Overview of EIC Physics

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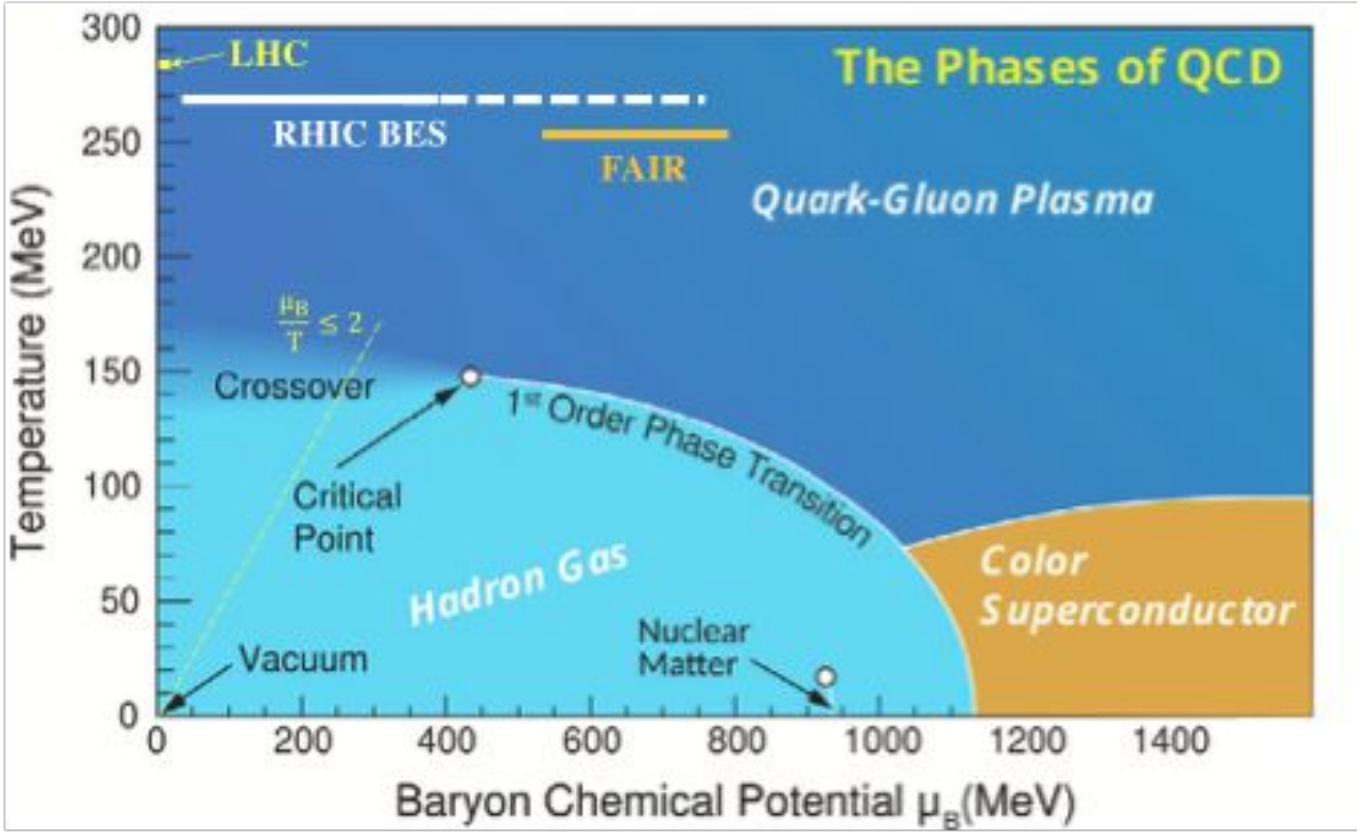
Hot and Cold QCD

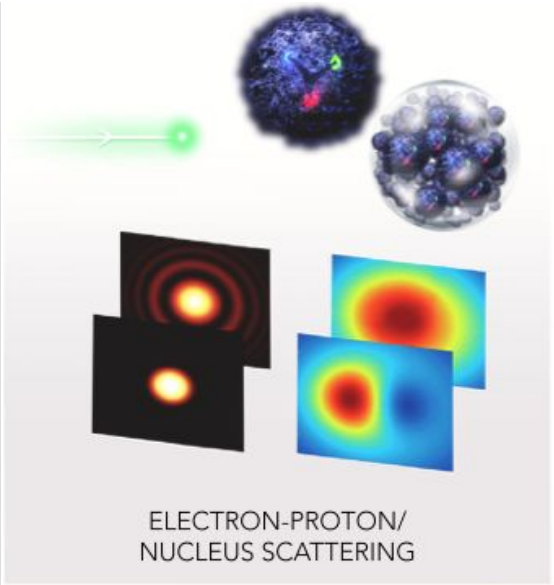
RHIC@BNL
LHC@CERN

JLab

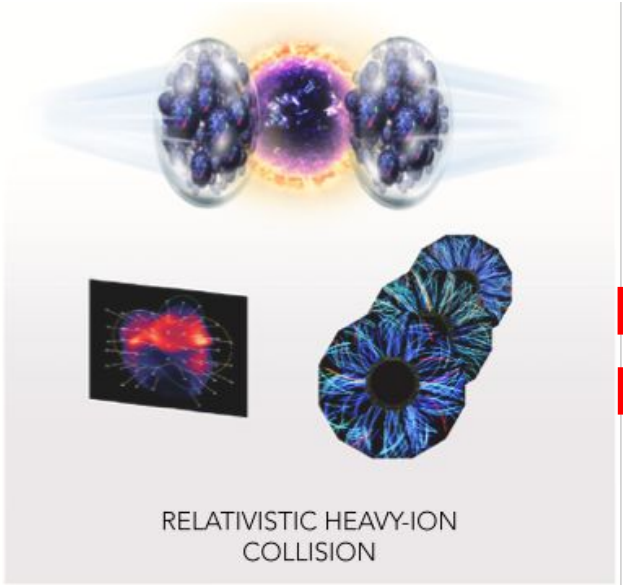


Cold and Hot QCD

JLab



ELECTRON-PROTON/
NUCLEUS SCATTERING



RELATIVISTIC HEAVY-ION
COLLISION

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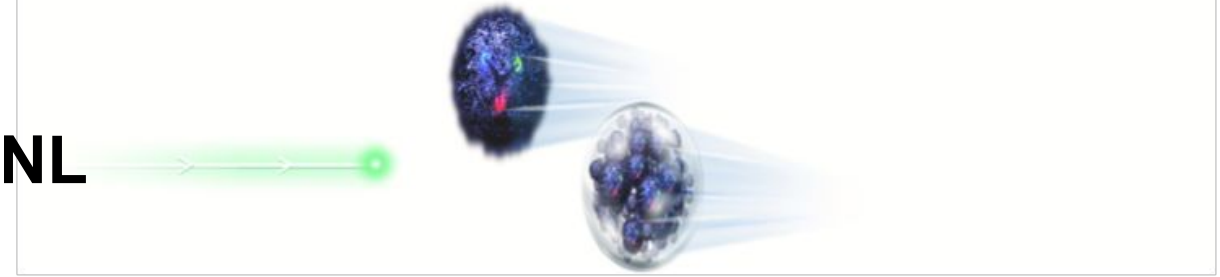
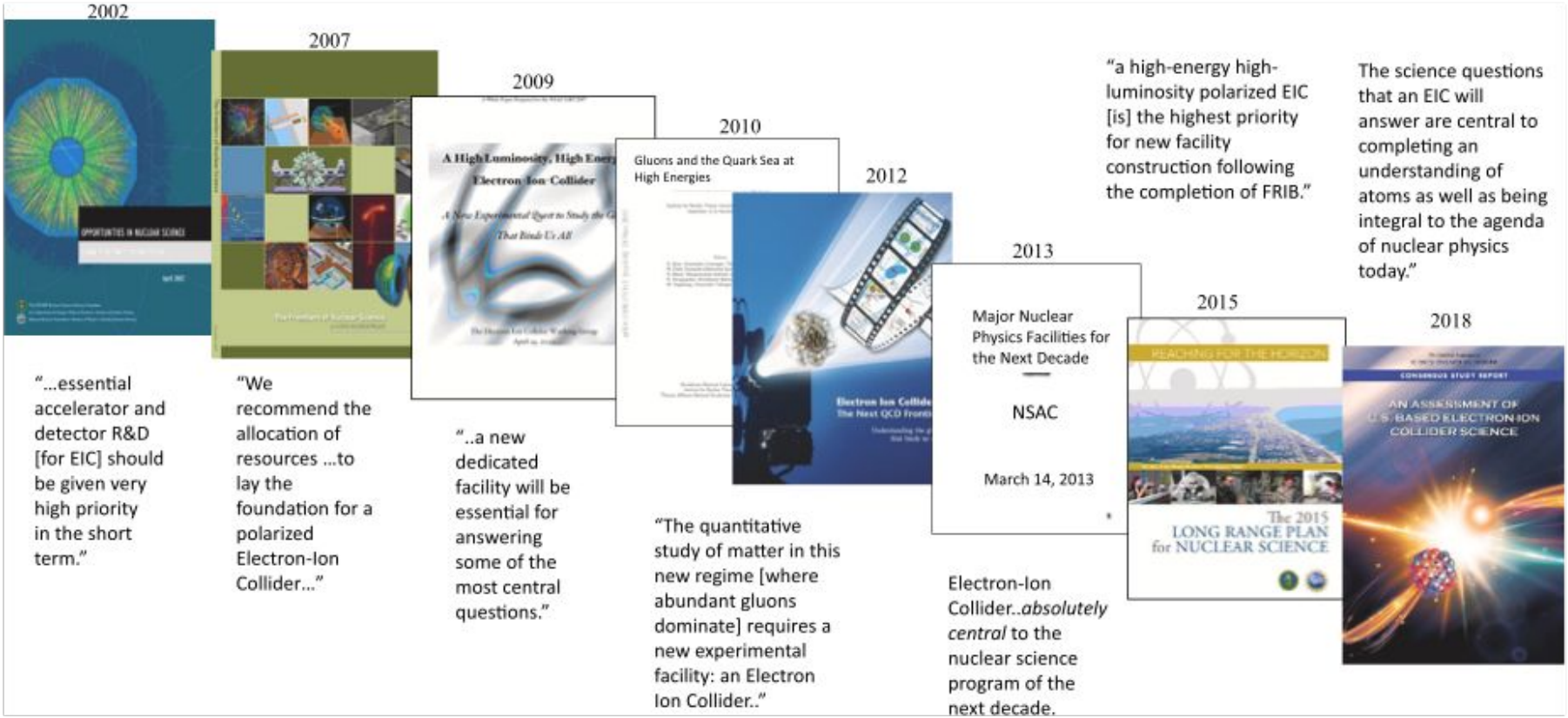
EIC@BNL



ELECTRON-PROTON/
ION COLLISION

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

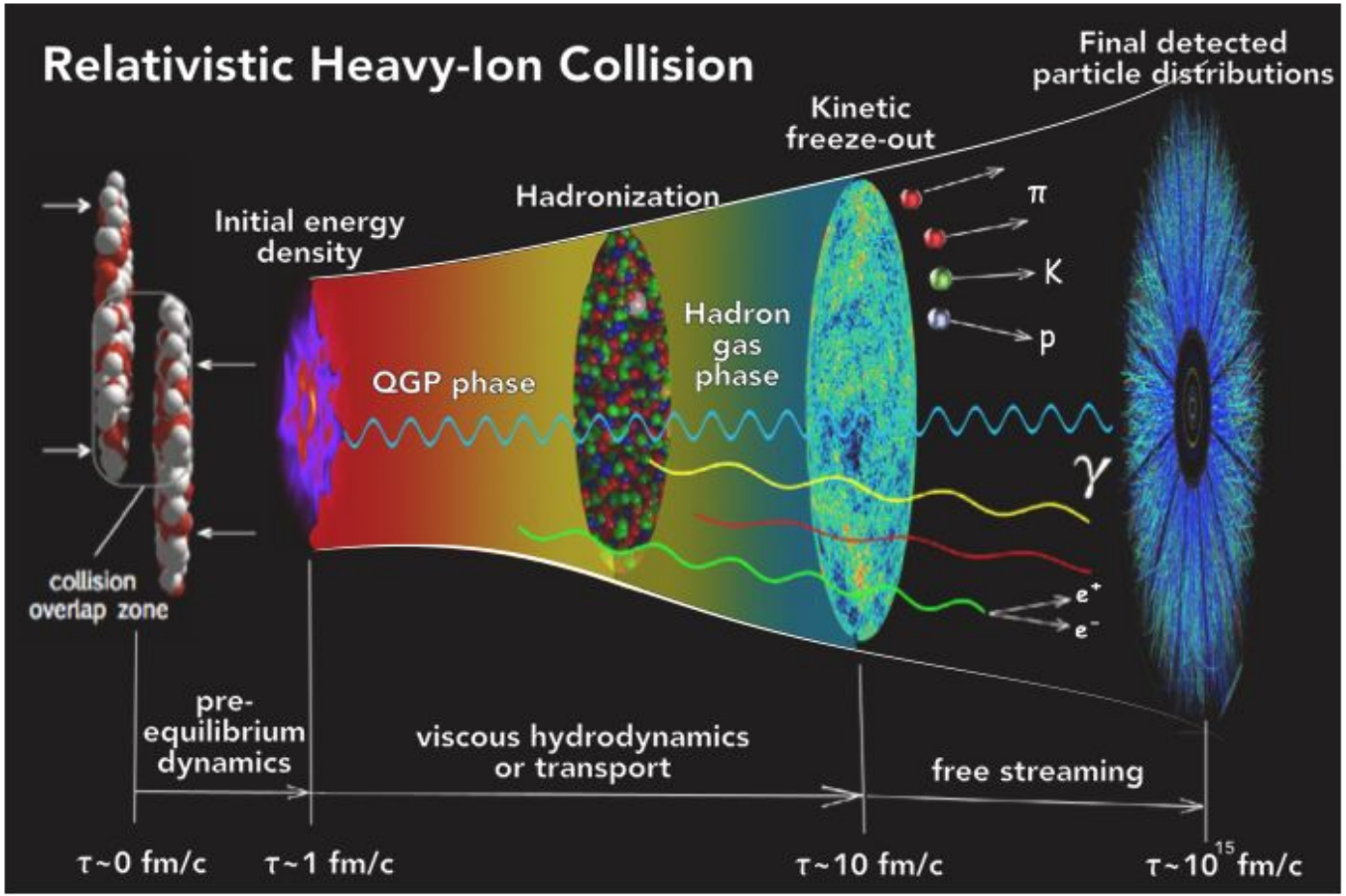
P. Achenbach, D. Adhikari, A. Afanasev et al. — *Nuclear Physics, Section A 1047 (2024) 122874*

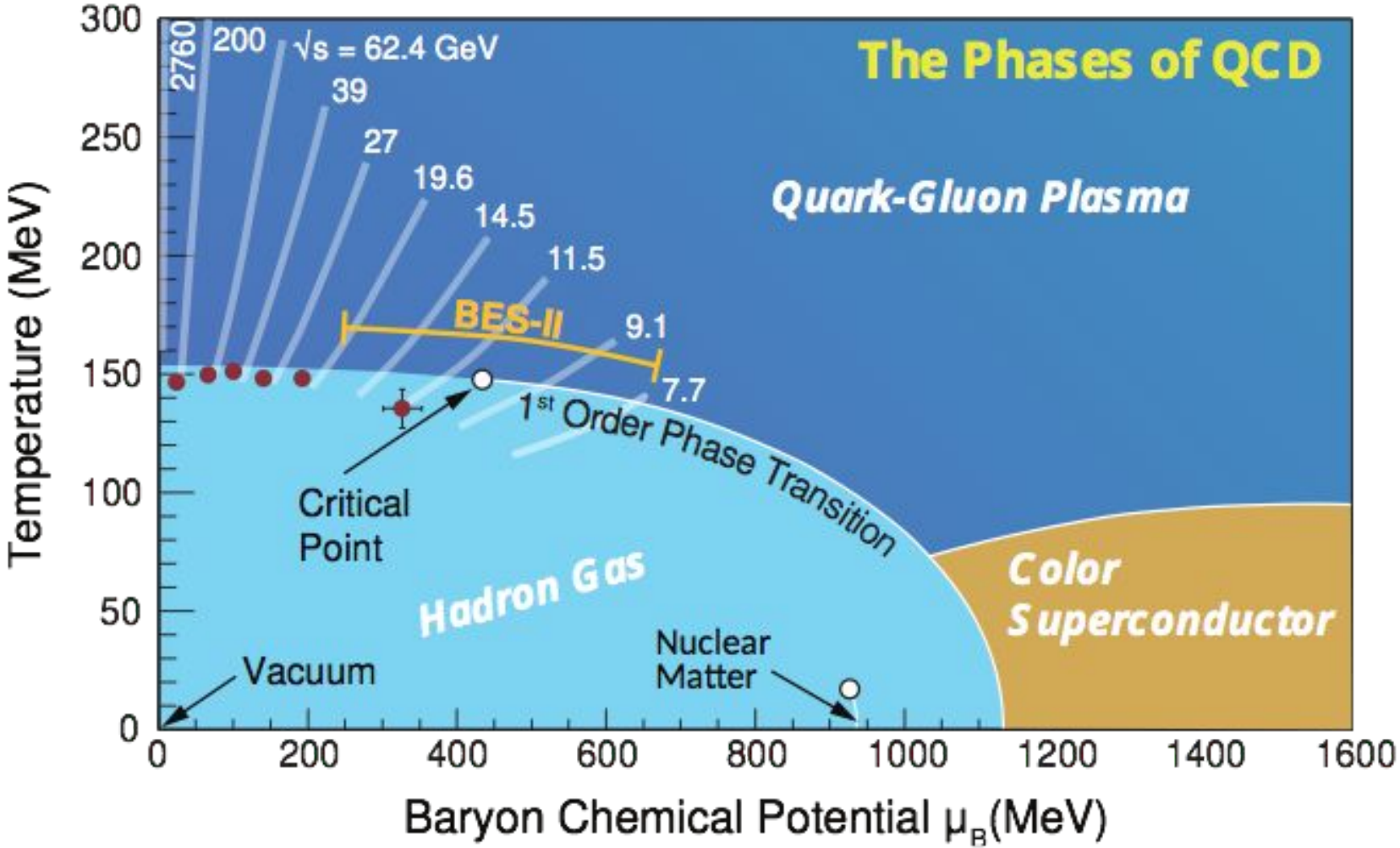


Outline

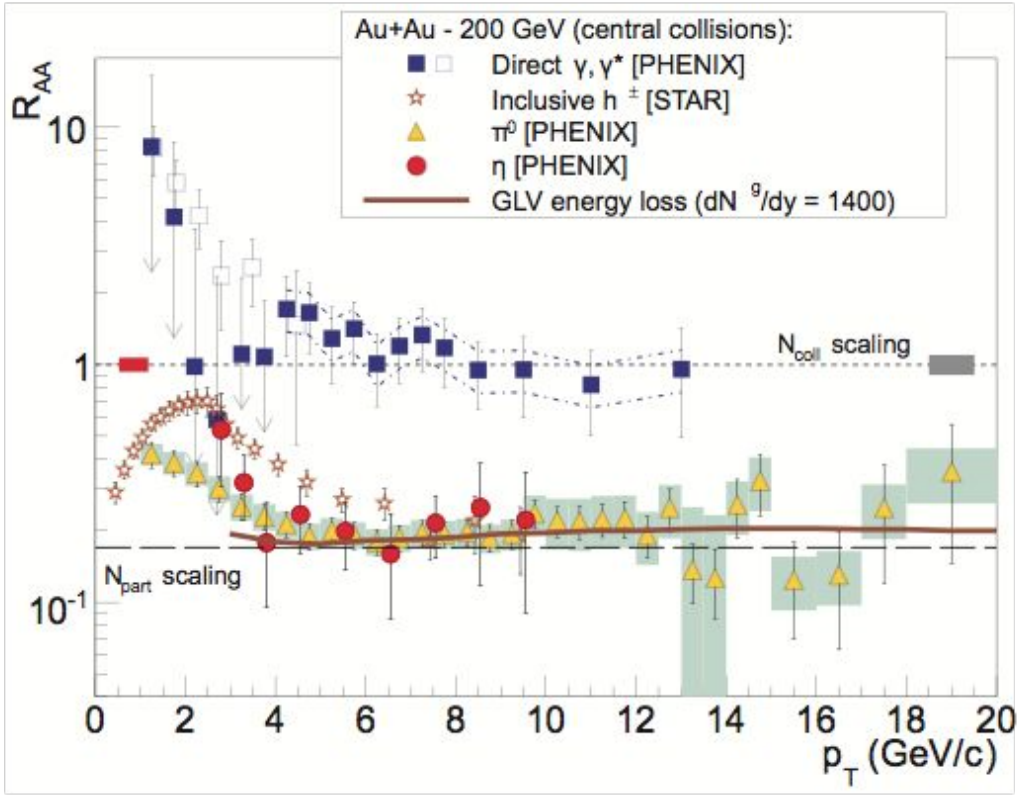
1. Progress in Hot QCD
2. Progress in Cold QCD
3. EIC Project
4. Summary and Outlook

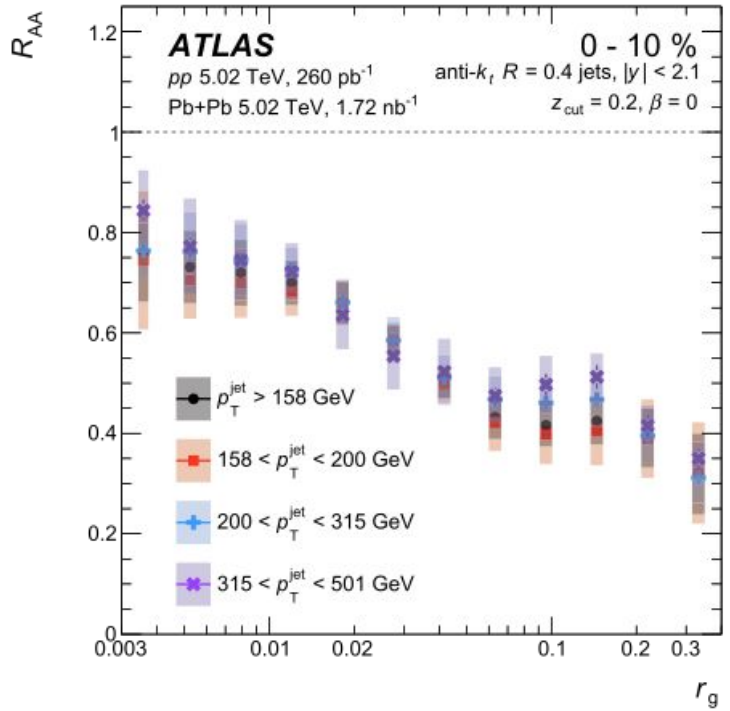
Progress in Hot QCD



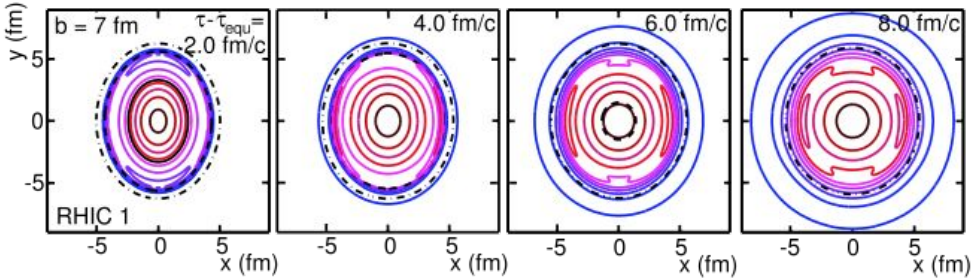

The Phases of QCD
Quark-Gluon Plasma
Color Superconductor
Hadron Gas
Critical Point
1st Order Phase Transition
BES-II
Vacuum
Nuclear Matter
√s = 62.4 GeV
2760
200
39
27
19.6
14.5
11.5
9.1
7.7
Temperature (MeV)
Baryon Chemical Potential μB(MeV)
0
50
100
150
200
250
300
0
200
400
600
800
1000
1200
1400
1600

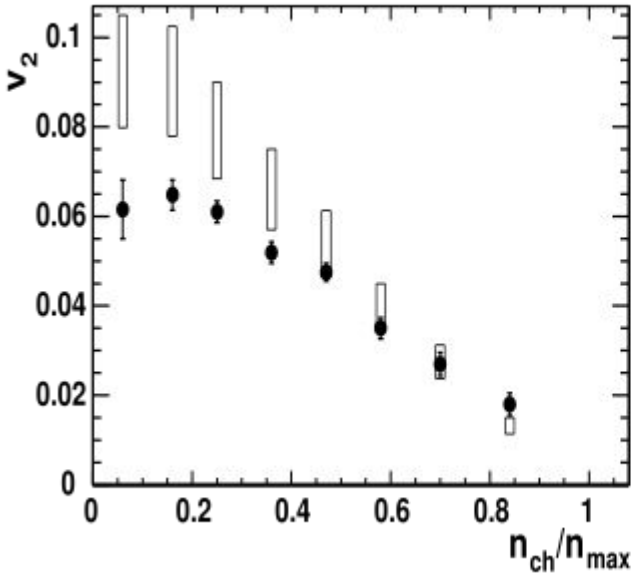
$$R_{\mathrm{AA}}(p_T) = \frac{dN_{\mathrm{AA}}/dp_T}{N_{\mathrm{coll}} dN_{\mathrm{pp}}/dp_T}$$

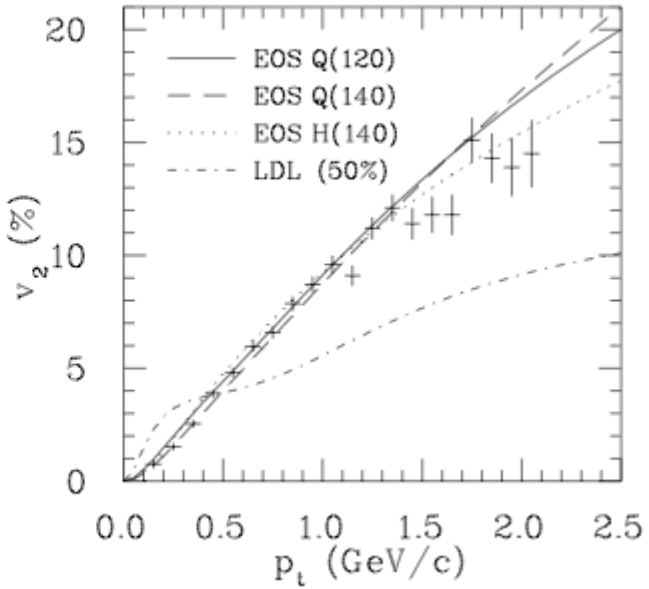


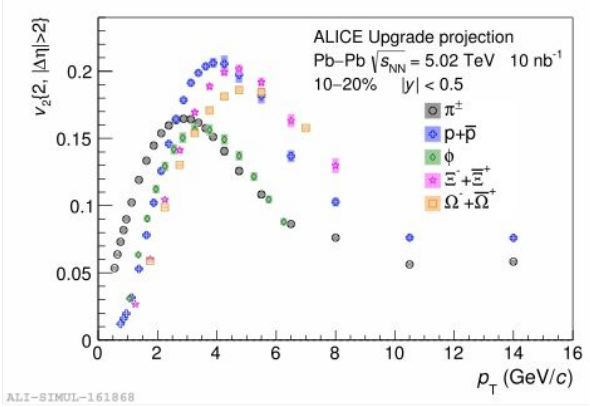


$$\frac{dN_i}{p_T dp_T\, dy\, d\varphi_p}(b) = \frac{1}{2\pi}\frac{dN_i}{p_T dp_T\, dy}(b)\left(1 + 2\, v_2^i(p_T, b)\cos(2\varphi_p) + \ldots\right)$$





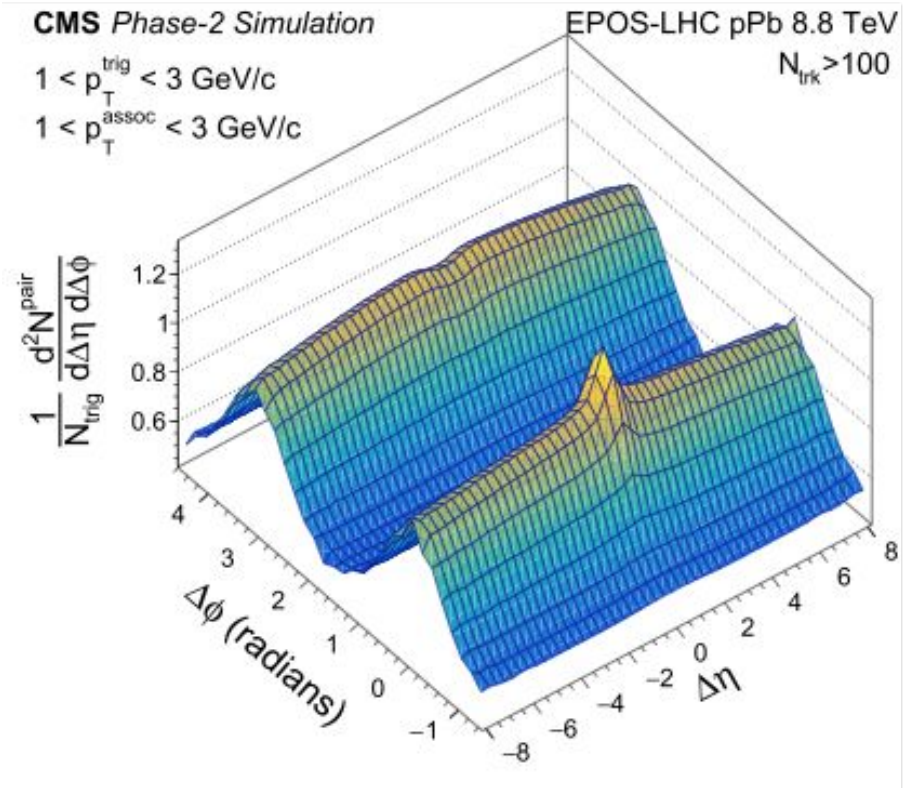




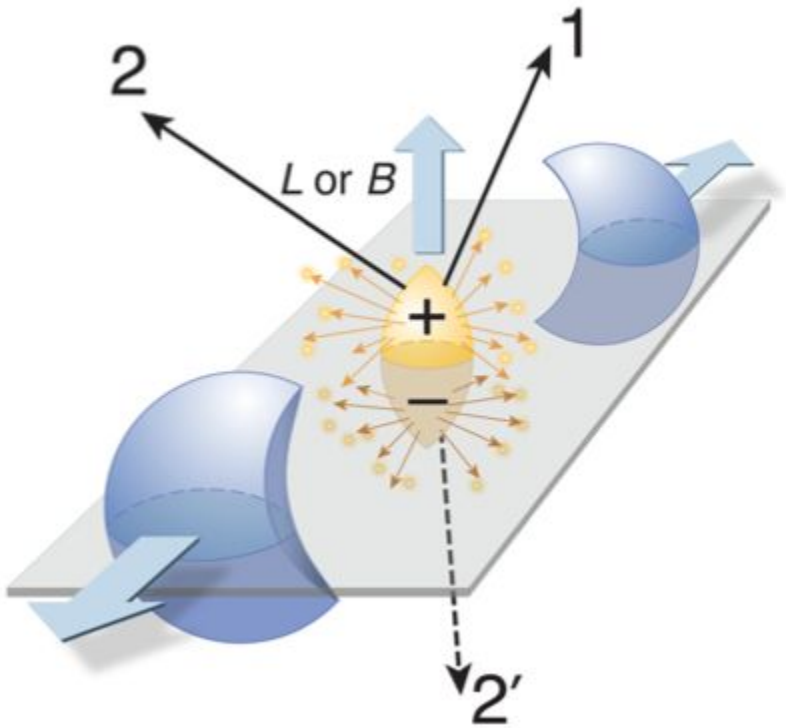
"$\bar{p}/\pi^- > 1$ anomaly"

long range rapidity correlations

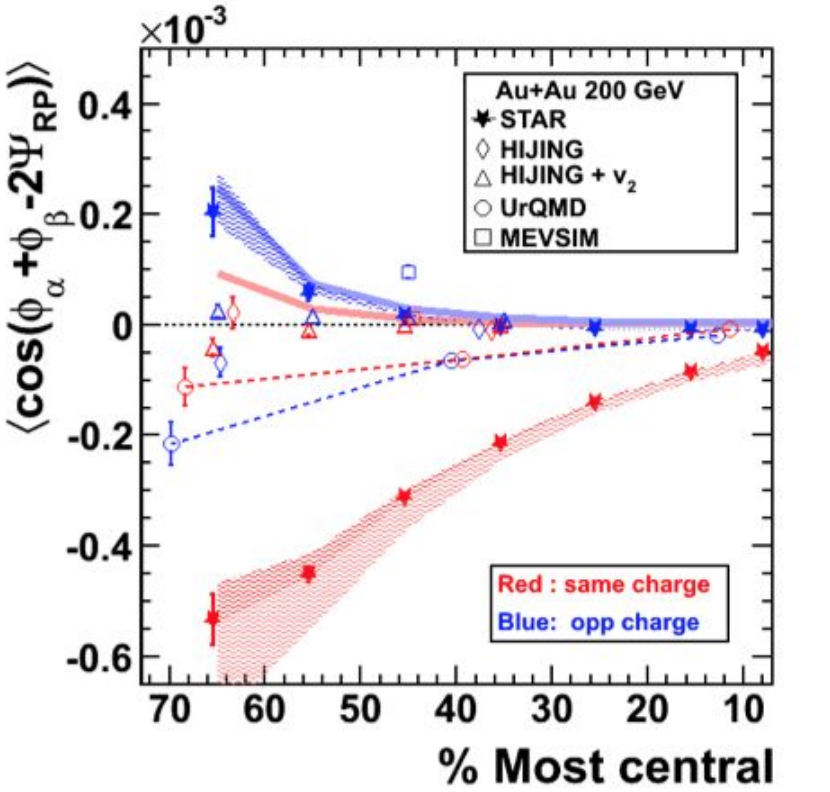
Color Glass Condensate Glasma "ridge" events



Chiral Magnetic Effect

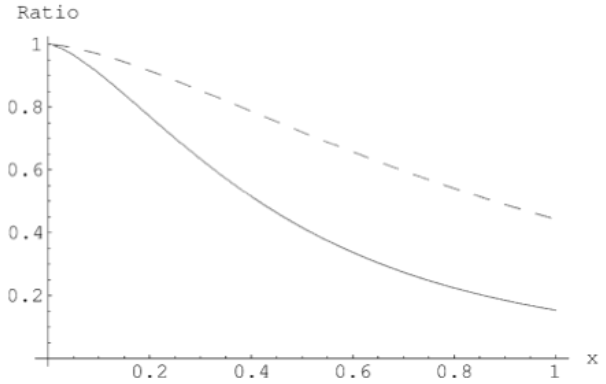


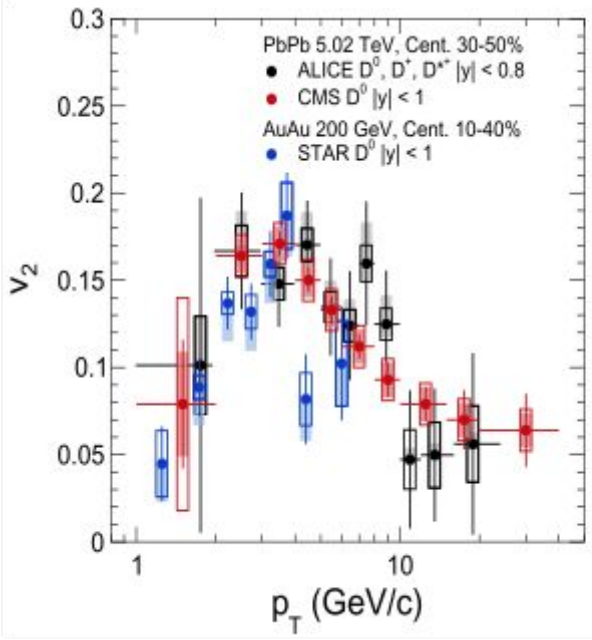
Phys. Rev. Lett. 103 (2009) 251601

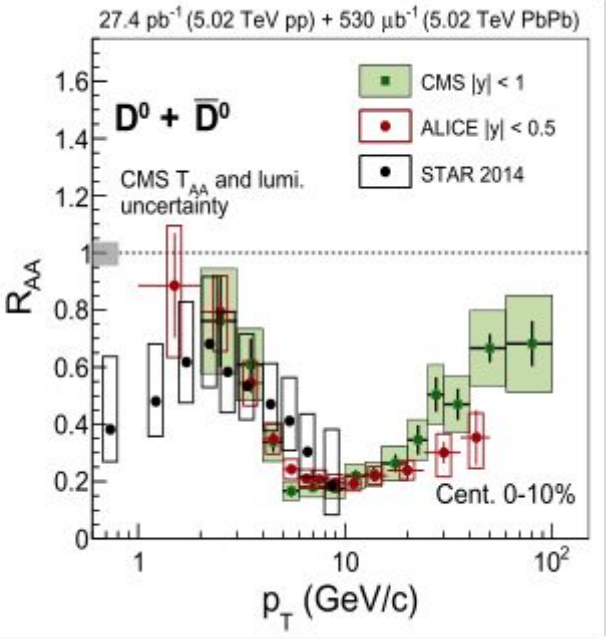


Heavy Quark vs. Light Quark

"dead cone" effect



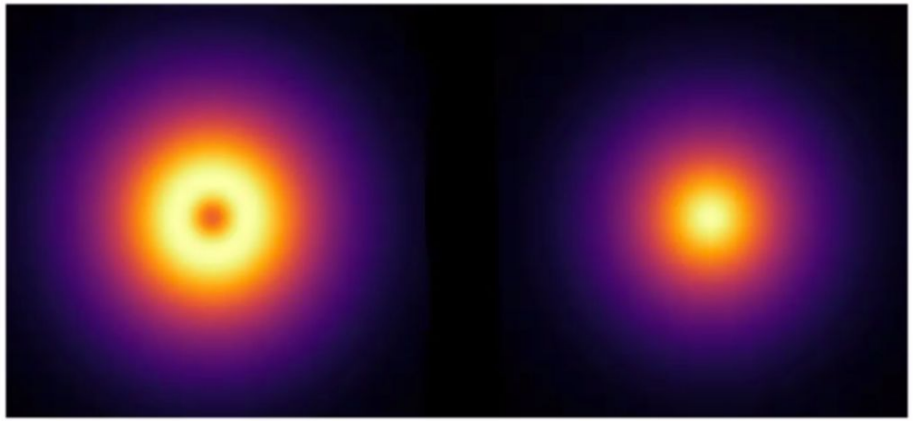


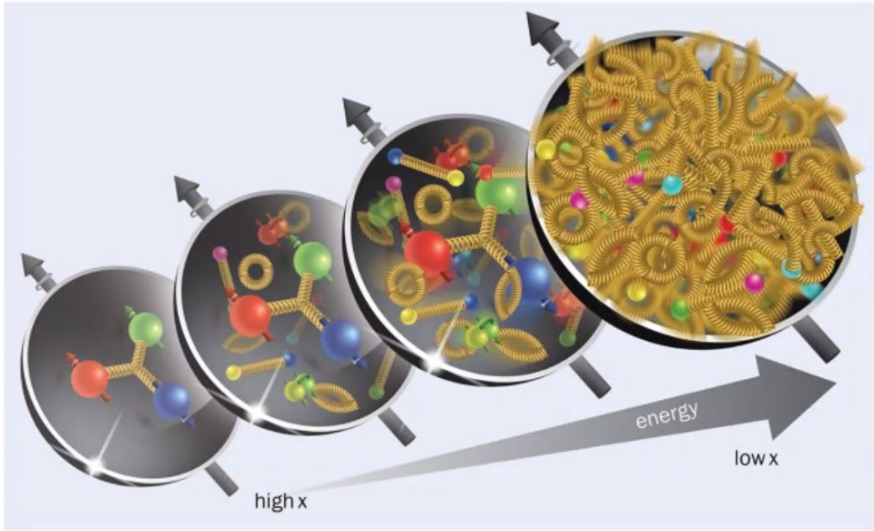


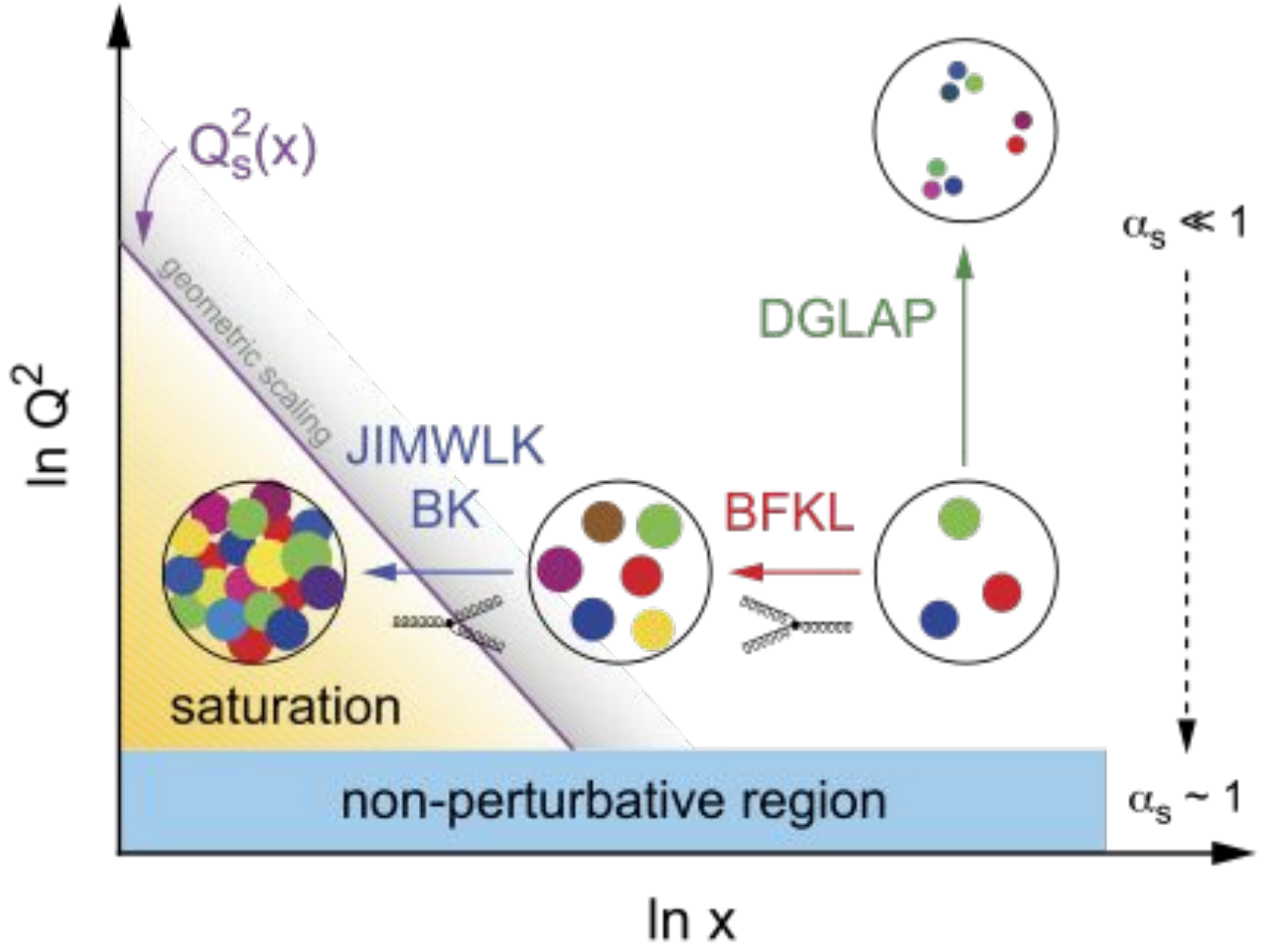
Progress in Cold QCD

Femtoscale imaging

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

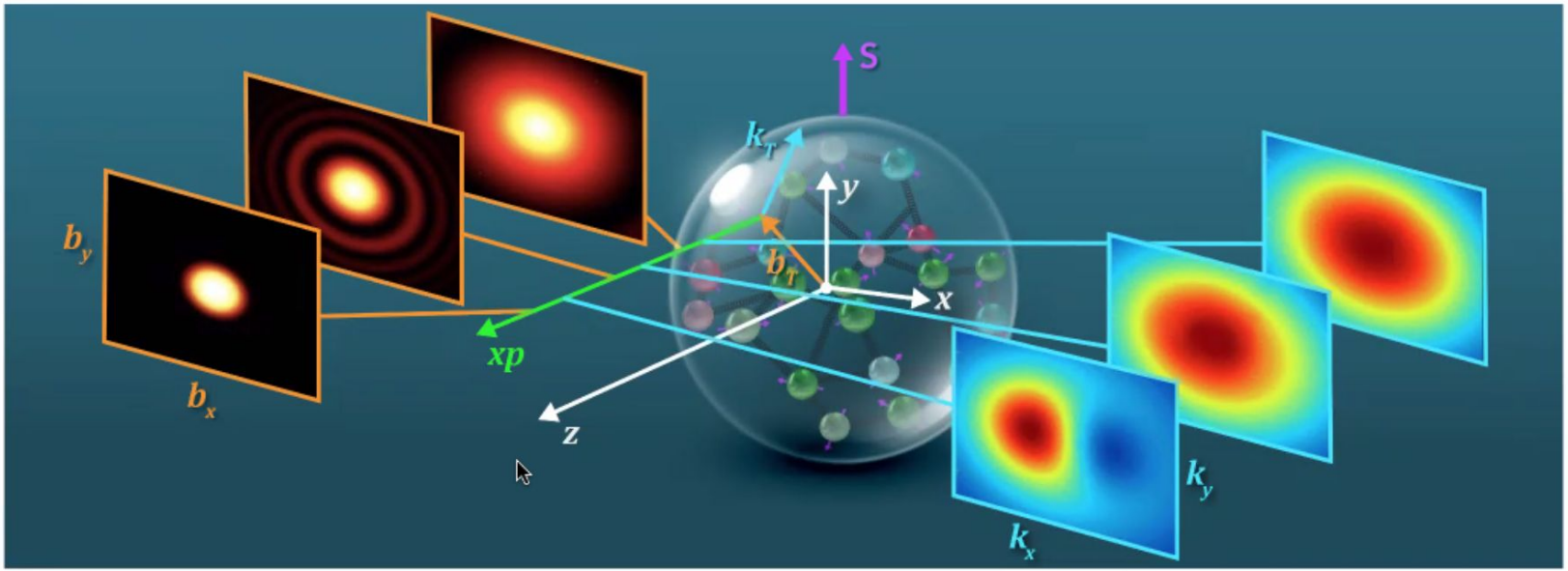





$Q_s^2(x)$
geometric scaling
JIMWLK
BK
BFKL
DGLAP
$\alpha_s \ll 1$
$\alpha_s \sim 1$
saturation
non-perturbative region
ln Q^2
ln x

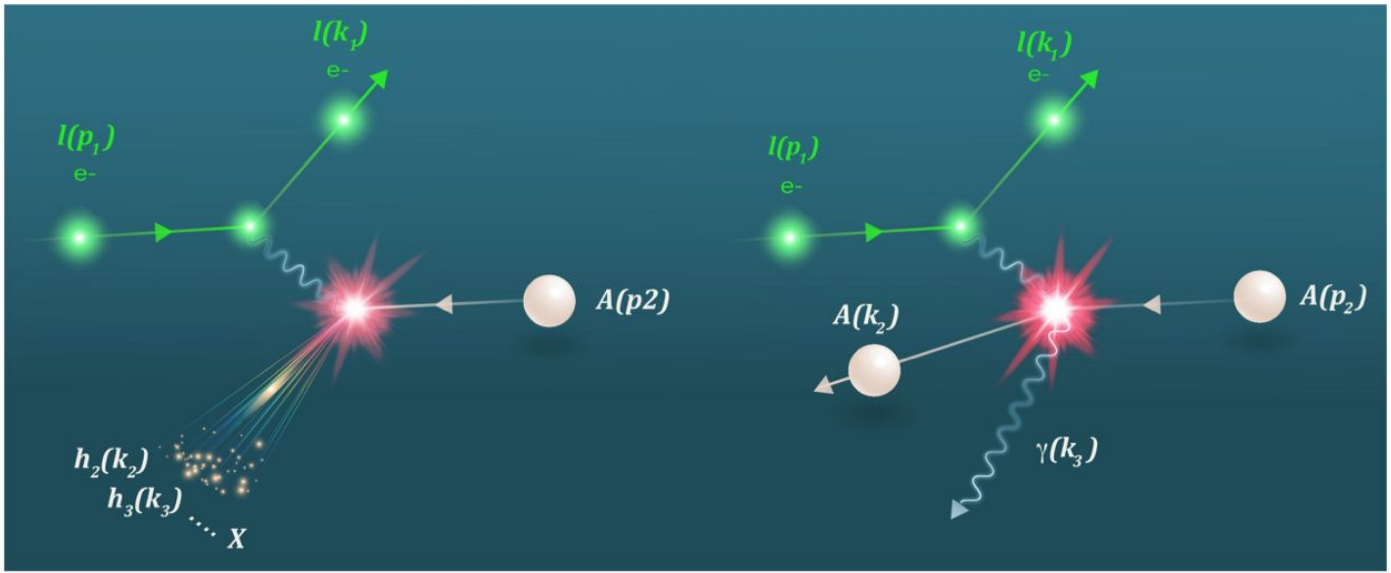
What are we looking for?

- Images of protons in coordinate and momentum space



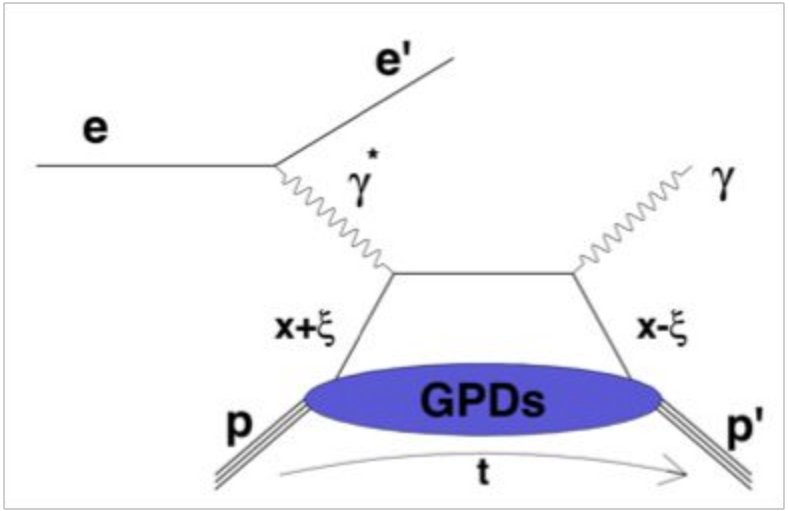
How do we do it?

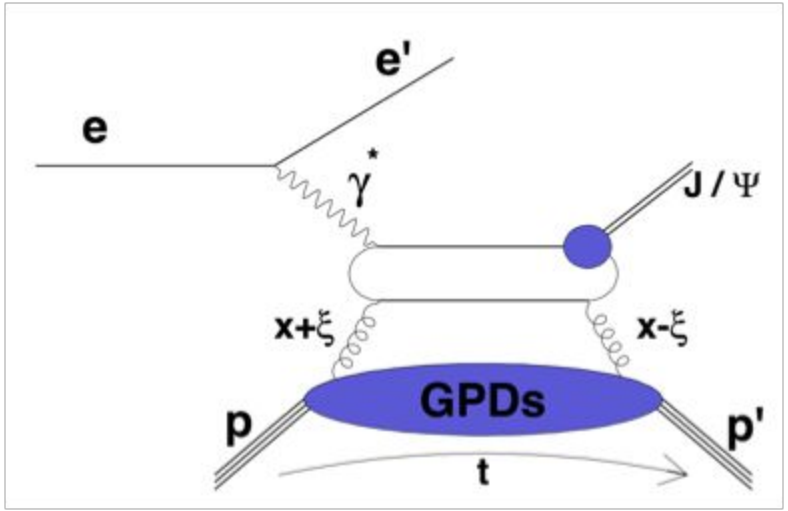
- Through experimental data in factorizable processes
- Focus on electron-induced reactions that can be realized at EIC and JLab



SIDIS -- TMDs

DVCS -- GPDs





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

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

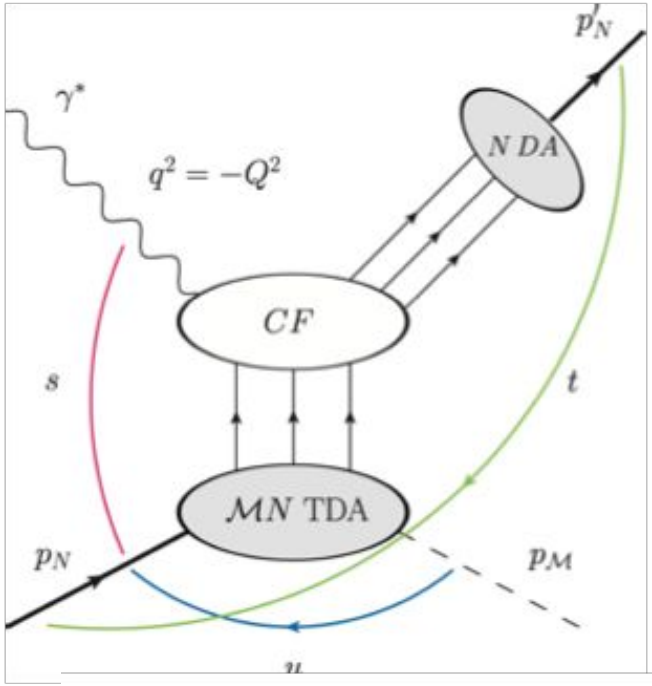
δg^{00} — Mass

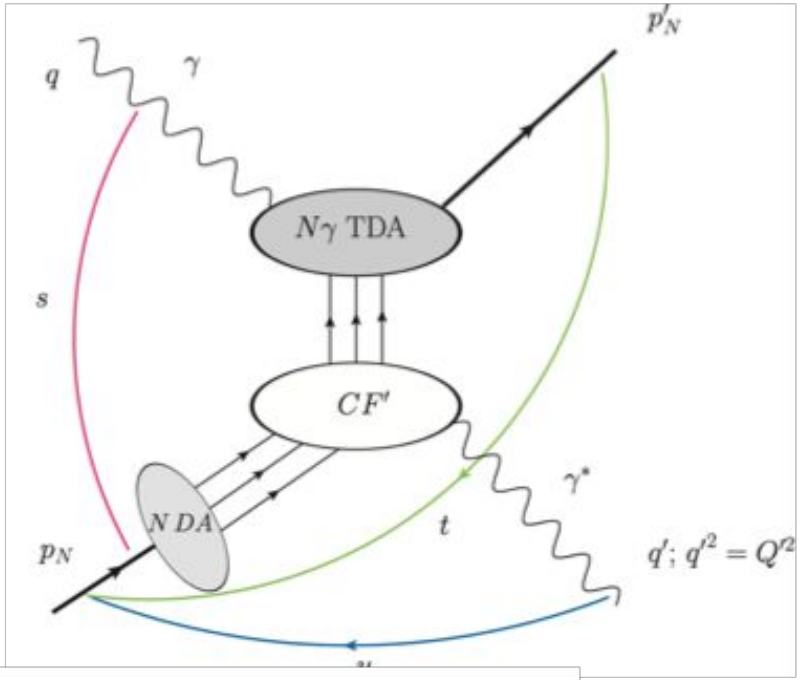
δg^{0i} — Spin

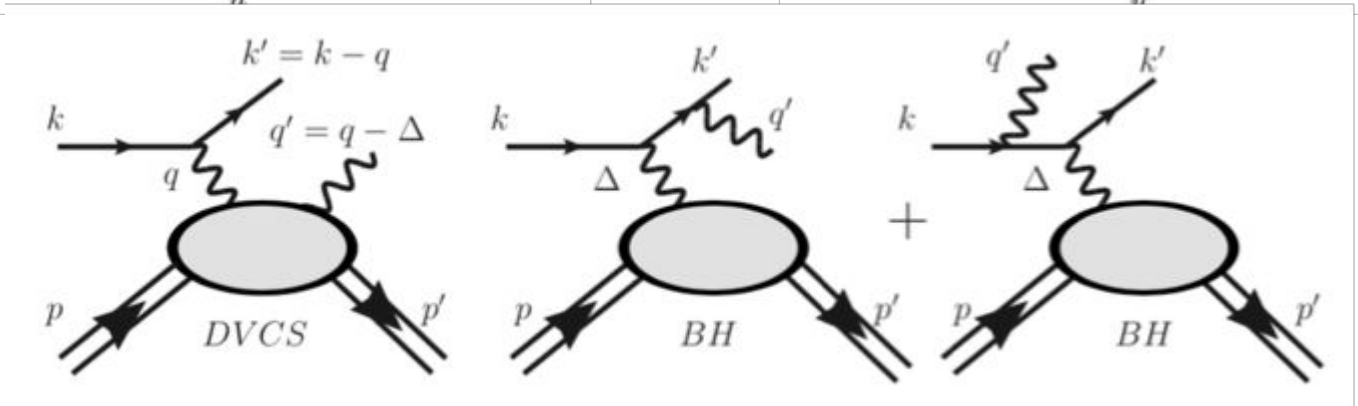
δg^{ij} — deformation of space = elastic properties of N

non − conservation of EMT pieces

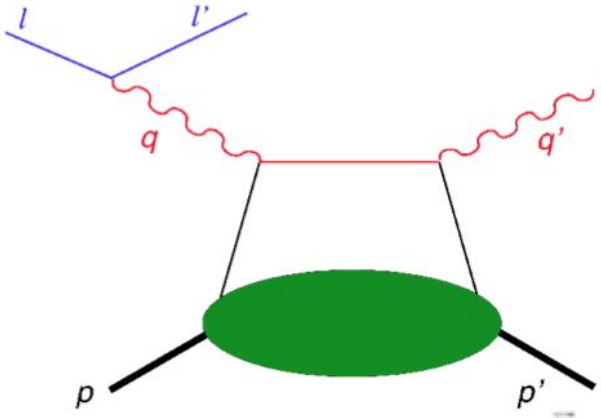
$$\sum_a A^a(0) = 1 \qquad \sum_a J^a(0) = \frac{1}{2} \qquad \sum_a \bar{c}^a(t) = 0$$

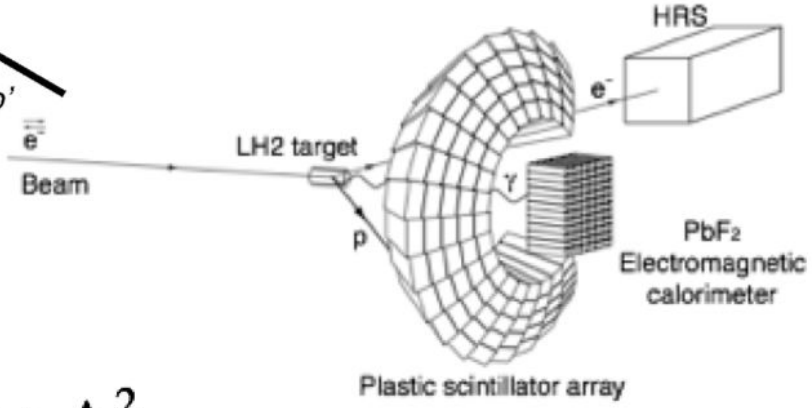

p'_N
γ^*
$q^2 = -Q^2$
N DA
CF
s
t
$\mathcal{M}N$ TDA
p_N
$p_{\mathcal{M}}$


p'_N
q
γ
$N\gamma$ TDA
s
CF'
γ^*
N DA
t
p_N
$q'; q'^2 = Q'^2$


$k' = k - q$
k
$q' = q - \Delta$
q
p
DVCS
p'
k'
k
q'
Δ
p
BH
p'
+
q'
k'
k
Δ
p
BH
p'

Better Work in Forward Direction





GPD

LFD

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

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,[1,*] Ho-Meoyng Choi,[2,†] Chueng-Ryong Ji,[3,‡] and Yongseok Oh[1,4,§]

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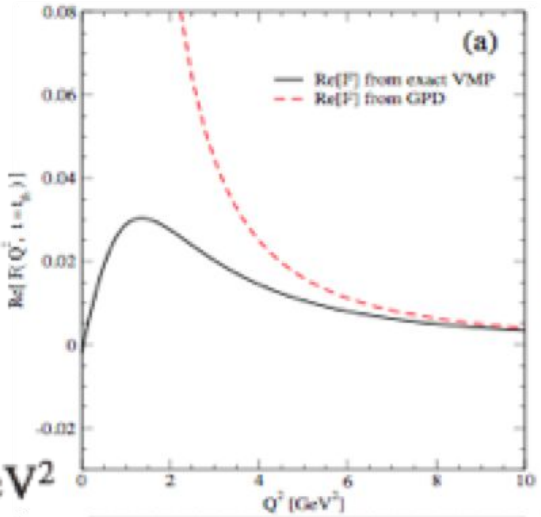
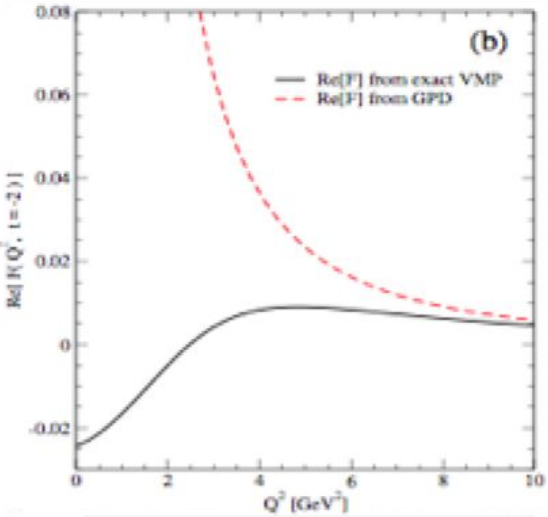
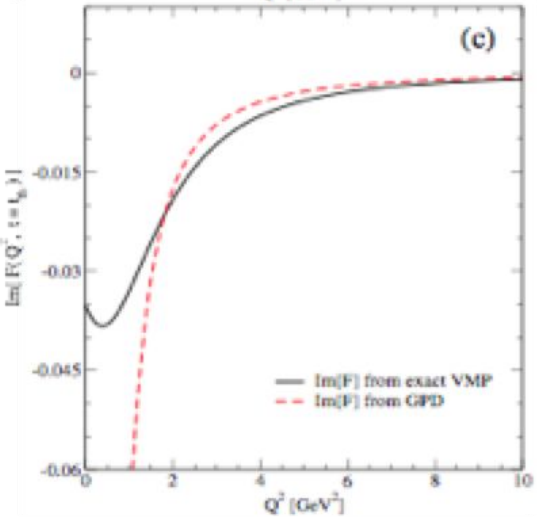
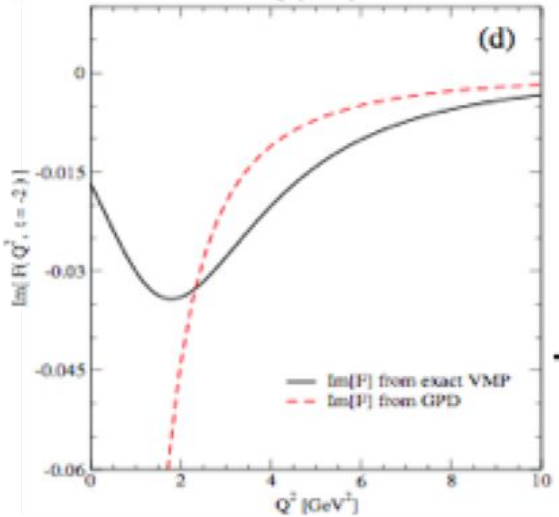




$t = t_{\text{th}} \simeq -0.7593\,\text{GeV}^2$

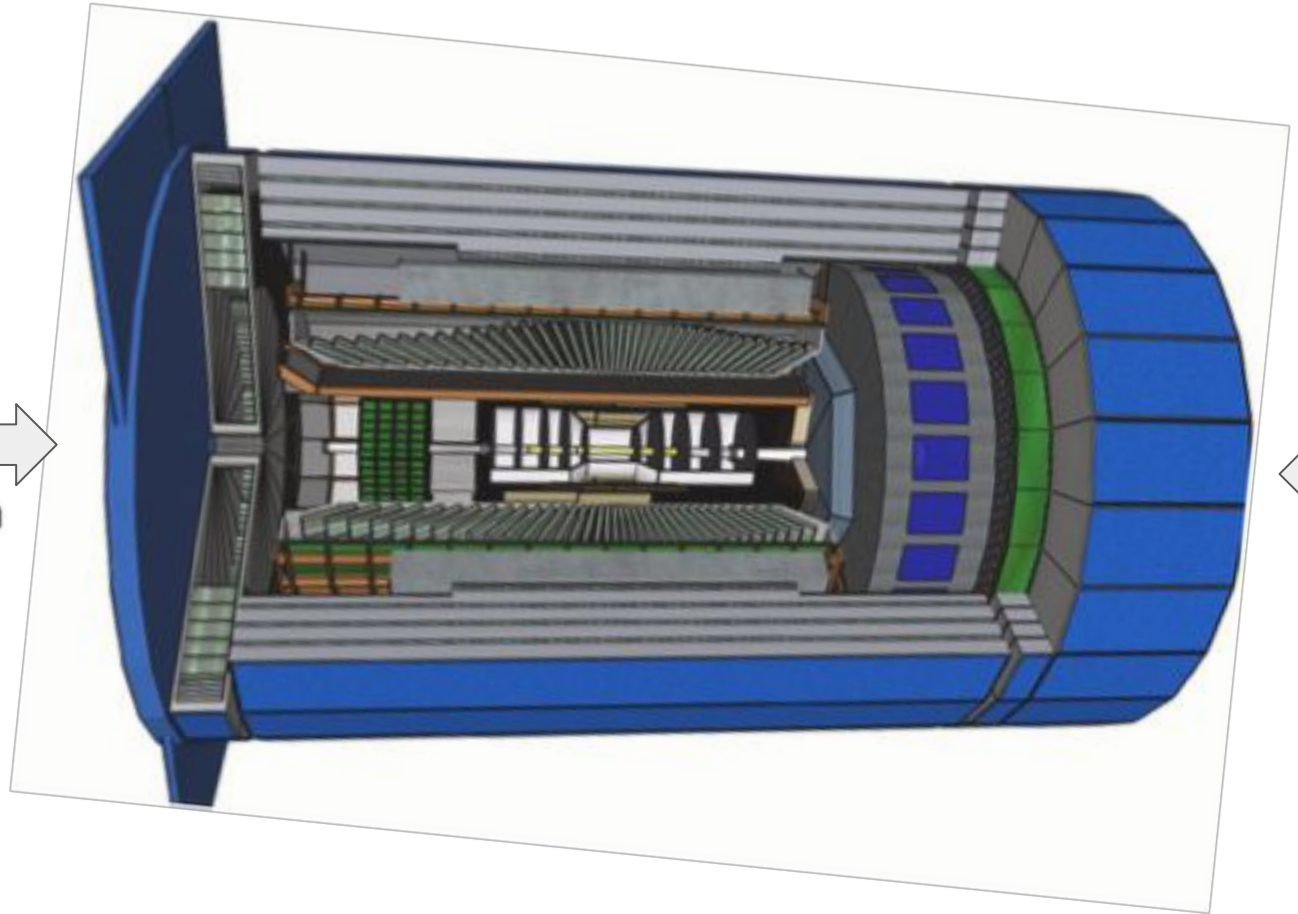
$t = -2\,\text{GeV}^2$





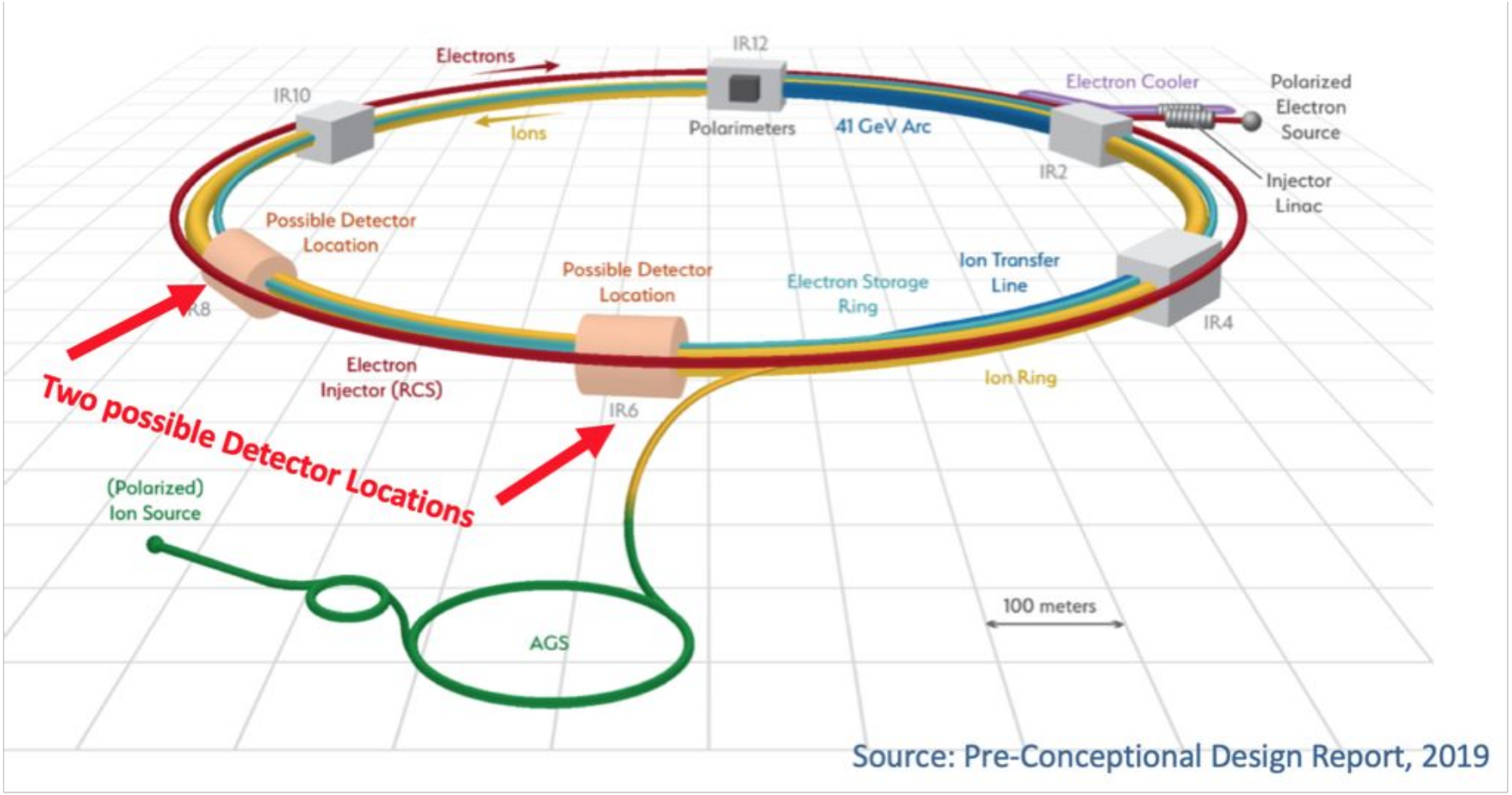
$-t/Q^2 \lesssim 0.1$

Electron-Proton/Ion Collider (ePIC)

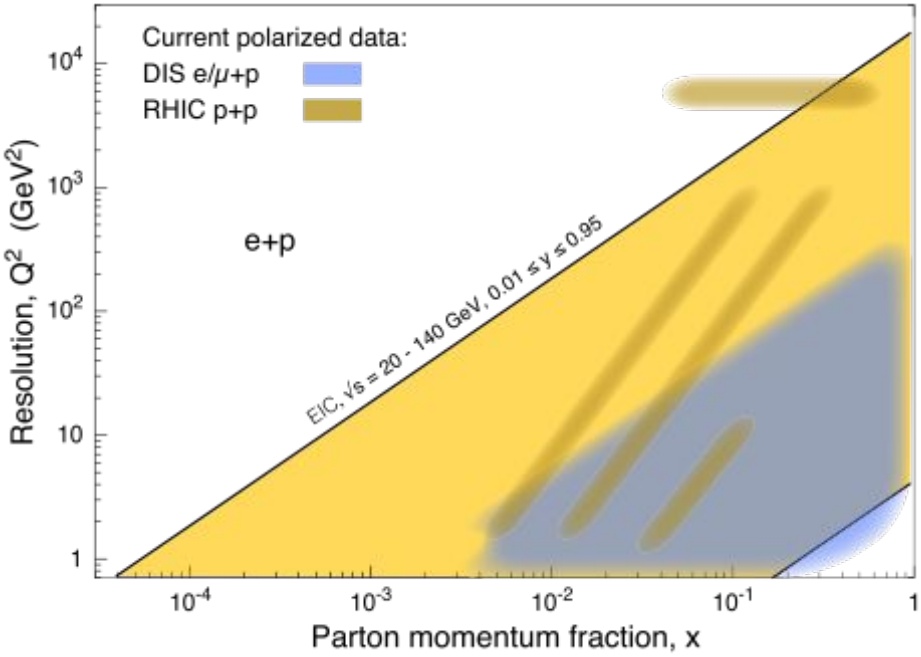


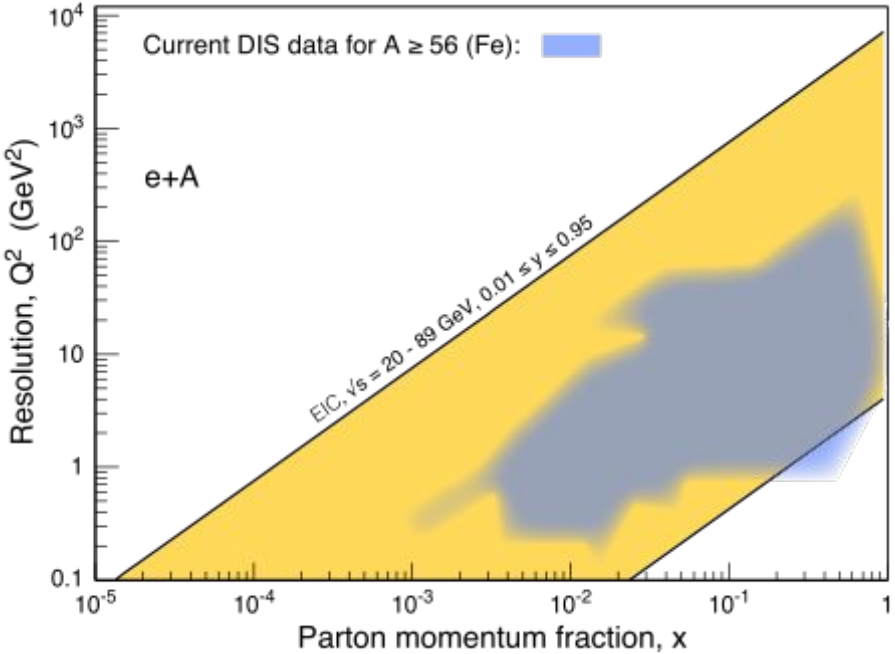
electron

proton



Source: Pre-Conceptional Design Report, 2019

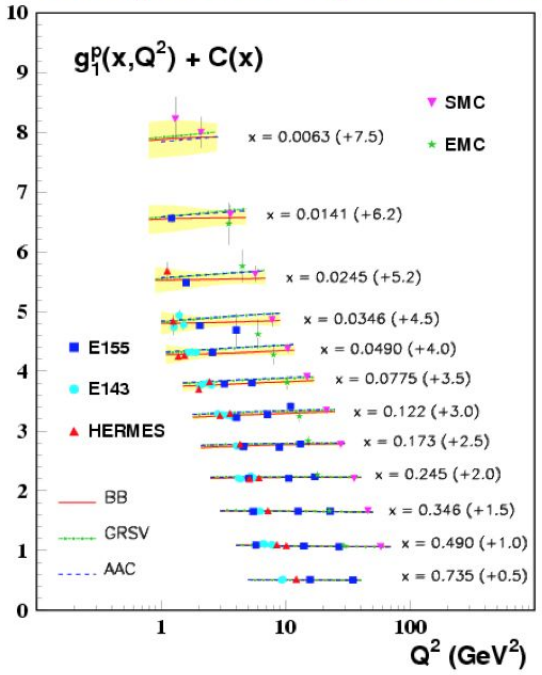




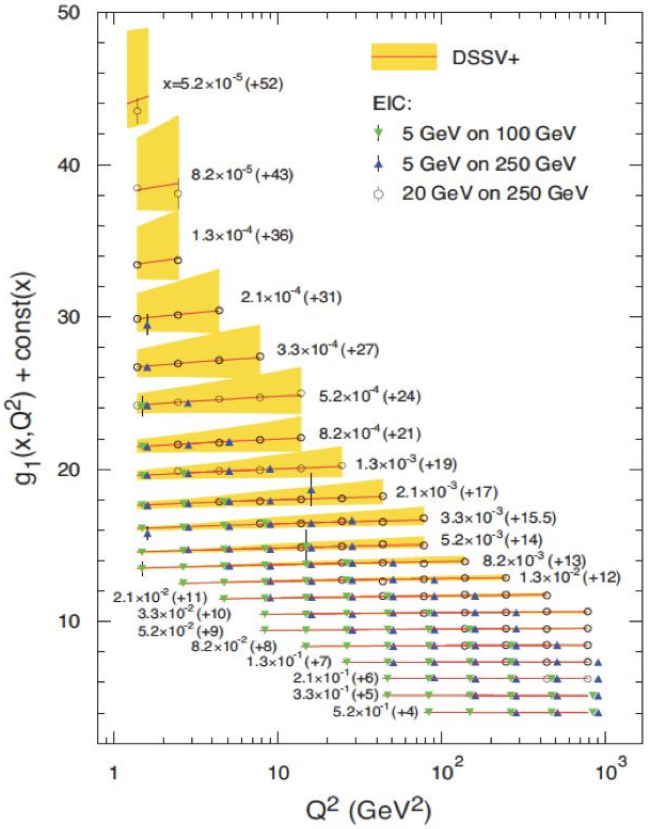
- Highly polarized electron (~70%) and proton (~70%) beams;
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium;
- Variable e+p center-of-mass energies from 28–100 GeV, upgradable to 28–140 GeV;
- High collision electron-nucleon luminosity 10^{33}–10^{34} cm^{-2} s^{-1};
- The possibility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

The Future: Challenges & opportunities

❑ The power & precision of EIC:



at EIC



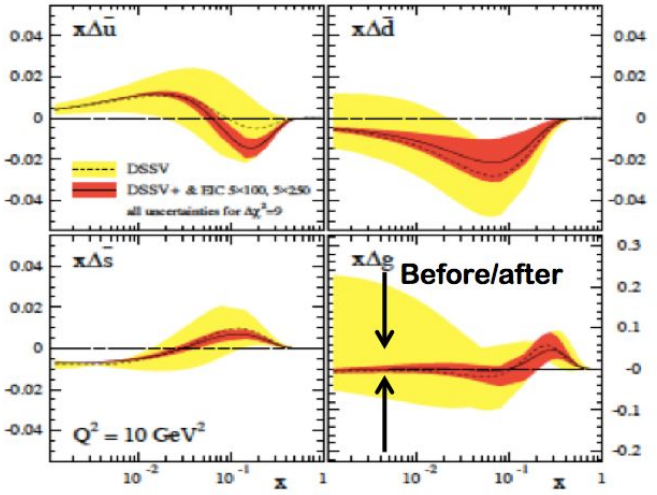
❑ Reach out the glue:

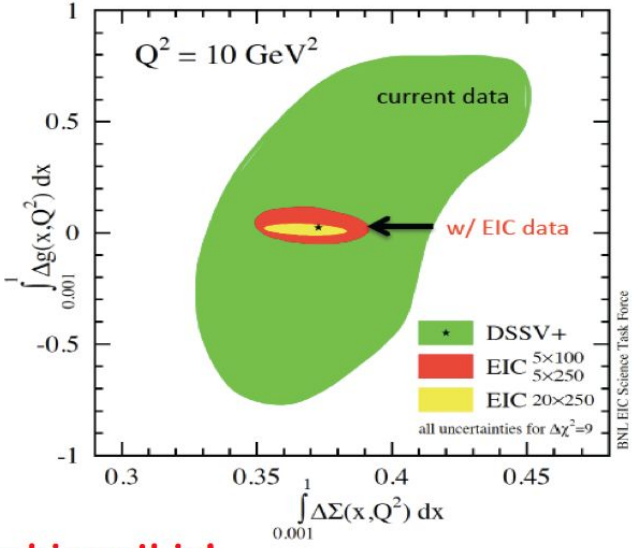
$$\frac{dg_1(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x,Q^2) + \cdots$$

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 Δg(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.