Stony Brook University | The State University of New York

Future physics at STAR and toward EIC

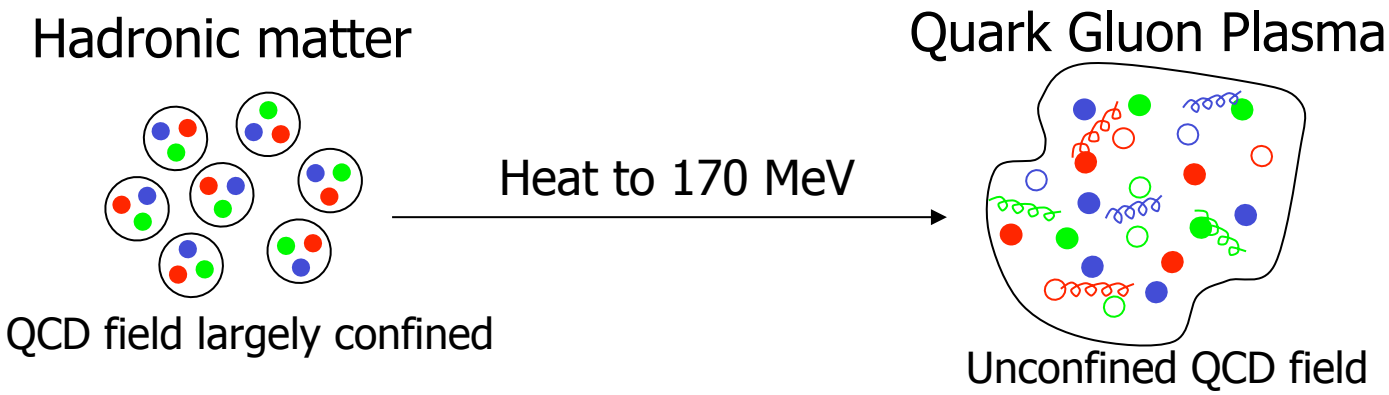
Jiangyong Jia

Stony Brook University & Brookhaven National Laboratory

July 28, 2018

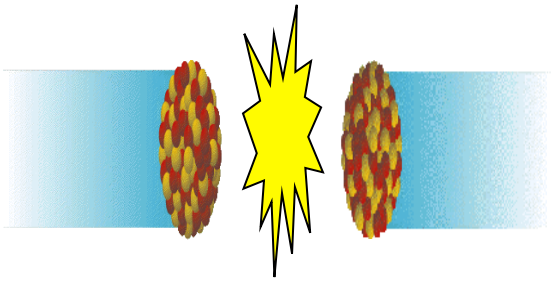
Heavy-ion physics

- Study of non-Abelian QCD matter
  - Consists of nucleons, hadrons, quarks or gluons
  - Occupy extended volume, has finite lifetime



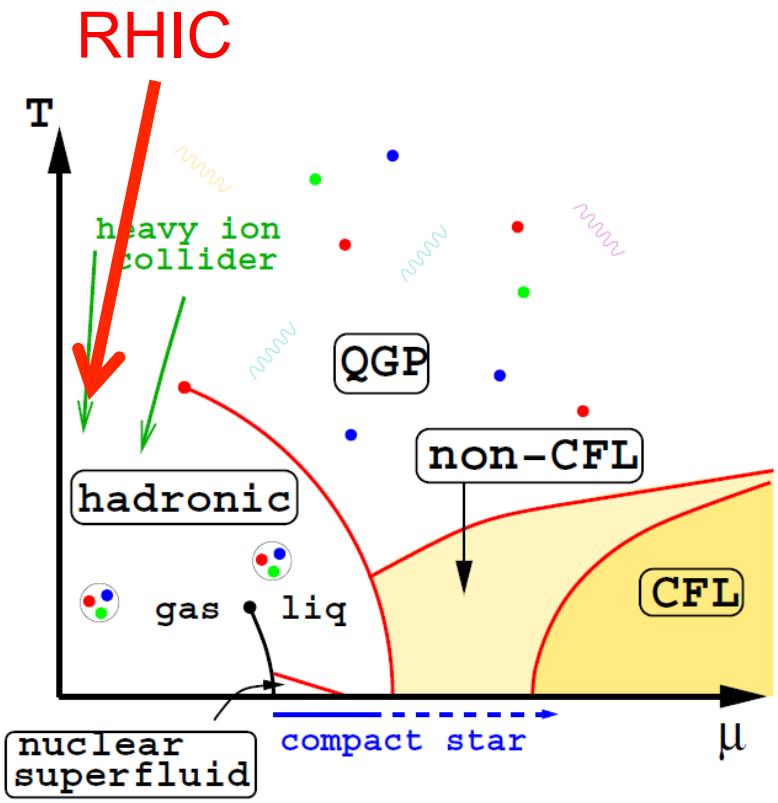
Phases of QCD Matter

- Regions reached by varying √s
  - Matter at RHIC/LHC has high T (~0.4 GeV) and low chemical potential.



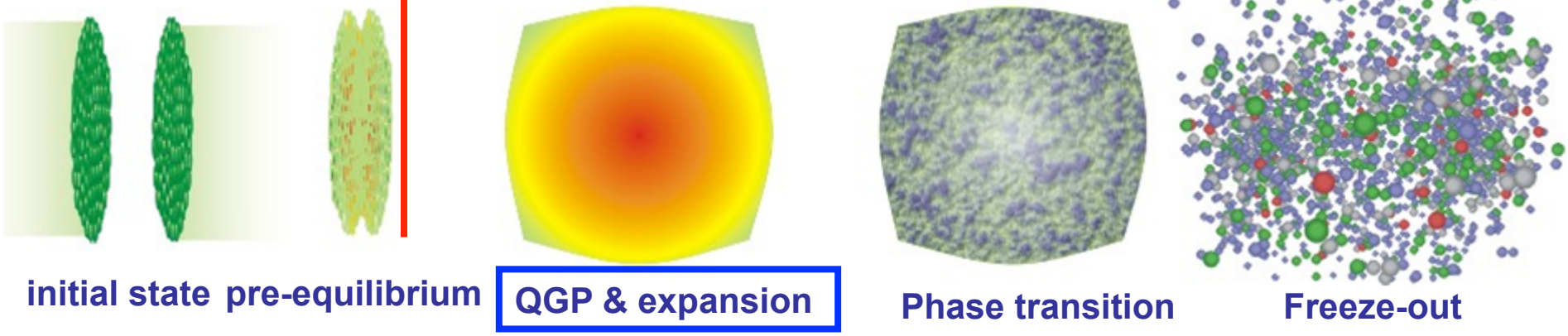
Kinetic energy ➔ heat/matter

- Some big questions:
  - Confinement and Chiral symmetry restoration.
  - Phase boundaries & Phase transitions.
  - QGP equation of state & various transport properties.
  - QCD at finite T: local parity violation and polarization.
  - …



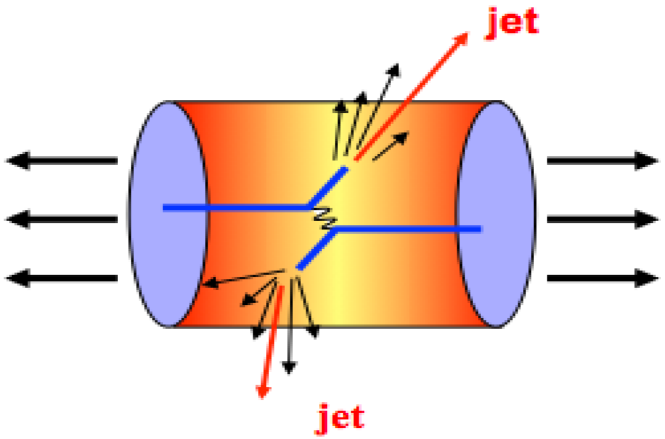
How to study the QCD matter?

DIS ⟷ HI Physics



initial state | pre-equilibrium | QGP & expansion | Phase transition | Freeze-out

Large uncertainty from initial state



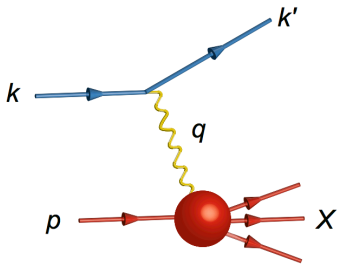
Structure of matter via high-Q^2 probes

Space-time dynamics via bulk particles

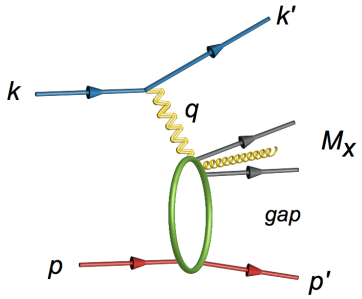
DIS and Heavy Ion

- DIS: Probe initial constituent distribution (one-body Wigner func.)
  - Precise control on collision kinematics

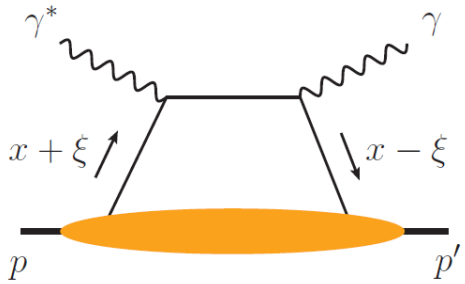
Inclusive

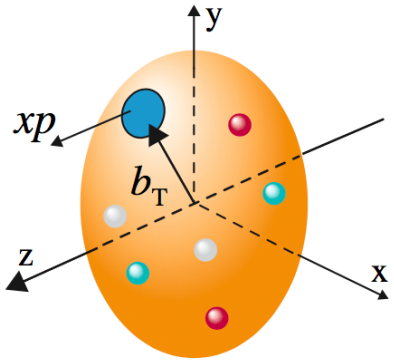


Semi-Inclusive



Exclusive

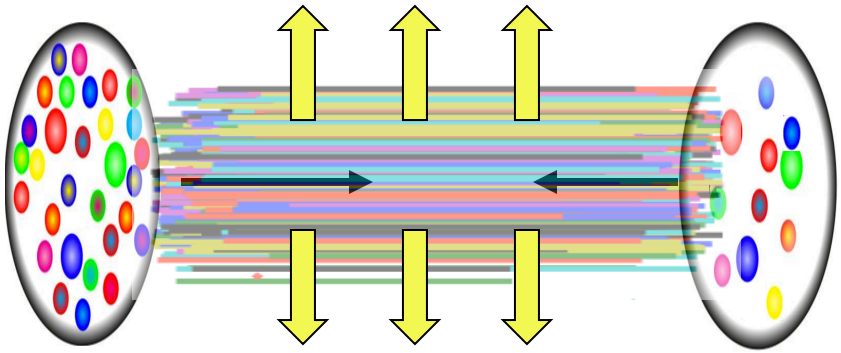




- Heavy-ion: Multi-parton interactions (many-body Wigner function)

Frozen PDF fluctuation

Frozen PDF fluctuation

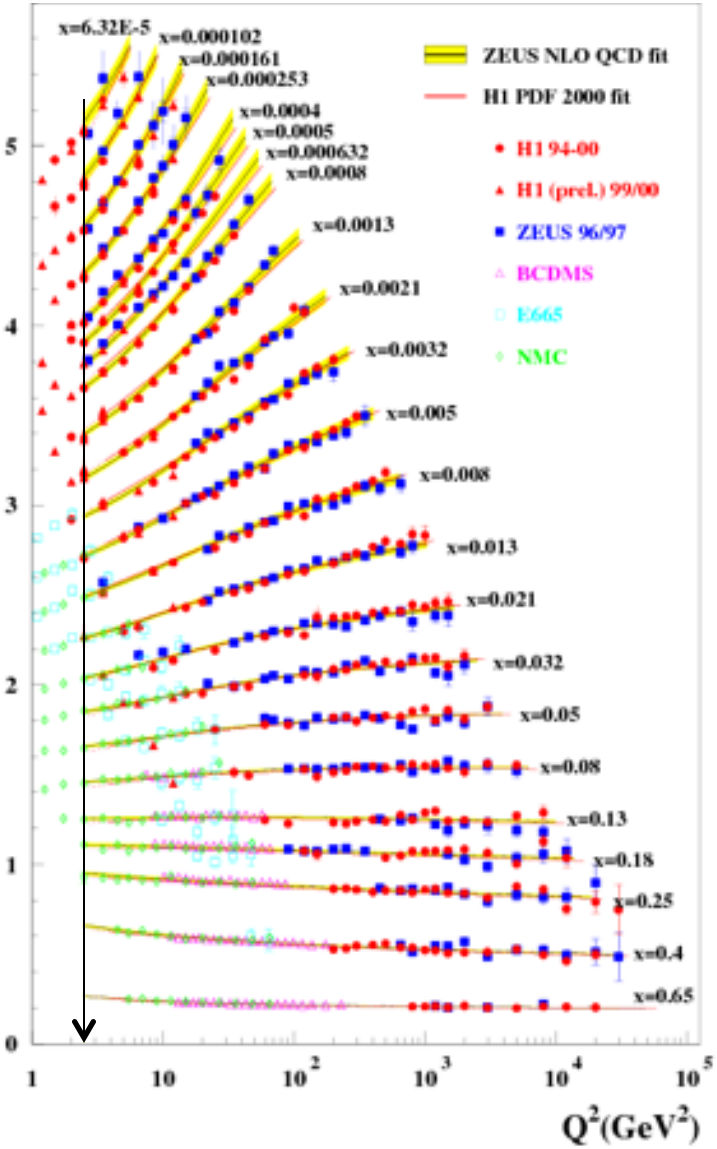


Number of sources and their distributions

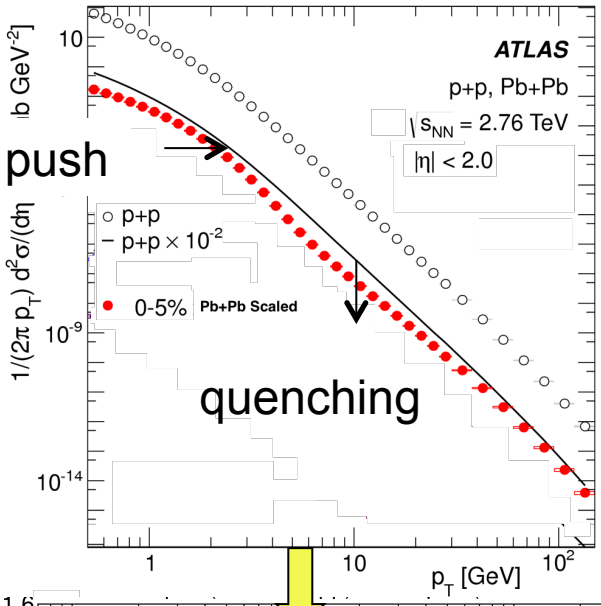
DIS and Heavy Ion

DIS: pQCD works down to Q~1-2GeV

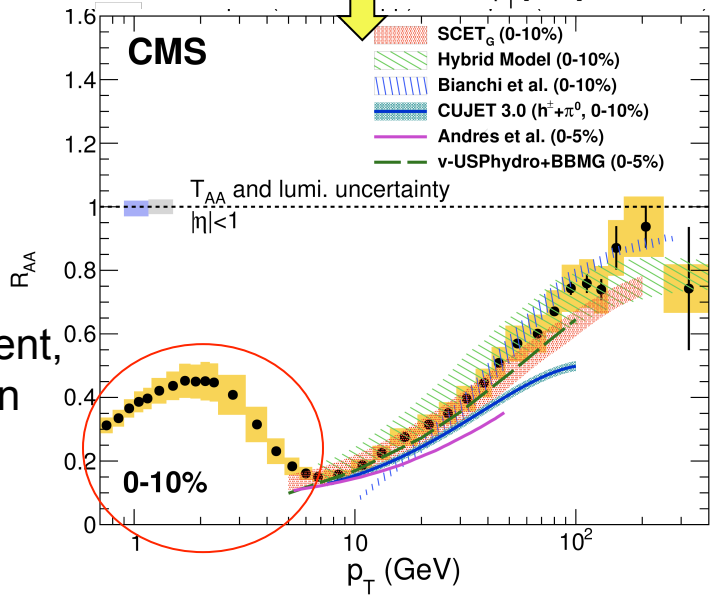
HI: pQCD works only for p_T>5-10 GeV



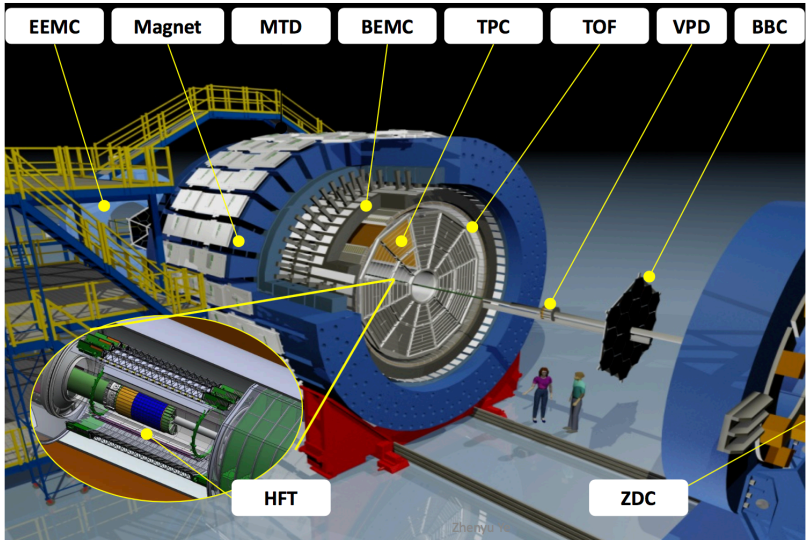
Hydro push



process-dependent, non-pQCD region



STAR at Relativistic Heavy Ion Collider



- **Tracking and PID (full 2π)**
  TPC: $|\eta| < 1$
  TOF: $|\eta| < 1$
  BEMC: $|\eta| < 1$
  EEMC: $1 < \eta < 2$
  HFT (2014-2016): $|\eta| < 1$
  MTD (2014+): $|\eta| < 0.5$
- **MB trigger and event plane reconstruction**
  BBC: $3.3 < |\eta| < 5$
  EPD (2018+): $2.1 < |\eta| < 5.1$
  FMS: $2.5 < \eta < 4$
  VPD: $4.2 < |\eta| < 5$
  ZDC: $6.5 < |\eta| < 7.5$
- **On-going/future upgrades**
  iTPC (2019+): $|\eta| < 1.5$
  eTOF (2019+): $-1.6 < \eta < -1$
  FCS (2021+): $2.5 < \eta < 4$
  FTS (2021+): $2.5 < \eta < 4$

Past runs 2000-2017

Various A+A species $\sqrt{s_{NN}}$ = 5 - 200 GeV

Hot QCD, Phase diagram

p+A or d+A at $\sqrt{s}$=20-200 GeV

Cold QCD: nPDF, Saturation physics.

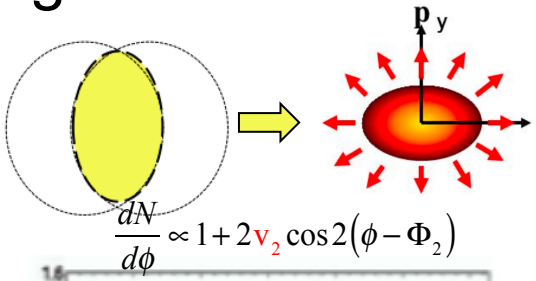
p-p, p↑-p↑ @ $\sqrt{s}$=22-500 GeV

Spin physics, ref for HI

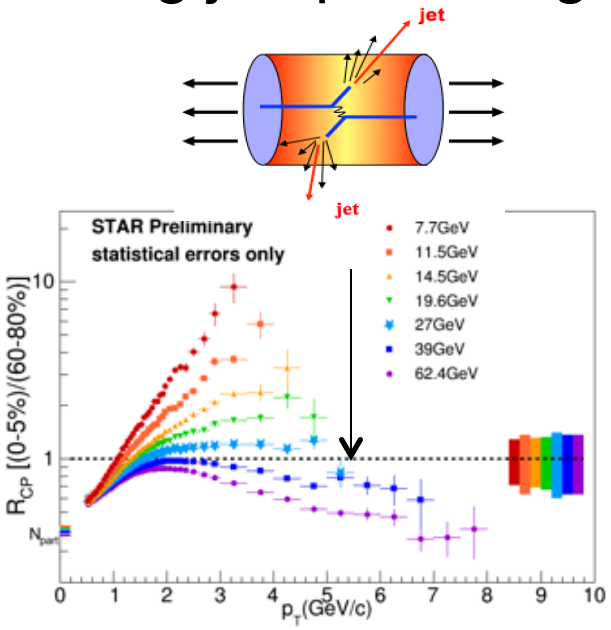
√s [GeV]	p+p	p+Al	p+Au	d+Au	^{3}He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

Some highlights of heavy ion program

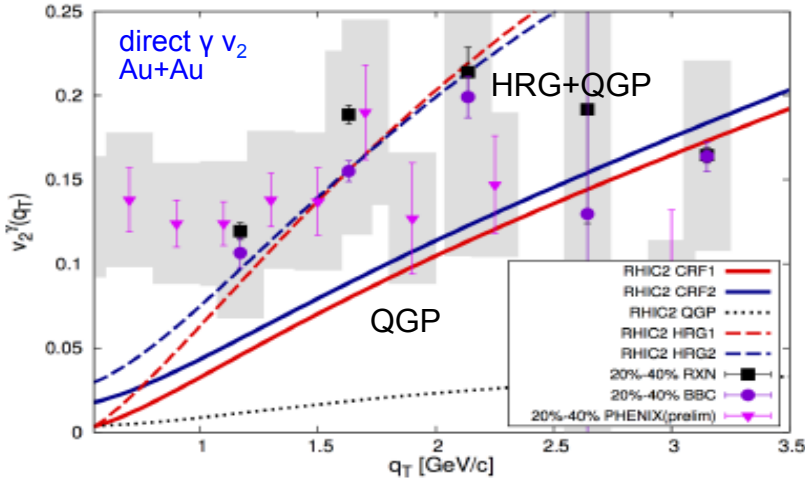
Large collective flow



Strong jet quenching

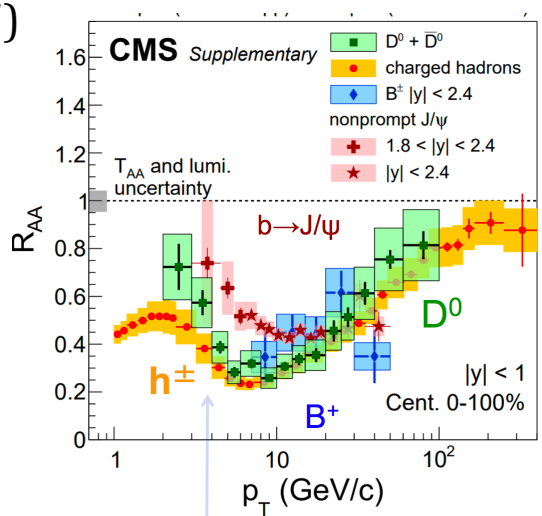


Blue-shift of an expanding source



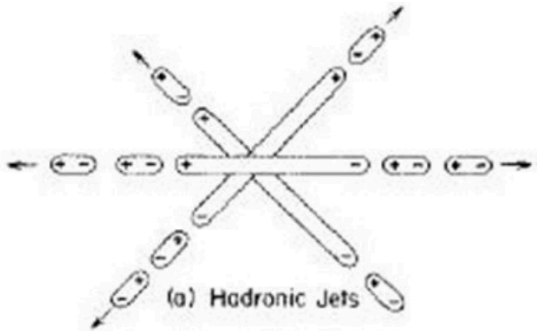
$$\Delta E \sim c\hat{q}L^n f(m)g(E)$$

Flavor dependent

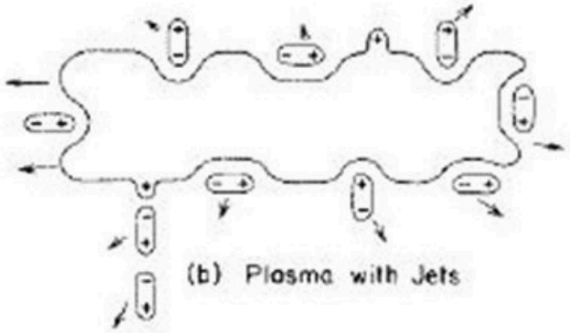


Some highlights of heavy ion program

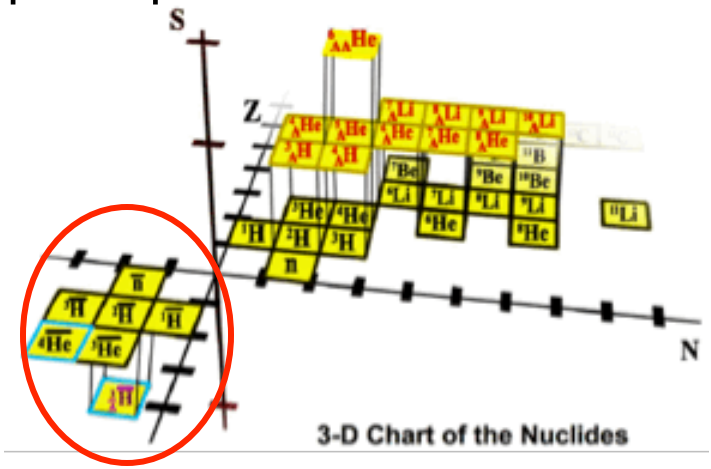
Fragmentation



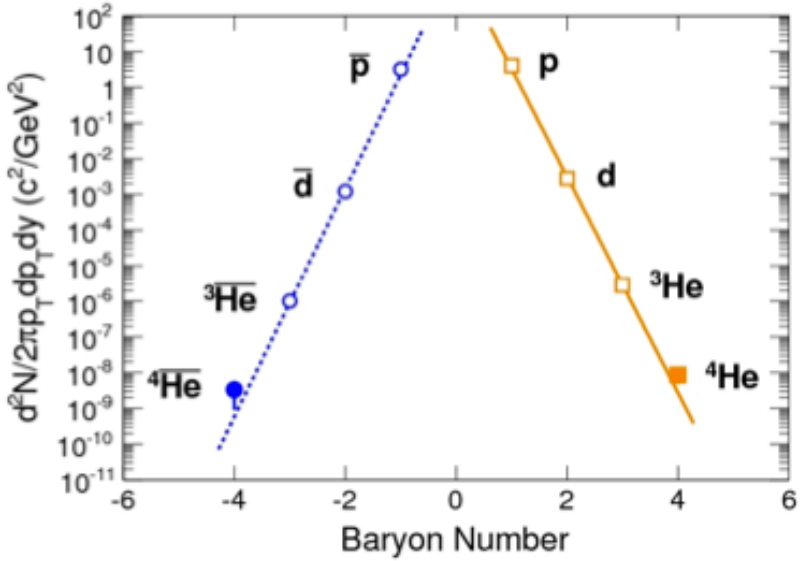
Recombination



Copious production of anti-nuclei



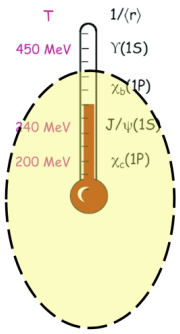
Science.1183980
Nature 473, 353

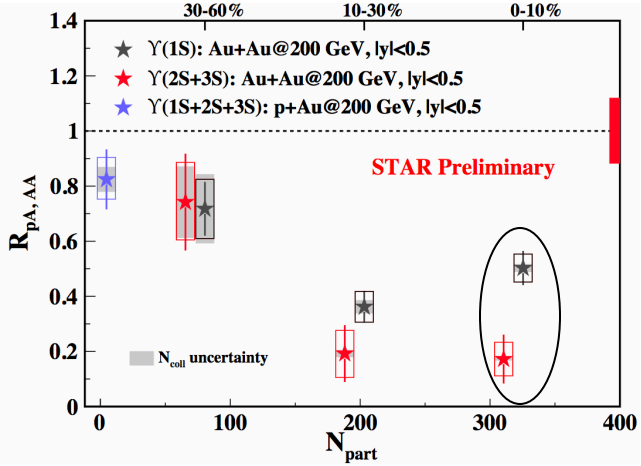


Require dense population q & qbar over an extended volume

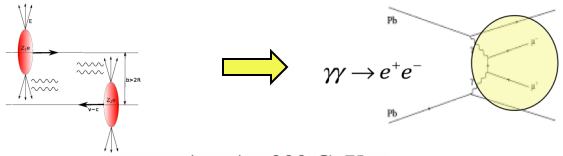
Other accomplishments

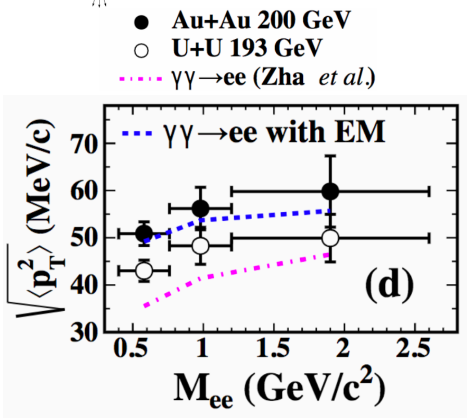
- Quarkonium sequential melting





- γγ→e+e- as probe of QGP?

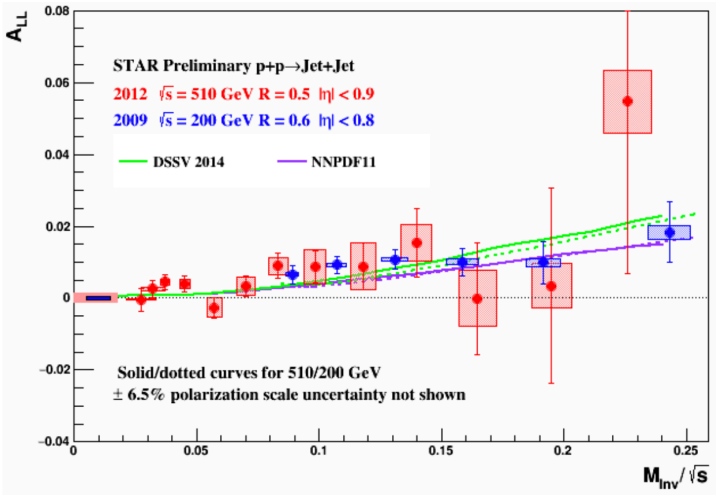




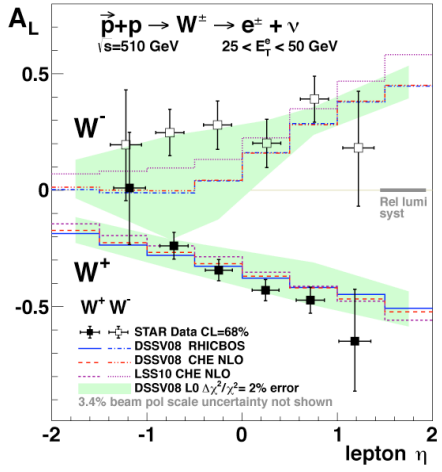
- Also proton spin physics

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

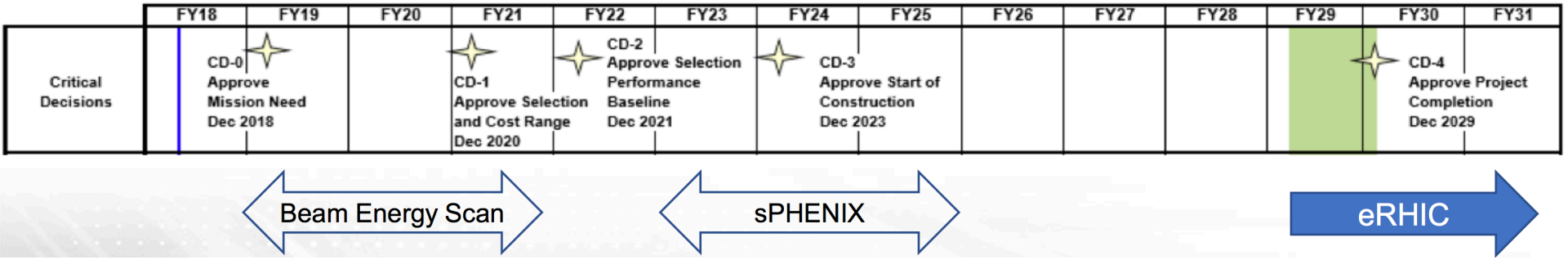
Gluon contribution



Sea contribution

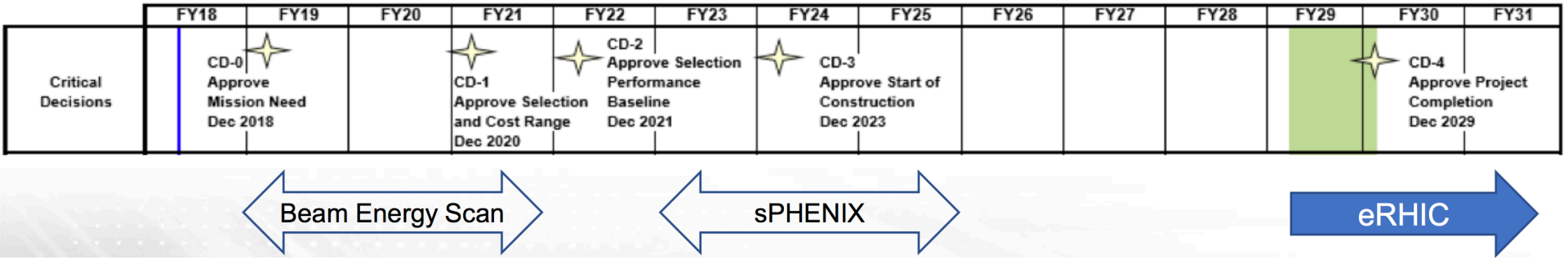


Road-Map for STAR leading to EIC



- RUN 2018
  - 200 GeV isobar system (^{96}Ru vs ^{96}Zr) and 27 GeV Au+Au
  - Search for Chiral Magnetic Effect and measurement of vorticity
- Beam energy scan II: 2019-2021
  - Low energy ($\sqrt{s_{NN}}$ = 7.7, 9.1, 11.5, 14.5, 19.6 GeV) Au+Au runs using electron cooling to increase luminosity at lowest energies
  - Fixed target runs at $\sqrt{s_{NN}}$ = (3.0), 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV
  - Search for critical phenomena in event-by-event fluctuations
- Possible joint run with sPHENIX: 2023-2025
  - 200 GeV Au+Au, p+p, p+Au, p+Al
  - Constrain longitudinal dynamics of HI and ebye fluctuations
  - Unique opportunity for cold QCD physics (TMD, nPDF and saturation).

Road-Map for STAR leading to EIC

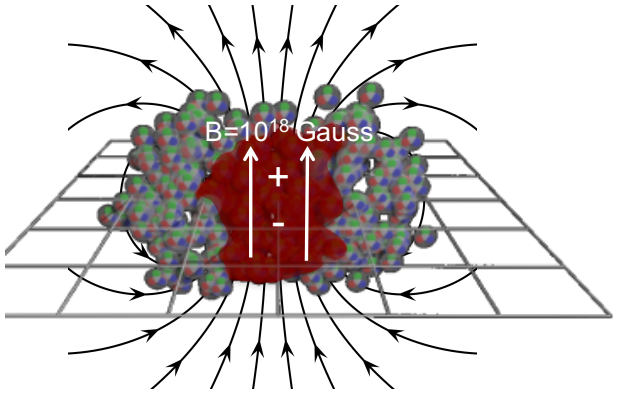


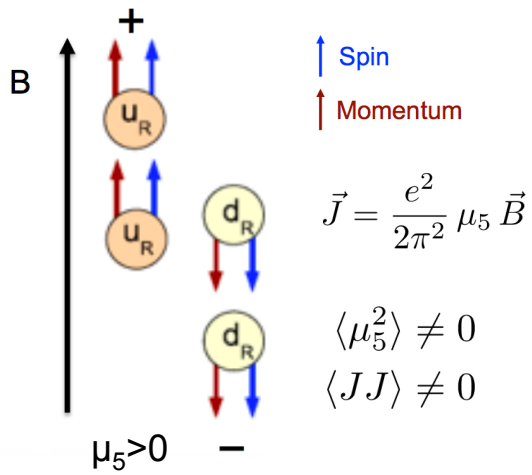
- RUN 2018
  - 200 GeV isobar system (^{96}Ru vs ^{96}Zr) and 27 GeV Au+Au
  - Search for Chiral Magnetic Effect and measurement of vorticity
- Beam energy scan II: 2019-2021
  - Low energy ($\sqrt{s_{NN}}$ = 7.7, 9.1, 11.5, 14.5, 19.6 GeV) Au+Au runs using electron cooling to increase luminosity at lowest energies
  - Fixed target runs at $\sqrt{s_{NN}}$ = (3.0), 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV
  - Search for critical phenomena in event-by-event fluctuations
- Possible joint run with sPHENIX: 2023-2025
  - 200 GeV Au+Au, p+p, p+Au, p+Al
  - Constrain longitudinal dynamics of HI and ebye fluctuations
  - Unique opportunity for cold QCD physics (TMD, nPDF and saturation).

Chiral magnetic effects

- QCD chiral anomaly leads to imbalance of left and right handed quarks at finite T (QGP), characterized by a chiral chemical potential μ_5.
- This imbalance generates an electric current along the magnetic field (chiral magnetic effect)→ a fundamental prediction of QCD

electric charge separation





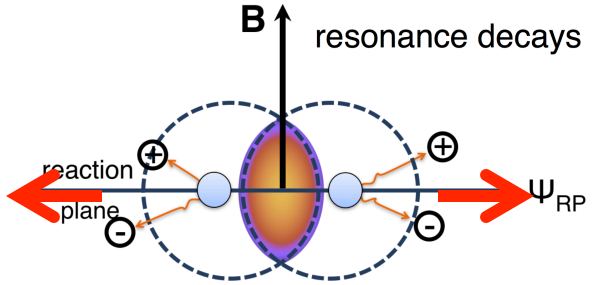
$$\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

$$\langle \mu_5^2 \rangle \neq 0$$

$$\langle JJ \rangle \neq 0$$

Kharzeev, McLerran, Warringa, NPA 803 (2008) 227

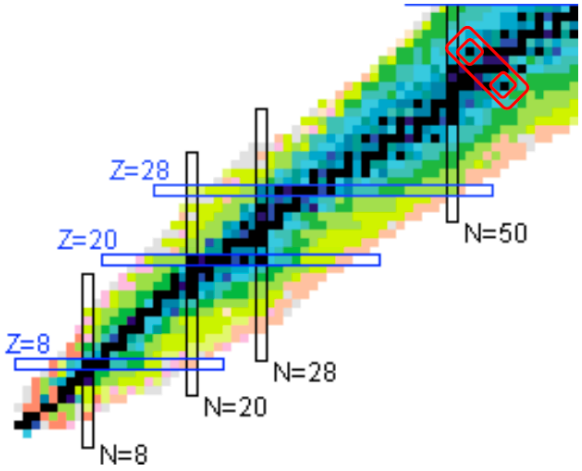
Challenge: charge separation driven by elliptic flow



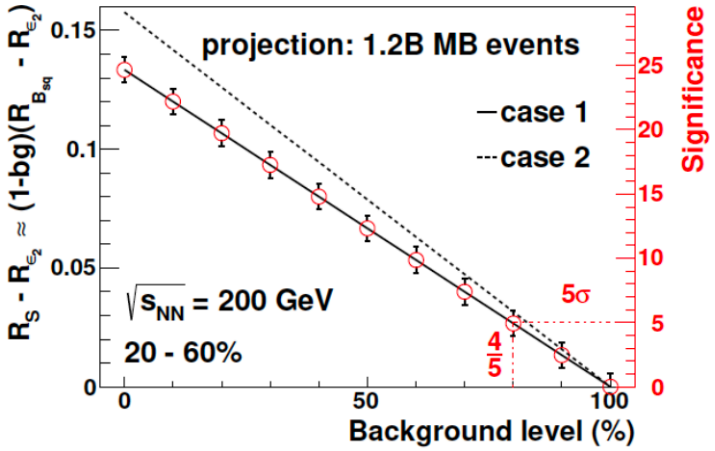
Chiral magnetic effects

- Choose systems with similar collision geometry i.e. collective dynamics (v_2) but different B-field (by 20%)

$^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr}$ vs. $^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru}$



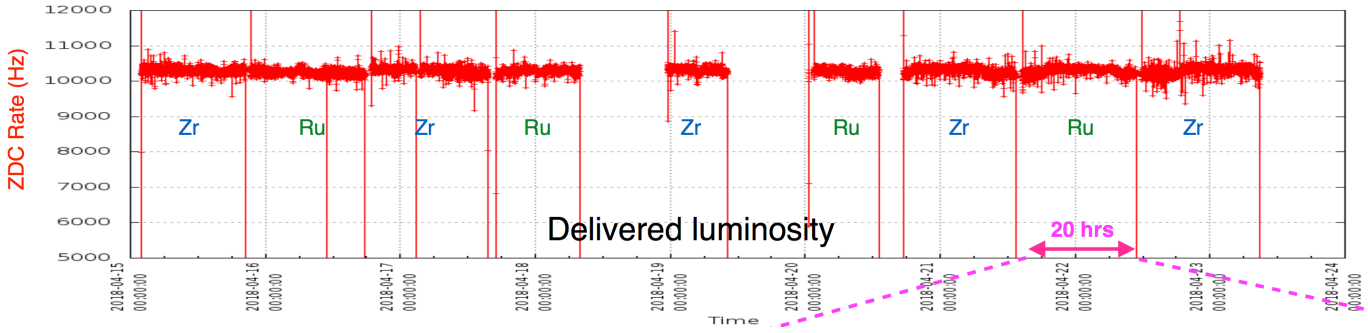
Relative difference in charge separation effects (Ru vs Zr)



Control systematics to <10% of the observed effects.

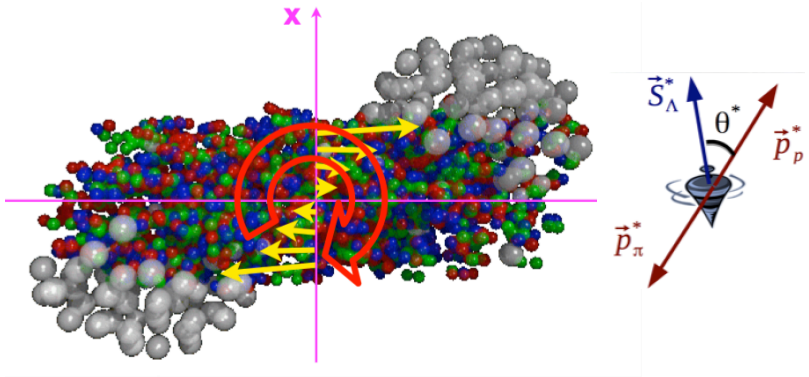
- Fill-by-fill switching between Ru and Zr with same condition minimize all systematics

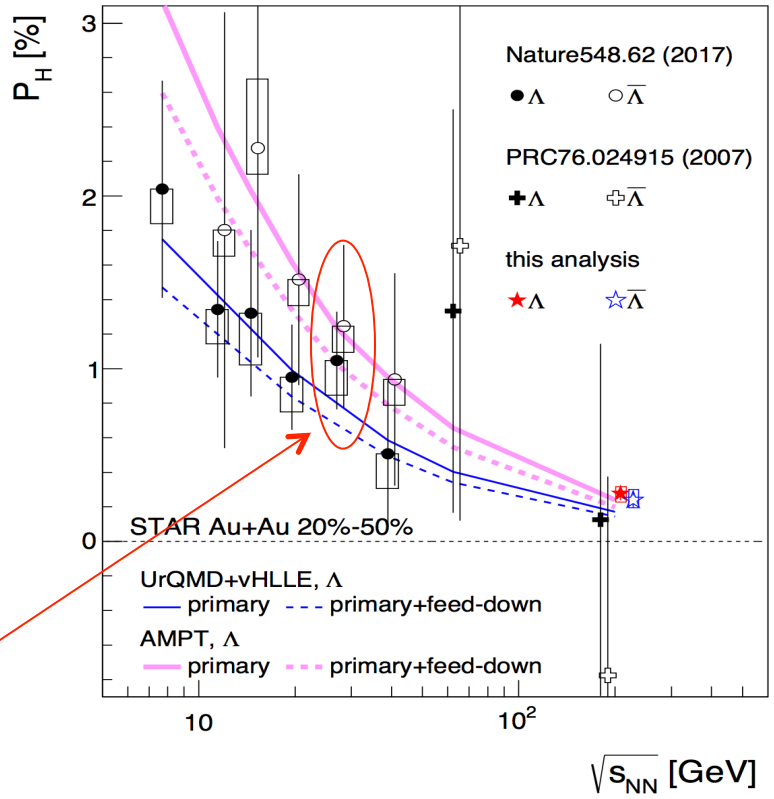
2018



Vorticity of QGP via global Λ polarization

Fluid vorticity ➔ polarization of Λ➔ transfer to proton via parity violating decay





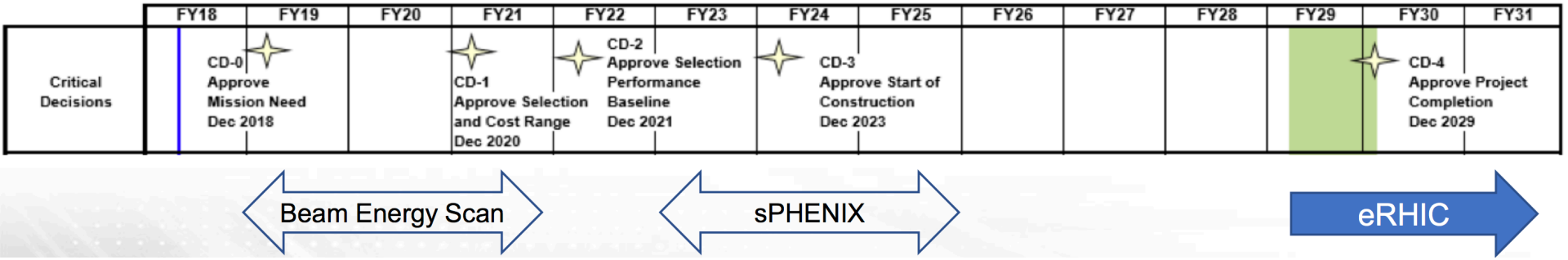
27 GeV Au+Au run will reduce statistical error bar by x5

Most vortical fluid ever observed

$$\omega = (P_\Lambda + P_{\bar{\Lambda}}) k_B T/\hbar$$
$$\sim 10^{22}\ s^{-1}$$ (T=160 MeV)

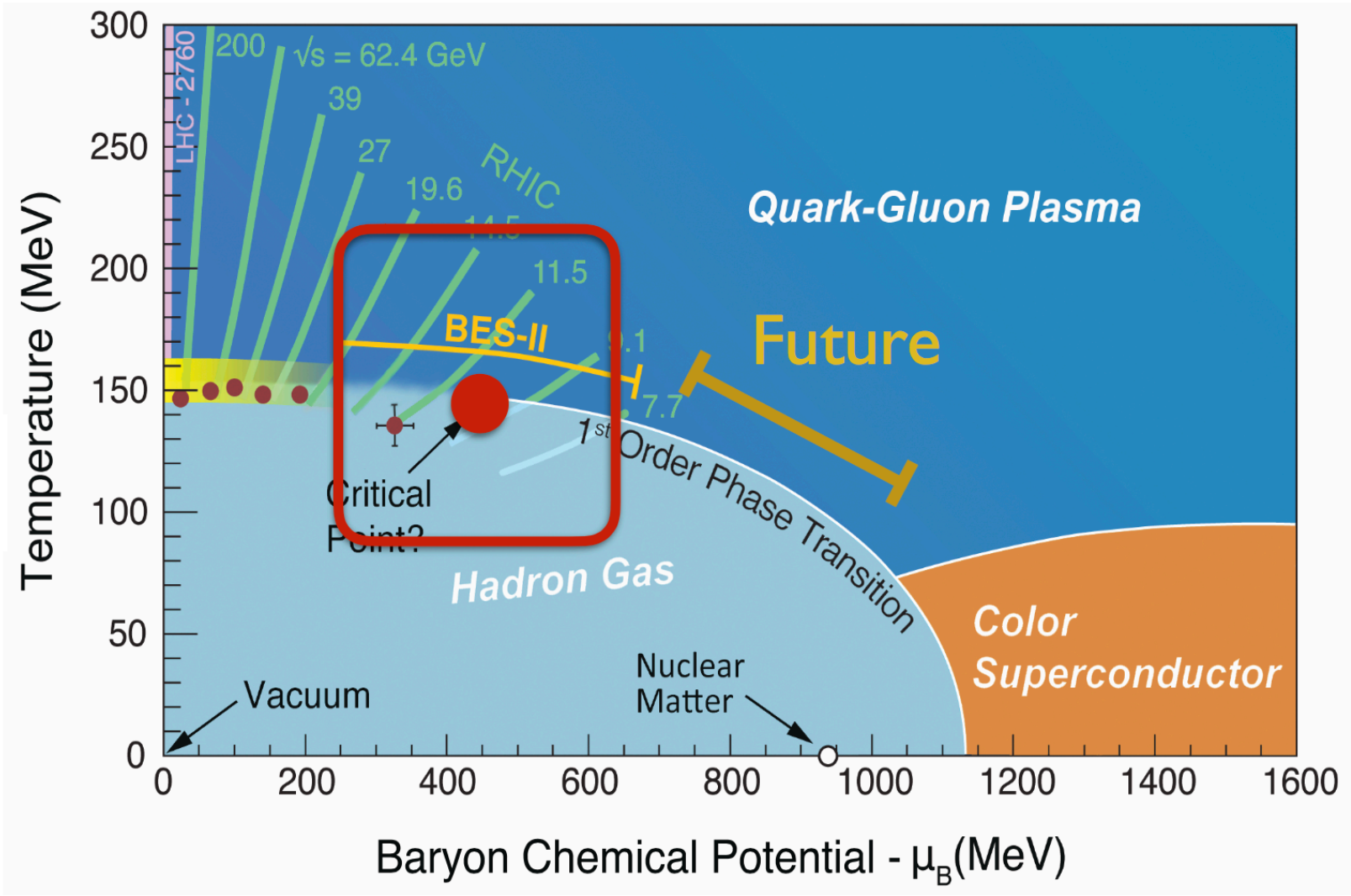
New tool to study QGP and relativistic quantum fluid vorticity

Road-Map for STAR leading to EIC



- RUN 2018
  - 200 GeV isobar system (^{96}Ru vs ^{96}Zr) and 27 GeV Au+Au
  - Search for Chiral Magnetic Effect and measurement of vorticity
- Beam energy scan II: 2019-2021
  - Low energy ($\sqrt{s_{NN}}$ = 7.7, 9.1, 11.5, 14.5, 19.6 GeV) Au+Au runs using electron cooling to increase luminosity at lowest energies
  - Fixed target runs at $\sqrt{s_{NN}}$ = (3.0), 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV
  - Search for critical phenomena in event-by-event fluctuations
- Possible joint run with sPHENIX: 2023-2025
  - 200 GeV Au+Au, p+p, p+Au, p+Al
  - Constrain longitudinal dynamics of HI and ebye fluctuations
  - Unique opportunity for cold QCD physics (TMD, nPDF and saturation).

QCD phase diagram–BESII



Explore the largely uncharted region of the QCD diagram

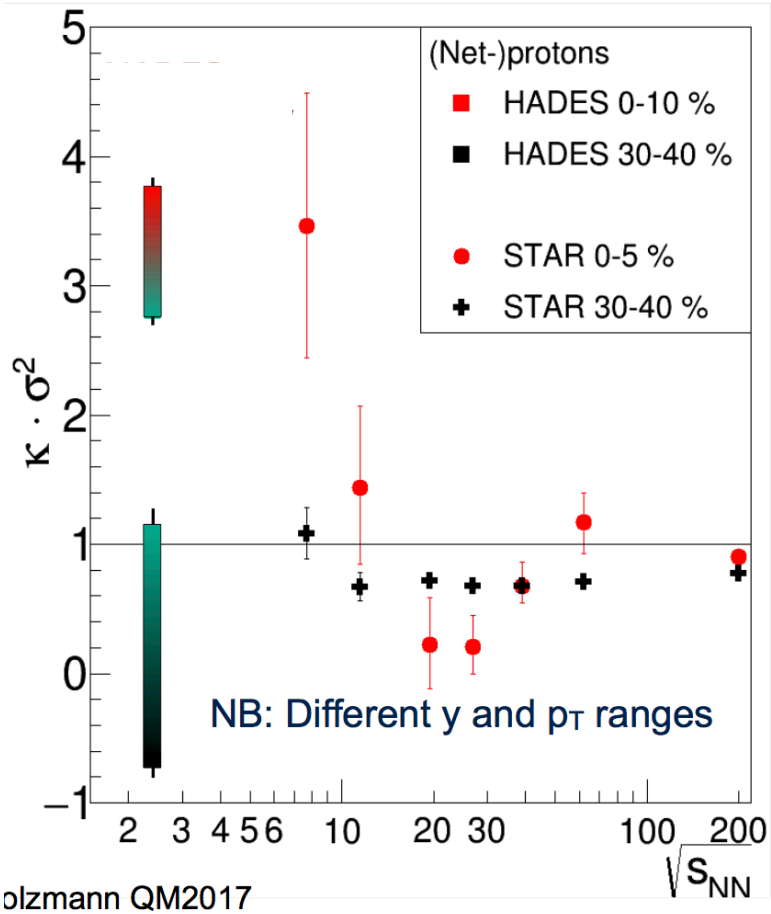
Including regions around the conjectured critical point

Main tool: Fluctuation of conserved charge

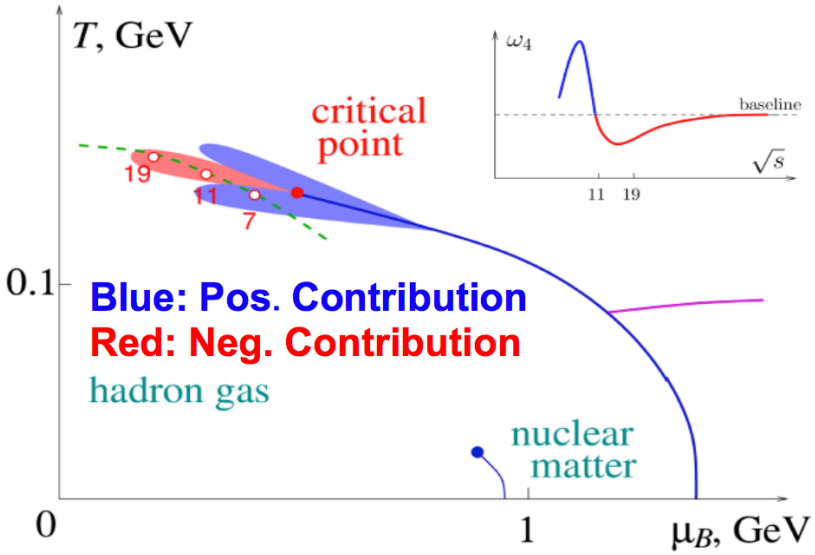
- Signatures: enhanced thermodynamic fluctuations and increased correlation length

$$K_2 \sim \xi^2 \qquad K_3 \sim \xi^{4.5} \qquad K_4 \sim \xi^7$$

- Top 5% central collisions show non-monotonic behavior vs √s

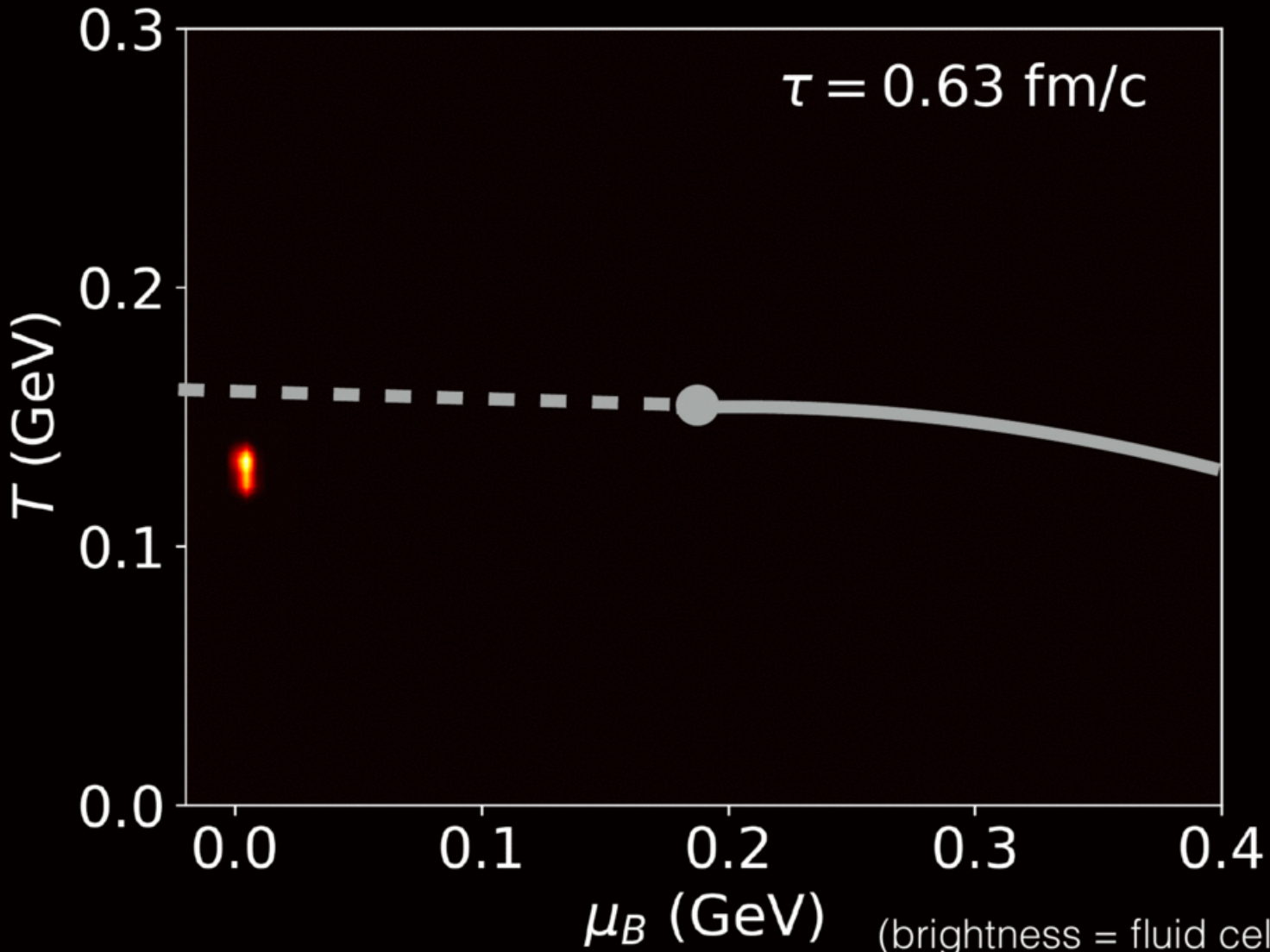


Kurtosis sign depends on trajectory relative to CEP



M. Stephanov. PRL 107:052301(2011)

Sailing in the phase diagram

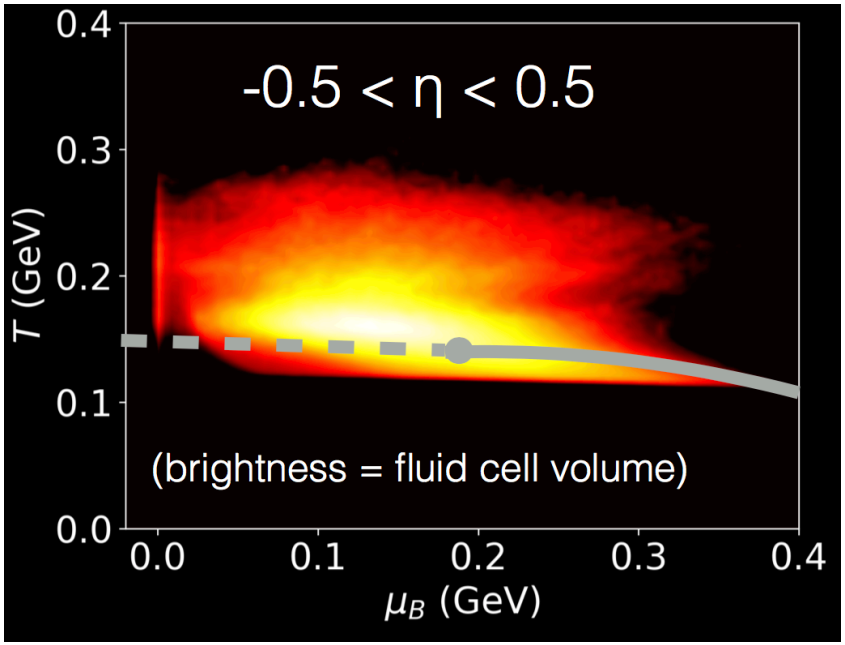


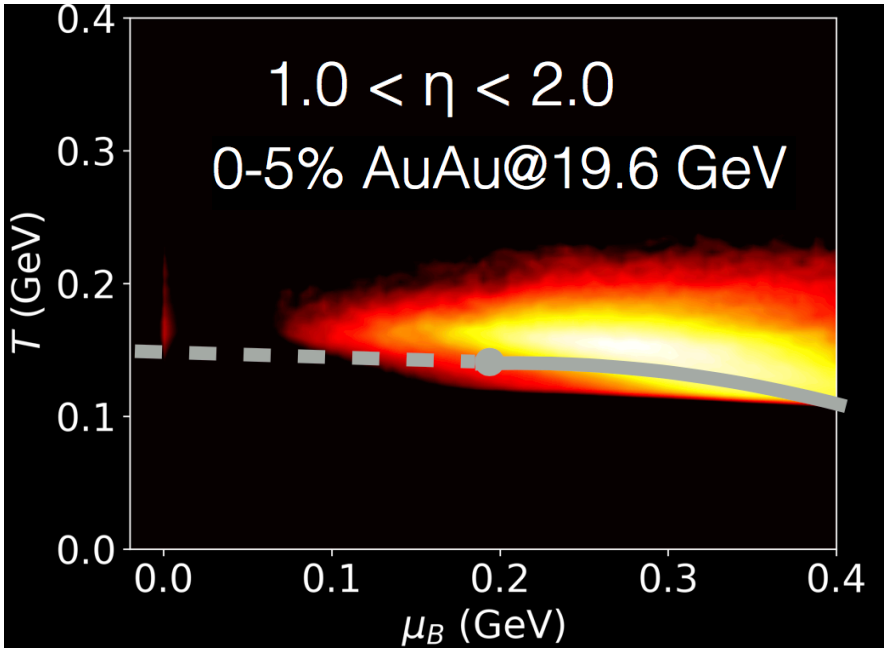
(brightness = fluid cell volume)

(The critical point is only for eye guidance)

0-5% AuAu@19.6 GeV

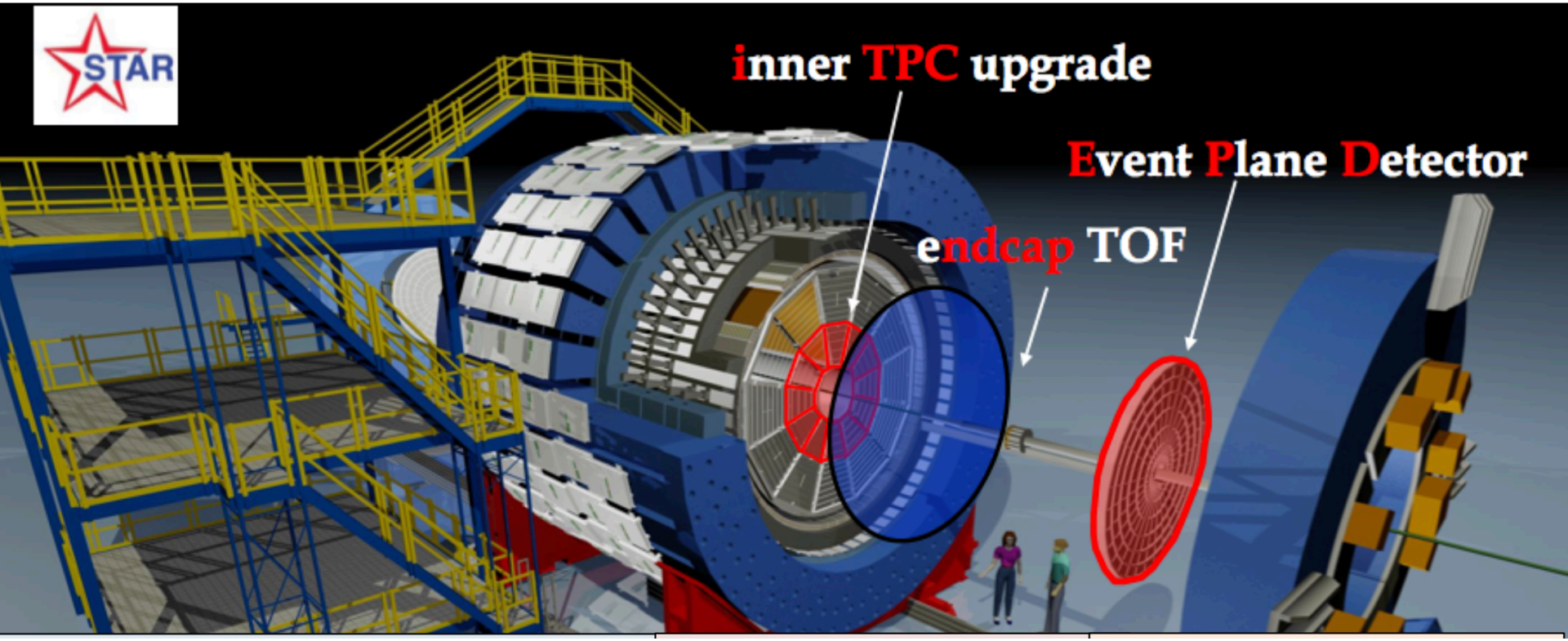
Sailing in the phase diagram





- Knowledge on the full space-time evolution is necessary for the CEP search: the fireball trajectory and how fast it flows in the phase diagram
- Rapidity dependence provides additional handle (e.g. baryon stopping)

Detector upgrades for BES-II



EPD upgrade: DONE

- Better and independent determination of collision geometry $2<|\eta|<5$
- Improves trigger

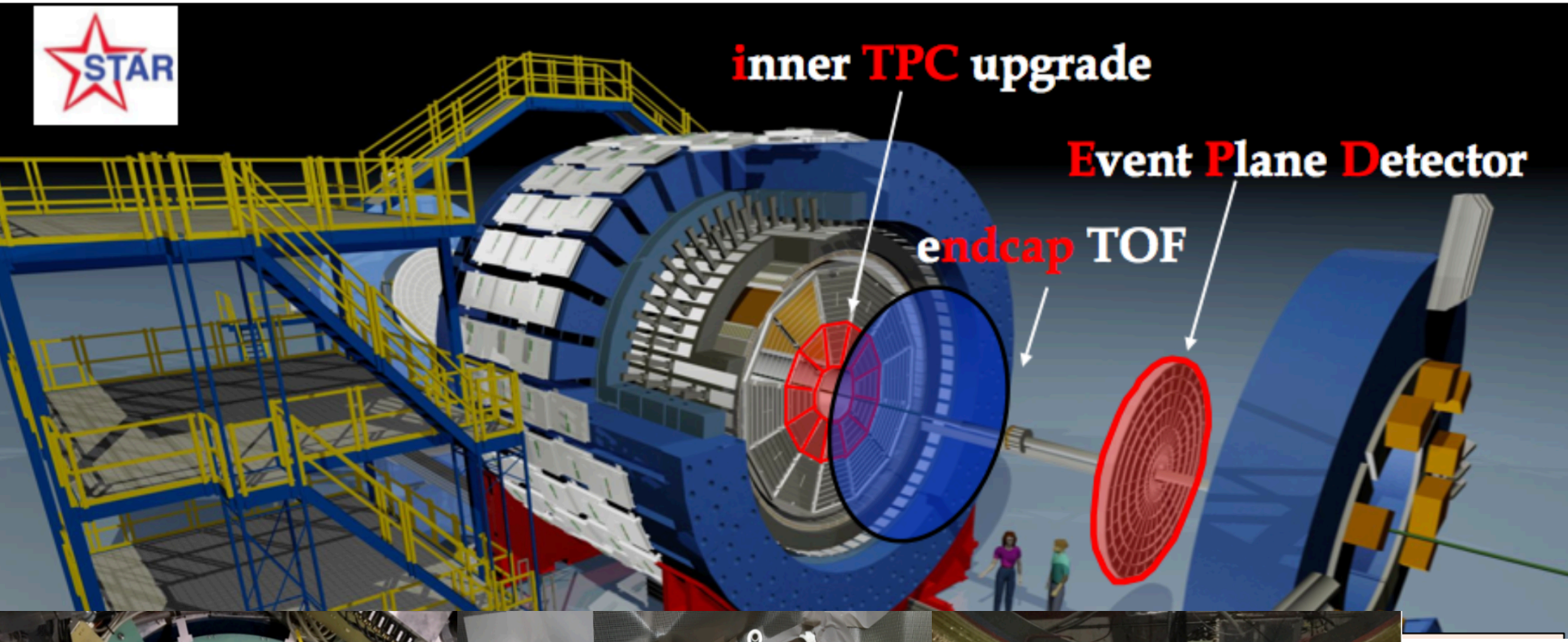
iTPC upgrade:

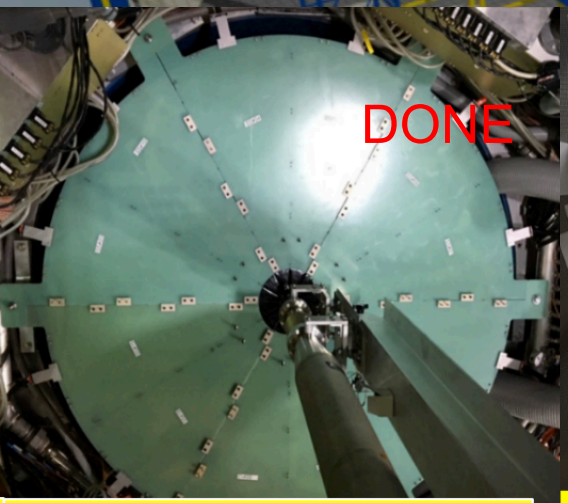
- Extends PID coverage from $|\eta|<1.0$ to 1.5
- Improves dE/dx resolution

eTOF upgrade:

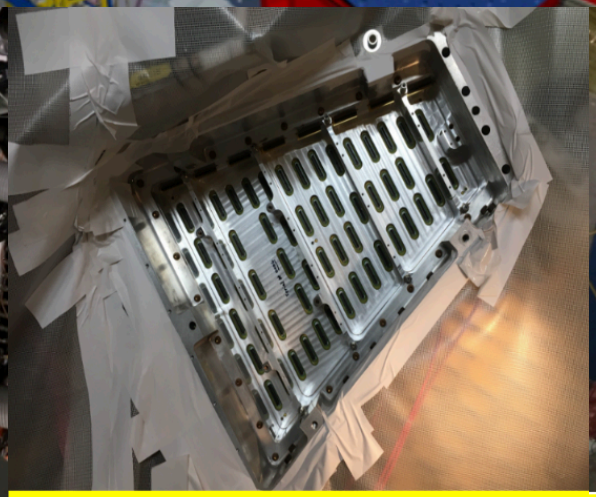
- Additional PID for $\eta=1.1$-1.6 to higher p_T
- Very important for fixed target program

Detector upgrades for BES-II

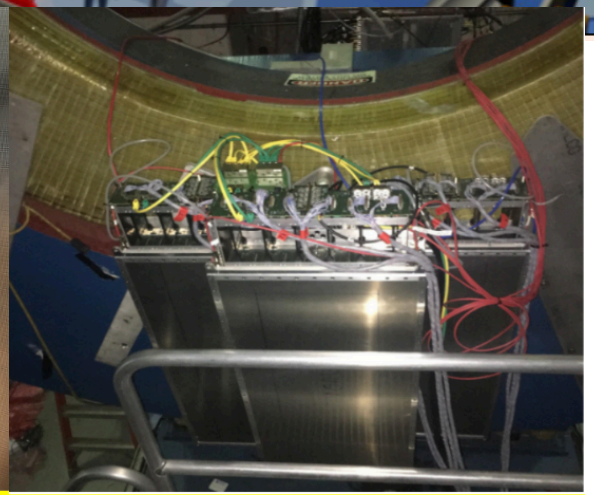




Full EPD has been installed

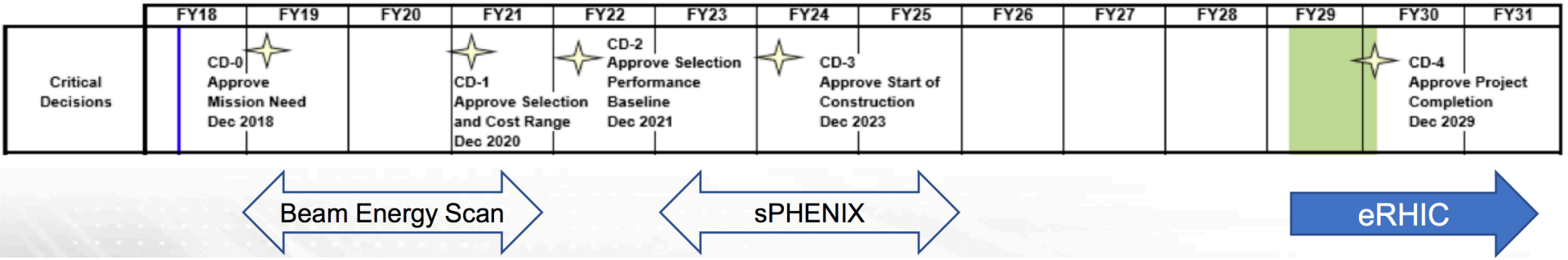


One iTPC sector has been installed



3 eTOF modules have been installed

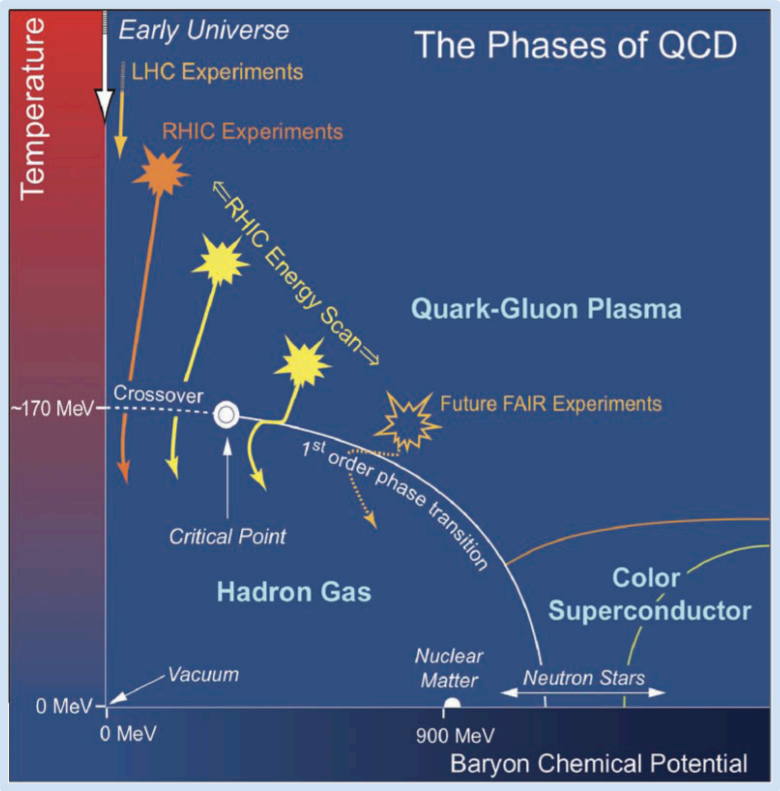
Road-Map for STAR leading to EIC



- RUN 2018
  - 200 GeV isobar system (^{96}Ru vs ^{96}Zr) and 27 GeV Au+Au
  - Search for Chiral Magnetic Effect and measurement of vorticity
- Beam energy scan II: 2019-2021
  - Low energy ($\sqrt{s_{NN}}$ = 7.7, 9.1, 11.5, 14.5, 19.6 GeV) Au+Au runs using electron cooling to increase luminosity at lowest energies
  - Fixed target runs at $\sqrt{s_{NN}}$ = (3.0), 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV
  - Search for critical phenomena in event-by-event fluctuations
- Possible joint run with sPHENIX: 2023-2025
  - 200 GeV Au+Au, p+p, p+Au, p+Al
  - Constrain longitudinal dynamics of HI and ebye fluctuations
  - Unique opportunity for cold QCD physics (TMD, nPDF and saturation).

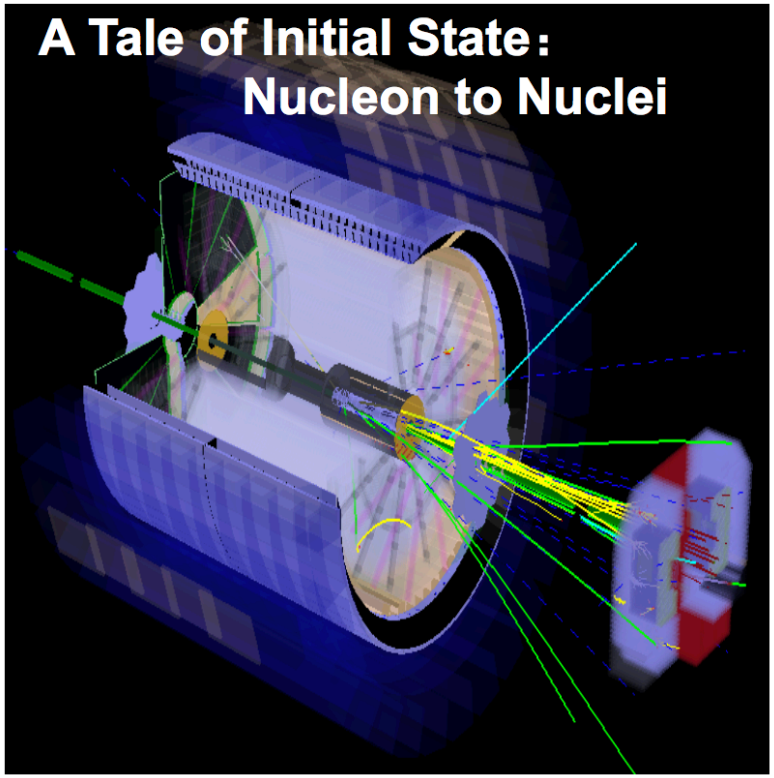
Forward upgrades beyond BESII

Beam Energy Scan II
2019~2021



iTPC, eToF, EPD

Forward Physics
2023-2025



- ✓ Forward Tracking System
- ✓ Forward Calorimeter System

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

Continued operation endorsed by 2017 & 2018 PAC $2.5<\eta<4.2$

STAR Forward Upgrade components

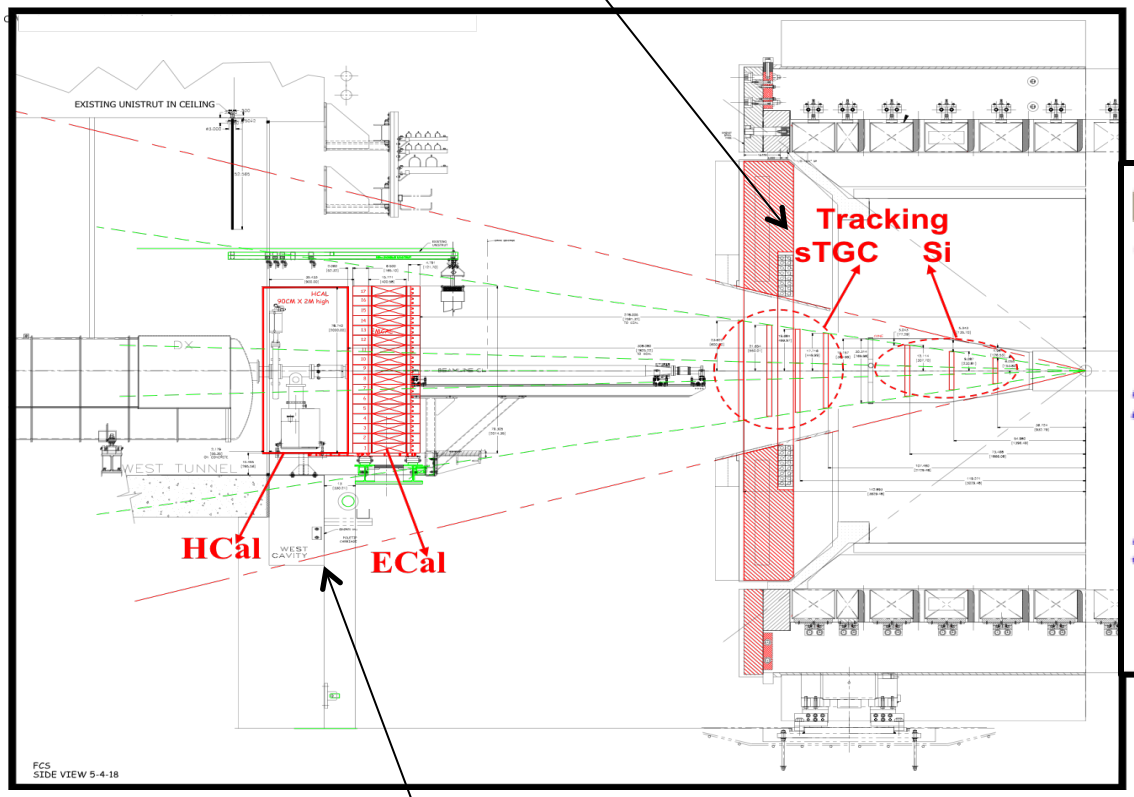
3 silicon disks + 4 sTGC

90, 140, 187, 270, 300, 330, 360 cm

p_T reach : 0.2-2 GeV, 25% reso
efficiency: 80%@ 100 track/evt

Cost: $3.3M

- **Si : 3M**
- **sTGC: 0.3 M**



Funding sources (allocated and planned):

1) Forward sTGC Tracker (FTT):
   (BNL LDRD 4EIC/SDU/Operation)
   Team: BNL(HI+Spin)/SDU/IU
2) Forward Silicon Tracker (FST):
   NSFC/SDU/NCKU
   Team: SDU/Huzhou/UIC/BNL/NCKU
3) Forward Calorimeter System (FCS)
   NSF/DOE?
   Team: RHIC Spin Collaboration + HI

ECal and HCal

reuse PHENIX PbSc — $\sim 10\%/\sqrt{E}$

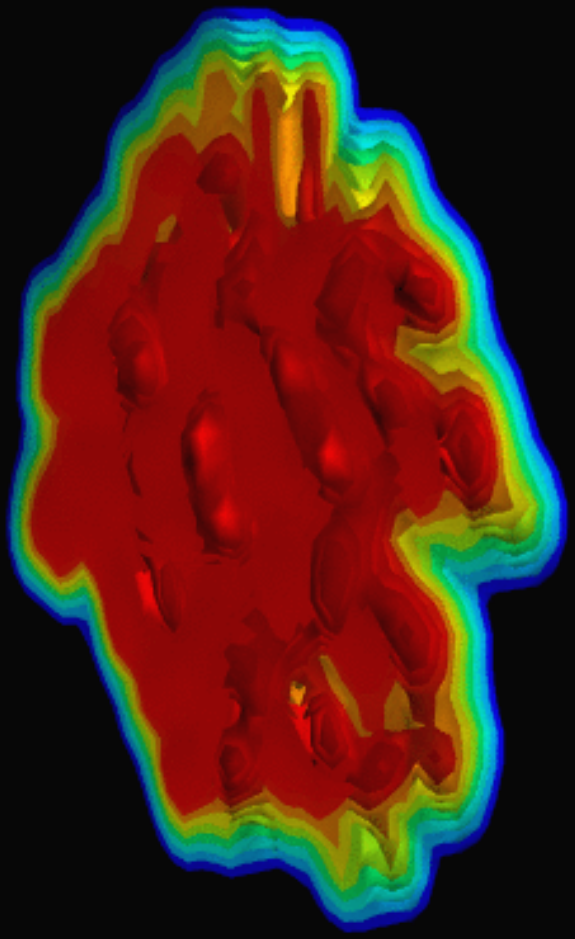
Sampling iron-scintillator — $\sim 60\%/\sqrt{E}$

Cost: $2.0M

-ECAL $ 0.41M

-HCAL $ 1.56M

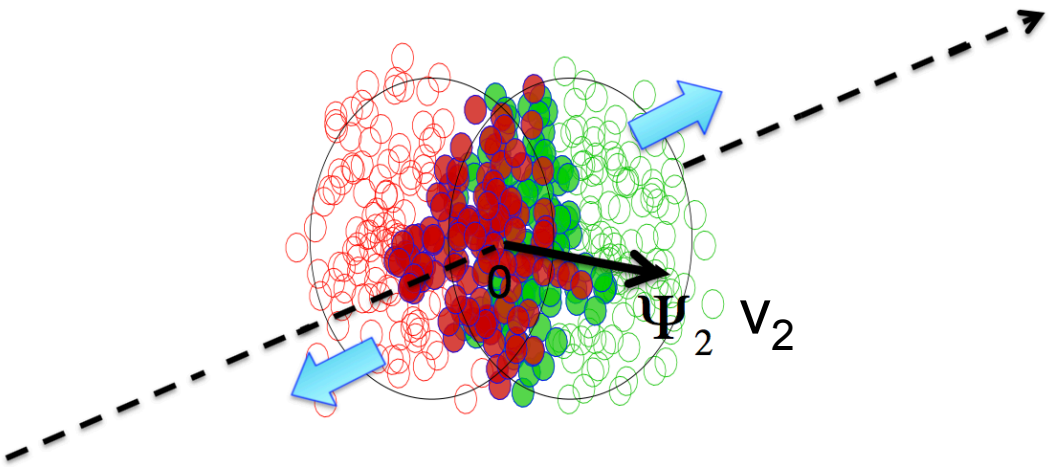
Dynamics in longitudinal direction



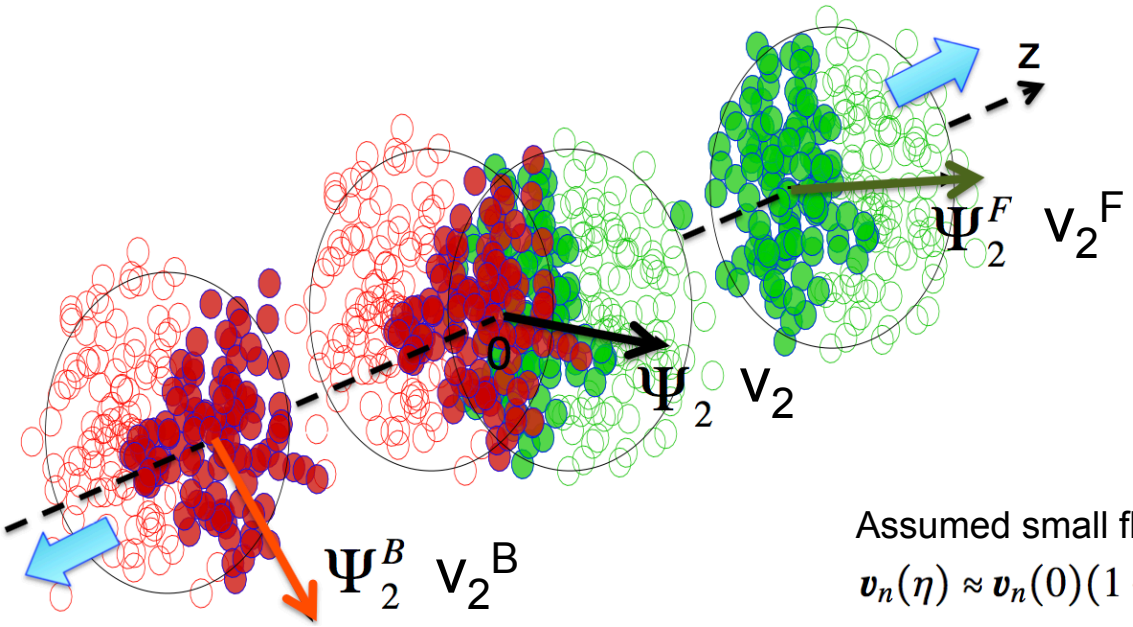
Credit: Bjoern Schenke

Initial state in 3D

$$\boldsymbol{v}_n = v_n e^{in\Psi_n}$$



Initial state in 3D



$$\boldsymbol{v}_n = v_n e^{in\Psi_n}$$

Observables:

$$r_2(\eta) = \frac{\langle \boldsymbol{v}_2(-\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_2(\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\rangle}$$

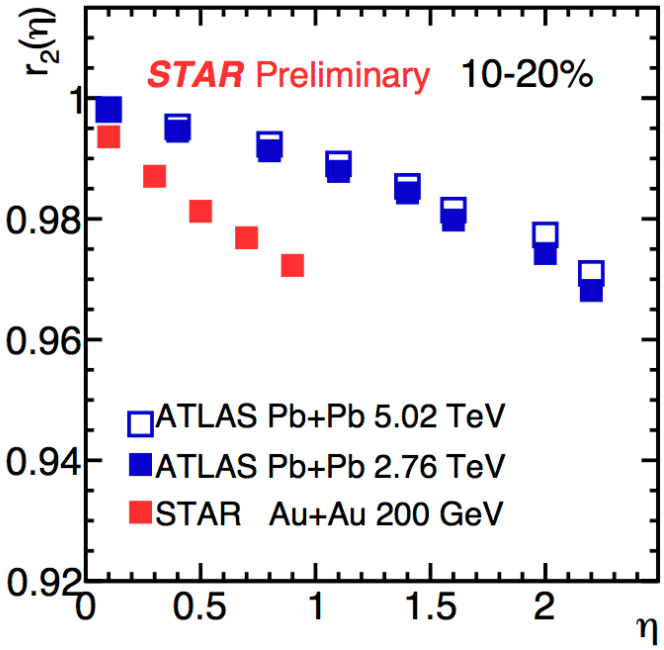
Assumed small fluct:

$$\boldsymbol{v}_n(\eta) \approx \boldsymbol{v}_n(0)(1+\alpha_n\eta)e^{i\beta_n\eta}$$

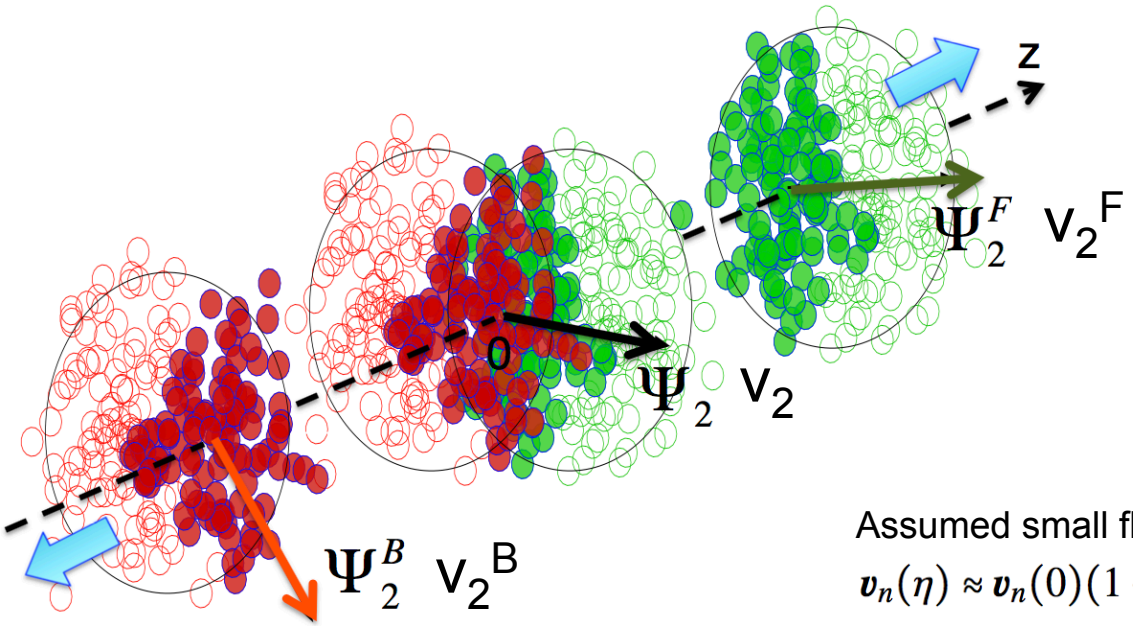
$$\approx 1 - 2F\eta$$

Initial geometry is twisted along η,
Final-state flow direction is also twisted

- Decorrelation effects stronger at RHIC



Initial state in 3D



$$\boldsymbol{v}_n = v_n e^{in\Psi_n}$$

Observables:

$$r_2(\eta) = \frac{\langle \boldsymbol{v}_2(-\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_2(\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\rangle}$$

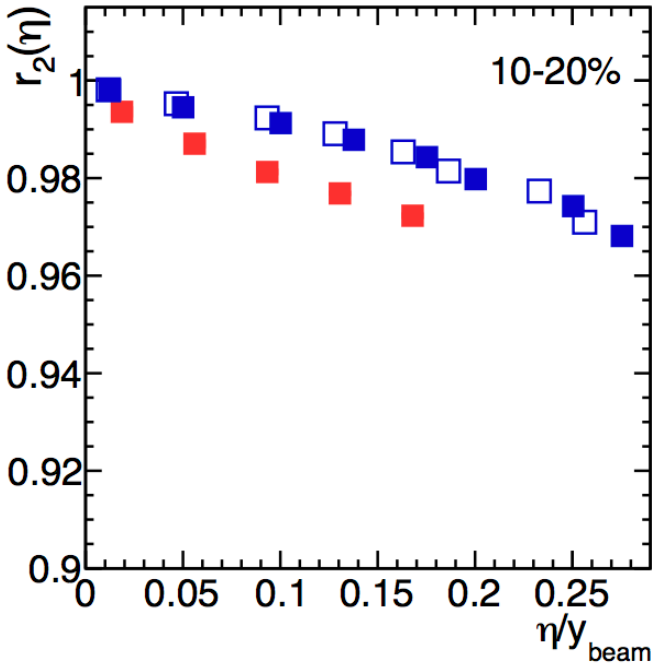
Assumed small fluct:

$$\boldsymbol{v}_n(\eta) \approx \boldsymbol{v}_n(0)(1+\alpha_n\eta)e^{i\beta_n\eta}$$

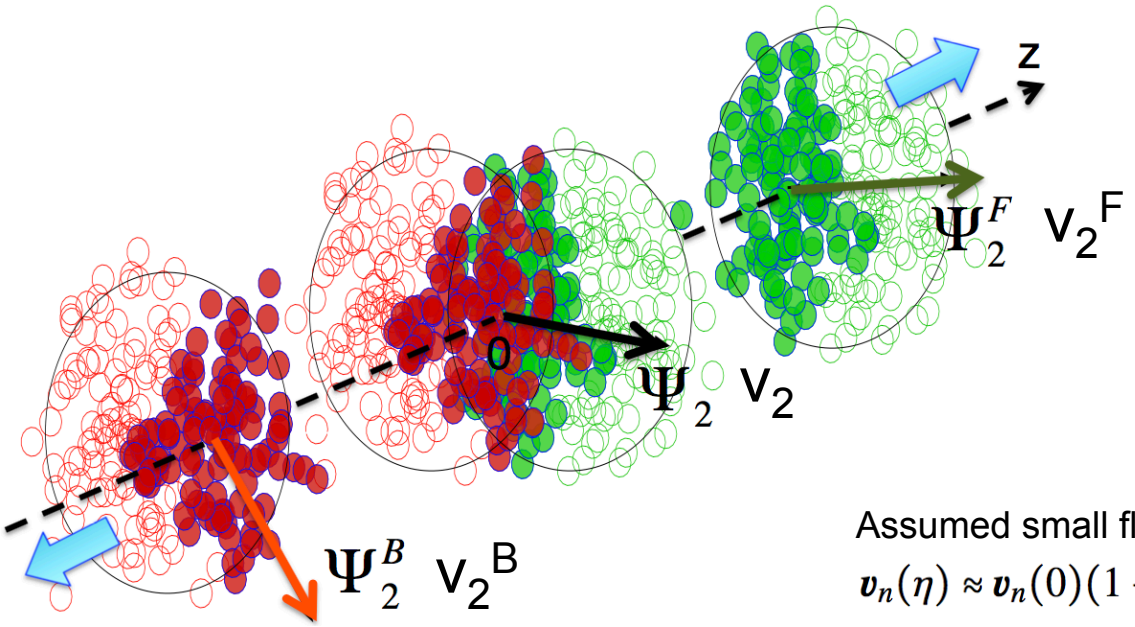
$$\approx 1 - 2F\eta$$

Initial geometry is twisted along η,
Final-state flow direction is also twisted

- Decorrelation effects stronger at RHIC
- Difference remains after scaling by beam rapidity η/y_{beam}.



Initial state in 3D



$$\boldsymbol{v}_n = v_n e^{in\Psi_n}$$

Observables:

$$r_2(\eta) = \frac{\langle \boldsymbol{v}_2(-\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_2(\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\rangle}$$

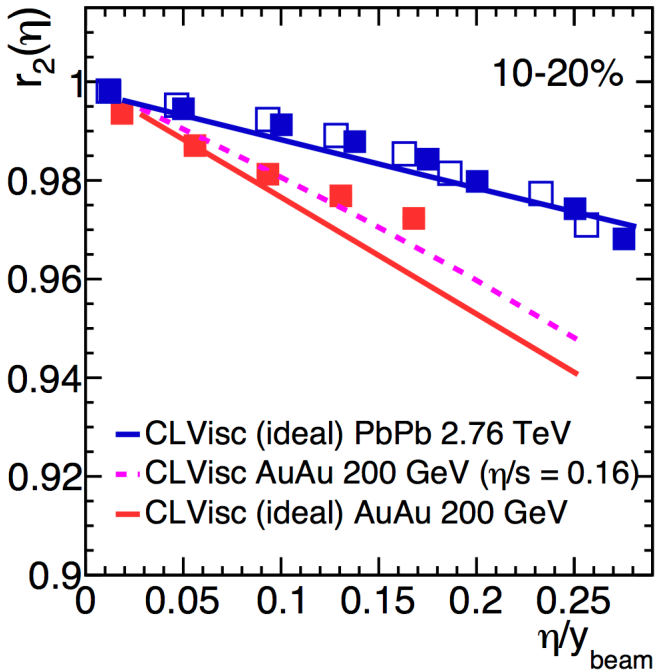
Assumed small fluct:

$$\boldsymbol{v}_n(\eta) \approx \boldsymbol{v}_n(0)(1+\alpha_n\eta)e^{i\beta_n\eta}$$

$$\approx 1 - 2F\eta$$

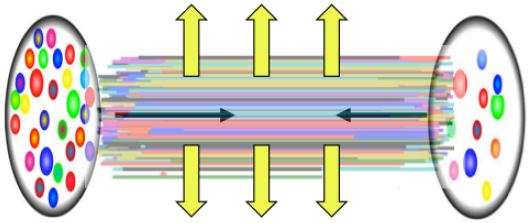
Initial geometry is twisted along η,
Final-state flow direction is also twisted

- Decorrelation effects stronger at RHIC
- Difference remains after scaling by beam rapidity η/y_{beam}.
- Most due to initial state effects (ideal hydro), but also has sensitivity to final state viscosity.

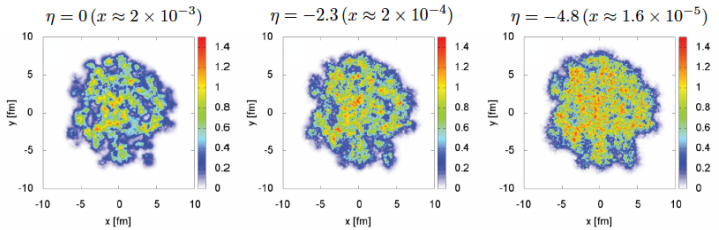


Example: Control initial state of HI via pA

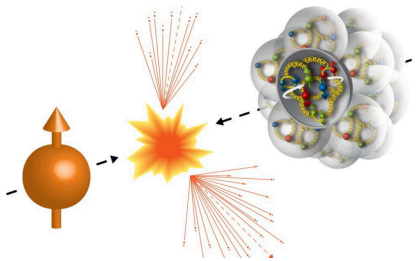
Initial geometry driven by nPDF $f_{Au}(x,\vec{b})$



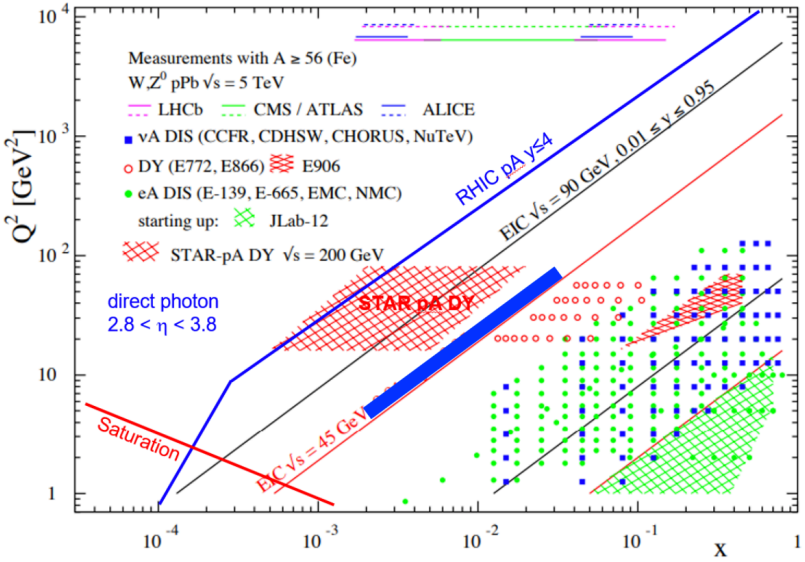
Strong rapidity evolution towards low x: non-linear QCD a.la CGC

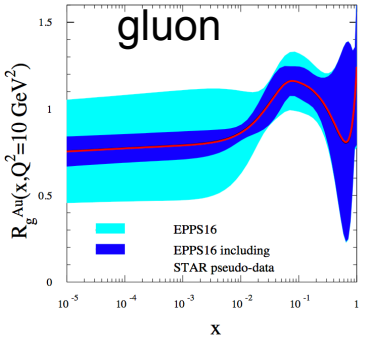


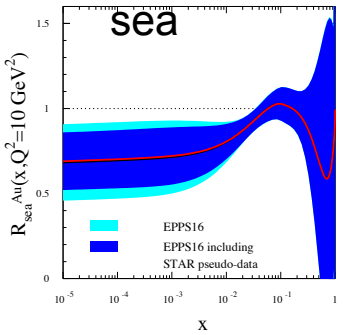
Probes by pA at RHIC



- Use observables free of final state effects
  - Gluons: R_{pA} for direct photons
  - Sea-quarks: R_{pA} for DY
- pA at RHIC explore unique x-Q^2 region
  - A-scan to constrain prediction of CGC
- Good precision with a run concurrent with sPHENIX
- Alternative observables and kinematics to EIC

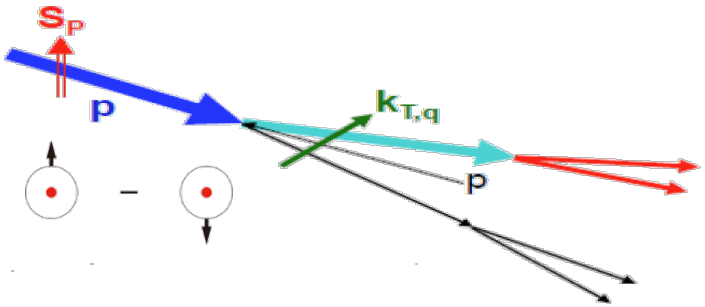


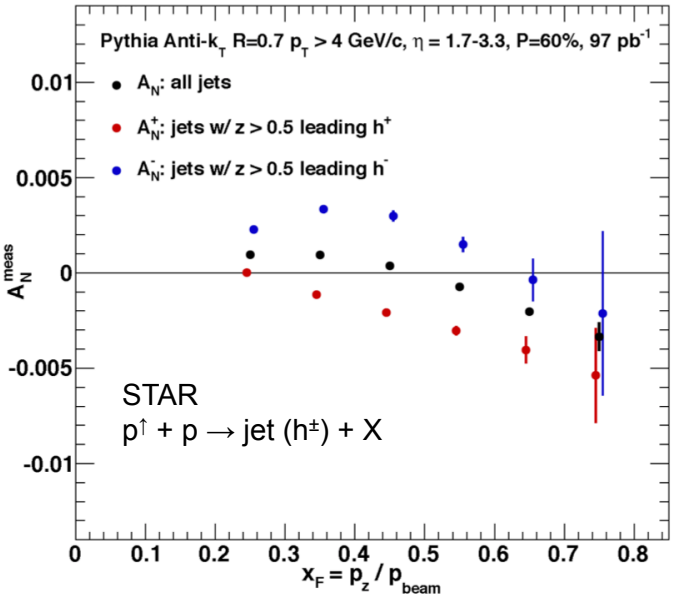




Example: origin of A_N via forward jet

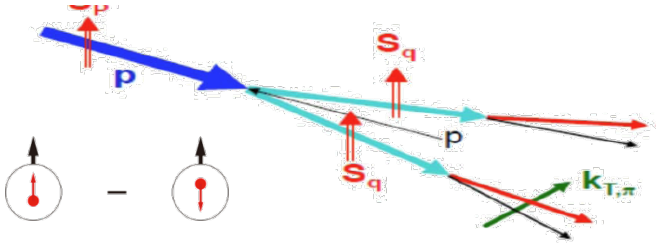
Charge-track tagged jet asymmetry
→ Access Sivers effect

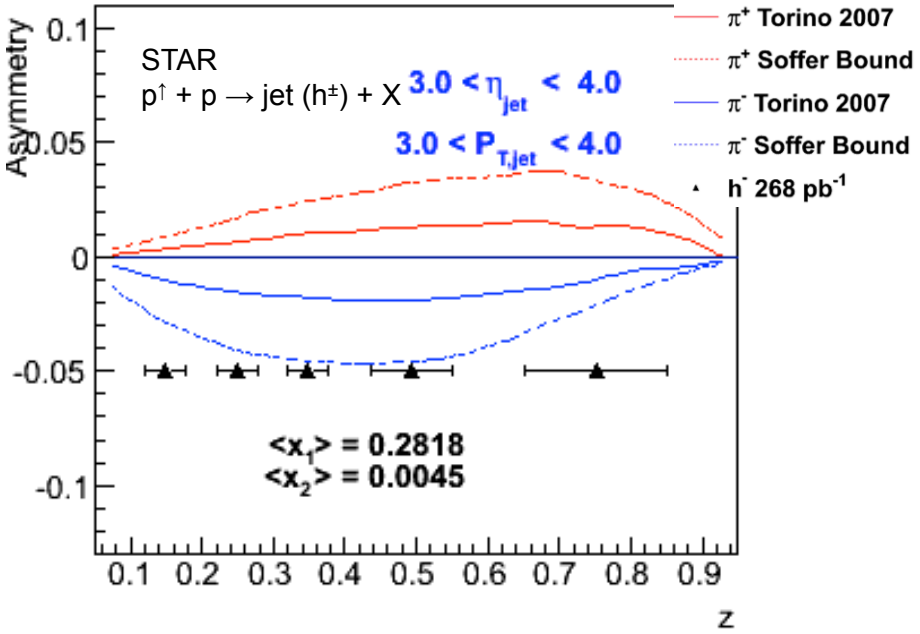




Forward jet reconstruction by tagging an additional charged hadron

Charge-track asymmetry in jet
→ Access Transversity @ large x





Test universality of transversity @ SIDIS

Talk by Qinghua Xu

Summary

- Rich set of accomplishments at STAR so far
- Large discovery potential expected in the years leading to EIC (2018~2025)
- Enabled by modest mid-rapidity upgrade and forward-rapidity upgrades
  - During BES-II: EPD, iTPC, eTOF
  - Leading to EIC: forward tracking/calo upgrade, complimentary to sPHENIX running:

- Essential to the mission of RHIC physics in hot and cold QCD
- Help lay the groundwork for the EIC.