# Femtoscopy & Polarization in the RHIC Beam Energy Scan

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Ohio State University

# 12 June 2000, 9pm – First Au+Au collision observed

- Energy Scans in RHICs
- RHIC BES
- Probing geometrical substructure of the bulk
  - Femtoscopy
  - Polarization
- Summary

# Beam Energy Scans

- Bevalac (=Bevatron + SuperHILAC): (1954-)1971-1992
  - almost always ran at highest possible energy
  - Energy Scan was final experimental campaign before shutdown
    - 1991-92: EOS - $\sqrt{s_{NN}}$ =2.0 - 2.32 GeV
- AGS: 1960-1996
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    - 1995-96: E895 - $\sqrt{s_{NN}}$ = 2.64-4.28 GeV
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    - 2011-17: NA61/SHINE, CERES - $\sqrt{s_{NN}}$ =5.28-16.88 GeV
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  - Energy Scan begun significantly earlier
    - STAR BES & FXT: $\sqrt{s_{NN}}$ =3…39 GeV

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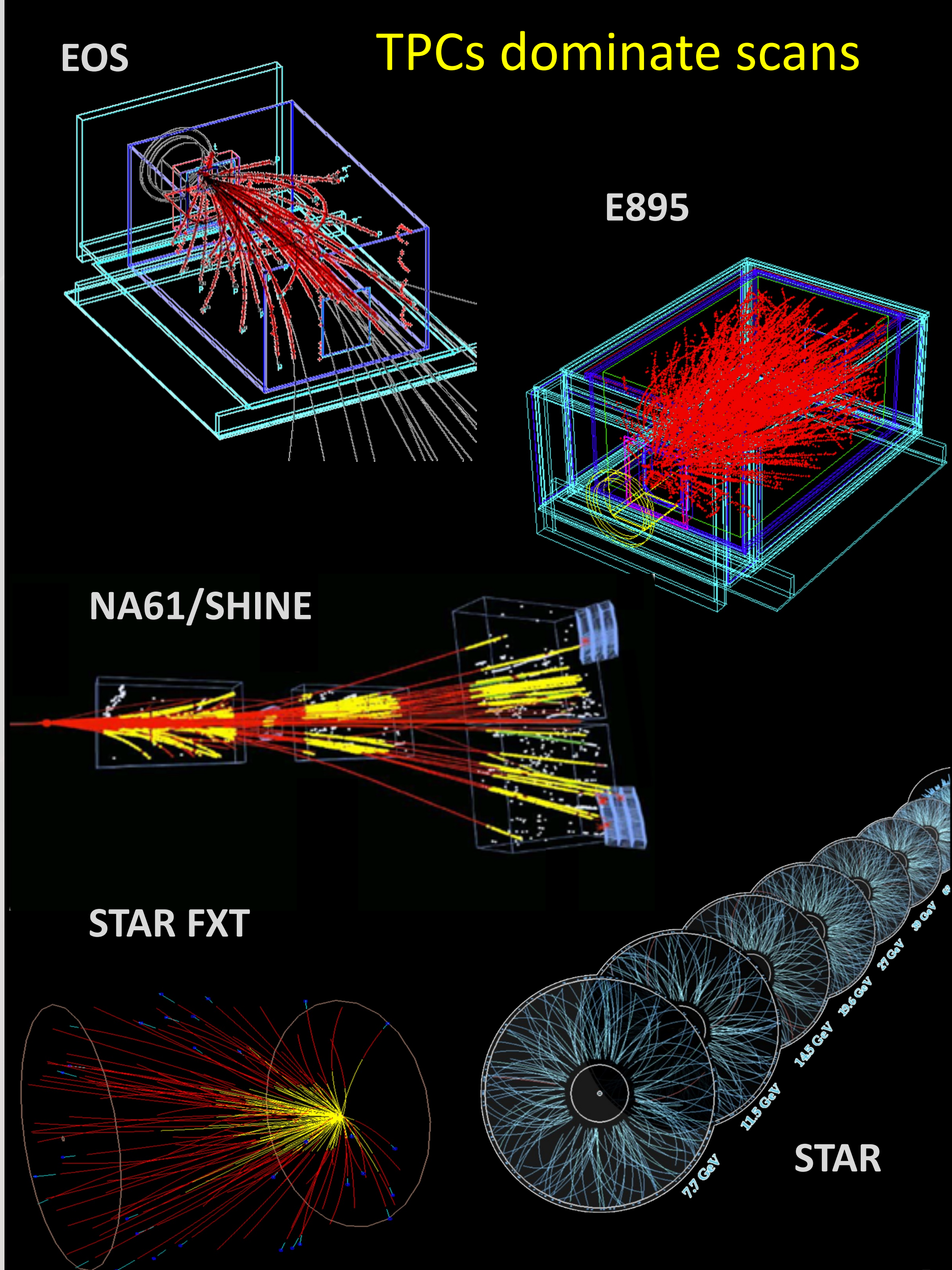
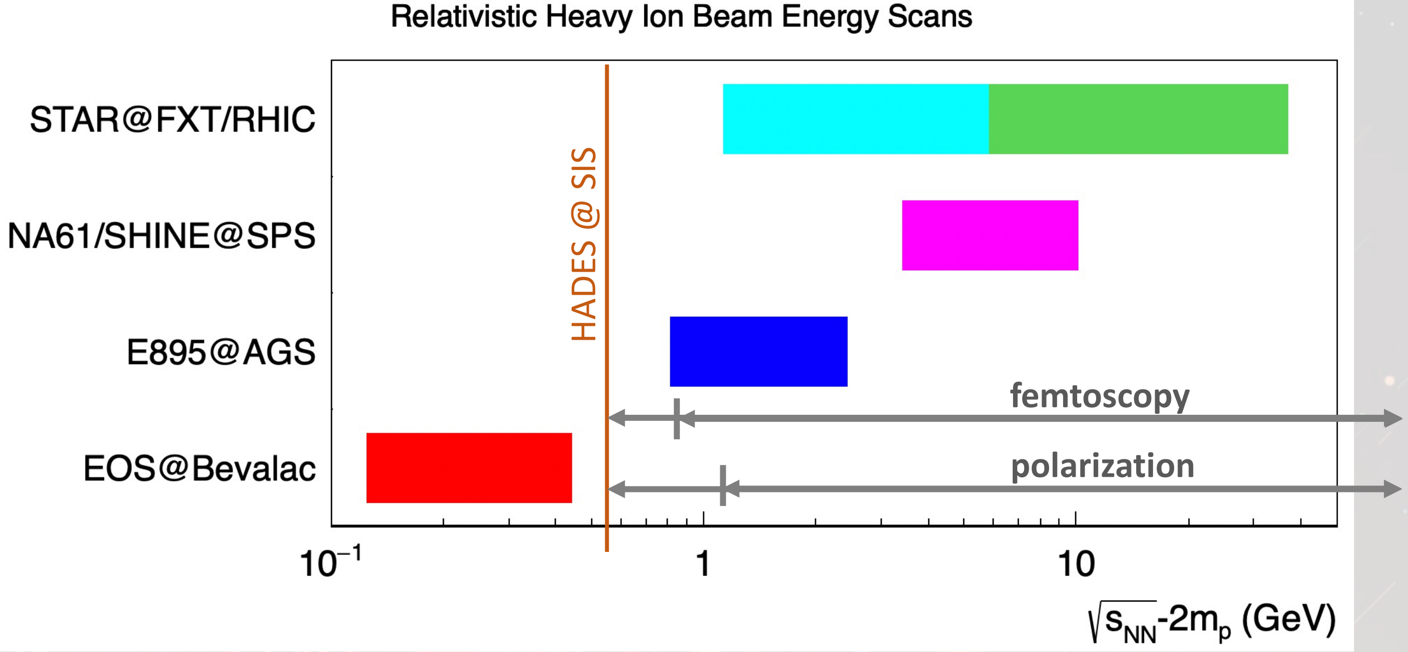


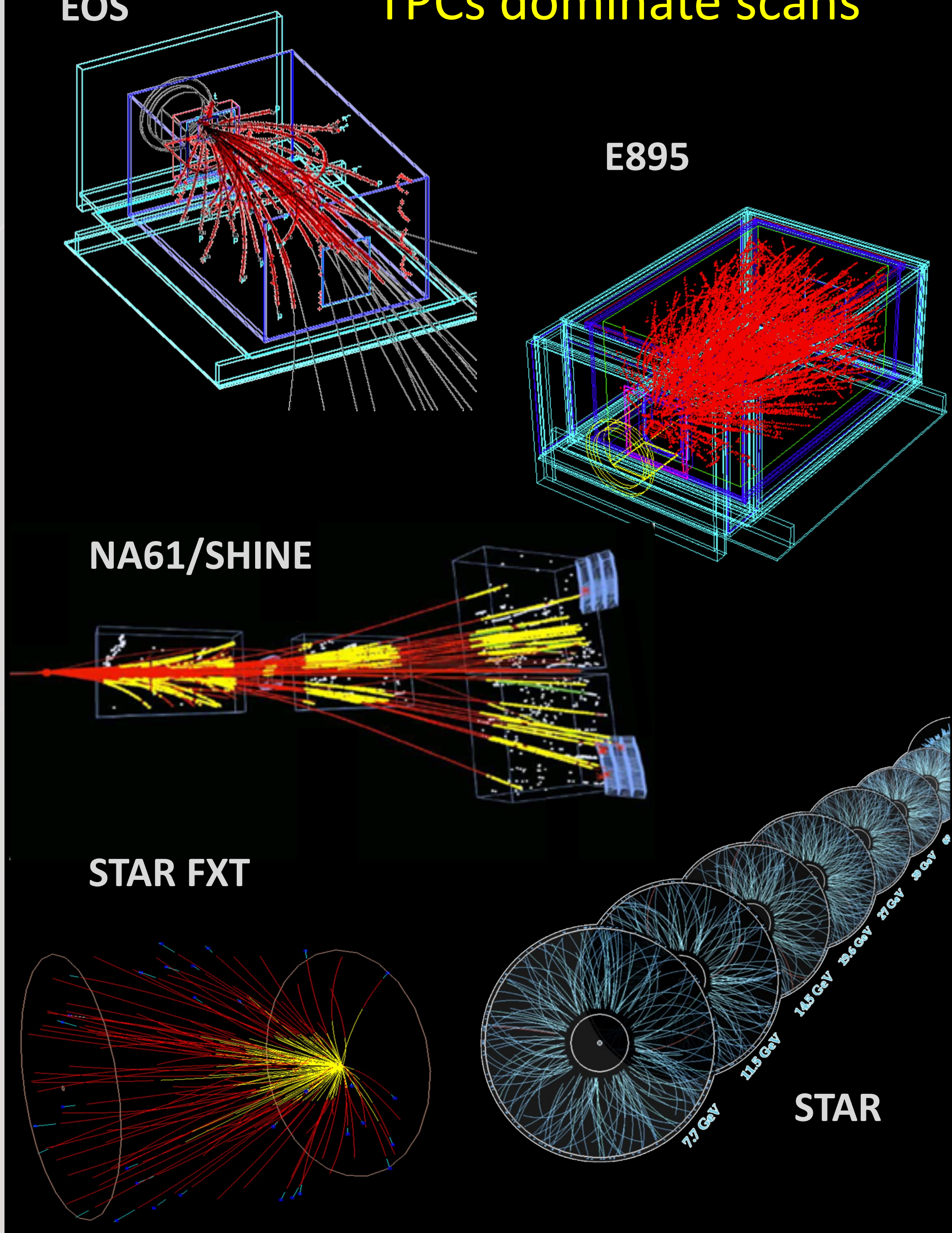
# Beam Energy Scans



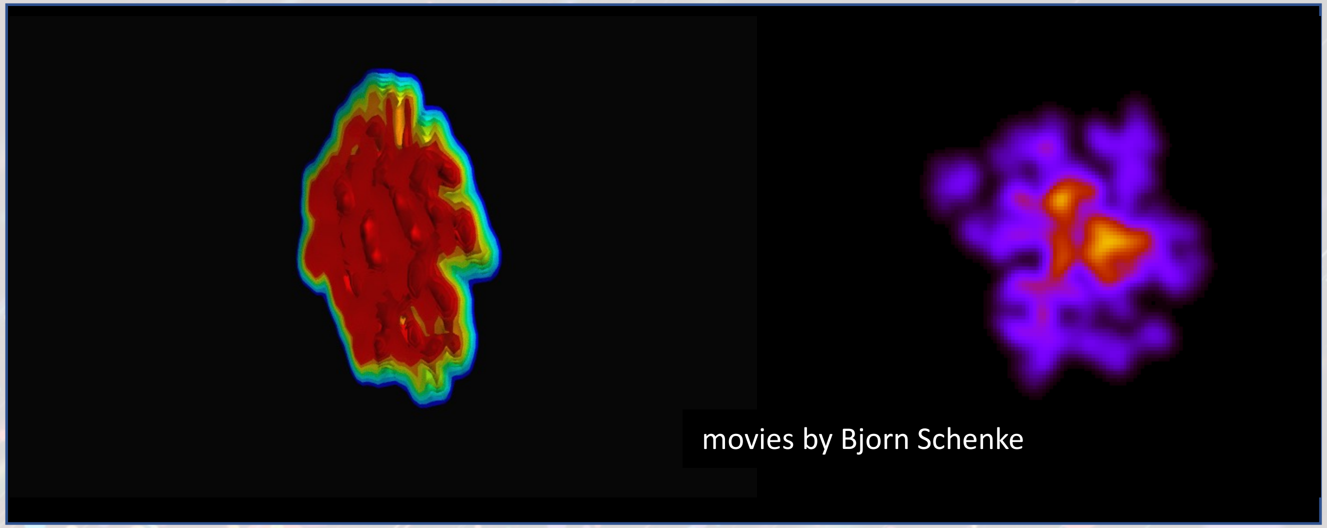

Large acceptance, multipurpose devices capturing “all” hadrons with PID

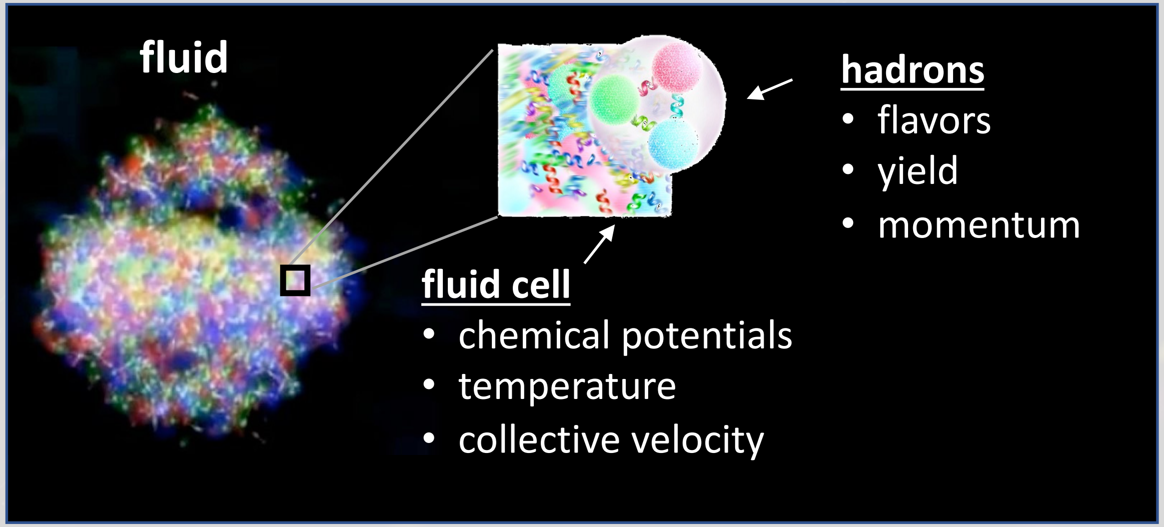
- perfect for multiparticle correlations
  - femtoscopy (esp azimuthally-sensitive)
  - polarization
  - $v_n$ …

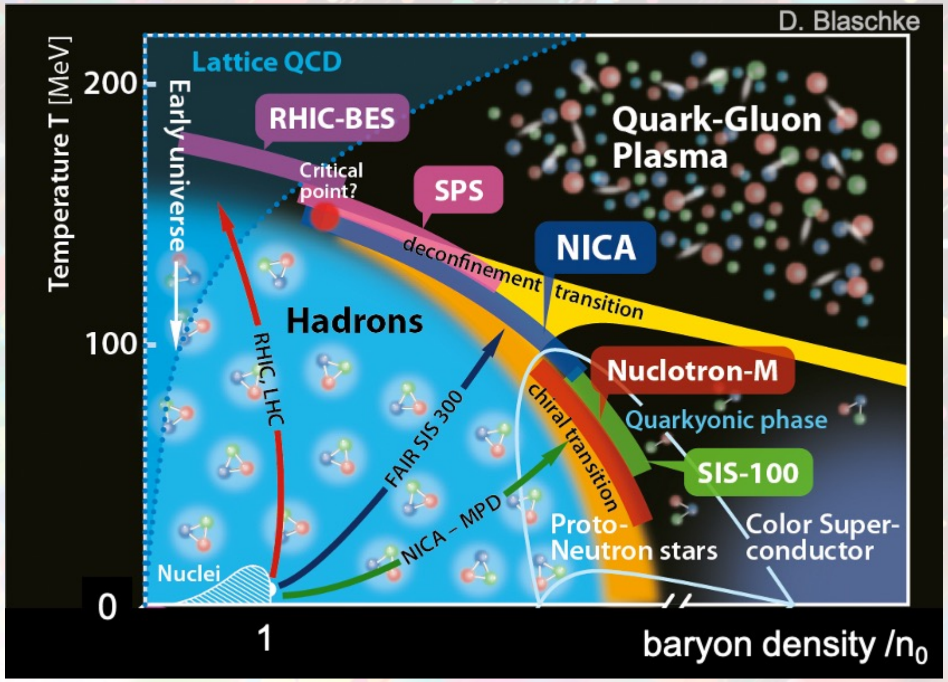
TPCs dominate scans

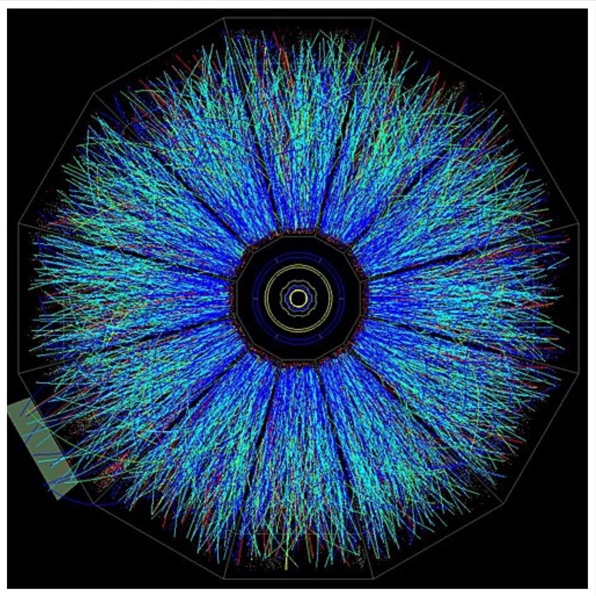


# Standard model of H.I.C. : viscous hydrodynamics + Cooper-Frye


movies by Bjorn Schenke

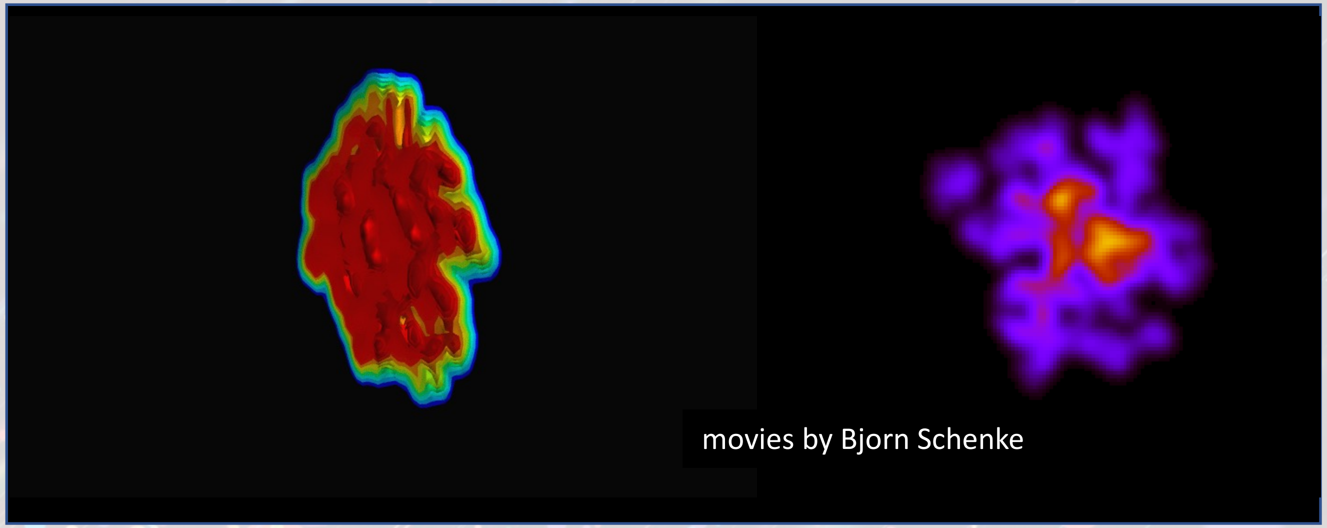


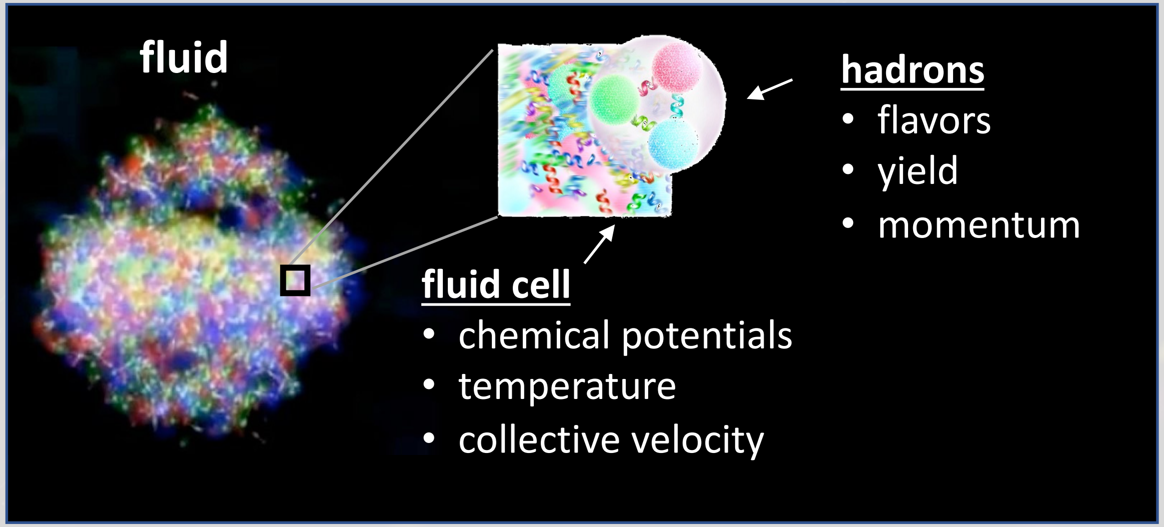



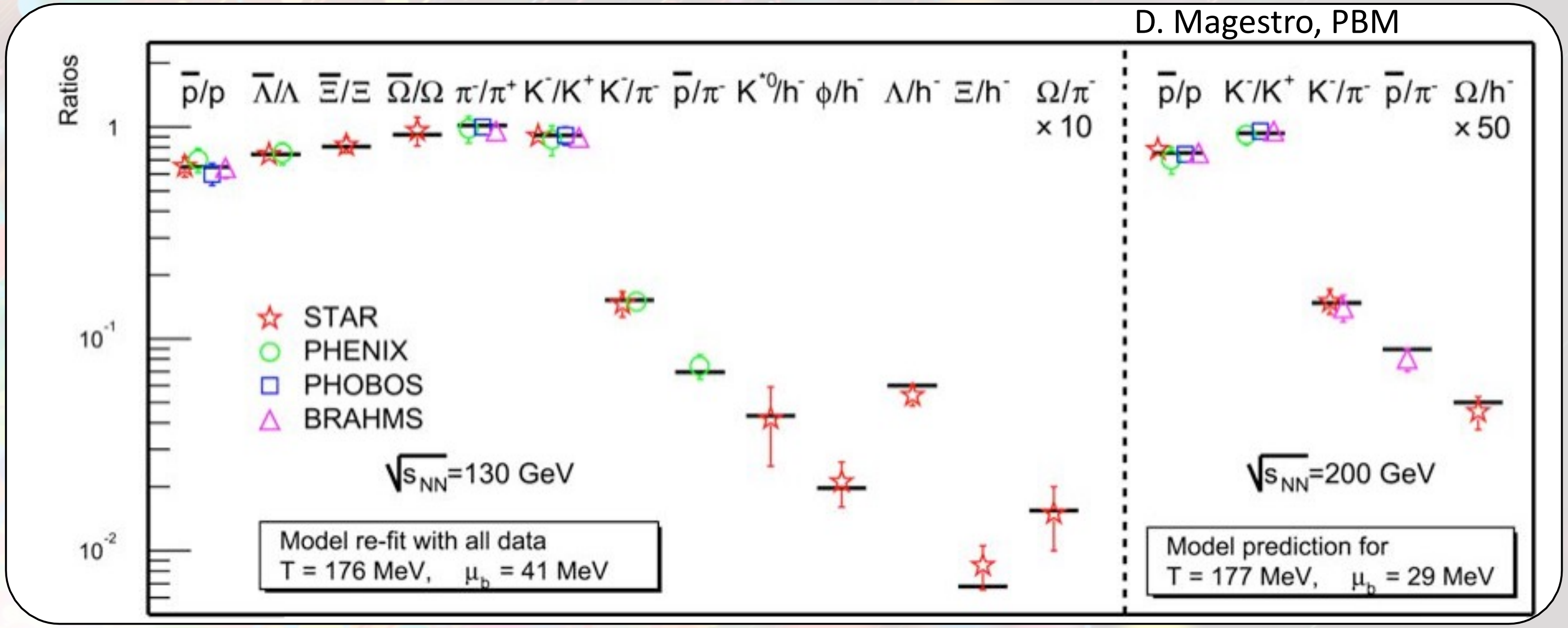



- Dynamic evolution of locally equilibrated matter
- Hadronization/freezeout driven by conservation laws
- emitted particles (*measurable!)* reflect properties of parent fluid cells

# Probing in increasing detail

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- Yields

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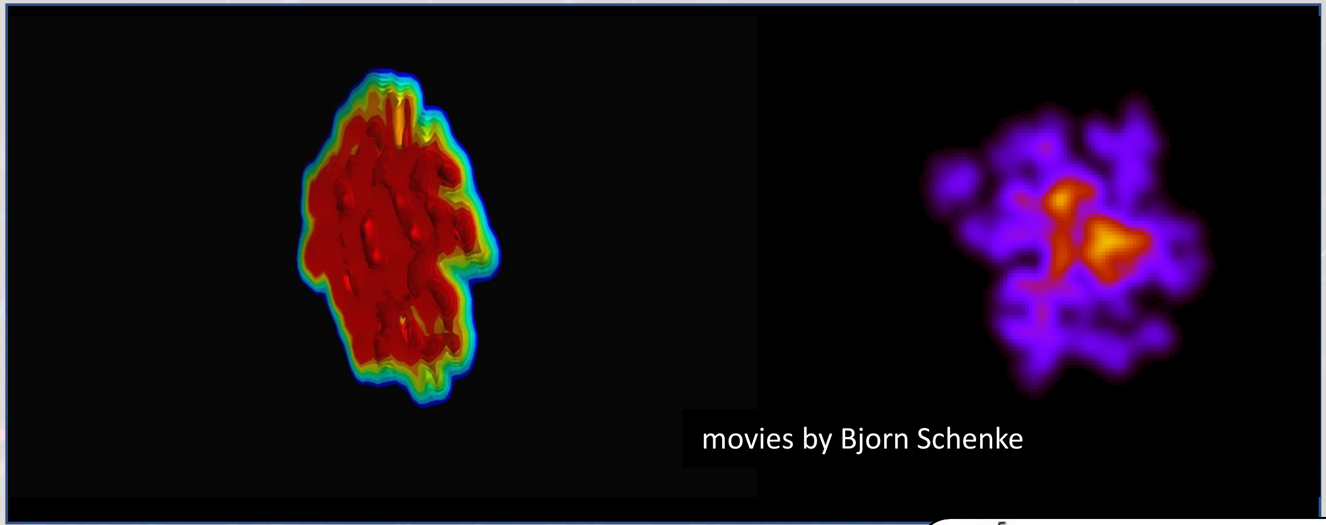
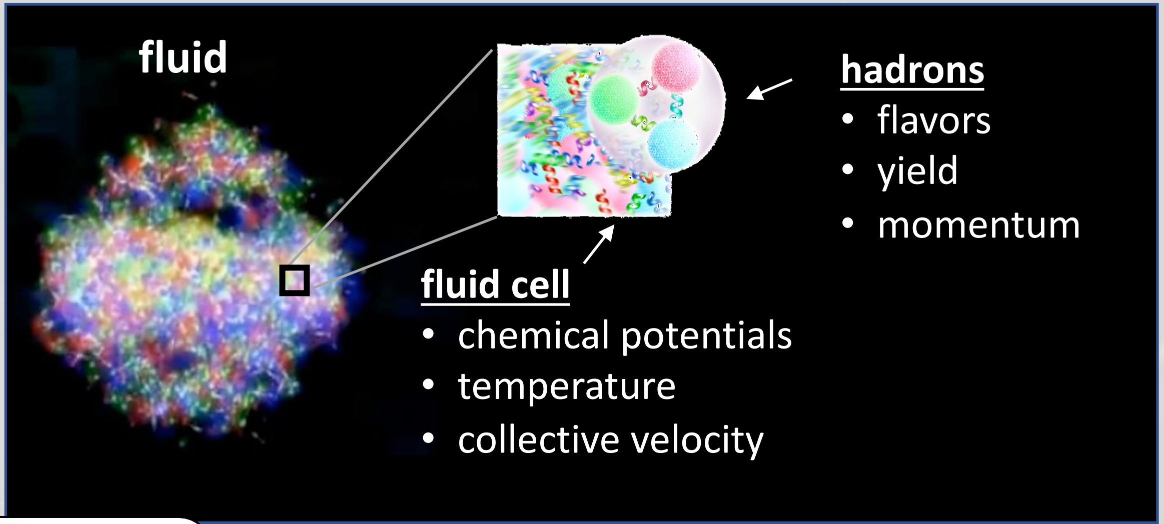
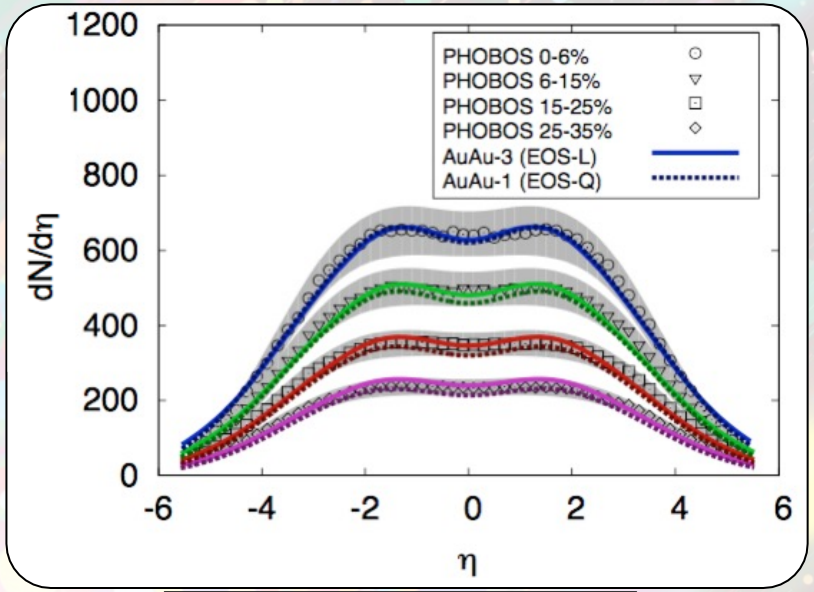
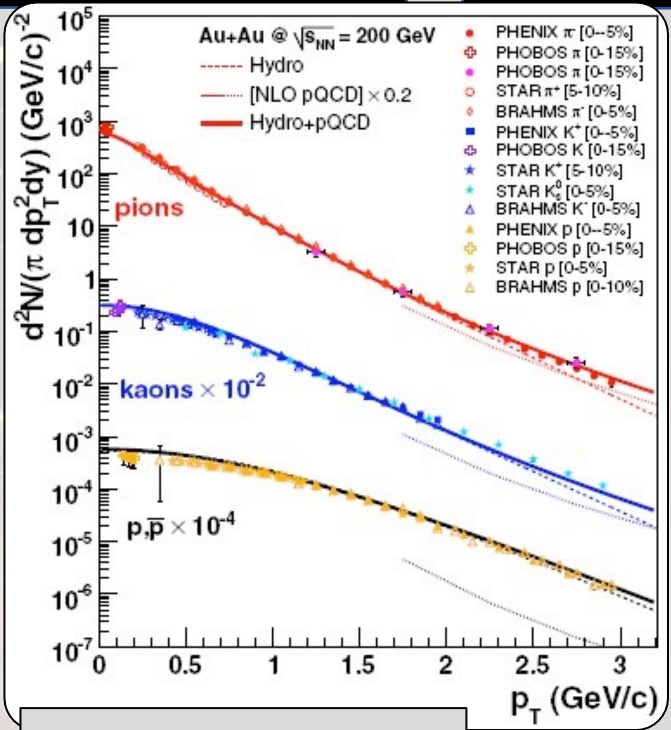



Longitudinal momentum




Transverse momentum

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- Yields
- longitudinal, transverse distributions

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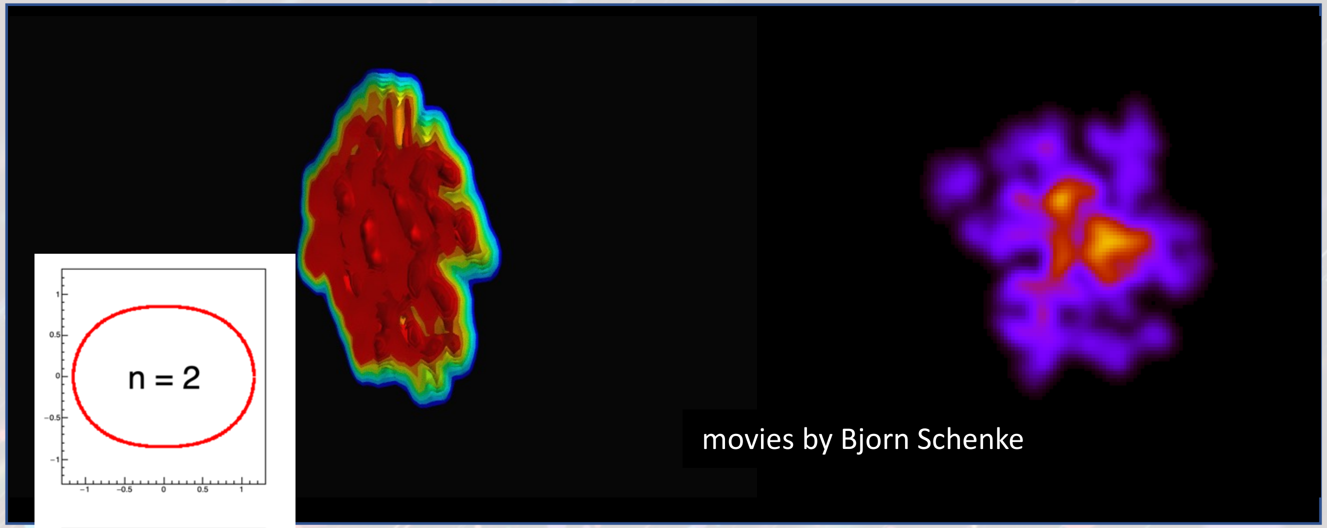
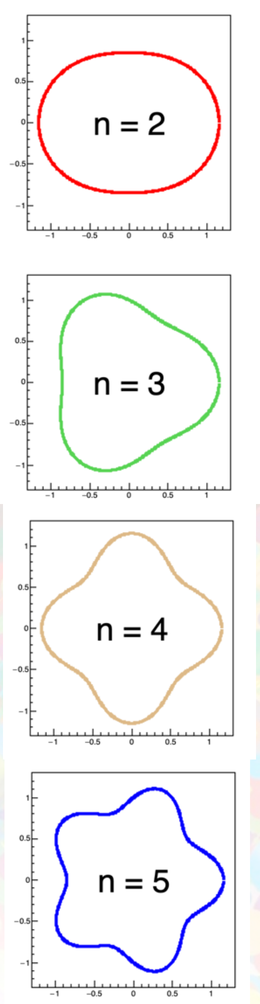
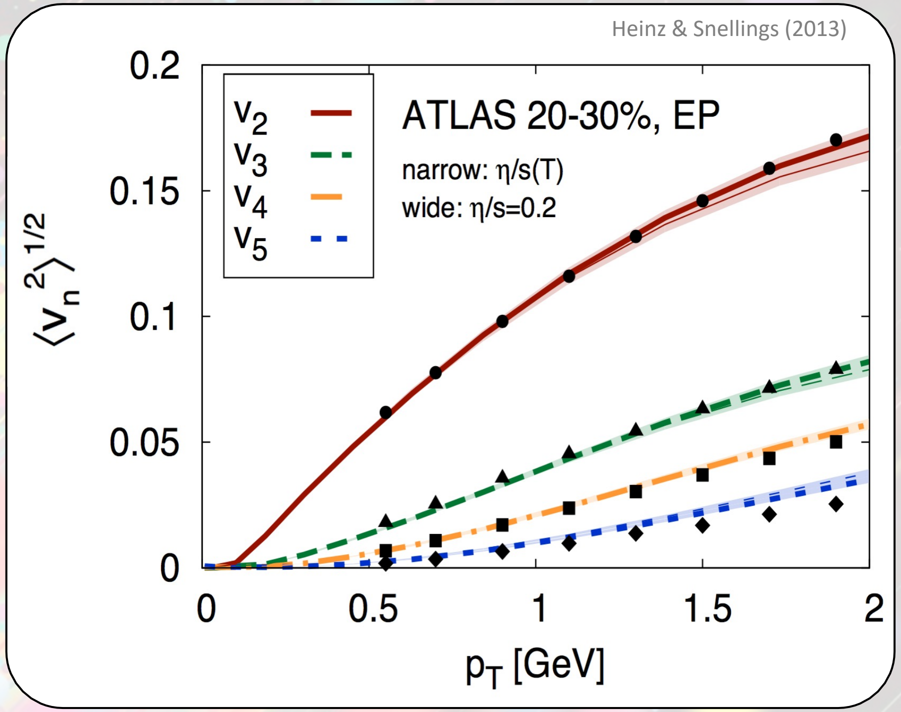
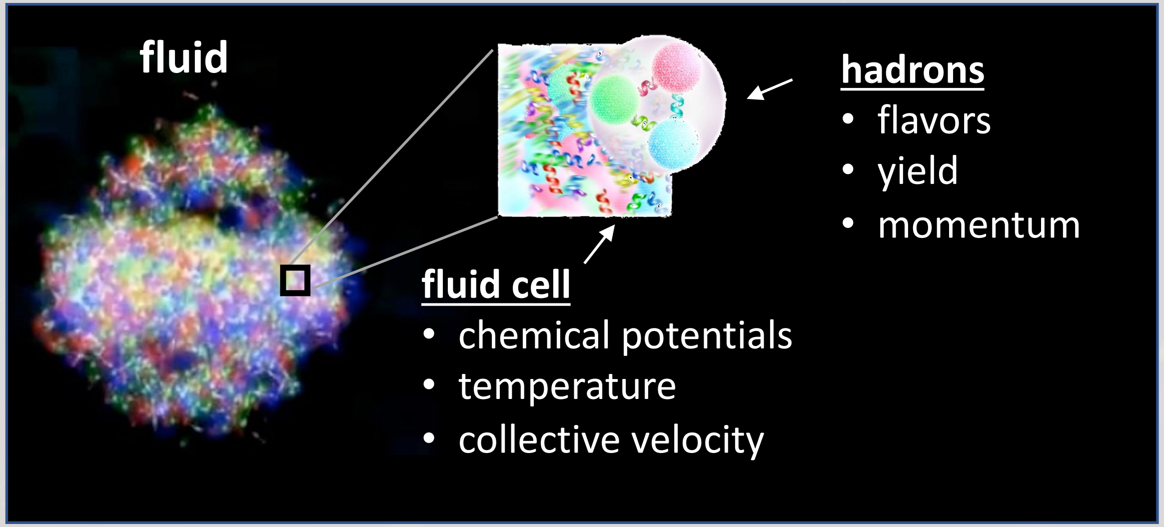

movies by Bjorn Schenke

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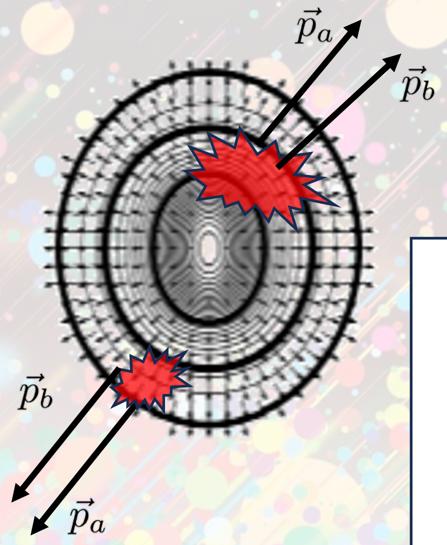
finer detail ↓

- Yields
- longitudinal, transverse distributions
- azimuthal flow anisotropy

# Probing in increasing detail

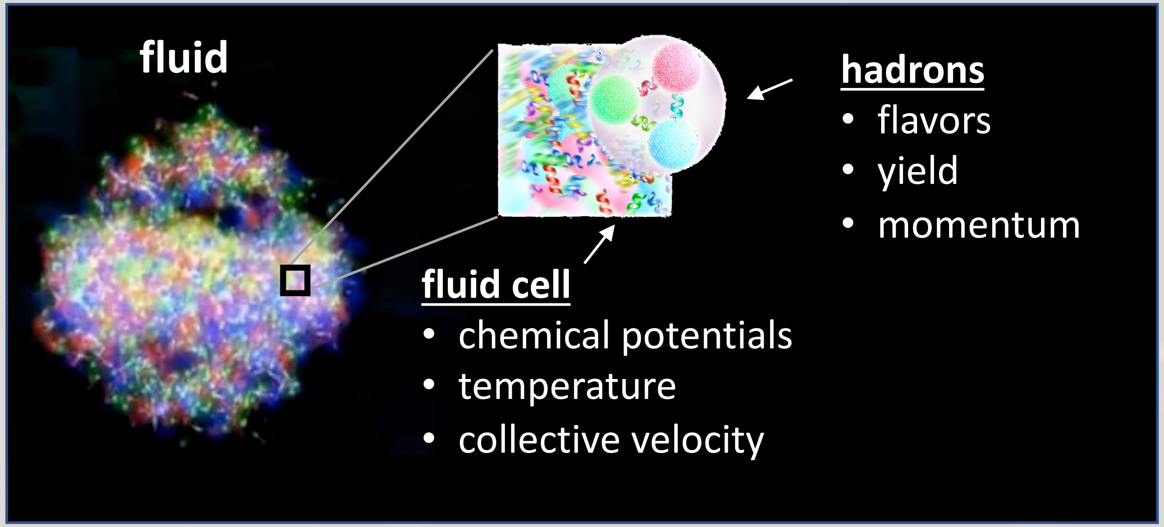
### Intensity interferometry / femtoscopy / ``HBT''

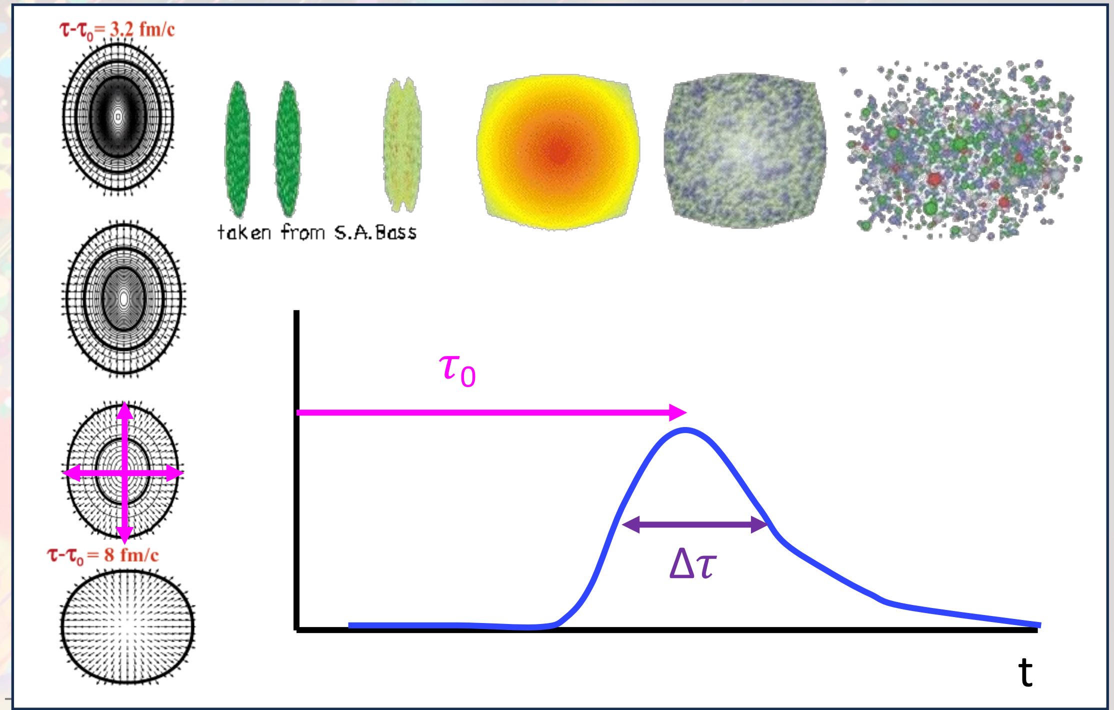
- probes spatial/temporal scales
- spatial shape – ellipticity/tilt
- spatial substructure of flow field on scale ~fm
  - flow *is* a space-momentum correlation




$$C^{ab}_{\vec{\beta}}(\vec{q}) = \int d^3\vec{r}\,' \cdot S^{ab}_{\vec{\beta}}(\vec{r}\,')\, |\psi(\vec{q}, \vec{r}\,')|^2$$

$$\vec{q} \equiv \vec{p}_a - \vec{p}_b \qquad \vec{\beta} \equiv \frac{\vec{p}_a + \vec{p}_b}{E_a + E_b}$$

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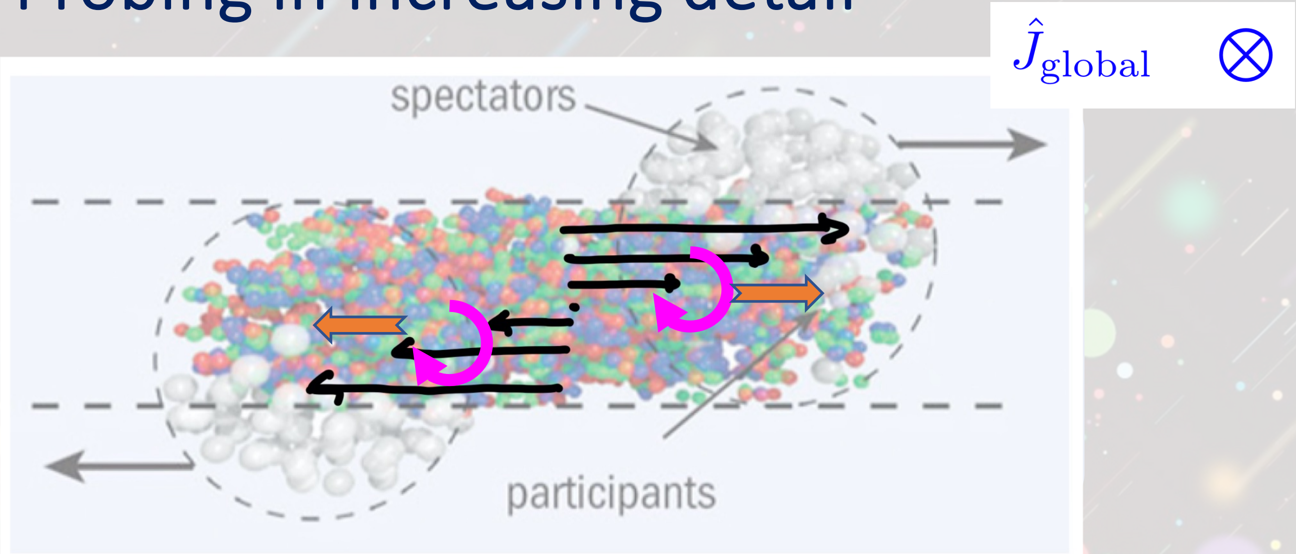


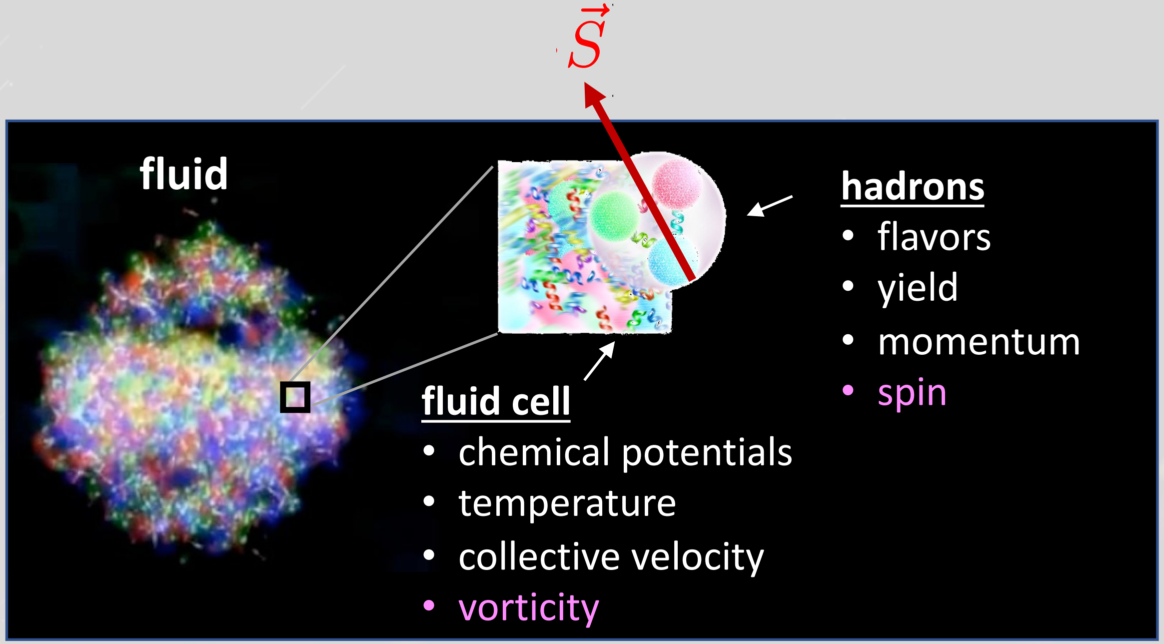


**Polarization / spin alignment**

- probes vorticity: rotational flow substructure at hadron scale
- evolution/distribution of angular momentum density is new terrain
- magnetic field (& CME?)
- new discovery of coherent field??

$$P \propto e^{-\left(E+\mu_B B+\mu_Q Q+\vec{\omega}\cdot\vec{S}\right)/T}$$

$$\vec{\omega}_{\rm NR} = \frac{1}{2}\vec{\nabla}\times\vec{\beta} \qquad \vec{\mathcal{P}} \equiv \frac{\langle\vec{S}\rangle}{|S|}$$

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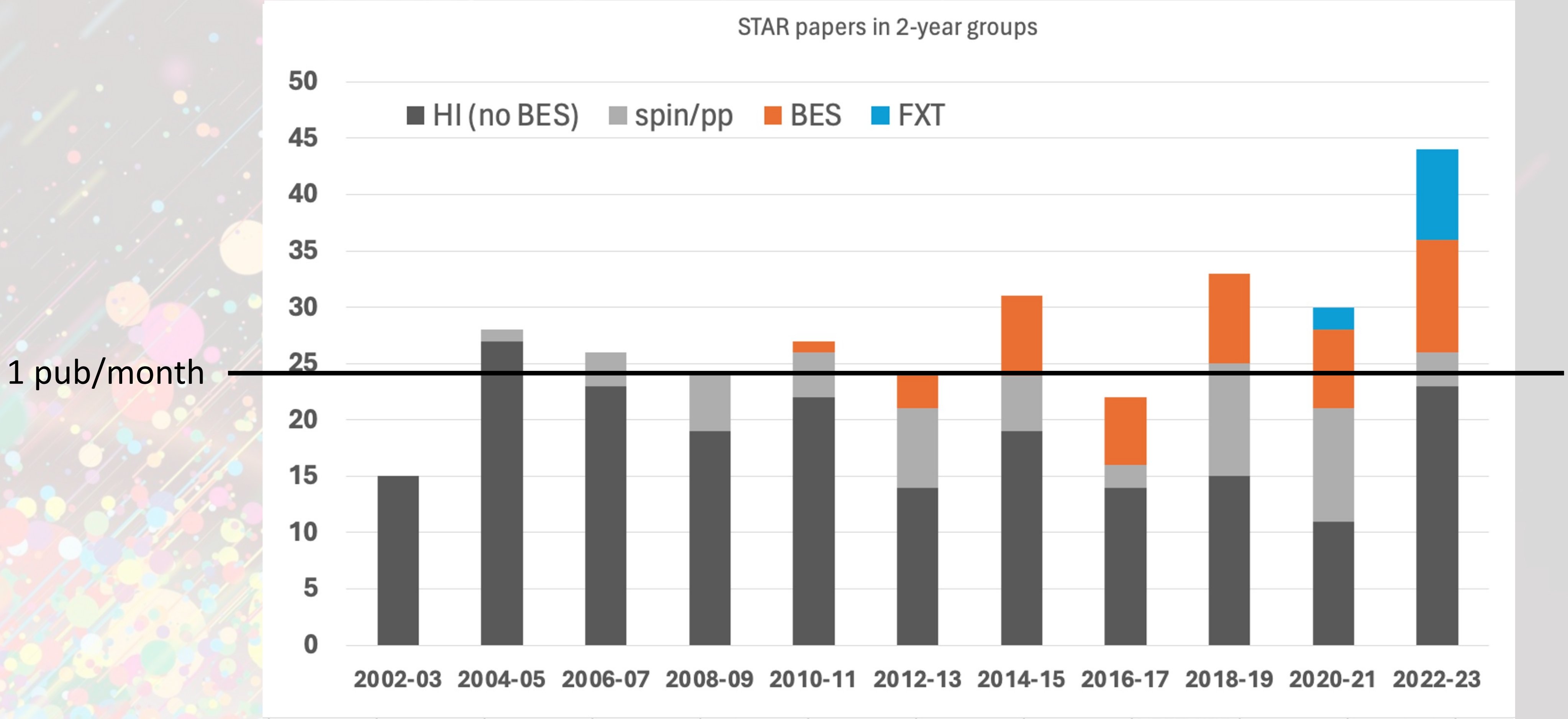
finer detail ↓

- Yields
- longitudinal, transverse distributions
- azimuthal flow anisotropy
- femtoscopy
- polarization

# STAR journal publications




BES & FXT programs are a strong *addition* to STAR's scientific output

# Femtoscopy and Polarization in BES & FXT


[1] L. Adamczyk *et al.*, "Beam-energy-dependent two-pion interferometry and the freeze-out eccentricity of pions measured in heavy ion collisions at the STAR detector," *Phys. Rev. C*, vol. 92, no. 1, p. 014904, 2015.

[2] J. Adam *et al.*, "Flow and interferometry results from Au+Au collisions at $\sqrt{s_{NN}} = 4.5$ GeV," *Phys. Rev. C*, vol. 103, no. 3, p. 034908, 2021.


in progress:

- pi-K / pi-p / K-p femtoscopy
- p-Λ, d-Λ correlations
- $1^{st}$-order azimuthally-sensitive femtoscopy
- $K^+$-$K^+$ , $K^0$-$K^0$ at FXT
- differences between (+) and (-) signed mesons


[3] L. Adamczyk *et al.*, "Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid," *Nature*, vol. 548, pp. 62–65, 2017.

[4] M. S. Abdallah *et al.*, "Global Λ-hyperon polarization in Au+Au collisions at $\sqrt{s_{NN}}$=3 GeV," *Phys. Rev. C*, vol. 104, no. 6, p. L061901, 2021.

[5] M. S. Abdallah *et al.*, "Pattern of global spin alignment of $\phi$ and $K^{*0}$ mesons in heavy-ion collisions," *Nature*, vol. 614, no. 7947, pp. 244–248, 2023.

[6] M. I. Abdulhamid *et al.*, "Global polarization of Λ and $\Lambda^-$ hyperons in Au+Au collisions at sNN=19.6 and 27 GeV," *Phys. Rev. C*, vol. 108, no. 1, p. 014910, 2023.


in progress:

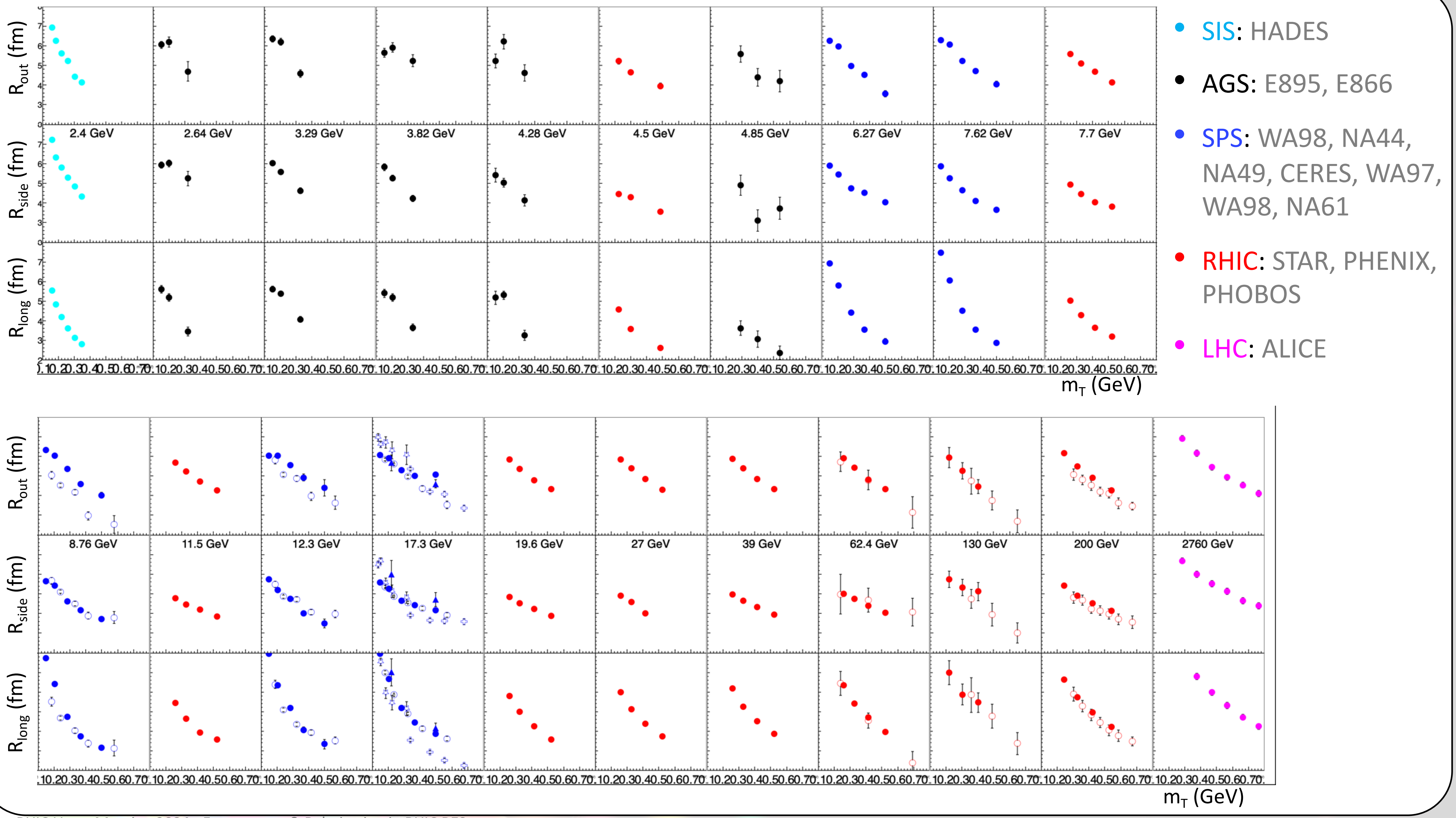
- higher-precision/statistics Λ polariization
- multi-strange hyperon polarization
- longitudinal polarization

Femtoscopy review: Ann.Rev.Nucl.Part.Sci. 55 (2005) 357; arxiv:0505014

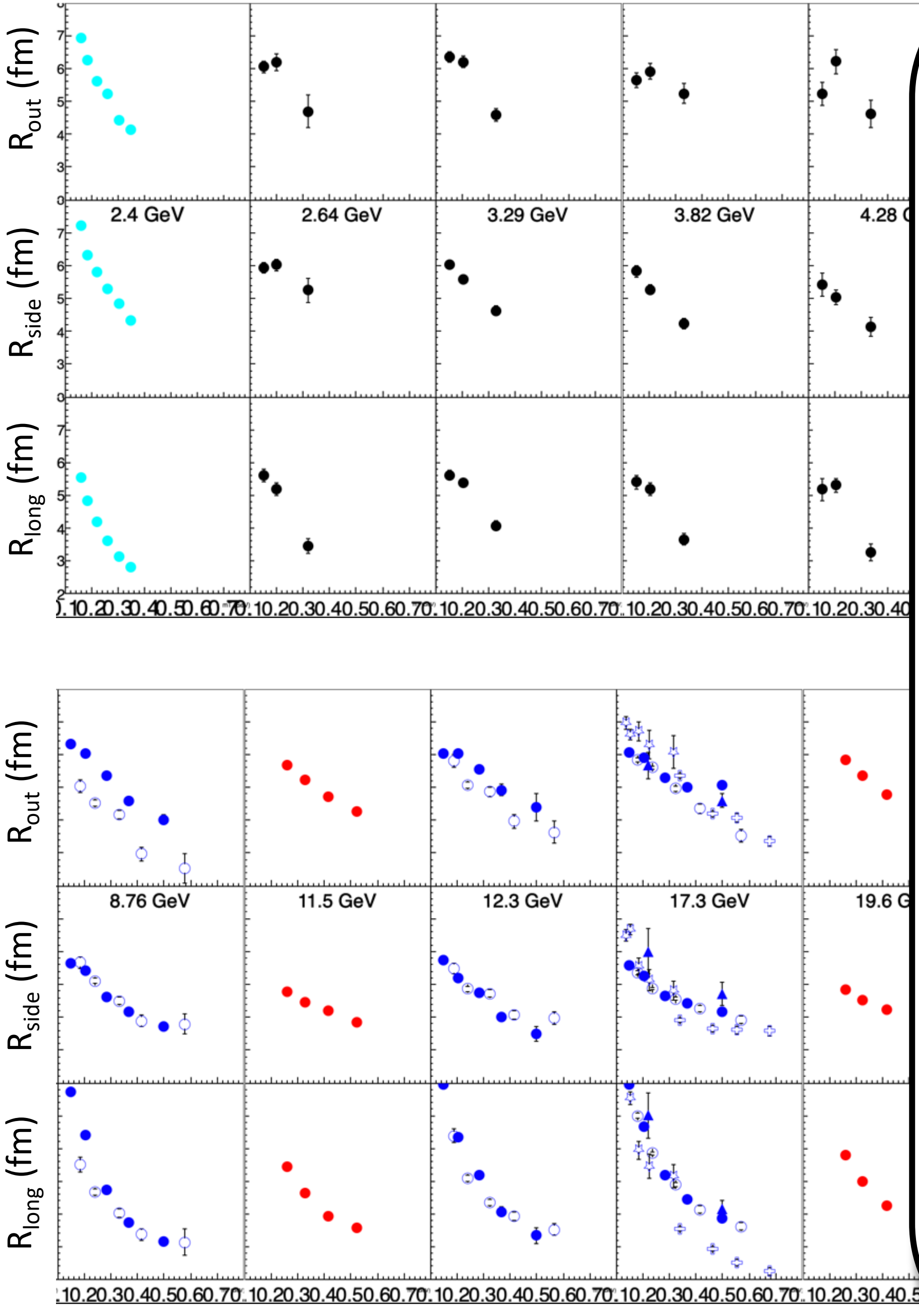
Polarization review: Ann.Rev.Nucl.Part.Sci. 70 (2020) 395; arxiv:2003.03640

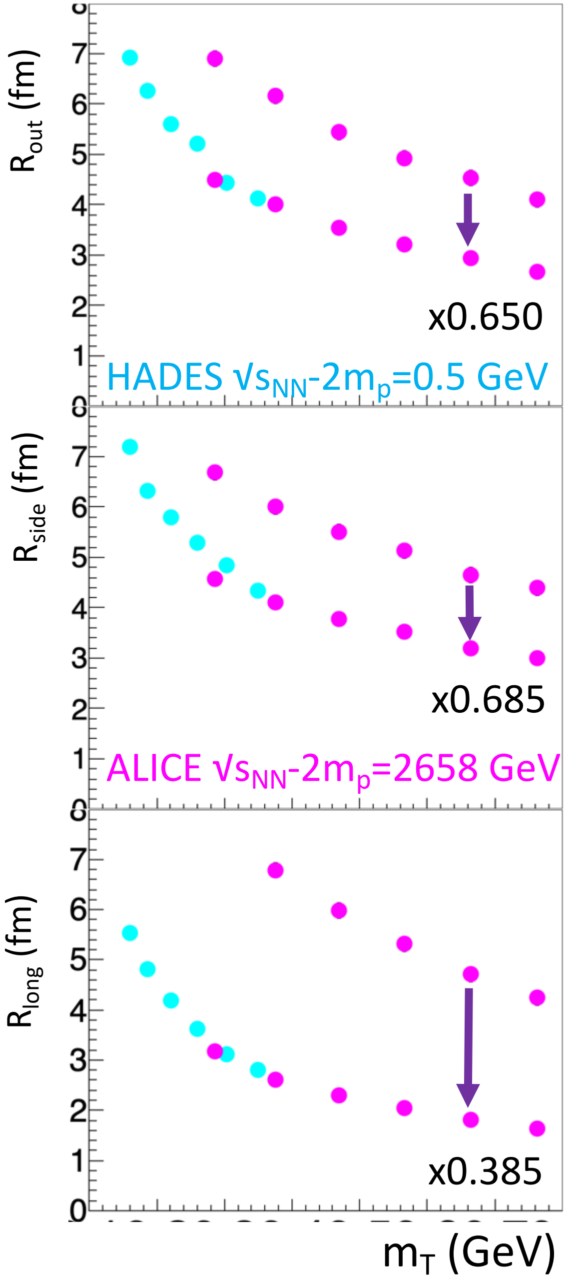
# Pion "HBT radii"

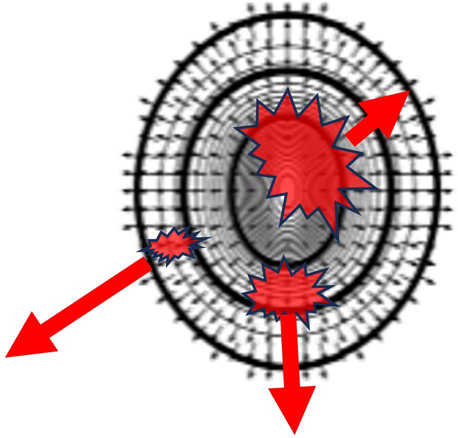
You want systematics?  We got systematics.



R_out (fm)
R_side (fm)
R_long (fm)
2.4 GeV
2.64 GeV
3.29 GeV
3.82 GeV
4.28 GeV
4.5 GeV
4.85 GeV
6.27 GeV
7.62 GeV
7.7 GeV
8.76 GeV
11.5 GeV
12.3 GeV
17.3 GeV
19.6 GeV
27 GeV
39 GeV
62.4 GeV
130 GeV
200 GeV
2760 GeV
m_T (GeV)
SIS: HADES
AGS: E895, E866
SPS: WA98, NA44, NA49, CERES, WA97, WA98, NA61
RHIC: STAR, PHENIX, PHOBOS
LHC: ALICE



66

A44,

WA97,

HENIX,

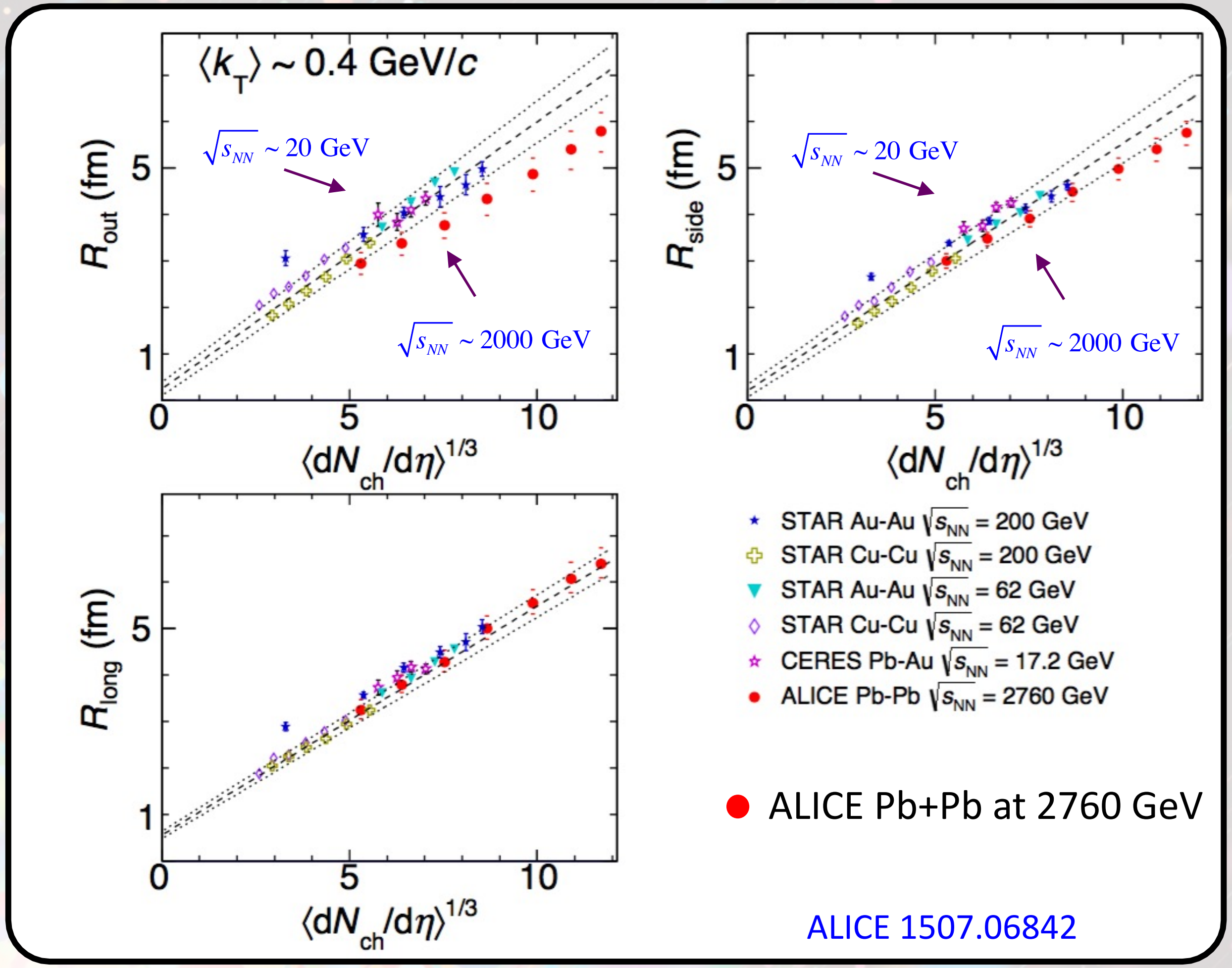
Message #1: very similar $\beta_{rad}$/T in HIC at *all* energies

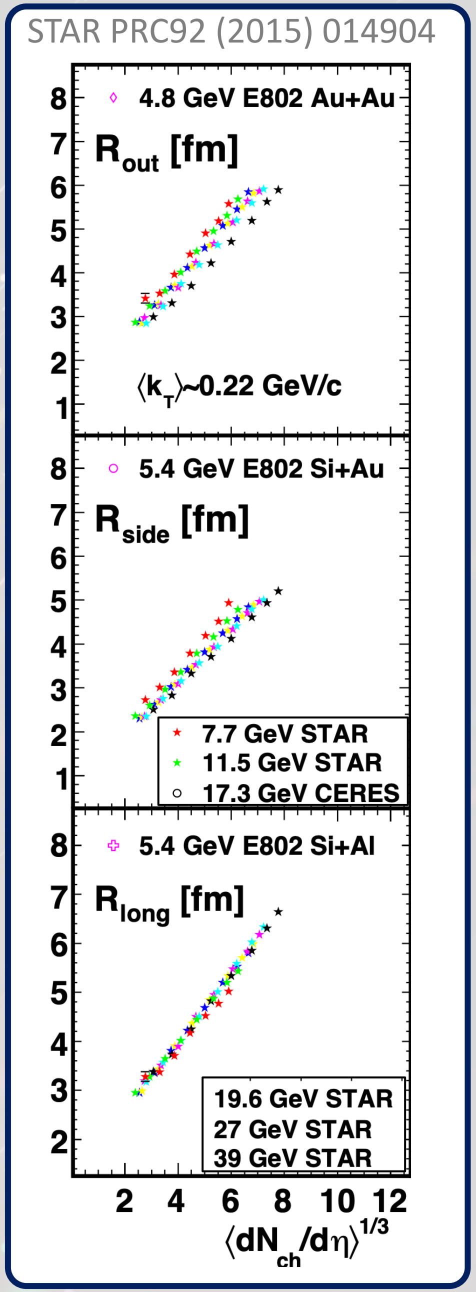
Mostly, scales change with energy (trans: x1.5, long: x2.5)

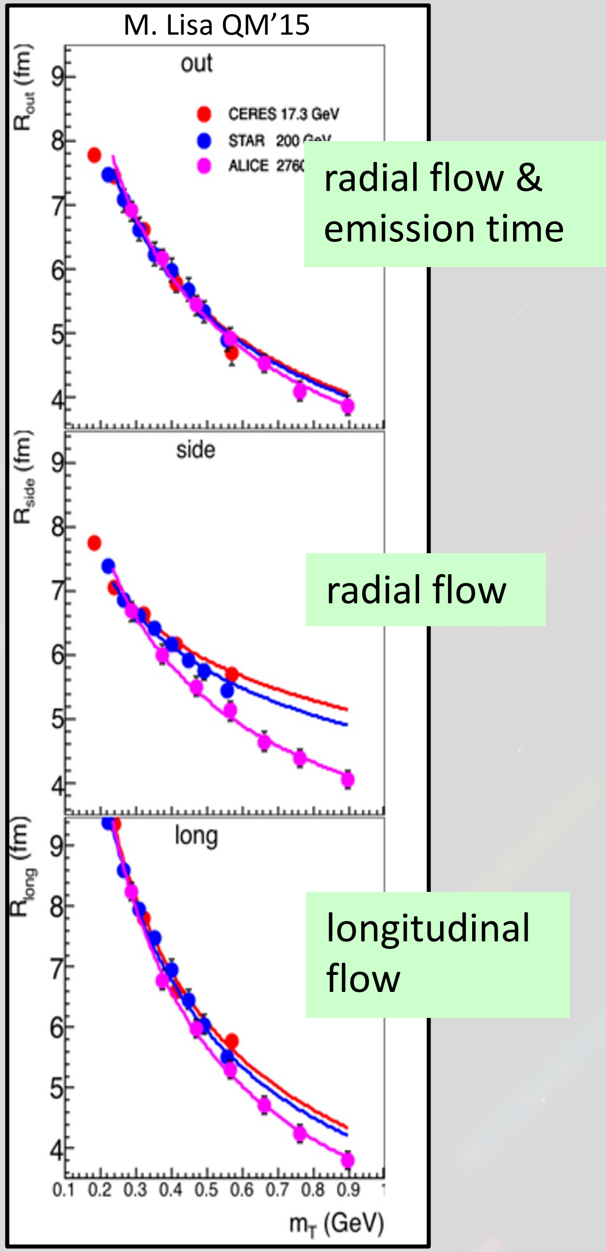
Well known that femtoscopic measurements by different experiments vary due to various systematic effects and cuts.

Detailed comparisons best made within *one* experiment

# Known: Spatiotemporal scales set mostly by multiplicity

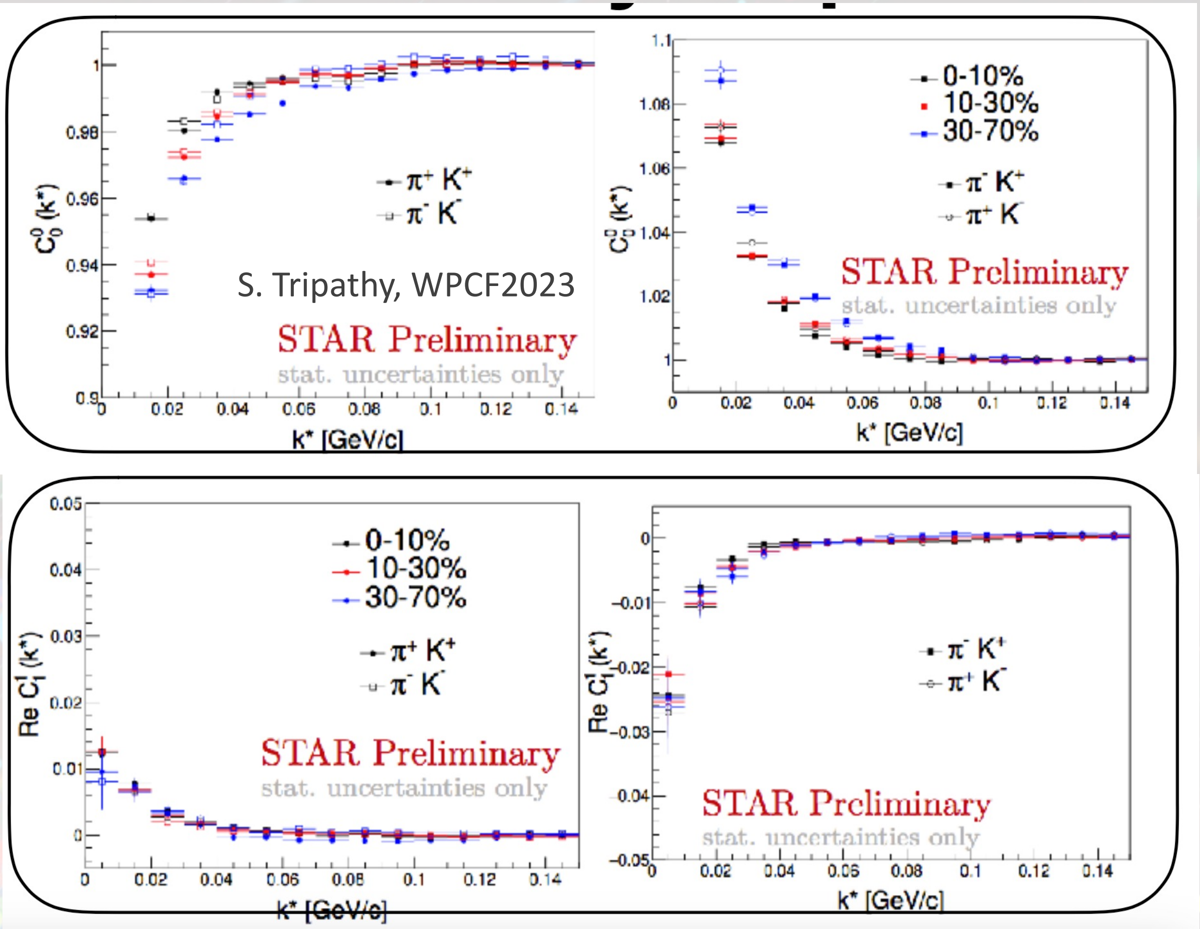


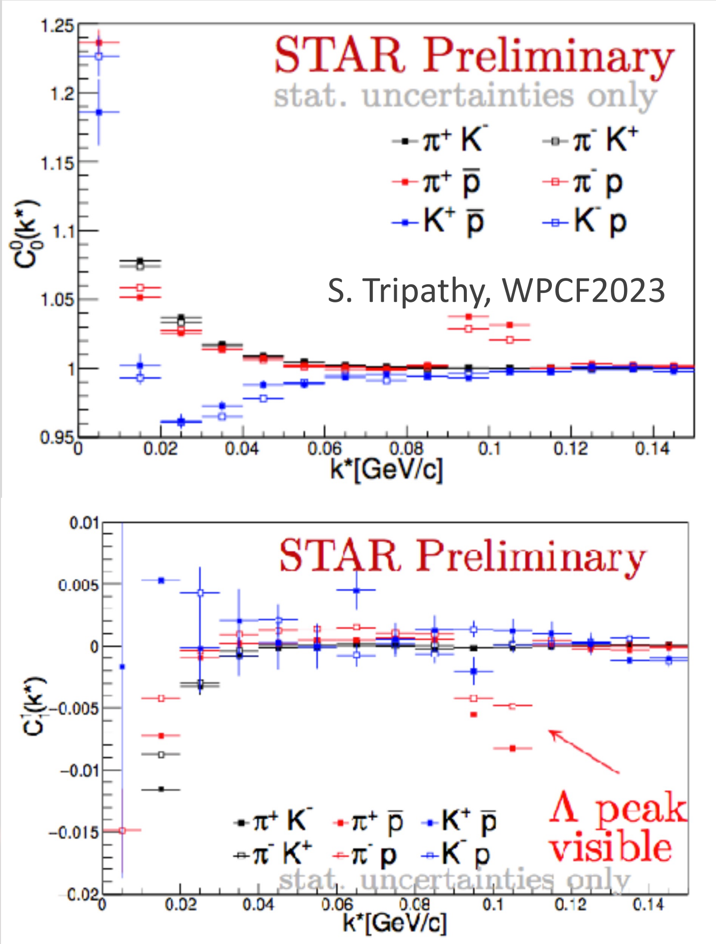




pion HBT radii

# New – non-identical particle femto at 7.7, 11.4, 39 GeV







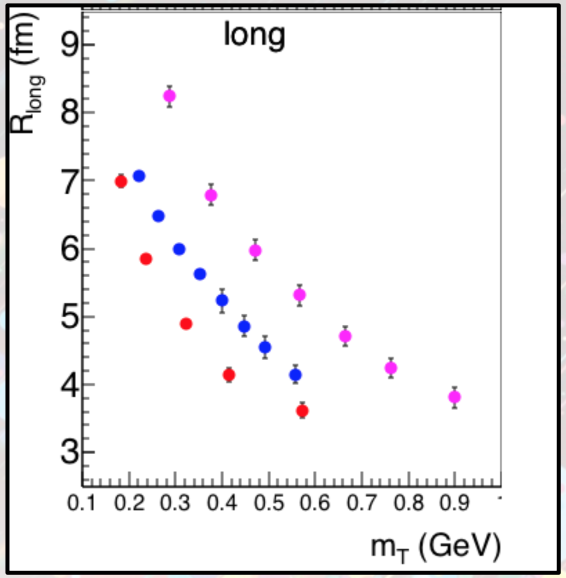

- no-id correlations driven by "Final-state interactions" (mostly Coulomb)
- SHD: $C_0^0$ probes size; Re[$C_1^1$] probes emission asymmetry – geometric *sub*-structure of flowing system
- **Confirms flow-driven asymmetry pattern** as seen at 200 GeV
- same story from pi-K, pi-p, (prob K-p) correlations

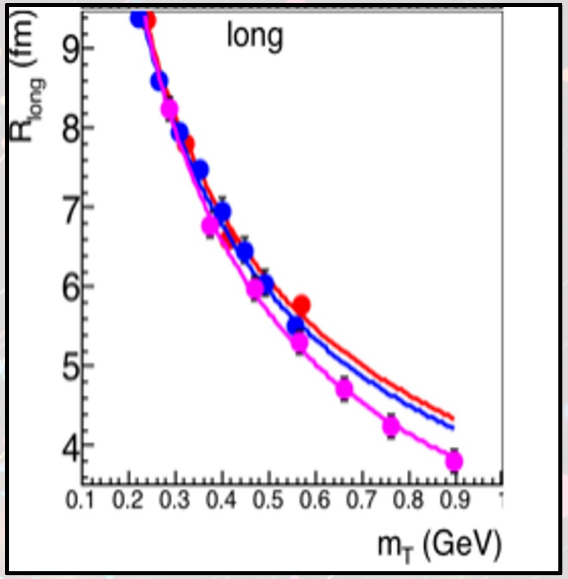
# Evolution time

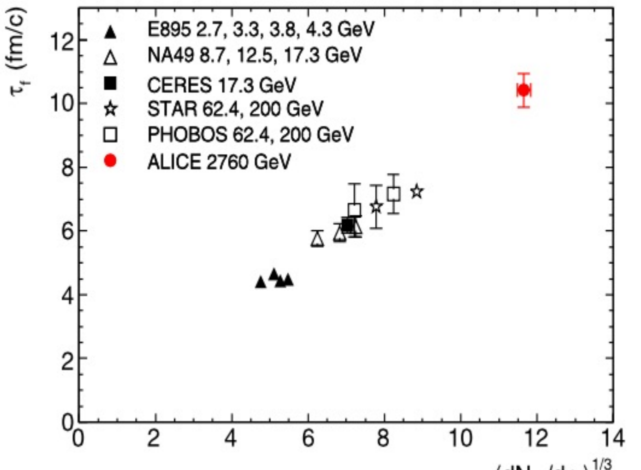
**Hydro-inspired relation**

Makhlin ZPC39 (1988) 69
Wiedemann PRC53 (1996) 918

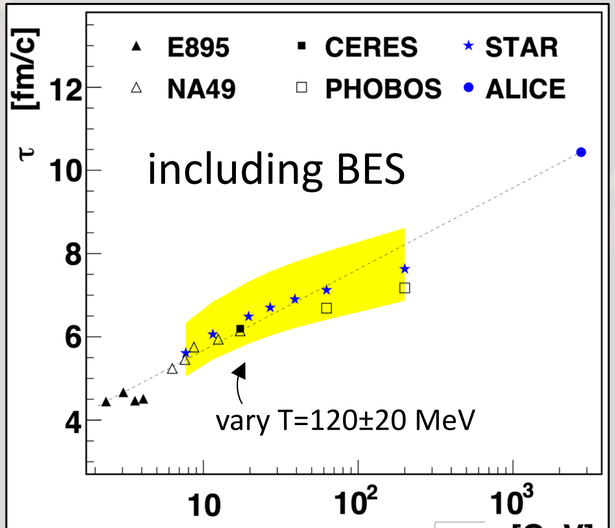
$$R_l^2 \approx \tau_0^2 \frac{T}{m_T} \frac{K_2\left(m_T/T\right)}{K_1\left(m_T/T\right)}$$



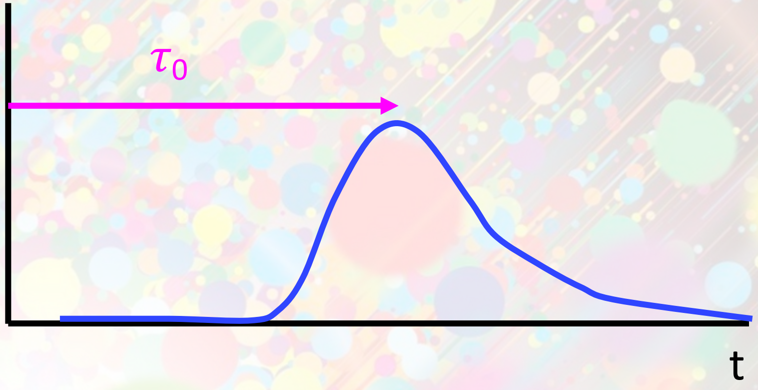



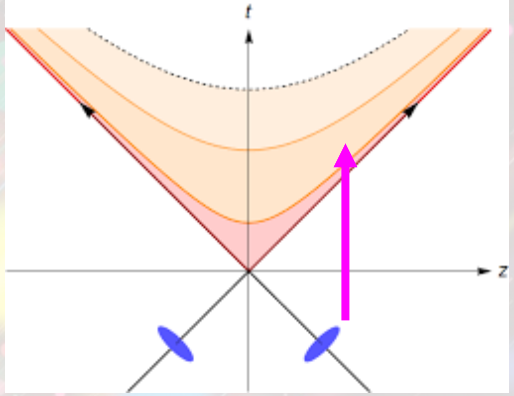




ALICE PLB 696 328 (2011)



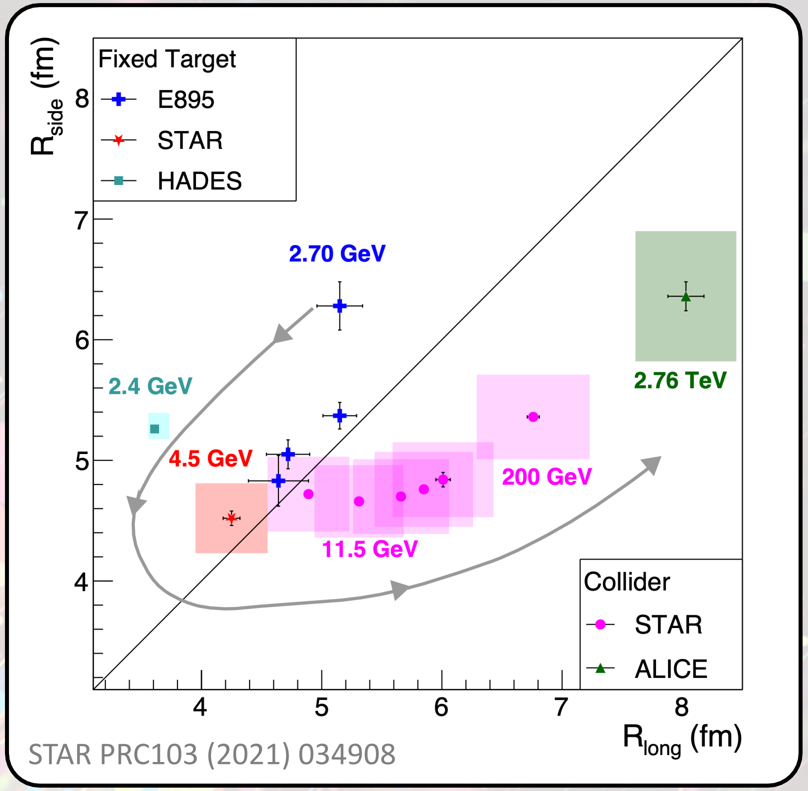

STAR PRC92 (2015) 014904



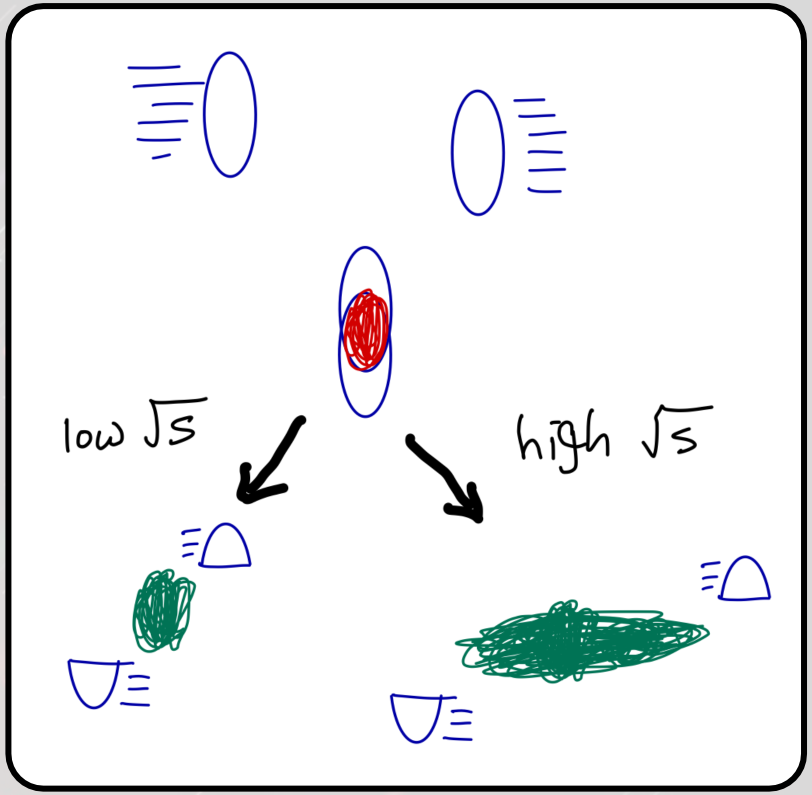




Simple message:
Multiplicity-driven evolution time varies smoothly

# Beyond size & time scales – shapes (1/3): prolateness




STAR PRC103 (2021) 034908

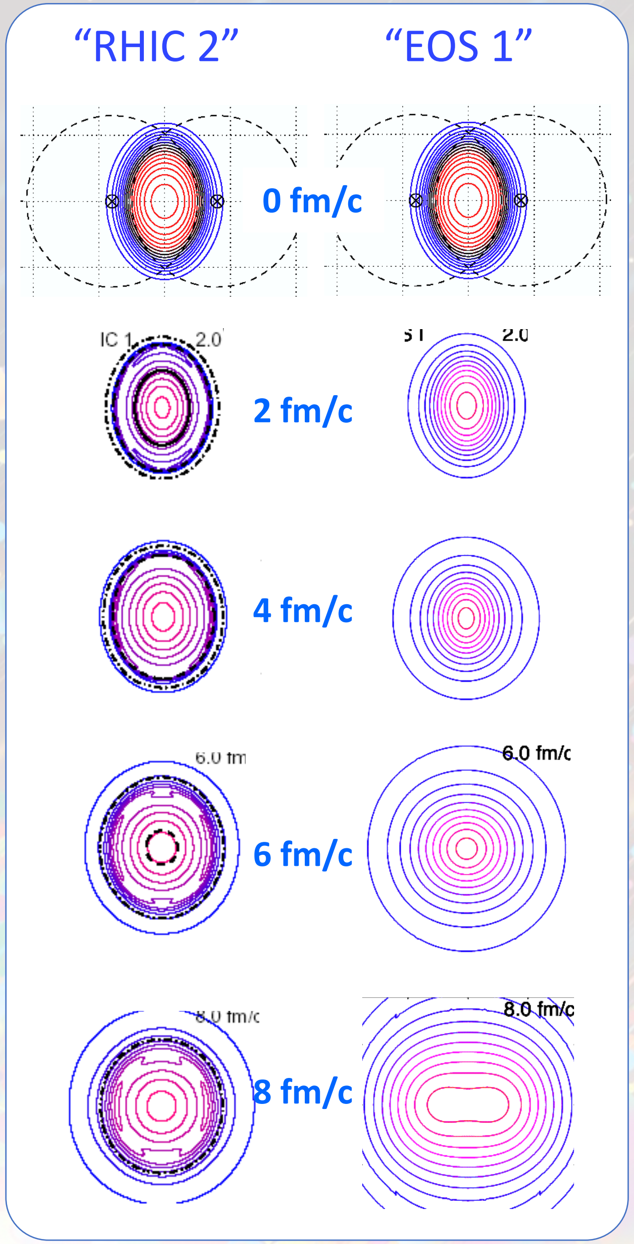


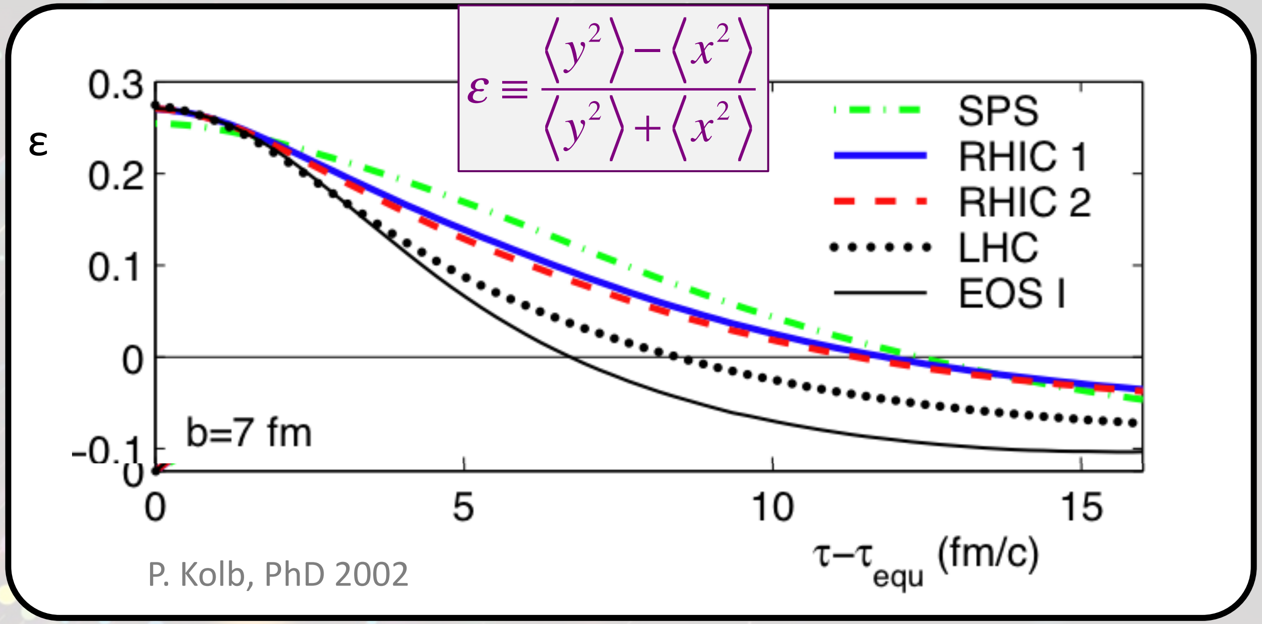

Message 3: oblate -> prolate evolution reasonable; FXT is roughly the transition point

Evolution from oblate to longitudinally-extended, boost-invariant prolate emission region

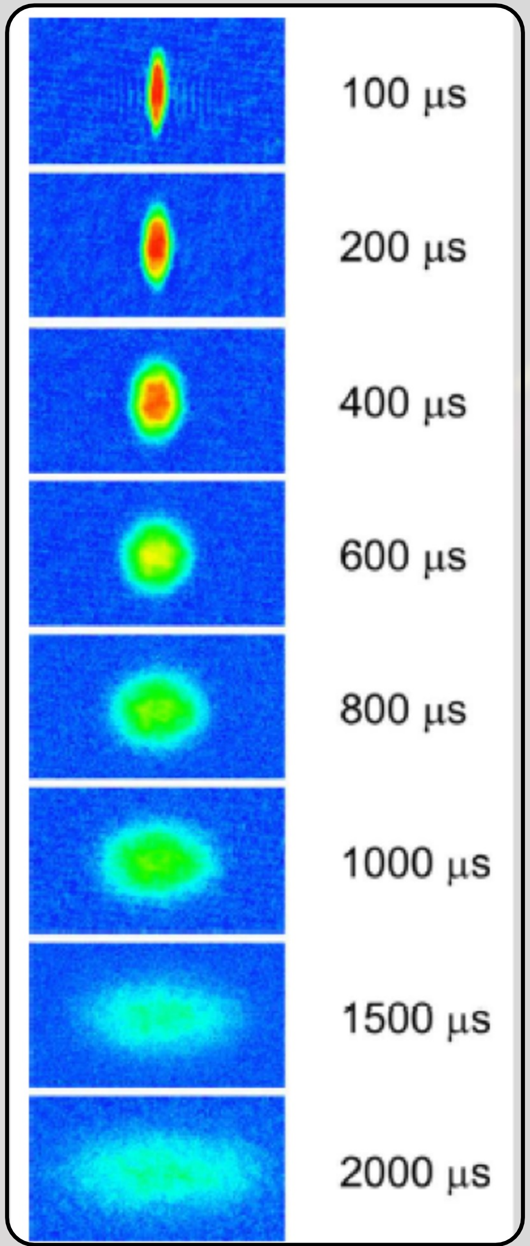
- system in BES is explicitly not boost-invariant & requires 3D treatment

# Beyond size & time scales – shapes (2/3): ellipticity




P. Kolb, PhD 2002




[6]Li released from an asymmetric trap
O'Hara, *et al*, Science **298** 2179 (2002)

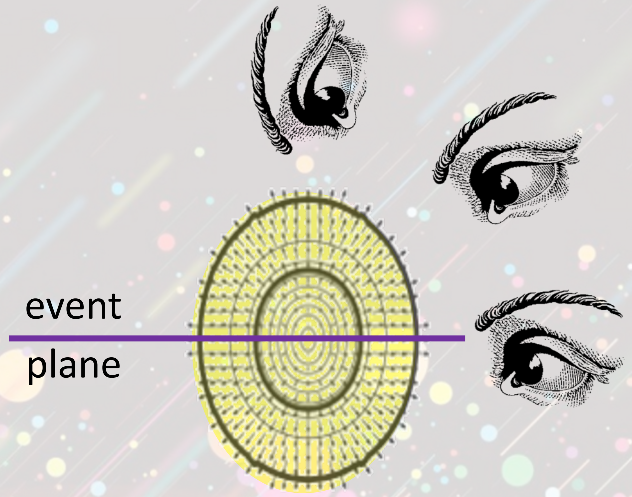
evolution from initial shape depends on

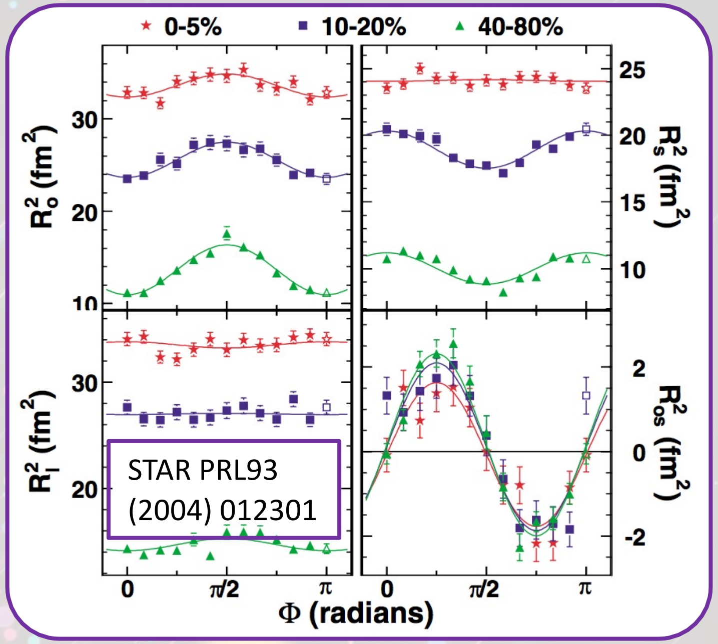
- pressure anisotropy ("stiffness") (Equation of State)
- lifetime

Both are interesting!

- model needed

# Beyond size & time scales – shapes (2/3): ellipticity



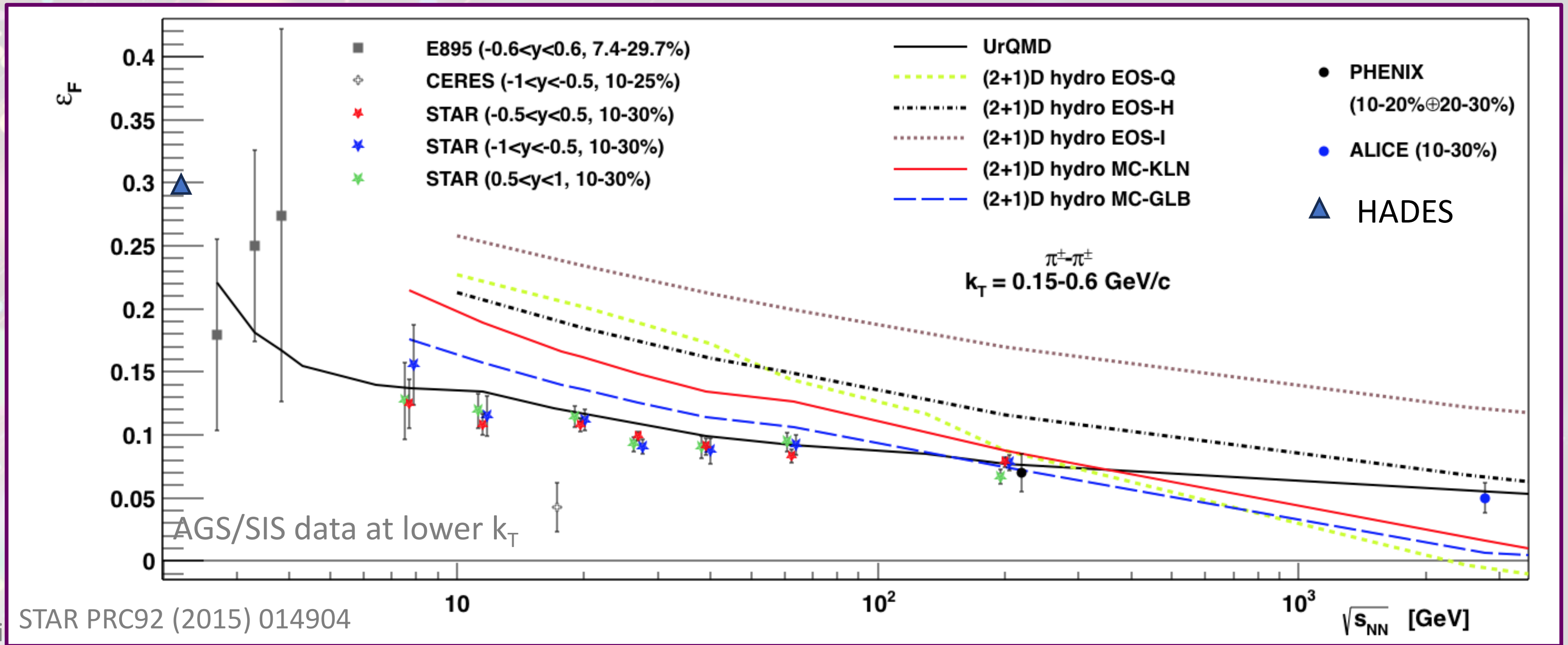




- HBT radii relative to 2nd-order plane reveal f.o. ε
- Sensitive to model parameters
- All collider experiments consistent with ... UrQMD (?!)

$$R_{s,n}^2 \equiv \left\langle R_s^2(\phi) \cdot \cos(n\phi) \right\rangle$$

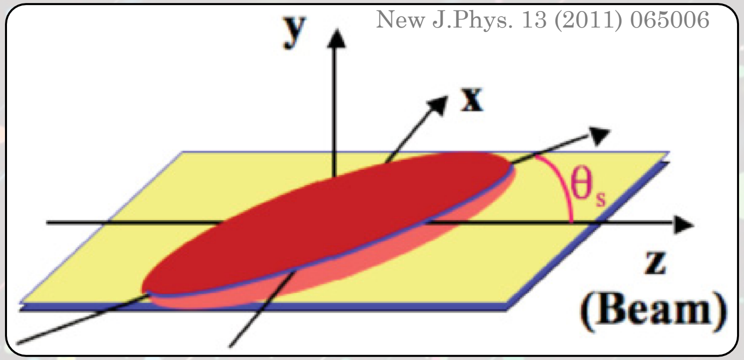
$$\varepsilon \approx 2\frac{R_{s,2}^2}{R_{s,0}^2} \approx 2\frac{R_{os,2}^2}{R_{s,0}^2} \approx -2\frac{R_{o,2}^2}{R_{s,0}^2}$$

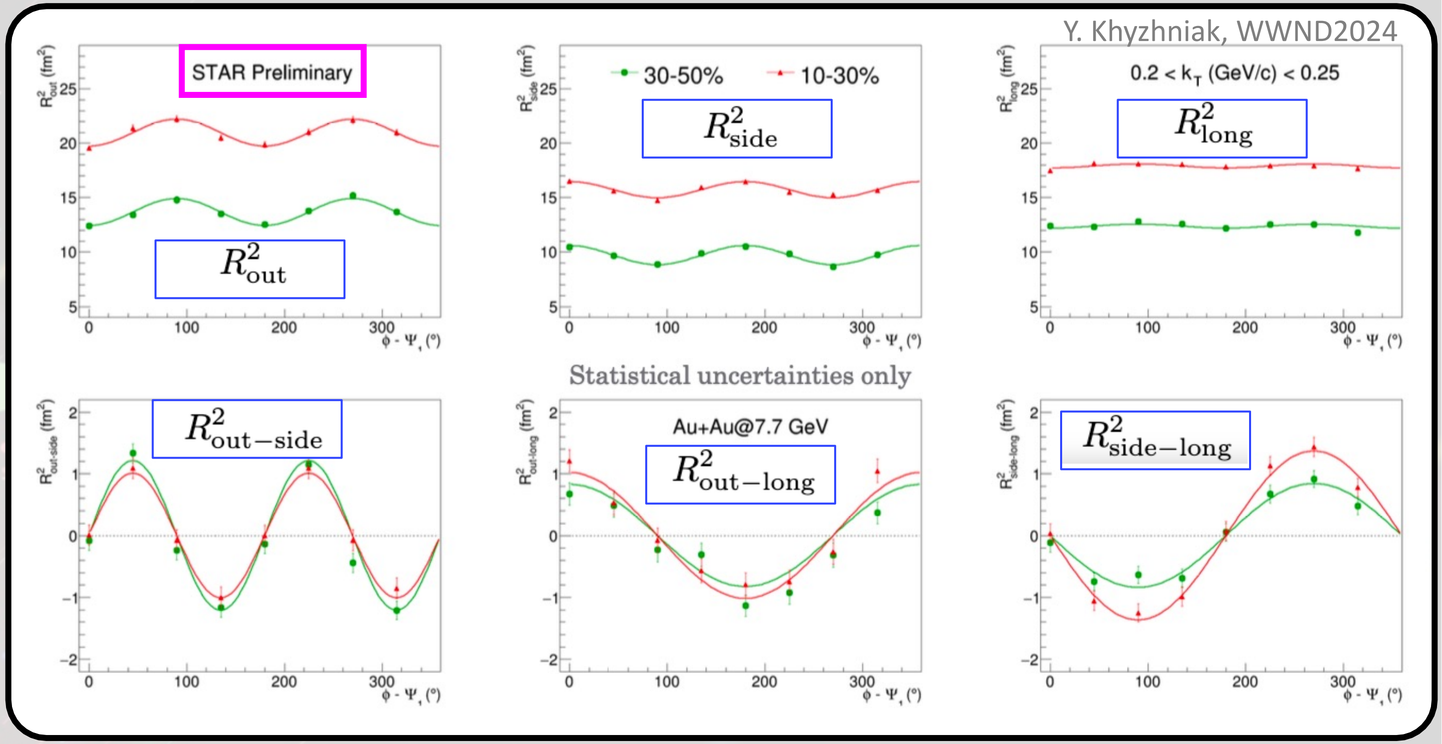
Retiere&MAL PRC70 (2004) 044907

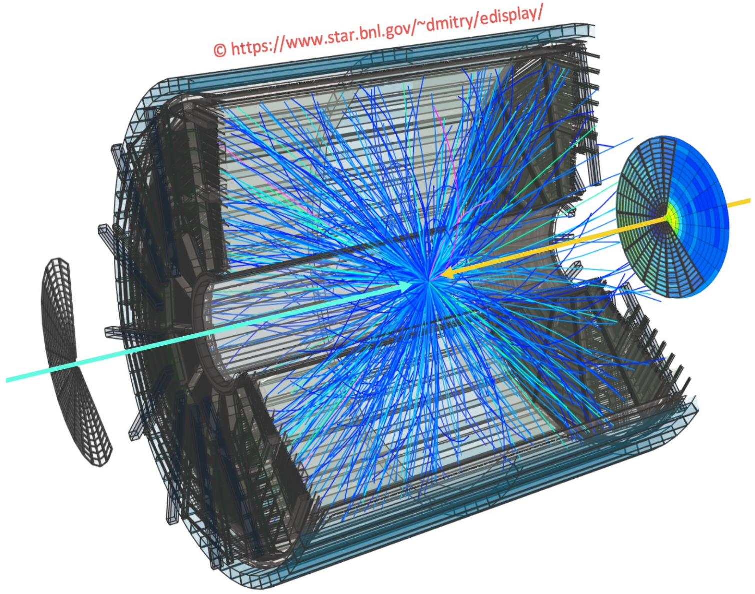


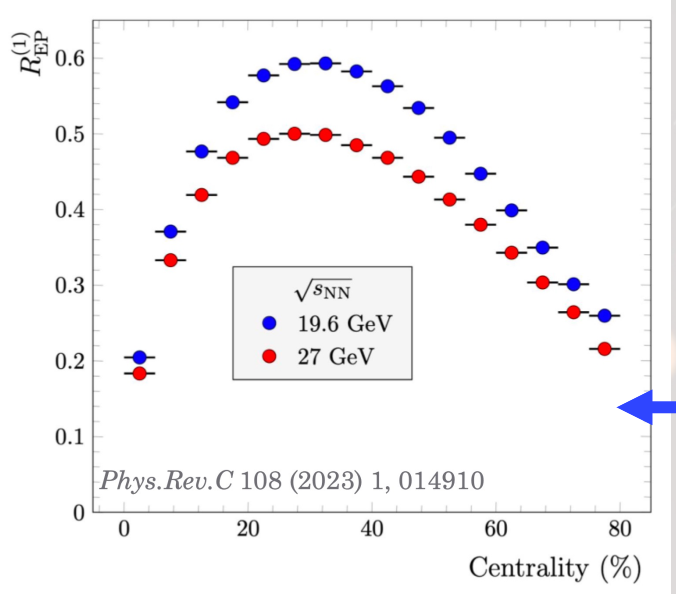
# Beyond size & time scales: shapes (3/3): tilt

- ✓ lifetime
- ✓ size
- ✓ prolateness
- ✓ ellipticity
- ✓ **(spatial) tilt**




$$R^2_{sl,1} \equiv \langle R^2_{sl}(\phi) \sin\phi \rangle$$
$$R^2_{s,2} \equiv \langle R^2_{s}(\phi) \cos 2\phi \rangle$$
$$R^2_{s,0} \equiv \langle R^2_{s}(\phi) \rangle$$
$$R^2_{l,0} \equiv \langle R^2_{l}(\phi) \rangle$$

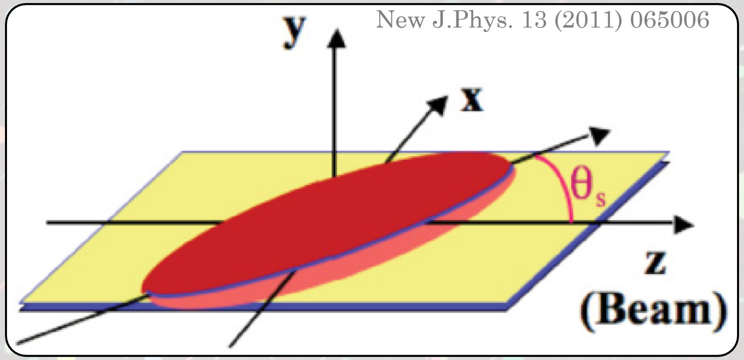
$$\theta = \frac{1}{2} \tan^{-1}\left( \frac{-4R^2_{sl,1}}{R^2_{l,0} - R^2_{s,0} + 2R^2_{s,2}} \right)$$

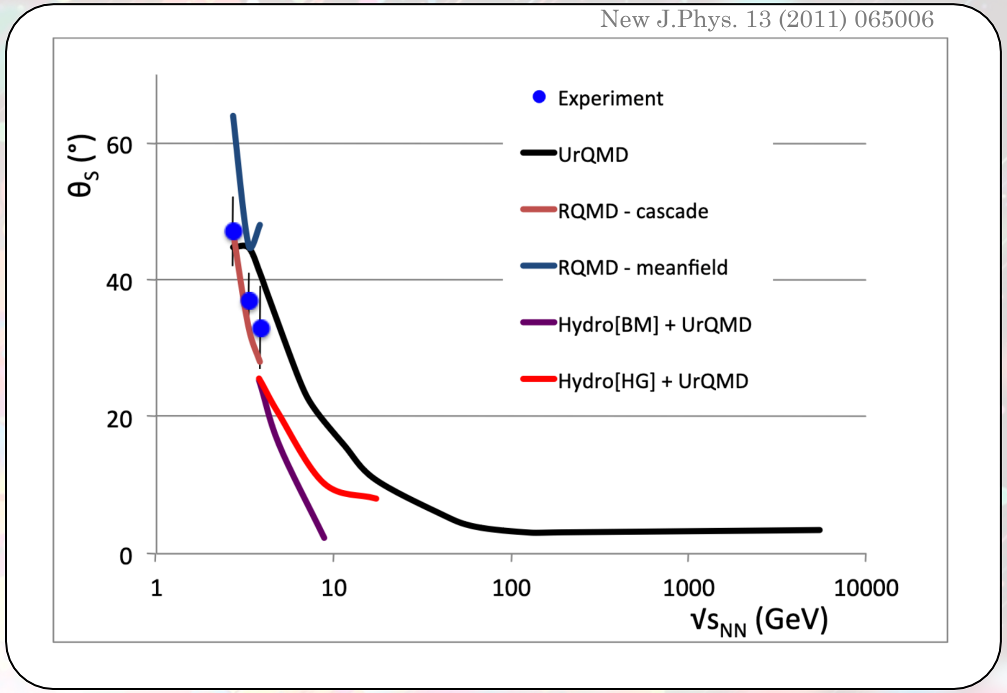
PRC84 (2011) 014908

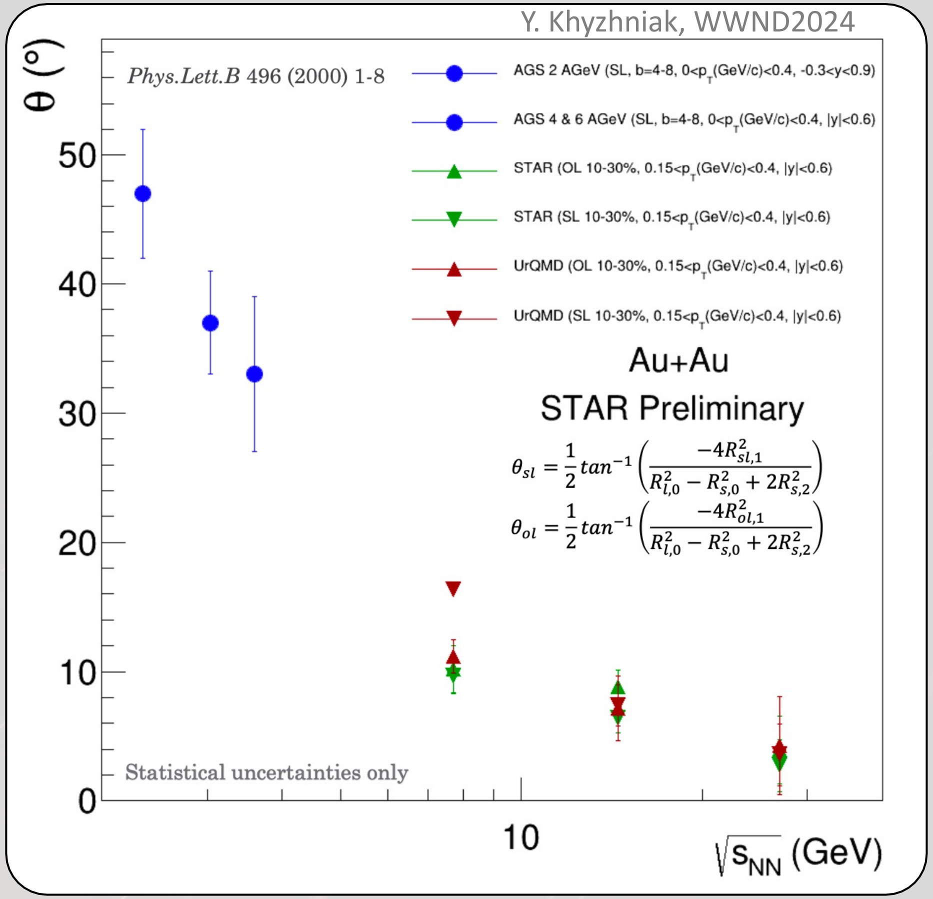
Precision measurement possible due to resolution from STAR upgrade detector EPD

# Beyond size & time scales: shapes (3/3): tilt

- ✓ lifetime
- ✓ size
- ✓ prolateness
- ✓ ellipticity
- ✓ **(spatial) tilt**



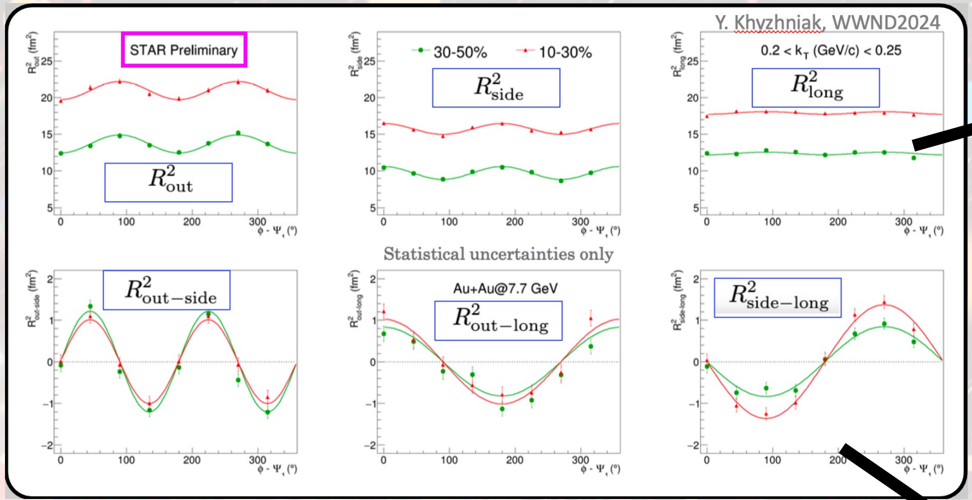



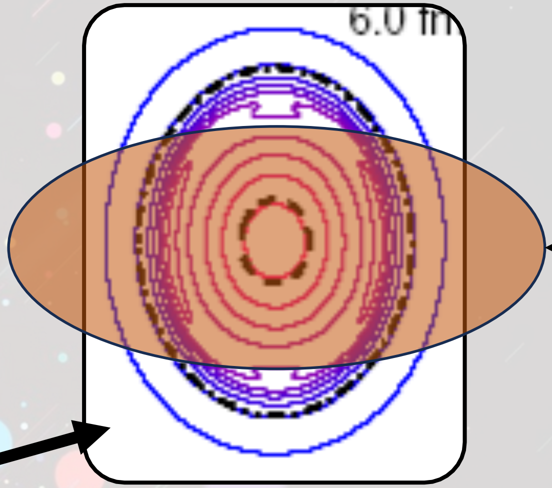



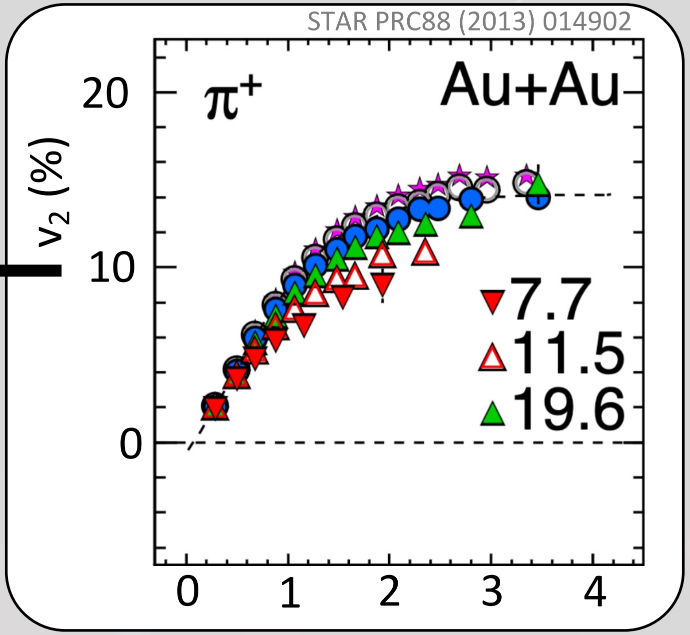

Explicitly non-boost-invariant spatial feature of system
- especially relevant at BES energies
- sensive to stopping, EOS in hydro/meanfield

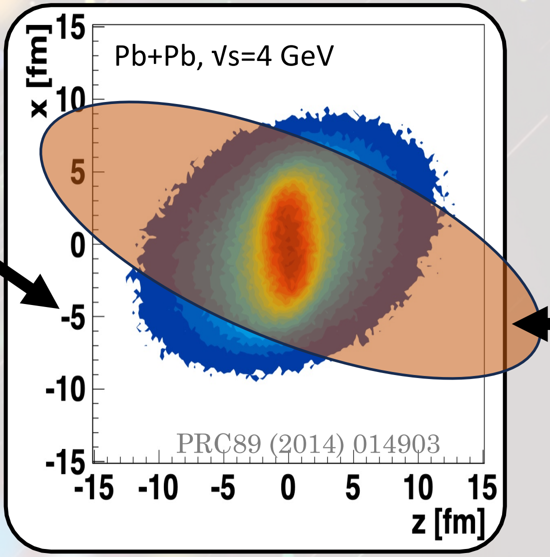
Very clear signal at RHIC BES

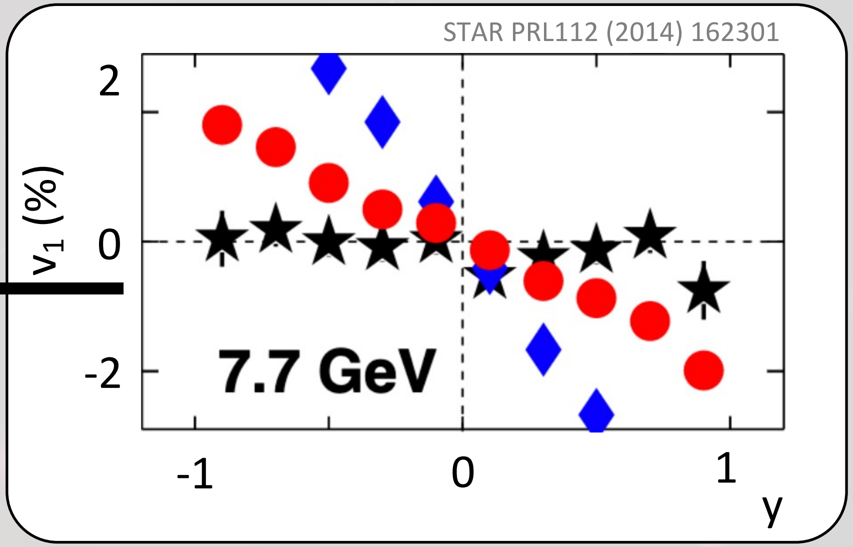
# Ellipticity and tilt – space versus momentum



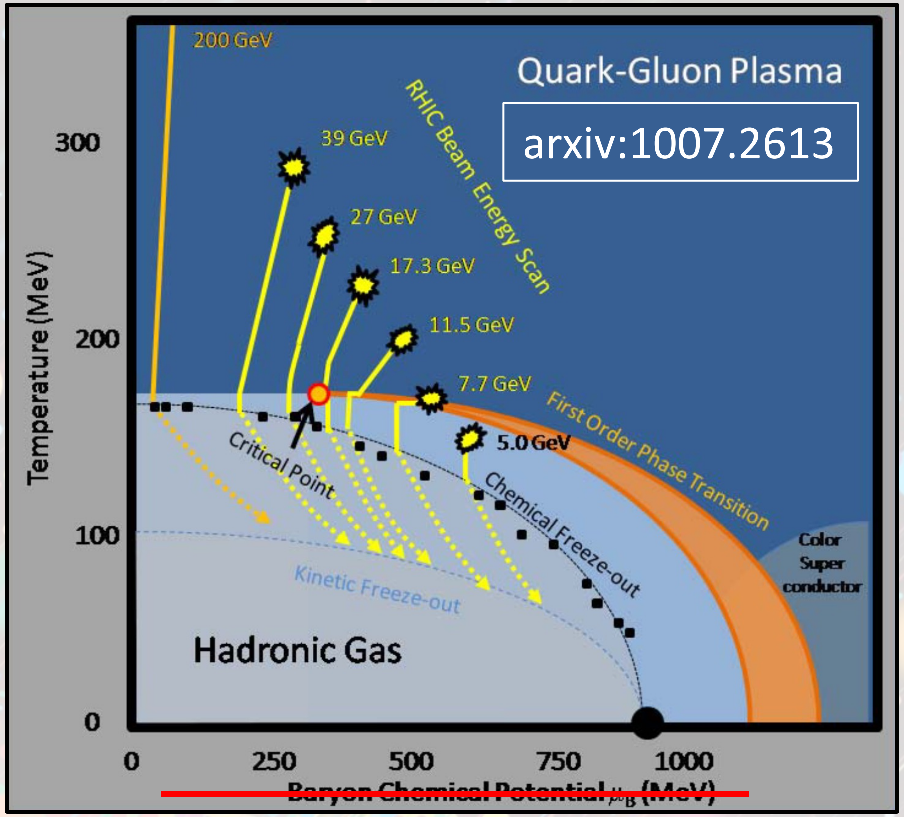



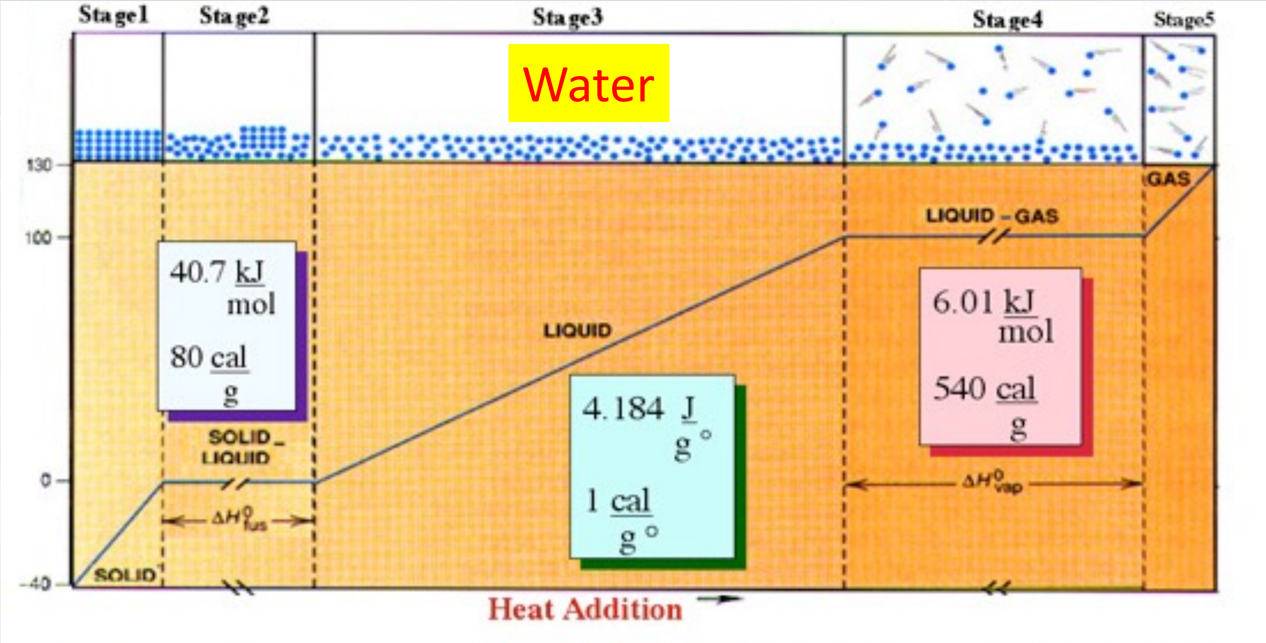




What does the spatial tilt tell us about the (anti)flow at midrapidity?

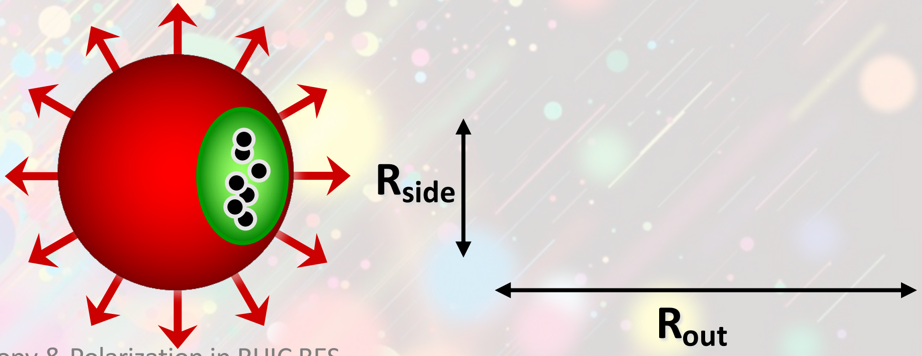
# Weren't we supposed to be talking about this?

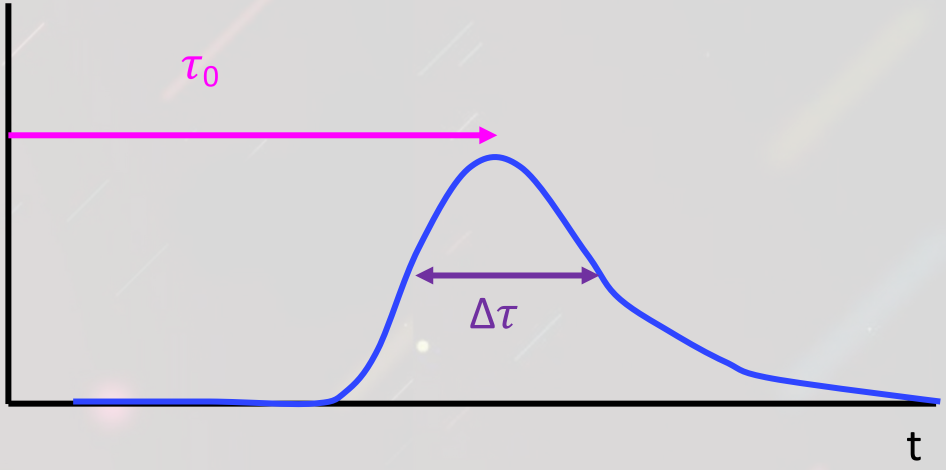



1st-order P.T. is a region in *density*

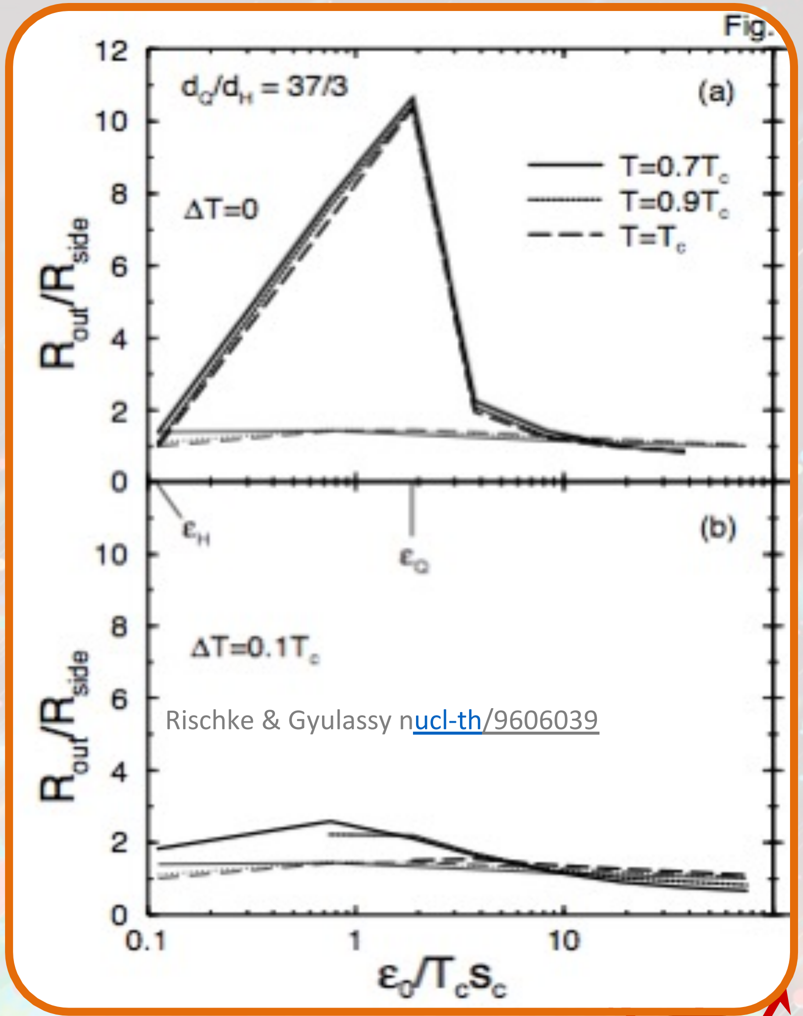
A long emission duration results in $R_{out} > R_{side}$




Pratt PRD33 (1986) 1314
Bertsch PRC37 (1988) 1896

# Weren't we supposed to be talking about…




Rischke & Gyulassy nucl-th/9606039

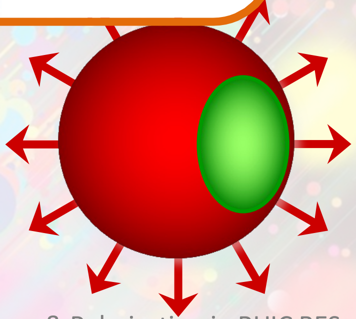
One of the most-anticipated "golden" signatures of QGP formation at RHIC

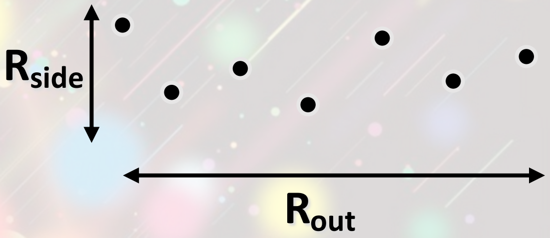
- generic expectation
- magnitude unclear

"HBT Puzzle"

1) $R_o/R_s$ : RHIC~AGS (~1.1)
2) difficult to calculate HBT radii in models

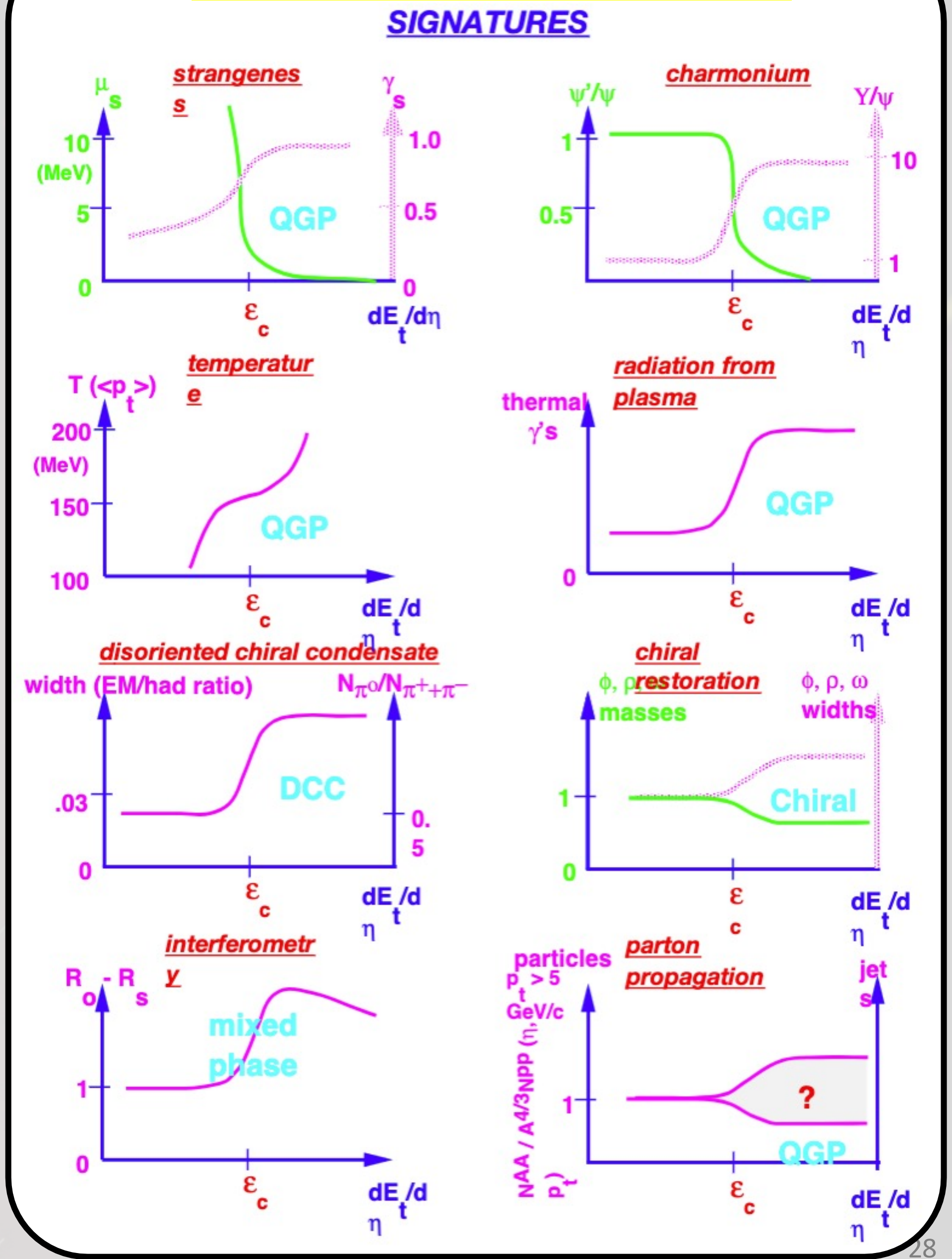
A long emission duration results in $R_{out} > R_{side}$



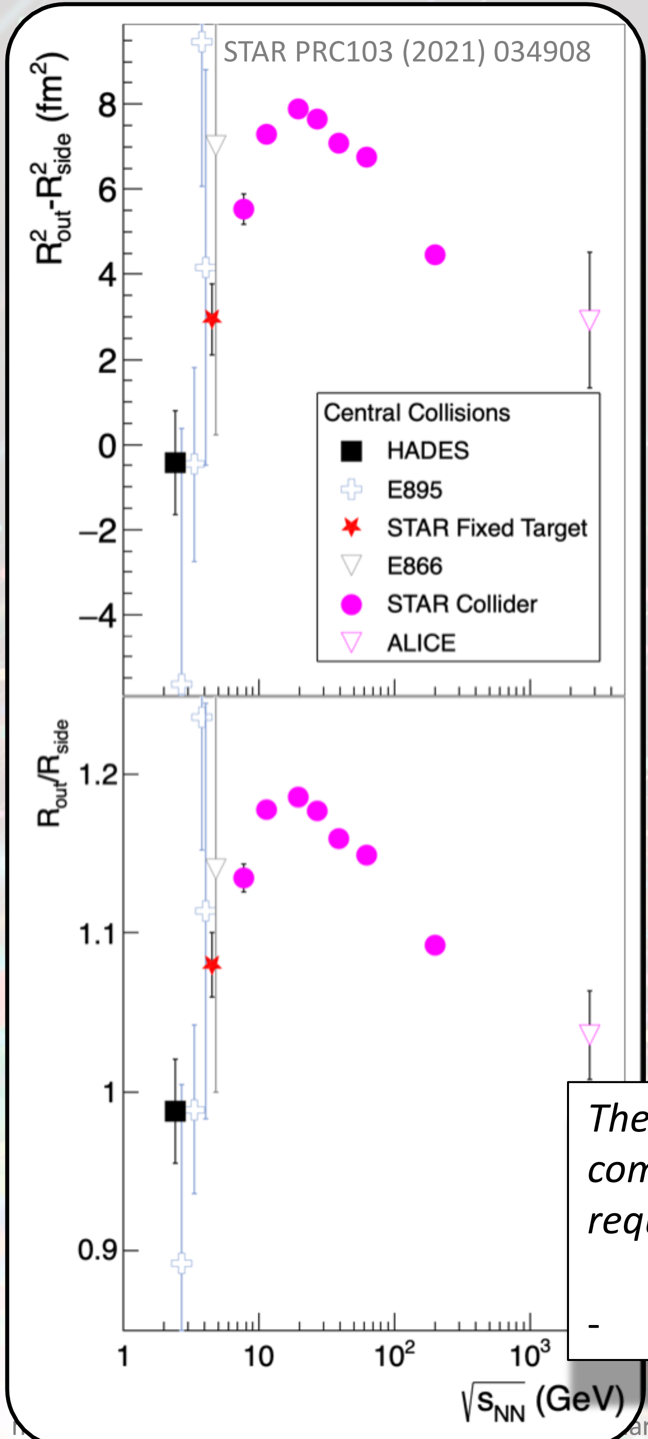



Pratt PRD33 (1986) 1314
Bertsch PRC37 (1988) 1896

J. Harris & B. Müller ARNPS46 (1996) 71



# Weren't we supposed to be talking about…




One of the most-anticipated "golden" signatures of QGP formation at RHIC

- generic expectation
- magnitude unclear

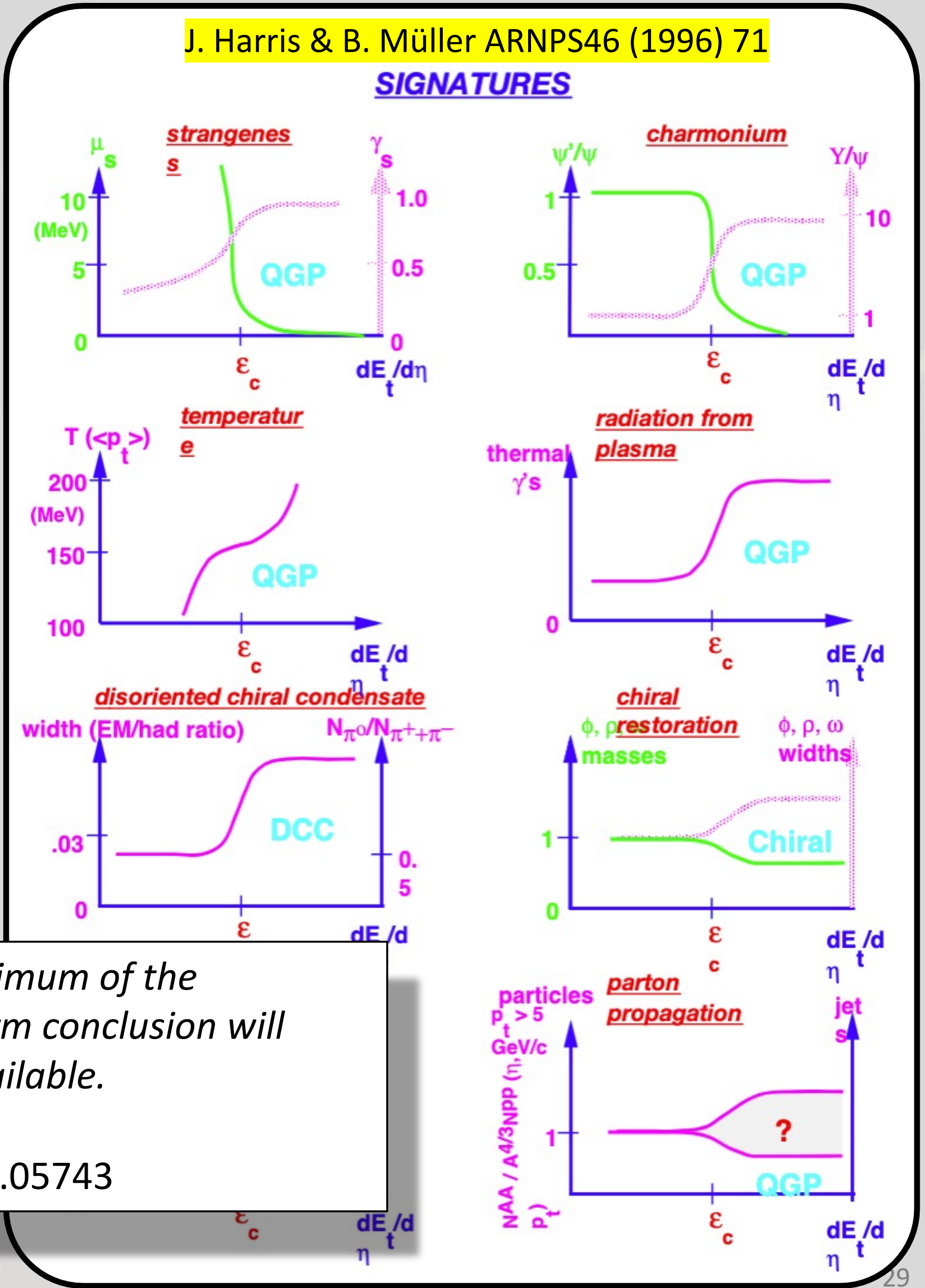
"HBT Puzzle"

1) $R_o/R_s$ : RHIC~AGS (~1.1)
2) difficult to calculate HBT radii in models

Consistent methods (Coulomb, fitting, etc), consistent phasespace coverage, and high statistics…..

This golden signature is clearly seen.

… but barely touched by theory community.




*The behavior is consistent with the interpretation of a minimum of the compressibility around $T_c$ during hadron emission, but a firm conclusion will require a detailed theoretical analysis, which is not yet available.*

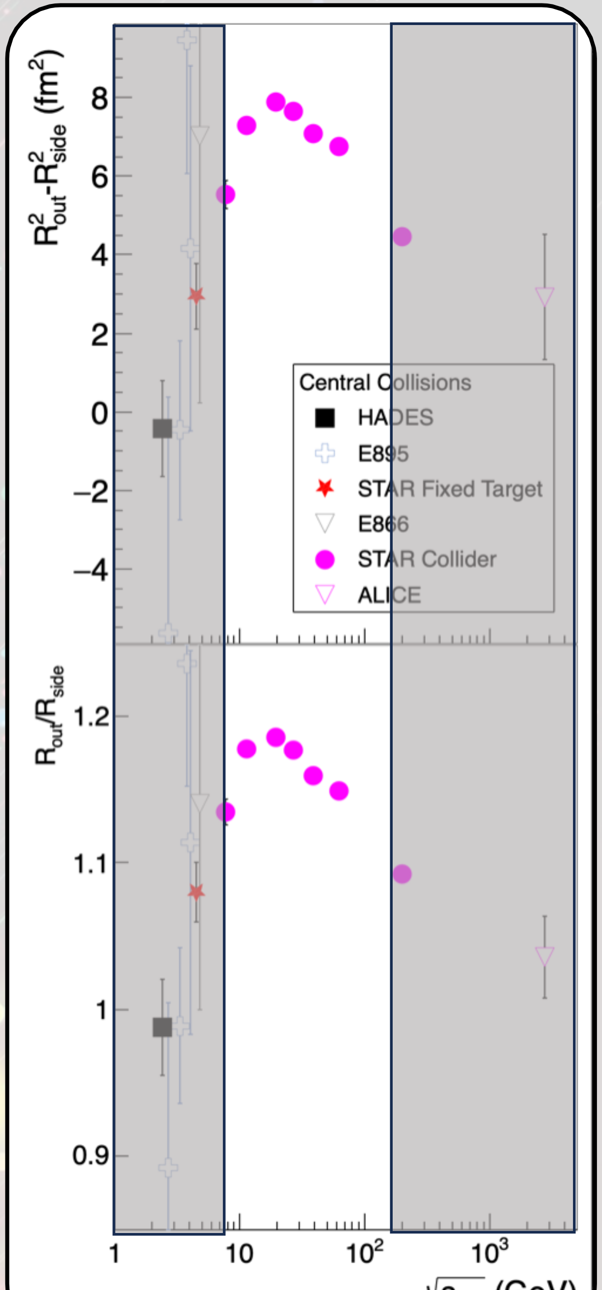
- Harris & Müller, "QGP Signatures Revisited" arxiv:2308.05743

# Extracting the EoS and signs of phase transition

Li, Steinheimer, Reicher, Kittiratpattana, Bleicher, Li https://arxiv.org/abs/2209.01413
**Effects of a phase transition on two-pion interferometry in heavy-ion collisions at $\sqrt{s_{NN}}$=2.4–7.7 GeV**

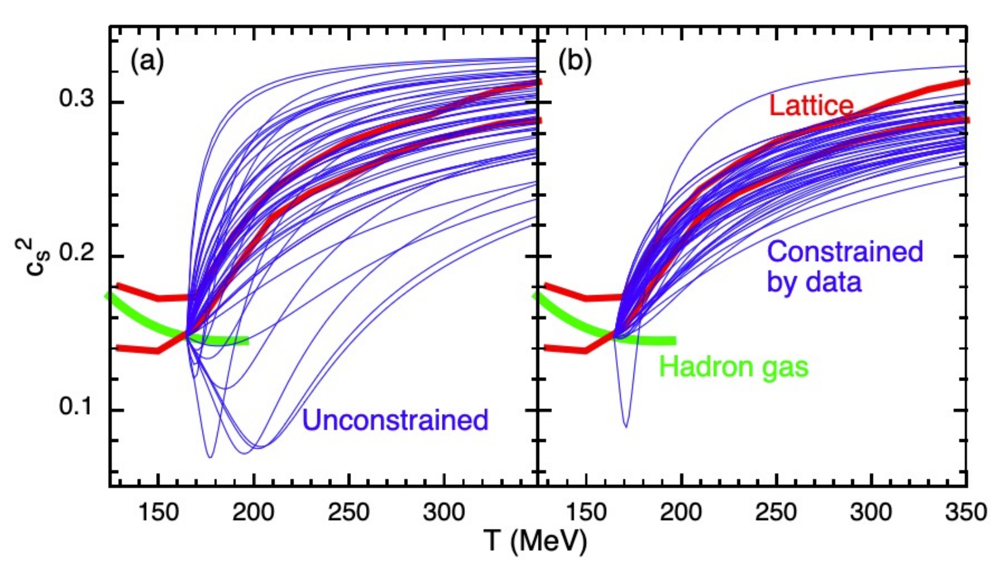
*"Our results highlight that the pion's $R_O/R_S$ and $R^2_O-R^2_S$ ...can be used to constrain and understand the QCD equation of state.*

*We exclude a strong [1st-order] phase transition…"*



STAR PRC103 (2021) 034908

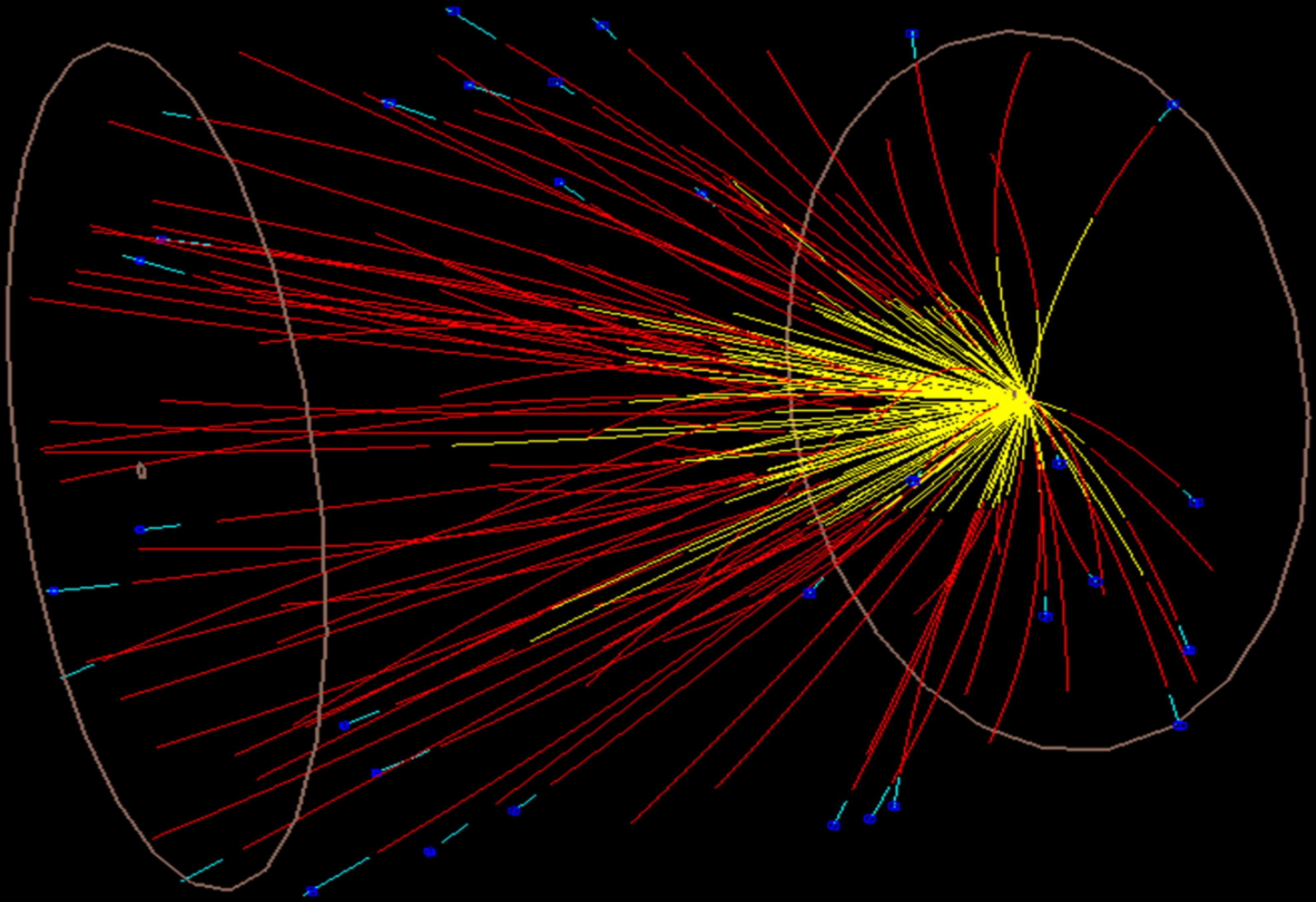
S. Pratt et al
PRL114 (2015) 202301
PRC93 (2016) 024908
**Constraining the Eq. of State of Super-Hadronic Matter from Heavy-Ion Collisions**



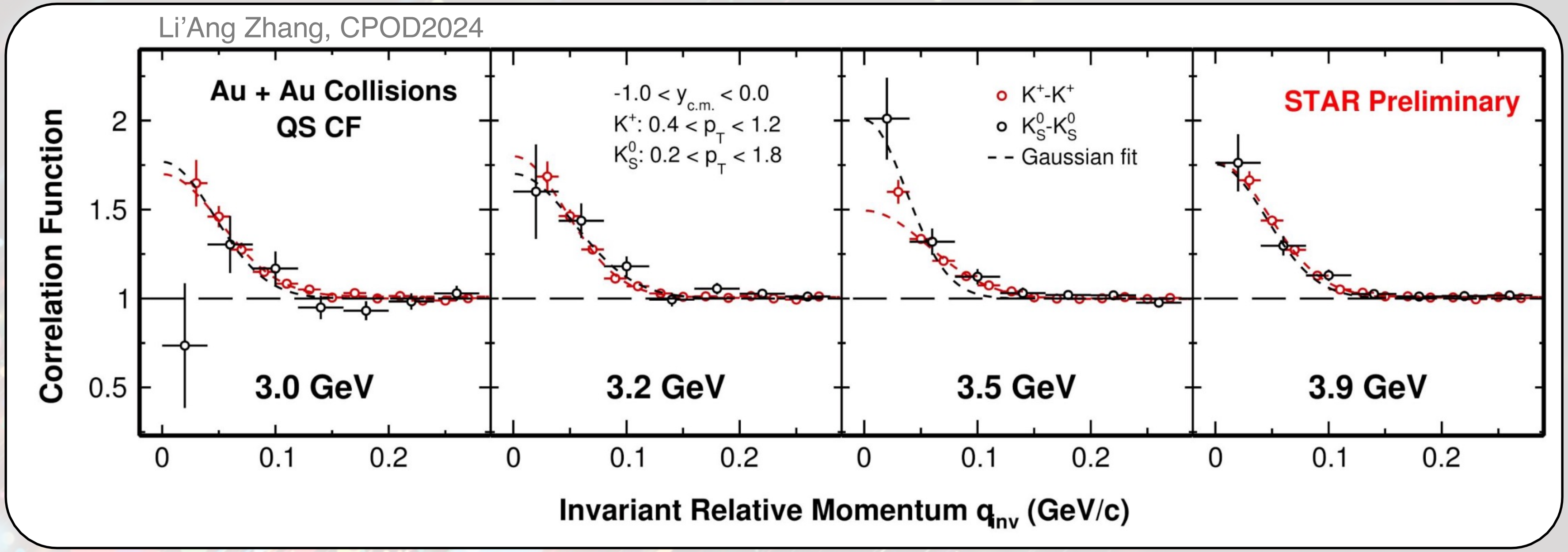

*"For constraining the equation of state, femtoscopic radii seem to provide the most resolving power…*

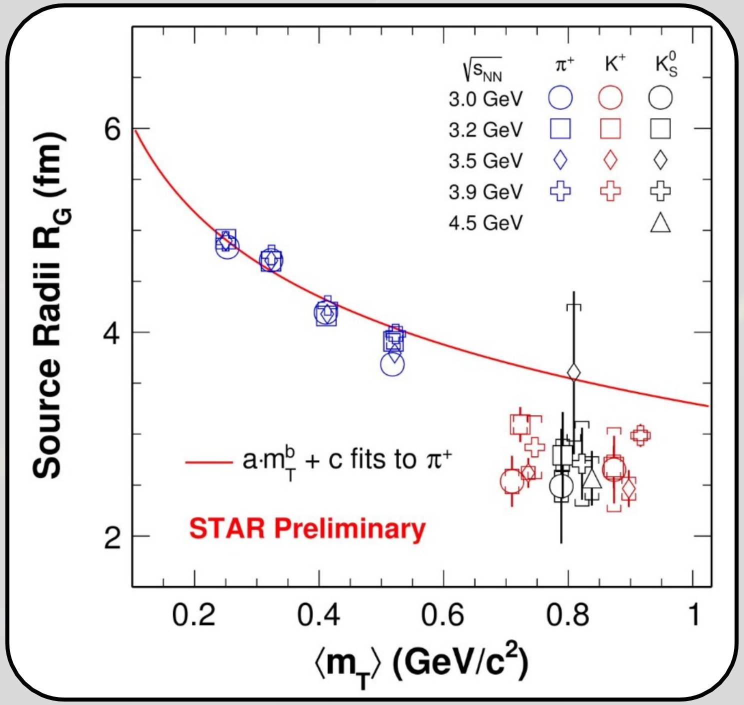
*it appears that the speed of sound cannot fall much below ~0.15…"*

# More from the lowest energies



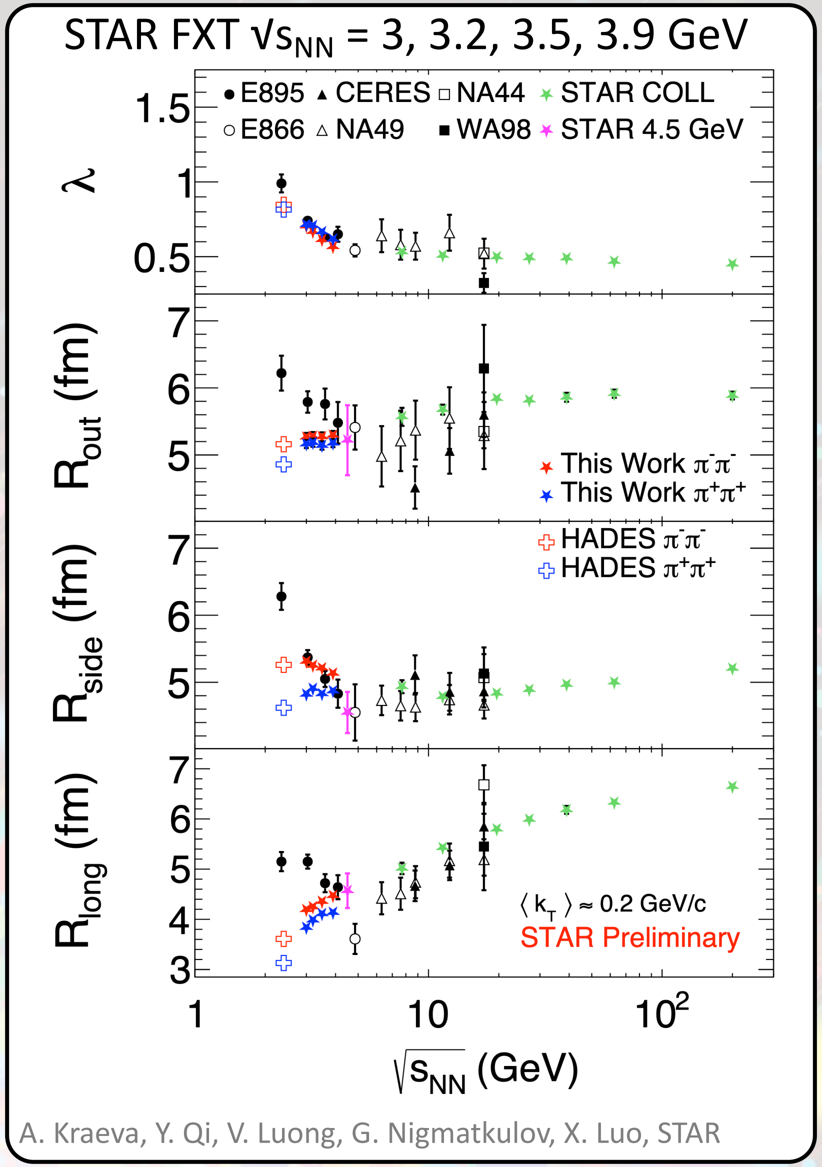
# FXT results – high baryon-density region



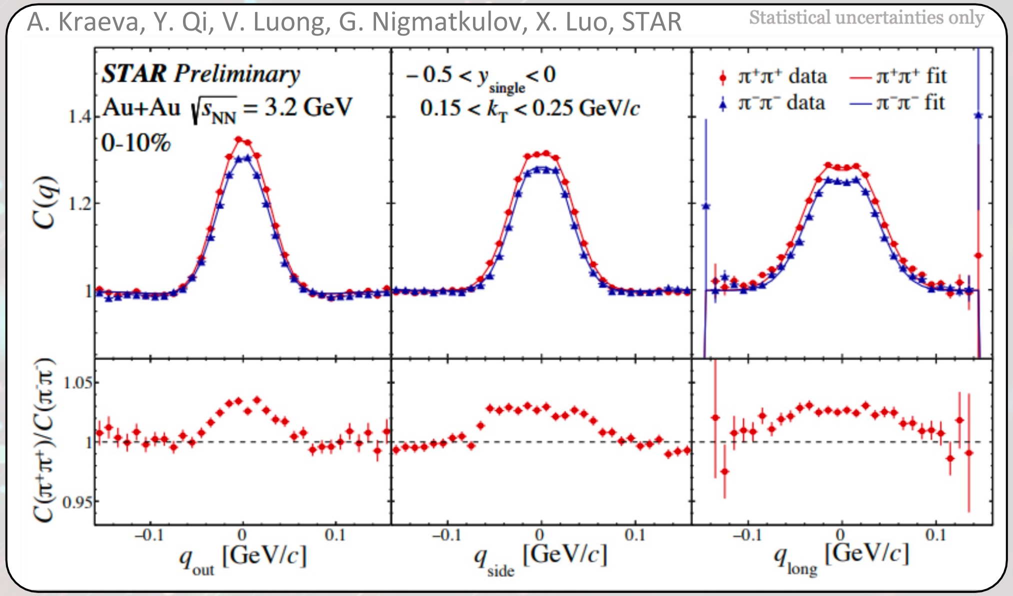

- 1D $K^0$ CFs agree with "Coulomb-corrected" $K^+$
- No significant energy dependence over this small range
- Cannot draw a conclusion on $m_T$ scaling with 1D radii

# Differences between +/- mesons at ~~low~~ all √s

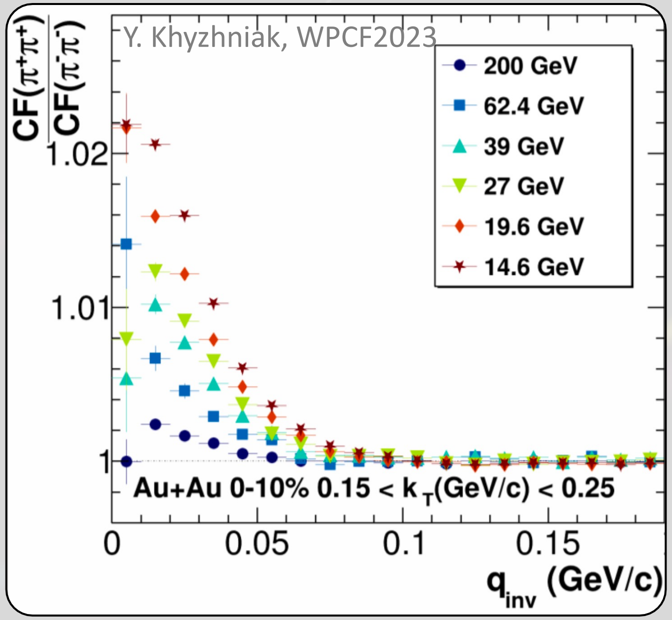


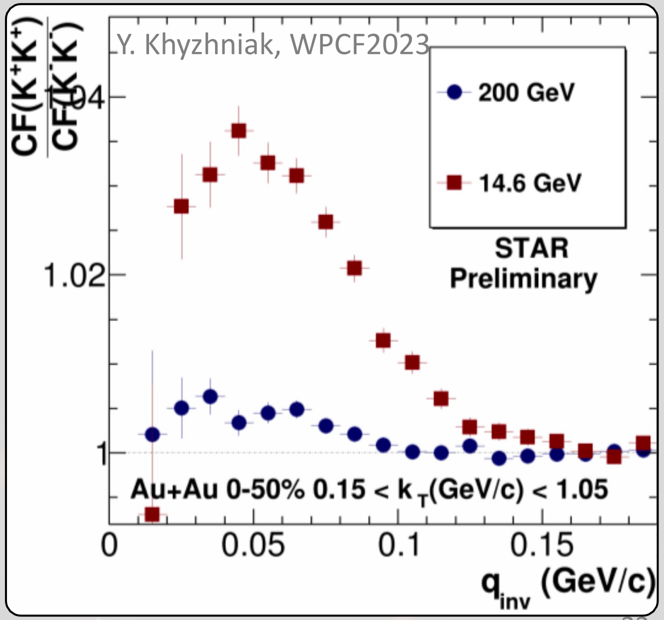

?? Larger radii for $\pi^-$- $\pi^-$ than for $\pi^+$- $\pi^+$

- also reported by HADES
- is the $\pi^-$ source actually larger?




- Difference clear in correlation functions themselves
- Also at higher √s! (radii reported "consistent")
- And also for kaons
- Coulomb/isospin effect from residual source?
  - under investigation
- Precision study of low-energy systematics forces us to re-visit higher energies



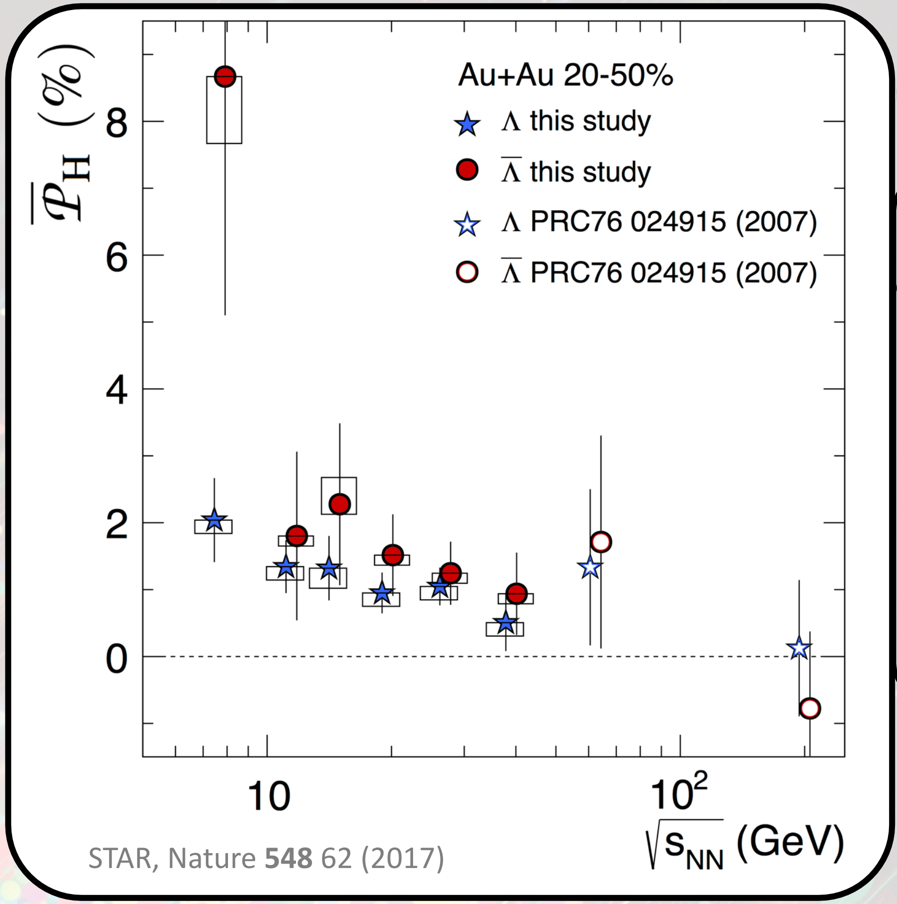



# Femtoscopy

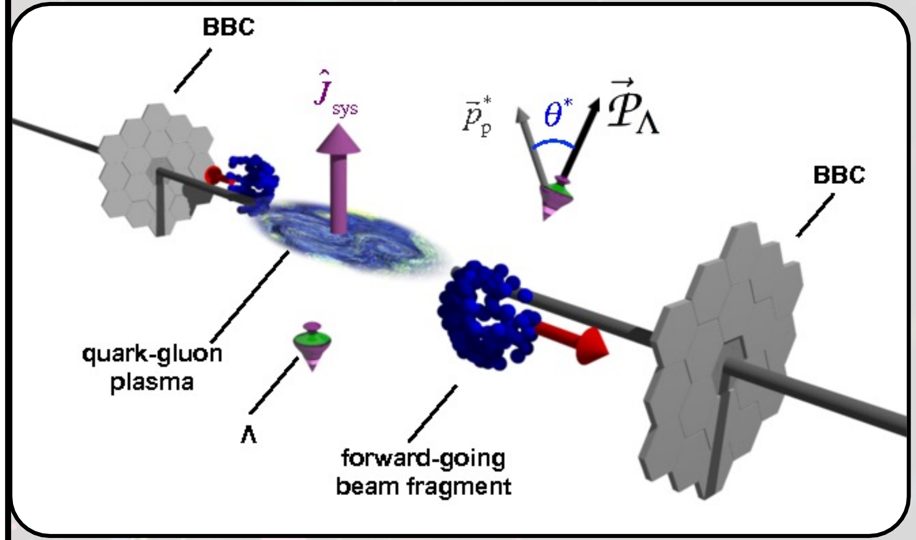
- Tremendous systematics over 4 orders of magnitude in $\sqrt{s_{NN}}$-2$m_p$
- Broad consistency in $m_T$ (and y, dN/dη,…) dependence
  - very similar flow profiles
  - detailed systematics require common method
- Pion correlation systematics with energy
  - Smoothly increasing system evolution time
  - Shape evolves
    - From oblate to prolate
    - Towards in-plane-extended
    - Steadily falling tilt
  - "Golden" QGP signal clearly observed – emission duration grows and falls
- More FXT results emerging
  - $K^+$, $K^0$, (p-Λ, d-Λ)
  - Difference between ($\pi^-$- $\pi^-$, $\pi^+$- $\pi^+$), ($K^-$- $K^-$, $K^+$- $K^+$) at ~~low~~ *all* energies

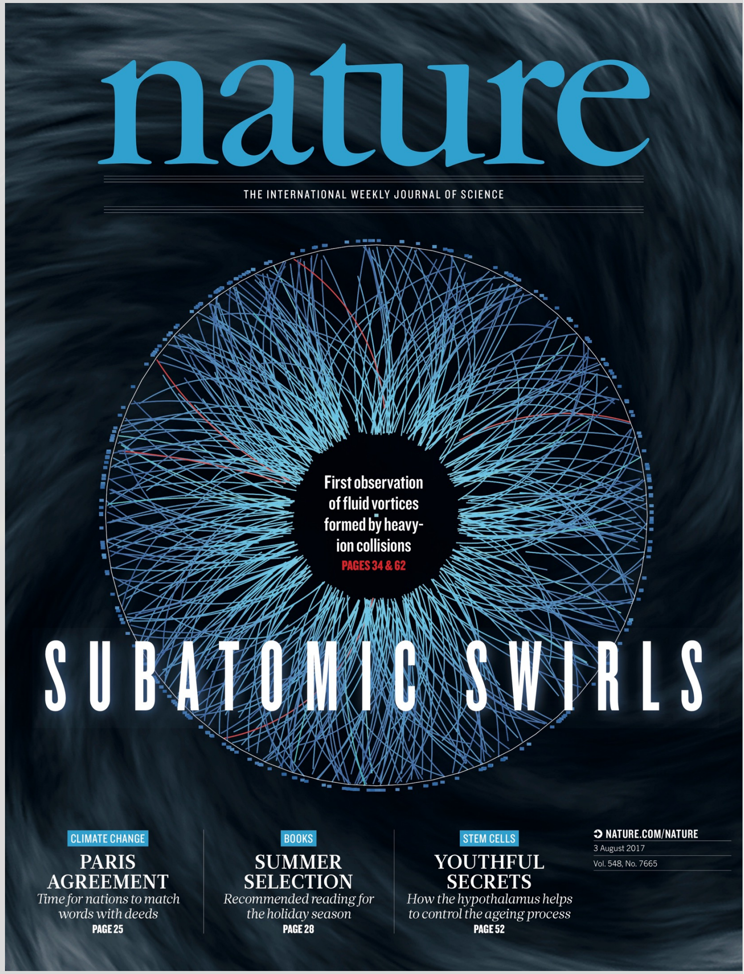
HBT correlations are **cumulants** quantifying the second-order coherence of the pion wavefunction

# Polarization



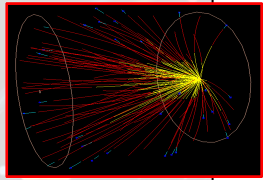

Global Polarization ≡ Alignment of $\vec{J}_{sys}$ and $\vec{S}_{\Lambda}$.

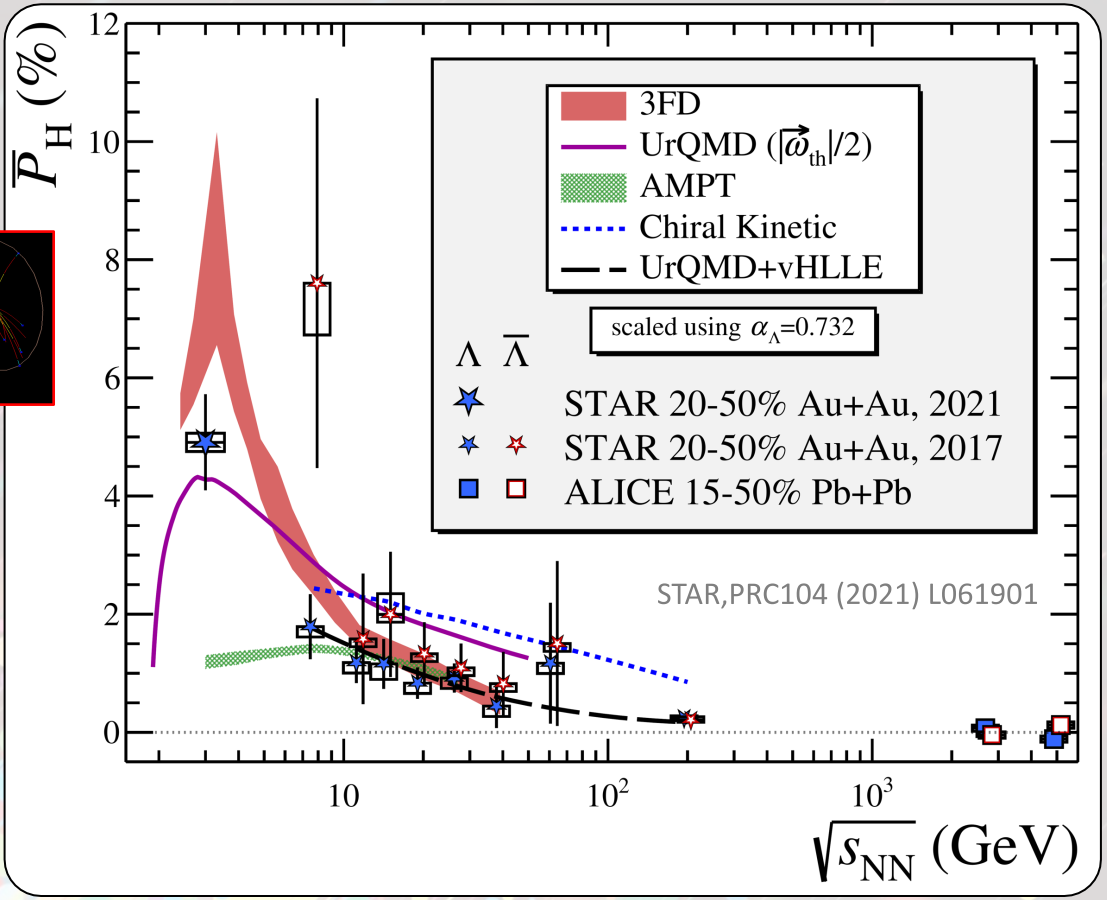


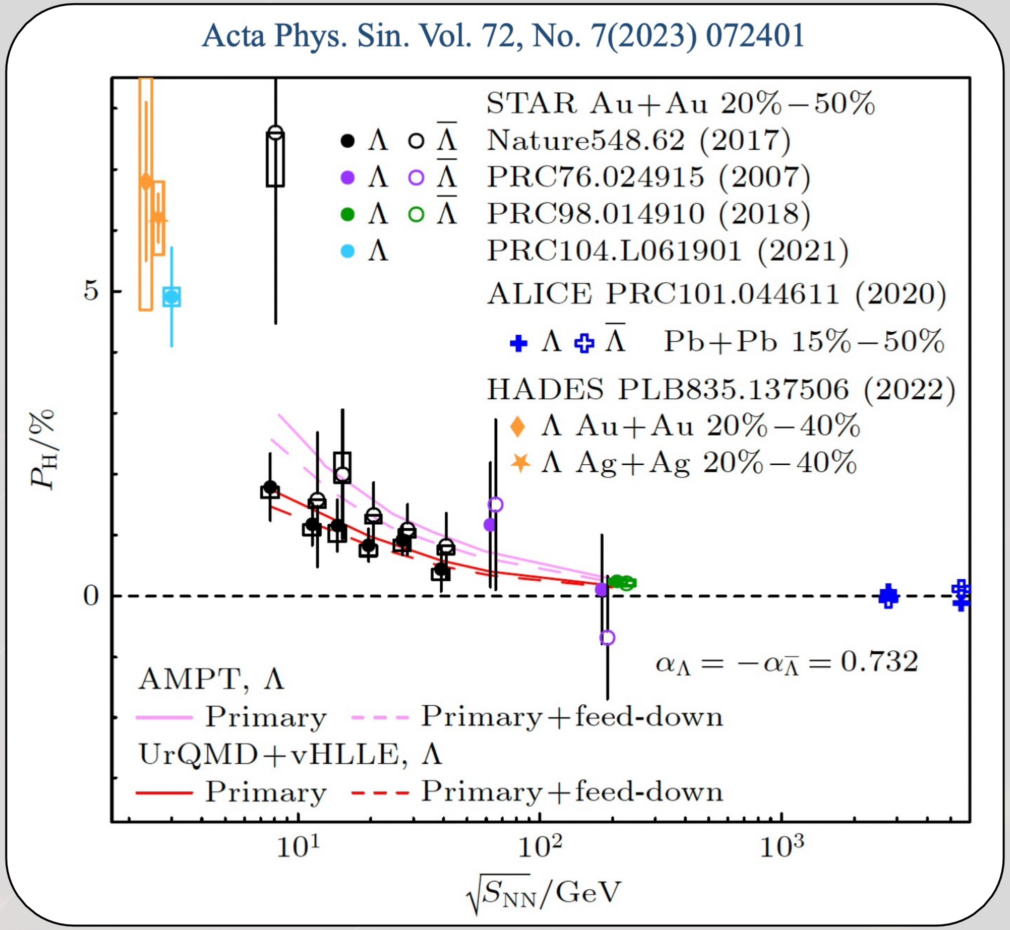




- Rare situation: “new” phenomenon appears in an active but quite mature field
- Possible through flexibility of detector system & collider
  - BES was the “Goldilocks region” for discovery
    - big signal, but reasonable **Λ** statistics

# World dataset on global Λ polarization



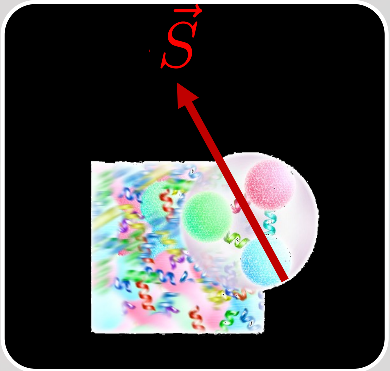


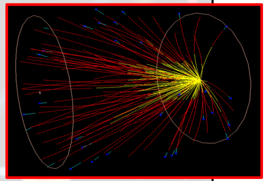

**3D** hydro & transport "out of the box" reproduce overall systematics impressively well

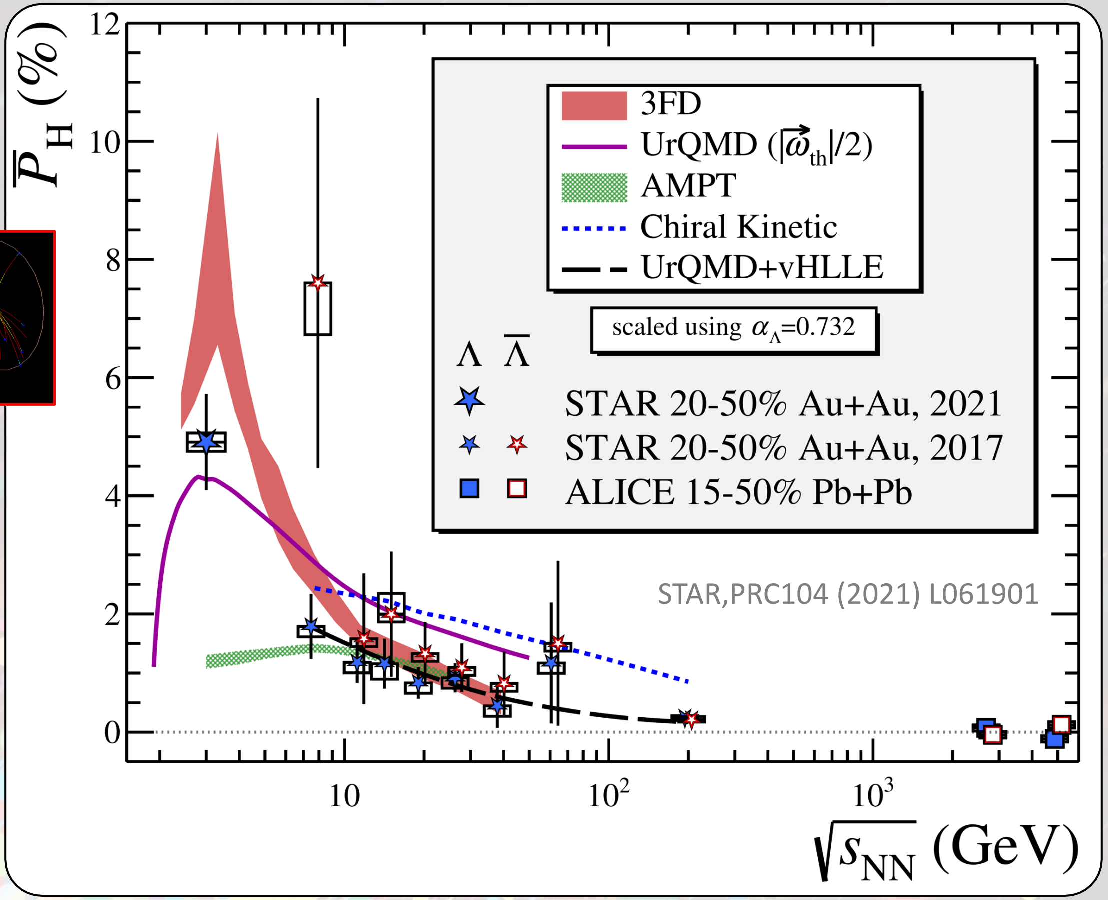
- **vorticity** coupling to spin through Cooper-Frye-like f.o.
- explicitly non-boost-invariant treatment crucial at BES

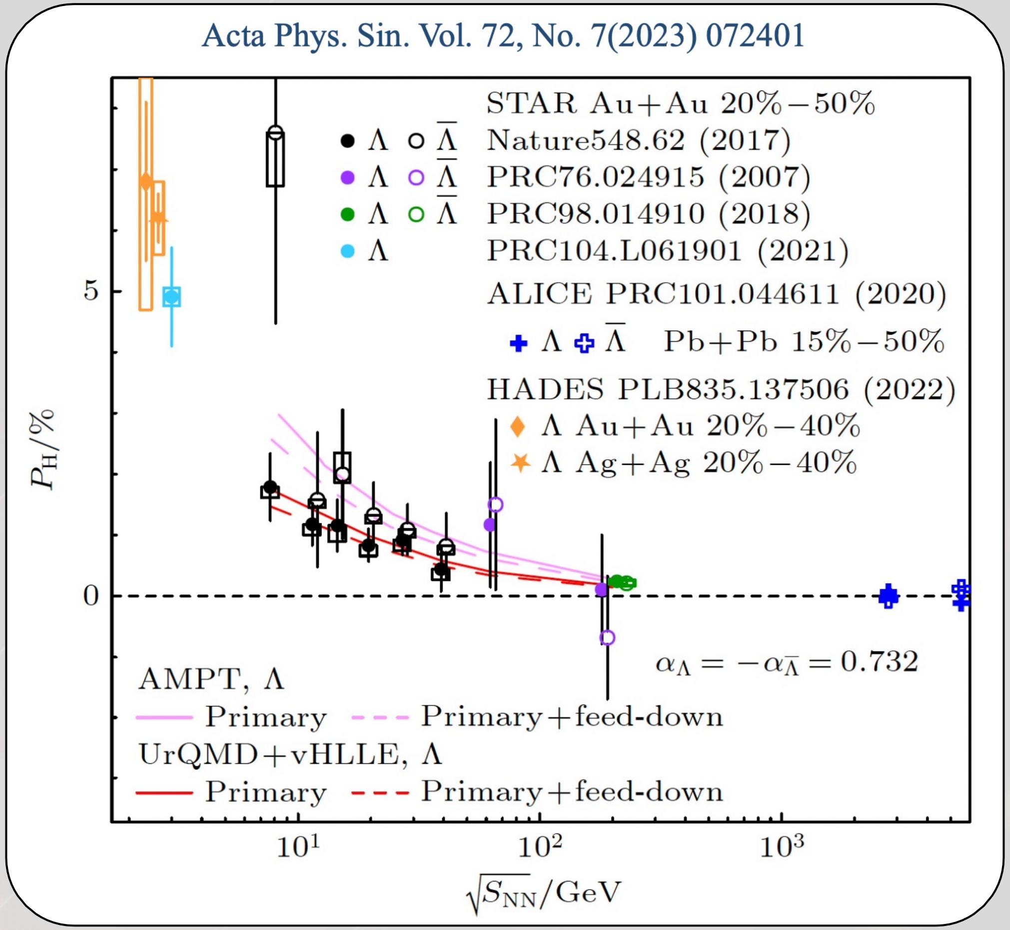
Expansion of systematics to low $\sqrt{s_{NN}}$ in FXT challenges models



# Is there a hint of “hyperfine magnetic splitting”?

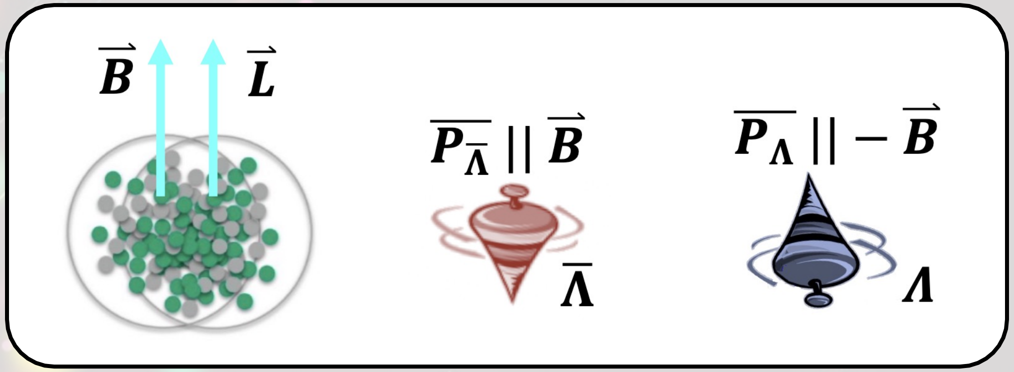




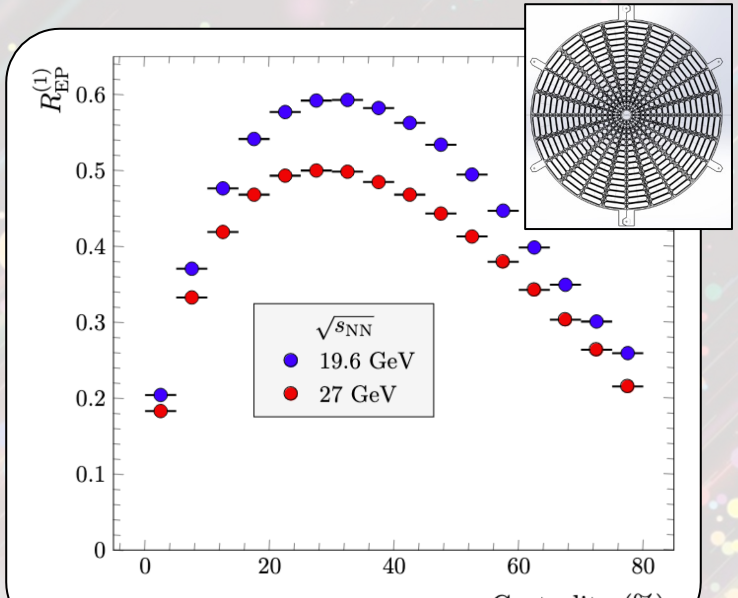

Vorticity: $\vec{P}_\Lambda \cdot \hat{L} = \vec{P}_{\overline{\Lambda}} \cdot \hat{L}$

Magnetic field $\vec{P}_\Lambda \cdot \hat{B} = -\vec{P}_{\overline{\Lambda}} \cdot \hat{B}$

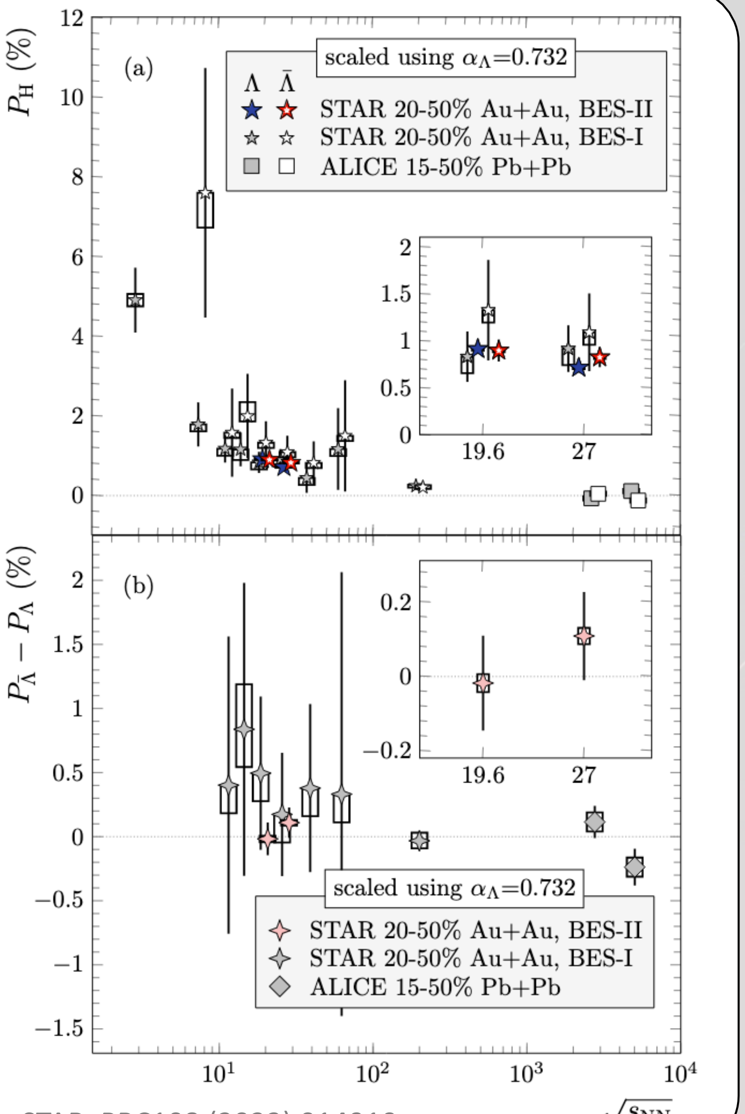


# Improved EP resolution, statistics in BES-II

Improved EP resolution (BBC → EPD)
Improved statistics




STAR, PRC108 (2023) 014910

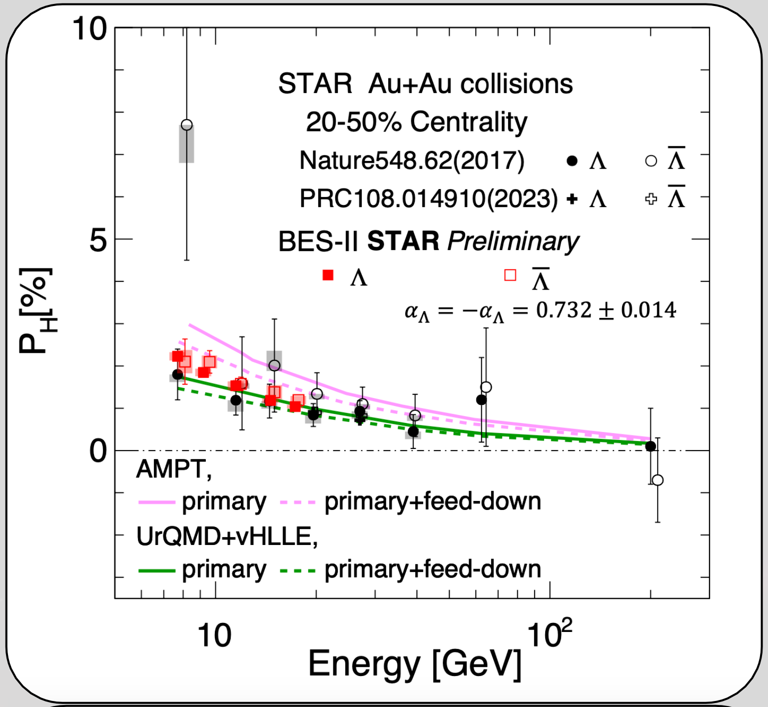


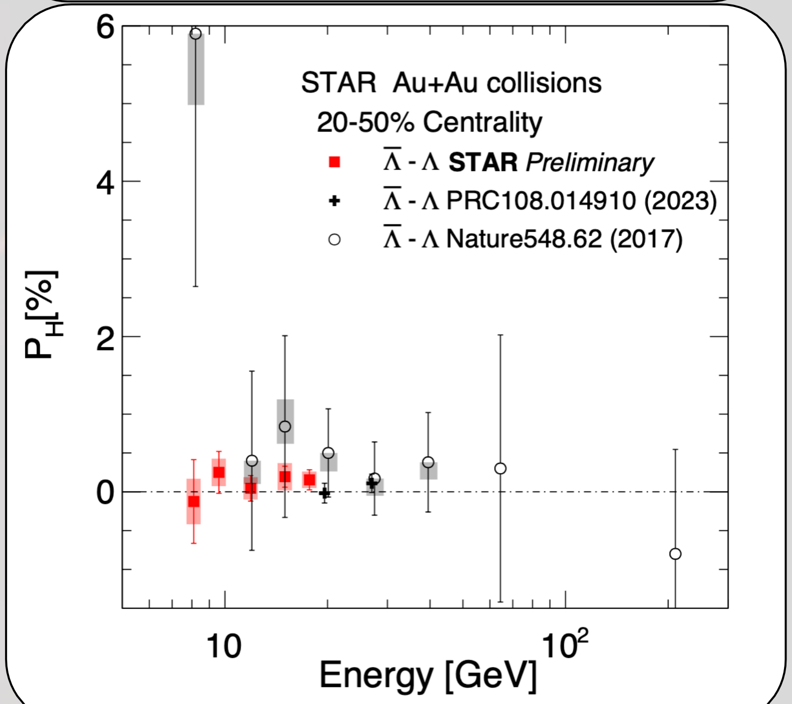

STAR, PRC108 (2023) 014910

No B-field splitting observed

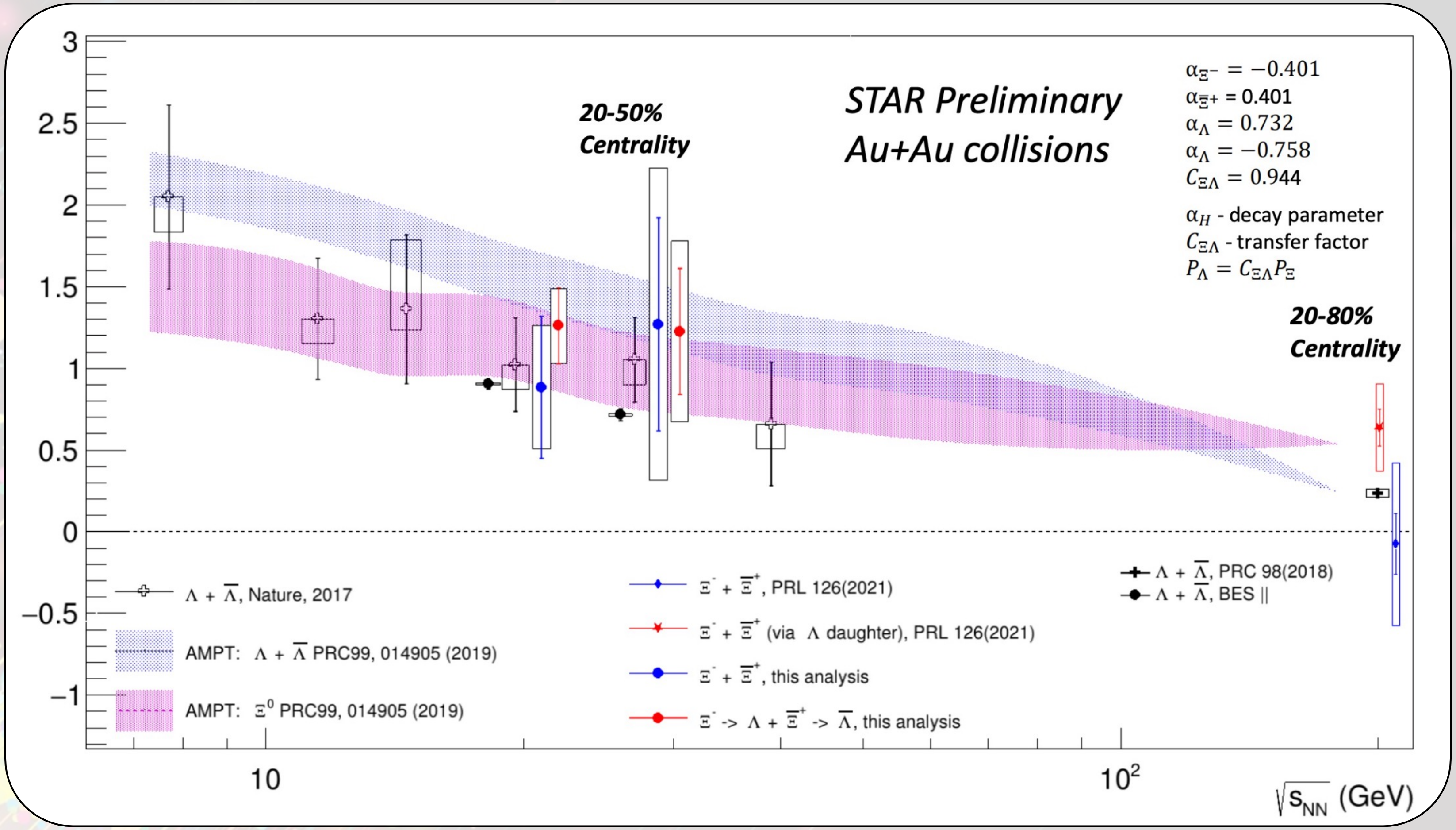
B < $10^{13}$ T at freezeout

- meaningful implication for CME



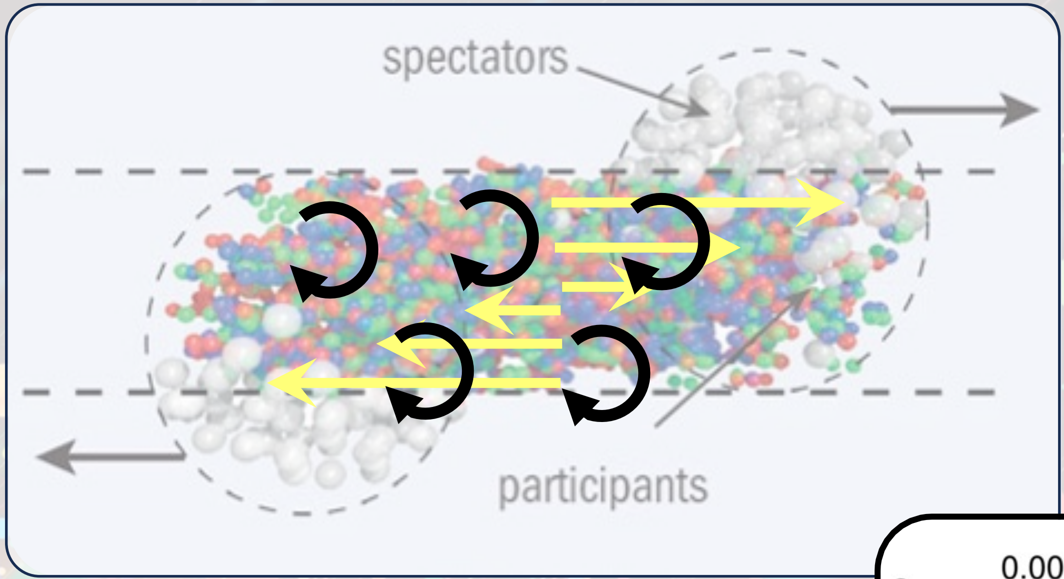



# Improved EP resolution, statistics in BES-II




- Multistrange hyperon polarization – consistent with message from Λs
- mass effect slightly increases the polarization in Cooper-Frye

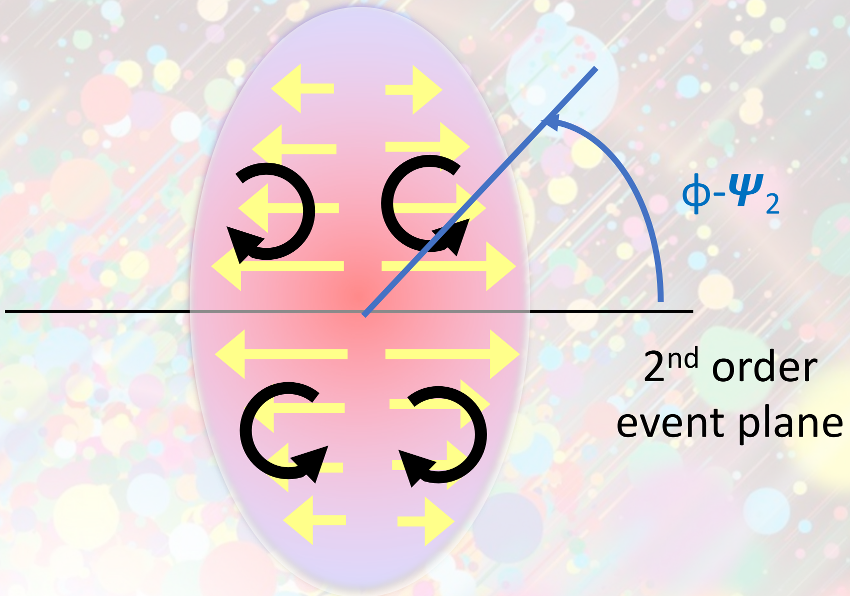
# Longitudinal Polarization

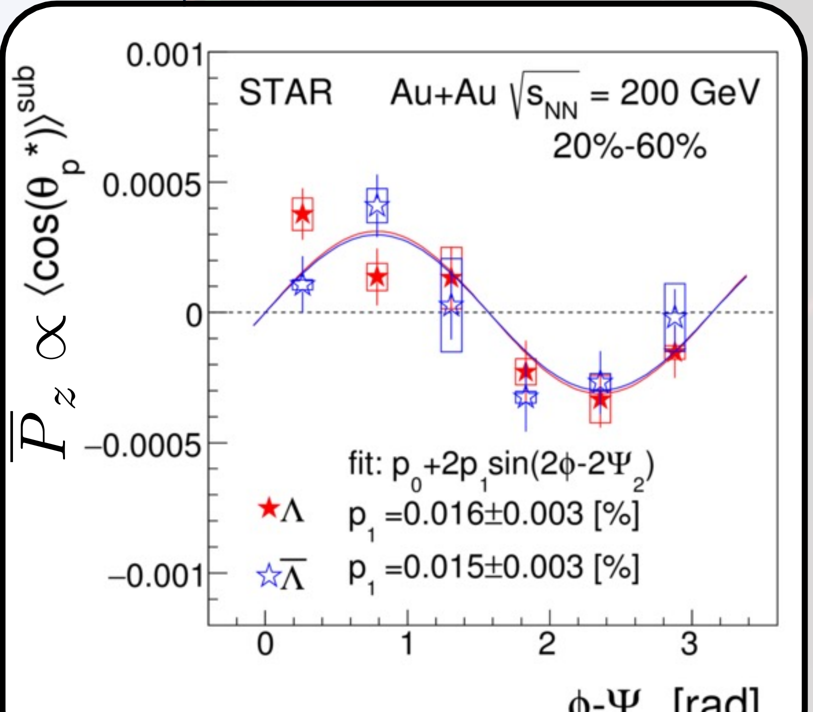



Is polarization along the z-axis driven by the same physics that generates global polarization?

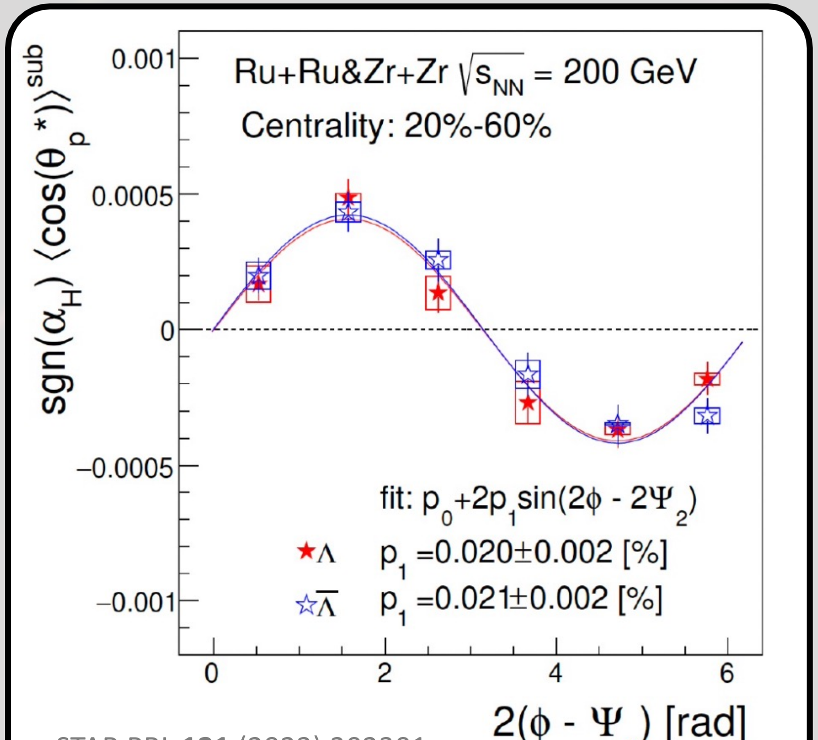
$$\vec{P}_{\text{global}} \sim \vec{\omega}_{\text{NR}} = \vec{\nabla} \times \vec{\beta}$$

✓ In a naïve BW scenario, it seems so



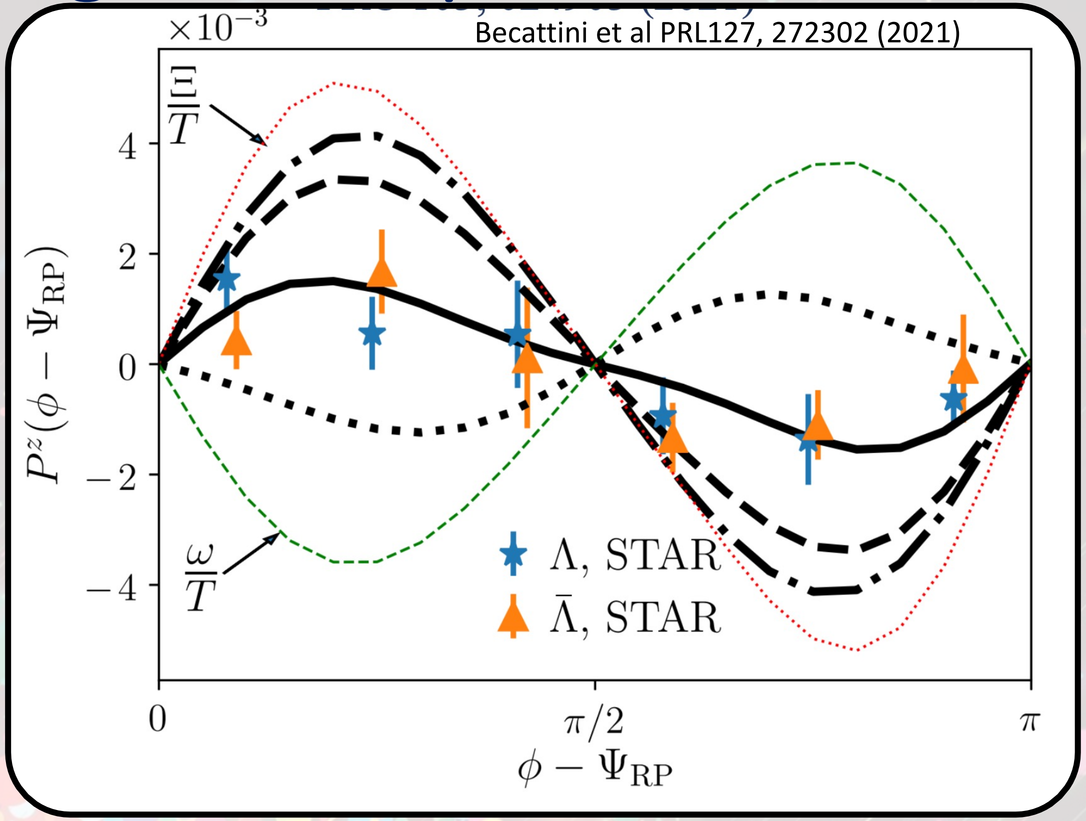



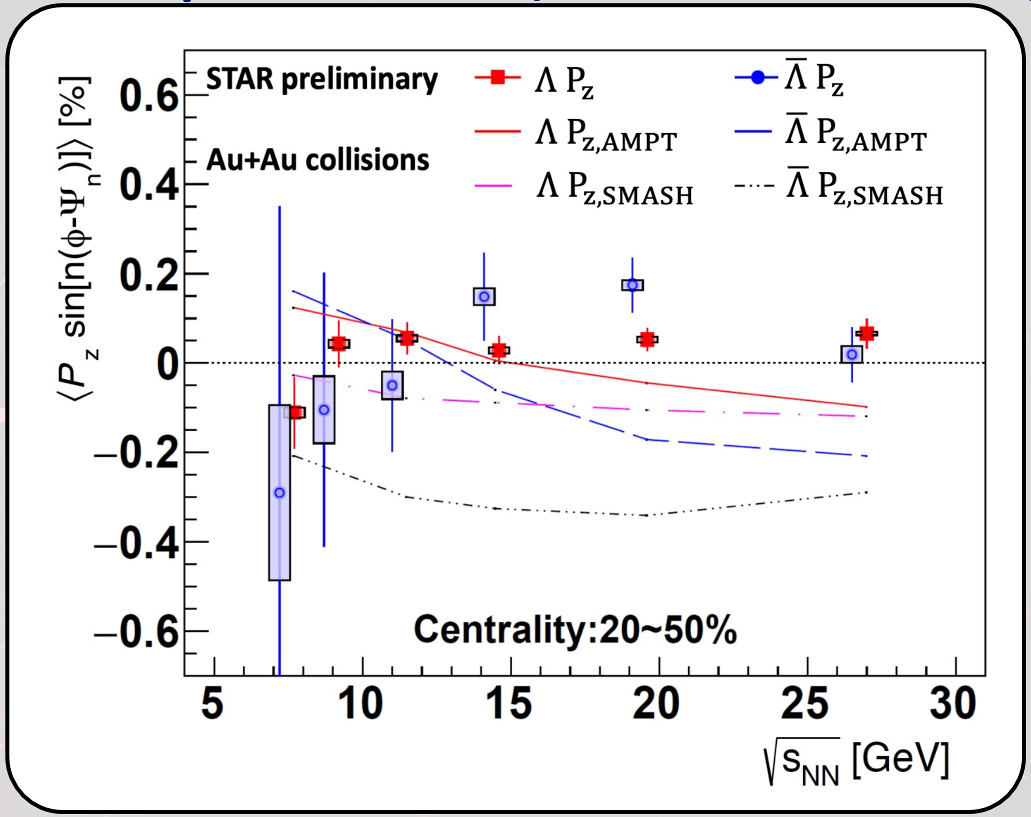

STAR PRL **123** (2019) 132301




STAR PRL **131** (2023) 202301

# Longitudinal polarization is more complicated (& interesting!)




Blast-wave is not hydrodynamics

Full hydrodynamic calculation: vorticity alone predicts a polarization with incorrect sign!

- "longitudinal polarization sign puzzle"

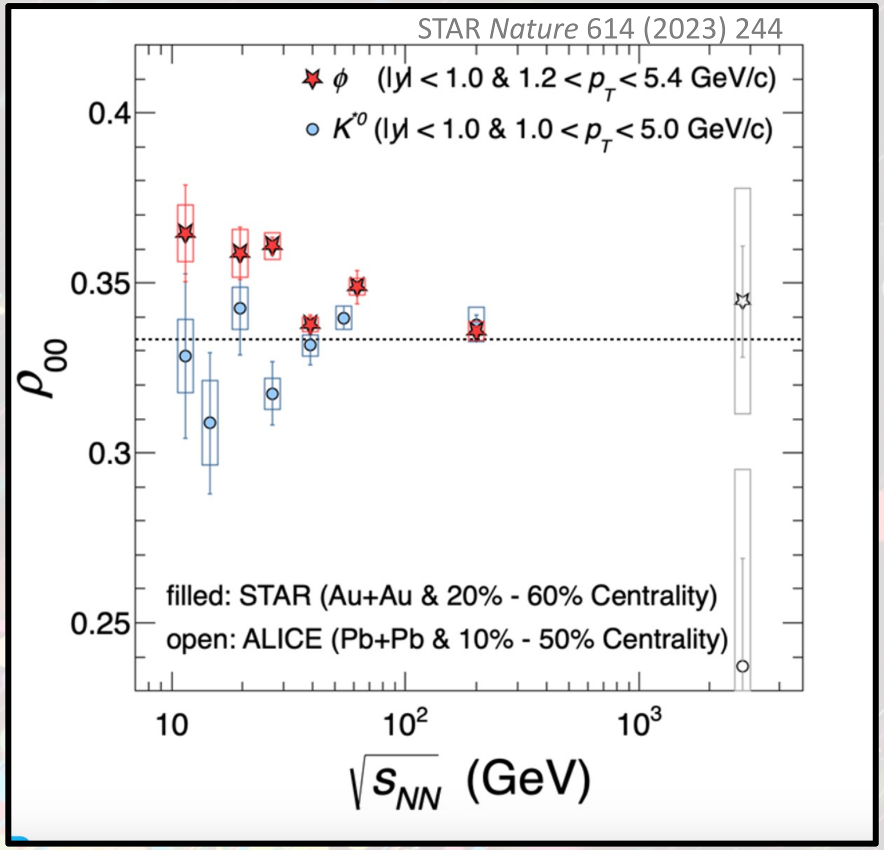
Shear-induced polarization generates (large) polarization, that competes

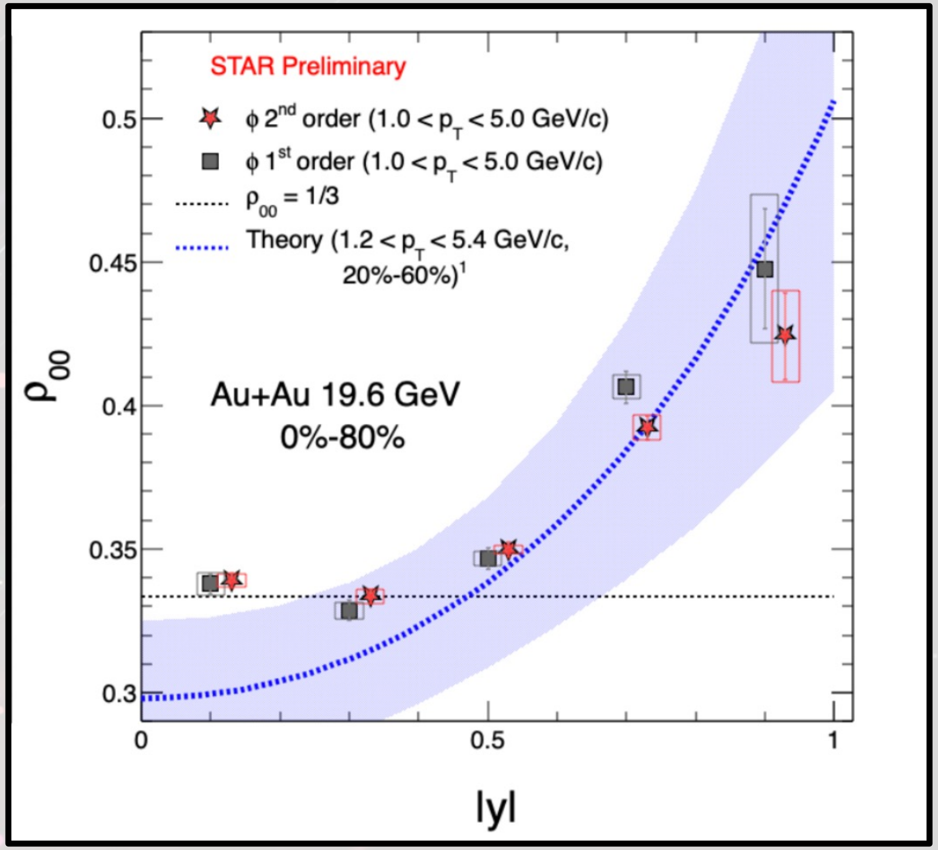
- different groups have different formulations, with different trends and admixtures

New STAR BES results may yield insight on this fundamental question

Becattini PRL127 272302 (2021)
Fu PRL127 142301 (2021)
Yi PRC104 064901 (2021)
Florkowski PRC105 064901 (2022)
Sun PRC105 034911 (2022)
Alzharani PRC106 014905 (2022)

# Spin-alignment of phi meson – surprise discovery!




$\rho_{00} > 1/3$ → ϕ is aligned with system angular momentum

Vorticity-driven alignment (consistent with hyperon polarization) vastly underpredicts alignment

Likely that *correlated* s, s-bar spin alignments are at play

- "only" a coherent phi field explains the magnitude of the effect – what else does it predict?

New BES-II precision results may constrain theory!!

# Polarization

- Discovery of medium-induced polarization
  - A new phenomenon into a mature field
- Global polarization of multi-strange hyperons consistent with Λ
- Tighter constraint on B-field from "splitting"
- Excitation function of longitudinal polarization may shed light on shear terms
- Discovery of spin alignment of vector mesons intriguing!  May be of fundamental importance.

Probing the spatial substructure of the system through…

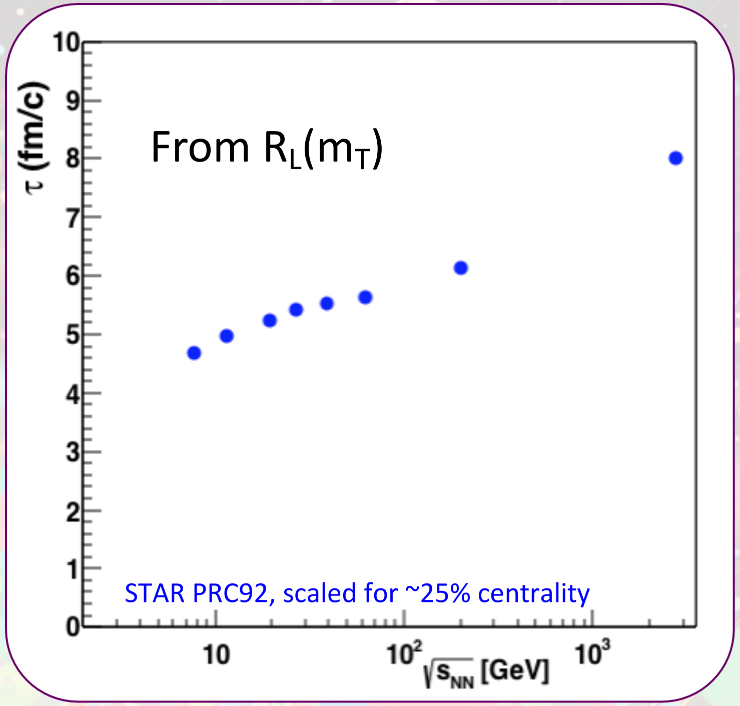
- one  of the oldest observables (femtoscopy)
- one of the newest observables (polarization/alignment)

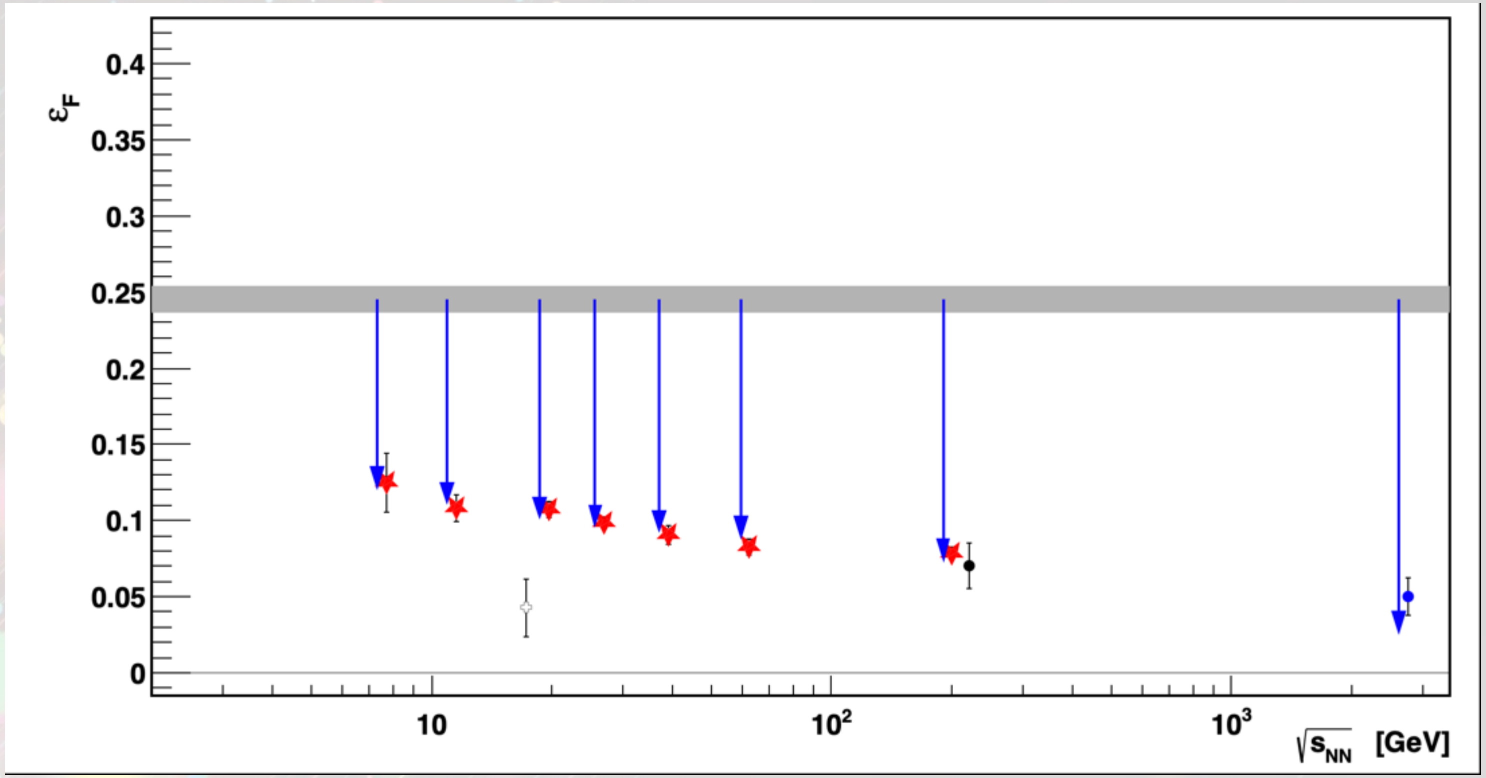
… continue to reveal insights.  *And BES energies are crucial*

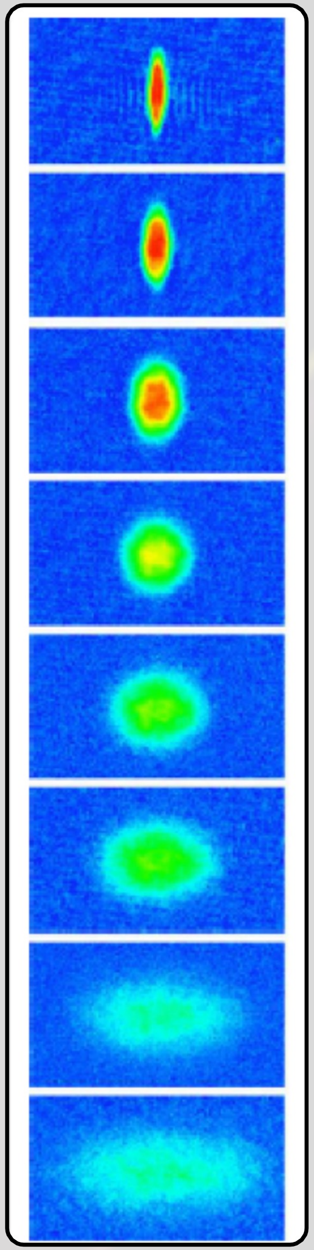
# Beyond size & time scales – shapes (2/3): ellipticity

Mostly for fun: Toy calculation:
Using flow velocities from PHENIX BW fits for semi-peripheral events at 200 GeV for *all* energies

$$\varepsilon(\tau)=\frac{\bar{\sigma}_0^2\varepsilon_0-\frac{1}{2}\left(\beta_y^2-\beta_x^2\right)\tau^2}{\bar{\sigma}_0^2+\frac{1}{2}\left(\beta_y^2+\beta_x^2\right)\tau^2}$$



# Unintuitive preliminary result on charged K*s

## First measurement of charged K* $\rho_{00}$

### Naive expectation

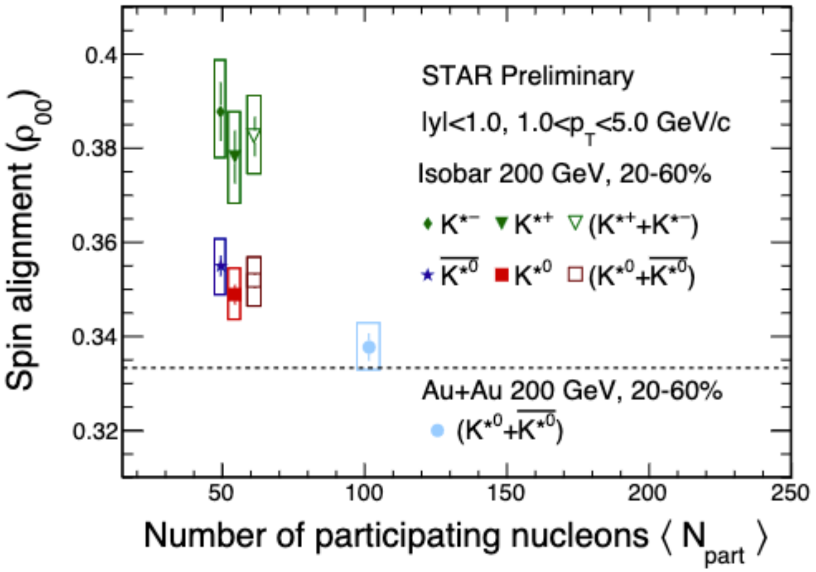
| Particle Species | Magnetic moment ($\mu_N$) |
|---|---|
| $K^{*0}(d\bar{s})$ | $\mu_d \approx -0.97, \mu_{\bar{s}} \approx 0.61\mu_N$ |
| $K^{*+}(u\bar{s})$ | $\mu_d \approx 1.85, \mu_{\bar{s}} \approx 0.61\mu_N$ |

$$\rho_{00}(K^{*0}) > \rho_{00}(K^{*\pm})$$

Yang, et. al.,
Phys. Rev. C 97, 034917 (2018)

$$\rho_{00}(B) \approx \frac{1}{3} - \frac{4}{9}\beta^2\mu_{q_1}\mu_{q_2}B^2$$

### Observation from STAR




STAR: Quark Matter 2022

- First observation of $K^{*\pm}$ $\rho_{00}$ in HIC
- Surprising ordering in $\rho_{00}$

$$K^{*+} + K^{*-} >> K^{*0} + \overline{K}^{*0}$$

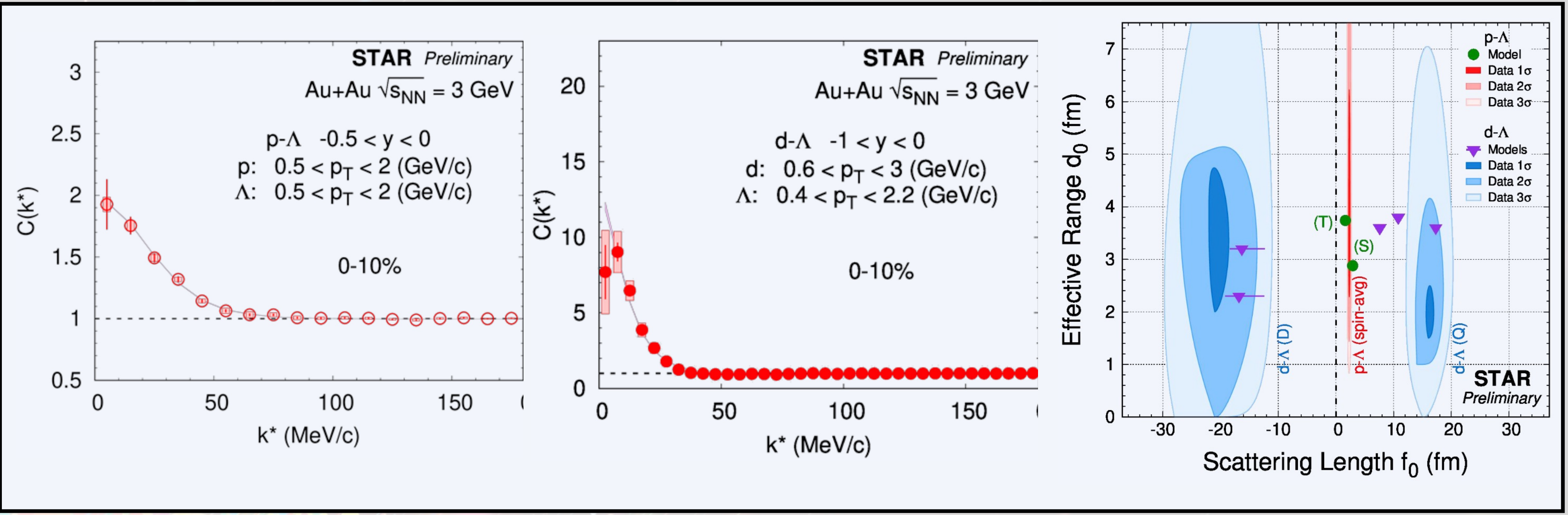
(Opposite to naive expectation from B-field)

???!?

* difficult to understand this

STAR: QM2022, Chirality2023

# Baryon-Baryon correlations in the baryon-rich sector (FXT)




- High-precision p-Λ and d-Λ (first ever) from lowest-energy at RHIC
- scattering parameters *from individual spin states* of d-Λ extracted (!)