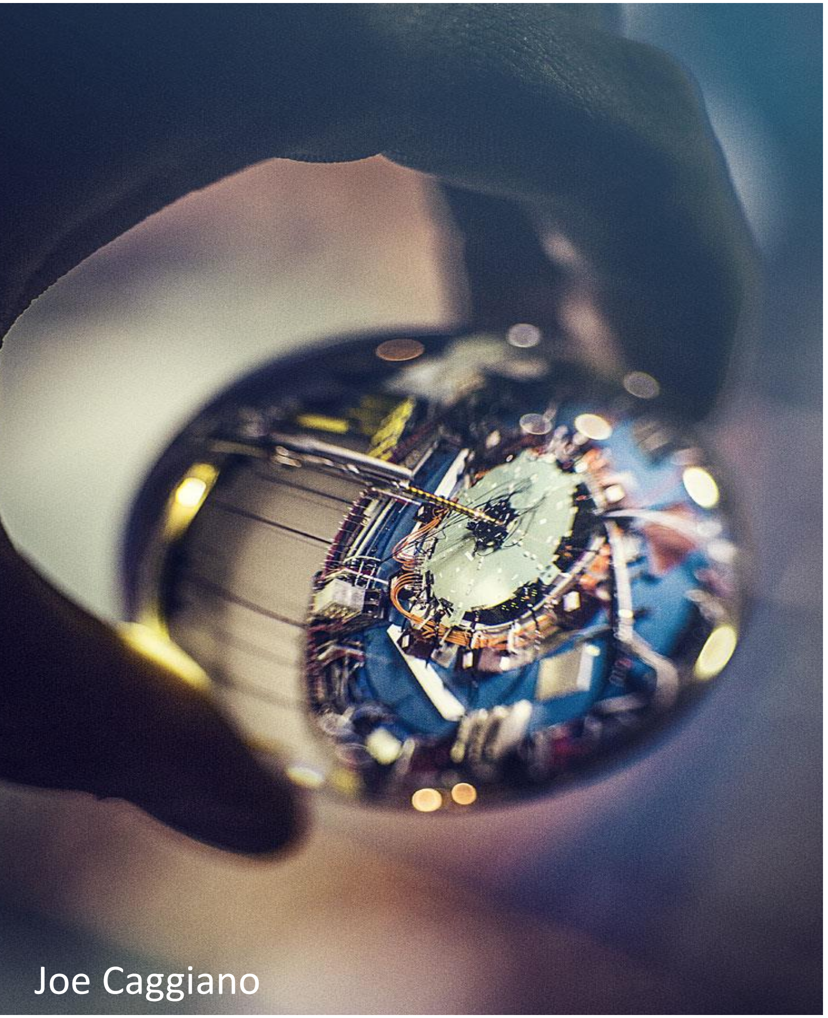
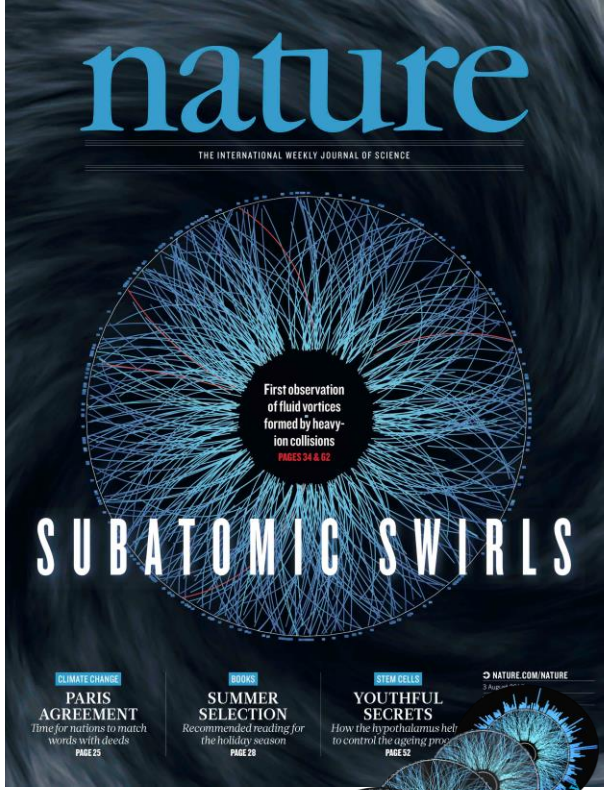
# STAR Plan for future Heavy-Ion Physics


Joe Caggiano

Zhangbu Xu
for the STAR Collaboration

- 2021+ Unique Physics cases
  - **nPDF**
    forward jets/γ/DY
  - **Viscosity [η/s(T)]**
    Multiple Harmonics and Rapidity Correlations
  - **Vorticity**
    Rapidity Dependence of Global Hyperon Polarization
  - **Luminosity**
    Dilepton Radiation, Chiral Symmetry resolving photon puzzle
  - **Conductivity**
    Create and Probe Magnetic Field





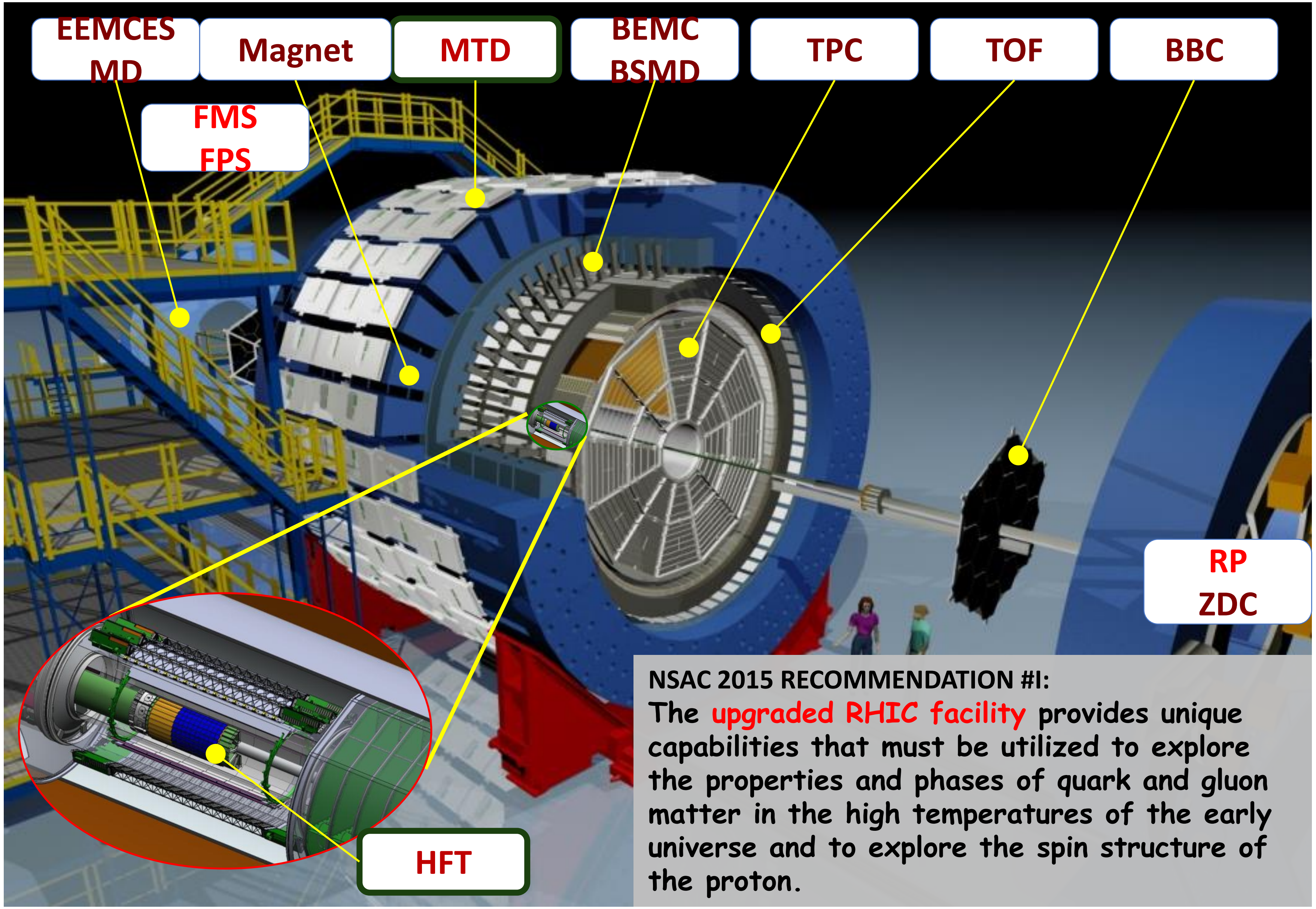
www.star.bnl.gov

The STAR experiment
at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory

SHANDONG UNIVERSITY 1901

BROOKHAVEN NATIONAL LABORATORY

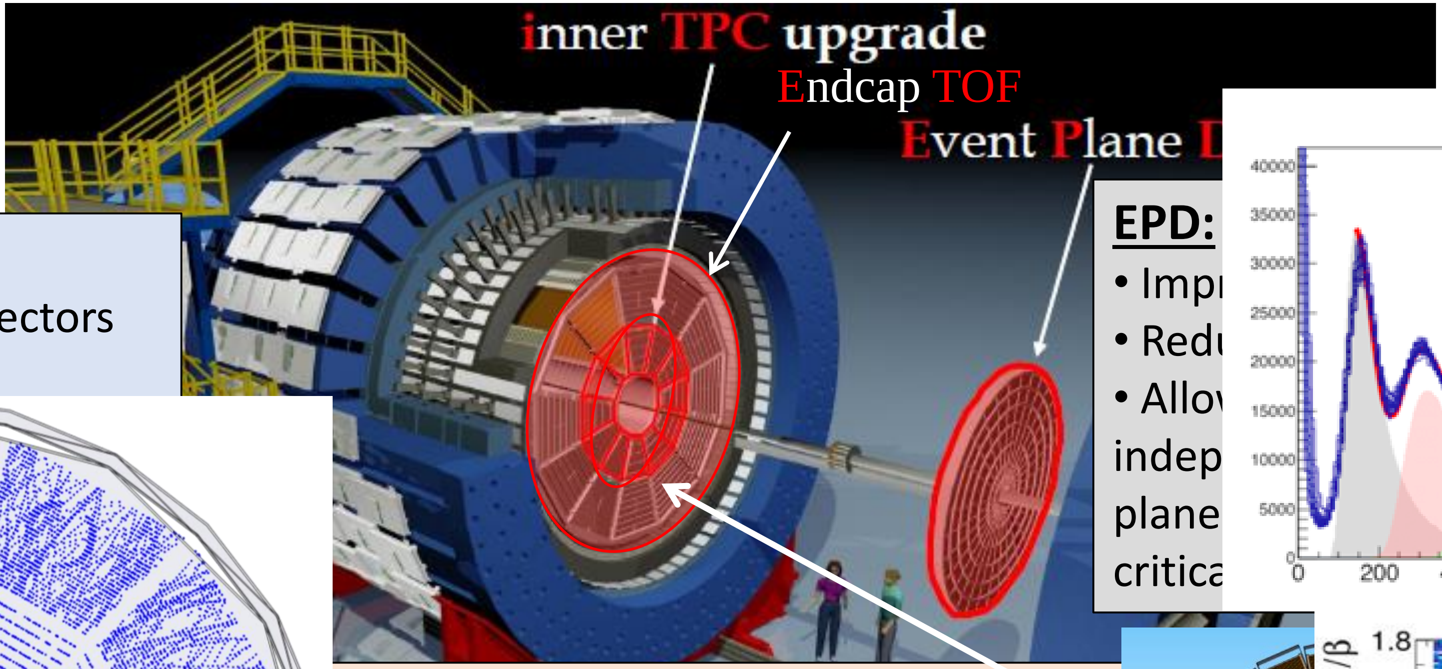
# Current STAR Detector System



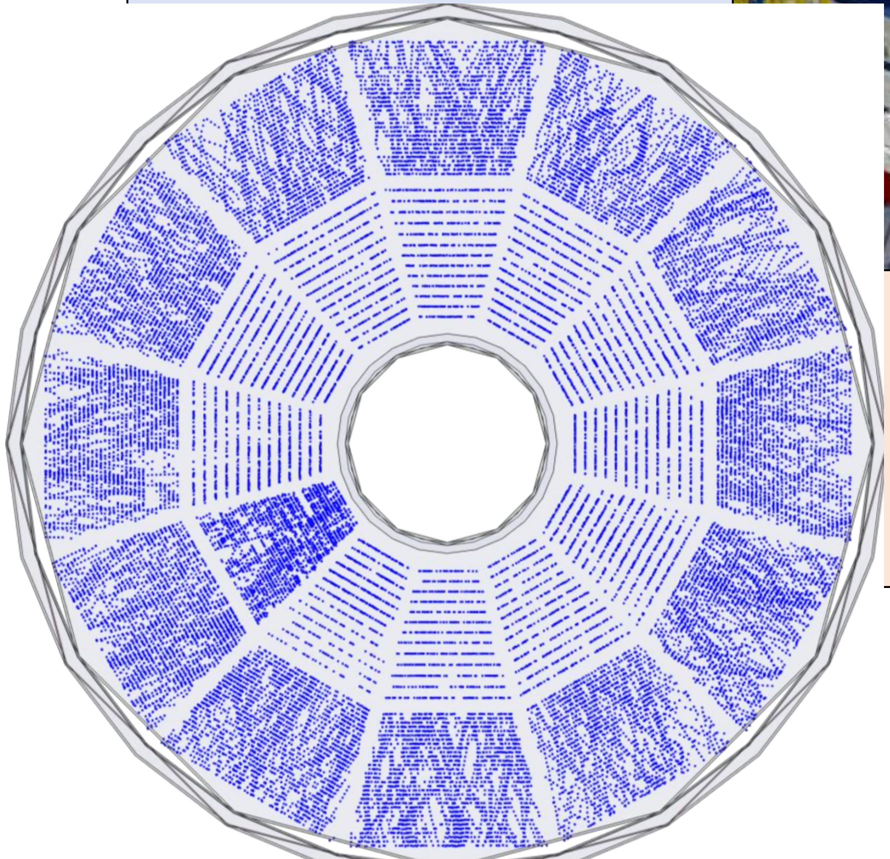

NSAC 2015 RECOMMENDATION #I:
The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.

x10$^3$ increases in DAQ rate (4000Hz) since 2000, most precise Silicon Detector(HFT 2014-16)

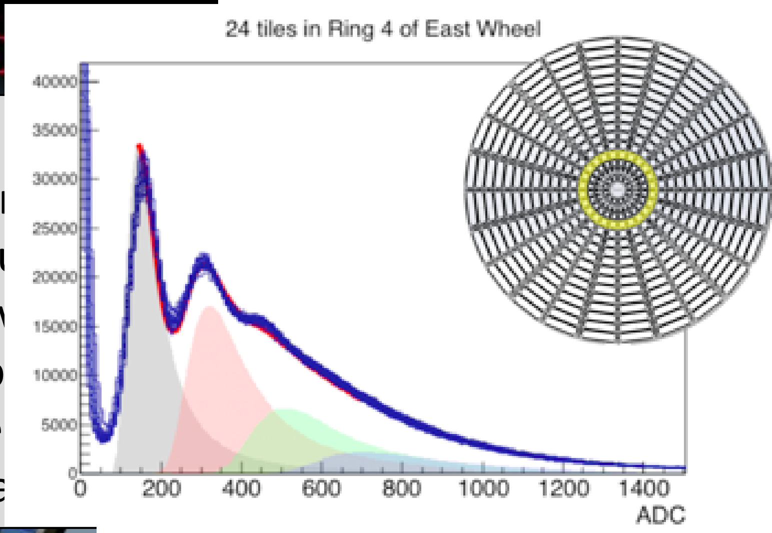
# STAR Major Upgrades for BES-II (2019-2021)



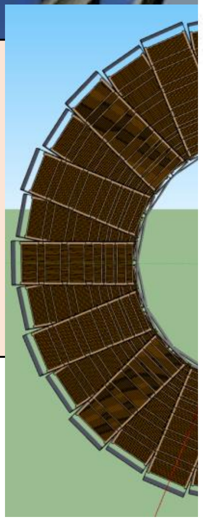

**iTPC:**
- Replace the inner sectors of the TPC

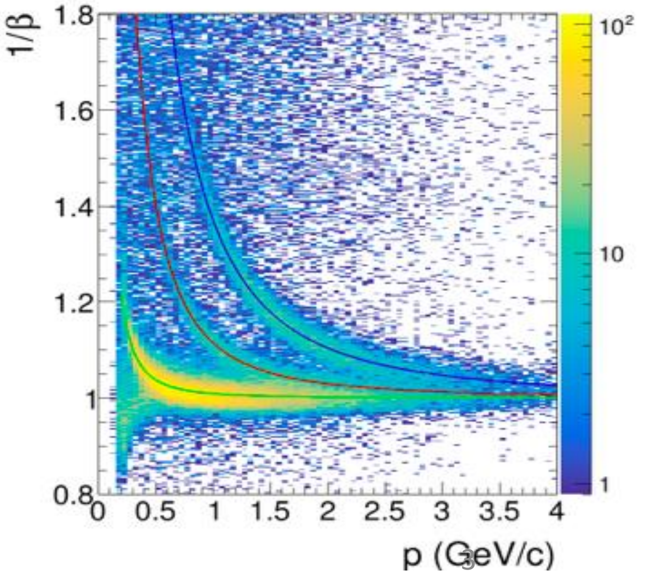


**EPD:**
- Impr
- Redu
- Allov indep plane critica




**EndCap TOF:**
- Rapidity coverage is critical
- PID at η = 0.9 to 1.5
- Improves the fixed target program
- Provided by CBM (FAIR Phase-0)






**Tracking and PID**
**From rapidity±1**
**Extend to (±)1.5**

# The STAR Forward Upgrade

| Detector | pp and pA | AA |
|---|---|---|
| ECal | ~10%/√E | ~20%/√E |
| HCal | ~60%/√E | --- |
| Tracking | charge separation photon suppression | $0.2<p_T<2$ GeV/c with 20-30% $1/p_T$ |

Forward Tracking System:

**3 Silicon disks:** at 90, 140, 187 cm from IR
Built on successful experience with STAR IST

- Single-sided double-metal mini-strip sensors
- Existing IST FEE, DAQ and cooling system

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

- Position resolution: ~100 mm
- Readout: reuse current STAR TPC electronics
- 1st sTGC prototype to be installed in STAR in 2019
  - 1/4 size of ATLAS sTGC

Forward Calorimeter System:

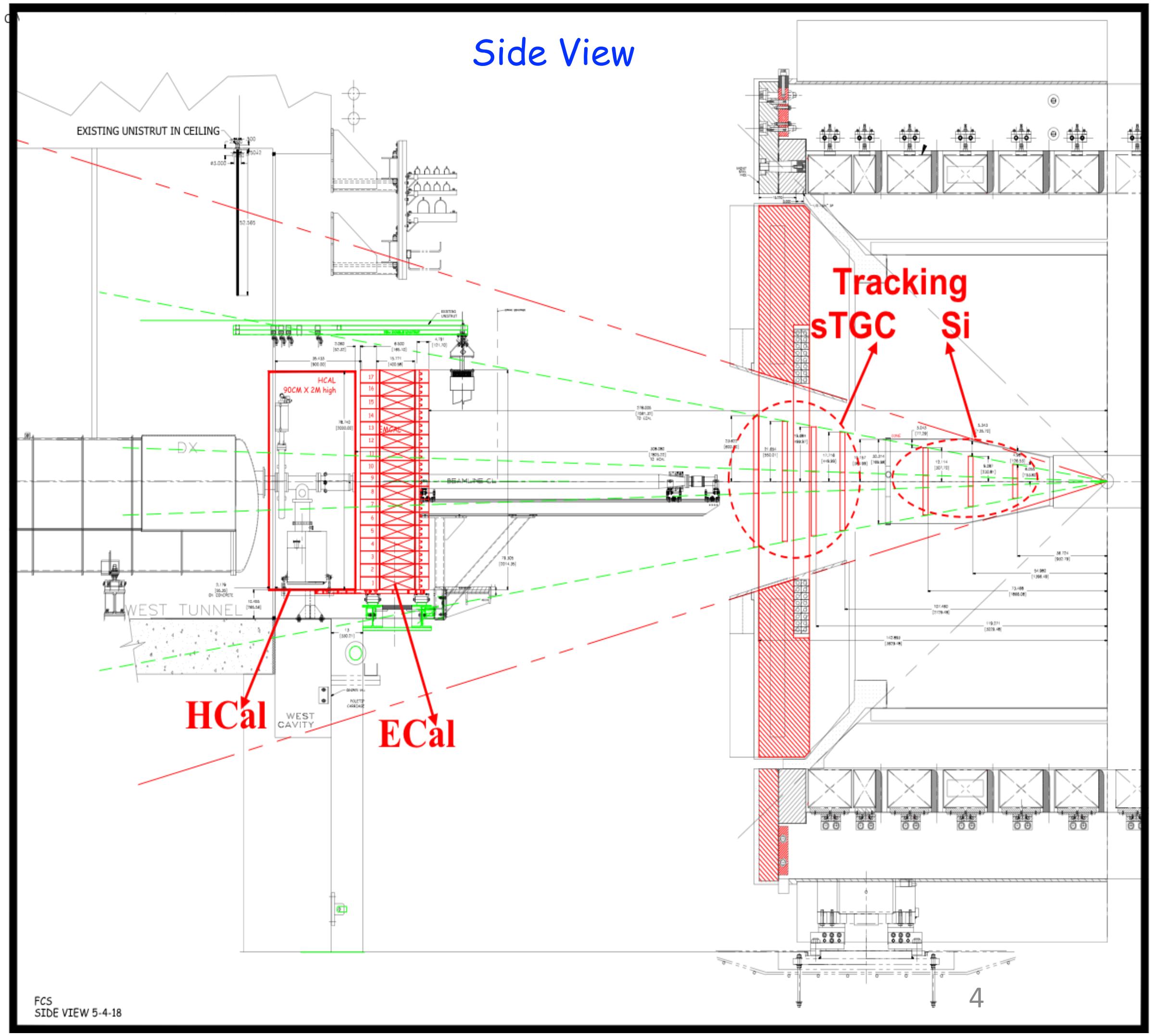
**ECal:**

- reuse PHENIX PbSC calorimeter with new readout on front phase

**HCal:**

- sandwich iron-scintillator plate sampling Calo

Same readout for both calorimeters → cost



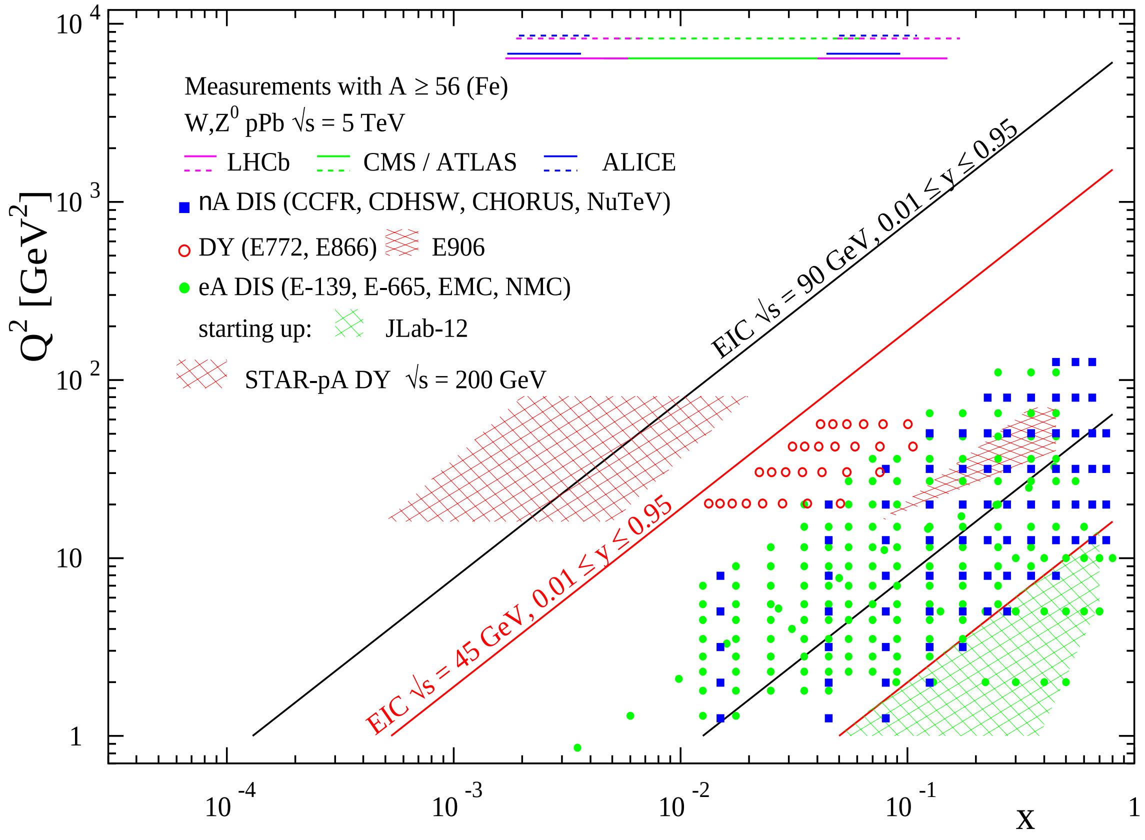
# Nuclear PDF and Initial Conditions for A+A collisions

measure nPDF in a $x$-$Q^2$ region where nuclear effects are large

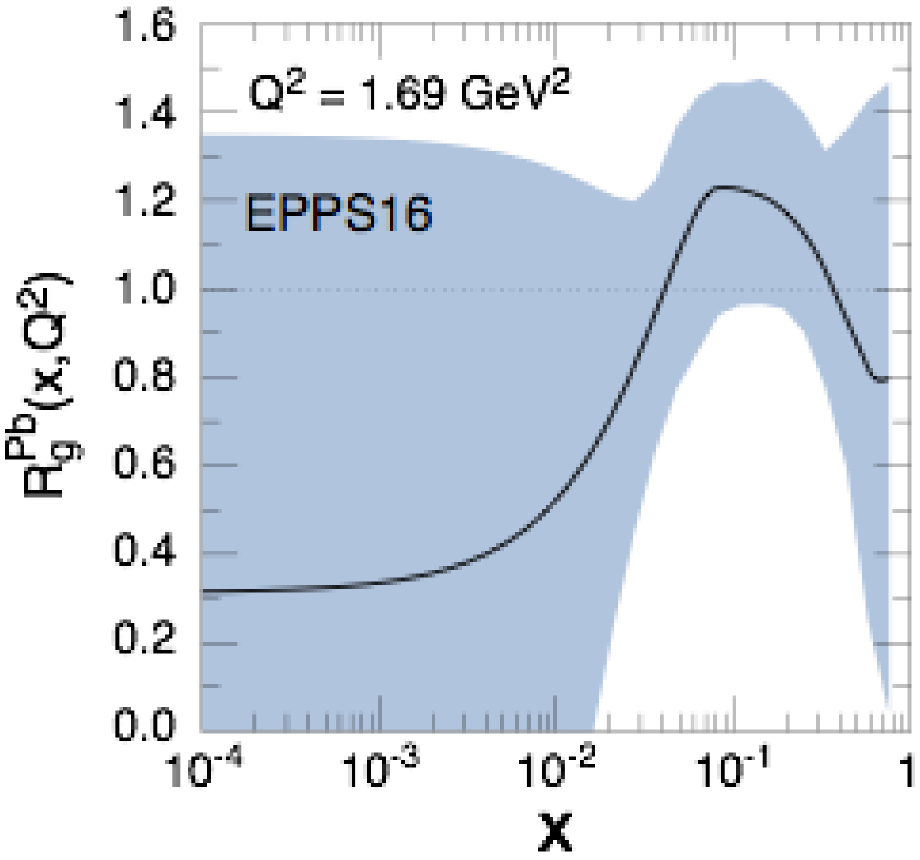
$Q^2 > Q_s^2$ over a wide range in $x$

Forward upgrade essential

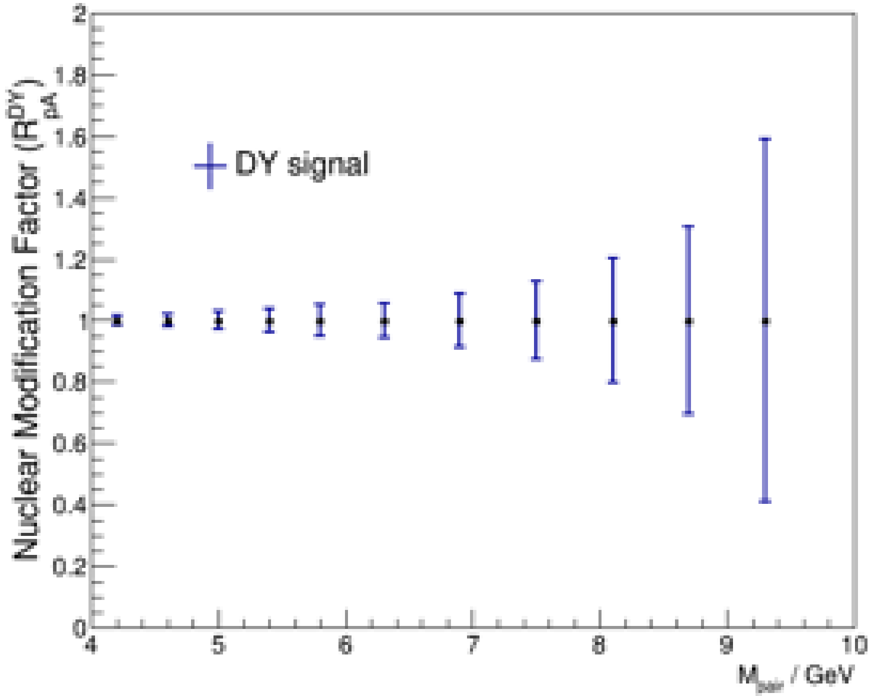
pA@RHIC: unique kinematics




Current knowledge

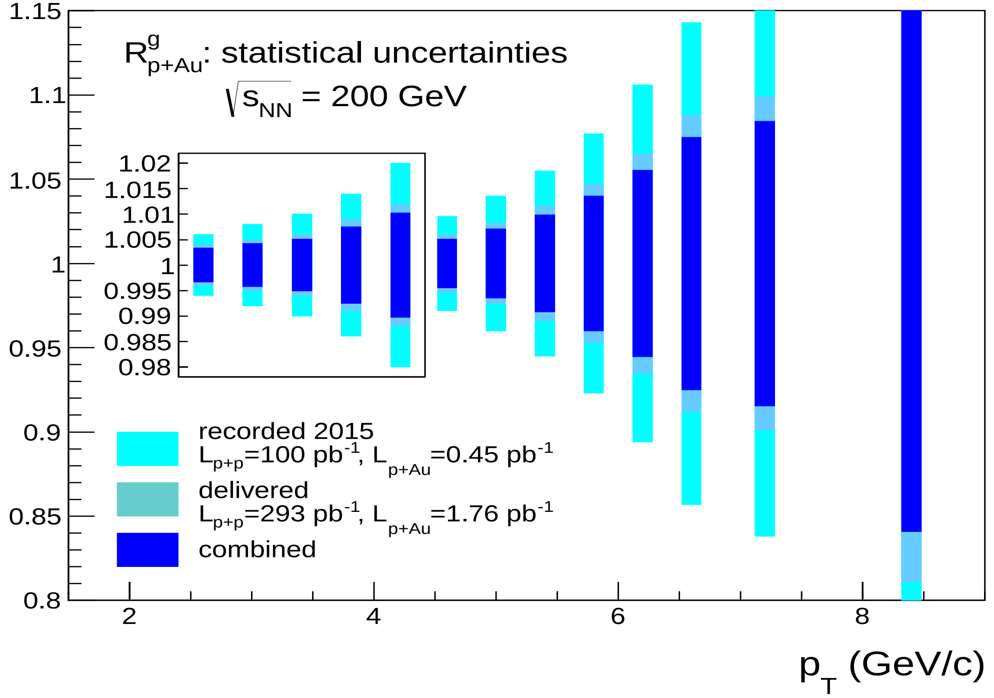


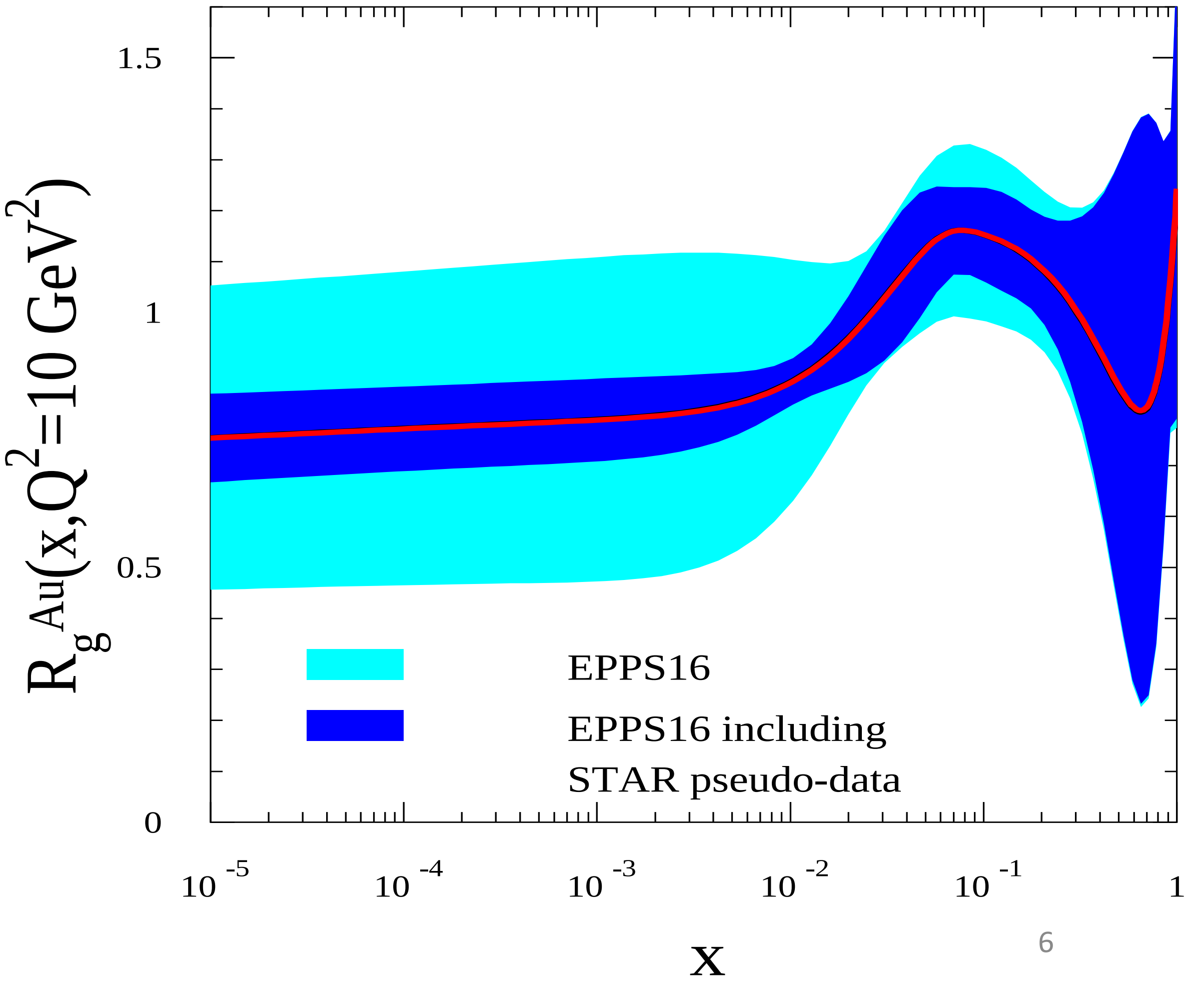
# Forward DY and Photon Measurements




DY and direct photon $R_{pA}$ give significant constraints on nPDF
Important input for initial condition in heavy-ion collisions

Forward upgrade essential

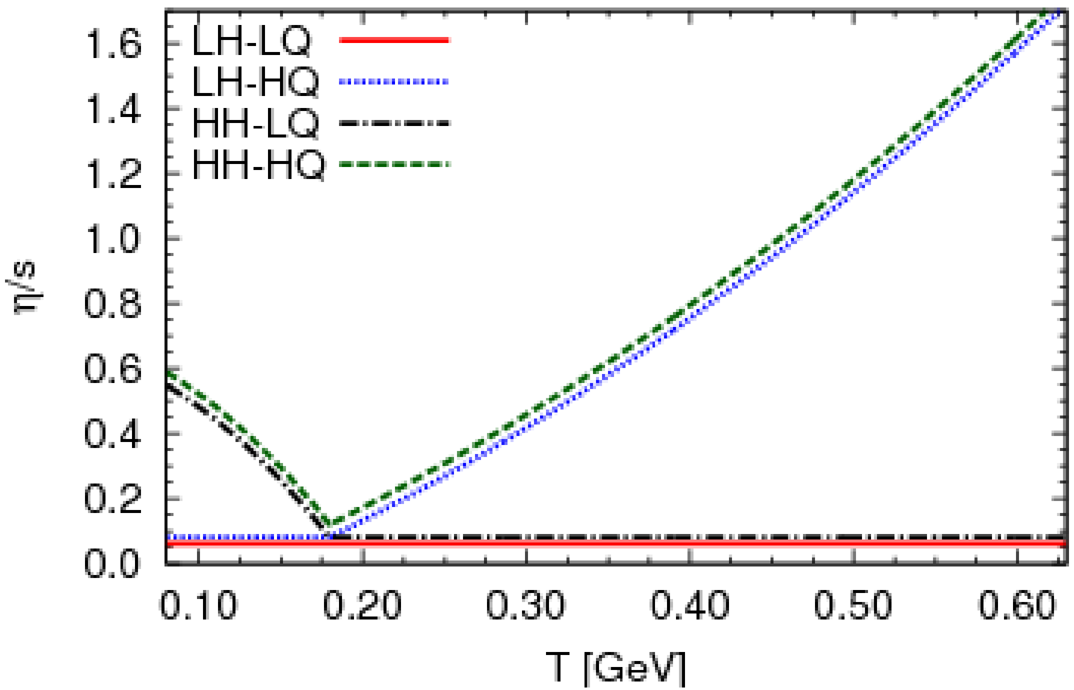


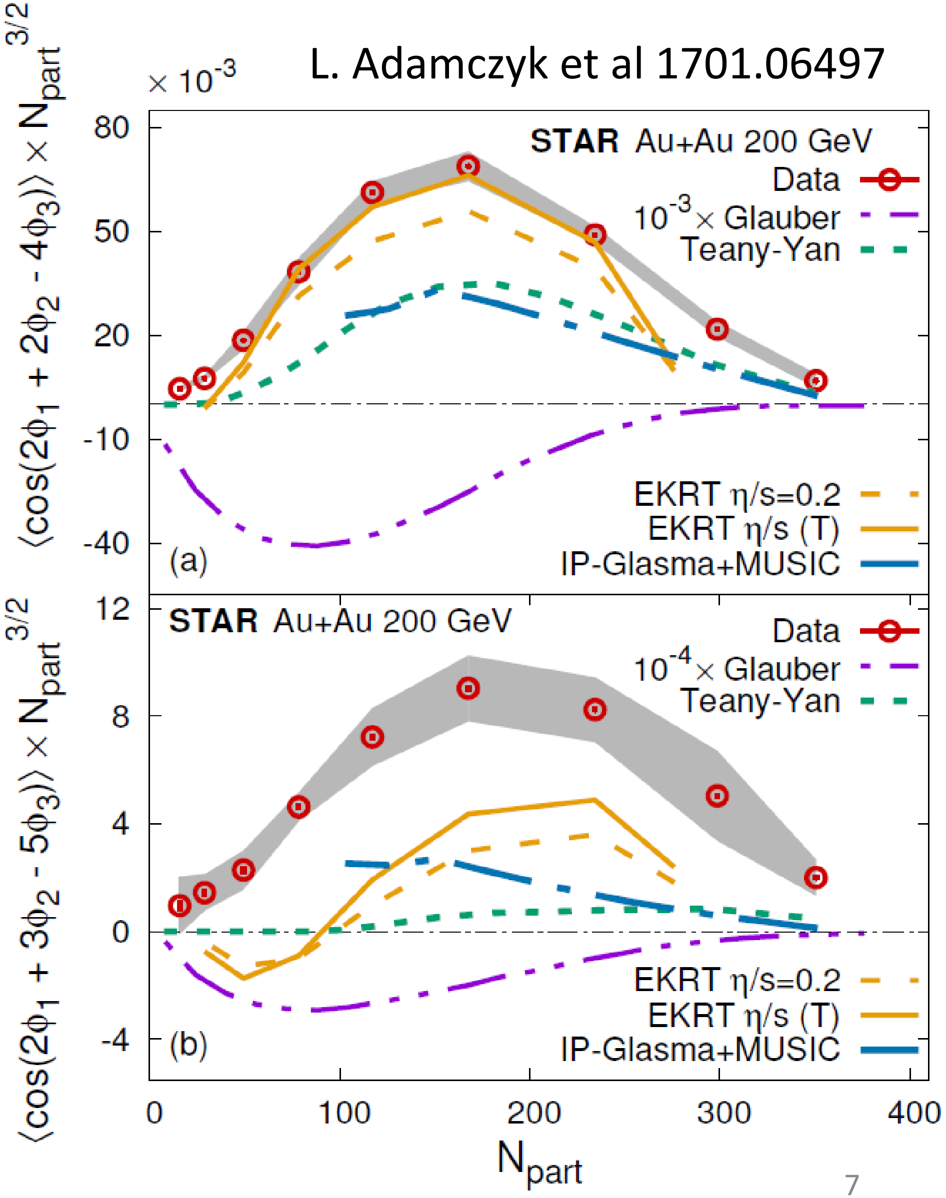
# Temperature Dependent Viscosity

2015 US Nuclear Long Range Plan (#22):
comparative analyses of the wealth of bulk observables being measured hint that the hotter QGP created at the LHC has a somewhat larger viscosity.
This temperature dependence will be more tightly constrained by upcoming measurements at RHIC and the LHC.

Niemi *et al.*, PRL 106 (2011)212302




L. Adamczyk et al 1701.06497



# Multiple Flow Harmonic Correlations

Sparse RHIC data for higher order flow harmonics ($v_3$, $v_4$, $v_5$) & rapidity density correlations/fluctuations

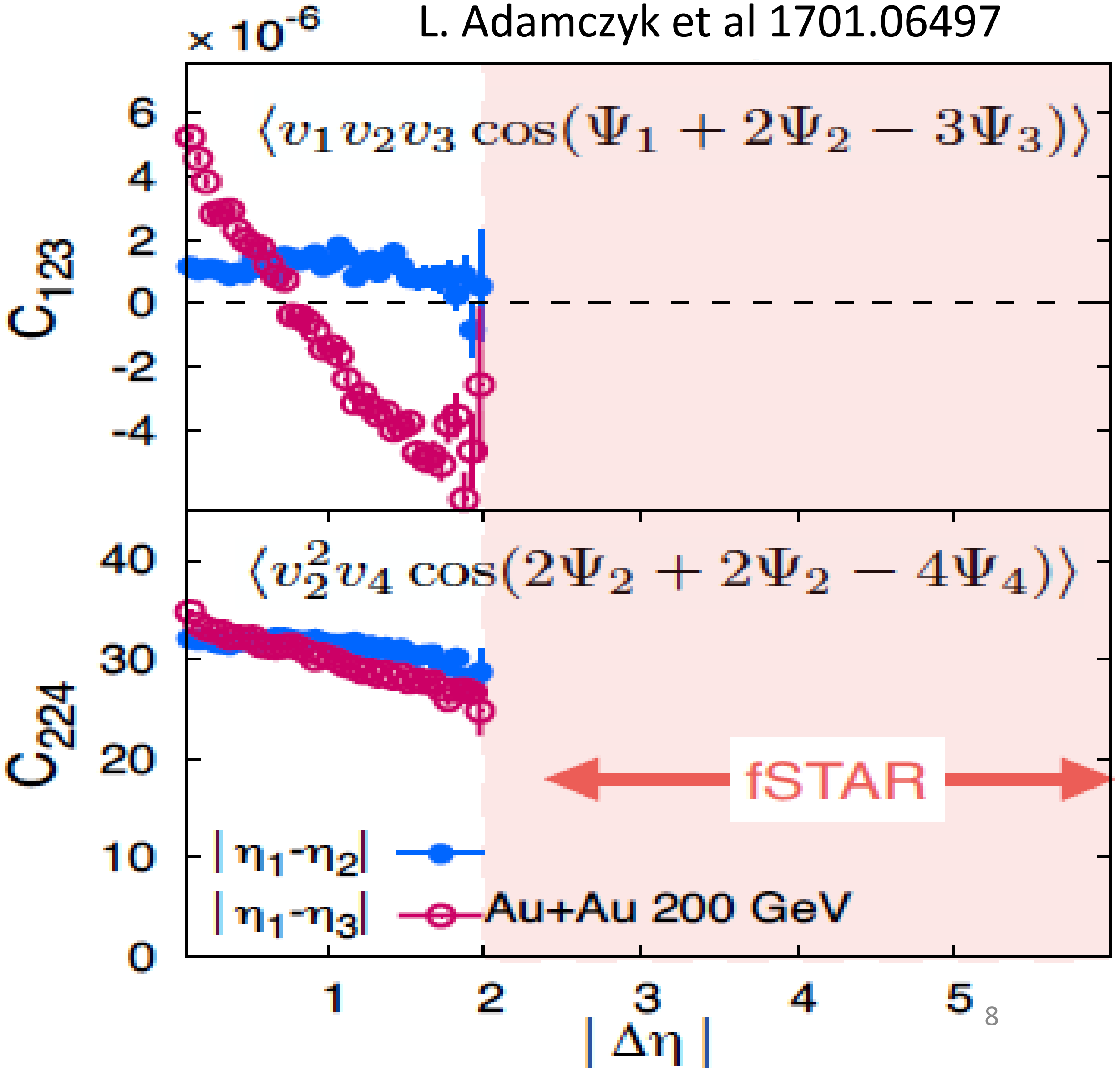
Why do we need wider window in rapidity?

- Flow like correlations are early time long-range → large $\Delta\eta$
- Background comes from Jets & non-flow → small $\Delta\eta$

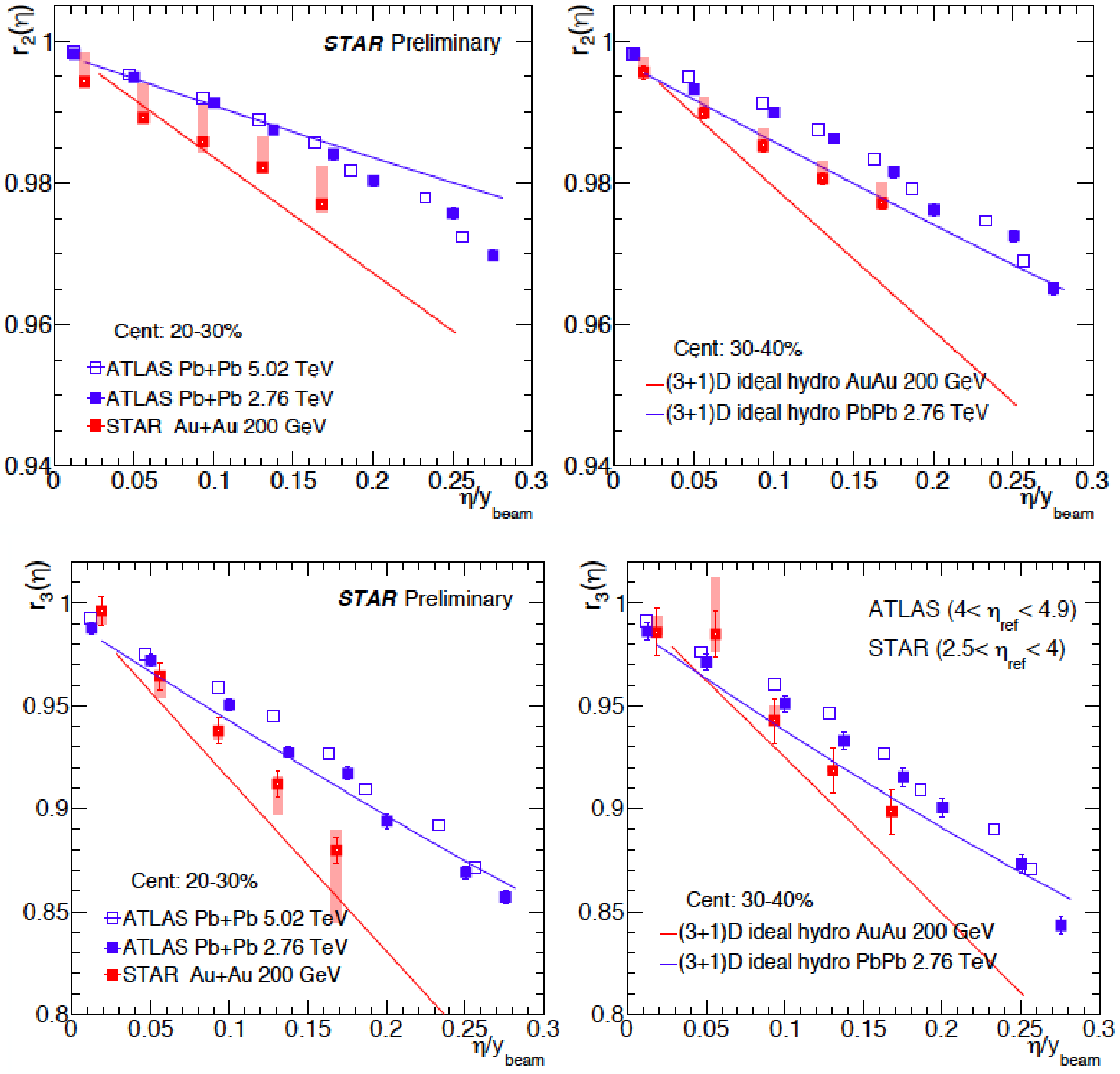
Precise extraction of flow (azimuthal correlations) requires measurements over wide window of rapidity

Forward upgrade essential

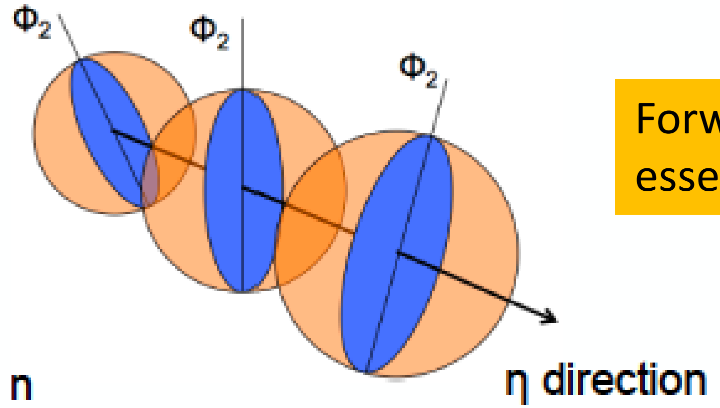
L. Adamczyk et al 1701.06497



# Rapidity Decorrelation and Initial State Fluctuations




## Torque/twist of event plane



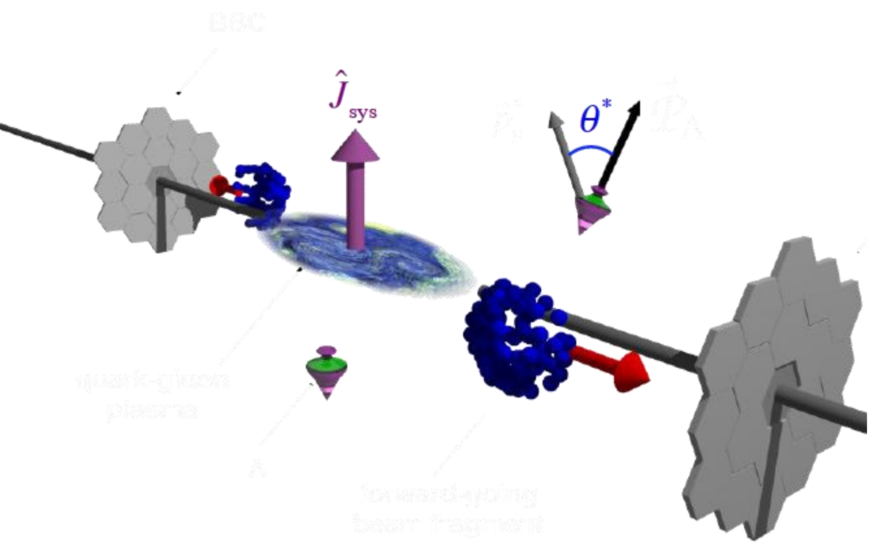

Forward upgrade + EPD essential

$$\Psi_n(\eta_1) \neq \Psi_n(\eta_2)$$

- Rapidity decorrelation sensitive to initial state fluctuations
- Observe large flow decorrelation in longitudinal direction at RHIC
- (3+1)D hydrodynamics tuned for LHC, over-predicts decorrelation at RHIC
- Large uncertainty at RHIC with FTPC and FMS

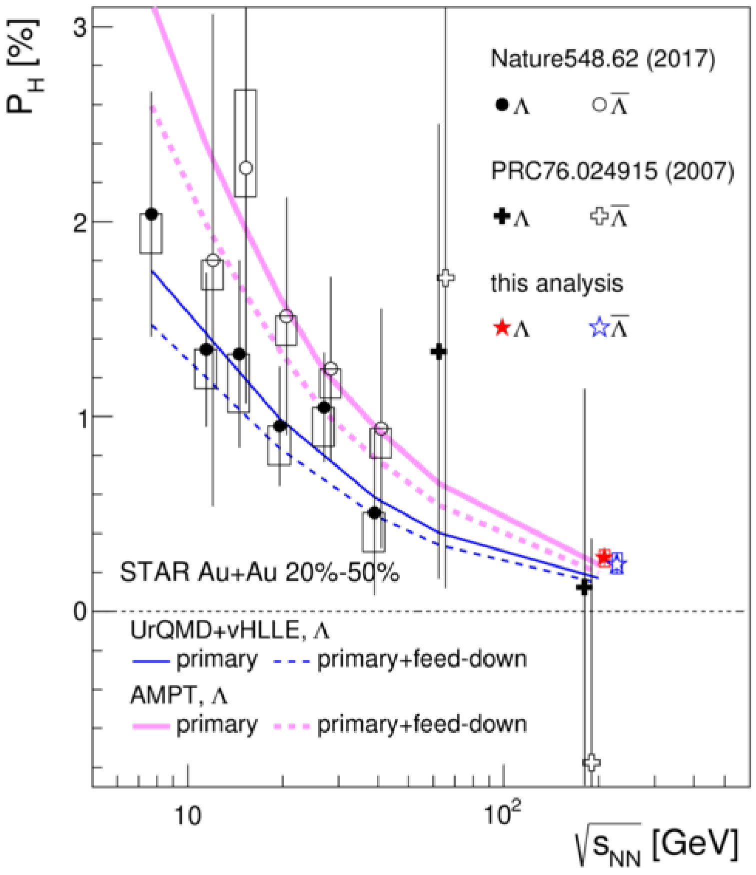
# Global Hyperon Polarization in QGP

new tool to study QGP and Relativistic Quantum Fluid Vorticity in general

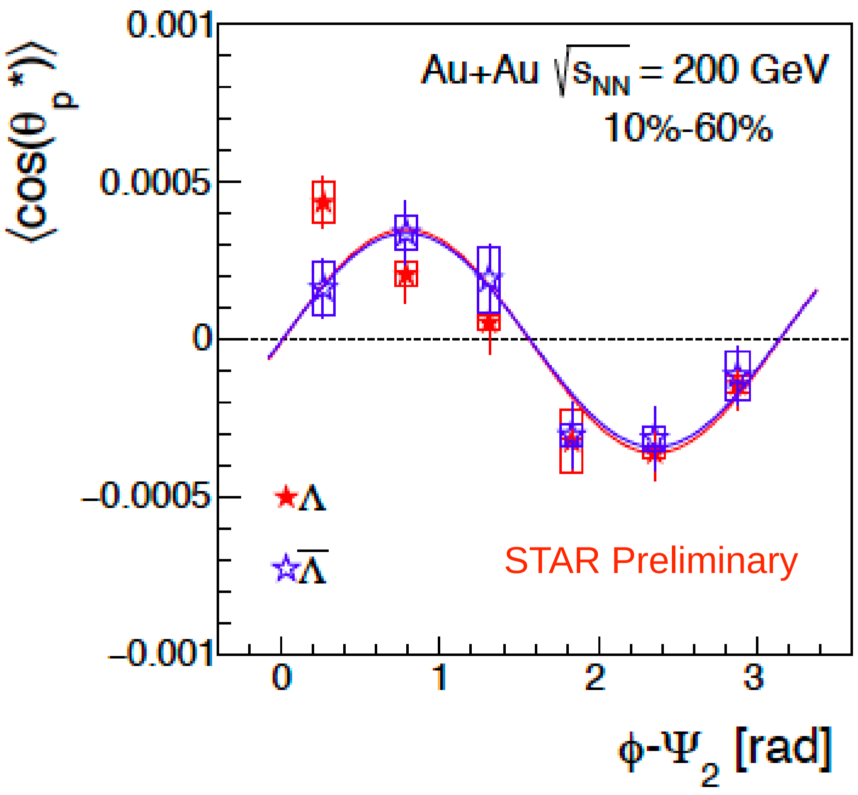



Non-zero global angular momentum transfer to hyperon polarization

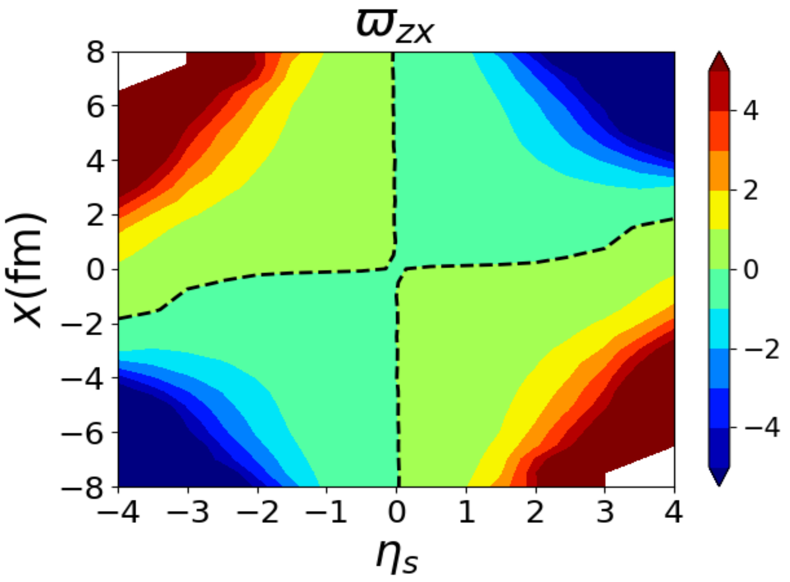
STAR, PRC 98 (2018) 14910

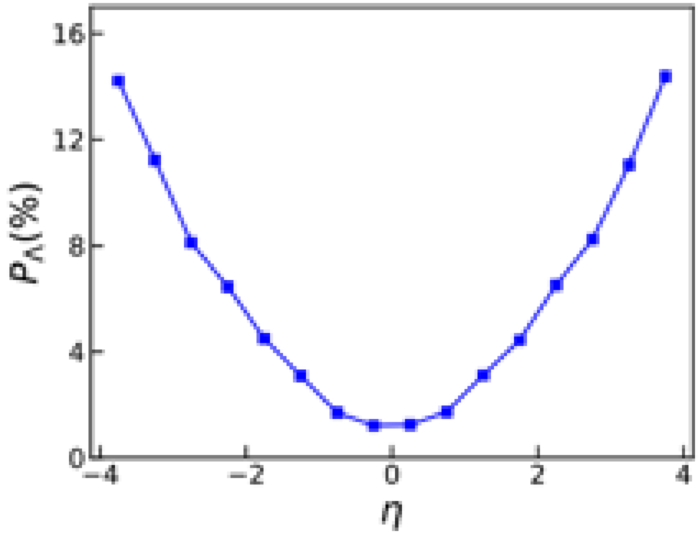



First observation of quadrupole structure of polarization along beam direction;
"sign" opposite to hydro prediction



# Rapidity Dependent Global Polarization



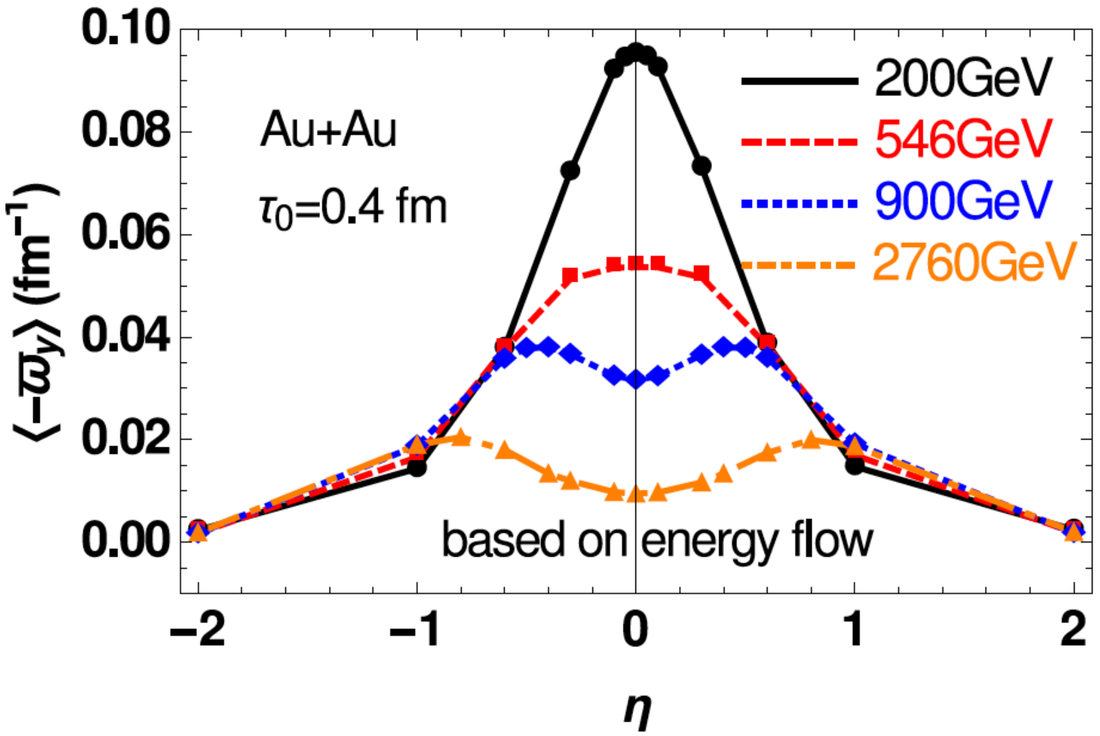




Polarization increases with viscosity and decreases with thermalization,

Rapidity dependence is key;

Different models predict opposite rapidity trend

Forward upgrade + EPD + iTPC essential




Hydrodynamic calculations:
Li,Pang,Wang & Xia, PRC 96 (2017) 054908; (private comm.)
F. Beccattini et al. EPJC 75(2015)406; arXiv:1501.04468

HIJING with energy flow:
Deng & Huang, PRC 93 (2016) 064907

# Quantifying Chiral Symmetry Restoration and Thermal Radiation

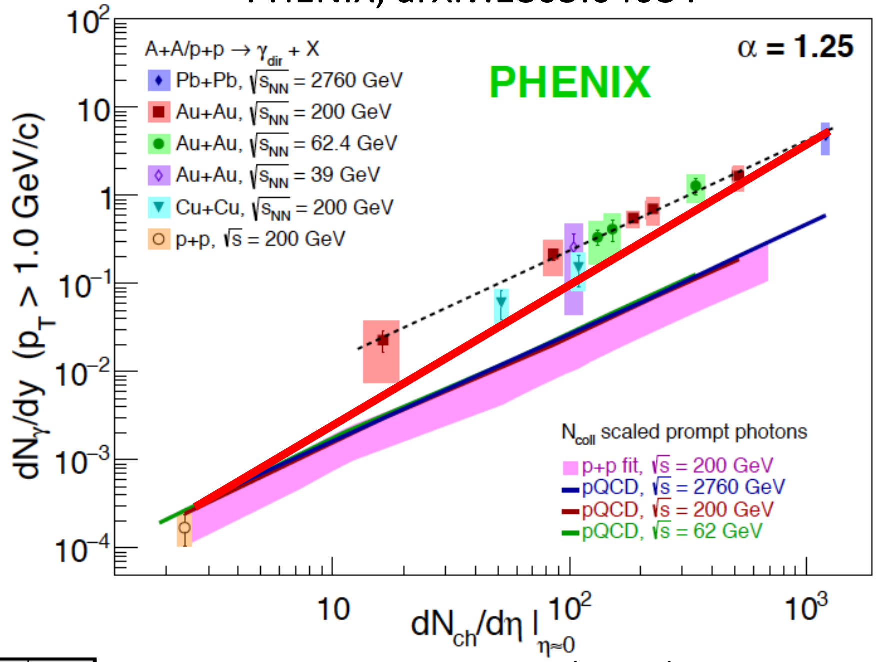
**QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS**

E.V. SHURYAK
*Institute of Nuclear Physics, Novosibirsk, USSR*

Received 16 March 1978

The best known example is dilepton production ($\mu^+\mu^-$, $e^+e^-$), in which deviations from the Drell–Yan model [1] for dilepton mass $M \lesssim 5$ GeV reach a factor

PHENIX, arXiv:1805.04084




**Photon Puzzle:**

yields of photons above model prediction at RHIC

photon $v_2$ systematically above model

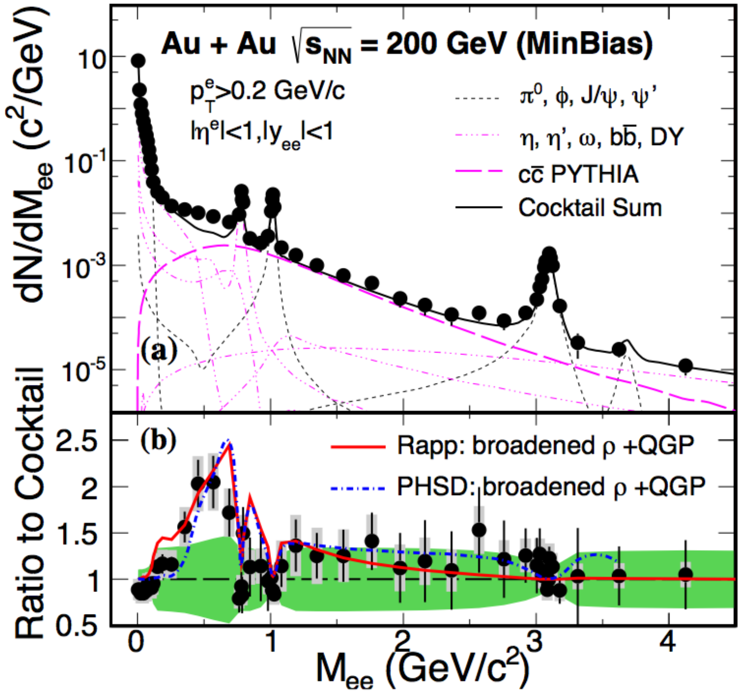
STAR at RHIC:

virtual photon spectra match Model

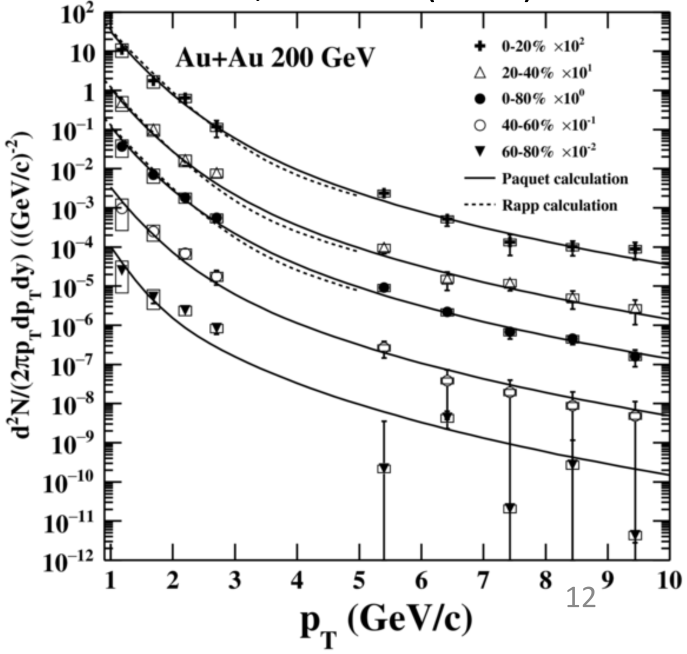
Low-mass dilepton excess matches model

**Important to resolve the puzzle**

STAR, PRL113(2014)




STAR, PLB 770 (2017) 451

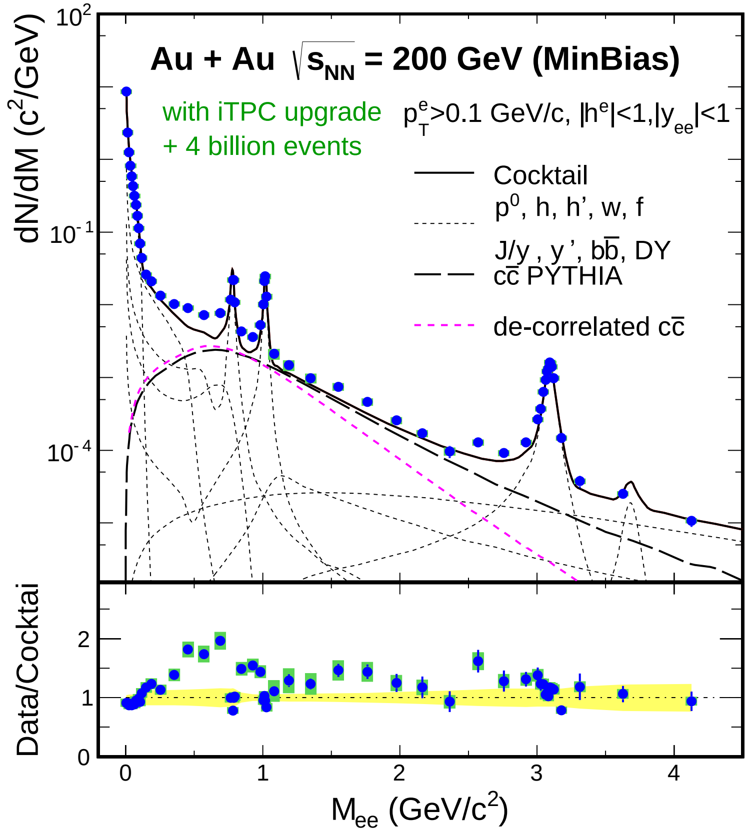


# Thermal Dilepton at Low and Intermediate Mass

Mid-rapidity $e^+e^-$ measurement at $\mu_B \sim 0$:

- Connection to chiral symmetry restoration
- Thermal radiation from QGP

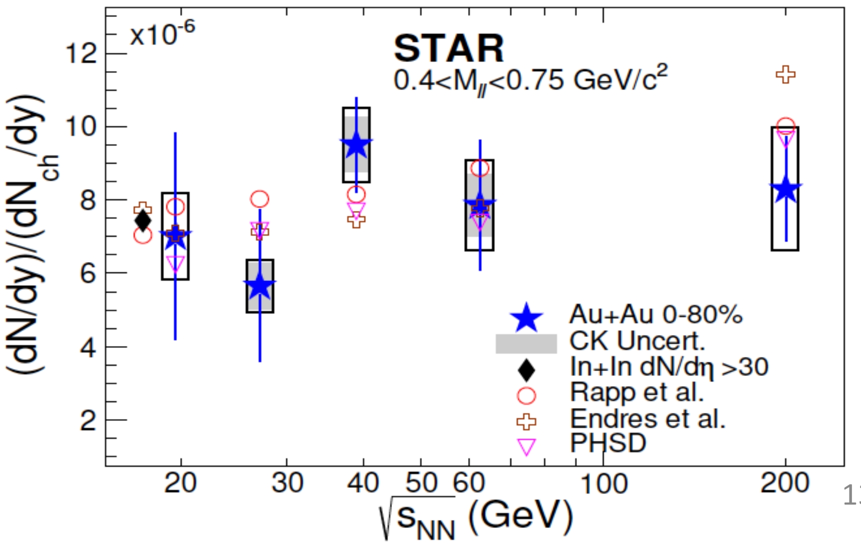
iTPC upgrade essential




Low-mass di-lepton emission:
T, total baryon density, and life time; more importantly dynamics of approaching Chiral Symmetry

The slope T in IMR:
the true average temperature T of the medium.

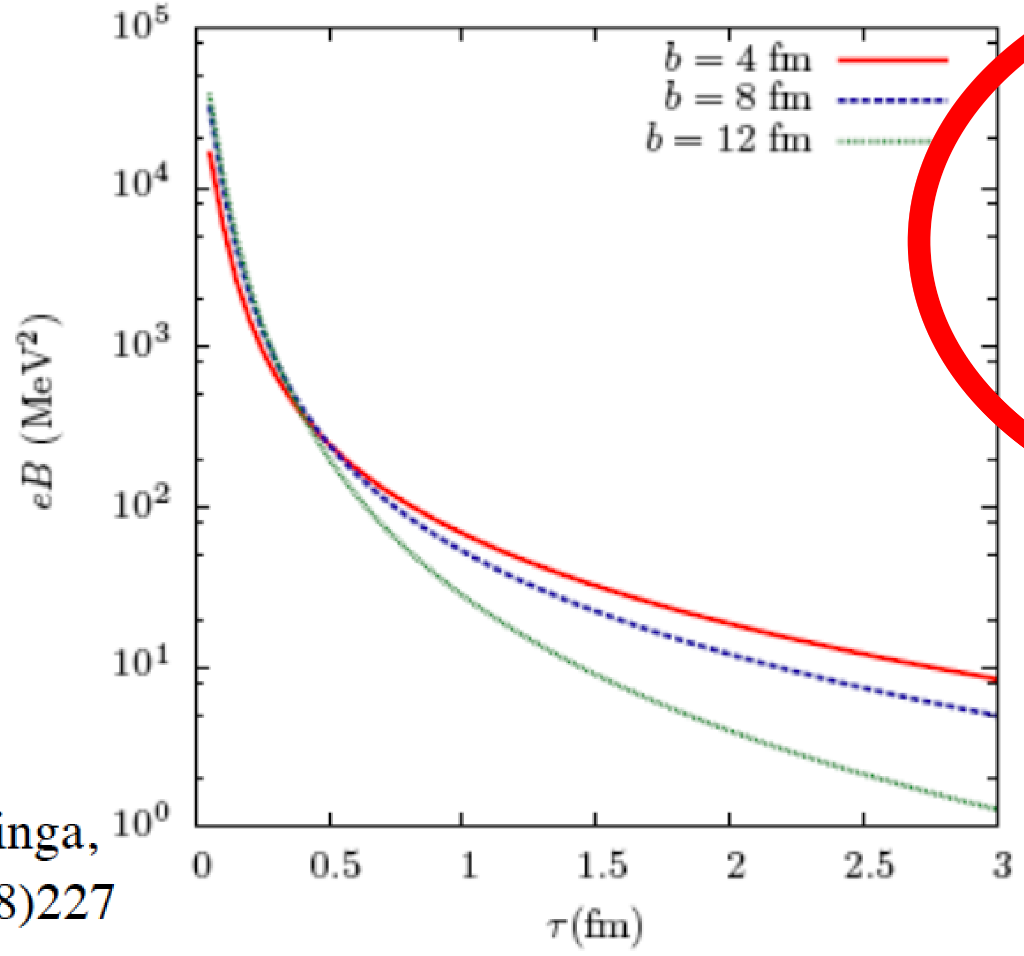
(no blue shift by flow)




Improvement:
Factor 2 smaller systematic uncertainties
Factor 5.5 more statistics

# Heavy ion collisions as a source of the strongest magnetic fields available in the Laboratory

Also:
V. Skokov,
V. Toneev,
A. Illarionov...




In a conducting plasma, Faraday induction can make the field long-lived:
K.Tuchin, arXiv:1006.3051

**QGP as conductor**

NB: magnetic flux is conserved in MHD! - expect the effect at LHC

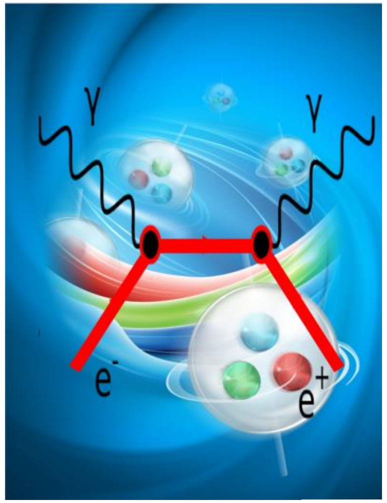
DK, McLerran, Warringa, Nucl Phys A803(2008)227

Fig. A.2. Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).

**D. Kharzeev**

QUARK MATTER ANNECY 2011

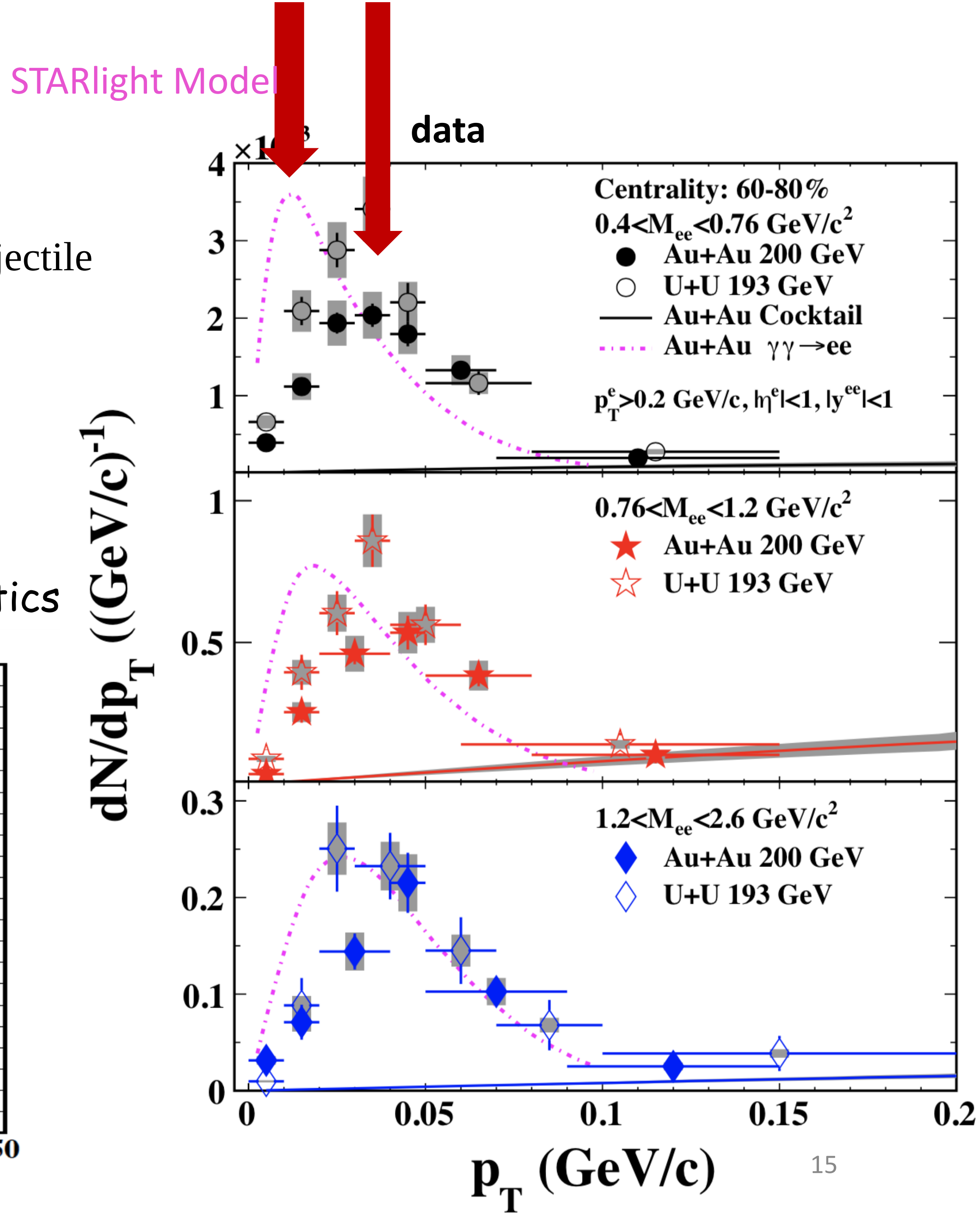
# Probe Magnetic Field and QGP Conductivity



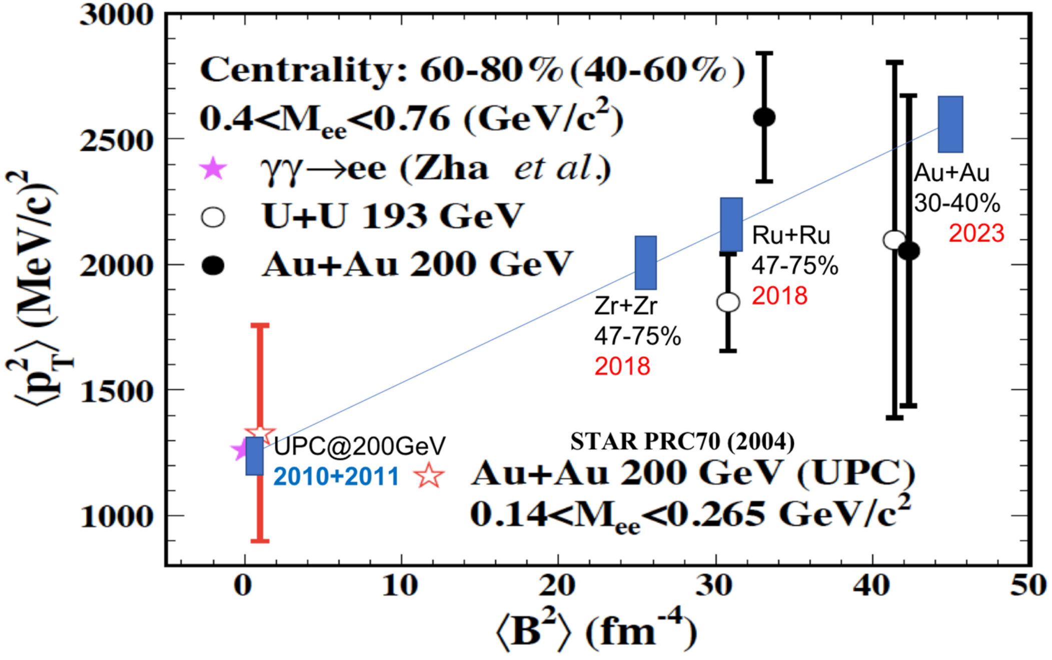

$e^+e^-$ pair from Photon-photon collisions generated by the passing of target and projectile nuclei, accompanying formation of QGP

Spectra peaks at $p_T$=30-50MeV,
right magnitude to be very sensitive to magnetic field

*Clean probe with unique characteristics*

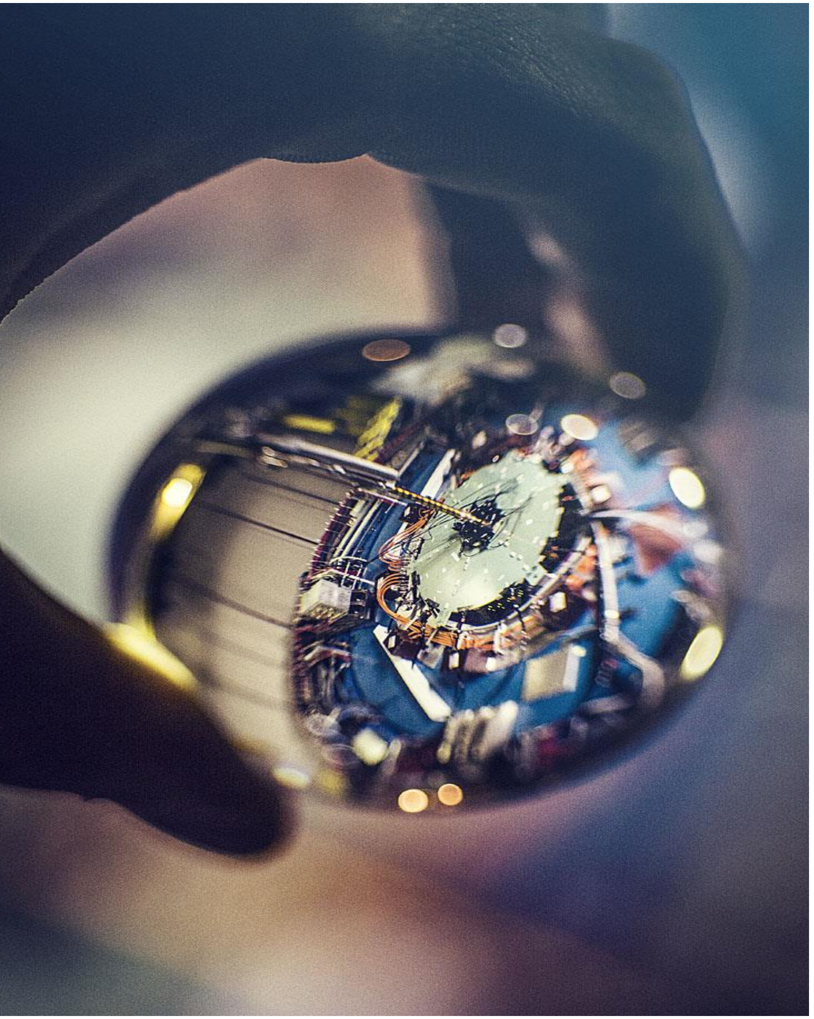



iTPC upgrade essential



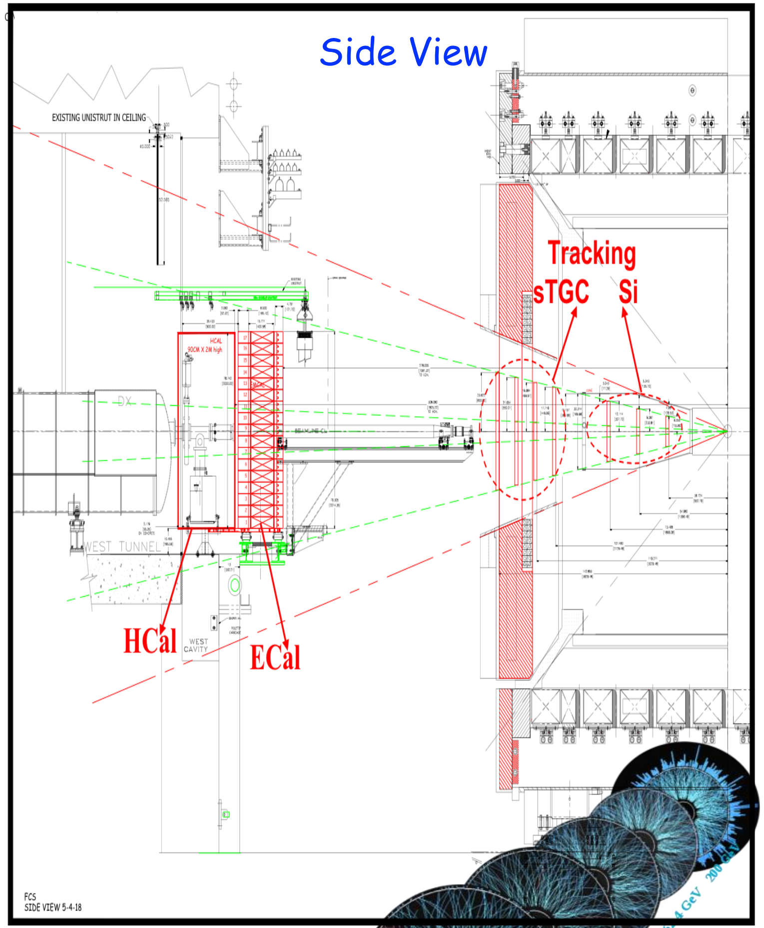

Need more statistics for mid-central centrality

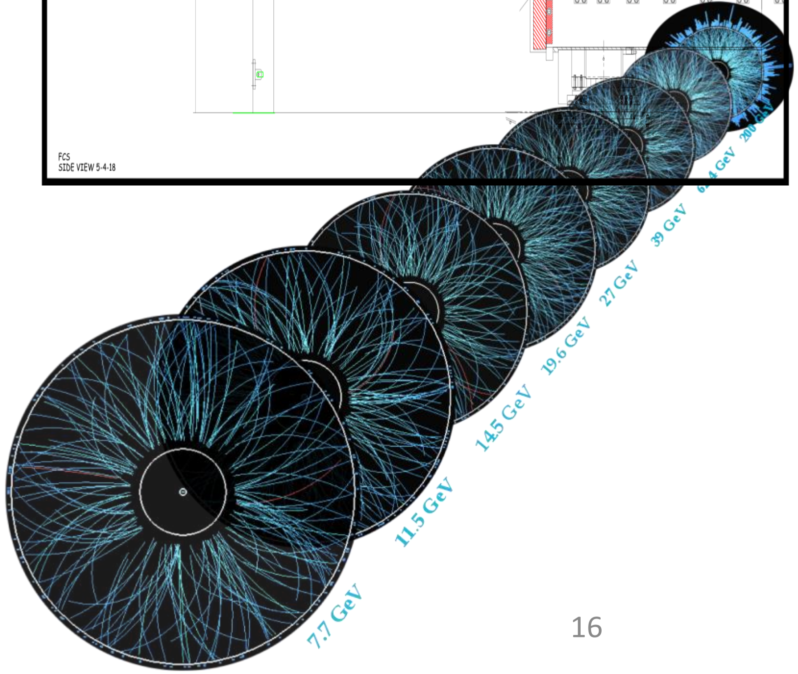
# Summary on STAR future 2021+



- Quantitatively improve nuclear PDF
- Quantifying QGP properties of Viscosity, understanding mechanics of Vorticity and polarization
- Quantifying degree of freedom and resolving photon puzzle
- Potential new study of QGP properties: Conductivity
- Jets, Quarkonia, Beam Energy Scan phase II and many other measurements

**Unique Detector Capability and beam species/energies To address fundamental physics**



# ***Backup slides***

# STAR Public documents on future programs and upgrades

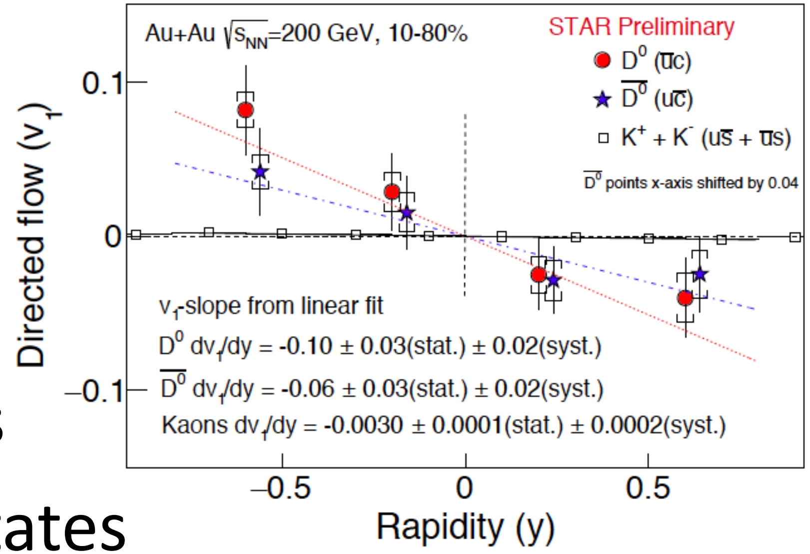
1. SN0696-May. 1, 2018,*STAR Collaboration Beam Use Request for Runs 19 and 20*
2. SN0669-May. 11, 2017,*The STAR midrapidity pp, pA, AA physics program beyond BES-II*
3. SN0688-Mar. 9, 2018,*Results from Large Scale STAR Raw Data Reconstruction on NERSC HPC*
4. SN0670-May. 15, 2017, *STAR Collaboration Beam Use Request for run 18 and run 19*
5. SN0657-May. 30, 2016, *The STAR Beam Use Requests for run 17 and run 18 (2016)*
6. The RHIC Cold QCD Plan from 2017 to 2023: A portal to the EIC - Jan. 2016, draft: **December 2015**
7. SN0666-May. 1, 2016,*An Event Plane Detector for STAR*
8. SN0665-Sep. 16, 2016,*Physics Program for the STAR/CBM eTOF Upgrade*
9. SN0648 - January, 2016, **STAR Forward Calorimeter and Forward Tracking Systems beyond BES-II**
10. SN0644 - Nov. 29, 2016, **Technical Design Report for the iTPC Upgrade**
11. SN0640-Oct. 19, 2015, **Physics Opportunities with STAR in 2020+**
12. SN0639-Oct. 15, 2015, **Letter of Interest: CBM TOF as STAR Endcap TOF for BES-II at RHIC**
13. SN0625-May. 19, 2015, **RHIC Beam Use Request for runs 16 and 17**
14. SN0619-Feb. 18, 2015, **A Proposal for STAR Inner TPC Sector Upgrade (iTPC)**
15. SN0617-Jan. 19, 2015, **a case for run16 pp510 (supplementary material)**
16. e-Print: **arXiv:1502.02730**, The Hot QCD White Paper: Exploring the Phases of QCD at RHIC and the LHC
17. e-Print: **arXiv:1501.06477**, Exploring the properties of the phases of QCD matter - research opportunities and priorities for the next decade
18. SN0606-Jun. 2, 2014, **STAR Beam Use Request (BUR) for run-15 and run-16**
19. SN0605-Jun. 1, 2014, **A polarized p+p and p+A program for the next years**
20. SN0598-Mar. 28, 2014, **Studying the Phase Diagram of QCD Matter at RHIC**
21. SN0592-Oct. 1, 2013, **eSTARLetter of Intent**
22. 2014 Computing plan https://drupal.star.bnl.gov/STAR/starnotes/private/psn0622
23. SN0588-Aug. 21, 2013, **EsNETHEP/NP Science Network Requirements 2013**
24. STAR Decadal Plan, December 2010, **https://drupal.star.bnl.gov/STAR/starnotes/public/sn0645**

# STAR Collaboration Institutes from Europe (13/66)

- **AGH University of Science and Technology, Poland**
- **Warsaw University of Technology, Poland**
- **Institute of Nuclear Physics - Polish Academy of Sciences**
- **Czech Technical University in Prague, Czech**
- **Nuclear Physics Institute, The Czech Academy of Sciences**
- **Technische Universität Darmstadt, Germany**
- **Max-Planck-Institut fuer Physik, Germany**
- **University of Heidelberg, Germany**
- **Eotvos Lorand University, Hungary**
- **University of Zagreb, Croatia**
- **Joint Institute for Nuclear Research, Russia**
- **National Research Nuclear University MEPhI, Russia**
- **Institute of High Energy Physics – Protvino, Russia**

# Recent Highlights

- Charm Flow $v_0, v_1, v_2$
- Jet Deflection Angle
- CME Background Estimates
- $R_{AA}$ of Separated Upsilon States




STAR, PRC 96 (2017)