Navigating through Directed Flow in RHIC

“My journey with Declan on Directed Flow”

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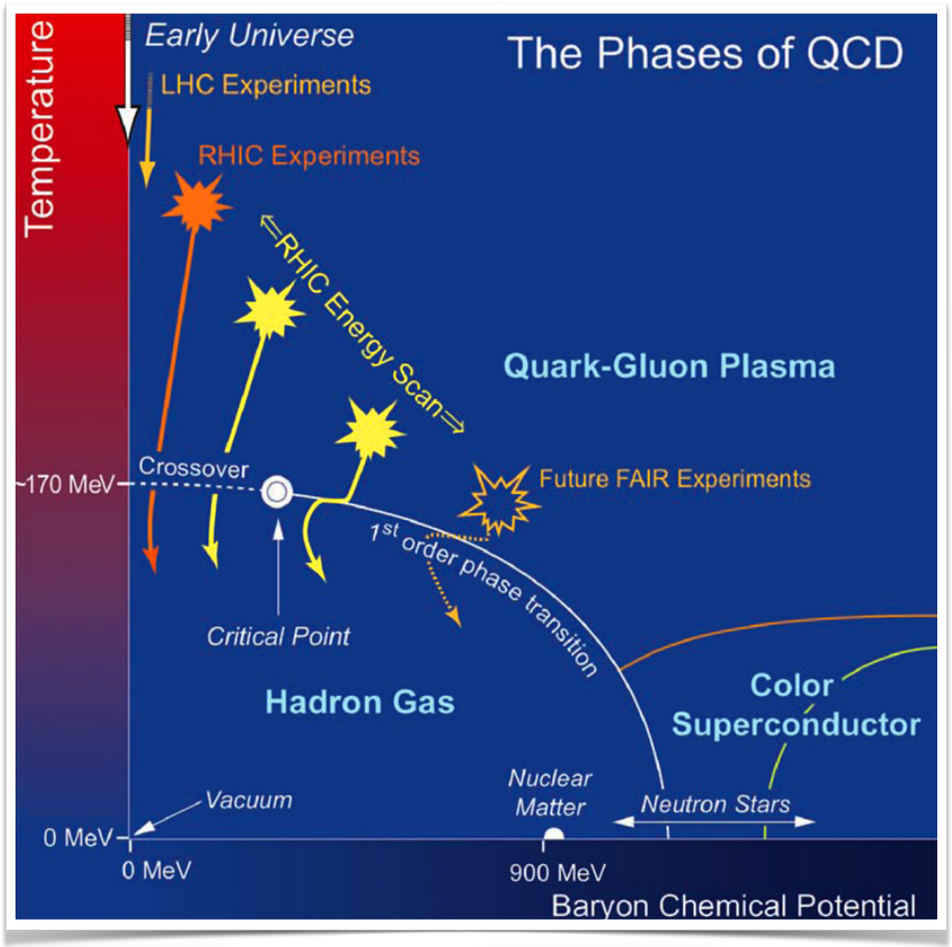
Advances in Nuclear Matter Dynamics: A Tribute to Declan Keane

December 1-2, Kent State University

QCD phase diagram

QCD phase diagram and RHIC Beam Energy Scan

Conjectured QCD Phase diagram

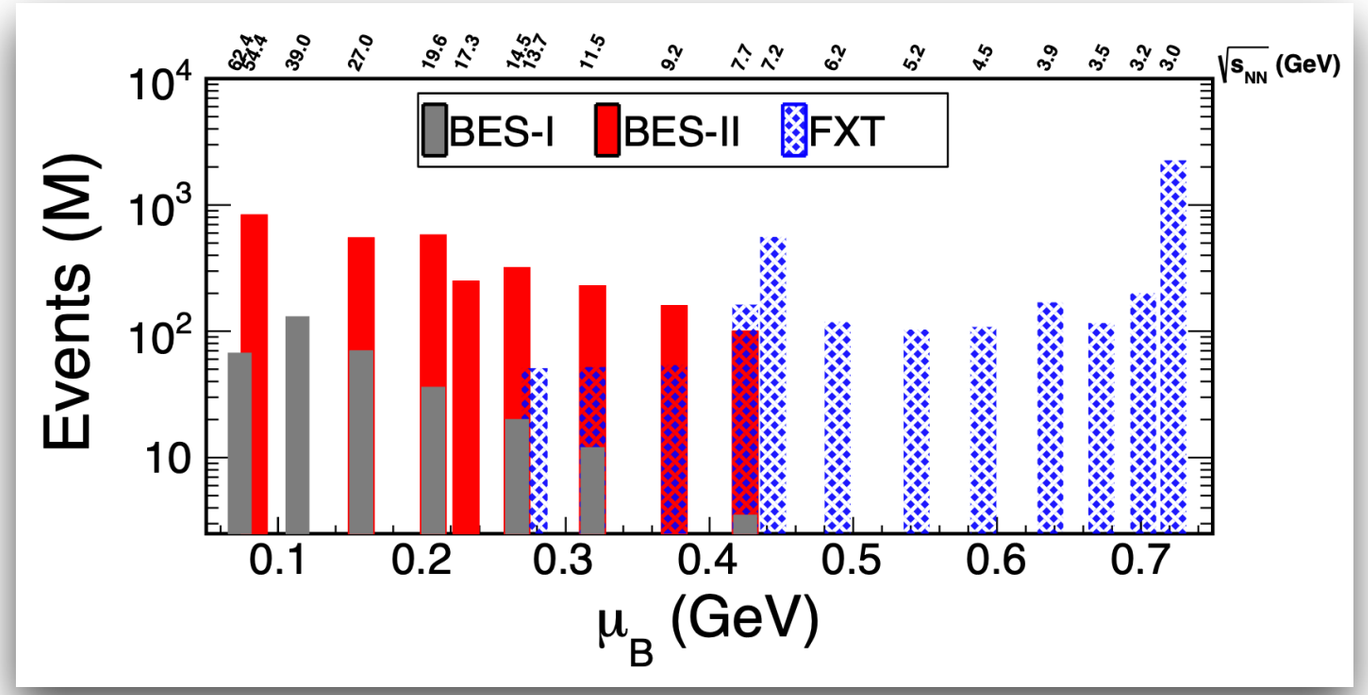


Partonic dominant → Hadronic dominant

Meson dominant → Baryon dominant

- Find signatures of Phase Transition
- QCD Critical point
- Turn-off of QGP signatures

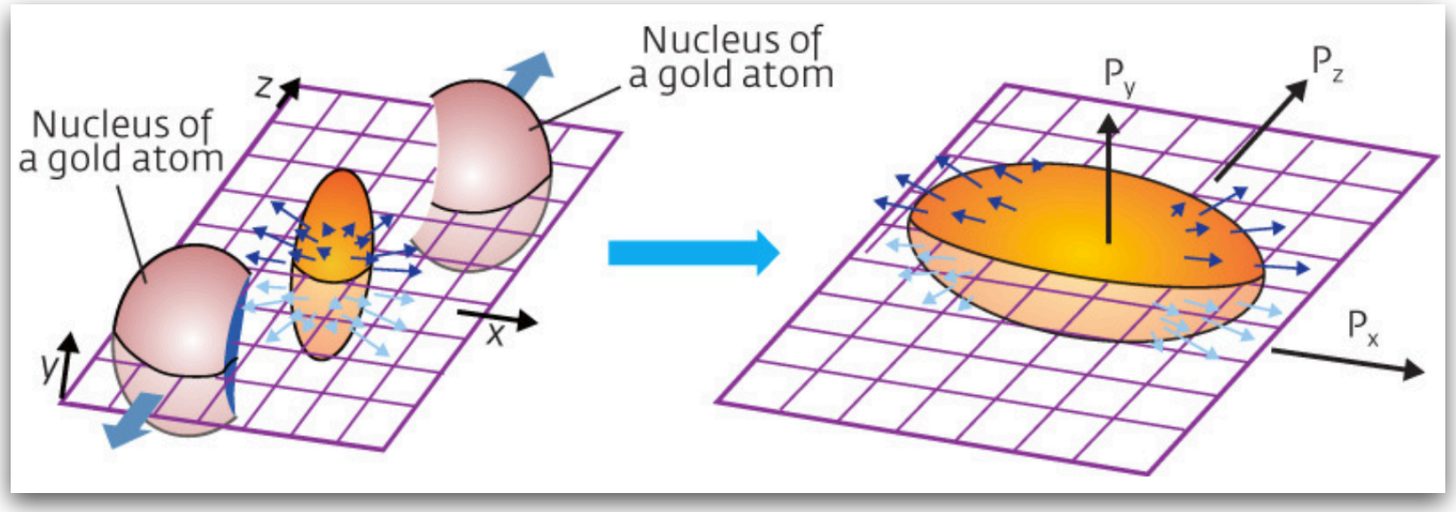
BES Program:



Collider: 7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27, 39, 54.4, 62.4, 200 (GeV)
Fixed Target: 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2, 7.7, 9.2, 11.5, 13.7 (GeV)

most precise data to map the QCD phase diagram

Collective flow



Co-ordinate space anisotropy → **Momentum space anisotropy**

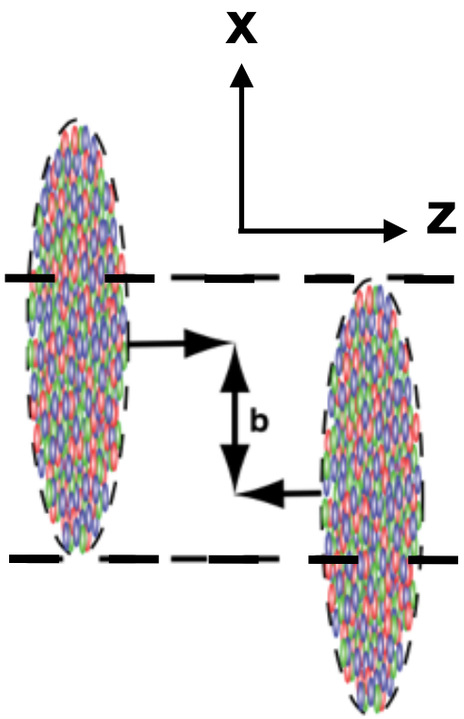
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum 2v_n \cos\, n(\phi - \Psi_n^{EP})\right)$$

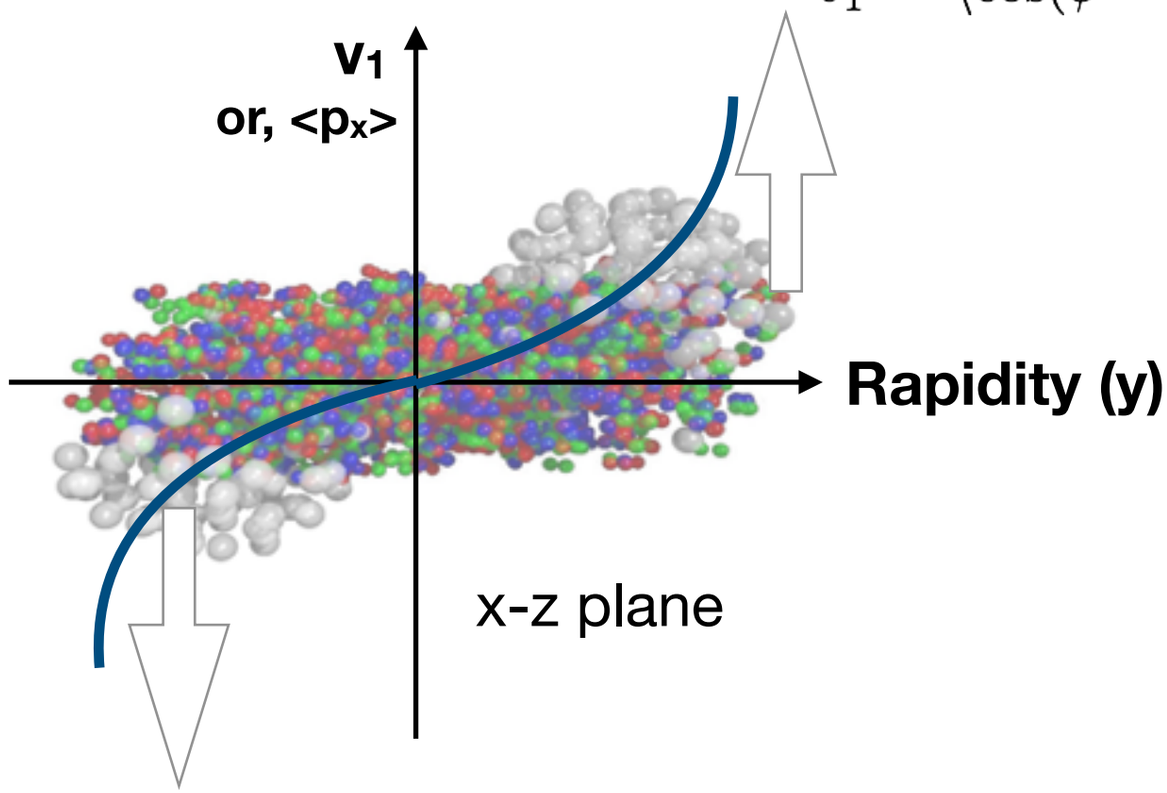
Observables

- v_1 : Directed flow
- v_2 : Elliptic flow
- v_3 : Triangular flow

Flow coefficients are sensitive to:
initial/final state properties of the medium, EoS and degrees of freedom

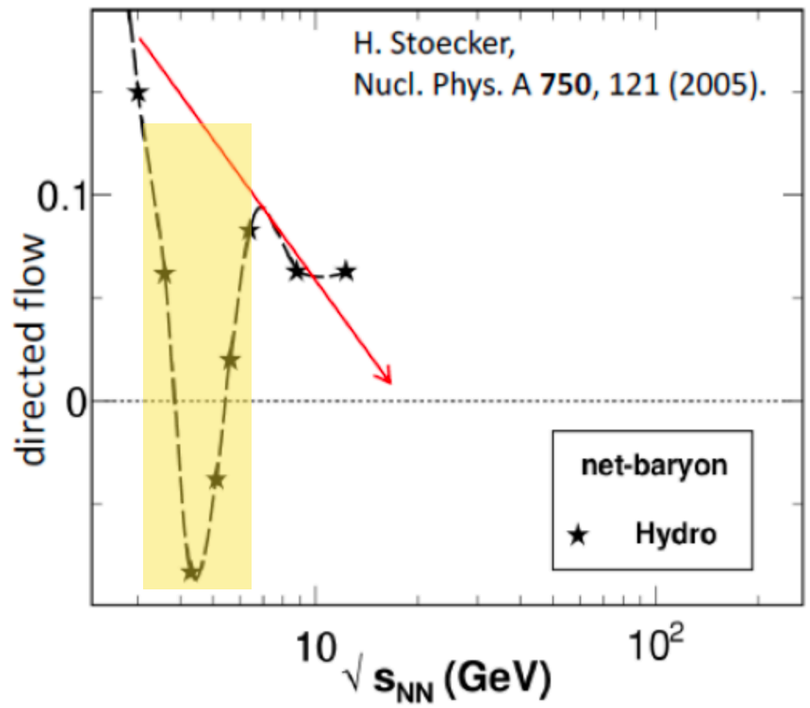
Directed flow in heavy ion collisions





$v_1 \sim \langle \cos(\phi - \Psi_R) \rangle$ Declan's favorite flow coefficient

Hydro: Net-baryon v_1

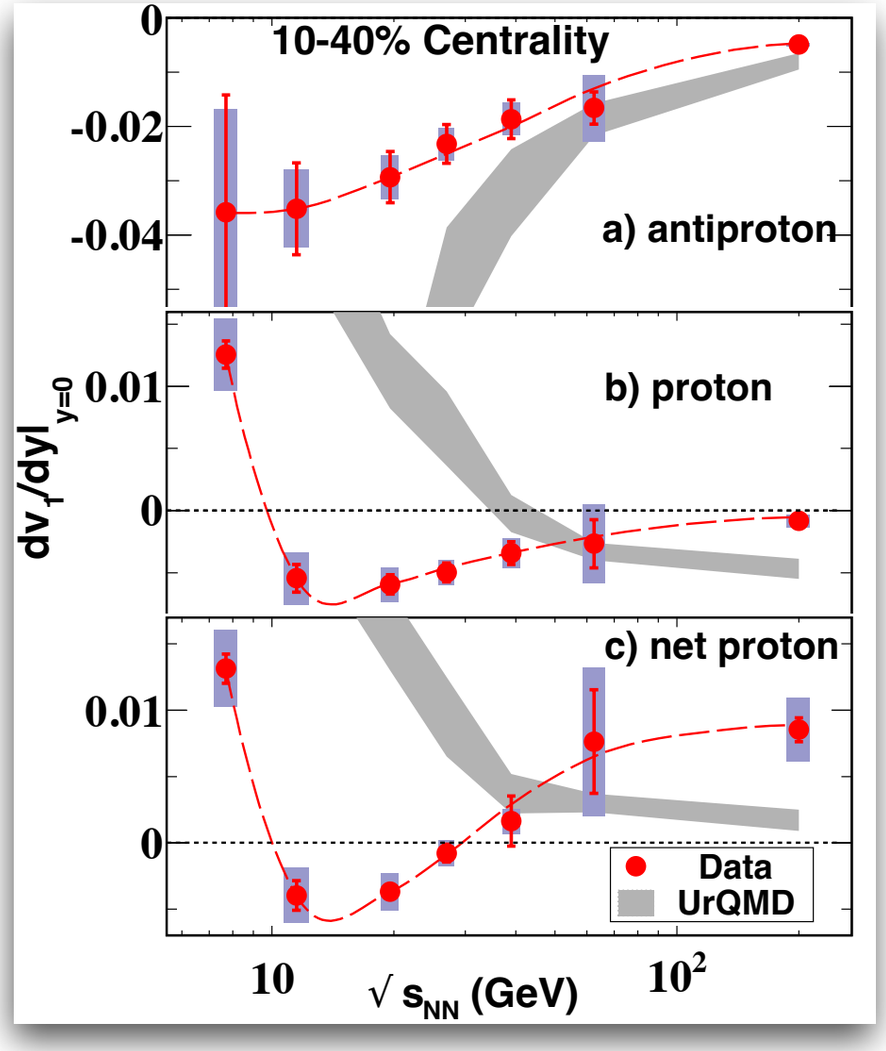


- Directed flow is the sideward collective motion of the produced particles within the reaction plane (x-z plane)
- Directed flow developed early in the collisions around time scale 2R/γ ~ 0.1 fm/c
- Probe of early stage of collisions
- Sensitive to the pressure
- Sensitive to the EoS

- EoS **without** 1st order PT
  Monotonic energy dependence
- EoS **with** 1st order PT
  Non-Monotonic energy dependence, dip in dv_1/dy

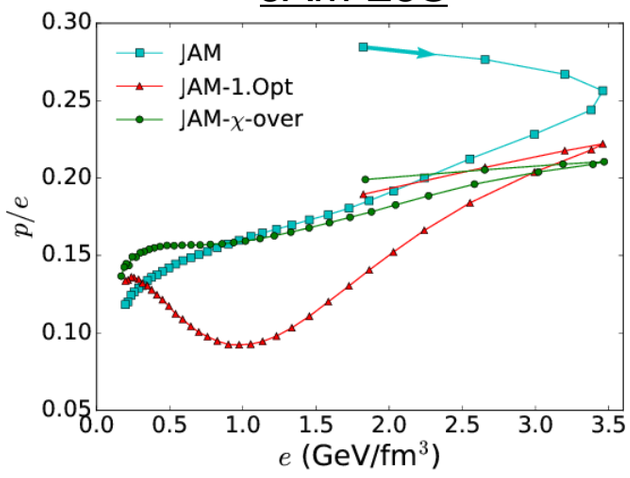
Directed flow of pion and proton from BES-I

BES-I STAR: PRL 112, 162301 (2014)

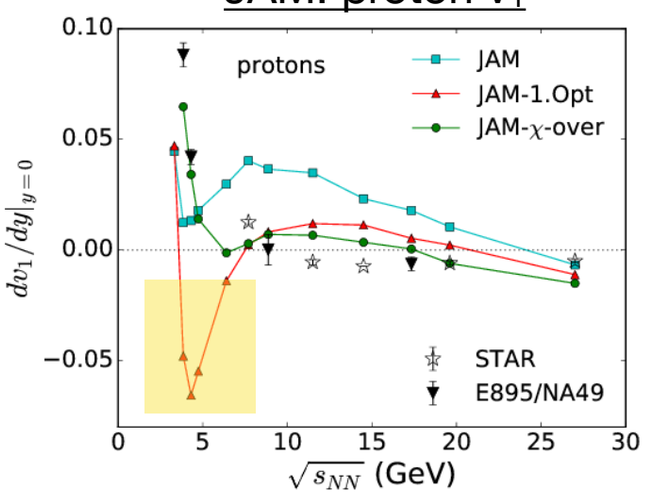


Model

JAM EoS



JAM: proton v_1



At 1st order phase transition, pressure drops as speed of sound goes to zero

Y. Nara et al, PLB 769, 543-548 (2017)

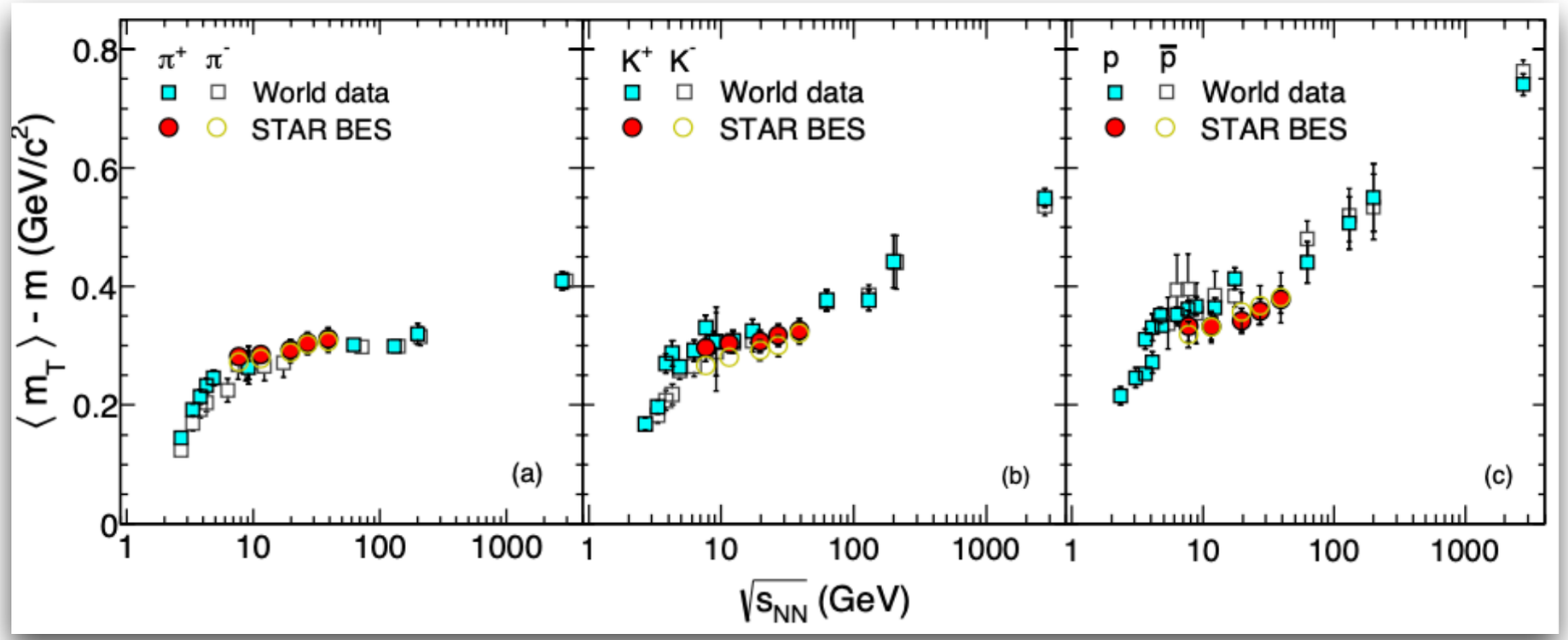
Primary observations

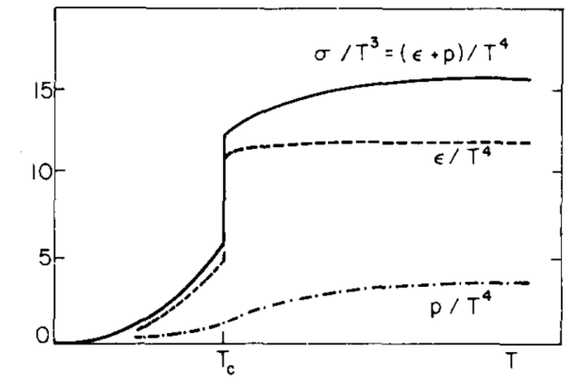
Around 10-20 GeV:
- proton v_1 changes sign
- net-proton v_1 change sign twice with a minima

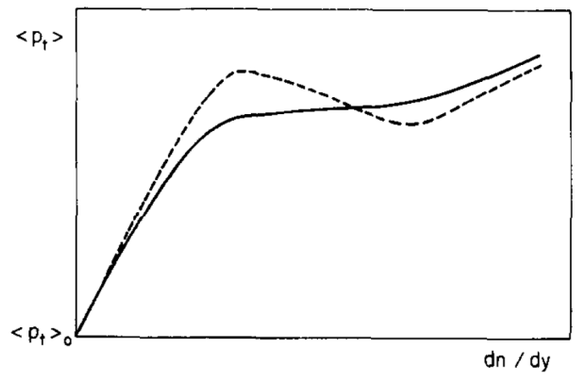
→ Features qualitatively resemble the model prediction with 1st order phase transition

Mean transverse momentum

BES-I







L. Van Hove, Phys. Lett. B 118, 138 (1982)

- Constant $(\langle m_T \rangle - m)$ around BES region (expected from 1st order Phase Transition) ?

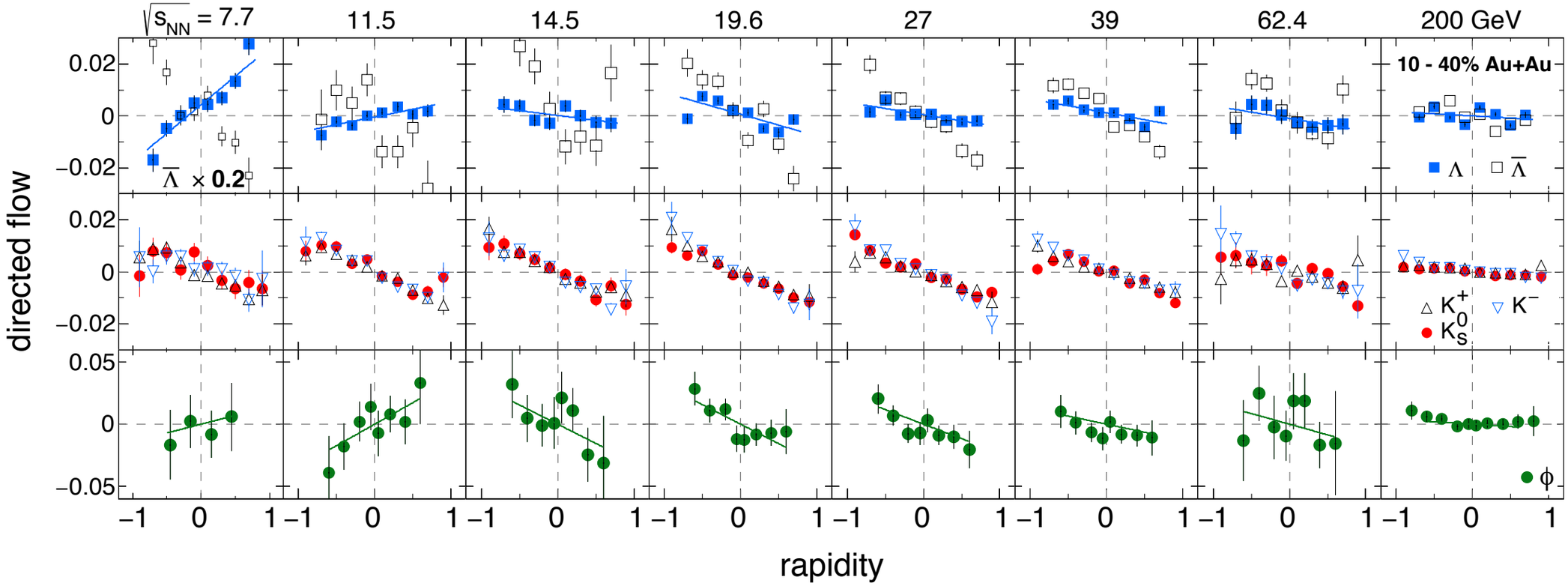
  Van Hobe type signature

STAR: PRC 96, 044904 (2017); PRC 101, 024905 (2020); PRC 102, 034909 (2020);

Directed flow of more species from BES-I

Beam-Energy Dependence of Directed Flow of Λ, $\bar{\Lambda}$, $K^{\pm}$, K^0_s, and ϕ in $\mathbf{Au + Au}$ Collisions

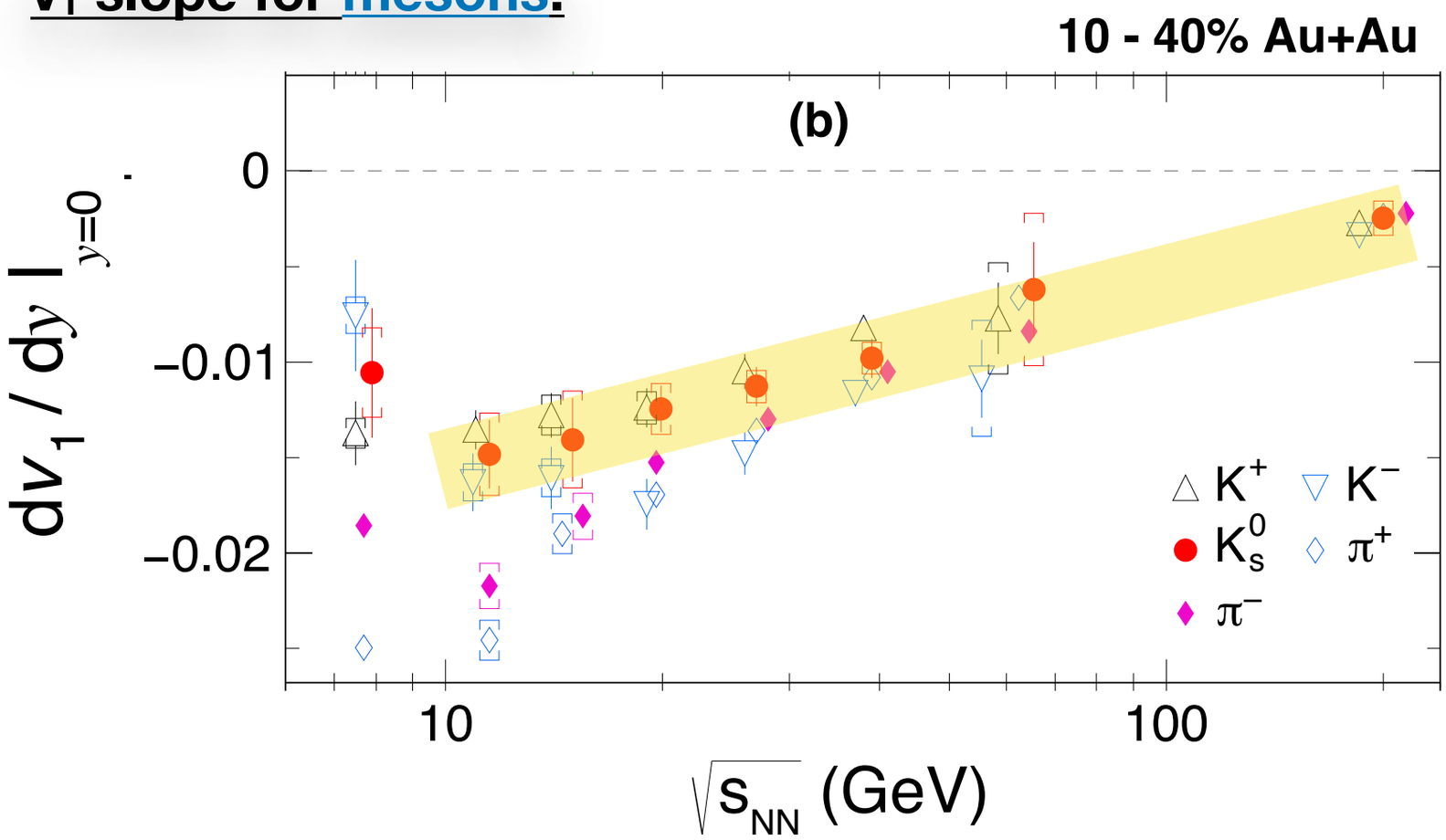
L. Adamczyk *et al.* (STAR Collaboration)
Phys. Rev. Lett. **120**, 062301 – Published 6 February 2018



Comprehensive measurement of v_1 of ten different particle species over 8 beam energies

Directed flow of mesons from BES-I

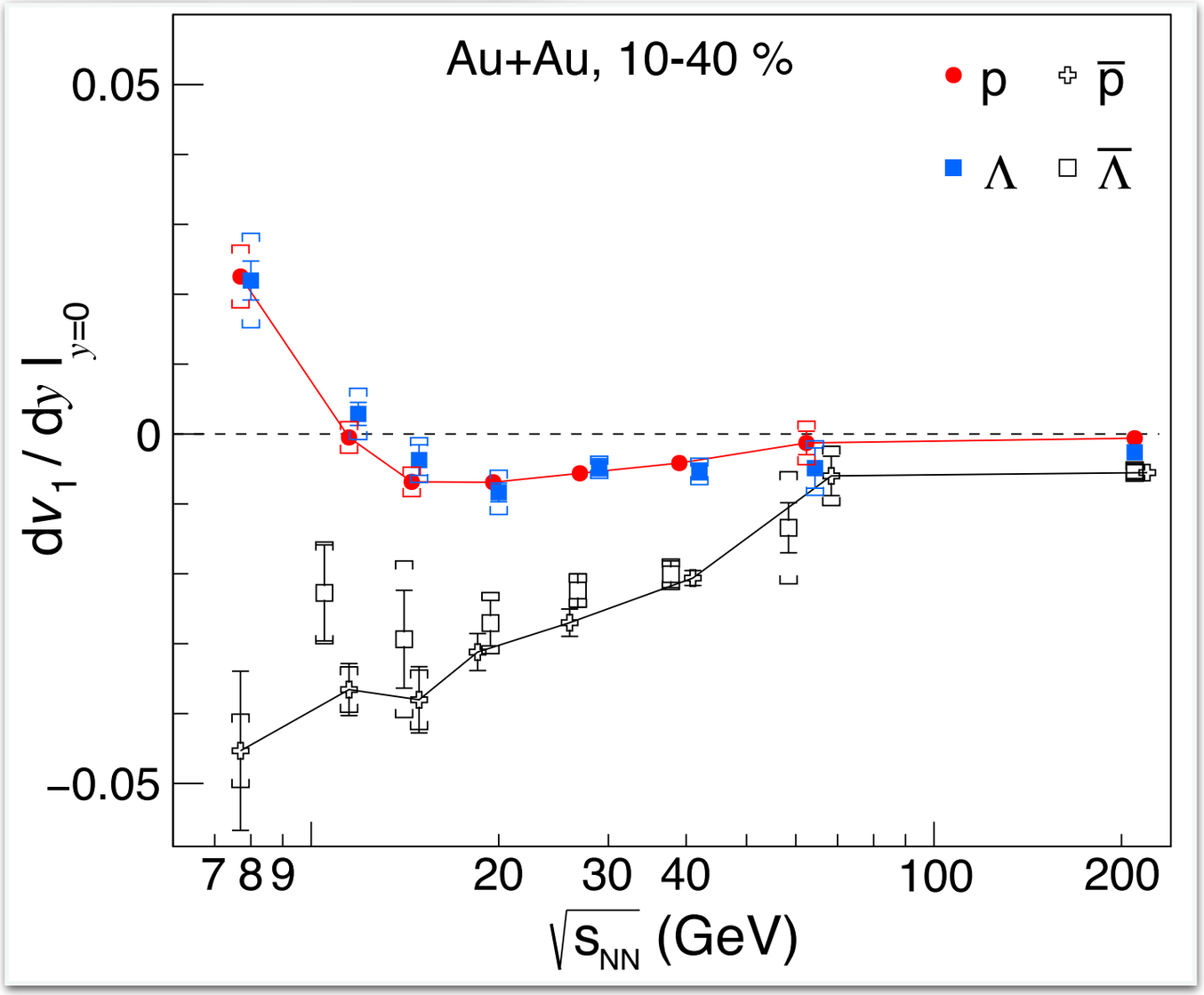
v_1 slope for mesons:



- $v_1(\pi), v_1(K) \sim$ negative across beam energies

Directed flow of baryons from BES-I

v_1 slope for baryons:

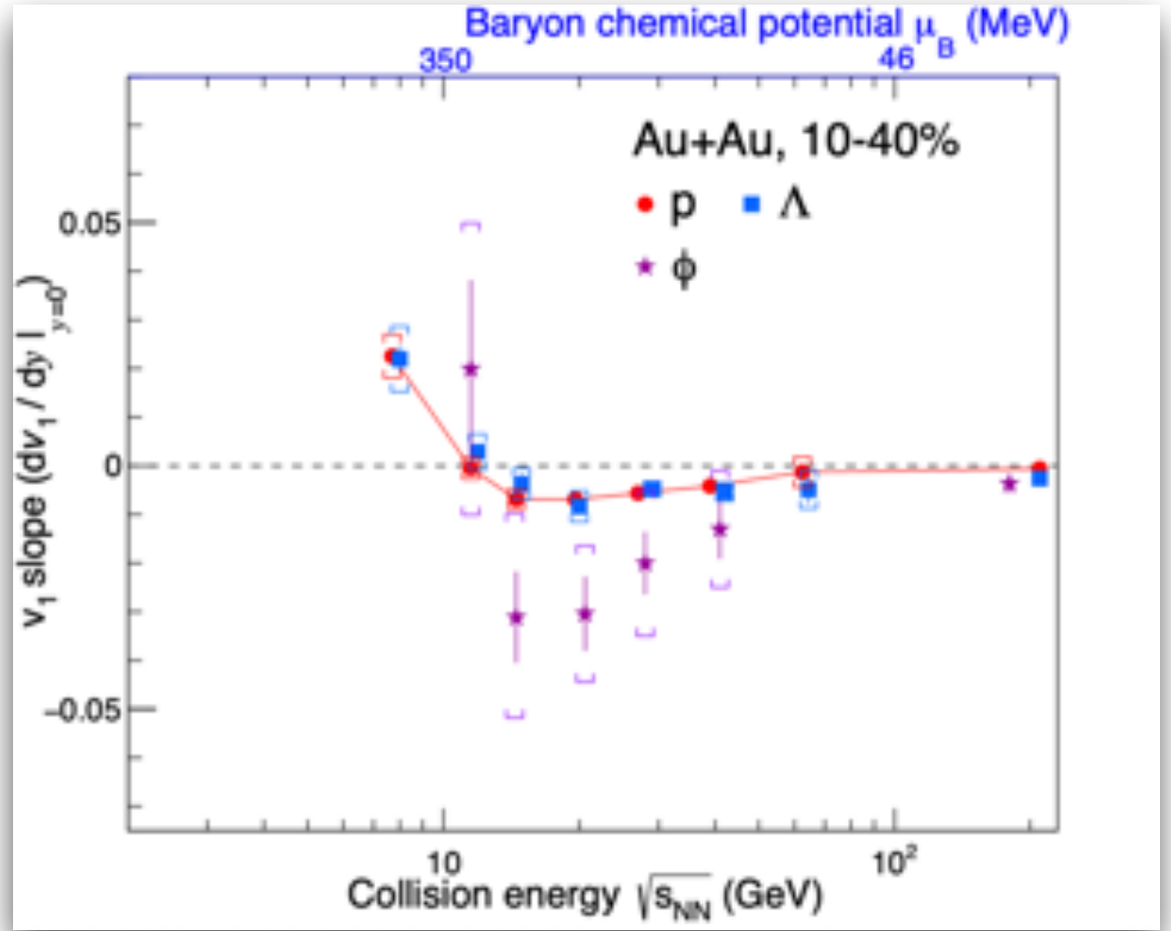


Particle	Quark content
anti-Λ	$\overline{uds}$
anti-p	$\overline{uud}$

- $v_1(p) \sim v_1(\Lambda)$ both changes sign around 10-15 GeV
- $v_1(\bar{p}) \sim v_1(\bar{\Lambda})$ negative across beam energies

Directed flow of ϕ meson from BES-I

BES-I: v_1 slope p and Λ vs ϕ meson



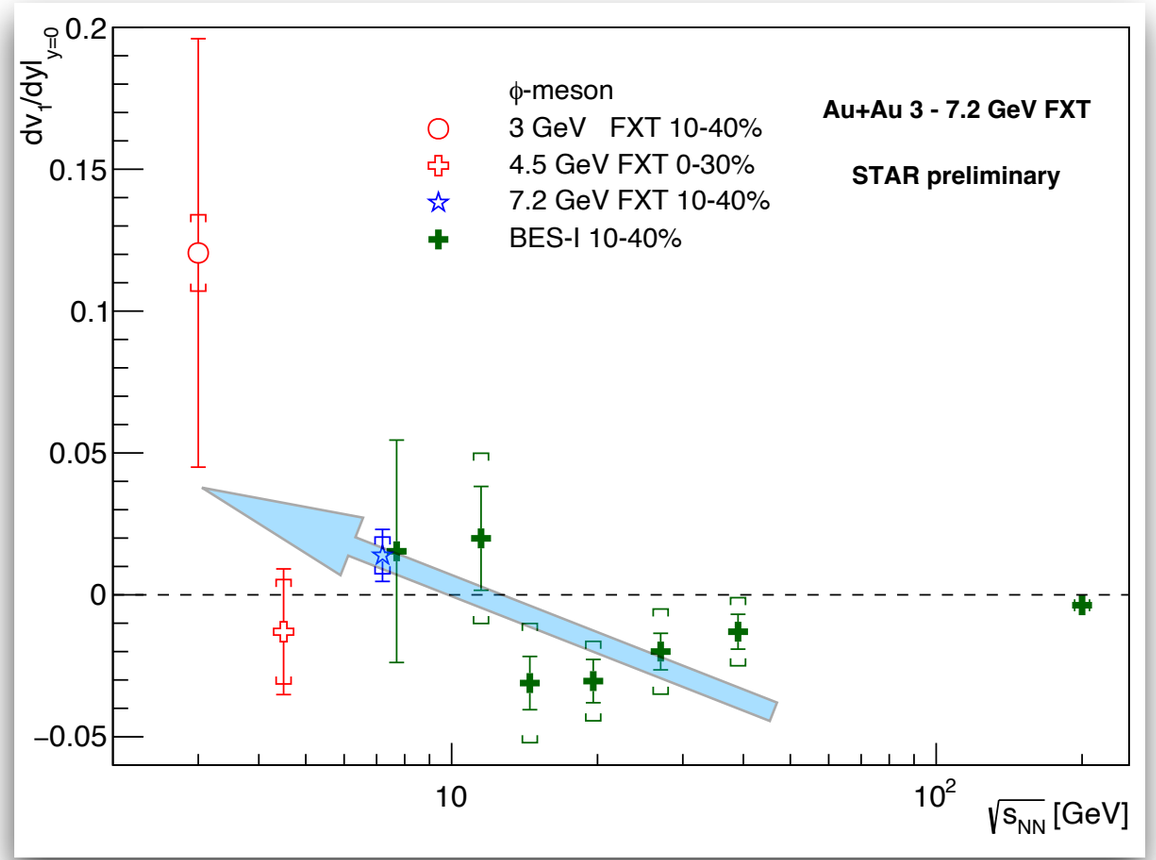
p	udd
Λ	uds
ϕ	ss

ϕ is a meson, but mass close to baryon

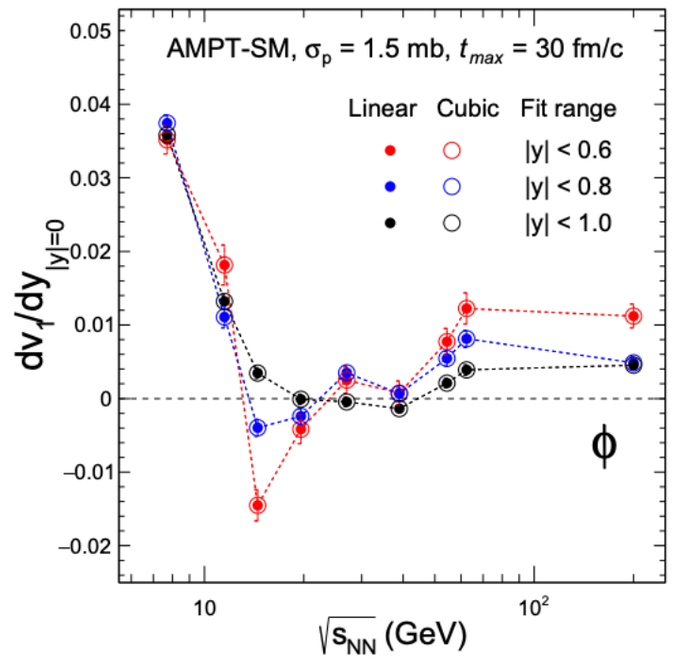
- Like both the baryons, p and Λ, ϕ meson show a change sign $\sqrt{s_{NN}} \sim 10 - 15$ GeV !

Directed flow of ϕ meson at high μ_B

BES-I: v_1 slope of ϕ meson: recent data



AMPT



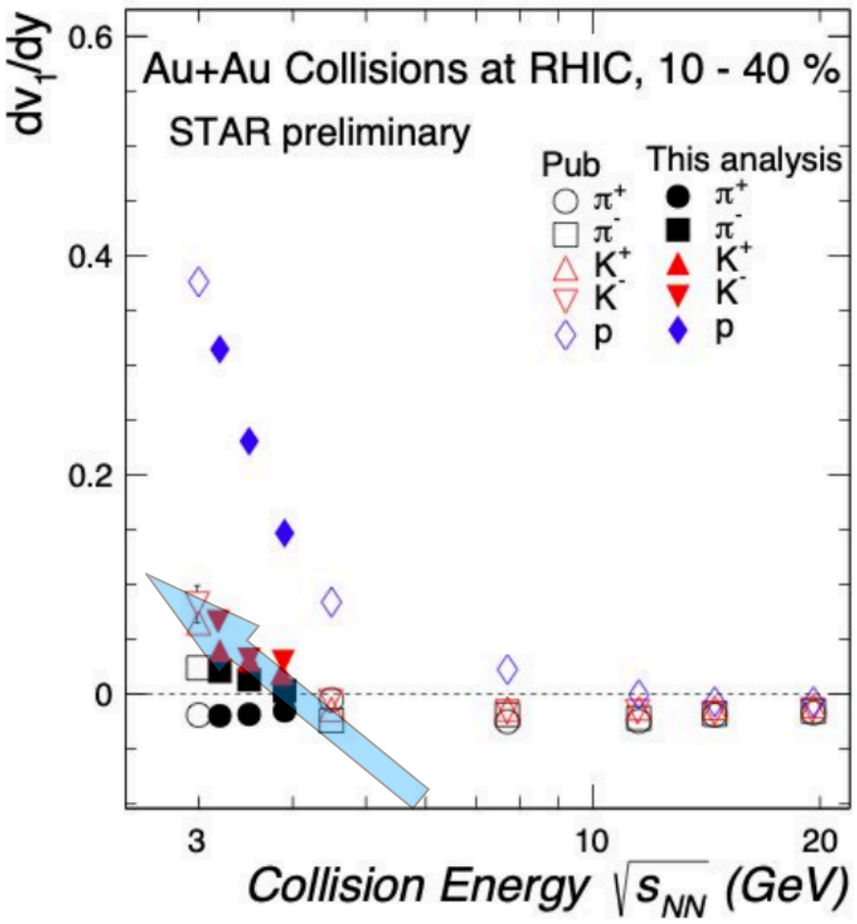
Pair production: s and $\bar{s}$ are symmetric in space
String Melting: melting of strange mesons & hyperons

"*may be an artifact of string melting, but it may be a more general physics question about whether the finite μ_B in the system affects the symmetry of s and $\bar{s}$.*" … Ziwei Lin

- First observation of ϕ meson directed flow
- Like baryons, ϕ meson also showing a change sign $\sqrt{s_{NN}} < 11$ GeV !!

Directed flow of strange mesons at high μ_B

STAR FXT: high μ_B region



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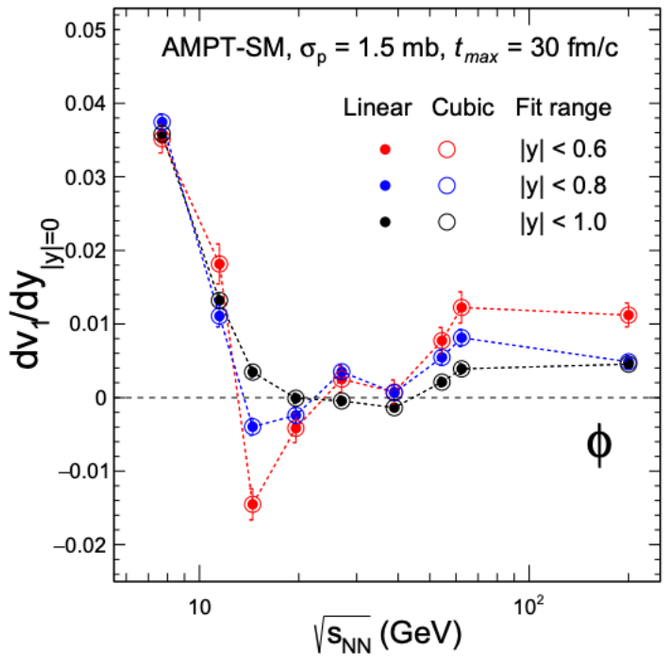

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- Like baryons, ϕ meson also showing a change sign $\sqrt{s_{NN}} < 11$ GeV
- $K^{\pm}$ also showing a change sign $\sqrt{s_{NN}} < 4.5$ GeV

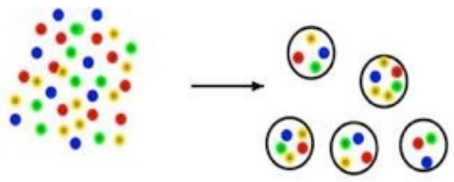
Quark coalescence hypothesis with directed flow

Test the assumption that the de-confined quarks acquired v_n, then they form hadrons:

$$v_n^{\text{hadron}} = \sum v_n^{\text{constituent-quarks}}$$

The origin of scaling is interpreted as an evidence for dominance of quark degrees of freedom

Particle	Quark content
anti-Λ	uds
anti-p	uud
K-	us



qq vs. qqq

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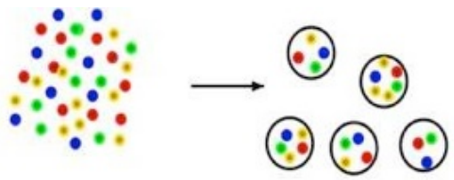

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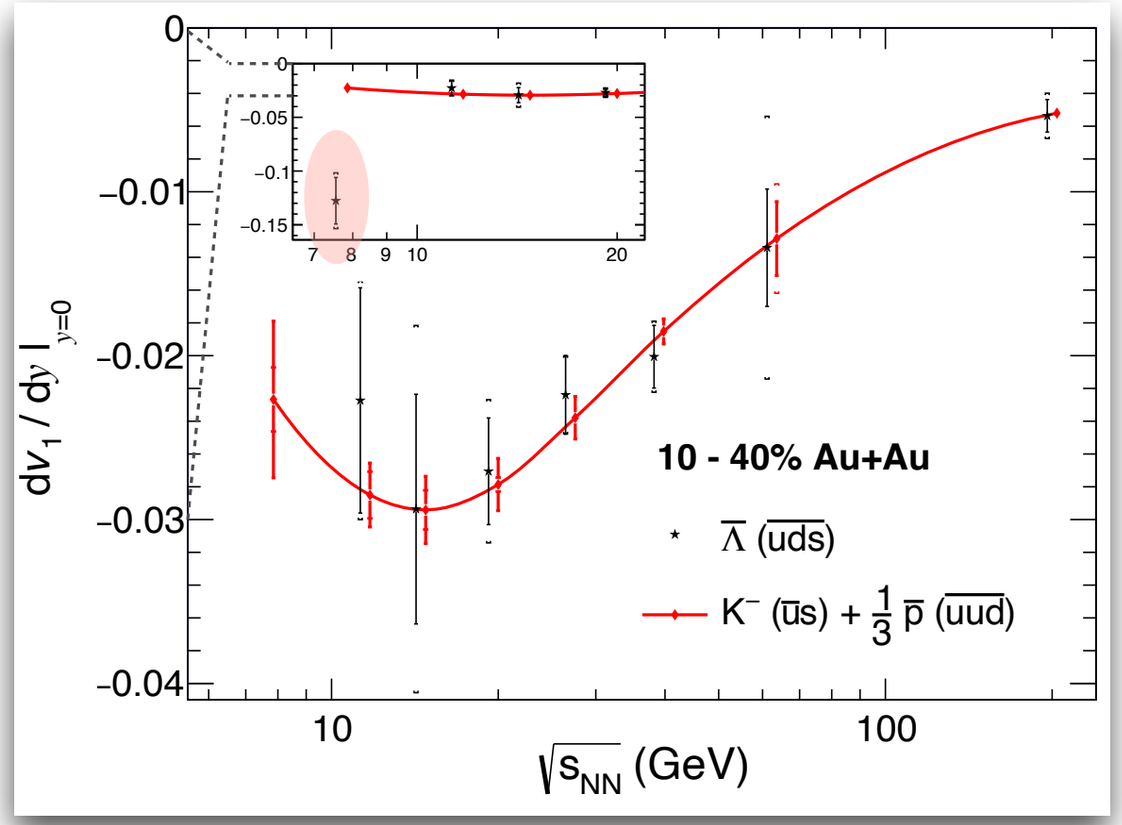


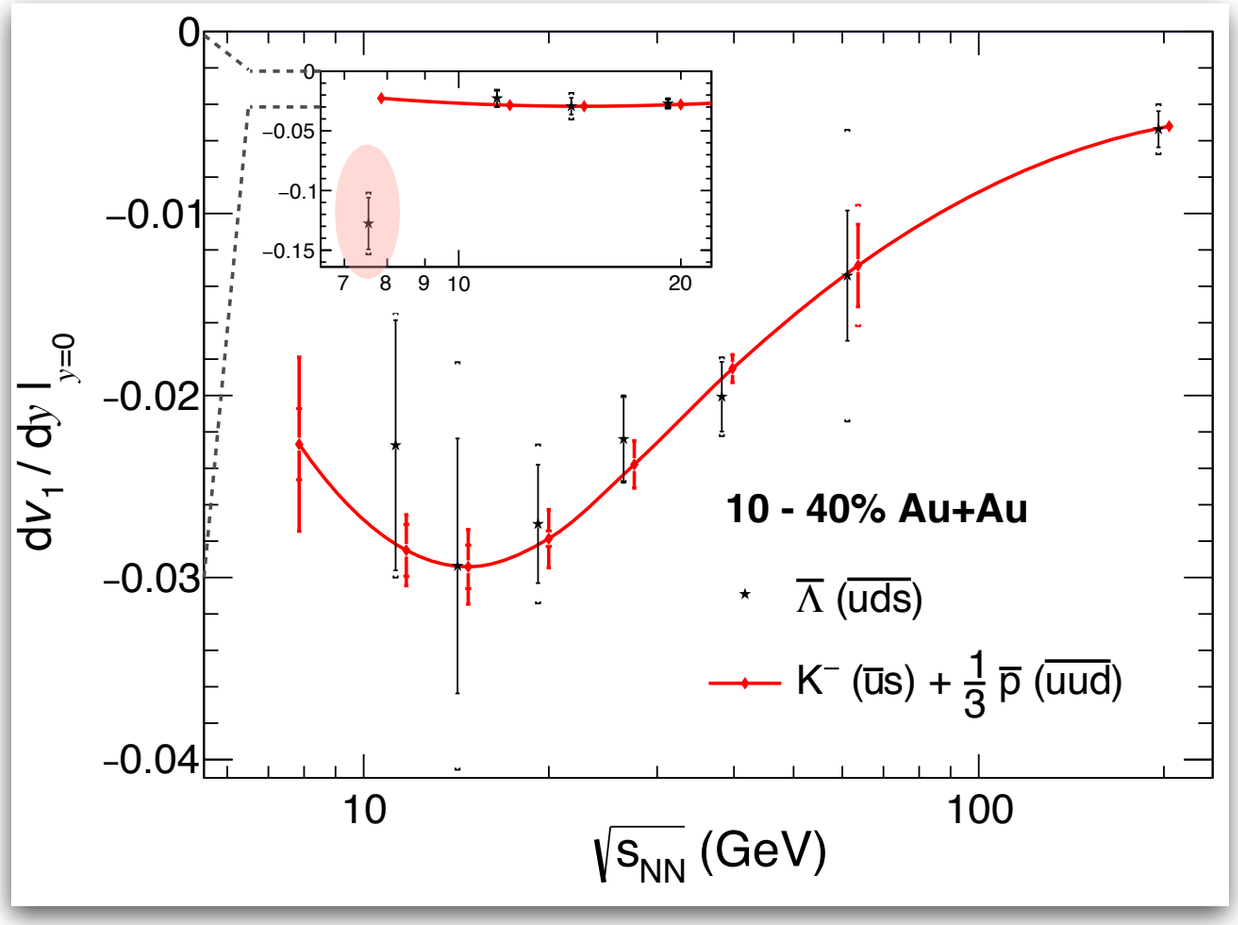
Indication of *partonic* collectivity and its disappearance at lower energies

STAR: PRL 112, 162301 (2014)
PRL 120, 062301 (2018)

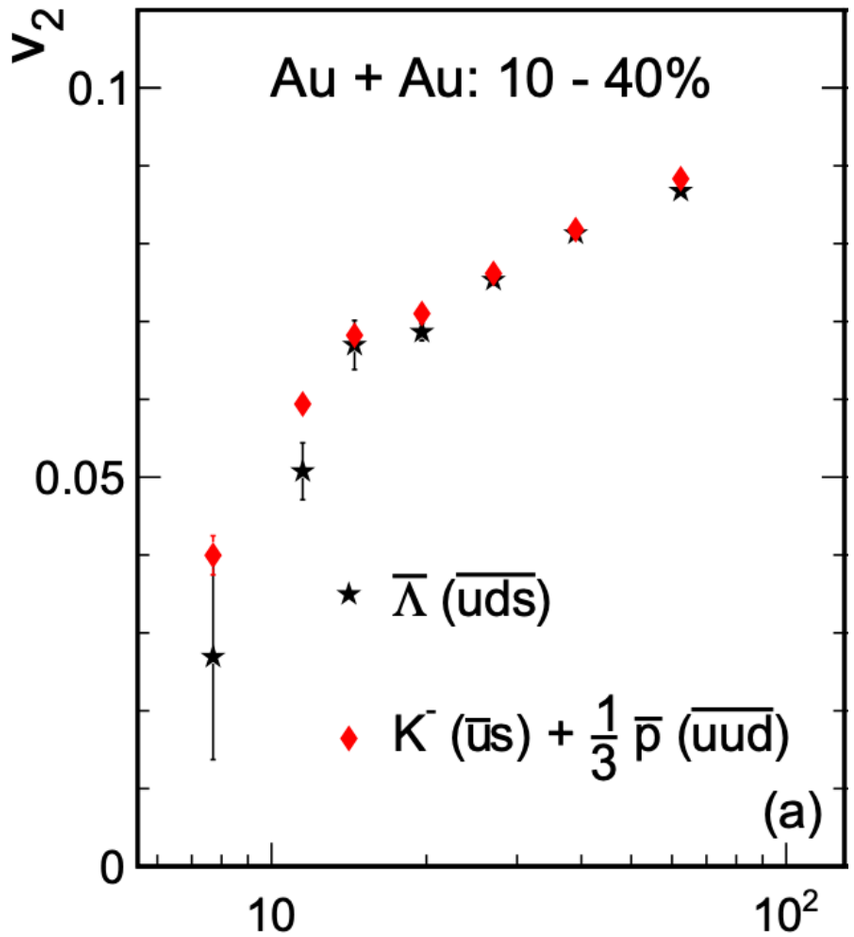
- Using anti-particles quark coalescence sum rule:
- Holds for $\sqrt{s_{\text{NN}}} \geq 11.5$ GeV
- Breaks at $\sqrt{s_{\text{NN}}} = 7.7$ GeV

Quark coalescence hypothesis with collective flow

Directed flow



Collective flow



- To be tested with better precision using BES-II data

Review article on directed flow

Review Article | Open Access
Volume 2016 | Article ID 2836989 | https://doi.org/10.1155/2016/2836989

Show citation

The First Moment of Azimuthal Anisotropy in Nuclear Collisions from AGS to LHC Energies

Subhash Singha,[1] Prashanth Shanmuganathan,[1] and Declan Keane[1]
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Academic Editor: Emil Bjerrum-Bohr

Received	Accepted	Published
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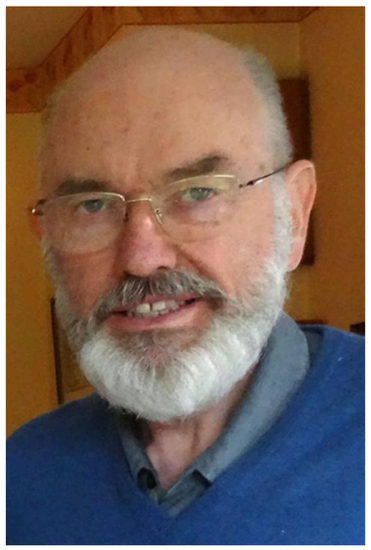
Abstract

We review topics related to the first moment of azimuthal anisotropy (v_1), commonly known as directed flow, focusing on both charged particles and identified particles from heavy-ion collisions. Beam energies from the highest available, at the CERN LHC, down to projectile kinetic energies per nucleon of a few GeV per nucleon, as studied in experiments at the Brookhaven AGS, fall within our scope. We focus on experimental measurements and on theoretical work where direct comparisons with experiment have been emphasized. The physics addressed or potentially addressed by this review topic includes the study of Quark Gluon Plasma and, more generally, investigation of the Quantum Chromodynamics phase diagram and the equation of state describing the accessible phases.

Declan's exceptional proficiency in crafting manuscripts

One of favorite GPC chair/member in STAR



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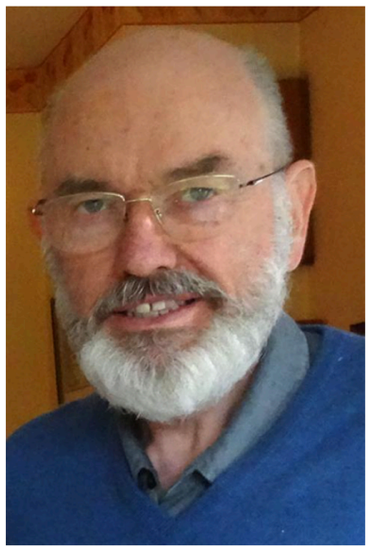
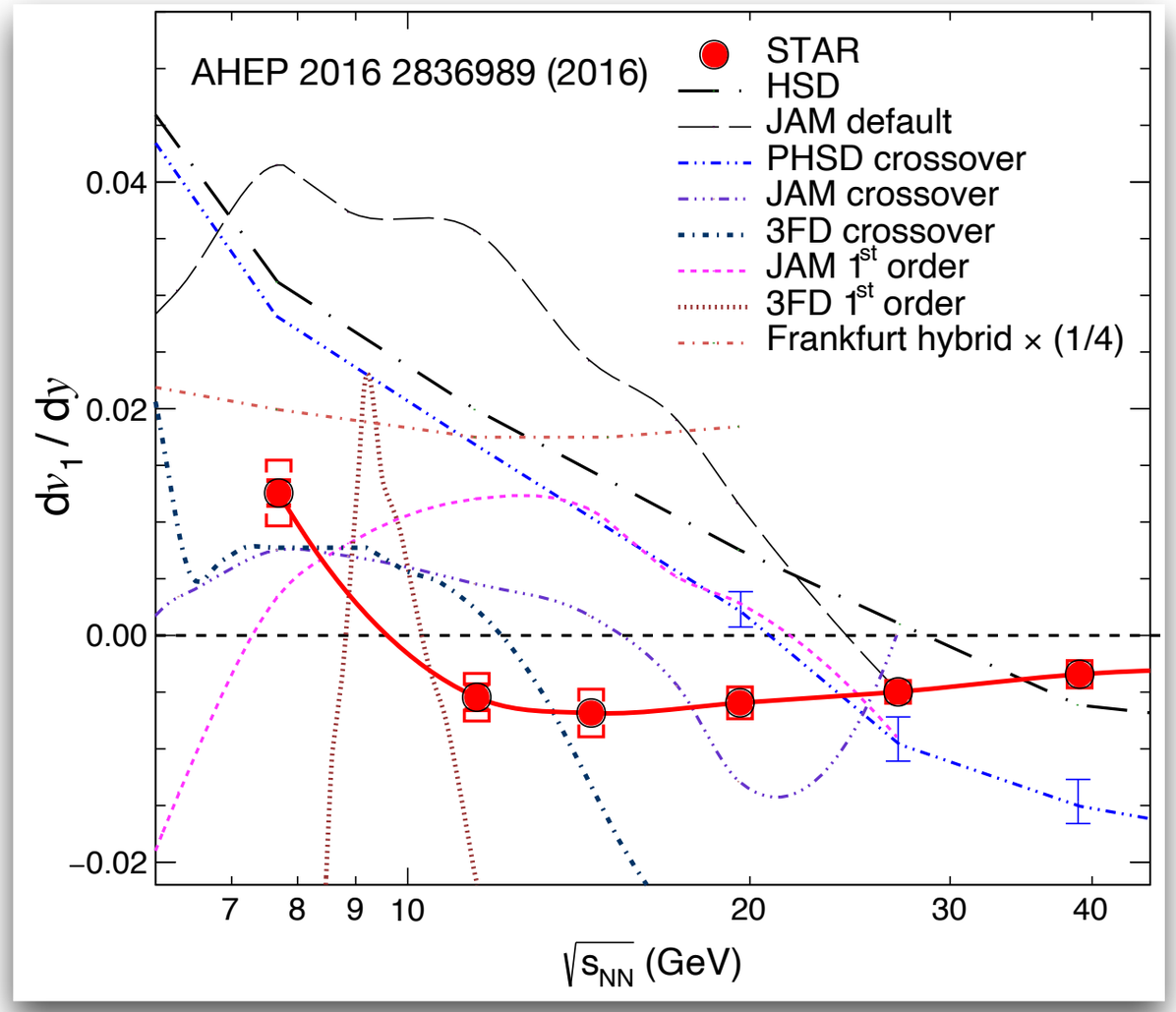


proton v_1 vs model

We looked “keanly" on proton v_1



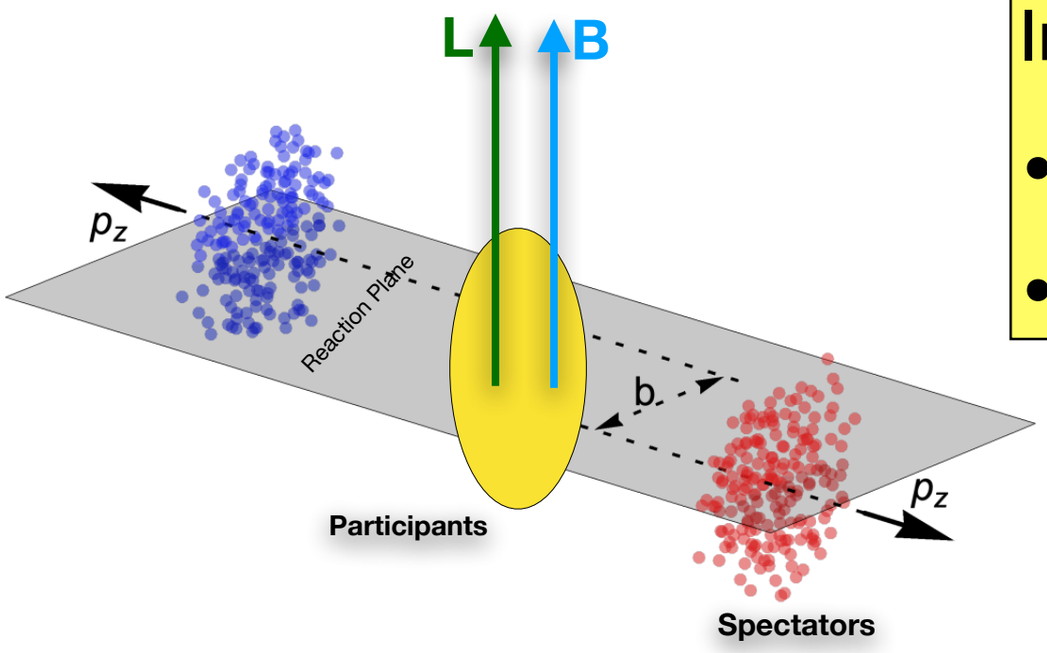
STAR Collaboration PRL 120, 062301, (2018)

HSD: Cassing et. al., arXiv: 1408.4313
PHSD: Khonchakovski et. al., PRC 90, 014903, (2014)
Hybrid: Steinheimer et. al., PRC 89, 054913 (2014)
3FD: Ivanov et. al., PRC 91, 024915, (2015)
JAM: Nara et. al., PLB 769, 543 (2017)

- Excellent precision provided by STAR
- Tough time for any theory to capture the pattern in data
- Systematics associated within the models is quite large

QCD matter under extreme conditions

QCD matter under extreme conditions



In non-central heavy-ion collisions

- **Initial rapid rotation** (ω ~ 10^{21} s^{-1})
- **Initial strong magnetic field** (B~ 10^{18} Gauss)

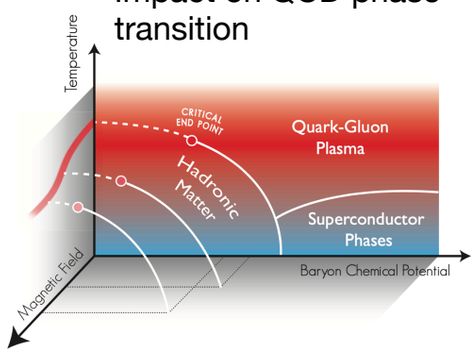
Heavy-ion collisions:

Controlled experiment to study QCD medium under rapid rotation and electro-magnetic field

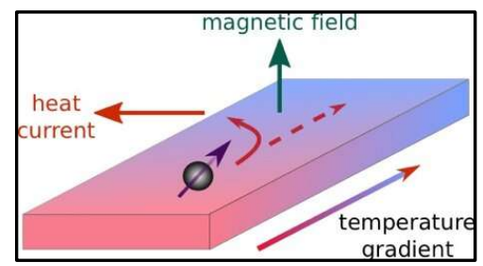
New frontier research to understand The properties of QCD medium

Neutron star with rapid rotation and **B** field

Impact on QCD phase transition

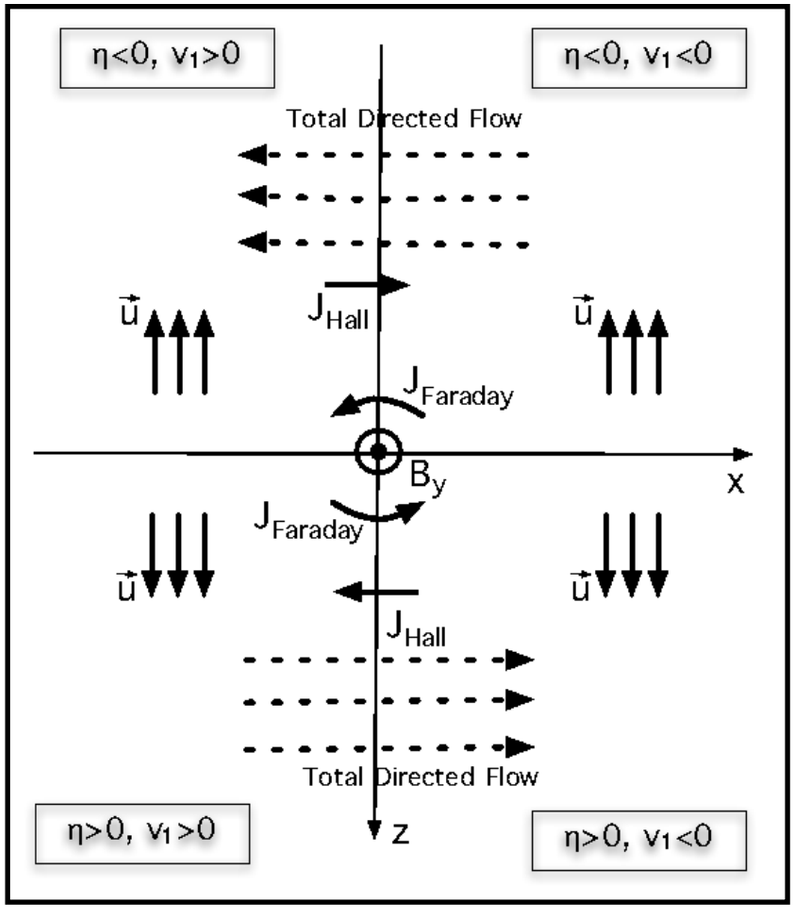


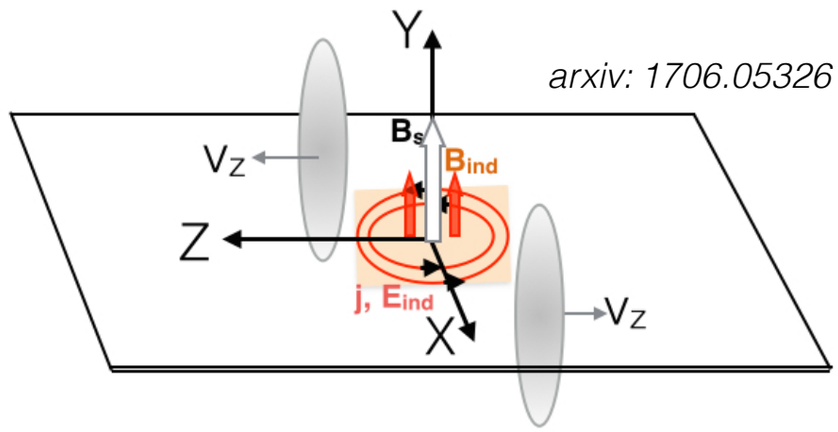
Enhanced thermal Hall effect under B-field



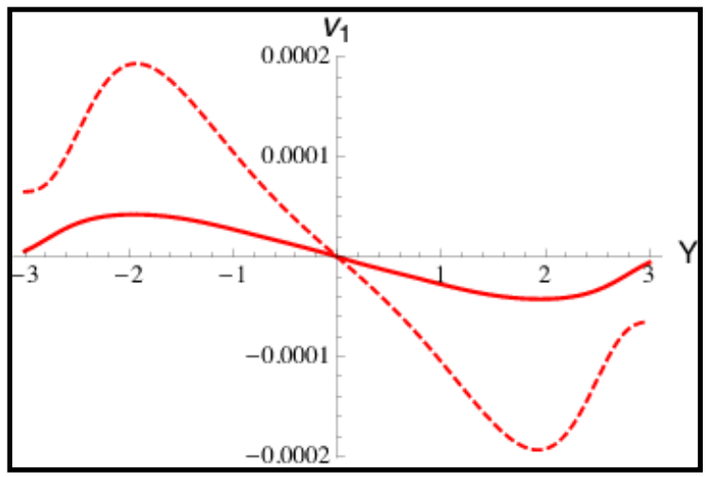
Charge dependent directed flow

Gursoy et.al. Phys. Rev. C 89, 054905 (2014)





arxiv: 1706.05326



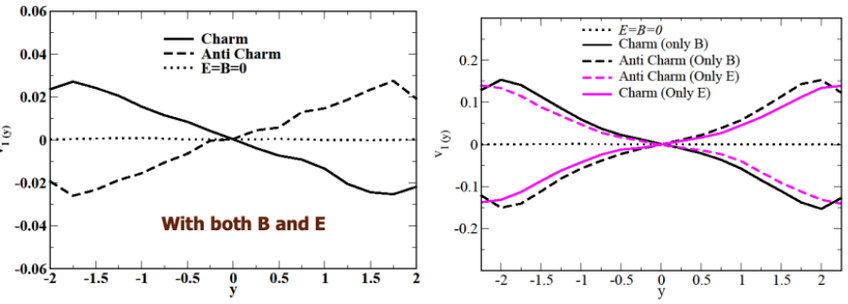
For light quarks:
predicted v_1-splitting
below sub-percent level

- The moving spectators can produce enormously large **B** field (eB ~10^{18} G)
- There could be two competitive effects
- Hall effect: $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$
  Lorentz force directed along -ve X-direction in +ve rapidity and vice-versa
- Faraday effect: $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
  Time dependent **B** field generates a large **E** field
  Induced Faraday current will oppose the drift due to **B** field

Charge dependent charm directed flow

Initial theory input

S. Das @ SQM 2016

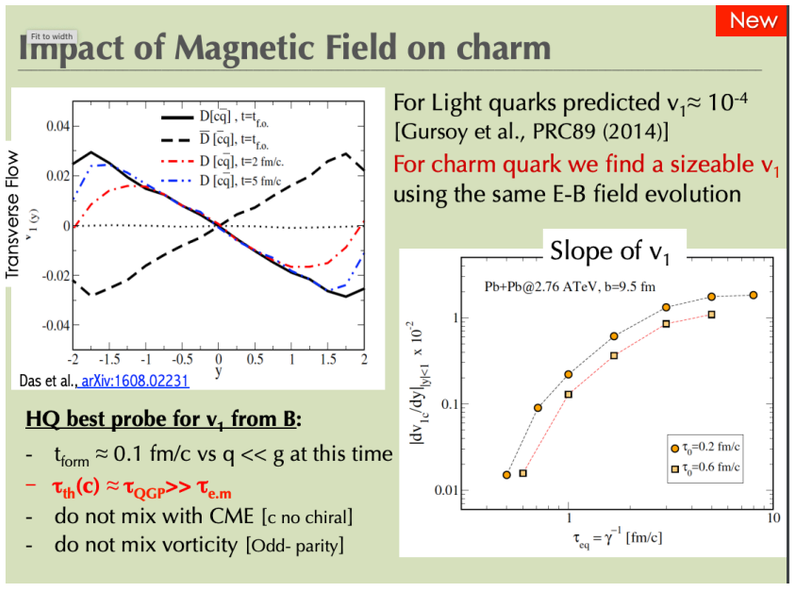


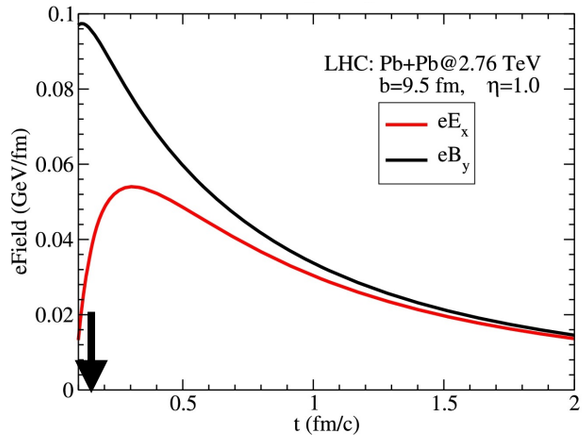
The simulation is done starting from tau_0=0.2 fm.
The sign of v1 due to B is decided by $v \times B$
E act opposite to B.

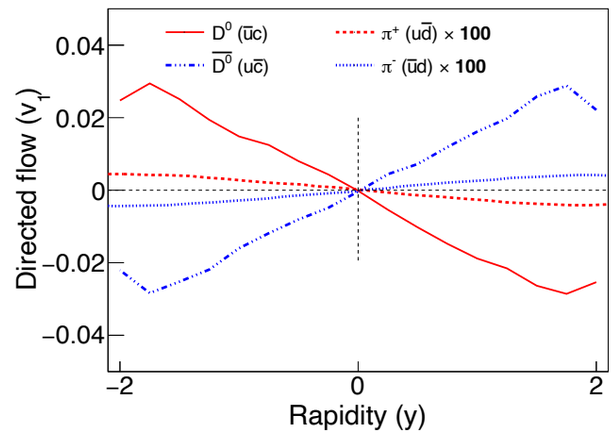
Das, Plumari, Chartarjee, Scardina, Greco, Alam
Under preparation

At RHIC the v1 could be around 1-2 % on which we are working currently.

V. Greco @ QM 2018







Charm quark

Formation time: τ_{CQ}~ 0.1 fm/c
Long relaxation time

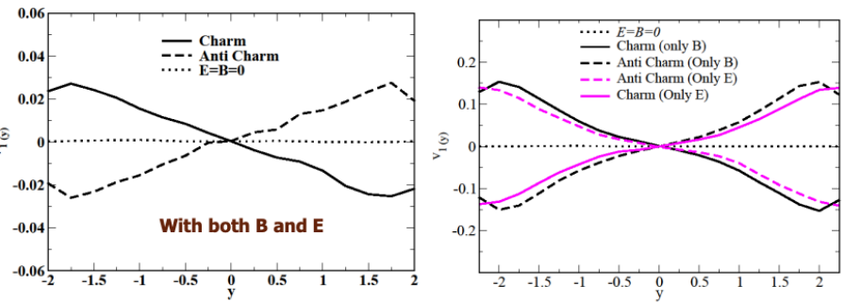
Sensitive to early time B-field
Can retain its memory

Predicted splitting at a measurable range for charm hadrons

Charge dependent charm directed flow

Initial theory input

S. Das @ SQM 2016

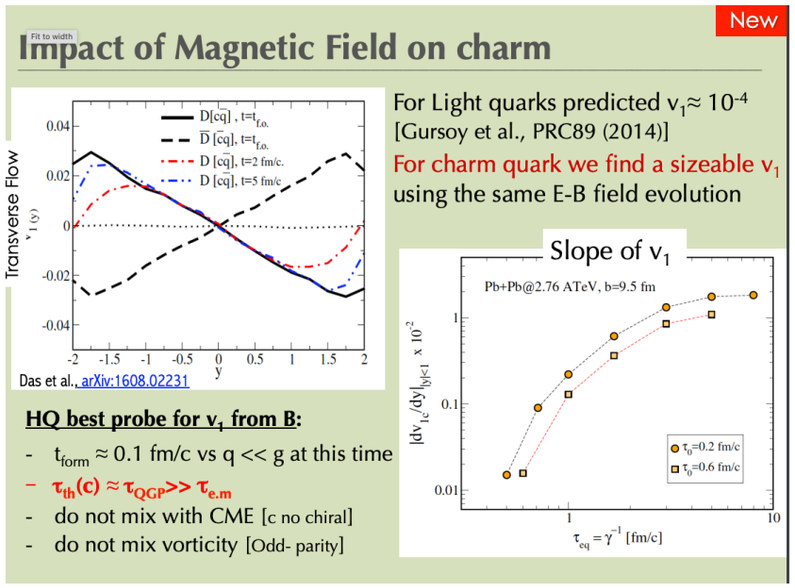


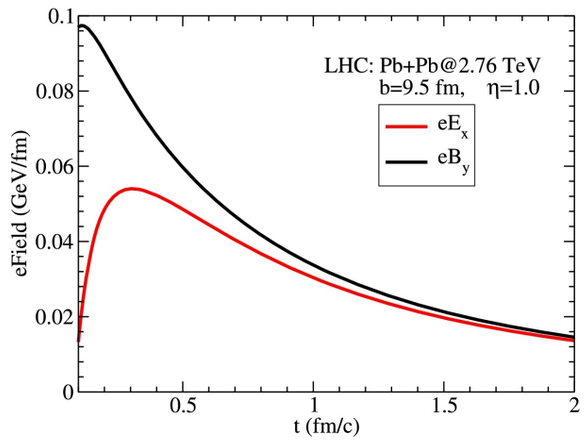
The simulation is done starting from tau_0=0.2 fm.
The sign of v1 due to B is decided by $v \times B$
E act opposite to B.

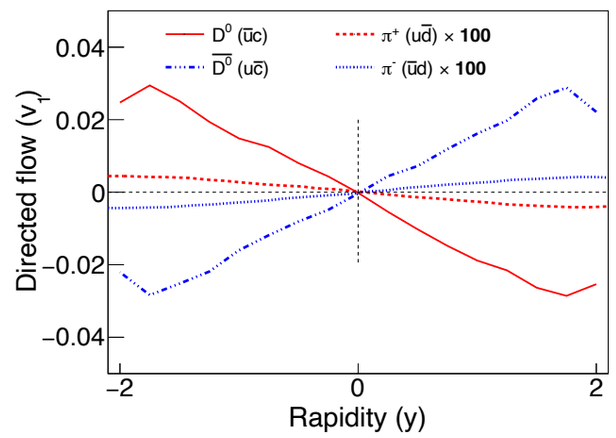
Das, Plumari, Chartarjee, Scardina, Greco, Alam
Under preparation

At RHIC the v1 could be around 1-2 % on which we are working currently.

V. Greco @ QM 2018





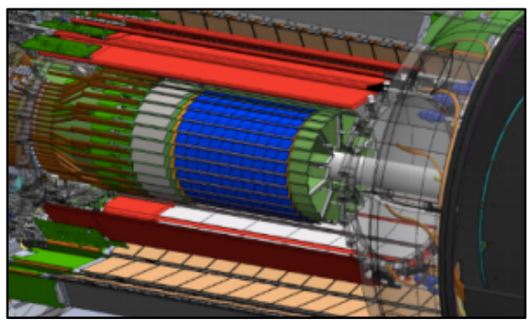


Predicted splitting at a measurable range for charm hadrons

When we took this idea to Declan and in his words:

*It was a marriage between **HFT** (D^0) and **ZDC** ($v_1(\Psi_1)$)*

HFT

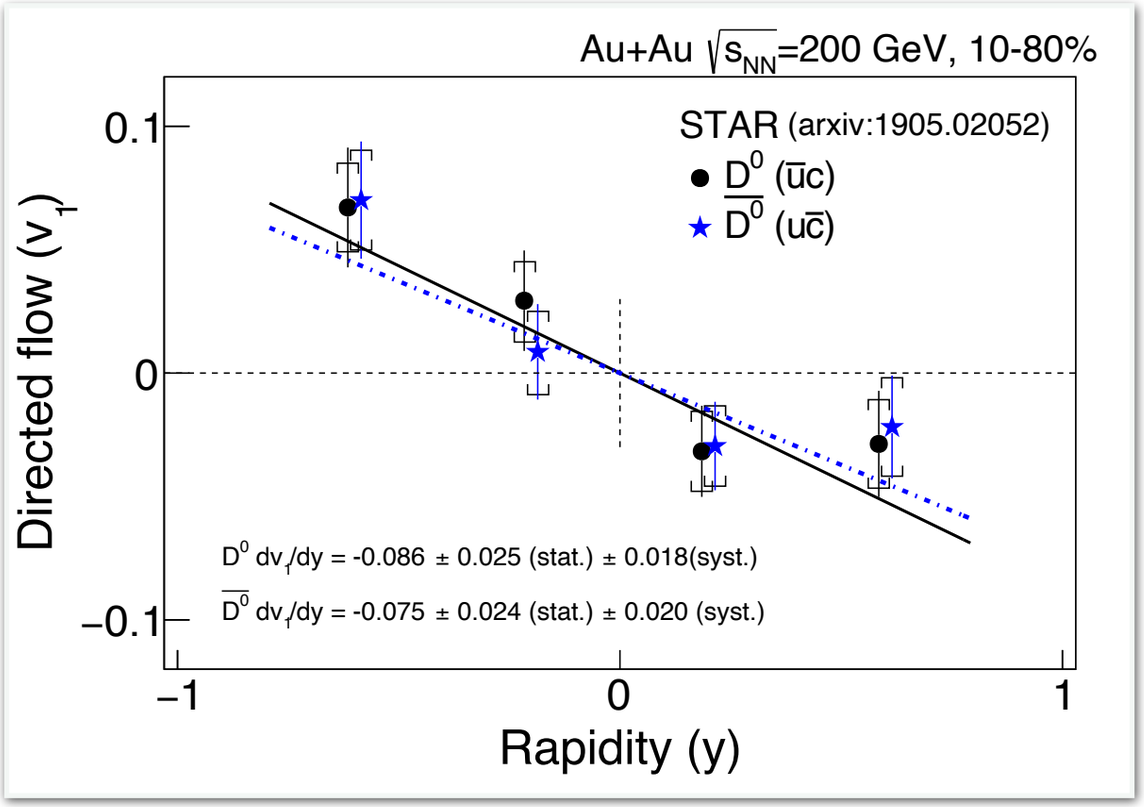


ZDC

First observation of D^0 directed flow

First Observation of the Directed Flow of D^0 and $\overline{D^0}$ in $\mathrm{Au}+\mathrm{Au}$ Collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$

J. Adam *et al.* (STAR Collaboration)
Phys. Rev. Lett. **123**, 162301 – Published 16 October 2019



The marriage was successful with a but …

Nature always surprise us with unexpected findings

- First observation of charm quark v_1
- Remarkably large magnitude of charm hadron v_1

First observation of D^0 directed flow

First Observation of the Directed Flow of D^0 and $\overline{D^0}$ in $\mathrm{Au}+\mathrm{Au}$ Collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$

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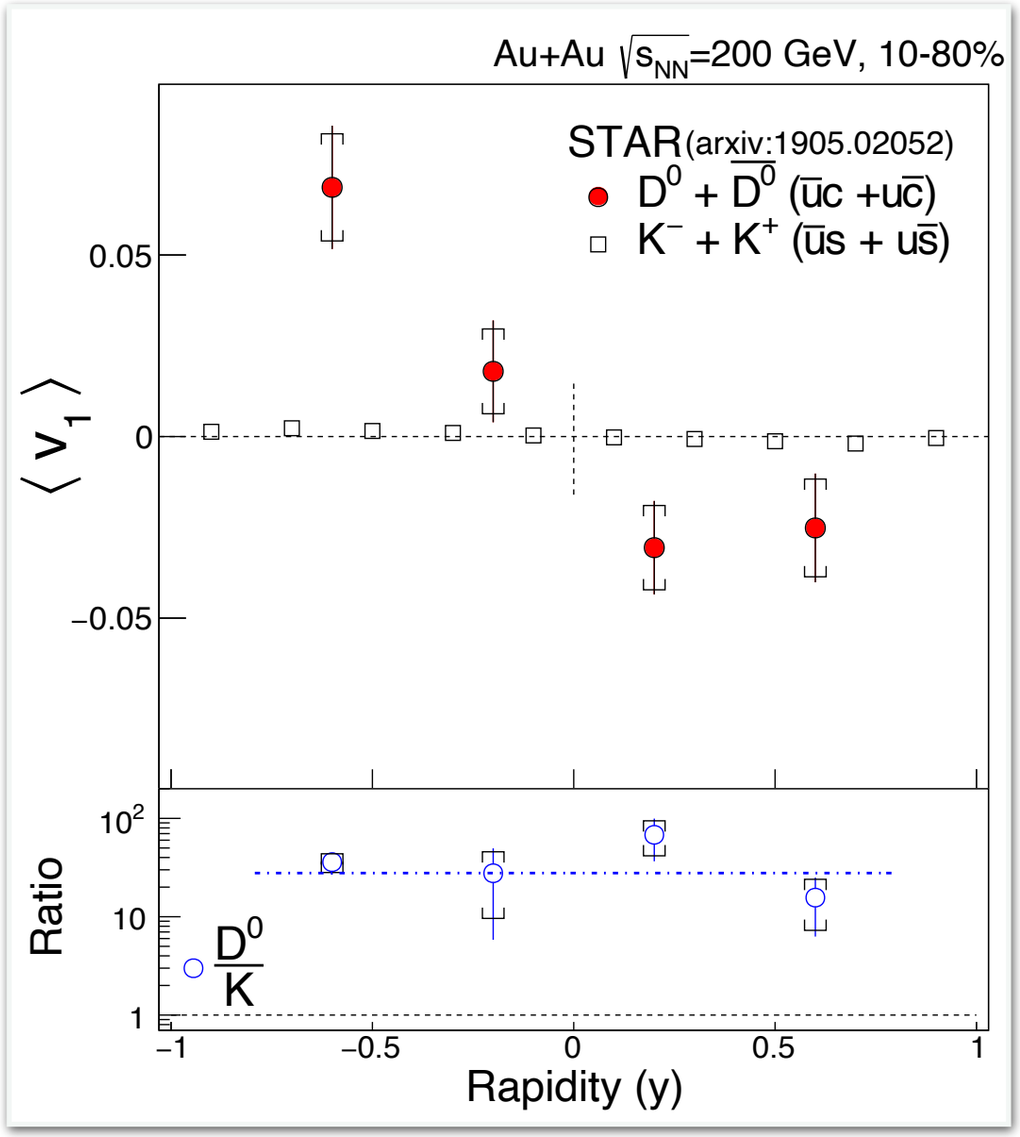


Initially, quite hard to interpret these data

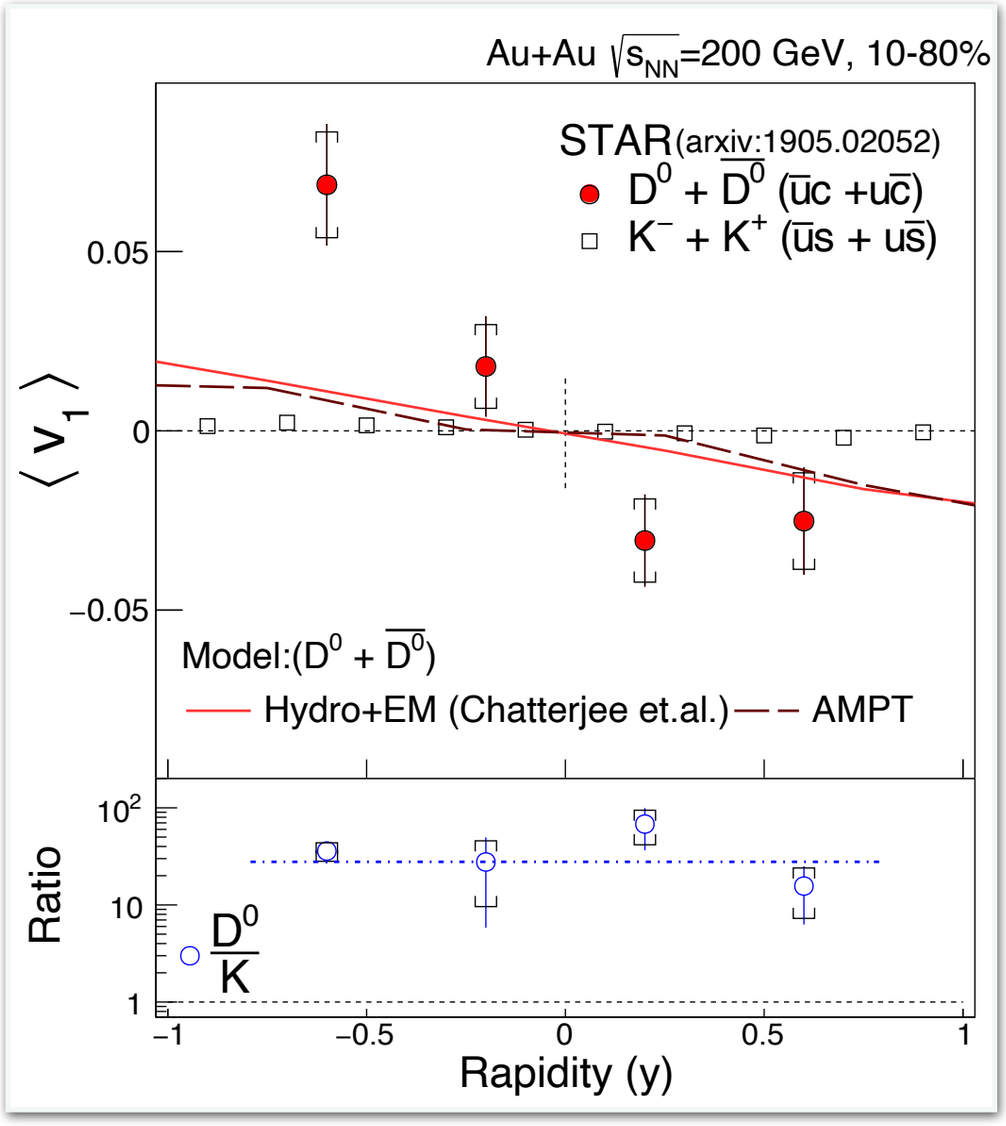
Nature always surprise us with unexpected findings

- First evidence of charm quark v_1
- Charm v_1 slope ~ 25 × Light-flavor v_1 slope

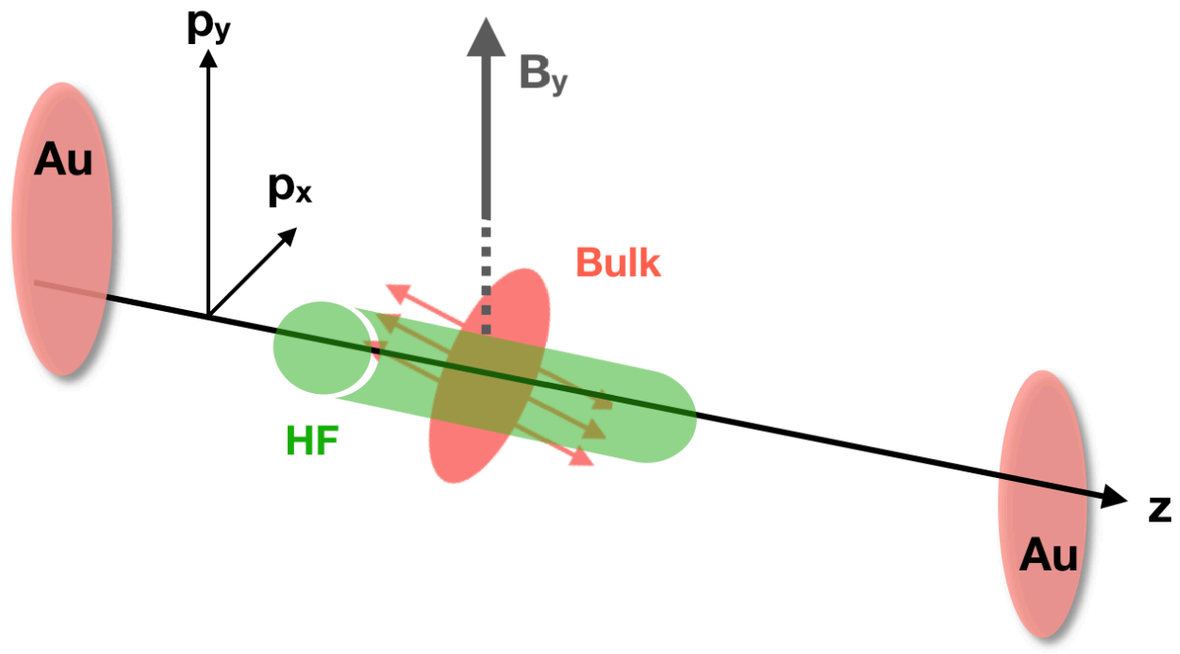
In Declan's word

QCD vs QED

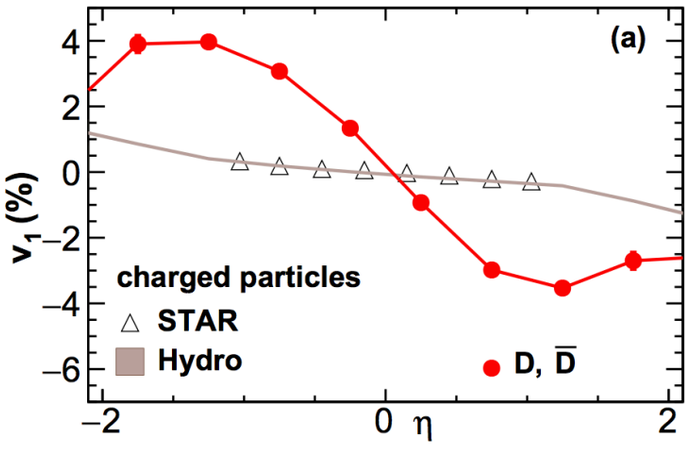
First observation of D^0 directed flow: interpretation

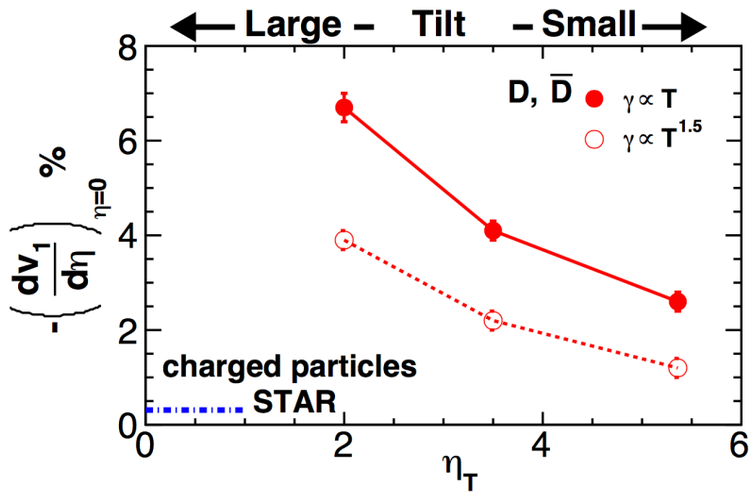


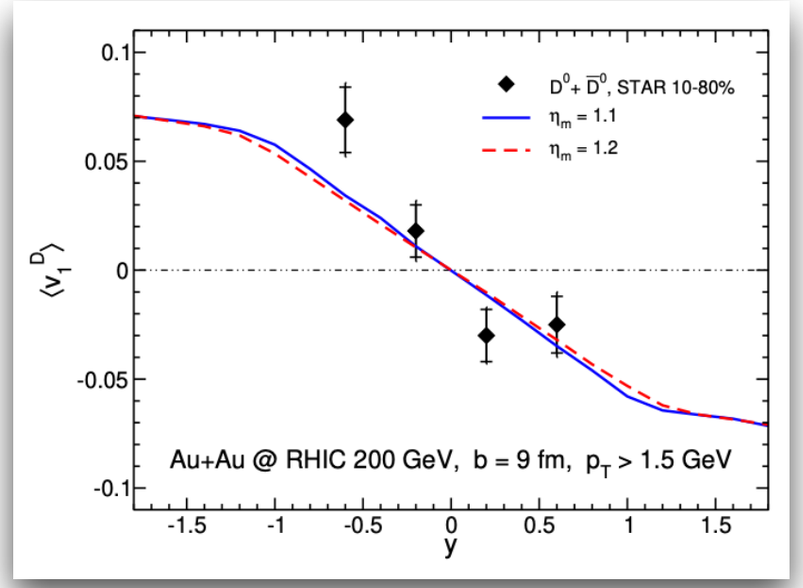
- Role of initial "*tilted*" geometry
- Charm transport "*drag*" coefficient

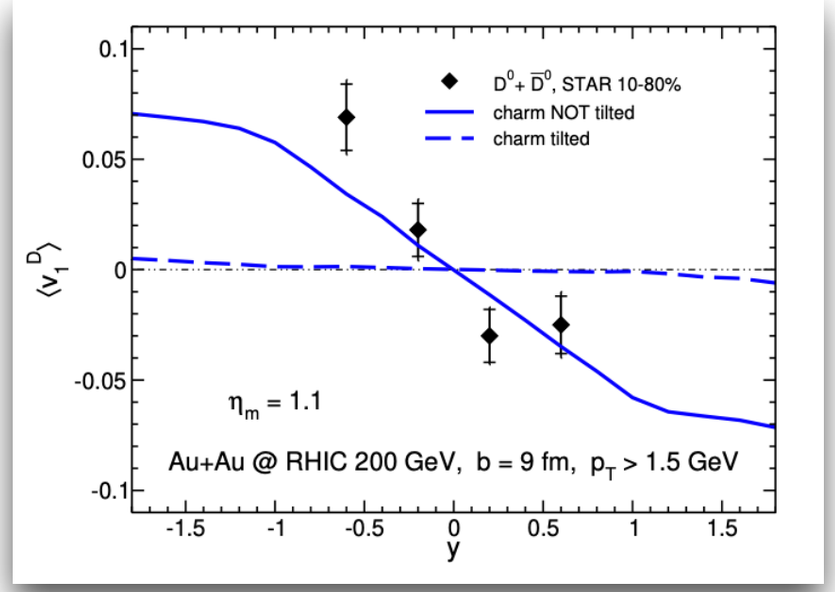


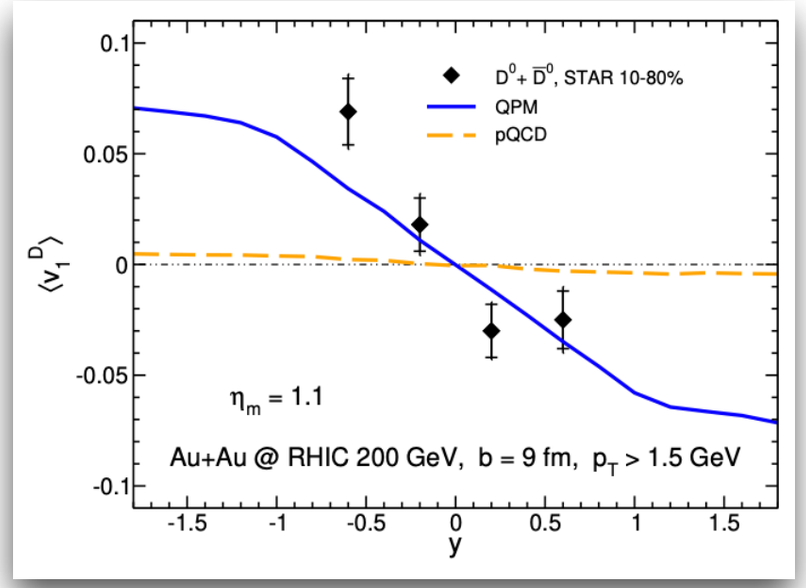
D^0 directed flow: data vs model









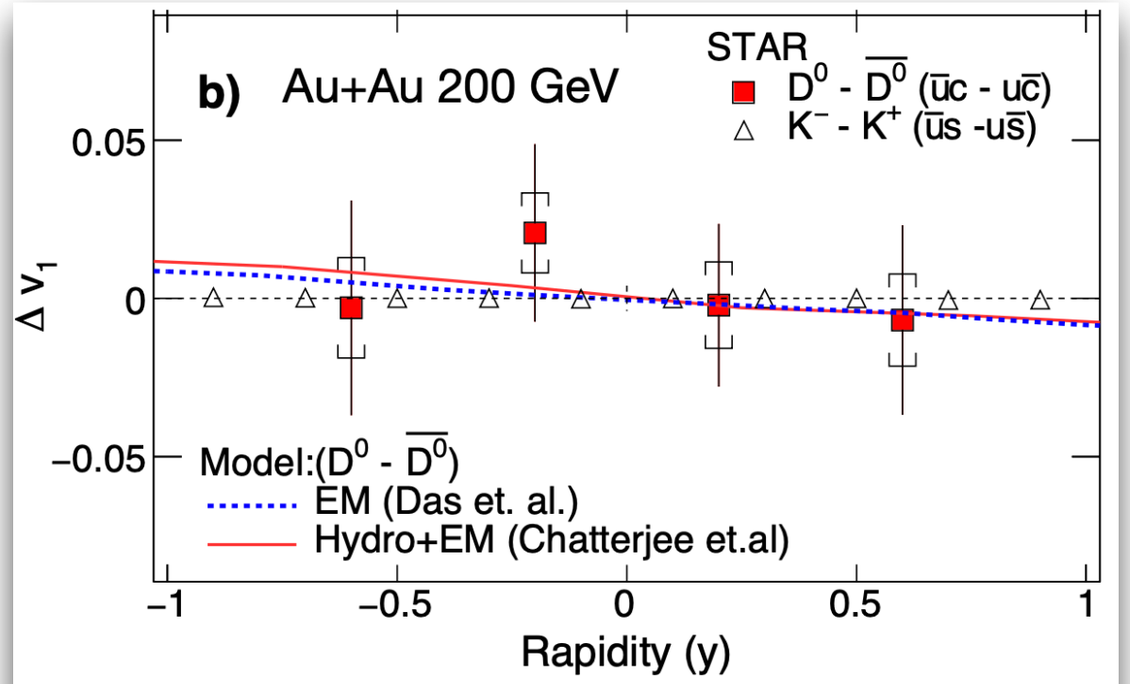


JHEP 05 (2021) 034

- Initial "*tilted*" geometry and "*drag*" force can explain data

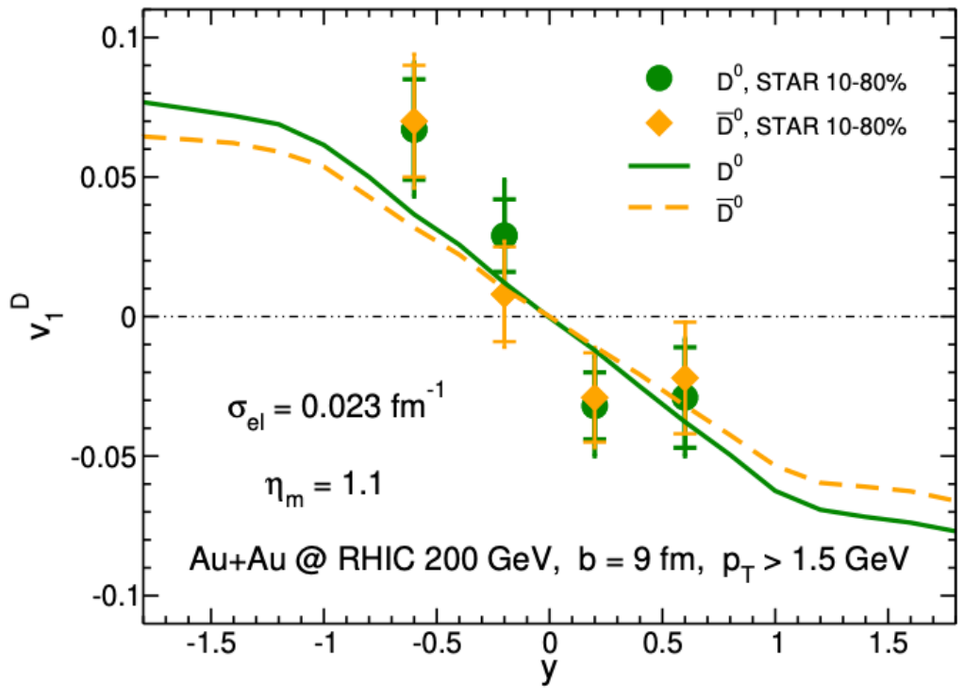
Charge dependent charm directed flow

Not sufficient precision at STAR



Model: with electrical conductivity of QGP

JHEP 05 (2021) 034

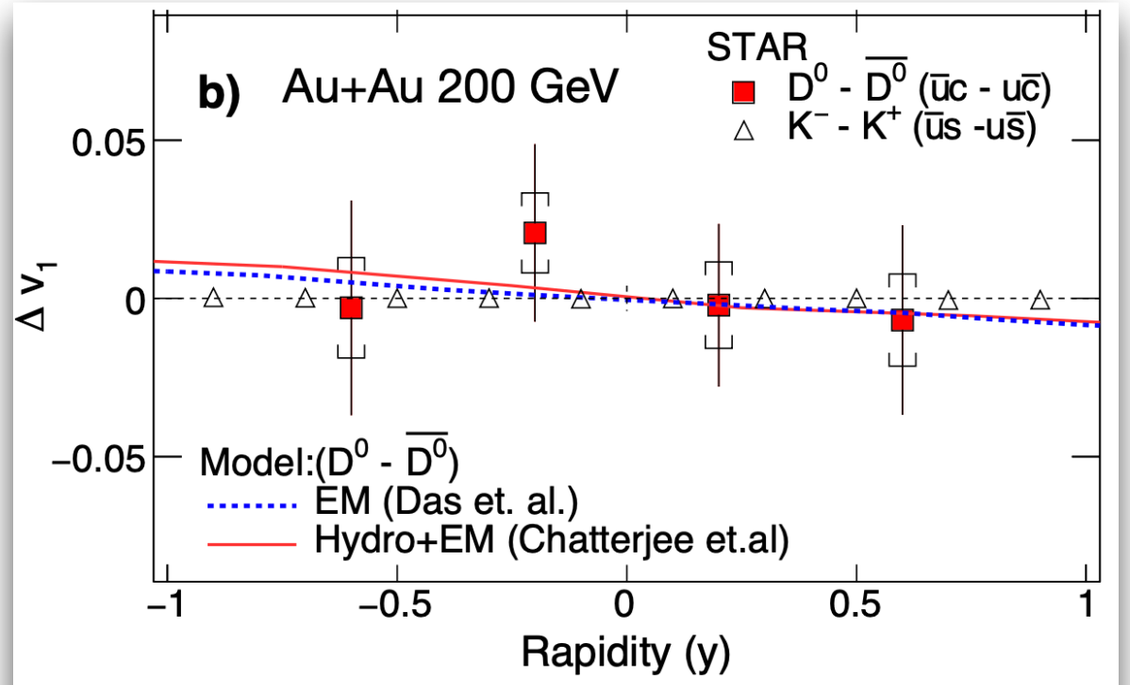


- First attempt to probe ultra-strong electro-magnetic field via charge dependent charm v_1
- Results were inconclusive, not enough precision to constrain QGP conductivity

Charge dependent charm directed flow

Not sufficient precision at STAR

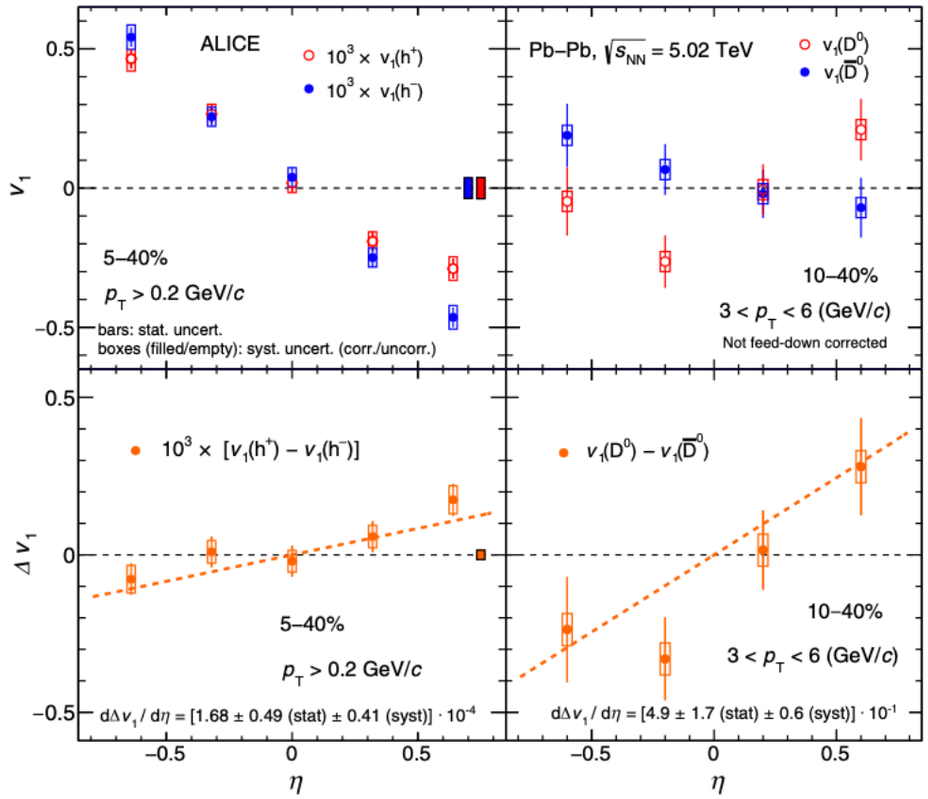
STAR



1905.02052 arXiv posting:
Mon, 6 May 2019 14:04:01 UTC

Not sufficient precision at ALICE
(Run-3 can provide good precision)

ALICE



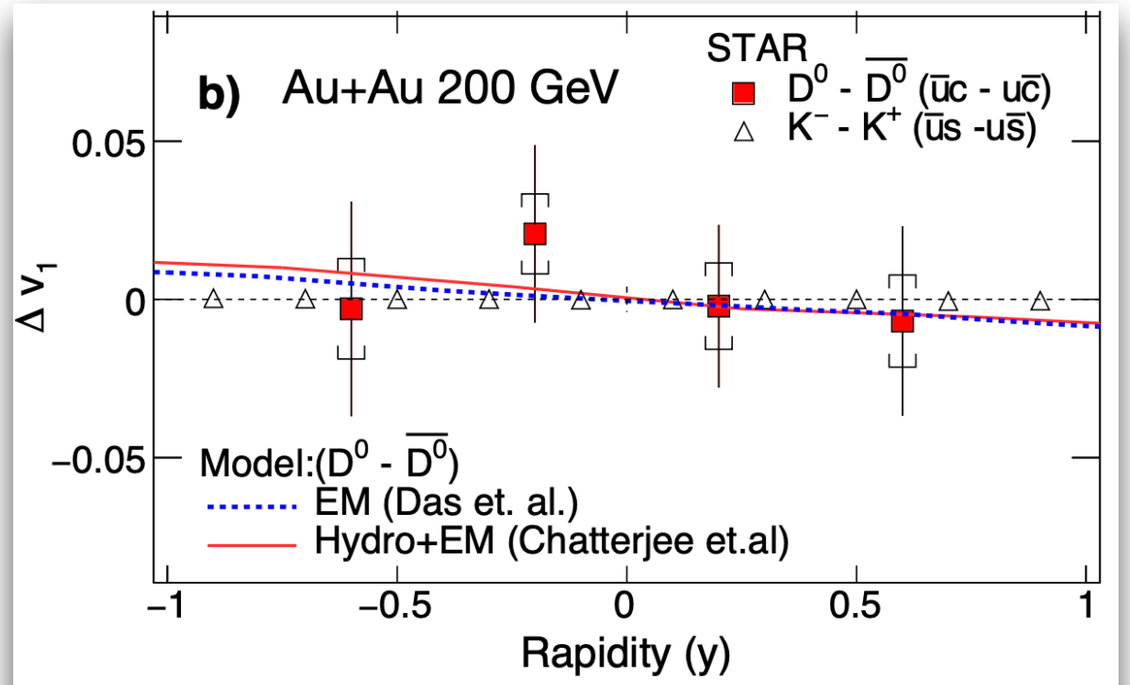
1910.14406 arXiv posting:
Thu, 31 Oct 2019 12:00:24 UTC

- First attempt to probe ultra-strong electro-magnetic field via charge dependent charm v_1
- ALICE: about 2.7σ
- Note: splitting sign seems to be opposite at RHIC and LHC

Charge dependent charm directed flow

Not sufficient precision at STAR

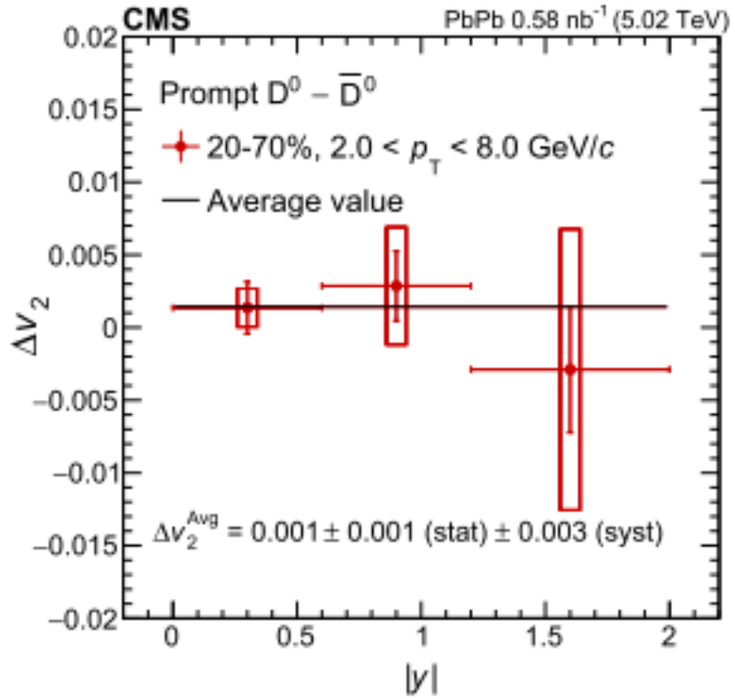
STAR



1905.02052 arXiv posting:
Mon, 6 May 2019 14:04:01 UTC

in search for strong electric field using v_2

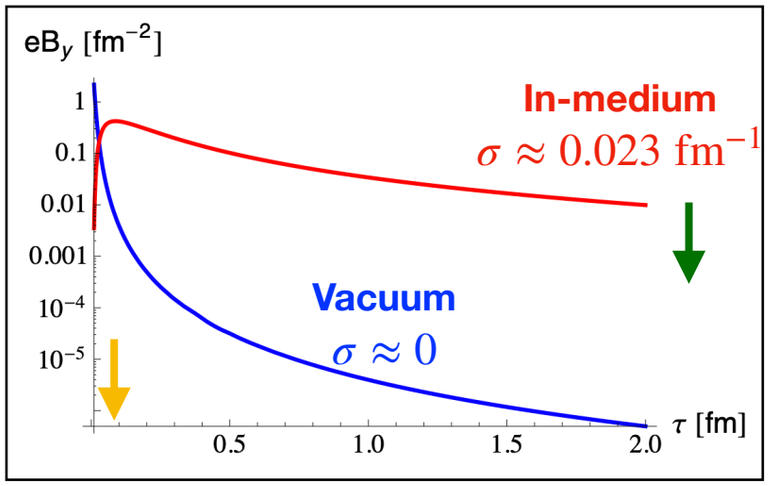
CMS



2009.12628 arXiv posting:
Sat, 26 Sep 2020 15:55:49 UTC

- First attempt to probe ultra-strong electro-magnetic field via charge dependent charm v_1
- CMS: In search of strong electric field

Charge dependent light quark directed flow



B-field at freeze-out

Initial B-field

Hall dominant

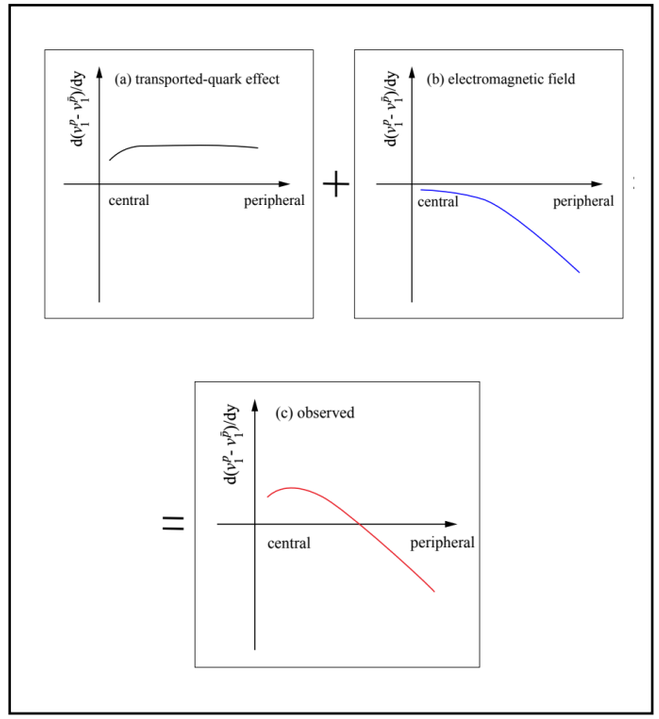
STAR did a "trial" with light hadron species

Recent high precision Au+Au, isobar and BES-II came in handy

Expectation

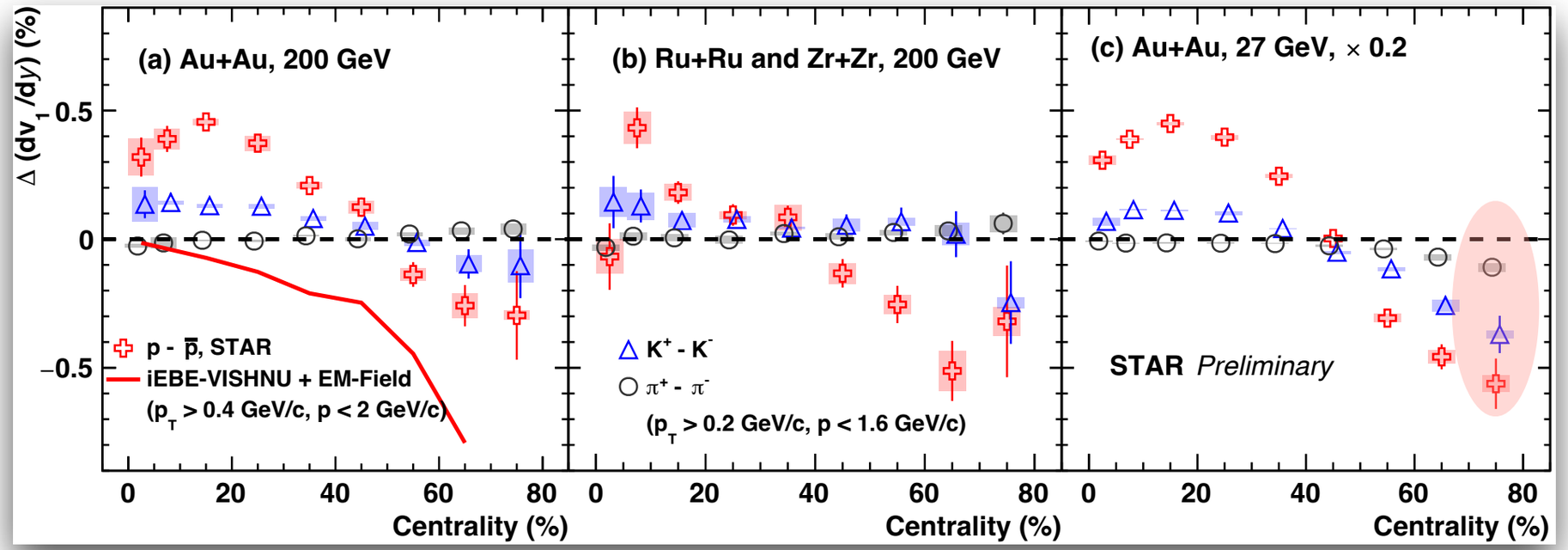
- **EM field effects**
- Hall: positive Δv_1
- Faraday: negative Δv_1
- Coulomb: negative Δv_1

- **Non-EM field effects**
- Transport: positive $\Delta v_1^{\dagger}$
- ....

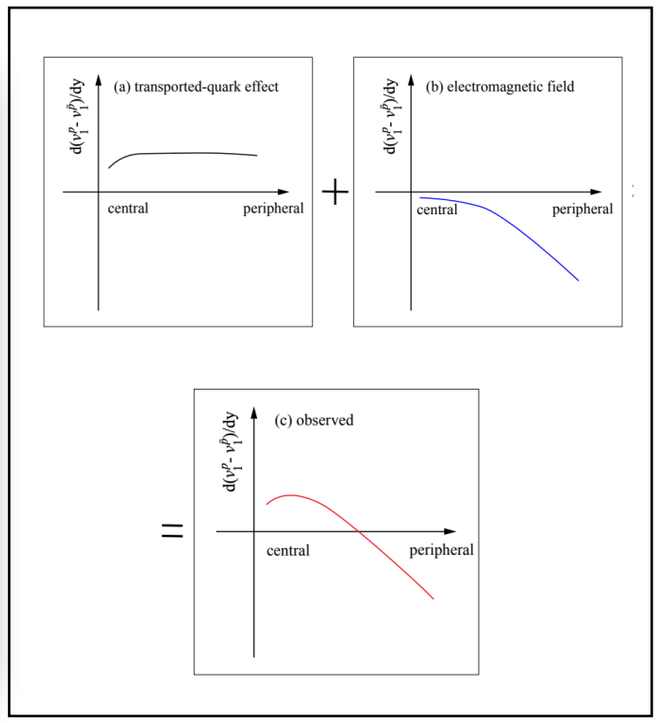


Charge dependent light quark directed flow

Observation



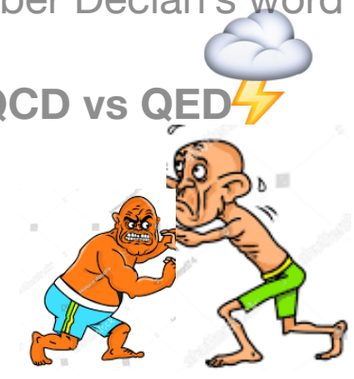
Expectation



- Charge dependent Δv_1 consistent with expectation from EM-field
- Consistent with dominance of Faraday and coulomb effect

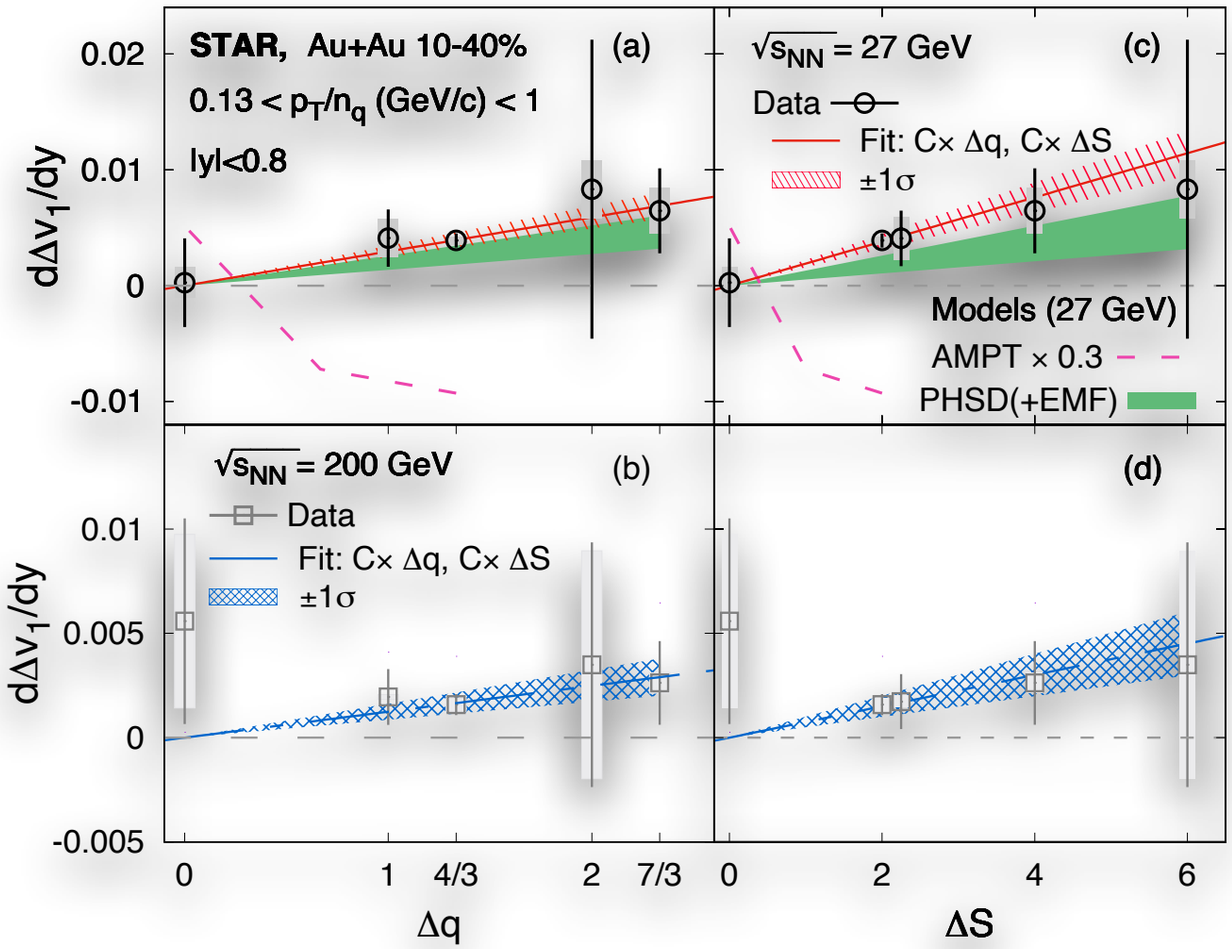
Remember Declan's word

Have we observed the effect from *strongest electromagnetic* (?) in QGP

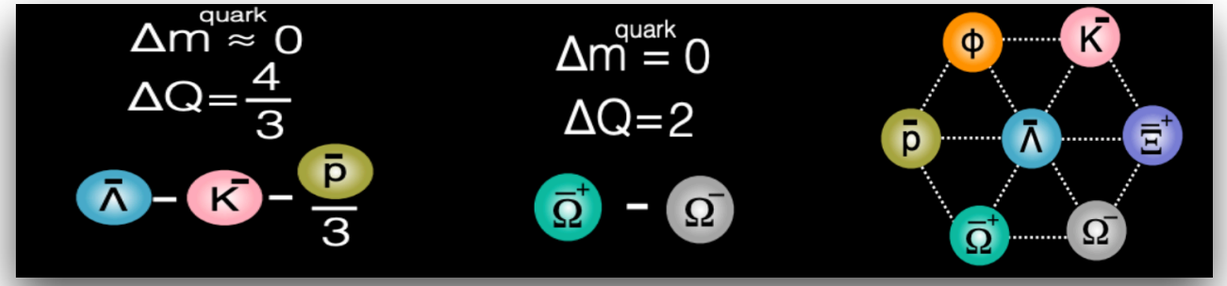


Charge dependent light quark directed flow

Au+Au and BES-II data



v_1 splitting measured using combination of *transported-quark-free* hadrons



- **v_1-slope difference** observed as function of charge difference (Δq) and strangeness difference (ΔS)
- **Larger v_1-slope difference** at 27 GeV than 200 GeV

- More intricacies in EM field evolution in QGP, quark species dependence, centrality dependence …

Remember Declan's word

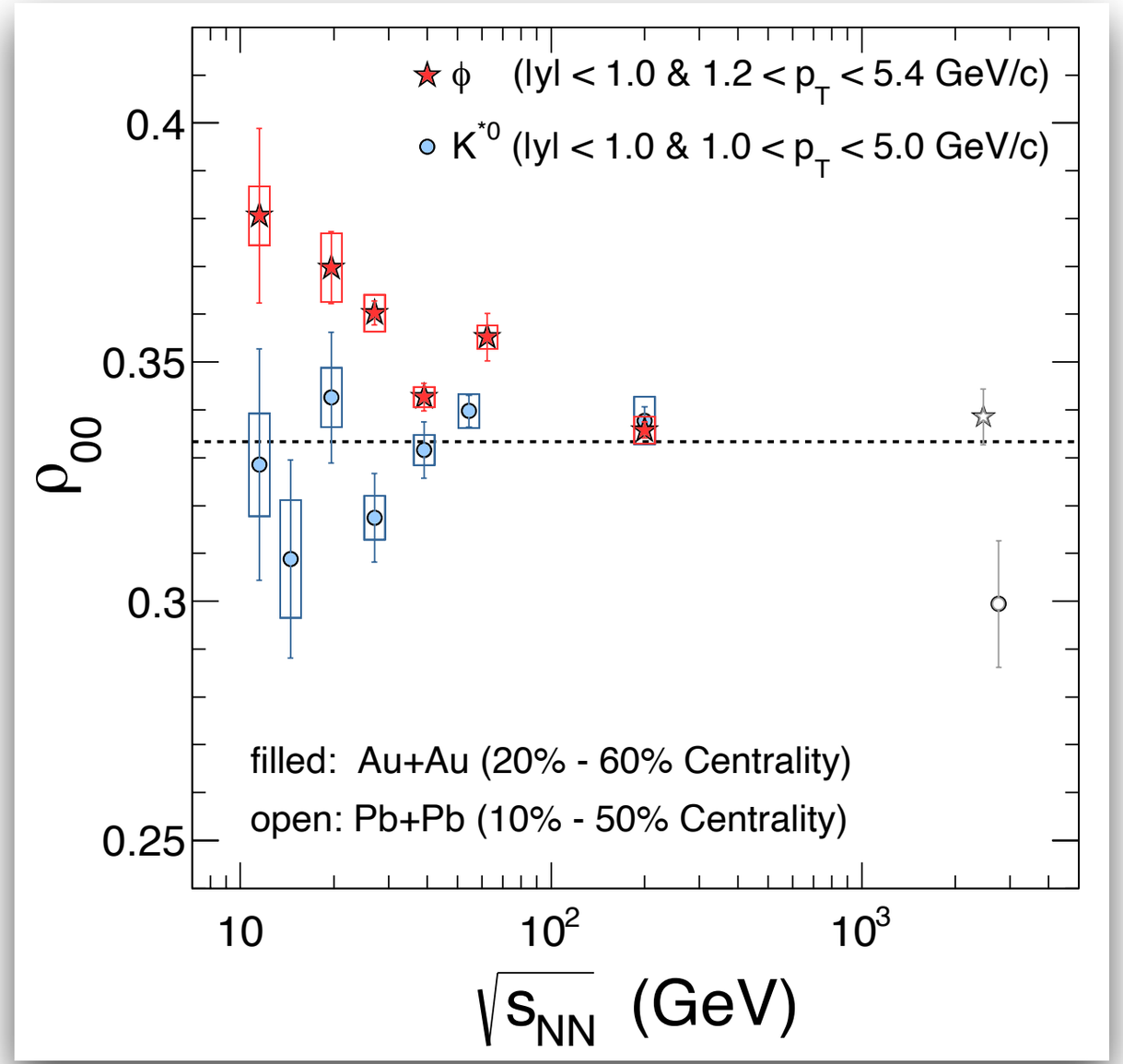
QCD vs QED

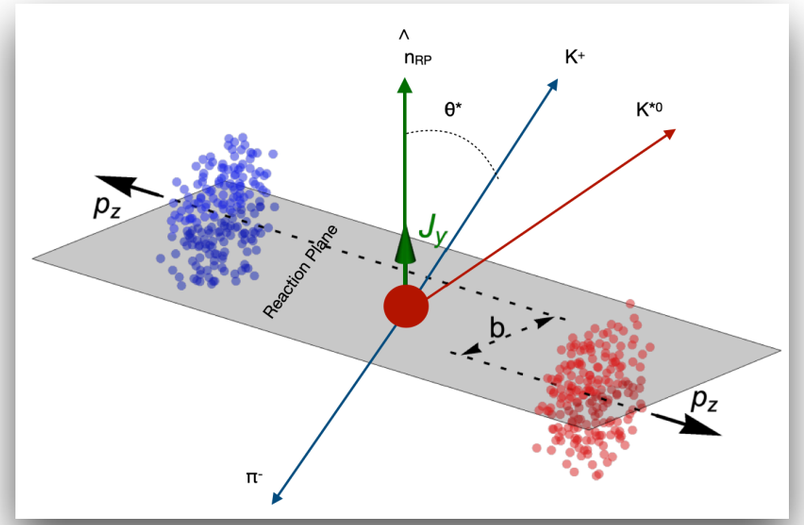
Have we observed the effect from *strongest electromagnetic* (?) in QGP

Spin alignment of vector mesons

STAR: **Nature**, 614, 244-248, (2023)
https://www.nature.com/articles/s41586-022-05557-5

$$\rho^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$





$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

- Surprisingly, ϕ **ρ_{00} >> 1/3** but K^{*0} ρ_{00} ~ 1/3
- Can not be explained by *conventional* polarization mechanisms
- ϕ meson results can be accommodated by a model invoking a strong force field of vector meson

$$\rho_{00}(\phi) \approx \frac{1}{3} + c_\Lambda + c_\epsilon + c_E + c_\phi$$

STAR publications with Declan

Beam-Energy Dependence of Directed Flow of Λ, $\bar{\Lambda}$, $K^{\pm}$, K^0_s, and ϕ in $\mathrm{Au}+\mathrm{Au}$ Collisions

L. Adamczyk *et al.* (STAR Collaboration)
Phys. Rev. Lett. **120**, 062301 – Published 6 February 2018

First Observation of the Directed Flow of D^0 and $\overline{D^0}$ in $\mathrm{Au}+\mathrm{Au}$ Collisions at $\sqrt{s_{NN}} = 200$ GeV

J. Adam *et al.* (STAR Collaboration)
Phys. Rev. Lett. **123**, 162301 – Published 16 October 2019

Bulk properties of the system formed in $\mathrm{Au}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 14.5$ GeV at the BNL STAR detector

J. Adam *et al.* (STAR Collaboration)
Phys. Rev. C **101**, 024905 – Published 7 February 2020

Pattern of global spin alignment of φ and K^{*0} mesons in heavy-ion collisions

STAR Collaboration

Nature **614**, 244–248 (2023) | Cite this article

3985 Accesses | **21** Citations | **172** Altmetric | Metrics

and a review article

Review Article | Open Access
Volume 2016 | Article ID 2836989 | https://doi.org/10.1155/2016/2836989

Show citation

The First Moment of Azimuthal Anisotropy in Nuclear Collisions from AGS to LHC Energies

Subhash Singha,[1] Prashanth Shanmuganathan,[1] and Declan Keane[1]

It was a wonderful and learning experience on *directed flow* (and productive)

Navigated various aspects : from light-quarks to heavy-quarks (and spin alignment)

From phase diagram (**QCD**) to electromagnetic field (**QED**)

The contest continues … and the winner to be announced …

Thank you Declan for your excellent mentorship, kind support and wisdom

We wish you a happy and healthy life ahead

Look forward to meet you in person