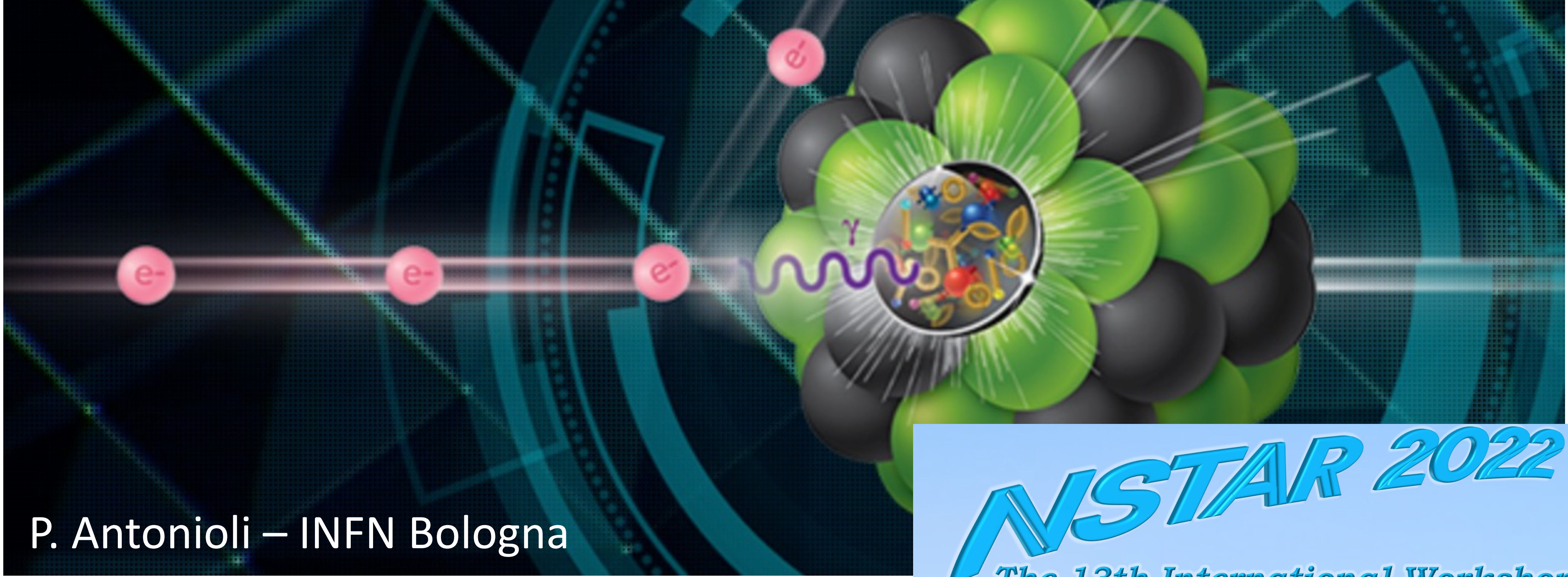
Physics at the Electron Ion Collider



P. Antonioli – INFN Bologna

NSTAR 2022

The 13th International Workshop on the Physics of Excited Nucleons

17-21 October 2022 Santa Margherita Ligure, Italy

Why the Electron Ion Collider?

A new pair of glasses to look into the nucleon

Resolution is a few times smaller than target

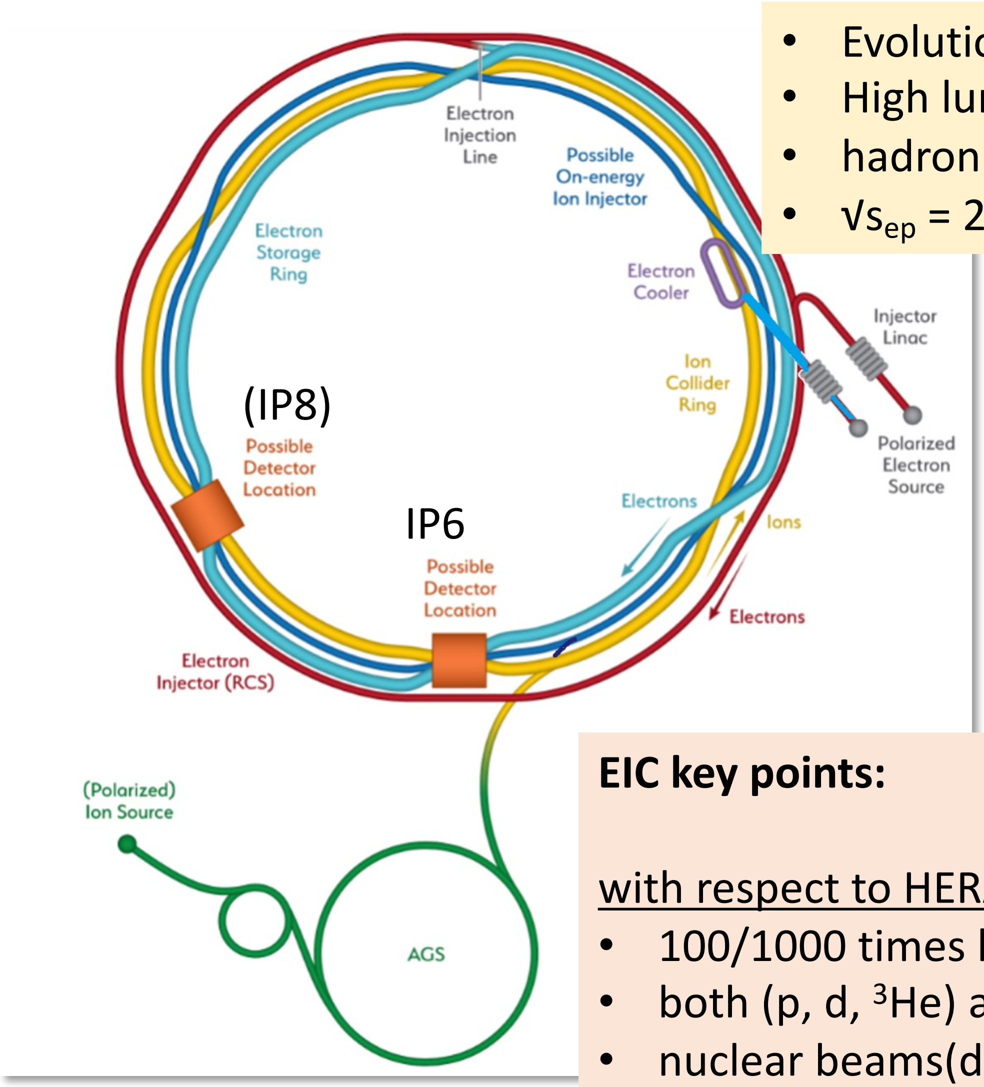
Resolution **10's** of times smaller than target

Resolution **100's** of times smaller than target

Credit: Yulia Furletova

The EIC project in one slide

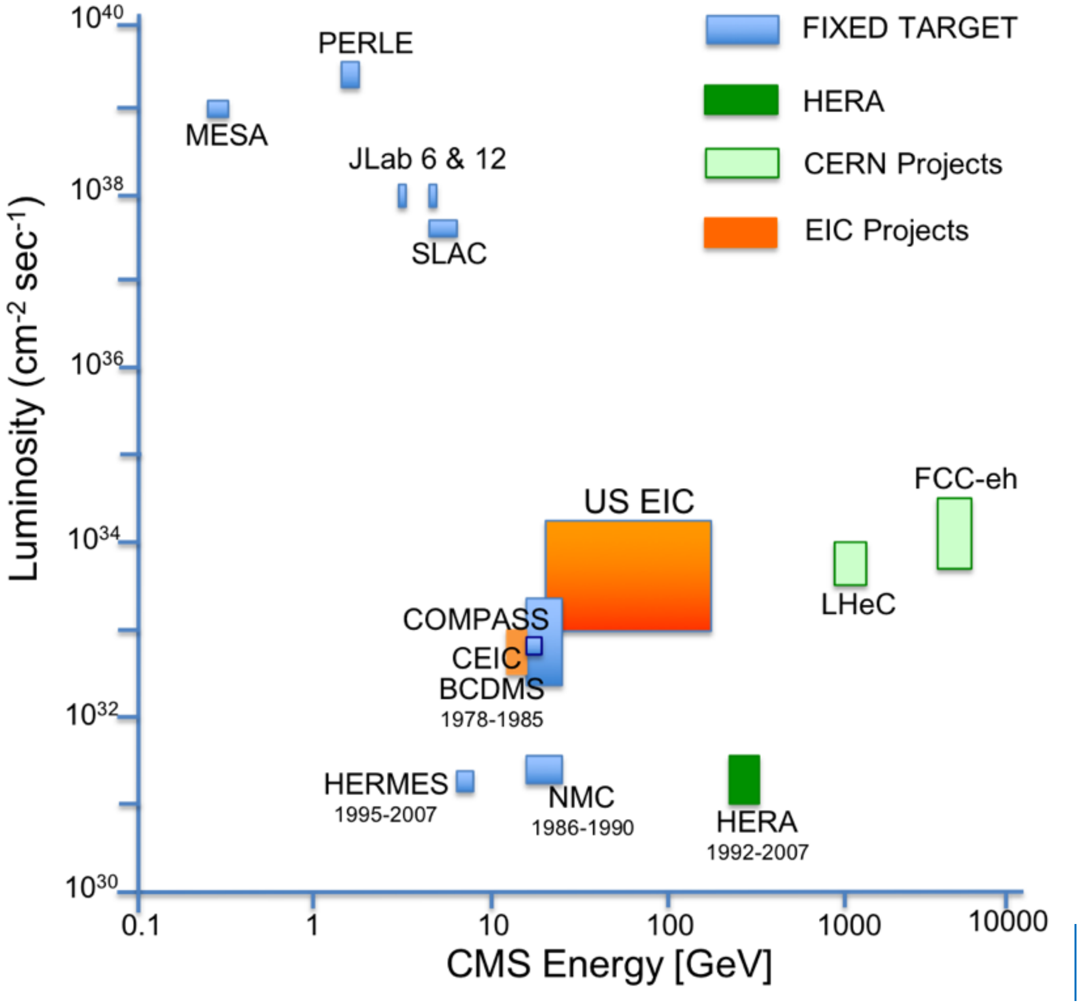
- Evolution of RHIC facility (pp/pA/AA)@BNL → electron ring (E_e = 5-18 GeV)
- High luminosity (10^{33} – 10^{34} $cm^{-2}s^{-1}$), polarized beams
- hadron ring (E_p = 40 – 275 GeV)
- $\sqrt{s_{ep}}$ = 28 – 140 GeV



EIC key points:

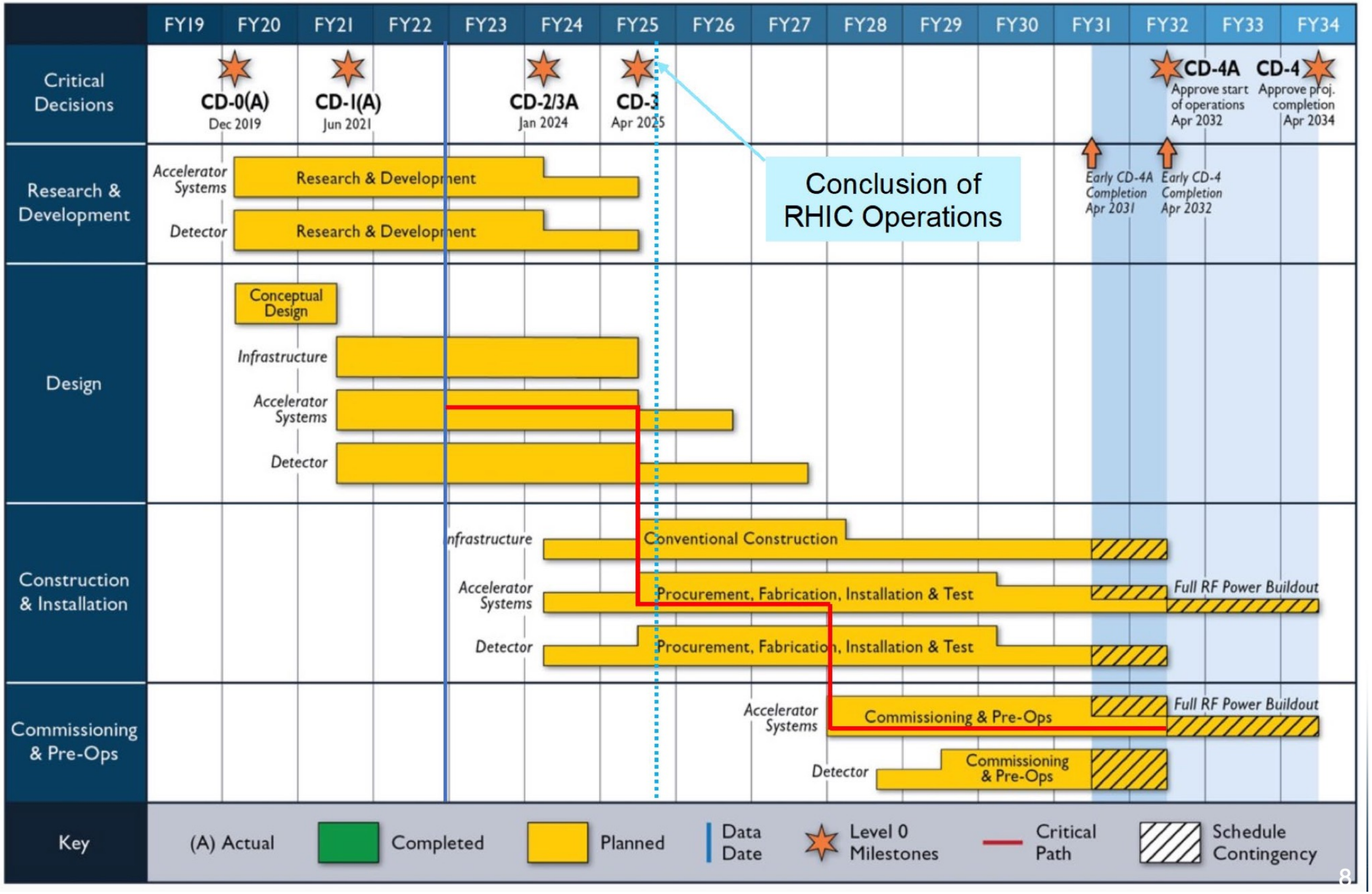
with respect to HERA:
- 100/1000 times higher lumi
- both (p, d, ^{3}He) and e polarized
- nuclear beams(d → U)

with respect to fixed target facility
- two decades growth in kinematic space



2.25 B$ project

The EIC status/timeline in one slide



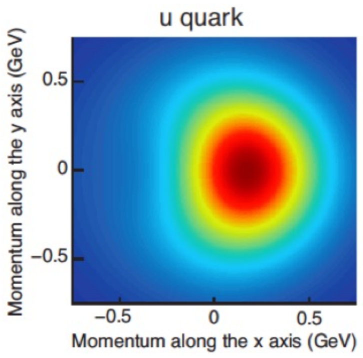
start of operations in **2031**
full-fledged accelerator in **2034**

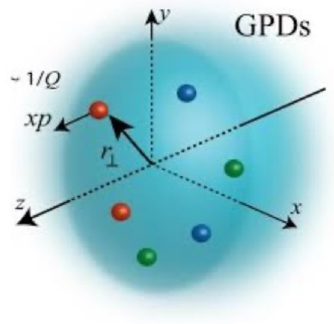
pre-TDR by October 2023
TDR by end of 2024

recent approval of Inflation Reduction Act by US Congress brings decisive (>100 M$) funds to ensure CD-2/3A

EIC physics: the big picture

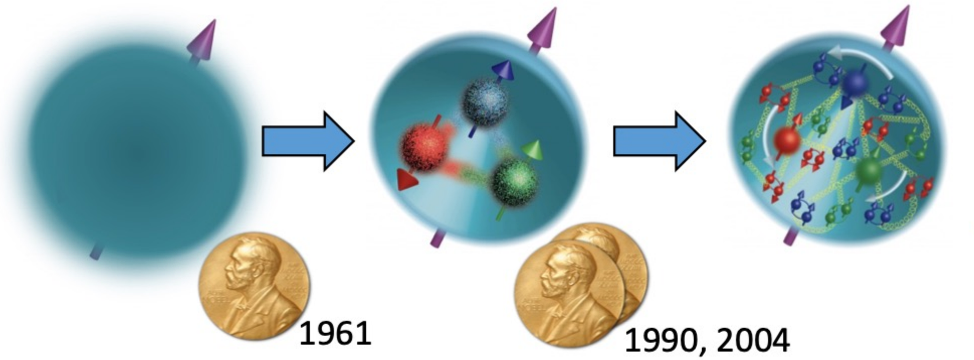
Multidimensional imaging of the structure of the proton; Origin of Mass, Spin, …





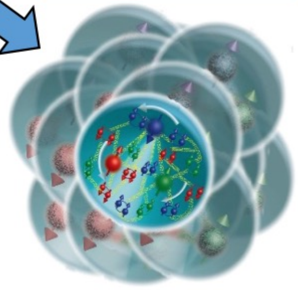
The Proton

Early 1900s | 1970s | 2000s



2012 2015 2017 2020

The Proton in a nucleus



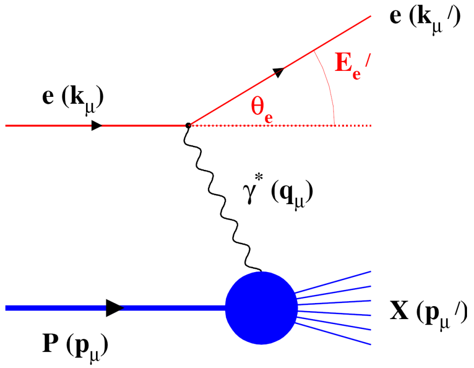
QCD dynamics that can affect the identity of nucleons in a nucleus

(credit: O. Hen)

EIC physics in one slide

Parton Distributions in nucleons and nuclei

QCD at high parton density Saturation



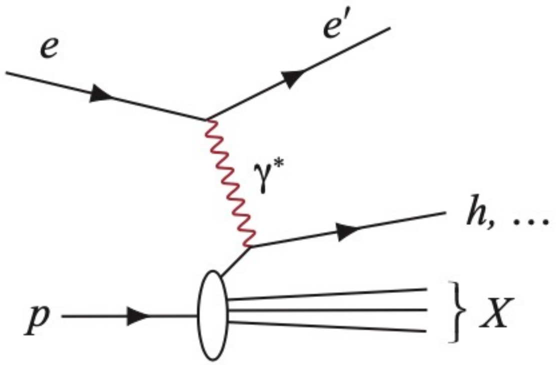
inclusive DIS

e-measurement!
→ e/h PID
→ EM calorimetry

∫Ldt: 1 fb^{-1}

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.



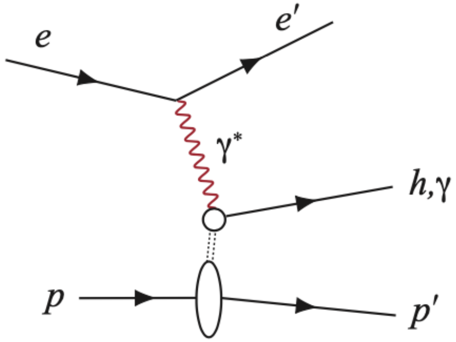
semi-inclusive DIS (SIDIS)

eletrons and hadrons
→ hadron PID

10 fb^{-1}

QCD at high parton density Saturation

Tomography: Spatial Imaging

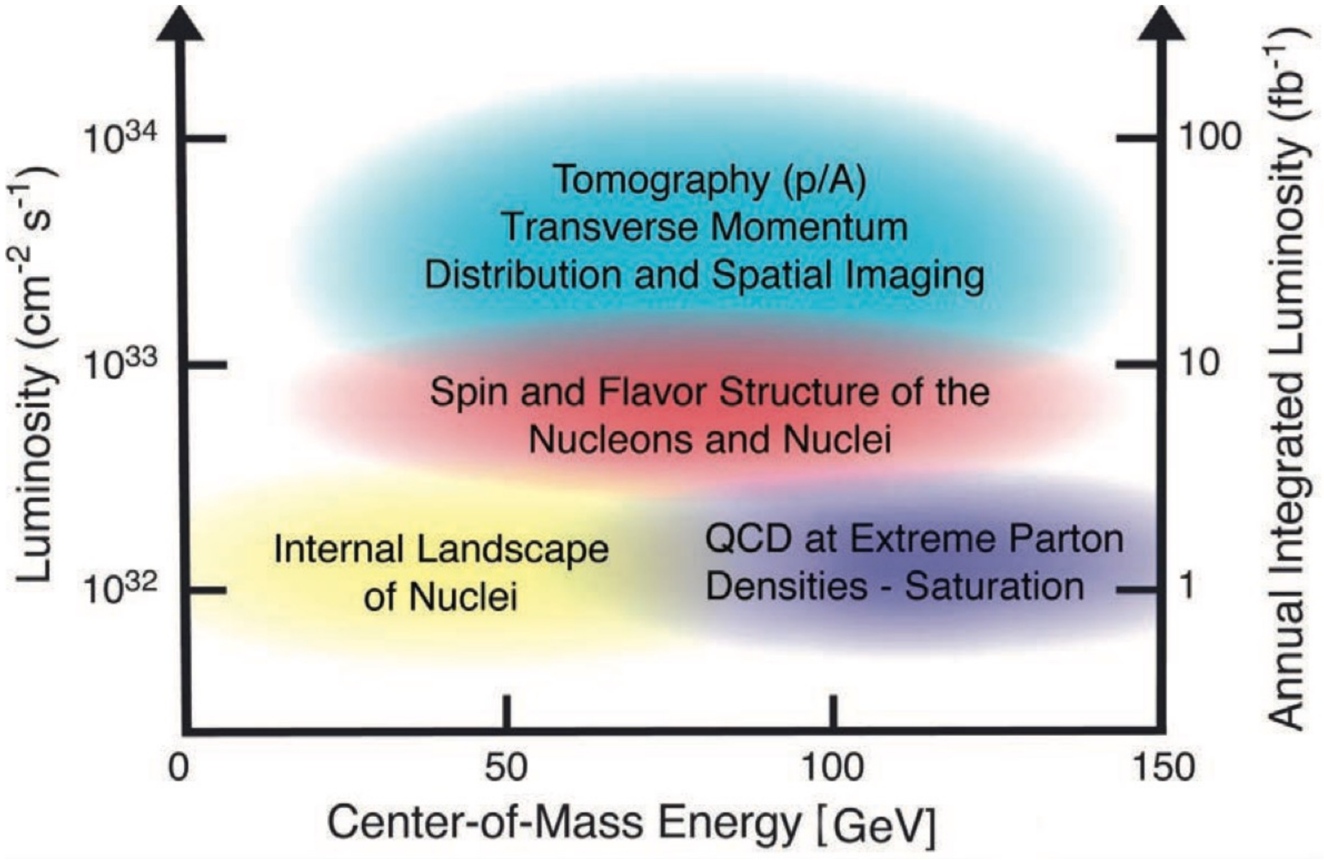


exclusive processes
get all particles
→ hermeticity
→ IR design + forward region

10 - 100 fb^{-1}

EIC extra-bonus: DIS in nuclei
- nPDF modifications
- gluon saturation g(A-dependent) [jets]
- hadronization in CNM

EIC science and required luminosity



In the following:

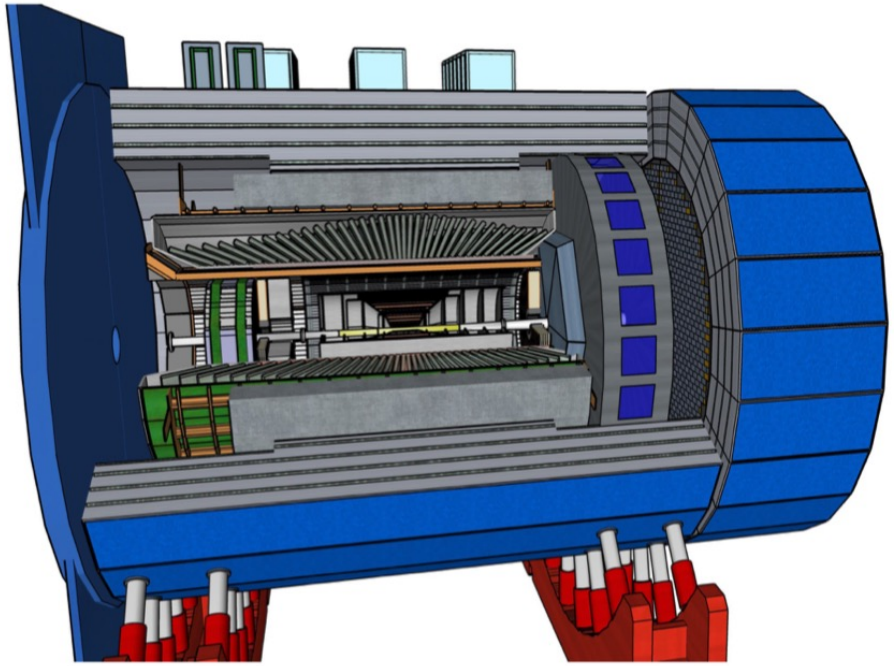
- just some highlights of this rich program
- a little bit more on heavy-flavours / hadronization and hadron spectroscopy

The EIC detector status

Yellow Report process 2020/2021 (detector requirements to deliver EIC physics) → released March 2021
Call for detector proposals issued March 2021 → deadline 1/12/2021

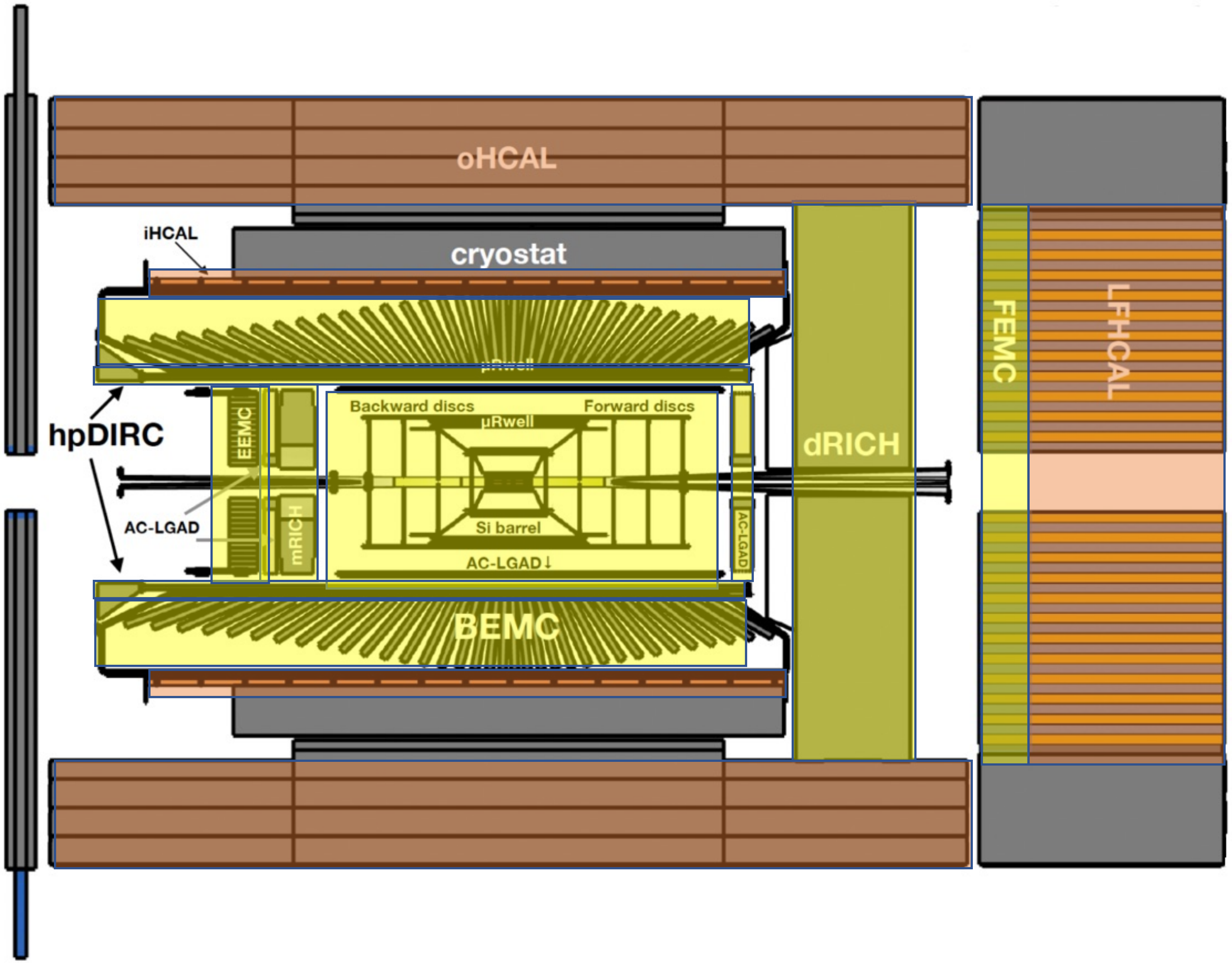
- ECCE was general purpose detector for IP6 re-using 1.4 T Babar magnet (bore diameter 2.8)
- ATHENA was general purpose (full EIC science) for IP6 with new 3T solenoidal magnet (and larger bore diameter – 3.2 m)
- CORE was a more "compact" proposal, potentially for IP8 (3T solenoid as well)

ECCE selected as reference design (March 2022) → Community working over one general purpose detector for IP6: **ePIC**



key differences on design: bore diameter and magnet

ePIC Detector Design (Current)



Tracking:

- **New 1.7T solenoi**d
- Si MAPS (65nm) Tracker
- MPGDs (µRWELL/µMegas)

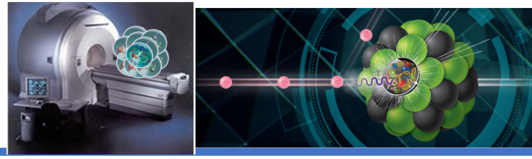
PID:

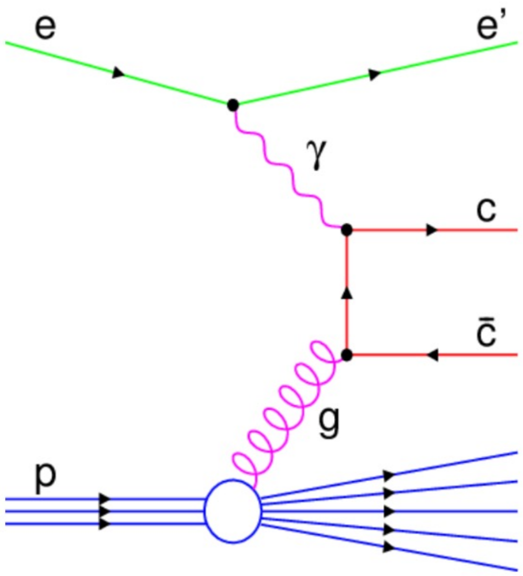
- hp-DIRC
- mRICH/pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

Calorimetry:

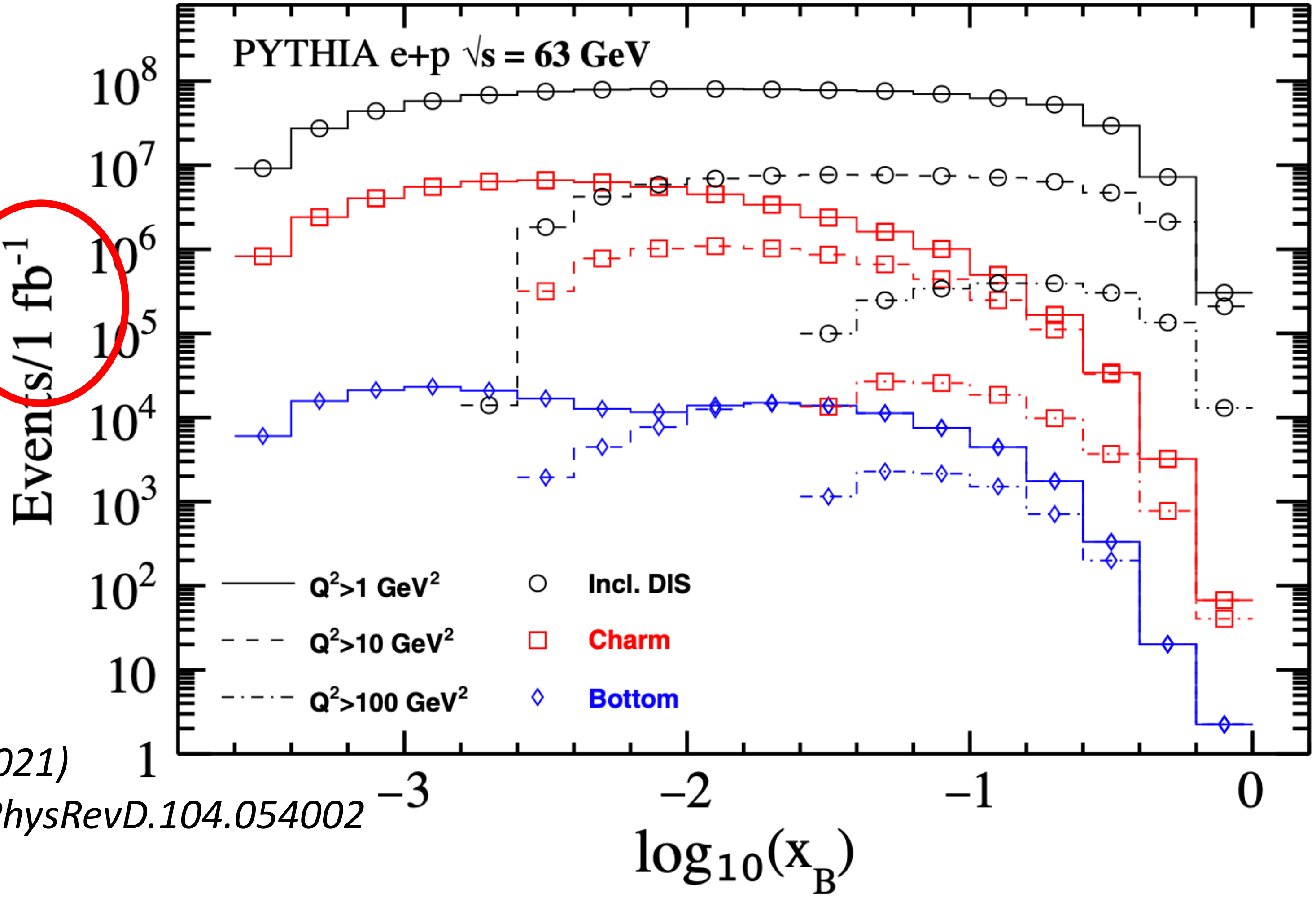
- SciGlass/Imaging Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)

Heavy flavours @ EIC as CT scanners





Heavy quark production in DIS: leading order contribution from photon gluon fusion process → a scanner for gluon distributions

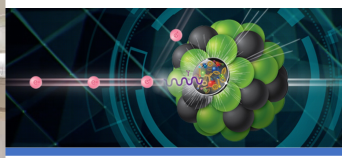


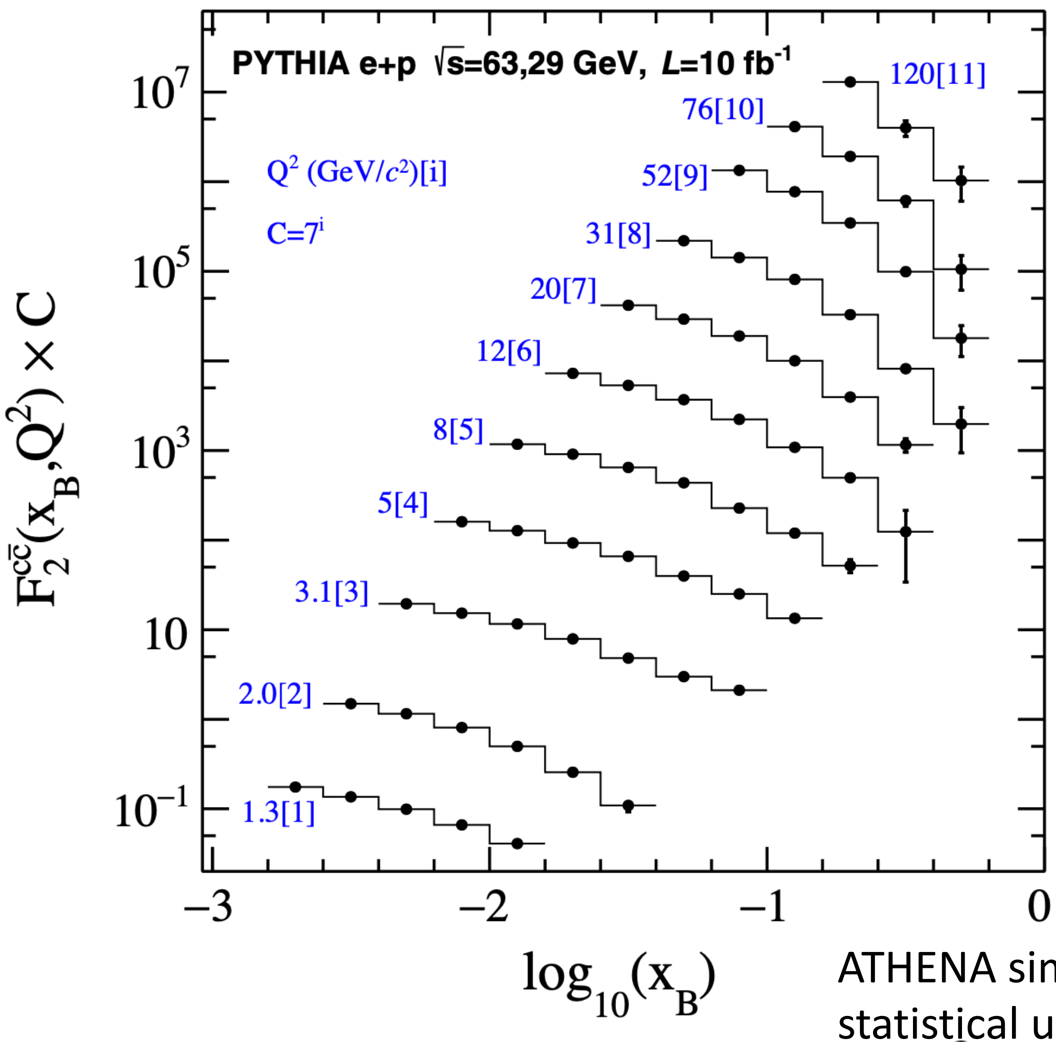
@EIC rich c/b production over x

M. Kelsey et al. Phys. Rev. D 104, 054002 (2021)

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.104.054002

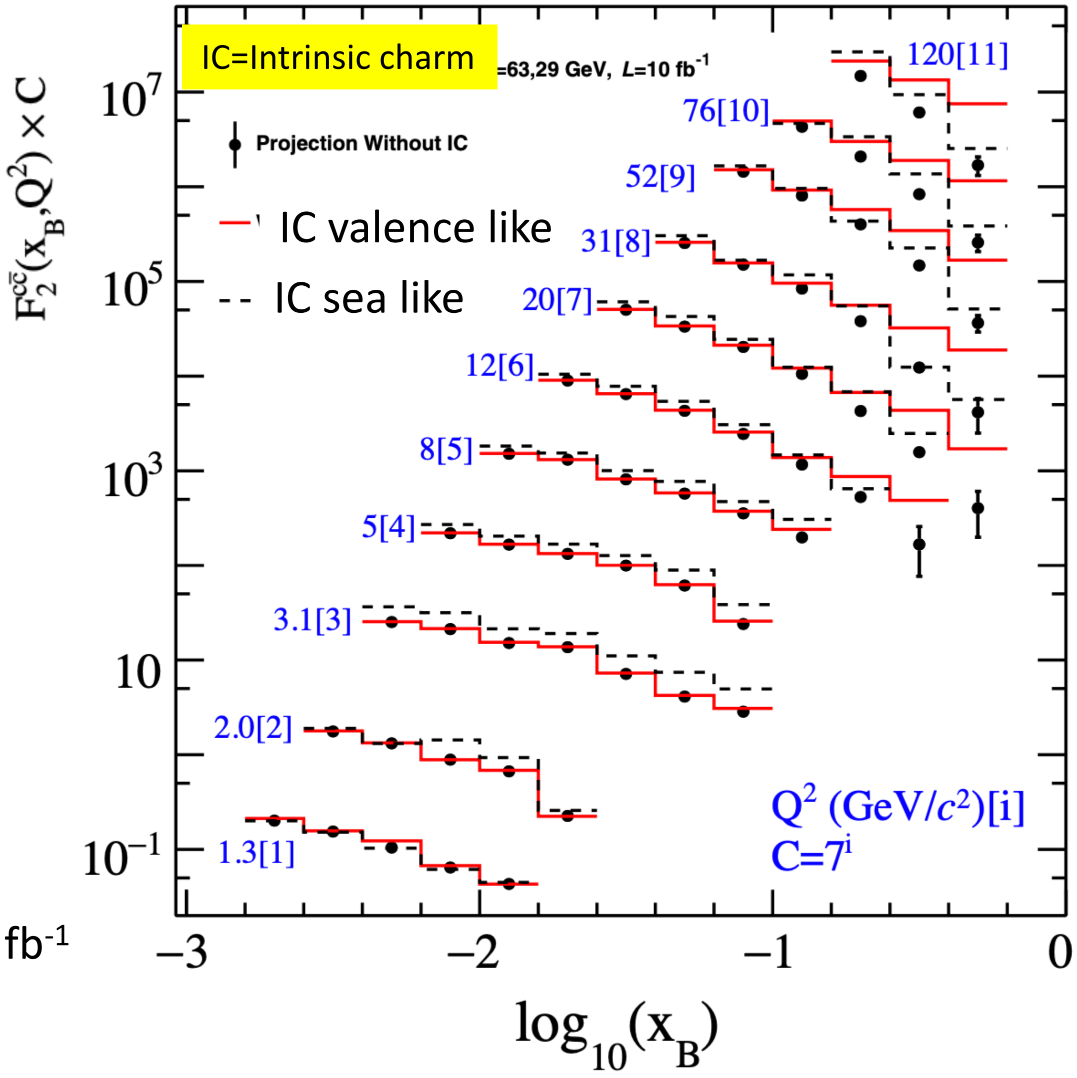
Heavy flavours @ EIC as CT scanners





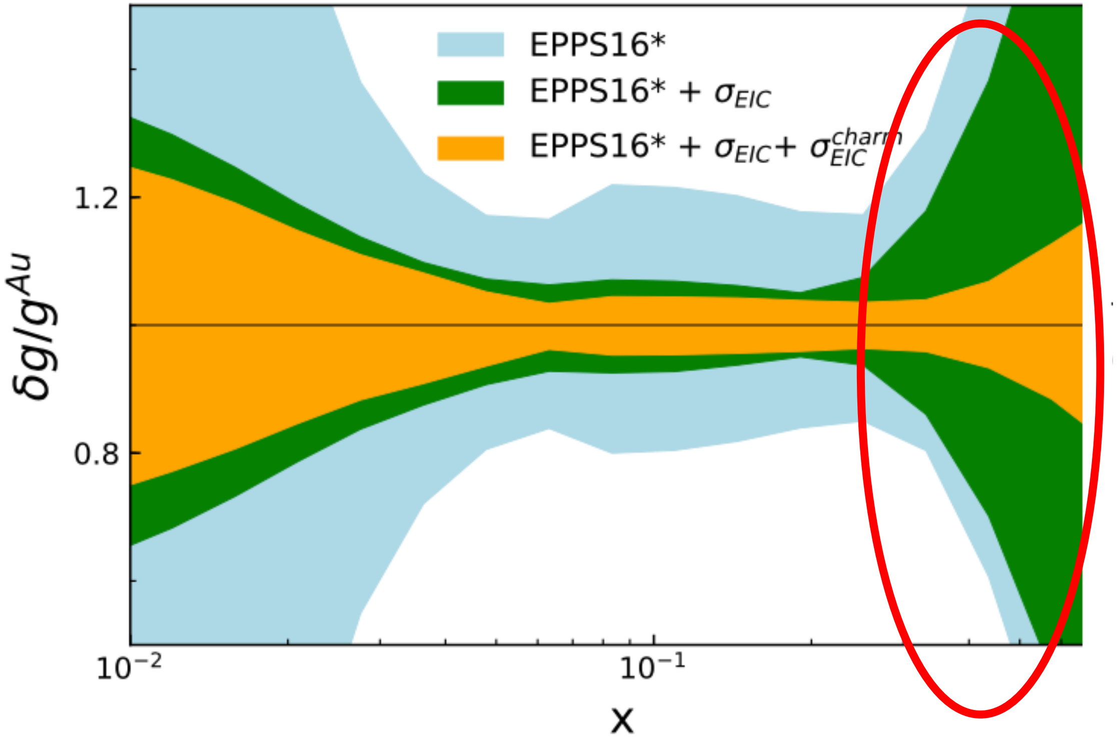
ATHENA simulation
statistical uncertainties at 10 fb-1

M. Kelsey et al. Phys. Rev. D 104, 054002 (2021)



$$\sigma_r^{c\bar{c}}(x_B, Q^2) = F_2^{c\bar{c}}(x_B, Q^2) - \frac{y^2}{Y^+} F_L^{c\bar{c}}(x_B, Q^2)$$

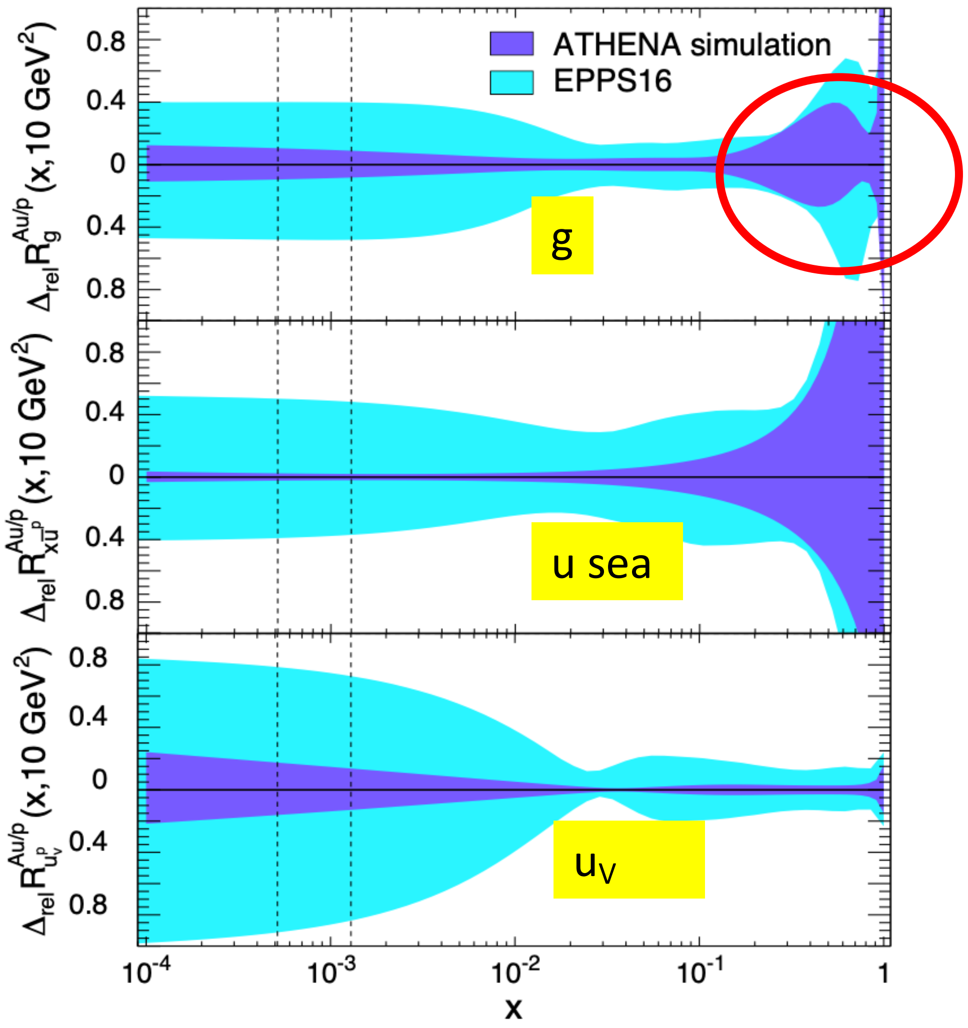
HF as CT scanners → nPDF



EIC Yellow Report (https://arxiv.org/abs/2103.05419)

Big uncertainty about for x > 0.1

Photon-gluon fusion probes gluon PDF for $x > ax_B$ with $a = 1 + 4m_h^2/Q^2$



Test of intrinsic HF components in the nPDF:
A. Accardi, et al., Eur. Phys. J. C 76 (8) (2016) 471

D meson tagging key. Charm reconstruction increased adding PID capabiities

Heavy flavours @ EIC as CT scanners

Courtesy: S. Fazio

Multi-dimensional imaging of the nucleon: a modern formalism
Lorce´ C., Pasquini B. and Vanderhaeghen M., JHEP, 1105 (2011) 041.
http://dx.doi.org/10.1007/JHEP05(2011)041

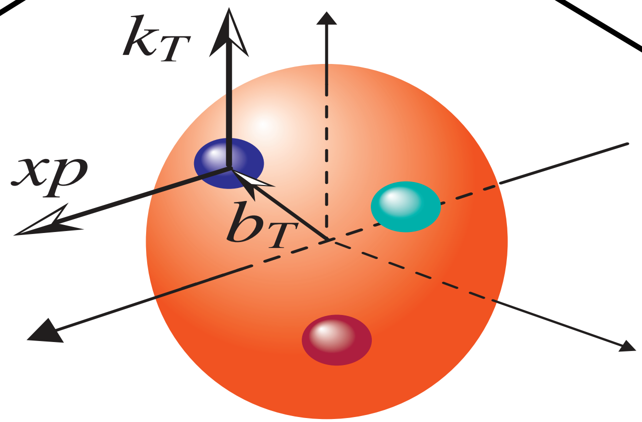
Wigner functions

$W(x,b_T,k_T)$

Momentum space

$\int d^2b_T$

$f(x,k_T)$



$\int d^2k_T$

$f(x,b_T)$

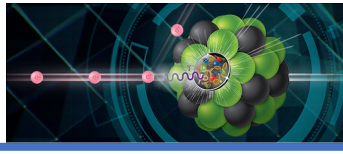
Coordinate space

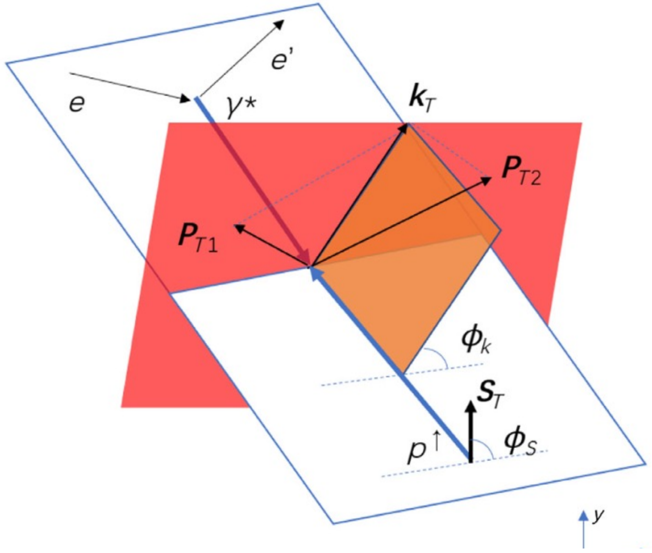
Spin-dependent 3D **momentum space** images from **semi-inclusive scattering**
→ **TMDs**

Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from **exclusive scattering**
→ **GPDs**

A.V. Belitsky et al. Phys.Rev.D69 (2004) 074014

Access to gluon Sivers function: TMD





- access to Sivers TMD (D. W. Sivers, Phys. Rev. D 41, 83 (1990))
- access to gluon Sivers TMD via di-hadron and di-jet
- The Sivers function $f^{\perp}_{1T}$ encapsulates the correlations between a parton's transverse momentum inside the proton and the spin of the proton
- GSF (Gluon Sivers functions) poorly known (U. D'Alesio et al, JHEP 119 (2015))

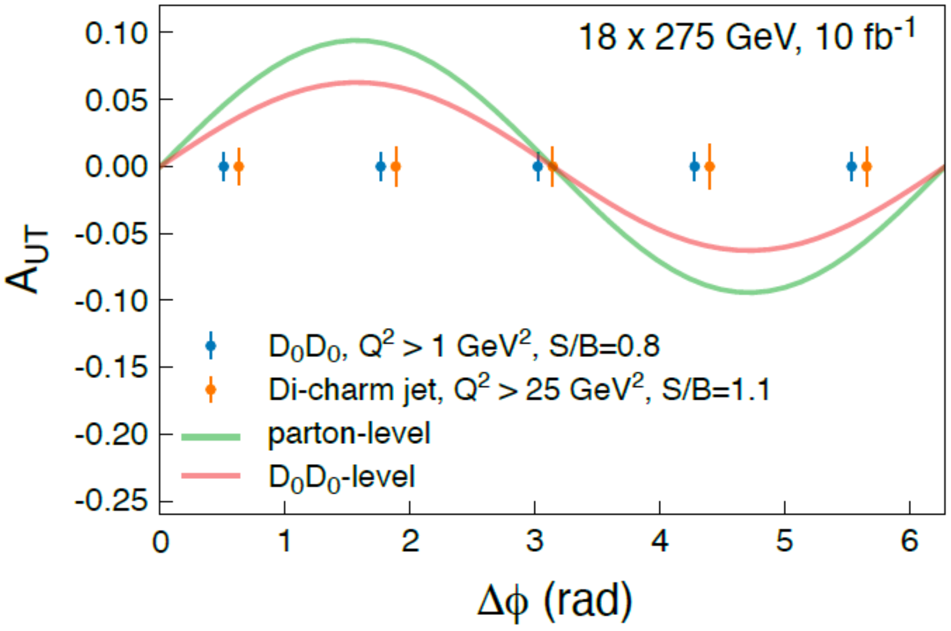
SSA: Single Spin Asymmetry

$$A_{UT}(\phi_{kS}, k_T) = \frac{d\sigma^\uparrow(\phi_{kS}, k_T) - d\sigma^\downarrow(\phi_{kS}, k_T)}{d\sigma^\uparrow(\phi_{kS}, k_T) + d\sigma^\downarrow(\phi_{kS}, k_T)}$$

$$\propto \frac{\Delta^N f_{g/p^\uparrow}(x, k_\perp)}{2 f_{g/p}(x, k_\perp)},$$

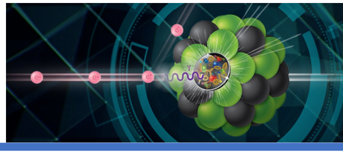
$$\Delta^N f_{a/p^\uparrow}(x, k_\perp) = -\frac{2k_\perp}{M_p} f_{1T}^{\perp a}(x, k_\perp)$$

L. Zheng et al., Phys. Rev. D98 (2018) 034011

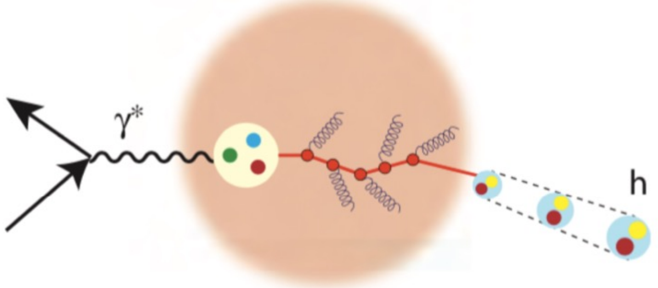


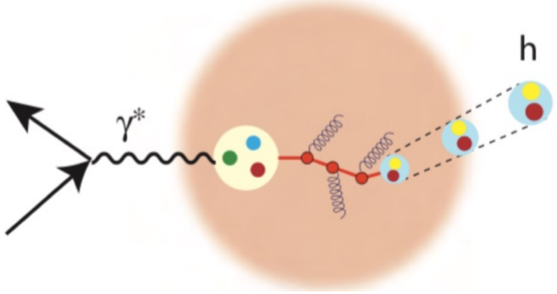
Sensitivity for SSA in di-charm
ATHENA simulation

Heavy flavours @ EIC as travelers



EIC White Paper
https://arxiv.org/abs/1212.1701





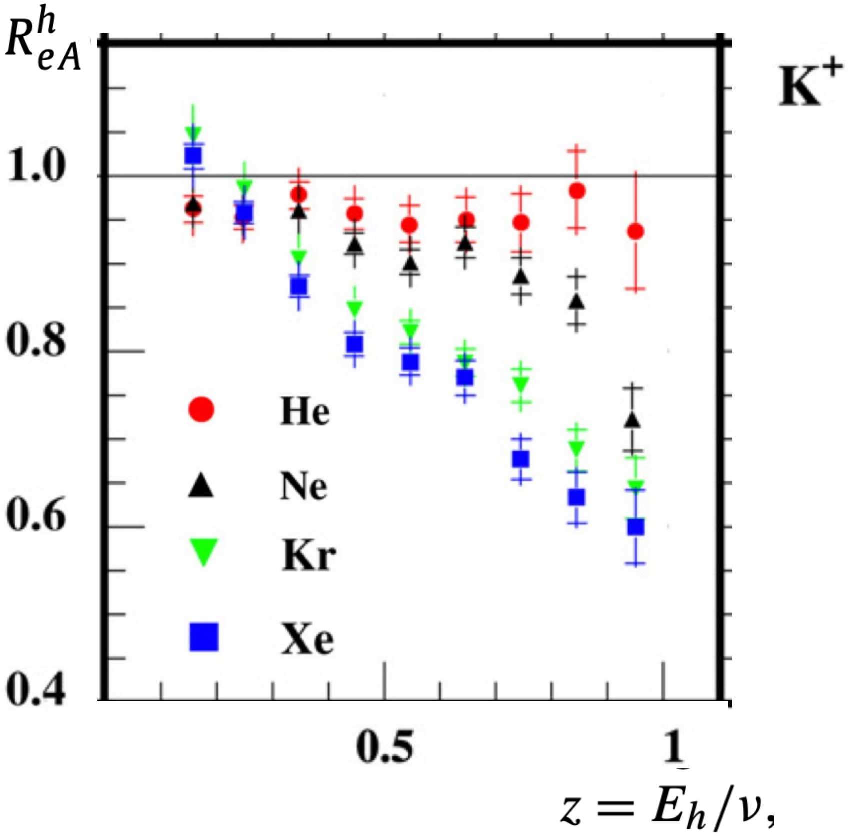
Basic idea: use Q^2 and $\nu = q{\cdot}p/M$ to control **where** hadronization happens

- effect foreseen for D^0/π (based on different FF) might be there also for HF baryons
- usually pre-hadron and absorption in CNM discussed for mesons (Kopeliovich et al., Nucl.Phys. A740 (2004) 211-245)
- role of **di-quark** for baryon hadronization (Adamov et al., Phys.Rev. D64 (2001) 014021

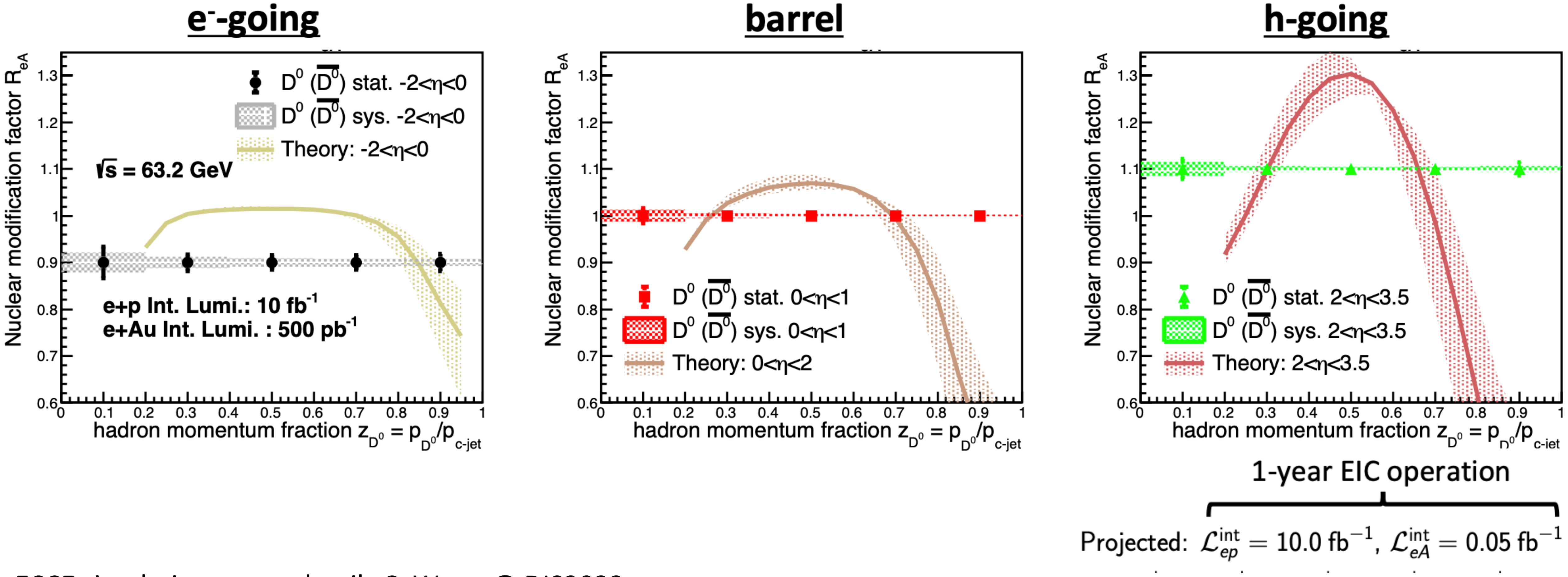
HERMES results
Nuclear Physics B 780 (2007) 1

Results for <u>light hadrons only</u> at <u>much lower energy</u> (fixed target e beam 27.6 GeV)

$$R^{\pi}_{eA}(\nu, Q^2, z) = \frac{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_A}{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_D}$$



Heavy flavours @ EIC as travelers



ECCE simulation: more details C. Wong @ DIS2022

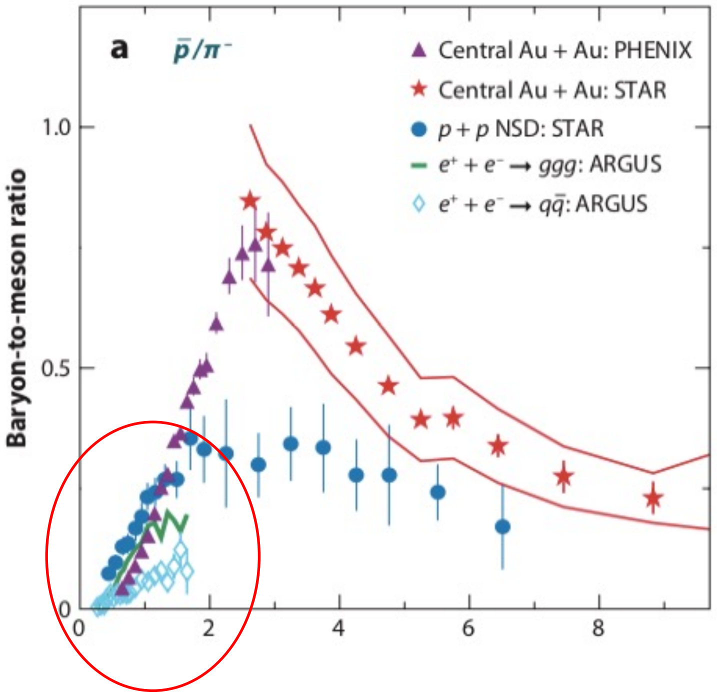
Theory curves from: Li H, Liu Z and I. Vitev, PLB 816 (2021) 136261

Simulation: PYTHIA8 + EPS09 for e+A re-weight

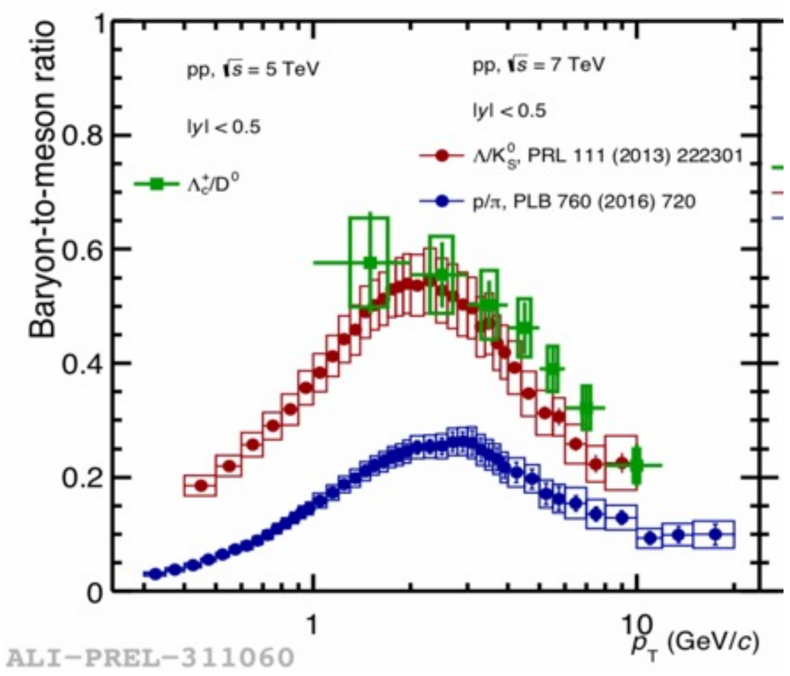
Nuclear modification factor studied in HF-tagged jet

Baryon-meson ratio (at LHC and in e^+e^- / ep)

R. Fries et al. Ann.Rev.Nucl.Part.Sci 58 (2008) 177



ALICE



- in e^+e^- (ep) data limited to p_T <2 (2.5) GeV/c
- in vacuum, fragmentation function (Albino et al., NPB 803 (2008)) predicts < 0.25 for baryon-to-meson ratio

Baryon-meson ratio (at LHC and in e^+e^- / ep)

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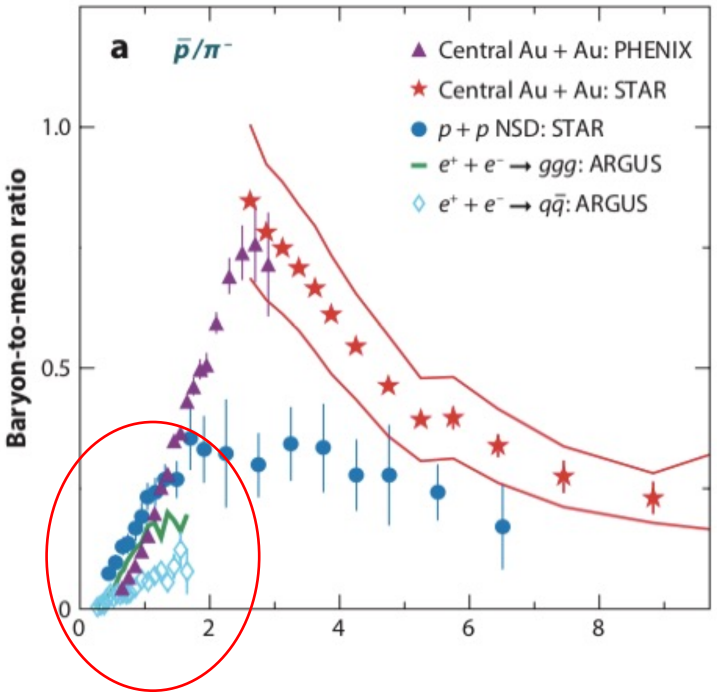

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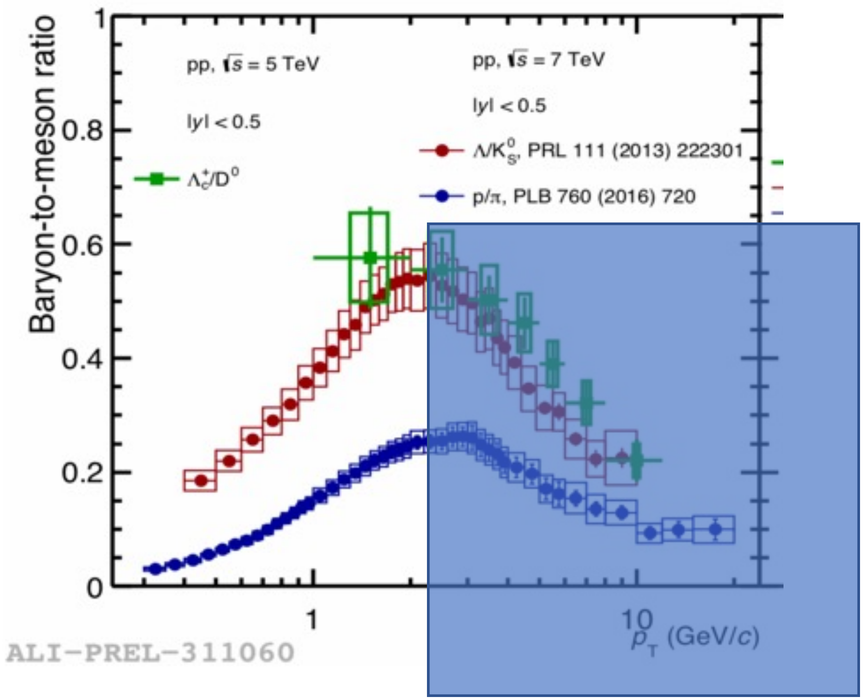
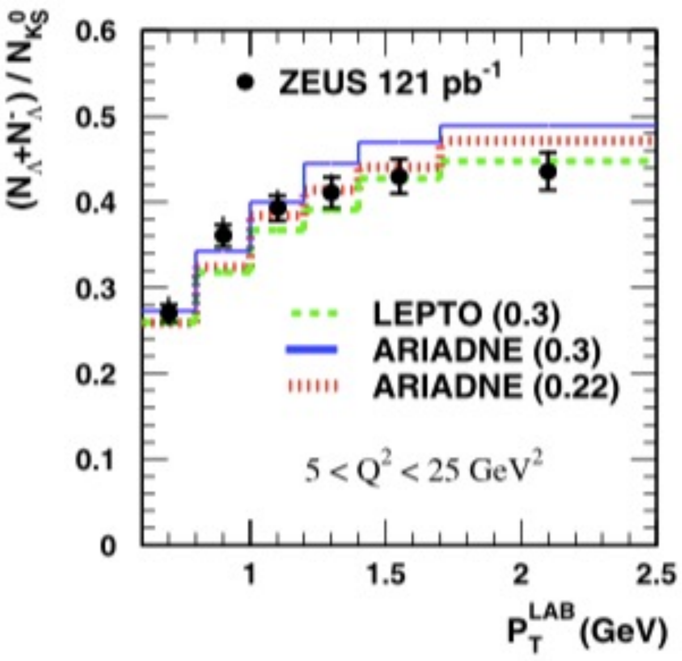
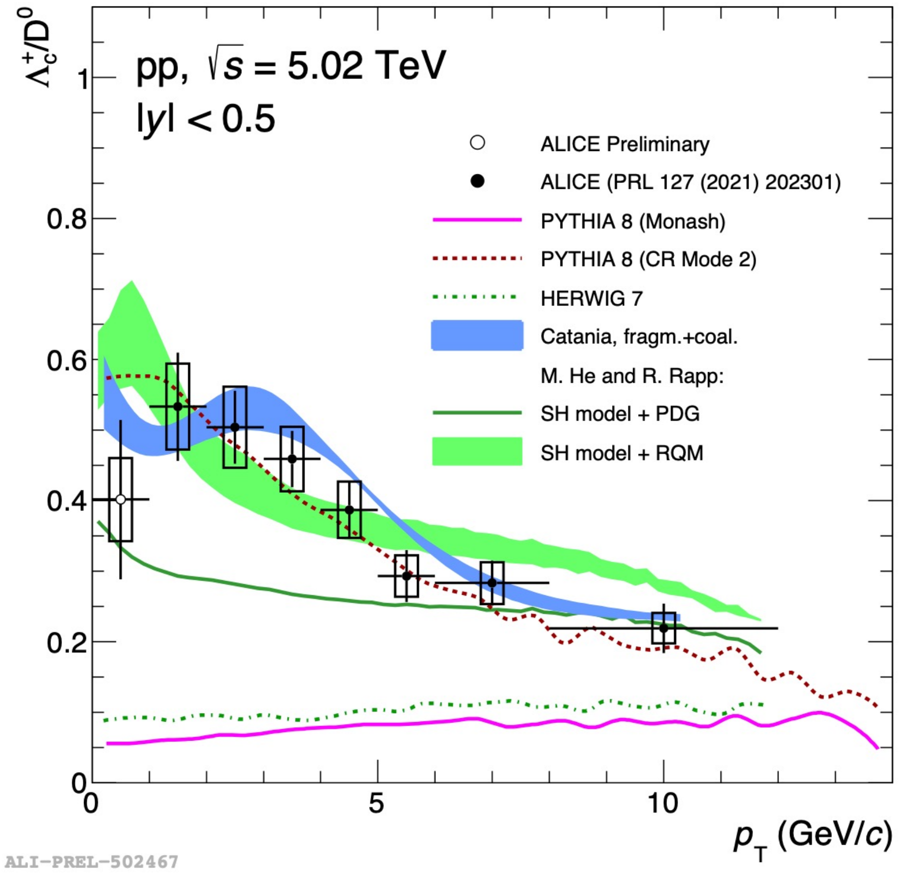


ZEUS, Eur. Phys. J. C 51, 1–23 (2007)



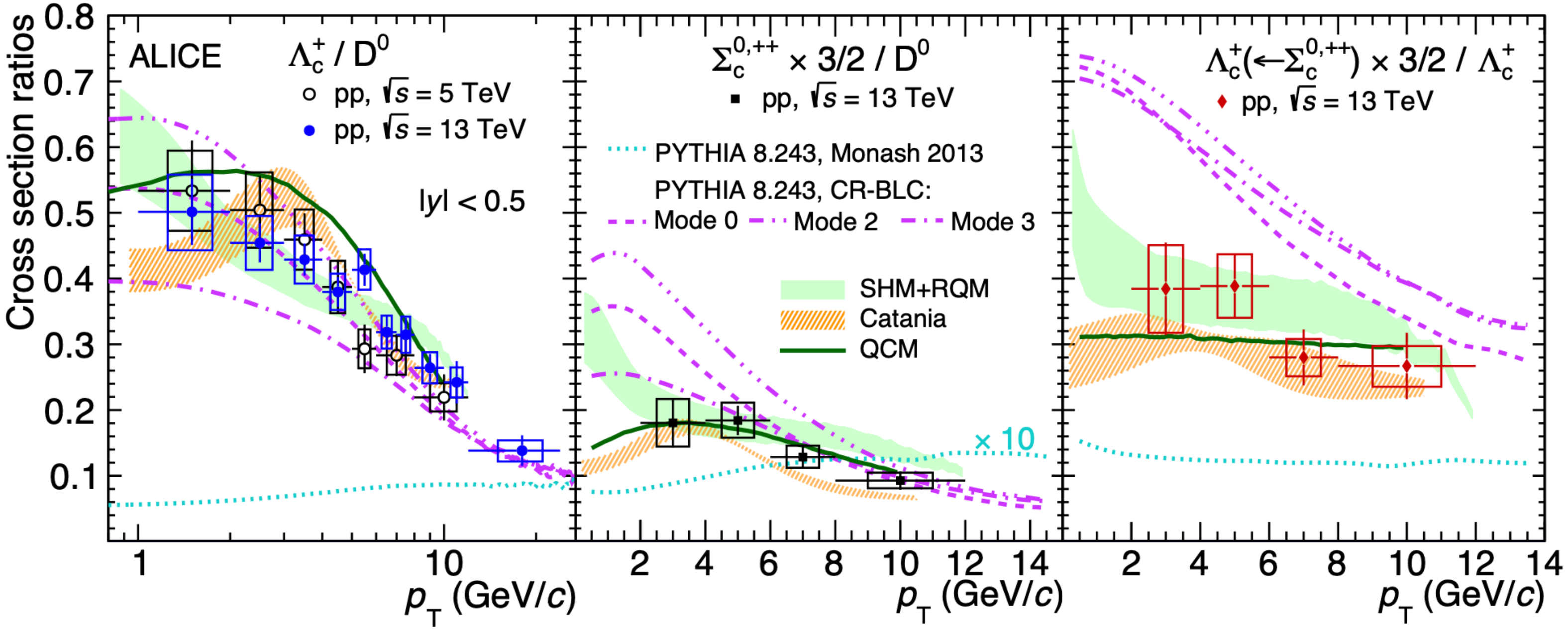
- in e^+e^- (ep) data limited to p_T <2 (2.5) GeV/c
- in vacuum, fragmentation function (Albino et al., NPB 803 (2008)) predicts < 0.25 for baryon-to-meson ratio
- larger values seen already at HERA in strange sector

Baryon-meson ratio (LHC) and RQM



one of LHC surpises is heavy baryon production at low p_T
https://arxiv.org/pdf/2207.07590.pdf

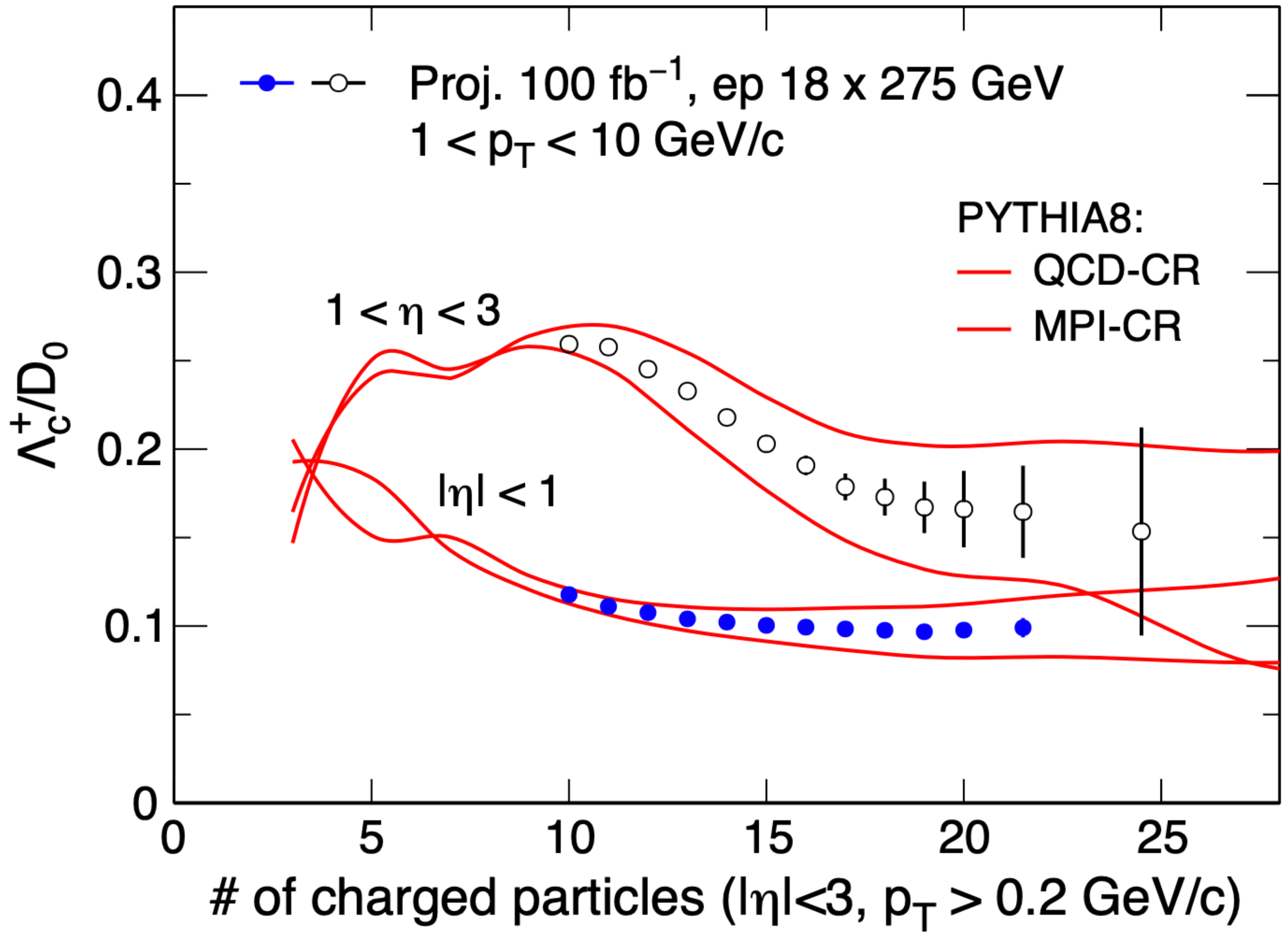
Are we seeing feed-down from "missing baryons" states predicted by Relativistic Quark Model ?



30% of Λ_c @LHC are coming from Σ_c indeed

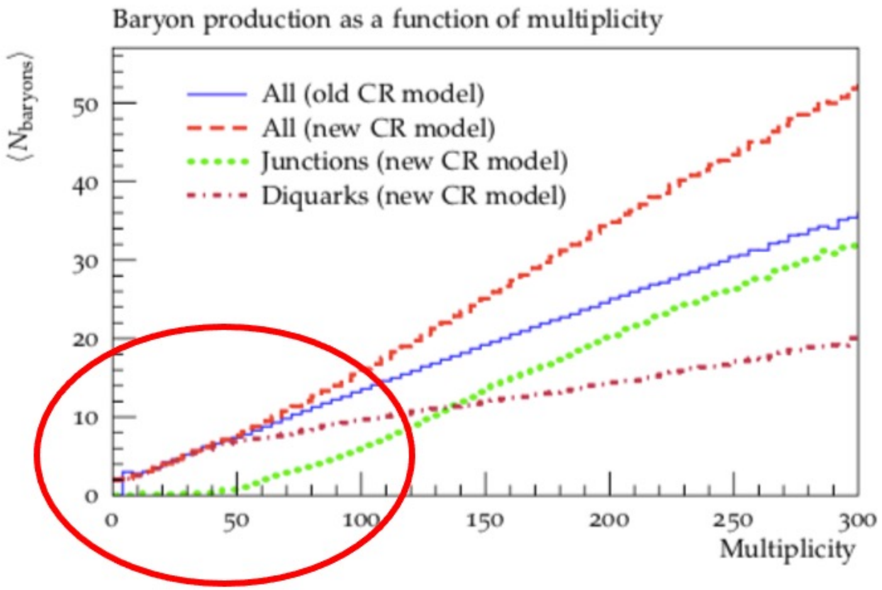
ALICE, Phys. Rev. Lett. 128 (2022) 012001

Baryon/meson ratio at EIC (Λ_c/D^0)



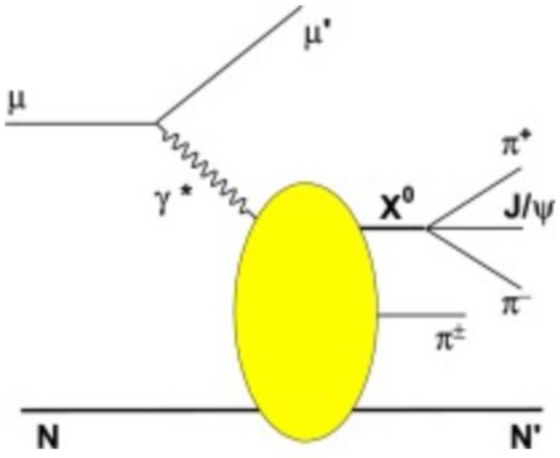
ATHENA simulation

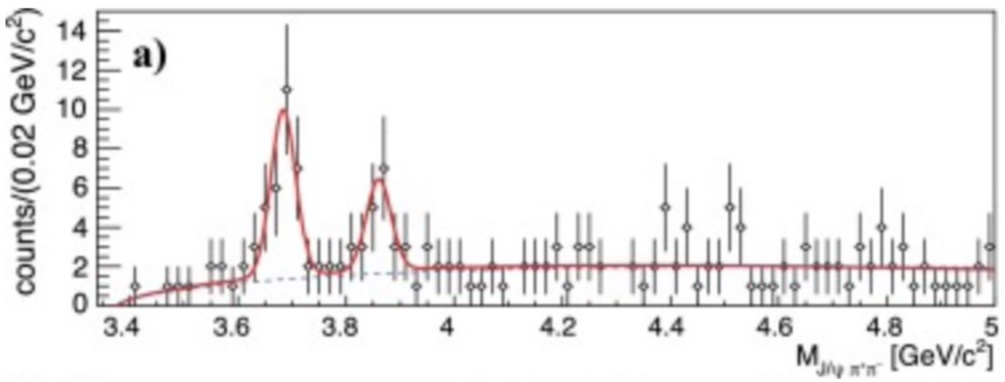
- increase from central to forward might be "drag effect" of baryon number transport
- no big difference between QCD-CR (enhanced "new") and MPI-CR (standard "old")
- HERA2 Λ_c total lumi 120 pb^{-1}



Christiansen J. and Skands P, JHEP08 (2015) 3

Exploring exotic hadrons via photoproduction



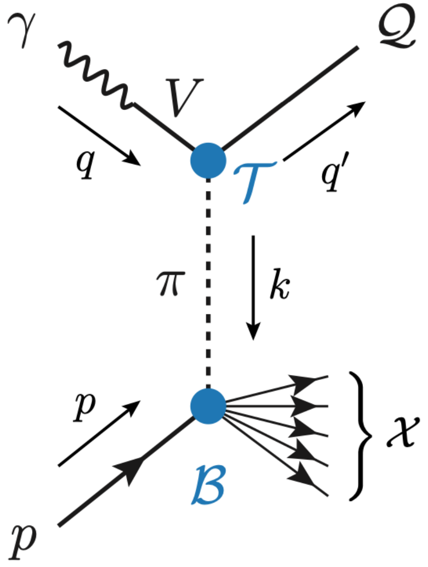


COMPASS, PLB 783 (2018) 334

XYZ photoproduction @EIC can be more favorable (than at COMPASS or JLAB) due to luminosity and center of mass energy

O (10^5) XYZ events in six months at 10^{33} cm^{-2} s^{-1} luminosity @EIC

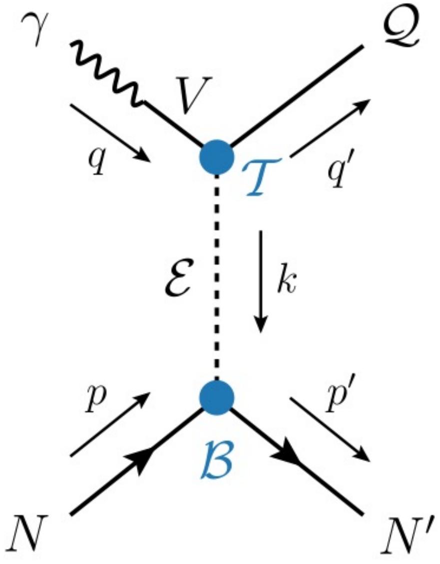
Z → J/ψ π+ (and J/ψ → e⁺e-)



semi-inclusive

semi-inclusive photoproduction
D. Winney et al,, arXiv:2209.05882

exclusive processes
M . Albaladejo et al. PRD 102 (2020) 1



exclusive

Comprehensive studies presented by JPAC Collaboration

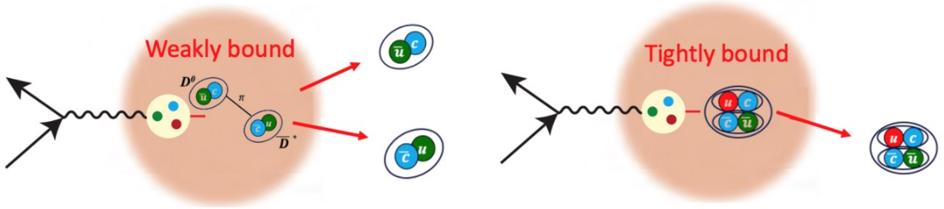
EoI presented at SNOWMASS21

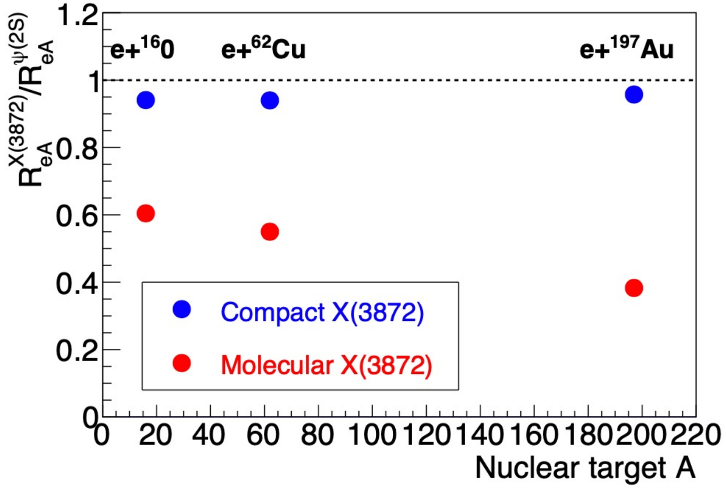
Studying exotic hadrons nature via eA

	Constituents	$IJ^{P(C)}$	Binding energy [MeV]	EicC [pb]	US-EIC [pb]
T_{cc}^{+}	DD^*	01^+	0.273 [55, 56]	0.3×10^{-3} (1.2×10^{-3})	$\boxed{0.1\ (0.5)}$
T_{cc}^{*}	D^*D^*	01^+	0.503 [73]	0.2×10^{-3} (1.0×10^{-3})	0.1 (0.4)
P_{cs}	$\Xi_c\bar{D}$	$0\frac{1}{2}^-$	0.3 (3.53) [61]	0.1 (1.6)	1.8 (30)
P_{cs}	$\Xi_c\bar{D}^*$	$0\frac{1}{2}^-$	18.83 [74]	0.1 (0.5)	1.3 (8.8)
P_{cs}	$\Xi_c\bar{D}^*$	$0\frac{3}{2}^-$	18.83 [74]	0.1 (0.9)	2.6 (18)
	$\Lambda_c\bar{\Lambda}_c$	00^{-+}	1.98 (33.8) [61]	0.3 (3.0)	9.6 (110)
	$\Sigma_c\bar{\Sigma}_c$	00^{-+}	11.1 (60.8) [61]	0.7×10^{-3} (5.2×10^{-3})	0.04 (0.29)
	$\Sigma_c\bar{\Sigma}_c$	10^{-+}	8.28 (53) [61]	0.7×10^{-3} (5.3×10^{-3})	0.04 (0.29)
	$\Xi_c\bar{\Xi}_c$	00^{-+}	4.72 (42.2) [61]	1.4×10^{-3} (1.1×10^{-2})	0.1 (0.5)
	$\Xi_c\bar{\Xi}_c$	10^{-+}	18.2 (0.39) [61]	0.1×10^{-3} (1.7×10^{-3})	3.9×10^{-3} (7.1×10^{-2})
	$\Lambda_c\bar{\Sigma}_c$	10^-	2.19 (33.9) [61]	0.01 (0.12)	0.5 (5.5)
	$\Lambda_c\bar{\Xi}_c$	$\frac{1}{2}0^-$	1.29 (8.42) [61]	0.01 (0.14)	0.2 (5.3)
	$\Xi_c\bar{\Sigma}_c$	$\frac{1}{2}0^-$	5.98 (46.4) [61]	0.8×10^{-3} (7.3×10^{-3})	0.04 (0.36)

Pan-Pan Shi et al., arXiv:2208.02639

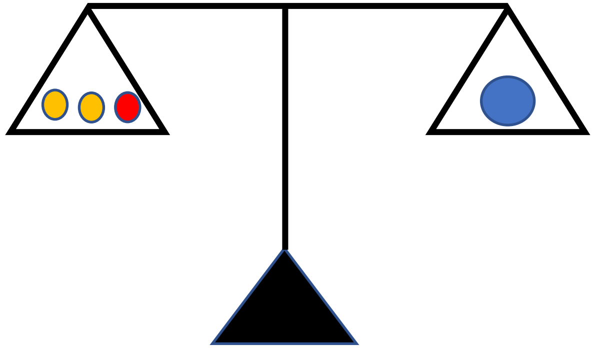
3 10^4 – 1.5 10^5 events assuming 300 fb^{-1} intergrated luminosity





Quarkonia @ EIC as weight scales

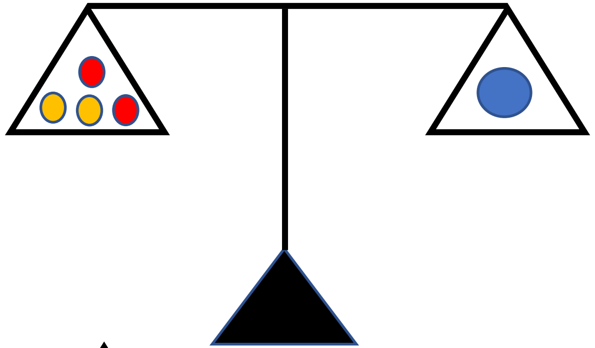
Hadronic matter sums up its components, very differently w.r.t. atoms and nuclei



- Hydrogen
- Oxygen

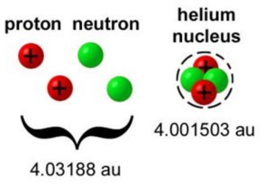
Water

Molecular Formula	H_2O
Synonyms	water 7732-18-5 Distilled water Dihydrogen oxide Purified water More...
Molecular Weight	18.015



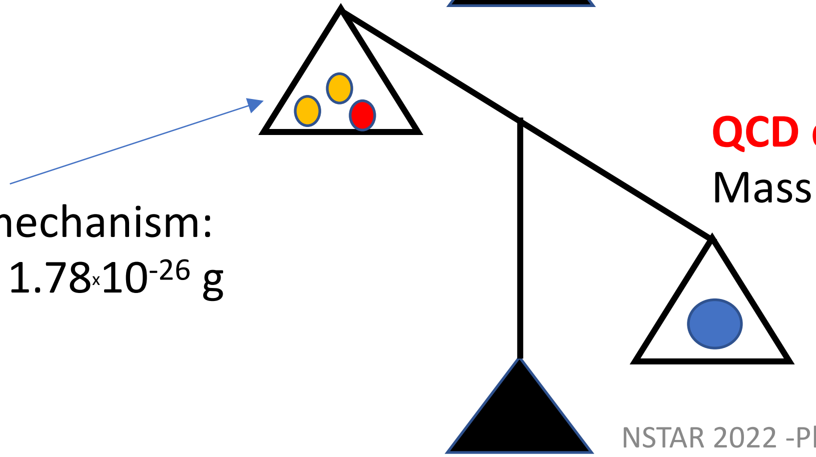
- Proton
- Neutron

Helium



5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.99840316
13 Al Aluminum 26.981538	14 Si Silicon 28.085	15 P Phosphorus 30.97376200	16 S Sulfur 32.07	17 Cl Chlorine 35.45

- d quark
- u quark



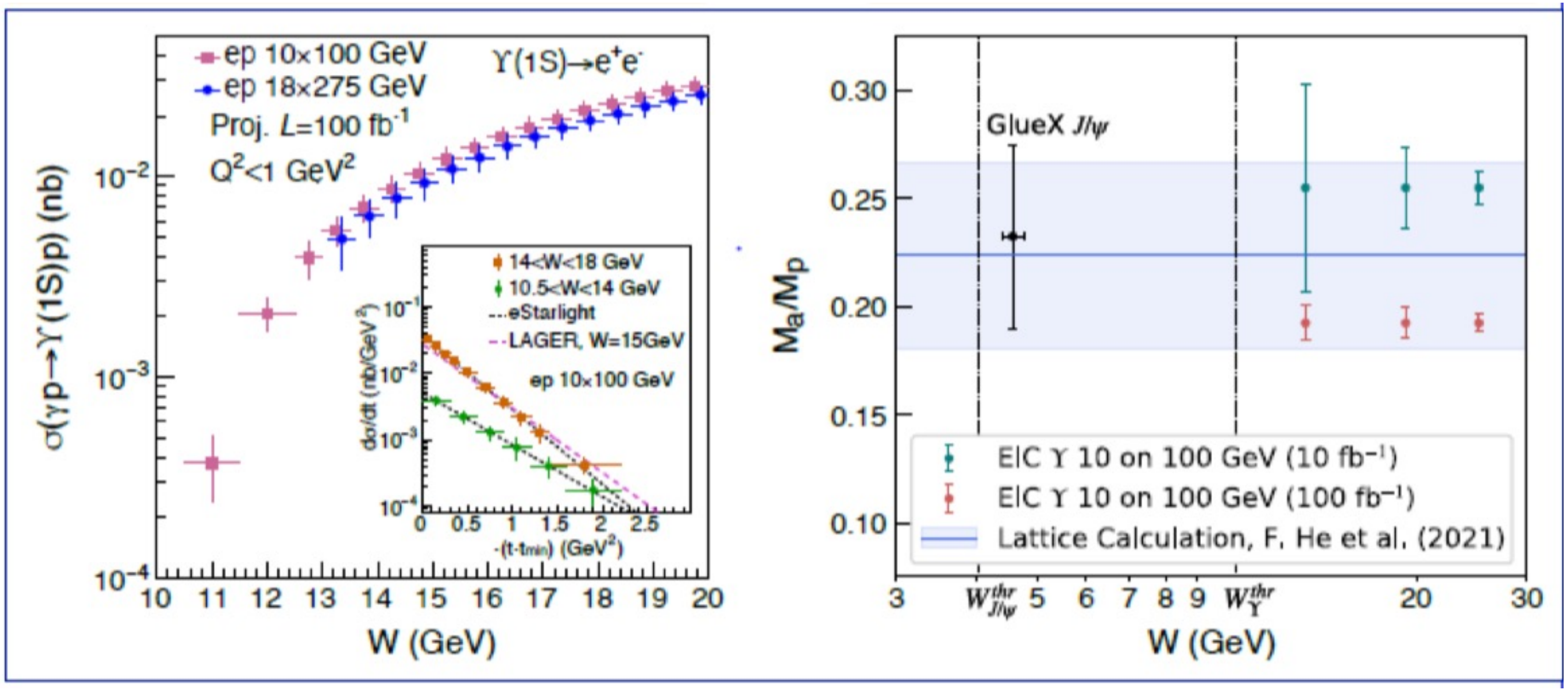
Higgs mechanism:
Mass ≈ 1.78×10^{-26} g

QCD dynamics makes 98% of proton mass
Mass ≈ 168×10^{-26} g

(and baryonic matter is just 5% of the Universe)

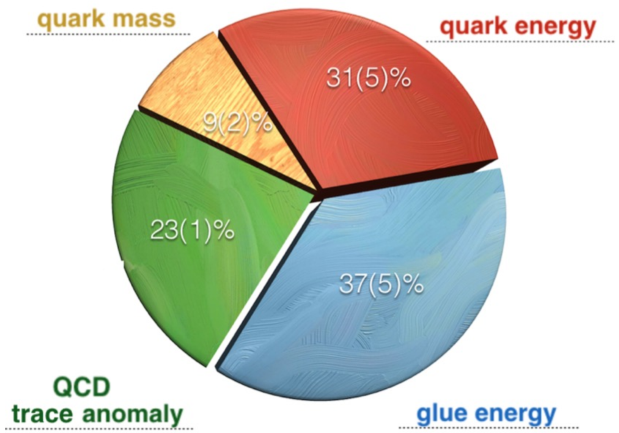
Proton

Quarkonia @ EIC as weight scales



$$M_N = M_m + M_q + M_g + M_a$$

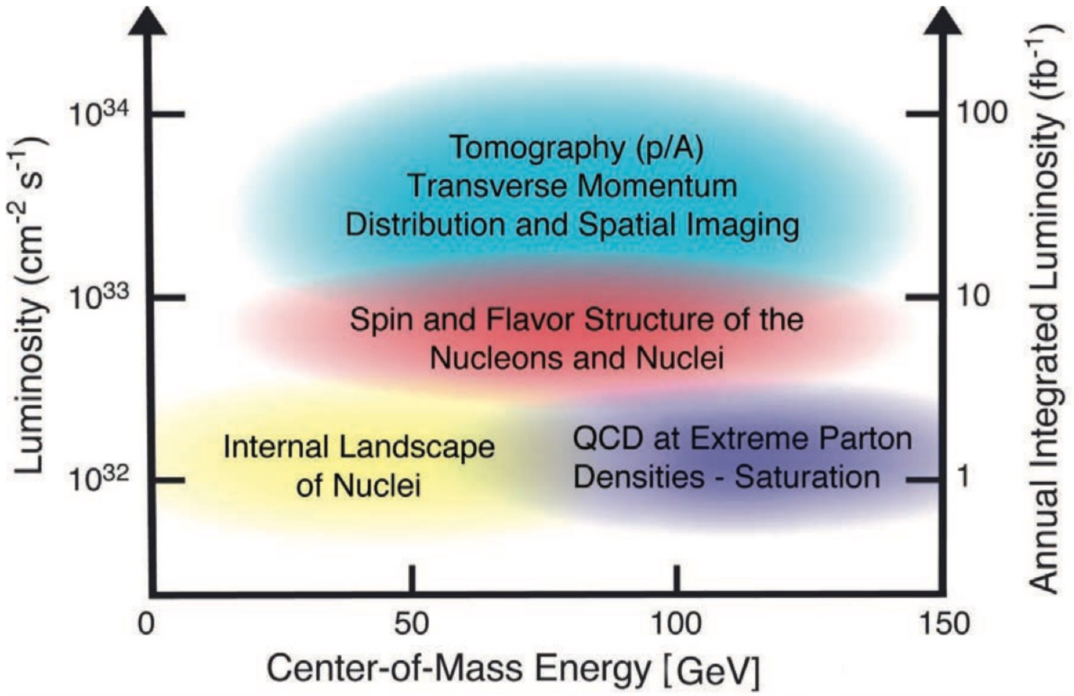
$$T^{\mu}_{\mu} = \underbrace{\frac{\tilde{\beta}(g)}{2g} G^2}_{\text{Trace Anomaly}} + \underbrace{\sum_{q=u,d,s} m_q (1+\gamma_m) \bar{\psi}_q \psi_q}_{\text{Light Quark Mass}}$$



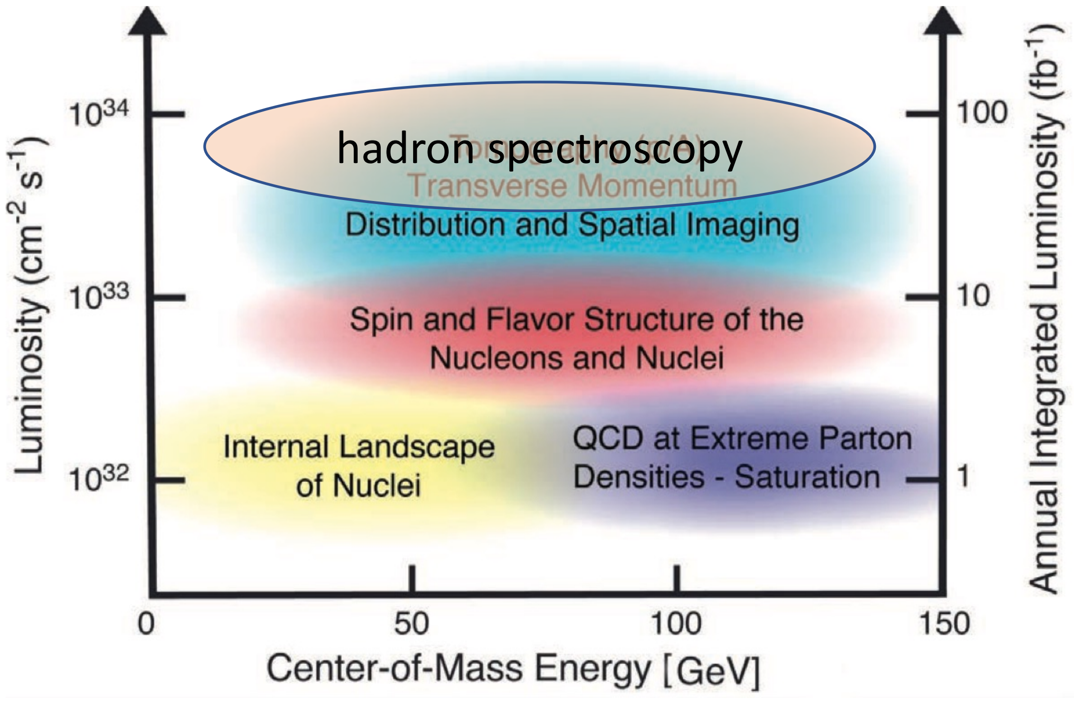
Yi-Bo Yang et al, Lattice 2017

J/ψ and ϒ near threshold production gives access to trace anomaly
Wang R. et al, Eur.Phys.J.C 80 (2020)

EIC science and hadron spectroscopy

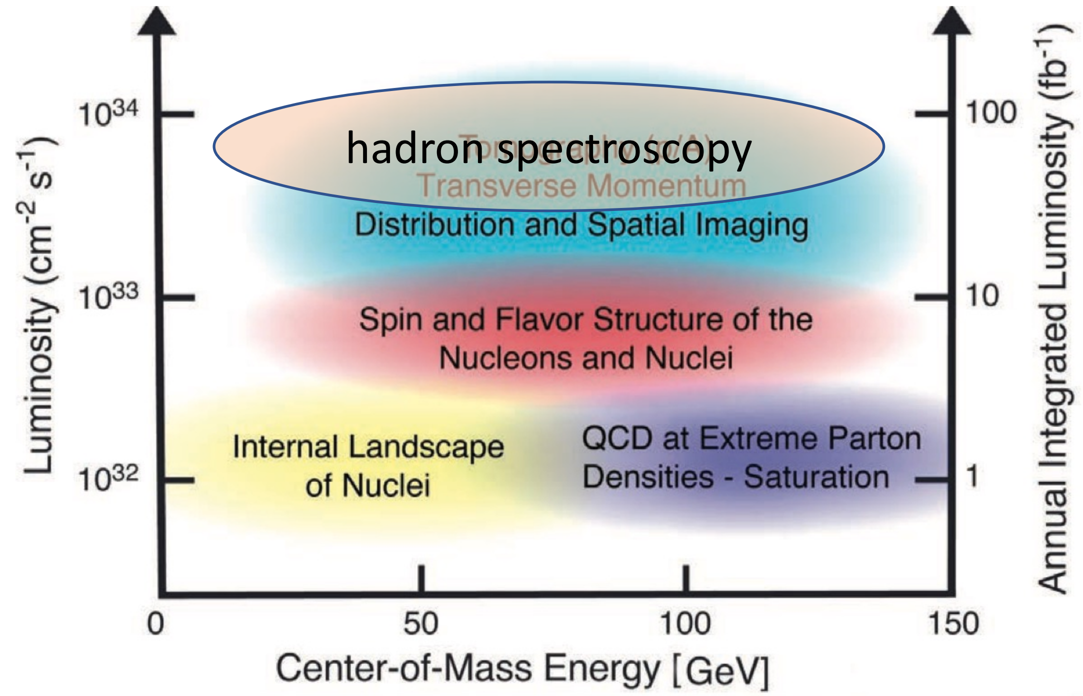


EIC science and hadron spectroscopy



This is the exact time to build a comprehensive hadron spectroscopy program at EIC with finally realistic detector design

EIC science and hadron spectroscopy



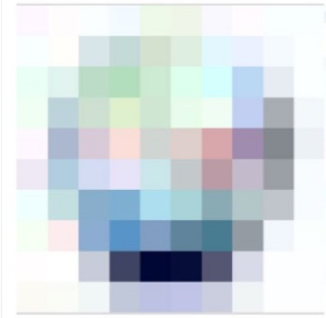
This is exact time to build a comprehensive hadron spectroscopy program at EIC with finally realistic detector design

Λ_c, D, and J/ψ (will be "building blocks" for exotic hadron detection XYZ

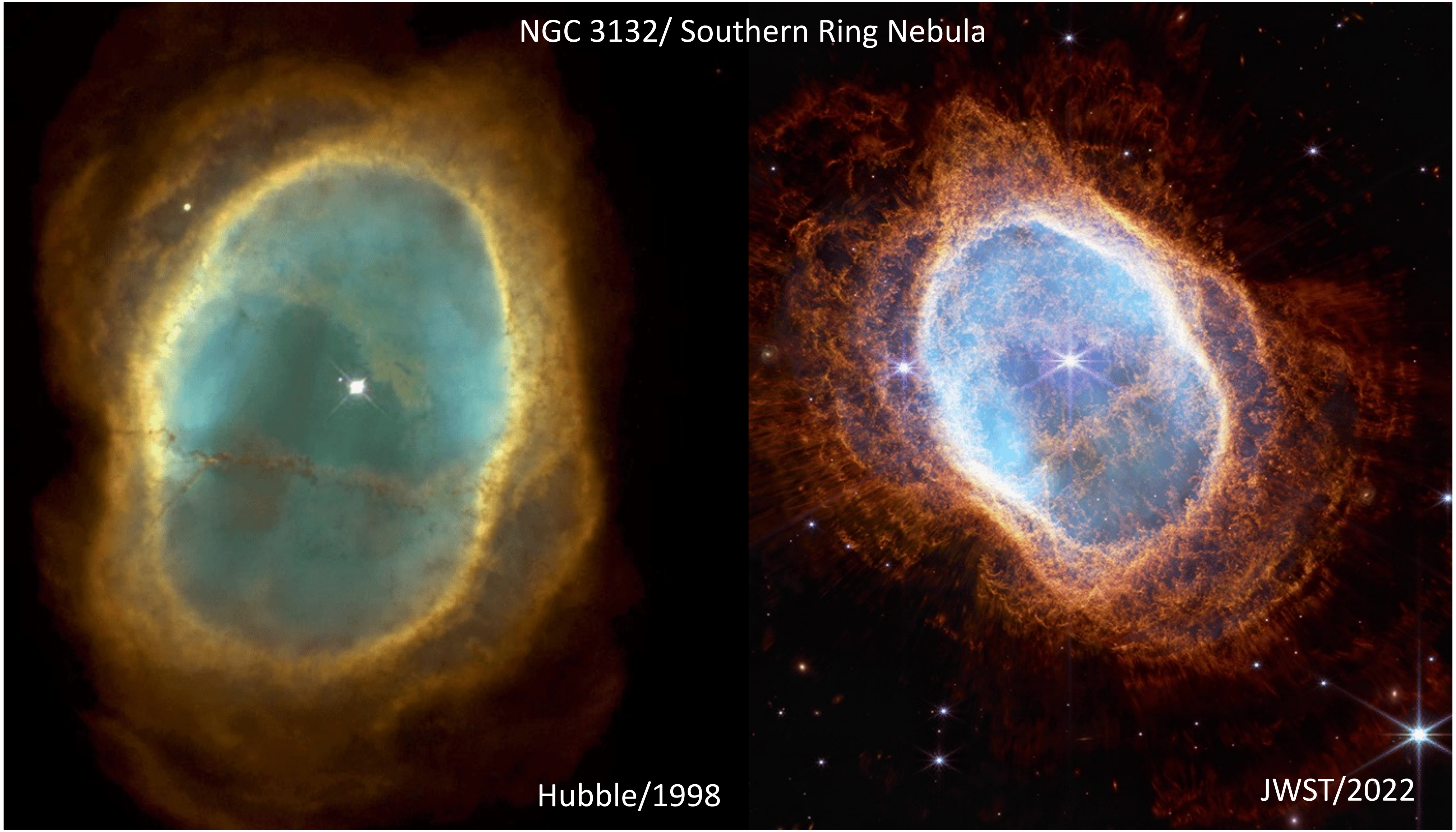
In addition to the rich "treasure" they are bringing for our understanding of the nucleon:

- the structure of the nucleon (and when bound in nuclei): seen in 1D, 3D and revealing its IC component (if any)
- hadronization (in the vacuum and in the CNM)
- the origin of the mass of the nucleon from gluons and (

=

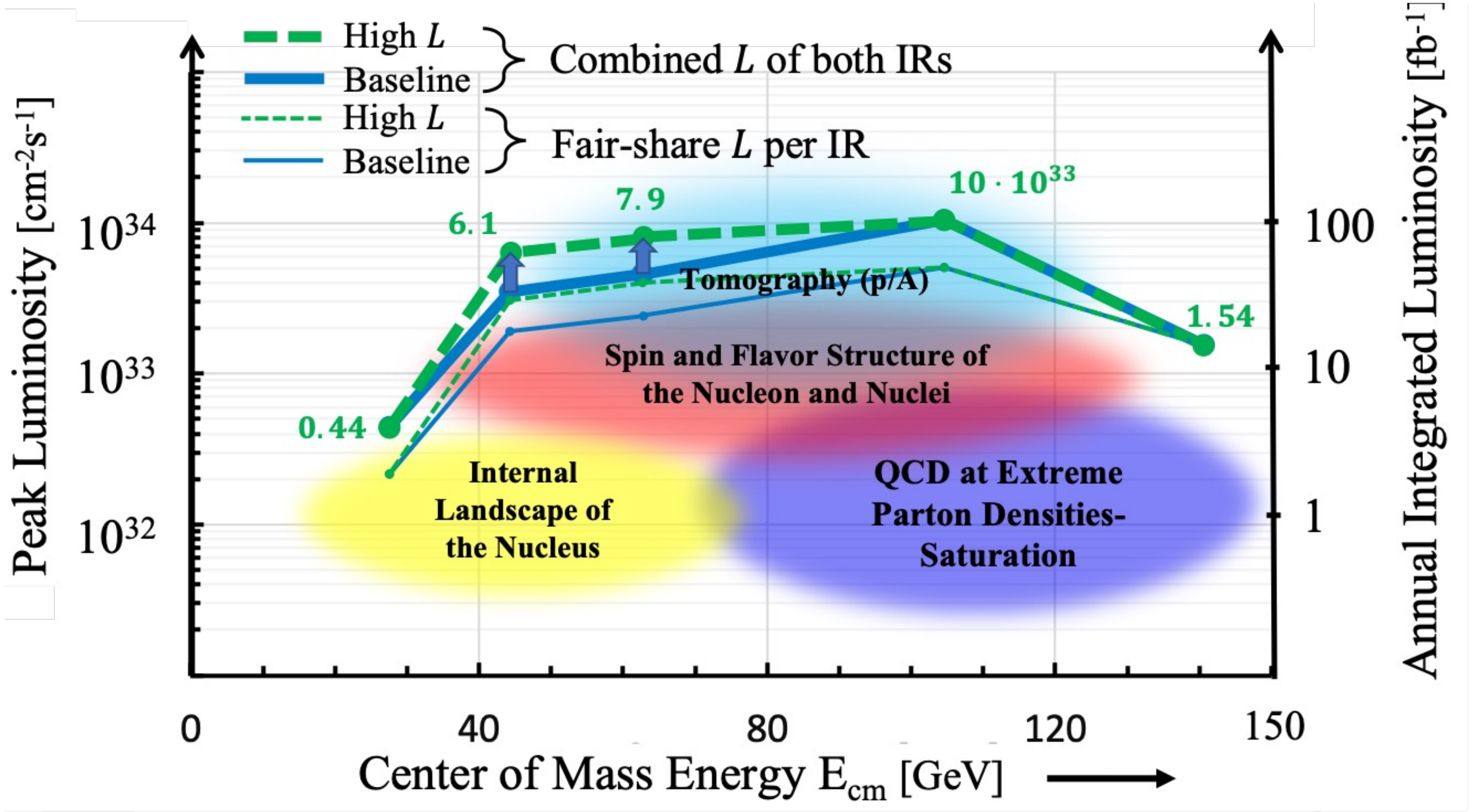


A new pair of glasses helps!

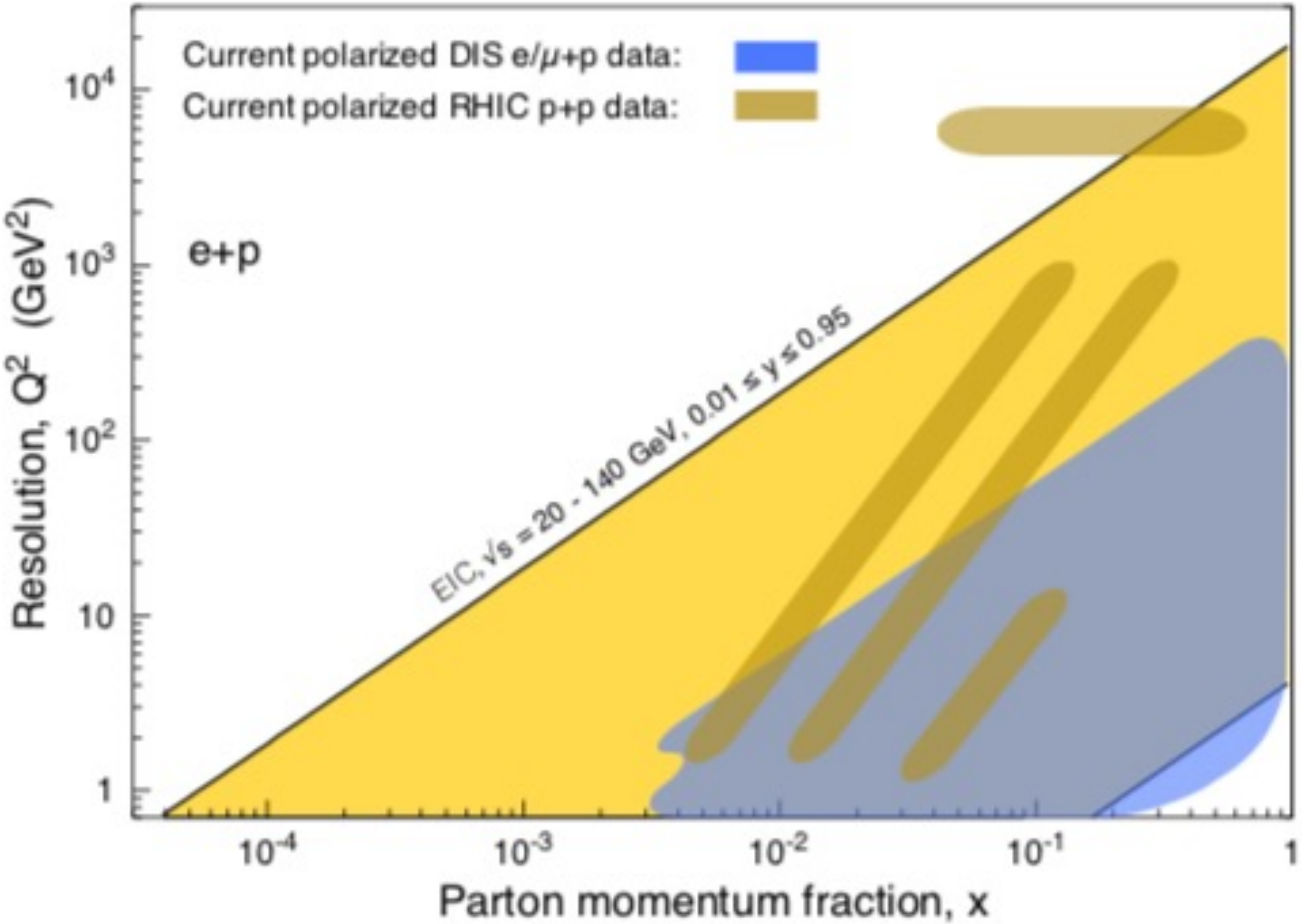


Miscellanea backup

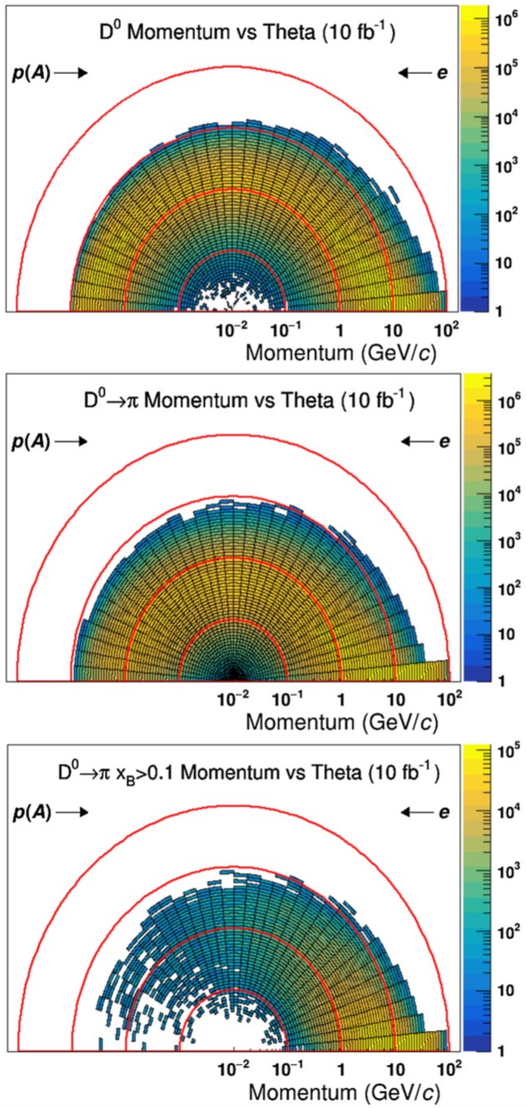
EIC science & luminosity

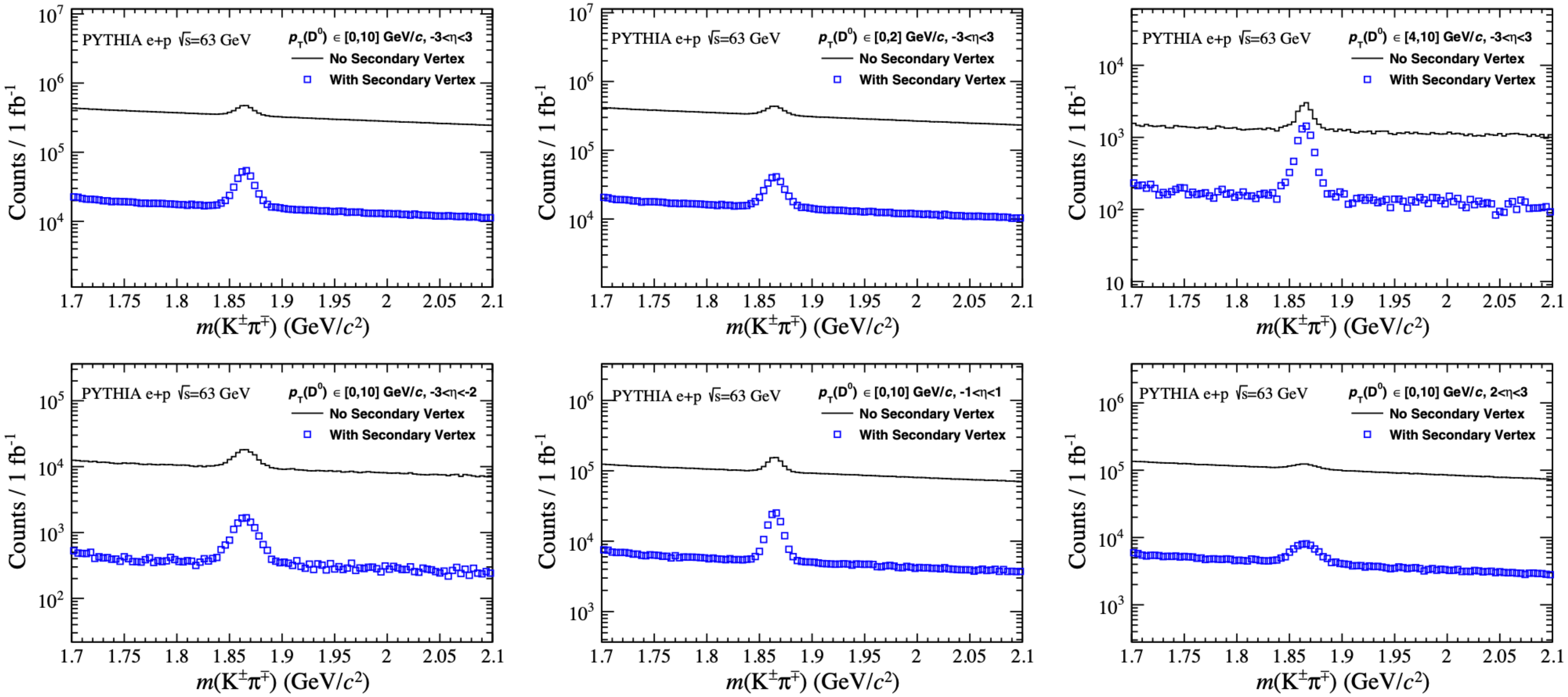


EIC kinematic space



D^0 production/acceptance/reconstruction





secondary vertex identification is key!

M. Kelsey et al. Phys. Rev. D 104, 054002 (2021)

Trace anomaly and J/ψ- Υ production near threshold

Wang R. et al, Eur.Phys.J.C 80 (2020) 6, 507 arXiv:1912.12040

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) M_N$$

$$M_g = \frac{3}{4}(1-a)M_N,$$

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)} b M_N,$$

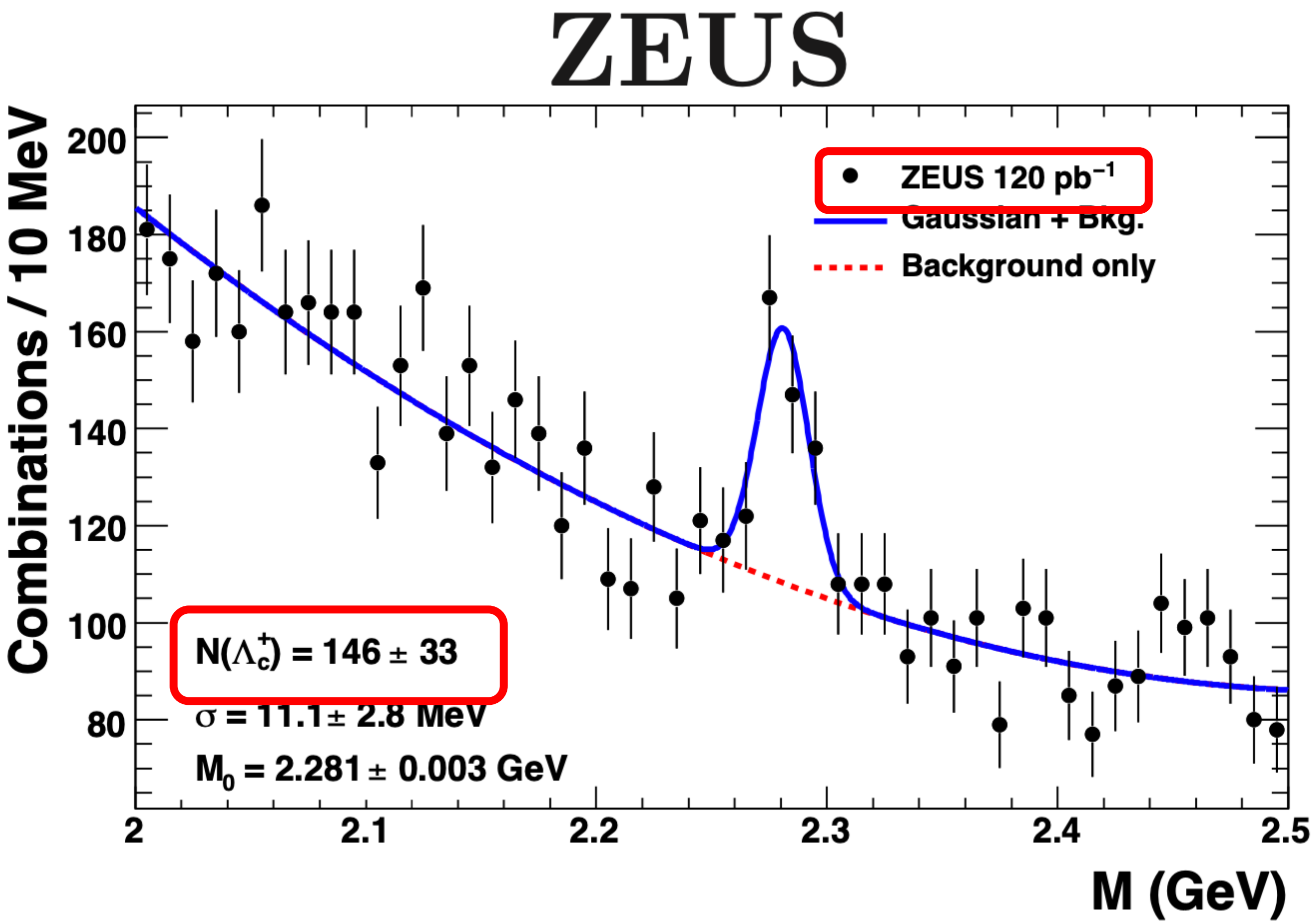
$$M_a = \frac{1}{4}(1-b)M_N,$$

$$\left.\frac{d\sigma_{\gamma N \to J/\psi N}}{dt}\right|_{t=0} = \frac{3\Gamma(J/\psi \to e^+e^-)}{\alpha m_{J/\psi}} \left(\frac{k_{J/\psi N}}{k_{\gamma N}}\right)^2 \left.\frac{d\sigma_{J/\psi N \to J/\psi N}}{dt}\right|_{t=0}$$

$$\begin{aligned} F_{J/\psi N} &\simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - \left\langle N \left| \sum_{i=u,d,s} m_i \bar{q}_i q_i \right| N \right\rangle\right) \\ &\simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - 2bM_N^2\right) \\ &\simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2 \boxed{(1-b),} \end{aligned}$$

$$\left.\frac{d\sigma_{J/\psi N \to J/\psi N}}{dt}\right|_{t=0} = \frac{1}{64\pi} \frac{1}{m_{J/\psi}^2 \left(\lambda^2 - m_N^2\right)} \left|F_{J/\psi N}\right|^2 .$$

Luminosity matters



JHEP 1011 (2010) 009

HERA2 DIS data integrating all statistics... (and two detection channel)

1 p_T bin (0-10 GeV/c), 20% statistical error