

# Studying Nuclear Matter with Jets in the sPHENIX Experiment at RHIC

John Lajoie  
*Iowa State University*



U.S. DEPARTMENT OF  
**ENERGY**

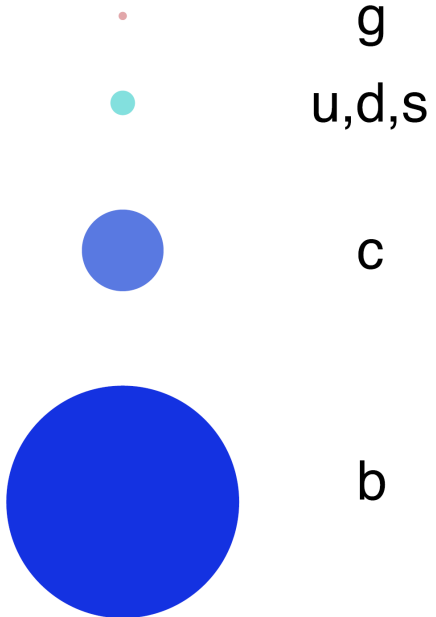




# The sPHENIX Physics Program

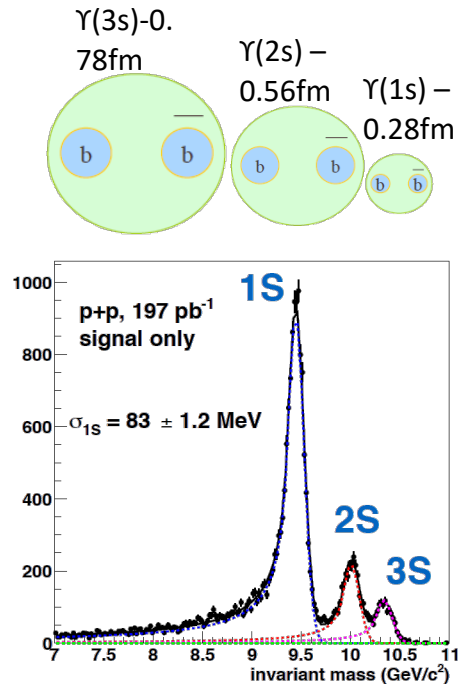
## Parton energy loss

Vary mass/momentum  
of probe



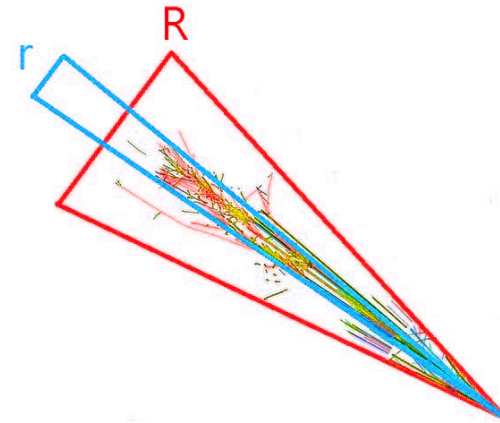
## Upsilon spectroscopy

Vary size of the probe



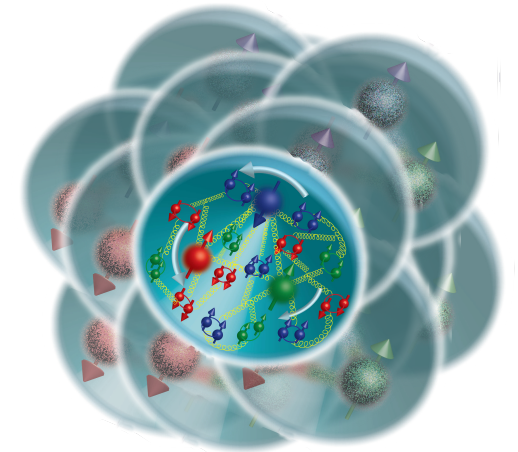
## Jet cor. & substructure

Vary momentum/angular  
size of probe



## Cold QCD

Spin-orbit correlations  
in the nucleon  
CNM effects and  
hadronization





# The sPHENIX Experiment



15 kHz calo trigger + 10% streaming DAQ  
10 GB/s data logging

5/5/2022

OUTER HCAL

SC MAGNET

INNER HCAL

EMCAL

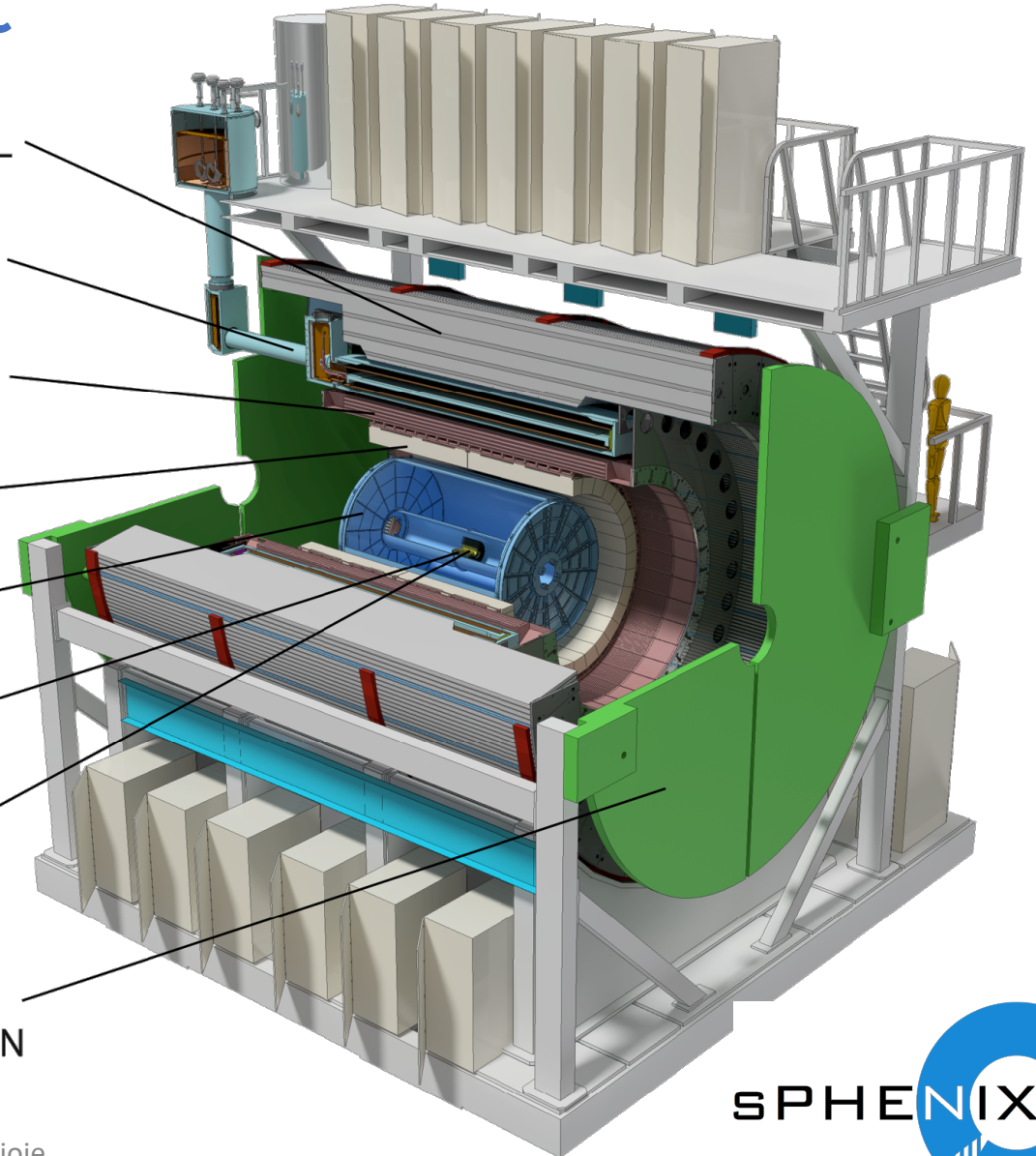
TPC

INTT

MAPS

ENDCAP

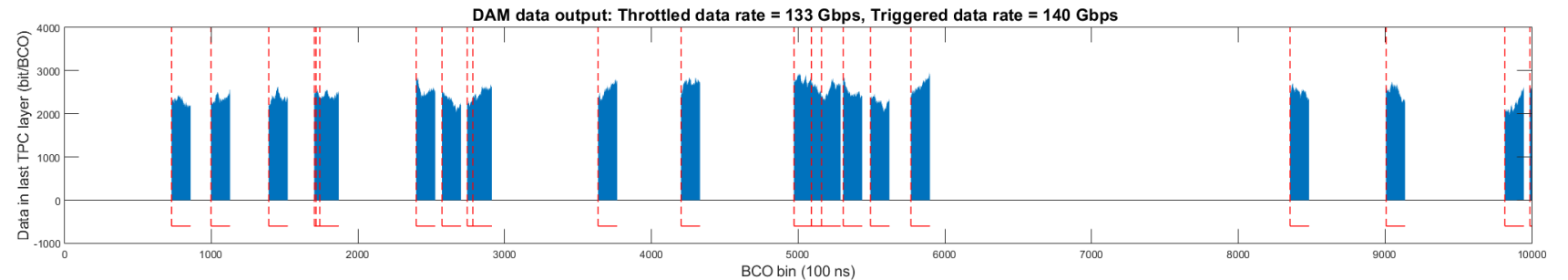
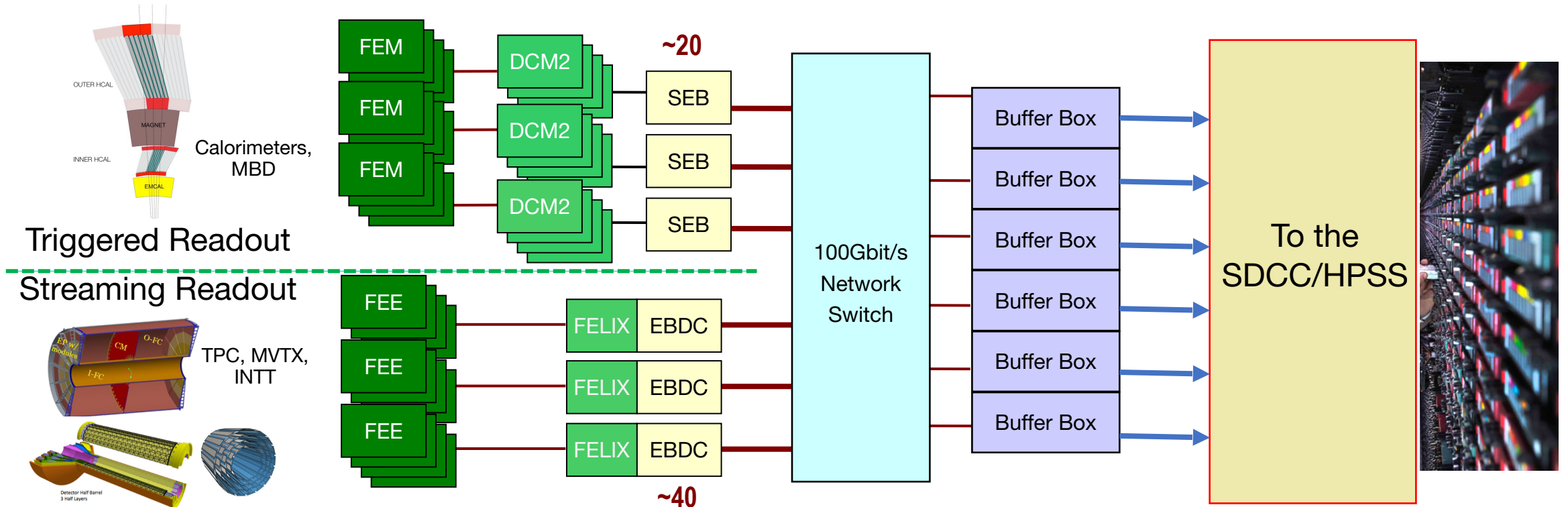
FLUX RETURN



DIS 2022 - J. Lajoie

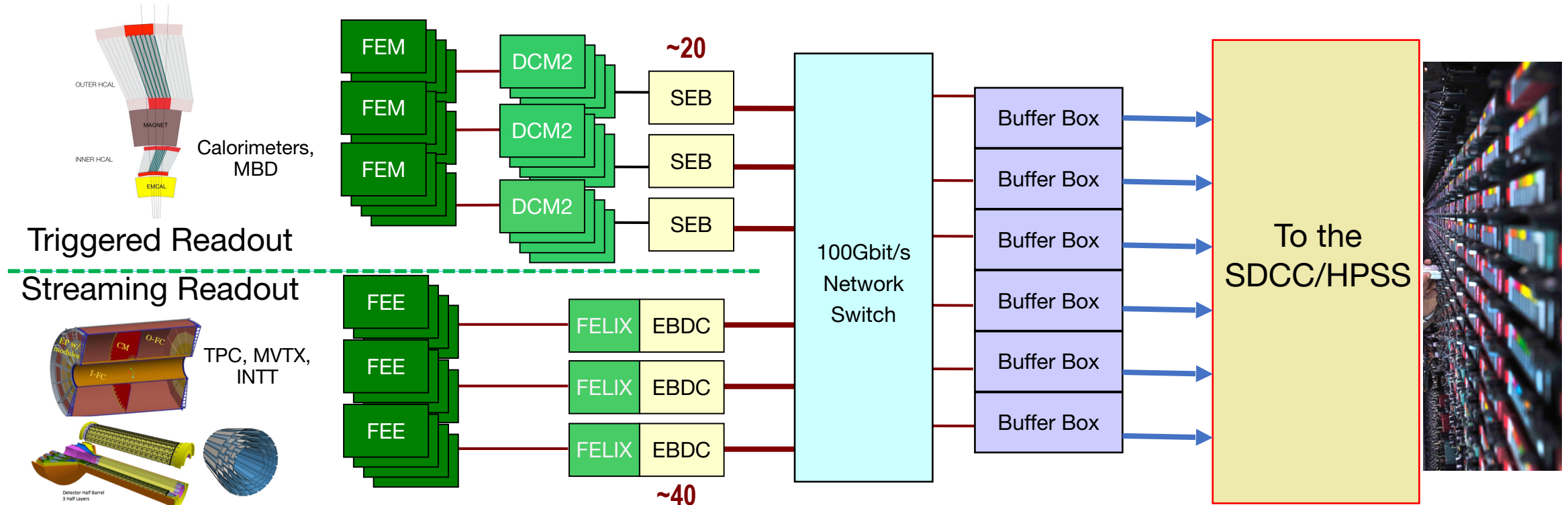


# sPHENIX Hybrid Streaming DAQ



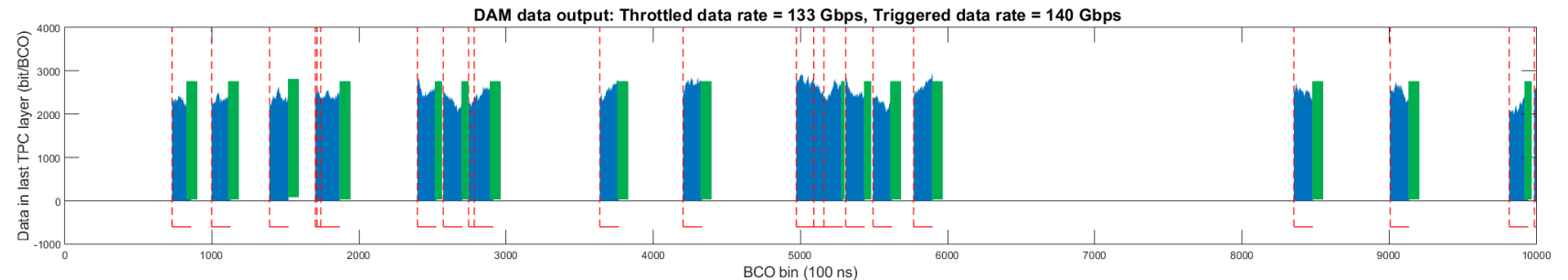


# sPHENIX Hybrid Streaming DAQ



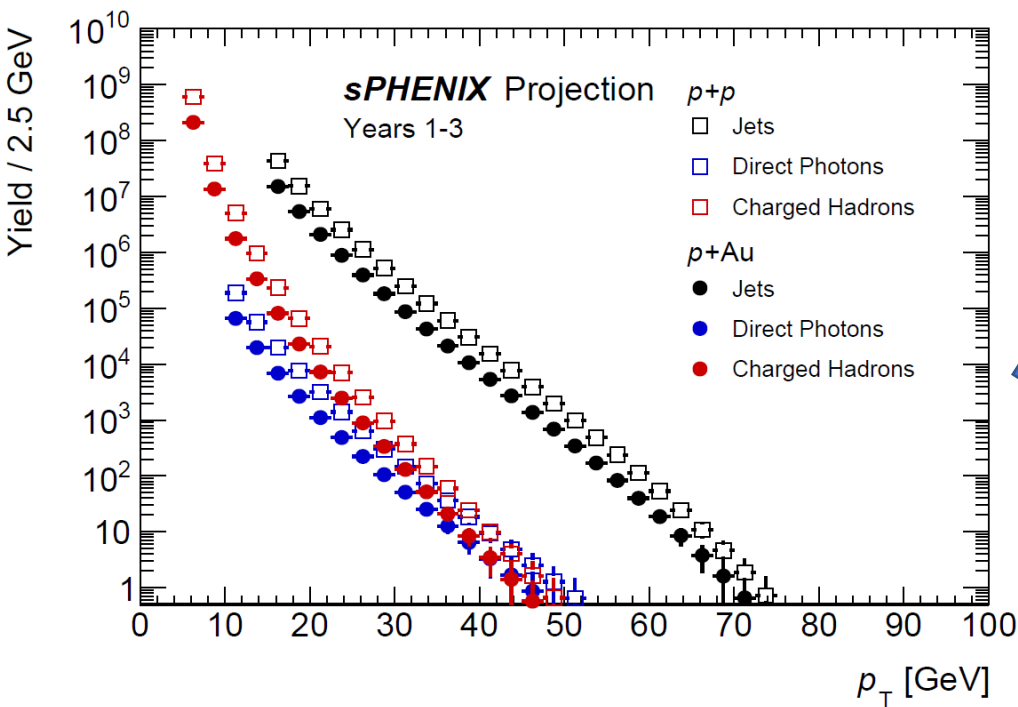
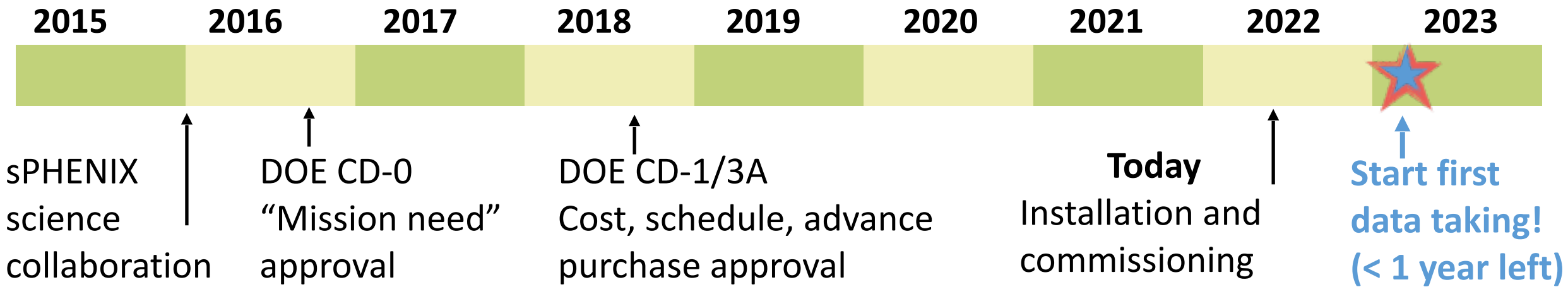
Extending the stream time for the tracking detectors gains track-only MB events.

S. Lim, WG4, Thursday 11:30





# sPHENIX Run Plan

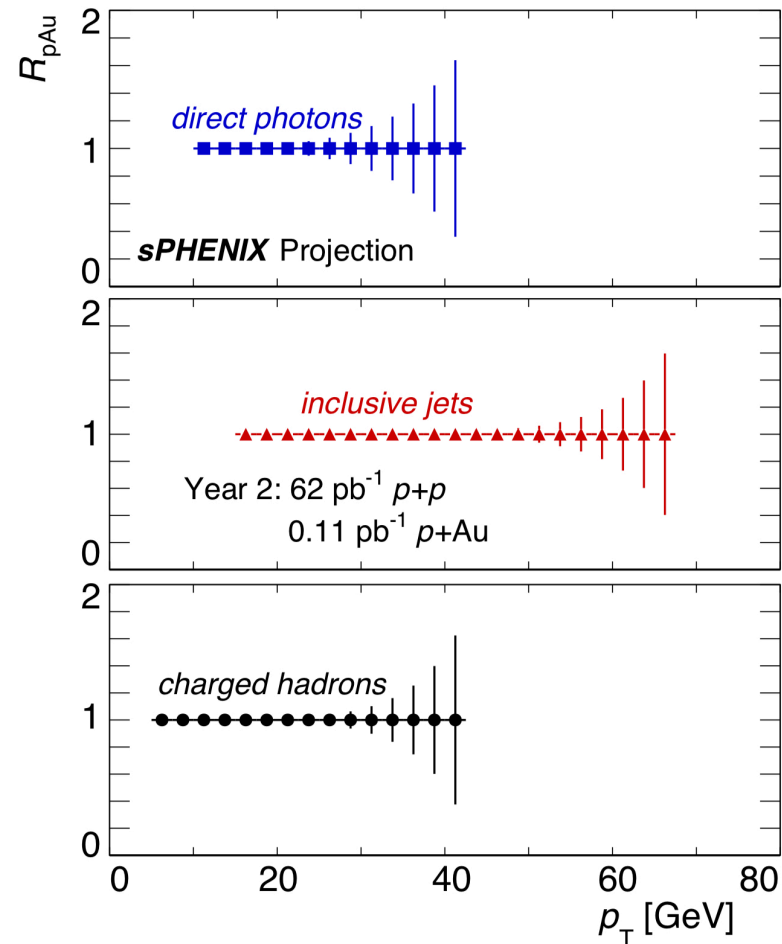


DIS 202

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $ z  < 10$ cm	Samp. Lum. $ z  < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb <sup>-1</sup>	4.5 (6.9) nb <sup>-1</sup>
2024	$p^\uparrow p^\uparrow$	200	24 (28)	12 (16)	0.3 (0.4) pb <sup>-1</sup> [5 kHz] 4.5 (6.2) pb <sup>-1</sup> [10%-str]	45 (62) pb <sup>-1</sup>
2024	$p^\uparrow + Au$	200	–	5	0.003 pb <sup>-1</sup> [5 kHz] 0.01 pb <sup>-1</sup> [10%-str]	0.11 pb <sup>-1</sup>
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb <sup>-1</sup>	21 (25) nb <sup>-1</sup>

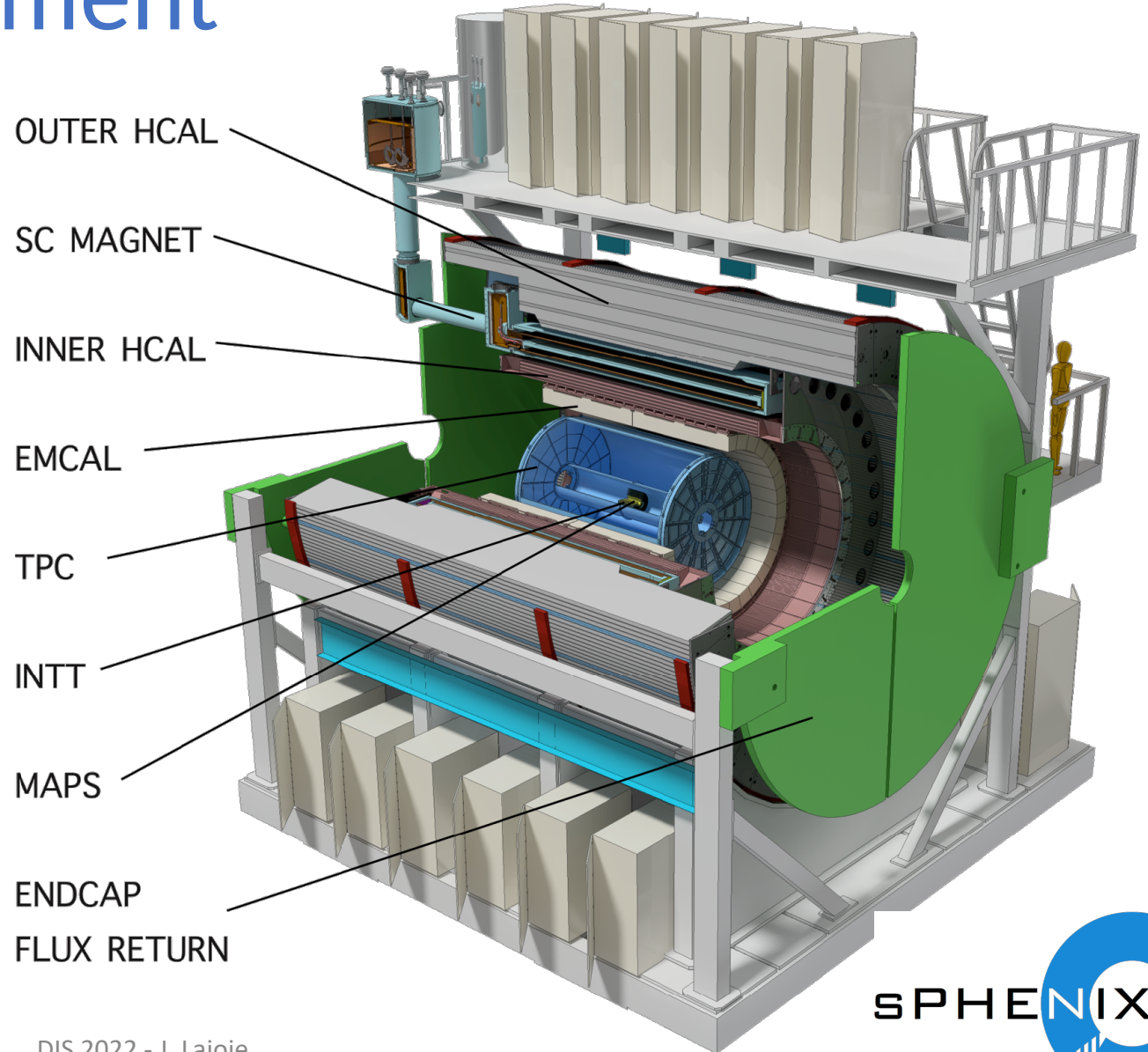


# The sPHENIX Experiment



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5/5/2022



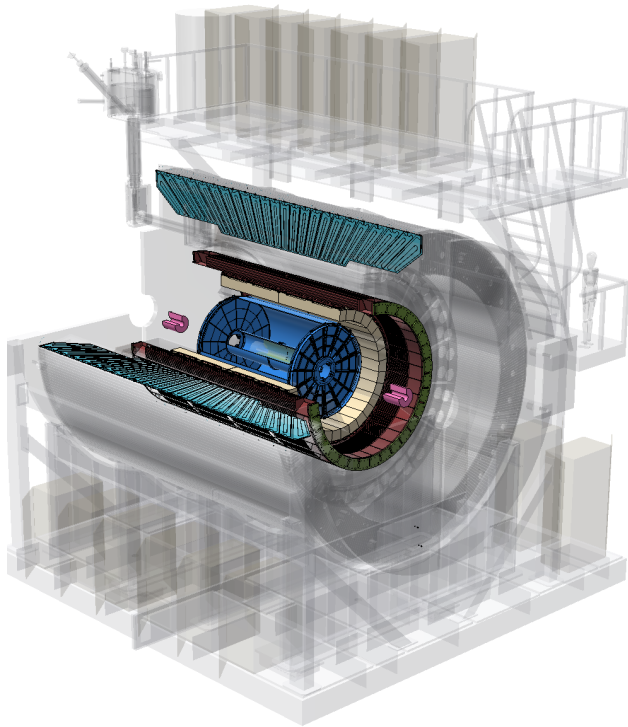
DIS 2022 - J. Lajoie





# The sPHENIX Cold QCD Program

Many unpolarized and polarized measurements in  $p+p$  and  $p+A$  are possible utilizing the jet, heavy flavor and direct photon strengths of the sPHENIX barrel:



## Unpolarized

Quarkonia Polarization :

Nuclear PDF :

Hadronization in Nuclear Env. :

$J/\Psi$ ,  $\Upsilon$

$h$ , jet, di-jet,  $\gamma$ -jet,  $DY$

$h$  in jet, di-jet,  $\gamma$ -jet

## Polarized

Hadron  $A_N$ ,  $p+p$  vs.  $p+A$  :

Transversity x Collins FF :

Transversity x Interference FF:

Sivers asymmetry :

Gluon Dynamics (Twist-3) :

$h$

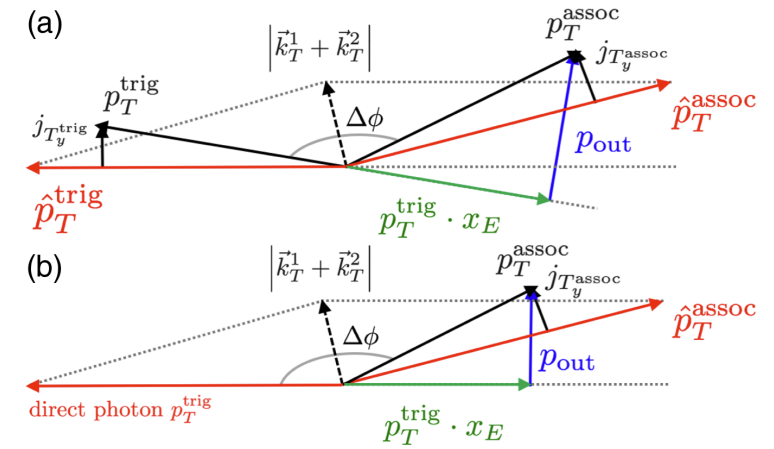
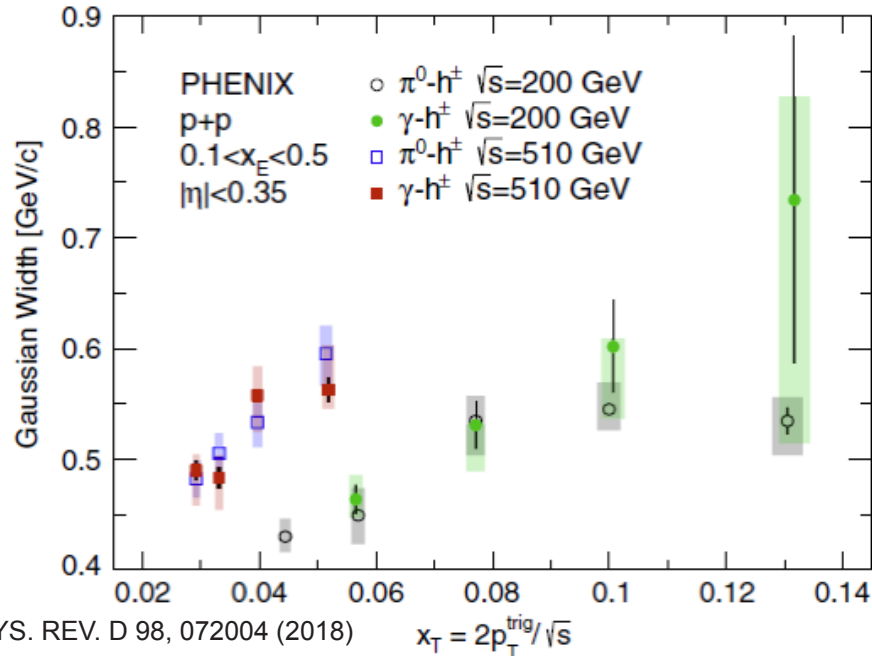
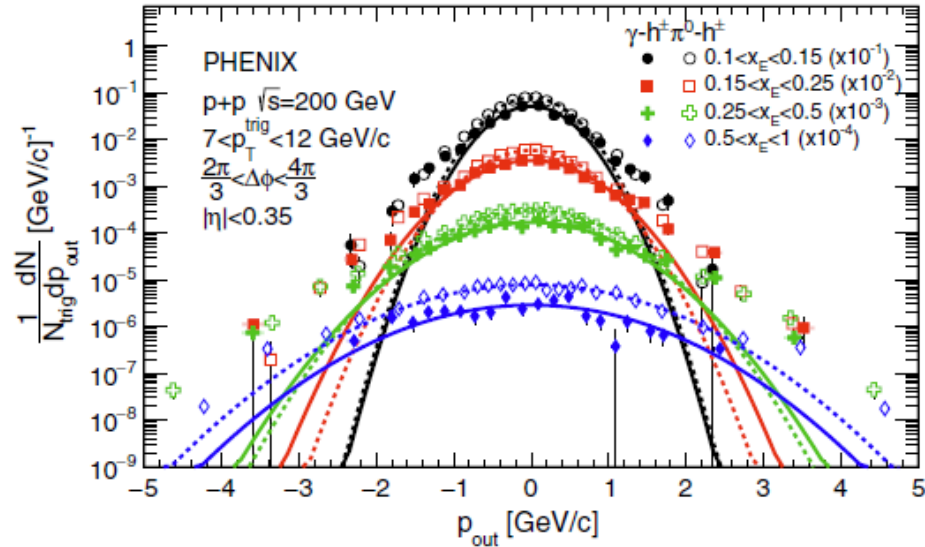
$h$  in jet

di- $h$

$\gamma$ -jet, jet-jet

$\gamma$ , HF ( $D^0$ , etc.)

# TMD Factorization Breaking



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.

Behavior of non-perturbative component of  $p_{\text{out}}$  consistent with DY – no clear qualitative evidence for factorization breaking effects.

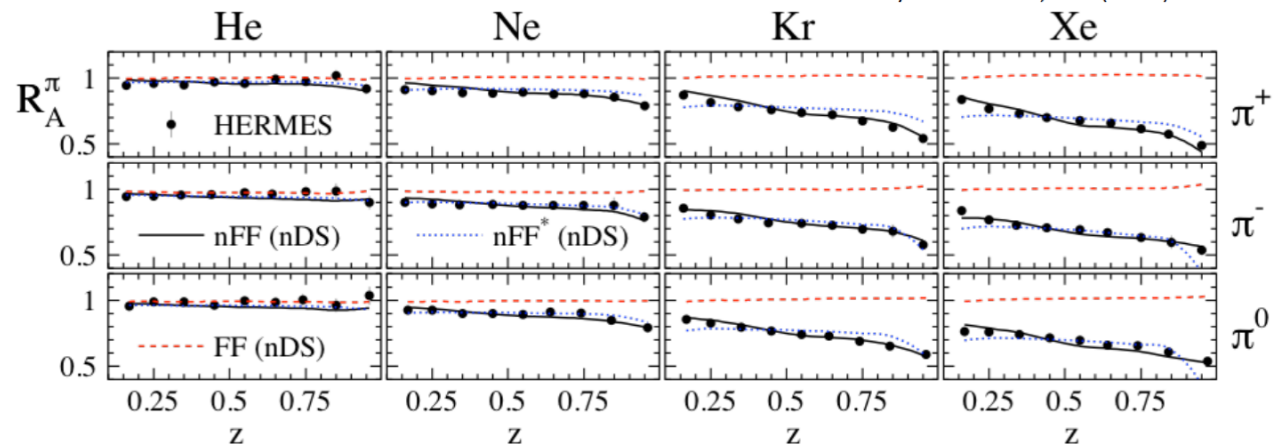
## sPHENIX:

- Full jet reconstruction – access to better proxies for parton kinematics
- Spin asymmetries in photon+jet – breakdown of factorization can lead to additional spin asymmetries
- Spin asymmetries in  $p \uparrow + A$  - nuclear dependence changes color exchanges

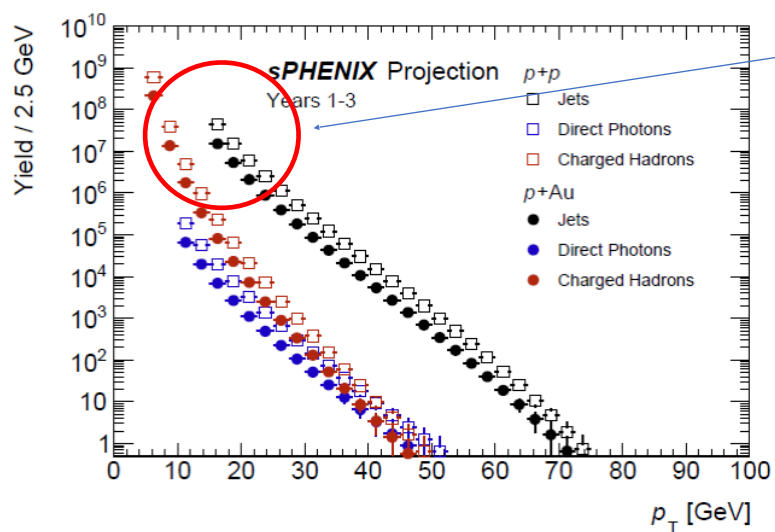


# Hadronization in a Nuclear Environment

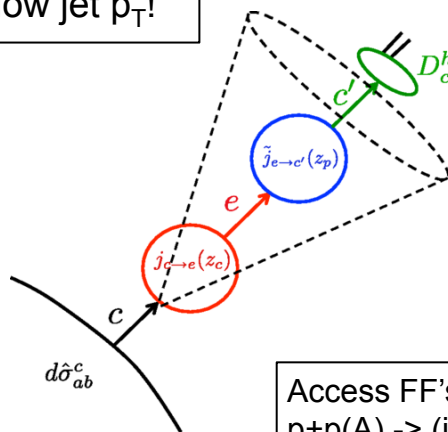
Phys. Lett. B577, 37 (2003)  
Phys. Lett. B684, 114 (2010)



Hadron production in e+A suppressed compared to e+p – must be a fragmentation effect, but at low- $Q^2$ ....

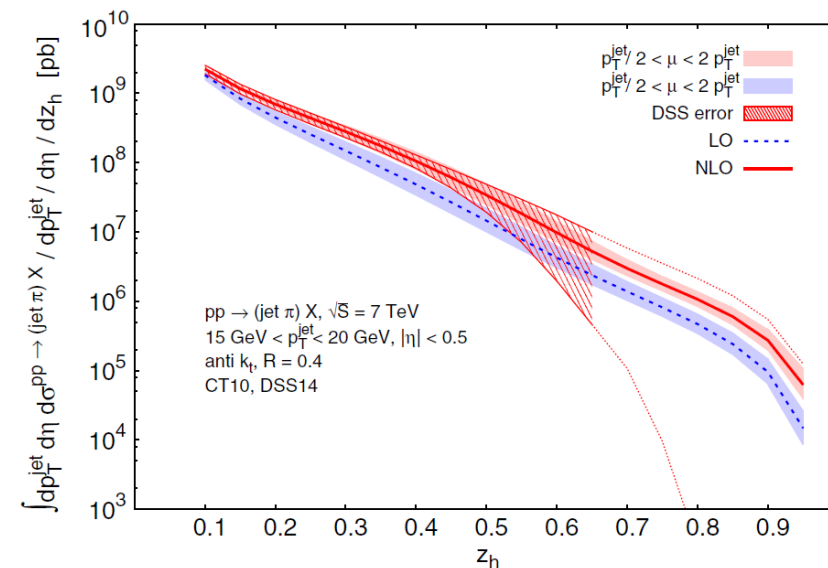


Enormous statistics available at low jet  $p_T$ !



Access FF's through  
 $p+p(A) \rightarrow (\text{jet } h) X$

Kaufmann, Mukherjee and Vogelsang Phys.Rev.D 92 5, 054015



# Jet Substructure at RHIC

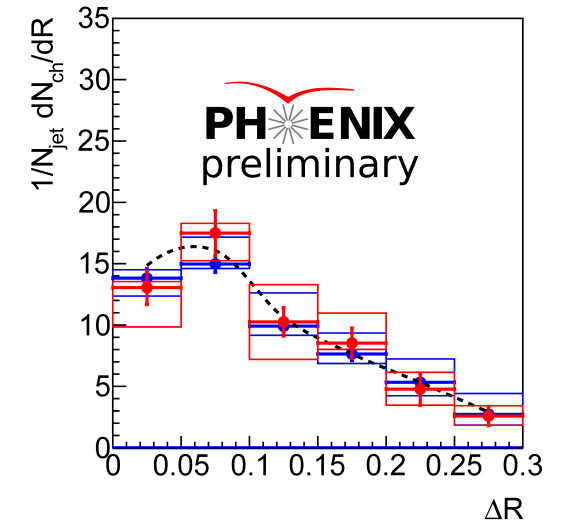
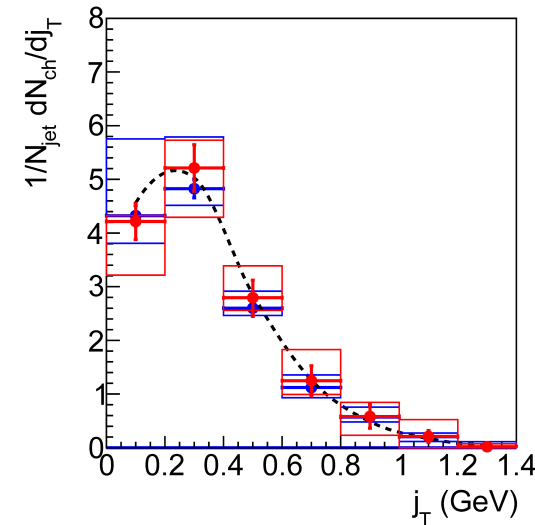
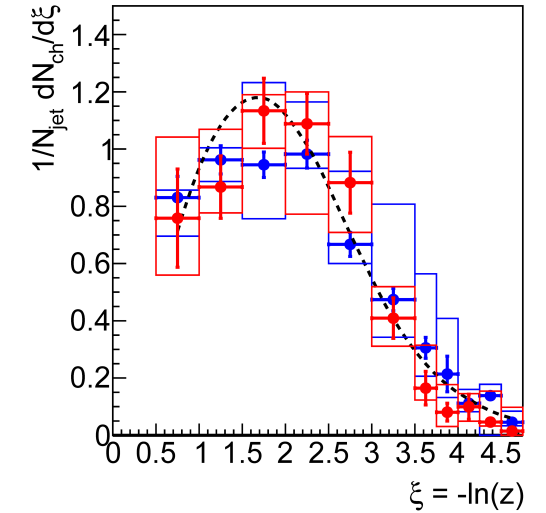
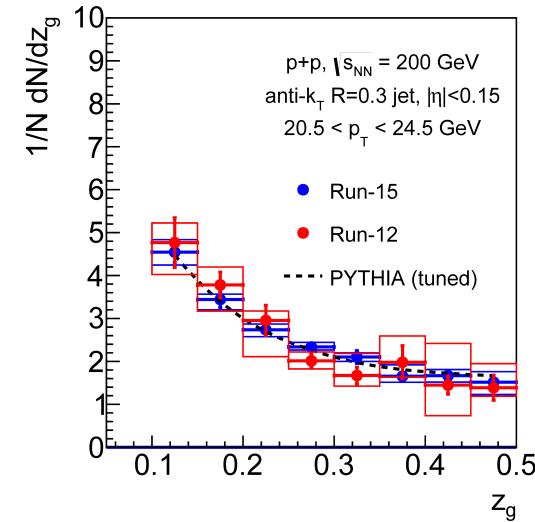
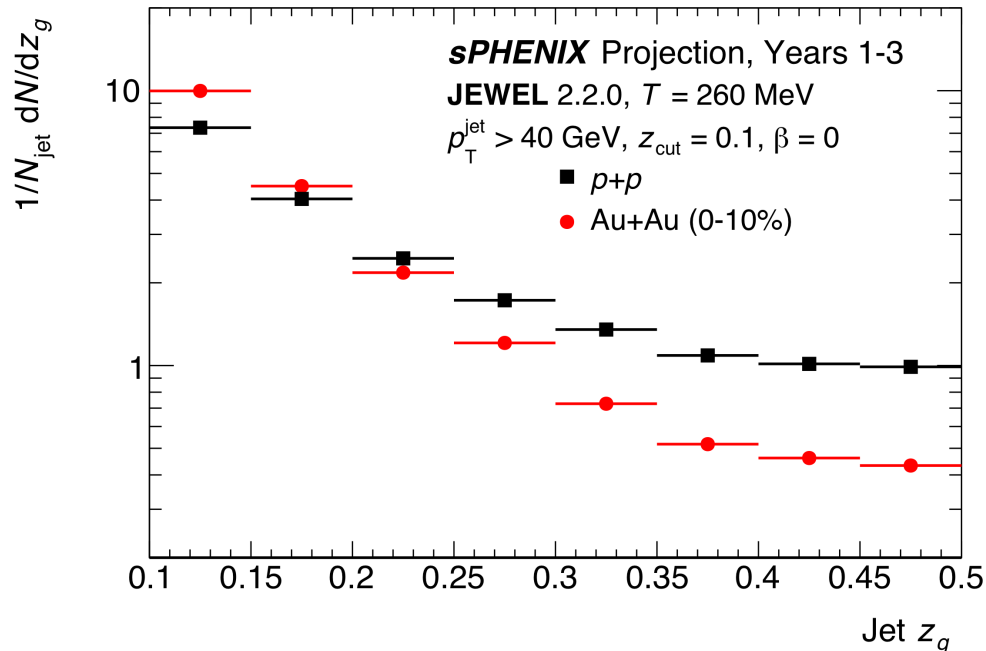
Results in the pipeline for PHENIX, STAR...

...but PHENIX and STAR were not designed as Jet detectors!

- Substantial corrections to the JES and fragmentation bias
- Relatively large systematic errors, hard to look for subtle effects

sPHENIX will enable a full suite of jet measurements with full tracking and calorimetry coverage.

***This is necessary to understand hadronization in CNM!***





# Energy Correlations in Jets

Analyzing N-point Energy Correlators Inside Jets with CMS Open Data

<https://arxiv.org/pdf/2201.07800.pdf>

$$ENC(R_L) = \left( \prod_{k=1}^N \int d\Omega_{\vec{n}_k} \right) \delta(R_L - \Delta \hat{R}_L) \cdot \frac{1}{(E_{jet})^N} \langle \epsilon(\vec{n}_1) \epsilon(\vec{n}_2) \dots \epsilon(\vec{n}_N) \rangle$$

$\epsilon$ , is the asymptotic energy flow operator

2-points correlation:

$$\frac{1}{\sigma} \frac{d\Sigma}{d\phi} \equiv \frac{1}{N} \sum_{A=1}^N \frac{1}{\Delta\phi} \sum_{pairs \text{ in } \Delta\phi} \frac{E_{T_a}^A E_{T_b}^A}{(E_T^A)^2}$$

More information:

arxiv:1205.1689

- TEEC in NLO in  $\alpha_s$  at the LHC

arxiv:1707.02562

- $\alpha_s$  measurement from multijet events by ATLAS

Analyzing N-point Energy Correlators Inside Jets with CMS Open Data

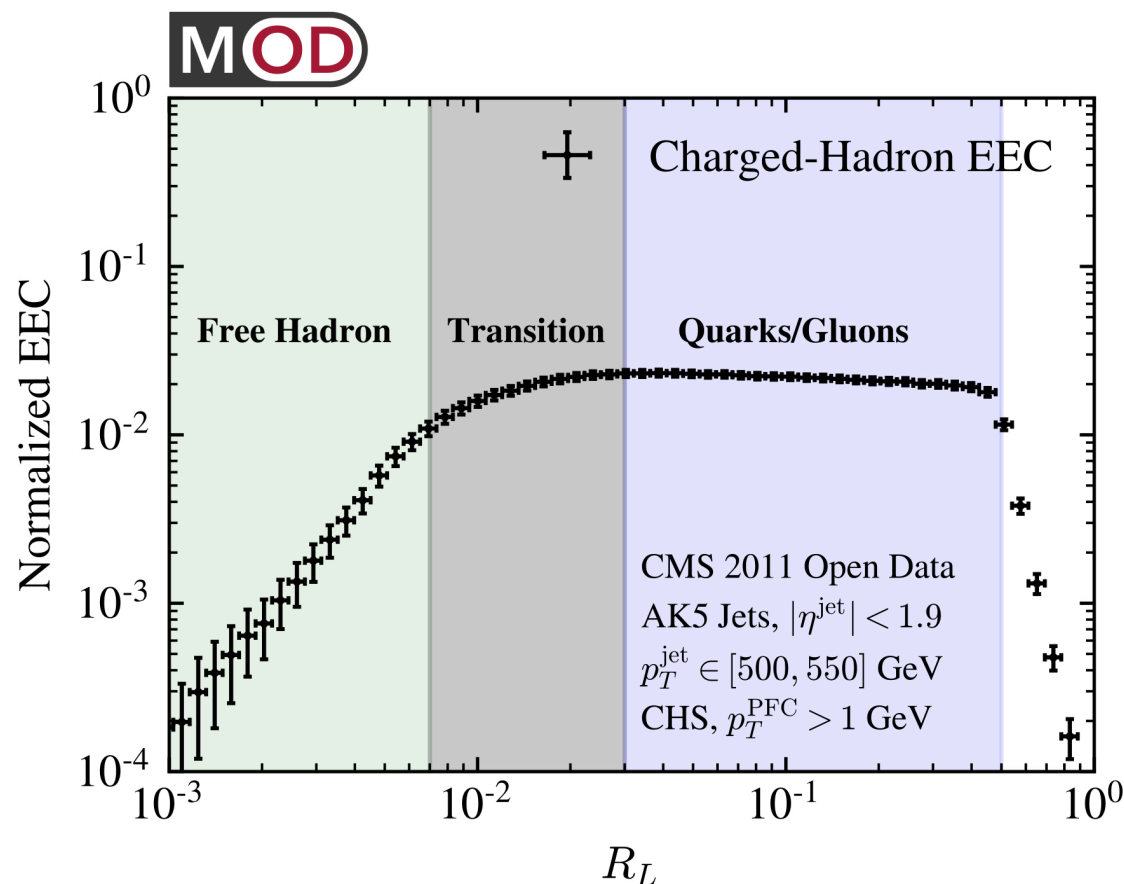
Patrick T. Komiske,<sup>1,\*</sup> Ian Moutt,<sup>2,†</sup> Jesse Thaler,<sup>1,‡</sup> and Hua Xing Zhu<sup>3,§</sup>

<sup>1</sup>Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

<sup>2</sup>Department of Physics, Yale University, New Haven, CT 06511

<sup>3</sup>Zhejiang Institute of Modern Physics, Department of Physics, Zhejiang University, Hangzhou, 310027, China

Jets of hadrons produced at high-energy colliders provide experimental access to the dynamics of asymptotically free quarks and gluons and their confinement into hadrons. In this paper, we show that the high energies of the Large Hadron Collider (LHC), together with the exceptional resolution of its detectors, allow multipoint correlation functions of energy flow operators to be directly measured within jets for the first time. Using Open Data from the CMS experiment, we show that reformulating jet substructure in terms of these correlators provides new ways of probing the dynamics of QCD jets, which enables direct imaging of the confining transition to free hadrons as well as precision measurements of the scaling properties and interactions of quarks and gluons. This opens a new era in our understanding of jet substructure and illustrates the immense unexploited potential of high-quality LHC data sets for elucidating the dynamics of QCD.

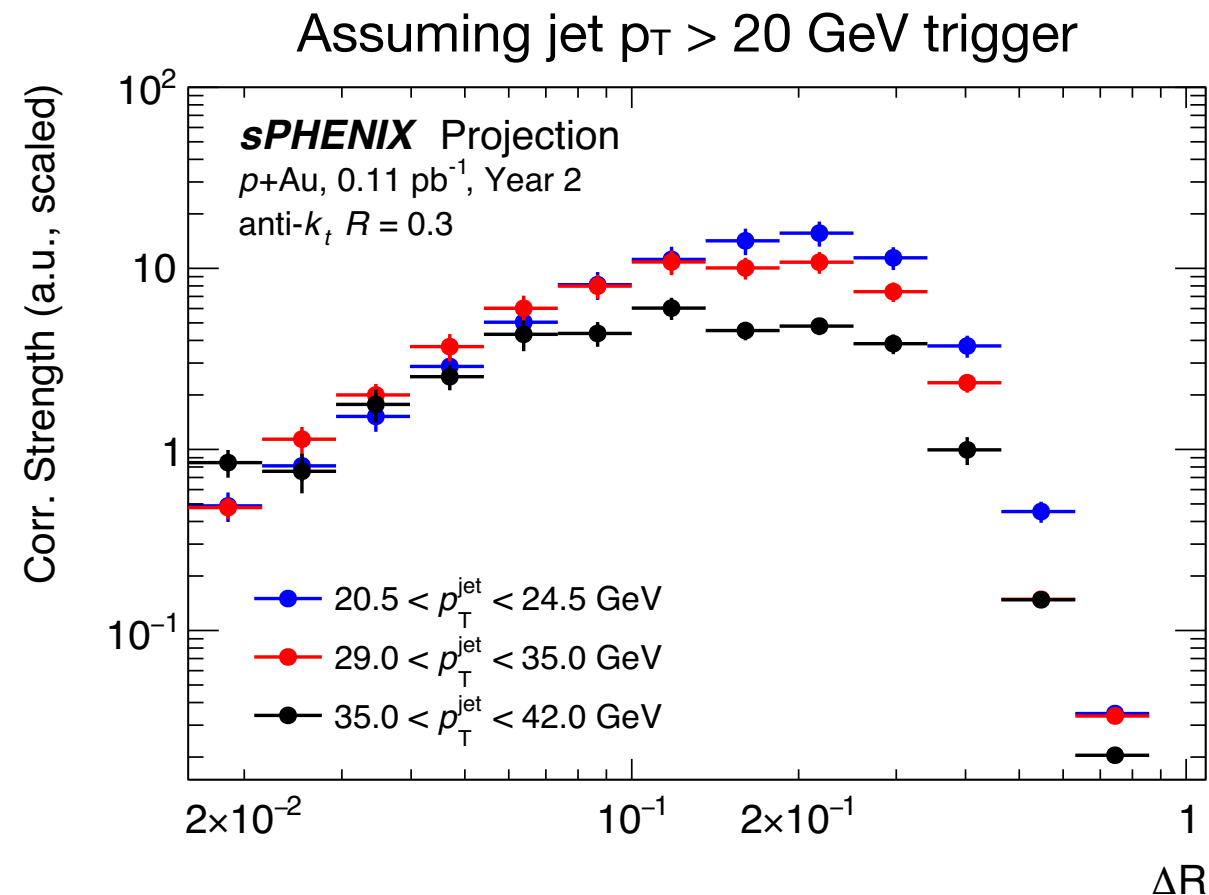
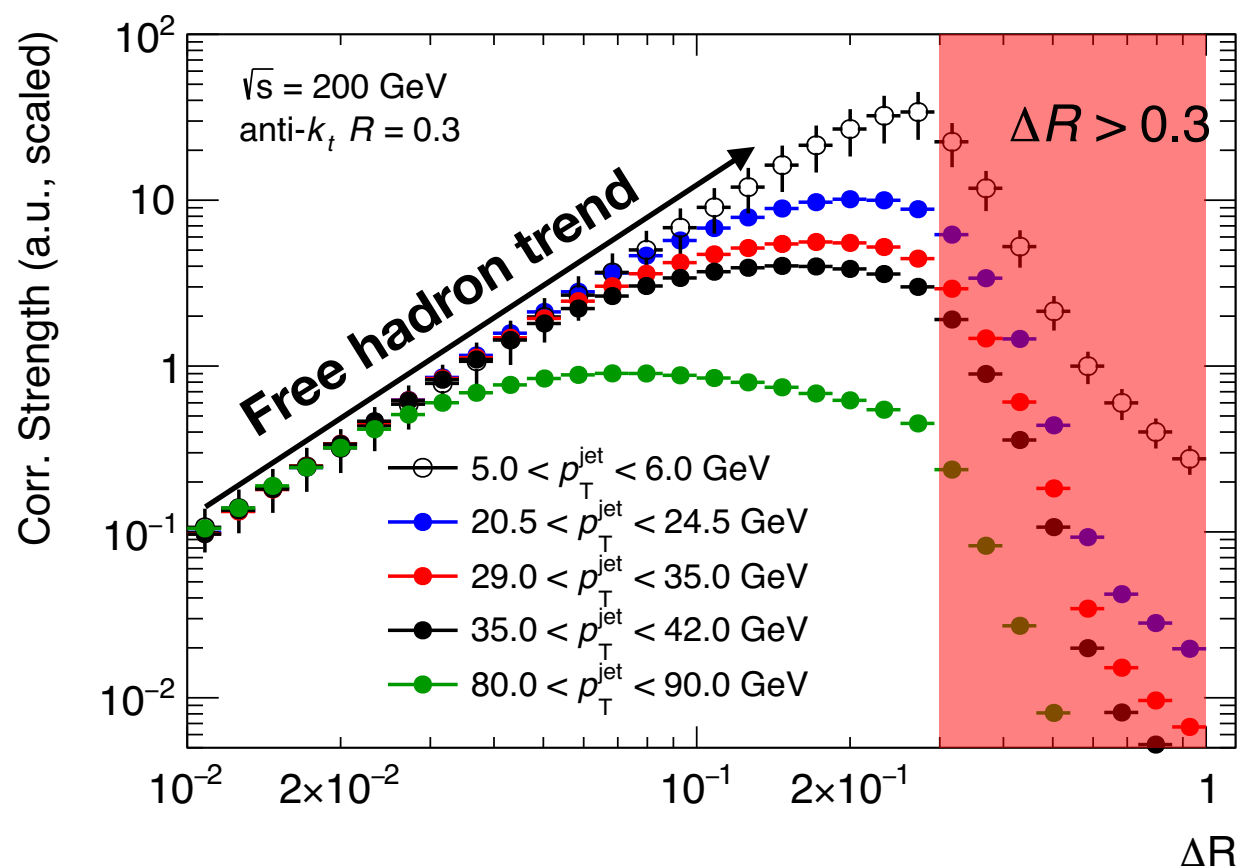


# 2-Point Correlations in Simulation

Using public code at <https://github.com/pkomiske/EnergyEnergyCorrelators>  
from Analyzing N-point Energy Correlators Inside Jets with CMS Open Data  
<https://arxiv.org/pdf/2201.07800.pdf>

Details:

- anti-kt  $R = 0.3$
- $|\eta| < 1$
- Only charged tracks
- Assuming 90% tracking efficiency





# sPHENIX Construction Status

Carriage installation  
complete!  
- Jun. 2021





# sPHENIX Construction Status

Carriage installation  
complete!  
- Jun. 2021



Magnet installation complete!  
- Oct. 2021





# sPHENIX Construction Status

Carrier installation  
complete!  
- Jun.

OHCAL installation complete!  
- 28th Feb. 2022



Magnet installation complete!  
- Oct. 2021





# sPHENIX Construction Status

Carrier installation  
complete!  
- Jun.

OHCAL installation complete!  
- 28th Feb. 2022

Magnet installation complete!  
- Oct. 2021

IHCAL Barrel assembly complete!  
- 18th Mar. 2022





# sPHENIX Construction Status

Magnet installation complete!  
- Oct. 2021

Carrier installation  
complete  
- Jun.

OHCAL installation complete  
- 28th Feb. 2022

EMCal Assembly Test  
- 29 April 2022

iHCAL barrel on the north  
slider beam

EMCAL installation lift  
fixture



# sPHENIX Construction Status



EMCAL sector assembly complete!  
- March 2022

# sPHENIX Construction Status





# sPHENIX Construction Status

TPC GEM assembly complete!



EMCAL sector assembly complete!  
- March 2022

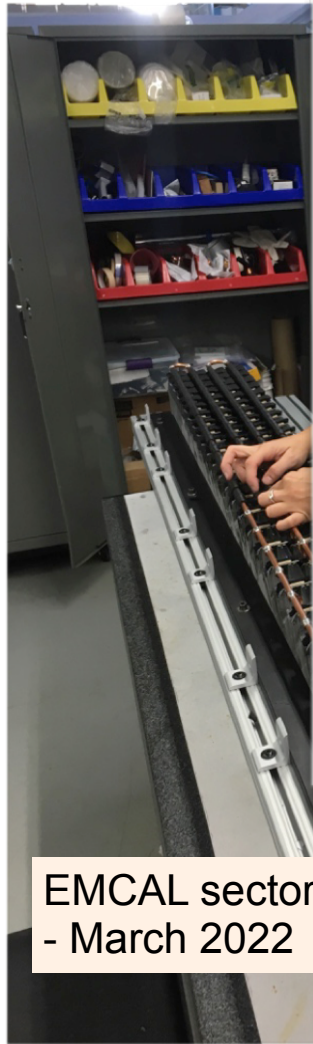


TPC support assembly complete!





# sPHENIX Construction Status

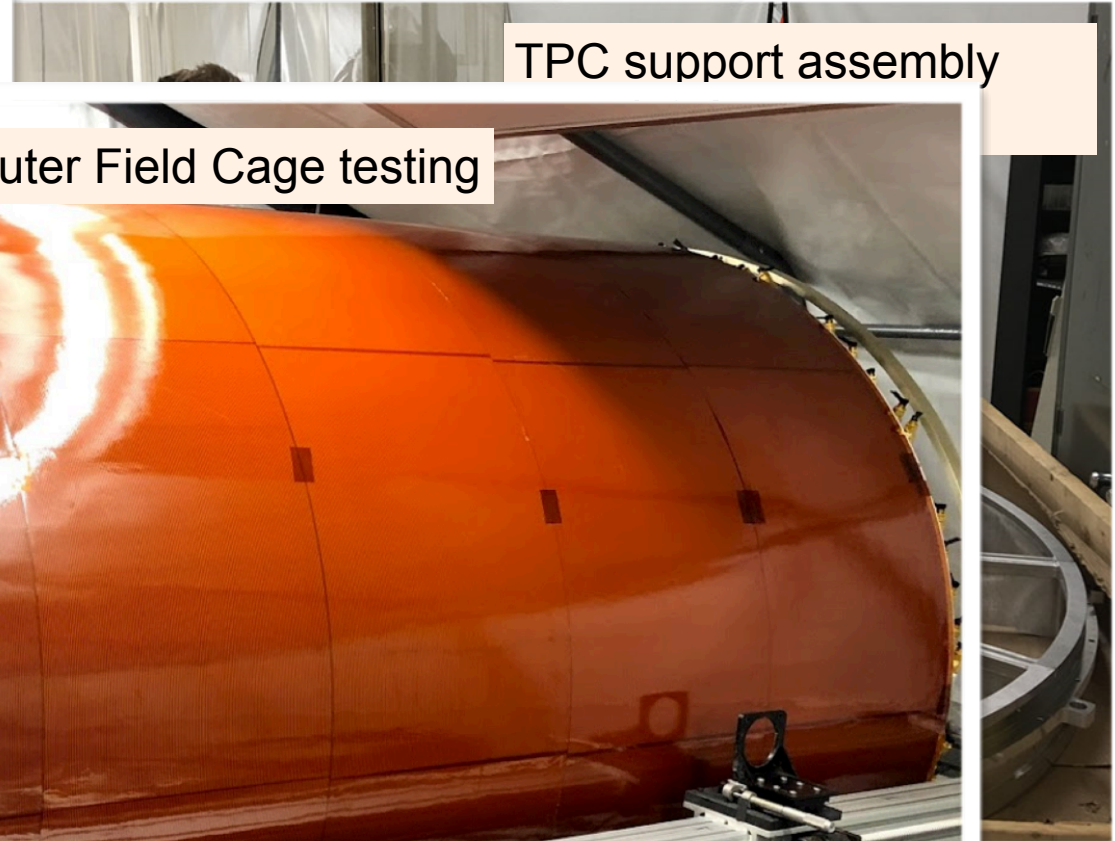


EMCAL sector assembly c  
- March 2022

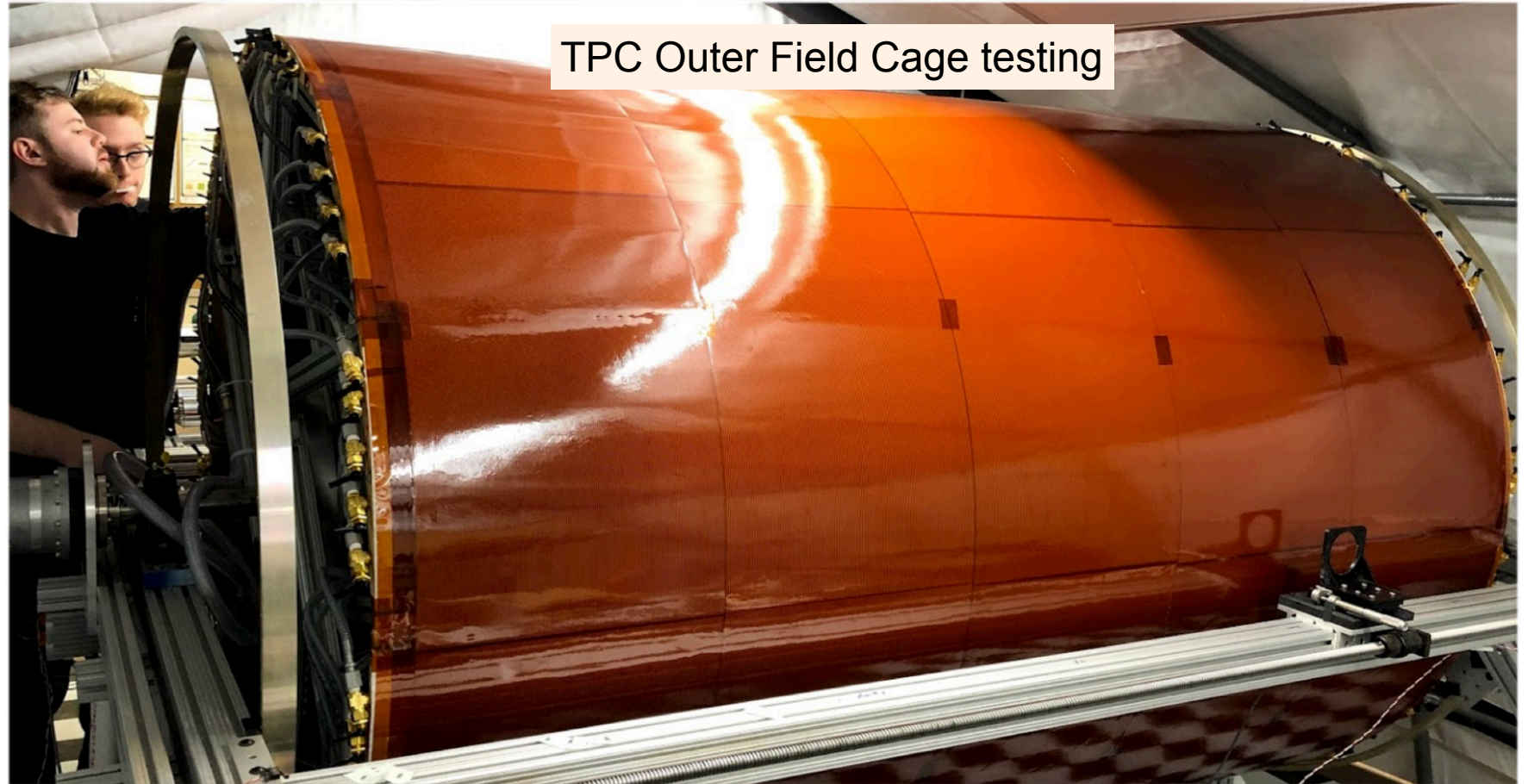
TPC GEM assembly complete!



TPC support assembly



TPC Outer Field Cage testing

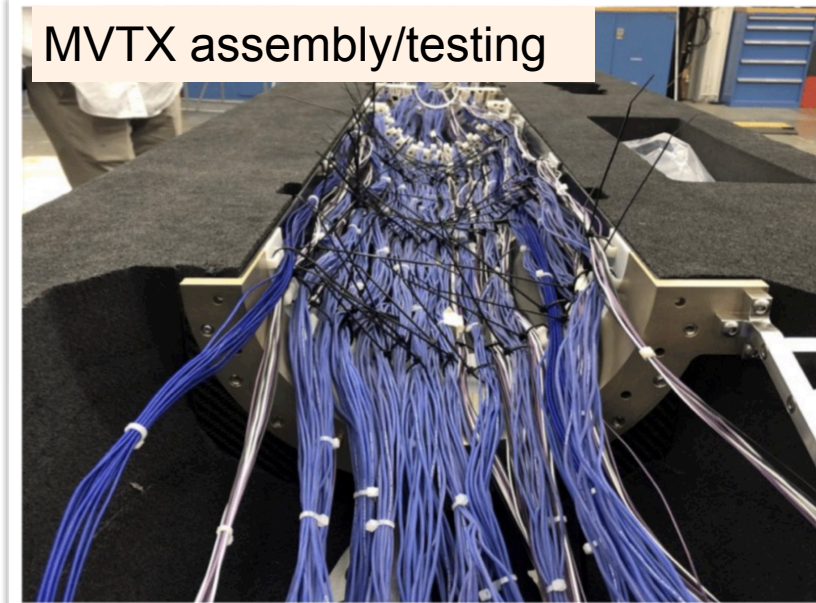


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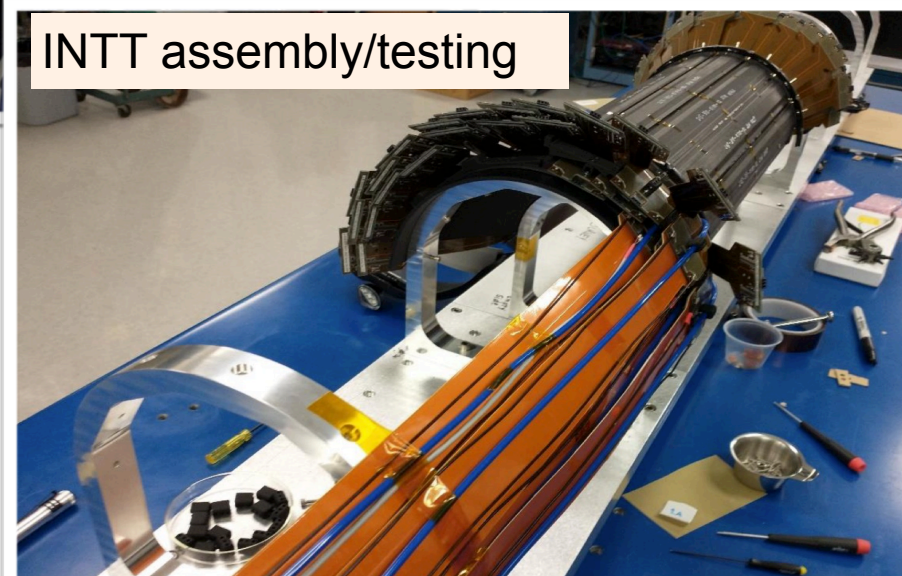
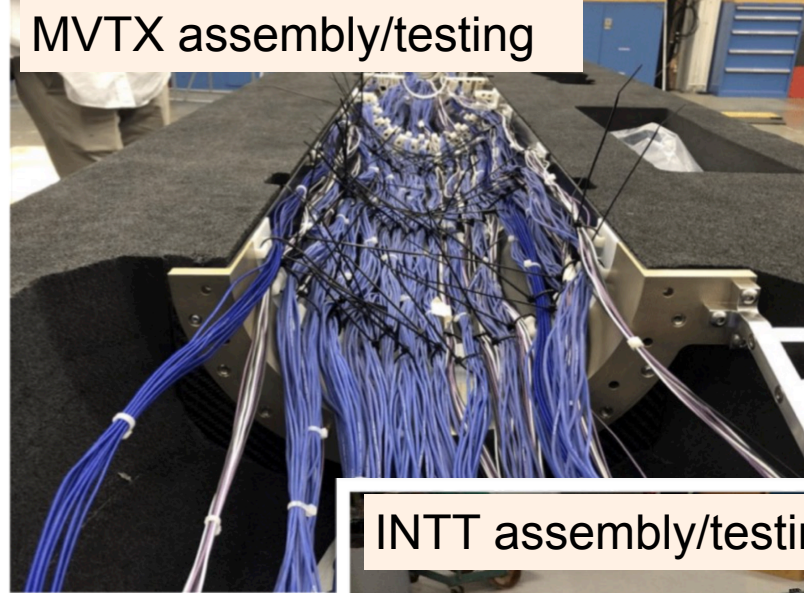


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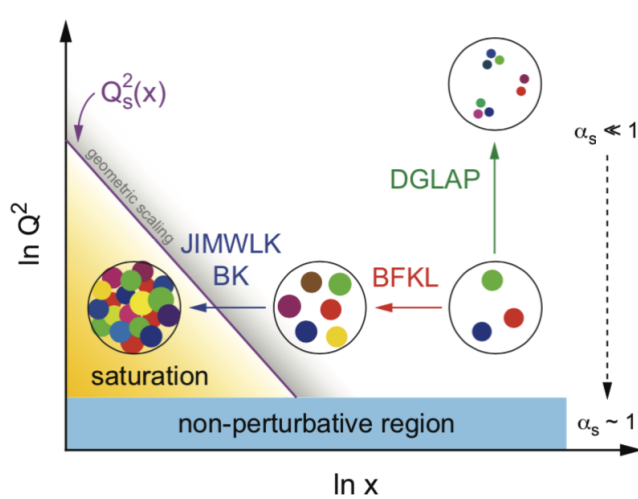


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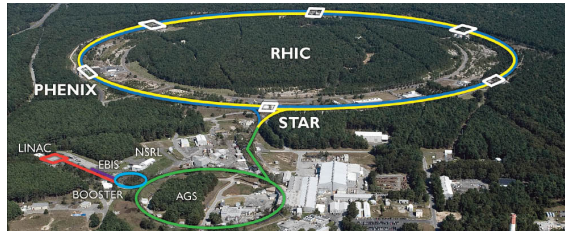
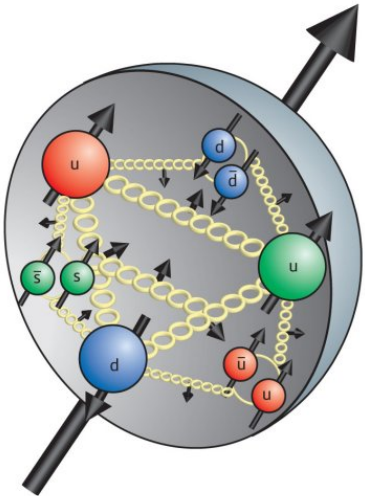
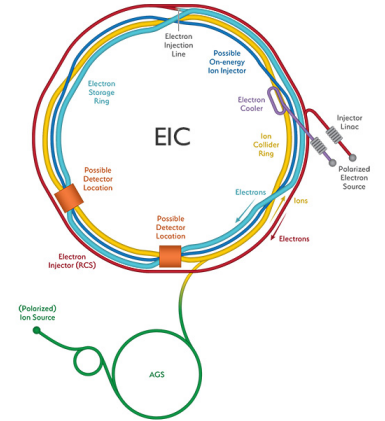


# The Big Picture *from* RHIC to the EIC...

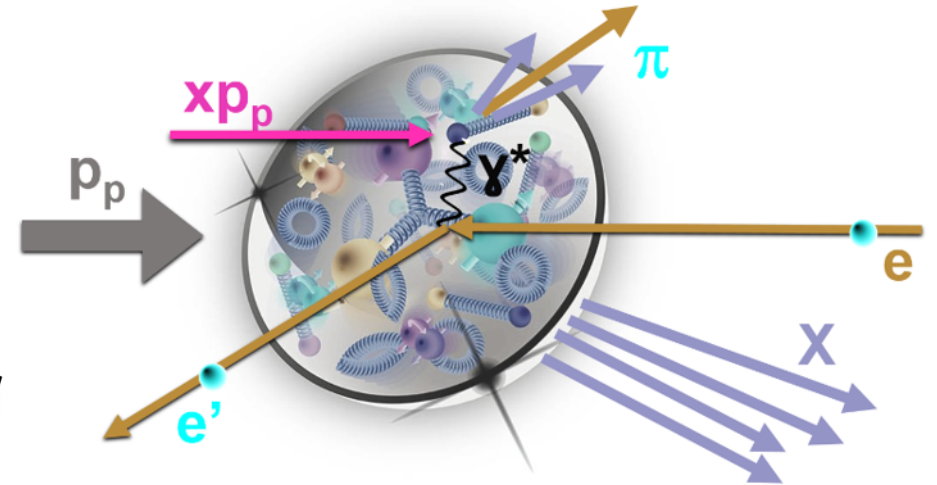
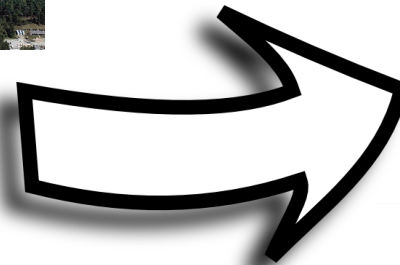
p+A Collisions



***How do collective, many-body phenomena arise from first-principles QCD?***



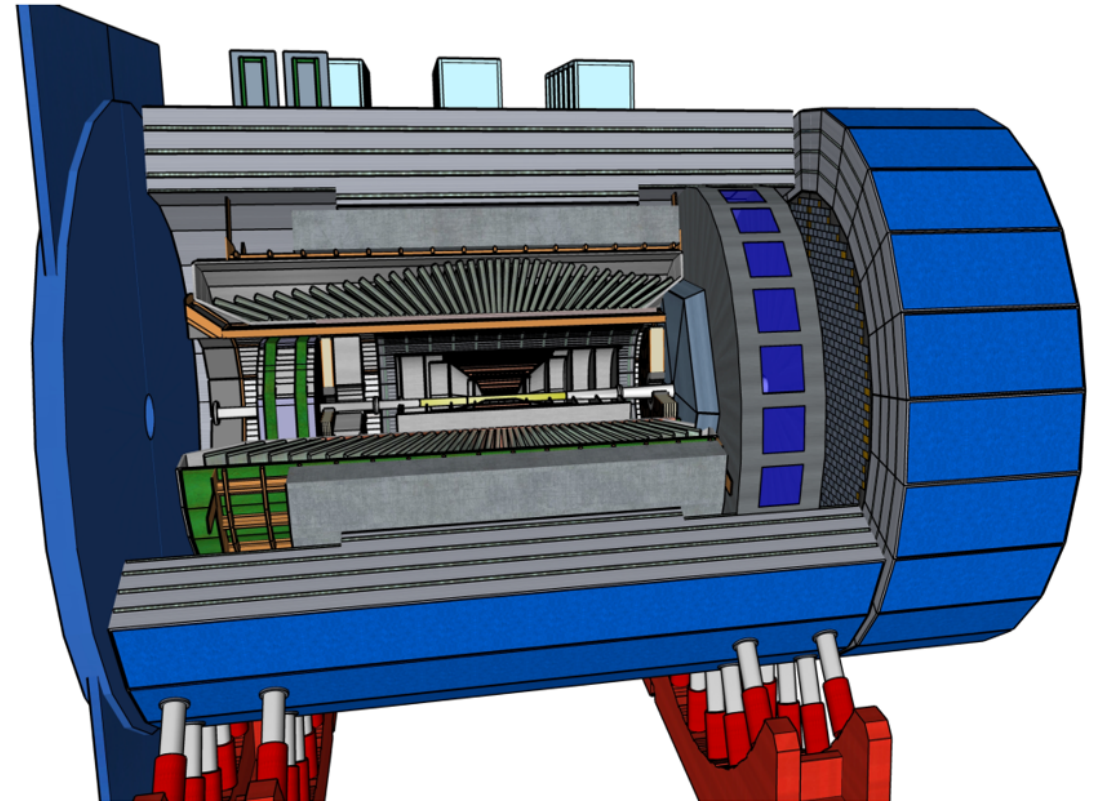
p+p Collisions





# From RHIC to the EIC

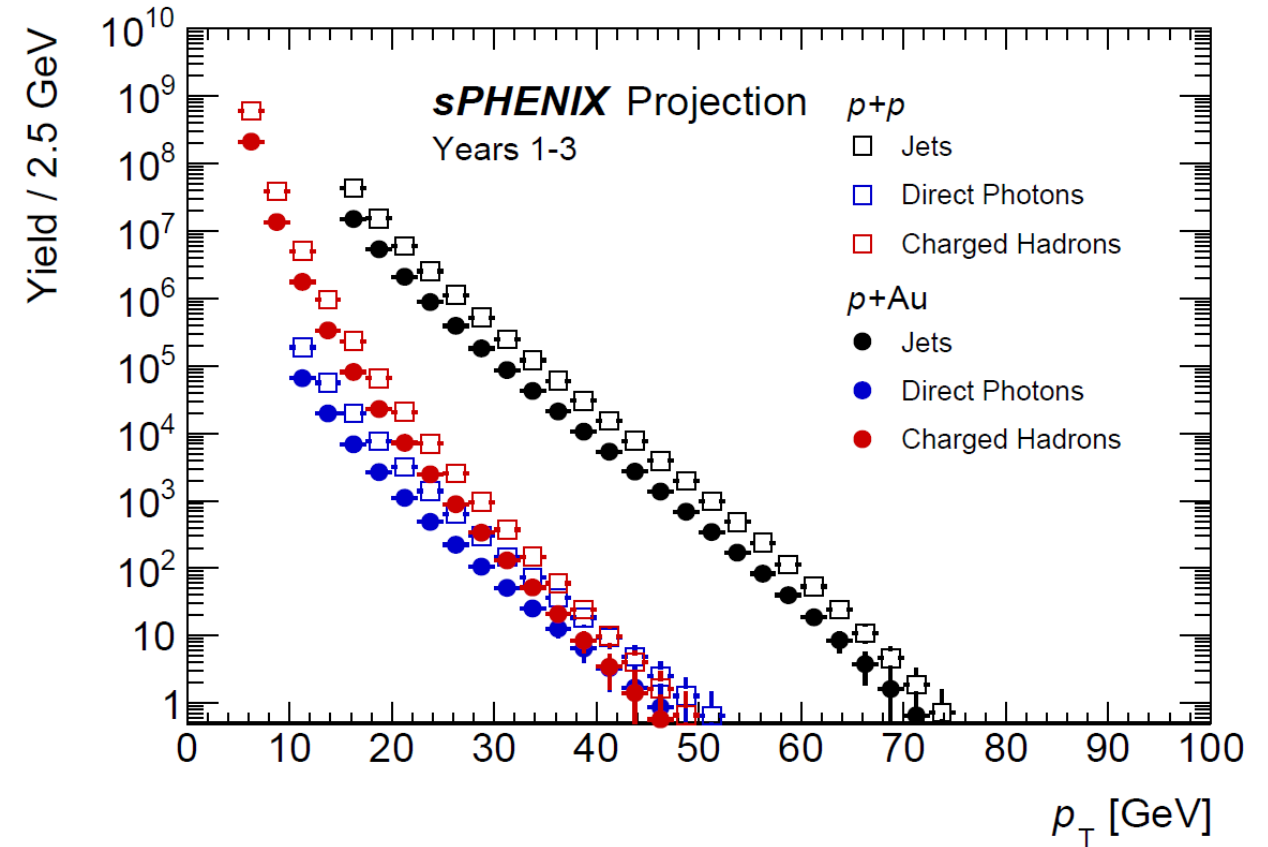
The 1.4T BaBar solenoid and Outer Hadronic calorimeter will be repurposed from sPHENIX for use in the EIC project detector.



# Summary

- A rich data set of transversely polarized  $p + p$ ,  $p + A$  data planned in sPHENIX Run-24
  - Long Run-24 essential for completing both  $p + p$ ,  $p + A$  program
- High statistics observables uniquely enabled by high rate calo trigger and tracker's streaming capability
- Address puzzles and explore new directions using spin/nuclei as tool to study QCD

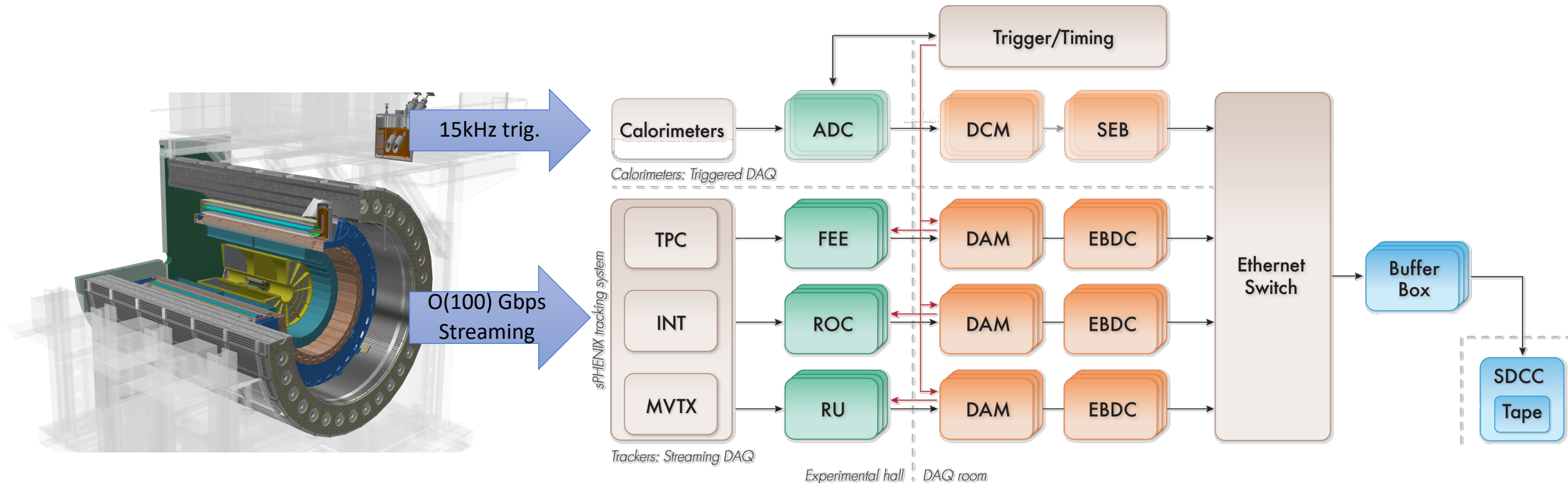
[sPHENIX BUP2021 \[sPH-TRG-2021-001\]](#)





# BACKUP

# sPHENIX Streaming Hybrid DAQ

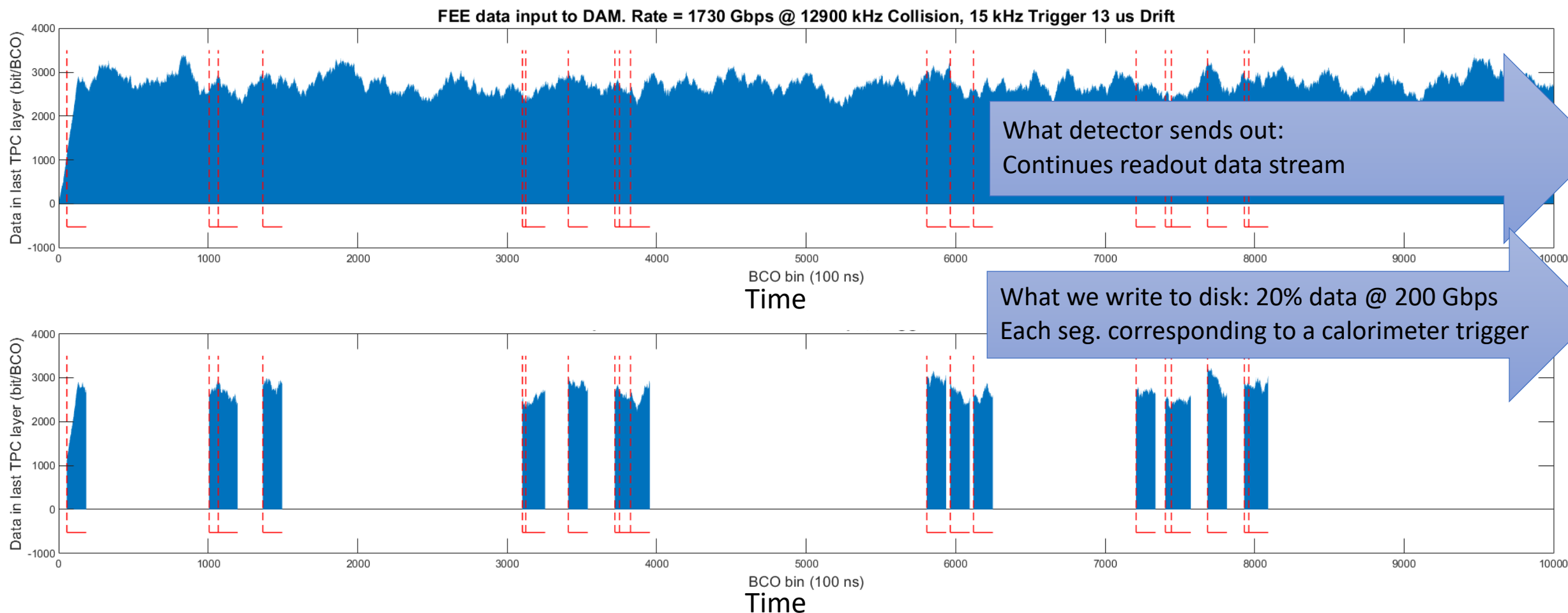
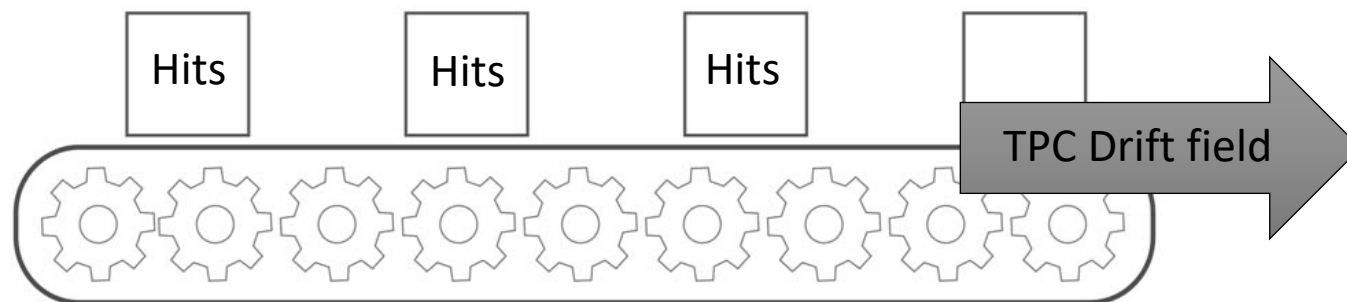


All sPHENIX tracker support streaming readout → Plan to archive 10% all pp collisions in streaming mode:

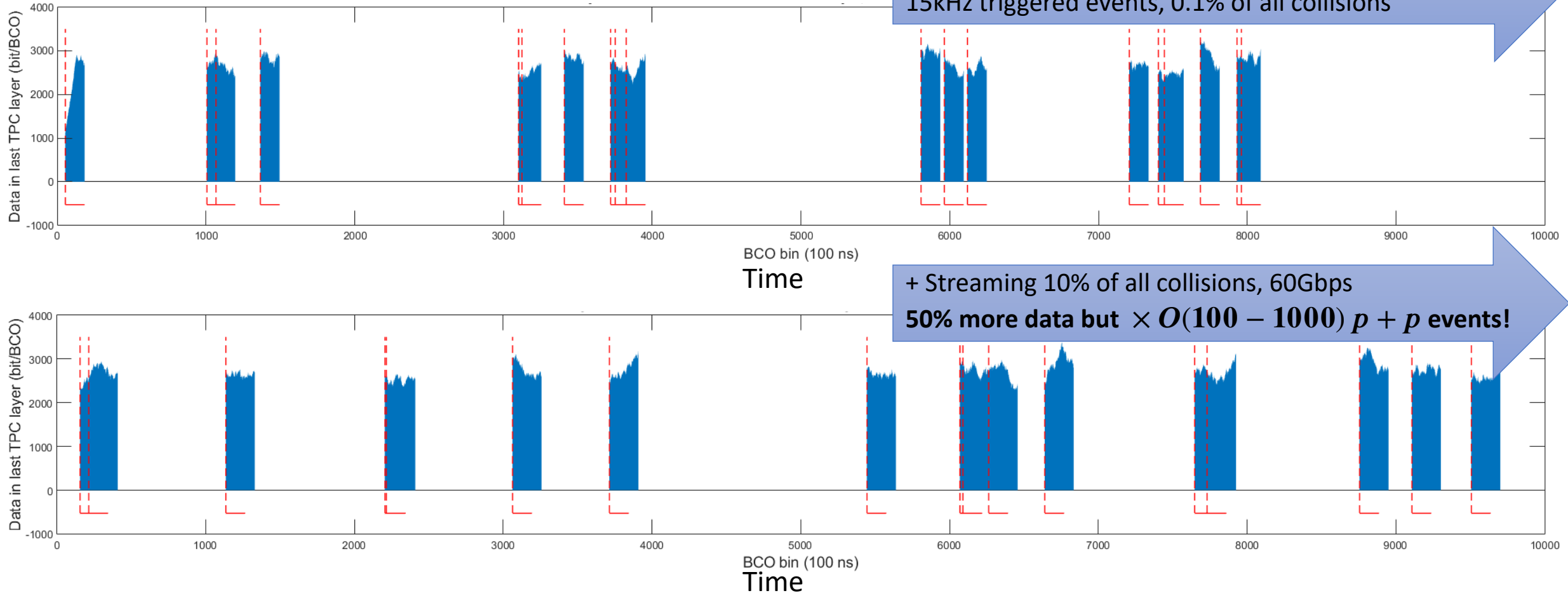
- Allowing un-triggerable measurement, e.g. low  $p_T$  HF→h
- Increasing spin-tagged M.B. p+p/p+A collisions by 2 to 3 orders of magnitude
- Data preservation from the collection stage for the last high-energy polarized hadron collisions → new analysis w/ EIC



# TPC data stream in sPHENIX triggered DAQ



# Extending streaming time window, a partial triggerless DAQ → $\times O(100)$ gain in statistics!





# Run Plan

[sPHENIX BUP2021 \[sPH-TRG-2021-001\]](#), 24 (& 28) cryo-week scenarios

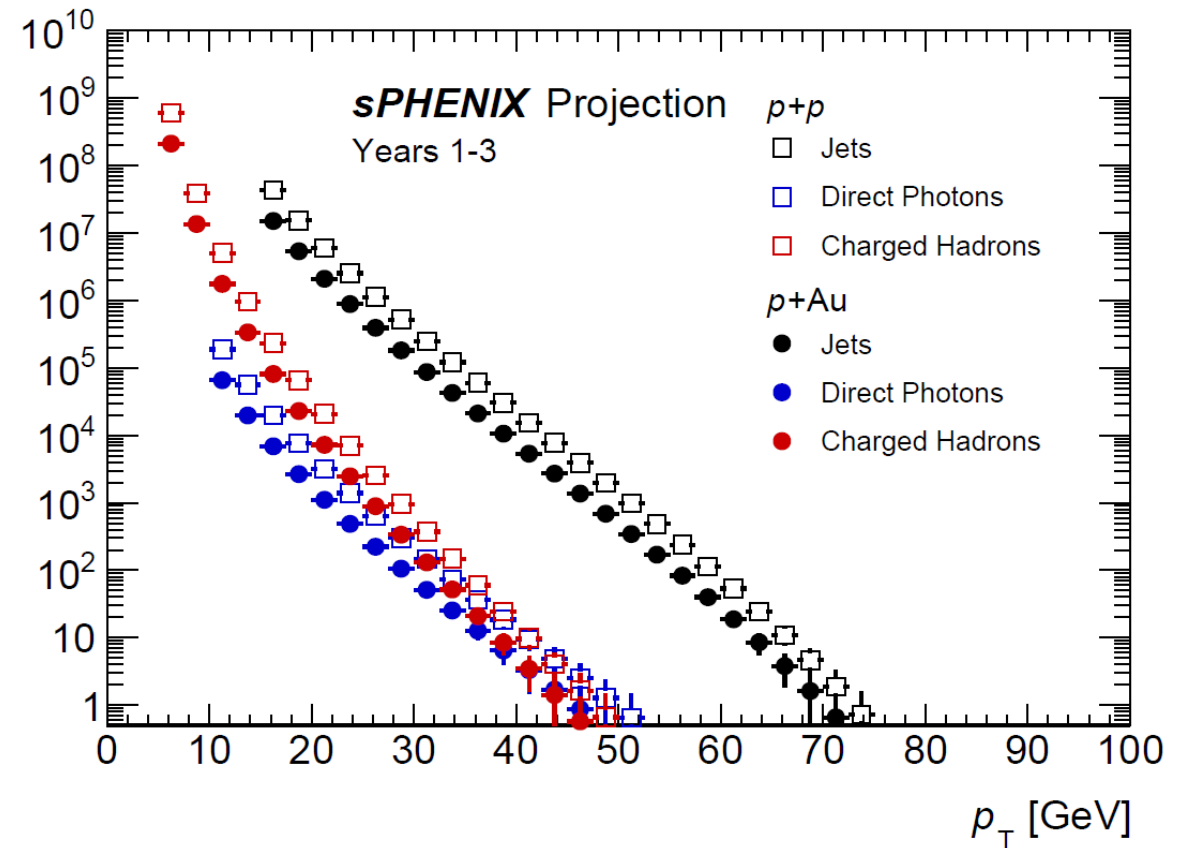
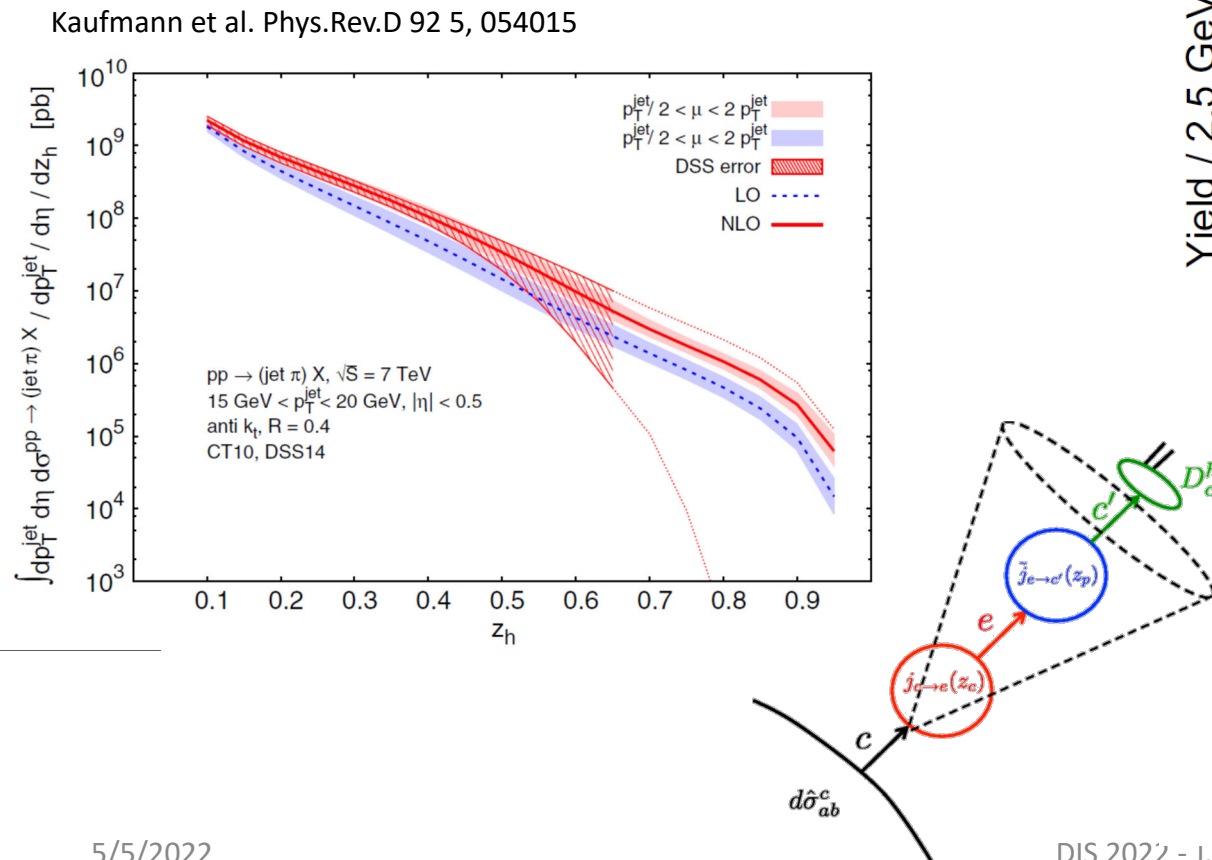
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2024	$p^\uparrow + \text{Au}$	200	–	5	0.003 pb <sup>-1</sup> [5 kHz] 0.01 pb <sup>-1</sup> [10%-str]	0.11 pb <sup>-1</sup>
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb <sup>-1</sup>	21 (25) nb <sup>-1</sup>

sPHENIX asked to consider 20-28 week runs in 2024

- (Trans-)polarized  $p + p$ ,  $p + A$  with streaming readout for 28 weeks in Run24
- But short Run24 would endanger the  $p + A$  data!

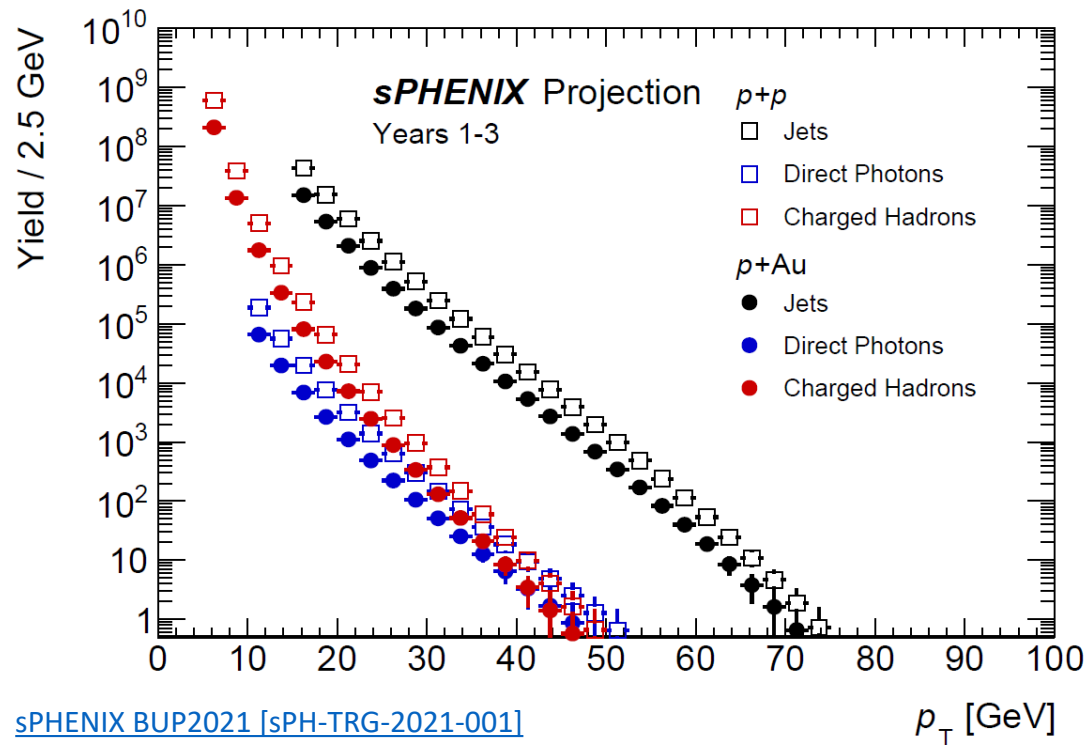
# Fragmentation in p+A

- Access gluon fragmentation function (FF) in  $p + p$ ,  $p + A$  via jet FF
- Calorimetric triggered jet + precision tracking





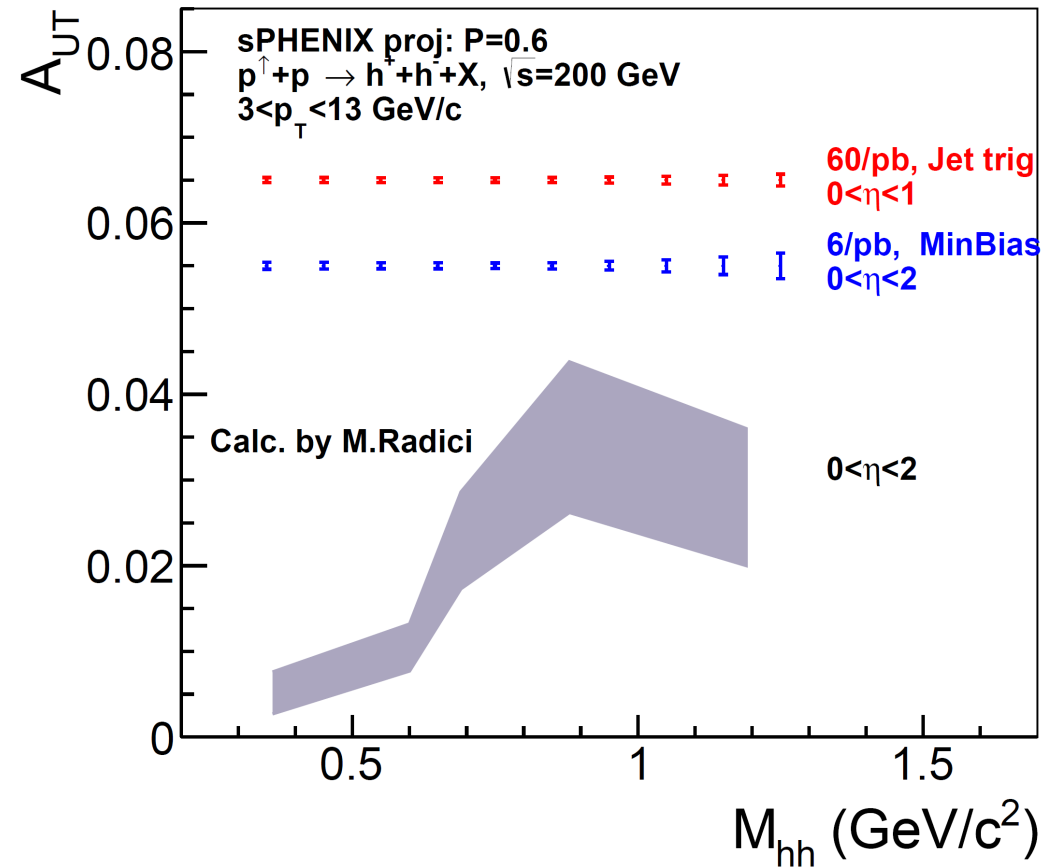
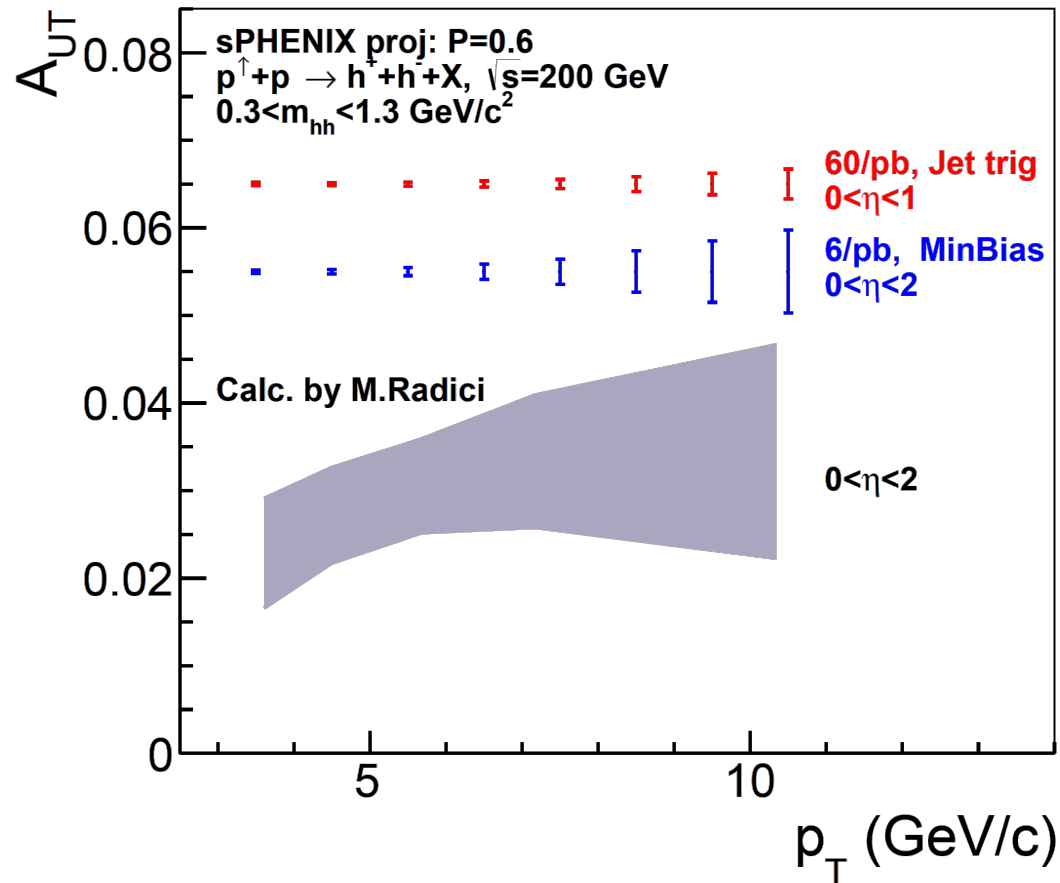
# Cold QCD Observables



- Transversely polarized observables
  - Sievers-type tri-gluon correlation:  $\gamma$ , HF
  - Hadron  $A_N$ ,  $p+p$  vs.  $p+A$ :  $h$
  - Sivers effects:  $\gamma$ -jet, di-jet
  - Transversity via Collins FF & IFF:  $h$  in jet, di- $h$
- Spin-averaged observables
  - Quarkonia polarization:  $J/\psi$ ,  $\Upsilon$
  - nPDF:  $h$ , jet, di-jet,  $\gamma$ -jet
  - Hadronization,  $pp$  vs  $pA$ :  $h$  in jet,  $\gamma$ -jet, di-jet

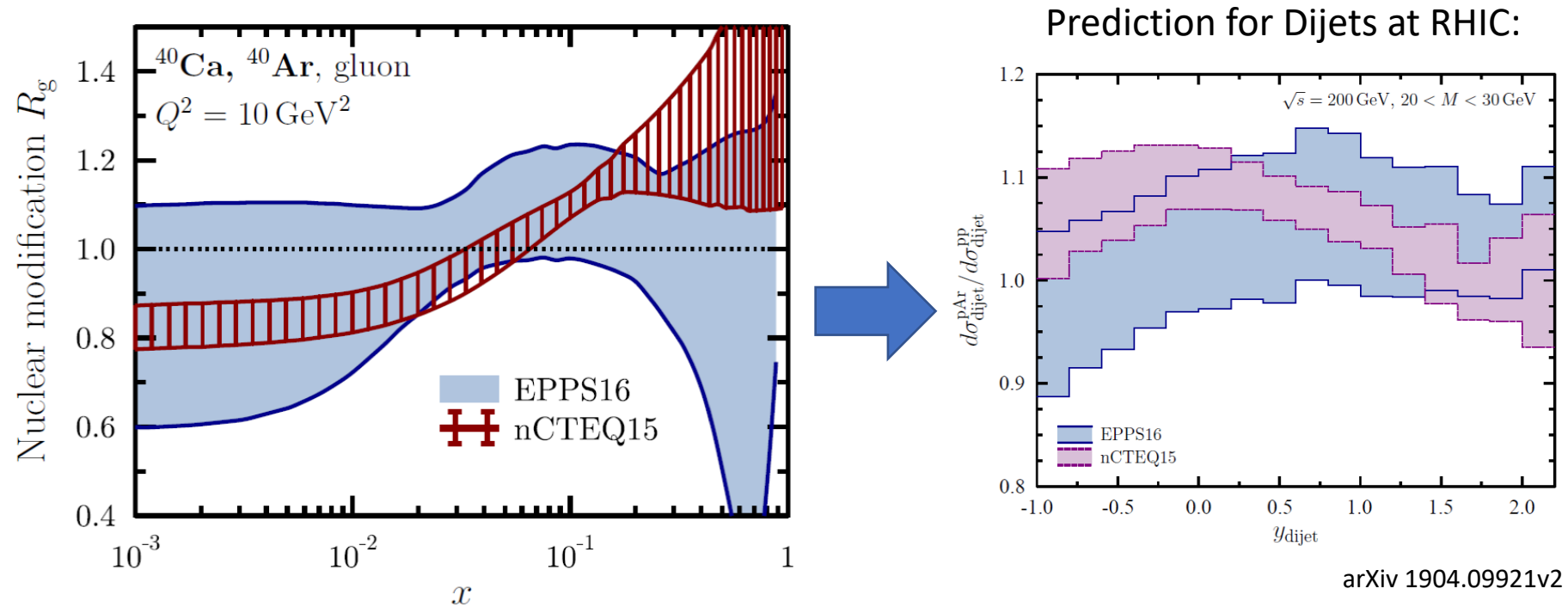
# Transversity via Charged Particle IFF

- Tremendous stat. enabled by both calorimetric **jet trigger** and **streaming readout**
- Need theory collaboration in the treatment of no-PID charged tracks & multi-dim binning





# Other nPDF benefits at RHIC

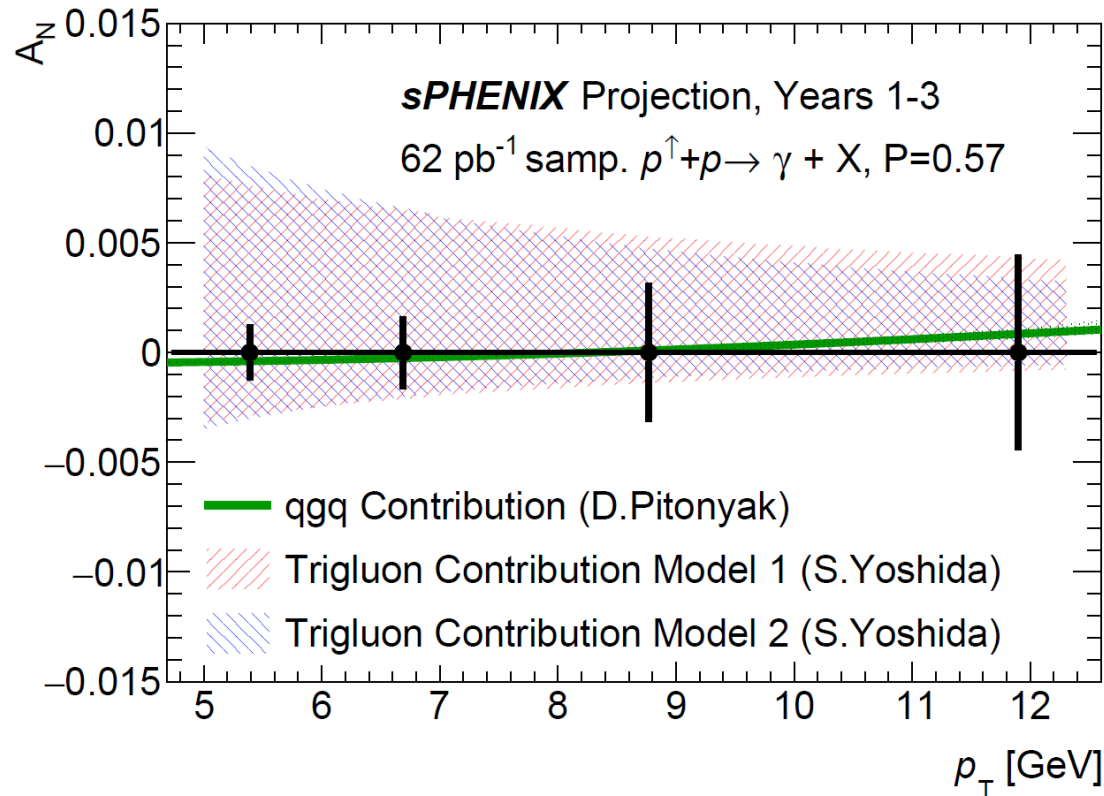


Mass-number ( $A$ ) dependence is not well-constrained between nPDF models.  
Light ion data at RHIC should have the power to improve this.

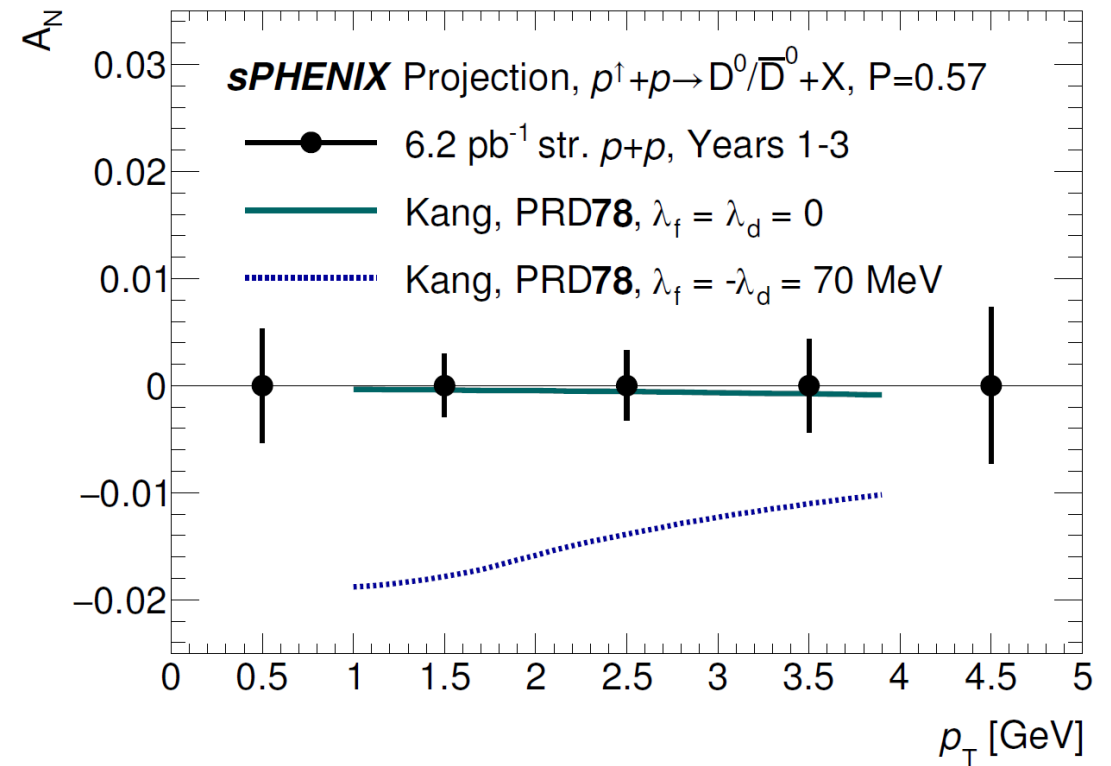
Test isospin asymmetry with  $(\text{p+Ru})/(\text{p+Zr})$  ratios.

# Gluon dynamics via $\gamma$ , HF TSSA

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TSSA of prompt photon  
EMCal-based trigger

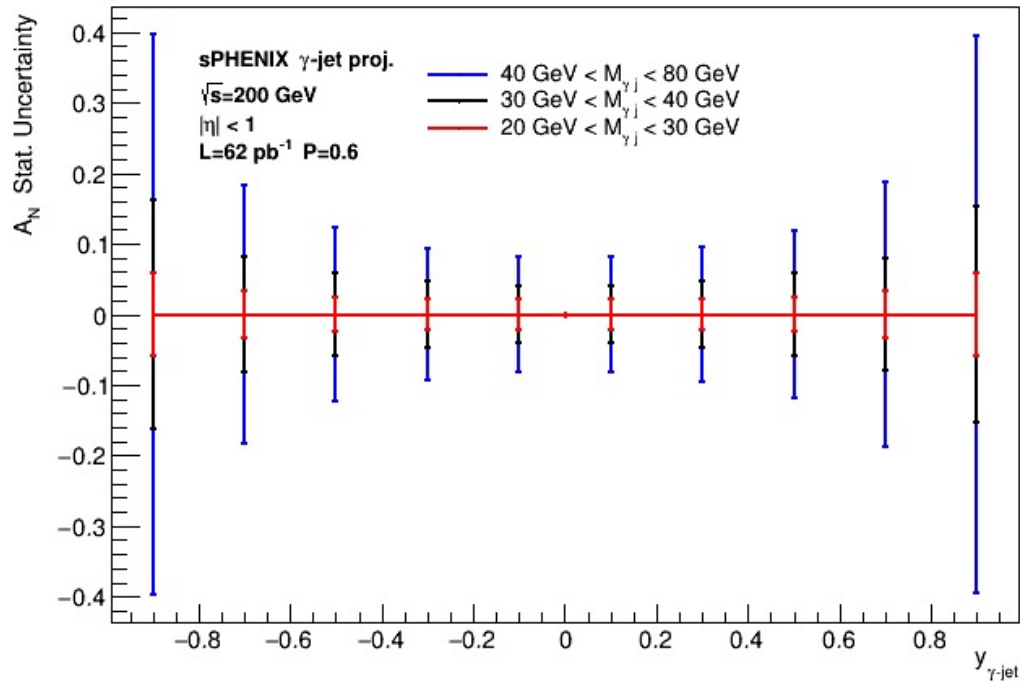


TSSA of prompt  $D^0 \rightarrow \pi K$   
Enabled by streaming readout

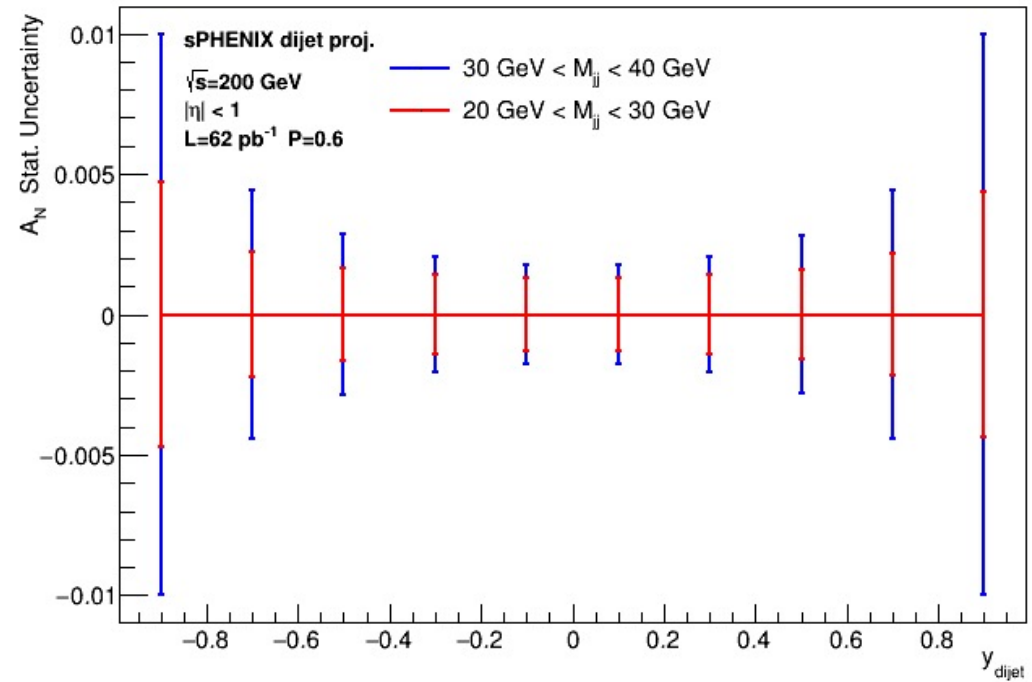


# Sivers Effect via $\gamma$ -jet, di-jets

- Enabled by high stat. calorimetric jet/photon detection provided by sPHENIX
- Exploring ideas of spin dependent  $\gamma$ -jet, di-jet correlation observables e.g.  $p_{\text{out}}$ , co-planarity, charge-tagged jets



Photon-jet

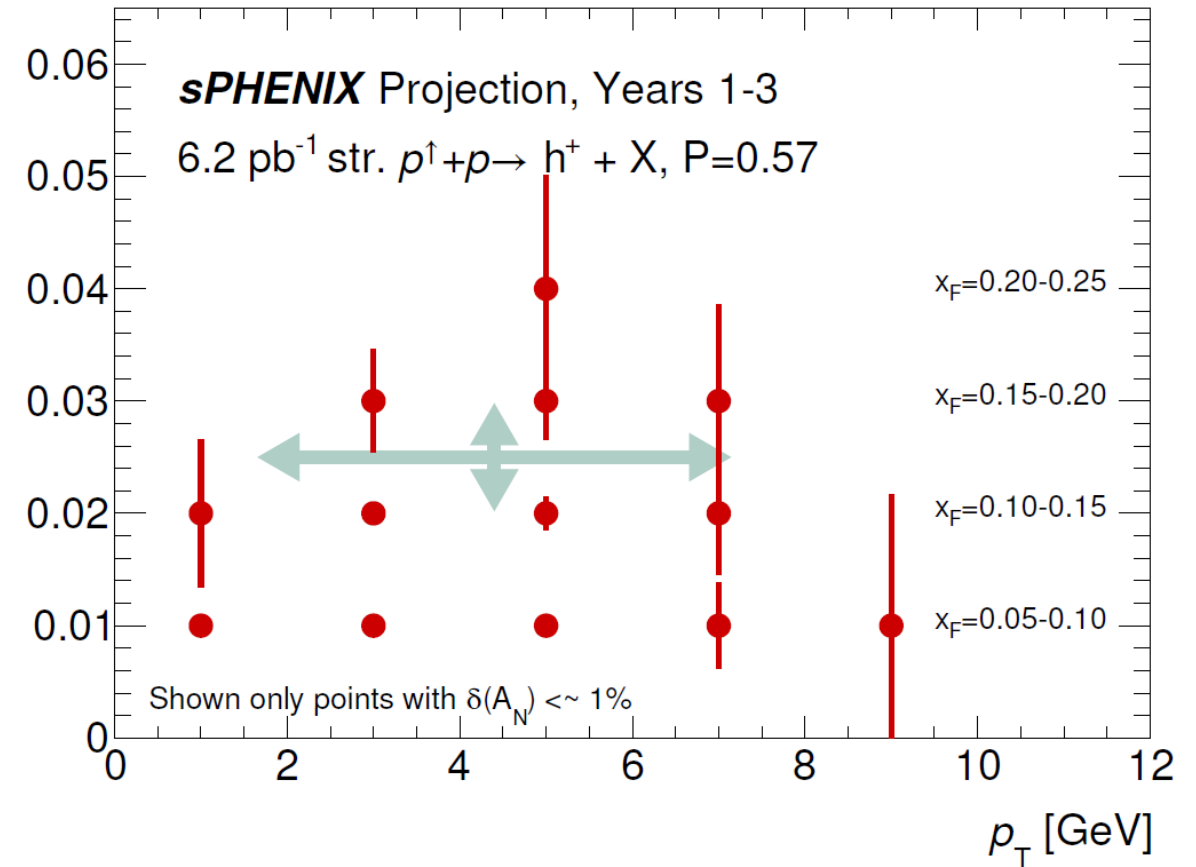


Di-jets

# Nature of Hadron $A_N$ in p+p and p+A (I)

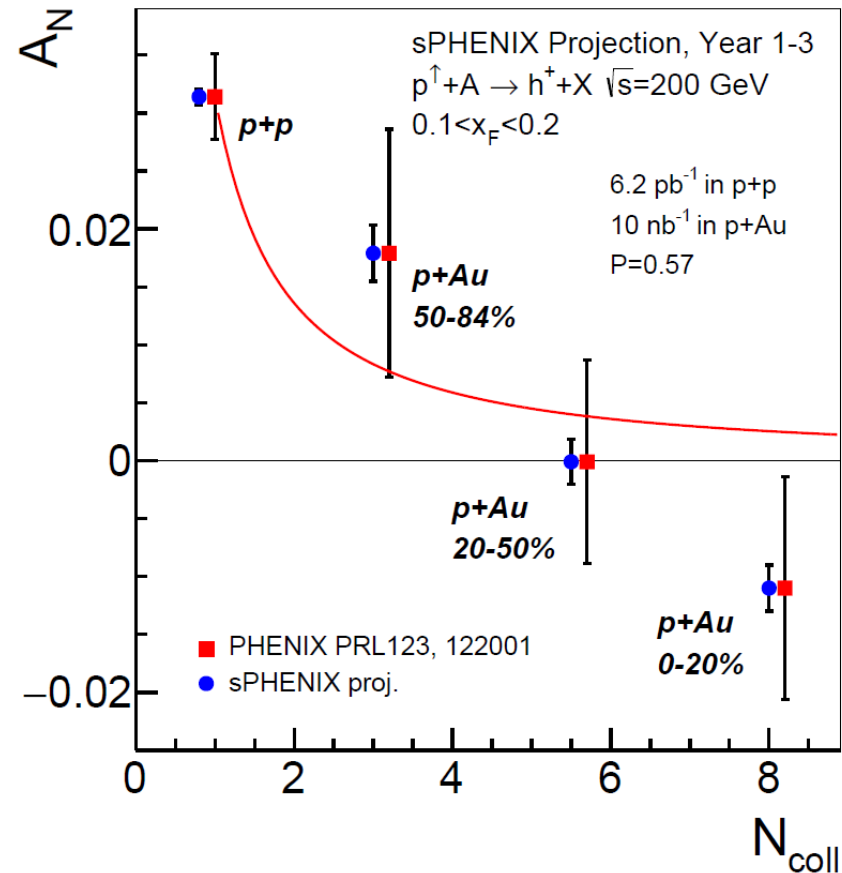
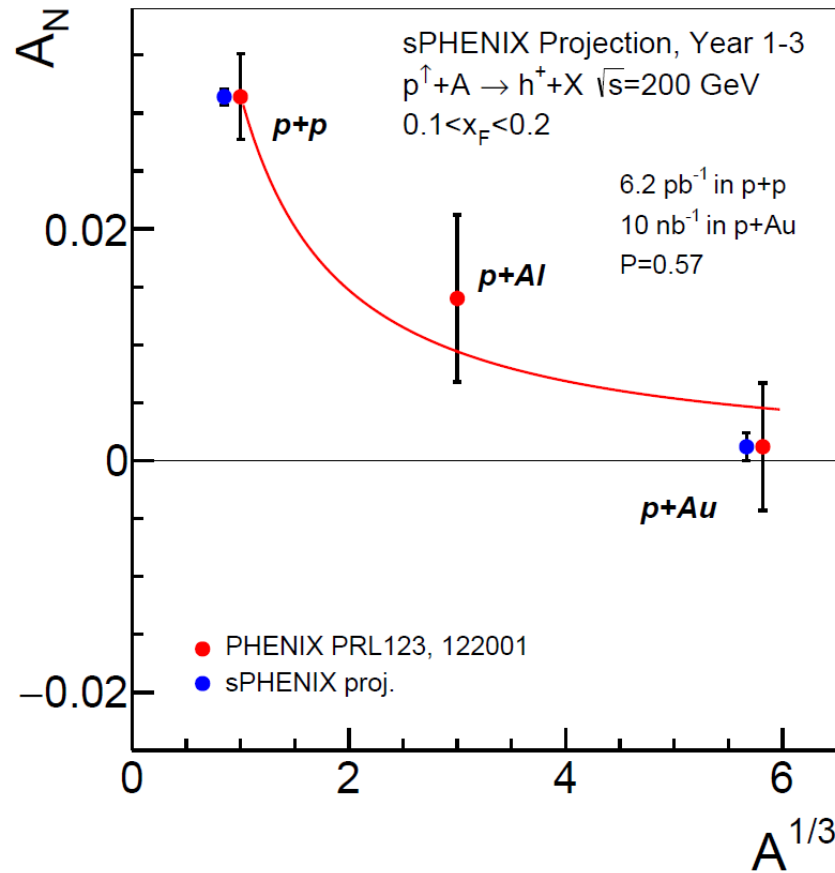
- PHENIX and STAR show significant different suppression of hadron  $A_N$  from p+p to p+A in distinct kinematic regions
- sPHENIX hadron  $A_N$  will explore wider region to help disentangle initial/final state effects
- Enabled by streaming recorded  $p + p$  collision from far vertex collisions

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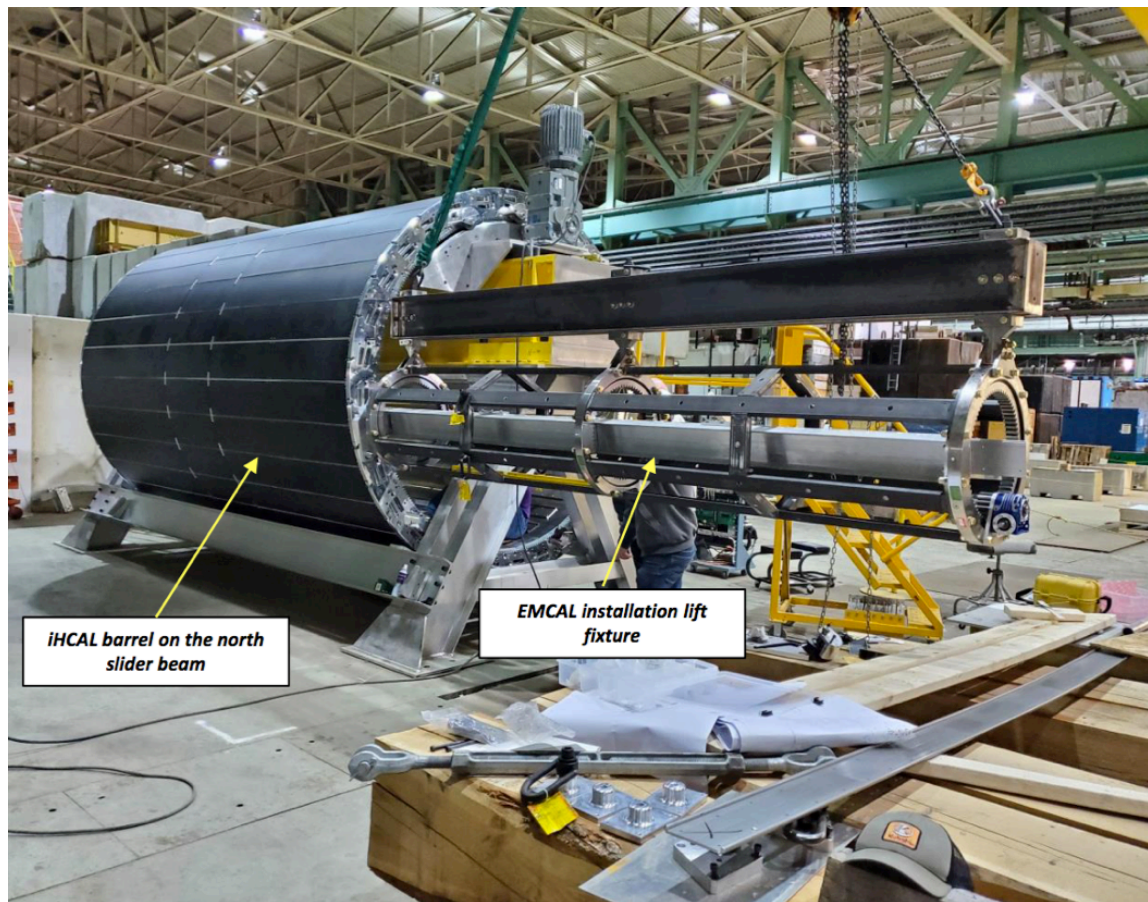
# Nature of Hadron $A_N$ in p+p and p+A (II)

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Substantial improvement comparing to the published PHENIX data





*iHCal barrel on the north  
slider beam*

*EMCAL installation lift  
fixture*

