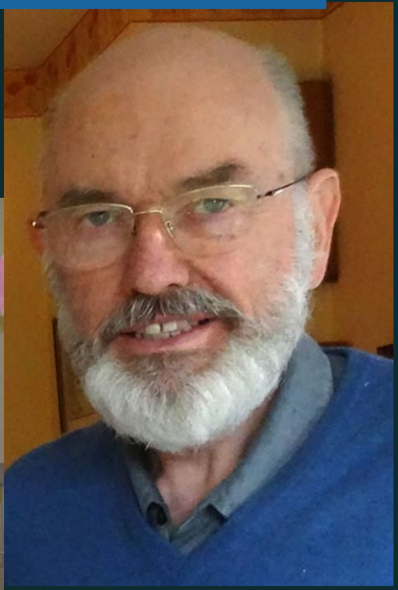
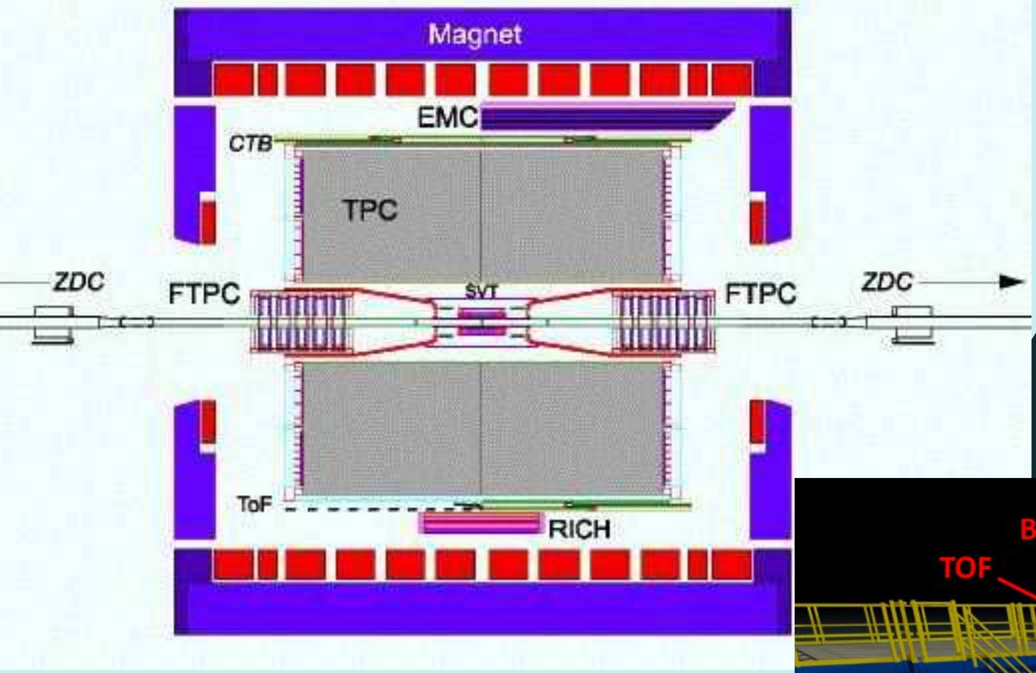
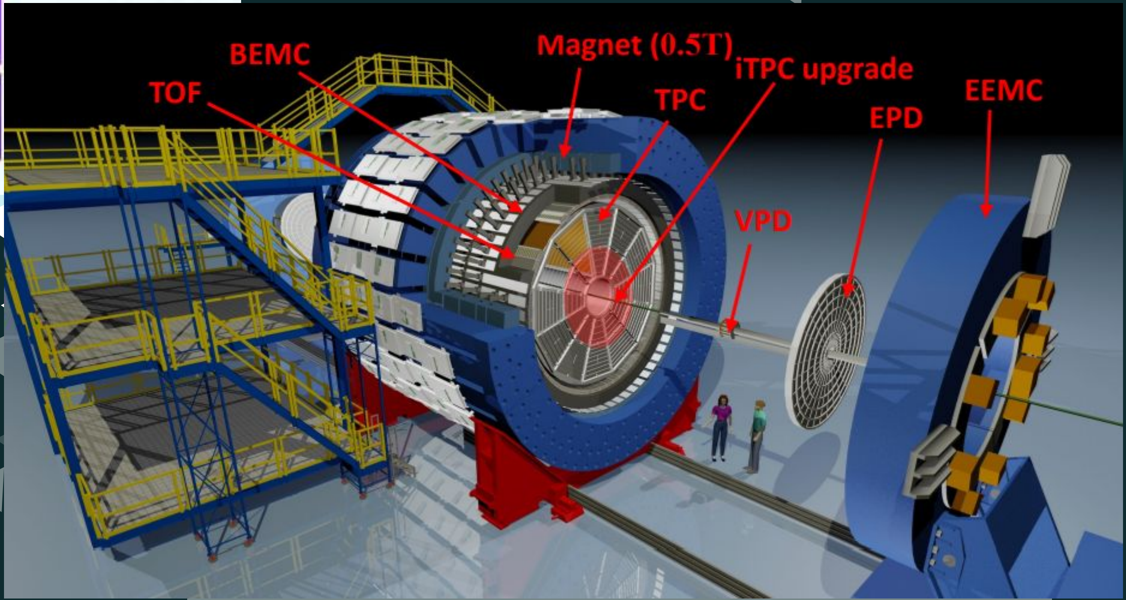
STAR Zero-Degree Calorimeter Shower Max Detector and its Physics



Gang Wang
(UCLA)



Over the past 20 years, the STAR detector subsystems have greatly evolved.

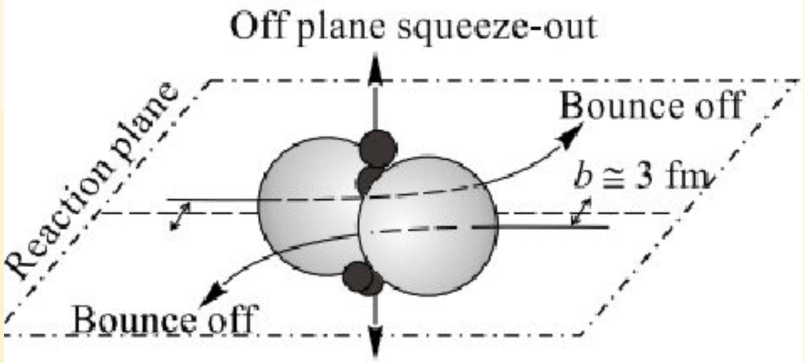


I was lucky enough to contribute to a small part, starting in 2003.

Flow: time-honored probe

BEVALAC (1983), using "Plastic ball" spectrometer for Nb+Nb at 400 MeV

Original predictions for flow: bounce-off /side-splash (v_1) and squeeze-out (v_2)



nuclear shock wave models and ideal fluid dynamics

$$\frac{d^2N}{dP_t d\phi} = \frac{dN}{dP_t}\left[1 + \sum_{n=1}^{n=\infty} 2v_n(y, P_t)\cos(n\phi)\right]$$

$$v_n = \langle \cos(n\phi) \rangle$$

Here, ϕ is the particle's azimuthal angle w.r.t the reaction plane.

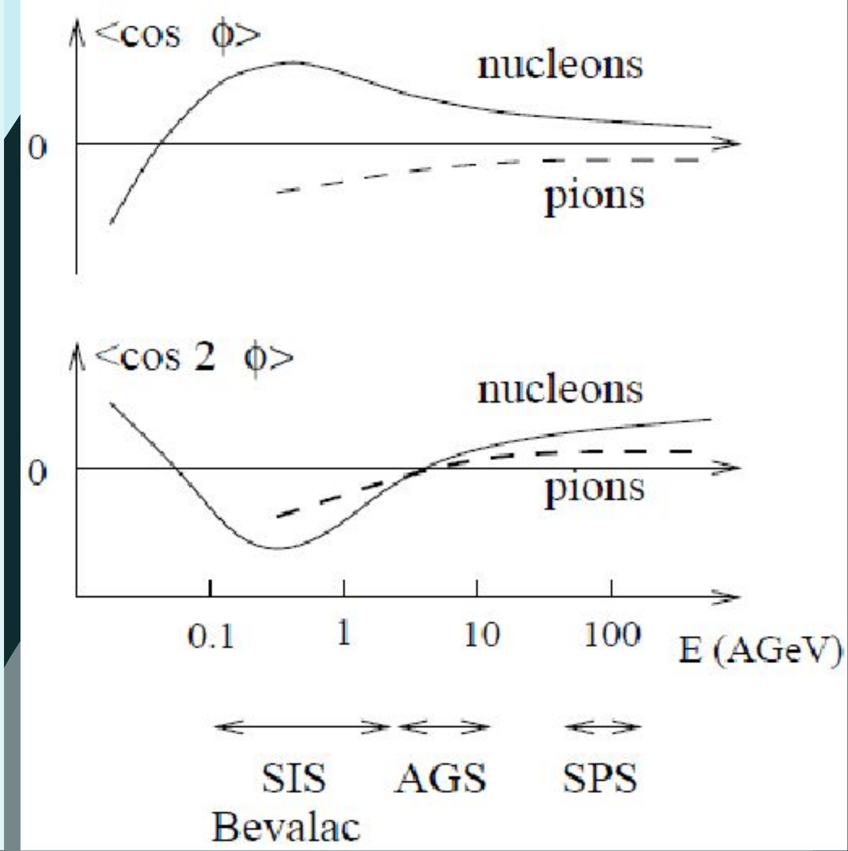
The big picture

J. -Y. Ollitrault, Nucl. Phys. A638, 195c (1998).

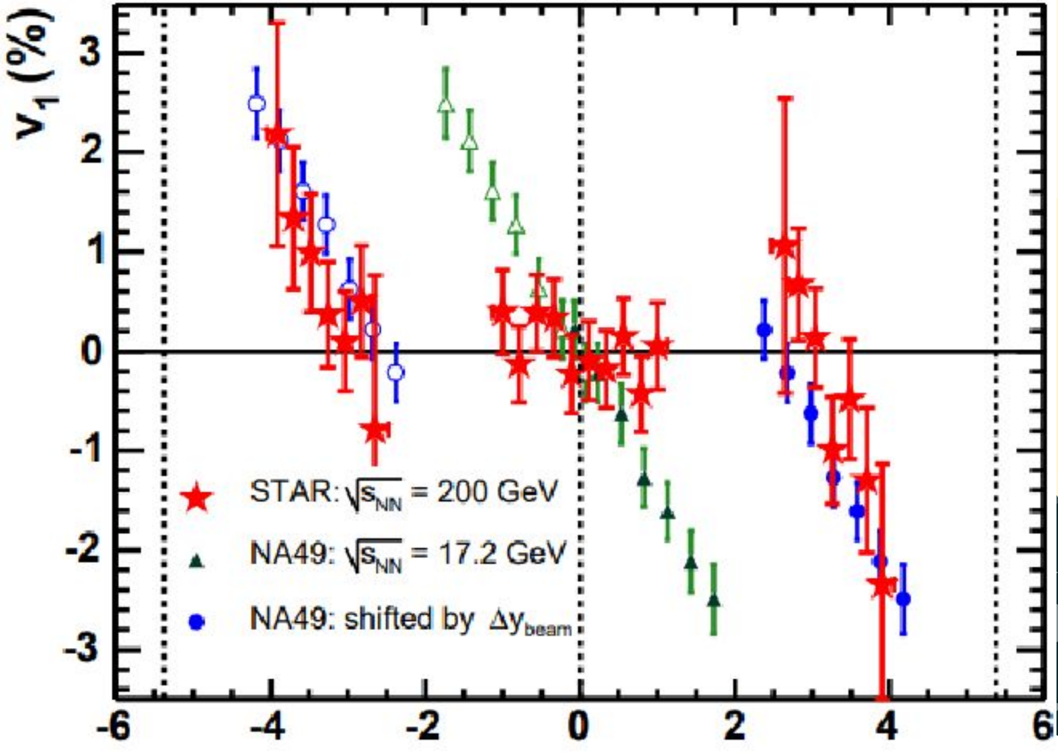
Below ~100 MeV, attractive nuclear mean field:
Projectile nucleons are deflected towards target
→ negative v_1
Rotating system of projectile and target, centrifugal force
→ positive v_2

Intermediate energies, individual n-n collisions
→ a positive pressure:
Bounce-off and side-splash
Squeeze-out

High energies:
Shorter passage time → smaller v_1
Pressure on eccentricity → larger, positive v_2



First v_1 results from STAR



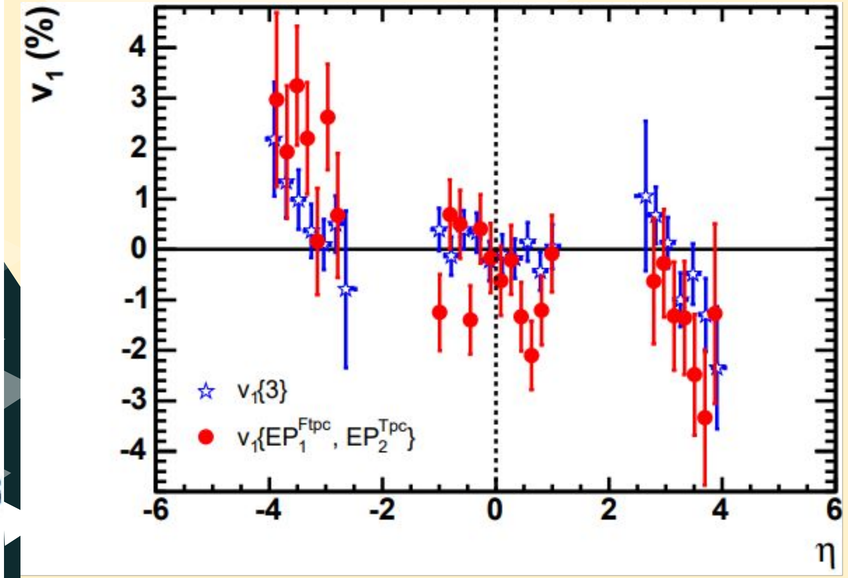
Only 70k events were used to include FTPC.

STAR: 10-70%, Phys. Rev. Lett. 92 (2004) 062301
NA49: 12.5-33.5%, Phys. Rev. C 68 (2003) 034903

Three-particle cumulant, $v_1\{3\}$, (isn't it just the γ correlator?)

$$\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle \approx v_{1,a} v_{1,b} v_{2,c}$$

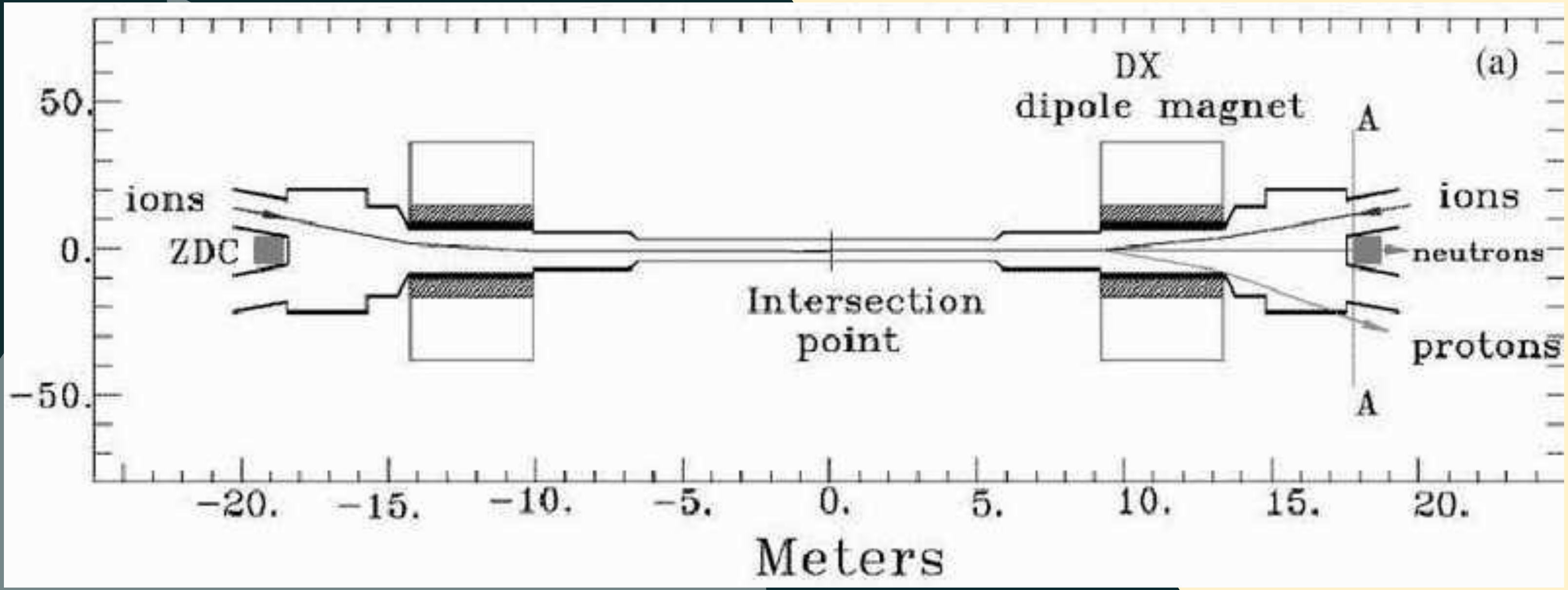
except charges aren't separated.



STAR: 20-60%, Phys. Rev. Lett. 92 (2004) 062301

Design of Zero Degree Calorimeters

- 18 meters vs 5 cm: almost zero degree
- 100 GeV vs 270 MeV: most spectators at $\sqrt{s_{NN}}$ = 200 GeV
- DX dipole magnet sweeps away protons, so only spectator neutrons are detected by the ZDCs.



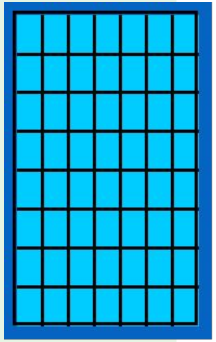
Proposed Addition of an SMD to the STAR ZDCs

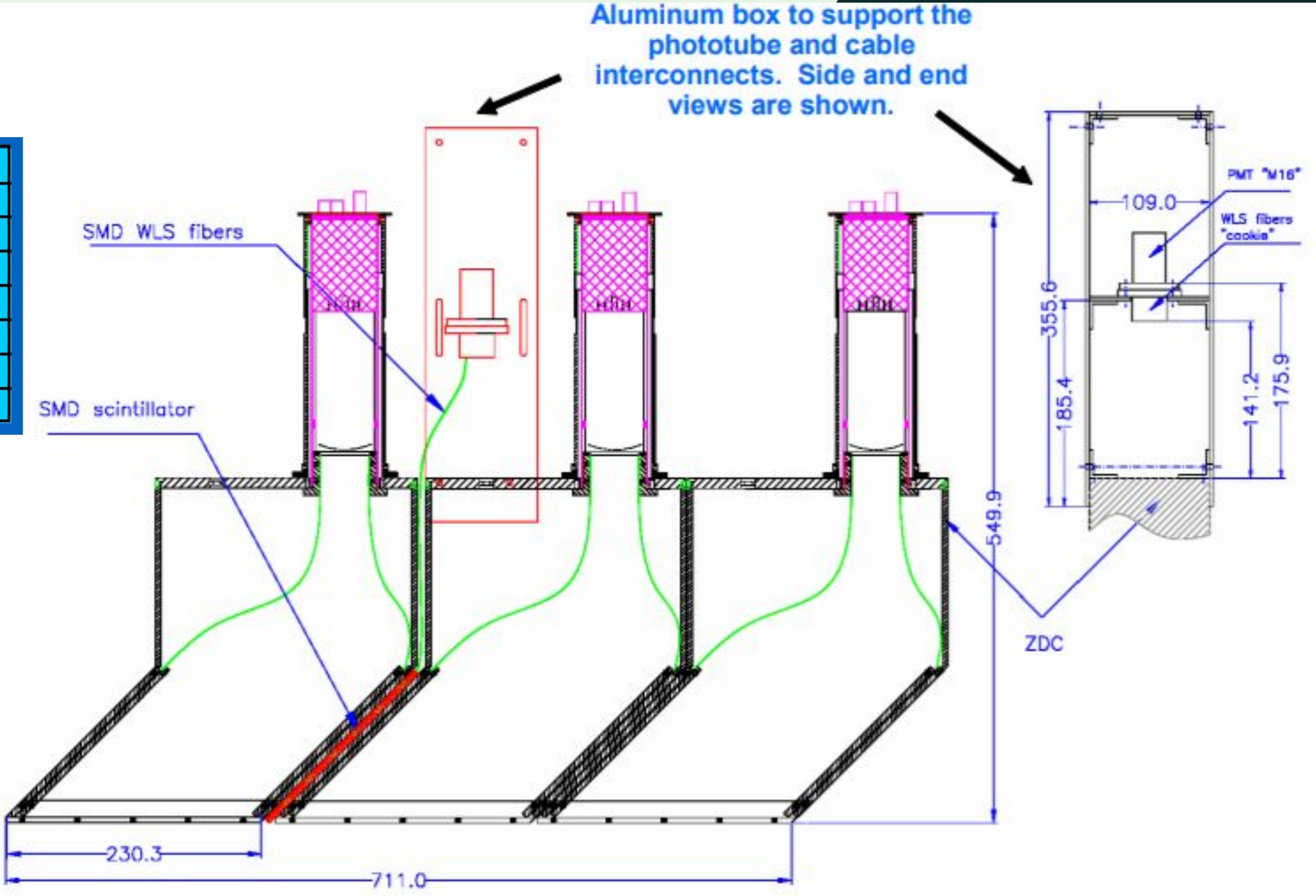
H. Crawford*, D. Keane†, M. Kopytine†, B. Surrow**, A. Tang‡, S. Voloshin§, G. Wang† and Z. Xu**

** UC Berkeley Space Sciences Laboratory*
† Kent State University
*** Brookhaven National Laboratory*
‡ Brookhaven National Laboratory / NIKHEF
§ Wayne State University

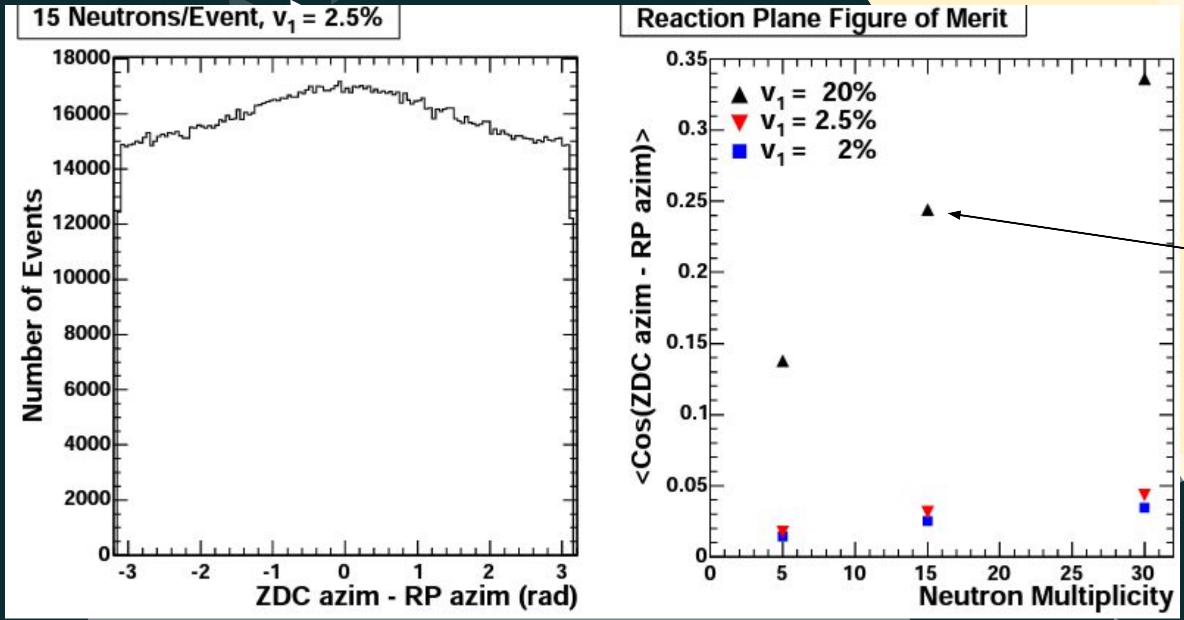
EXECUTIVE SUMMARY

We propose the addition of a Shower Max (one plane of 7 vertical slats and another of 8 horizontal slats) to the STAR Zero Degree Calorimeters, patterned after the ZDC-SMD already installed by PHENIX. This SMD would add significant capability to STAR in two areas of physics that are addressed in this document: collective flow and strangelet searching. New capabilities in spin physics are not addressed here. An ample manpower effort is available to implement this upgrade for RHIC run IV.




Aluminum box to support the phototube and cable interconnects. Side and end views are shown.
SMD WLS fibers
SMD scintillator
PMT "M16"
WLS fibers "cookie"
109.0
355.6
185.4
141.2
175.9
549.9
ZDC
230.3
711.0

Simple Monte Carlo simulations on the performance of the proposed Shower Max Detectors.

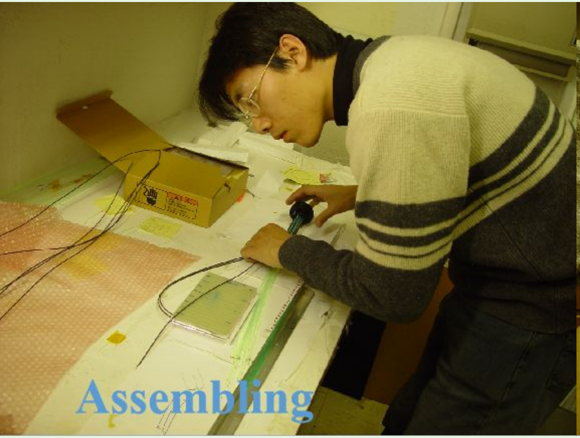


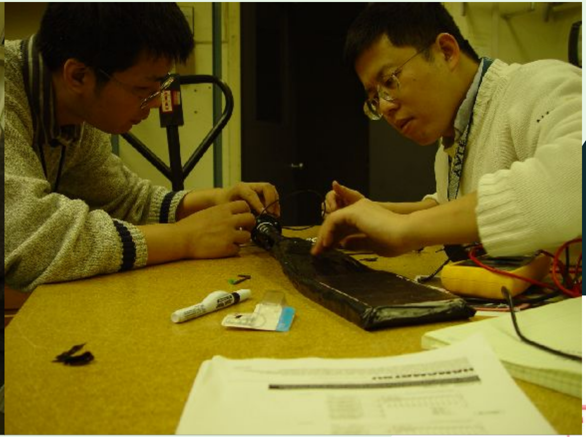
The event plane resolution is a figure of merit: the higher, the better.

The final product of ZDC-SMDs actually delivered a resolution pretty close to what we promised.

Cosmic ray test

- high voltage over 1000 volts
- Each test took 8 hours

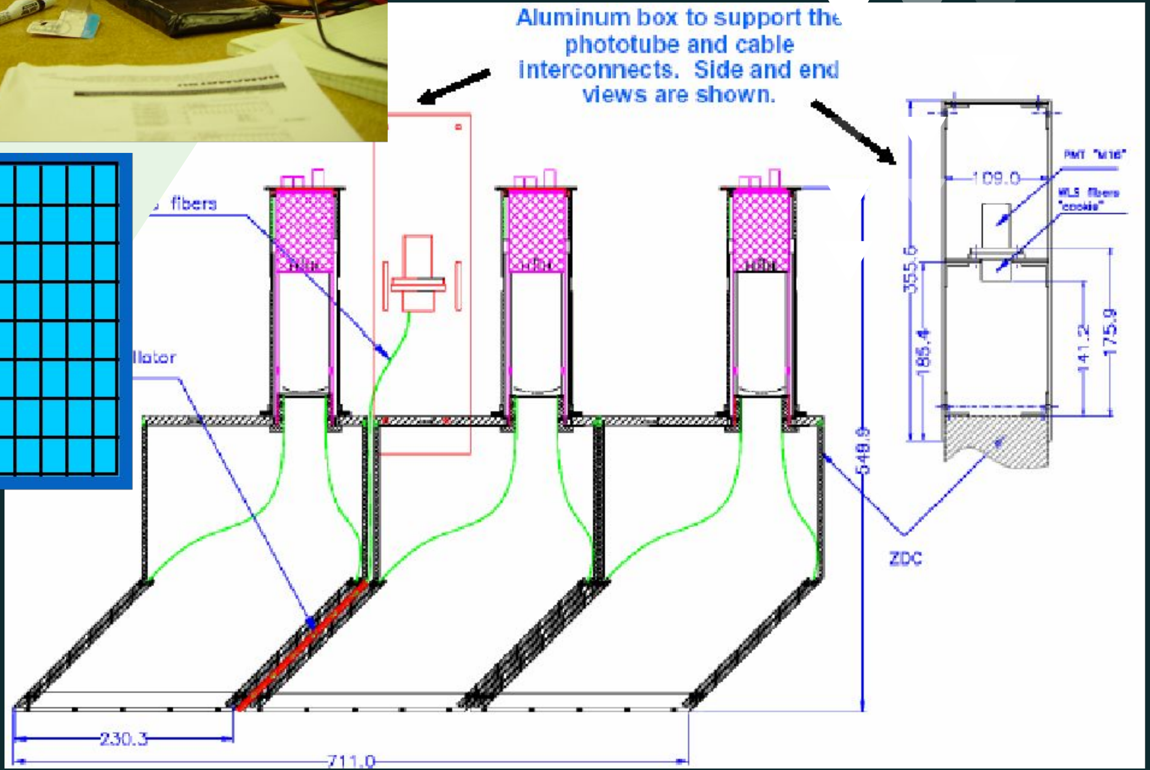




SMD: 8 horizontal & 7 vertical slats, located at ⅓ depth of the ZDC

Failure is not an option!

Feb 4, 2004

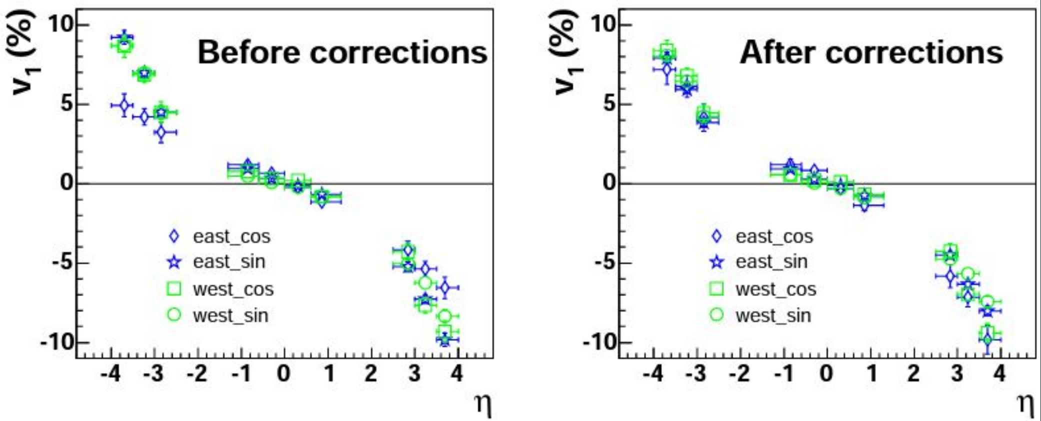


On June 8, 2004, my daughter arrived. Since then, I calibrated ZDC-SMDs at midnight to 2 a.m., and devoted the rest of the day to the baby...

Meanwhile, my wife was also doing her own Ph.D. thesis. We used to be young and energetic.

Calibrations:

- Pedestal subtraction
- Gain correction
- Beam center (p_T = 0)
- Event plane flattening



Method improvement: Separate the measurement into four terms, each with its own corrections.

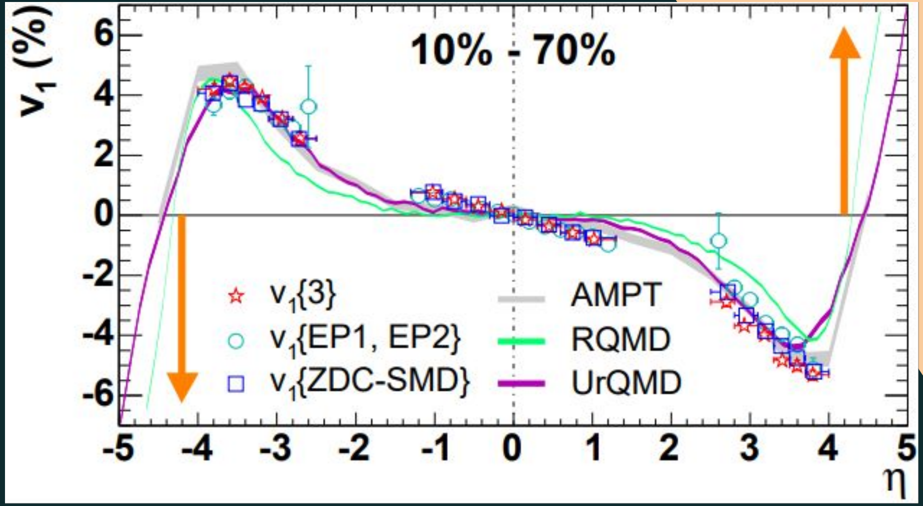
$$v_{n\_east\_cos} = \frac{1}{\langle \cos^2 n\varphi \rangle} \cdot \frac{\langle \cos n\varphi \cos n\psi_{east} \rangle}{\sqrt{2\langle \cos n\psi_{east} \cos n\psi_{west} \rangle}} \cdot \sqrt{\frac{\langle \cos n\psi_{west} \cos n\psi^* \rangle}{\langle \cos n\psi_{east} \cos n\psi^* \rangle}}$$

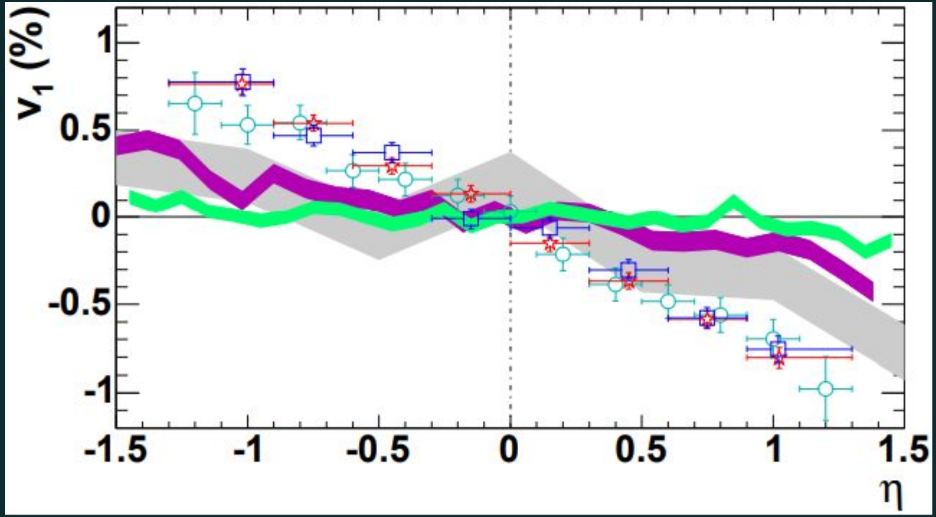
$$v_{n\_east\_sin} = \frac{1}{\langle \sin^2 n\varphi \rangle} \cdot \frac{\langle \sin n\varphi \sin n\psi_{east} \rangle}{\sqrt{2\langle \sin n\psi_{east} \sin n\psi_{west} \rangle}} \cdot \sqrt{\frac{\langle \sin n\psi_{west} \sin n\psi^* \rangle}{\langle \sin n\psi_{east} \sin n\psi^* \rangle}}$$

$$v_{n\_west\_cos} = \frac{1}{\langle \cos^2 n\varphi \rangle} \cdot \frac{\langle \cos n\varphi \cos n\psi_{west} \rangle}{\sqrt{2\langle \cos n\psi_{east} \cos n\psi_{west} \rangle}} \cdot \sqrt{\frac{\langle \cos n\psi_{east} \cos n\psi^* \rangle}{\langle \cos n\psi_{west} \cos n\psi^* \rangle}}$$

$$v_{n\_west\_sin} = \frac{1}{\langle \sin^2 n\varphi \rangle} \cdot \frac{\langle \sin n\varphi \sin n\psi_{west} \rangle}{\sqrt{2\langle \sin n\psi_{east} \sin n\psi_{west} \rangle}} \cdot \sqrt{\frac{\langle \sin n\psi_{east} \sin n\psi^* \rangle}{\langle \sin n\psi_{west} \sin n\psi^* \rangle}}$$

v_1 @62 GeV in Au+Au



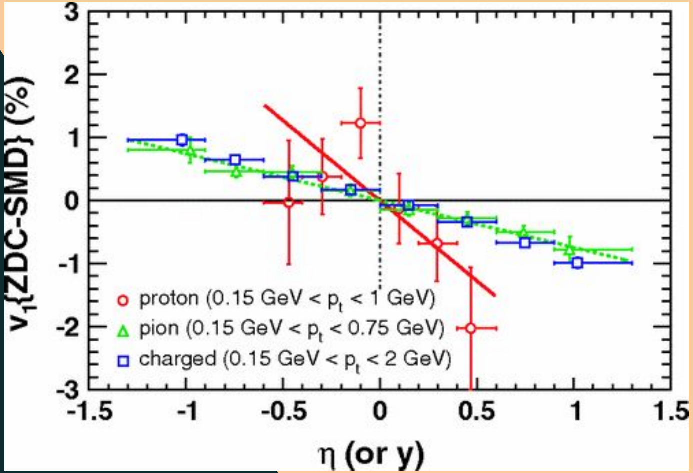


The first STAR paper for which I played a leading role: Phys. Rev. C 73 (2006) 34903

v_1 at forward rapidities:
- reasonably well reproduced by models

v_1 at midrapidities:
- statistically significant
- confirmed with 3 approaches

1st attempt to PID v1.

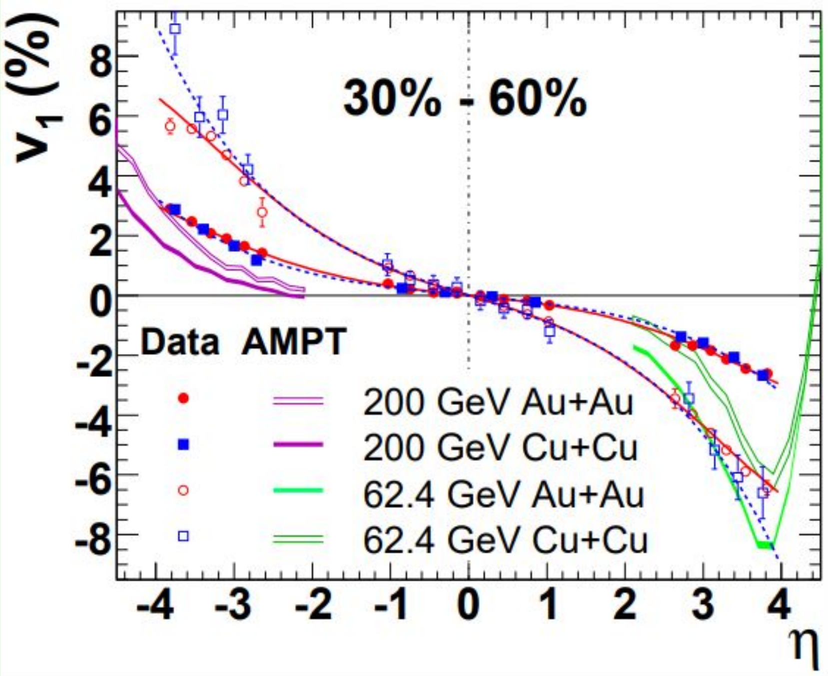


2006

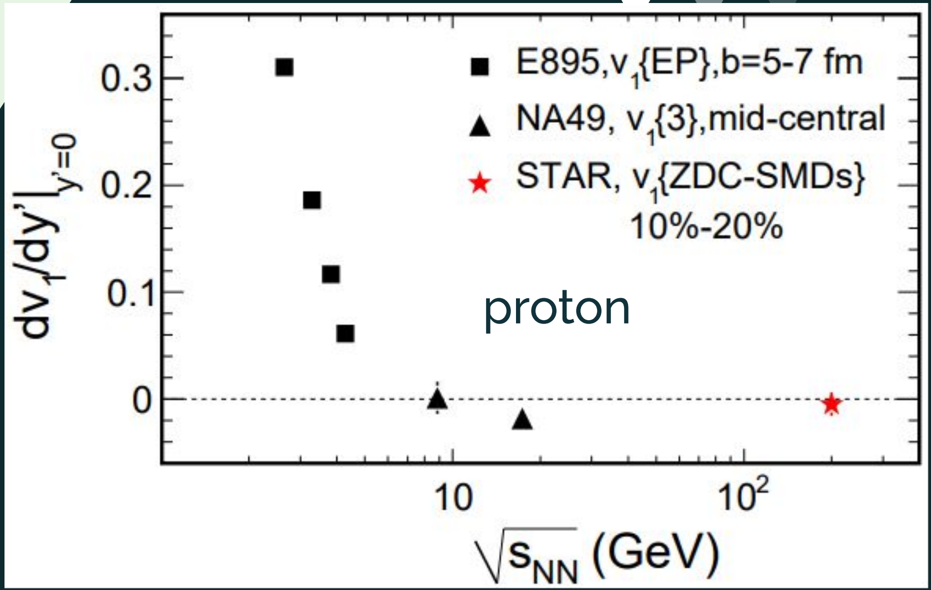
Milestones:

- Aug. 2001, started Ph.D. program (Kent)
- Feb. 2003, married and joined STAR
- Nov. 2003, built ZDC-SMDs at BNL
- June 2004, daughter
- Nov. 2004, first talk (DNP, Chicago)
- Aug. 2005, first QM talk (Budapest)
- Dec. 2005, defended my thesis
- June 2006, degree!

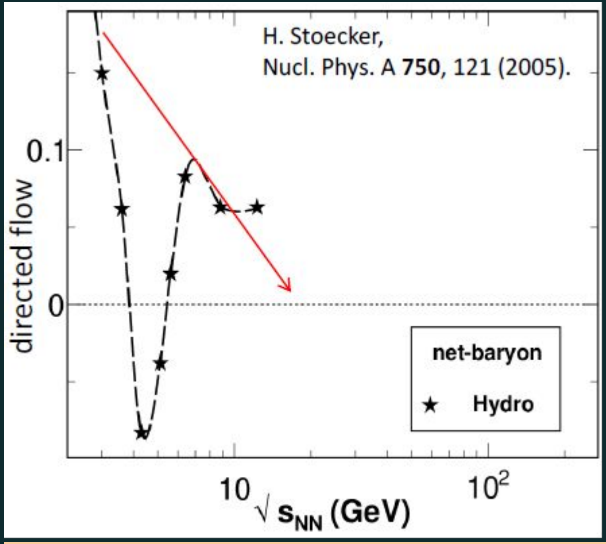
In May 2006, I joined UCLA as a postdoc, starting new works like heavy quarks and the chiral magnetic effect. However, my collaboration with Declan and my use of the ZDC-SMDs continued to thrive.



STAR: Phys. Rev. Lett. 101 (2008) 252301



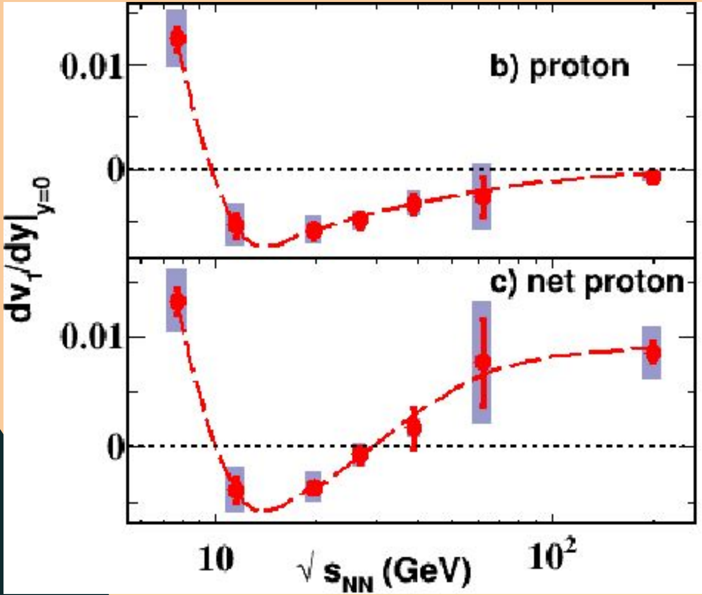
STAR: Phys. Rev. Lett. 108 (2012) 202301



Softest point

- "Softest Point" in EOS => a minimum in the ratio of pressure to energy density
- Strong softening consistent with the 1st-order PT
- Weaker softening is more likely due to crossover

Y. Nara *et al*, Phys. Lett. B769 (2017) 543.
Yu. B. Ivanov *et al*, Phys. Rev. C91 (2015) 024915.



STAR, Phys. Rev. Lett. 112 (2014) 162301

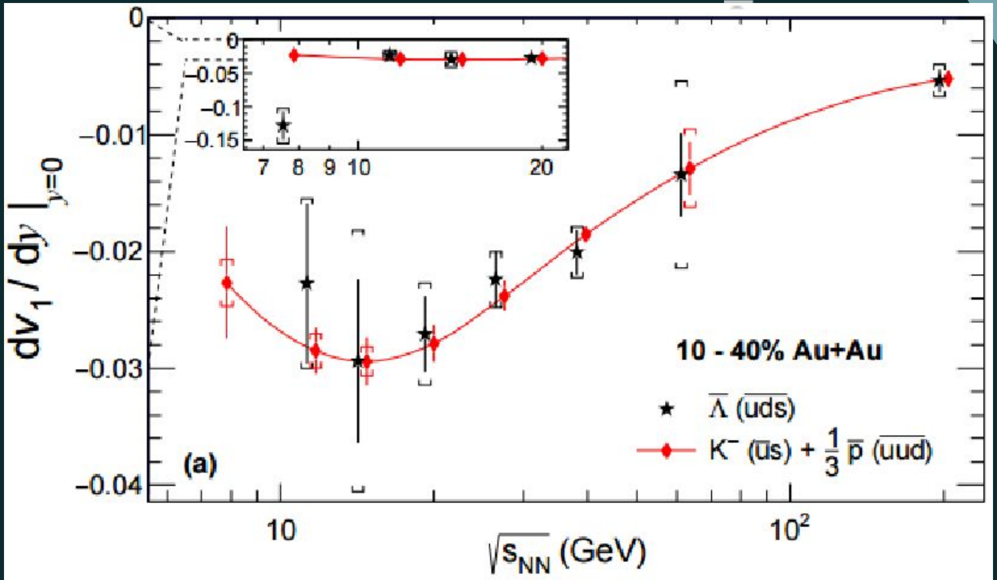
Equation of State without phase transition (PT): a monotonic trend

Equation of State assuming 1st-order PT: a dip in v_1 as a function of beam energy

Coalescence sum rule

Assumptions:

- v_1 is developed in prehadronic stage
- Hadrons are formed via coalescence: $(v_n)_{hadron} = \Sigma(v_n)_{constituent\ quarks}$
- $(v_1)_{\bar{u}} = (v_1)_{\bar{d}}$ and $(v_1)_s = (v_1)_{\bar{s}}$



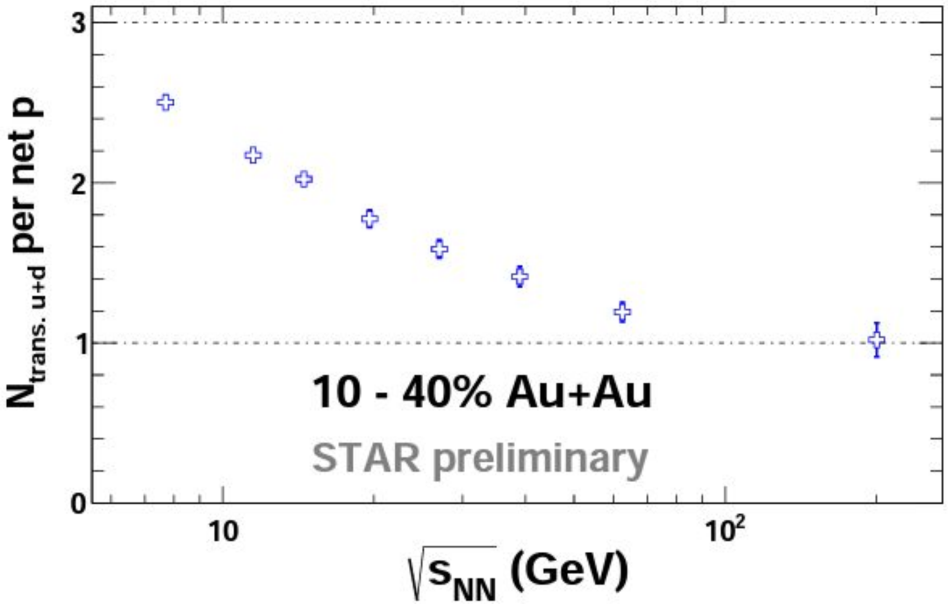
- Constituent quarks of anti-p, anti-Λ and K^- are all produced in the collision.
- For anti-Λs, prediction using coalescence sum rule agrees with measured v_1 above $\sqrt{s_{NN}}$ = 11.5 GeV.
- Disagreement at 7.7 GeV implies the failure of one or more of the assumptions below 11.5 GeV.

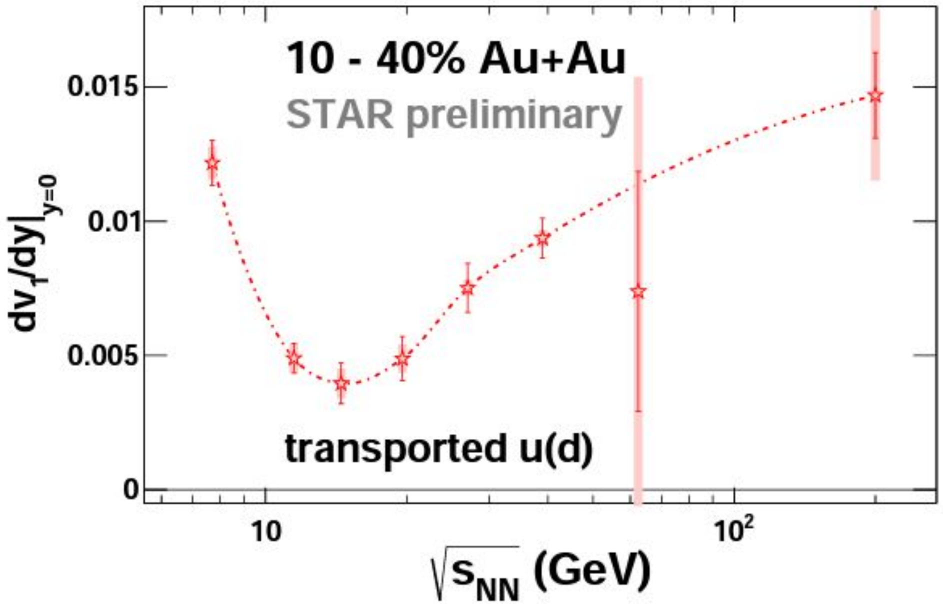
STAR, Phys. Rev. Lett. 120 (2018) 62301

v_1 of transported u(d) quarks

$(v_1)_{trans.\ u(d)} = [(v_1)_{net\ p} - (3 - N_{trans.\ u+d}) * (v_1)_{\bar{u}(\bar{d})}] / N_{trans.\ u+d}$

G. W. [STAR]: Nucl. Phys. A 982 (2019) 415

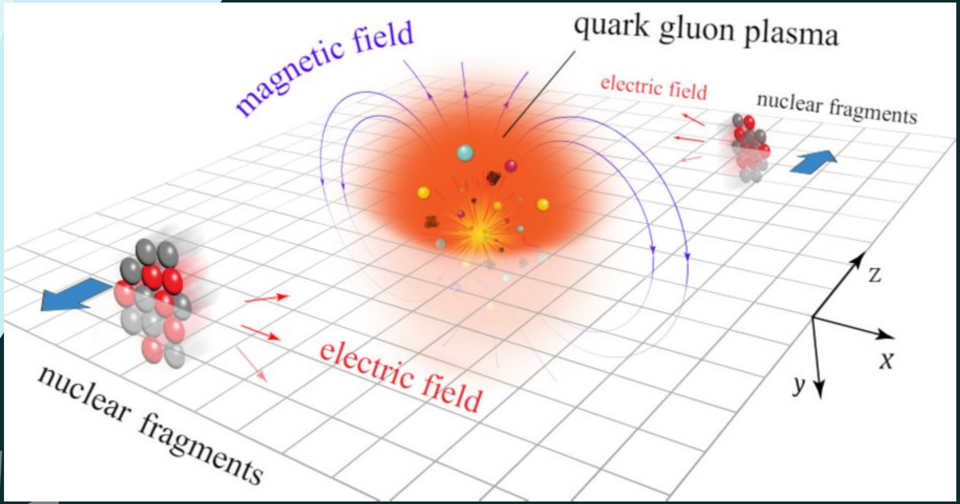




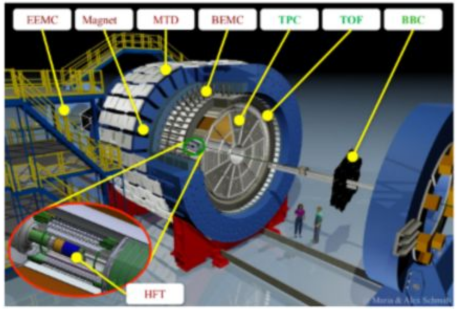
v_1 of transported u(d) is positive for all beam energies.
A minimum at ~14.5 GeV

EM fields in heavy-ion collisions

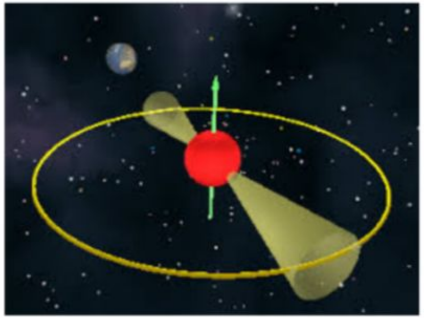
Strongest man-made magnetic field:
$-eB_y \sim 10^{18}$ Gauss
(rough estimate for 200 GeV Au+Au at b = 5 fm, t = 0)



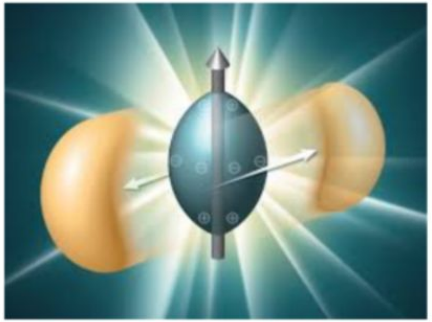
Earth
~0.5 Gauss



STAR magnet
~5000 Gauss

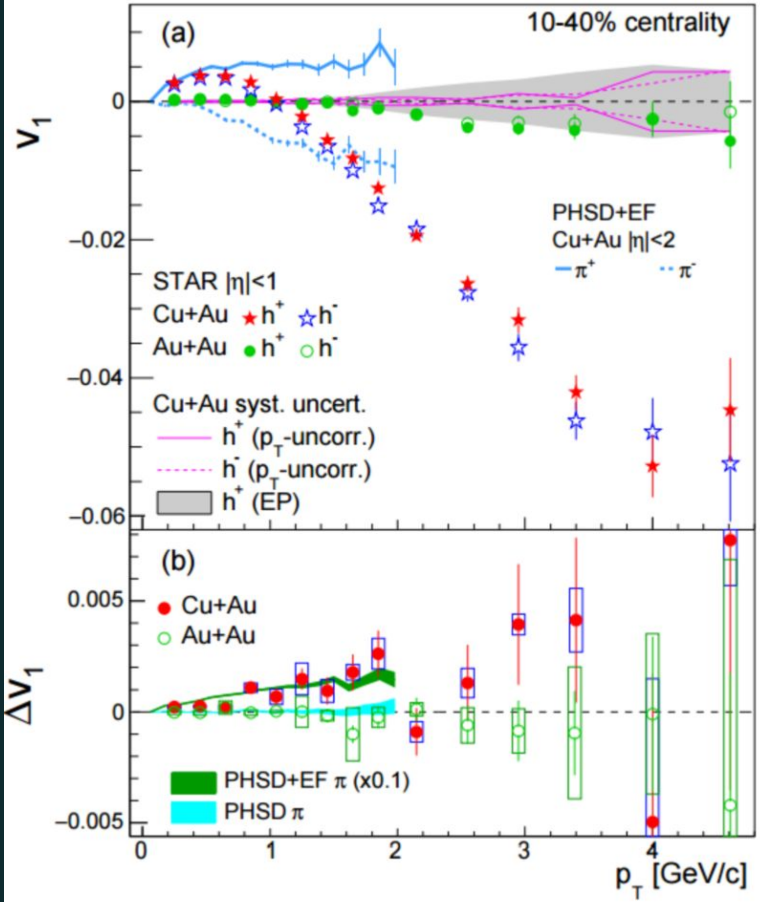


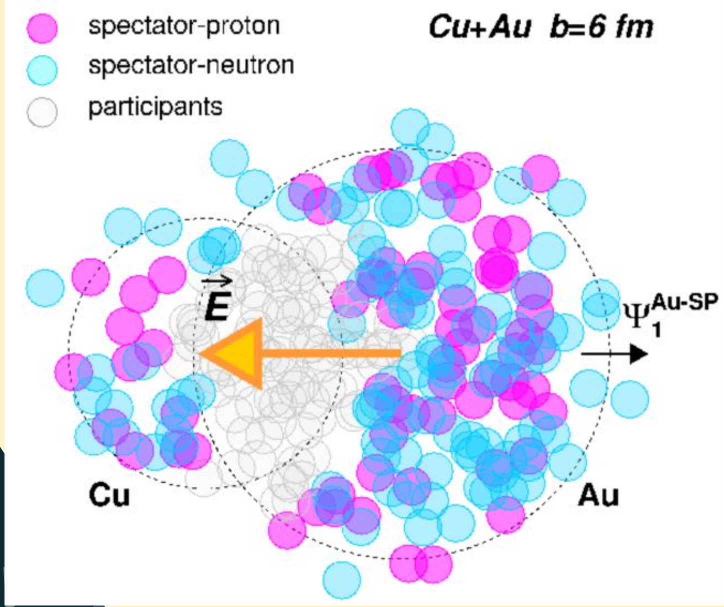
Neutron Star (Magentar)
$\sim 10^{14}$ Gauss



Heavy ion collisions
$\sim 10^{18}$ Gauss

Evidence of Coulomb field: v1 in Cu+Au at 200 GeV





$$v_1^{\pm} = v_1 \pm d_E \langle \cos(\Psi_1 - \psi_E) \rangle$$

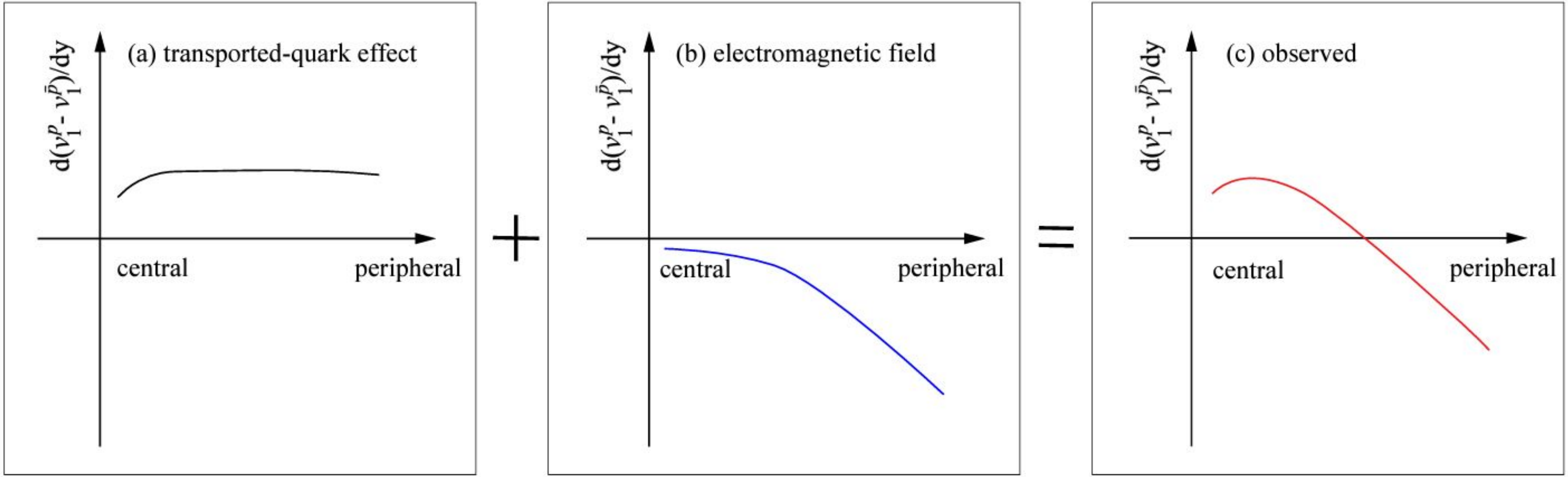
$v_1(p_T)$ splits between h^+ and h^-. The initial electric field does leave an imprint on final-stage particles!

STAR, Phys. Rev. Lett. 118 (2017) 12301

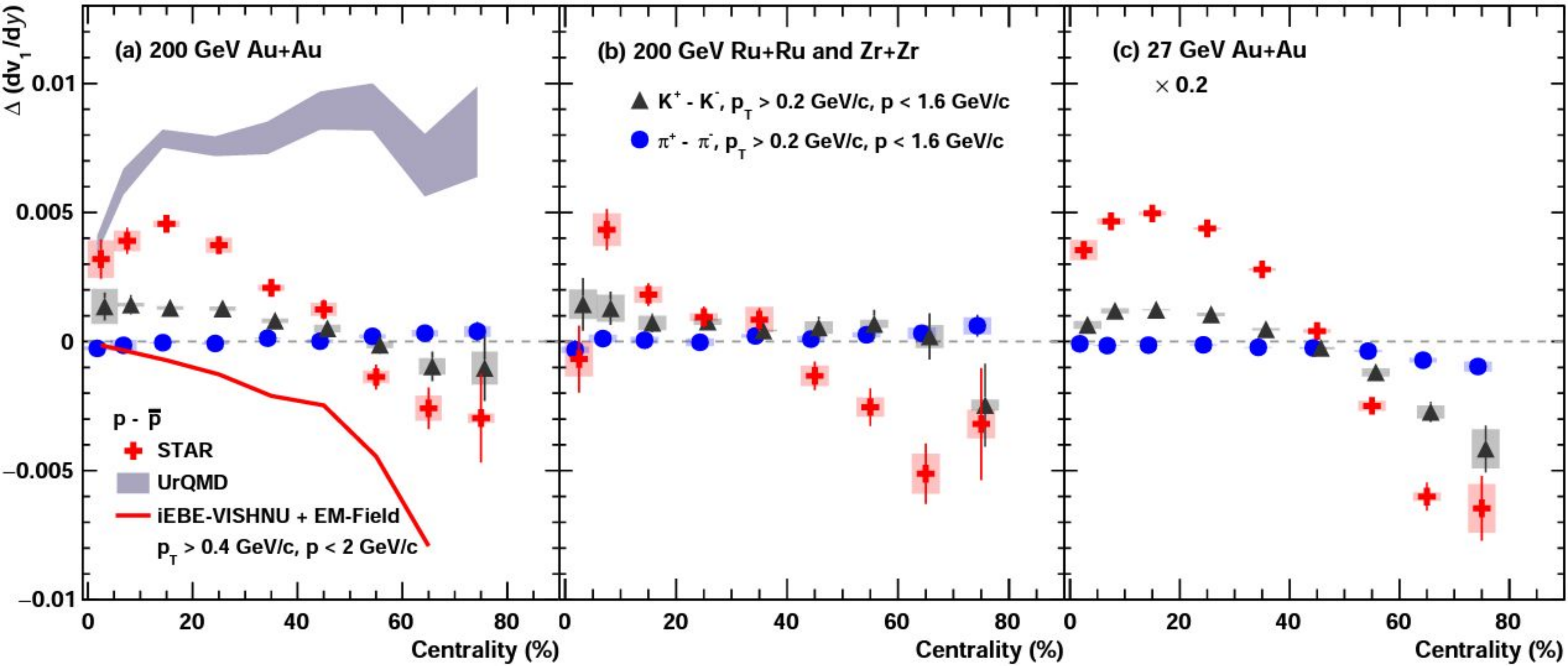
Interplay between all known effects

Illustration for v_1 slope difference between protons and antiprotons.

- Transported quarks always give a positive value.
- Theory predicts Faraday+Coulomb > Hall: net EM effect is negative.
- The sign change from positive (central collisions) to negative (peripheral) will signify of Faraday+Coulomb effect.

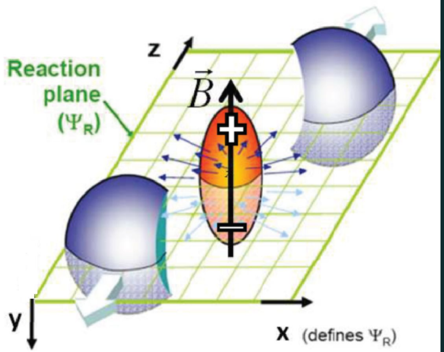


v_1 splitting and sign change:
Faraday + Coulomb > Hall + Transported Quarks



STAR, arXiv:2304.03430

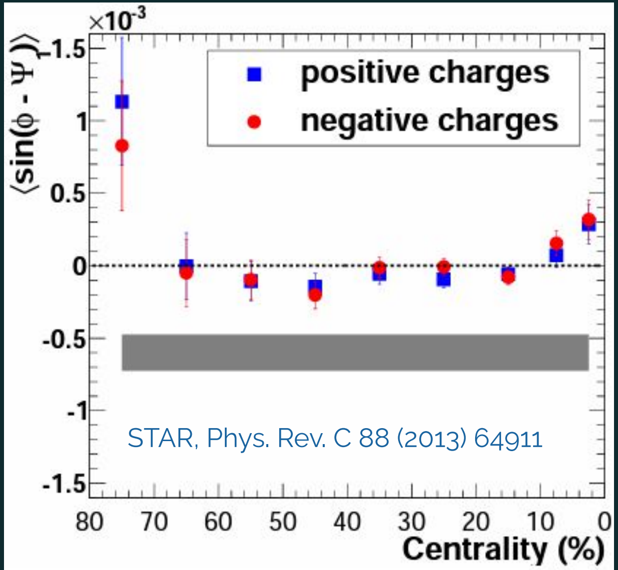
And many more: the chiral magnetic effect



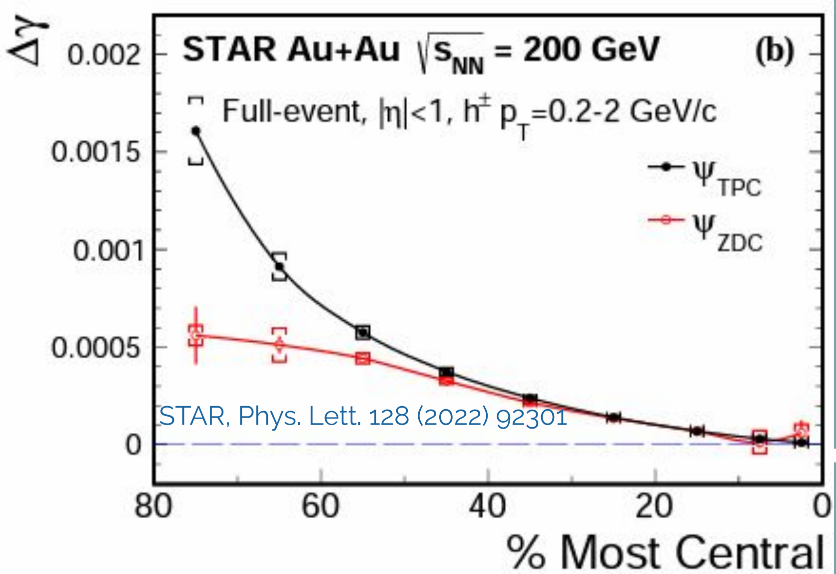
$$\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

$$\frac{dN_\pm}{d\phi} \propto 1 + 2a_\pm \cdot \sin\left(\phi^\pm - \Psi_{RP}\right)$$

$$\gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \right\rangle$$



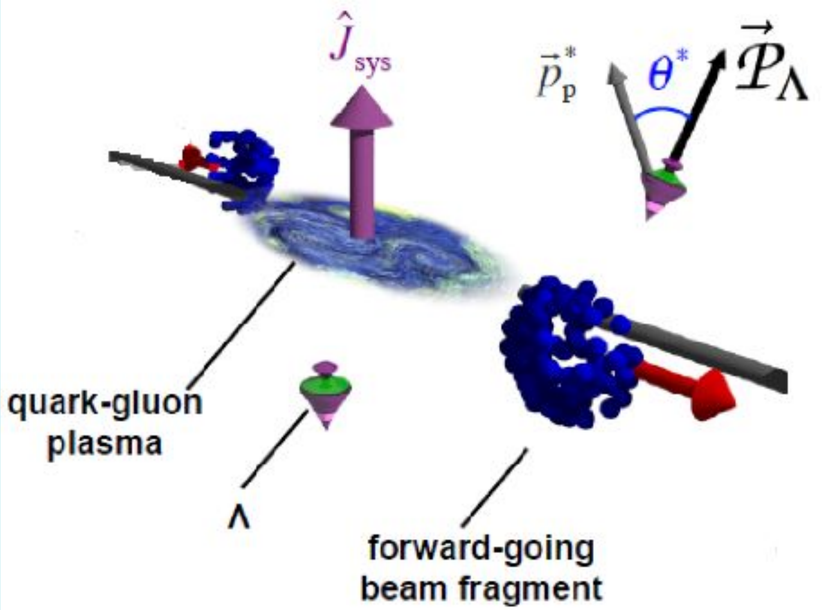
STAR, Phys. Rev. C 88 (2013) 64911



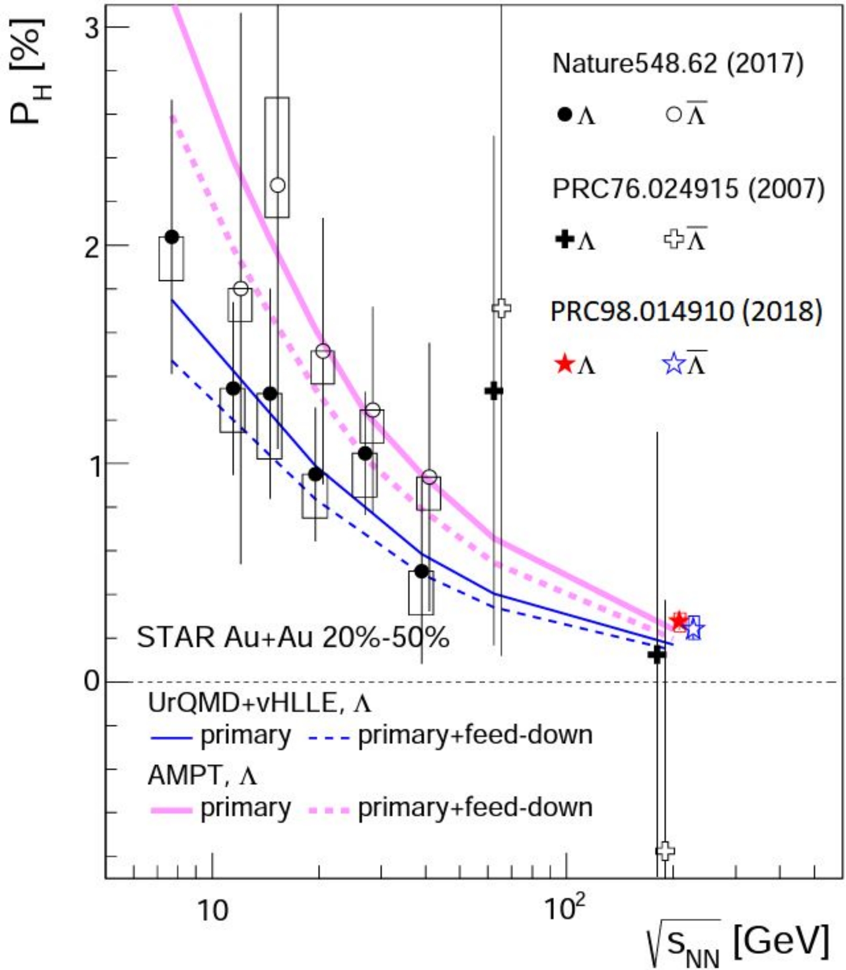
STAR, Phys. Lett. 128 (2022) 92301

Spectators provide the B field direction.

And many more: hyperon global polarization



$$P_H = \frac{8}{\pi\alpha}\frac{\langle\sin(\Psi_1 - \phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}\mathrm{sgn}_\Lambda$$



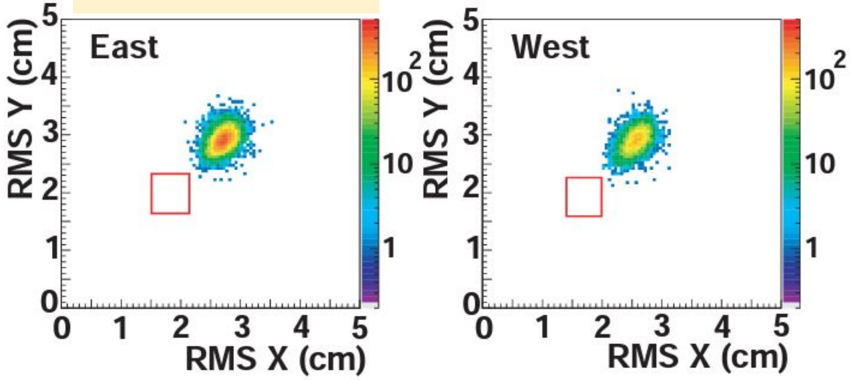
Spectators provide direction of the system angular momentum.

ZDC-SMD: maybe the most cost-effective subsystem in STAR

Utilizing as many spare parts from others' leftover as possible, the cost was only around $5k!

The aforementioned works only form a fraction of the STAR publications related to the ZDC-SMDs over the past 20 years.

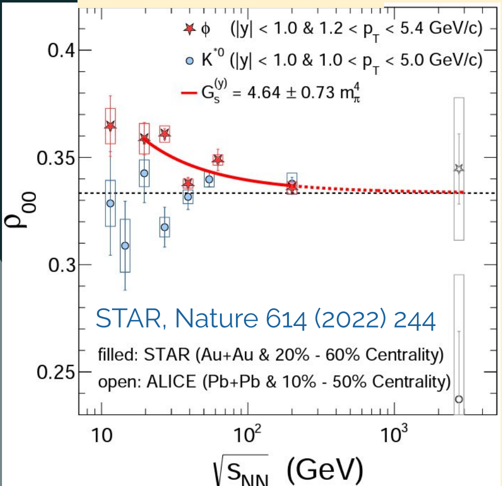
Strangelet search



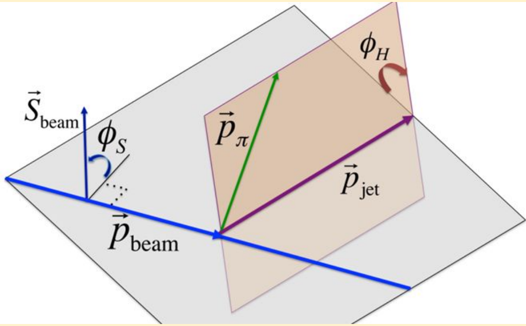
STAR, Phys. Rev. C 76 (2007) 11901

FIG. 4: (Color online) The distribution of RMS from east SMD (left) and west SMD (right).

Spin alignment



Beam polarization



STAR, Phys. Rev. D 106 (2022) 72010

A poem by ChatGPT

In fair Kent State, where intellects intertwine,
There dwells a sage, Declan, from Ireland's line.
A physicist profound in realms unseen,
In heavy-ion collisions, his expertise keen.

Seventy years, a tapestry well-woven,
In the quark-gluon plasma, his mind is proven.
Directed flow, a measure of his art,
In the quark coalescence, he played his part.

The zero-degree calorimeter, his craft refined,
Shower max detector, secrets it defined.
In the laboratory's hallowed domain,
Declan's legacy, like stars, shall remain.