

# Overview of EIC Physics

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North Carolina State University

2024

한국고에너지물리학회

봄 학술대회

주제 : 양자 우주와 양자기술

5월 23일(목) | 전자-핵 충돌기 및 대충강연

5월 24일(금) | 미래 충돌 가속기

국제 산학 협력 세션

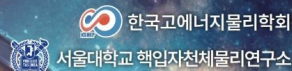
5월 25일(토) | 미래 중성 미자 실험

장소 | 서울대학교 500동 목암홀(23일), 관정도서관 양두석 홀(24일, 25일)



학회 홈페이지 <https://kshep2.sccc.uos.ac.kr/event/804/>  
QR코드

주 관



한국고에너지물리학회  
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후 원

CTP 서울대학교 이론물리학연구소

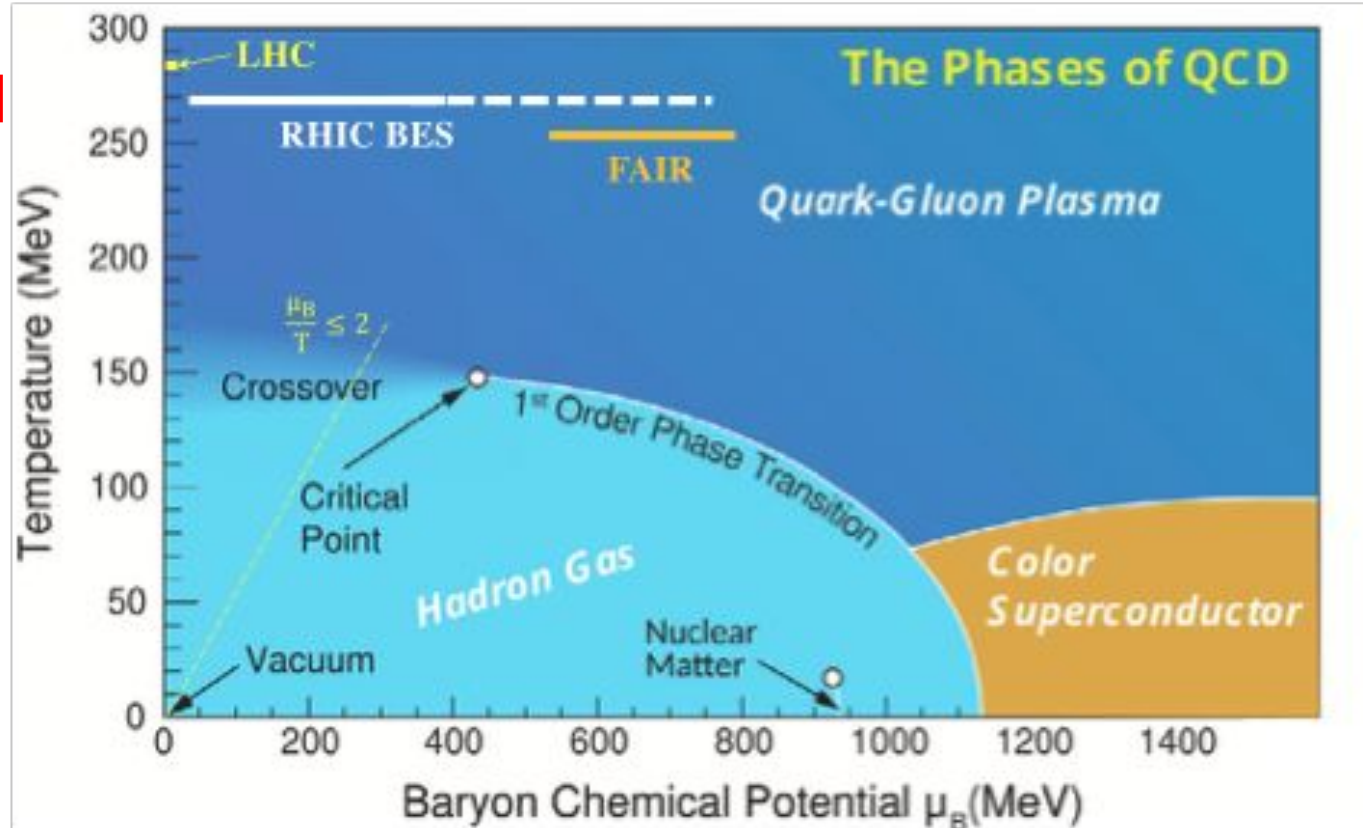
한국-CMS 연구센터

KoALICE 연구센터

# Hot and Cold QCD

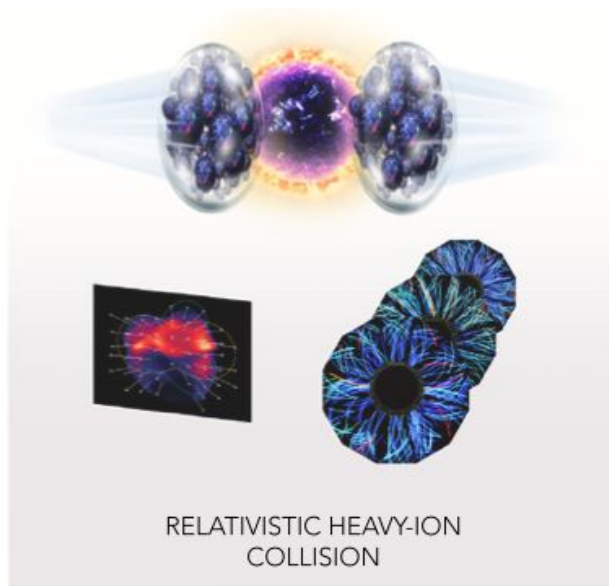
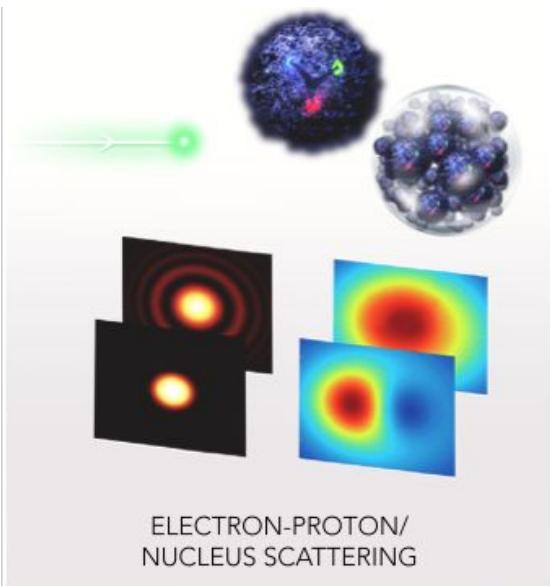
RHIC@BNL  
LHC@CERN

JLab



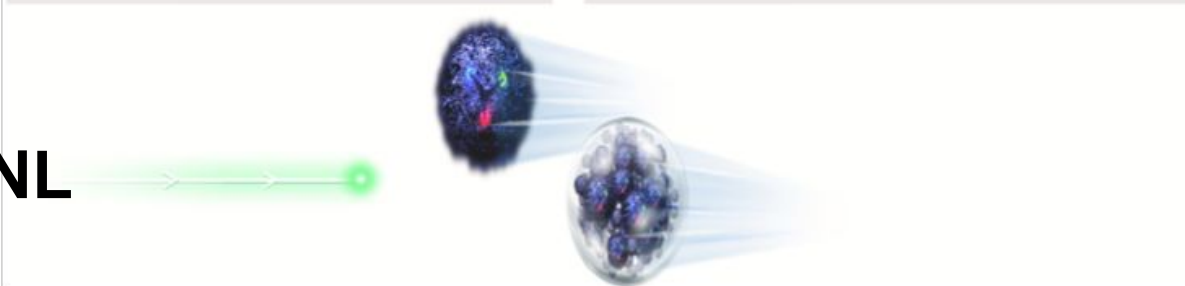
# Cold and Hot QCD

JLab



RHIC@BNL  
LHC@CERN

EIC@BNL



ELECTRON-PROTON/  
ION COLLISION

# The scientific foundation for the EIC has been built for over two decades.

P. Achenbach, D. Adhikari, A. Afanasev et al.

Nuclear Physics, Section A 1047 (2024) 122874

**2002**

“...essential accelerator and detector R&D [for EIC] should be given very high priority in the short term.”

**2007**

“We recommend the allocation of resources ...to lay the foundation for a polarized Electron-Ion Collider...”

**2009**

*A High Luminosity, High Energy Electron Ion Collider*  
*A New Experimental Quest to Study the Gluons and the Quark Sea That Bind Us All*

“...a new dedicated facility will be essential for answering some of the most central questions.”

**2010**

Glue and the Quark Sea at High Energies

**2012**

*Electron Ion Collider: The Next QCD Frontier*  
*Understanding the Gluon and the Quark Sea*

“The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider..”

**2013**

Major Nuclear Physics Facilities for the Next Decade  
 NSAC  
 March 14, 2013

Electron-Ion Collider..*absolutely central* to the nuclear science program of the next decade.

**2015**

*REACHING FOR THE HORIZON*  
 THE 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

**2018**

*AN ASSESSMENT OF U.S.-BASED ELECTRON ION COLLIDER SCIENCE*  
 CONSENSUS STUDY REPORT

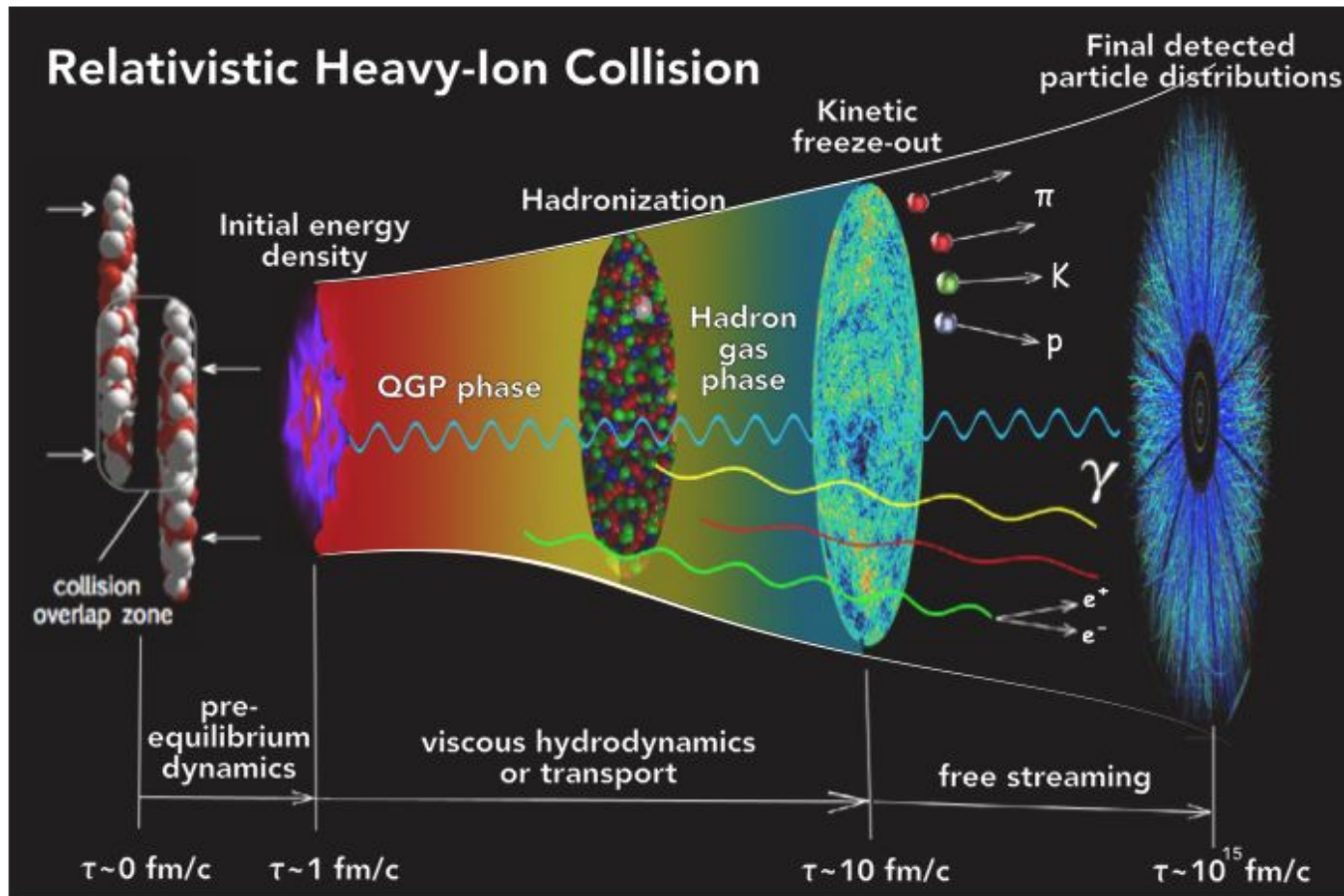
“a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB.”

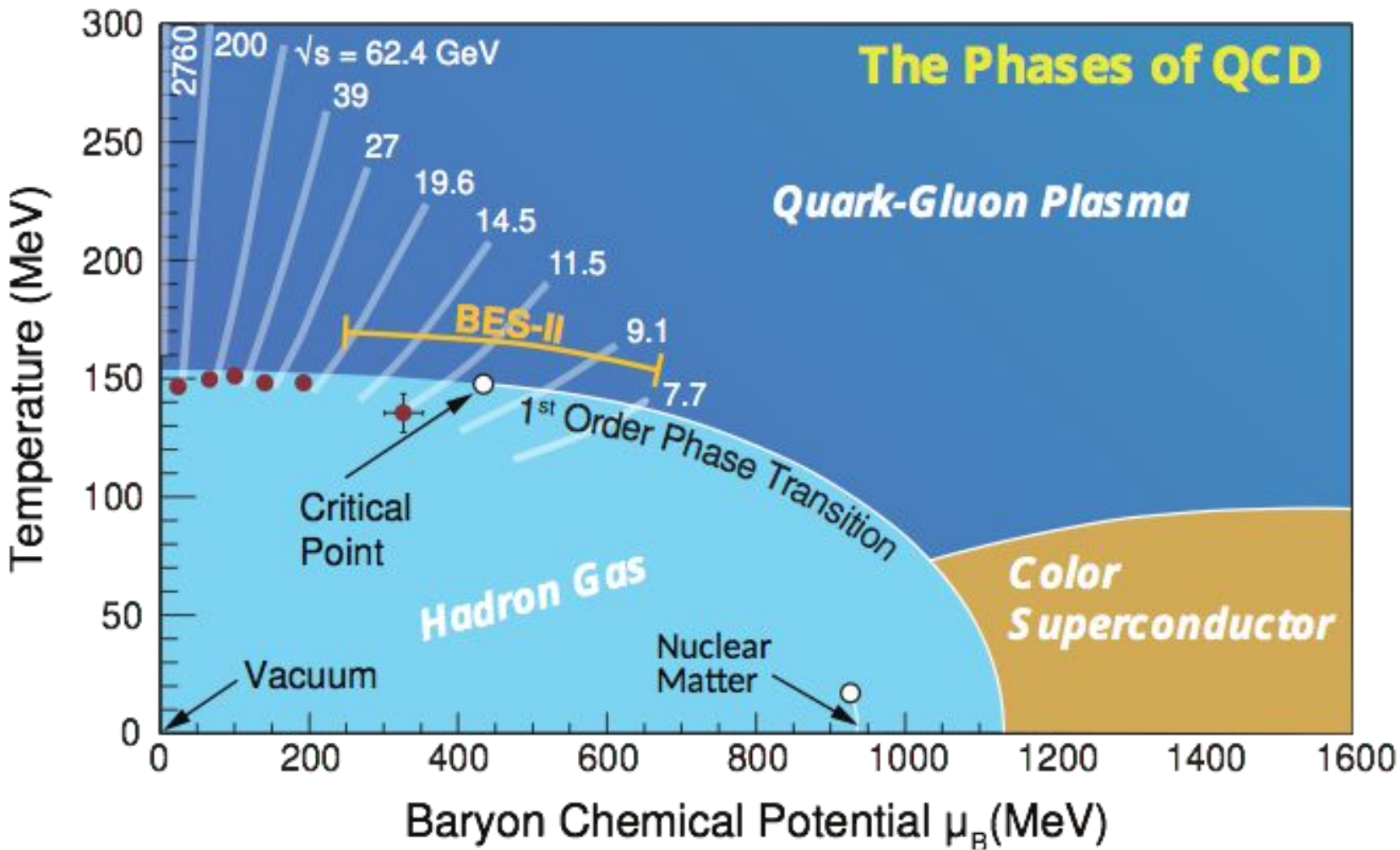
The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today.”

# Outline

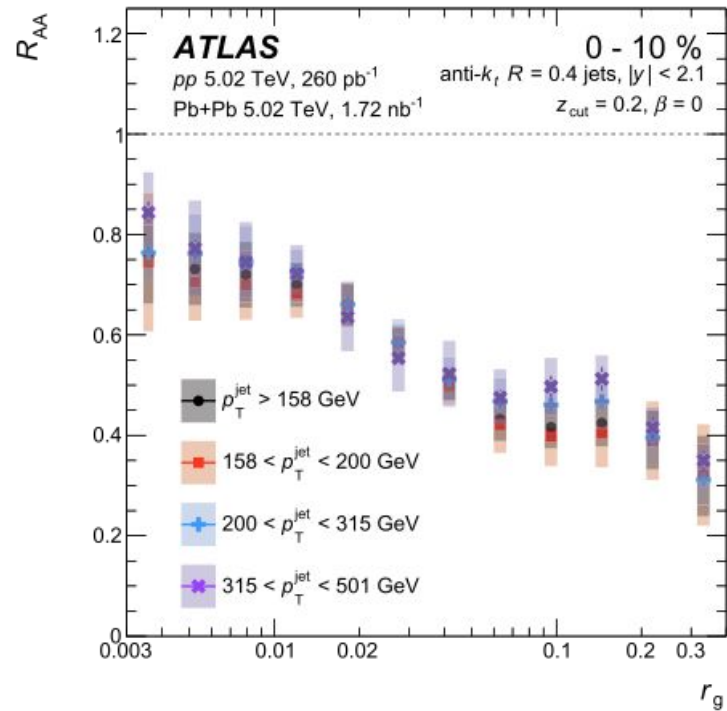
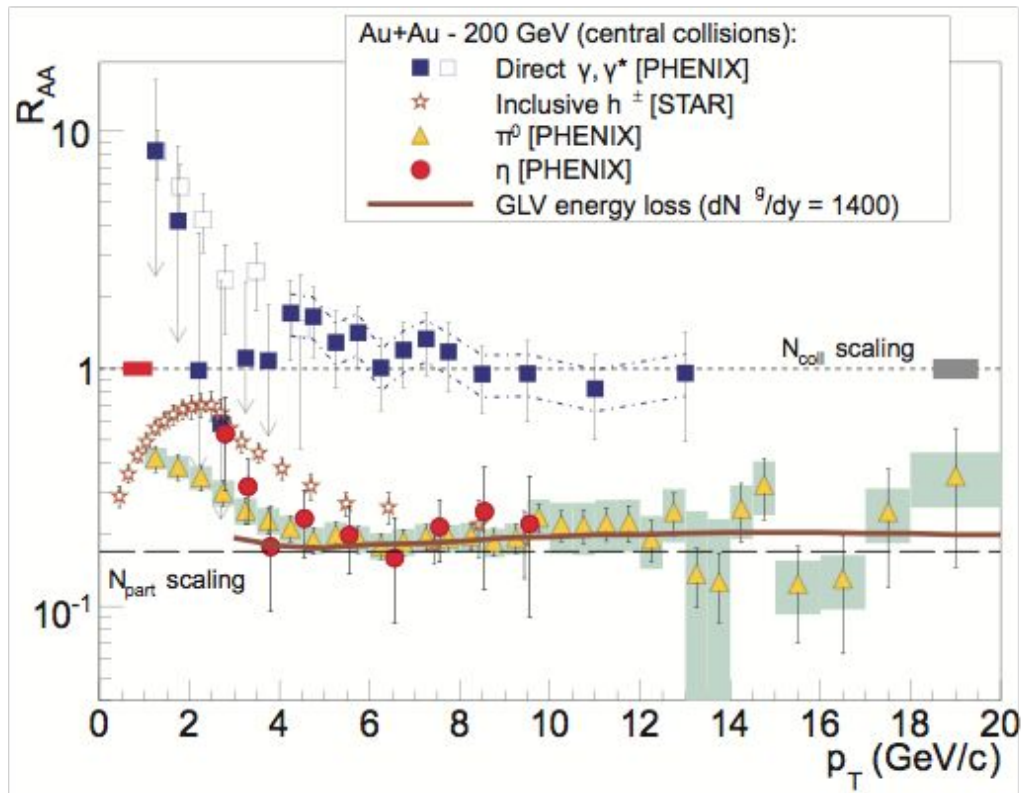
1. Progress in **Hot** QCD
2. Progress in **Cold** QCD
3. EIC Project
4. Summary and Outlook

# Progress in Hot QCD



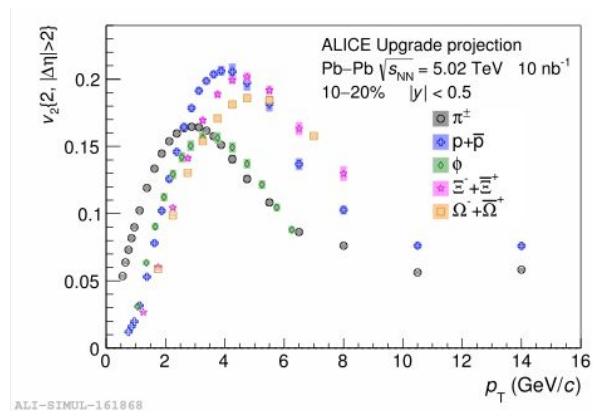
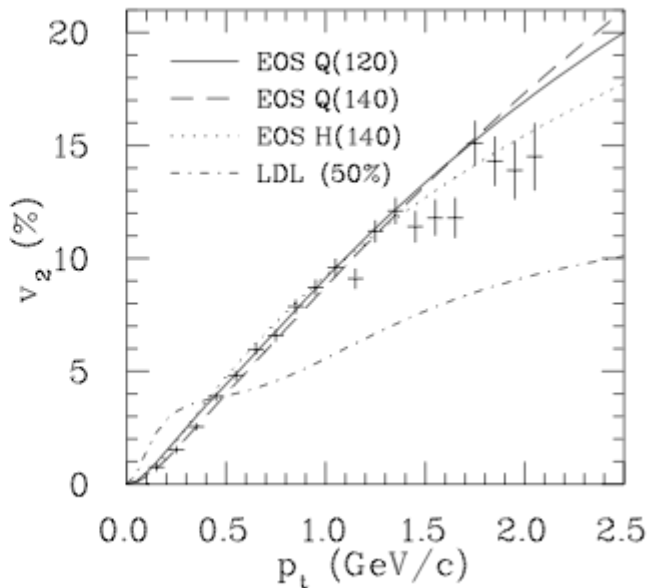
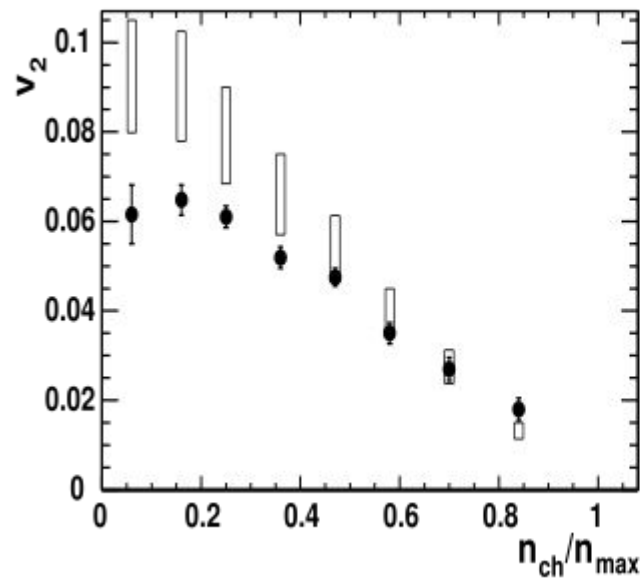
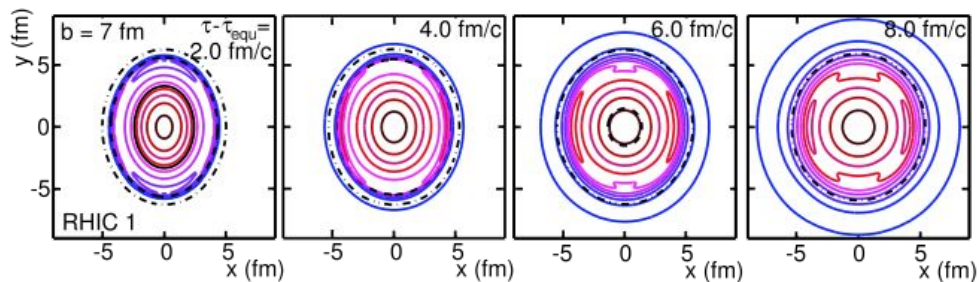


$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{\text{coll}}dN_{pp}/dp_T}$$





$$\frac{dN_i}{p_T dp_T dy d\varphi_p}(b) = \frac{1}{2\pi} \frac{dN_i}{p_T dp_T dy}(b) \left( 1 + 2 v_2^i(p_T, b) \cos(2\varphi_p) + \dots \right)$$

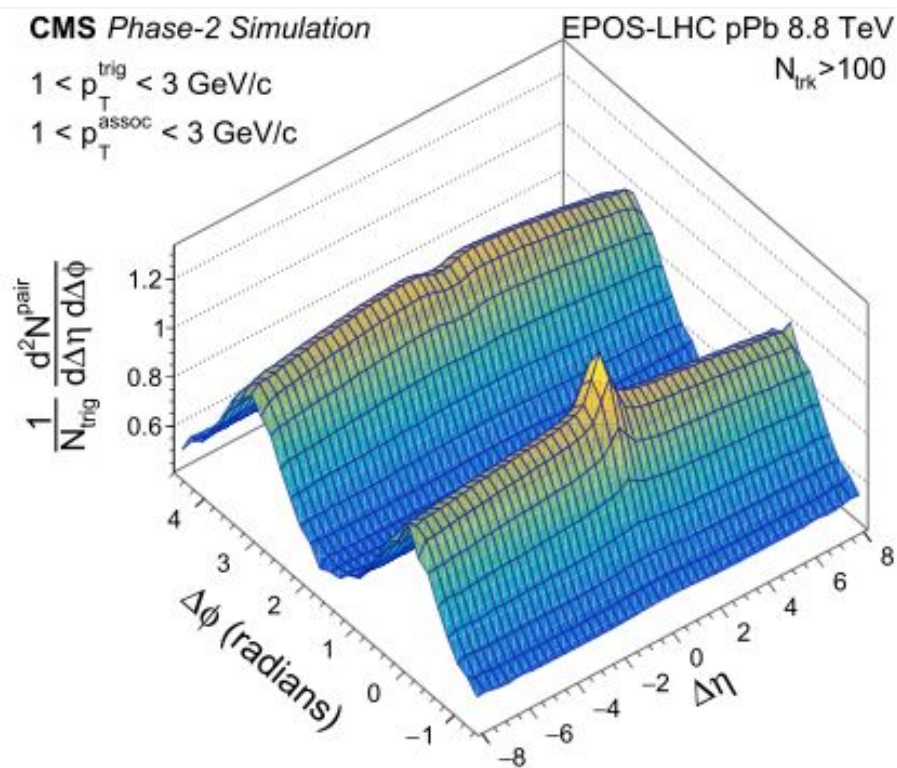


“ $\bar{p}/\pi^- > 1$  anomaly”

# long range rapidity correlations

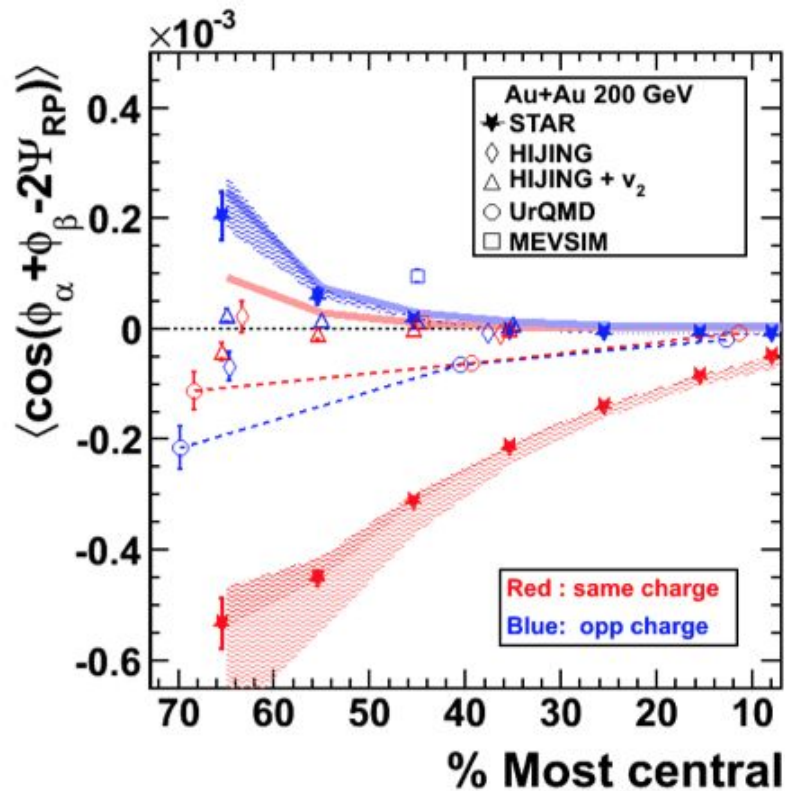
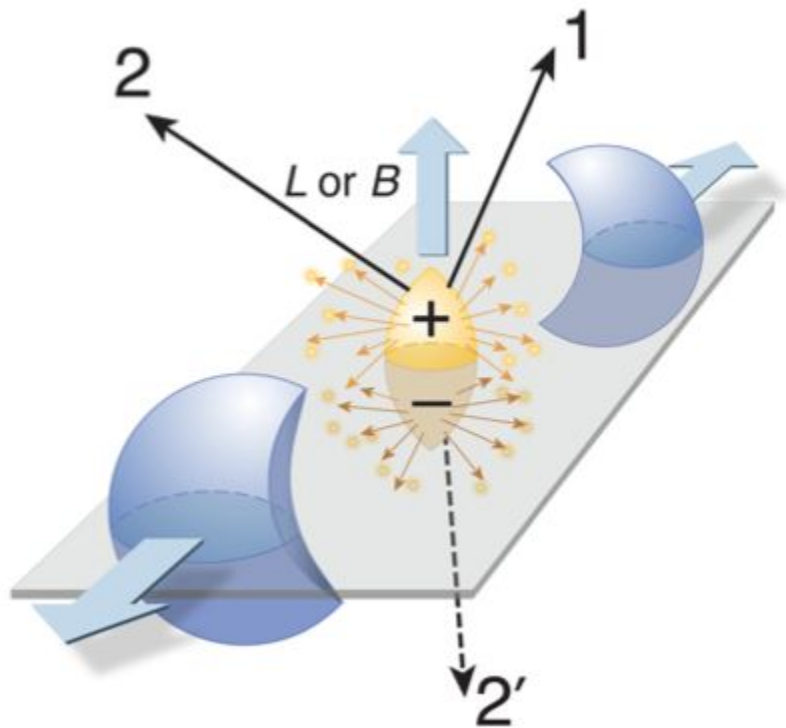
Color Glass Condensate

Glasma “ridge” events



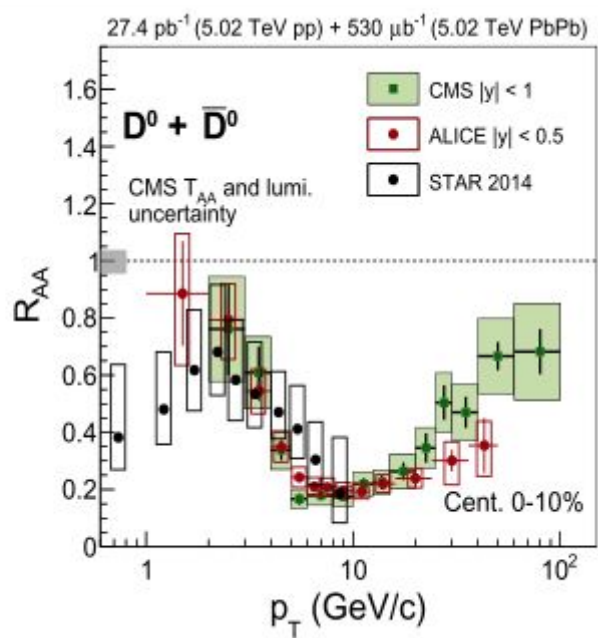
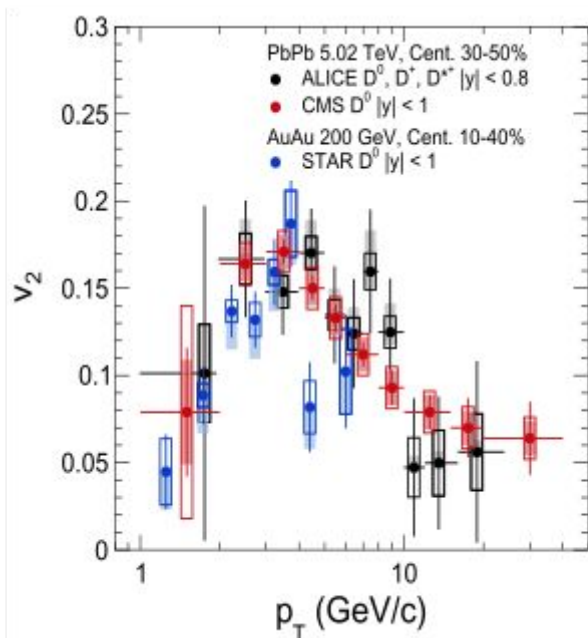
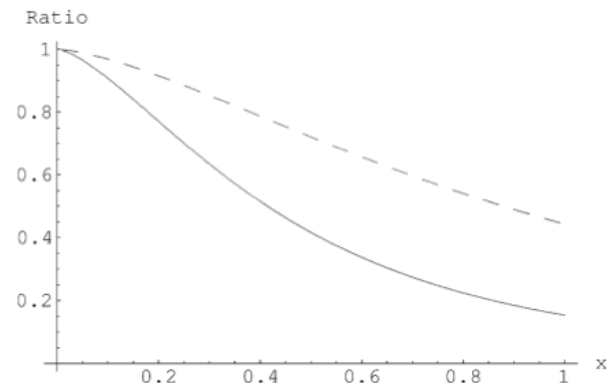
# Chiral Magnetic Effect

Phys. Rev. Lett. 103 (2009) 251601



# Heavy Quark vs. Light Quark

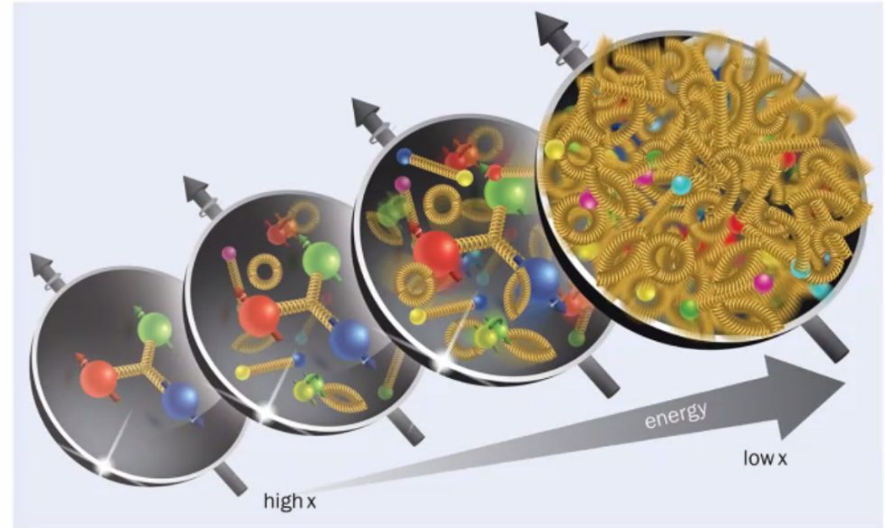
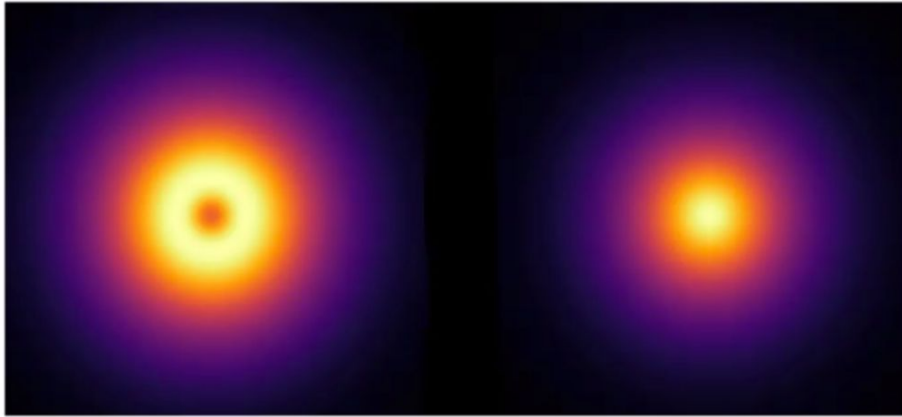
## “dead cone” effect

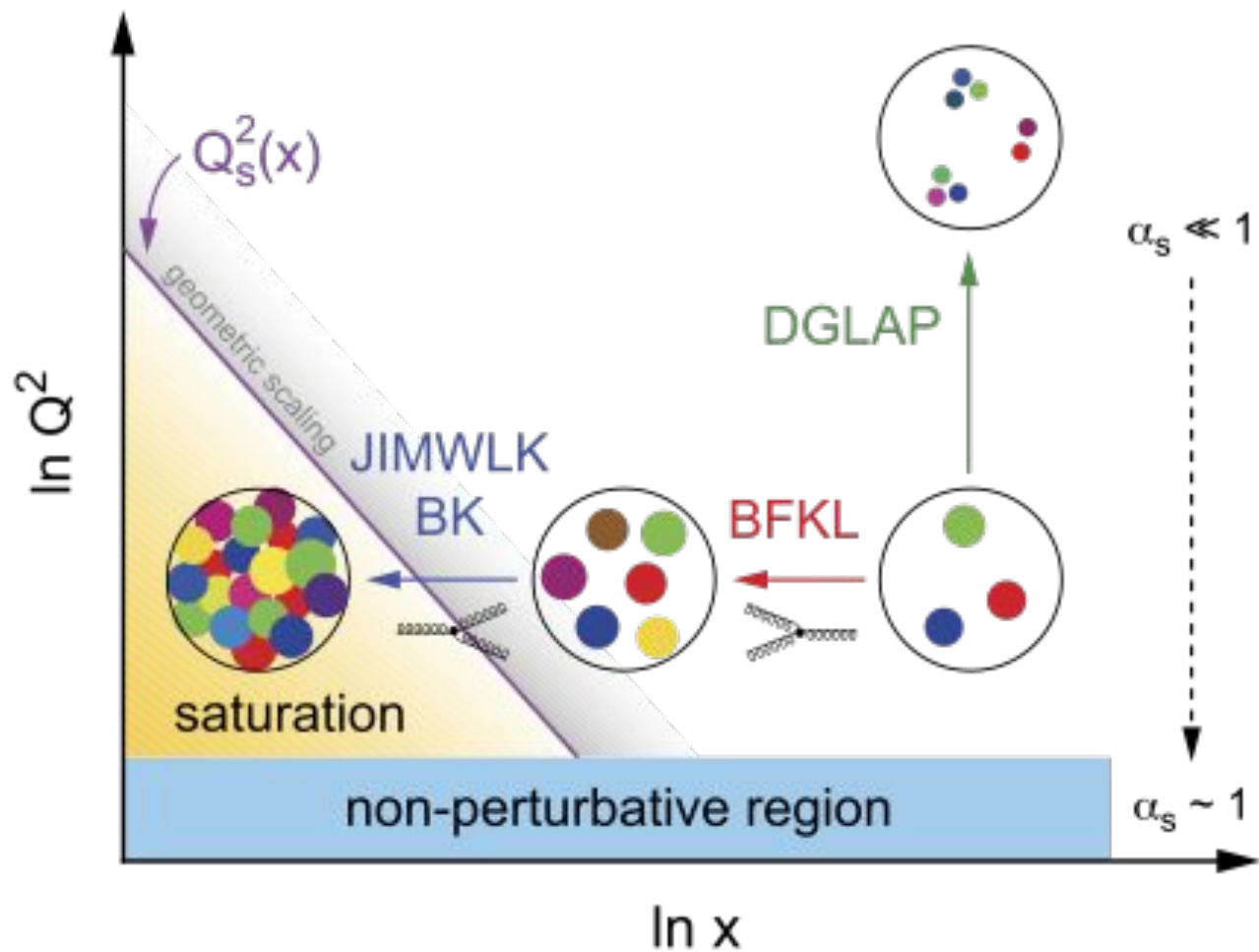


# Progress in **Cold** QCD

## Femtoscale imaging

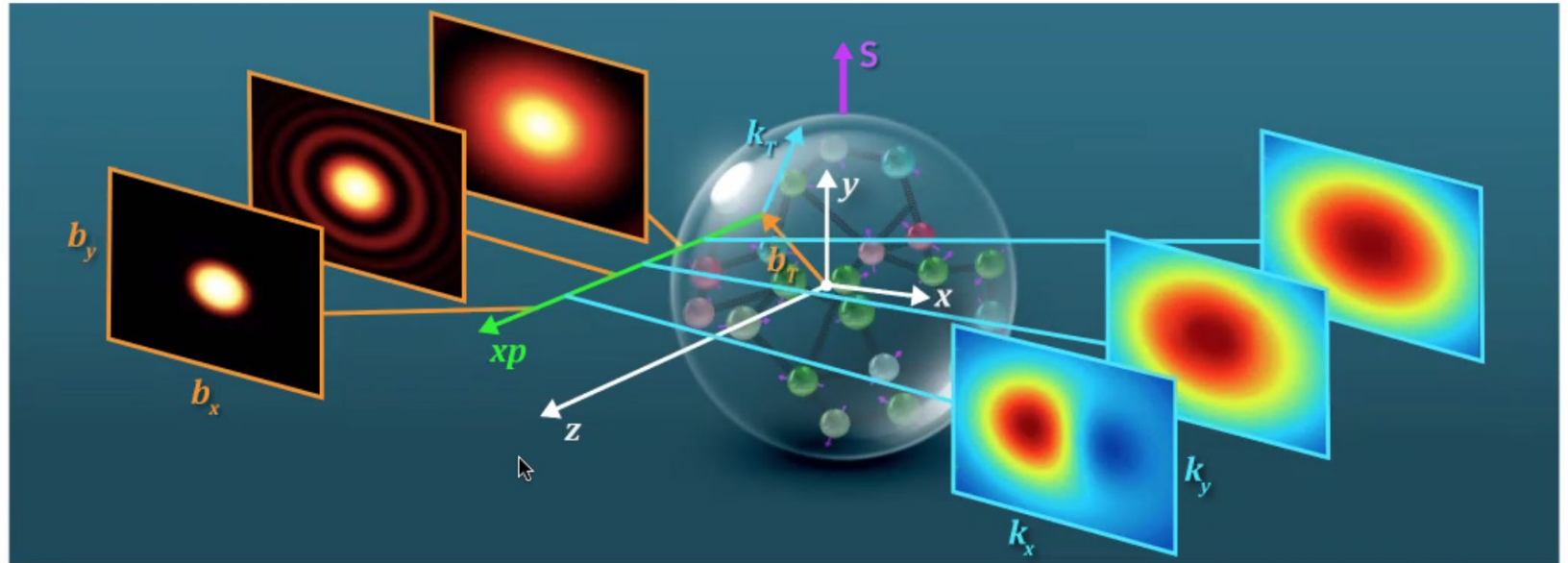
- Taking “pictures” of the proton as a function of scale





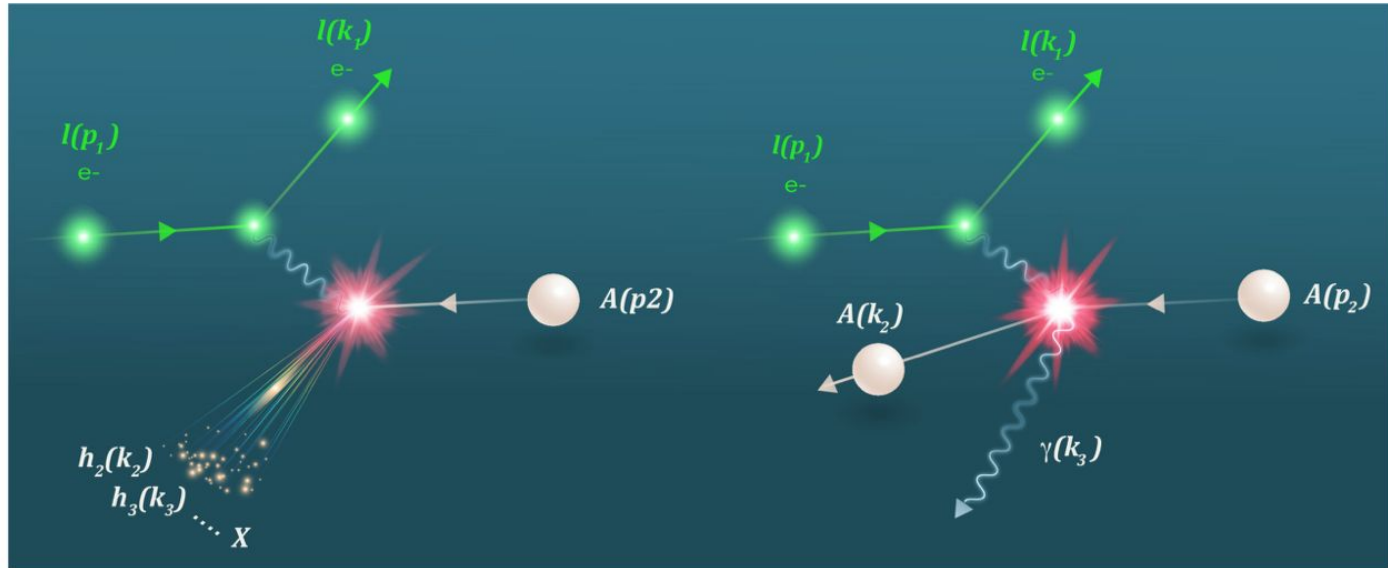
# What are we looking for?

- Images of protons in coordinate and momentum space



# How do we do it?

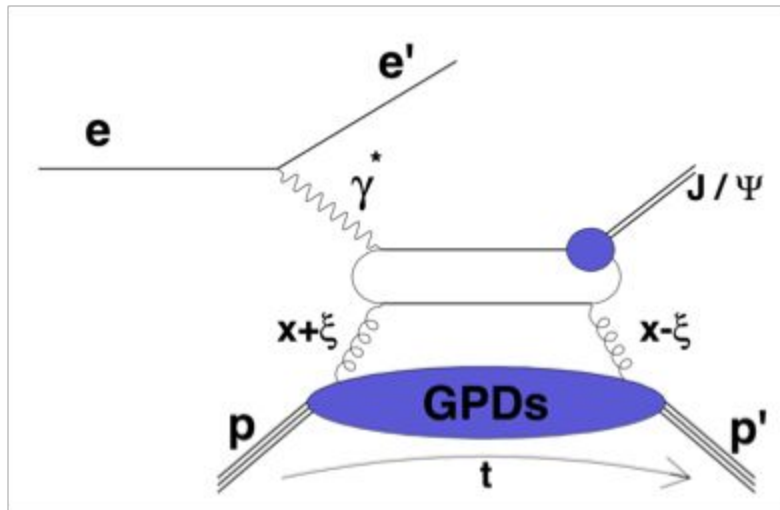
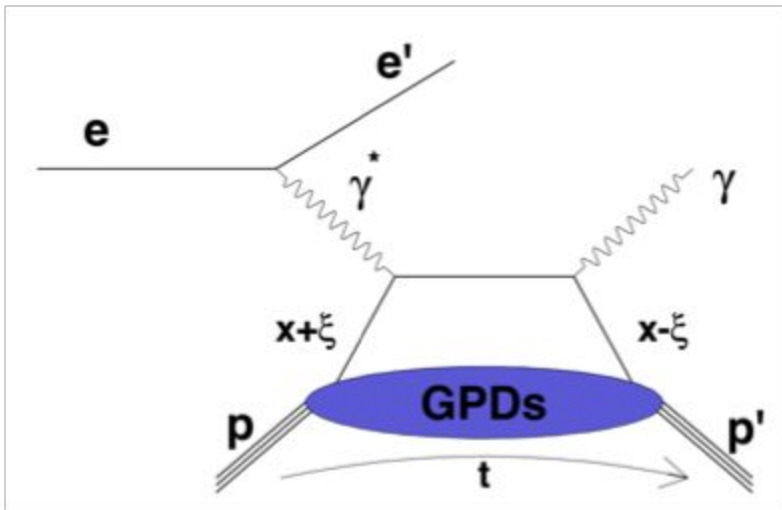
- Through experimental data in factorizable processes
- Focus on electron-induced reactions that can be realized at EIC and JLab



SIDIS -- TMDs

DVCS -- GPDs





$$\langle p' | T_{\mu\nu}^a(0) | p \rangle = \bar{u}' \left[ A^a(t) \frac{P_\mu P_\nu}{M_N} + J^a(t) \frac{i P_{\{\mu} \sigma_{\nu\} \rho} \Delta^\rho}{2M_N} + D^a(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2}{4M_N} + M_N \bar{c}^a(t) g_{\mu\nu} \right] u$$

$a = g, Q$  (gluon or quark parts)

$\delta g^{00}$

$\delta g^{0i}$

$\delta g^{ij}$

non - conservation of EMT pieces

Mass

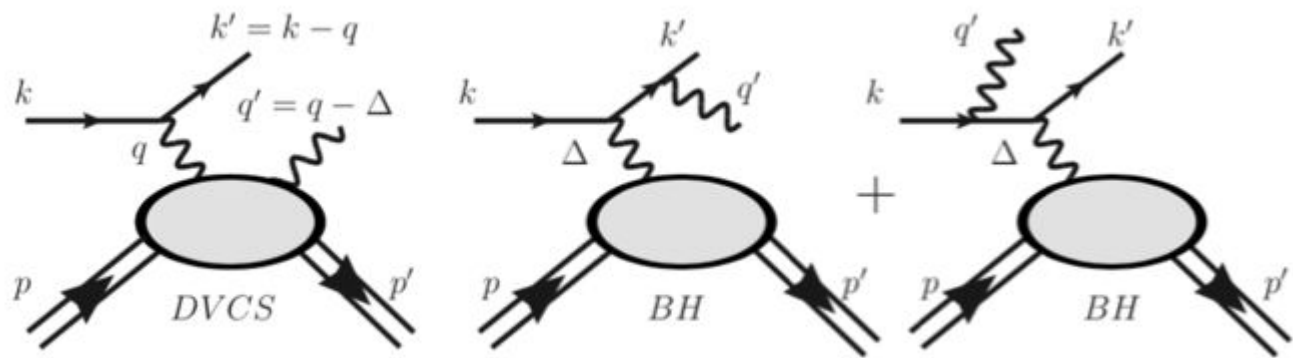
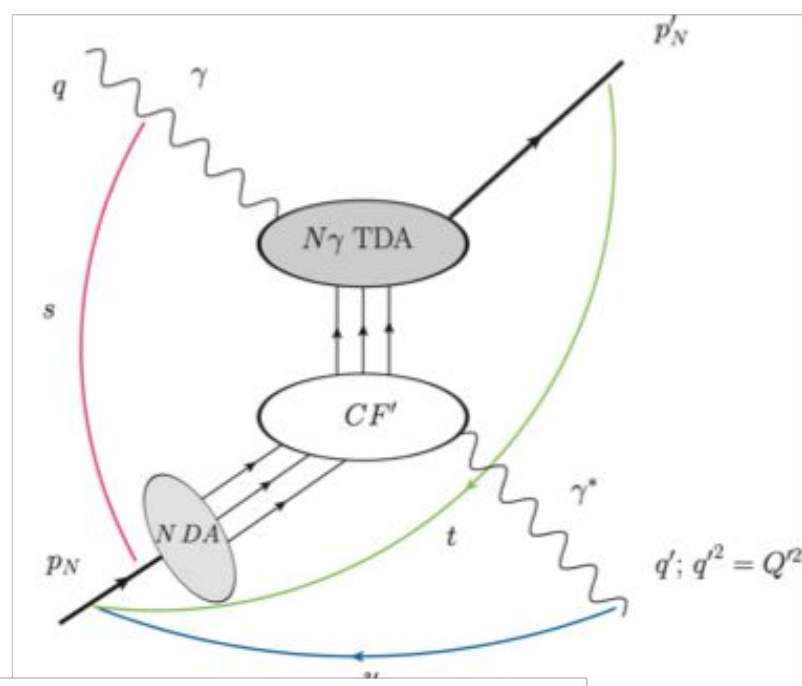
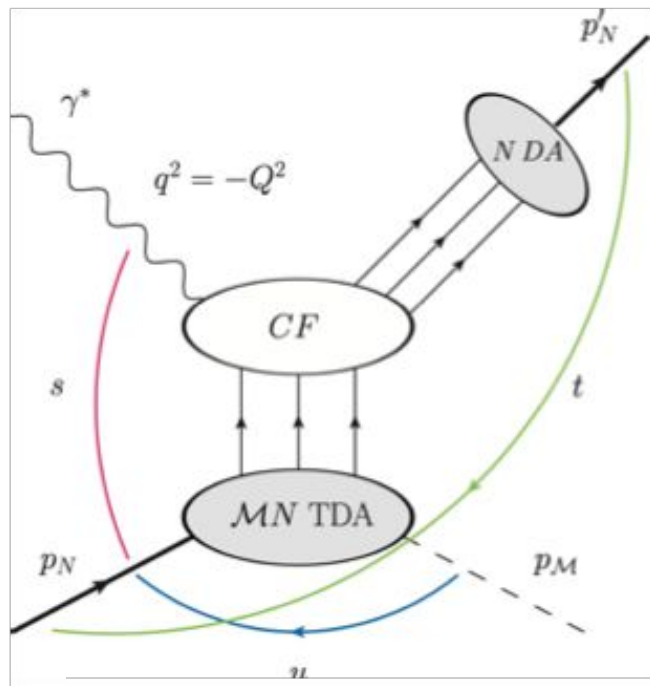
Spin

deformation of space =  
elastic properties of  $N$

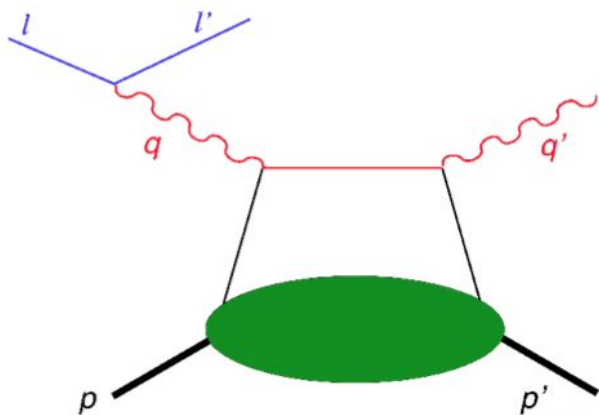
$$\sum_a A^a(0) = 1$$

$$\sum_a J^a(0) = \frac{1}{2}$$

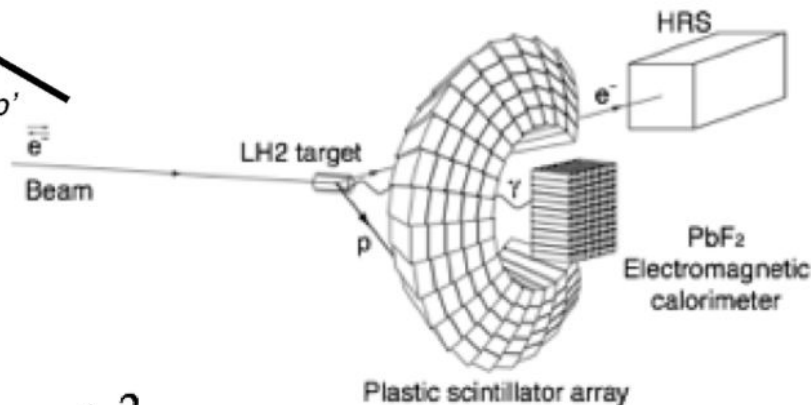
$$\sum_a \bar{c}^a(t) = 0$$



# Better Work in Forward Direction



**GPD**



**LFD**

$$t = \Delta^2 = -\frac{\xi^2 M^2 + \Delta_{\perp}^2}{1 - \xi}; \Delta^+ (\equiv \Delta^0 + \Delta^3) = \xi P^+; \Delta_{\perp}^2 > \Delta_{\perp \min}^2 \neq 0$$

# Theoretical Simulation of the Virtual Meson Production in the Forward Direction

## Analysis of virtual meson production in a (1 + 1)-dimensional scalar field model

Yongwoo Choi<sup>1,\*</sup>, Ho-Meoyng Choi<sup>2,†</sup>, Chueng-Ryong Ji<sup>3,‡</sup> and Yongseok Oh<sup>1,4,§</sup>

<sup>1</sup>*Department of Physics, Kyungpook National University, Daegu 41566, Korea*

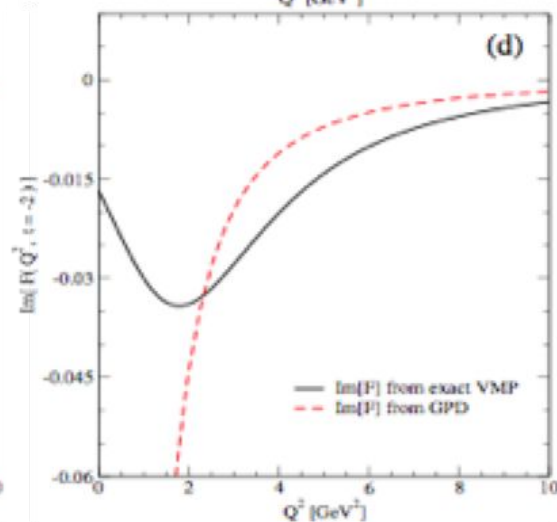
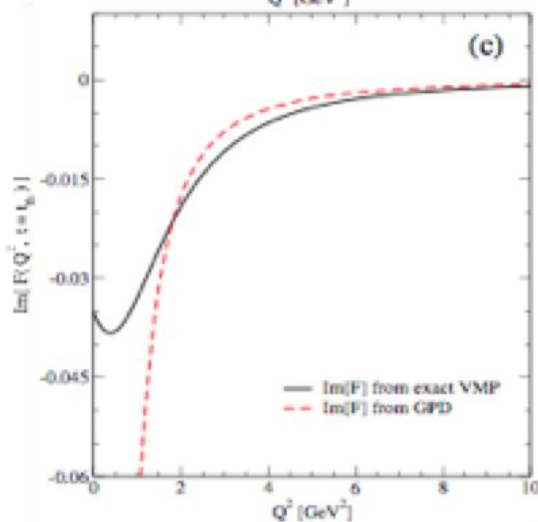
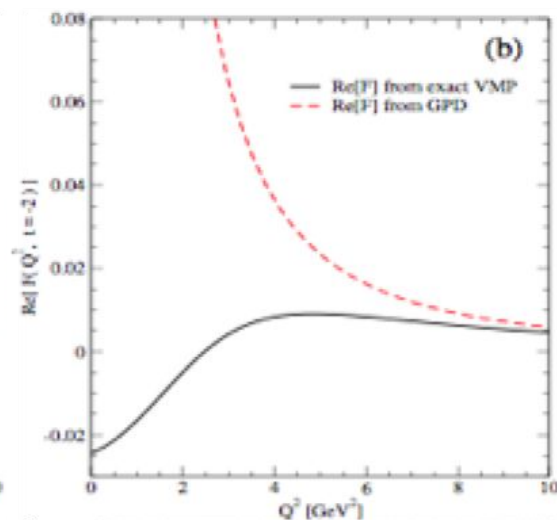
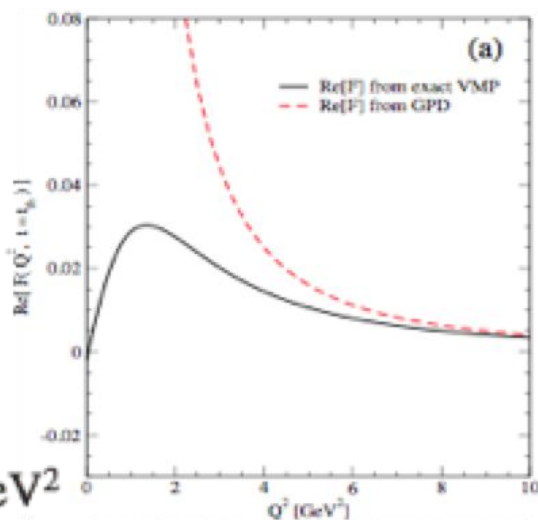
<sup>2</sup>*Department of Physics Education, Teachers College, Kyungpook National University, Daegu 41566, Korea*

<sup>3</sup>*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695-8202, USA*

<sup>4</sup>*Asia Pacific Center for Theoretical Physics, Pohang, Gyeongbuk 37673, Korea*



(Received 10 December 2021; accepted 30 March 2022; published 17 May 2022)

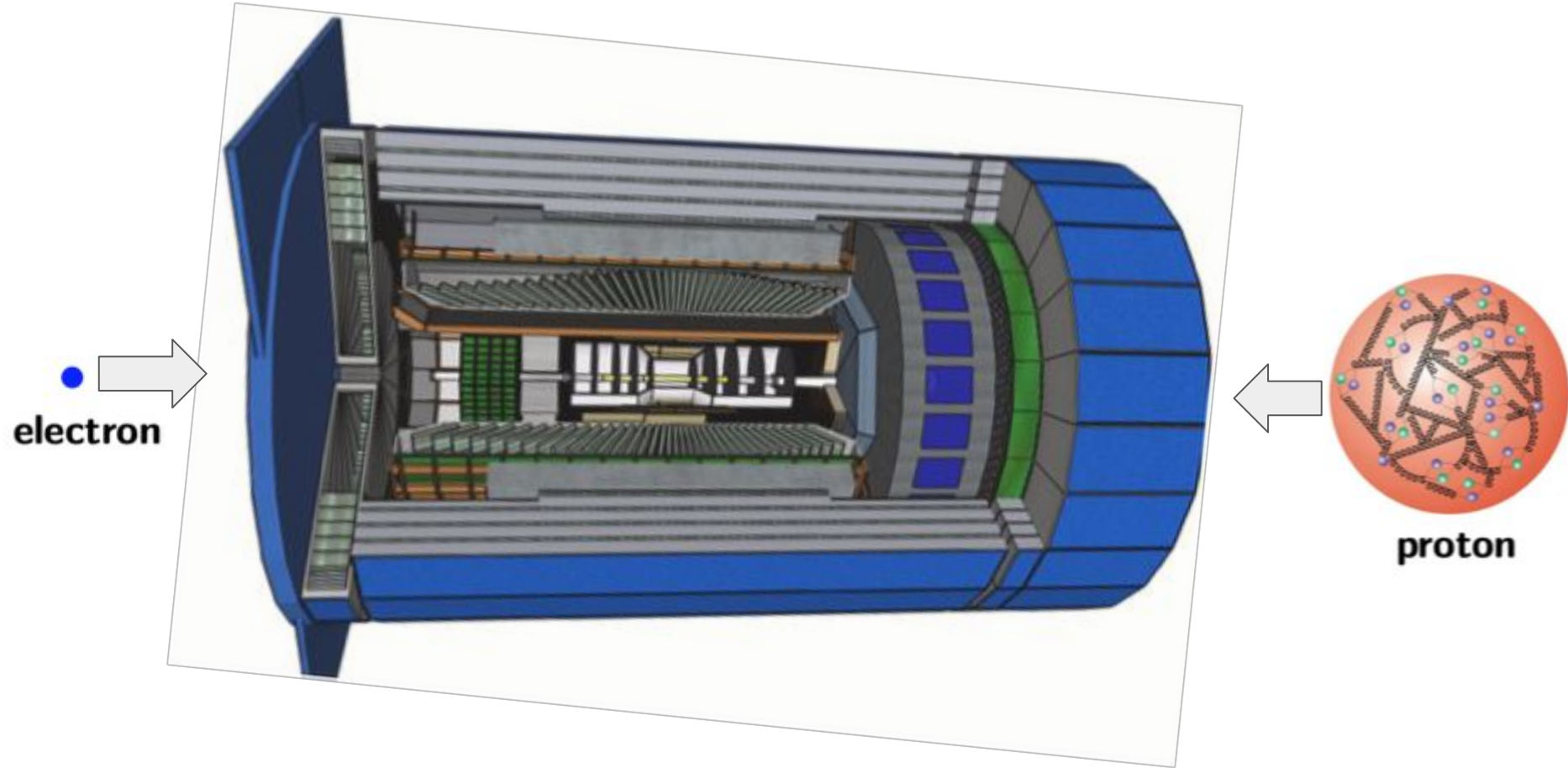


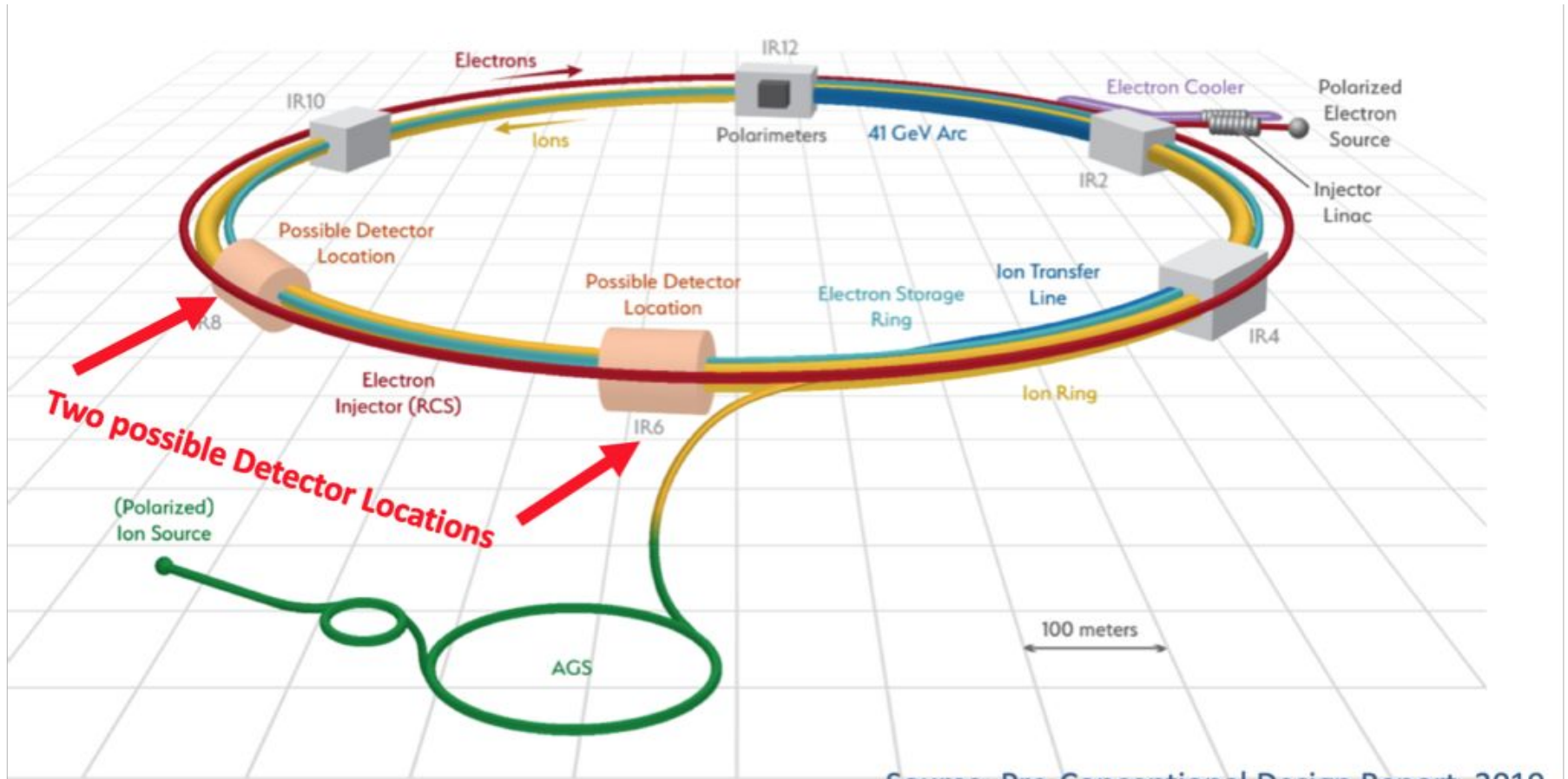
$$t = t_{\text{th}} \simeq -0.7593 \text{ GeV}^2$$

$$t = -2 \text{ GeV}^2$$

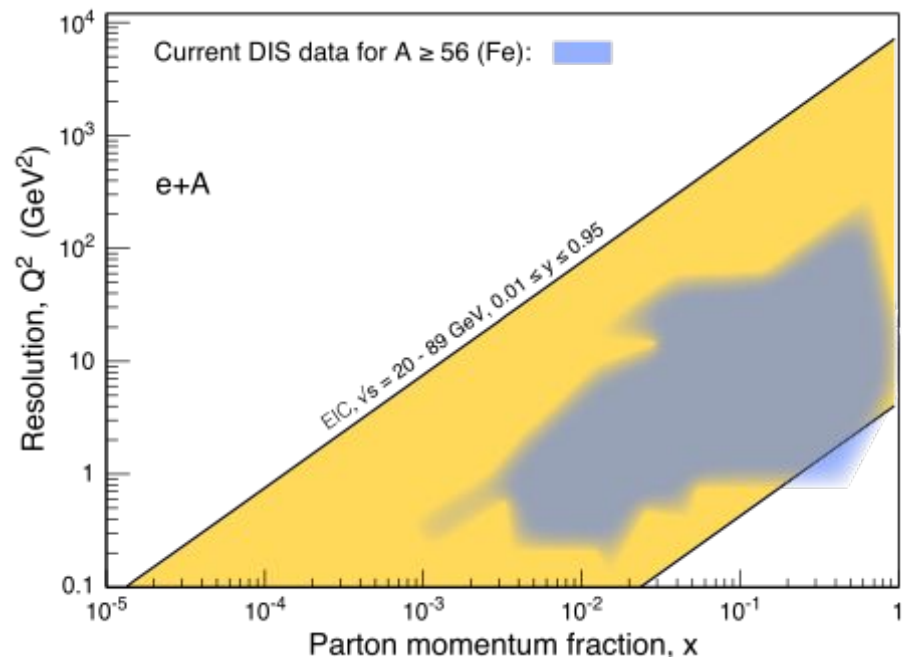
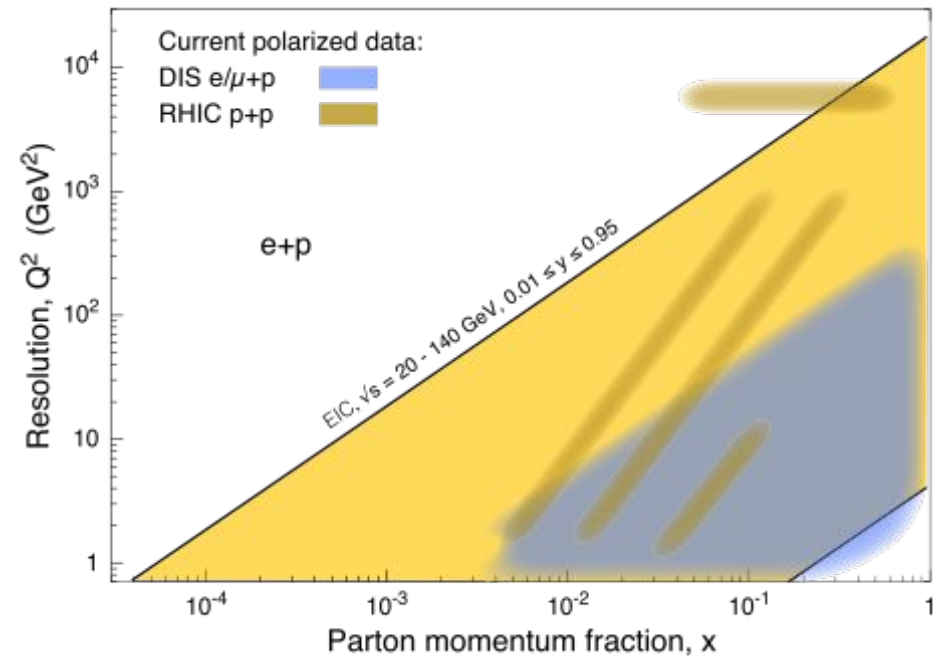
$$-t/Q^2 \lesssim 0.1$$

# Electron-Proton/Ion Collider (ePIC)





Source: Pre-Conceptual Design Report, 2019

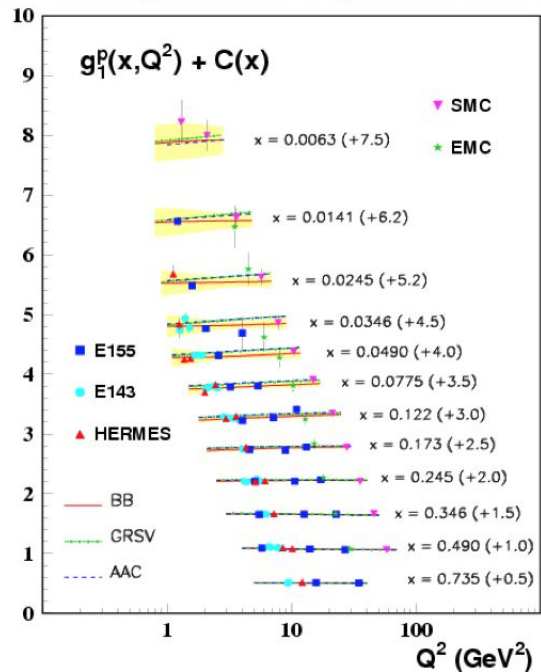


- Highly polarized electron ( $\sim 70\%$ ) and proton ( $\sim 70\%$ ) beams;
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium;
- Variable  $e+p$  center-of-mass energies from 28–100 GeV, upgradable to 28–140 GeV;
- High collision electron-nucleon luminosity  $10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ;
- The possibility of more than one interaction region.

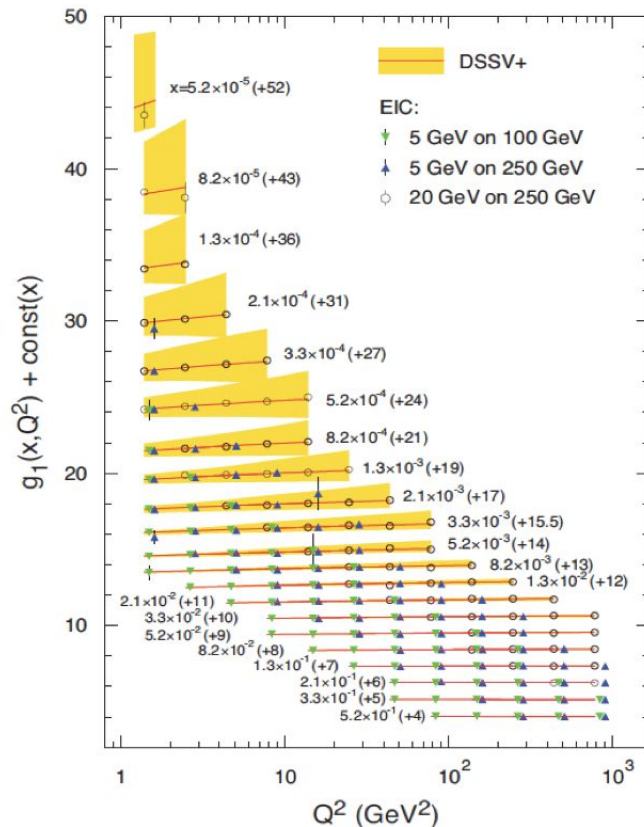


# The Future: Challenges & opportunities

## □ The power & precision of EIC:



at EIC



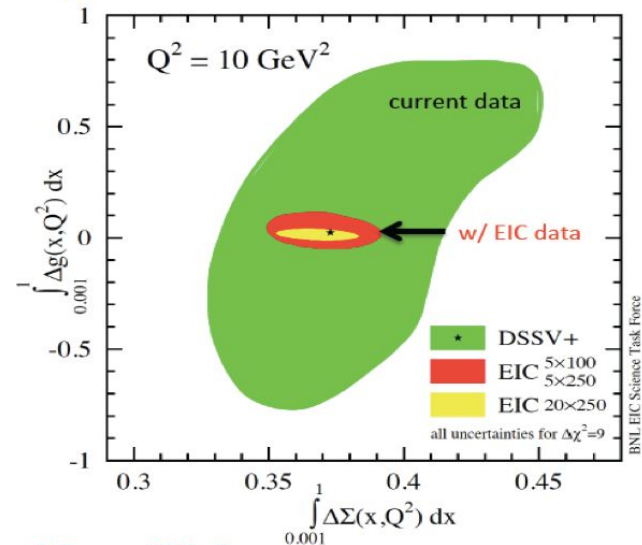
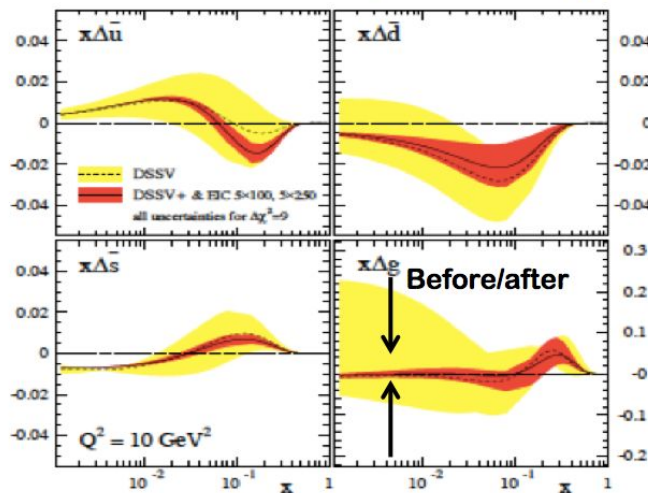
## □ Reach out the glue:

$$\frac{dg_1(x, Q^2)}{d \ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x, Q^2) + \dots$$

# The Future: Challenges & opportunities

## □ One-year of running at EIC:

Wider  $Q^2$  and  $x$  range including low  $x$  at EIC!



**No other machine in the world can achieve this!**

## □ Ultimate solution to the proton spin puzzle:

- ✧ *Precision measurement of  $\Delta g(x)$  – extend to smaller  $x$  regime*
- ✧ *Orbital angular momentum contribution – measurement of GPDs!*

# EIC Physics

- Proton spin
- Nucleon tomography and the origin of mass
- Gluon dynamics in a dense medium
- Nuclear modifications of parton distributions
- Hard probes in cold nuclei
- Fundamental symmetry physics
- AI/ML in data analysis
- Nuclear data

# **The case for an EIC Theory Alliance: Theoretical Challenges of the EIC**

**R. Abir, et al. [arXiv:2305.14572 [hep-ph]]**

- **WORKFORCE DEVELOPMENT AND DEI**
- **OPPORTUNITIES WITH AI/ML**
- **INTERSECTIONS OF QUANTUM INFORMATION SCIENCE AND EIC**

# Summary and Outlook

- We summarized the present state of EIC-related physics and identified the theory progress needed for maximizing the impact of EIC physics.
- There are many theoretical challenges that have to be addressed in the coming decades.
- Examples include higher order pQCD calculations interfacing them with phenomenology and lattice QCD.
- We need to pay attention to the importance of strong theory support alongside the experimental program to realize the full discovery potential of the EIC physics.