Center for Frontiers in Nuclear Science

Forward Physics with STAR and Detector Upgrades

Oleg Eyser
for the STAR Collaboration

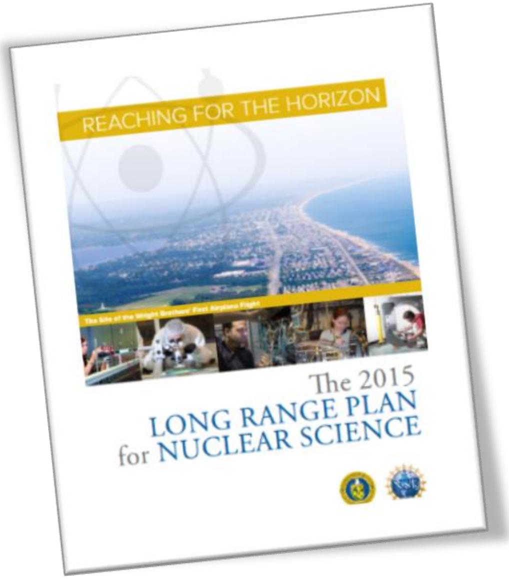
Forward Physics and Instrumentation from Colliders to Cosmic Rays

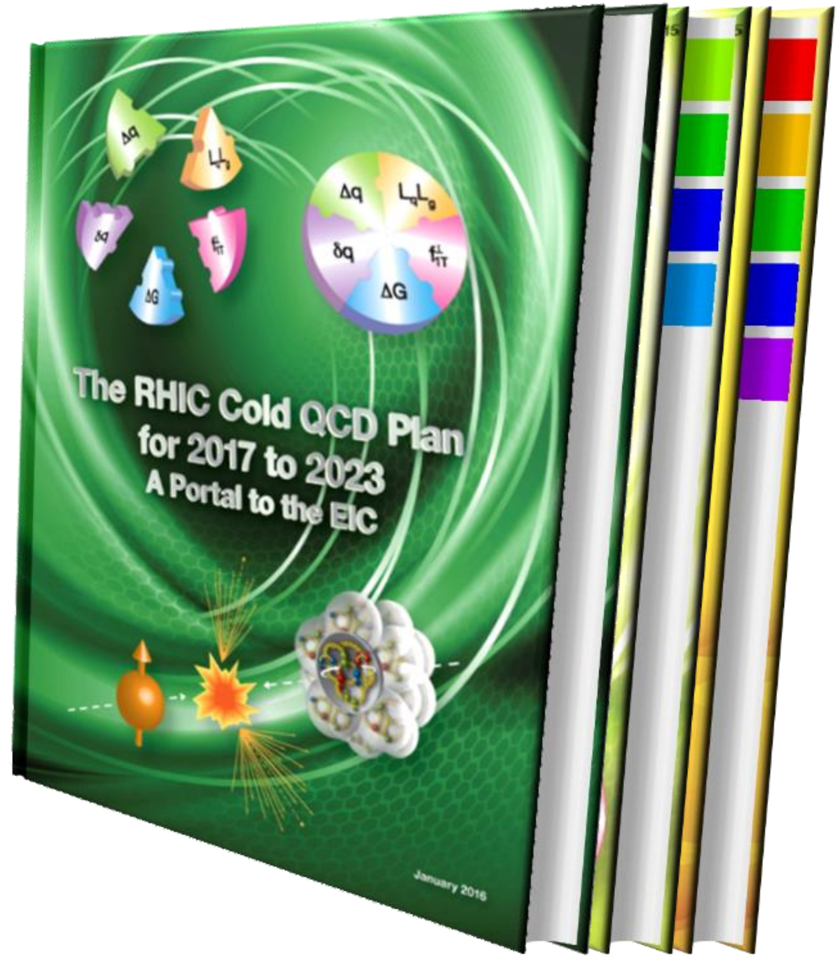
CFNS Stony Brook

U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

October 17-19, 2018

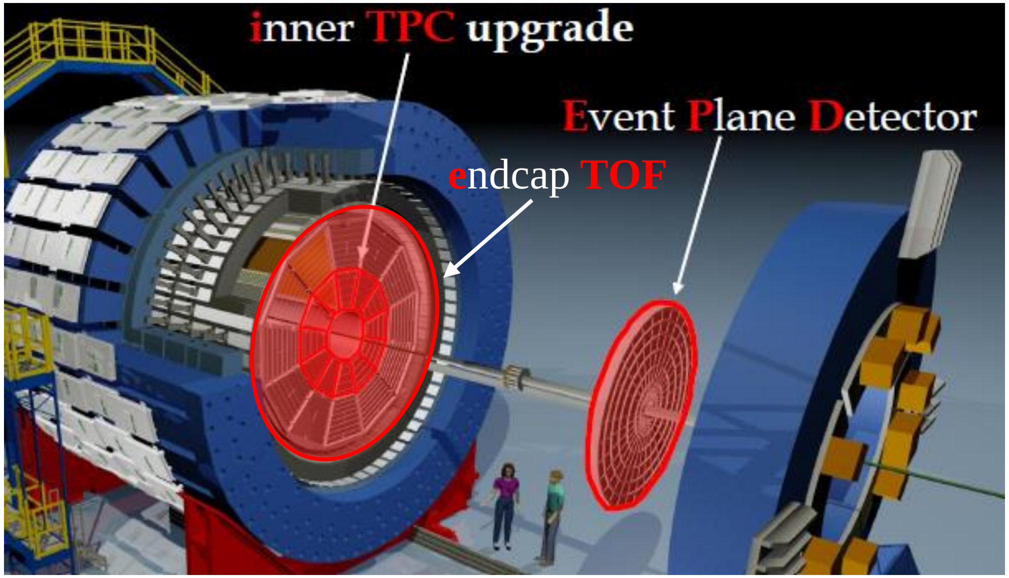


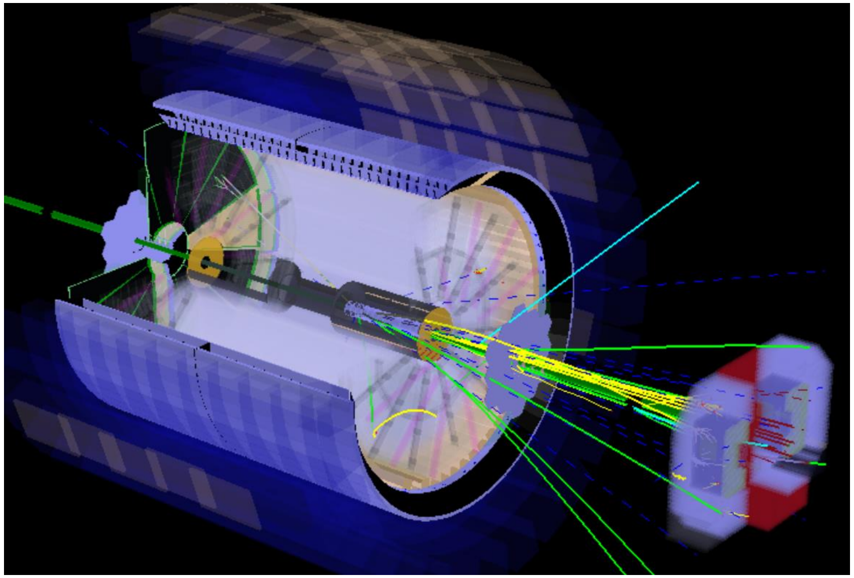


- Utilize existing RHIC infrastructure
- Complete measurements that are unique in $p + p$ and $p + A$
- Pursue measurements that will optimize the program at a future electron-ion collider

arxiv:1602.03922

RHIC after Beam Energy Scan II





The STAR Forward Calorimeter System and Forward Tracking System

- https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

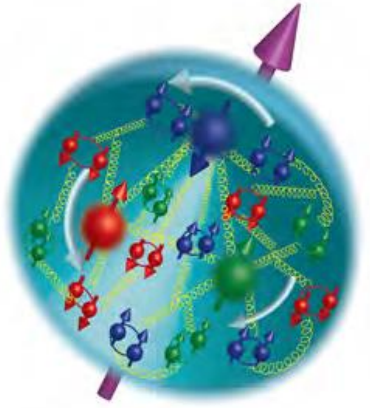
Highlights of the STAR midrapidity Physics Program after 2020

- https://drupal.star.bnl.gov/STAR/starnotes/public/sn0669

STAR

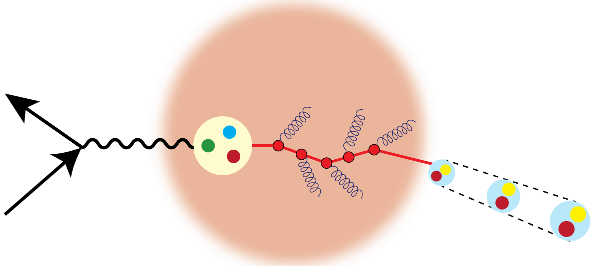
Detector upgrades for potential polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV

Open Questions in Cold QCD



1 Emerging Nucleons

How are gluons, sea quarks, and their intrinsic spins distributed in space and momentum in the nucleon?

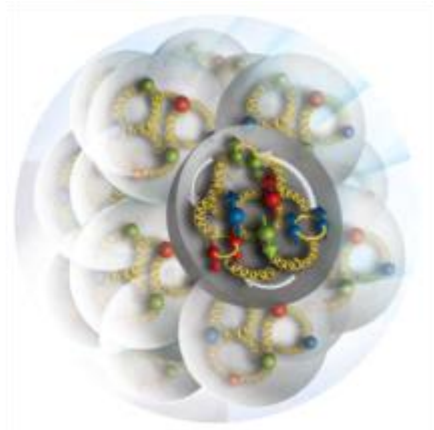


2 Nuclear Medium

How do colored quarks and gluons and colorless jets interact with the nuclear medium?

How does the nuclear environment affect quark and gluon distributions?

Are abundant low-momentum gluons confined within nucleons?

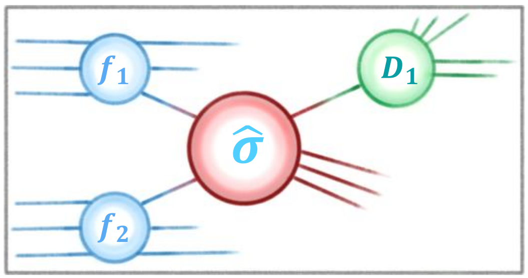


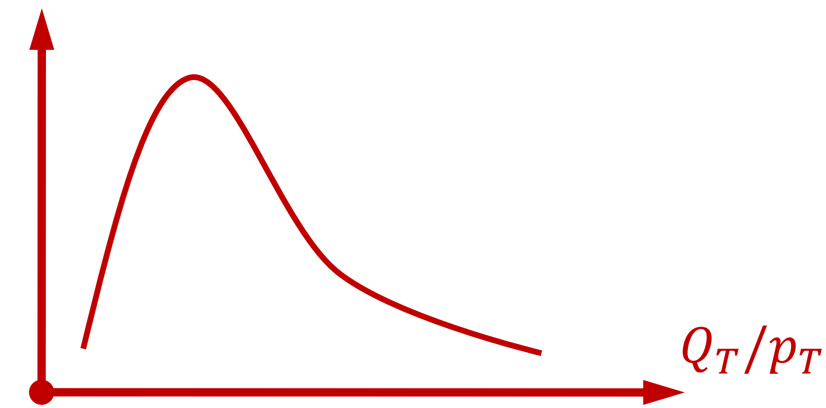
3 Gluon Saturation

What happens to the gluon density at high energy?

Are the properties of a saturated gluonic state universal among all nuclei?

Framework





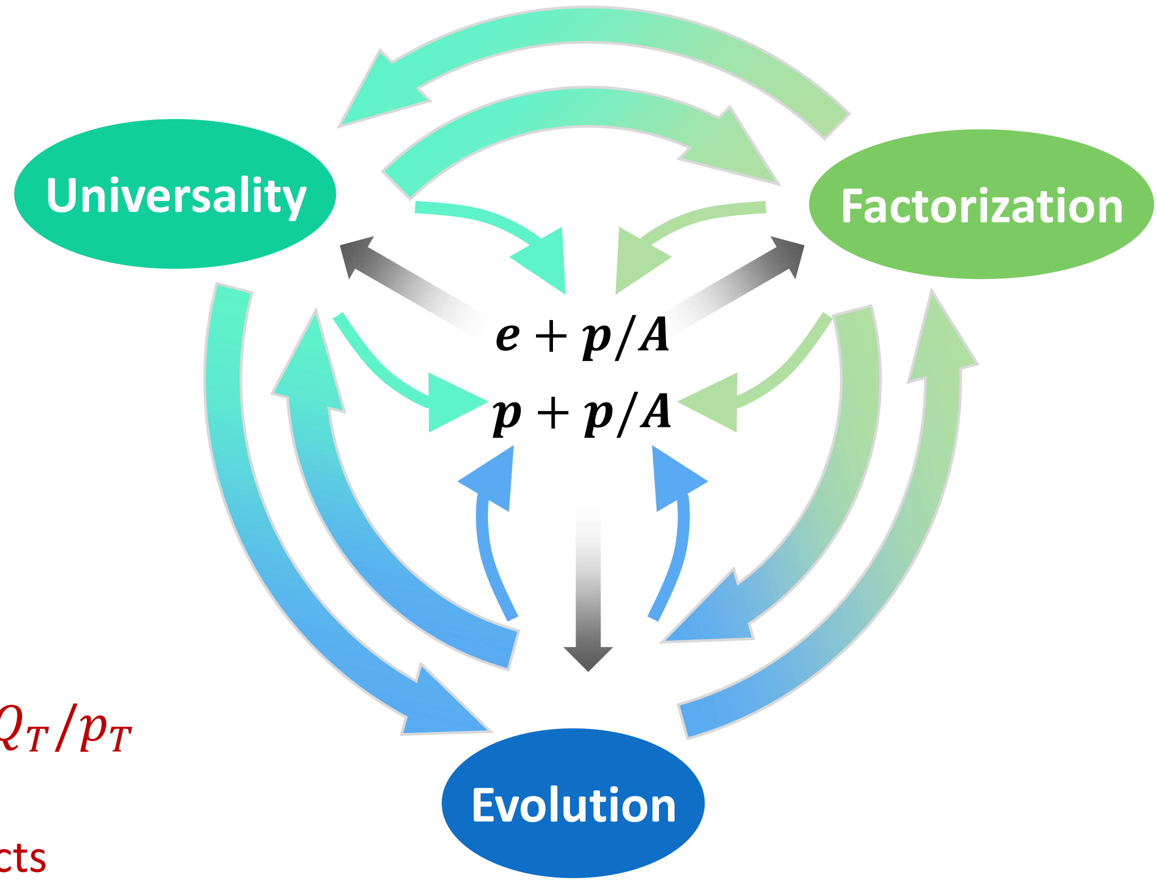
TMD Effects

$Q \gg Q_T \gtrsim \Lambda_{QCD}$

Twist-3 Effects

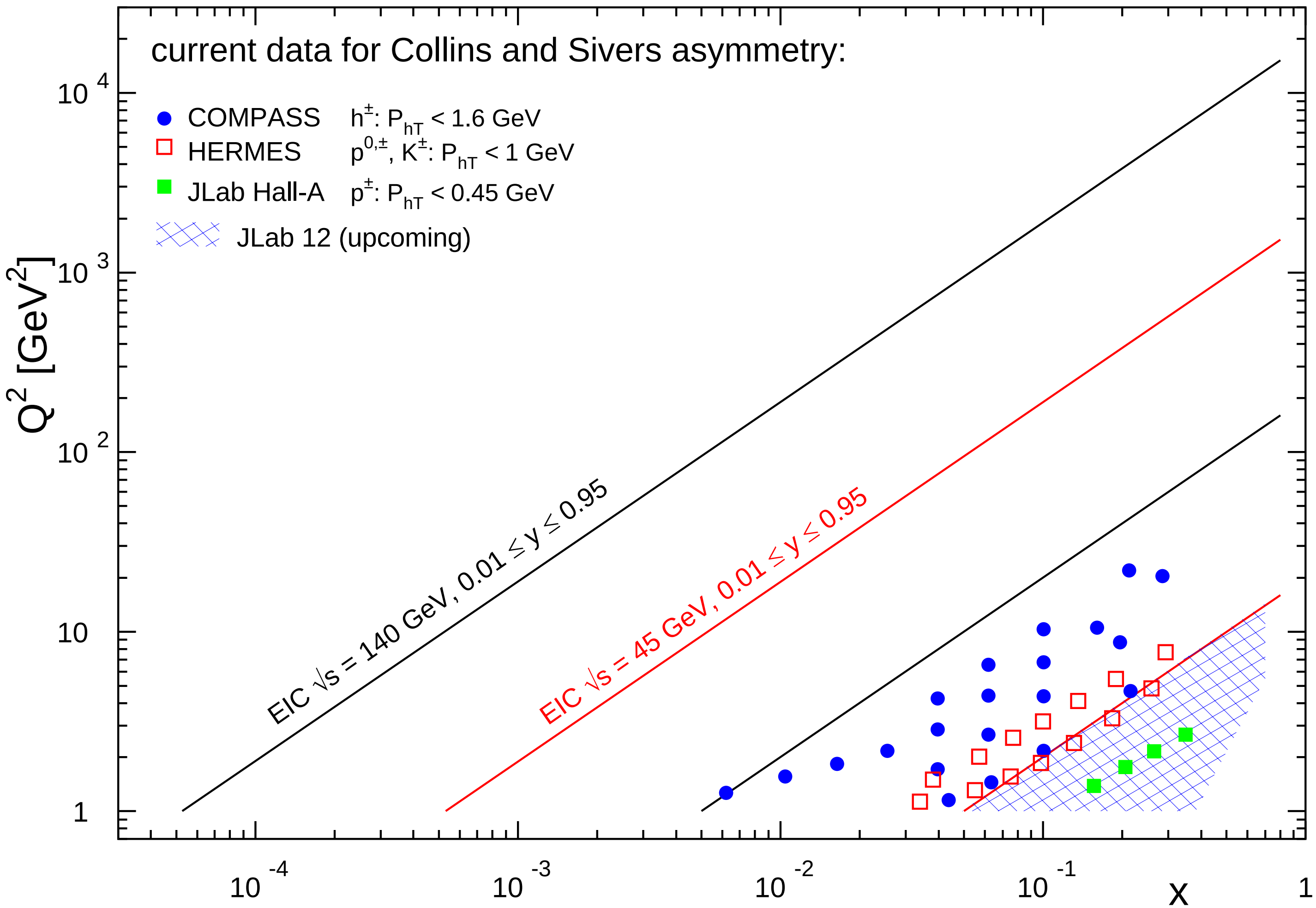
$Q, Q_T \gg \Lambda_{QCD}$

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x, k_\perp^2) = T_{q,F}(x,x)$$



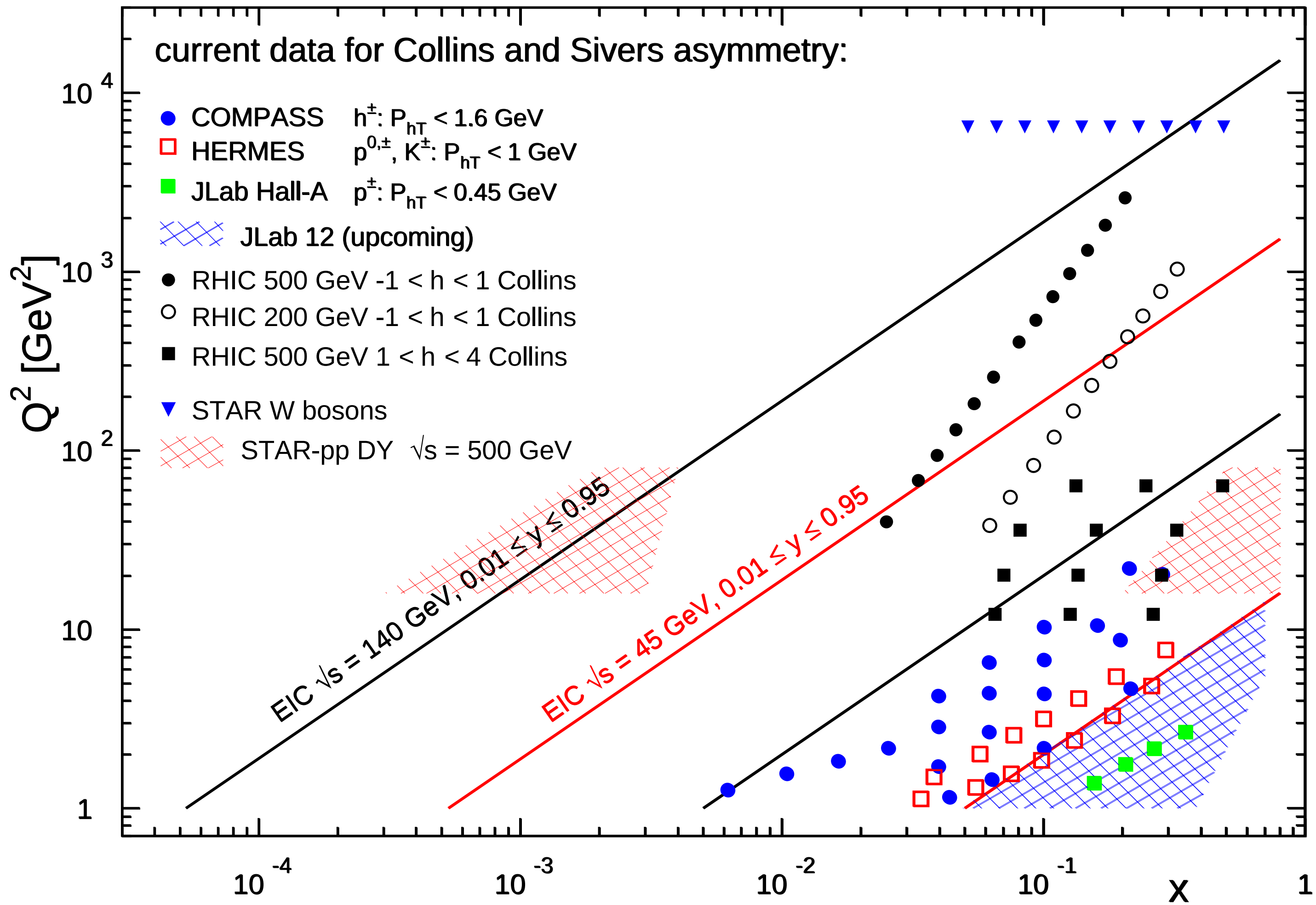
World Data: TMD Functions

Transversely polarized TMD functions: fixed target SIDIS



World Data: TMD Functions

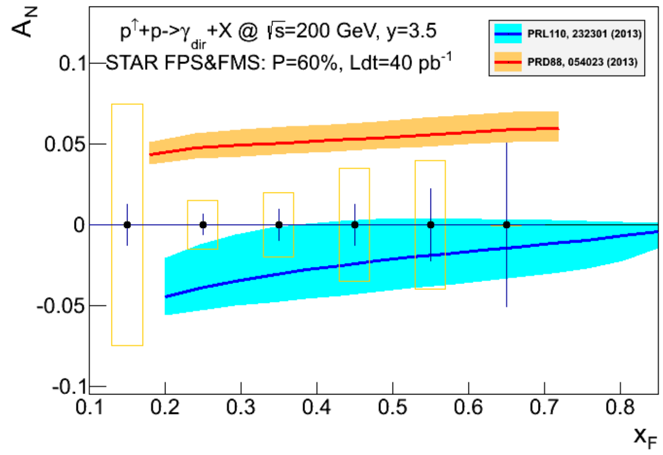
Transversely polarized TMD functions: fixed target SIDIS $\oplus$ $\vec{p} + p$ at RHIC

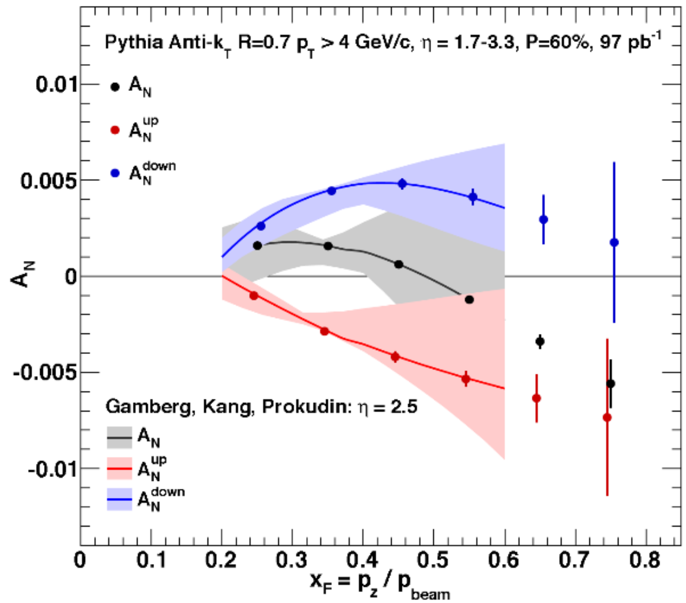


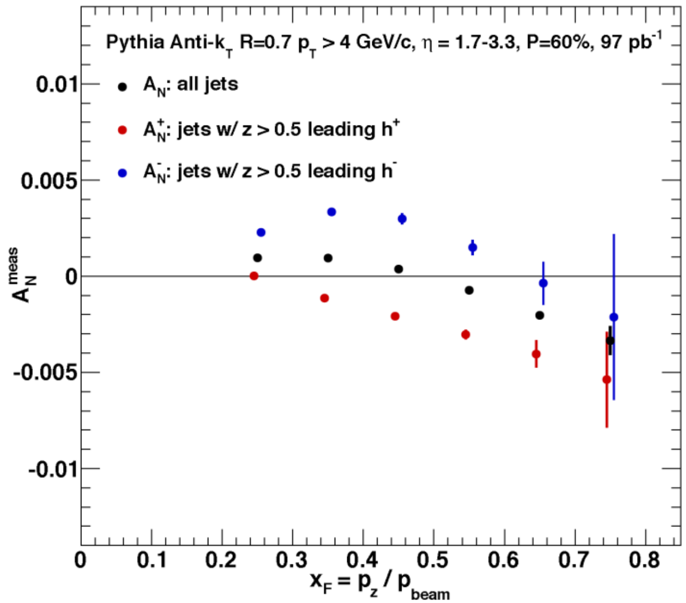
Spin Orbit Correlations

- Test origin of large transverse asymmetries
  - Cancellation of u & d quark Sivers in jets
  - Bias from high-z charged pion
  - Compare direct photons and jets

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x, k_\perp^2) = T_{q,F}(x, x)$$

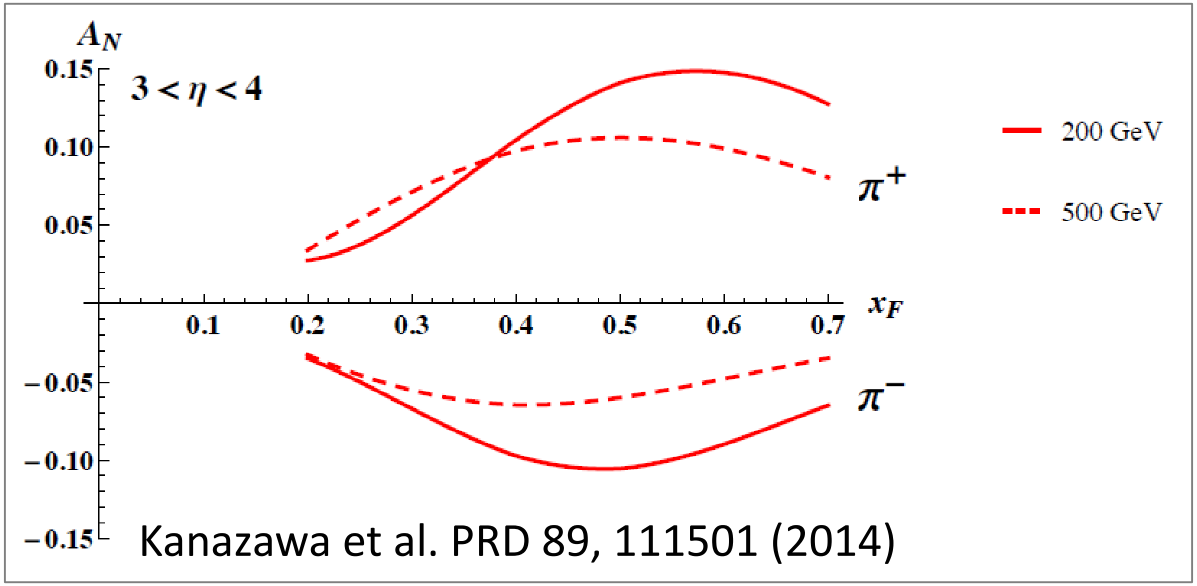






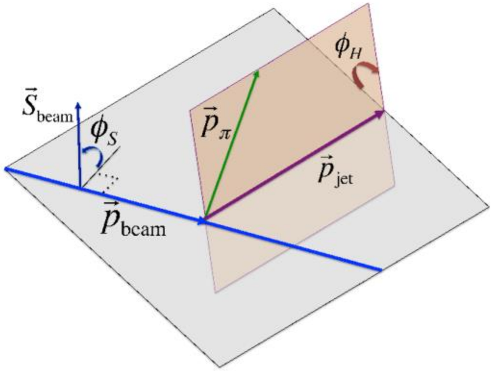
Spin Dependent Fragmentation

- Suggested large spin dependent effects in quark fragmentation
  - Collinear quark-gluon-quark correlations
  - $\widehat{H}_{FU}^{\Im}(z, z_z)$
  - Flavor dependence
  - Evolution effects of ETQS distribution functions

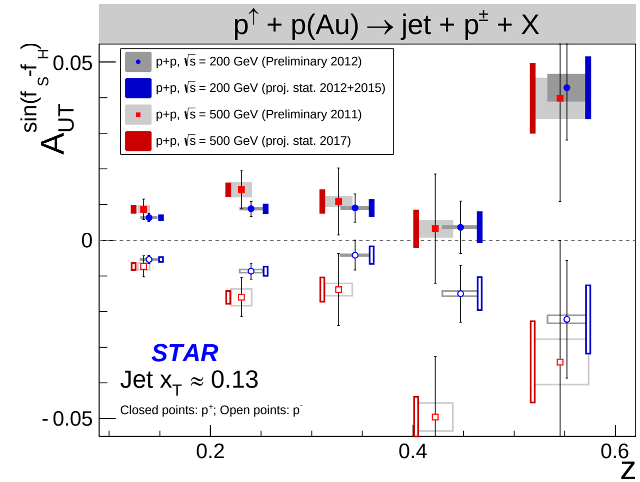


Spin Dependent Fragmentation

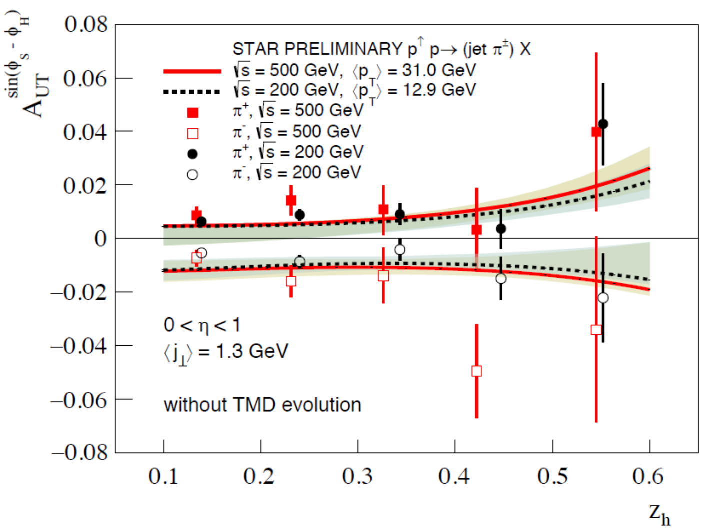
- Azimuthal hadron asymmetry in jet

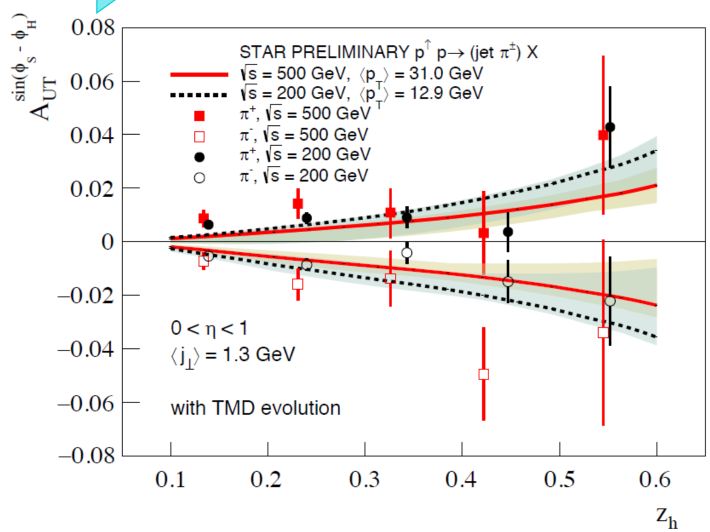


Projection / data on disk



TMD evolution





PRD 97, 032004 (2018)

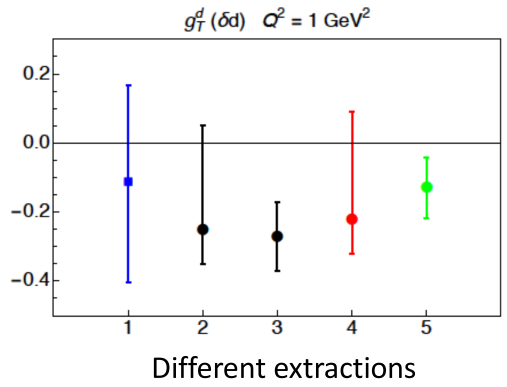
Comparison with
PLB 773, 300-306 (2017)
arXiv:1707.00913

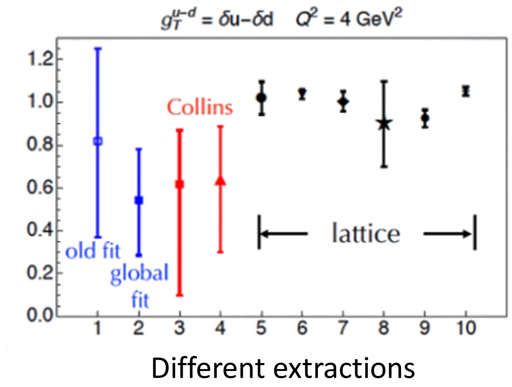
Transversity

- Tensor charge

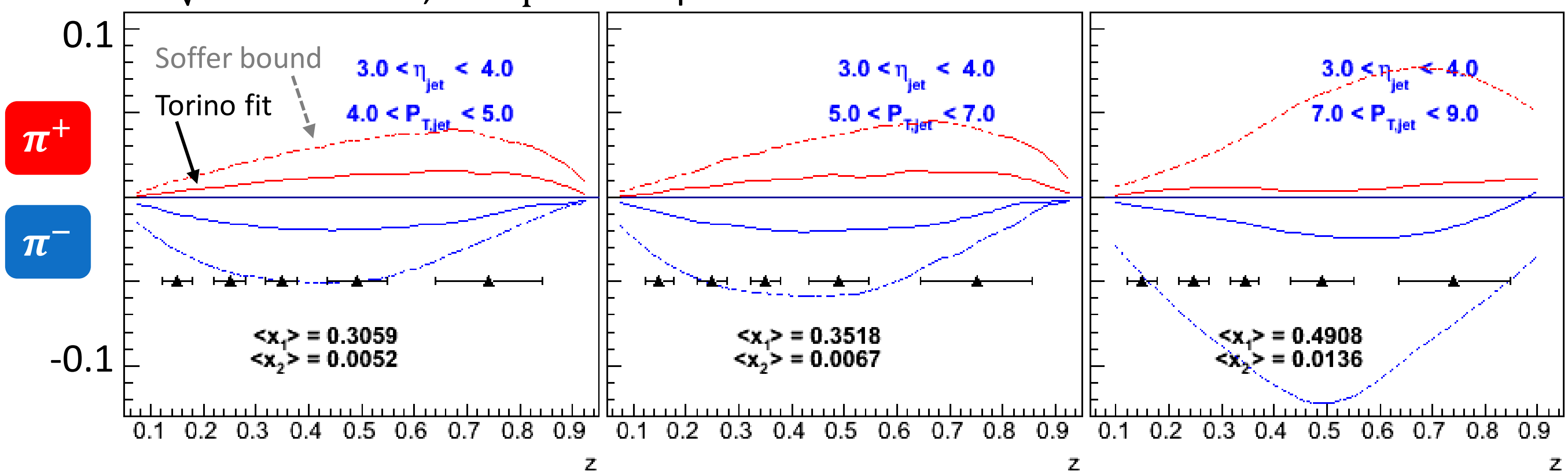
$$\delta q = \int_0^1 [\delta q(x) - \delta \bar{q}(x)]dx$$

- High x behavior is critical





$\sqrt{s} = 500$ GeV, 268 pb^{-1}sampled



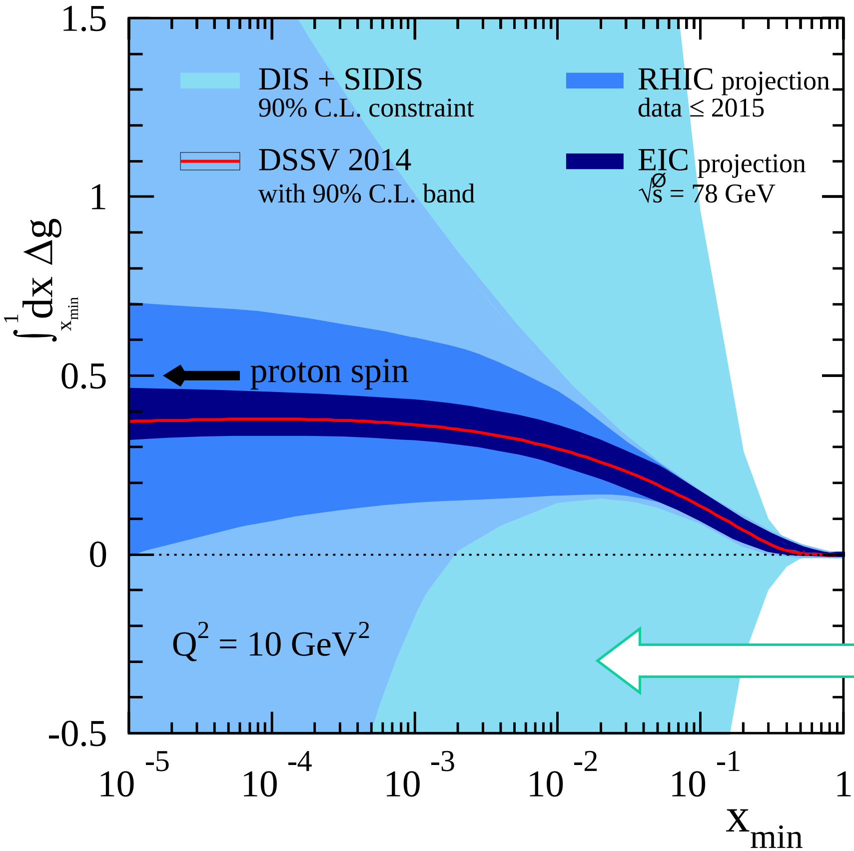
Torino: Phys. Rev. D87 (2013) 094019 Soffer bound&transversity: Phys. Rev. Lett. 74 (1995) 1292

Gluon Polarization

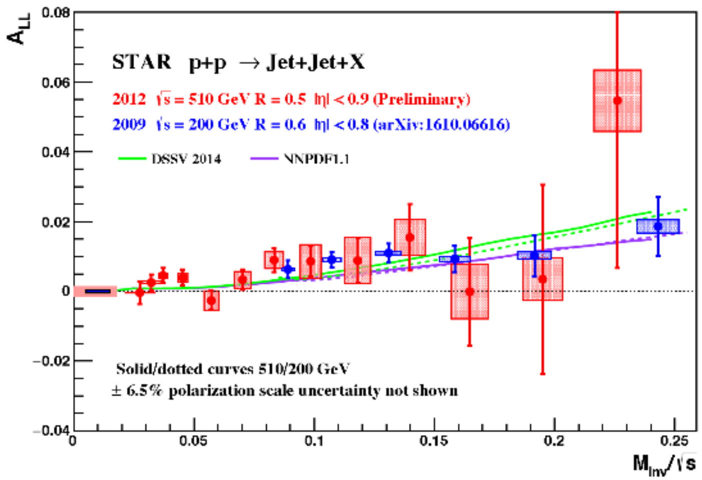
$$\frac{1}{2}\hbar = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$

$$\int_{0.05}^{1} \Delta g(x, Q^2)dx = 0.2^{+0.06}_{-0.07}$$

Phys. Rev. Lett. 113, 012001 (2014)



Phys. Rev D**95** 71103 (2017)



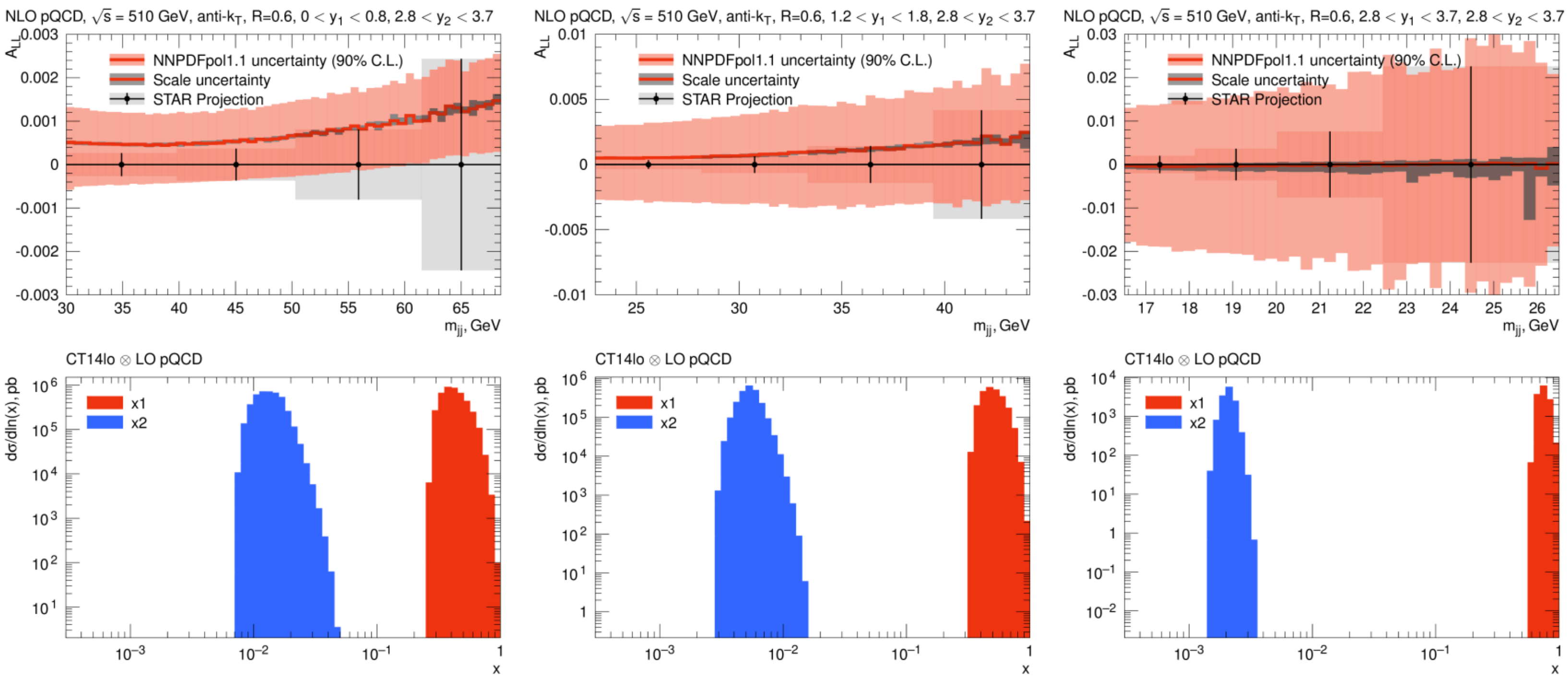
Helicity Asymmetry of Dijets

$\sqrt{s} = 510$ GeV $E_{T3} > 5$ GeV

anti-k_T, $R = 0.6$ $E_{T4} > 8$ GeV

$\sqrt{x_1} \cdot \sqrt{x_2} = m_{jj}/\sqrt{s}$

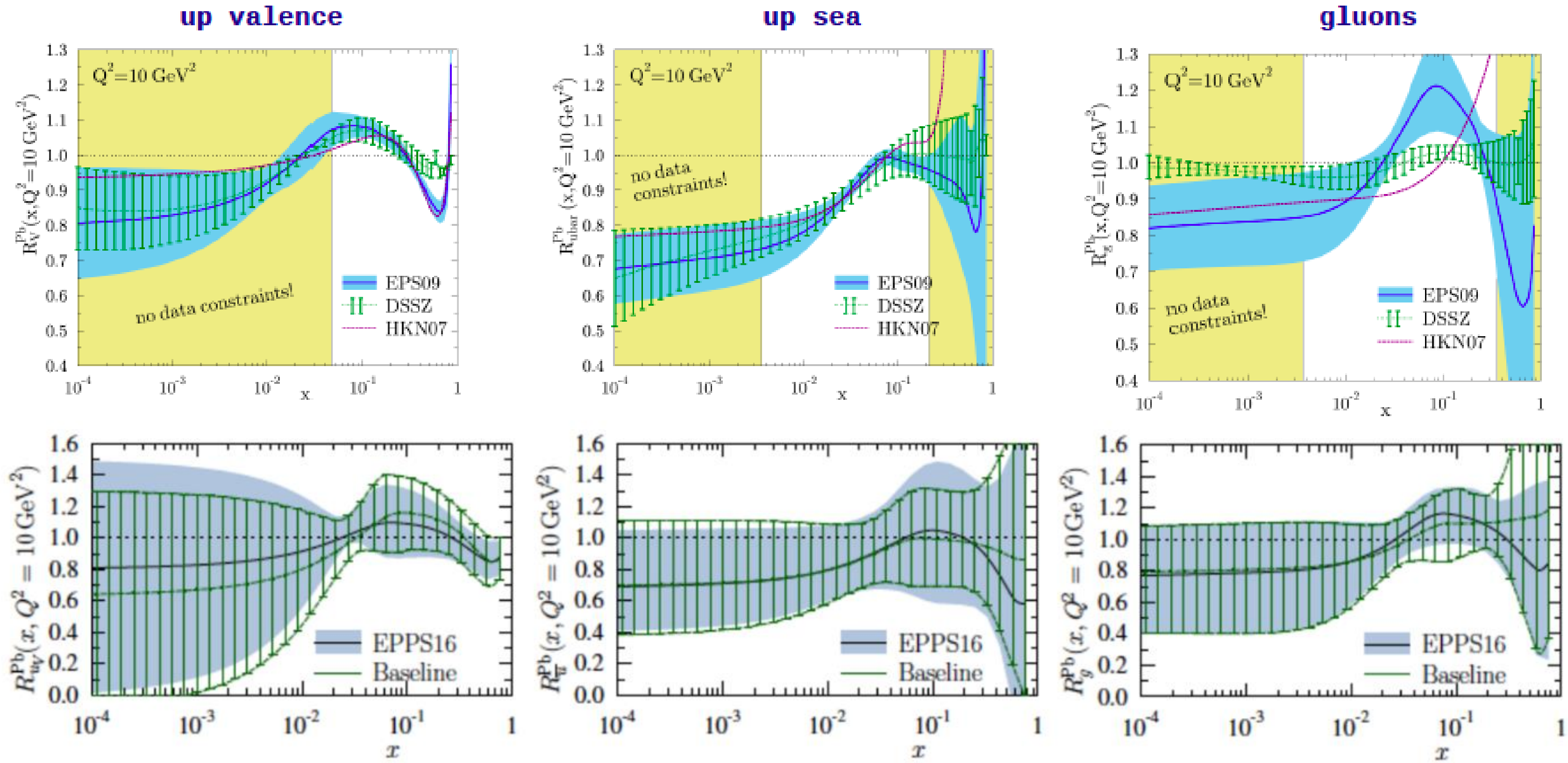
$0.0 < y_1 < 0.8$, $2.8 < y_2 < 3.7$ → $1.2 < y_1 < 1.8$, $2.8 < y_2 < 3.7$ → $2.8 < y_1 < 3.7$, $2.8 < y_2 < 3.7$



Nuclear Parton Distributions

- Initial conditions for heavy ion collisions (here Pb)
  - Largely unconstrained
  - LHC Run I $p + Pb$ data at very high Q^2

H. Paukkunen, DIS (2014)
K.J. Eskola et al. EPJ C77, 163 (2017)



Nuclear Modification: $R_{pA}(\gamma_{dir})$

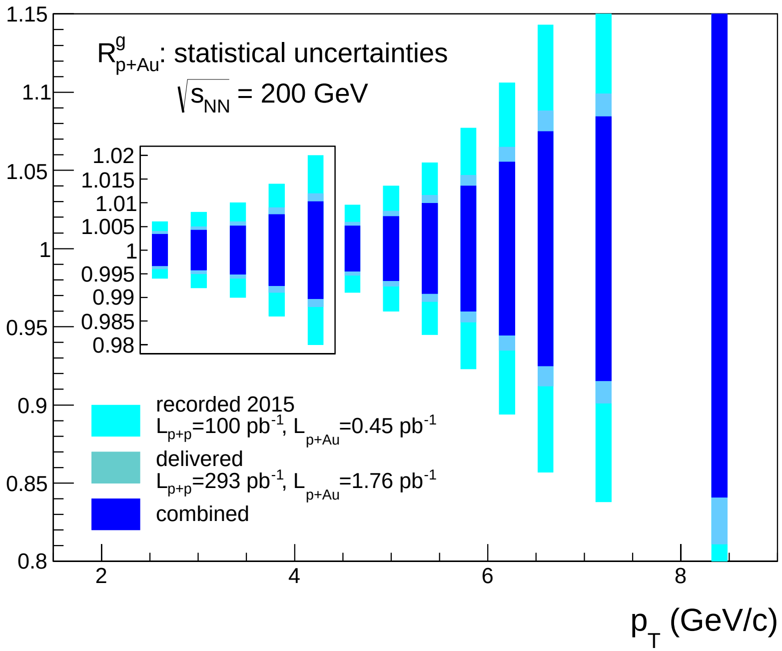
Direct photons

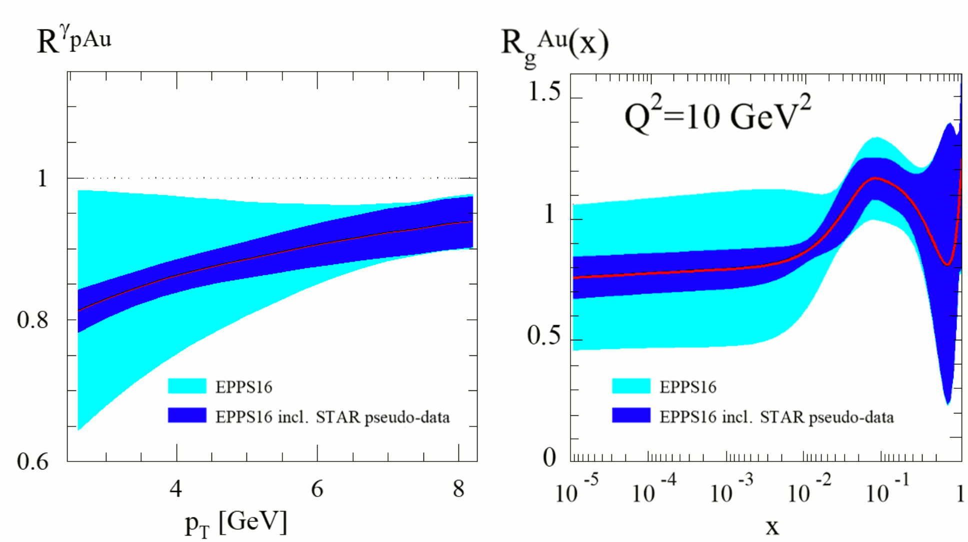
- $2.5 < \eta_\gamma < 4.0$
- Moderate Q^2
- Medium to low x

$$R_{pA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{pA}}{dN^{pp}}$$

RHIC 2015

- $\sqrt{s_{NN}} = 200$ GeV
- $p + Al$: $L_{\text{int}} = 1.0\ \text{pb}^{-1}$
- $p + Au$: $L_{\text{int}} = 0.45\ \text{pb}^{-1}$

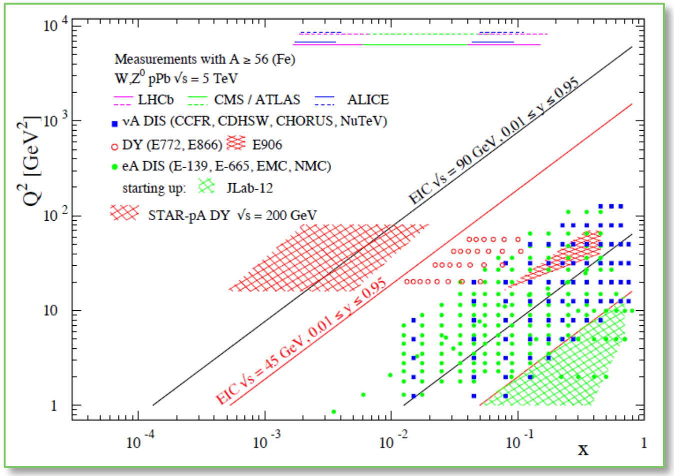




Nuclear Modification: $R_{pA}(\gamma^*_{DY})$

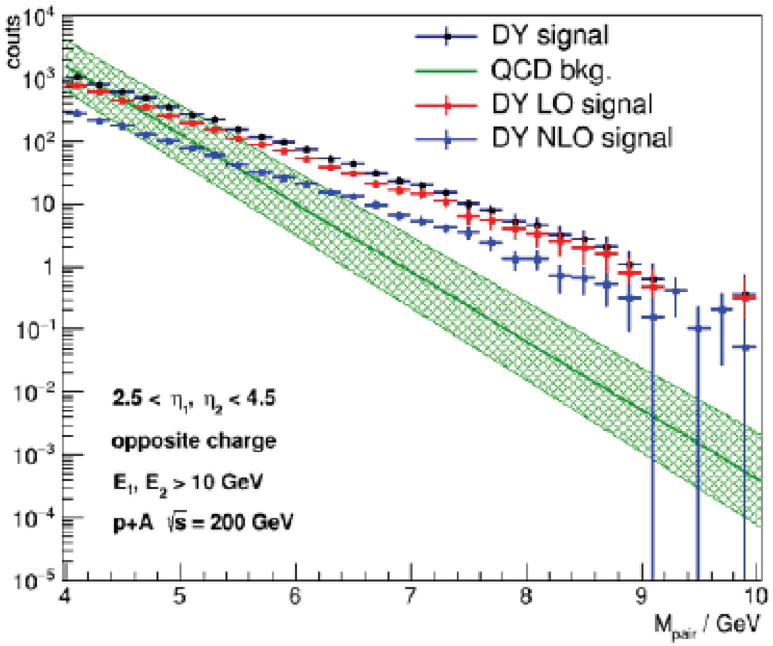
Drell-Yan production

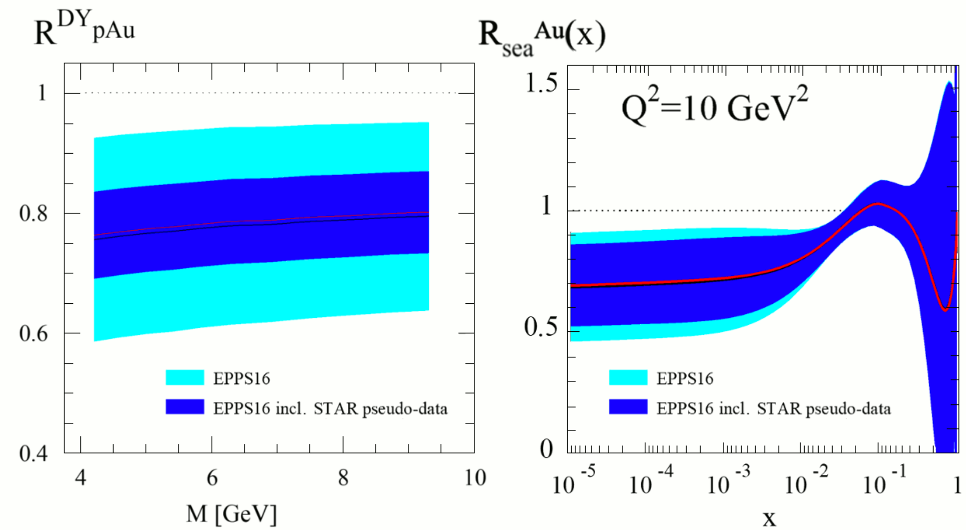
- $2.5 < \eta_{e^\pm} < 4.5$
- Moderate-high $Q^2 = M^2_{\gamma^*}$
- Medium x



RHIC 2017

- $p + p$ @510 GeV
- $L_{\text{int}} \approx 250\ \text{pb}^{-1}$

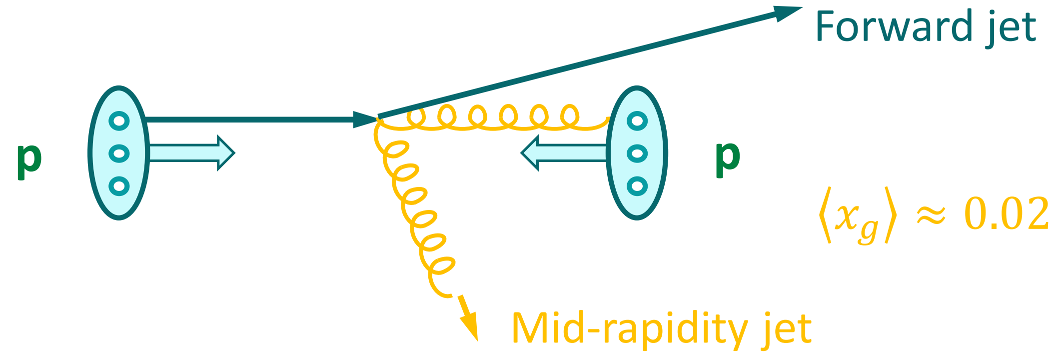




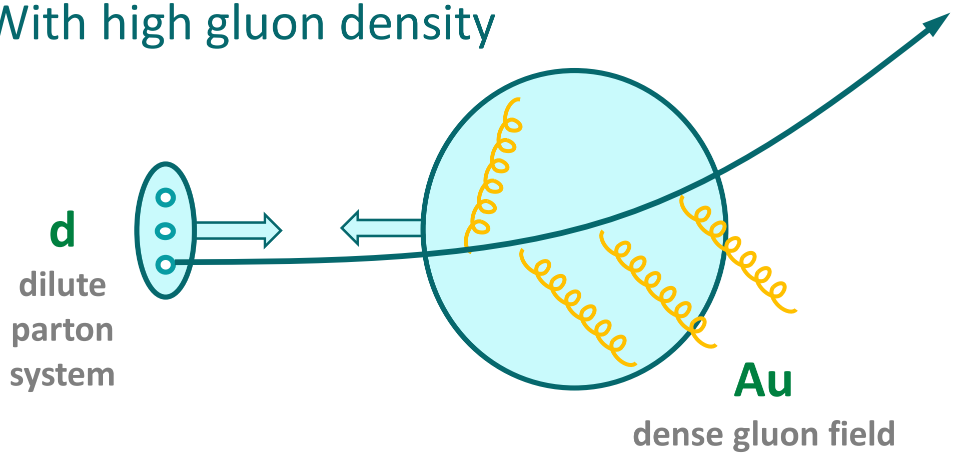
Back-to-back Correlations

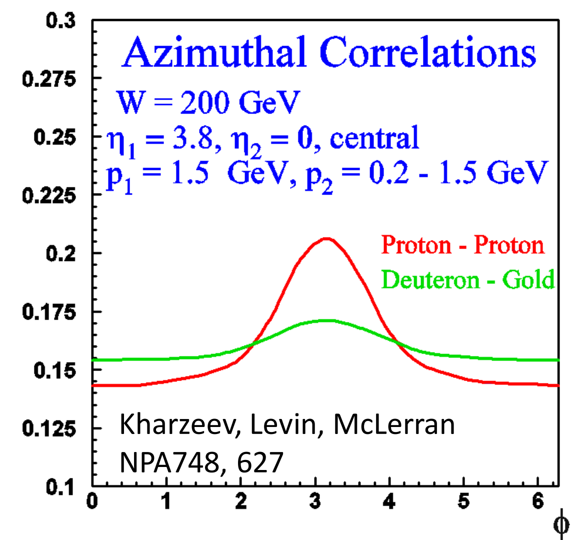
In $p + p$:

- pQCD $2 \rightarrow 2$ process
- Back-to-back dijet



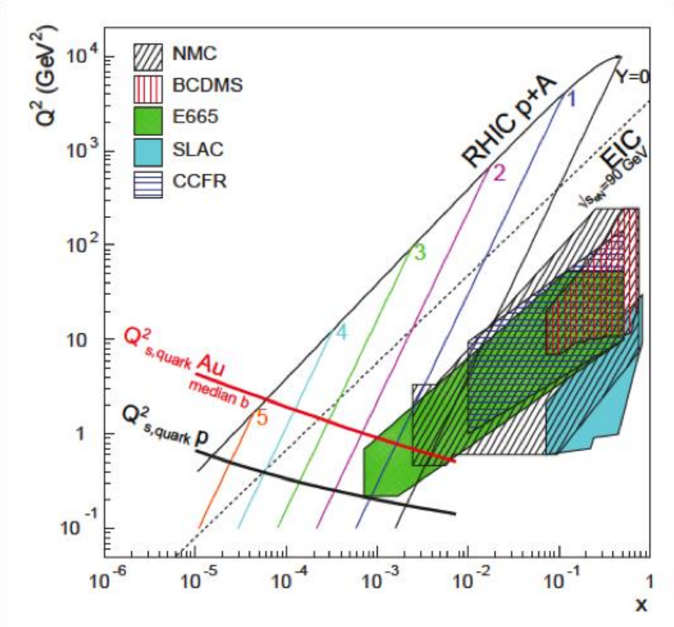
- With high gluon density





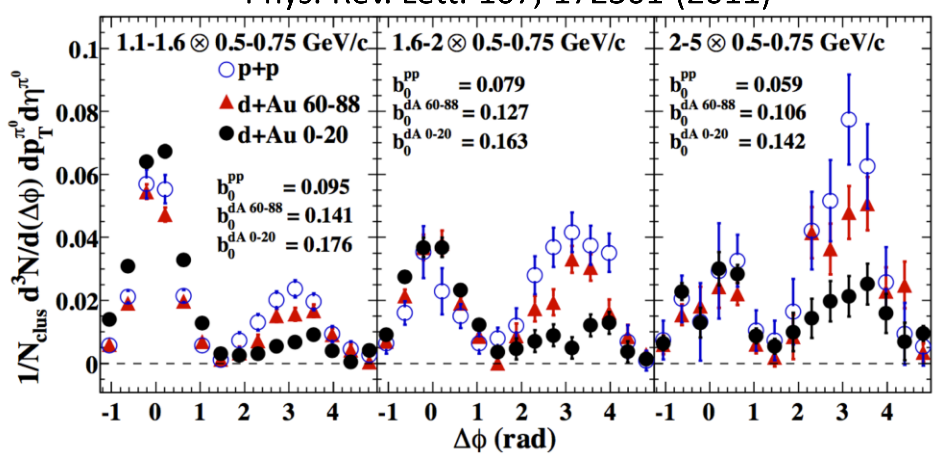
- Monojet: p_T is balanced by many gluons
- Color Glass Condensate predicts suppression of back-to-back correlation
- Forward kinematics: $x_g \approx 10^{-3} \sim 10^{-4}$ ($p + A \rightarrow \pi^0 + \pi^0$ in FMS)

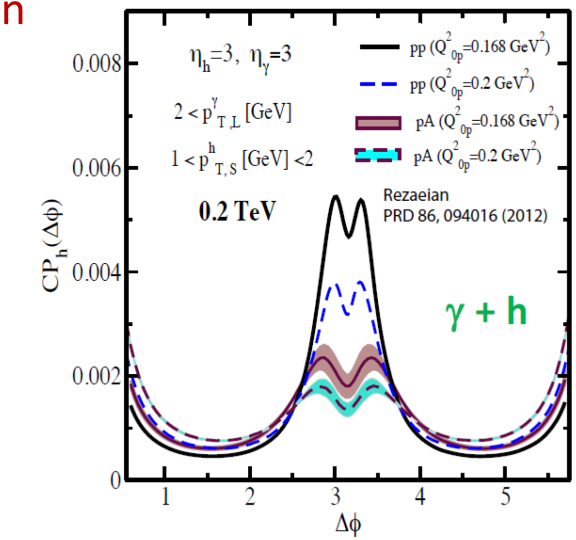
Gluon Saturation



- Saturation scale $Q_s^2(x)$
- Scan kinematic range: x & Q^2
  - Trigger p_T
  - Associated p_T
- Test A-dependence
- Other probes (forward)
  - γ-hadron correlation
  - γ –jet correlation

Phys. Rev. Lett. 107, 172301 (2011)



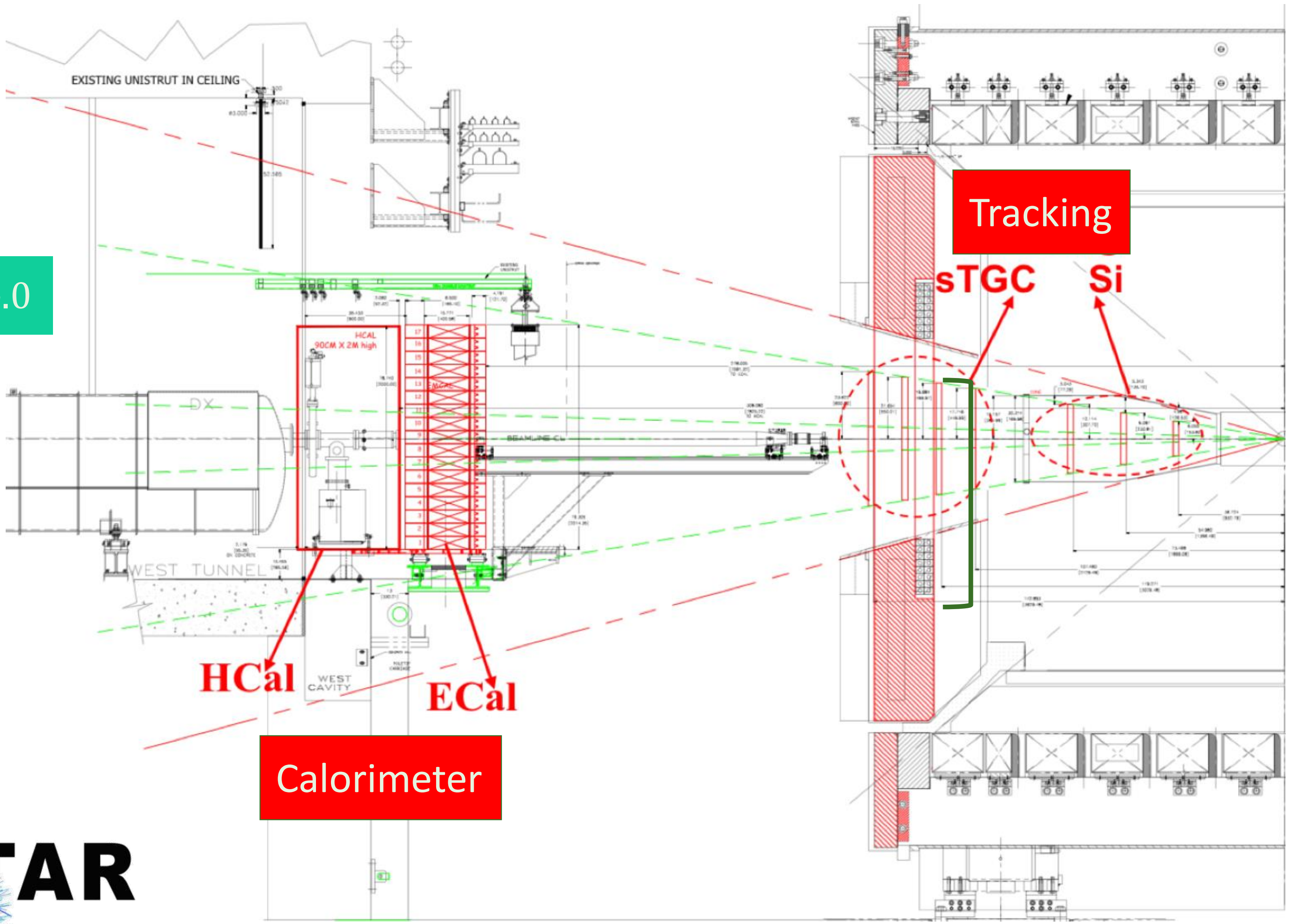


Summary of Observables

Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
2021	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
2021	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Forward instrum. ECal+HCal
2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
2023	$p^{\uparrow}$Au @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+Hcal+Tracking
2023	$p^{\uparrow}$Al @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking

Forward Detector Upgrade

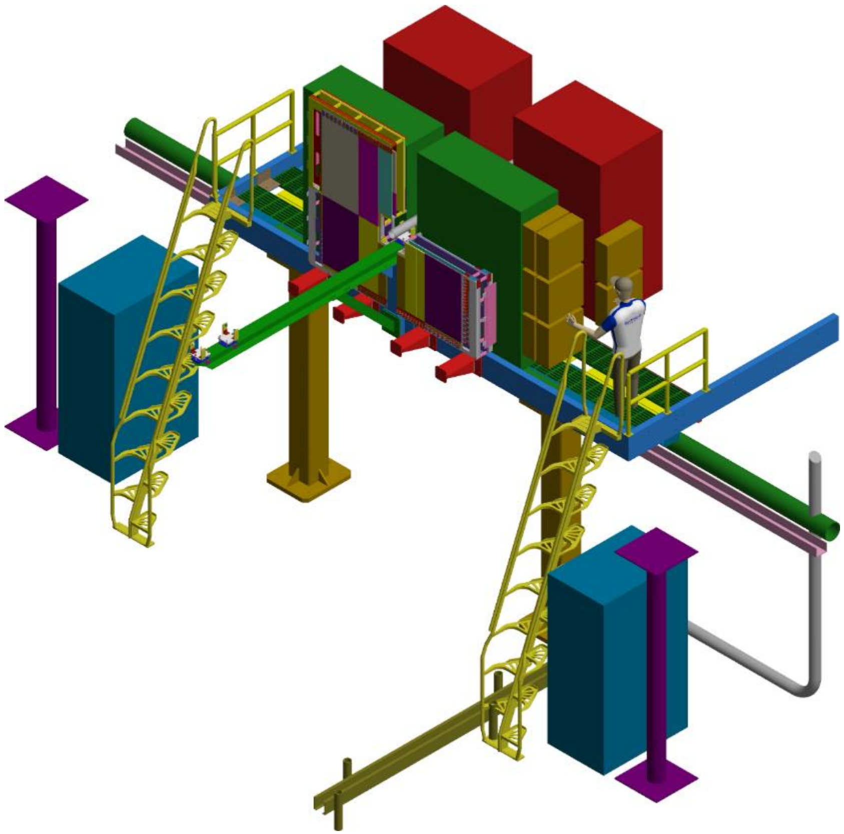
$2.5 < \eta < 4.0$



STAR

Forward Calorimeter System

	p+p / p+A	A+A
ECAL	$\approx 10\%/\sqrt{E}$	$\approx 20\%/\sqrt{E}$
HCAL	$\approx 60\%/\sqrt{E}$	n/a



Preshower detector

EM calorimeter

- PHENIX PbSc
- New readout SiPM/APD
- Not compensating

Hadronic calorimeter

- $L = 4 \cdot \lambda_I$
- Sampling iron-scintillator
- Same readout

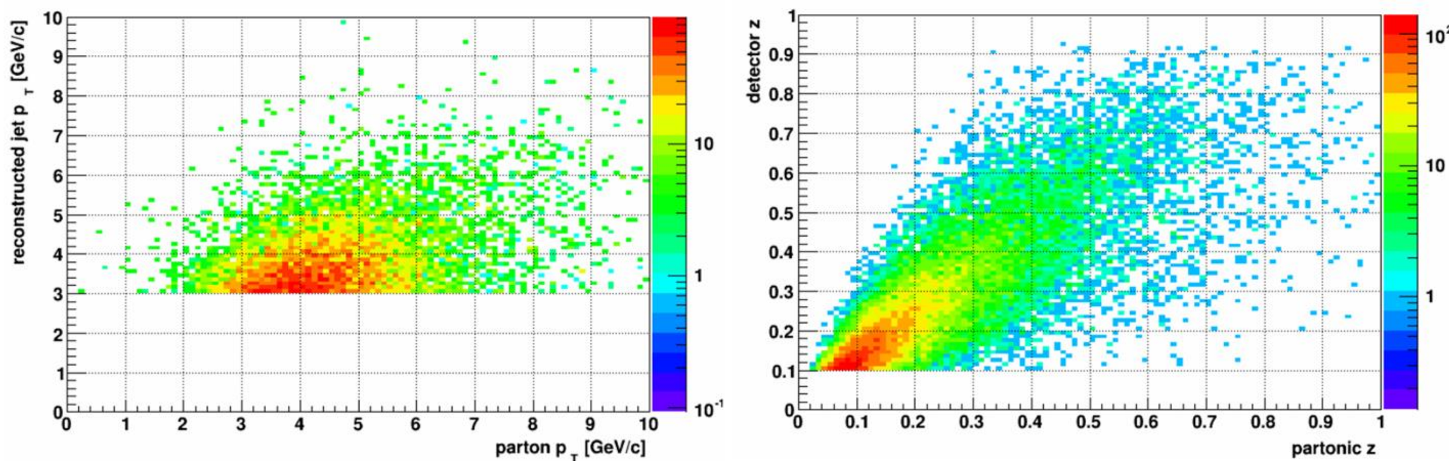
Calorimeter R&D as part of EIC studies, beam test, and in situ setup at STAR

Balance of cost and performance

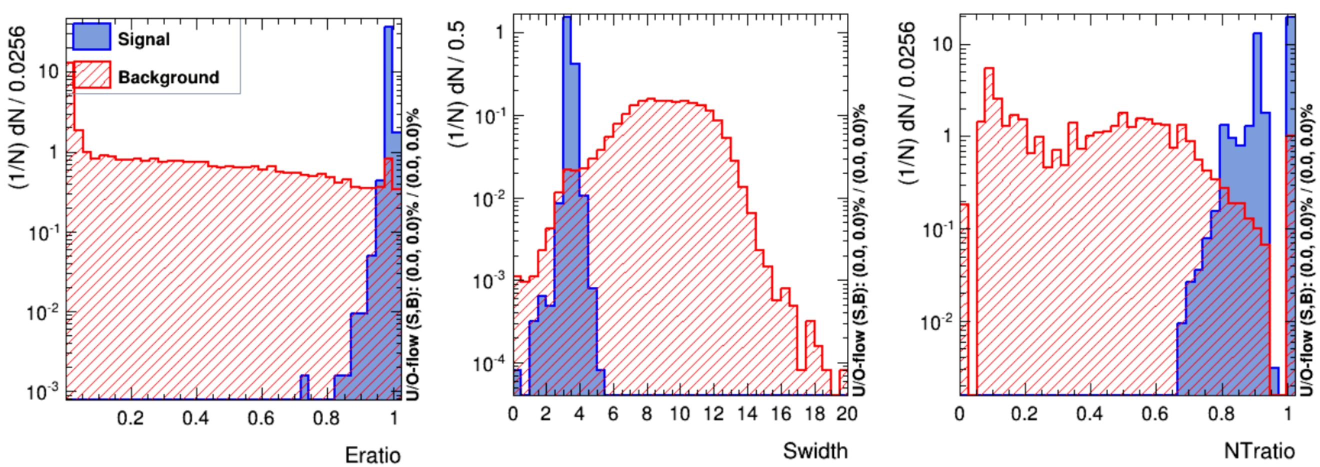
Cost ≈ $ 2.0 M

Physics Performance

Matching jet reconstruction and partonic kinematics (3<η<4)

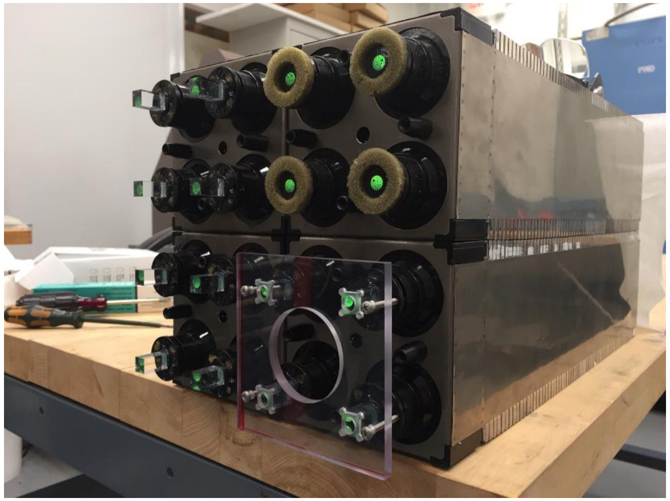


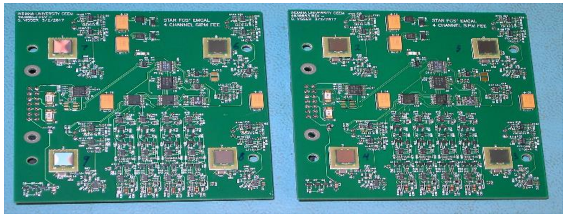
Drell-Yan identification (boosted decision trees)



FCS – Research & Development

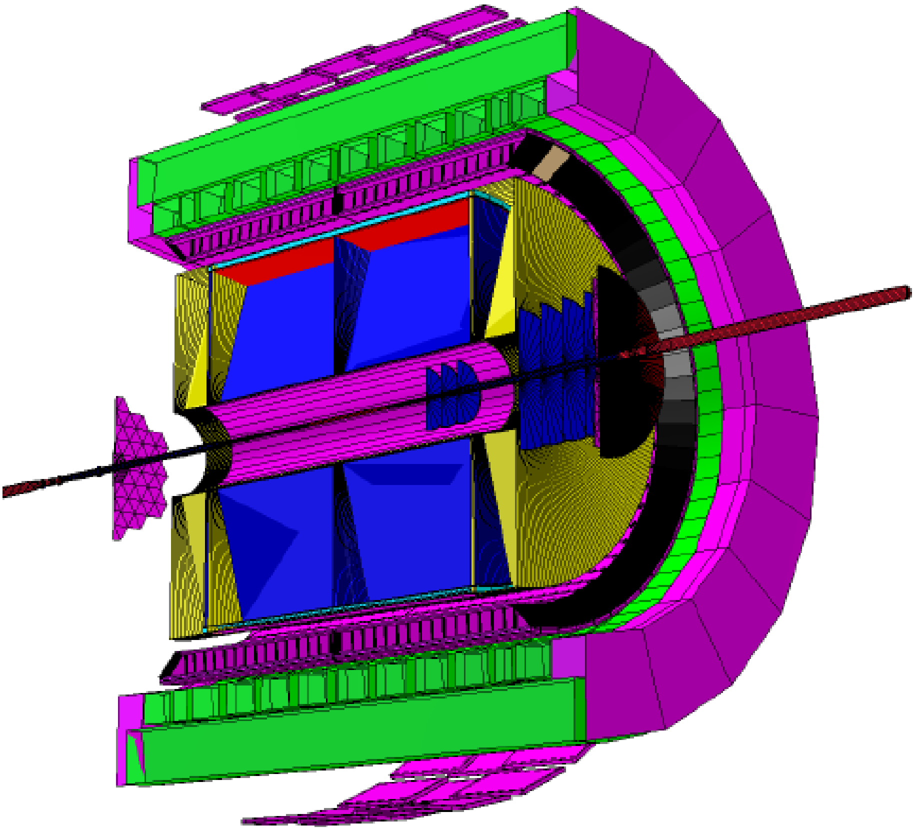
- Efforts for ECAL and HCAL as part of EIC R&D
- ECAL test in 2017
  - Hamamatsu SiPM $6 \times 6\ \mathrm{mm}^2$
  - FEE boards and digitizers
  - Integrated into STAR (DAQ, trigger)
- FCS test in 2018
  - Large scale ECAL prototype with HCAL towers





Forward Tracking System

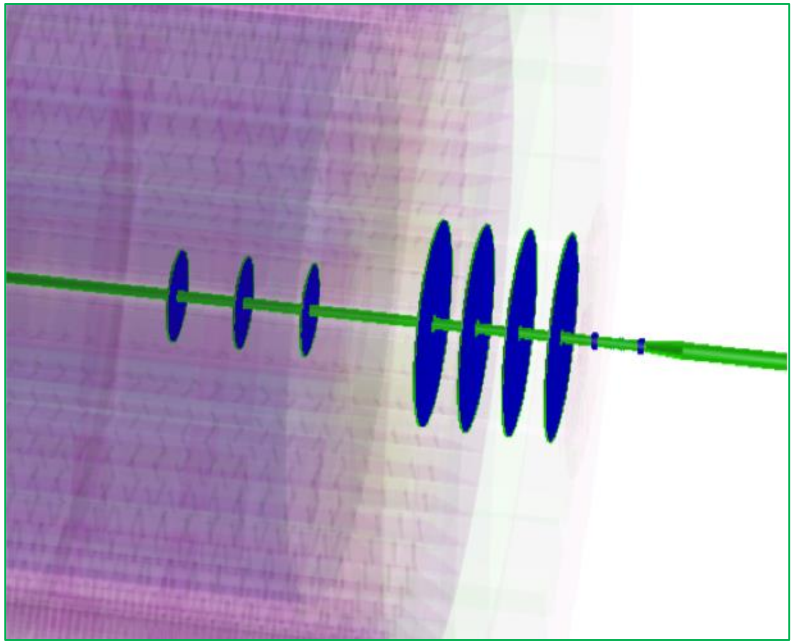
	p+p / p+A	A+A
Tracking	charge separation photon suppression	$\frac{\delta p}{p} \approx 20 - 30\%$ at $0.2 < p_T < 2.0$ GeV/c



- 3 layers of silicon mini-strip disk
  - $\mathrm{z} = 90, 140, 187$ cm
  - Builds on experience of STAR IST (Intermediate Silicon Tracker)
- 4 layers of small-strip Thin Gap Chambers
  - $z = 270, 300, 330, 360$ cm
  - Use of STAR TPC electronics for readout
  - Significant reduction of the project cost

Cost ≈ $ 3.3 M, mostly from Chinese consortium (with UIC and BNL)

FCS – Efficiencies & Resolution



Full detector simulation

$\delta p_T / p_T \approx 25 - 50\%$

$3^o < \theta < 8^o$

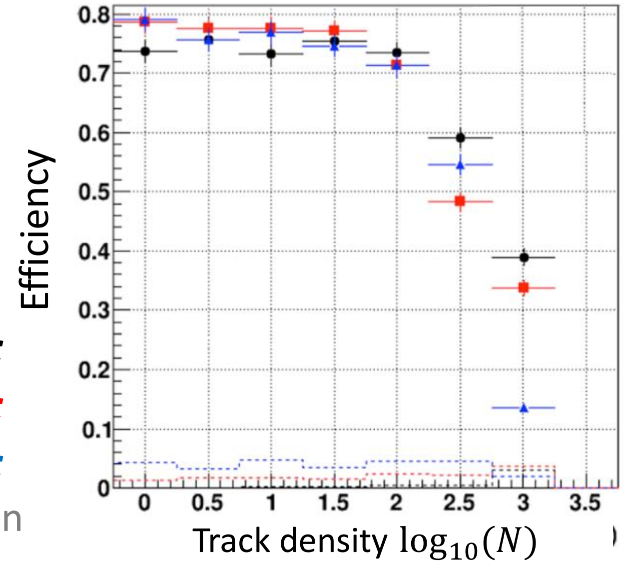
Pions

$p_T = 0.2$ GeV/c

$p_T = 1.0$ GeV/c

$p_T = 2.0$ GeV/c

dashed: wrong sign

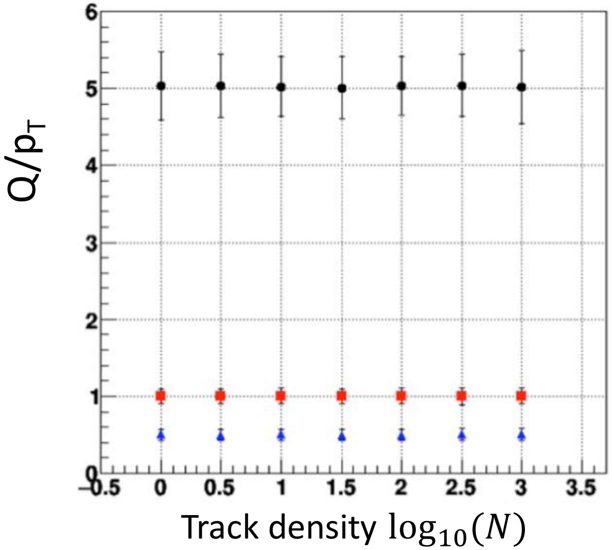


Muons

$p_T = 0.2$ GeV/c

$p_T = 1.0$ GeV/c

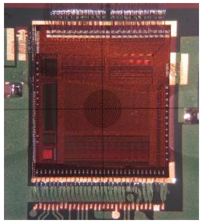
$p_T = 2.0$ GeV/c



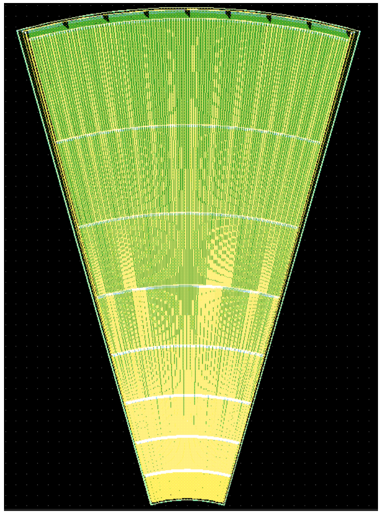
FCS – Research & Development

3 Silicon disks:

- 12 wedges, each with 128 azimuthal & 8 radial strips
- Single-sided double-metal Silicon Mini-strip sensors
  - under development @UIC
- Several different frontend chips, APV25-S1 chip (IST)
  - DAQ system for FTS same as IST
  - Replicating the IST cooling system

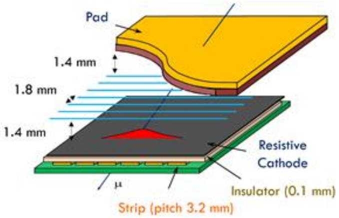


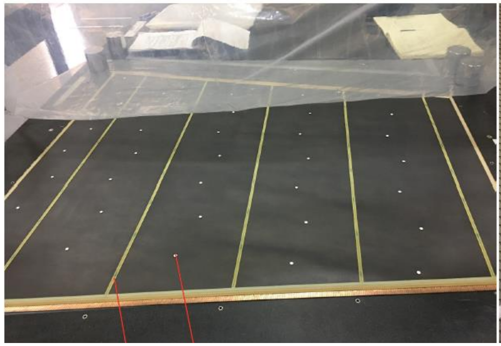
APC25-S1



4 sTGC disks:

- Based on ATLAS R&D from SDU
  - $\approx 0.5\% \, X_0$ per layer
  - Position resolution ~ 100 µm in x & y direction
- Read out with existing TPC electronics
- Prototype in preparation SDU in 2018
  - ¼ length of ATLAS module
  - 30 cm x 30 cm module with 2 layers

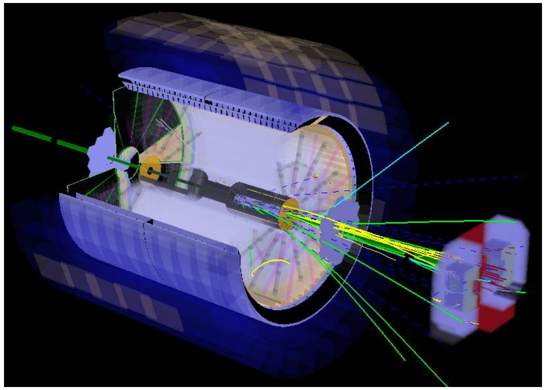




Summary / Outlook

- The STAR collaboration has proposed a forward detector upgrade that combines tracking and calorimetry at $2.5 < \eta < 4$.
- From the recommendations of the Program Advisory Committee (2018)

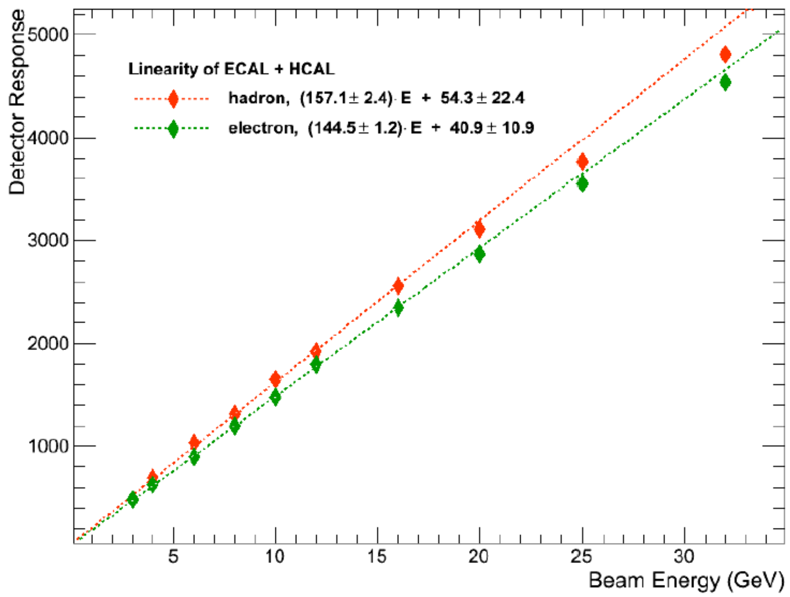
STAR presented a rich program for future operation after BES II that addresses many important and innovative topics in p+p, p+A and A+A physics. The most interesting of these is focused on forward physics that would be made possible by a forward upgrade covering rapidities up to 4.2 with $5.3 M further investment, and would enable studies of novel reaction channels including several specific diffractive reactions and ultra-peripheral collisions of interest to hadron structure and QGP physics alike. Hadron structure measurements, such as diffractive dijet production, are highly relevant for the physics to be investigated at EIC, both for their e+p and e+A components, and may help to further sharpen the EIC physics case.

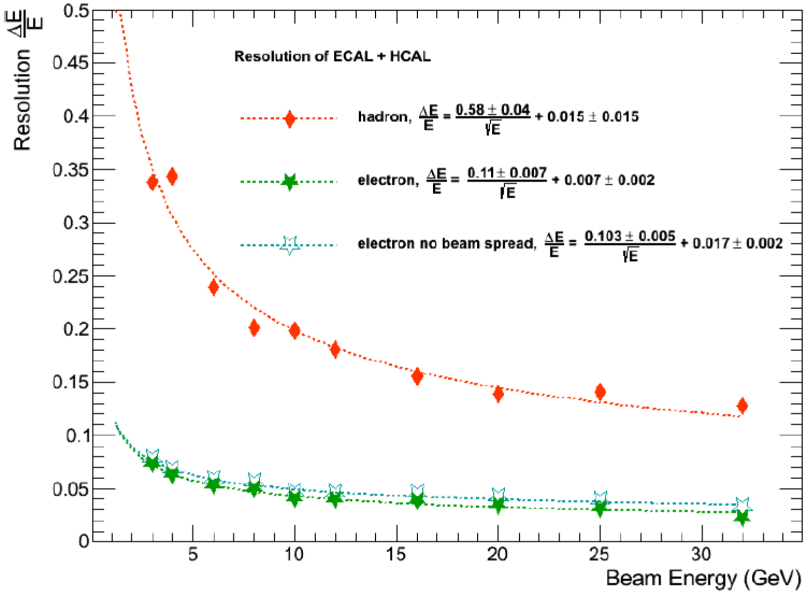


- Further tests are planned during 2019 RHIC operations for a full installation and readiness after the beam energy scan (phase II).

BACK UP

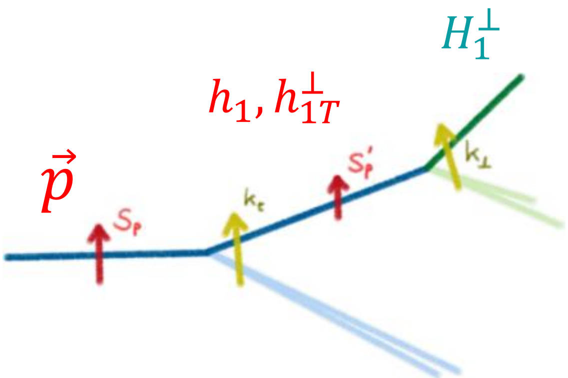
Calorimeter Resolution



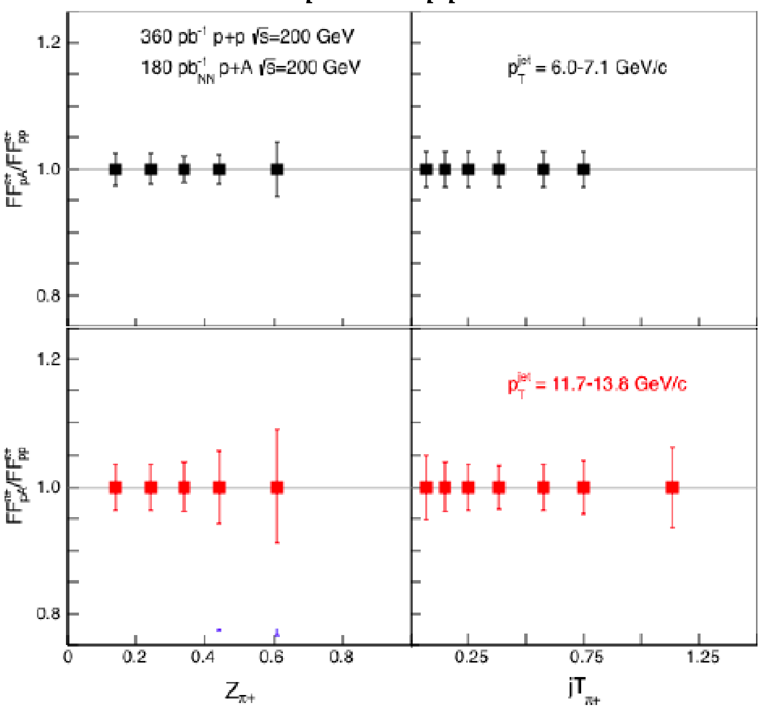


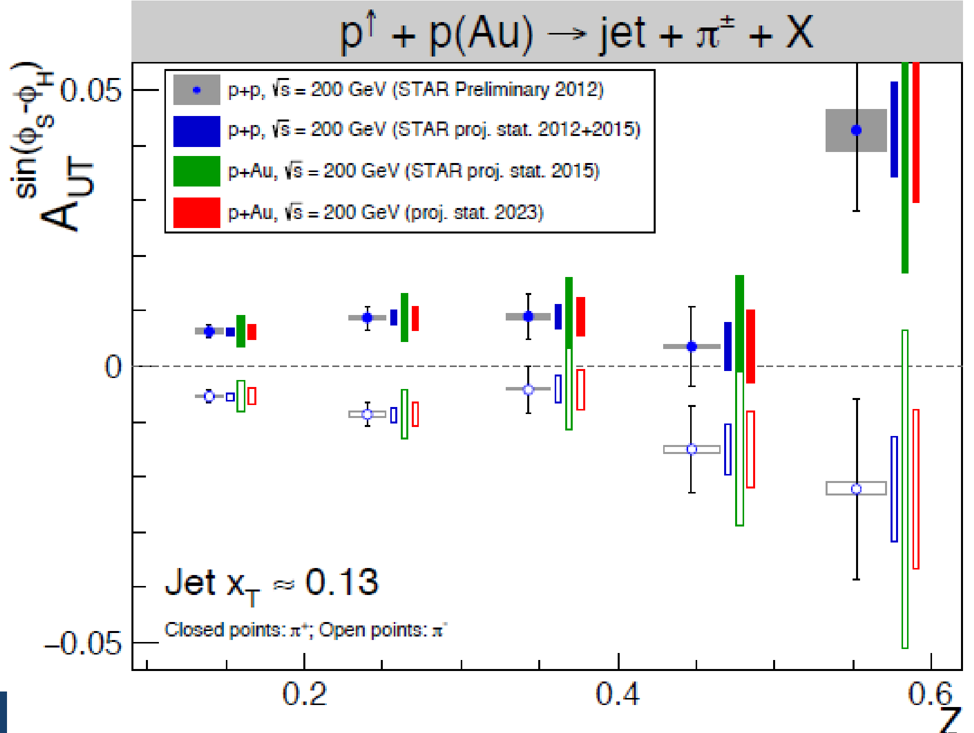
Nuclear Fragmentation Functions

- Identified hadron in jet ($|\eta| < 1$)
  - Transverse momentum dependent
- Test universality
  - $e + A$ and $p + A$
- Spin dependent fragmentation (Collins effect)



$FF_{pA}/FF_{pp}(\pi^+)$





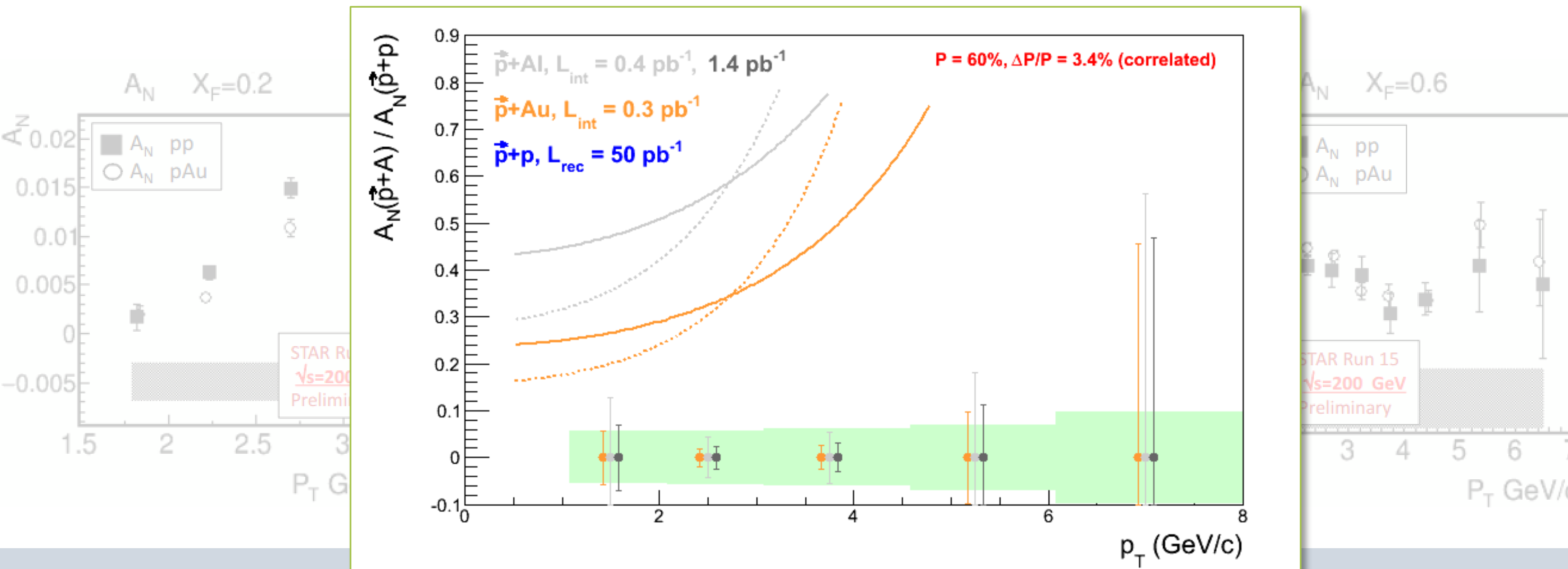
Nuclear Effects in $A_N(\pi^0)$

- Polarized: Transverse spin asymmetries of inclusive π^0 production
- Possibly gluon saturation effects (CGC)
- Nuclear effects on fragmentation process
- RHIC Run 2015
  - $\vec{p}+p$ / $\vec{p}+Al$ / $\vec{p}+Au$

STAR FMS

$2.5 < \eta_p < 4.0$

$p+p$ @ $\sqrt{s} = 200$ GeV



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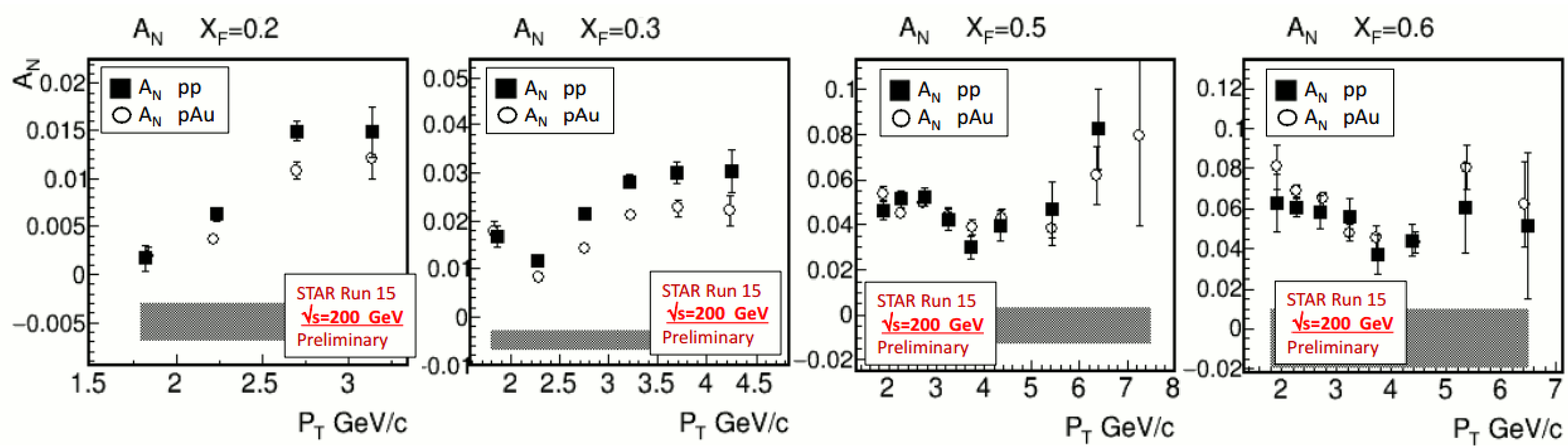

No suppression can be observed so far.

RHIC as a Polarized Proton Collider