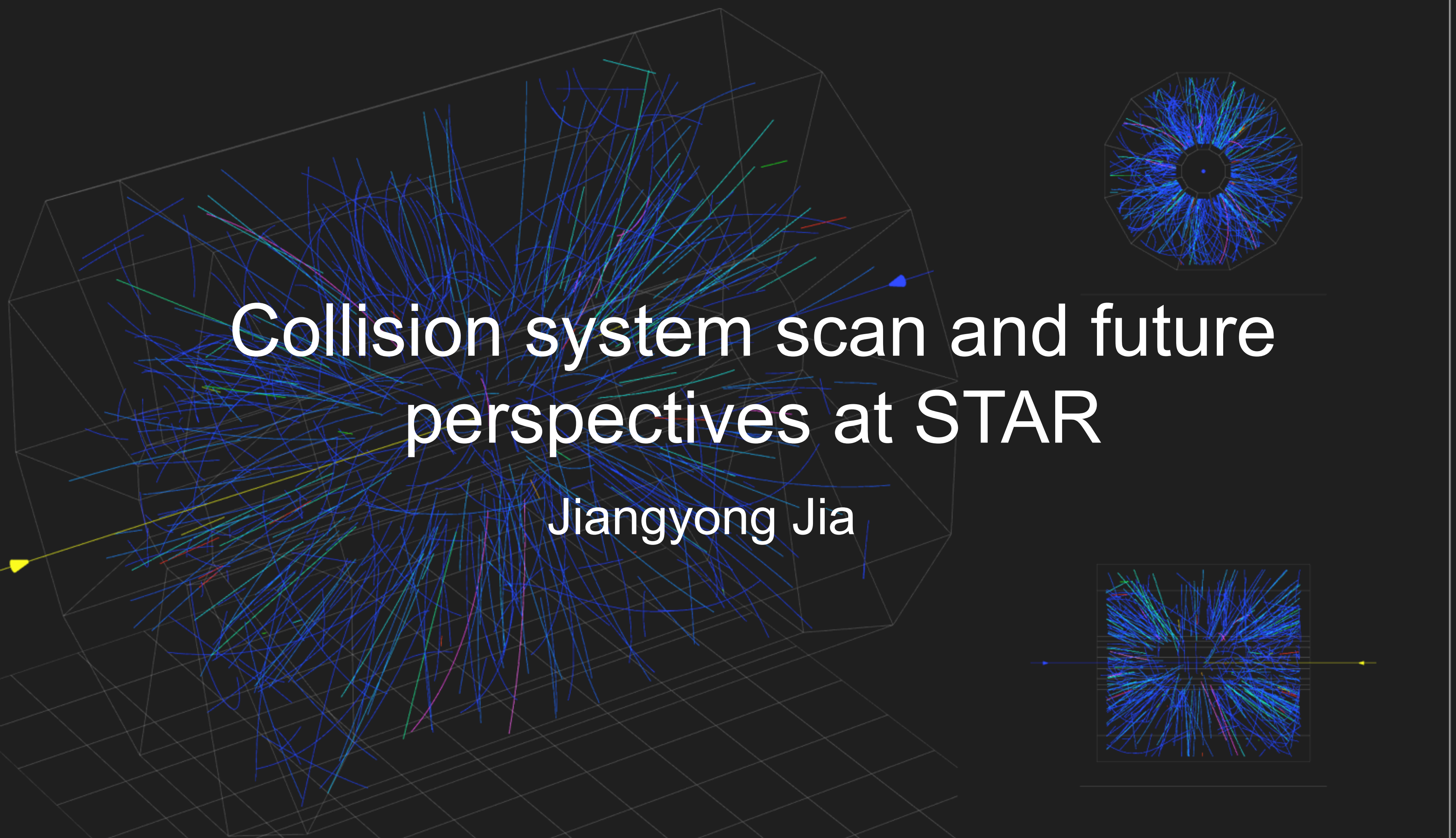
Supported in part by



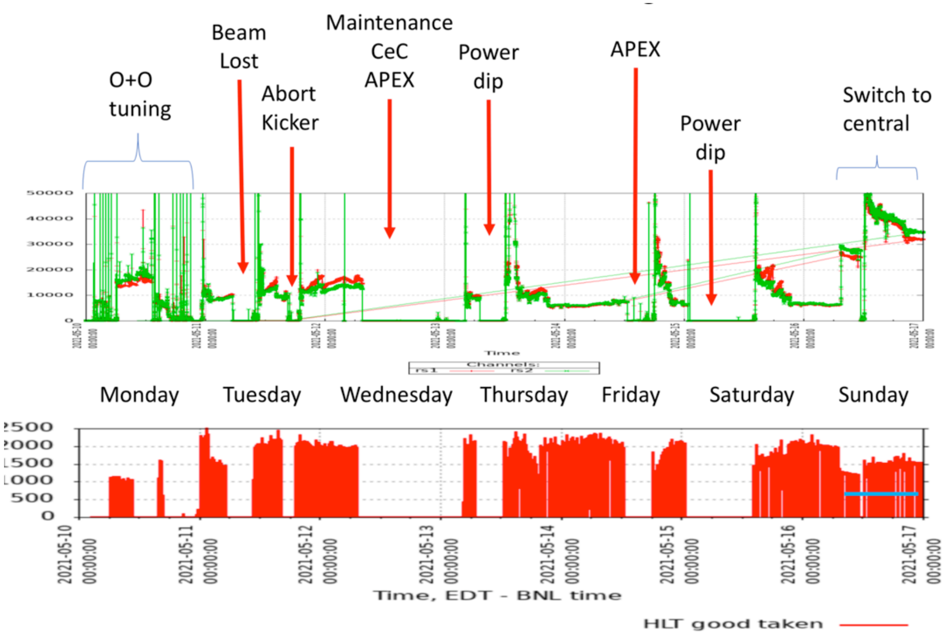
# Collision system scan and future perspectives at STAR

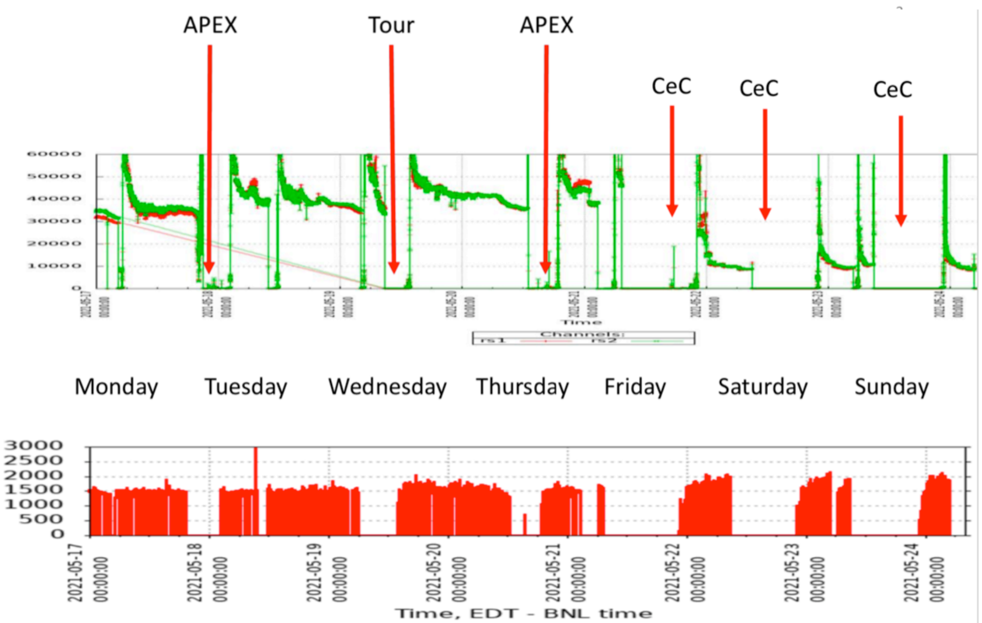
Jiangyong Jia

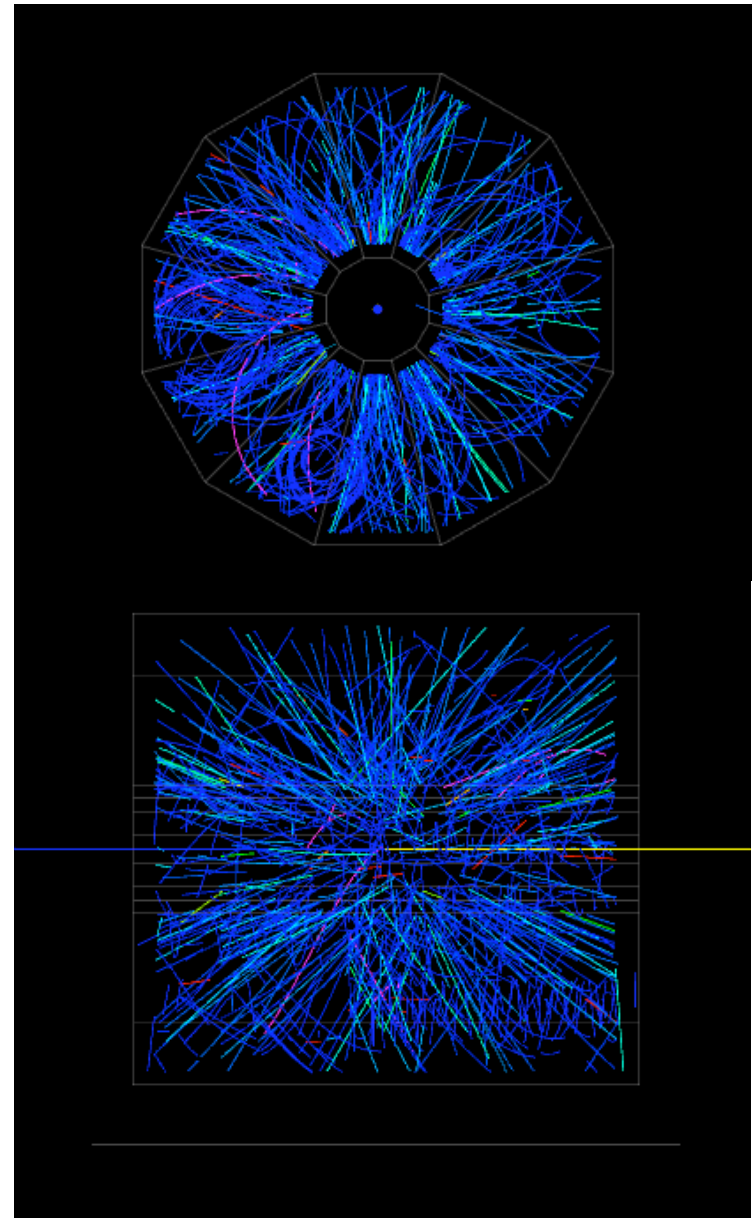


May 24, 2021

# 200 GeV O+O

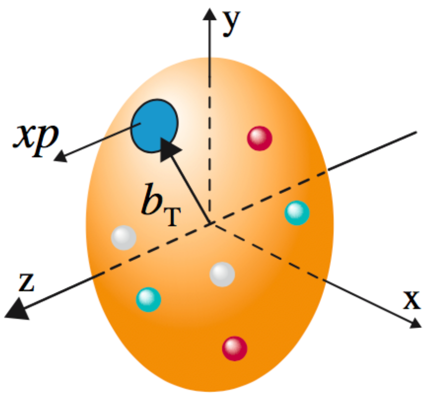

O+O tuning
Beam Lost
Abort Kicker
Maintenance CeC APEX
Power dip
APEX
Power dip
Switch to central
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
Time, EDT - BNL time
HLT good taken

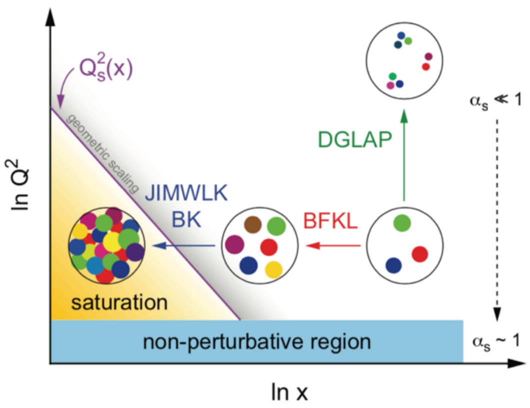

APEX
Tour
APEX
CeC
CeC
CeC
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
Time, EDT - BNL time



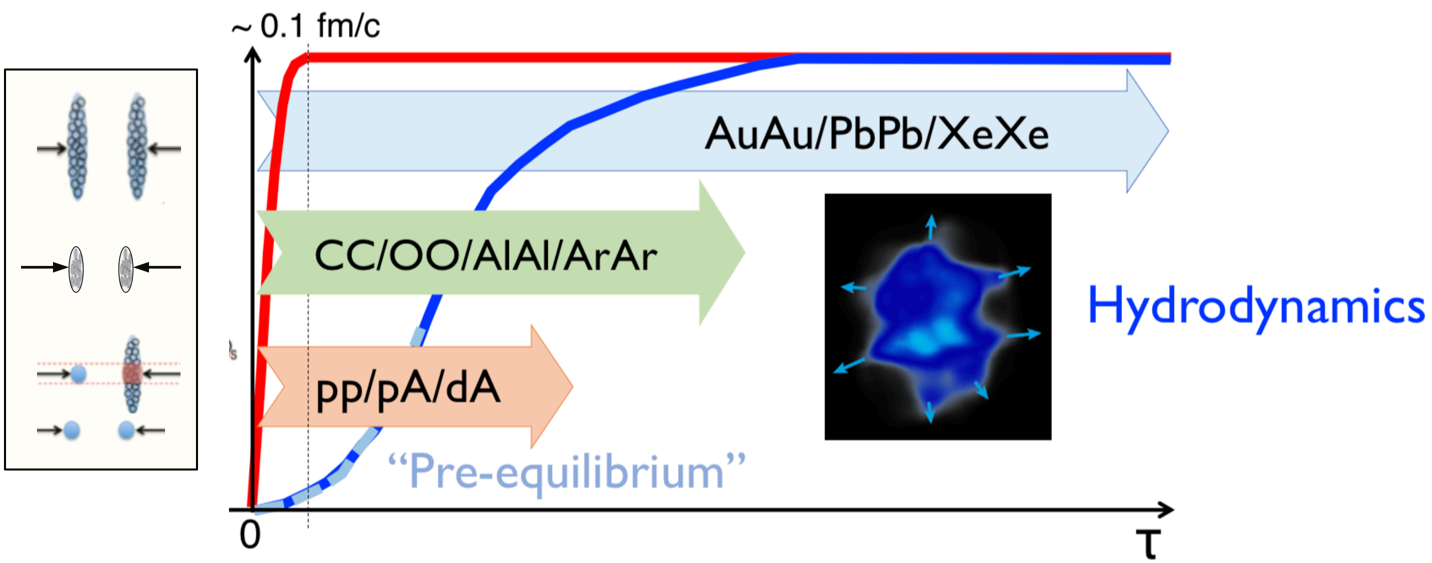
# e+p/A vs nuclear collisions

- EIC: structures of the initial state



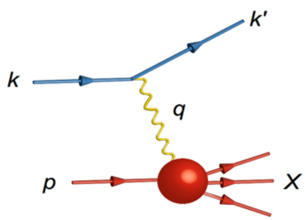

- HeavyIon: Initial state and emergence of collectivity.



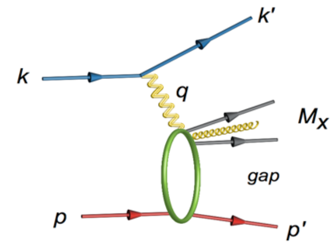
# e+p/A vs nuclear collisions

- EIC: structures of the initial state (one-body Wigner func.)
  - Precise control on kinematics

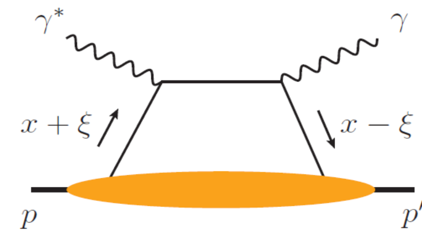
Inclusive



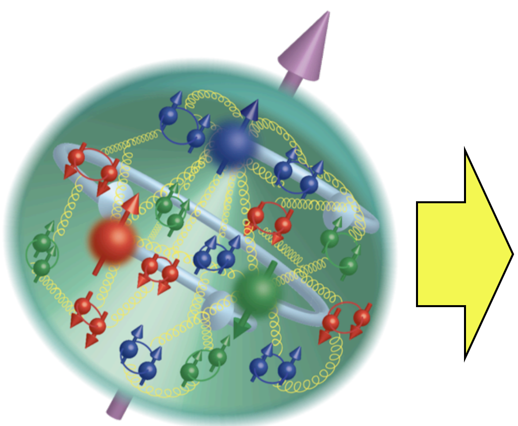

Semi-Inclusive



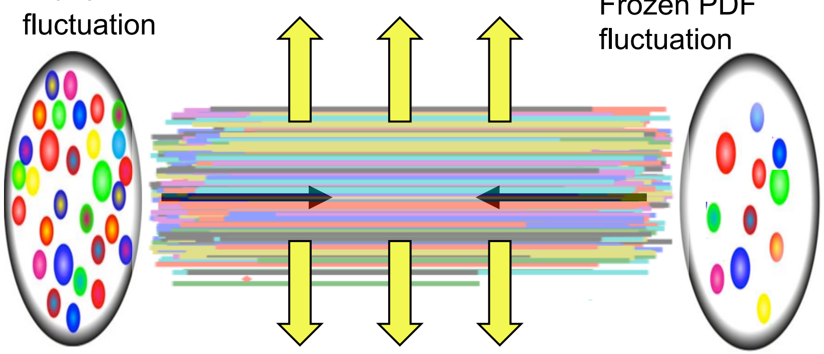

Exclusive



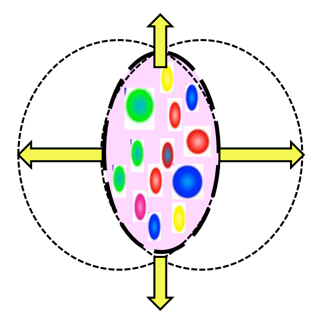

- Heavy-ion: Multi-Parton interactions (many-body Wigner function)



Longitudinal view




Transverse view

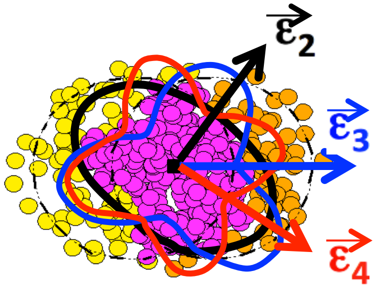


Probe different phase space (fock state) of the proton wave function

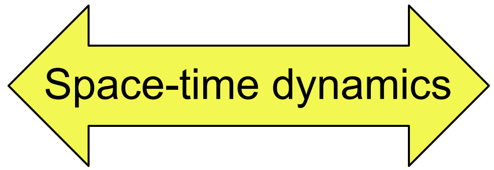
# Initial state imaging in large system

## Initial Shape

$$\mathcal{E}_n \propto \int r^n e^{in\phi} \epsilon(r,\phi)$$



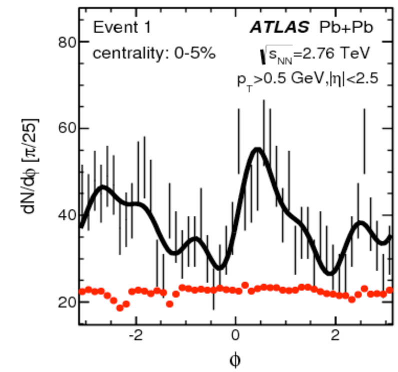

Hydro-response




$$V_n \propto \mathcal{E}_n$$

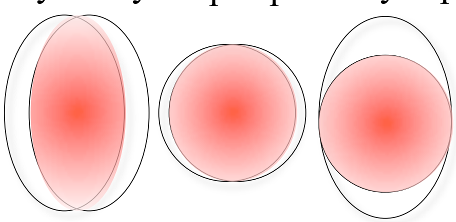
## Harmonic flow

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$



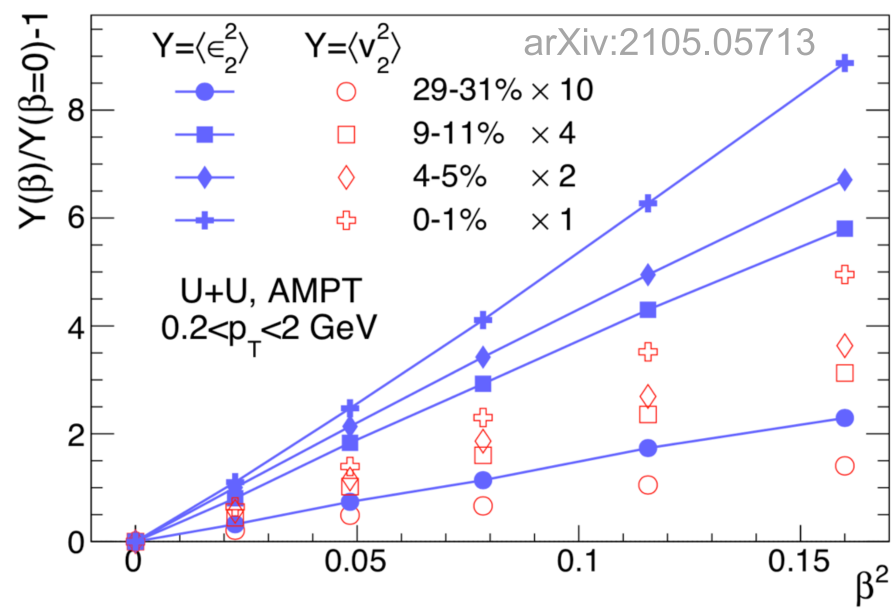

- Unfold to get initial state information

$$\rho(r,\theta) = \frac{\rho_0}{1 + e^{(r - R_0(1+\beta_2 Y_{20}(\theta))/a}}$$




U+U

$$\langle \epsilon_2^2 \rangle = a' + b'\beta_2^2 \qquad \langle v_2^2 \rangle = a + b\beta_2^2$$



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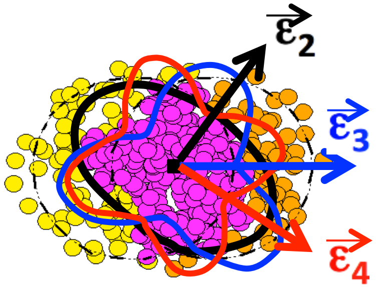
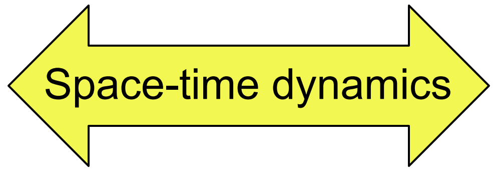



Hydro-response

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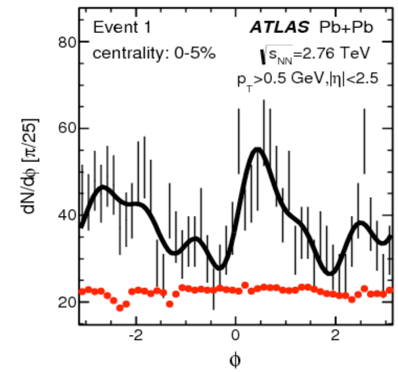
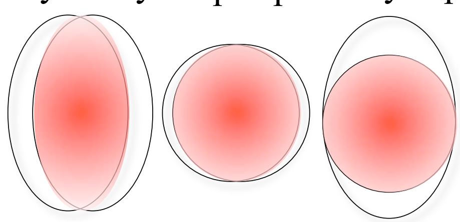



- Unfold to get initial state information

$$\rho(r,\theta) = \frac{\rho_0}{1 + e^{(r - R_0(1+\beta_2 Y_{20}(\theta))/a}}$$

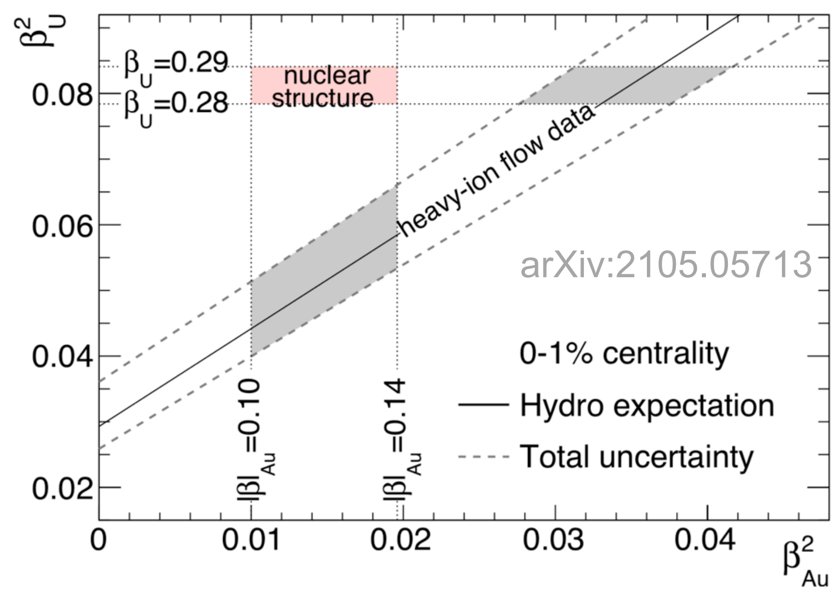
body+body tip+tip body+tip



U+U

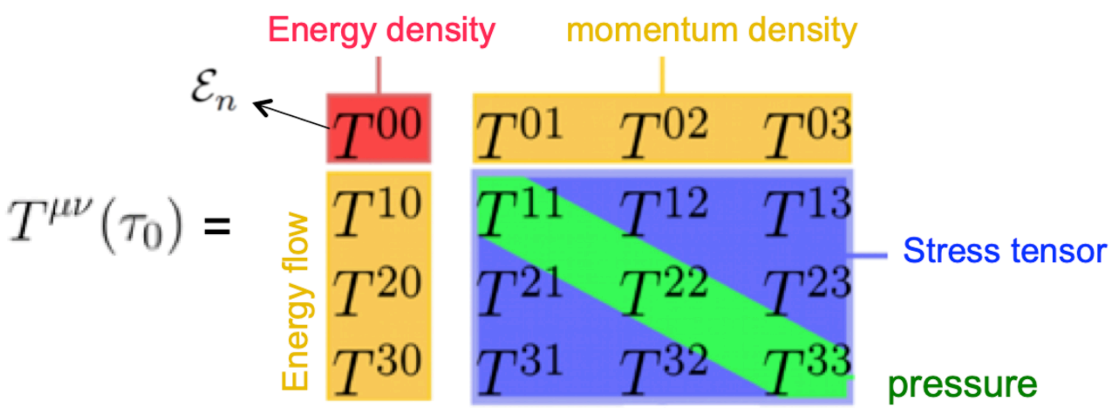
$$\langle \epsilon_2^2 \rangle = a' + b'\beta_2^2 \qquad \langle v_2^2 \rangle = a + b\beta_2^2$$

$$\boxed{\beta_{2,\mathrm{U}}^2 = \left(\frac{r_{v_2^2} r_a - 1}{r_\mathrm{U}}\right) + \left(r_{v_2^2}\right) \beta_{2,\mathrm{Au}}^2}$$



# Dynamics in the initial stages

- Initial condition generally (DIS&HI) described by energy-momentum tensor

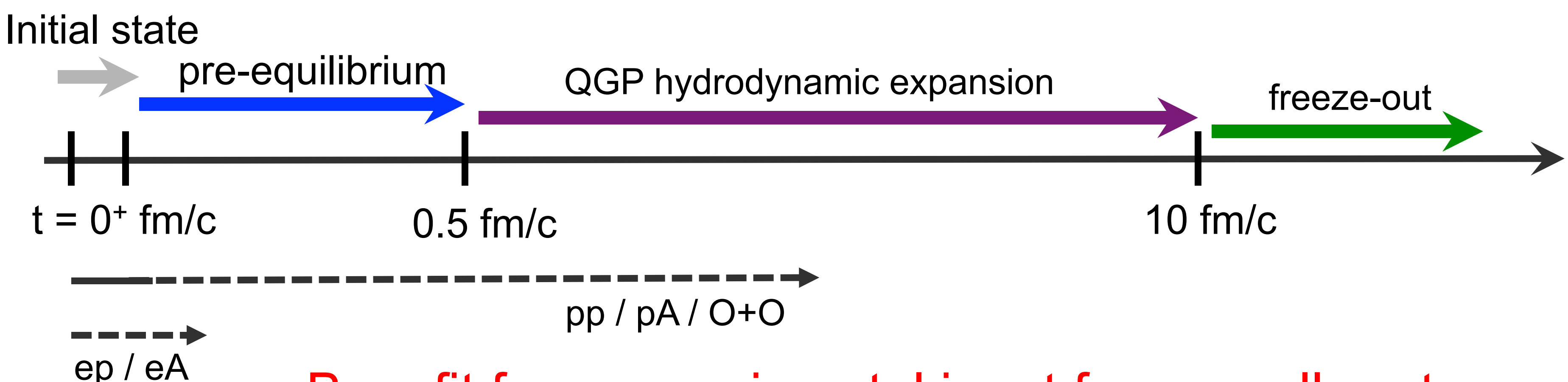



Only diagonal terms matter in large system, but non-diagonal terms important in small systems

"MOMENTUM" ANISOTROPIES

$$\mathcal{E}_{2p} \propto \langle T^{xx} - T^{yy} + 2iT^{xy} \rangle$$

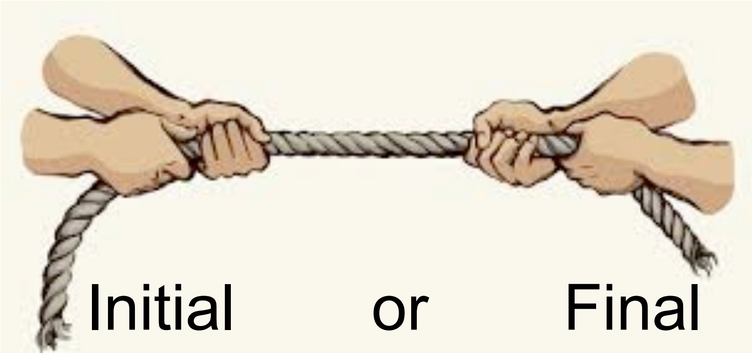
- Modified in heavy-ion collisions due to final-state interaction.
  - Huge theoretical effort/progress in study of hydrodynamization and non-hydro evolution




Benefit from experimental input from small systems

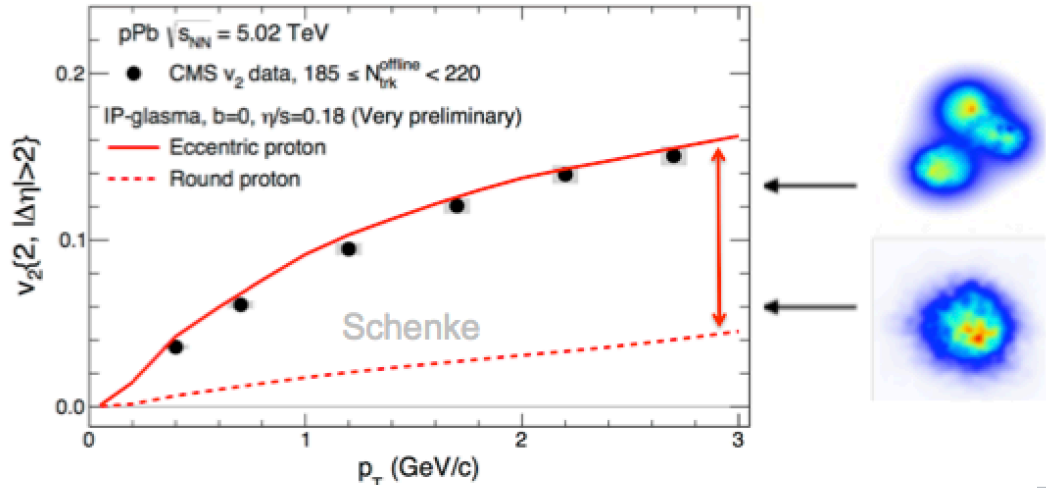
# Aspect of initial conditions from HI

- Small system scan
- Longitudinal correlations
- Covered by others: nPDF, UPC (γ+A, VM), entanglement etc
  - Zhoudunming Tu , Shuai Yang, Dmitri Kharzeev…
- Precision on initial state by improving hydrodynamic models

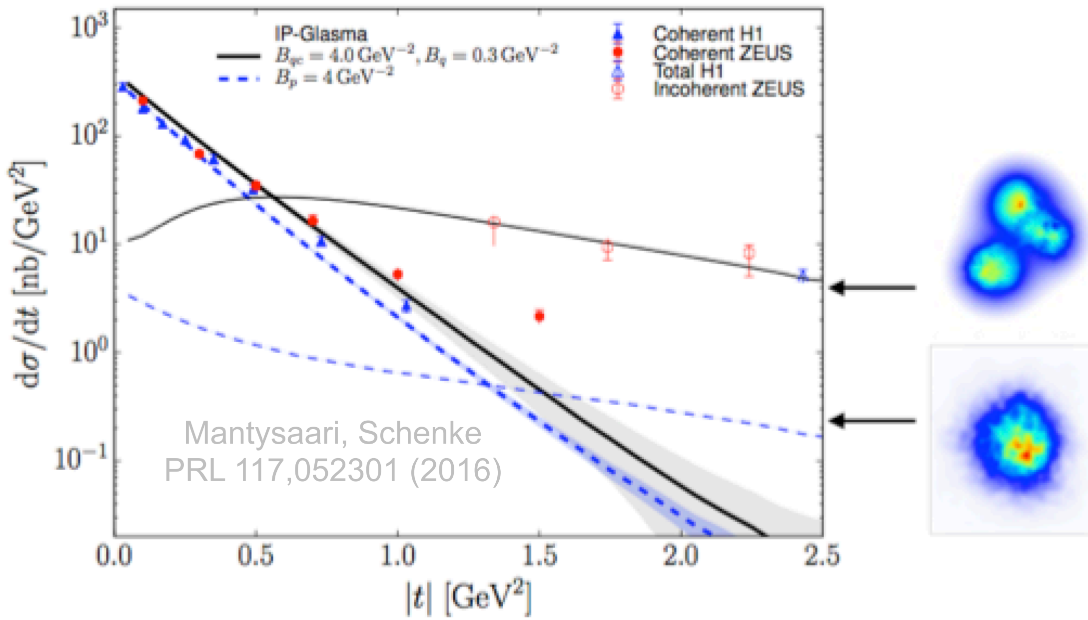


# Importance of subnucleon fluctuations

- Proton substructure essential to explain the pPb ridge




- Proton substructure required to describe incoherent e+p data

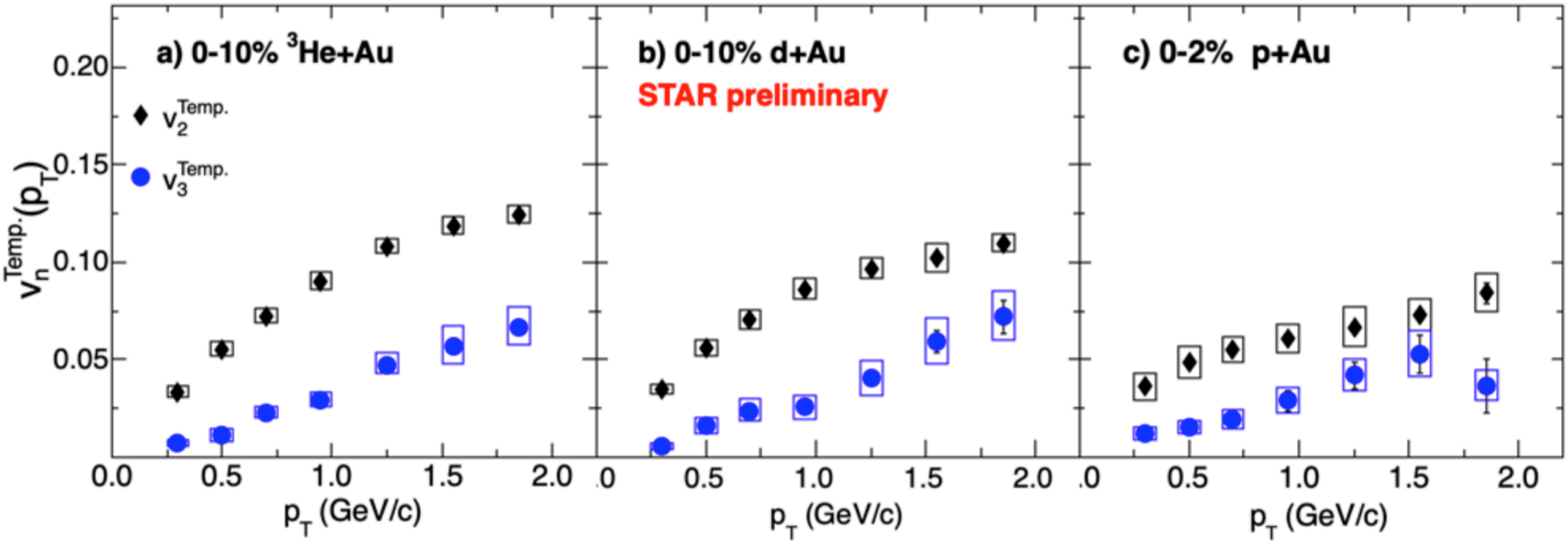



See 2001.10705, 2102.11189

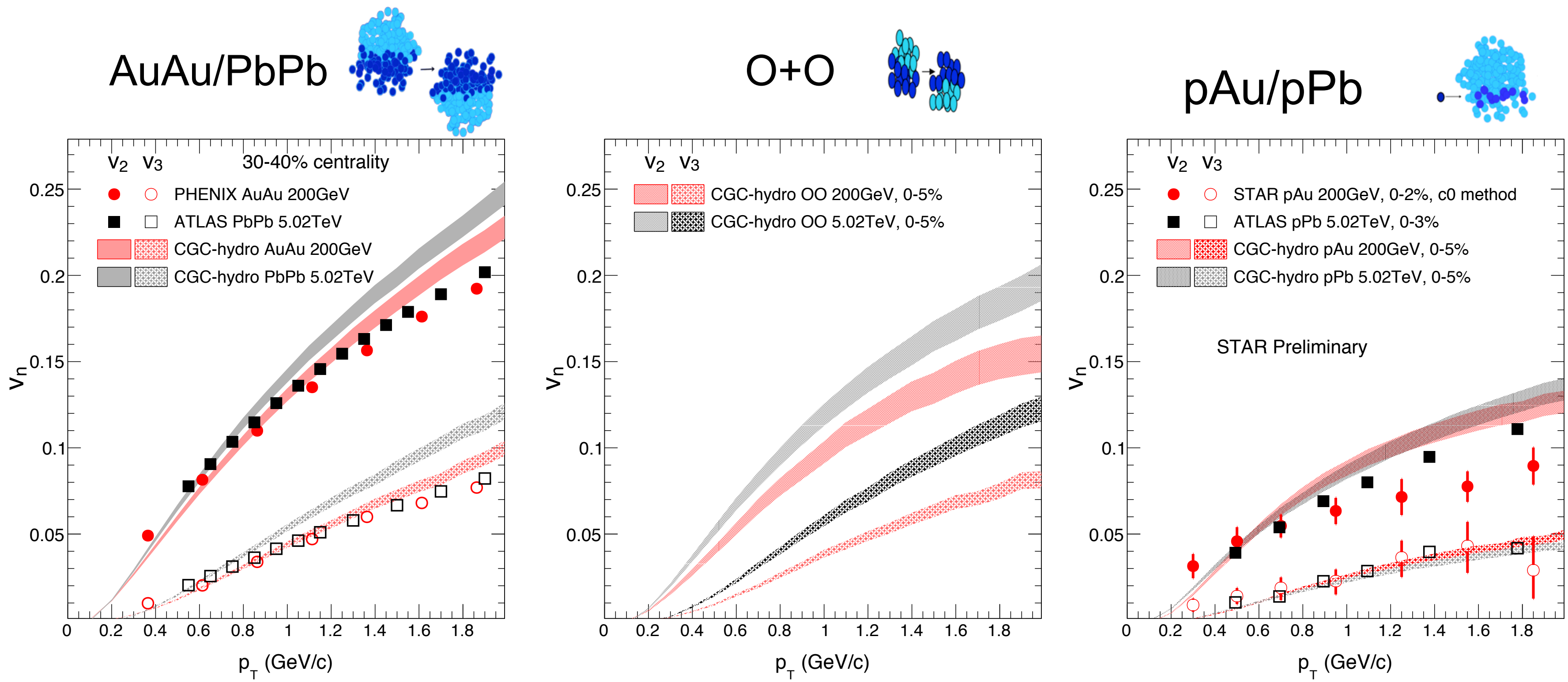
How to go beyond this qualitative picture with STAR data?

# Shape engineering in small system

- $v_2(^3HeAu) \sim v_2(dAu) > v_2(pAu)$, $v_3(^3HeAu) \sim v_3(dAu) \sim v_3(pAu)$
- Both nucleon fluctuation ($v_2$) and subnucleon fluctuations ($v_3$) are important.
  - Ongoing debate on the STAR/PHENIX differences



# Synergy between RHIC & LHC

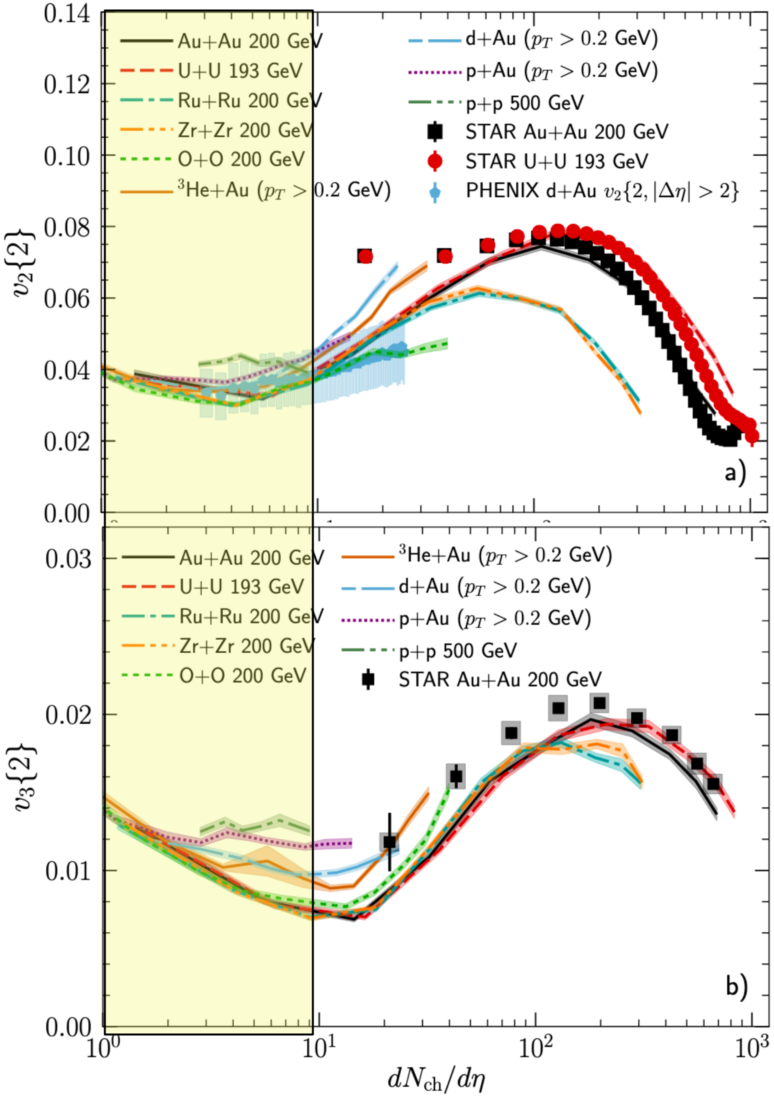



- Remarkable √s indep. of $v_n(p_T)$ in largest and smallest systems!
  - What does this mean?
- √s dependence of nucleon and subnucleon fluctuations?
  - Fill this gap with O+O data at RHIC (taken) and LHC (to be taken).

# Disentangle different contributions



- Geometry vs momentum anisotropy → initial $T_{uv}$
  - Systematic analysis of multiple observables in multiple systems ($v_n$, $[p_T]$, vn-$[p_T]$ )

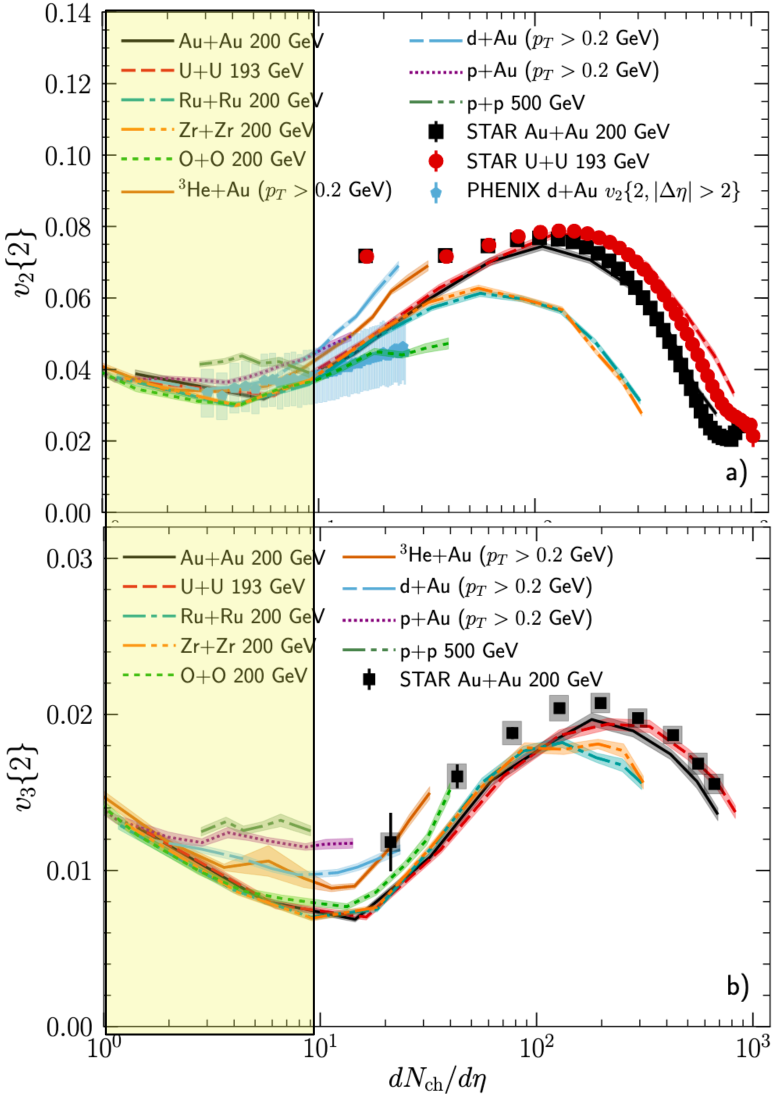



Exp. data + theory efforts

Understand non-flow

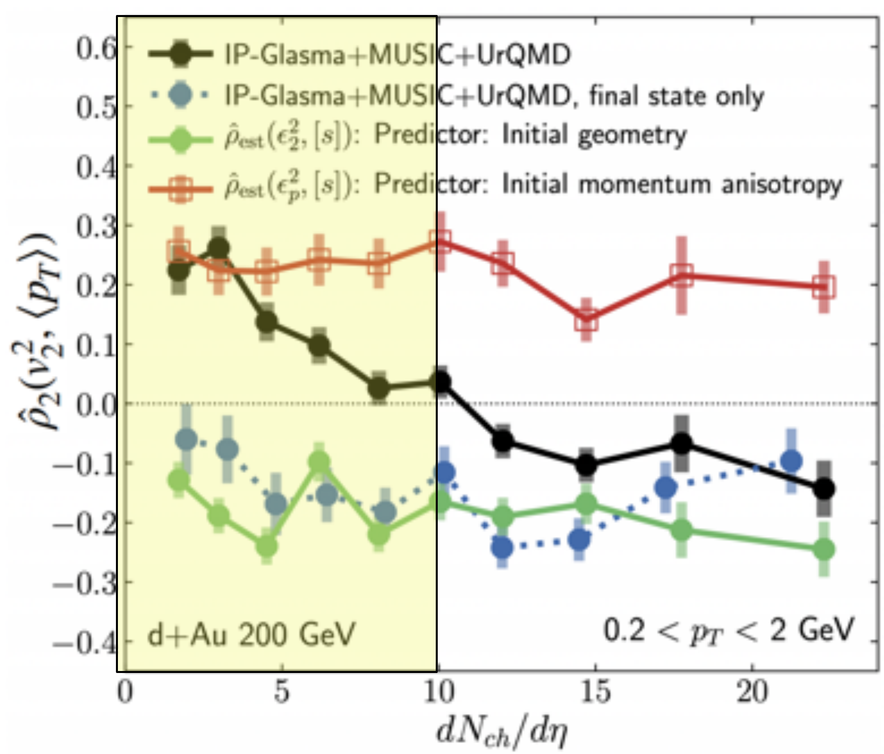
# Disentangle different contributions

- Geometry vs momentum anisotropy → initial $T_{uv}$
  - Systematic analysis of multiple observables in multiple systems ($v_n$, $[p_T]$, $v_n$-$[p_T]$ )




Exp. data + theory efforts

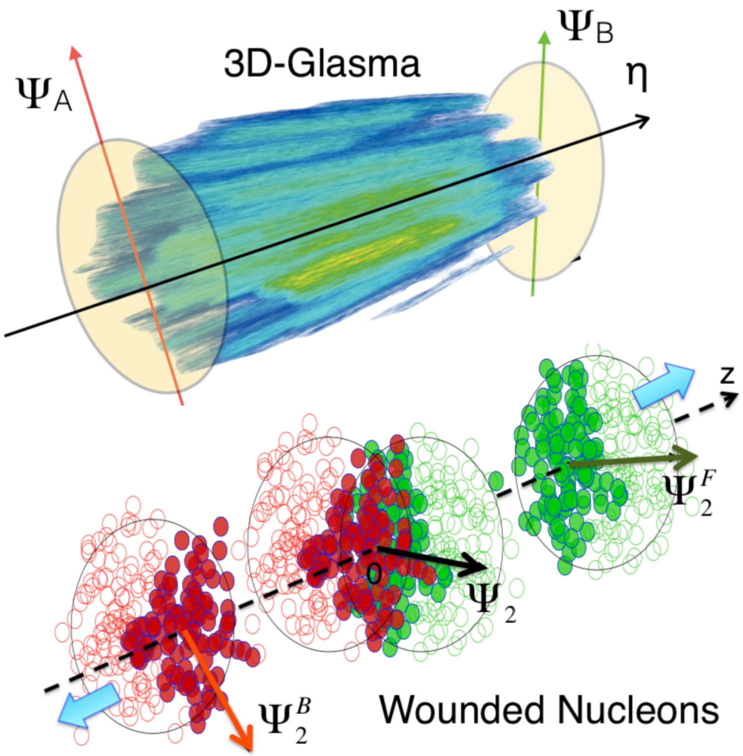
Understand non-flow

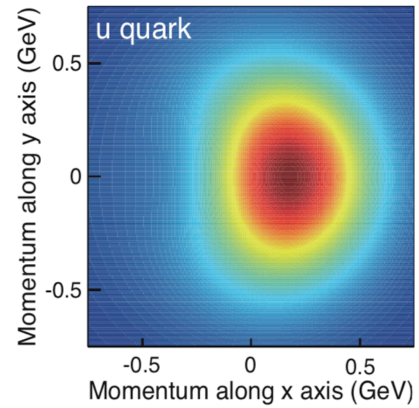


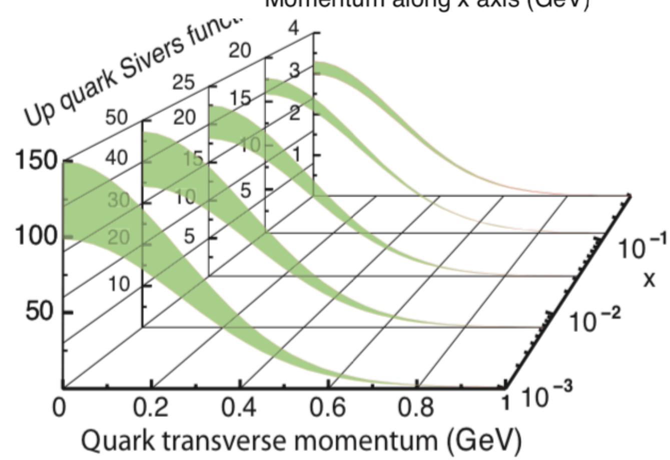
# Longitudinal structure and dynamics

3D partonic structure in A+A
Accessible via rapidity correlations

what about p+p, and
proton structure in 3D?



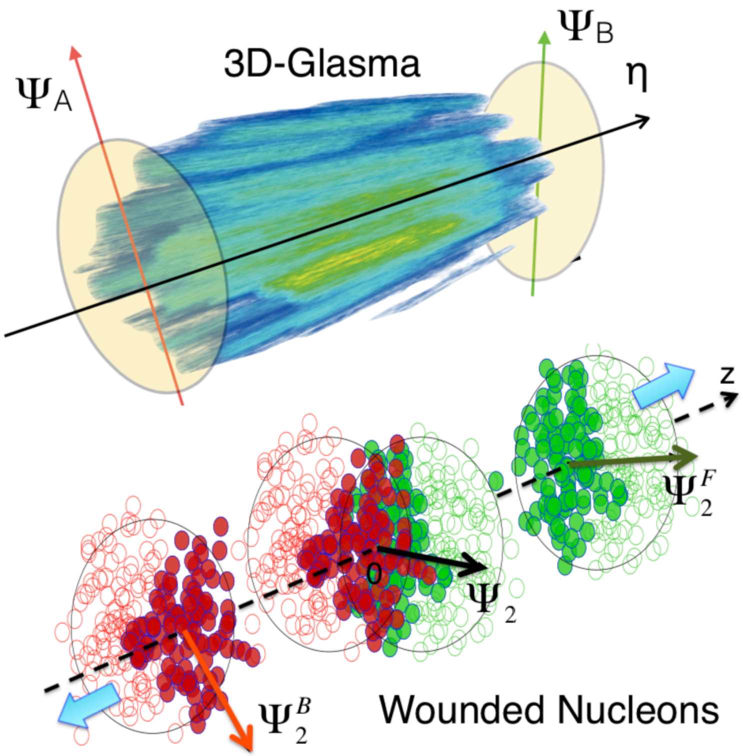




event-by-event

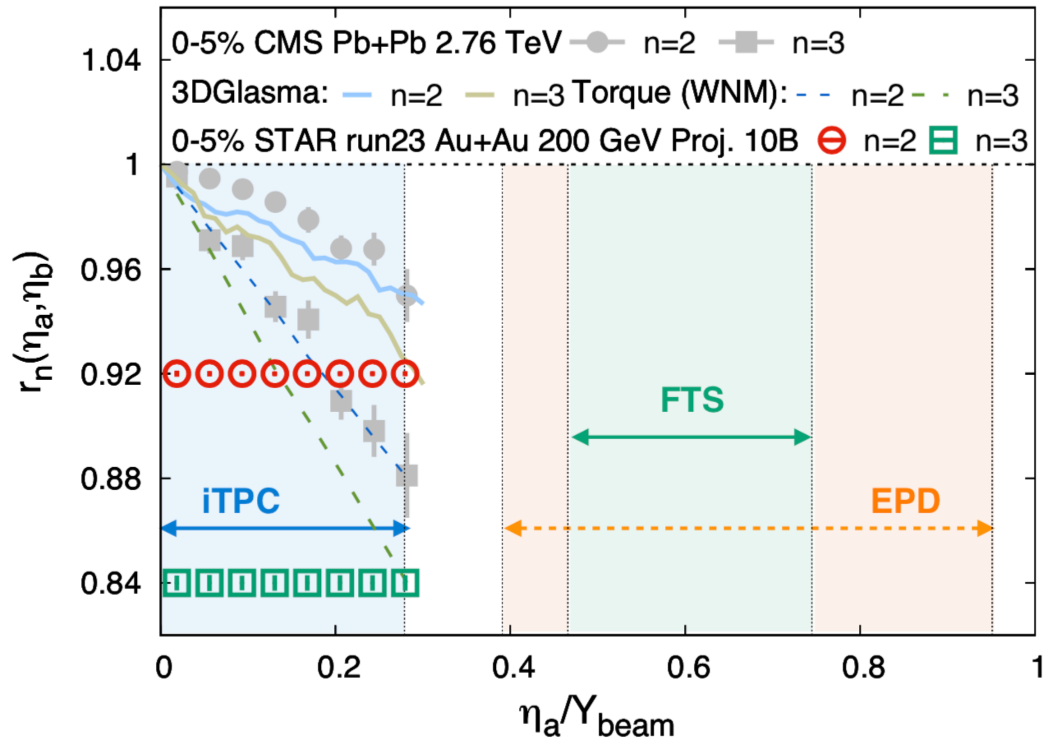
averaged over events

# Longitudinal structure and dynamics

3D partonic structure in A+A
Accessible via rapidity correlations



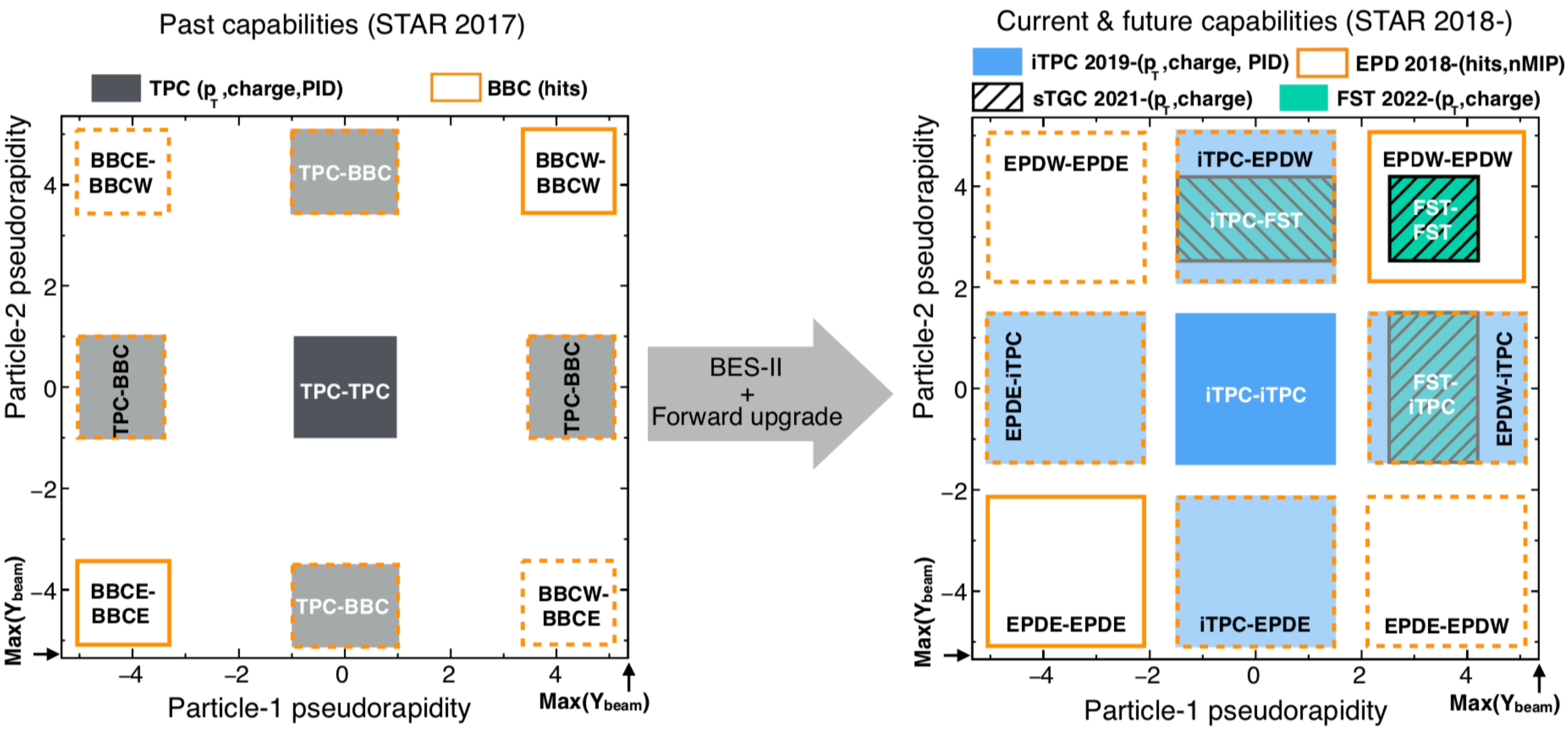

what about p+p, and proton structure in 3D?




Extended coverage of STAR will enable precision on the rapidity structure of IS in both small and large systems

Multiple particle correlations and explore new observables

# Extended STAR acceptance




- Recent upgrade + forward upgrade to be fully installed this year
- Collect pA/AA data to take advantage of the extended acceptance
  - Provide important information on nPDF& CGC in 2022 and 2024
  - Complimentary to sPHENIX by bring insight on the soft sector in particular in 2023-2025

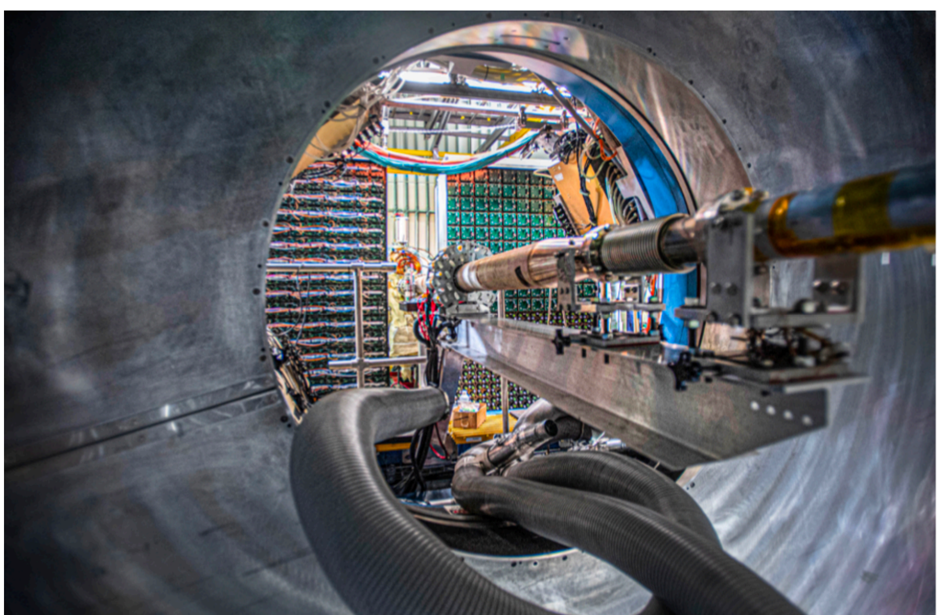
# Forward upgrade status

- FCS (EMCAL and HCAL) construction complete, commission with RUN2021
- Forward Silicon Tracker and sTGC Tracker expected to complete in June 2021, and will be installed before RUN2022

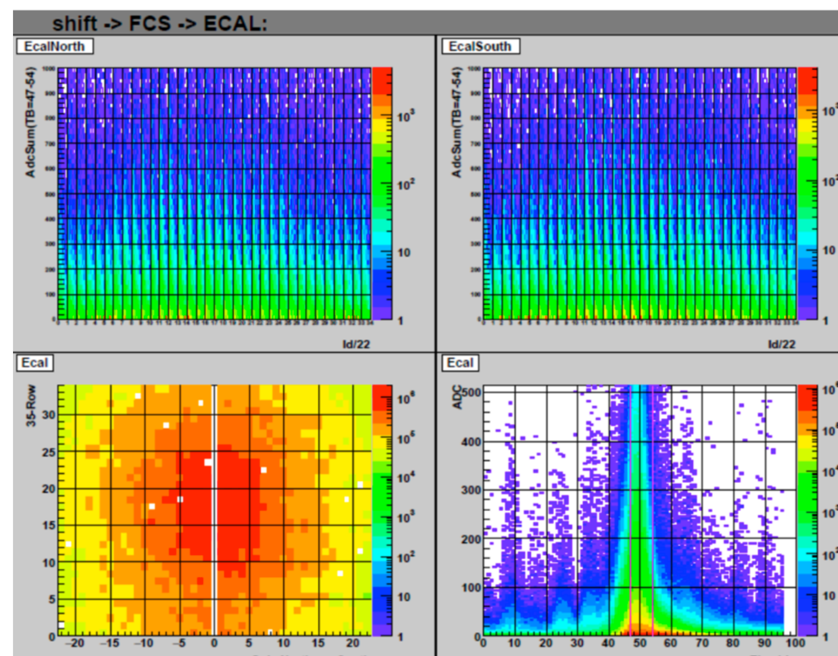
**'Forward' Jet-tracking Components Installed at RHIC's STAR Detector**

New calorimeters will give scientists a glimpse of the internal structure of protons and nuclei in particle smash-ups at the Relativistic Heavy Ion Collider

February 22, 2021



Commission data from O+O run

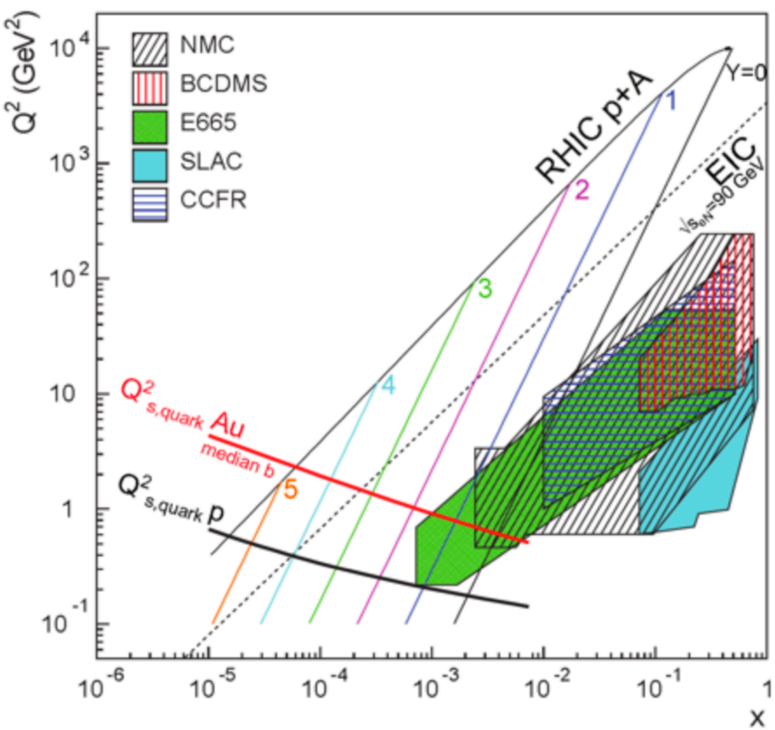


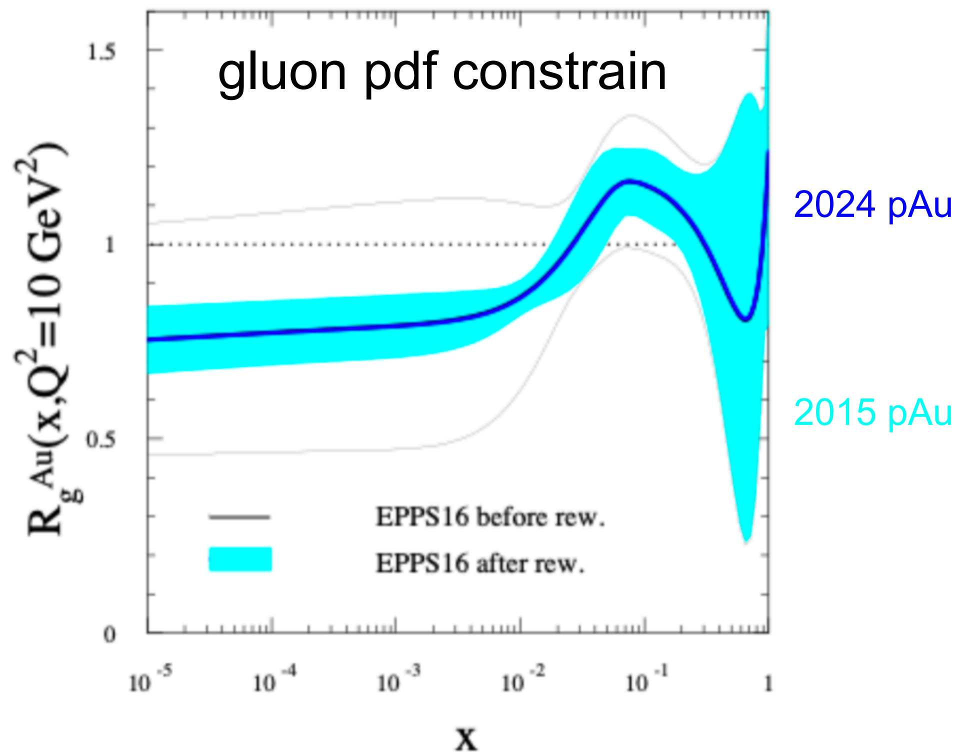
# Nuclear PDF

Xiaoxuan Chu

- Unique capability in moderate $Q^2$ and moderate to low x
  - Less affected by $Q^2$ evolution compared to LHC
- Golden channels: $R_{pA}$ for direct photon and DY,2.5< $\eta$<4
  - Constrains on sea quark and gluon pdfs.
- Forward di-hadron correlation & $\gamma$-jet in search for gluon saturation

More detailed in STAR BUR 2022

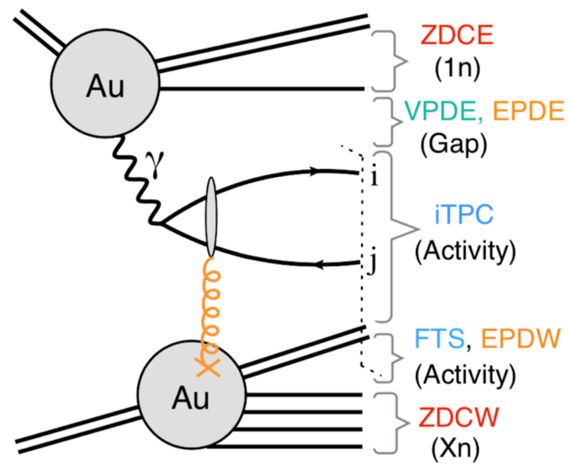


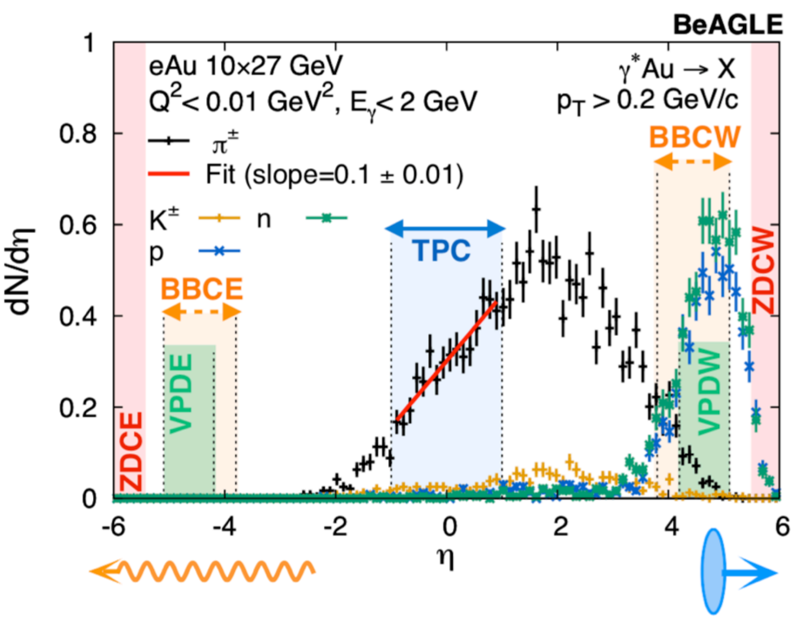



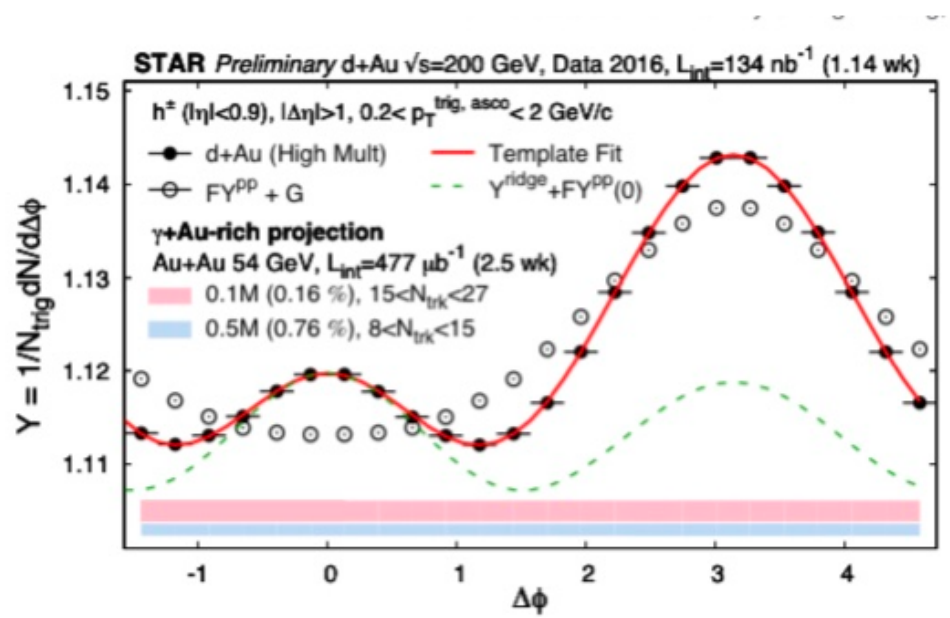
# Collectivity in γ+A

Prithwish Tribedy

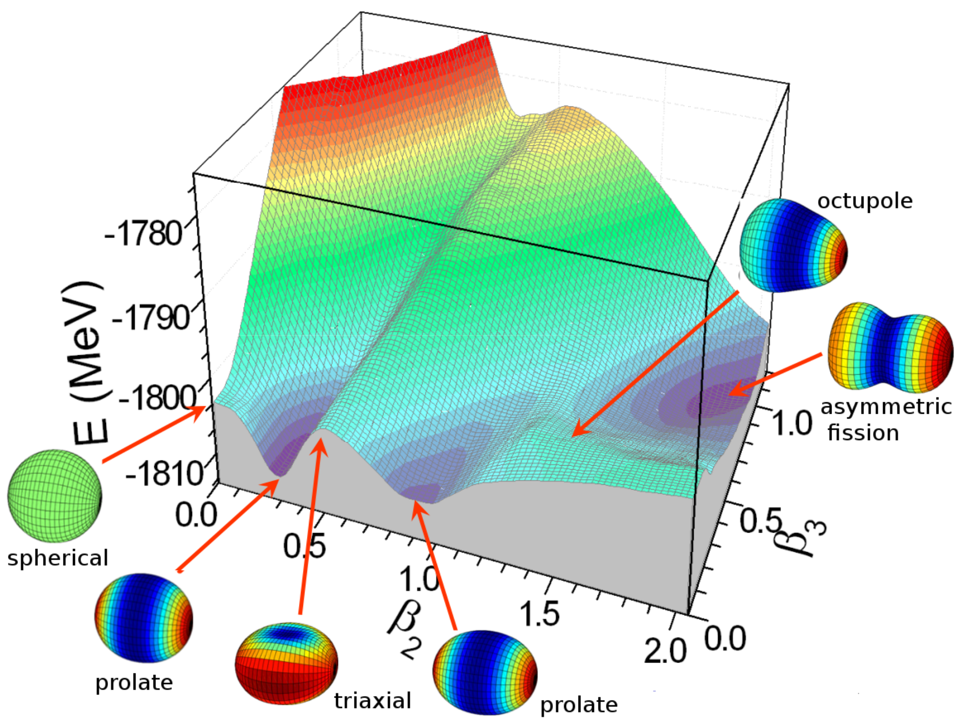
- Nature of collectivity in γA (LHC/HERA) not very clear.
- STAR will bring additional insight in the high Lumi running in 2023-2025
  - +Complementary info from other UPC process.



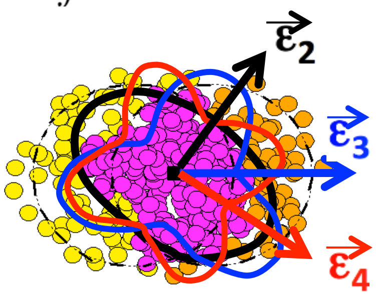
# Example: constrain nuclei shape with A+A



# Hydro is a precision tool for IS &FS

Initial Shape

$$\mathcal{E}_n \propto \int r^n e^{in\phi} \epsilon(r,\phi)$$



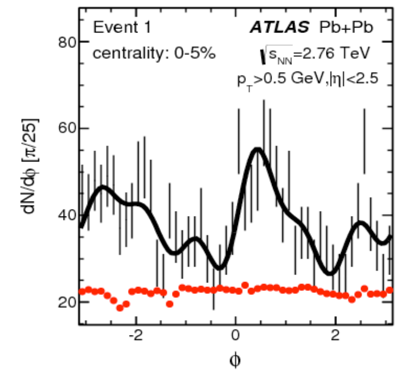

Hydro-response

Space-time dynamics

$$V_n \propto \mathcal{E}_n$$

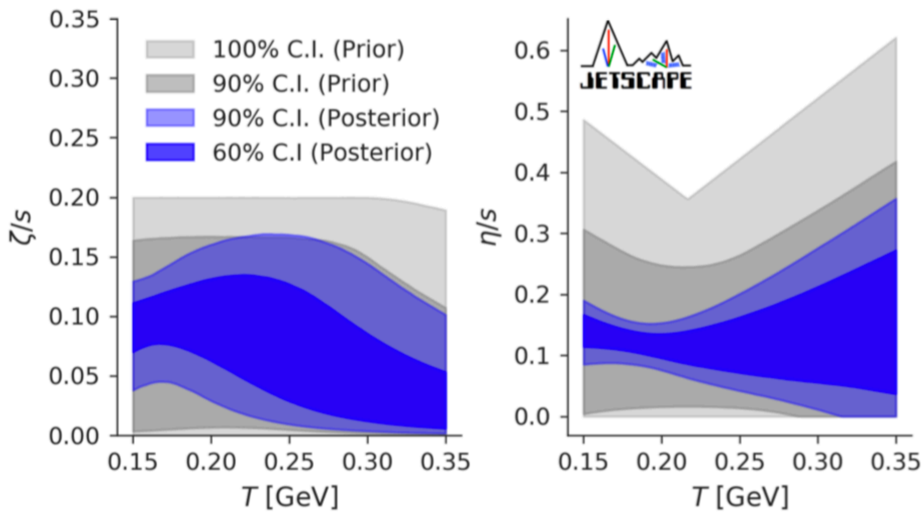
Harmonic flow

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$




1605.03954
2010.15130
2011.01430

Demonstrated by Multi-system Bayesian analysis




Predicated on knowing the initial state via Trento model

- Initial density profile

$$\left(\tilde{T}_A + \tilde{T}_B\right)/2 \quad \text{vs} \quad \sqrt{\tilde{T}_A \tilde{T}_B}$$

- pre-equalibrium dynamics

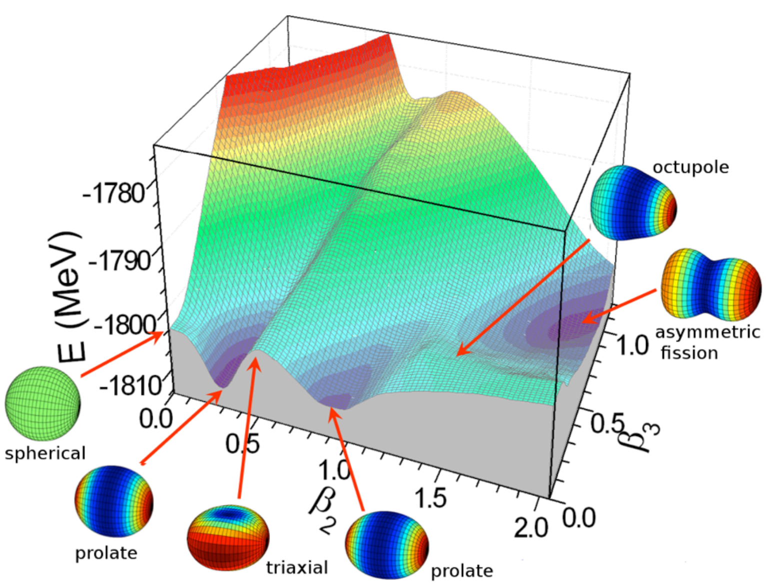
# Shape of nuclei

Most ground state stable nuclei are deformed

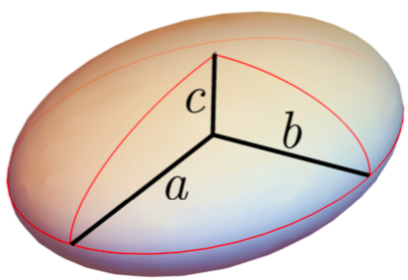
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi)/a}}$$

$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}]+\beta_3 Y_{3,0}+\beta_4 Y_{4,0}\right)$$

Shape determined by minimizing the energy




Triaxial spheroid: $a \neq b \neq c$.




Triaxility controlled by $0 \leq \gamma \leq \pi/3$

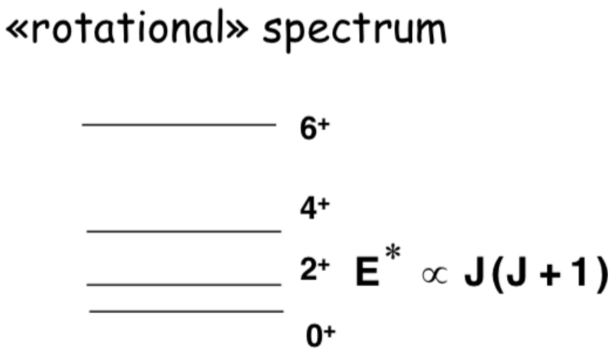
Prolate: a=b<c→$\beta_2$, γ=0

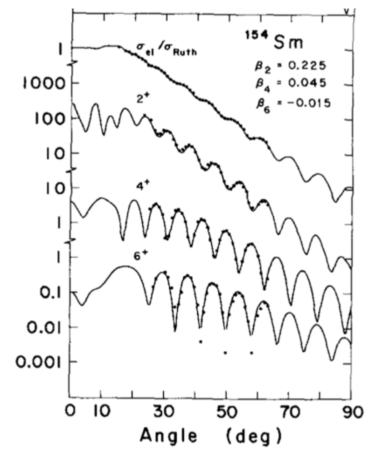
Oblate: a<b=c →$\beta_2$, γ=π/3

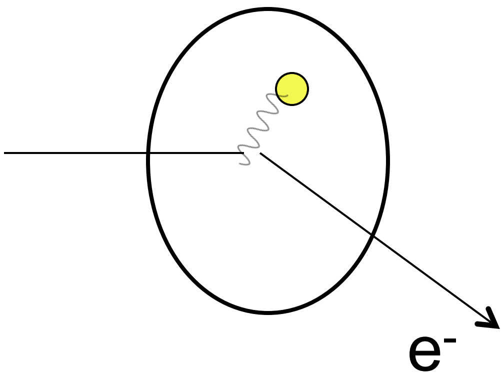
Main tool: transition rates B(En) among low lying states

# Nuclear shape tomography via flow

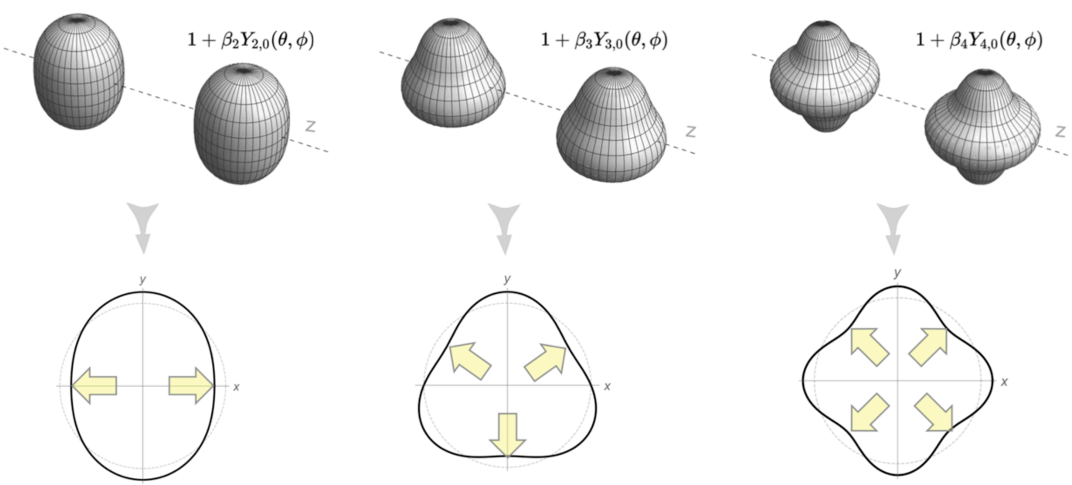
- Shape from B(E2), radial profile from e+A or ion-A scattering

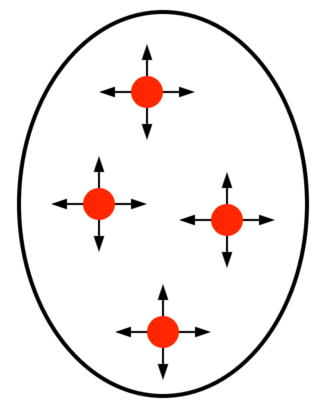



- Probe entire mass distribution: multi-point correlations



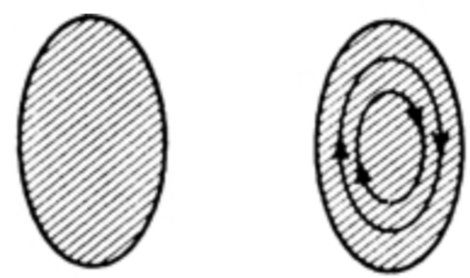
collective flow response to the shape

$$
\begin{aligned}
S(\mathbf{s}_1,\mathbf{s}_2) &\equiv \langle \delta\rho(\mathbf{s}_1)\delta\rho(\mathbf{s}_2)\rangle \\
&= \langle \rho(\mathbf{s}_1)\rho(\mathbf{s}_2)\rangle - \langle \rho(\mathbf{s}_1)\rangle\langle \rho(\mathbf{s}_2)\rangle .
\end{aligned}
$$

# Does HI probe the same information?

- Low energy exps. measure deformed charge distribution
  - HI measure the mass distribution
- B(En) exp. measure deformation at time scale of transtion~$10^{-21}$s, vs HI collision $10^{-24}$s.
  - The nuclear wave function probed might be different.
- B(En) exp. directly reflects the collective rotation. HI collision cares about the actual shape of mass distribution
  - Shed light on the rigidity on nuclear deformation?

Bohr and Mottelson[1] which assumes that the deformed nuclear system merely changes its shape to give the appearance of rotation, known as *irrotational flow motion*. The moment of inertia

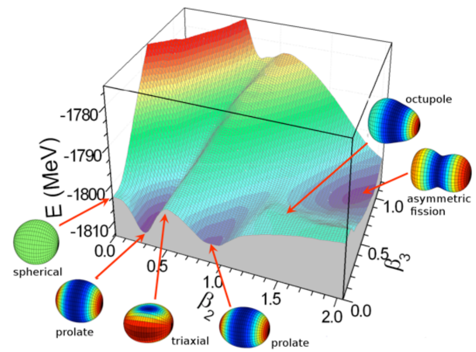


Rigid Irrotational

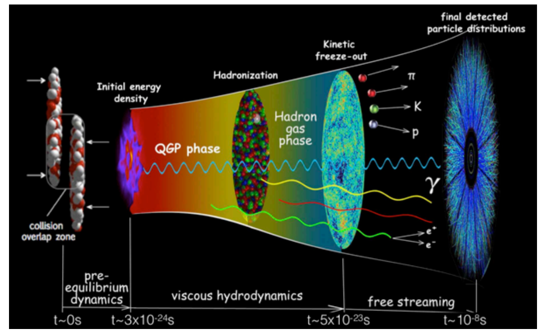
Scan systems with different deformation to constrain shape
and use that as extra control parameter on hydrodynamics
Can/will we be able to do something similar for p+p collisions?

# Concluding remarks

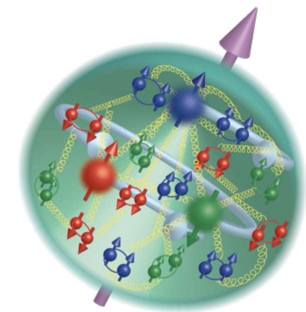
- HI relied on NS and DIS to provide inputs on initial state of A and p.
  - very different theoretical tools and experimental methods




Nuclear structure



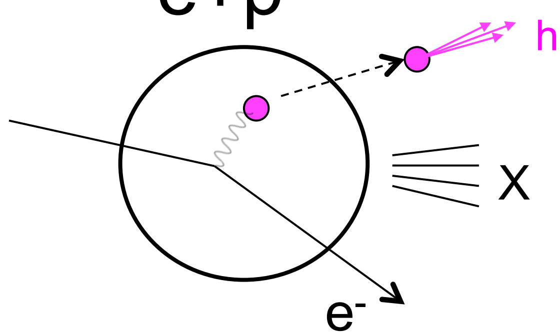

Heavy Ion physics



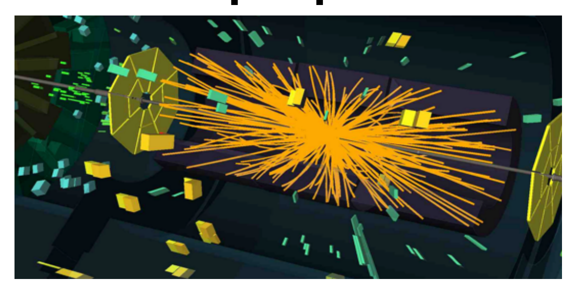
Partonic Structure

- HI physics now is precise enough to feedback to NS and DIS
  - Clearly possible in large A+A system. As our tool & understanding of early state improves, might be possible even for p+p? Continued analysis & interpretation of HI data is important

e+p



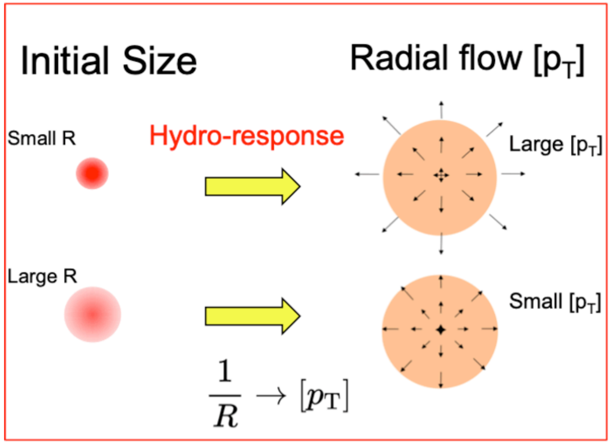

p+p

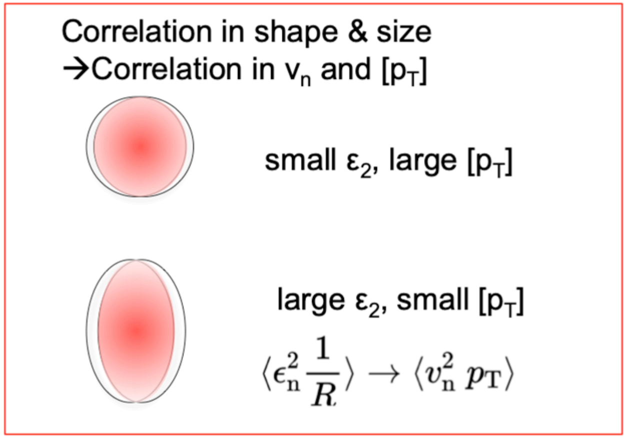


HI-like event ~600 particles

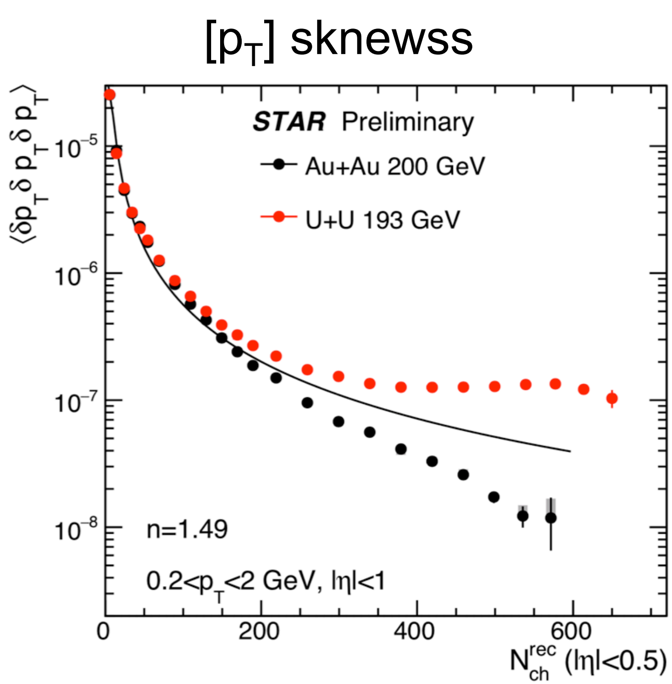
# Initial state mapping in large system

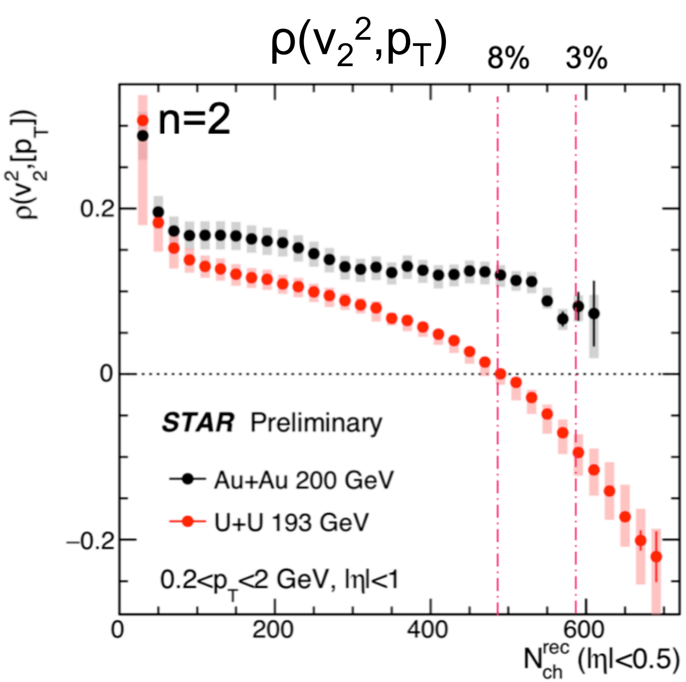
- Similarly we can unfold initial state size & shape-size fluctuations



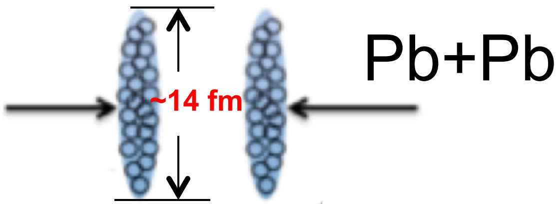



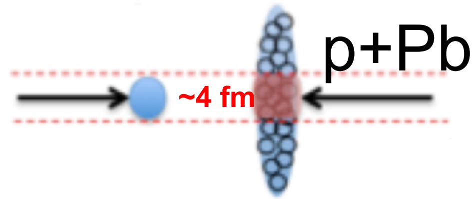

- Deformed system: enhanced size fluctuation, anti-correlation for $v_2$-[$p_T$]



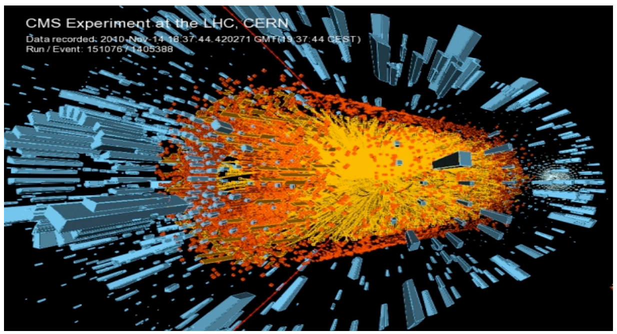



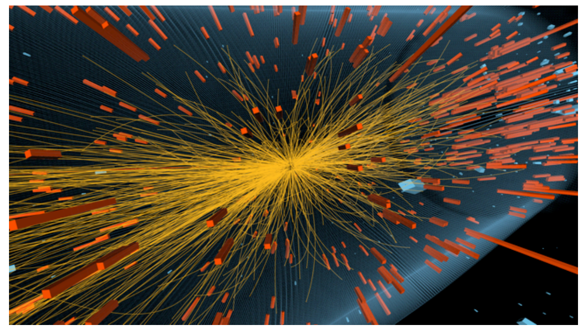
# Collectivity in different systems

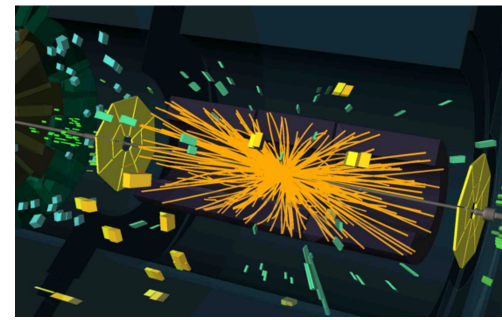








~30000 particles*

~2000 particles*

~ 600 particles*

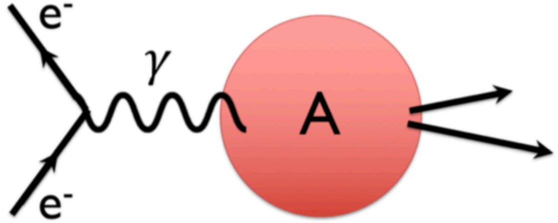
Change system size and shape at RHIC and LHC:

→ Control space-time dynamics!

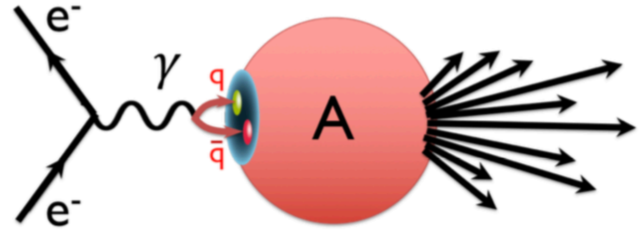
* Rough number in very high-multiplicity events, integrated over full phase space at LHC

# High-multiplicity e+A at EIC?

Typical e+A

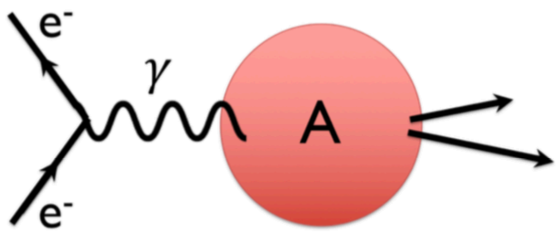



High-multiplicity e+A = ($q\bar{q}$)+A?

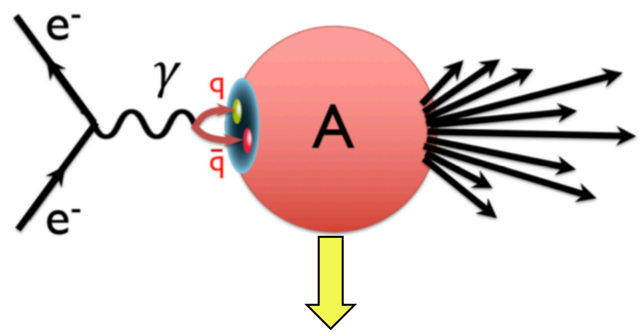


# High-multiplicity e+A at EIC?

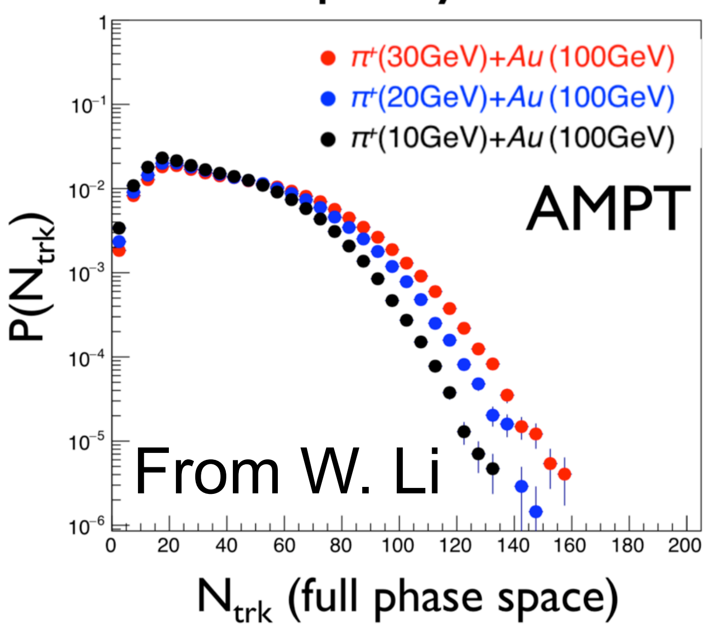
## Typical e+A

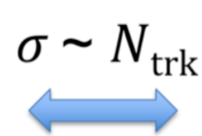



## High-multiplicity e+A = ($q\bar{q}$)+A?

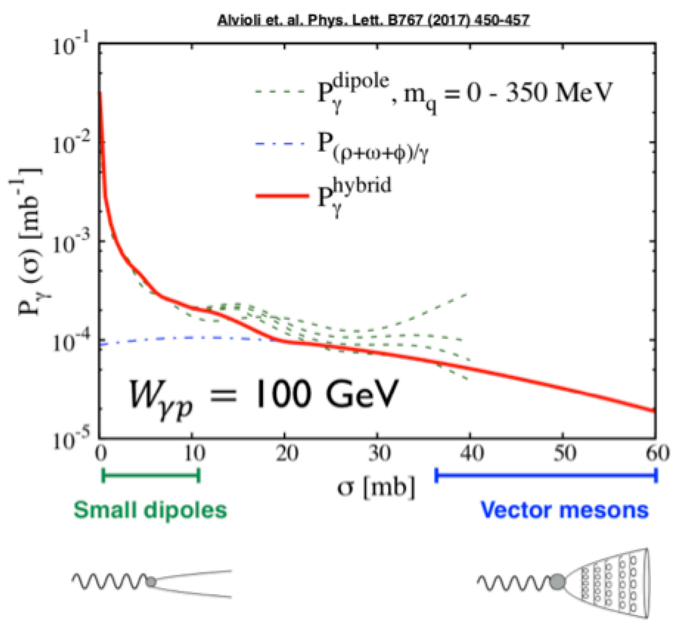



## Multiplicity fluct.




## Size/cross section fluct.




Control the size and energy of the probe via x and $Q^2$