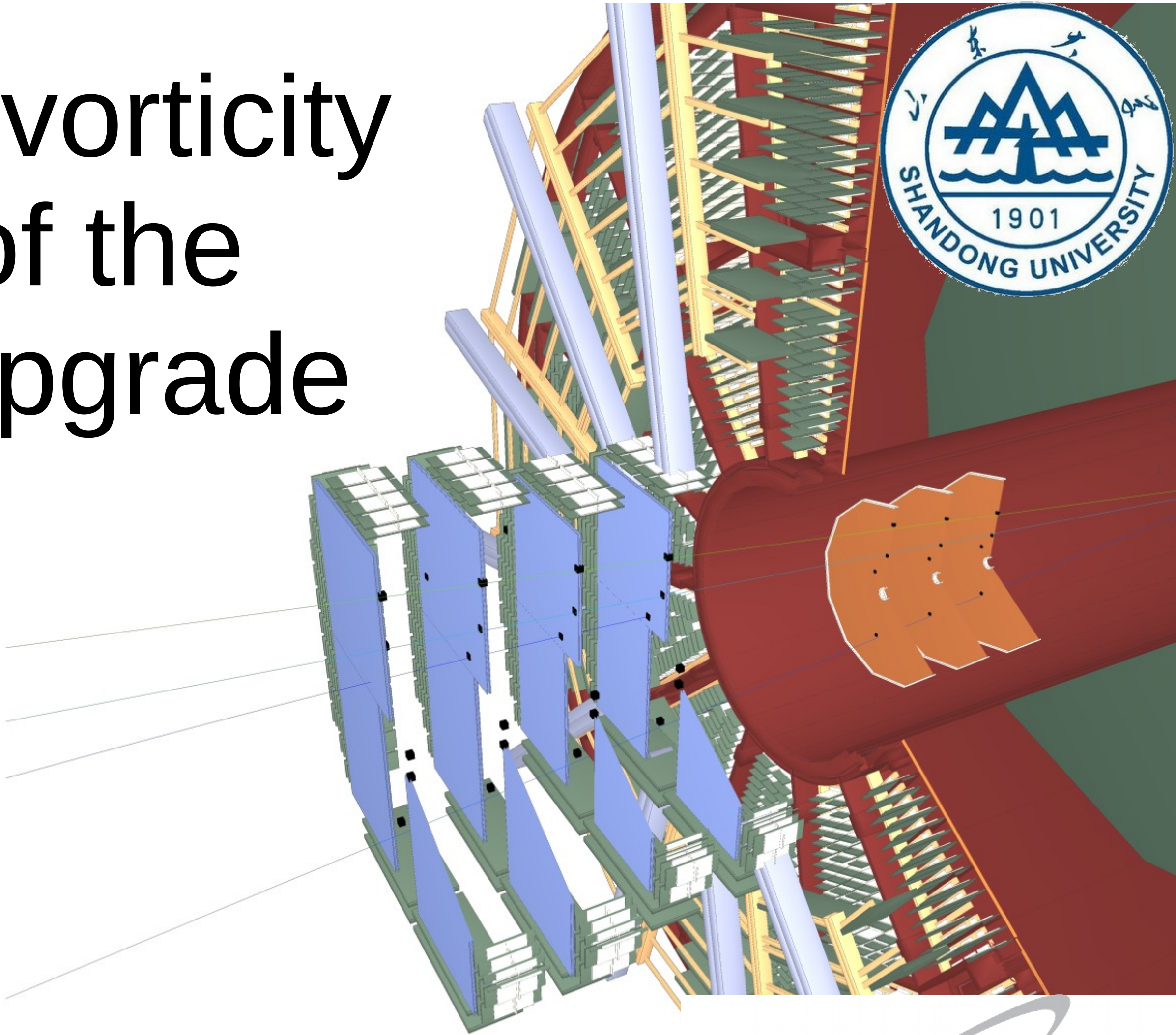
Polarization and vorticity in the region of the STAR forward upgrade

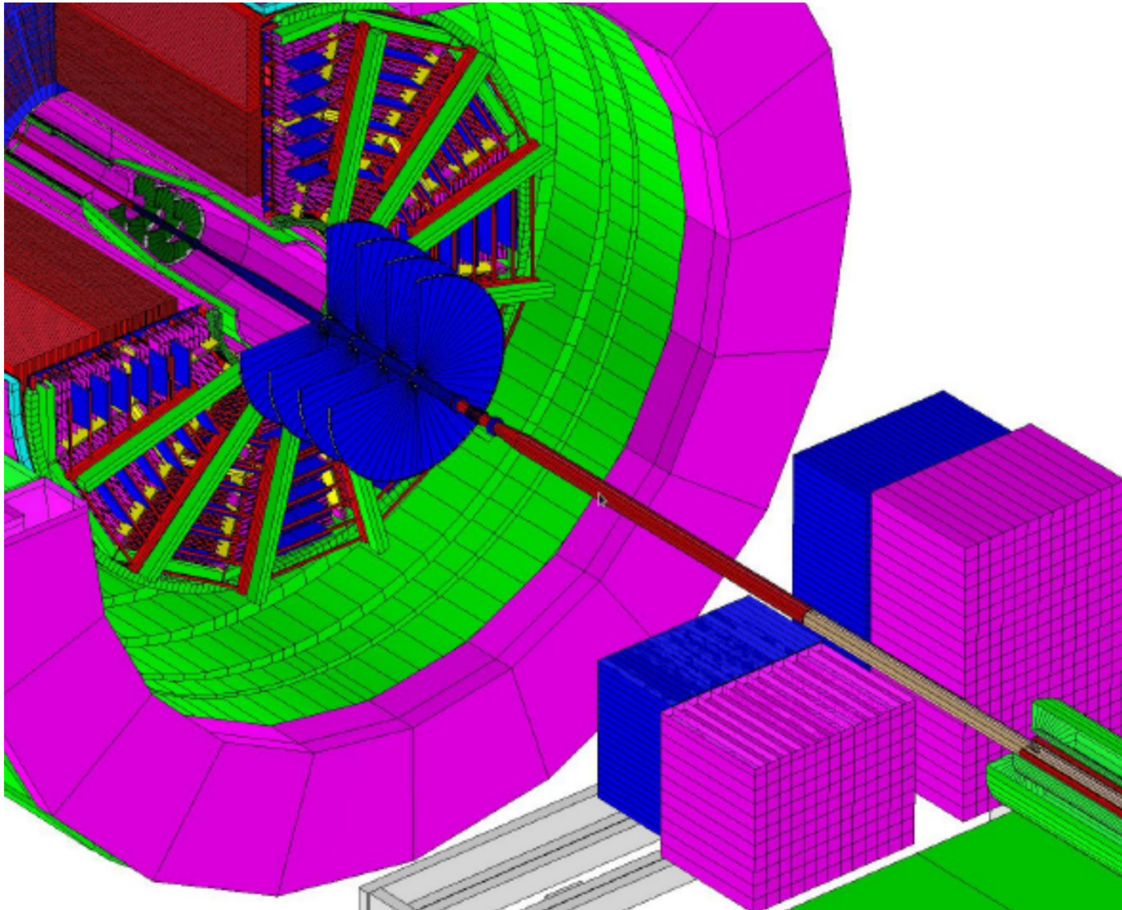
Isaac Upsal

07/21/19



Forward upgrade refresher

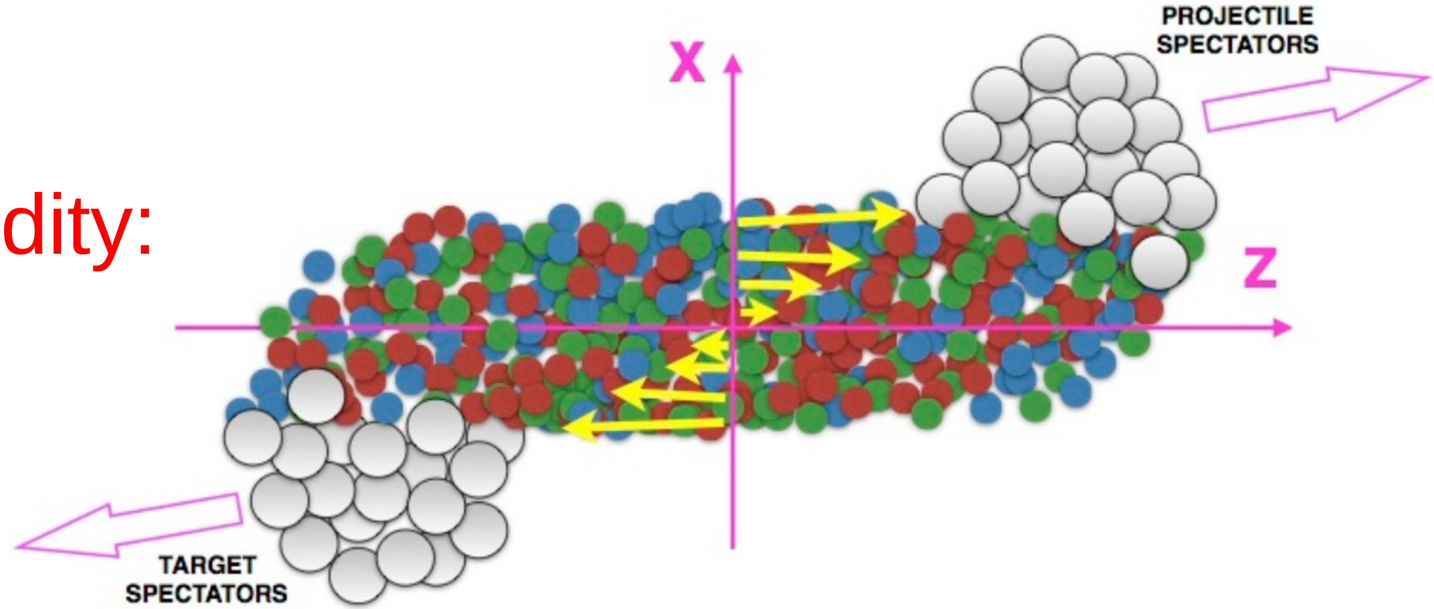
- Coverage ~ 2.5-4 in pseudorapidity
- Silicon disks and sTGC (tracking)
- ECal and HCal (calorimetry)
- See talks Friday afternoon for details



System angular momentum

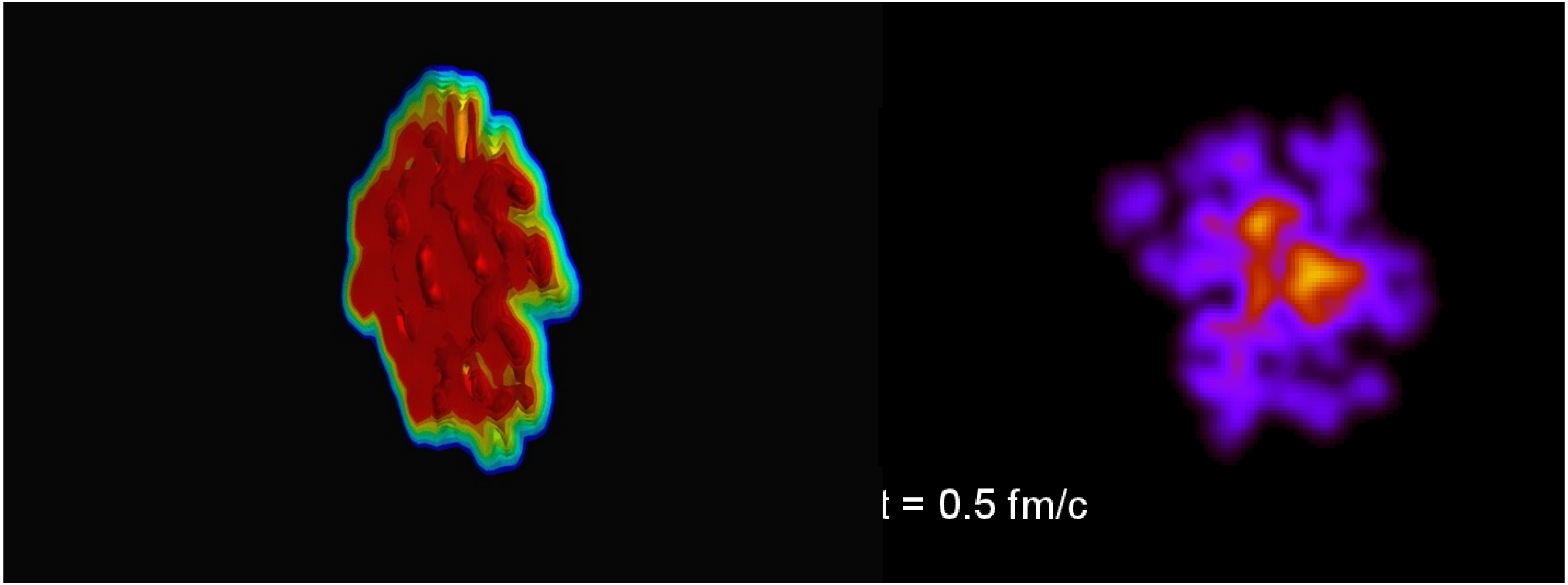
At mid-rapidity:

$\otimes \vec{L}$



- $|L| \sim 10^5\ \hbar$ in non-central collisions
- Dissipative processes → thermalization of angular momentum, transference to fireball
  - Hydrodynamically this is described by vorticity: $\vec{\omega} \equiv \frac{1}{2} \vec{\nabla} \times \vec{v}$

Hydrodynamic evolution



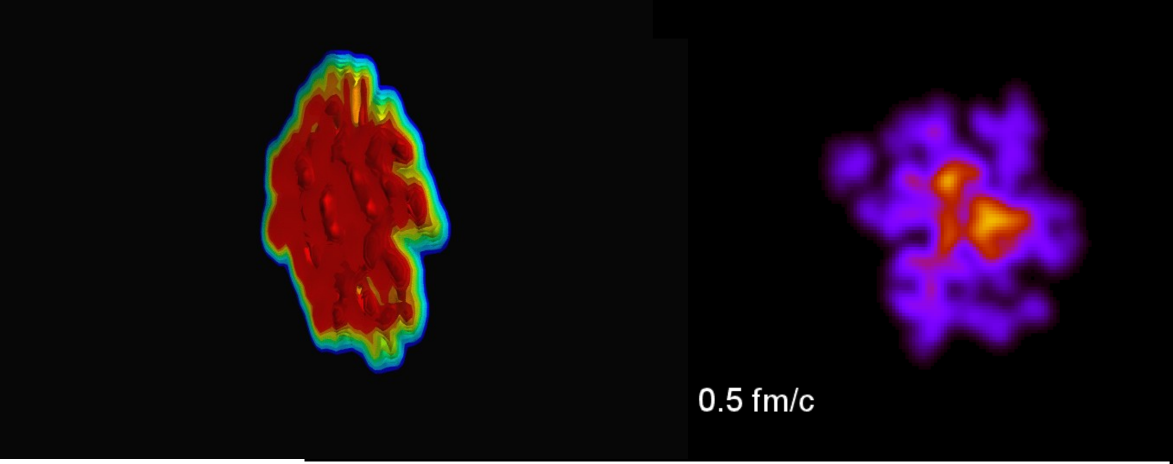
From a (lumpy) initial state, solve hydro equations:

movies by Bjorn Schenke

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu,\nu} = e u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

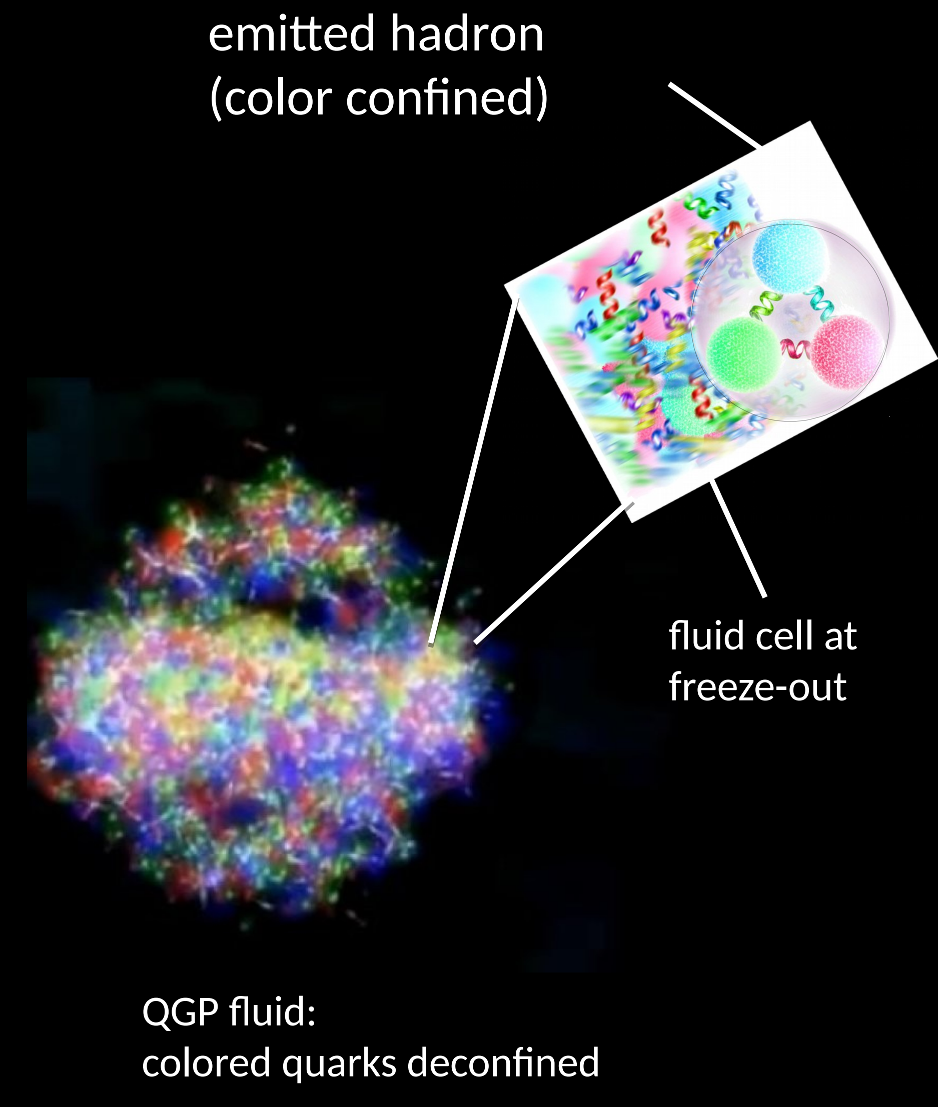
$$u^\mu \partial_\mu \Pi = -\frac{1}{\tau_\Pi}(\Pi + \zeta\theta) - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\lambda\left(\frac{\tau_\Pi}{\zeta T}u^\lambda\right)$$

& many more terms…



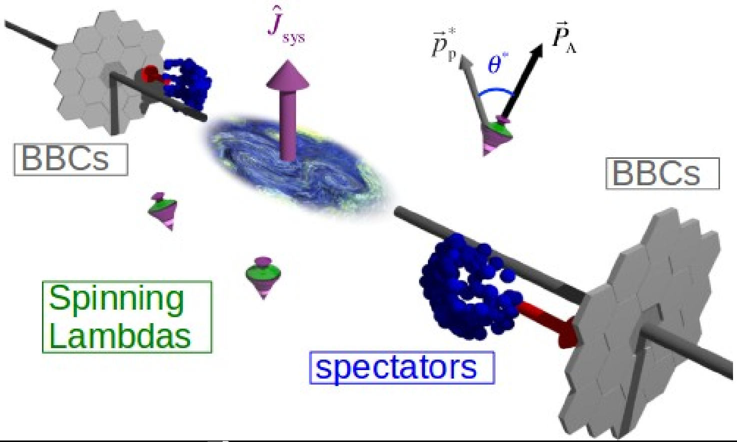
System cools & expands → Hadronization & "Freeze-out"

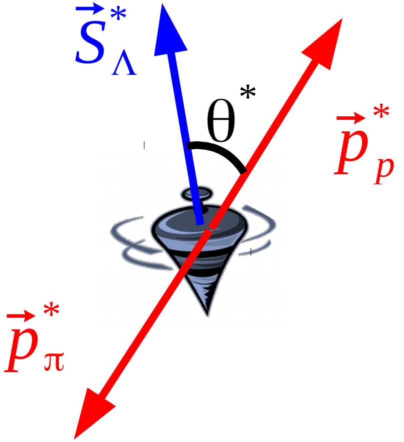
- emitted particles reflect properties of parent fluid cell
  - chemical potentials, thermal & collective velocities
  - In regions of local vorticity spin degrees of freedom are frozen out into particles with net polarization
  - In hydro: Cooper-Frye at freeze-out
  - In transport models: coarse-graining



Measuring polarization

- Lambdas are "self-analyzing"
  - Reveal polarization by preferentially emitting daughter proton in spin direction





Λs with Polarization $\vec{P}$ follow the distribution:

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1+\alpha\vec{P}\cdot\hat{p}_p^*\right) = \frac{1}{4\pi}\left(1+\alpha P\cos\theta^*\right)$$

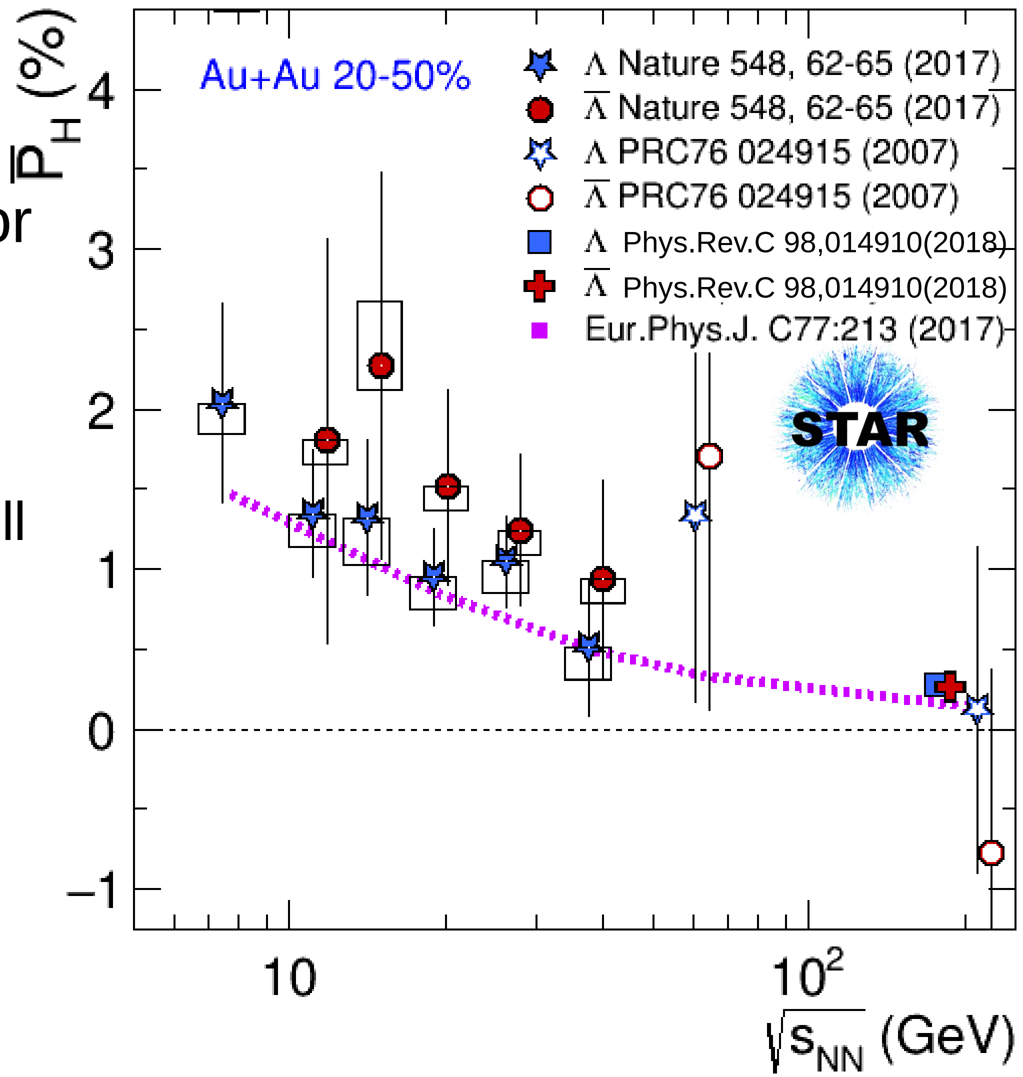
$\alpha = 0.642 \pm 0.013$ [measured]

$\hat{p}_p^*$ is the daughter proton momentum direction *in the Λ frame*

$$0<|\vec{P}|<1: \quad \vec{P} = \frac{3}{\alpha}\overline{\hat{p}_p^*}, \quad P_{AVE} = \frac{8}{\pi\alpha}\frac{\langle\sin(\Psi_1-\phi_p^*)\rangle}{R_{EP}^{(1)}}$$

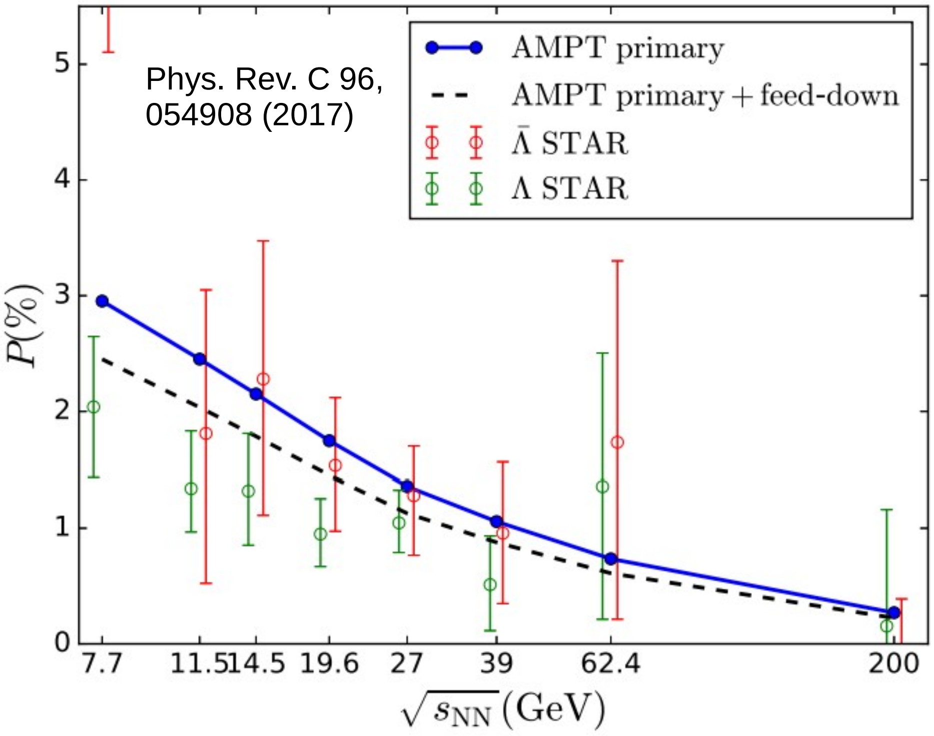
Measurements

- Positive polarization observed for both Lambda and Anti-Lambda
  - Drops with increasing beam energy
  - HADES and ALICE preliminary null results are out there
- At 200GeV this is ~ a 5σ result utilizing ~1.5B events (2010 + 2011 + 2014)
- Theory describes data very well

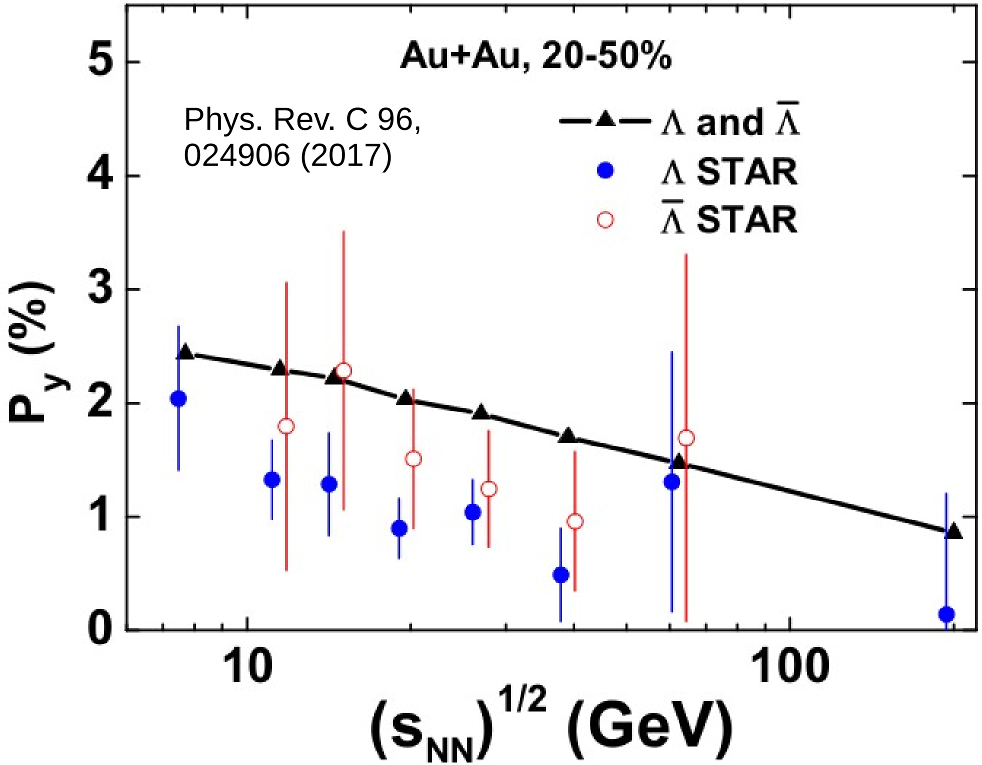


Theory comparison (I)

AMPT

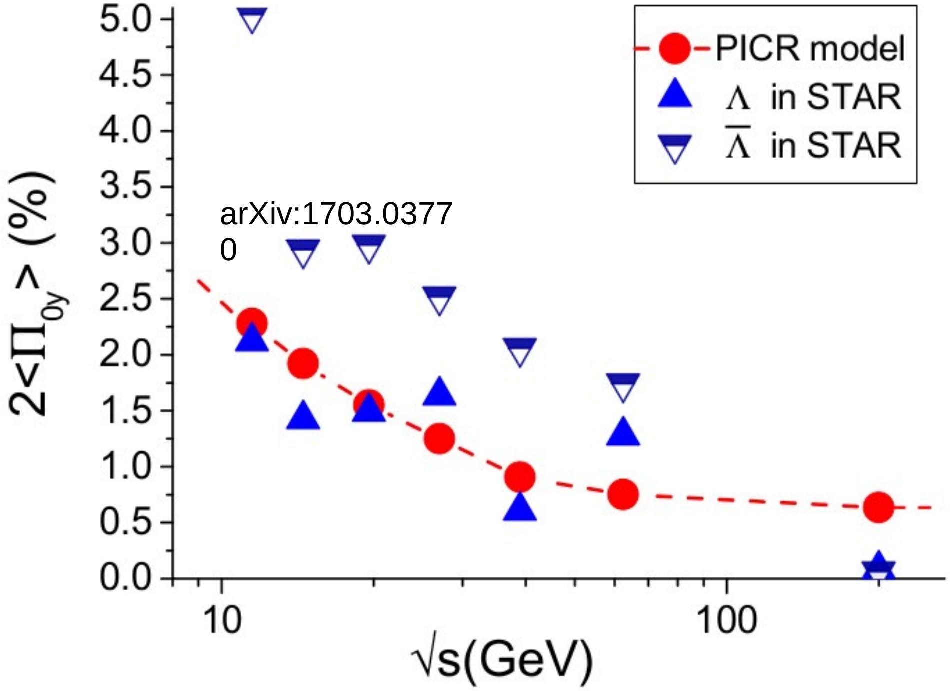


AMPT IC + chiral kinetic approach

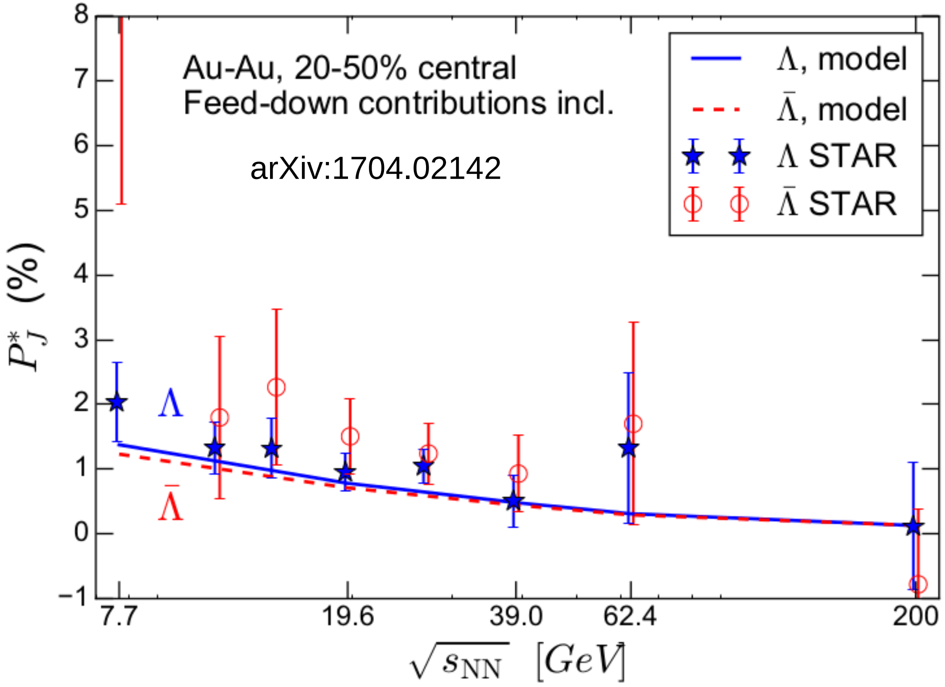


Theory comparison (II)

Yang-Mills flux-tube +
PICR ideal hydro



UrQMD IC + vHLLE 3D
viscous hydro



Comparison summary

- Clearly a diverse set of calculations can describe the data well, which makes one wonder how much we learn from the comparisons
- We need more granular studies to distinguish model predictions
- First I want to dive into the specifics of a model to get a sense of what constraints these measurements provide

Example model: UrQMD + vHLLE

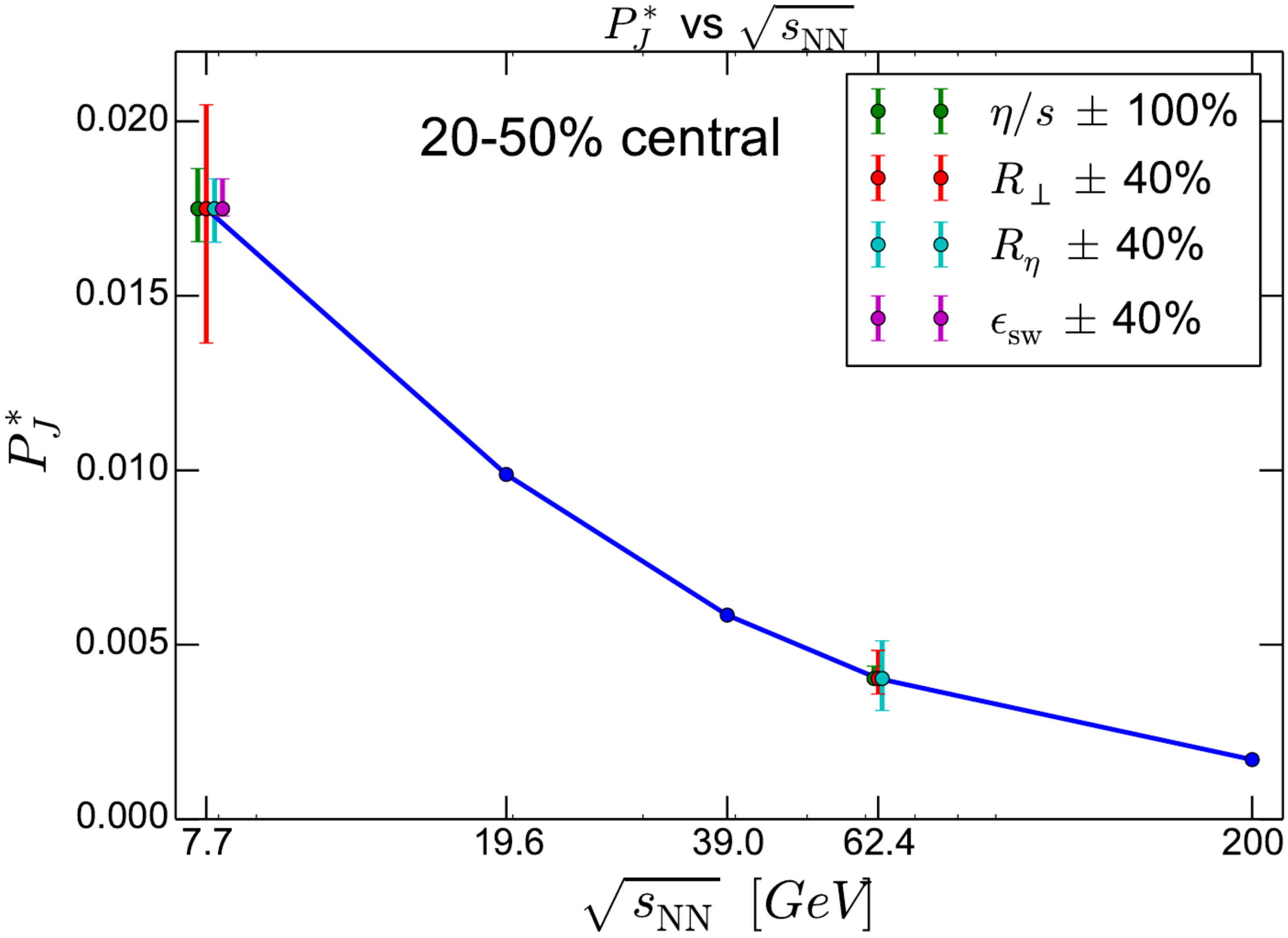
- To describe the manifestly not-boost-invariant system at low collision energies course-grained UrQMD is used to provide 3D initial conditions
- The model is evolved via 3D viscous (Israel-Stewart) hydrodynamics
- A UrQMD afterburner is run after freezeout, but not for polarization calculations
- Model parameters are chosen so that the model correctly describes basic hadron observables in relativistic heavy ion collisions
  - (pseudo)rapidity distributions
  - p_T distributions and
  - elliptic flow coefficients

Tunable parameters

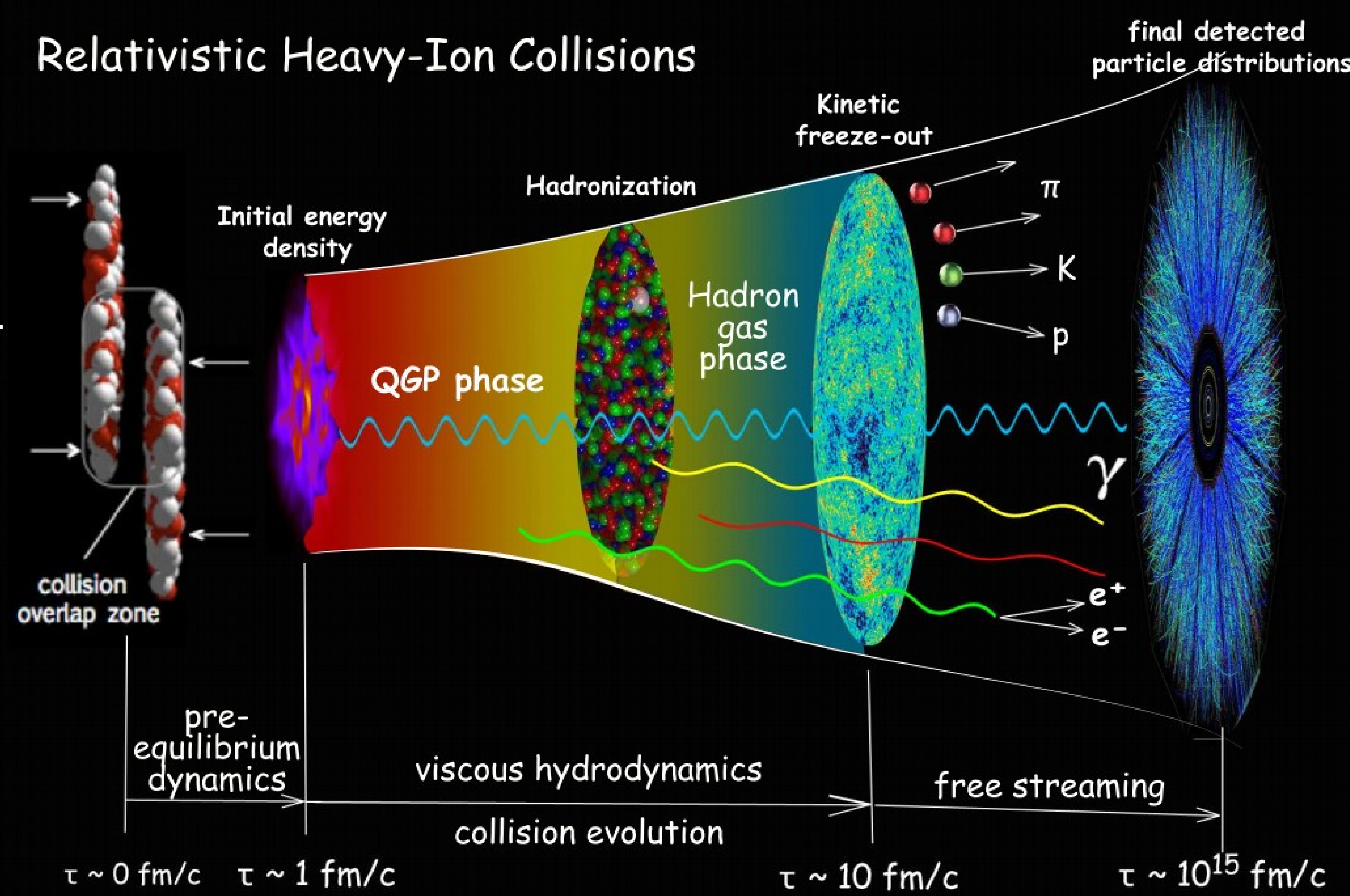
- Transverse granularity of the initial state: $R_\perp$
- Longitudinal granularity of the initial state: R_η
- Shear viscosity to entropy ratio of the fluid medium: η/s
- Particlization energy density ϵ_{sw}

Systematic study results

- The model is most sensitive to the parameters pertaining to initial conditions
- At low energies this is the transverse component, but at higher energies the longitudinal component takes over



Historically ICs and pre-equilibrium stage is poorly contrained

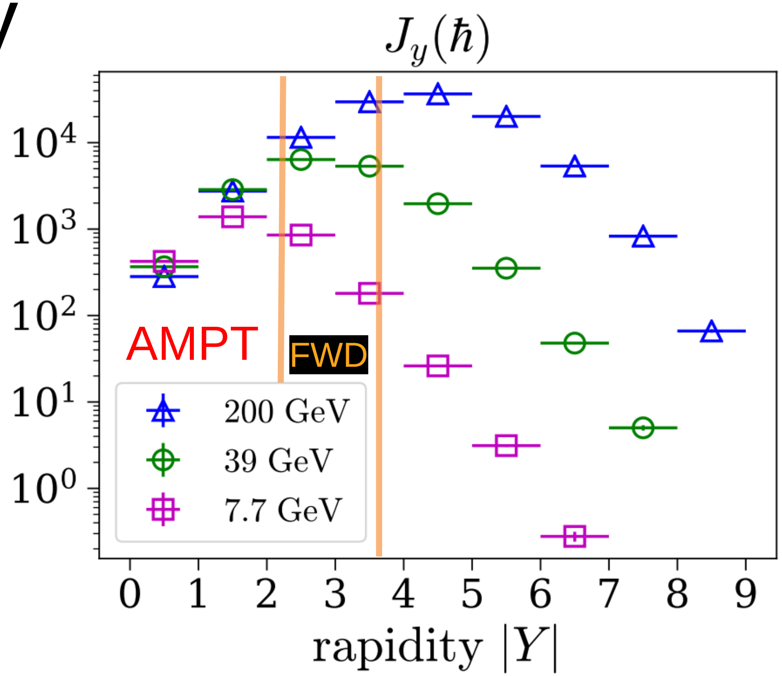


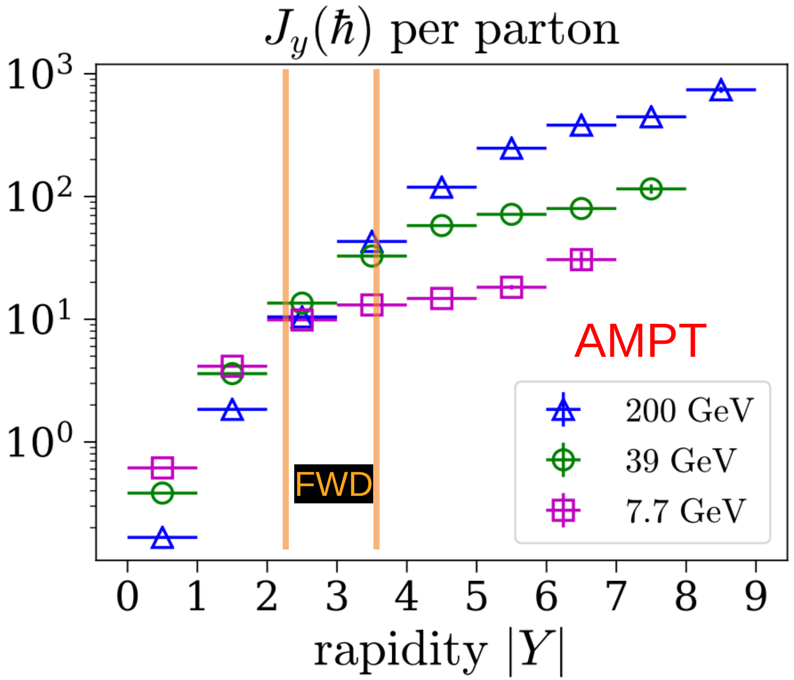
Forward polarization

- Previous model most sensitive to longitudinal parameter → rapidity dependence is a natural place to look for model discrepancy
- Typically we expect forward physics to mimic lower collision-energy physics (→ increase in polarization)
- Complementary goals to FWD
  - flow measurements (T dependence of η/s, decouple initial from final state effects)
  - nuclear-PDF measurements

FWD angular momentum

- The angular momentum (per parton) increases with rapidity

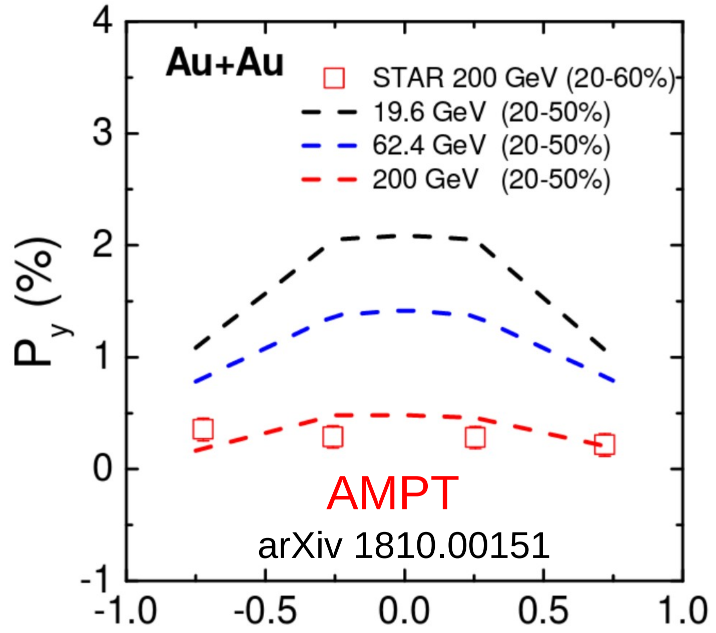


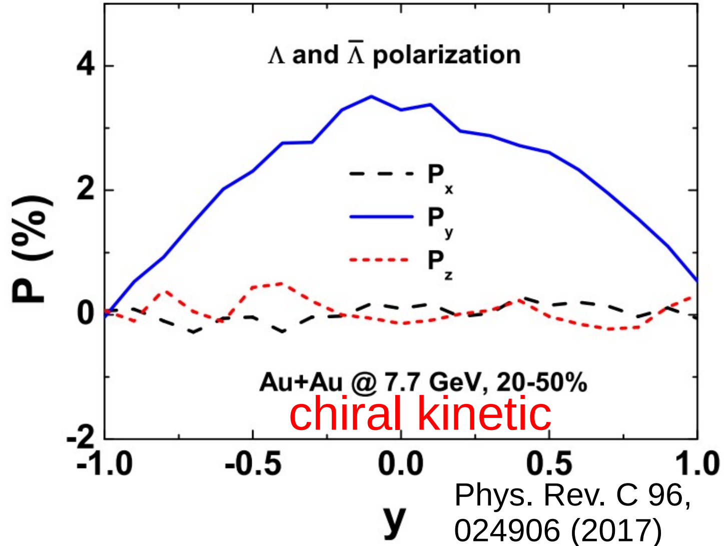


arXiv:1712.02677

FWD prediction (I)

- AMPT and chiral kinetic approach predict polarization will fall for forward Lambdas
- Both polarization signals clearly fall to zero inside the acceptance of the forward upgrade

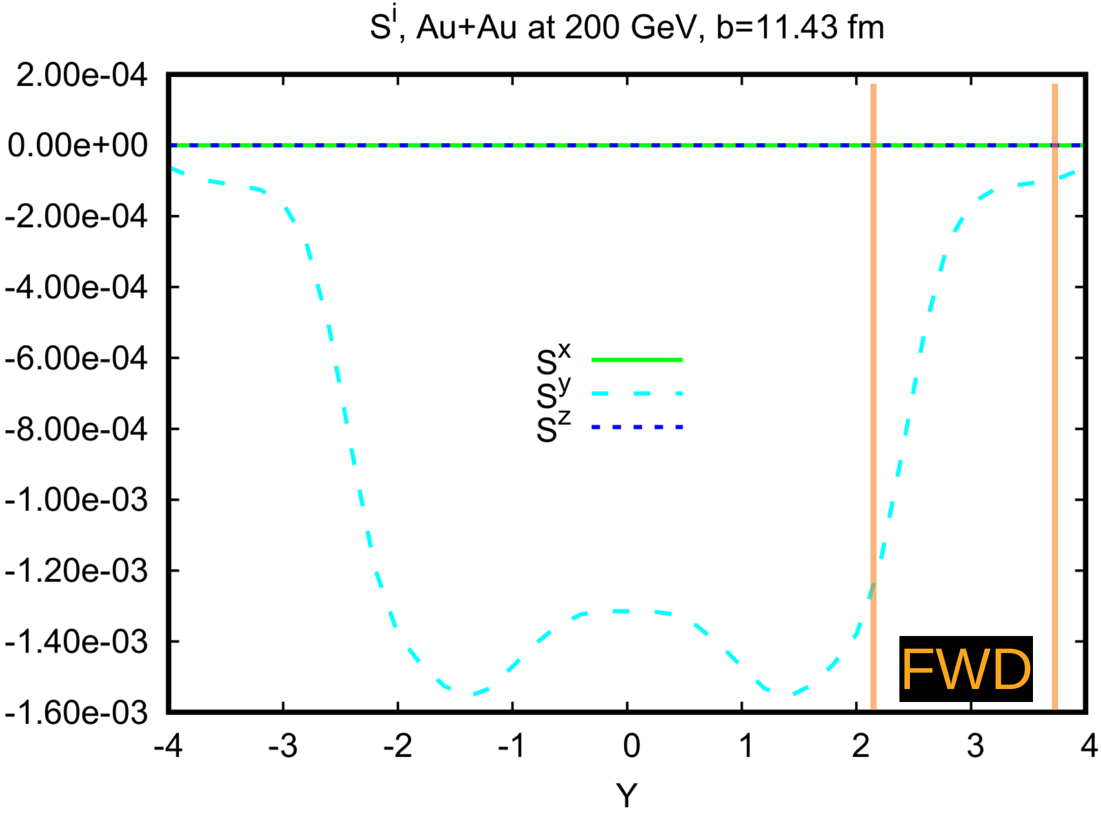




Phys. Rev. C 96, 024906 (2017)

FWD prediction (II)

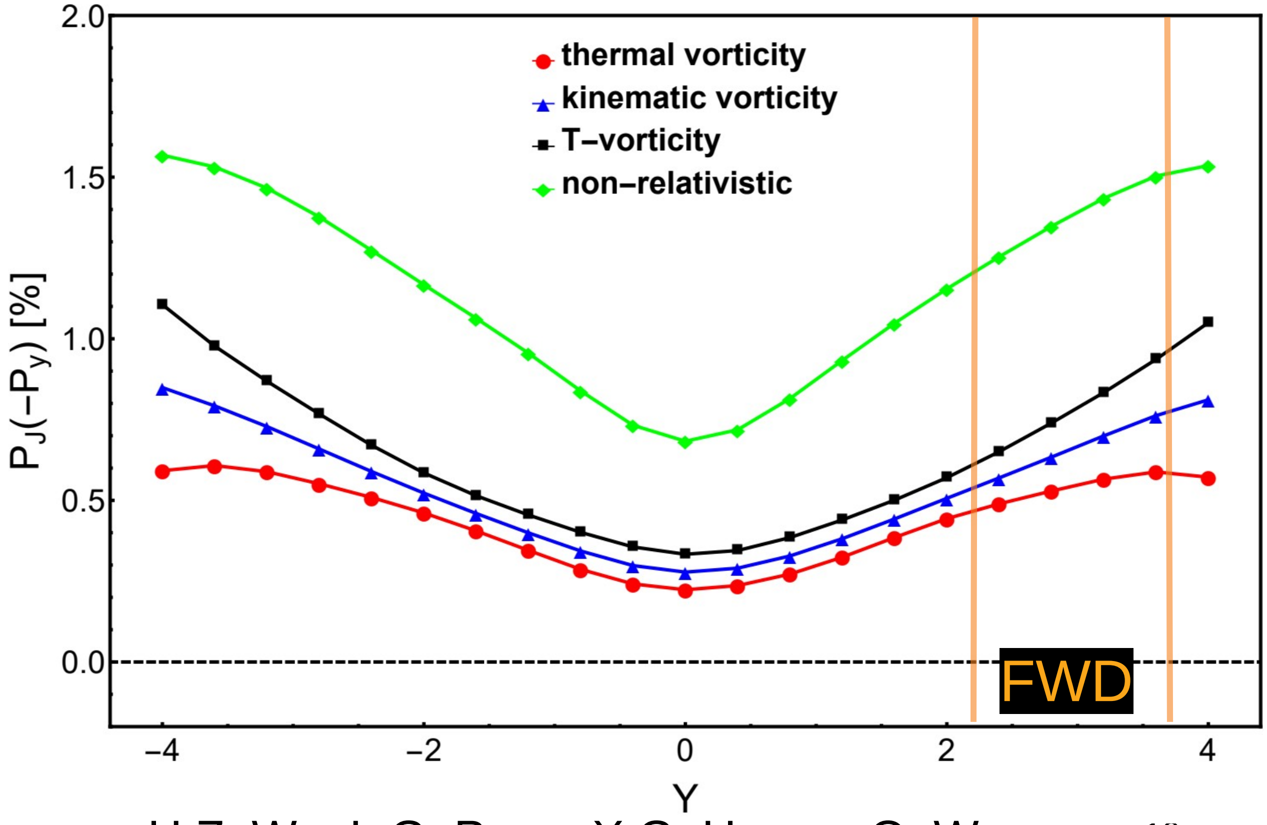
- UrQMD + vHLLE predicts similar fall of polarization with rapidity
  - Note: negative S^y is positive polarization
- Drops slower than AMPT
- Authors suspect ICs may not be valid this far forward



F. Becattini, G. Inghirami, and I. Karpenko (private communication)

FWD prediction (III)

- Alternate hydro calculation predicts increasing polarization
  - IC: AMPT + HIJING strings w/ finite fluctuating lengths
  - 3D viscous hydro (CLVisc)



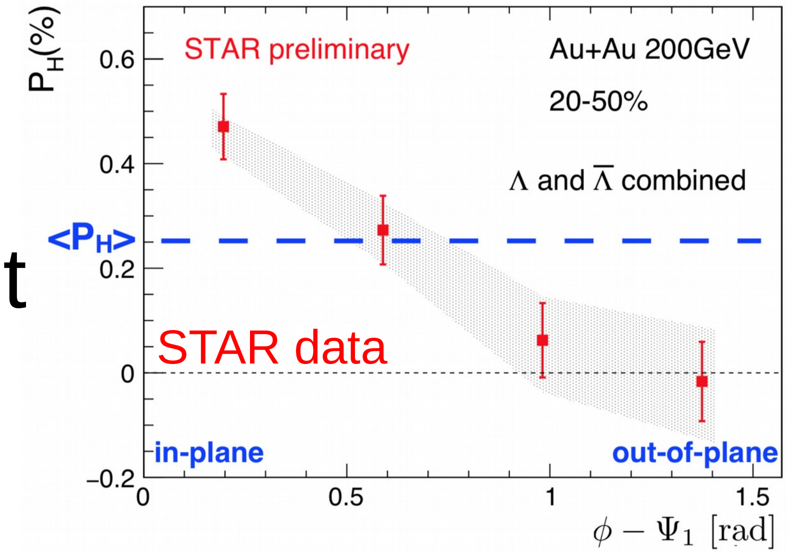
H.Z. Wu, L.G. Pang, X.G. Huang, Q. Wang (private communication)

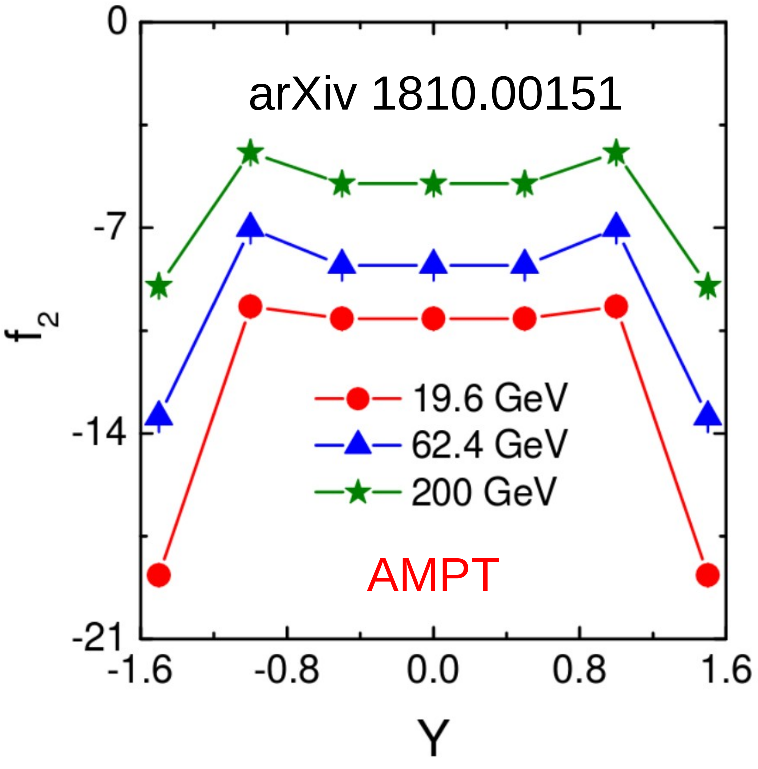
Measurement prospects

- In principle calorimeter + momentum from the tracking could provide p + π PID, but early simulations do not look good
  - Waiting for new tracker + cal. simulation to re-investigate
- However:
  - Spin is always oriented along the positive daughter
  - Combinatoric background has little/no signal, other than from Anti-Lambdas
  - Measurement could be performed with tracking alone
  - Note that we now have EPD and iTPC upgrades
- If we match previous statistics
  - ~ 3σ difference between FWD (NULL/increased ≳ 2x increase) and mid-rapidity
  - > 6σ difference between FWD (NULL) and increased ≳ 2x increase

Related measurements (I)

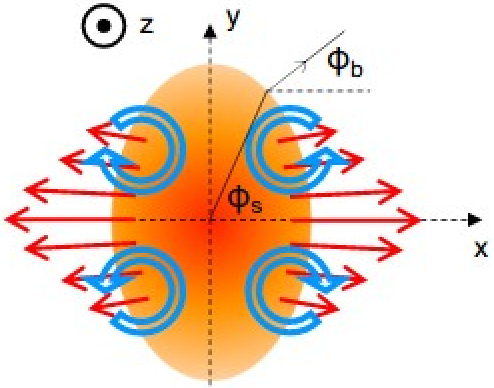
- Lambda emission angle dependence of polarization might be strongly dependent on rapidity
- f2 is proportional to the data fit by a cosine





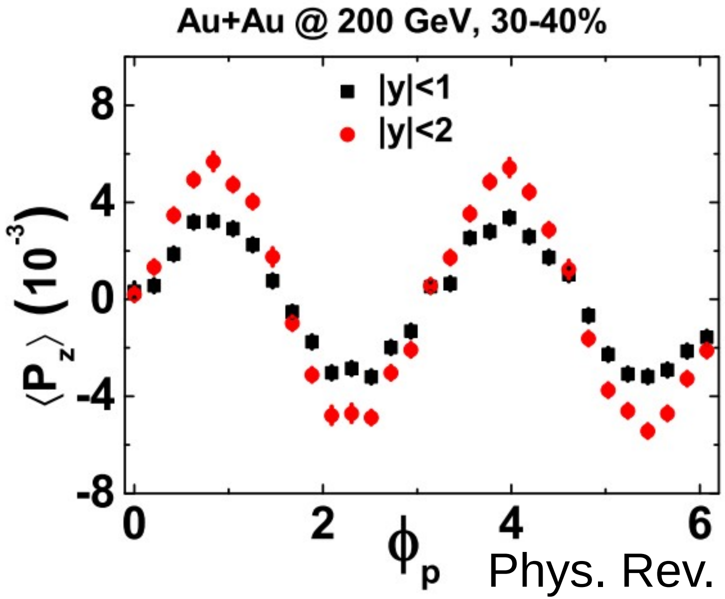
Biao Tu for STAR, poster @ QM18

Related measurements (II)



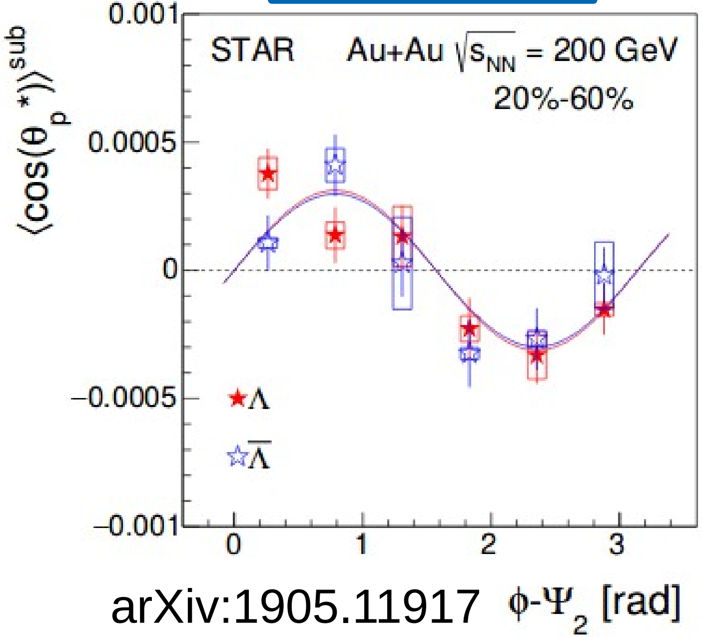
- Longitudinal polarization
  - v2 velocity gradients → vorticity quadrupole (see Takafumi)
- Measure as a function of rapidity

STAR measurement



Quark polarization in chiral kinetic calculation

Phys. Rev. C 99.011903



arXiv:1905.11917

Conclusion

- Lambda polarization modeling is most sensitive to the details of the early time dynamics
- Models describe mid-rapidity data well, but significant tension exists in the forward direction
- Measurements in the STAR forward upgrade may help distinguish models and fix model parameters so we can learn about the initial state of the collision

END

Becattini and Karpenko: IS parameters

$\sqrt{s_{\rm NN}}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_η [fm]	η/s
7.7	3.2	1.4	0.5	0.2
8.8 (SPS)	2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
17.3 (SPS)	1.42	1.4	0.5	0.15
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9*	1.0	0.7	0.08
62.4	0.7*	1.0	0.7	0.08
200	0.4*	1.0	1.0	0.08