

# A journey from the LHC to an **EIC** with a *short stop* at **RHIC** and **HERA**

Zhoudunming Tu (Kong)

Joined date: July 2, 2018

Senior Physicist at CFNS: Thomas Ullrich

# A journey from the LHC to an **EIC** with a short stop at **RHIC** and **HERA**



...what have we learned so far?

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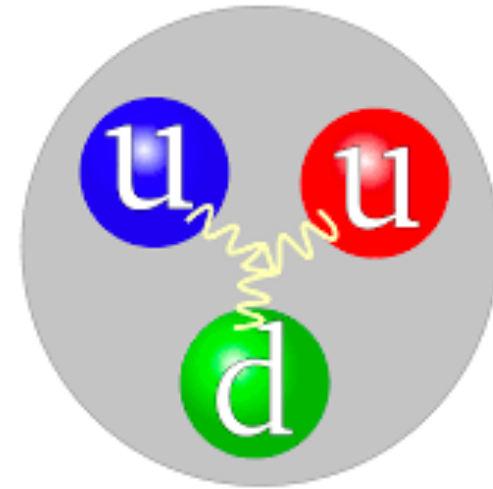
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# Collaborators - Mentors - Advisors

- Entanglement: Dmtriv Kharzeev, Thomas Ullrich
- H1 experiment: Stefan Schmitt, Hennes Jung, Karin Daum, Anastasia Grebenyuk, Zhenyu Chen, Austin Baty, Wei Li, (and many more coming..)
- STAR experiment: Shuai Yang, Zilong Chang, Thomas Ullrich...
- SRC: Raju Venugopalan, Mark Strikman, Christian Weiss, Mark Baker
- BeAGLE: Mark Baker, Elke Aschenauer, JH Lee, Liang Zheng, Wan Chang

# Proton



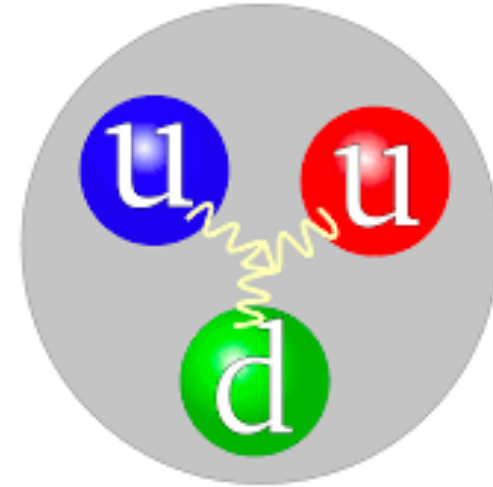
Looking at a proton...

# Proton

Color confinement – standing QCD problem

- No color object exists in nature.
- mysterious mechanism of *confinement*?
- Quantum entanglement?

(...totally obvious to some people,  
while totally insane to some others)



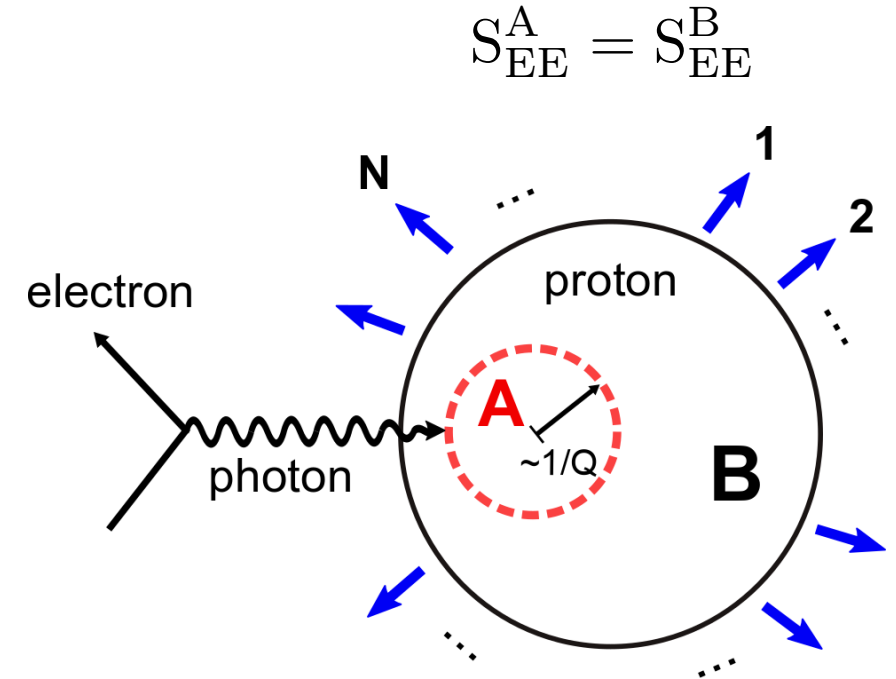
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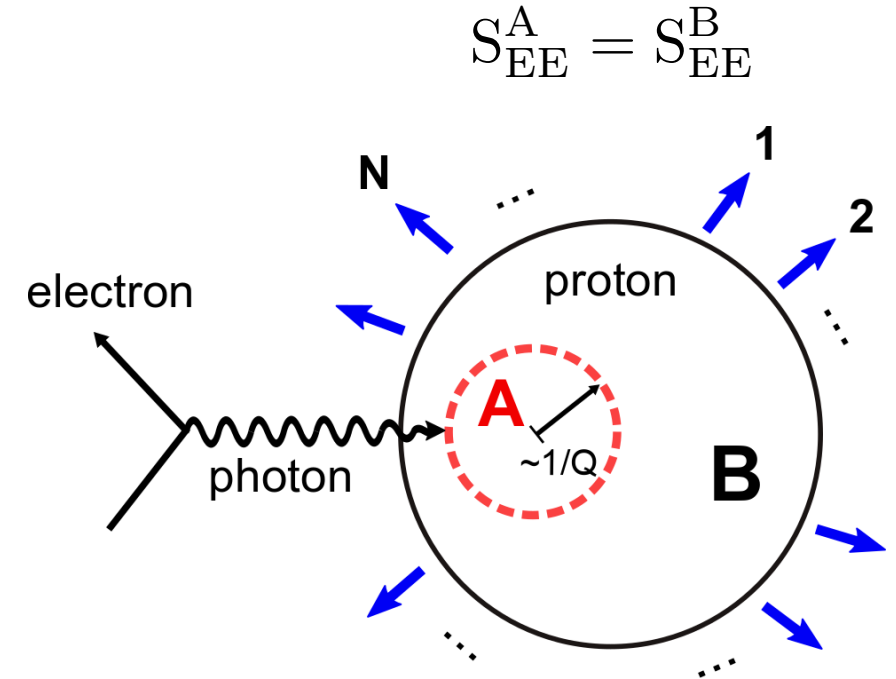
Entanglement entropy might provide evidence

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Entanglement entropy might provide evidence

$$S_{EE} = \ln [xG]$$

(~ at low-x gluon dominant)

prediction from theorists

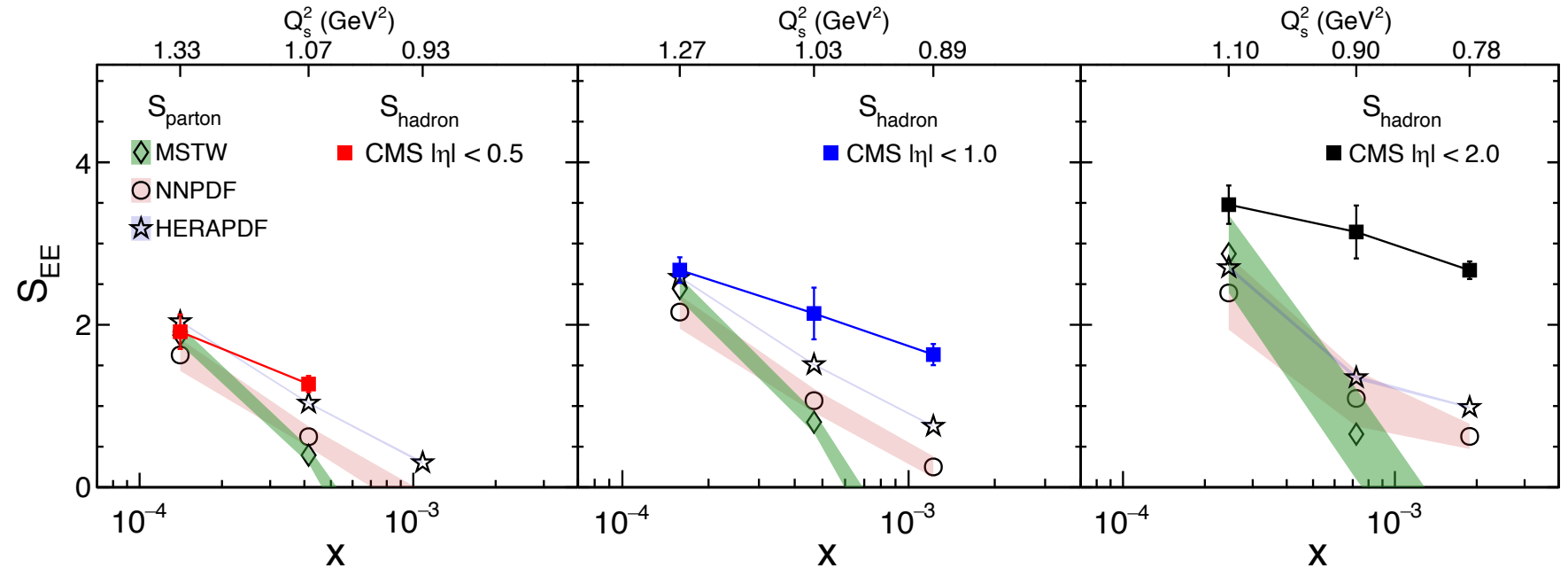
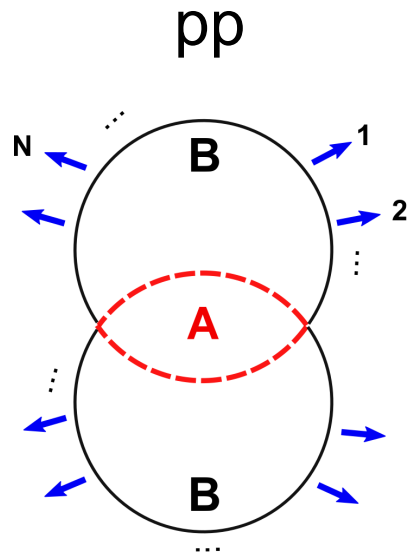


$$S_{\text{hadron}} = - \sum P(N) \ln [P(N)]$$

(~ local parton-hadron duality))

experiment via hadron  
multiplicity distributions

# Multiplicity in pp collisions



Submitted to PRL and under review (*arXiv:1904.11974*)

## A strong indication of quantum entanglement

- However, pp collisions are complicated and there are effects, e.g., MPI, color reconnections,...
- Deep inelastic scattering process is “cleaner” for physics interpretation



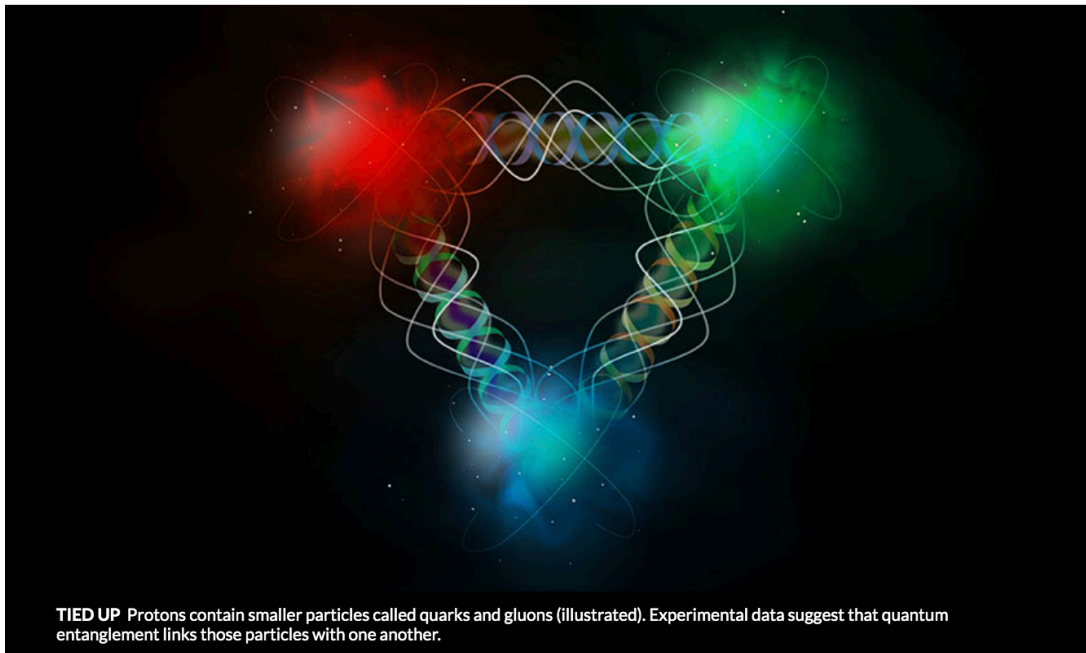
# Science News

NEWS QUANTUM PHYSICS, PARTICLE PHYSICS

## An experiment hints at quantum entanglement inside protons

LHC data suggests the subatomic particle's constituent quarks and gluons share weird links

BY EMILY CONOVER 11:18AM, MAY 17, 2019



**TIED UP** Protons contain smaller particles called quarks and gluons (illustrated). Experimental data suggest that quantum entanglement links those particles with one another.

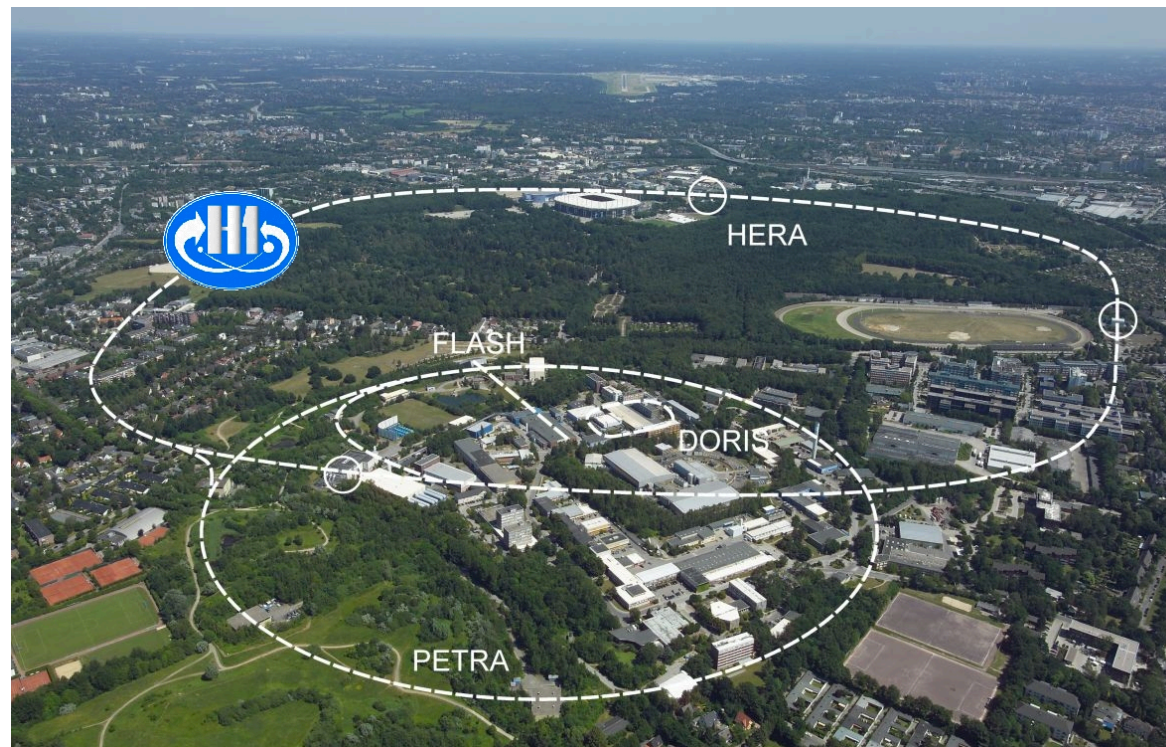
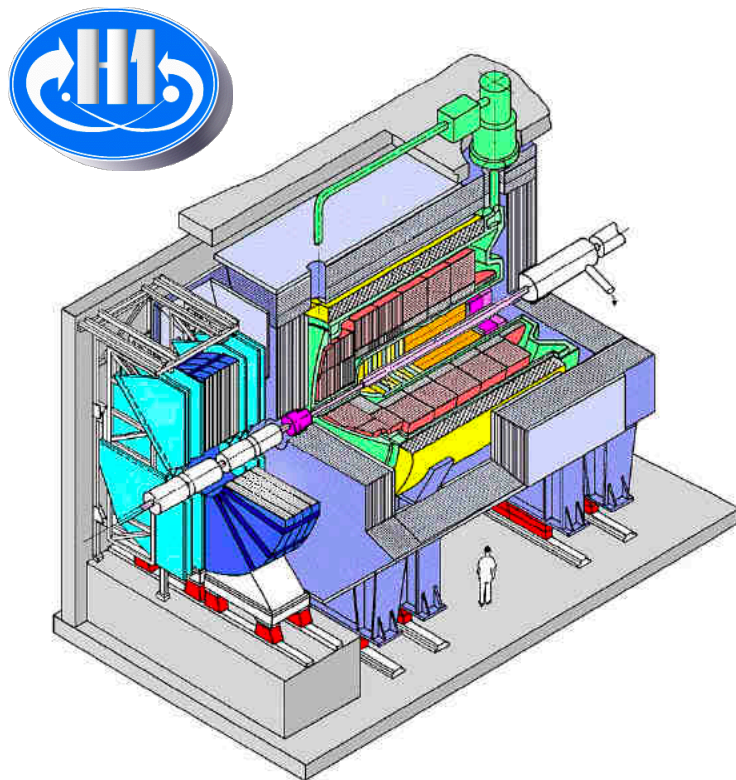
SCIFY/SHUTTERSTOCK

<https://www.sciencenews.org/article/experiment-hints-quantum-entanglement-inside-protons>

# Can we do it in ep DIS?

# H1 experiment at HERA

Highest ep collider machine



HERA runs from 1992-2007

# Multiplicity in ep DIS

- HERA 2 data from 2006-2007 have a lot of statistics of ep at highest energy
  - Previous analysis on multiplicity distributions were either not in the right kinematics nor as detailed.
  - This re-analysis of “old” data based on H1 will be a baseline for future EIC and will have its own significance to many aspects, e.g., MC tuning.
  - **This re-analysis is a *proof-of-principle* that the old data can be re-analyzed, can still be published, and make an impact!**
- 
- Total integrated luminosity used in this analysis  $\sim 136 \text{ pb}^{-1}$
  - $5 < Q^2 < 100 \text{ GeV}^2$ ,  $0.0375 < y < 0.6$

# Multiplicity in ep DIS @ H1

$$-1.2 < \eta < 1.6$$

$$0 < \eta^* < 4.0$$

# Summary on entanglement

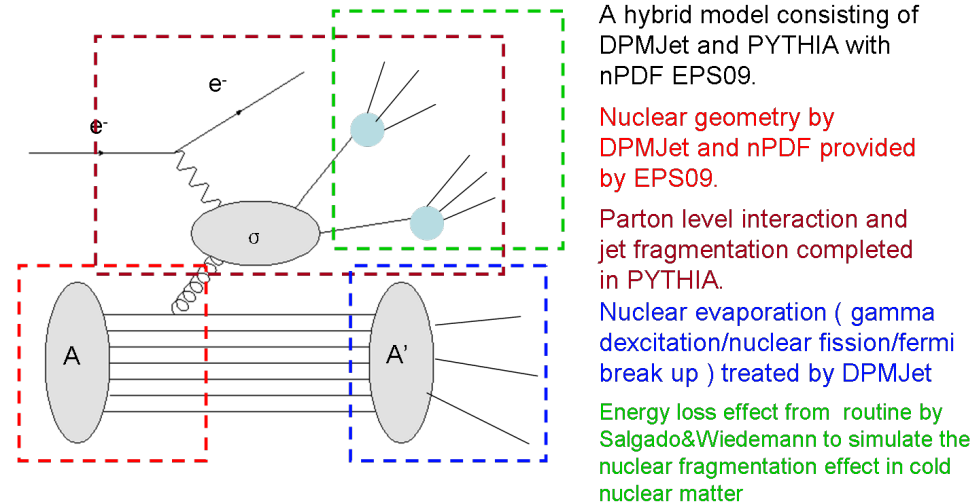
- H1 data has been re-analyzed successfully, target for submission to a peer-reviewed journal, e.g., EPJC, by DIS in March. Stay tuned!
- It's being discussed internally how to present the analysis with the idea of entanglement within H1.
- The result is not compatible with theory predictions from entanglement, but the main problem is – *theory needs to improve as many to-dos and knowns are not ready yet.* (for example,  $Q^2$  evolution on entanglement entropy)
- *This is also important to low- $Q^2$  and low- $x$  physics.*
- *New ideas have been developed and can be checked in ep DIS as well.*



# BeAGLE

## Benchmark eA Generator for Leptoproduction

- eA event generator based on Pythia 6, DPMJet, FLUKA...
- Embedding pythia event into a nuclear environment. Not a trivial job!
- Find the program here, <https://wiki.bnl.gov/eic/index.php/BeAGLE>, and will be soon published.
- Continued funding thru EIC Detector R&D, eRD17, for FY 2020.
- Recent talk at MCEG workshop 2019, <https://indico.cern.ch/event/845653/overview>
- Co-PIs: M. Baker and **Z. Tu**



# BeAGLE - SRC

BeAGLE made impacts on many different areas, including EIC R&D machine/detector designs, IR designs, physics simulations on various topics.

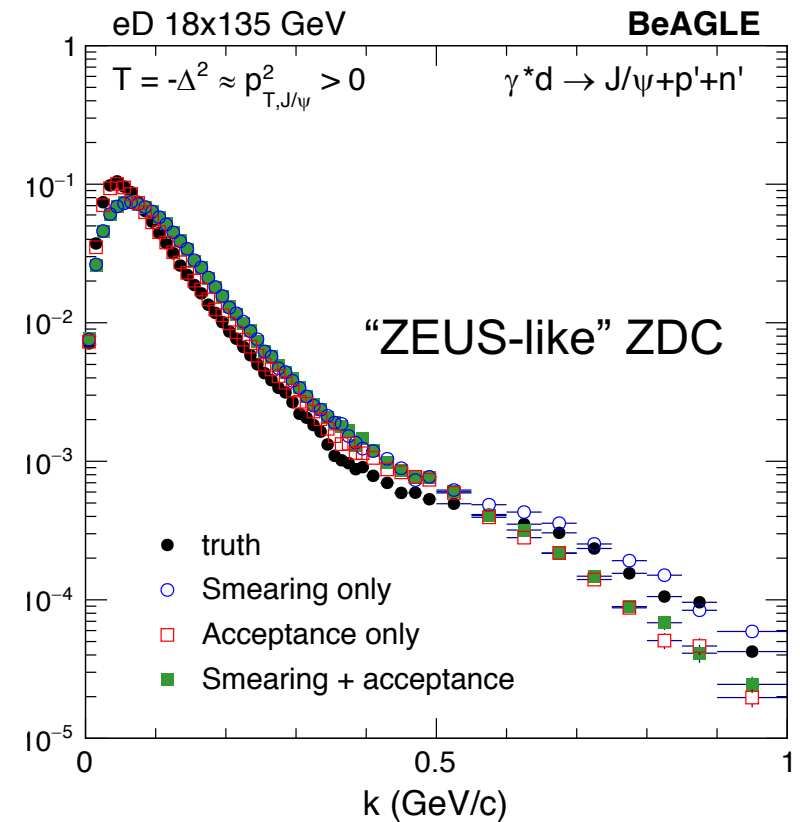
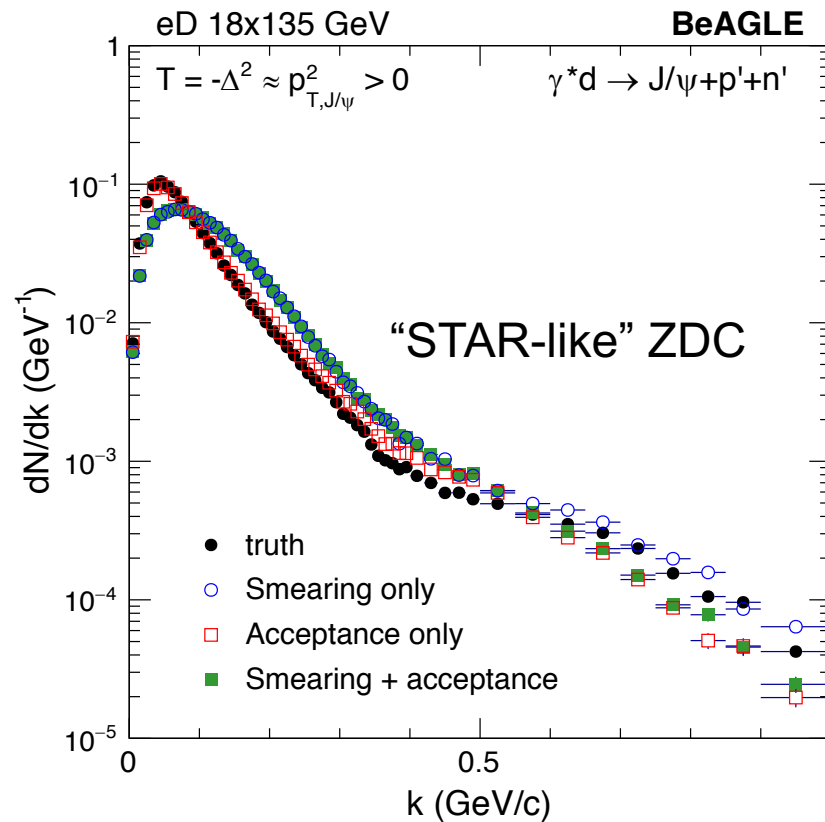
One quick example:

**ZDC < 4mrad**

Momentum distribution of nucleon,  $k$ , in the  $pn$  rest frame.

Reconstructed from BeAGLE event based on spectator tagging.

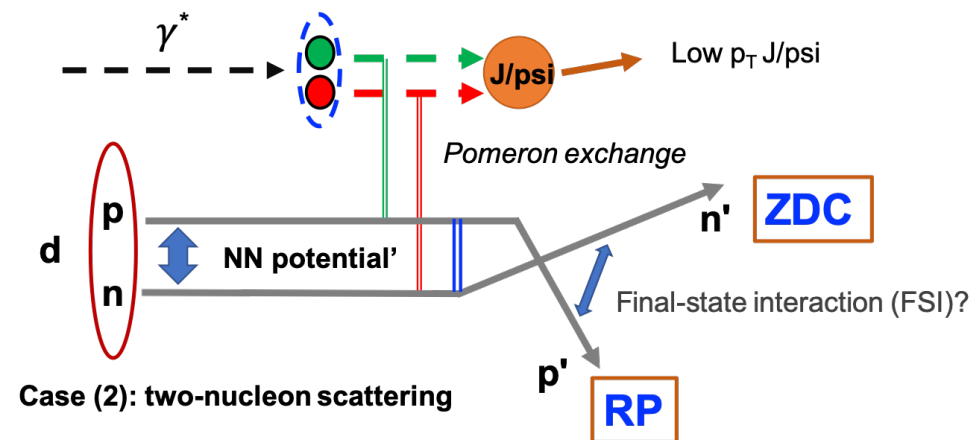
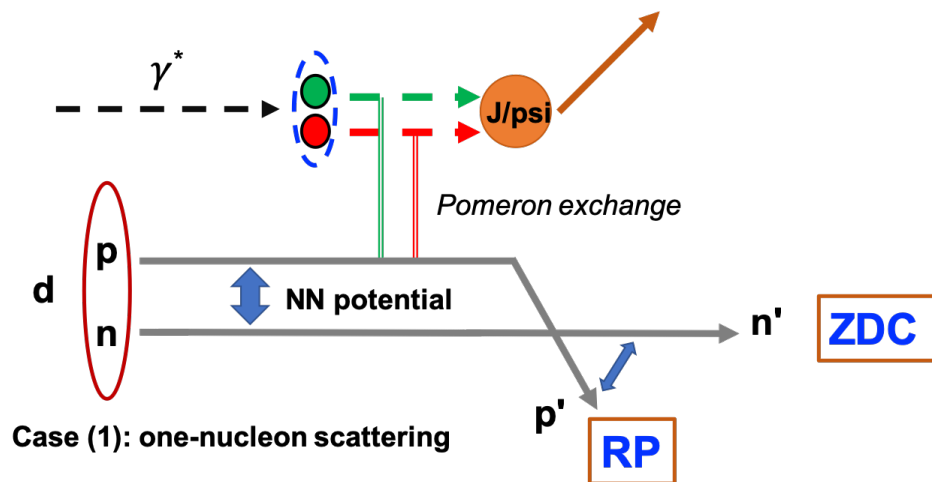
ZDC requirements





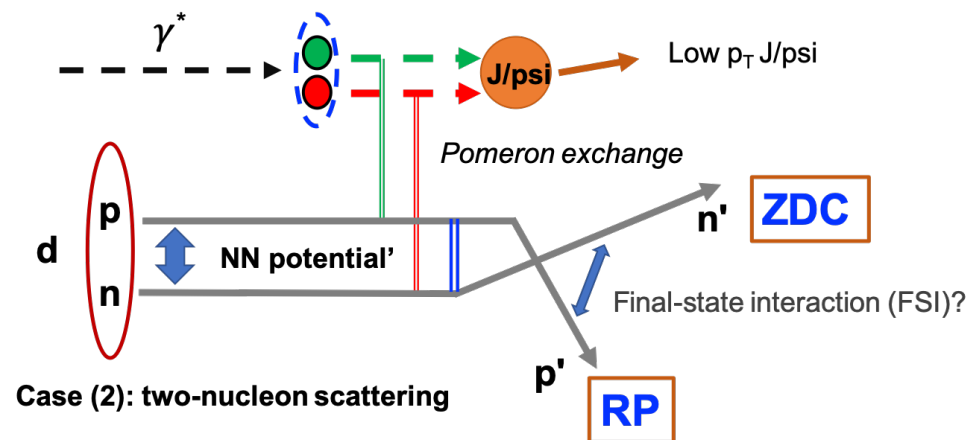
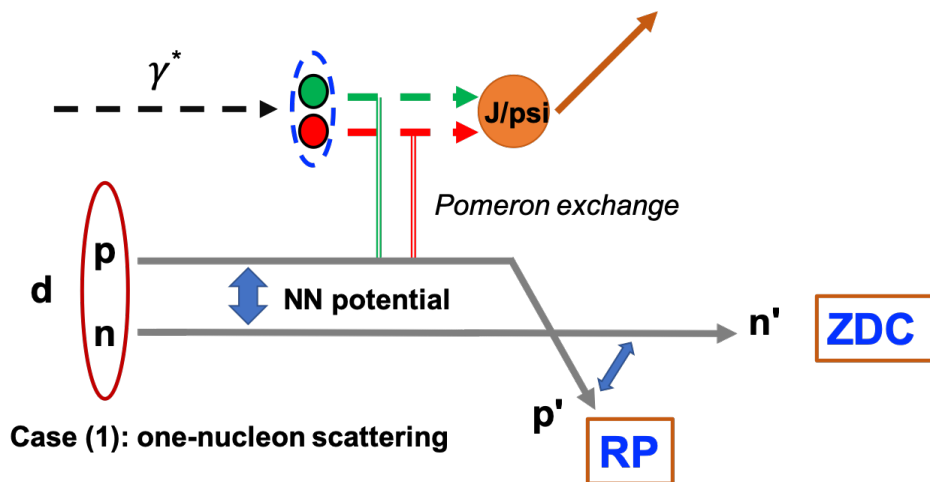
# Short-range correlation – deuteron

We are implementing these processes into BeAGLE and it's not trivial. We need more help from the theory side



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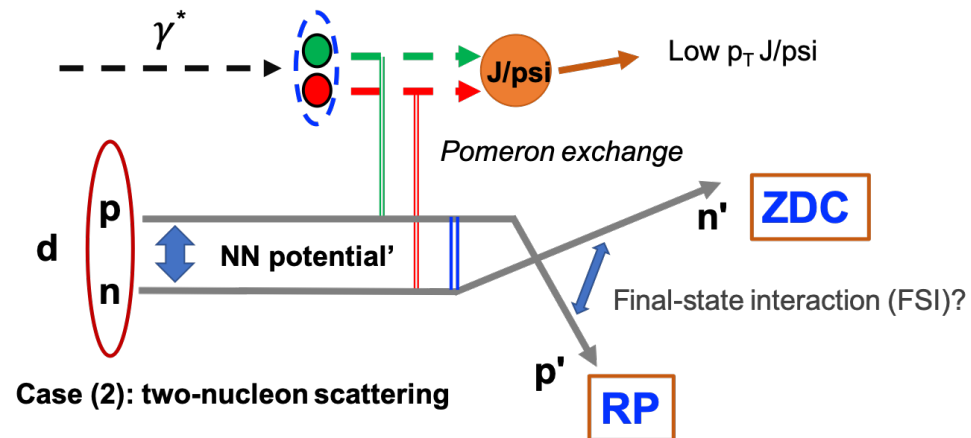
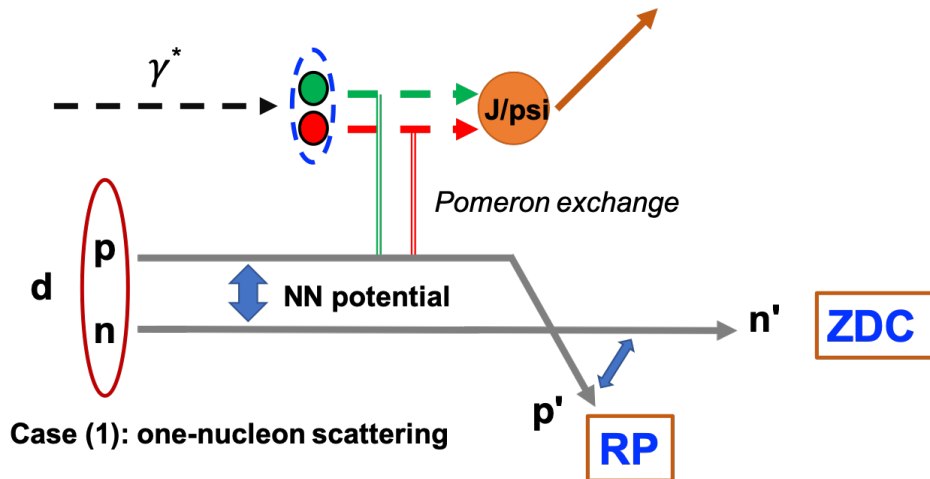


## Big questions:

- 1) What is the underlying physics of SRC? Dynamics at a very short distance.
- 2) Does SRC provide an ultimate explanation for nuclear modification?
- 3) What is the role of gluons?

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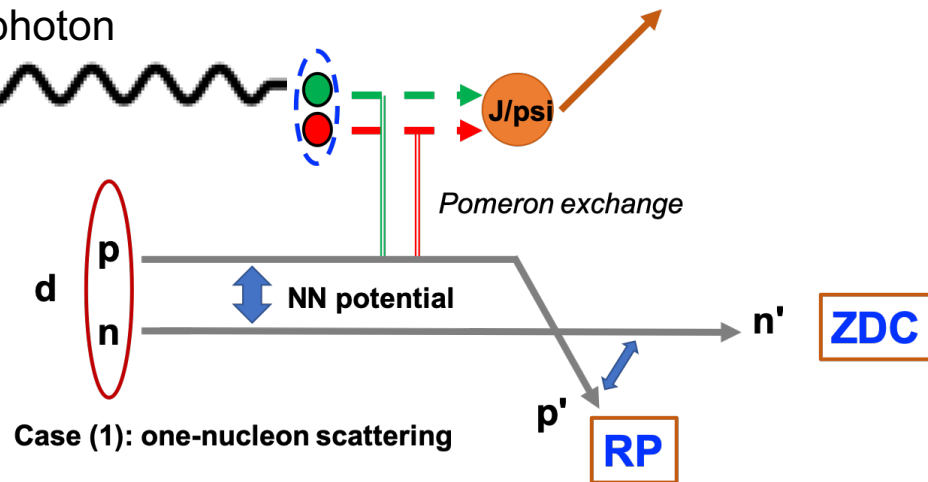
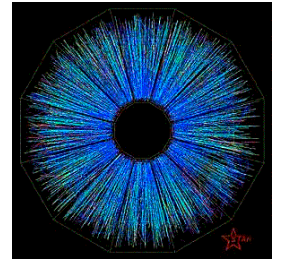


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- 1) What is the underlying physics of SRC? Dynamics at a very short distance.
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This is such a *rare* exclusive process, anything we can learn before EIC experimentally?

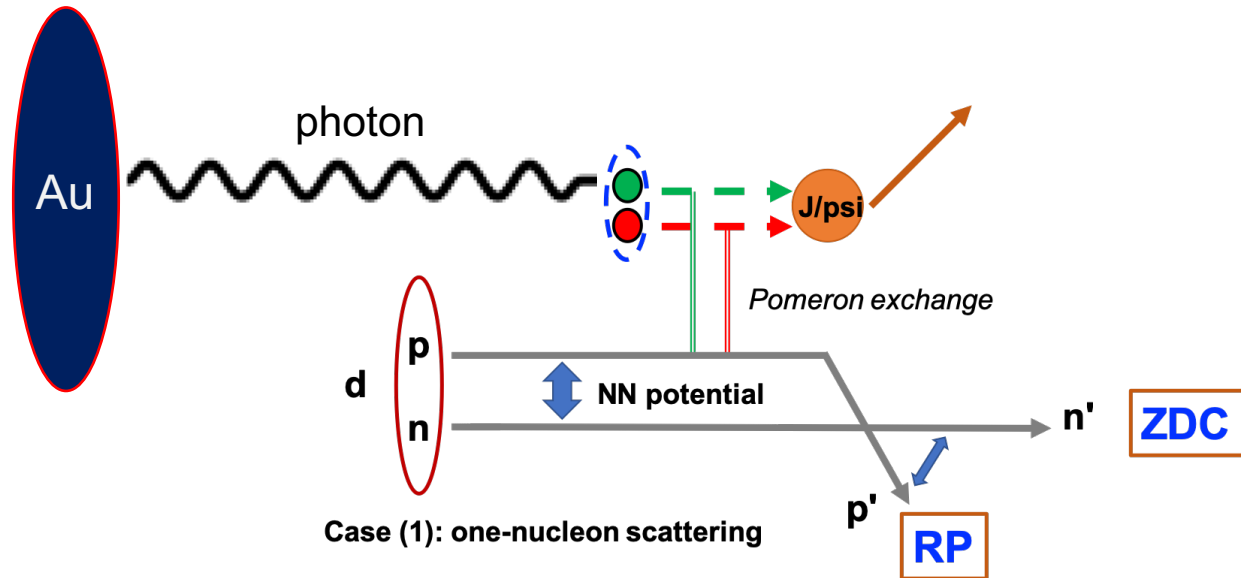
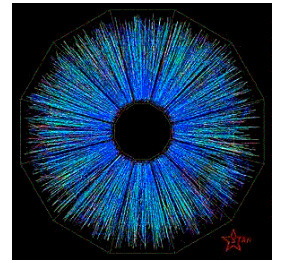
# UPC J/psi off Deuteron



Identical process with low  $Q^2$ :

- Gluon density in deuteron
- Shadowing/anti-shadowing in light nuclei
- Coherent/incoherent fractions and breakup mechanism.

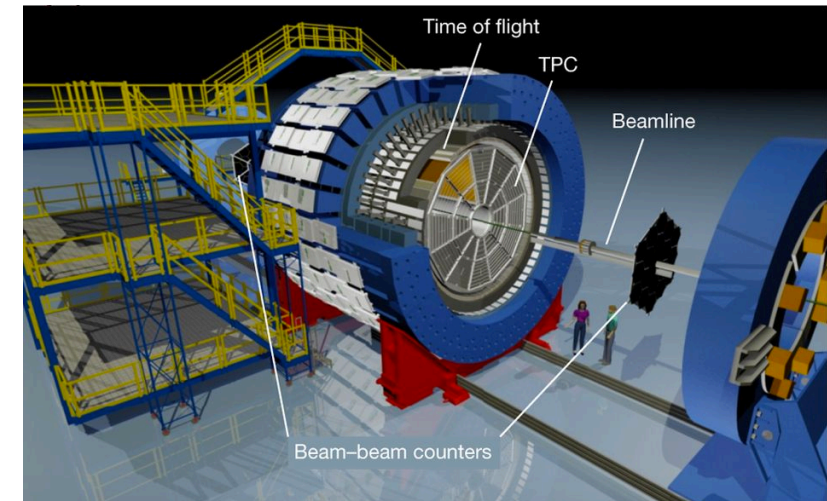
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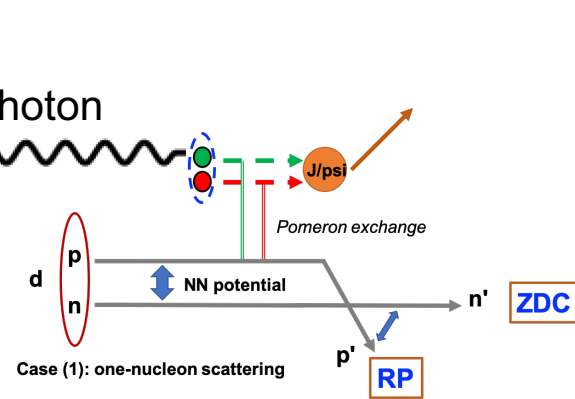
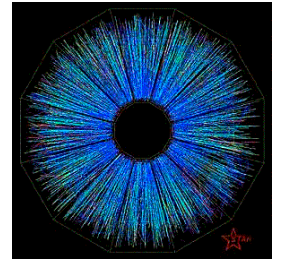
- Identical process with low  $Q^2$ :
- Gluon density in deuteron
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  - Coherent/incoherent fractions and breakup mechanism.

## STAR detector:

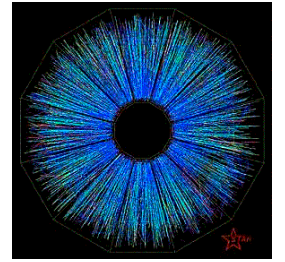
- Excellent PID capability, electron ID, for J/psi reco
- Mid-rapidity coverage of tracking, ZDC
- Designated runs on dAu @ 200 GeV with UPC J/psi trigger



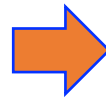
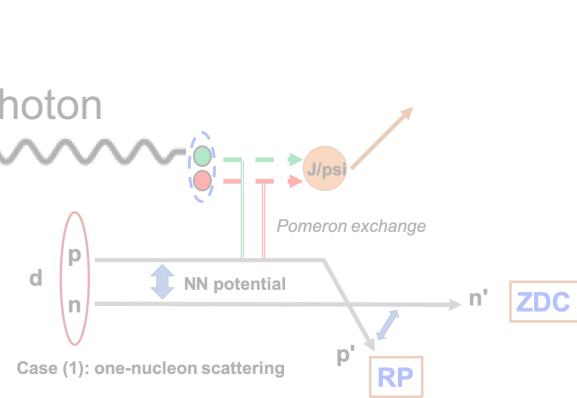
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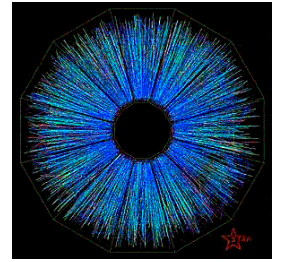


Template based on H1 HERA data for  
incoherent and dissociative

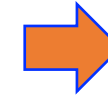
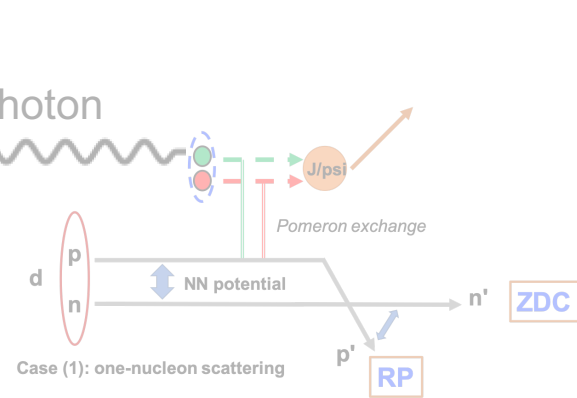


Very good description of fully unfolded data

# UPC J/psi off Deuteron



Template based on H1 HERA data for  
incoherent and dissociative



Charge density the *Hulthen*



# Other analysis in early stages

- Search for “ridge” in ep DIS and photoproduction
- Dijet photoproduction in ep, photon PDF.
- Azimuthal modulations in ep DIS, in related to Boer-Mulders function
- Entanglement in ep DIS via spin-spin correlation
- Diffractive J/psi and rho in ep collisions, with new observables.
- Photon-photon to dileptons in STAR in small systems (pAu, dAu...)

Ideas are (being) developed and will soon get to the list.

## Recent talks

- Plenary talk, “*Progress on BeAGLE eA event generator*”, Nov 2019, Vienna, Austria
- Plenary talk, “*Probing SRC via deuteron breakup at an EIC*”, Workshop on Physics and detector requirements at Zero-Degree of Colliders”, Sep 2019, Stony Brook University, USA
- Plenary talk, “*Quantum entanglement in high energy collisions*”, POETIC, Sep 2019, Lawrence Berkeley National Lab, USA
- Parallel talk, “*Quantum entanglement in high energy collisions*”, Initial Stages Conference, June 2019, Columbia University, USA
- Parallel talk, “*Quantum entanglement in high energy collisions*”, AGSRHIC User's meeting, May 2019, Brookhaven National Lab, USA
- Parallel talk, “*Quantum entanglement in high energy collisions*”, DIS, April 2019, Turin, Italy

# Summary

- We have done good physics towards the EIC.
- Many analysis (H1 & STAR) are in preparation of paper drafts.
- Many more are also coming along the way.

Thanks for all the supports and discussions happened @CFNS