Forward Physics at STAR

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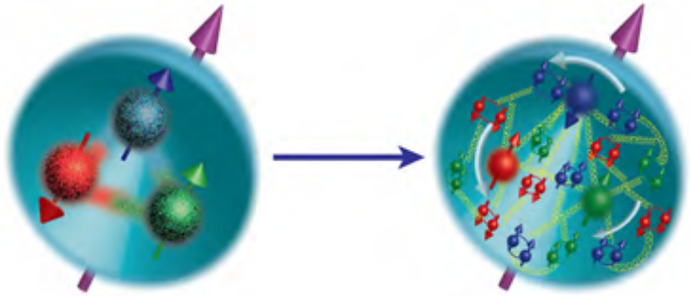
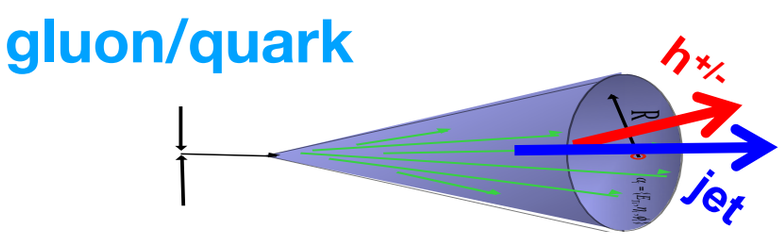
Physics in 2021+

- Unique measurements to answer the hot questions in cold QCD

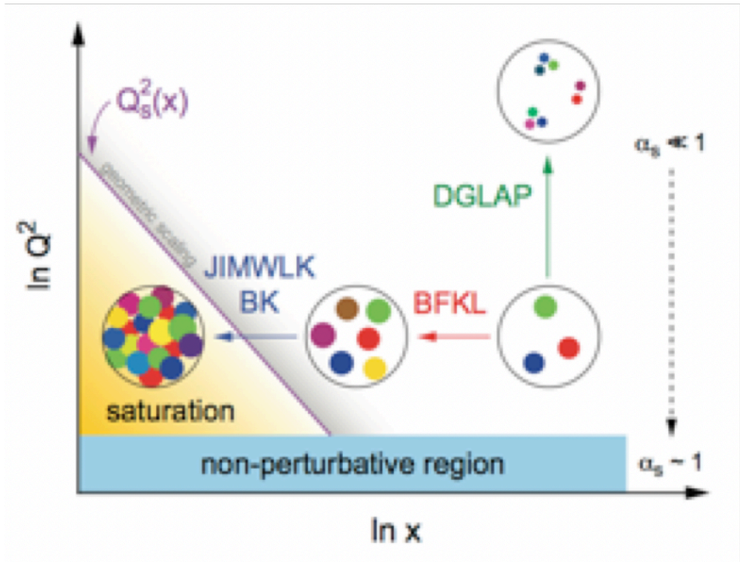
How are the sea quarks and gluons, and their spins distributed in space and momentum space inside the nucleon?



How do the confined hadronic states emerge from these quarks and gluons?

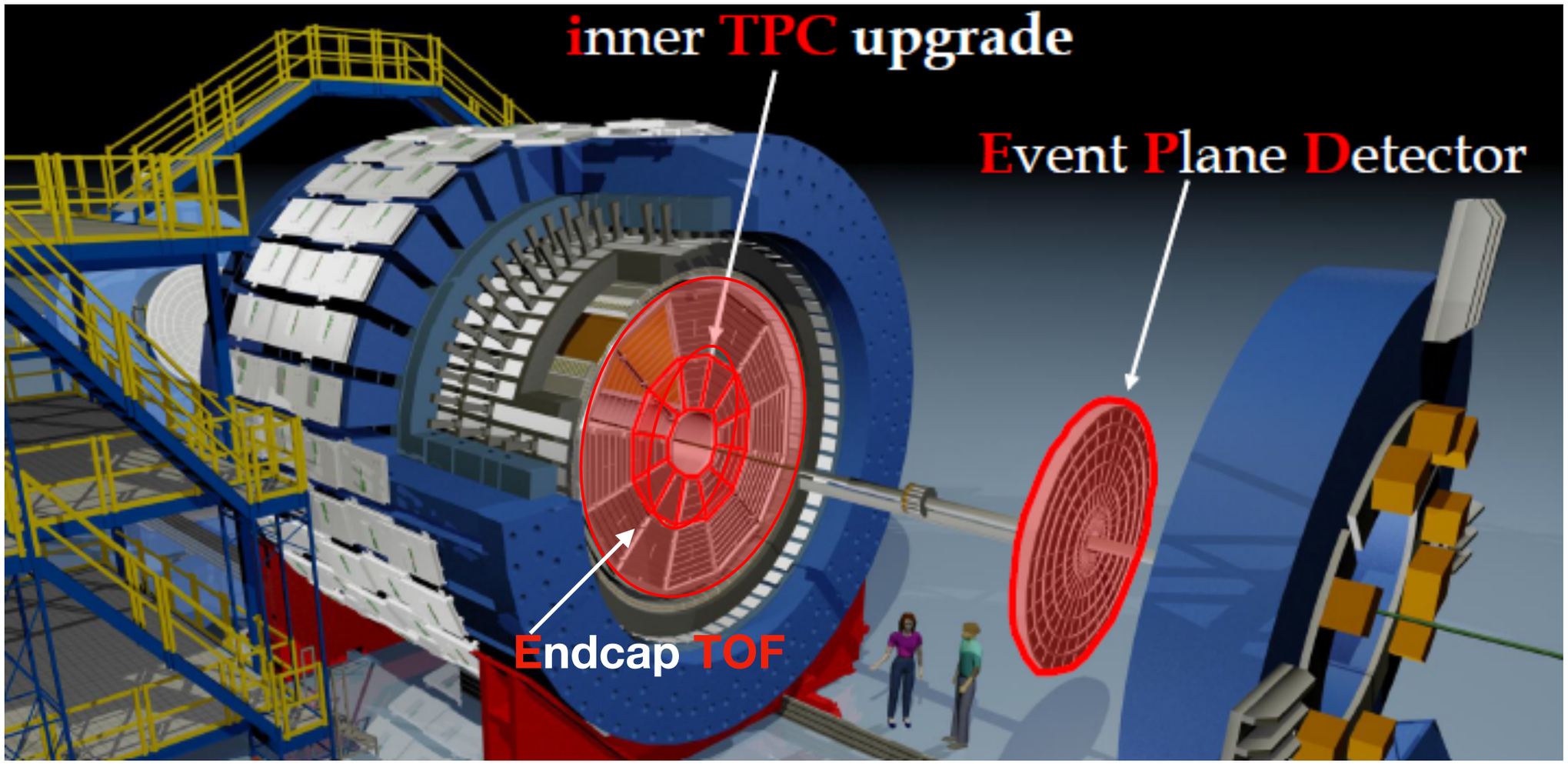


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?



More details: https://arxiv.org/pdf/1602.03922.pdf

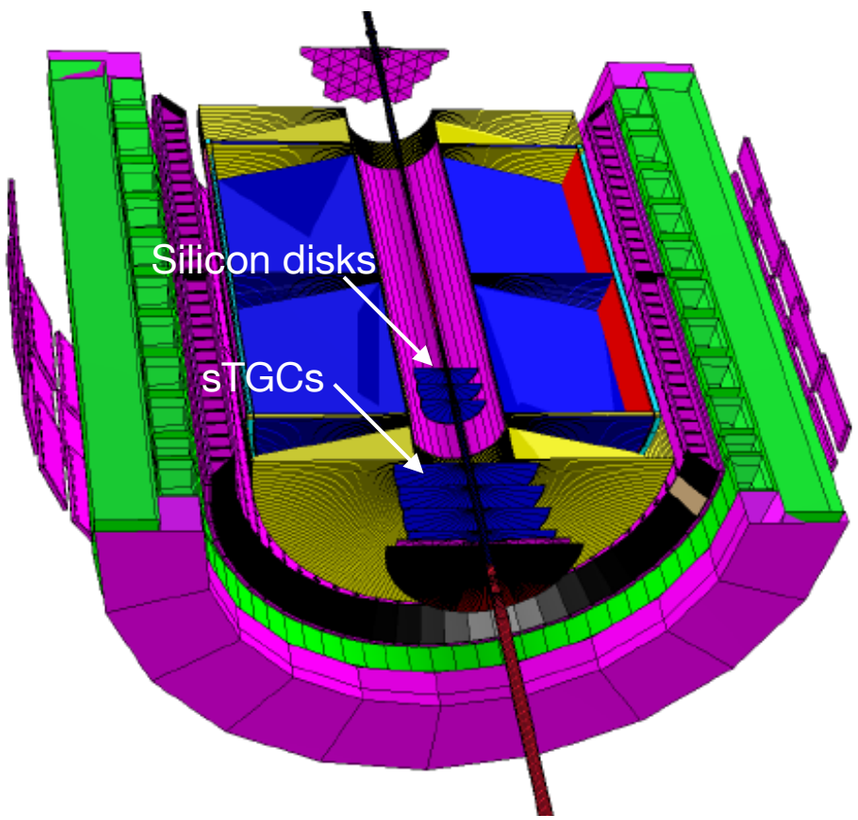
Current STAR



iTPC	EPD	eTOF
Continuous pad rows Replace all inner TPC sectors	Replace Beam Beam Counter	Add CBM TOF modules and electronics (FAIR Phase 0)
$\|\eta\|<1.5$	$2.1<\|\eta\|<5.1$	$-1.6<\eta<-1.1$
pT > 60 MeV/c	Better trigger &b/g reduction	Extend forward PID capability
Better dE/dx resolution Better momentum resoultion	Greatly improved Event Plane info	Allows higher energy range of Fixed Target Program

STAR Forward Upgrade in 2021

Forward Tracking System



3 Silicon disks: at 90, 140, 187 cm from IP

Built on successful experience with STAR IST

- Single-sided double-metal mini-strip sensors
  - Granularity: fine in ϕ and coarse in R
- Frontend readout: APV25, hybrid
- Mechanical supporting structure
- Reuse of the IST DAQ, cooling system

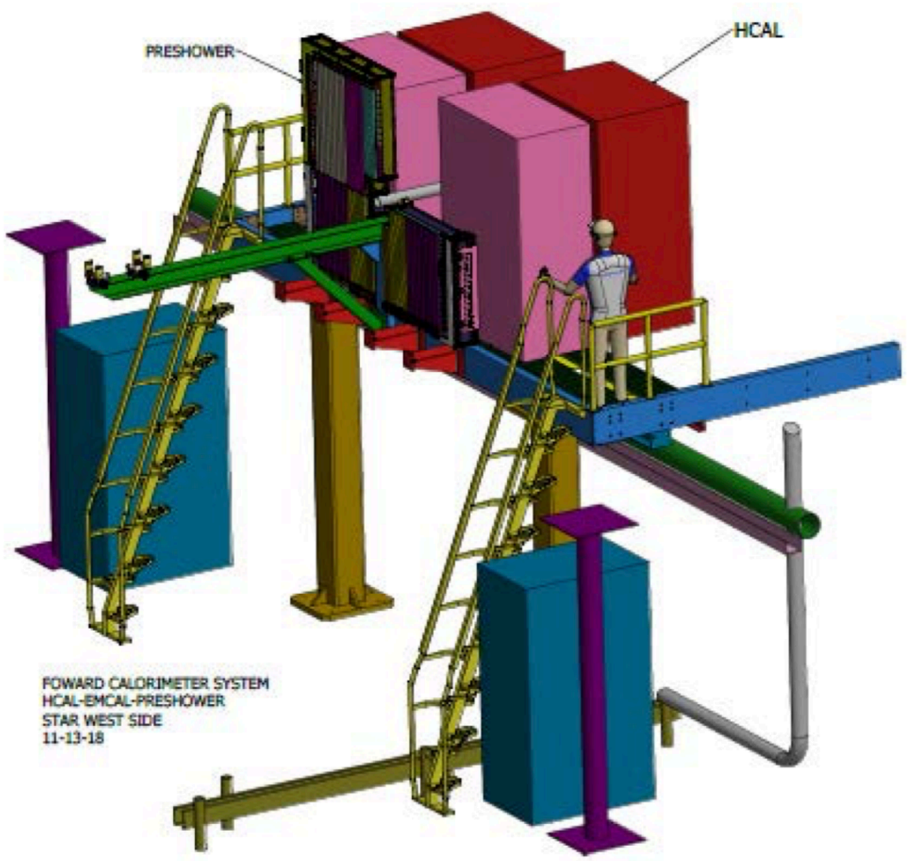
4 sTGC disks: at 270, 300, 330, 360 cm from IP

(outside Magnet)

- Position resolution: ~100 mm
- Material budget: ~0.5% per layer, 2 layers / disk
- Readout: reuse current STAR TPC electronics
- 1st sTGC prototype to be installed in STAR in 2019
  - 1/4 size of ATLAS sTGC
  - 50cmx60cm module with 2 layers

- Discrimination of charge
- 20-30% transverse momentum resolution for $0.2 < p_T < 2$ GeV/c
- Tracking finding efficiency: 80% @100 tr/evt

STAR Forward Upgrade in 2021



Calorimeter System:

Intensive R&D work on both Ecal and Hcal as part of STAR and EIC Detector R&D

- Several beam test and STAR in situ tests
- Projective geometry
- System optimized for cost and performance

Ecal:

- Reuse PHENIX PbSc calorimeter with new readout on front phase
- Secured on sector (2592 towers)

  PbSc towers: $5.52 \times 5.52 \times 33\ cm^3$ ($18X_0$)

Hcal:

- Sandwich iron-scintillator plate sampling Cal.

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E + 10%	—

Technical, Cost, Rise and Schedule Review

Associate Laboratory Director's Review
STAR Forward Upgrade
November 19, 2018
Charge to the Review Committee

The STAR detector, currently in operation at the Relativistic Heavy Ion Collider (RHIC), at Brookhaven National Laboratory (BNL) is devoted to the study of matter governed by Quantum Chromodynamics. To enhance the physics potential of STAR a forward upgrade program has been proposed that will address some of the scientific questions prioritized in the 2015 NSAC Long Range Plan and generally enhancing the physics reach afforded by the RHIC complex prior to the possible construction of an Electron Ion Collider (EIC).

The proposed forward upgrades of STAR combine a tracking system with electromagnetic and hadronic calorimeters to cover the region $2.5 < \eta < 4.5$, allowing for reconstruction of neutral pions, photons, electrons, jets and leading hadrons in the forward region. The STAR forward upgrade is expected to be in place after the Beam Energy Scan II and prior to the FY21/FY22 pp run at 500 GeV.

The committee is charged to evaluate the STAR forward upgrade plan focusing on technical, cost schedule and risks, and provide answer to the following questions:

1. Is the conceptual design technically sound and likely to meet the objectives of its scientific case?
2. Are the resources needed, including workforce, adequate and likely to be provided?
3. Are the material and workforce costs to BNL properly understood?
4. Is the schedule consistent with the RHIC FY21 run plan?
5. Are the risks understood, including external dependencies, and is there a plan that mitigates the risks?
6. Is the project being properly managed?
7. Is there a capable team in place to effectively manage risks and ensure quality?
8. Are the interfaces properly understood?
9. Are the ES&H aspects being properly addressed?

I very much appreciate your willingness to lend your time and expertise in this important process and look forward to receiving your assessment.

Berndt Mueller
Associate Laboratory Director for Nuclear and Particle Physics
Brookhaven National Laboratory

Outcome

A five-member review panel (S. Boose, C. Miraval, G. van Nieuwenhuizen, A.Tricoli, and chaired by G. Young) conducted a review of the resource requirements for the proposed forward upgrades to the STAR detector on November 19, 2018. The panel noted good progress on the proposed concept for a cold-QCD experiment to run in late 2021 at RHIC, with plausible plans for funding and conservative designs for all detector components, electronics, and support infrastructure. The panel opined that the major project risks are identified and that the experiment appears positioned to be ready for first operation in 2021, with the caveat that the critical path, which is the silicon detector, presently has very little float. BNL management has begun discussions with ONP about the implementation of the proposed upgrade.

Workforce

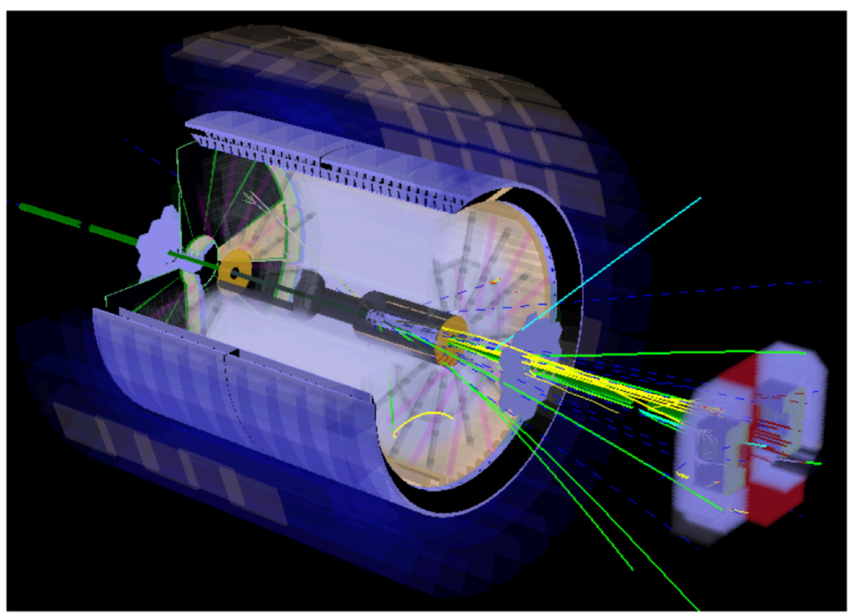
Design and Integration:
STAR Operations Group

Calorimetry Readout, Trigger and DAQ :
Consortium of ACU, BNL-STAR, IU, Kentucky, OSU, Rutgers, Temple, TAMU, UC-Riverside, UCLA, Valparaiso
A MRI-Proposal has been submitted to NSF in January 2019

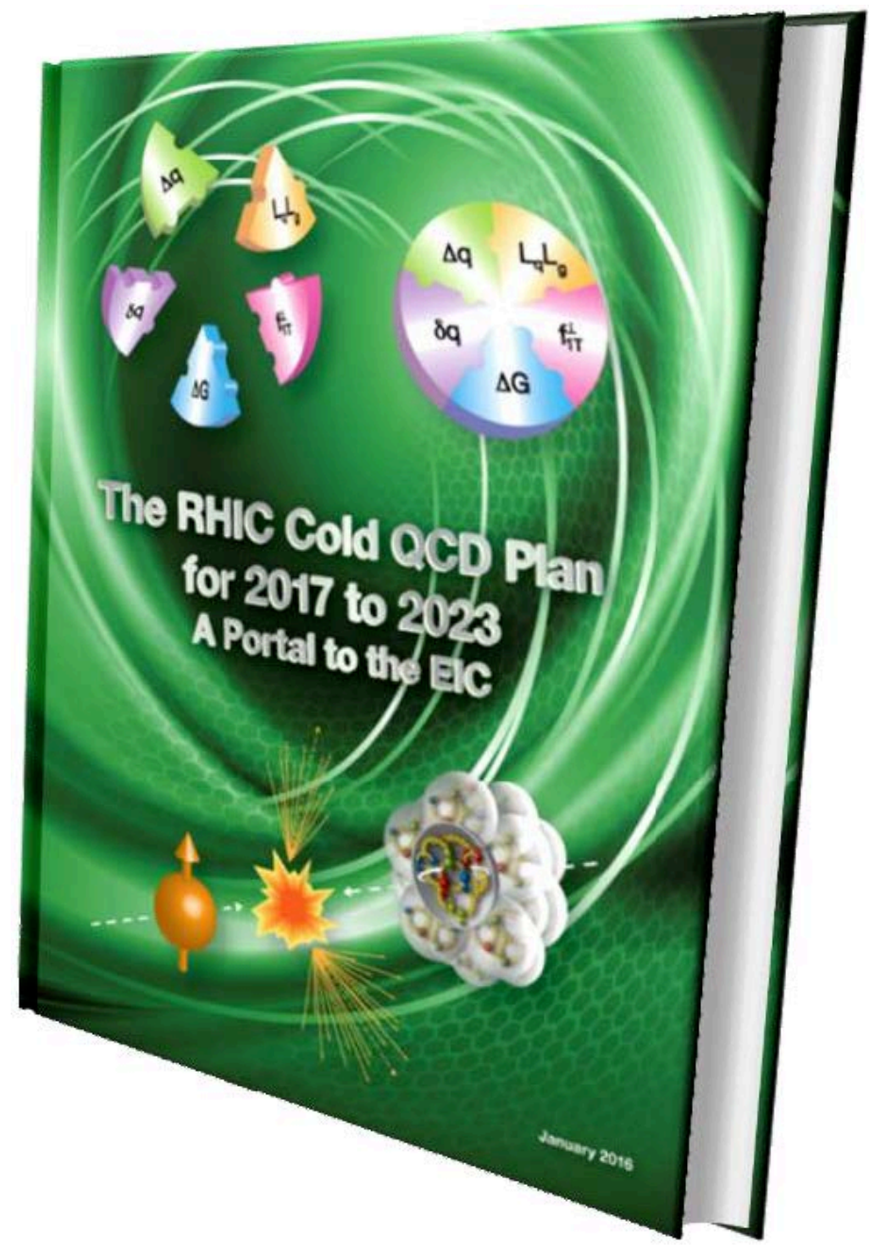
Tracking:
Consortium of BNL-STAR, IU, UIC, NCKU, SDU,USTC
- Si: BNL-STAR, IU, UIC, NCKU, SDU, USTC
- sTGC: BNL-STAR, SDU

BNL STAR OPS Group:
- Mechanical group
- Electronics group

The STAR Forward Calorimeter System and Forward Tracking System



Proposal
November 2018



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

arXiv:1602.03922

STAR Forward Physics Program in 2021+

Year	√s (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
2021/22	$p^{\uparrow}p$ @ 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 $\eta > 1$	Ecal + Hcal +Tracking
2021/22	$\vec{p}\vec{p}$ @ 510	1.1fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Ecal + HCal
2024	$p^{\uparrow}p$ @ 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	Ecal + Hcal +Tracking
2024	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	Nature of the initial state and hadronization in nuclear collisions Signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Ecal + Hcal +Tracking
2024	$p^{\uparrow}Al$ @ 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	Ecal + Hcal +Tracking
2023/25	Au Au	lots!	Early stages of QGP development	Long. correlation $C_n(\Delta\eta)$ $\eta/s(T)$, $\zeta/s(T)$	Ecal + Hcal +Tracking

2+1 Dimensional Imaging of Quarks & Gluons

Wigner function

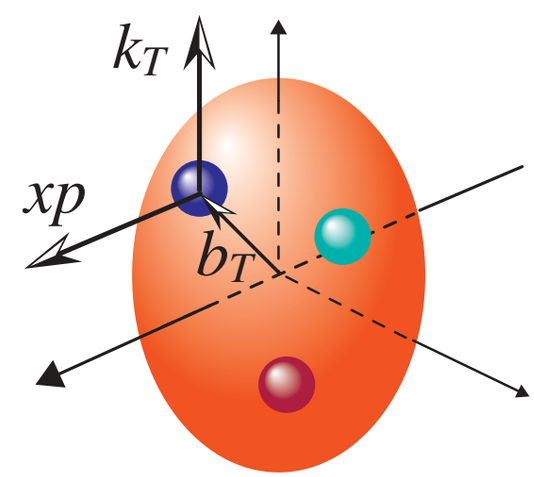
$W(x,b_T,k_T)$

Momentum space

Coordinate space

$\int d^2b_T$

$\int d^2k_T$



$f(x,k_T)$

TMDs

$f(x,b_T)$

GPDs

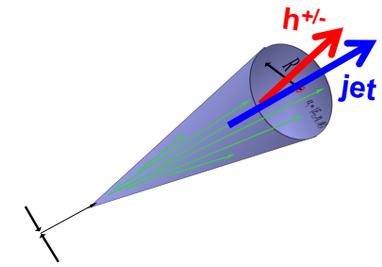
(Spin-dependent) 2+1D transverse momentum images

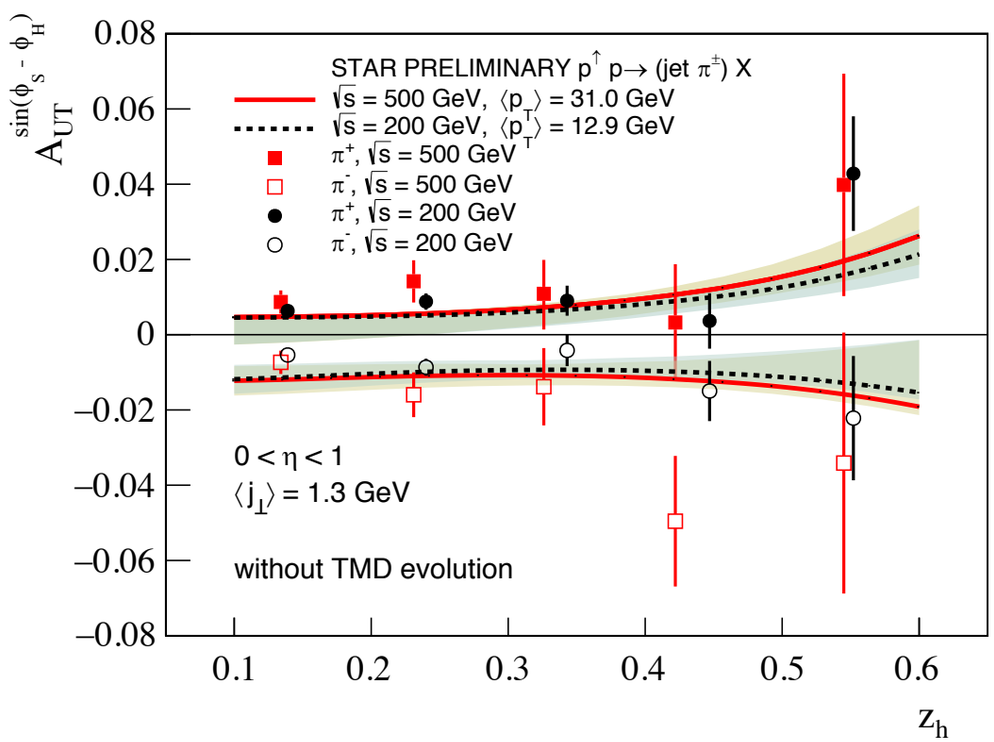
(Spin-dependent) 2+1D spatial images from exclusive scattering

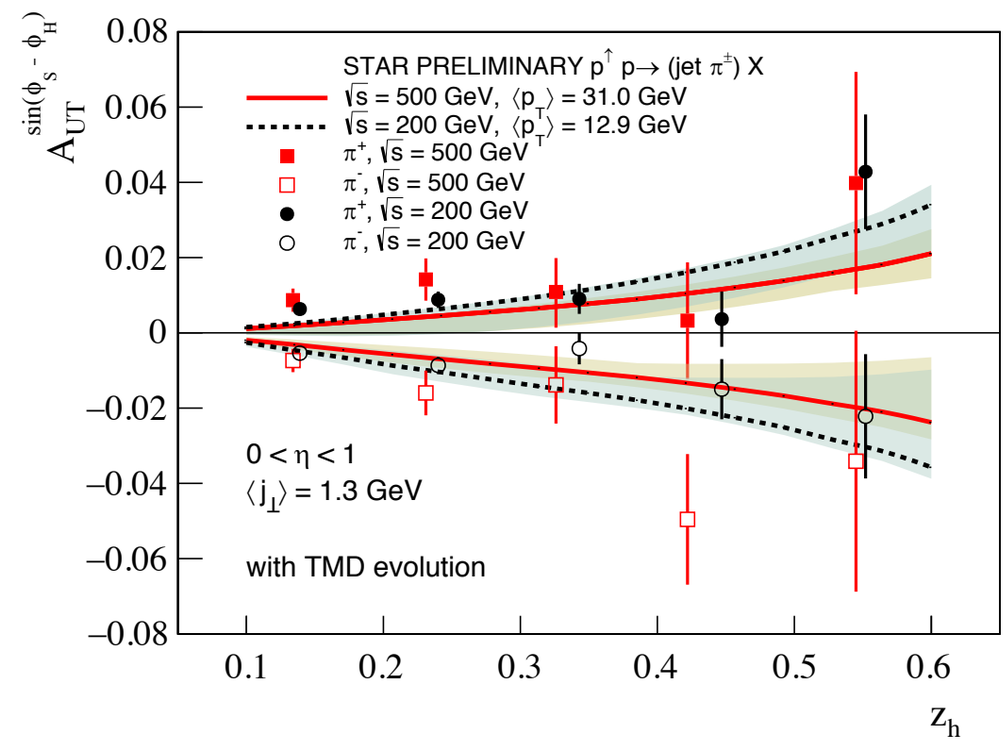
TMDs at STAR: Transversity & Collins

Transversity Collins FF

$$A_{UT}^{\pi^\pm} \approx \frac{h_1^{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{\sigma}_{UT}(\hat{s},\hat{t},\hat{u})\Delta D_{q_1}^{\pi^\pm}(z,j_T)}{f_{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{\sigma}_{UU} D_{q_1}^{\pi^\pm}(z,j_T)}$$



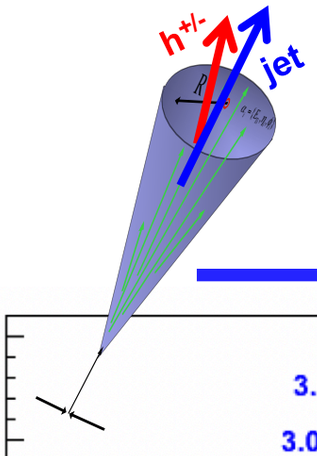




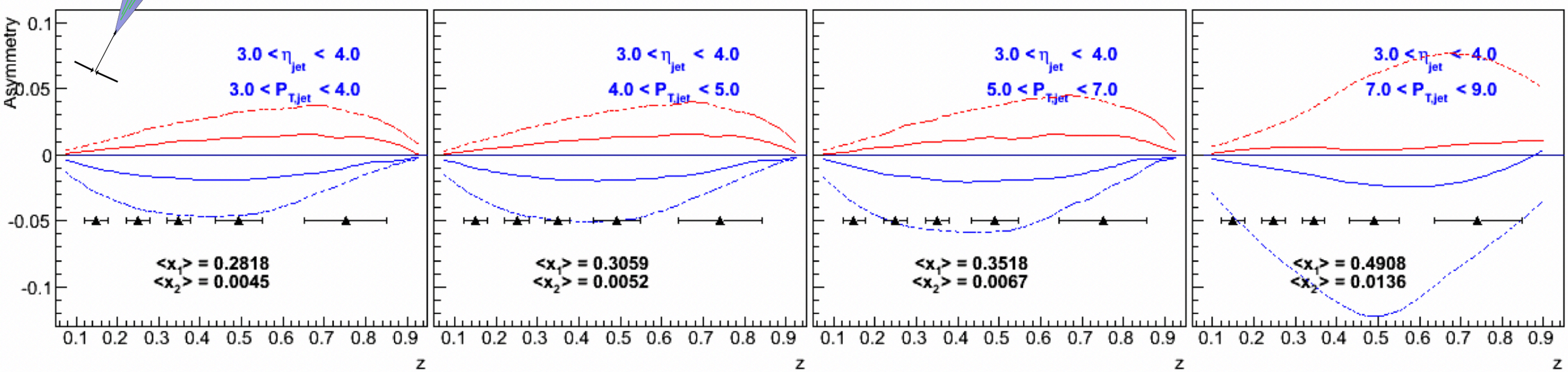
200 vs. 500 GeV Comparison:

- First observation of a TMD at low x and high Q^2
- TMD evolution: changed by a factor 3 in Q from 200 GeV to 500 GeV
- Test of factorization & universality

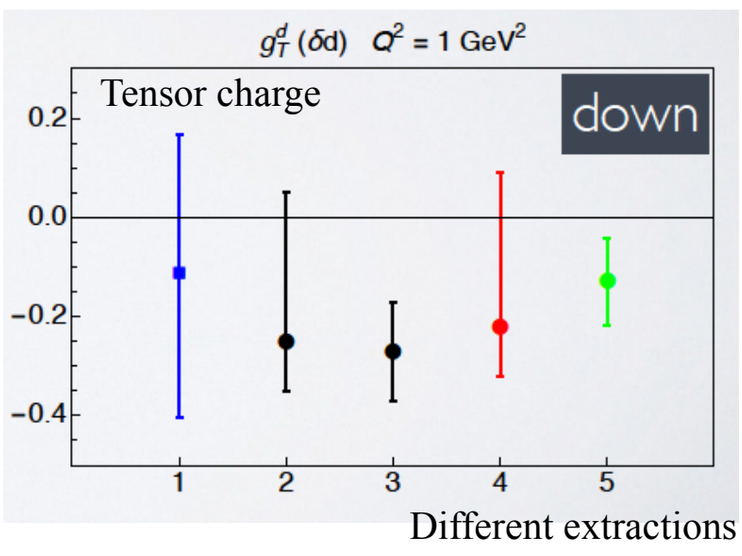
  → Compare with transversity from IFF & compare with SIDIS and e+e-

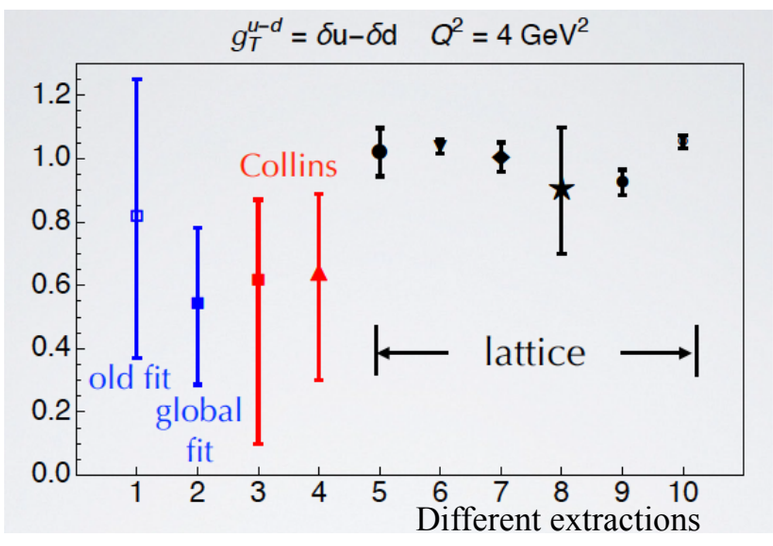


Transversity & Collins



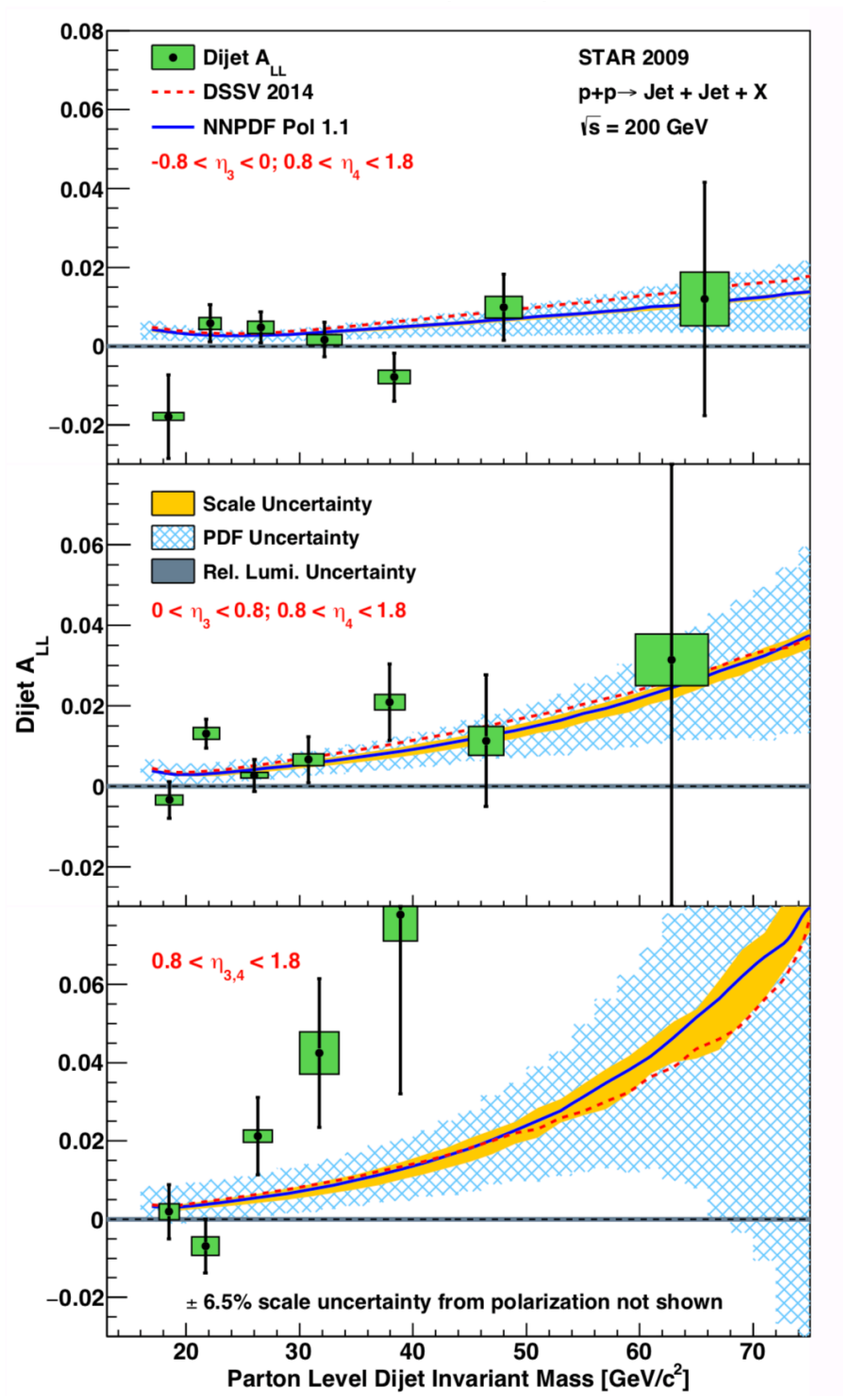
- Measure transversity at high x → hadron in jet
- Constrain tensor charge:
  - explorations of BSM new physics at low-energy
  - limited precision of current measurement



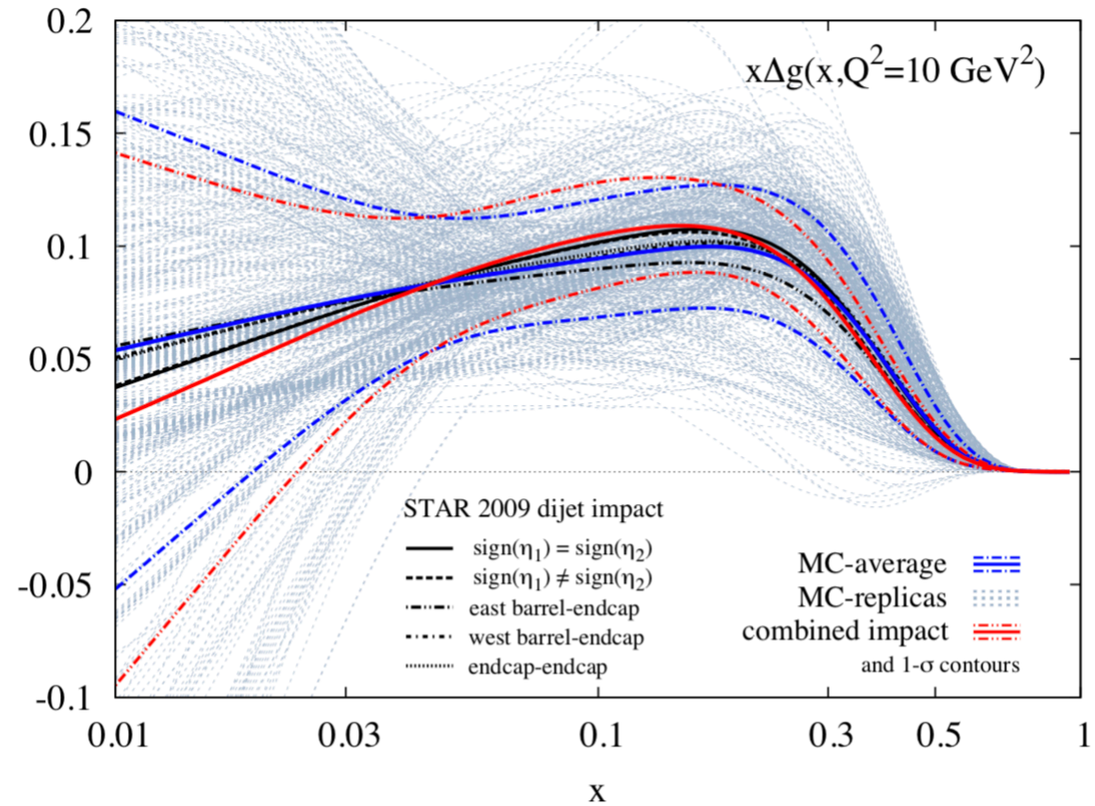


How Polarized are the Gluons in Proton

STAR: PRD98 (2018) 032011



Daniel de Florian et al. arXiv:1902.10548 (hep-ph)



$$\int_{0.05}^{1} \Delta g(x)dx = 0.126 \pm 0.023$$

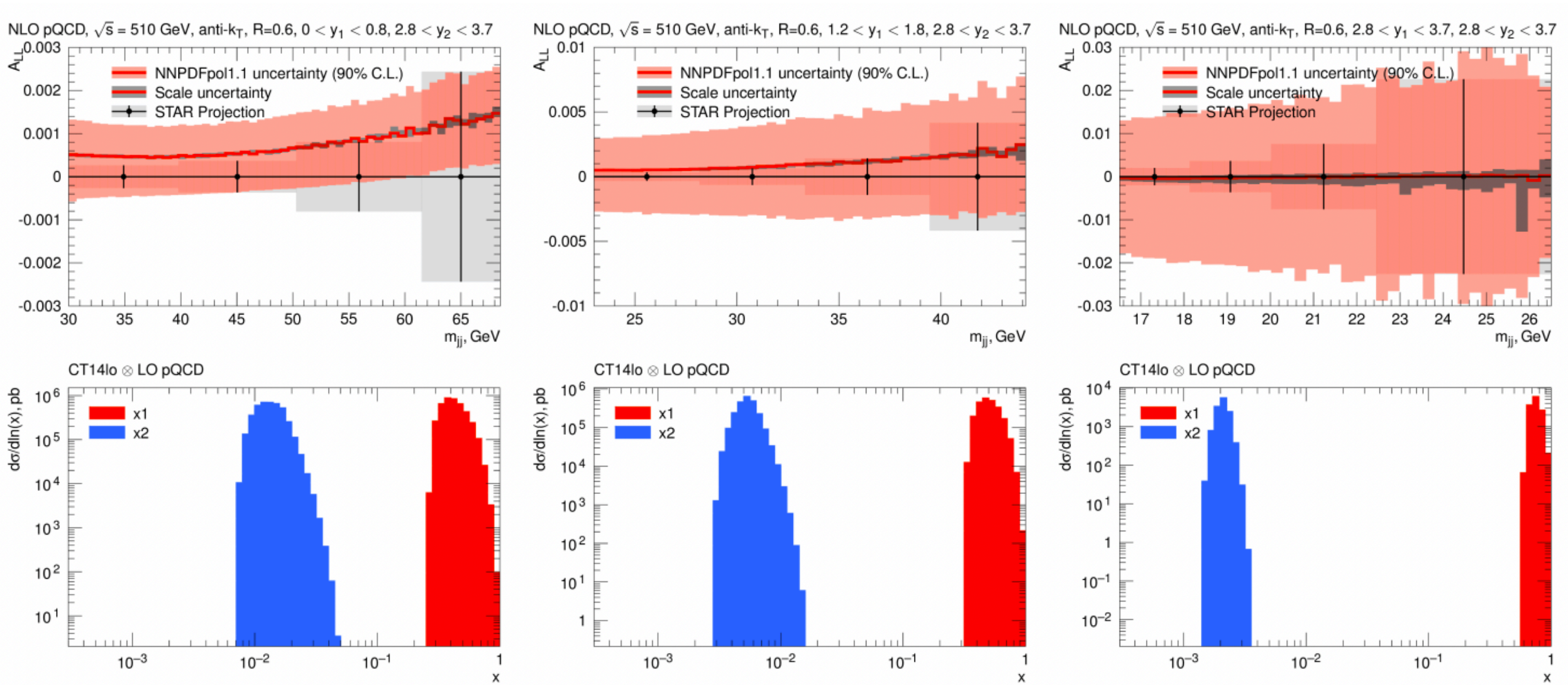
$$\int_{0.001}^{1} \Delta g(x)dx = 0.296 \pm 0.108$$

@ Q^2 = 10 GeV^2

Poor knowledge in small-x (<0.05) gluon helicity contribution to the total proton spin

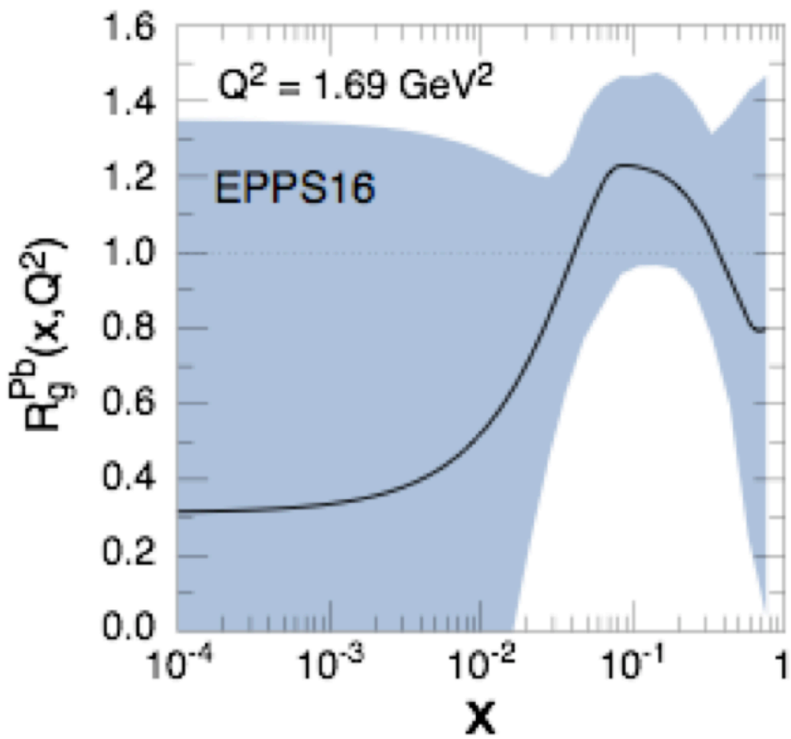
➜ go forward with Di-Jets @ $2.5 < \eta < 4.0$

How Polarized are the Gluons in Proton

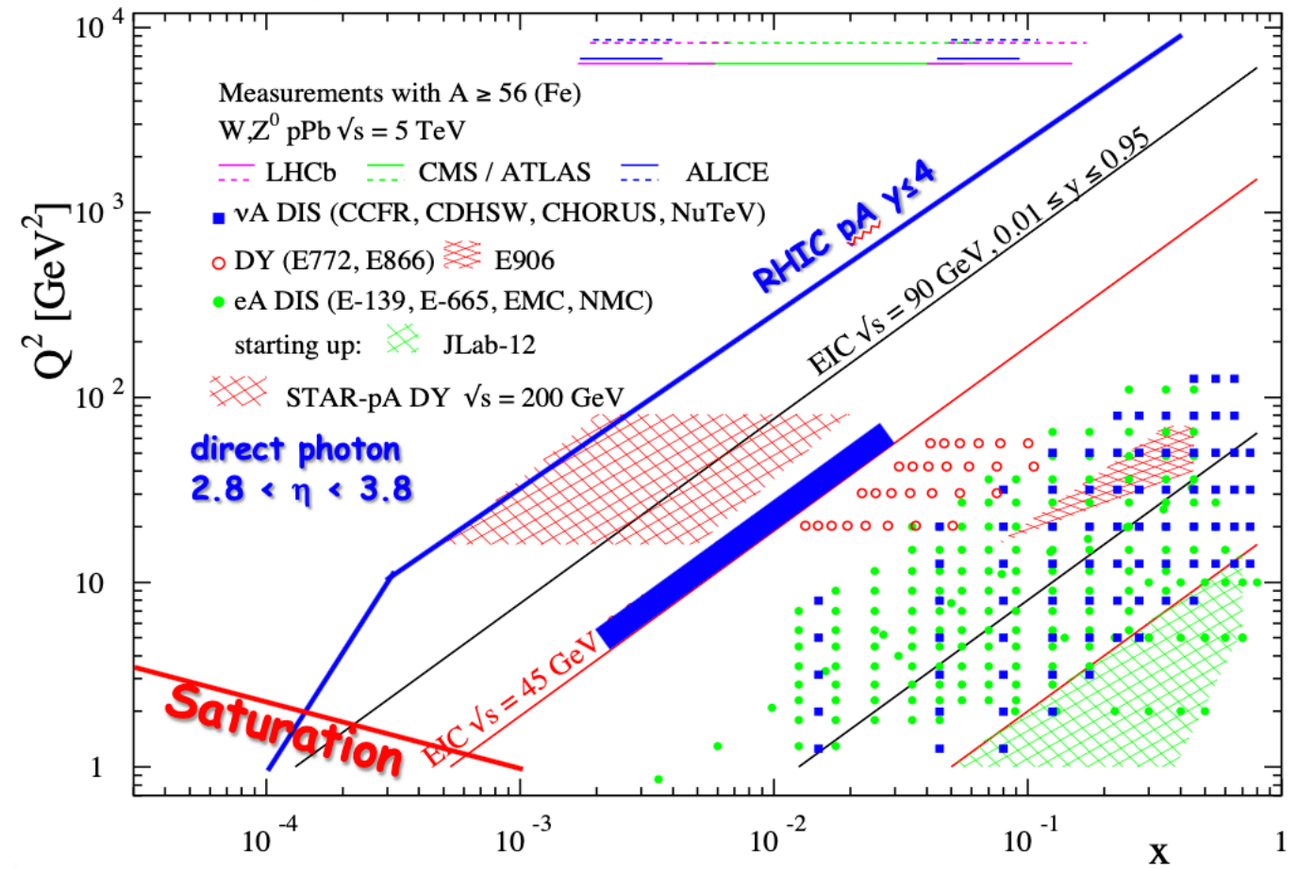


Di-jets A_{LL} at 510 GeV with STAR forward upgrade: constrain $\Delta g(x)$ at $x \sim 10^{-3}$

Constrain Nuclear PDFs



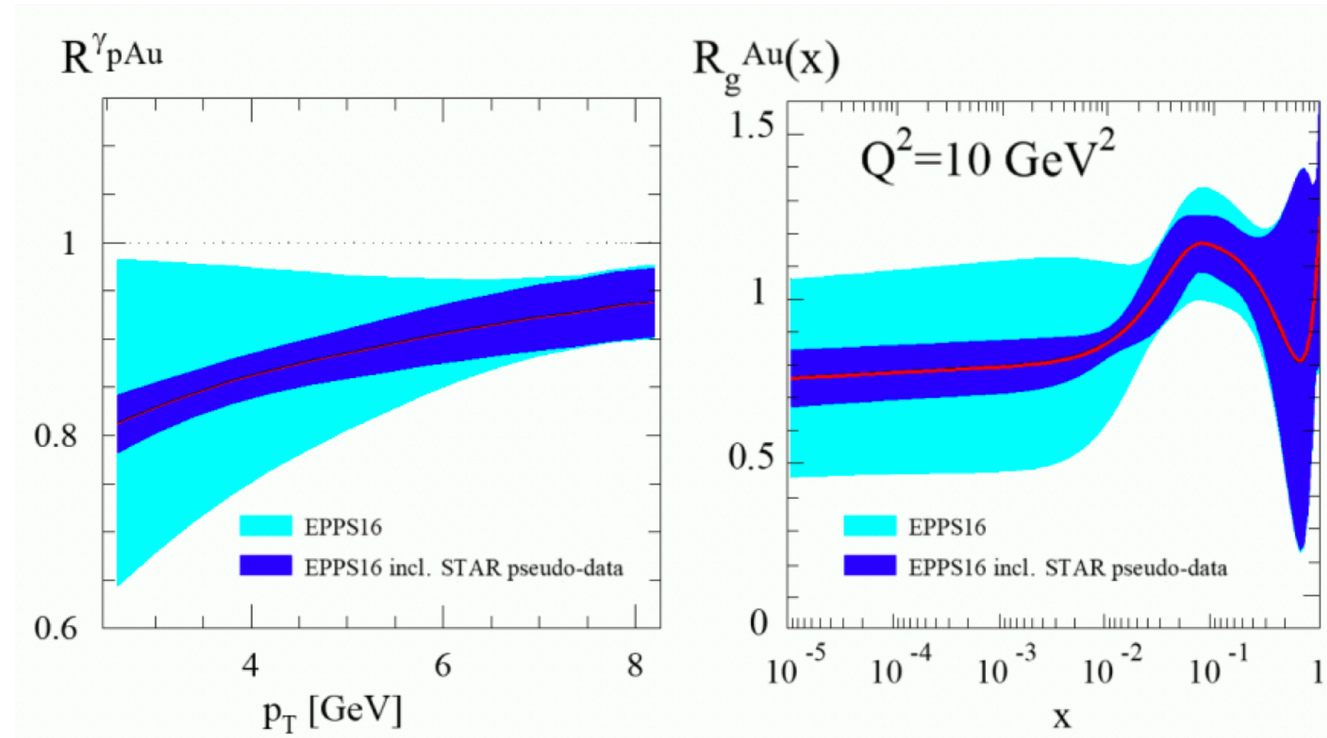
pA@RHIC: unique kinematics



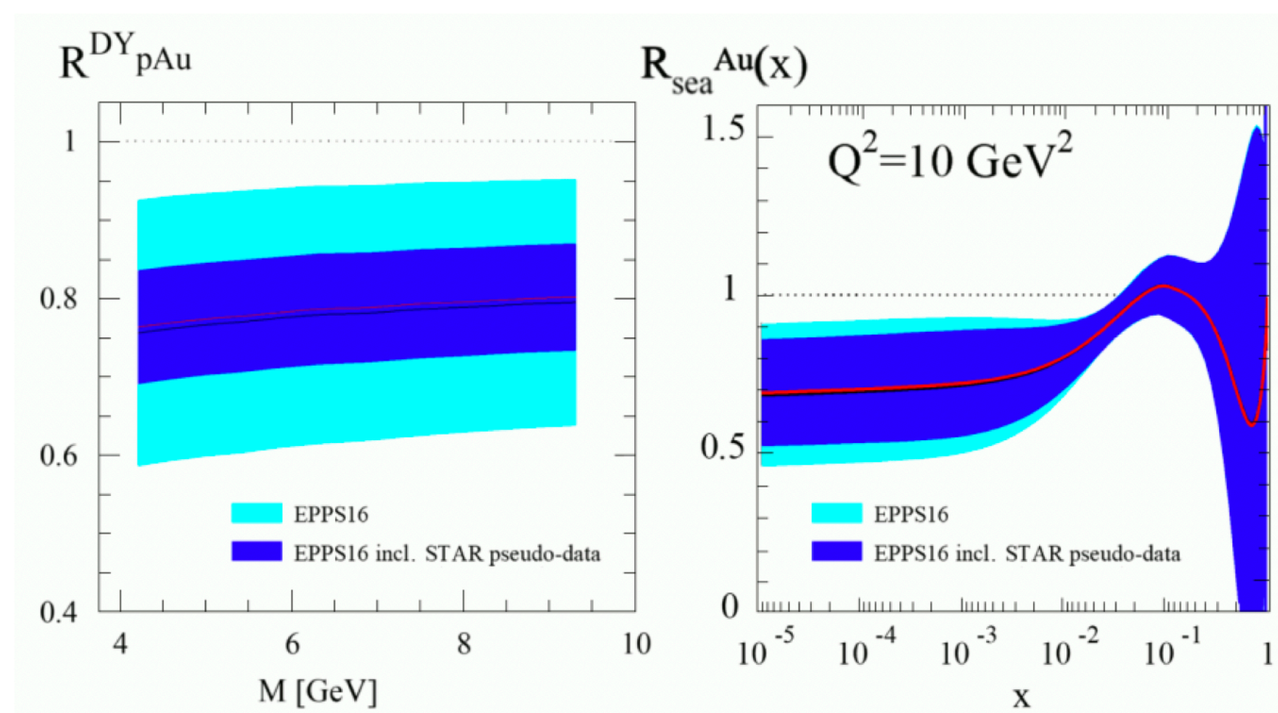
- Nuclear PDF are poorly constrained at low x
- Unique kinematic coverage by STAR forward detectors
  - can measure nPDF in a x-Q^2 region where nuclear effects are large
  - Observables free of final state effects
    - Direct photons → gluon PDF
    - Drell-Yan production → sea quarks

Constrain Nuclear PDFs

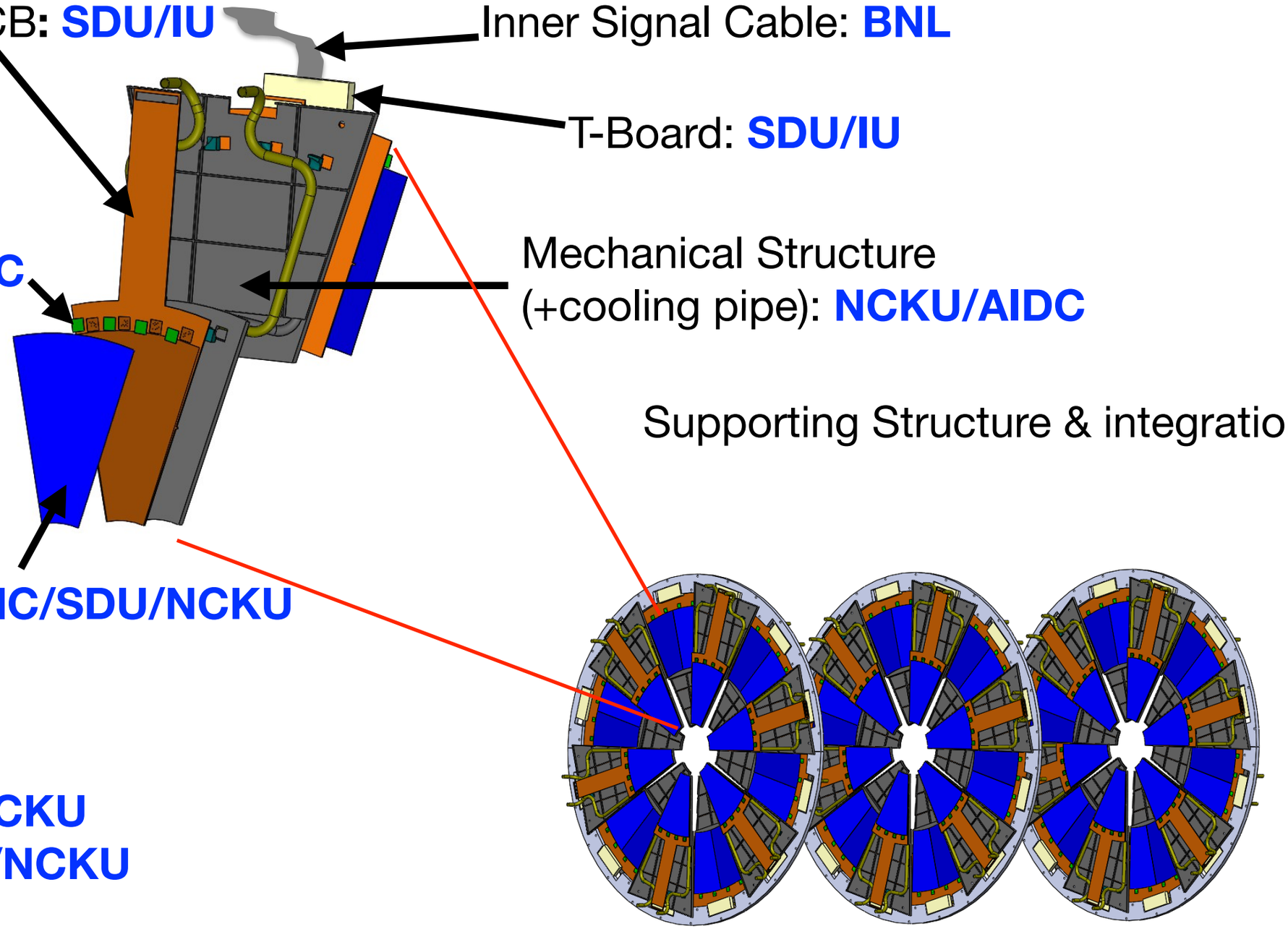
pA:
- Direct photon @ $2.5 < \eta < 4.5$
- Direct photon:
  - Q^2: $-p_T^2$
  - $Q^2 > 5\ \mathrm{GeV}^2$
- Impact on gluons nPDFs



pA:
- DY @ $2.5 < \eta < 4.5$
- DY:
  - Q^2: m^2
  - $Q^2 > 16\ \mathrm{GeV}^2$
- Impact on sea quarks nPDFs



Status: Silicon

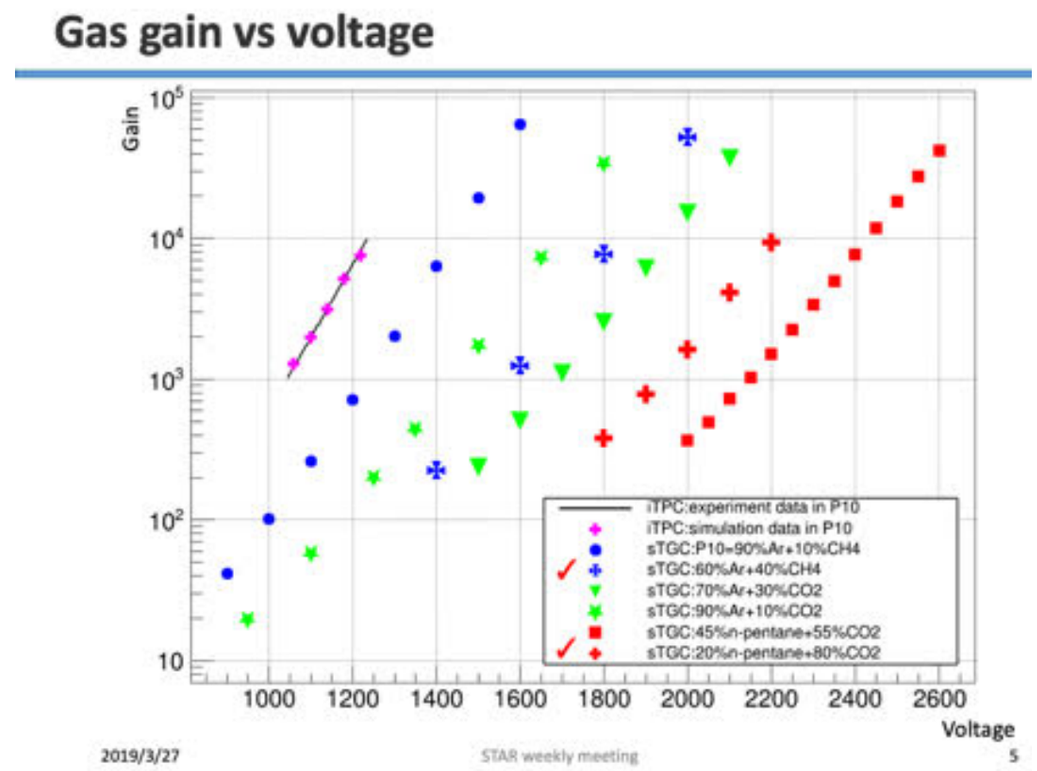


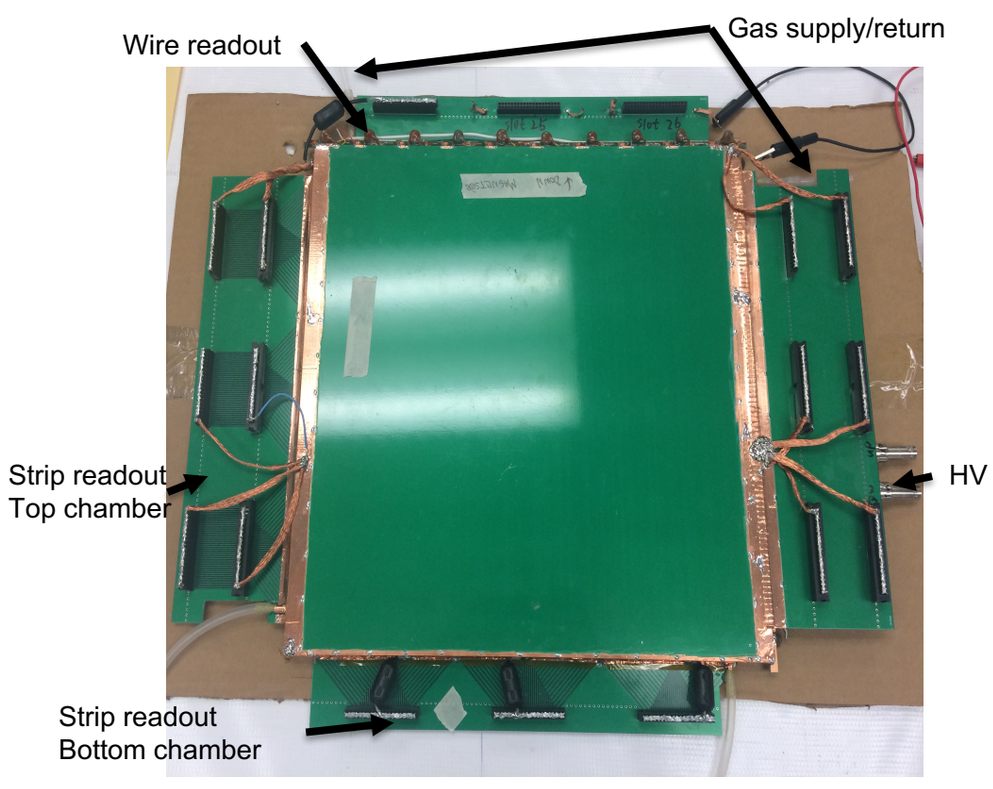
Cooling: **BNL/NCKU**
Simulation: **UIC/NCKU**

Status: sTGC

Prototype for 2019

- Made at SUD-China
- Two chambers, each 30×30×0.28 cm
  - Chamber volume (252×2) cc
  - 2D readout
  - 94 channels per chamber
- Intensive tests of best operating gas
  - leakage tests





Status: Calorimeters - ECal

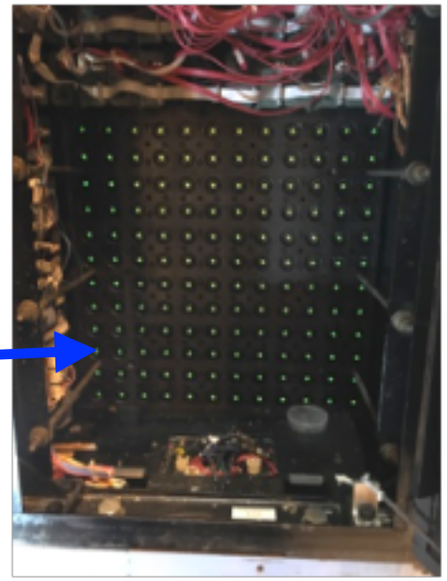
EM Module:

- Module has four independent towers
- Penetrating WLS fibers for light collection
- Sectors is 6 × 6 EM modules

Modifications:

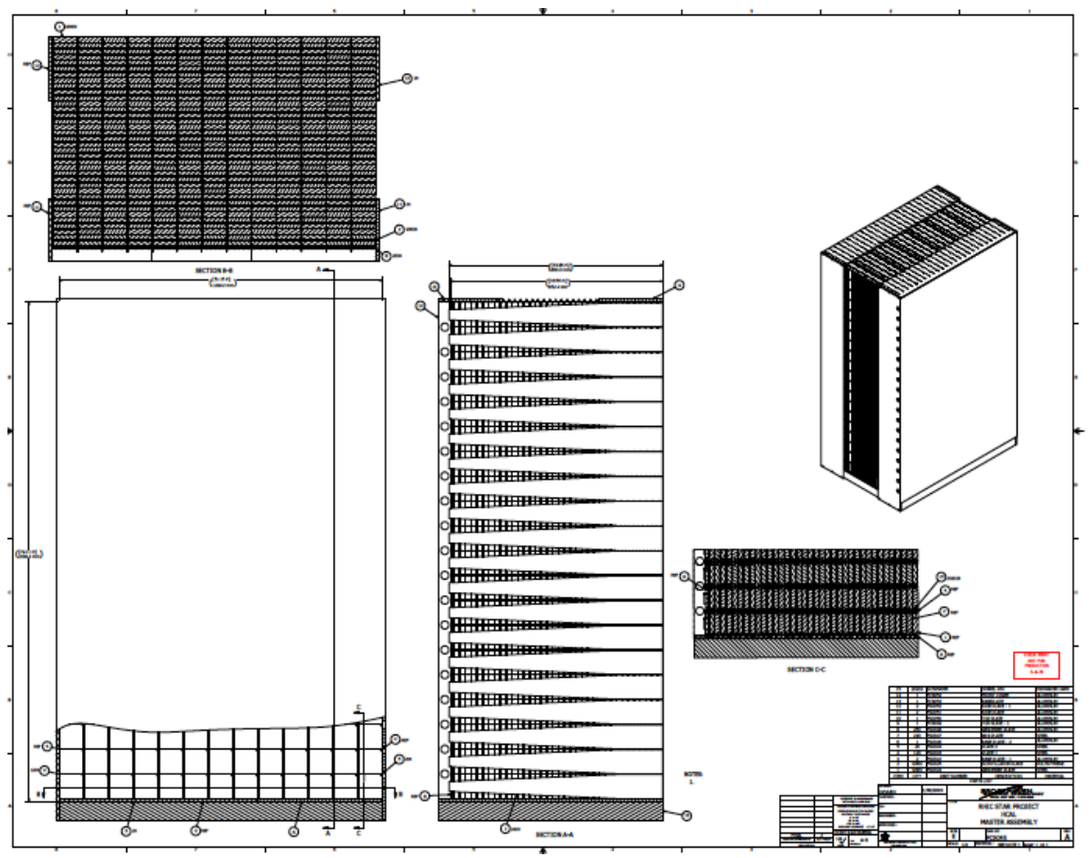
- Gluing four light guides/mixers at the end of WLS bundles
- Gluing SiPM carrying boards to LG
- Attaching FEE

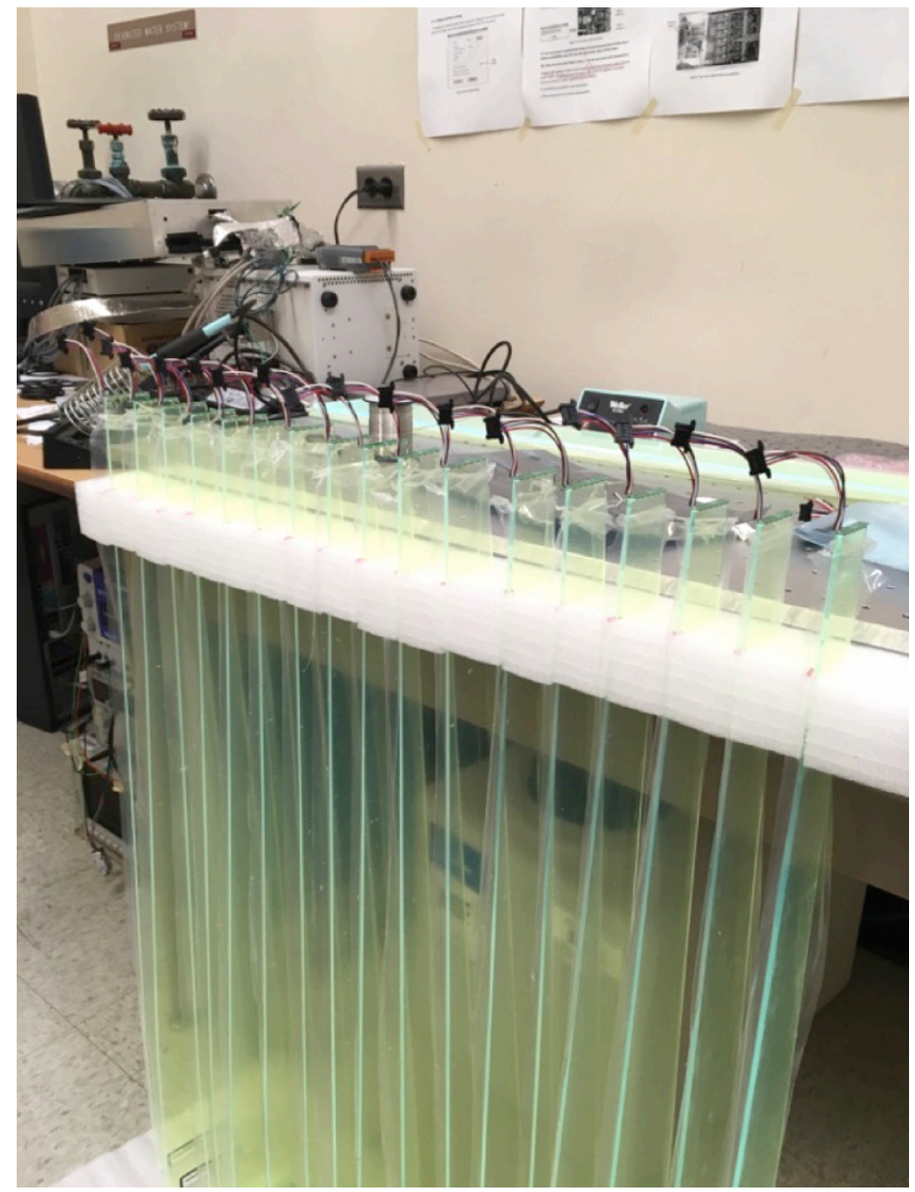
- Disassembling of electronics and monitoring system are done
- Next steps:
  - Remove Supersector Top
  - Extract sectors one by one
  - Start gluing Light Guides



Getting ready to install this summer

Status: Calorimeters - HCal





- SiPM boards produced similar to EMcal boards
- Individual boards were tested for leakage current
- Full set of production drawings is done
- Final check of drawing after the test run at FNAL
- Test Run at FNAL has been finished

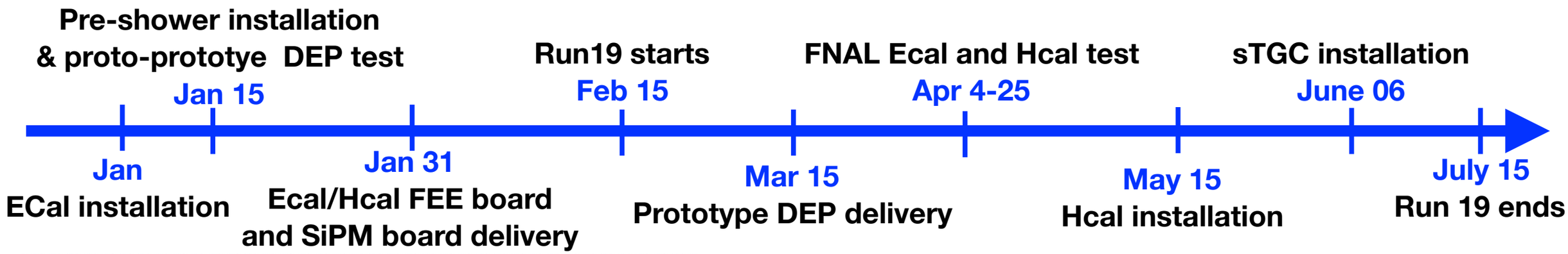
Prototyping in STAR during 2019

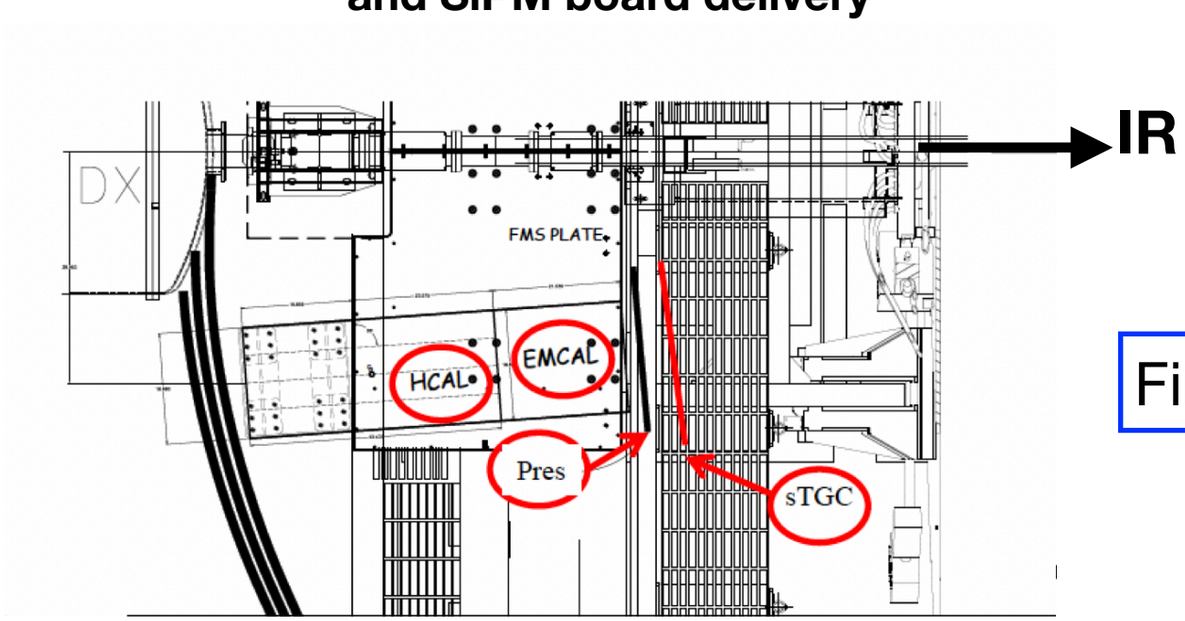
Install "mini" forward upgrade for Run-19 including:

- 64 (8×8) Ecal
- 16 (4×4) Hcal
- 1 layer (9 slats) Pre-shower (former FMS Post-Shower detector)
- 1 plane of sTGC

3 prototype DEP readout
+1 DEP/IO for trigger

TPC readout





Final prototypers are right now tested at STAR!!

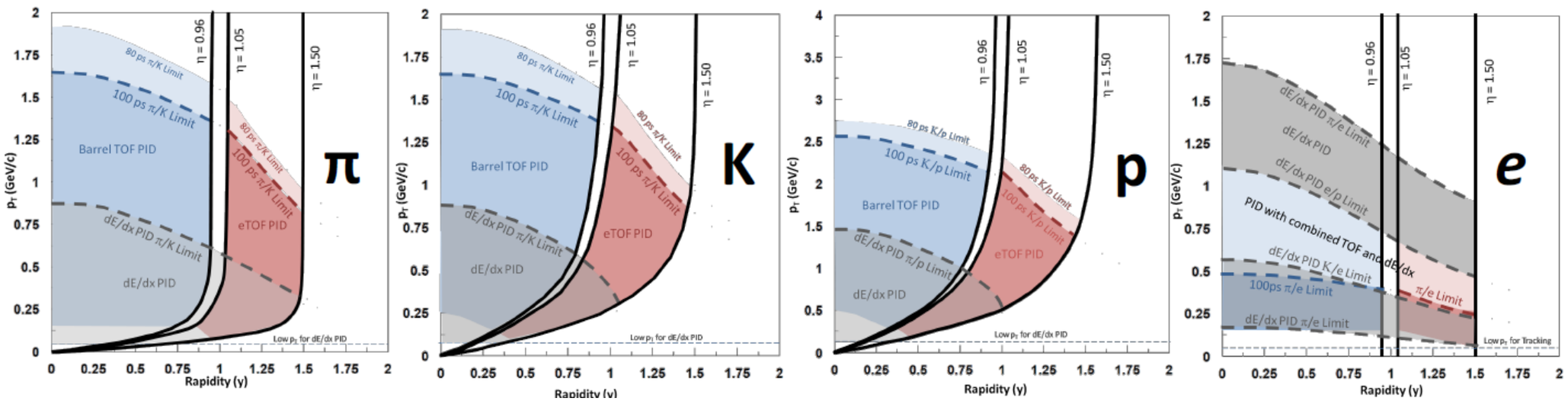
Summary

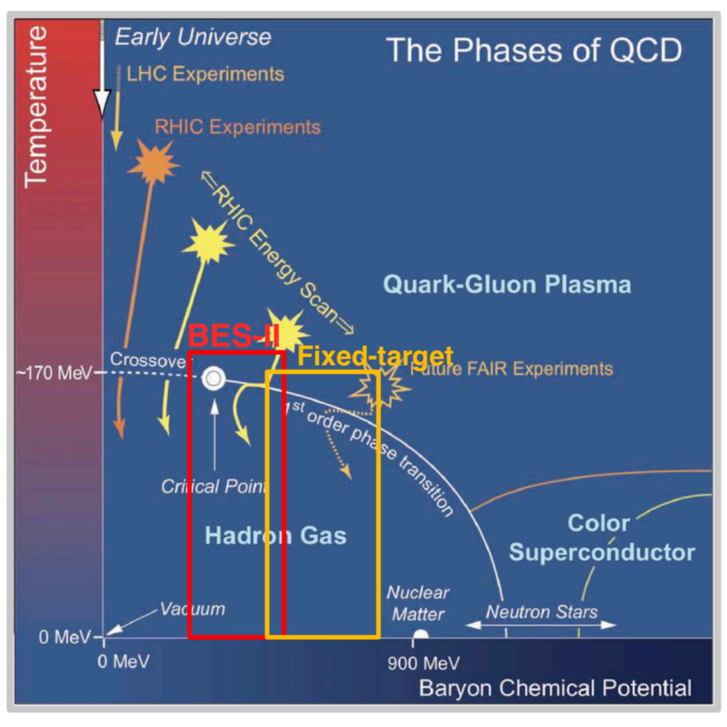
- Unique STAR forward plays a central role in expanding the frontier of cold-QCD
- The forward physics are based on the unique upgrade of STAR
  - Hcal + Ecal + tracking (Si + sTGCs) at $2.5 < \eta < 4$
- Essential to fully realize the scientific promise of the EIC program
  - Inform the physics program
  - Quantify experimental requirements
- Design of all sub-detector components finalized
- Ready for data taking Autumn CY21

Back-up

Beam Energy Scan Phase II

π,K,p,e Acceptance and PID capabilities with the combination of iTPC and eTOF





QCD phase diagram

Sivers Function

- **Test of TMD evolution and the sign change of the Sivers function**
  - **measure AN for W±, Z0 and DY production simultaneously**
- **Run 17 pp data**

	$A_N(W^{+/-},Z^0)$	$A_N(DY)$	$A_N(\gamma)$
Sensitive to Sivers effect non-universality through TMDs	**Yes**	**Yes**	No
Sensitive to Sivers effect non-universality through Twist-3 $T_{q,F}(x,x)$	No	No	**Yes**
Sensitive to TMD or Twist-3 evolution	**Yes**	**Yes**	**Yes**
Sensitive to sea quark Sivers or ETQS function	**Yes**	**Yes** ($x<10^{-3}$)	No
Detector upgrade needed	No	**Yes** FMS post-shower	No
Biggest experimental challenge	Integrated luminosity	Background suppression Integrated luminosity	----