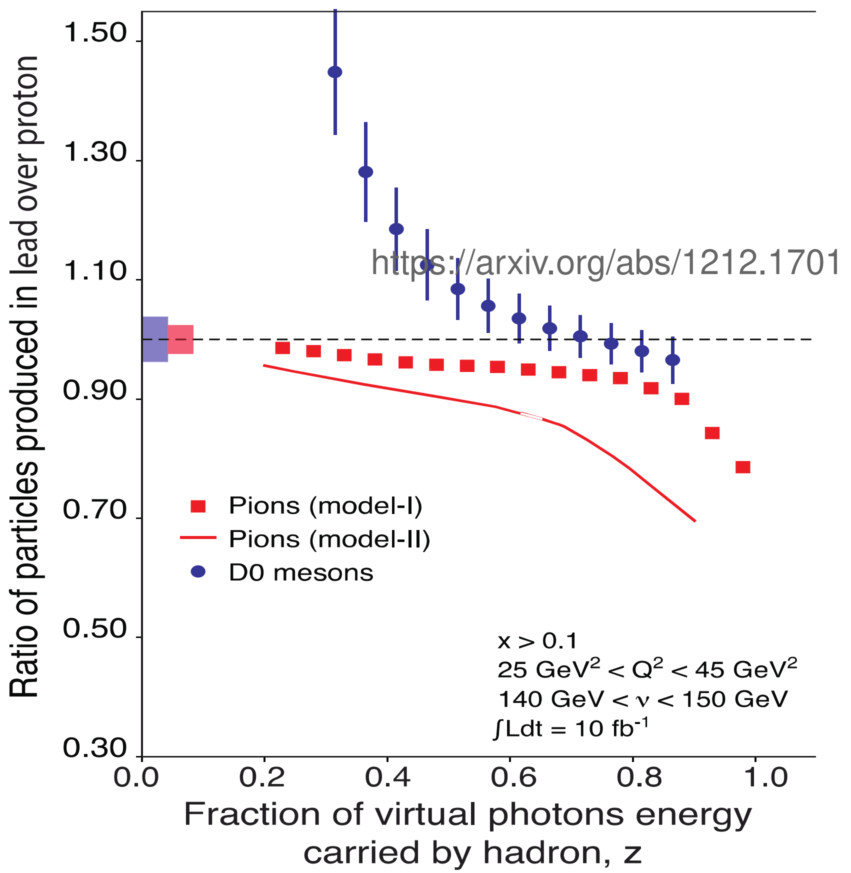
-Final state particle with known properties.

-Varying nuclei size and initial parton energy control fragmentation' length.

-Independent and complementary information essential for the understanding the response of the nuclear medium to a fast moving quark.



Energy loss by light vs. heavy quarks



4. Proton’s spin: How does nucleon spin emerge from quarks and gluons

Spin

How do quarks/gluons + their dynamics make up the proton spin?

$S(\mu) = \frac{1}{2}$

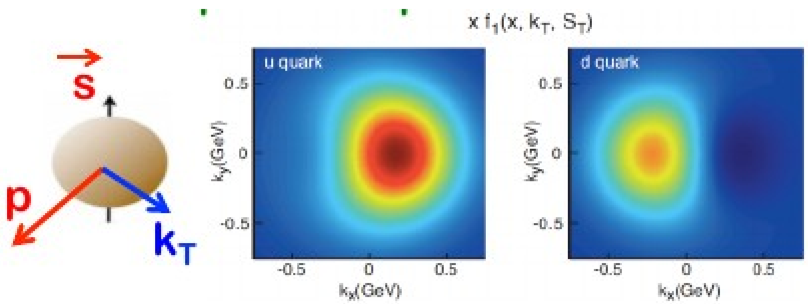
$\mu \Rightarrow \infty$

Quark helicities
Best known

Gluon helicities
Starting to know

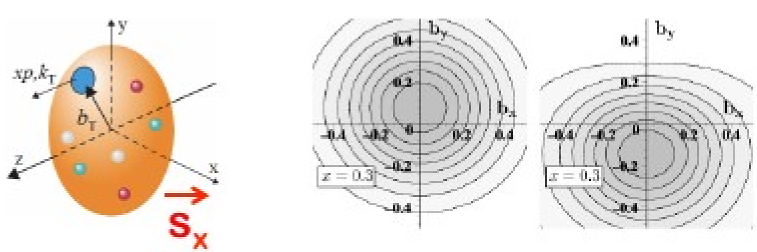
Orbital angular momentum
Largely unknown

How is proton's spin correlated with the motion of quarks/gluons?



TMD's
Transverse Momentum Distributions

How does proton's spin influence the spatial distribution of partons?

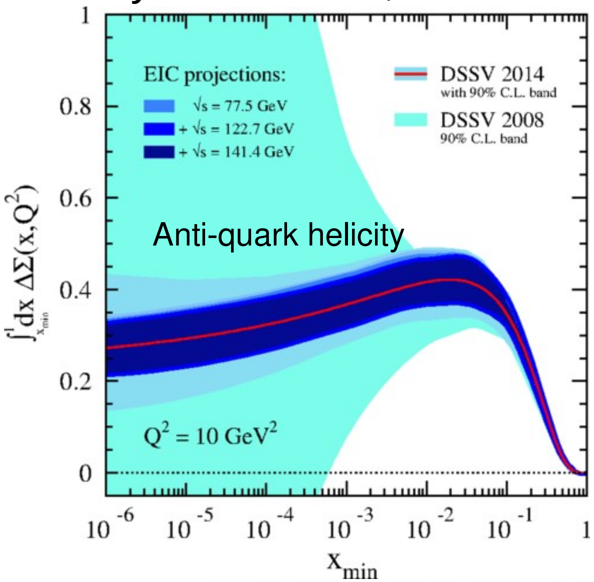


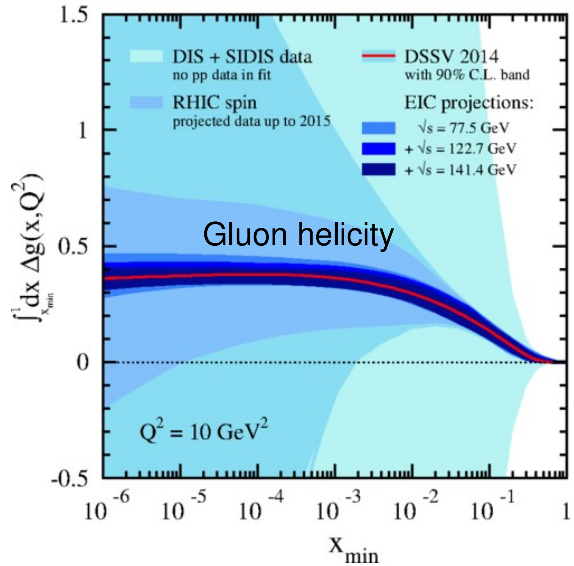
GPD's
Generalized Parton Distribution Functions

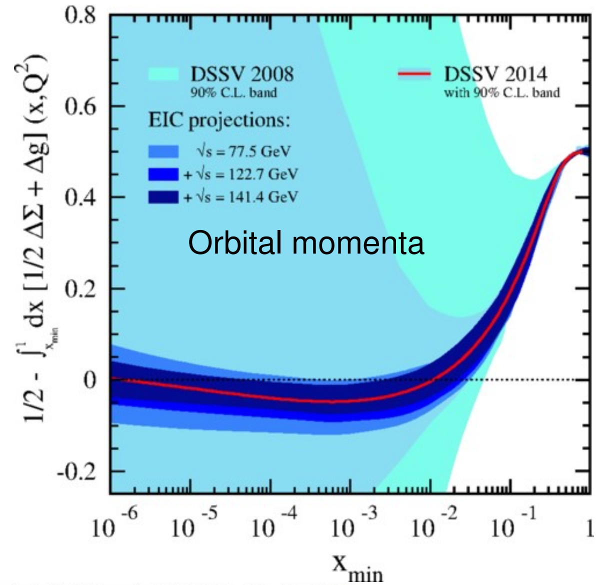
How much spin is at small-x?

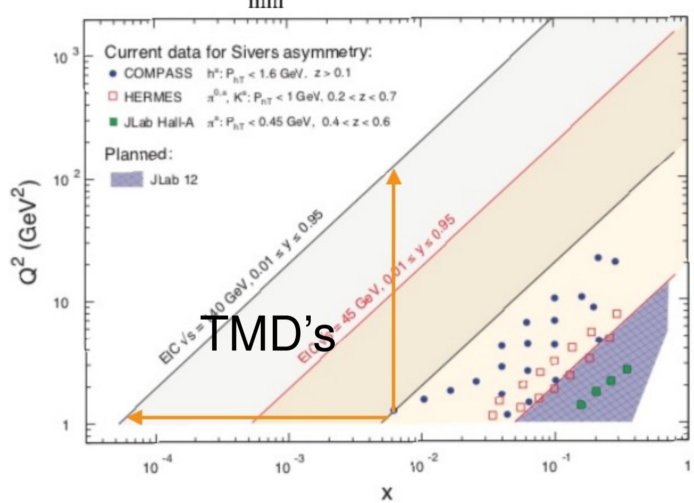
The EIC can help complete the story

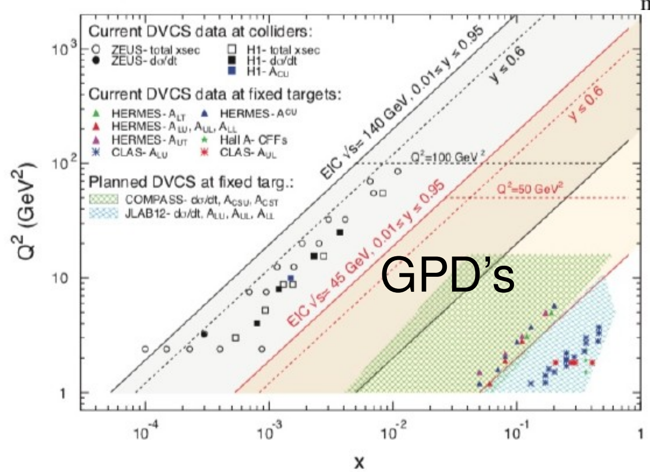
"Unveil the role of the intrinsic spin of quarks and gluons in the proton's spin budget"
Phys. Rev. D 92, 094030











Two orders in x and Q2 compared to existing/ planned SIDIS data

Two orders in x and Q2 compared to existing/ planned polarized data. Two to three orders of magnitude in luminosity for unpolarized data.

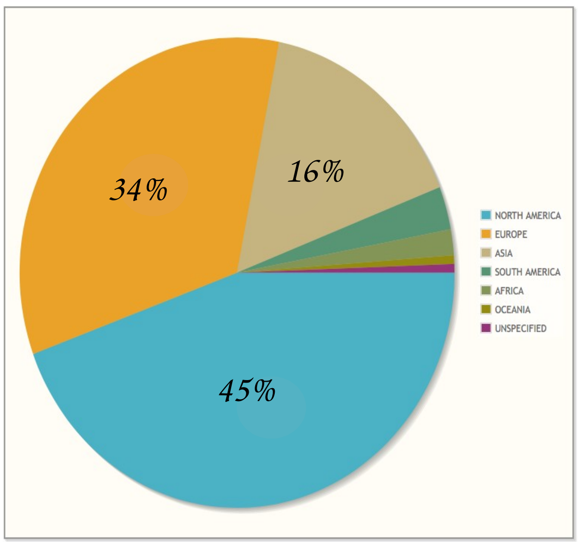
EIC Users group

EIC User Group and R&D activities

WWW-page: www.eicug.org

EIC User Group:

- EICUG organization established in summer 2016
- In numbers….: 817 members (470: Experimentalists / 163: Theorists / Accelerator Scientists: 142 / Support: 3 / Other: 39), 173 institutions, 30 countries, 7 world regions
- World map:



R&D activities:

- EIC Detector R&D program operated by BNL with ~$1M / year
- EIC Accelerator R&D with ~$7M / year

Summary

QCD studies have given us decades of discoveries. Many open questions remain on how the transition from a small system to a dense system occurs: this information is needed to fully understand the properties of the QGP. To this date we have yet not unraveled how partons and their dynamic interactions make up the proton spin.

Essential experimental bibliography from this presentation:

-The Electron-Ion Collider: Assessing the Energy Dependence of Key Measurements:
BNL-114111-2017 arXiv:1708.01527

-QGP:

-Strangeness enhancement in pp collisions:
Nature Physics 13 (2017) 535-539

-Particle production vs multiplicity
Phys. Lett. B 776 (2018) 91
Phys. Lett. B 724 (2013) 213

-Flow in large and small systems:
PbPb: Phys. Rev. Lett. 120.102301 (2018)
pPb: arxiv:1804.09767, JHEP 09 (2017) 032
pp: PRL116, 172301 (2016)

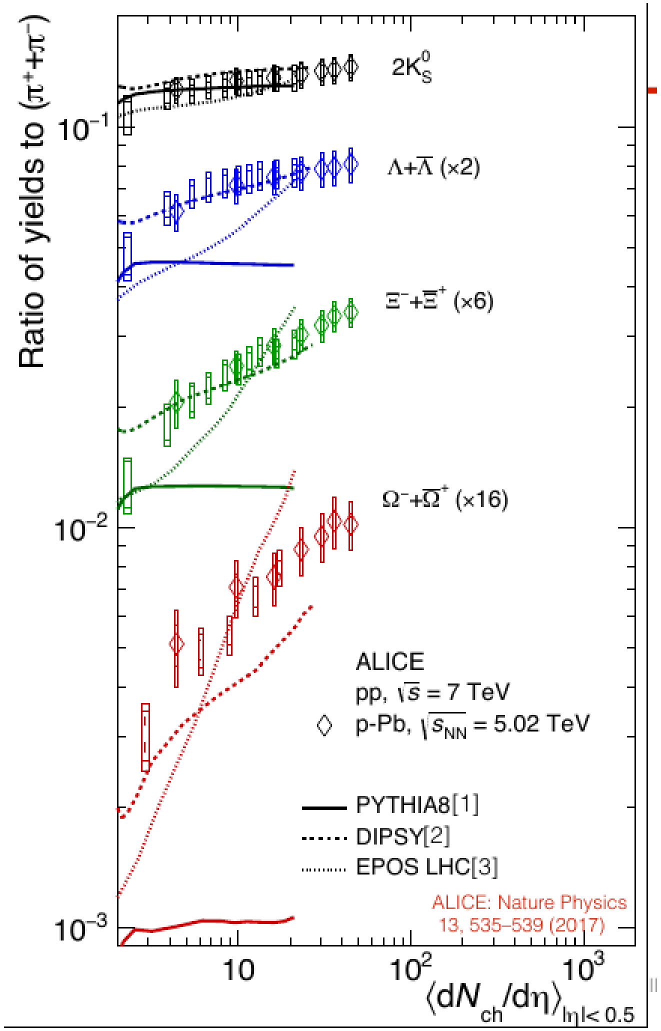
-Nuclear PDFs with dijets:
pA: arXiv:1805.04736

-Spin: -Unveiling the Proton Spin Decomposition at a Future Electron-Ion Collider:
Phys. Rev. D 92, 094030

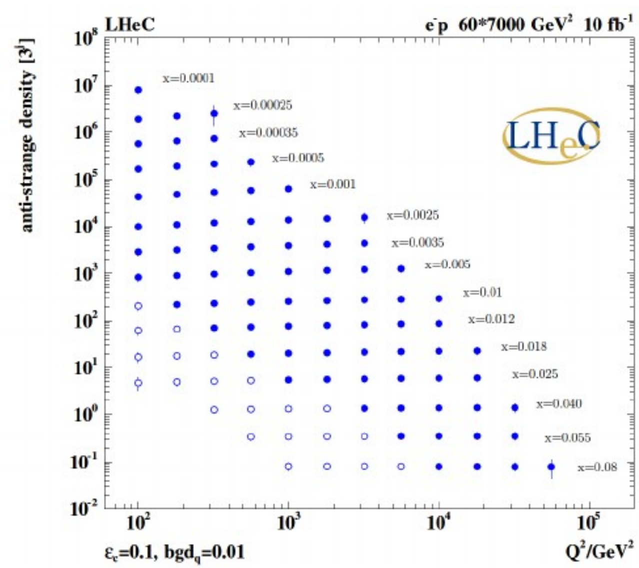
Backups

QGP Onset: Strangeness enhancement

Enhancement of strange particles with respect to non-strange yield **is also observed** for high multiplicity **pp** and **p-Pb** collisions



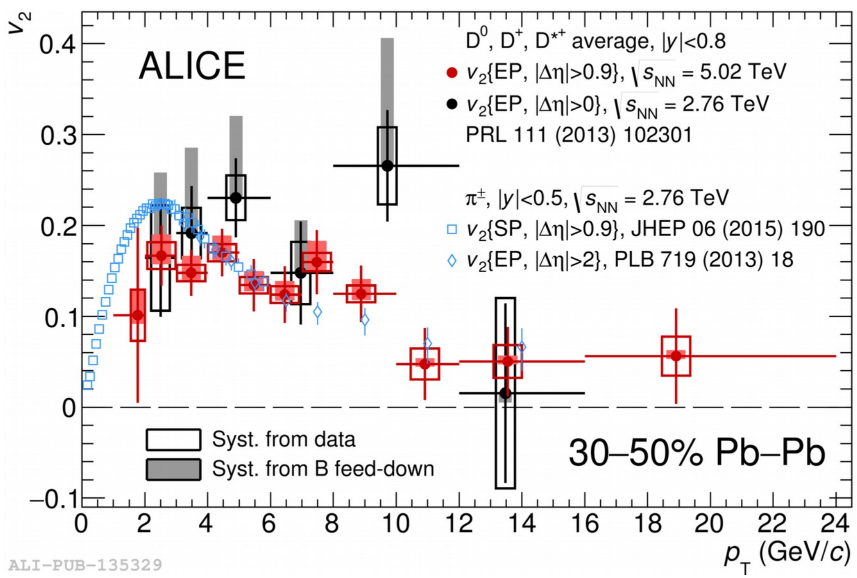
-Smooth transition connecting small and larger systems.
-These measurements may give us insights about the underlying dynamics
-eA can provide a more robust reference.

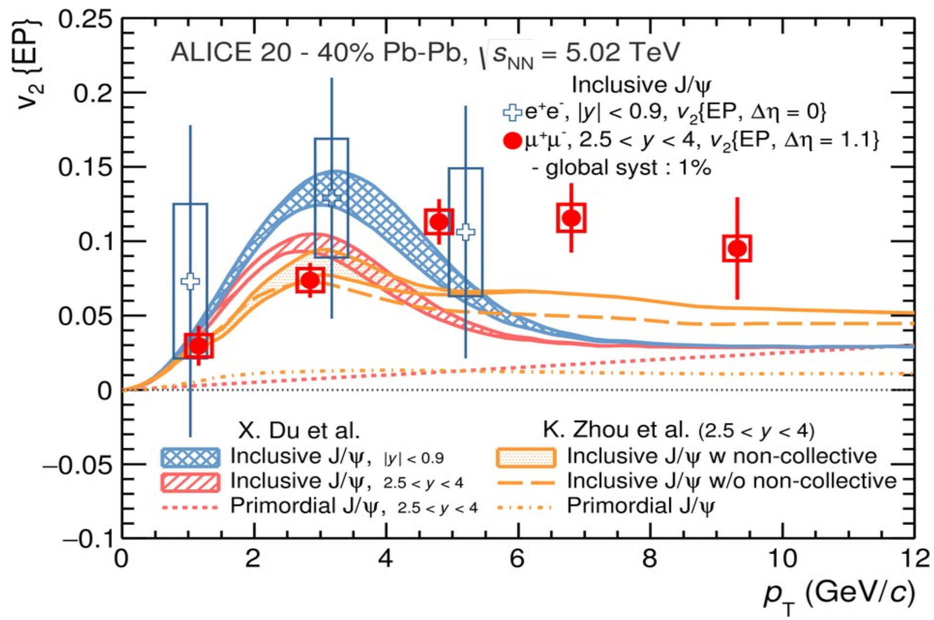


More experimental insight is needed to interpret the final state strangeness we are observing in large and small systems

https://arxiv.org/pdf/1305.0609 and https://cds.cern.ch/record/2302756

Charm flows





Non zero v_2 for D-meson

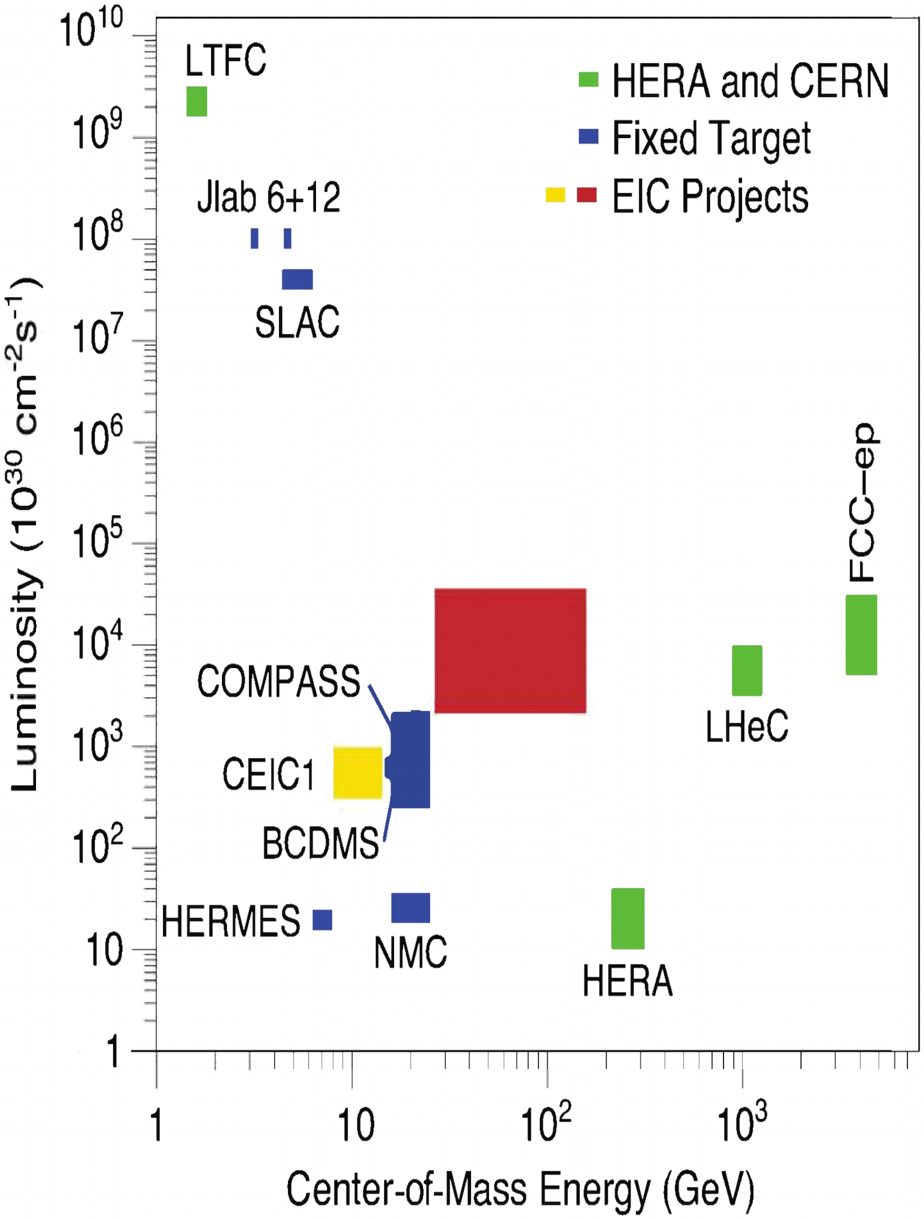
Non zero v_2 for J/ψ's

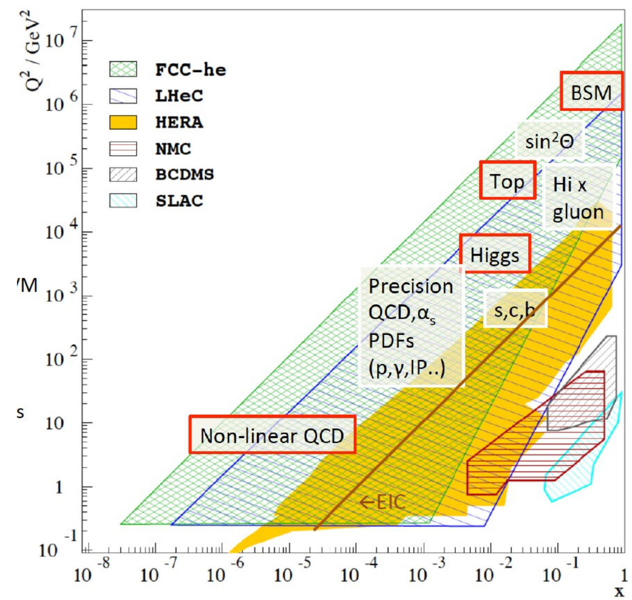
Strong coupling of c-quark with the medium
Participation of low p_T charm to collective motion in the QGP

Additionally for the J/ψ this is interpreted as proof of recombination.

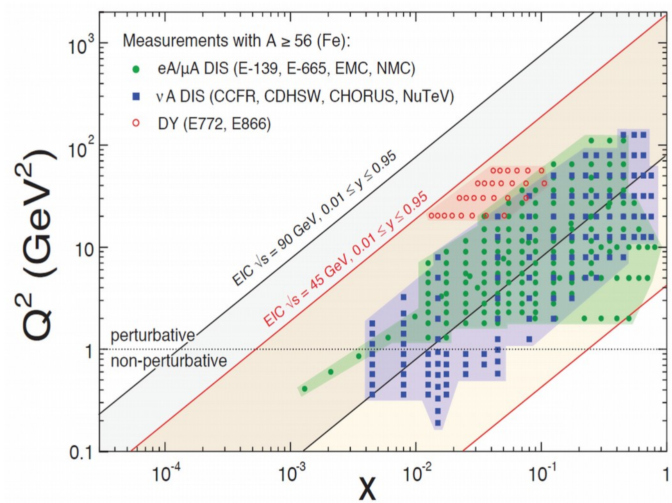
Phys. Rev. Lett. 120.102301 (2018)
Phys. Rev. Lett. 119, 242301 (2017)

Kinematic reach



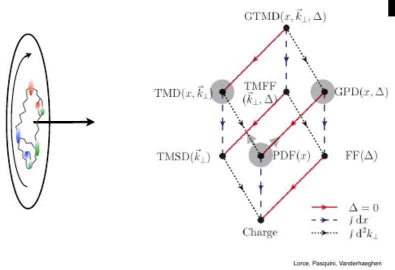


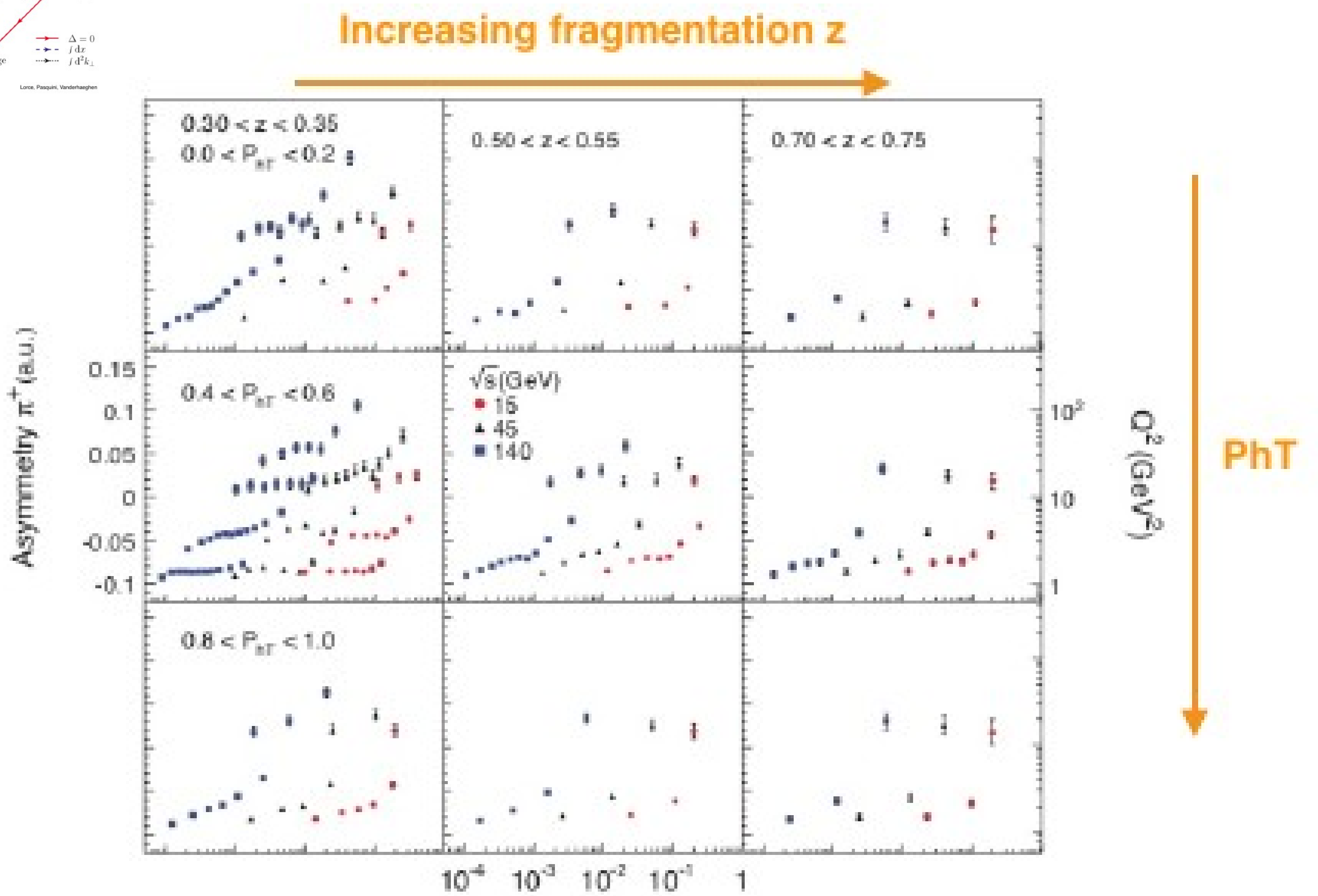
LHeC



EIC

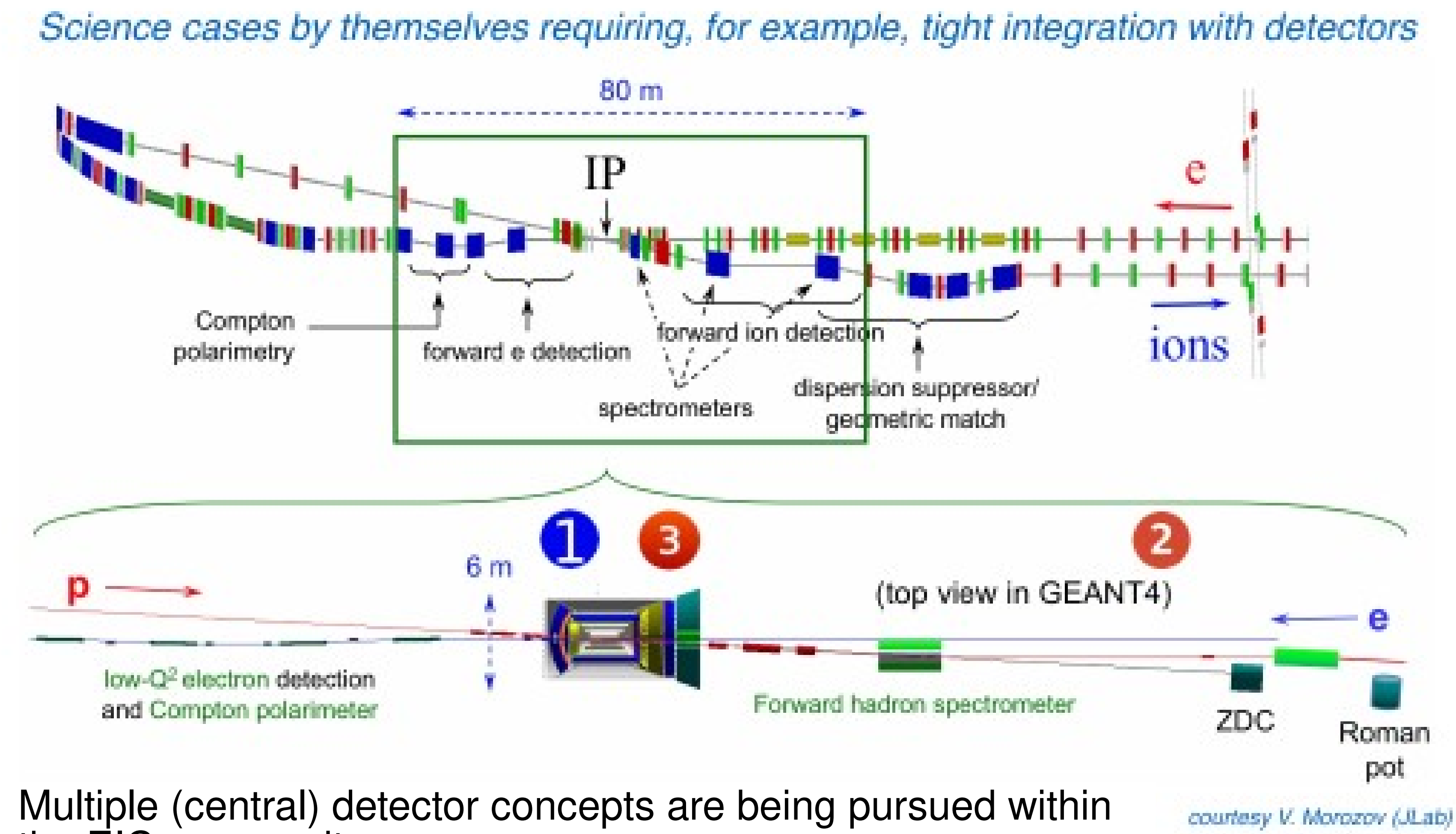
Beyond the longitudinal view





Representative charged pion measurements; positive PID essential
10 inv. fb, points at indicated x and Q2, uncertainties as indicated

Facility Concepts EIC



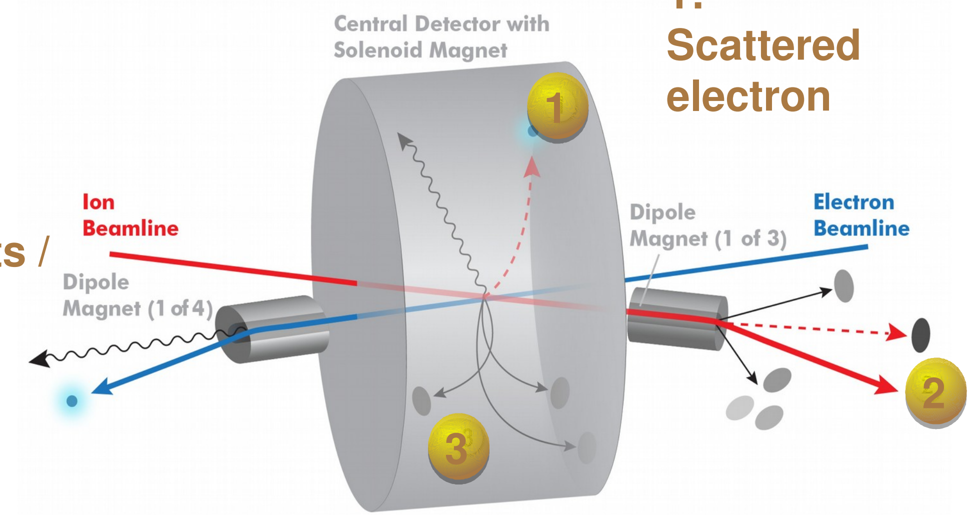
Multiple (central) detector concepts are being pursued within the EIC community.

https://wiki.bnl.gov/conferences/index.php/EIC_R%25D - generic detector R&D

Detector Concepts EIC: requirements

arXiv:1212.1701

3: Nuclear and nucleonic fragments / scattered proton



1: Scattered electron

2: Fragmented particles (e.g. π, K, p) of struck quark

-Acceptance: Close to 4π coverage with a η-coverage ($\eta = -\ln(\tan(\theta/2))$) of approximately $\eta < |3.5|$ combined calorimetry (EM CAL and hadron CAL at least in forward direction) and tracking coverage

-Low dead material budget in particular in rear direction (~5% X/X_0)

-Good momentum resolution $\Delta p/p$ ~ few %

-Electron ID for e/h separation varies with θ / η at the level of $1:10^4$ / ~2-3%/√E for $\eta<-2$ and ~7%/√E for $-2<\eta<1$

-Particle ID for π/K/p separation over wide momentum range (Forward η up to ~50GeV/c / Barrel η up to ~4GeV/c / Rear η up to ~6 GeV/c)

-High spatial vertex resolution ~ 10-20μm for vertex reconstruction

-Low-angel taggers:
Recoil proton
Low Q^2 electron
Neutrons on hadron direction

-Luminosity (Absolute and relative) and local polarization direction measurement

Detector Concepts EIC: requirements

Generic Detector R&D program for an EIC

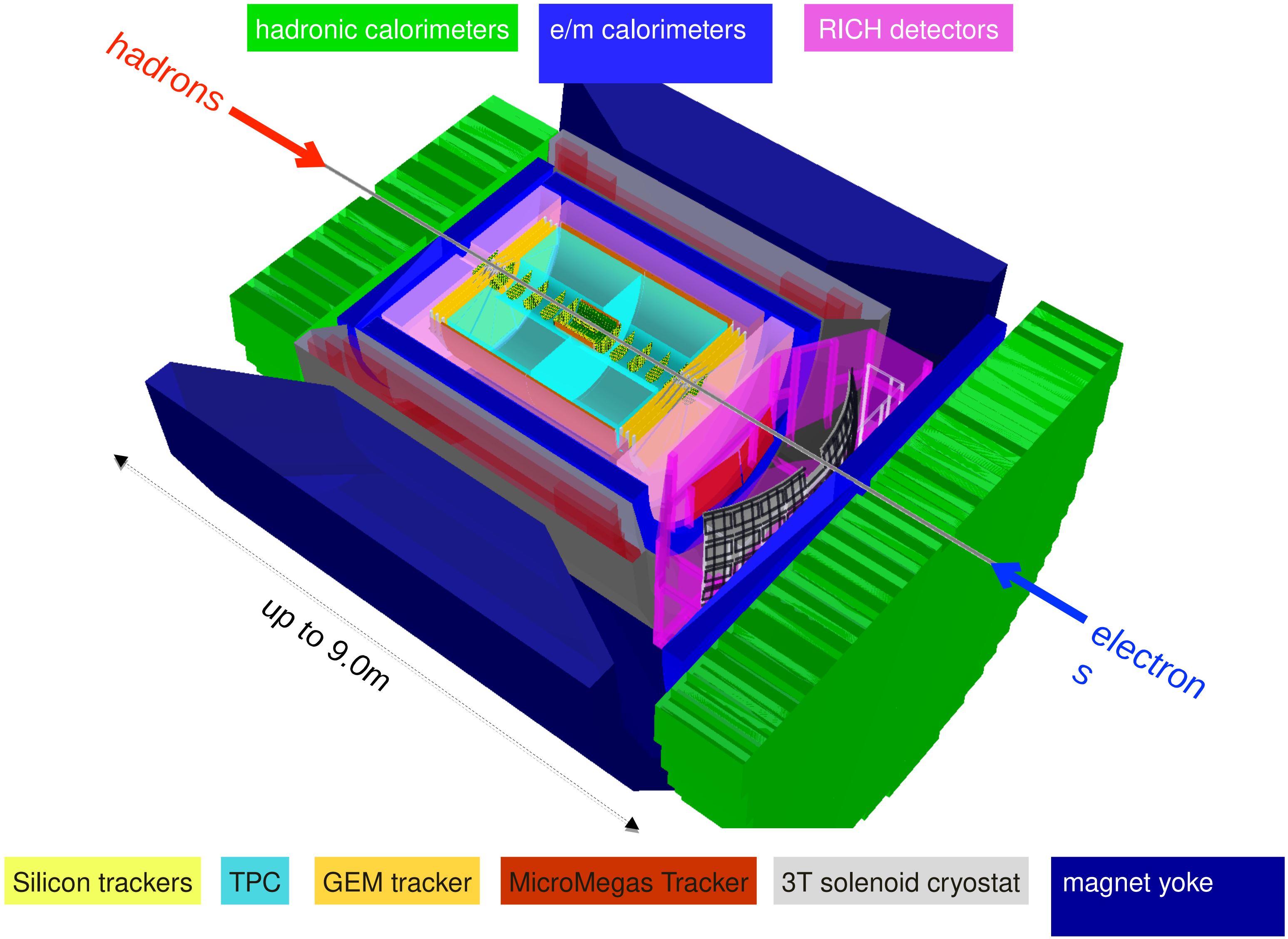
-In January 2011, BNL, in association with JLab and the DOE Office of NP, announced a -generic detector R&D program to address the scientific requirements for measurements at a future EIC facility.

Goals:

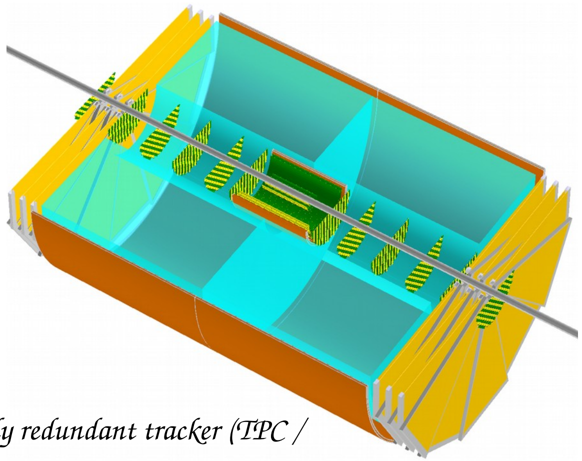
-Enable successful design and timely implementation of an EIC experimental program
-Develop instrumentation solutions that meet realistic cost expectations
-Stimulate the formation of user collaborations to design and build experiments
-Peer-reviewed program funded by DOE and managed by BNL with $1M/year to $1.5M/year Initiated and coordinated by Tom Ludlam (BNL) until 2014 / Since 2014 coordinated by Thomas Ullrich (BNL)

Detector Concepts EIC: BEAST

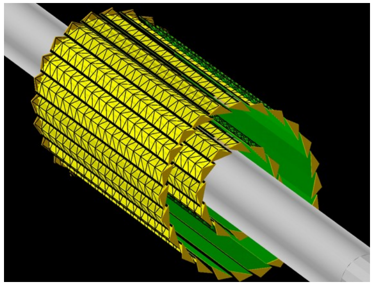
- *Detector design: BEAST (1) - BNL*



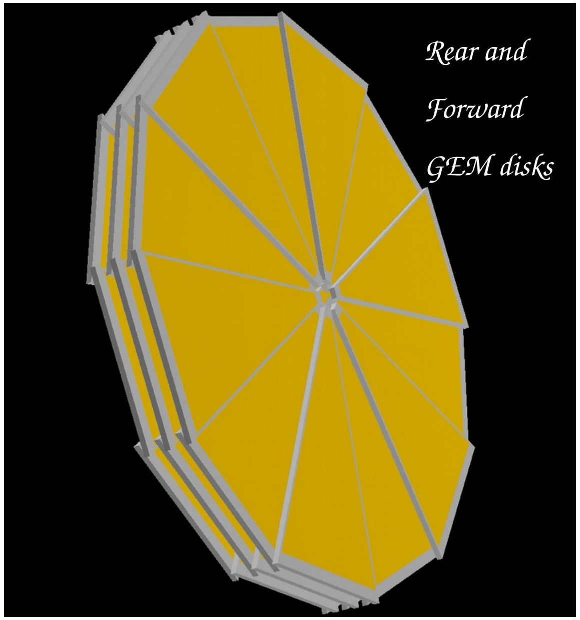
Detector Concepts EIC: BEAST

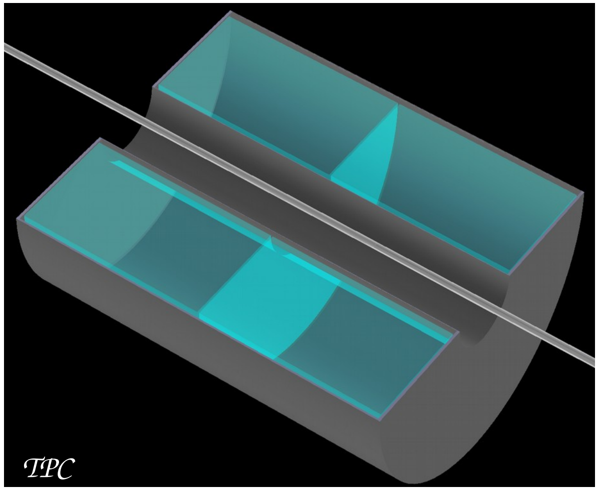


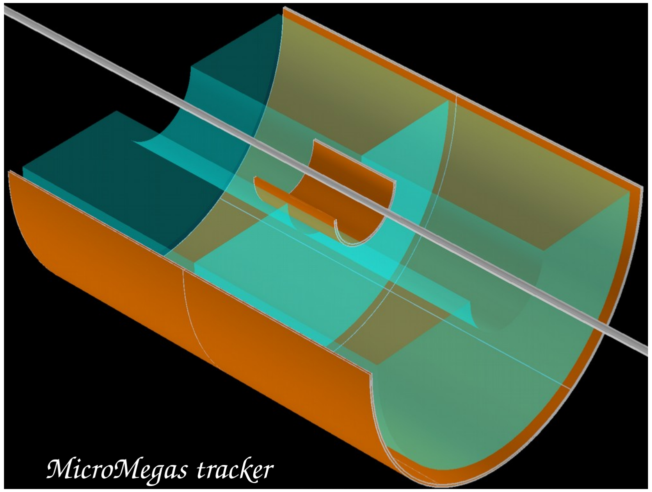
Highly redundant tracker (TPC / endcap GEM disks and MAPS vertex detector)



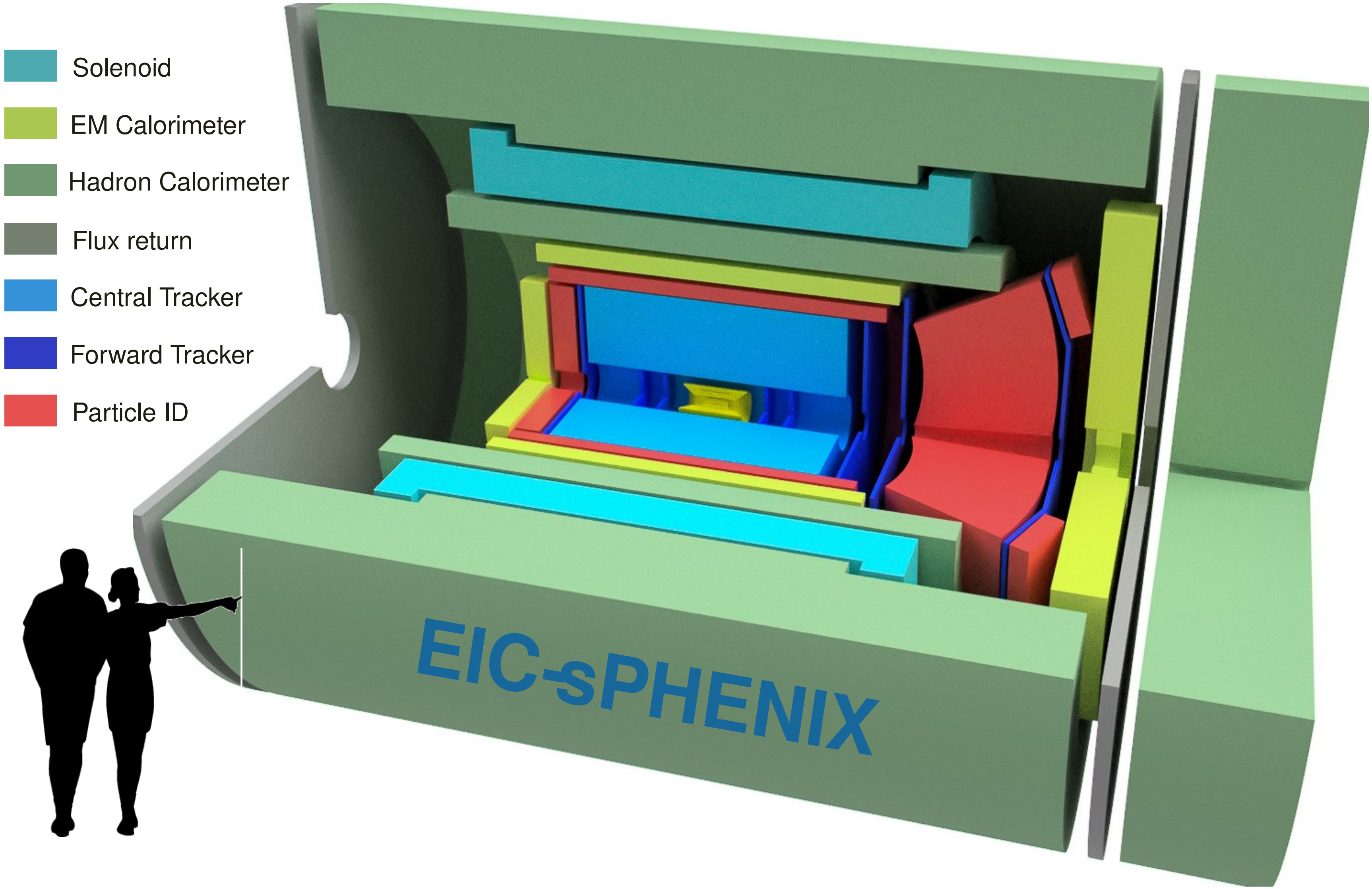
2 barrel layers of MAPS sensors (20X20µm2) with ~0.3% X/X_0 per layer / Similar technology for forward and rear disks



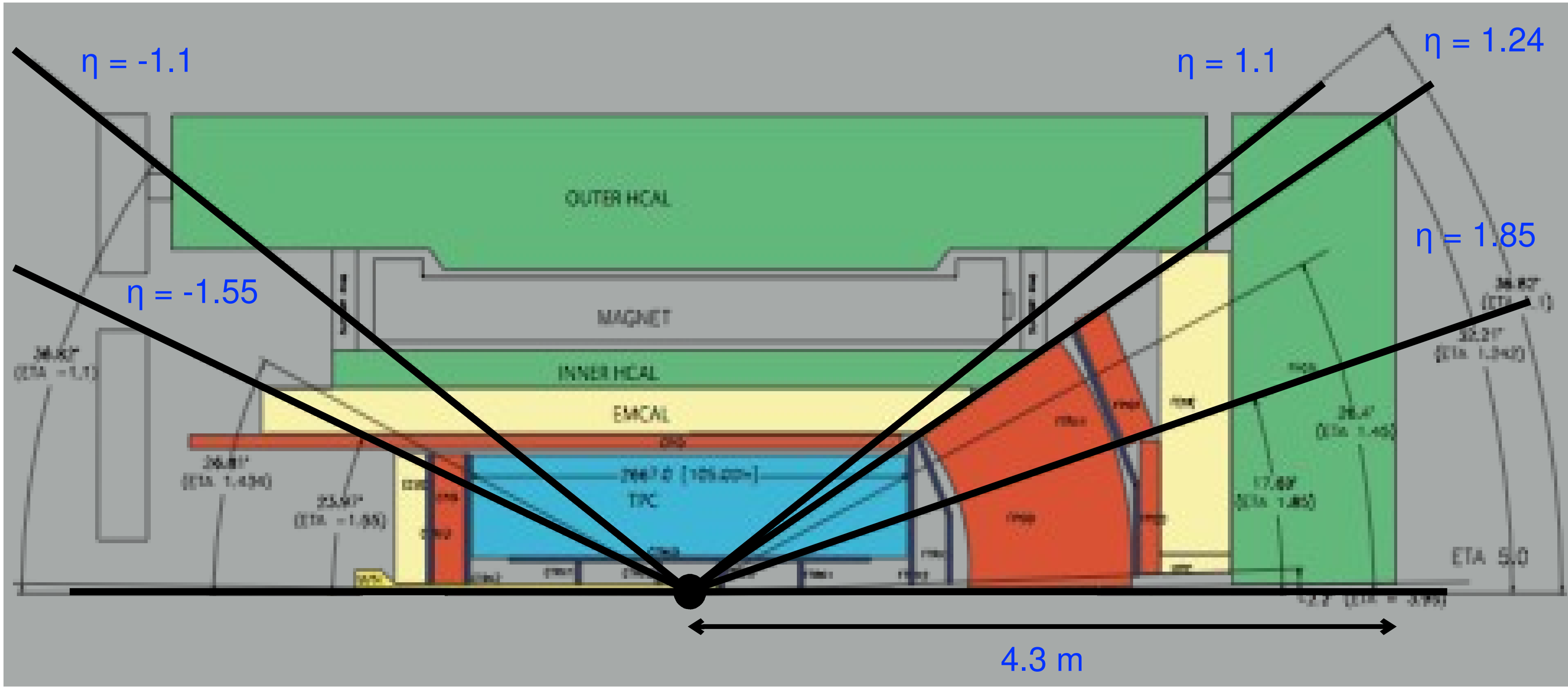




Detector Concepts EIC: sPHENIX

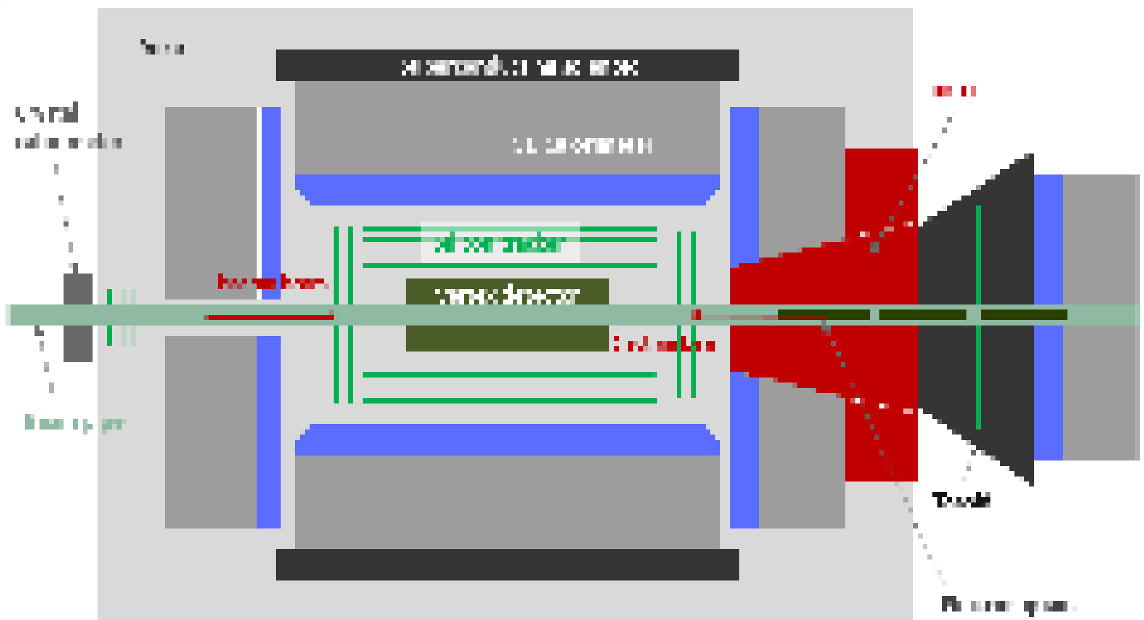


Detector Concepts EIC: sPHENIX



-4 < η < -1.55	$PbWO_4$	2 cm x 2 cm	*2.5% / √E ⊕ 1%*
-1.55 < η < 1.24	W-SciFi	0.025 x 0.025	16% / √E ⊕ 5%
1.24 < η < 3.3	PbScint	5.5 cm x 5.5 cm	8% / √E ⊕ 2%
3.3 < η < 4	$PbWO_4$	2.2 cm x 2.2 cm	12% / √E
-1.1 < η < 1.1	Fe Scint + Steel Scint	0.1 x 0.1	81% / √E ⊕ 12%
-1.24 < η < 5	Fe Scint	10 cm x 10 cm	*70% / √E*

Detector Concepts EIC:TOPSide

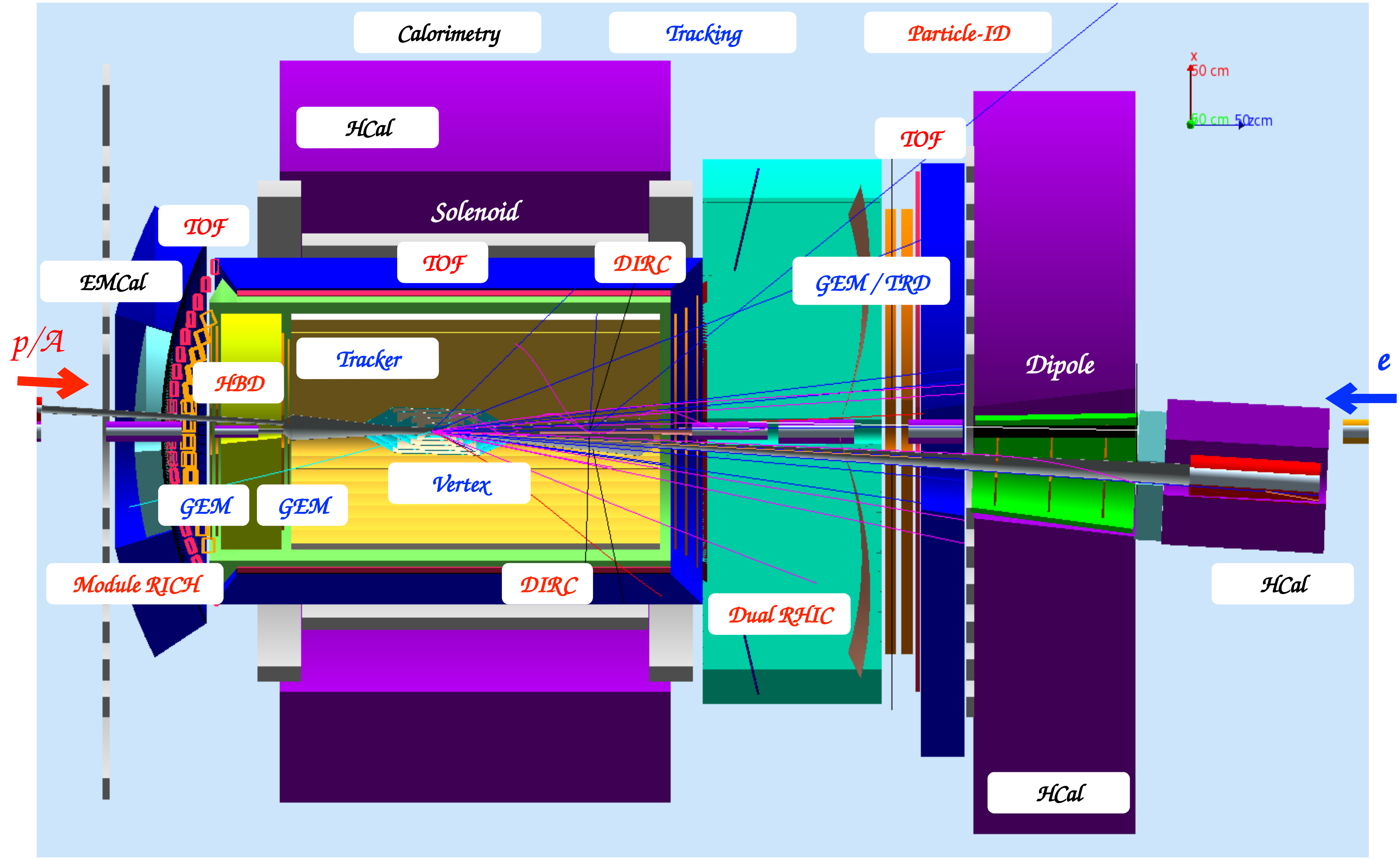


-TOPSiDE: Timing Optimized PID Silicon Detector for the EIC

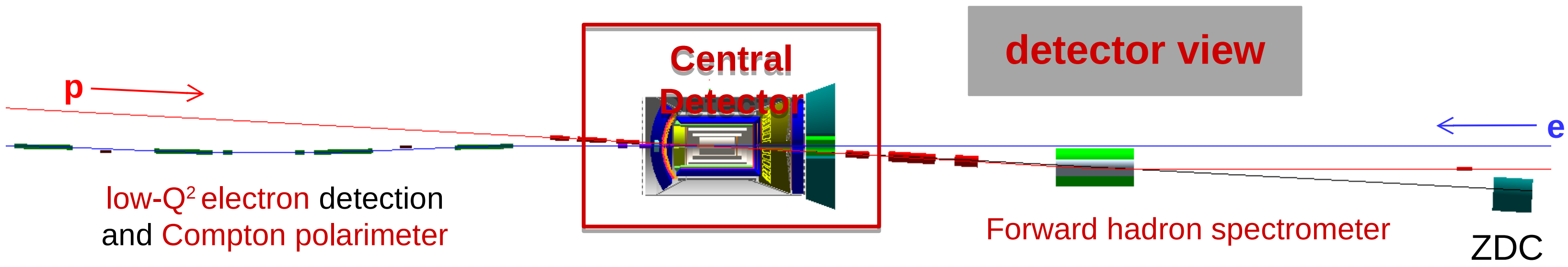
-Features:

- **-Ultra-fast Si detectors** (UFSD TOF) (PID π/K/p separation)
- **-Highly granular imaging calorimeters** and particle flow algorithms (PID of hadrons/neutrals and background rejection)
- **-Full particle-ID over entire central and rear regions** (-5 < η < 3)
- **-Forward detectors (3 < η < 5):** UFSD TOF and RICH PID (π/K/p separation for SIDIS) / Dipole or Toroid for p measurement
- **-Rear detectors (-5 < η < -3):** UFSD TOF for full PID (No RICH needed!) / Crystal calorimeter for optimal energy resolution

Detector Concepts EIC:JLEIC



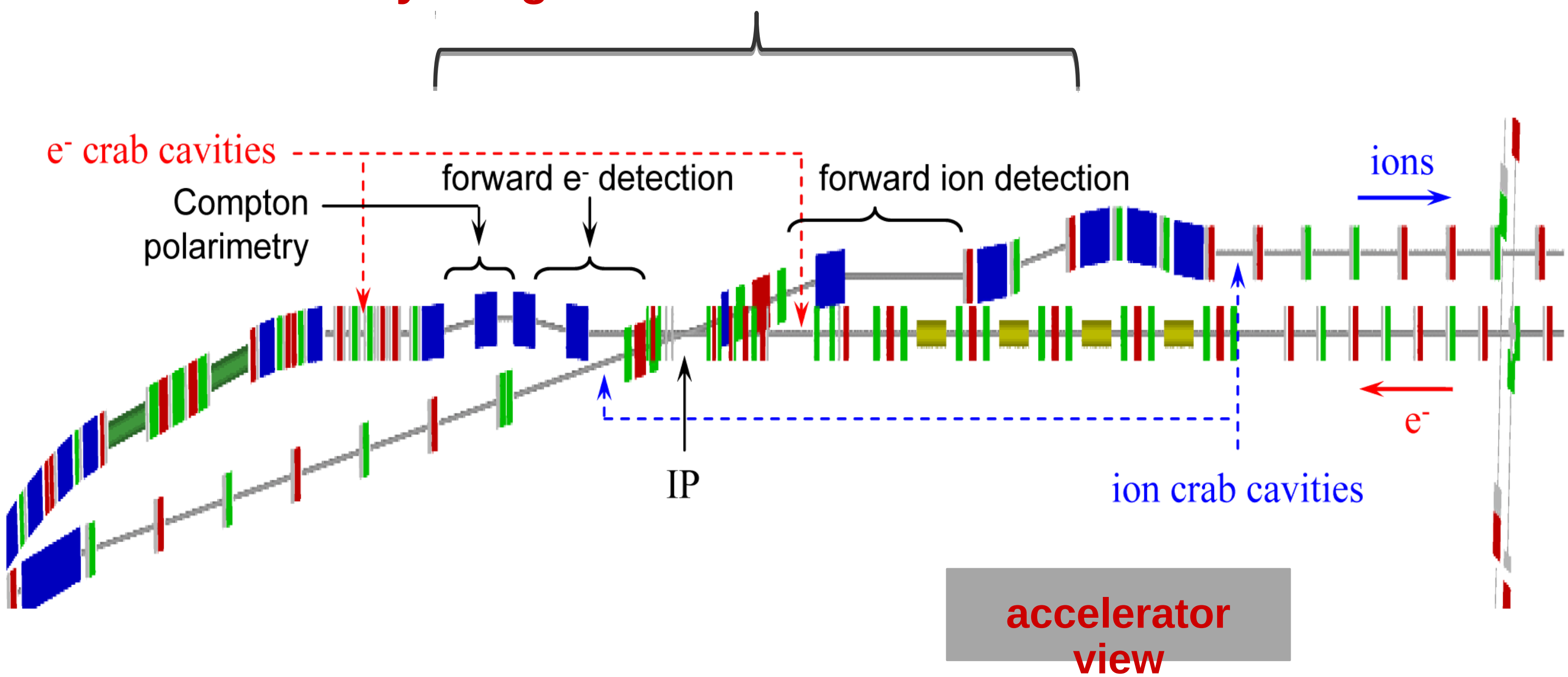
Detector Concepts EIC:JLEIC



Extended detector: 80m

30m for multi-purpose chicane, 10m for central detector, 40m for the forward hadron spectrometer

fully integrated with accelerator lattice



Detector Concepts EIC

arXiv:1212.1701

Auxiliary detector systems: Luminosity (Abs. / Rel.) and Polarimetry

Luminosity (Absolute / Relative)

Bethe-Heitler process ($e+p \rightarrow e+\gamma+p$) successfully used at HERA I/II (QED theory precision ~0.2%) / Systematic uncertainty achieved ~1-2%. For polarized beam-mode, polarization dependence. Systematic uncertainty of e/p polarization and theory uncertainty will limit abs./rel. luminosity - Critical for asymmetry measurements in particular at low x.

Polarimetry: Lepton

Compton back-scattering / HERA used two setups of measuring trans. (TPOL) and long. (LPOL) polarization and achieved for sys. uncertainties 3.5% (TPOL) and 1.6% (LPOL) at HERA I / 1.9% (TPOL) and 2.0% (LPOL) at HERA II. Prospect to improve precision to ~1%.

Polarimetry: Hadron

Extensive experience at RHIC from polarized p program. Two aspects are relevant: Absolute and relative polarization measurement.

Absolute: Elastic scattering of polarized p on polarized hydrogen jet target

Relative: High statistics bunch-by-bunch polarized proton on carbon fiber target

Achieved precision: 3.3% (Run 13 - 255GeV polarized p beam) for single-spin asymmetry

Further improvements from stability control of hydrogen jet target / carbon-fiber target and energy calibration of recoil silicon detectors.