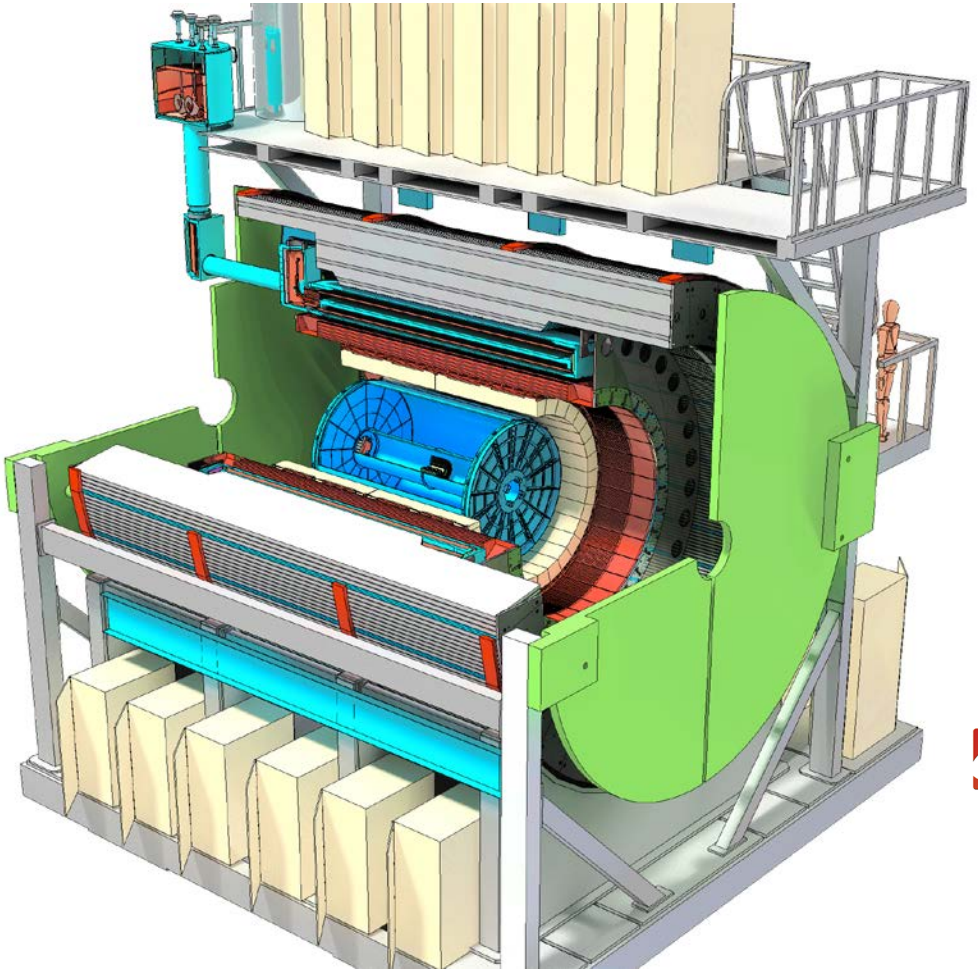
The sPHENIX Detector:

The Future of Heavy-Ion Collisions at RHIC, and a Foundation for an EIC Detector



J. Lajoie

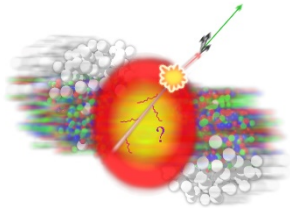
Iowa State University

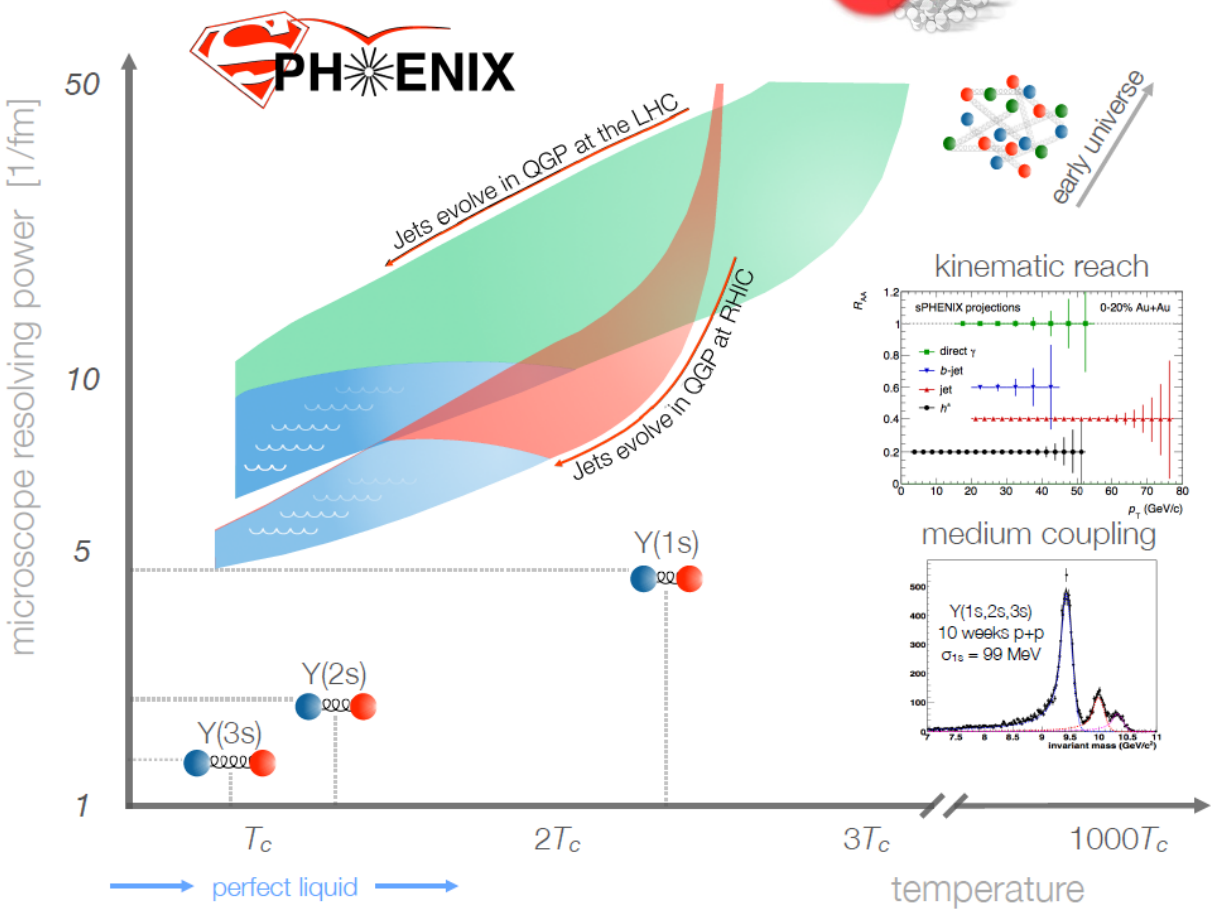
Outline

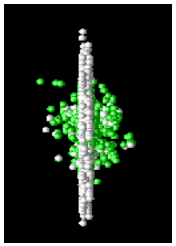
- HI Physics and the sPHENIX project at RHIC
- The RHIC Cold QCD Plan and Forward Physics
- The fsPHENIX concept
- Evolution to an EIC Detector
- Conclusions

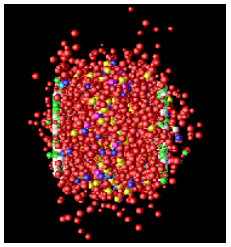
Future HI Physics @ RHIC

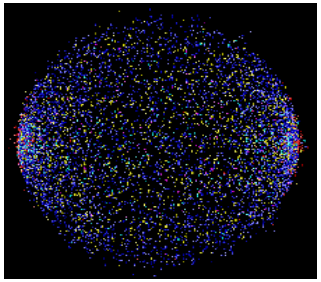
Evolution of a hard scattered parton in the QGP:

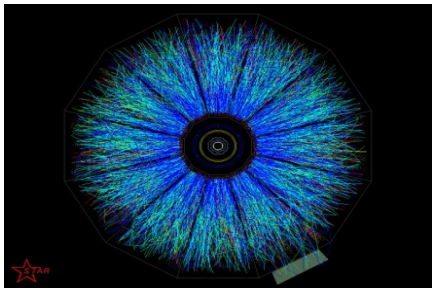


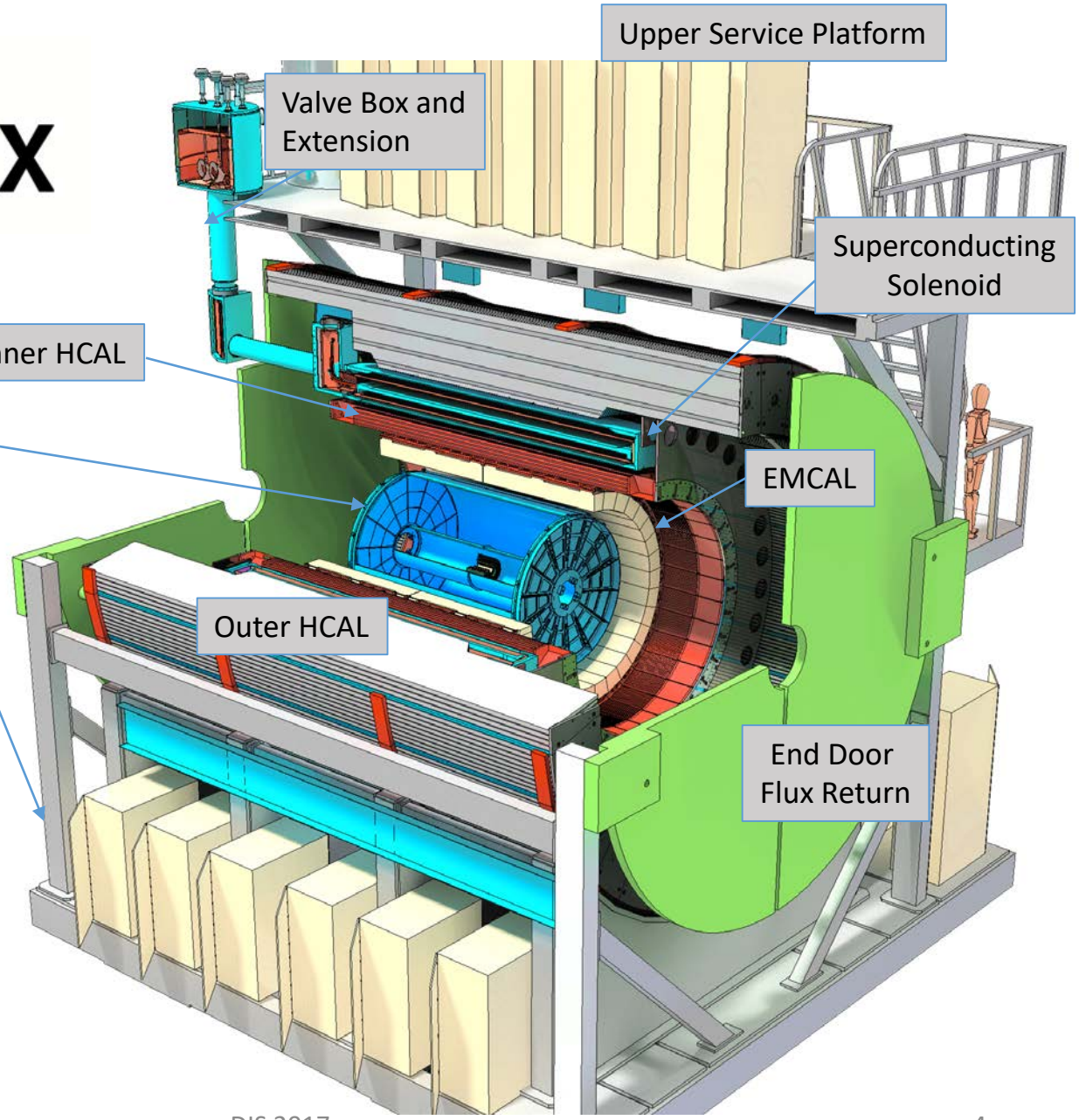












sPHENIX is a “next-generation” RHIC detector focused on jets and heavy flavor physics

The sPHENIX Detector Design

- **Uniform acceptance** $|\eta|<1.1$ and $0<\phi<2\pi$
- **Superconducting solenoid -** high resolution tracking
  - Acquired the BaBar solenoid!
- Compact **electromagnetic calorimeter** allowing fine segmentation at a small radius
- **Hadronic calorimeter** doubling as flux return
- **Solid state photodetectors** that work in a magnetic field, low cost, do not require high voltage, are physically small
- **Common readout electronics** in the calorimeters
- **15 kHz recorded** in A+A allows for large unbiased data sample
- **High resolution tracking (TPC, MAPS, INTT)** with an 80 cm radius
- Utilization of infrastructure in an **existing experimental hall** (cranes, rails, beam pipe, power, network…)

It's Been a Good Year!

- Collaboration formed (Dec 2015)
- Successful tests of BaBar Solenoid
- Successful Test Beam(s) of calorimeter system
- Tracking system more defined:
  - TPC and Silicon tracking
- Improved simulations
- Approve Mission Need: CD-0
  - October 2016

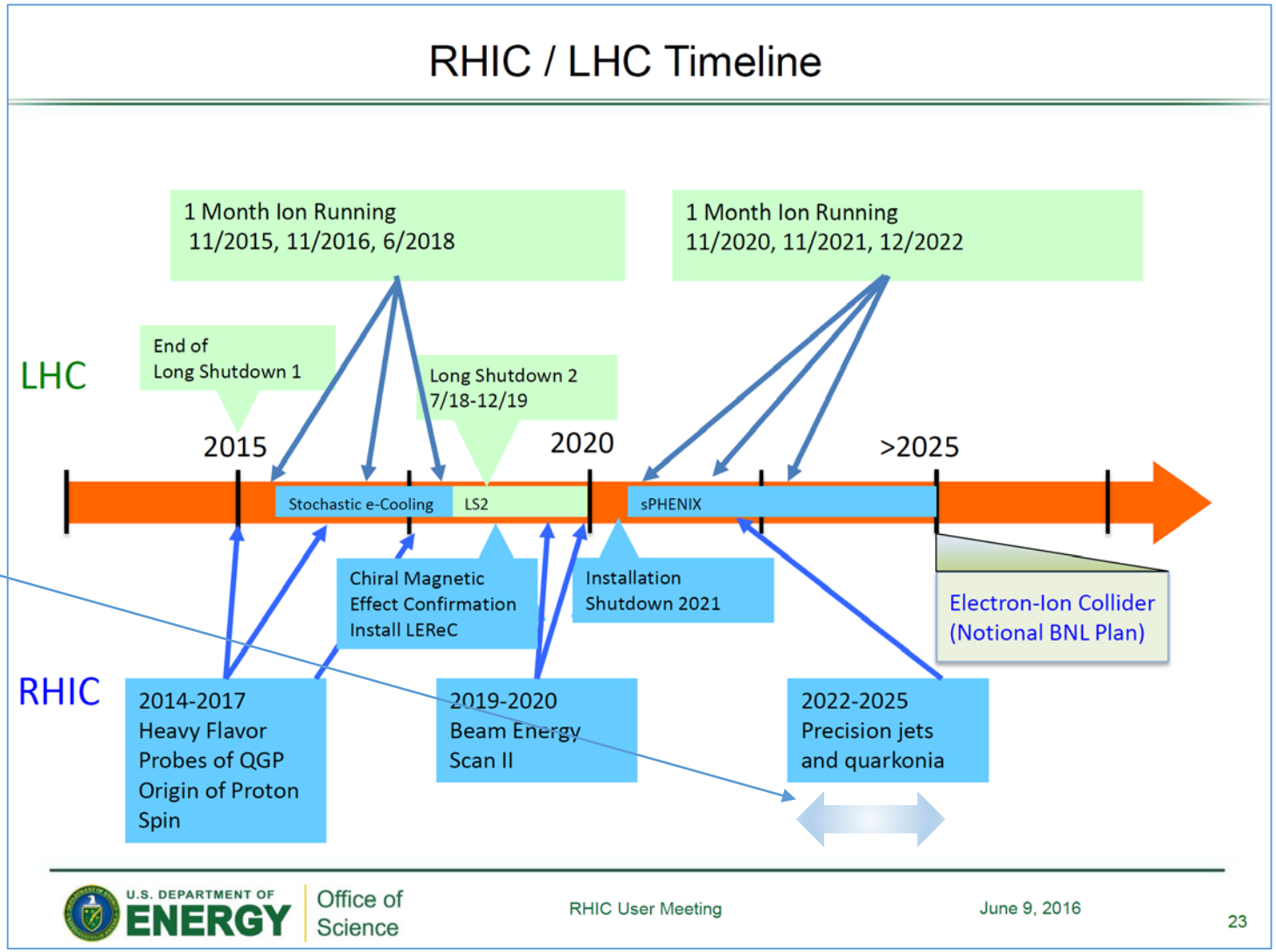
sPHENIX Gets CD0 for Upgrade to Experiment Tracking the Building Blocks of Matter

First step on a path toward a detector with unprecedented capabilities for deciphering how the properties of the hottest matter in the universe emerge from the interactions of its fundamental particles

January 13, 2017

RHIC/LHC Timeline

Is there an opportunity for a compelling physics program in p+p/p+A prior to realization of the EIC?

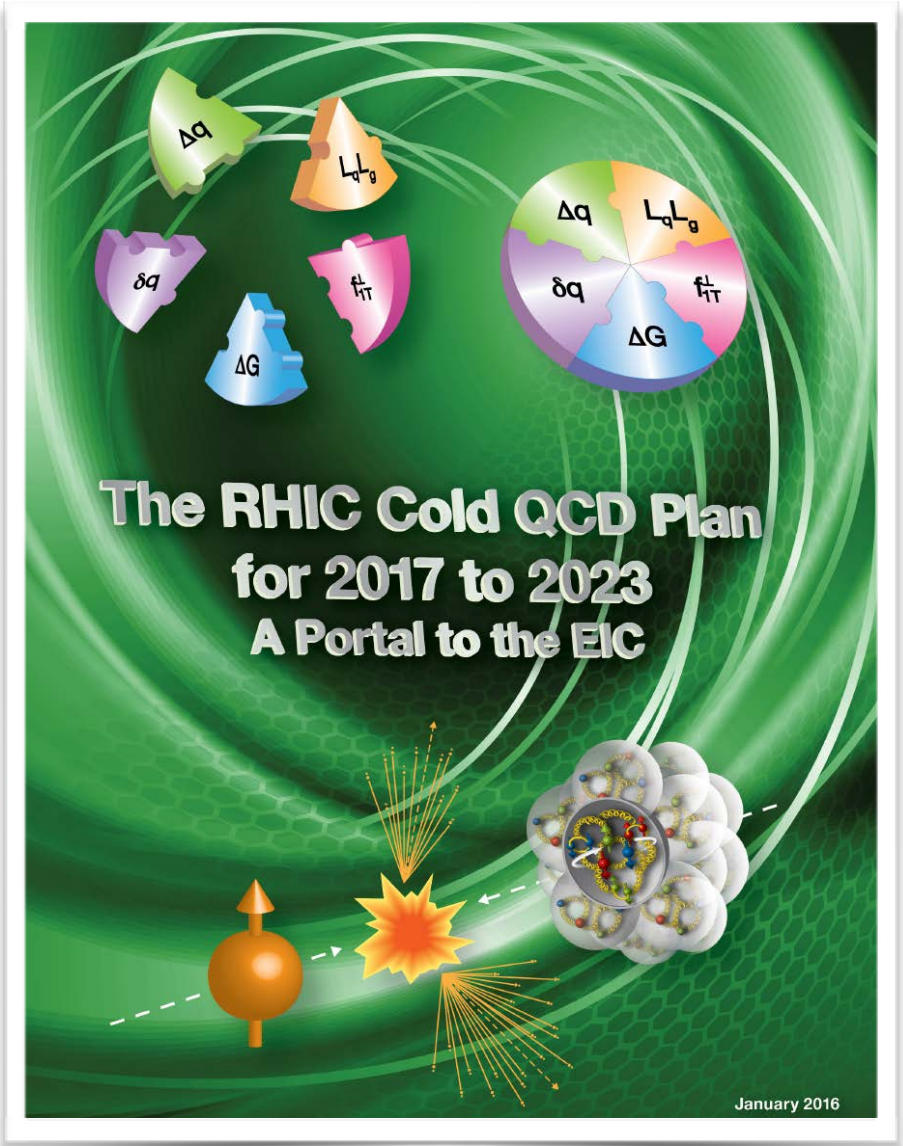


Slide from T. Hallman, DOE

RHIC Cold QCD Plan

- Requested by DOE, submitted Feb 2016
  - Subject of RBRC workshop

- Lays out a comprehensive set of important measurements to be made on the road to an EIC



http://arxiv.org/abs/1602.03922

RHIC Cold QCD Plan

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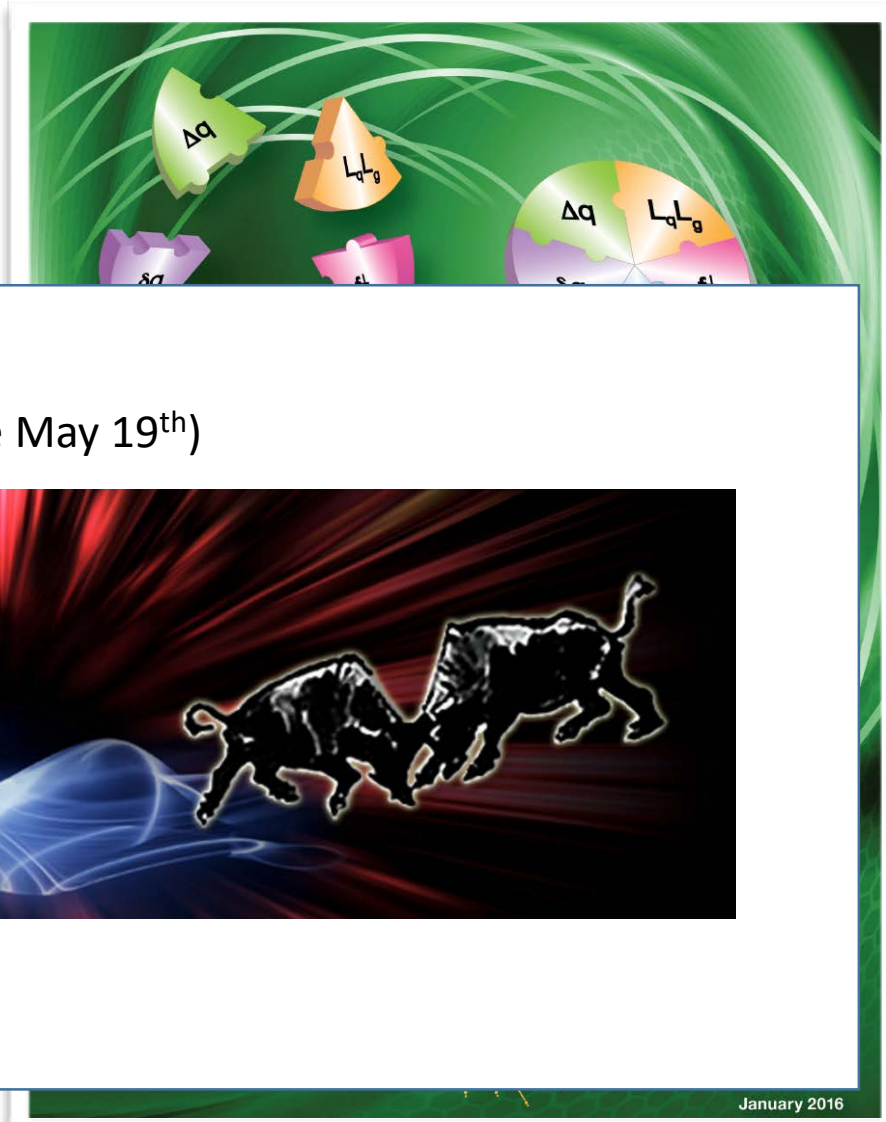

New RBRC workshop:
https://www.bnl.gov/pppa17/ (deadline May 19th)

http://arxiv.org/abs/1602.03922

Physics Goals From Cold QCD Plan

- **Key Physics Observables**:
  - **Jets in polarized p+p:**
    - Jet A_N : Sivers/Twist-3 for u/d quarks
    - Angular distribution in jets : transversity
    - Di-Jet A_{LL} : Δg at low-x
  - **nFF's in p+A:**
    - Important measurement on the road to the EIC
  - **Drell-Yan and Direct Photons in p+A:**
    - Measurements of saturation, A-scan essential
  - **Diffraction in polarized p+p (200 GeV):**
    - A_{UT} from single-diffractive events
  - **Ultraperipheral Collisions in p+Au:**
    - "p-shine": gluon impact parameter distribution in Au nucleus via J/Ψ
    - "Au-shine": access GPD E_g in polarized p via J/Ψ production (A_{UT})
      - Sets the scale for a program to measure GPD E_g at the EIC!

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For many of these measurements RHIC offers *unique* capabilities

Physics Goals From Cold QCD Plan

Need Forward Rapidity Coverage!
BNL ALD has called for LOI's – June 2017

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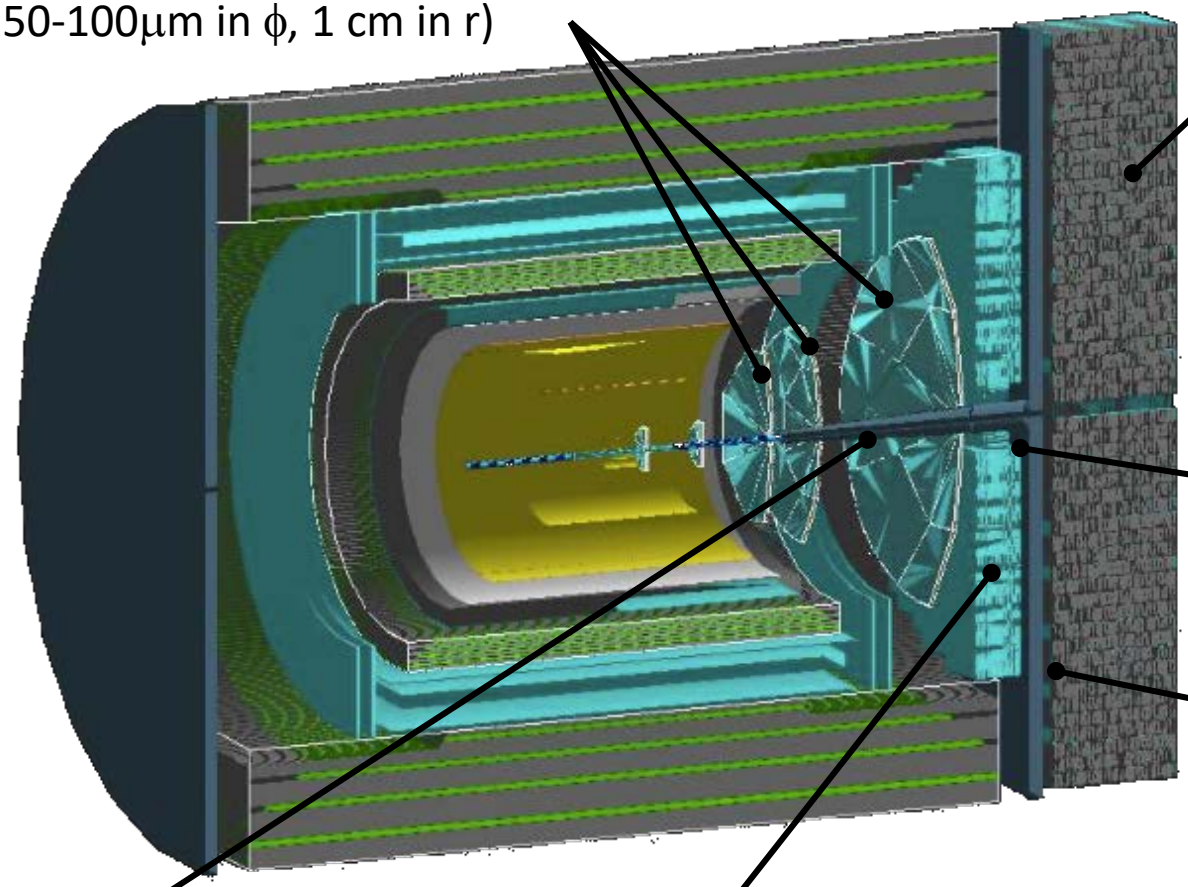
fSPHENIX

GEM/sTGC Tracking Stations (z = 120, 165, 275cm, 50-100μm in ϕ, 1 cm in r)

Pb/Sc sandwich hadronic calorimeter (NEW)
10 x 10 x 100 cm^3 towers
($1.2 < \eta < 4.0$)



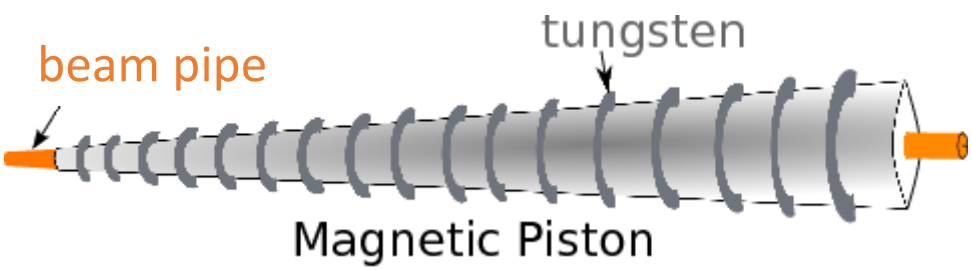
20x20 array of 2.2 x 2.2 x 18 cm^3 PbW (PHENIX MPC) crystals with 10x10 square hole (300 crystals total) $3.0\text{-}3.3 < \eta < 4.0$

Flux return door between FEMC and FHCAL (10.2 cm)

Field shaper piston

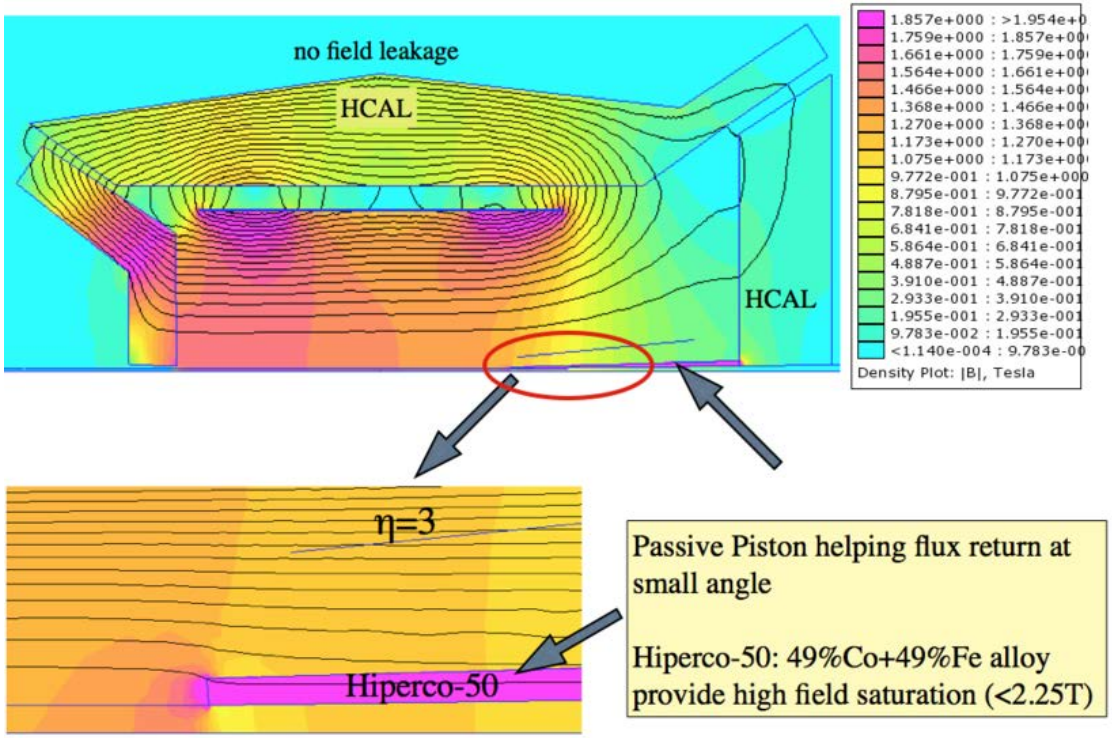
PHENIX PbSc modules (5.5 x 5.5 x 33 cm^3) organized in groups of four modules (3152 modules or 788 groups of 4) ($1.4 < \eta < 3.0\text{-}3.3$), energy resolution $8\%/\sqrt{E}$

Forward Magnetic Field



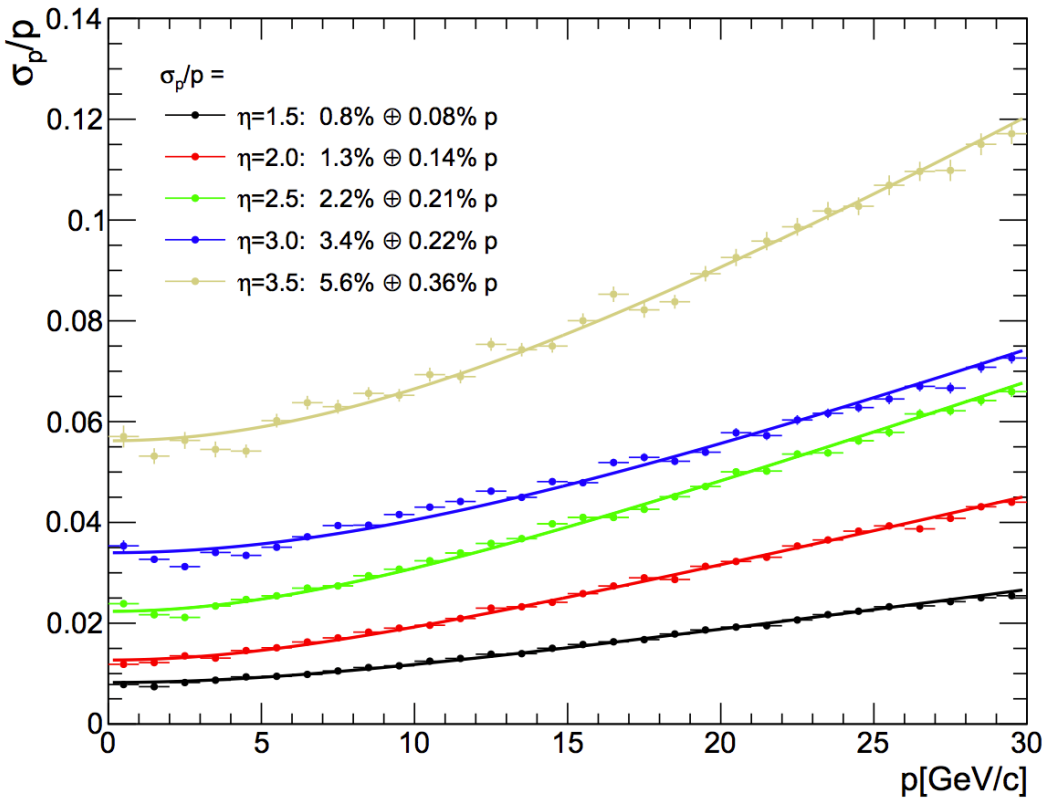
HIPERCO-50 high permeability piston around beam pipe, tungsten ribs reduce backgrounds around calorimeter hole.

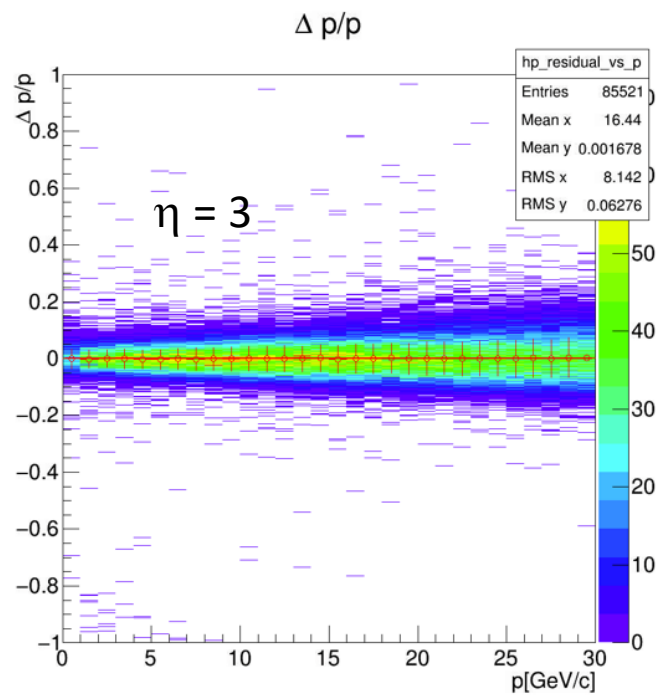
Piston enhances transverse component of magnetic field for η>3.0, improving momentum resolution.



Forward Tracking

- **G4 Simulation and (PH)GenFit** to extract $(p_{Reco} - p_{True})/p_{True}$ vs. p_{True} (right plot)
- For each slice of p_{True}, fit with Gaussian, extract mean as offset, sigma as resolution

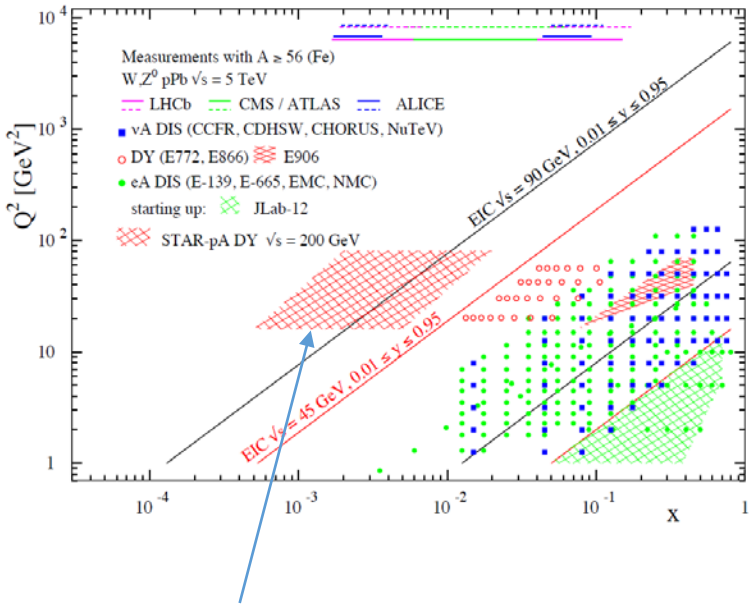




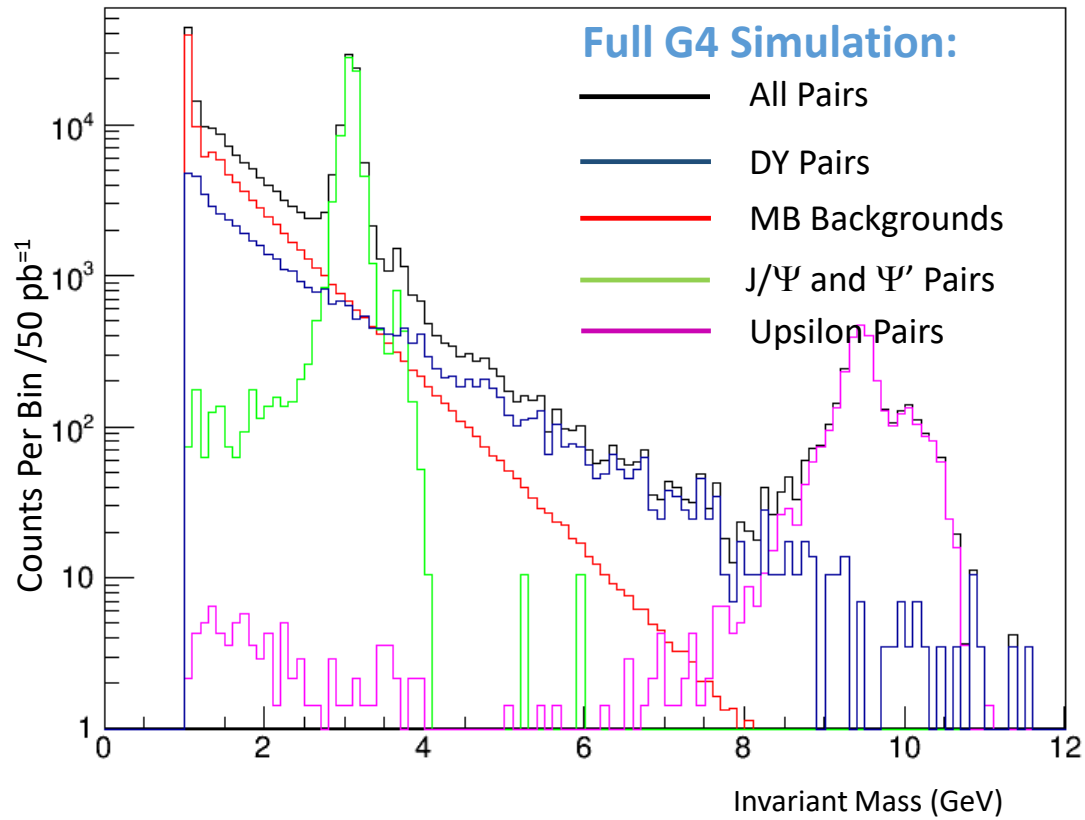
Excellent momentum resolution!

Tracking simulations by Haiwang Yu

Example: DY pairs @ 200GeV



DY measurements in p+A offer a unique physics reach compared to the EIC!

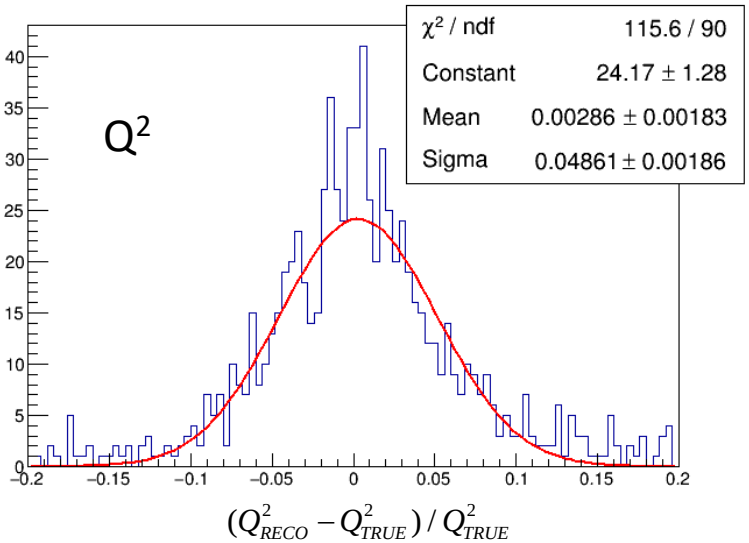


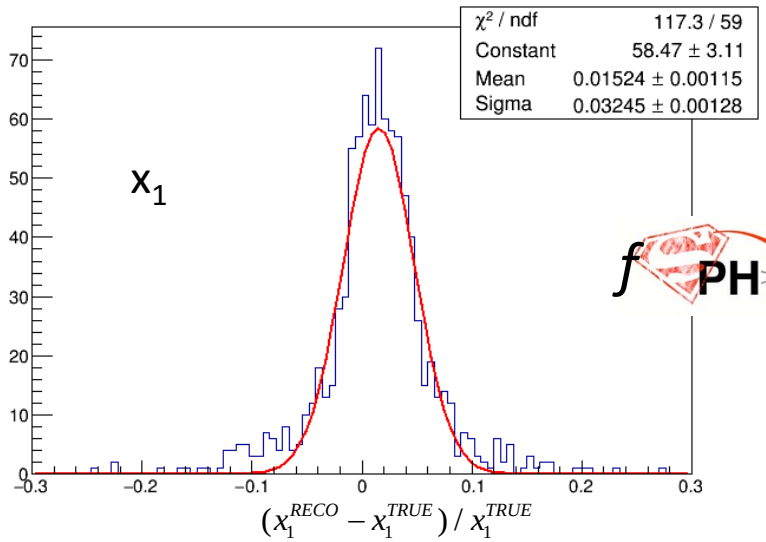
S/B ~ 1 above 5 GeV
~1900 DY pairs 5.0 < m < 8.0 GeV

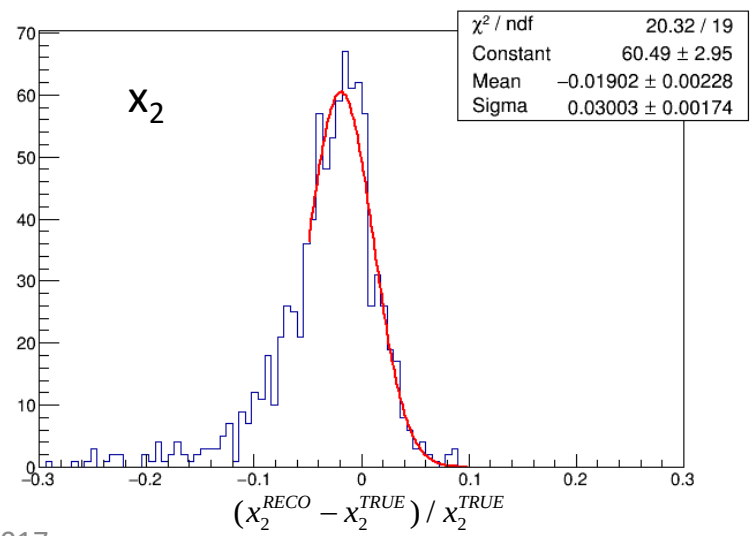
MB background includes additional assumptions about rejection of beam pipe conversions

DY Kinematic Resolution

DY pairs with 5.0 < m < 8.0 GeV

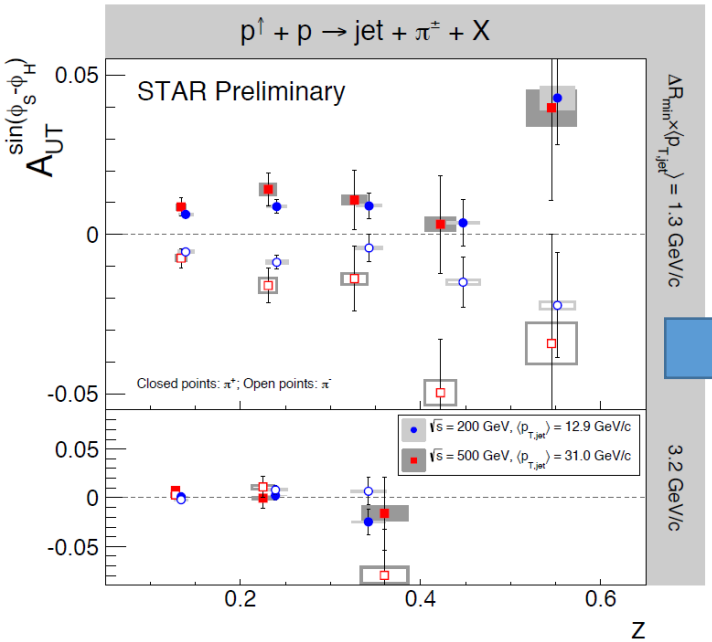


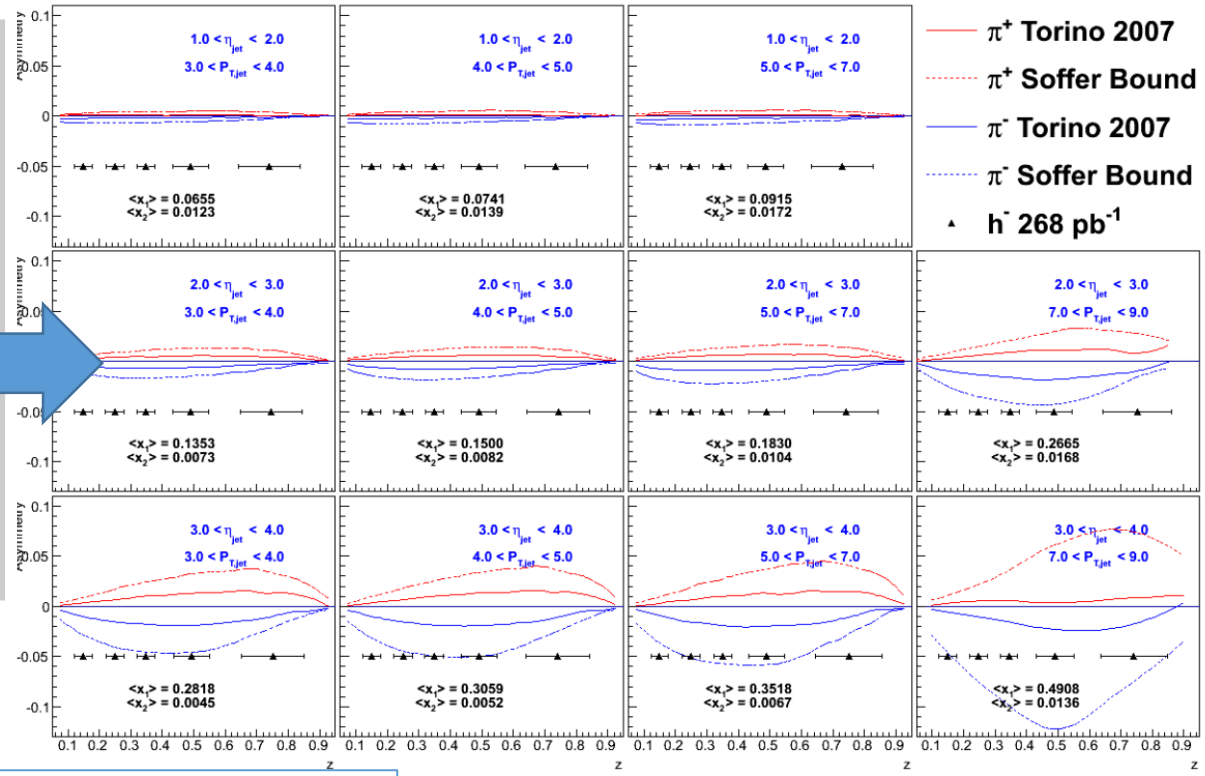




Fractional error in Q^2 about 5%.
Fractional error in x1, x2 about 3%.
x_1 shows a ~1.5% systematic shift up.
x_2 shows a ~2% systematic shift down, with asymmetric tail.

Jets and Polarized Jet Structure





Future high luminosity measurements will allow detailed differential study of spin-dependent fragmentation – access to transversity at high x.

Key to comparing tensor charge with Lattice QCD!

$$\delta q_a = \int_0^1 \left(\delta q_a(x) - \delta \bar{q}_a(x)\right)\, dx$$

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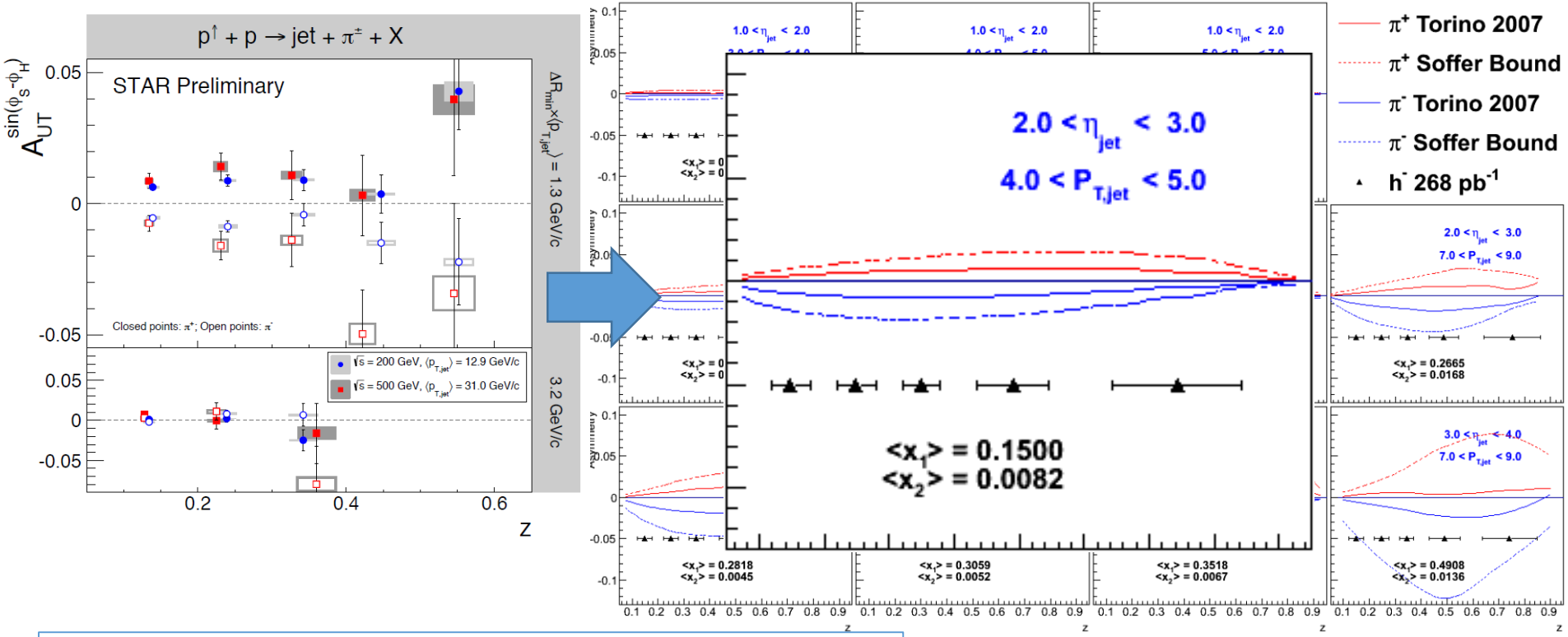

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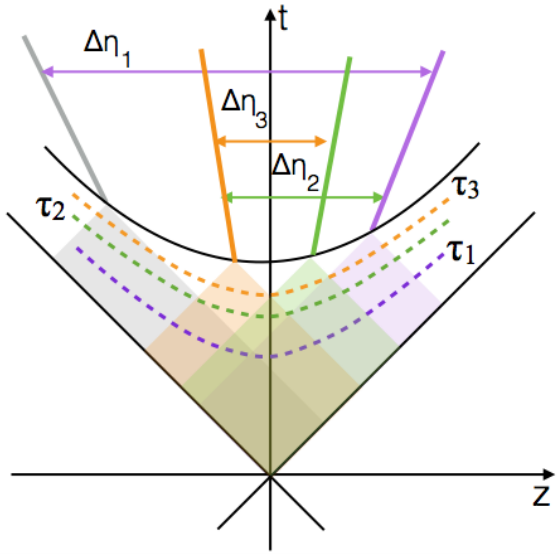
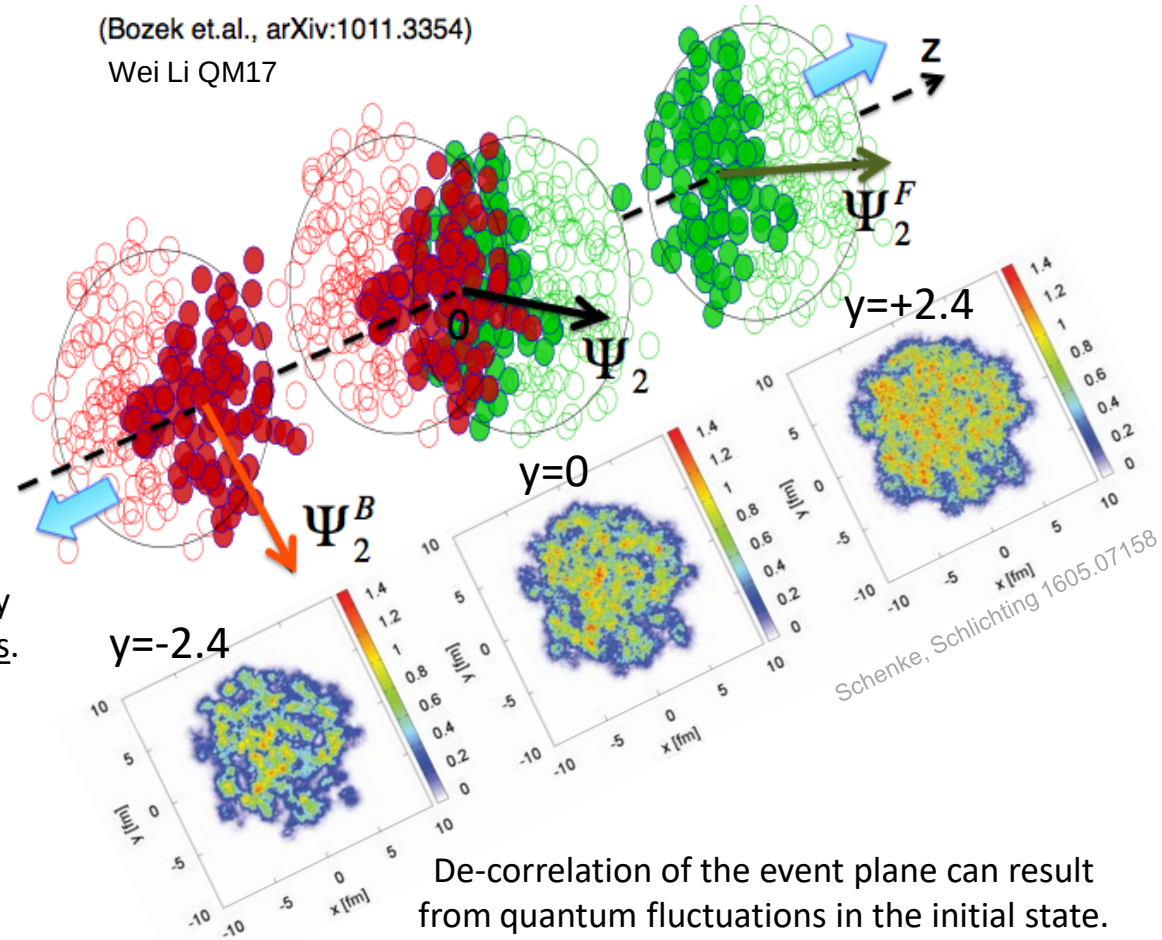
What About Heavy Ions?



Due to causality, correlations that are widely separated in rapidity probe the <u>earliest times</u>.

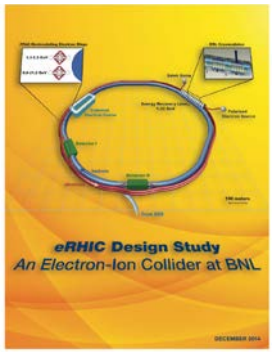


Adding forward capabilities to sPHENIX will enable a new, complementary physics program to study the initial conditions in HI collisions.

De-correlation of the event plane can result from quantum fluctuations in the initial state.

Need to understand this to be able to extract $\eta/s(T)$ from hydrodynamic models.

Evolution to an EIC Detector



arXiv:1409.1633

Central DIRC for PID

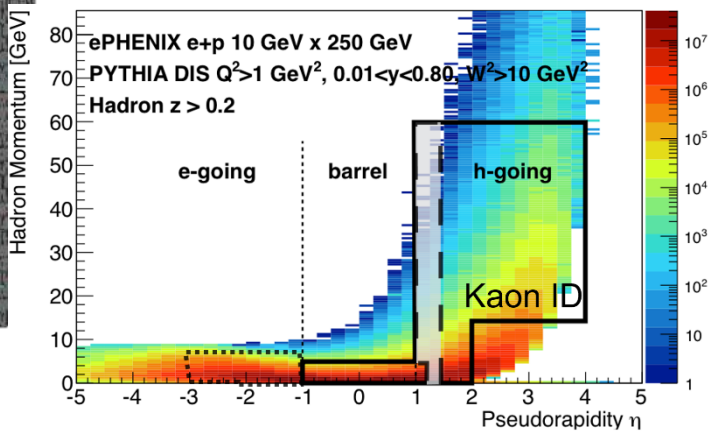
Forward RICH for hadron PID

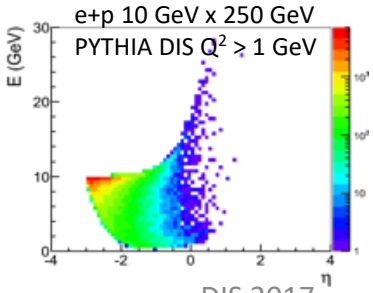
p/A

e-

Endcap crystal EMC for scattered e-:
$\sigma_E/E \sim 1.5\%/\sqrt{E}$
$\sigma_X < 3mm/\sqrt{E}$

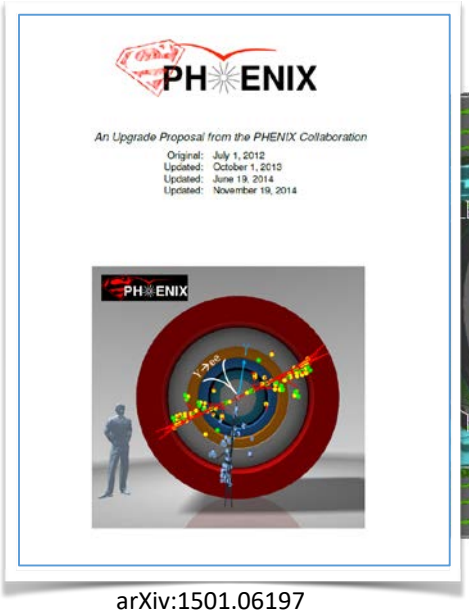
Hadrons from SIDIS:





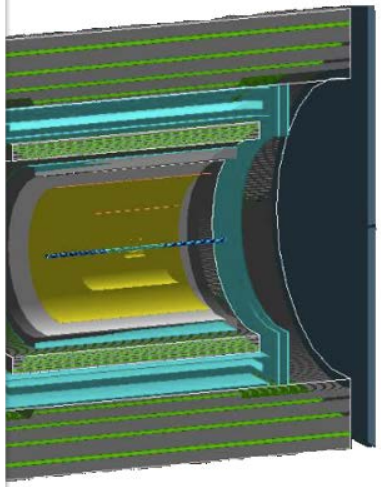
+ Plus Roman Pots (exclusive processes)

A Detector Evolution



arXiv:1501.06197

2022-2025+



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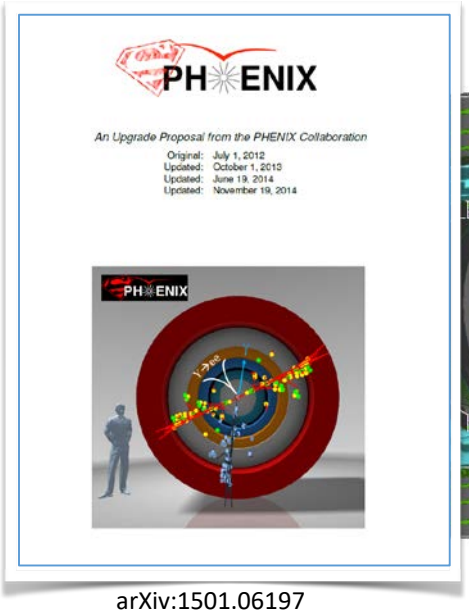

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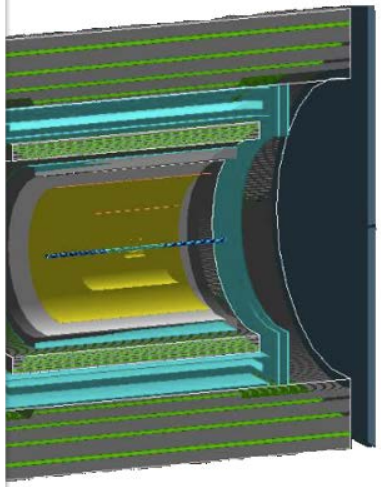
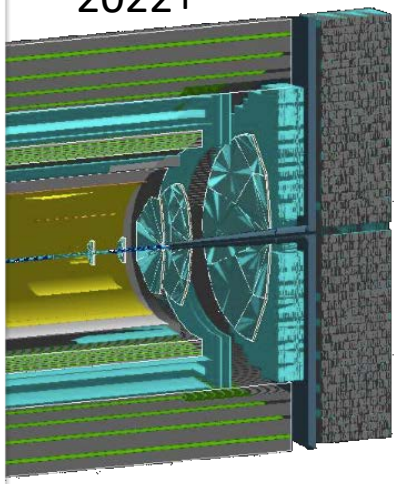
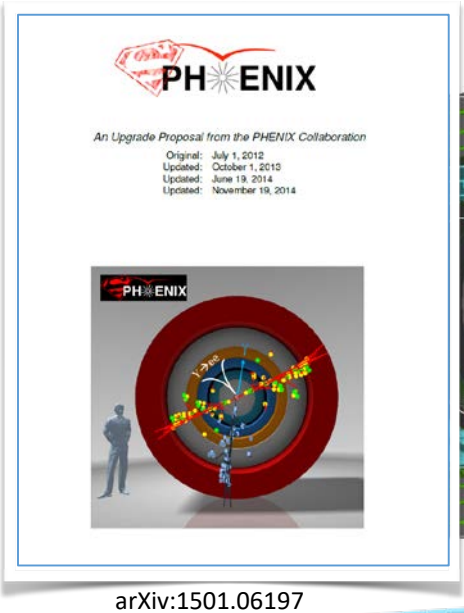


arXiv:1602.03922

2022+

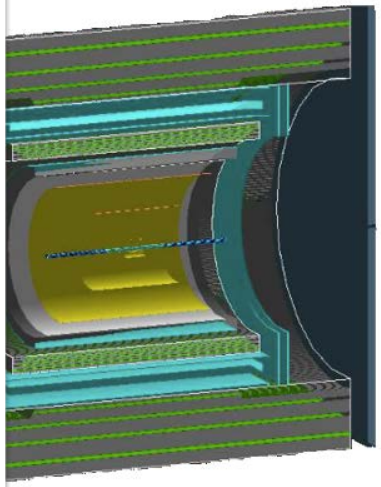


A Detector Evolution



arXiv:1501.06197

2022-2025+



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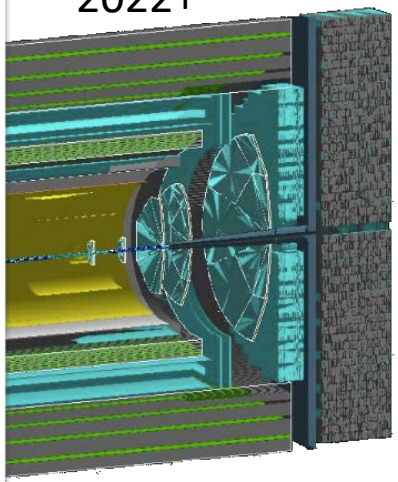
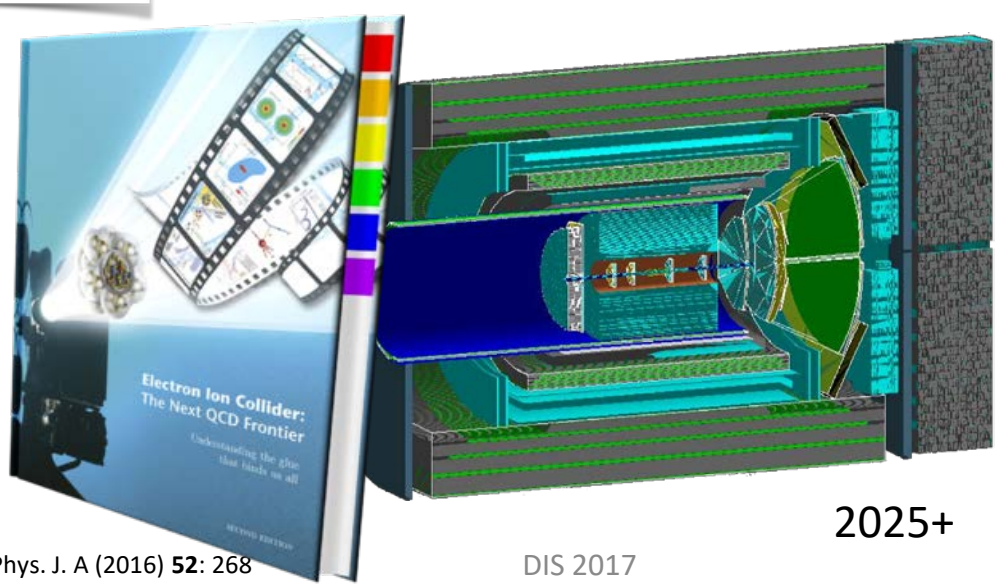
2022+





2025+

The forward detectors for fsPHENIX could be re-used for an EIC detector!

Eur. Phys. J. A (2016) **52**: 268

Conclusions

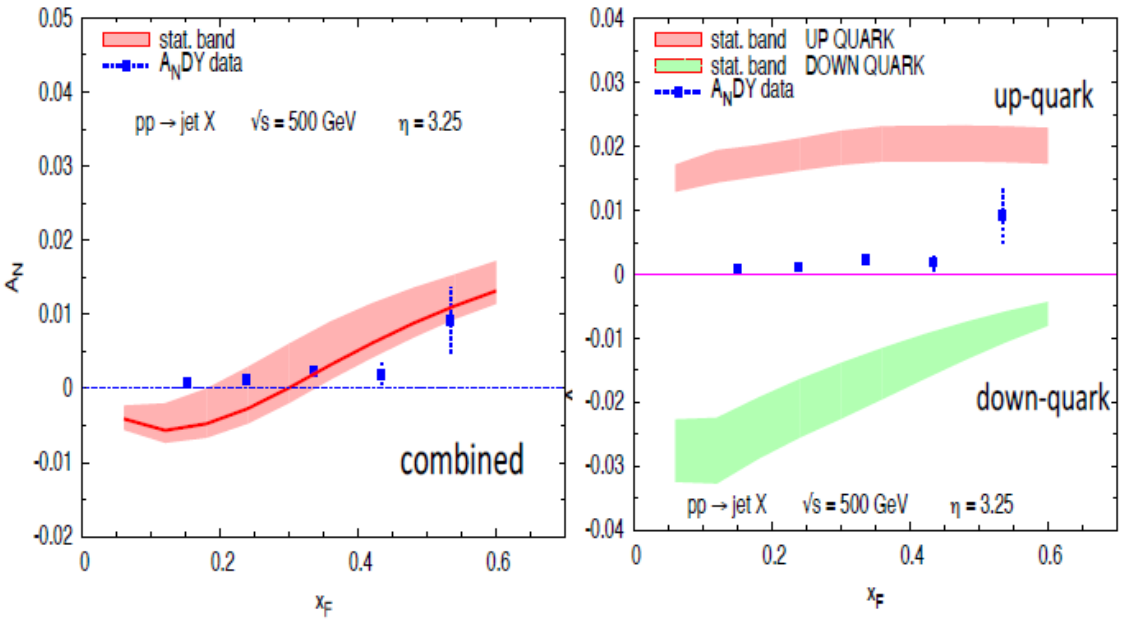
- sPHENIX is a major new project that will make available probes of the Quark Gluon Plasma with unprecedented precision.
- There is a wealth of unexplored physics in the forward region at RHIC!
  - Measurements in p+p/p+A that pave the road to an EIC
  - A complementary HI physics program in longitudinal dynamics
- The addition of forward instrumentation to sPHENIX (fsPHENIX) is being actively explored:
  - Substantial re-use of existing detector systems for calorimetry
  - Tie-ins with EIC R&D as well as potential re-use of equipment for future EIC detector
  - Updated fsPHENIX LOI to be submitted to BNL PAC June 2017

BACKUP

Jet Sources

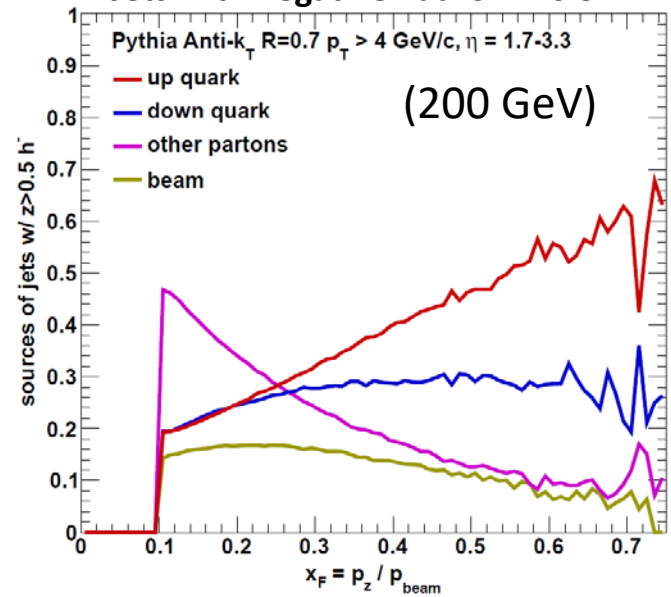
AnDY: Phys. Lett. B750 (2015) 660

Directly use Sivers function from SIDIS fit

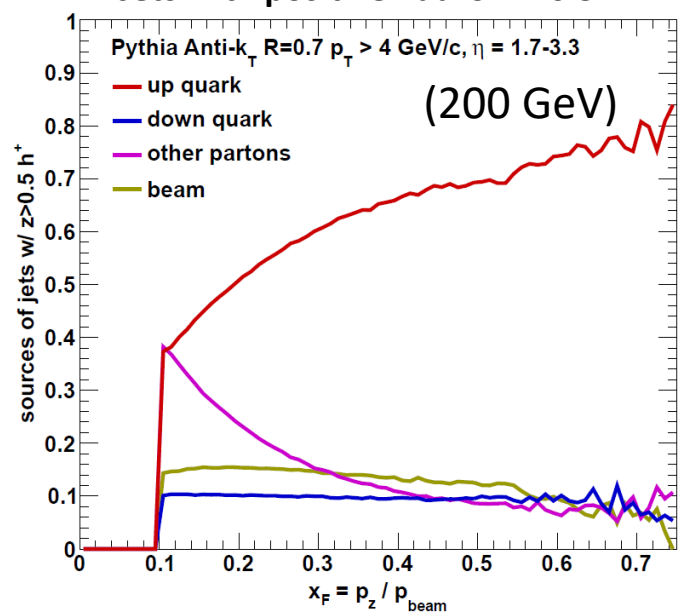


A cut on the charge of the leading hadron changes the composition of the jet sample.

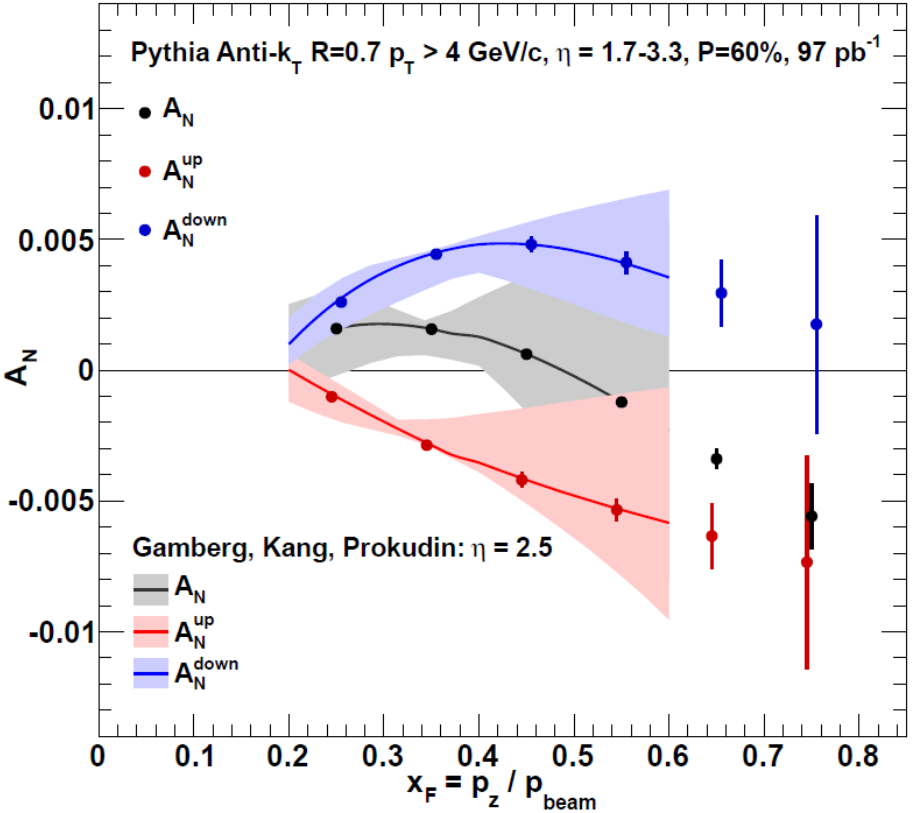
Jets with negative hadron z>0.5

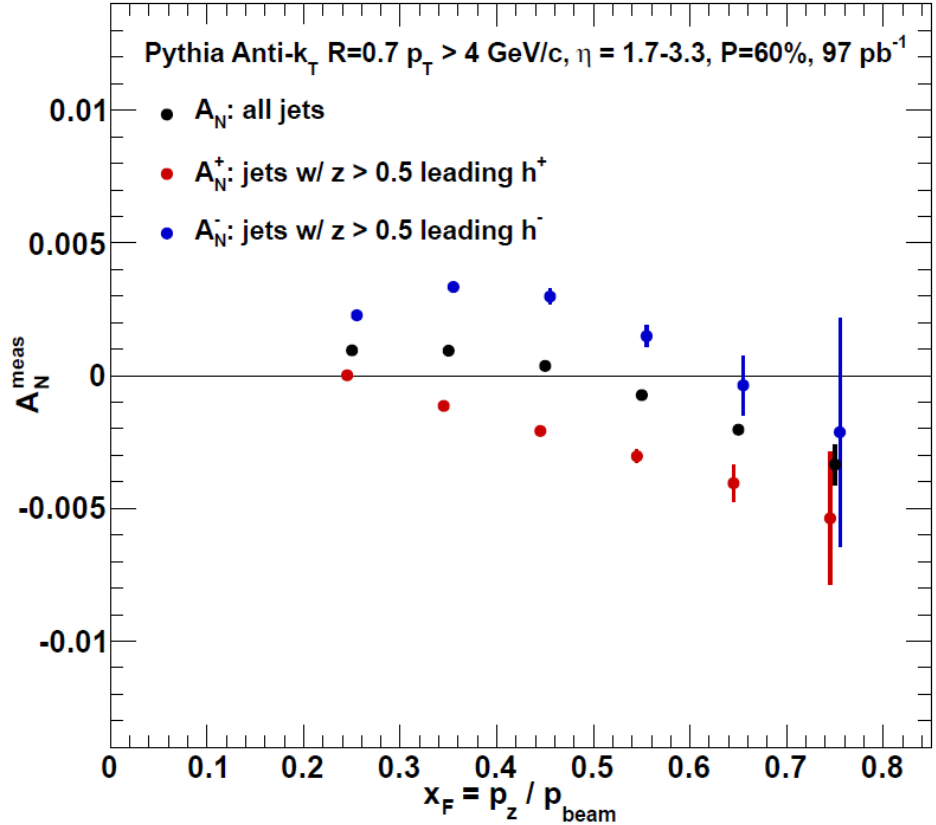


Jets with positive hadron z>0.5



Forward Jet Studies (200GeV)





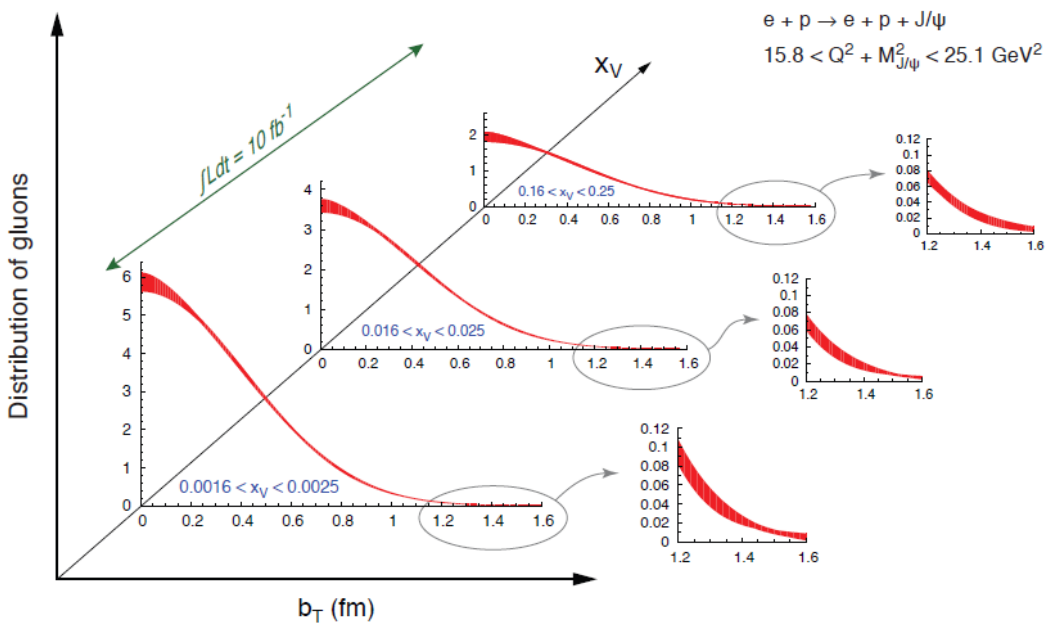
Gamberg, Kang and Prokudin: *Phys Rev. Lett*. 110:232301 (2013)

Projected fsPHENIX data points (~100 pb^{-1}) compared to theoretical model. Currently repeating these simulations at 510 GeV.

Gluon Tomography at the EIC

Eur. Phys. J. A (2016) **52**: 268

$$x_V = x_B\left(1+{M^2_{J/\Psi}}/{Q^2}\right)$$



EIC: 5(e⁻)/100(p) GeV and 20(e⁻)/250(p) GeV

Exclusive J/Ψ Production:

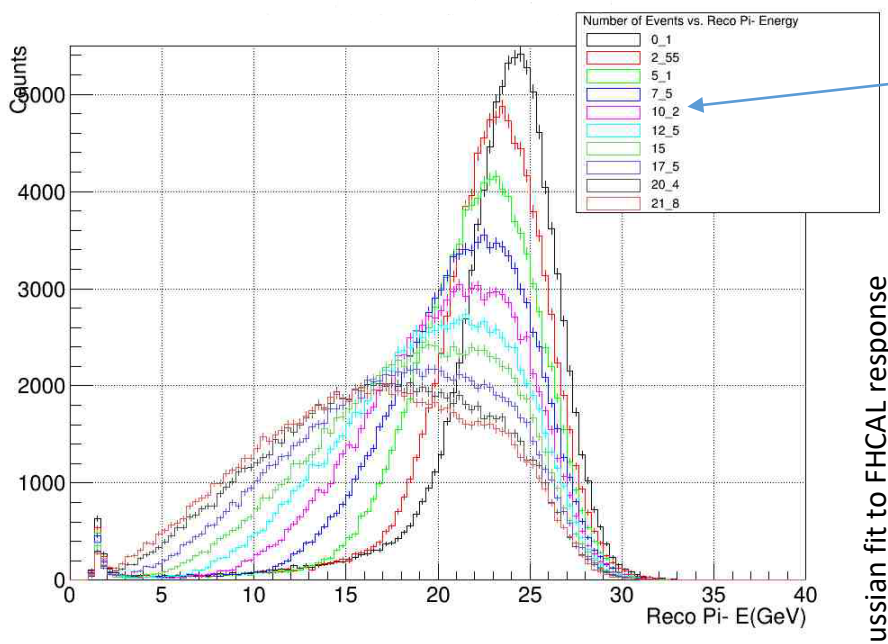
$$e^- + p \rightarrow e^- + p + J/\Psi$$

High precision measurement of the spatial distribution of gluons in the proton.

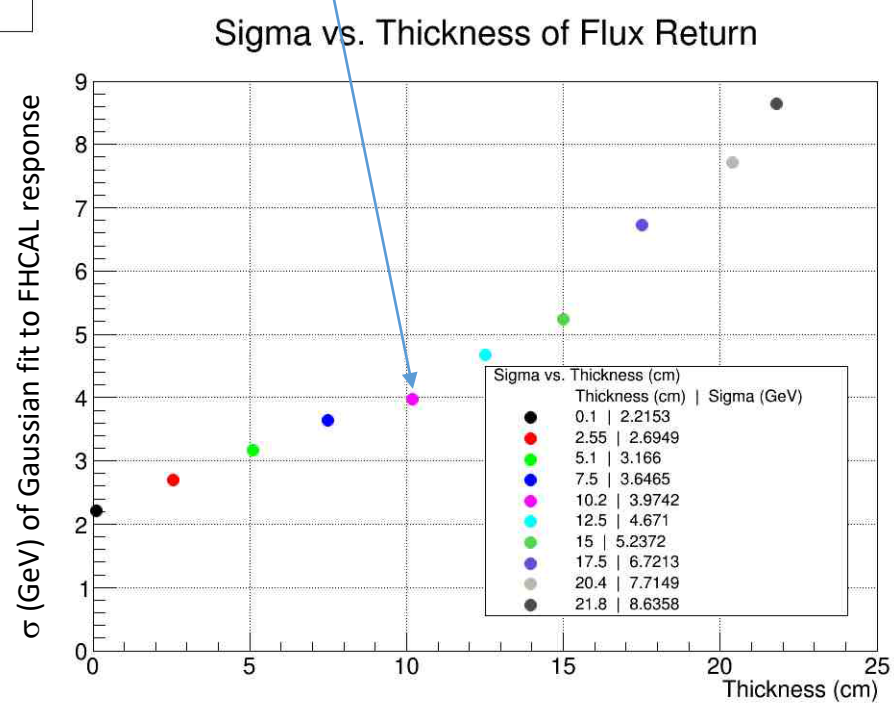
Forward HCAL Simulations

Studies by D. Kapukchyan

Studied the effect of the sPHENIX flux return on the FHCAL energy resolution (examples below are 30GeV pions).
Plug door could be replaced by magnetic FHCAL.



Nominal plug door thickness is 10.2 cm



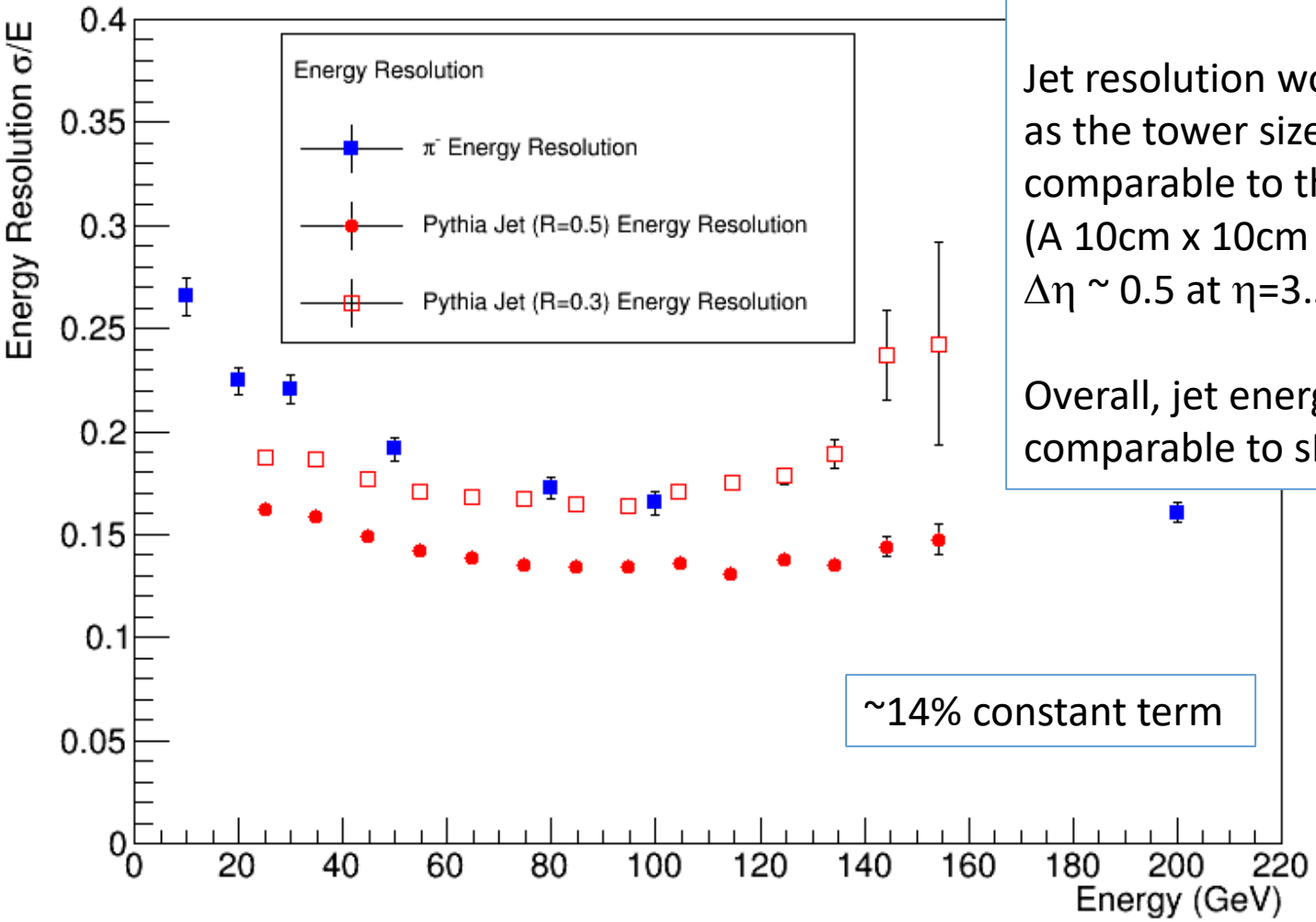
Plug door decreases response and generates a non-Gaussian tail.

Jet Energy Resolution

Jets from 510 GeV Pythia8, using jet trigger, jet energy is correlated with pseudorapidity. Required E>20GeV, p_T>5GeV.

Jet resolution worsens at high η as the tower size gets comparable to the cone size. (A 10cm x 10cm FHCAL tower is $\Delta\eta \sim 0.5$ at η=3.5.)

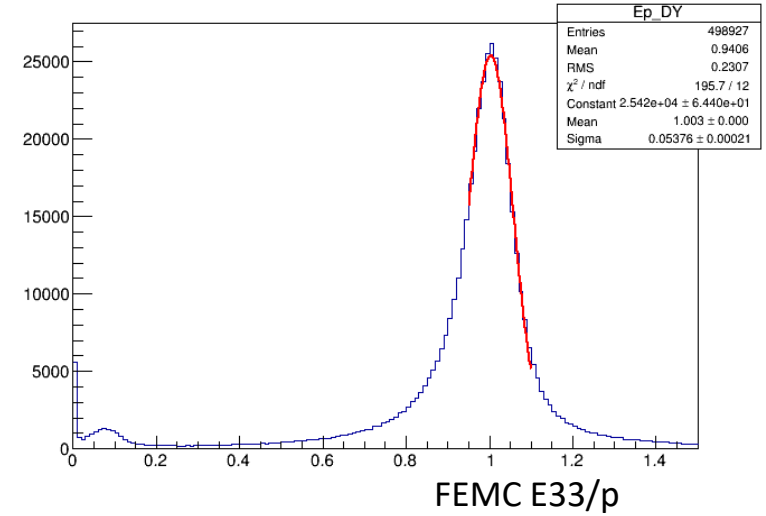
Overall, jet energy resolution comparable to sPHENIX barrel.

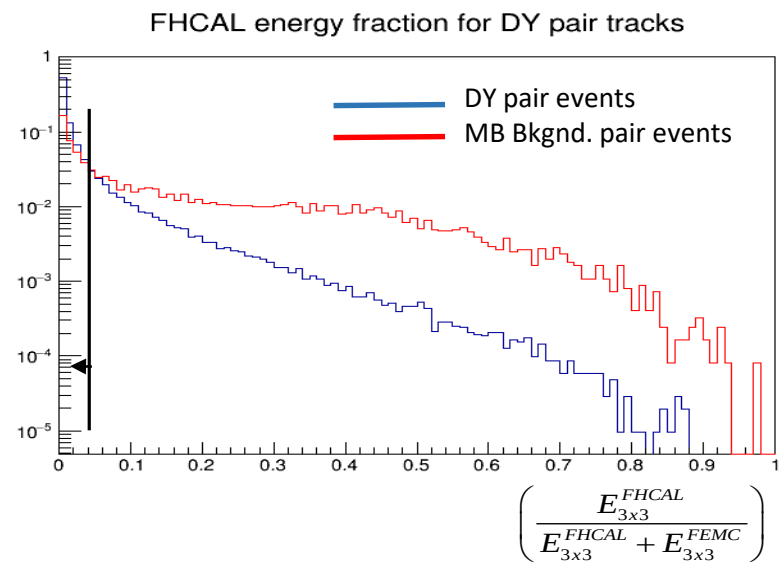


~14% constant term

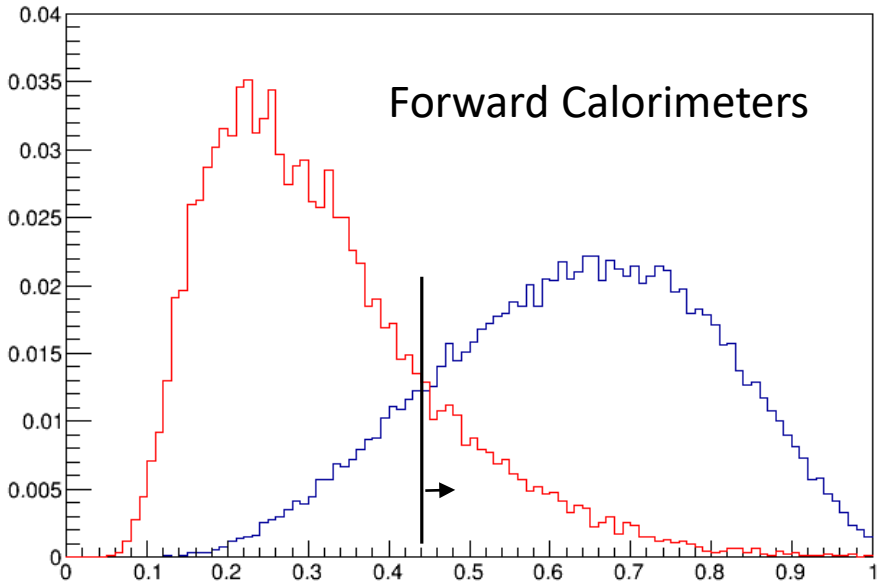
DY Cuts and Analysis

- A candidate DY pair requires:
  - Track Cuts:
    - $1.4 < \eta < 4.0$
    - One of the two tracks consistent with firing the electron trigger
    - >= 4 FGEM hits
    - abs(E/p – 1.0) < 3σ
    - FHCAL energy fraction < 0.04
  - Pair Cuts:
    - Tracks have opposite charge sign
    - Mass > 1.0 GeV
    - Only one pair in an event
  - Event Cuts:
    - Pair forward energy fraction >0.44
    - sPHENIX barrel energy < 5 GeV
  - 97% of pairs in DY events are true DY pairs (3% contamination)





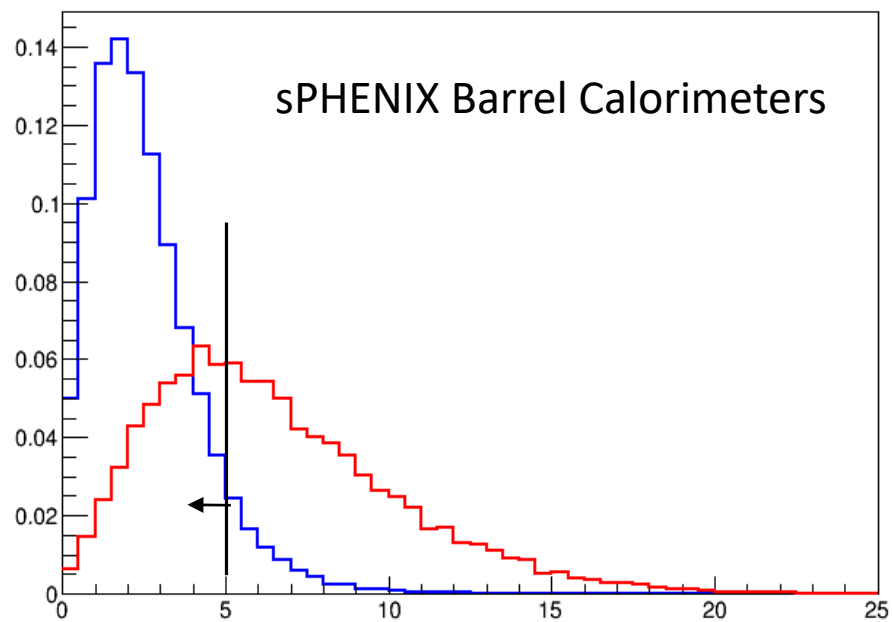
Event Charcterization Cuts



Sum Pair FEMC E33/(FEMC+FHCAL) > 0.44

DY pair events

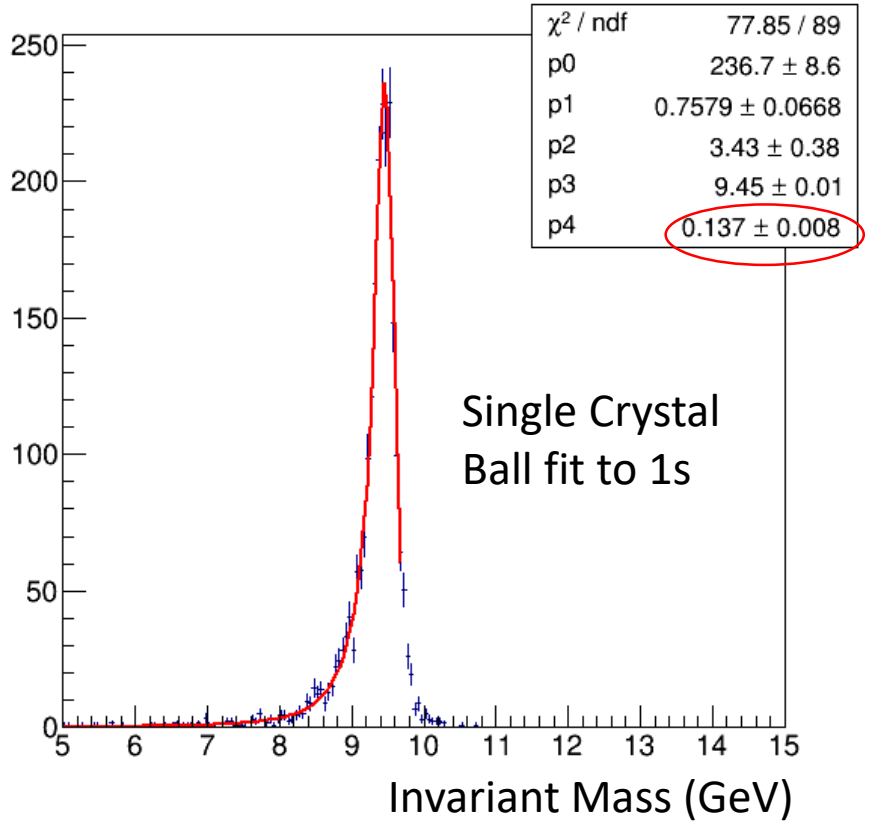
MB Bkgnd. pair events

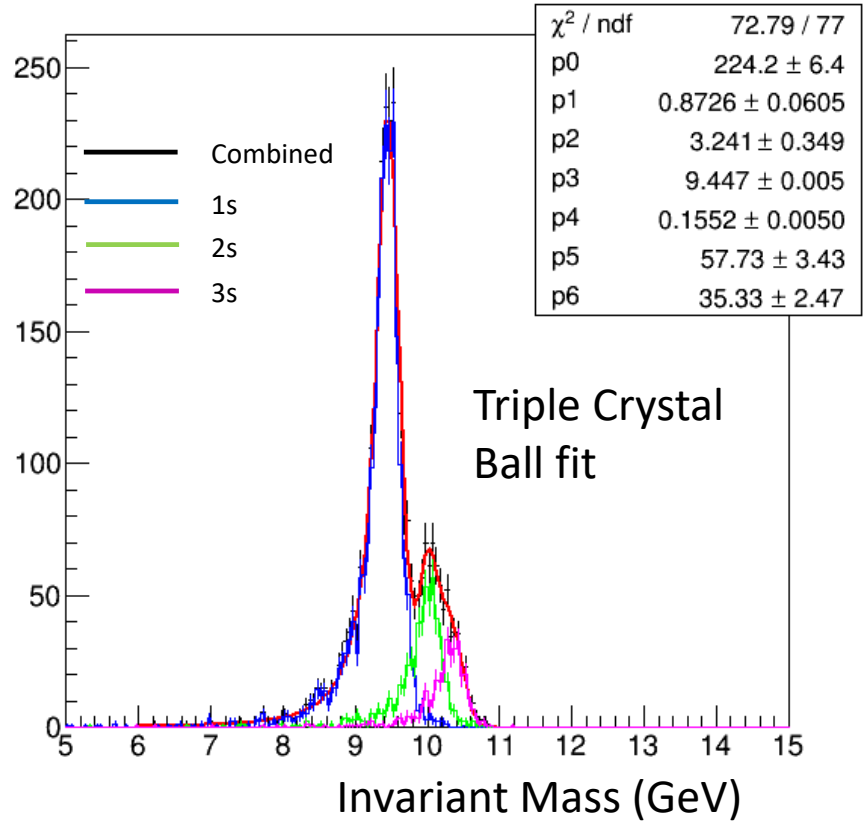


CEMC + IHCAL + OHCAL Energy (GeV)

Event topology cuts are effective in eliminating background processes that generate false DY pairs.

What about the Upsilon?





2s/1s ratio = 0.261 from 3CB fit (truth 0.260)
3s/1s ratio = 0.160 from 3CB fit (truth 0.145)

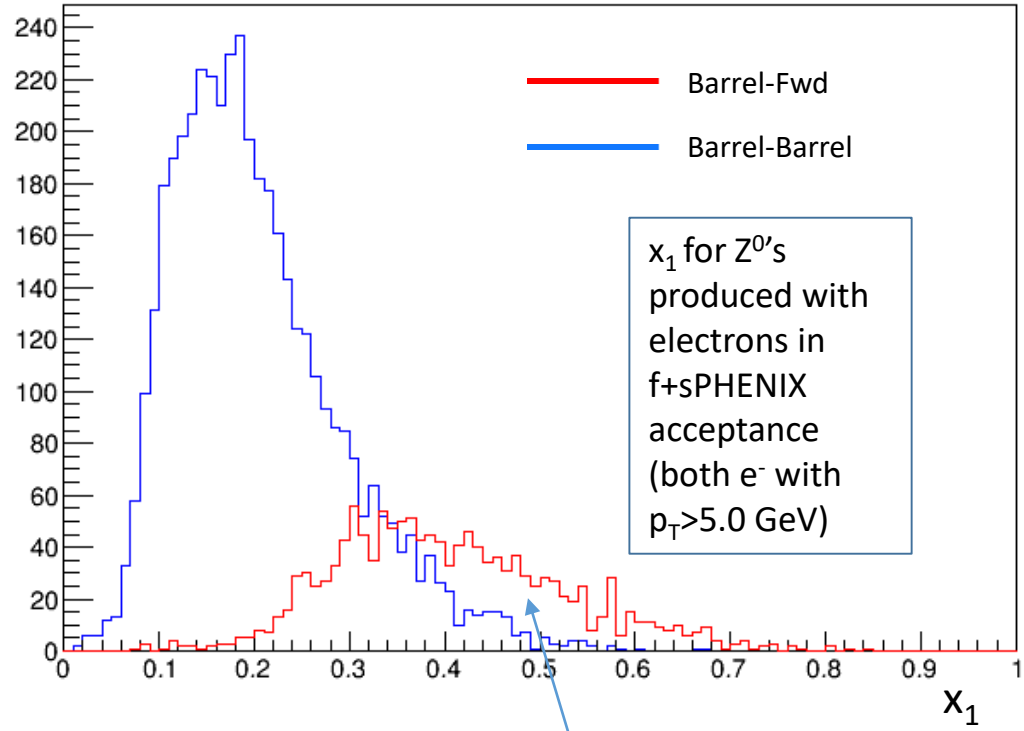
Z^0 Yield and x_1 Coverage

- Cold QCD Plan suggests a possible 510 GeV run could deliver as much 1.1 fb^{-1}
- Assume integrated lumi. is 600 pb^{-1} , this yields:

- 1300 Z^0 with one electron in the forward acceptance ($1.4<\eta<4.0$) and one in the barrel ($-1.1<\eta<1.1$), both with $p_T>5$GeV.

- 4100 Z^0 with both electrons in the sPHENIX barrel ($1.1<\eta<1.1$), both with $p_T>5$GeV.

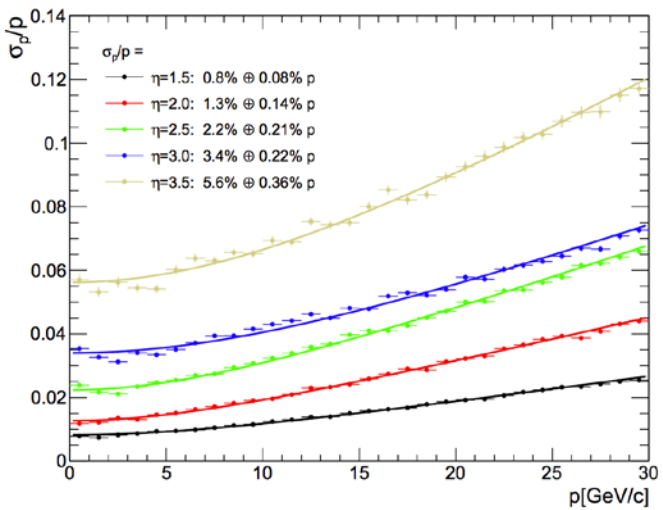
- W similar, but x10 higher cross section.



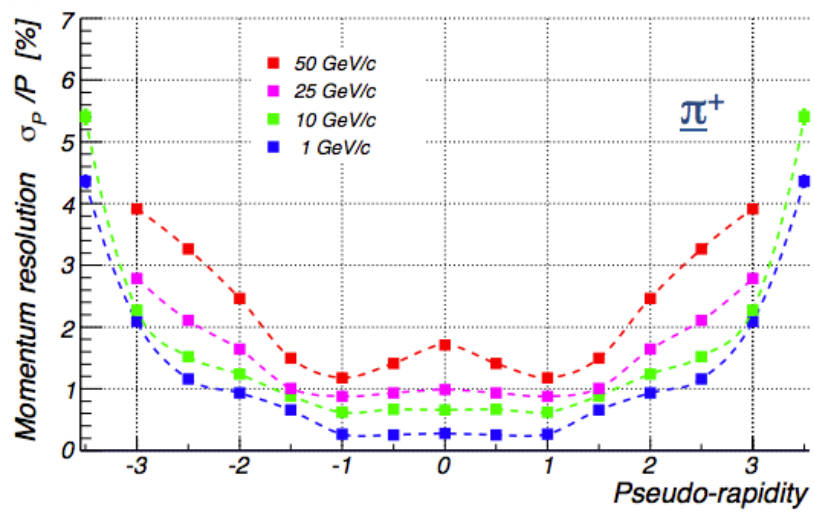
Barrel-Fwd correlations reach high x in the polarized nucleon!

Tracking Comparison

- Resolution is about x2 of BeAST: BeAST has a x2 stronger magnetic field + silicon tracker, fsPHENIX uses a much longer tracking arm.
- High momentum resolution could be improved by switching from GEM to high precision silicon tracker.



sPHENIX FGEM



BeAST

Tracking Comparison

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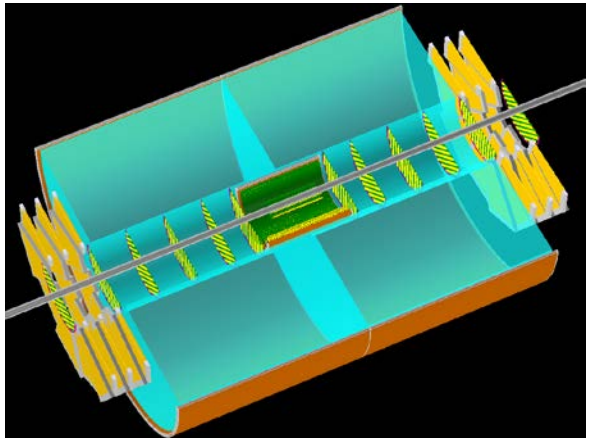
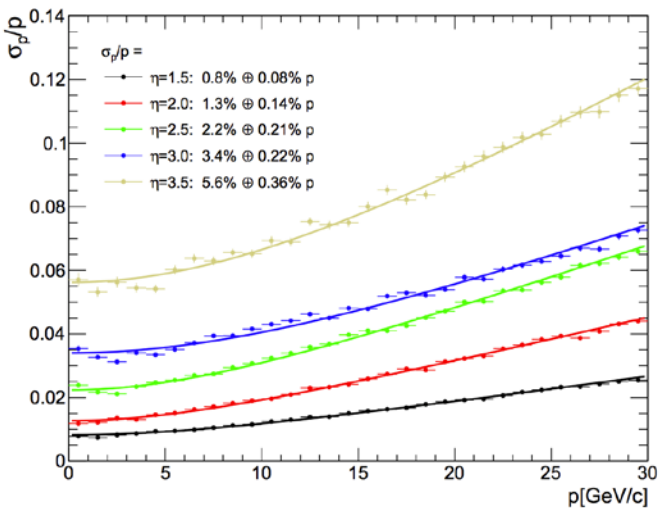
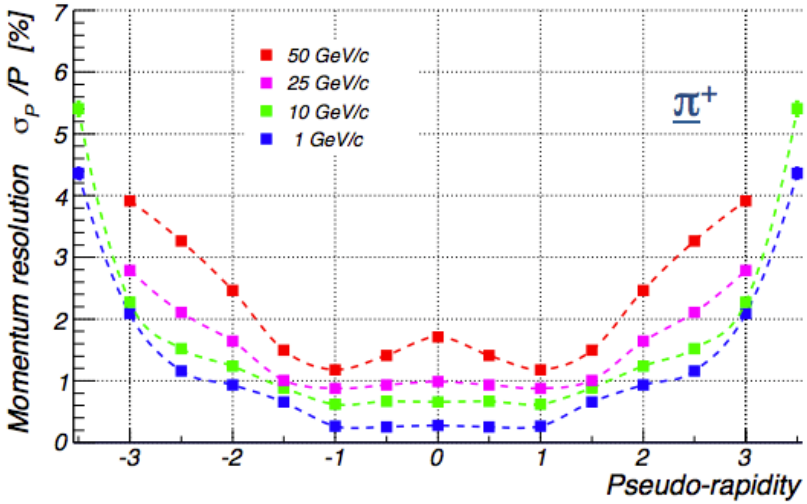




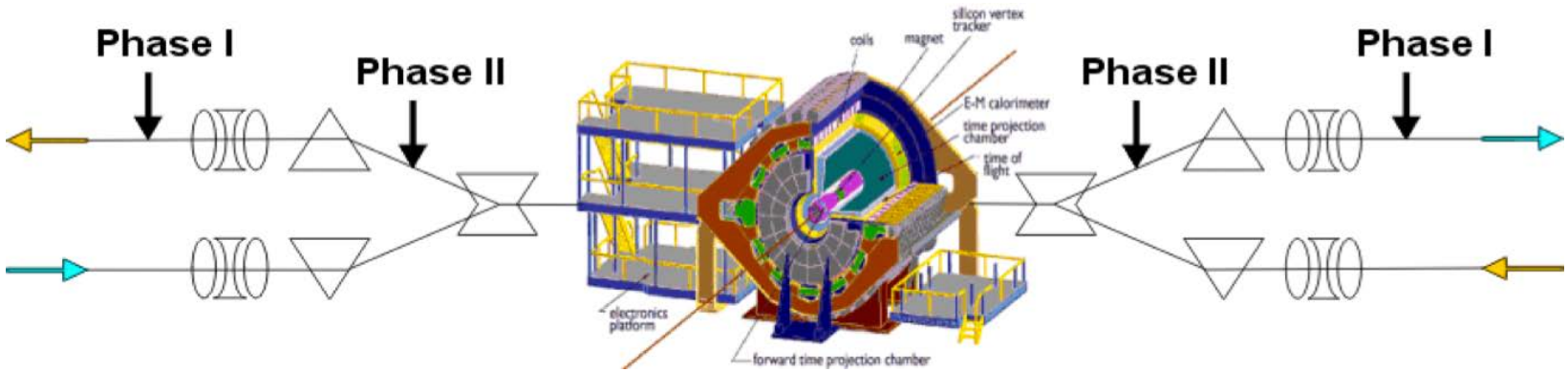
sPHENIX FGEM

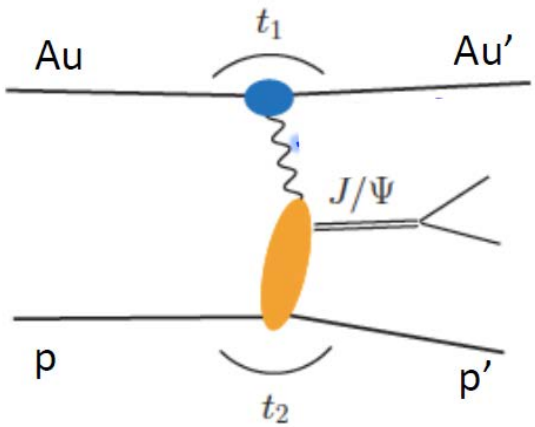


BeAST

Diffraction/UPC

Data taken in 2015/17 by STAR will elucidate the diffractive contribution to A_N a RHIC.





$$A_{UT}(\tau,t) \sim \frac{\sqrt{t_0 - t}}{m_p} \frac{\mathrm{Im}(E * H)}{|H|} \qquad t = \frac{M_{J/\Psi}^2}{s}$$

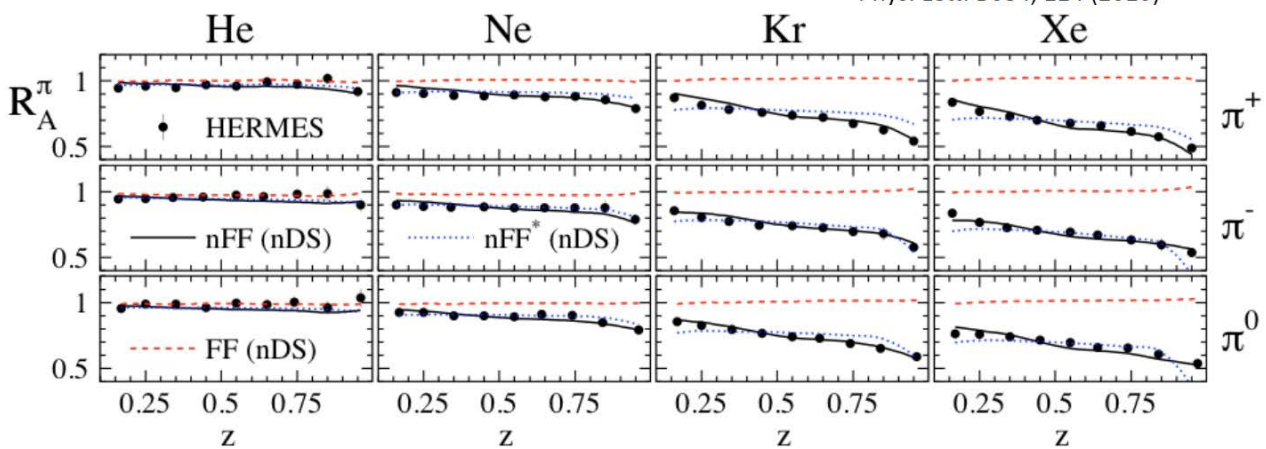
UPC collisions in p+A will allow study of:

- The gluon spatial distribution in nuclei ("proton shine")
- The gluon helicity flip Generalized Parton Distribution (GPD) E_g ("A-shine")

Requires Roman Pots, good t-acceptance and high luminosity

Nuclear Fragmentation Functions

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



Hadron production in e+A suppressed compared to e+p

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

Access fragmentation functions (FF) through p+p(A) -> (jet *h*) X