Discussion Session: Hard probe, new and open topics

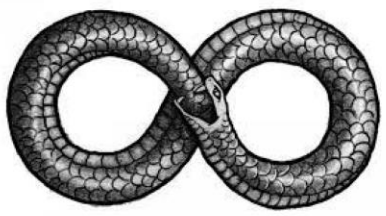
Jin Huang
Brookhaven National Lab

Special thanks to everyone contributed slides to this discussion!

John Lajoie : RHIC and EIC

EIC Connections…

EIC Yellow Report, page 17

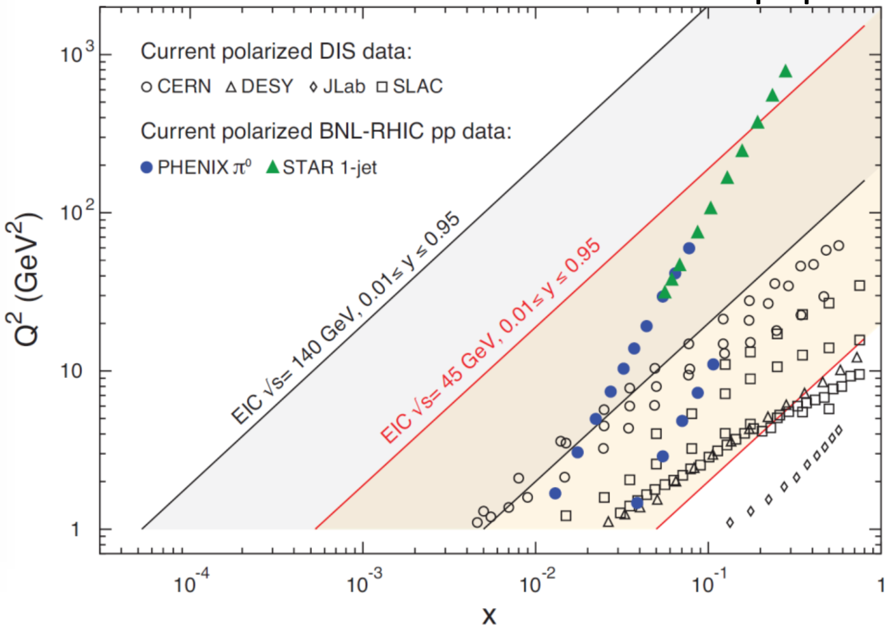


Measurements at the EIC are also expected to deliver important input for several areas of astroparticle physics. Fields such as cosmic-ray air showers and neutrino astrophysics will benefit from better constrained models of hadronic interactions. Deeply inelastic scattering and photo-nuclear processes have natural ties with the physics of hadronic collisions. These relate to the issue of small-x gluons and factorization in e+p and e+A versus p+p and p+A, and to the implications of the determination of parton distributions for p+A collision for an improved understanding of the initial conditions in heavy-ion collisions. Similar, the accurate characterization of parton distributions in nuclei provided by the EIC can directly benefit the neutrino physics program. In return, neutrino scattering can help better understand the parton structure of nucleons and nuclei, where the nucleon strangeness content is one example.

Joe Osborn: hard probes RHIC → EIC

- What can RHIC access now that EIC will not be able to?
  - Anything at large Q with adequate statistics
    - High p_T jets, γ-jet, TMDFFs
    - Anything W/Z related
    - b physics (e.g. b jets, hadrons, etc.)
  - Confined probes with color in the initial and final state
    - Polarized p+A
    - questions regarding TMD factorization/evolution/universality, etc.
    - Physics that benefits from access to gluons at LO
  - Measurements that are kinematically directly comparable to "day-1" EIC measurements

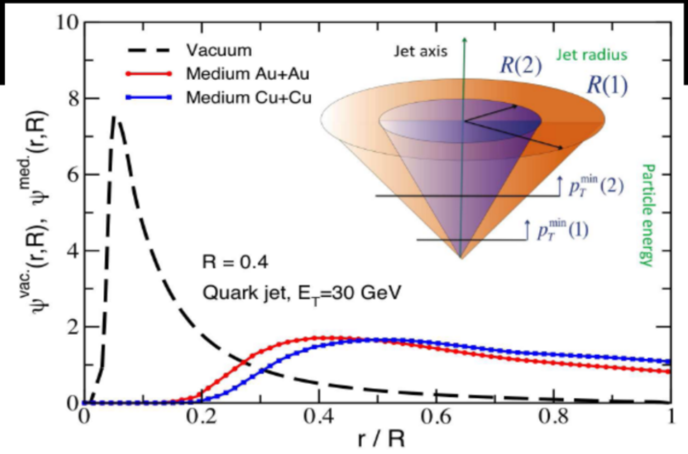
EIC Whitepaper



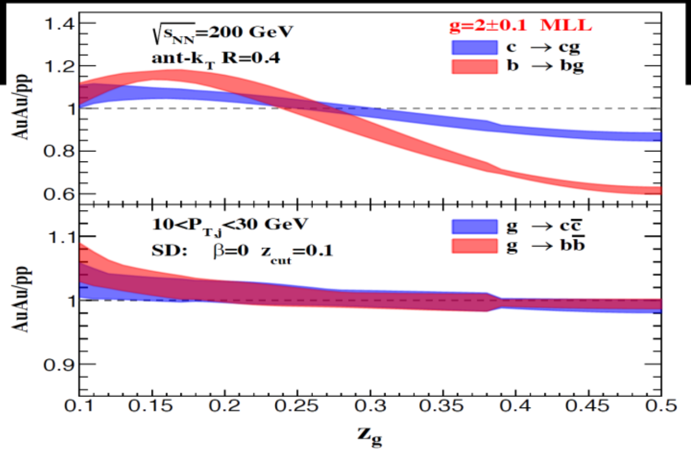
Ivan Vitev:

Important measurements at RHIC

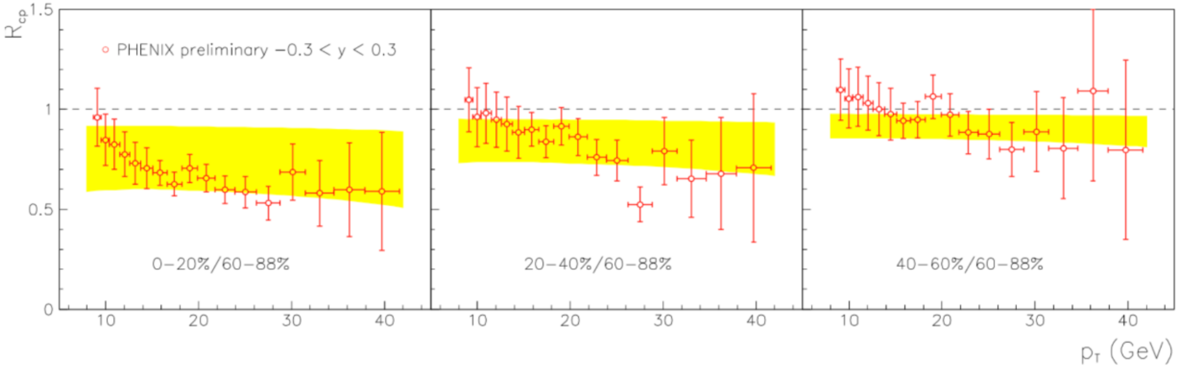
Try to adhere to the KISS principle in the measurements and presentation of results



Proper measurements of jet shapes and fragmentation functions AA.

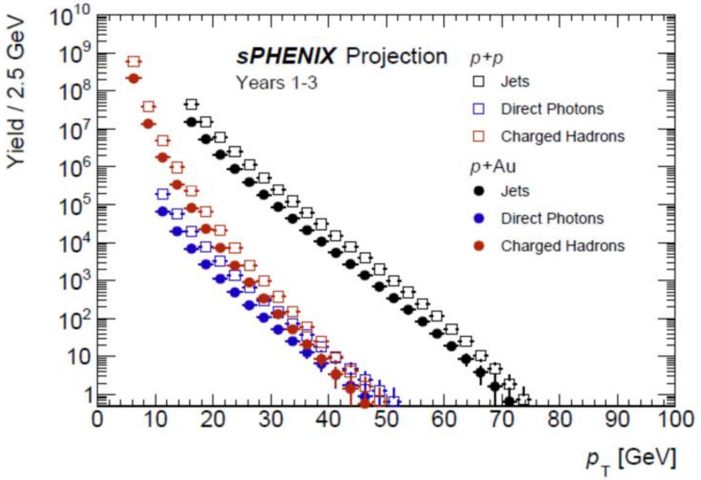


B-jet substructure and momentum sharing – dead cone in AA.

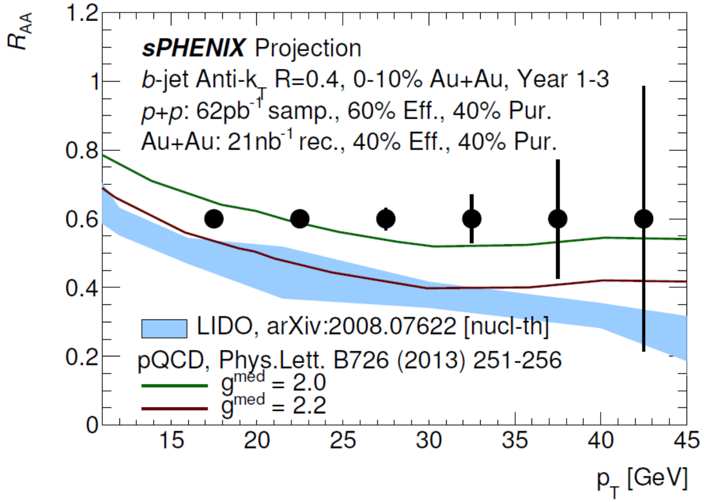


Revisit centrality determination in pA. Jet R_{pA} at large x_F (or x_1) . Energy loss in cold nuclear matter – Connection here is to DY in pA E906 more so than EIC.

John Lajoie:

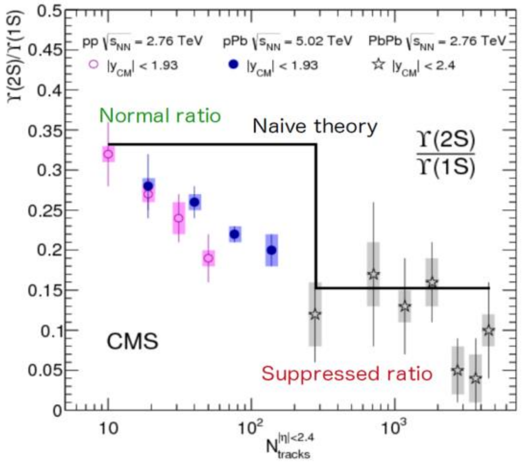


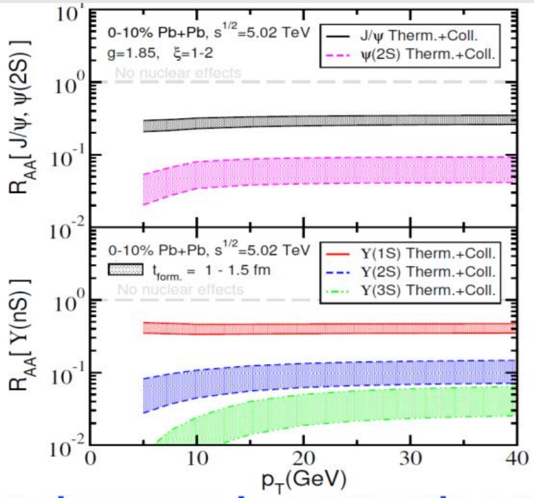
Xin Dong:



(see also: small system discussion)

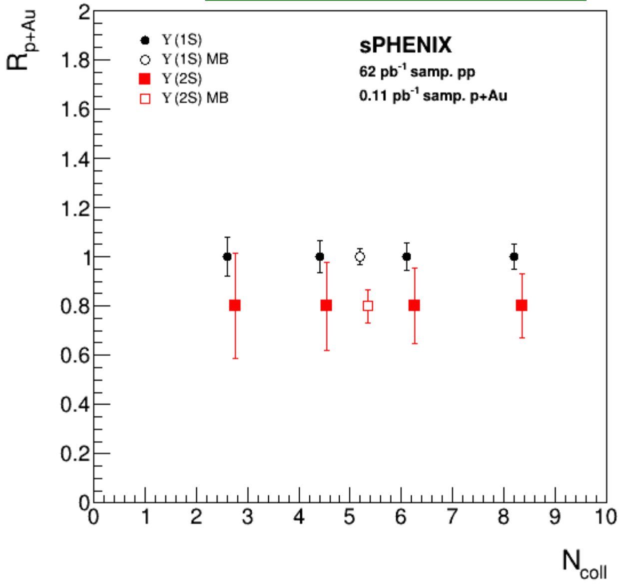
Ivan Vitev:





Excited to ground quarkonium states. In AA, but also more importantly pA. Will inform quarkonium physics in eA and also the study of exotics.

sPHENIX pA proj. [sPH-TRG-2021-001]



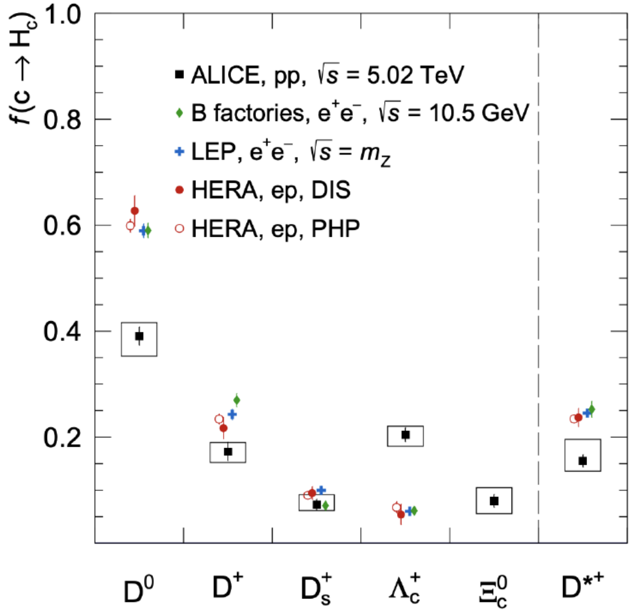
(see also: small system discussion)

Universality of HF hadronization and hadrochemistry

Joe Osborn:

Universality of FFs

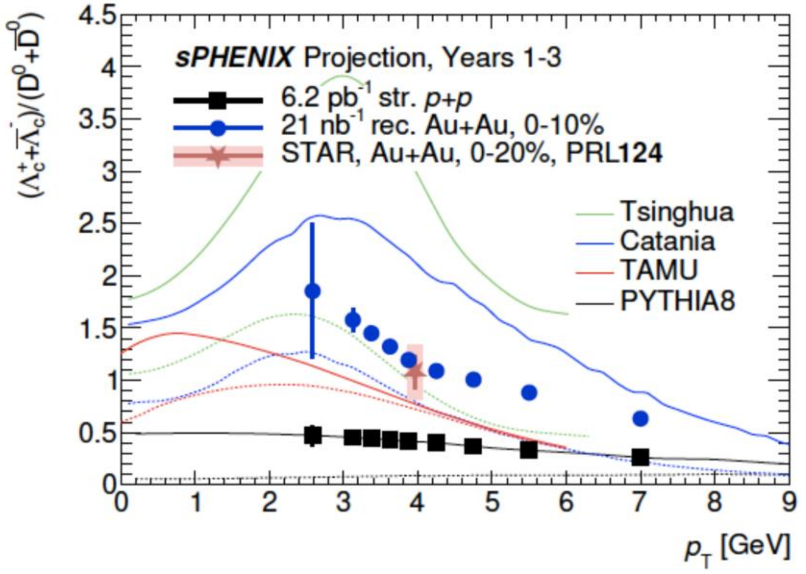
- New results from ALICE challenging universality of charm fragmentation fractions!
- More measurements like this needed, directly comparing observables between collision systems
- Can help guide EIC measurements



arXiv:2105.06335

Joe Osborn 15

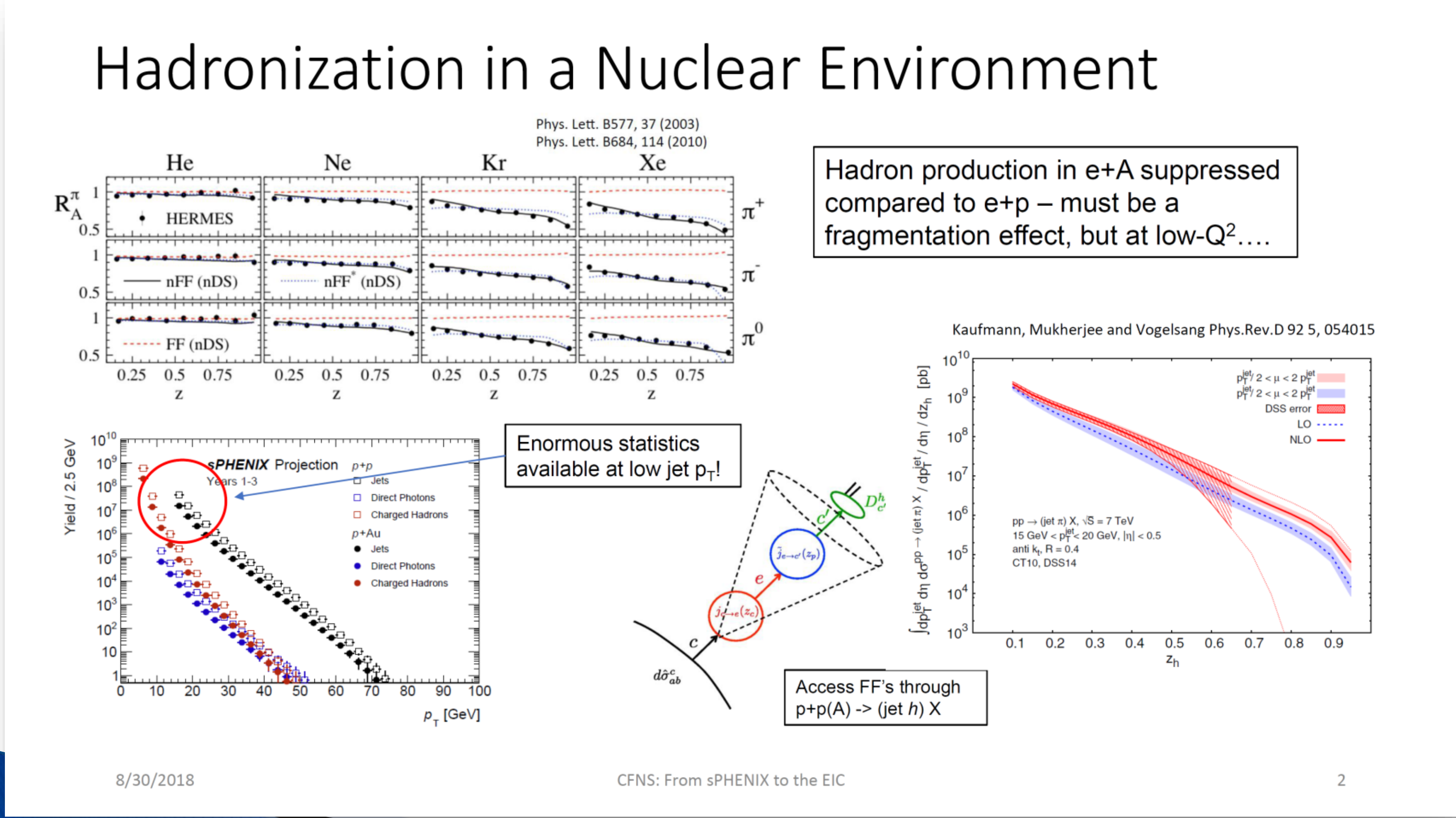
Xin Dong:



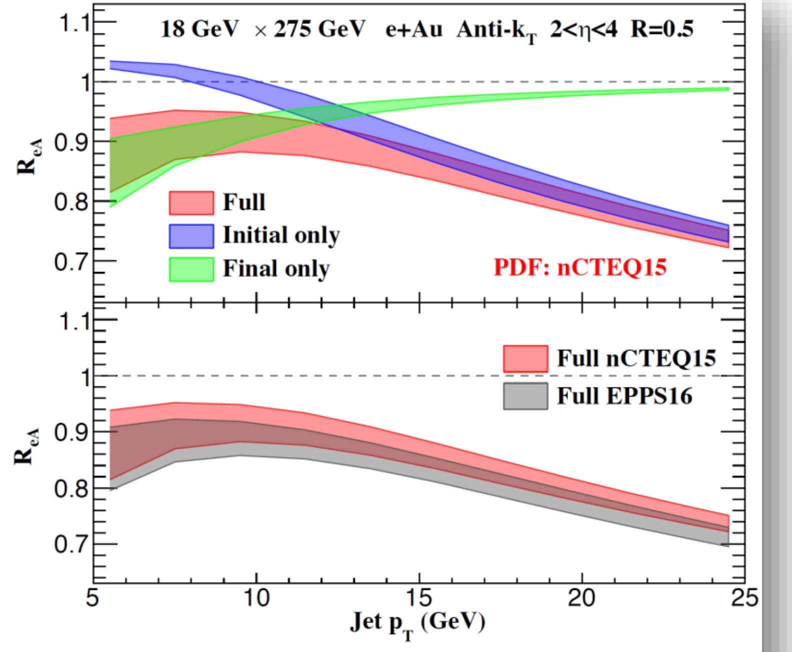
- Precise measurement of various charm hadrons (Λ_c^+, D_s^+)
- Enable access to open bottom hadrons (Λ_b, B_s etc)
- Detail investigation of charm baryon spectroscopy in p+p collisions

Jets and hadronization in nuclear env.

John Lajoie :



Ivan Vitev:

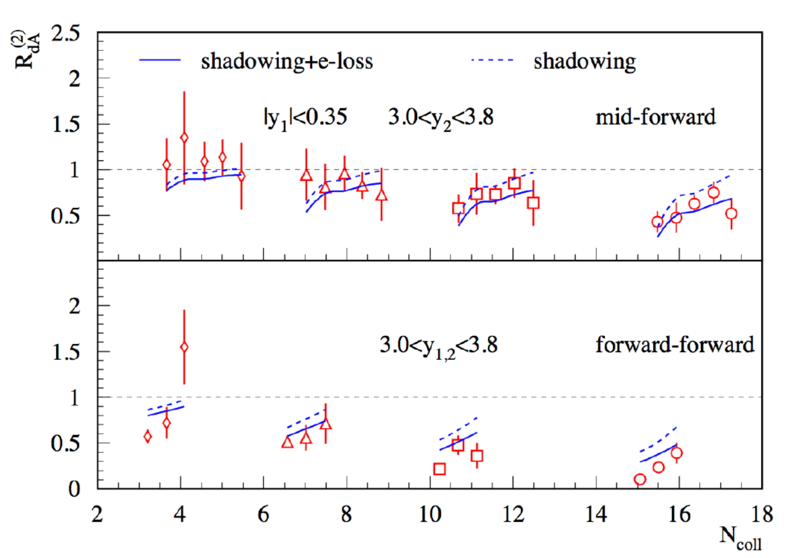


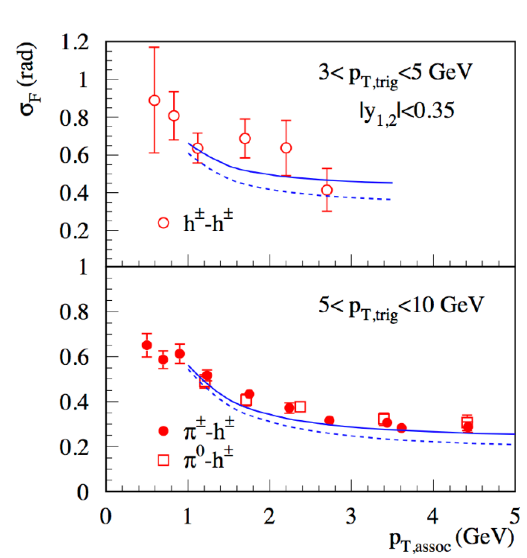
- Net modification 20-30% even at the highest CM energy
- E-loss has larger role at lower p_T. The EMC effect at larger p_T

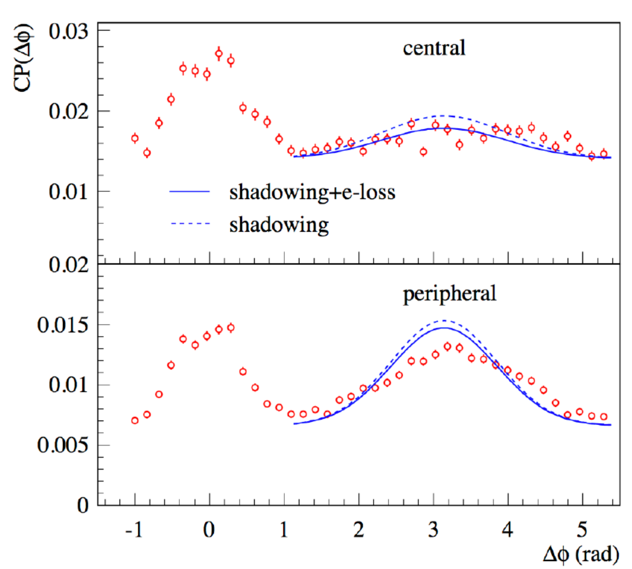
Ivan Vitev:

Important measurements at RHIC

Try to adhere to the KISS principle in the measurements and presentation of results







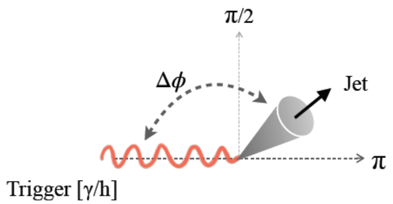
Definitive measurements in pA dihadron correlation cross sections and back to back distributions. Is there broadening or not, is there suppression or not?

(see also: small system discussion)

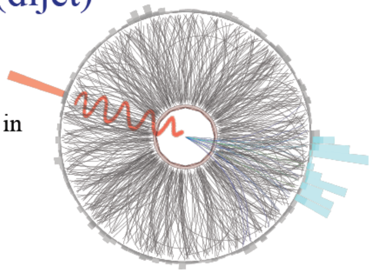
Correlation measurement with Photon jet

Nihar Sahoo :

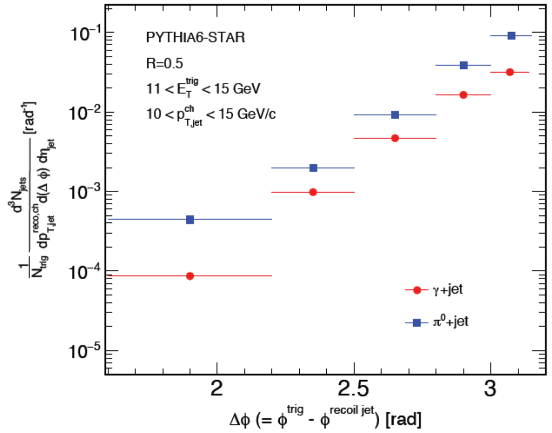
Ongoing STAR measurement γ+jet and h+jet (dijet)



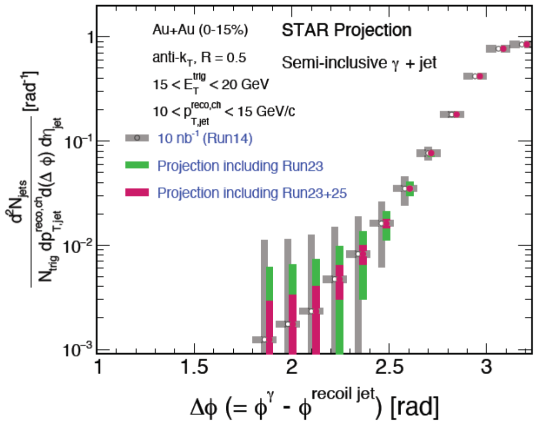
STAR γ+jet event display in A+A collisions



p+p PYTHIA6



STAR Projection (Au+Au)



[Pythia Shape + Uncertainty from HI projections]

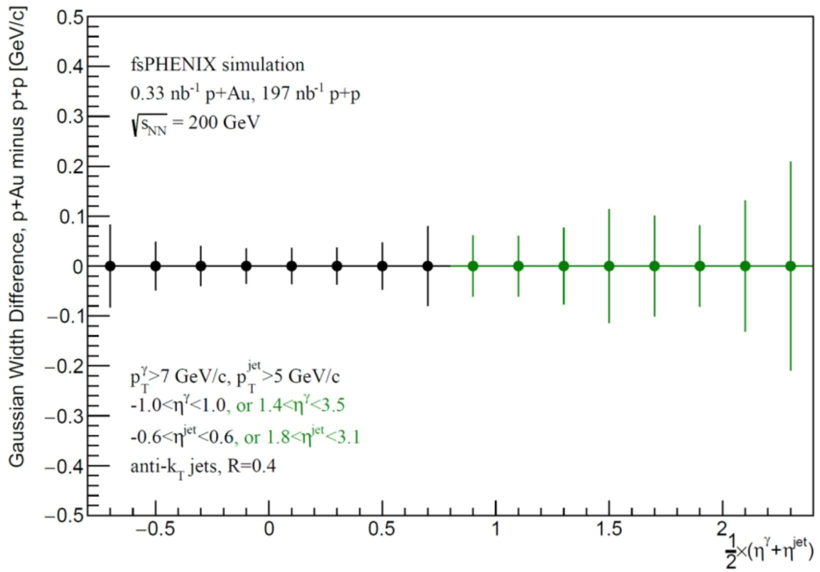
Jet cone size dependence of QCD radiation

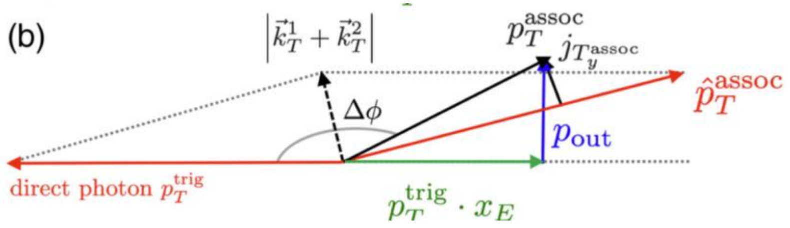
- Vacuum (p+p) vs. in-medium (A+A) gluon radiation
- Or Large-angle scattering off of QGP quasi-particles

Nihar Sahoo (SDU) 3

sPHENIX photon-jet p_{out} width

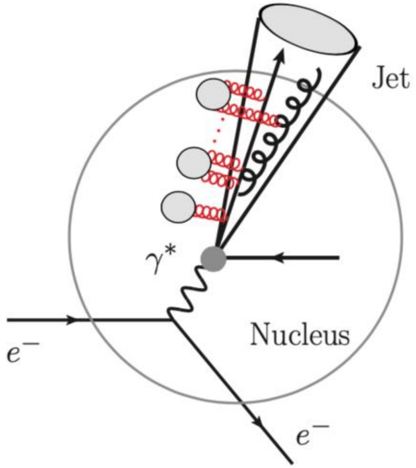
Plot by
Jordan Roth (UMich)
Joe Osborn (ORNL)





Nihar Sahoo : QED and QCD radiations

EIC Era: QED and QCD radiations



Li and Vitev, arXiv: 2010.05912

$$e + p/A \rightarrow e' + \text{jet} + X$$

Shape of electron tagged jet (or dijet) azimuthal (de)correlation in e+p/A event

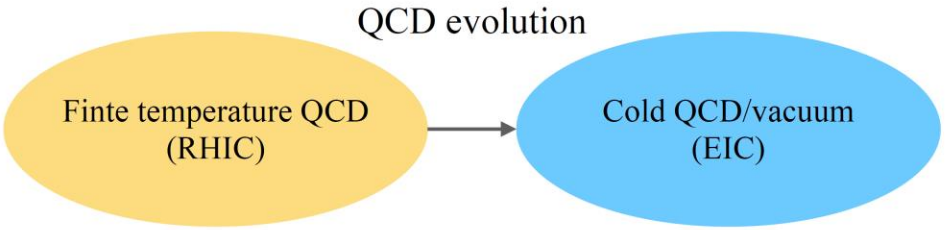
- Study anisotropy of in e+p/A events

  [Hatta, Xiao, Yuan, Zhou, arXiv: 2010.10774
  Arratia, Song, Ringer, Jacak, PRC 101, 065204 (2020)]

- Cold QCD vs Vacuum radiation

  [Li and Vitev, arXiv: 2010.05912]

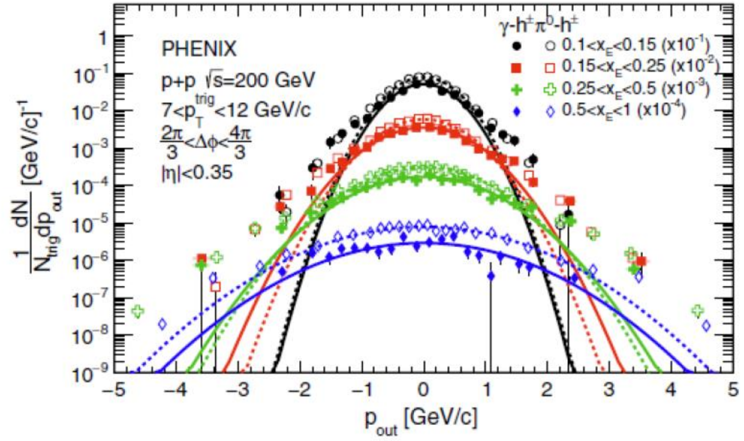
- Study QED radiations in election side as well [ISR and FSR]

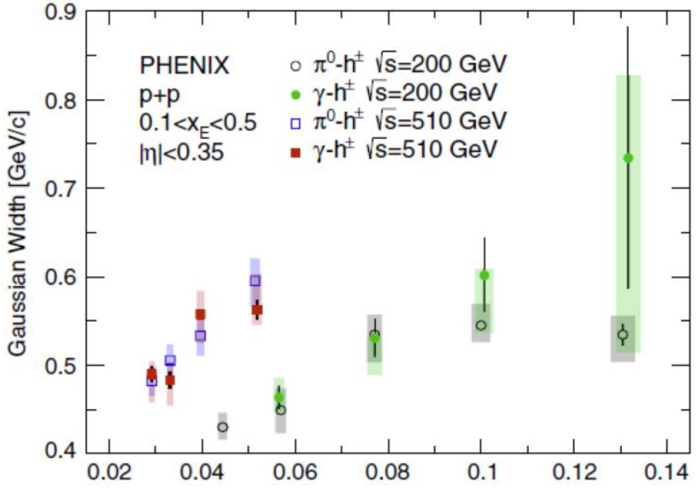


John Lajoie :

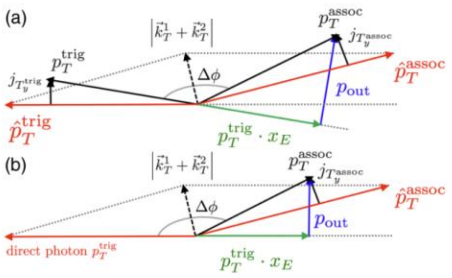
(see also: spin discussion)

TMD Factorization Breaking





PHYS. REV. D 98, 072004 (2018) $x_T = 2p_T^{trig}/\sqrt{s}$



Di-hadron and photon-hadron correlations studied in PHENIX. Predicted to violate TMD factorization due to quantum-correlated partons between colliding hadrons due to color flow.

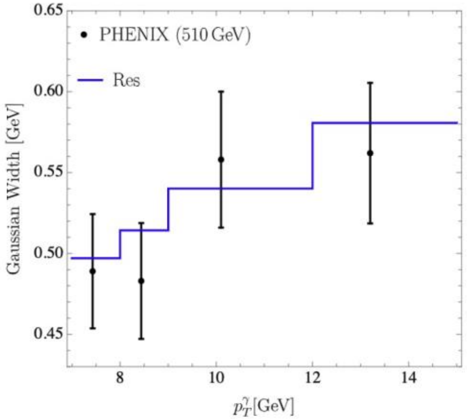
sPHENIX:

- Full jet reconstruction – access to better proxies for parton kinematics

See talk by Zhongbo Kang

Availability of theory calculations that *assume* factorization is key!

New data will be much more sensitive to even *subtle* effects of factorization breaking!



CFNS: From sPHENIX to the EIC

Dmitri Kharzeev:

Quantum mechanics of partons and entanglement

Proton is a pure state with zero entropy; a collection of quasi-free partons is not. The key to solving this apparent paradox may be quantum entanglement:

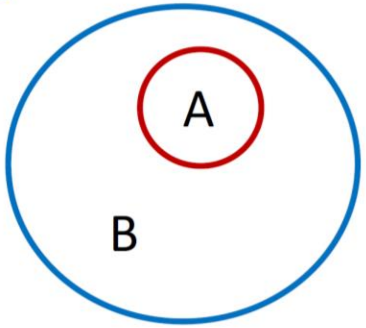
D. Kharzeev, E. Levin, arXiv:1702.03489; PRD (2017)

DIS probes only a part of the proton's wave function (region A). We sum over all hadronic final states; in quantum mechanics, this corresponds to accessing the density matrix of a mixed state

$$\hat{\rho}_A = \mathrm{tr}_B \hat{\rho}$$

with a non-zero entanglement entropy

$$S_A = -\mathrm{tr}\left[\hat{\rho}_A \ln \hat{\rho}_A\right]$$



2

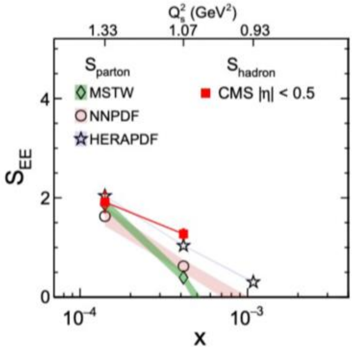
Dmitri Kharzeev:

Tests of the entanglement and the EIC

LHC data (CMS Coll.):

$$S = \ln[xG(x)]$$

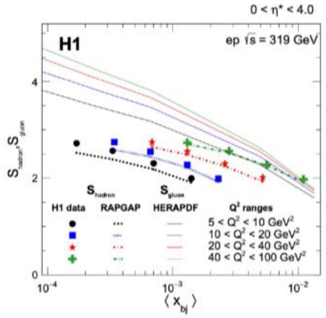
is satisfied at small x
(**maximal entanglement?!**)

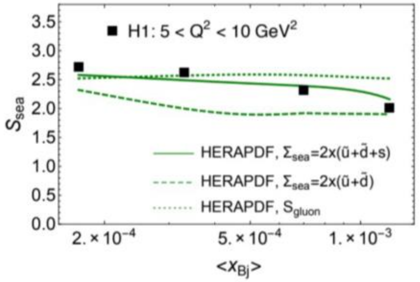


Z. Tu, D. Kharzeev, T. Ullrich,
arXiv:1904.11974; PRL(2020)

HERA DIS data (H1 Coll.):
Agreement with the data once the current fragmentation region is accounted for:
sea quark distribution

H1 Collaboration (Z. Tu et al)
arXiv:2011.01812; EPJC(2021)





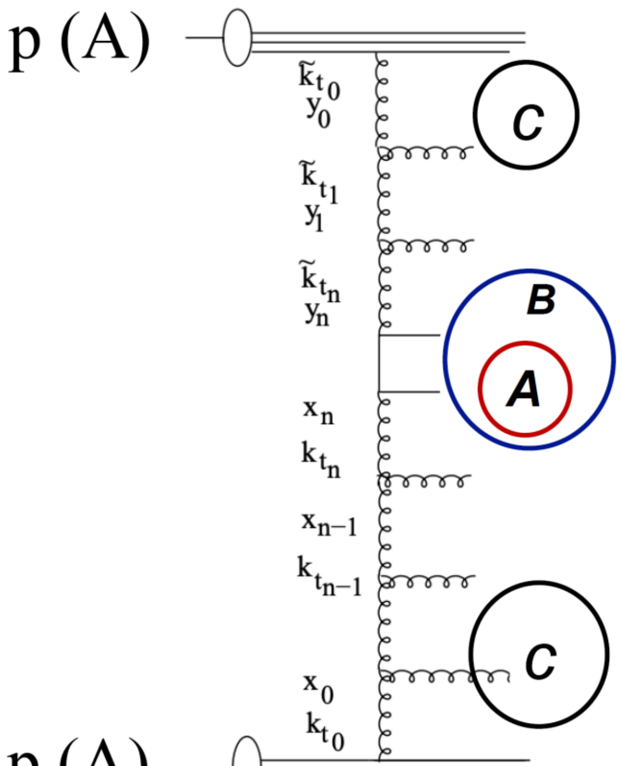
D. Kharzeev, E. Levin,
arXiv:2102.09773

EIC can perform pioneering measurements in the target fragmentation region (maximally entangled state); **Real discovery potential!**

Kong Tu:

Entanglement search at RHIC

- A first direct extension of our works[1,2,3,4] on EE at RHIC is thru hadron multiplicity measurements in **pp, pA, and AA** collisions.
  - RHIC Top energy – sensitive to $x \sim 10^{-2}$, complimentary to LHC data and HERA data.
  - pp → pA and AA collisions with nuclear PDF of seas and glues, putting the idea on another stringent experimental test
  - Hadron → PID (pi, k, p, heavy flavors, etc…), variations in calculating the hadron entropy?
  - Minimum-bias events → jets? Scale dep.?
  - Midrapidity → Forward rapidity? Rapidity correlation – entanglement among A, B, and C? (Strong subadditivity of quantum entropy)



1. *Phys.Rev.D* 95 (2017) 11, 114008. 2. *Phys.Rev.Lett.* 124 (2020) 6, 062001.
3. *Eur.Phys.J.C* 81 (2021) 3, 212.. 4. arXiv:2102.09773

Kong Tu:

Entanglement search at RHIC

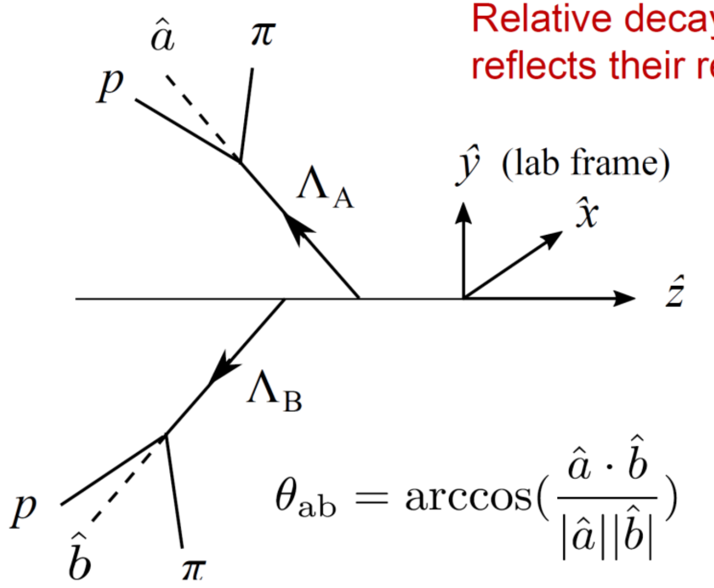
- Spin entanglement search at RHIC – new measurement has been proposed using double Λ polarizations.
- CHSH inequality test in high energy collisions – closest connection between QIS and NP.
- Sensitive to parton spin entanglement, origin of Λ hyperon polarizations in pp, etc.
- Dynamical nucleon spin structure and long-range correlations of QCD strings
- Approved BNL LDRD-22-027 project

(BNL is hiring[1], https://inspirehep.net/jobs/1863223)

[Manuscript in preparation for PRL]

ep or *pp* collisions

Relative decay angle reflects their relative spin



$$\theta_{ab} = \arccos\left(\frac{\hat{a}\cdot\hat{b}}{|\hat{a}||\hat{b}|}\right)$$

(W. Gong, G. Parida, ZT, R. Venugopalan)

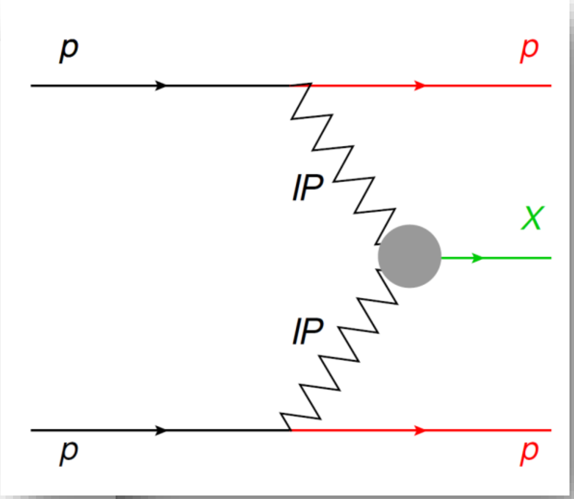
1. Contact: Z. Tu (kongtu@bnl.gov)

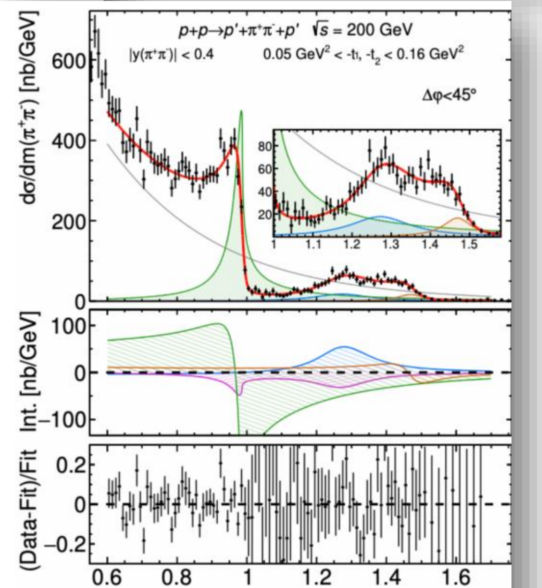
Wlodek Guryn: Glueball/Odderon/Exotics

Summary of Glueball/Odderon/Exotics

- RHIC program in proton-proton scattering can certainly inspire physics topics for the EIC in the exotic sector
- Given the quantum numbers of ep collisions, C = -1 of the photon, complementary channels for glueballs and exotic particles searches can be explored
- EIC with its high luminosity and detectors with excellent PID will have opportunity to address (answer) questions which eluded answers in pp colliders
- Odderon search in $ep \rightarrow e\pi^0 N^*$ channel is a great candidate for the day one topic since it does not require high luminosity
- Glueball Search $ep \rightarrow eK_S^0\,K_S^0 + \mathrm{X}$ is also a channel of interest.

CFNS May 24-26, 2021 Wlodek Guryn: RHIC Science Towards EIC 1





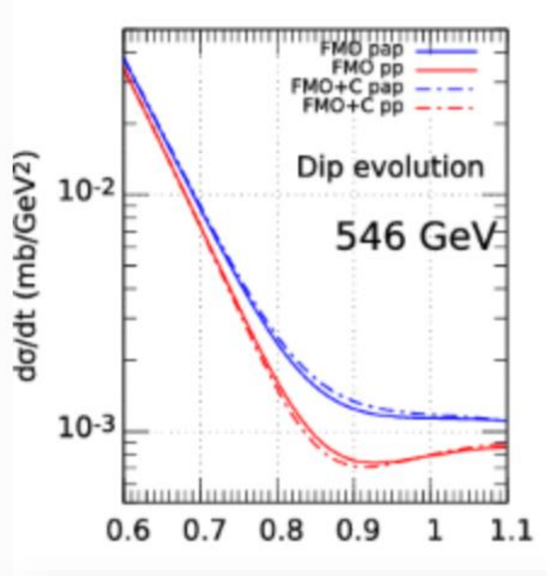
STAR (2020)

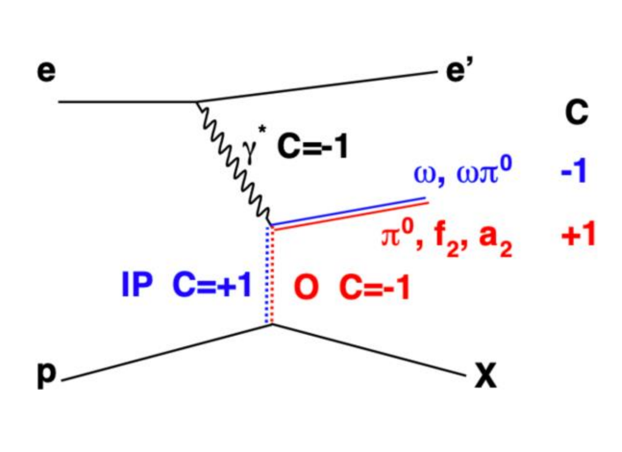
Wlodek Guryn: Glueball/Odderon/Exotics

Summary of Glueball/Odderon/Exotics

- RHIC program in proton-proton scattering can certainly inspire physics topics for the EIC in the exotic sector
- Given the quantum numbers of ep collisions, C = -1 of the photon, complementary channels for glueballs and exotic particles searches can be explored
- EIC with its high luminosity and detectors with excellent PID will have opportunity to address (answer) questions which eluded answers in pp colliders
- Odderon search in $ep \rightarrow e\pi^0 N^*$ channel is a great candidate for the day one topic since it does not require high luminosity
- Glueball Search $ep \rightarrow eK_S^0\, K_S^0 + \mathrm{X}$ is also a channel of interest.

CFNS May 24-26, 2021 Wlodek Guryn: RHIC Science Towards EIC 1

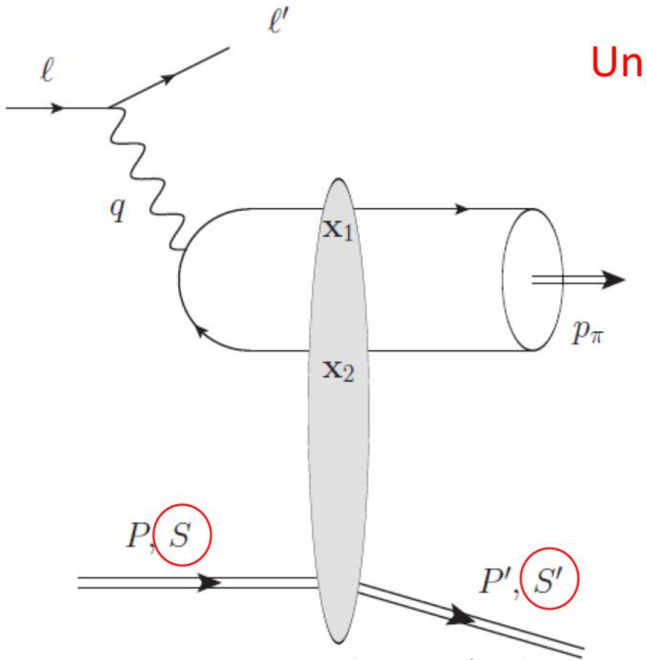




Yoshitaka Hatta:

Exclusive π^0 production at EIC

Boussarie, YH, Szymanowski, Wallon
PRL124, 172501 (2020)



Unpolarized cross section at small-x, $t \approx 0$

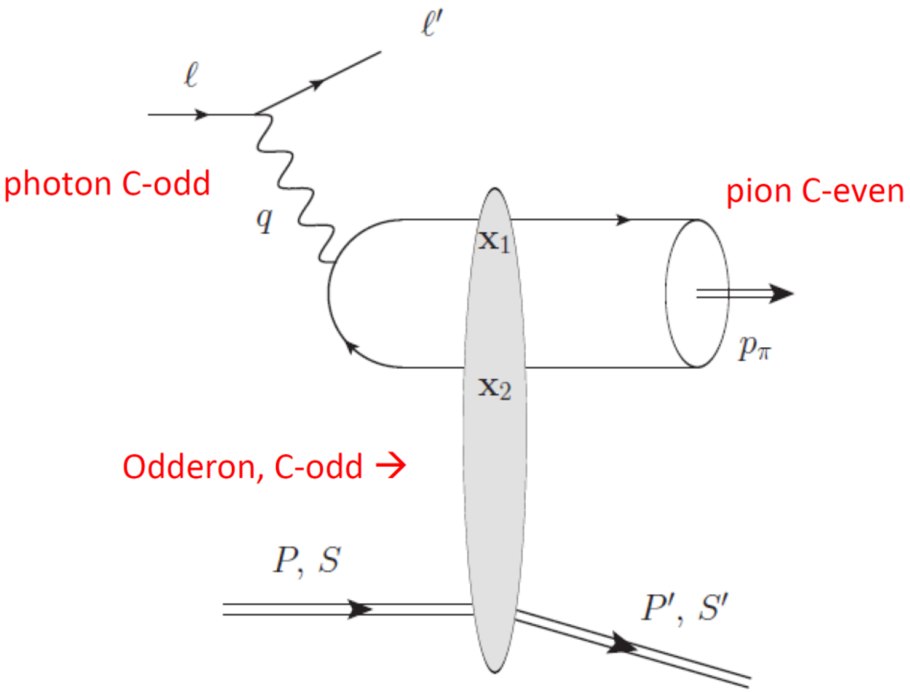
$$\frac{d\sigma}{dt} = \sum_{SS'=\pm} \frac{d\sigma_{SS'}}{dt} \approx \frac{d\sigma_{+-}}{dt} + \frac{d\sigma_{-+}}{dt}$$

$$\frac{d\sigma}{dx_B dQ^2 d|t|} = \frac{\pi^5 \alpha_{\rm em}^2 \alpha_s^2 f_\pi^2}{2^3 x_B N_c^2 M^2 Q^6}(1 - y + \frac{y^2}{2})$$
$$\times \left[\int_0^1 dz \frac{\phi_\pi(z)}{z\bar{z}} \int d\boldsymbol{k}^2 \frac{\boldsymbol{k}^2}{\boldsymbol{k}^2 + z\bar{z}Q^2} x f_{1T}^{\perp g}(x, \boldsymbol{k}^2)\right]^2$$

Cross section in the forward limit is dominated by gluon Sivers at small-x!

Yoshitaka Hatta:

Connection to Odderon



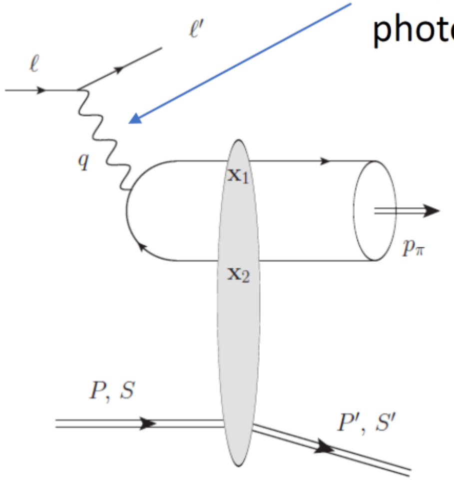
Spin-dependent odderon
=gluon Sivers at small-x

Jian Zhou; 1308.5912

Experimentally elusive for decades.
Finally found at the LHC? (TOTEM collaboration)

→ New connection between EIC and LHC

Yoshitaka Hatta:



Only the transversely polarized photon can contribute

Transverse polarization vector $\vec{\epsilon_\perp}$ has to be contracted by another transverse vector.

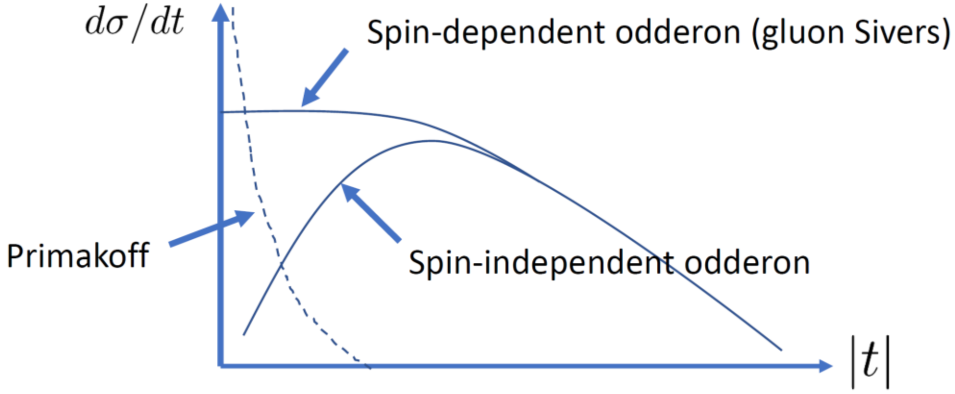
Naively, the only available vector is momentum transfer $\vec{\Delta_\perp}$
→ $d\sigma/dt$ vanishes as $t \to 0$

Theorists suggested to excite proton to a negative parity resonance.
(P-wave wavefunction contains a transverse vector.)
This is why H1 looked for neutrons from the decay $p \to N^* \to n$

But don't forget proton is a spin-1/2 particle.
We get a transverse vector when helicity flips

$$\bar{u}(P, -S_L)\sigma^{+i}u(PS_L) = (\pm i, -1)$$

$d\sigma/dt$ finite as $t \to 0$ without exciting proton!



Yoshitaka Hatta:

Gluon Sivers=Odderon in pp at RHIC and LHC

Elastic pp scattering, unpolarized

Hagiwara, YH, Pasechnik, Zhou; 2003.03680

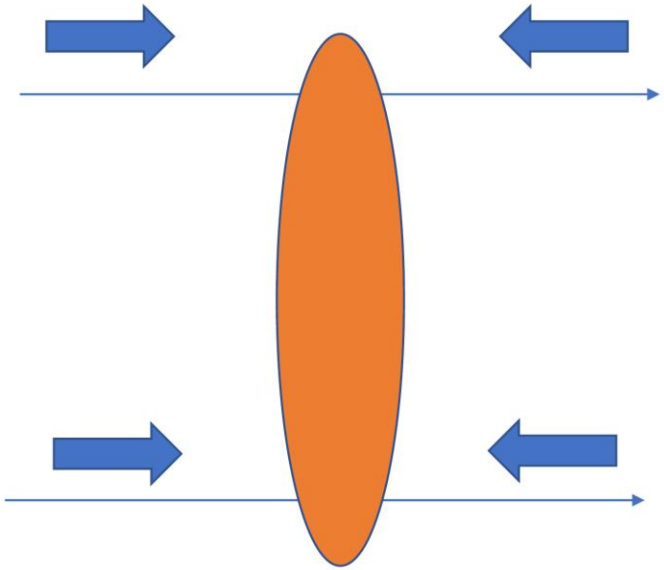
$$\frac{d\sigma}{dt} = \sum_{S_1S_2S_3S_4=\pm} \frac{d\sigma_{S_1S_2\to S_3S_4}}{dt}$$

Double helicity-flip from gluon Sivers=Odderon

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\sigma_{\rm tot}^2}{16\pi}(1+\rho^2+2|r_2|^2)$$

rho-parameter (spin non-flip)

$$\rho(s,t) = \frac{{\rm Re}T(s,t)}{{\rm Im}T(s,t)}$$



Koichi HATTORI :

- See also QED discussion

Muon-pair excess over electron pairs

KH, Taya, Yoshida [2010.13492]

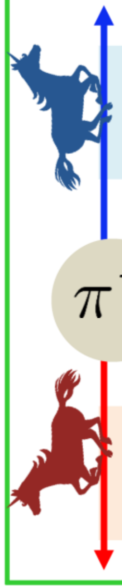
"Helicity suppression" in pion decay

PDG

$$\pi^- \to \mu^- \bar{\nu}_\mu \quad 99.9877\ \%$$
$$\pi^- \to e^- \bar{\nu}_e \quad 10.23 \times 10^{-4}\ \%$$

Opposite momentum

Opposite spin — Same helicity



ℓ^- $\quad S_\ell = \pm\frac{1}{2} \quad h_\ell = \pm\frac{1}{2}$

π^- $\quad S = 0$

Opposite chirality
→ Needs chirality mixing by finite mass.

$\bar{\nu}$ $\quad S_{\bar{\nu}} = \mp\frac{1}{2} \quad h_{\bar{\nu}} = \pm\frac{1}{2}$

The LLL (= soft photon)

$$\frac{N_{\mu^+\mu^-}}{N_{e^+e^-}} \propto \frac{m_\mu^2}{m_e^2} \sim 4.4 \times 10^4$$

Opposite spin along B-field — Same helicity

$S_{\ell^-} = -\frac{1}{2} \quad h_{\ell^-} = -\frac{1}{2}$

$S_\gamma = 0$

Superposition of $(\pm, L)$

Opposite chirality

$S_{\ell^+} = +\frac{1}{2} \quad h_{\ell^+} = -\frac{1}{2}$

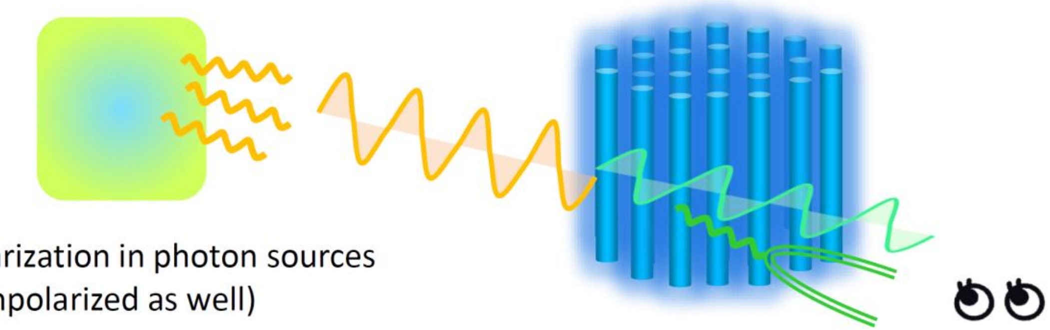
Especially, R neutrino (L antineutrino) does not exist at the QCD scale.
(However, this is not an essential reason for the helicity suppression.)

Koichi HATTORI :

See also QED discussion

Feasibility with HIC?

Ideal set-up

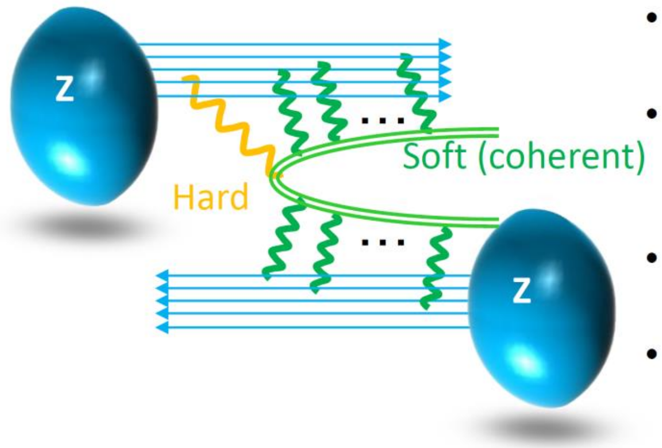


Inborn polarization in photon sources
(Possibly unpolarized as well)

- Acquired polarization due to the birefringence
- Some of photons decay into fermion pairs

UPC events

What is a photon source and what is a strong B field in HIC?



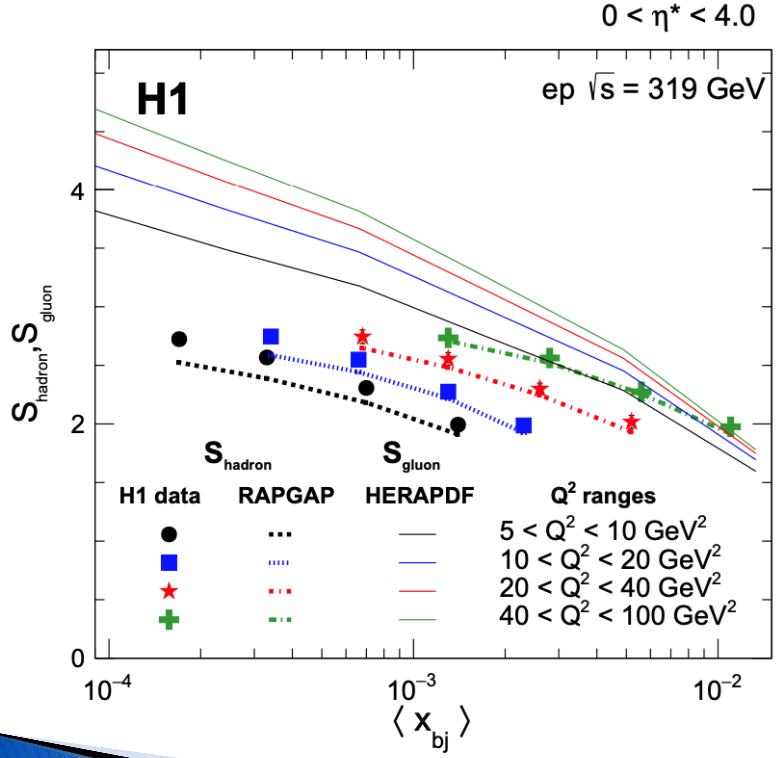
- There is no a priori difference: Both are Coulomb electric fields in the nucleus rest frame.
- The photon source has a momentum distribution: Fourier transform of the charge distribution, e.g., the Woods-Saxon profile.
- The hard and soft components of the distribution may be regarded as “photons” and a “magnetic field”.
- Needs quantitative estimates with a separation scale.

Importance of data preservation @ RHIC

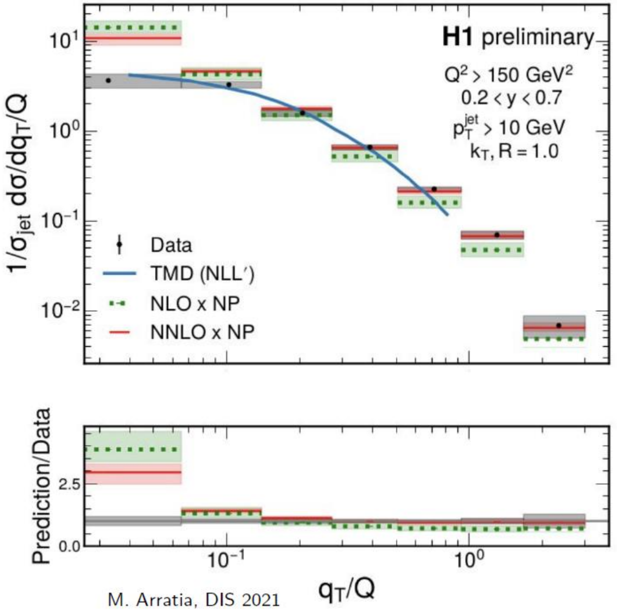
(see also: spin discussion)

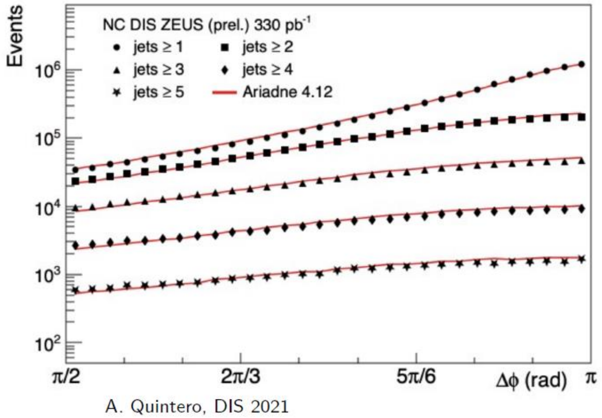
From talk Dmitri Kharzeev

H1 Collaboration (Z. Tu et al)
arXiv:2011.01812; EPJC(2021)



SIDIS TMD Data



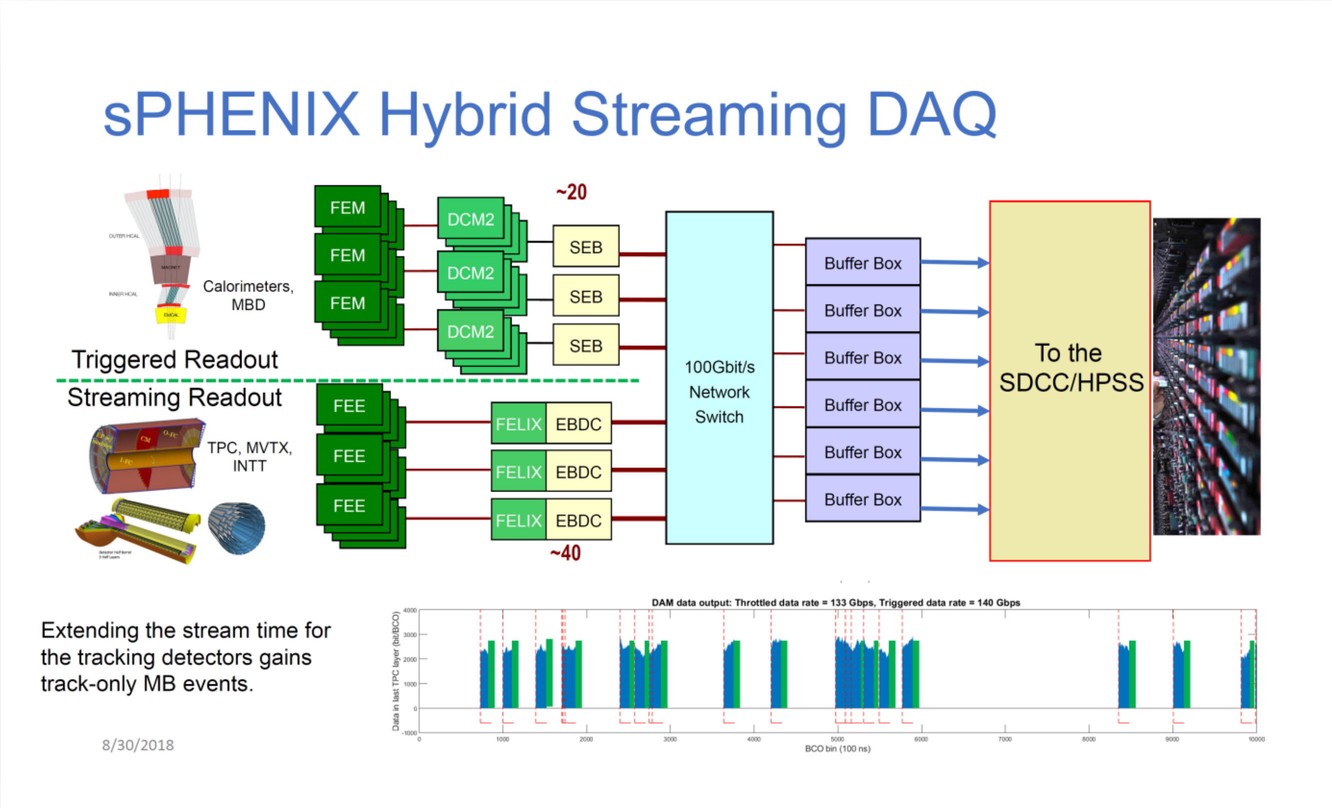


- HERA data being re-analyzed given new results from RHIC/LHC in last decade
- Emphasizes reusability of RHIC data! What will we want to re-analyze in the 2030s given new EIC information?

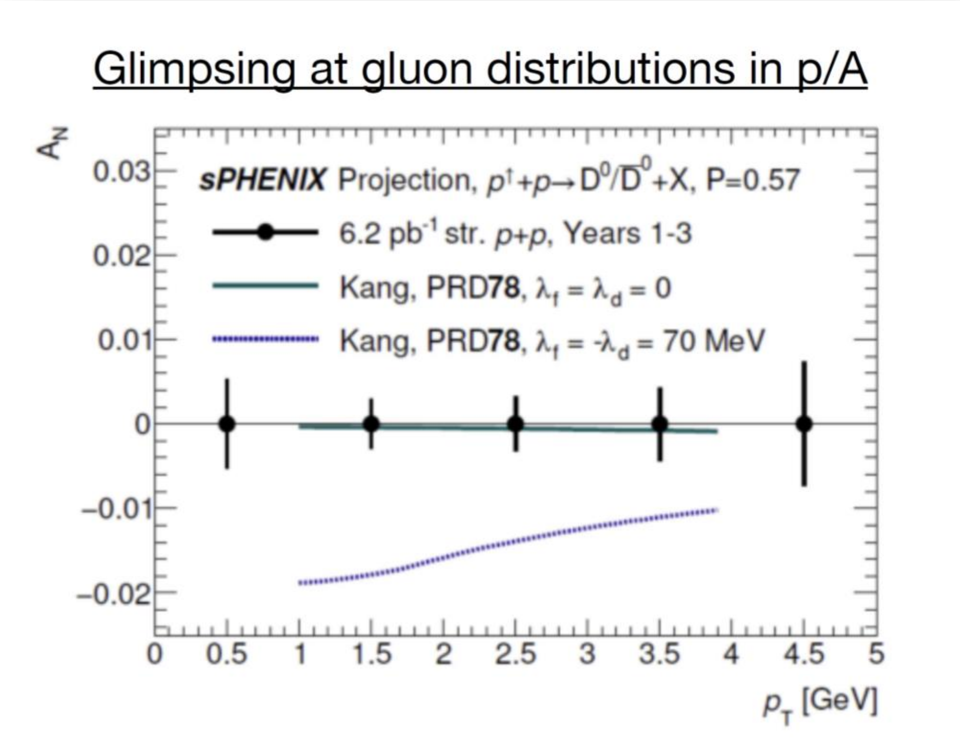
Joe Osborn 11

Streaming DAQ: preserve M.B. collisions at RHIC and EIC

John Lajoie :



Xin Dong:

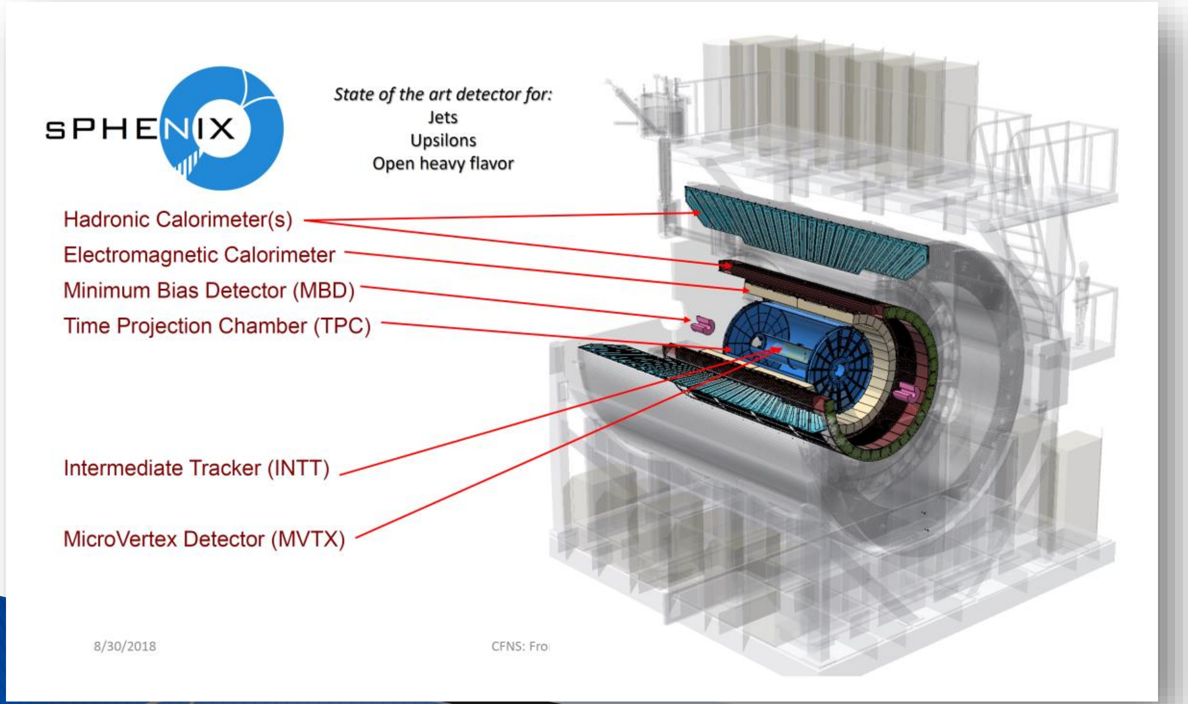


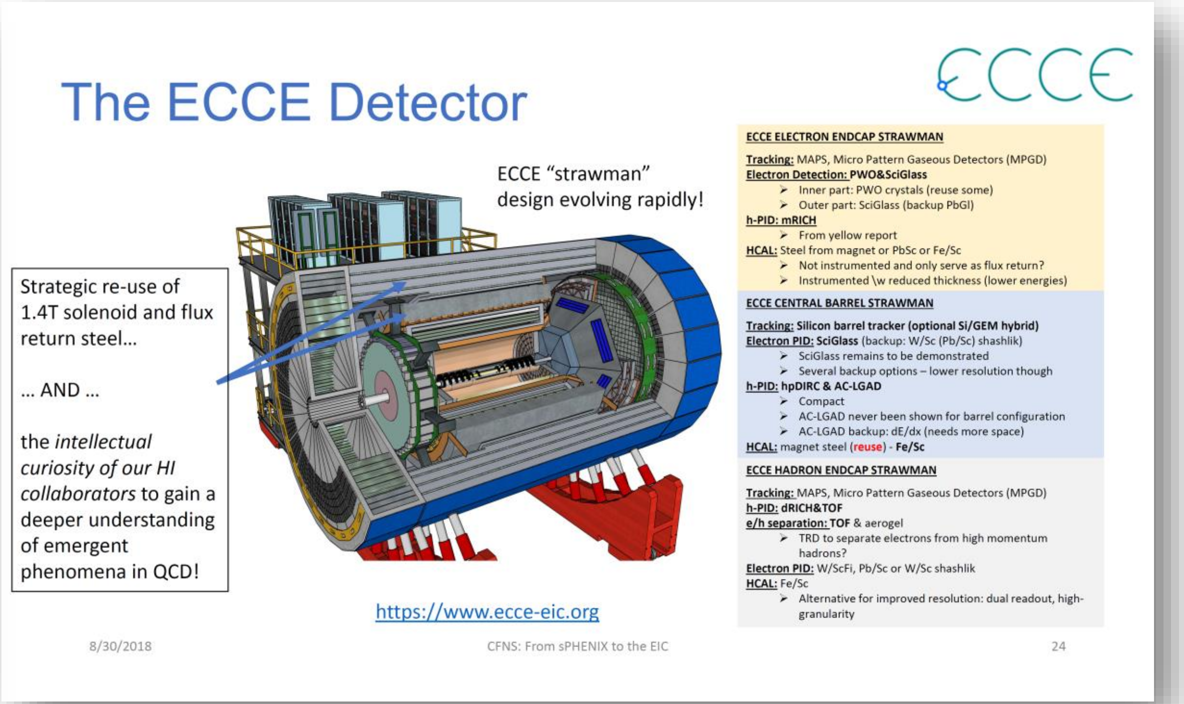
Wide adoption of streaming DAQ in EIC as in CDR & YR
https://indico.bnl.gov/event/7449/contributions/35877/

John Lajoie :

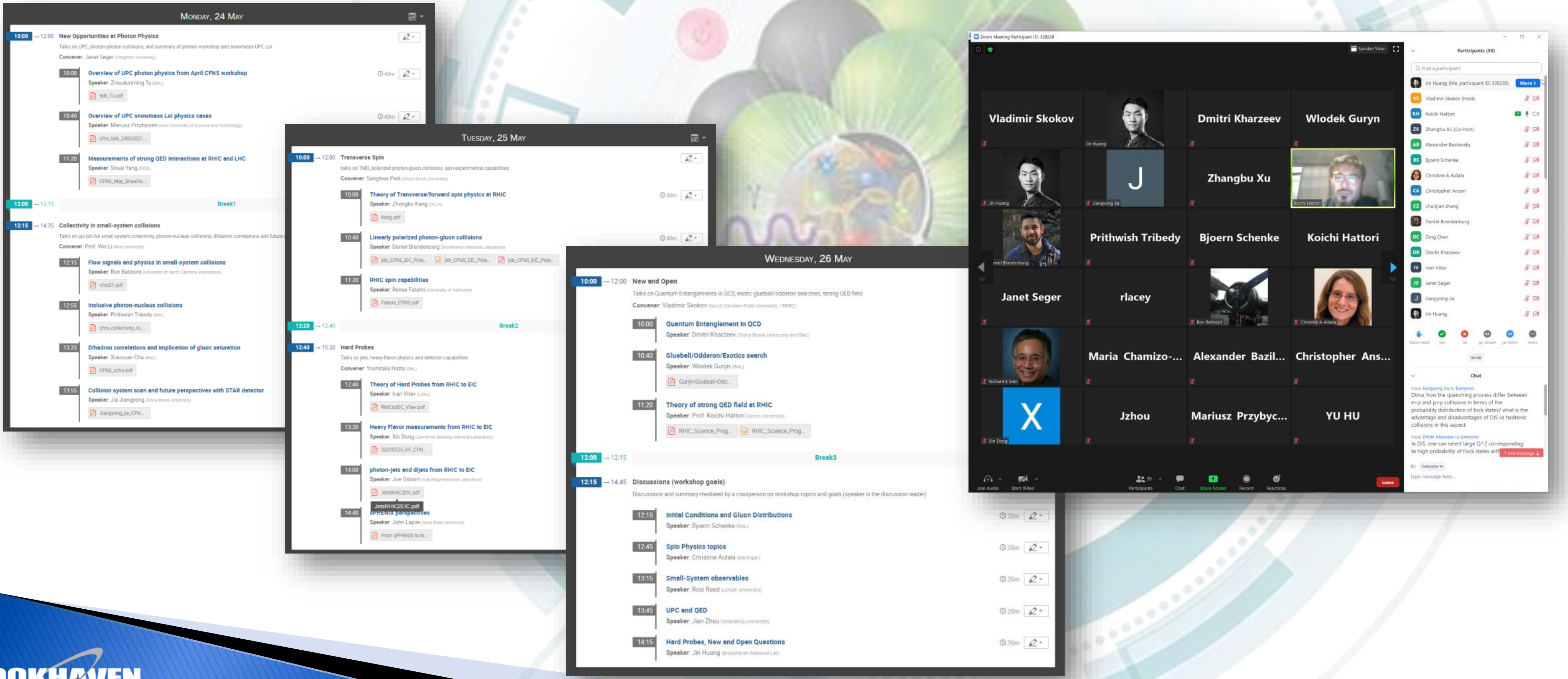
(… at EIC we could use) the intellectual curiosity of our HI collaborators to gain a deeper understanding of emergent phenomena in QCD!

See also, EIC proto-collaborations of ATHENA and CORE





Thanks for participating the workshop of RHIC Science Programs Informative Toward EIC in the Coming Years!



Extra slides

Contribution - Nihar Ranjan Sahoo (Shandong U.)

A brief discussion on
γ+jet and dijet (de)correlation in QCD medium

[in EIC, both QED and QCD Effects]

Nihar Ranjan Sahoo

Shandong University

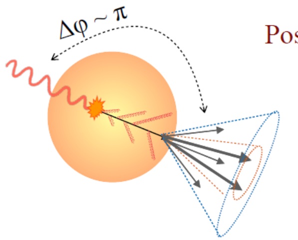
Workshop: RHIC Science Programs Informative Toward EIC in the Coming Years

26 May, 2021

1

Jet-medium interaction in hot-dense QCD medium

Literature



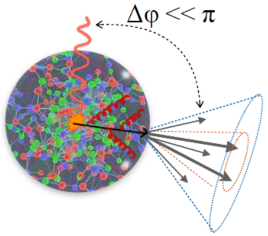
Possible sources of γ+jet (dijet) $\Delta\varphi$ (de)correlation in the medium

- Vacuum broadening (Sudakov radiation)
- Multiple soft-scattering in the QGP
- Radiative correction (reduces broadening)

Chen et al, PLB773 (2017) 672

M. Gyulassy et al, arXiv:1808.03238

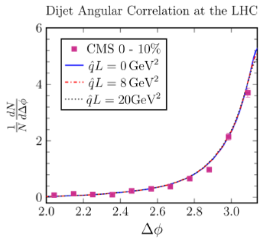
Zhakharov, arXiv:2003.10182

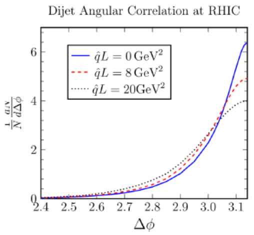


- Rutherford like-scattering: *energetic parton resolves the microstructure of the QGP* (Large-angle deflection of hard partons off quasi-particles)

D'Eramo, Rajagopal, Yin, JHEP 01 (2019) 172

- B-field effect? (No theory calculation yet)





Significant pt-broadening effect at RHIC than LHC
(Smaller Sudakov effect at RHIC)

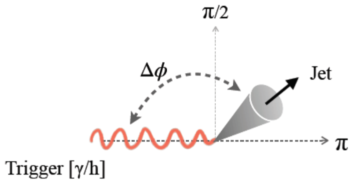
A. Mueller et al, PLB 763 (2016) 208

Important to study the shape of γ+jet, h+jet (dijet) azimuthal (de)correlation in heavy-ion collisions (and also in p+Au and e+p/A)

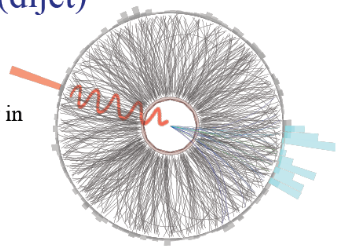
Nihar Sahoo (SDU) 2

Contribution - Nihar Ranjan Sahoo (Shandong U.)

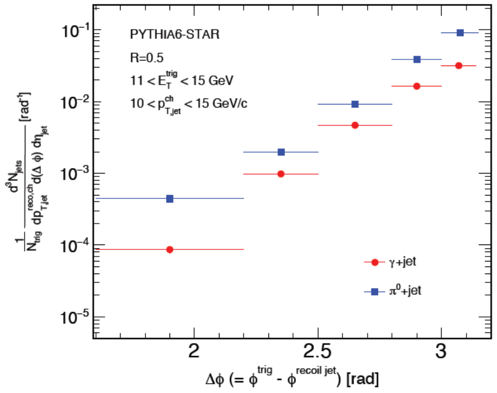
Ongoing STAR measurement γ+jet and h+jet (dijet)



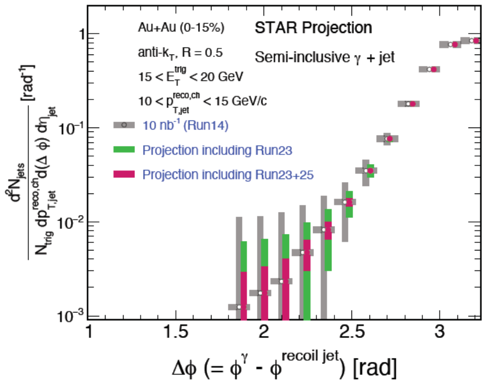
STAR γ+jet event display in A+A collisions



p+p PYTHIA6



STAR Projection (Au+Au)

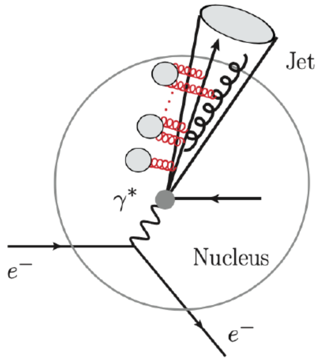


[Pythia Shape + Uncertainty from HI projections]

Jet cone size dependence of QCD radiation

- Vacuum (p+p) vs. in-medium (A+A) gluon radiation
- Or Large-angle scattering off of QGP quasi-particles

EIC Era: QED and QCD radiations

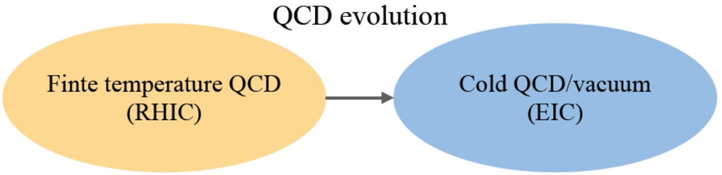


Li and Vitev, arXiv: 2010.05912

$$e + p/A \rightarrow e' + \text{jet} + X$$

Shape of electron tagged jet (or dijet) azimuthal (de)correlation in e+p/A event

- Study anisotropy of in e+p/A events
  [Hatta, Xiao, Yuan, Zhou, arXiv: 2010.10774
  Arratia, Song, Ringer, Jacak, PRC 101, 065204 (2020)]
- Cold QCD vs Vacuum radiation
  [Li and Vitev, arXiv: 2010.05912]
- Study QED radiations in election side as well [ISR and FSR]



Dmitri Kharzeev:

Quantifying entanglement: von Neumann entropy

$$\rho = \sum_n p_n |n\rangle\langle n|$$

Entanglement entropy:

$$S = -\mathrm{tr}\rho \ln \rho = -\mathrm{p_n} \ln \mathrm{p_n}$$

Pure states:

$$S = 0$$

e.g.

$$p_0 = 1, \; p_{n\neq 0} = 0$$

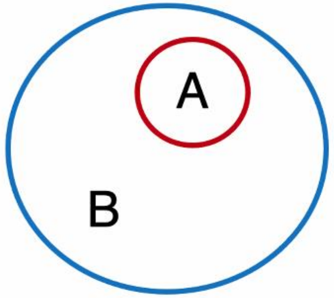
Mixed states:

$$S \neq 0$$

e.g. for EPR $\rho_A = \frac{\mathbf{I}}{2}$

$$p_0 = p_1 = \frac{1}{2} \to S = \ln 2$$

The quantum mechanics of partons and entanglement



The proton is described by a vector

$$|\Psi_{AB}\rangle = \sum_{i,j} c_{ij} \; |\varphi_i^A\rangle \otimes |\varphi_j^B\rangle$$

in Hilbert space $\mathcal{H}_A \otimes \mathcal{H}_B$

If $|\Psi_{AB}\rangle = |\varphi^A\rangle \otimes |\varphi^B\rangle$ only one term

contributes, then the state is separable (not our case!). Otherwise, the state is **entangled**.

18

Dmitri Kharzeev:

The entanglement entropy from QCD evolution

The (3+1) case is cumbersome, but the result is the same, with $\Delta = \bar{\alpha}_s \ln(r^2 Q_s^2)$

What is the physics behind this relation?

$$S = \ln[xG(x)]$$

It signals that all $\exp(\Delta Y)$ partonic states have about equal probabilities $\exp(-\Delta Y)$ – in this case the **entanglement entropy is maximal**, and the proton is a **maximally entangled state** (a new look at the parton saturation and CGC?)

Fluctuations in hadron multiplicity

Numerically, for $\bar{n} = 5.8 \pm 0.1$ at |η|<0.5, E_{cm}=7 TeV we get:

theory	exp (CMS)	theory, high energy limit
$C_2 = 1.83$	$C_2 = 2.0 \pm 0.05$	$C_2 = 2.0$
$C_3 = 5.0$	$C_3 = 5.9 \pm 0.6$	$C_3 = 6.0$
$C_4 = 18.2$	$C_4 = 21 \pm 2$	$C_4 = 24.0$
$C_5 = 83$	$C_5 = 90 \pm 19$	$C_5 = 120$

It appears that the multiplicity distributions of final state hadrons are very similar to the parton multiplicity distributions – this suggests that the entropy is close to the entanglement entropy

Dmitri Kharzeev:

Test of the entanglement at the l

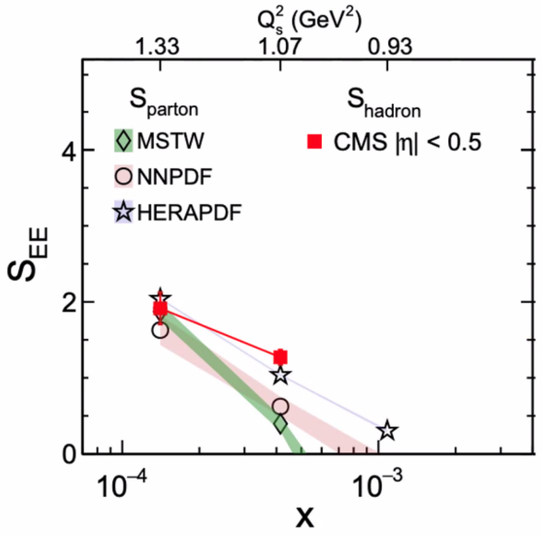
LHC data:

arXiv:19

$$S = \ln[xG(x)]$$

is satisfied at small x (**entangle**

K. Tu, DK, T. Ullrich, arXiv:1904.11974; PRL (2020)



Summary

1. Entanglement entropy (EE) provides a viable solution to the apparent contradiction between the parton model and quantum mechanics.
2. Indications from experiment that the link between EE and parton distributions is real. Further tests at RHIC and EIC, requirements for detector design.
3. Entanglement may provide a mechanism for thermalization in high-energy collisions. Need for further study of real-time dynamics by theorists (QCD+QIS) and experimentalists!

41