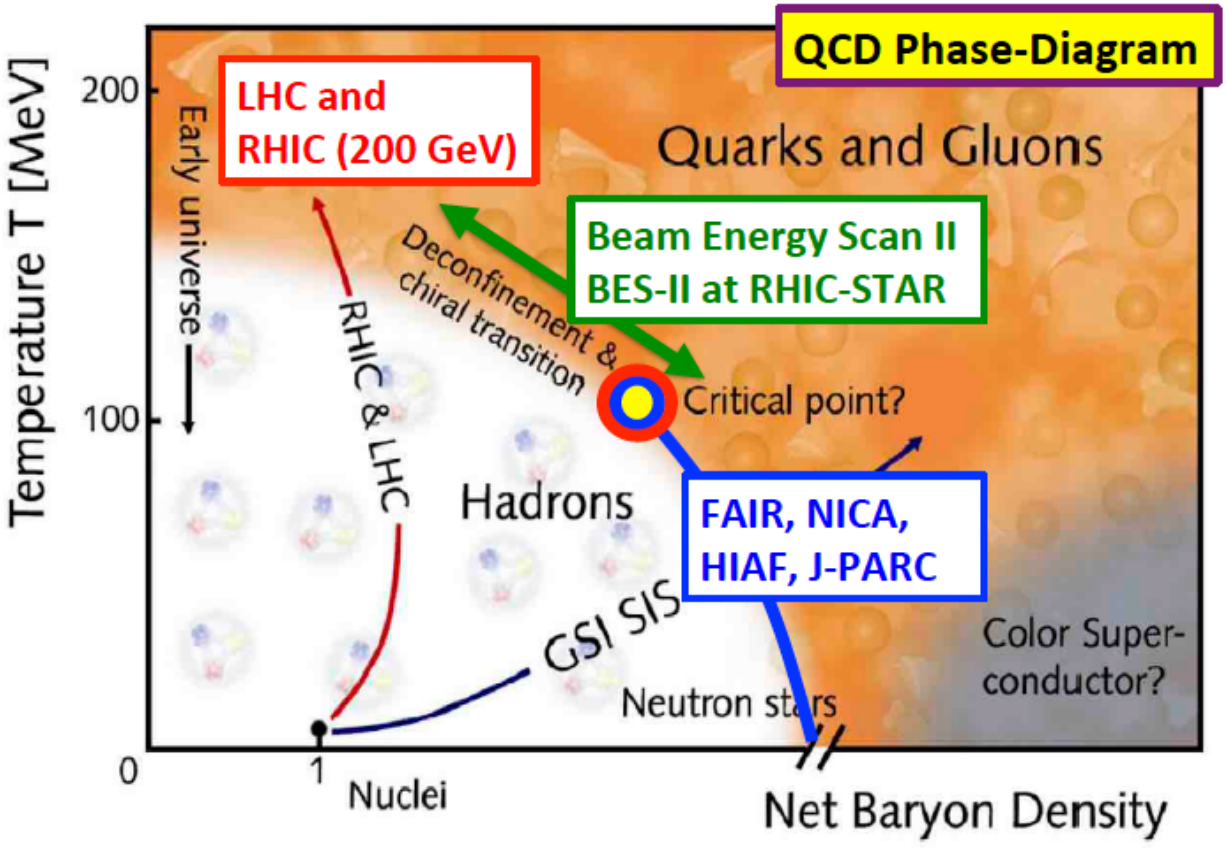
In part supported by
U.S. DEPARTMENT OF ENERGY | Office of Science

Results from Beam Energy Scan Program at RHIC-STAR

ShinIchi Esumi for the STAR collaboration

Inst. of Physics, Univ. of Tsukuba
Tomonaga Center for the History of the Universe



Contents

- Experimental setup
- Freeze-out and coalescence measurements
- Fluctuation and correlation measurements
- Elliptic and Directed flow measurements
- Vorticity and Chiral magnetic measurements

筑波大学 宇宙史研究センター Tomonaga Center for the History of the Universe

筑波大学 University of Tsukuba

8 additional talks from STAR experiment in this CPOD2021

(1) [Spectra, yield]

- Benjamin Kimelman : Meson production in Au+Au collisions at 3 GeV FXT
- Yue-Hang Leung : Hyper-nuclei lifetime, yield and directed flow at 3 GeV FXT

(2) [Fluctuation, correlation]

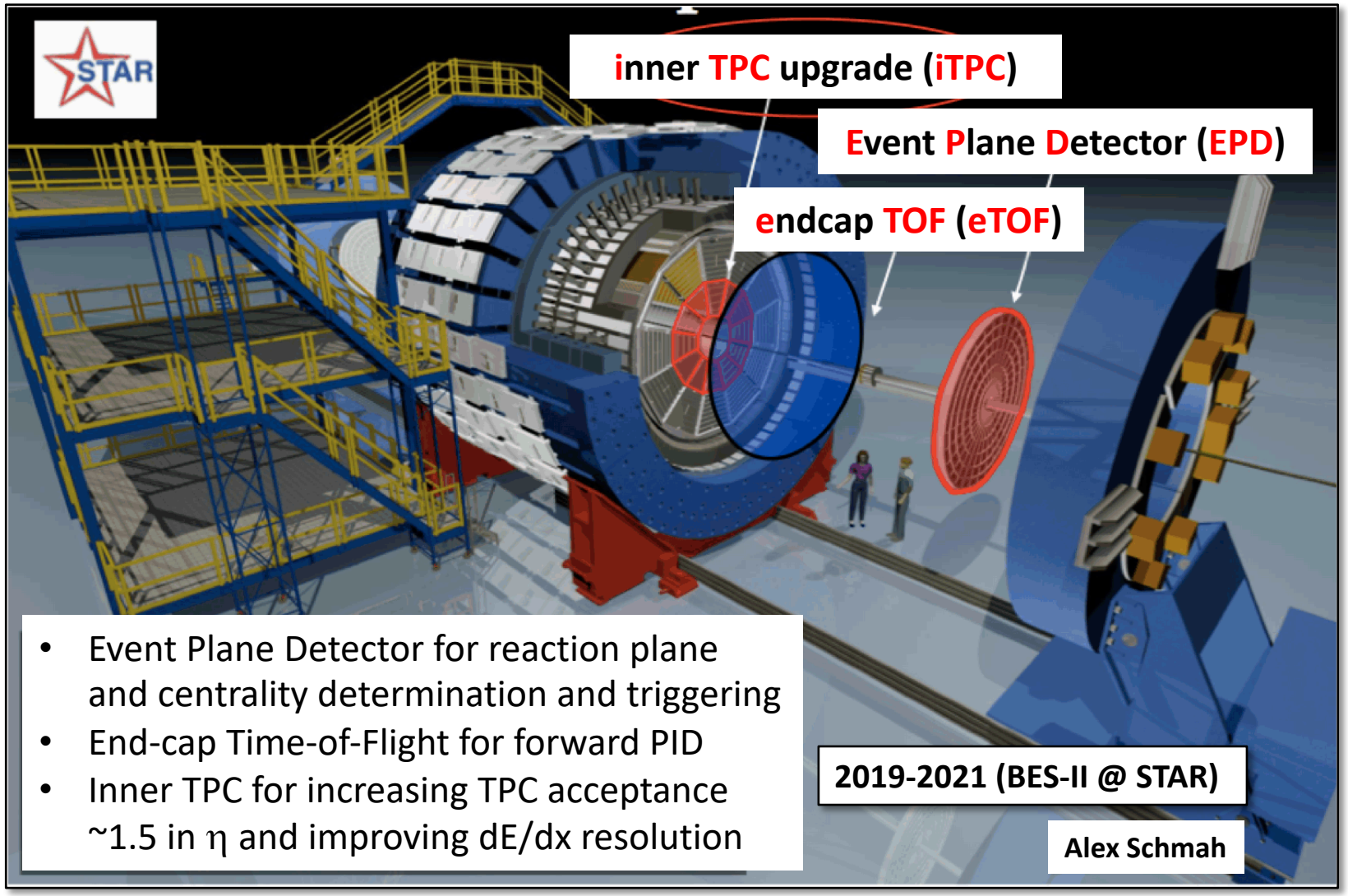
- Ashish Pandav : Beam energy dependence of net-proton c5 and c6
- Risa Nishitani : Higher order cumulants of net-proton in pp at 200 GeV
- Hanna Zbroszczyk : STAR results on femtoscopy at the BES program

(3) [Flow]

- Prabhupada Dixit : Yield and flow of strange- and multi-strange hadrons
- Shaowei Lan : Anisotropic flow measurements of identified particle
- Xionghong He : Light nuclei production and flow in Au+Au collisions at 3 GeV FXT

(4) [Vorticity, Chiral magnetic…]

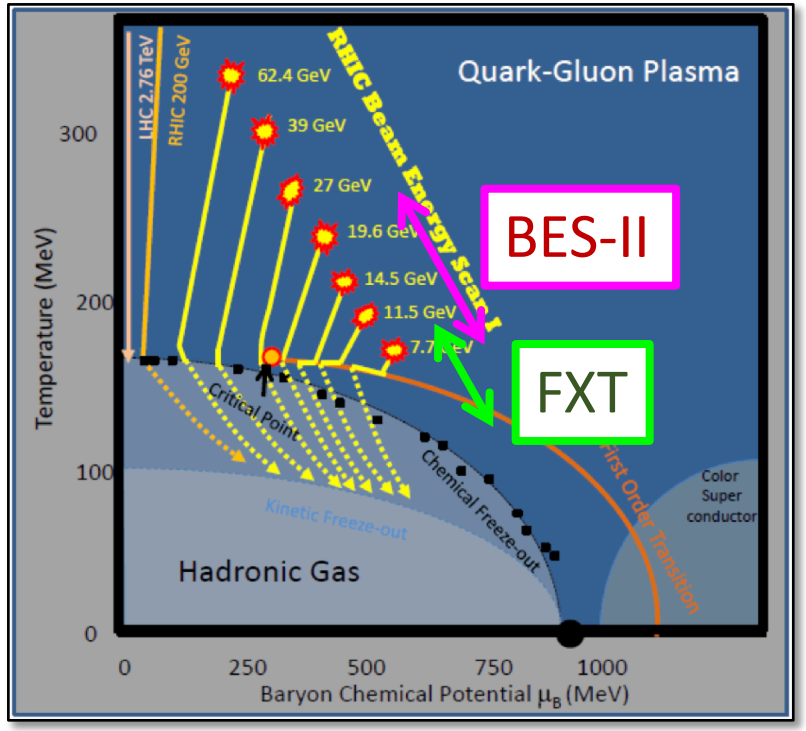
Beam Energy Scan Phase-II @ STAR



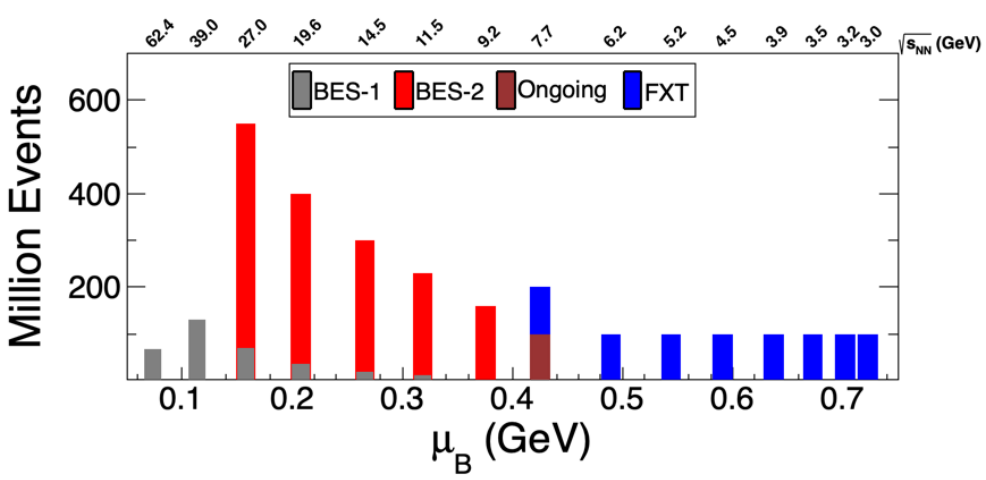
- Event Plane Detector for reaction plane and centrality determination and triggering
- End-cap Time-of-Flight for forward PID
- Inner TPC for increasing TPC acceptance ~1.5 in η and improving dE/dx resolution

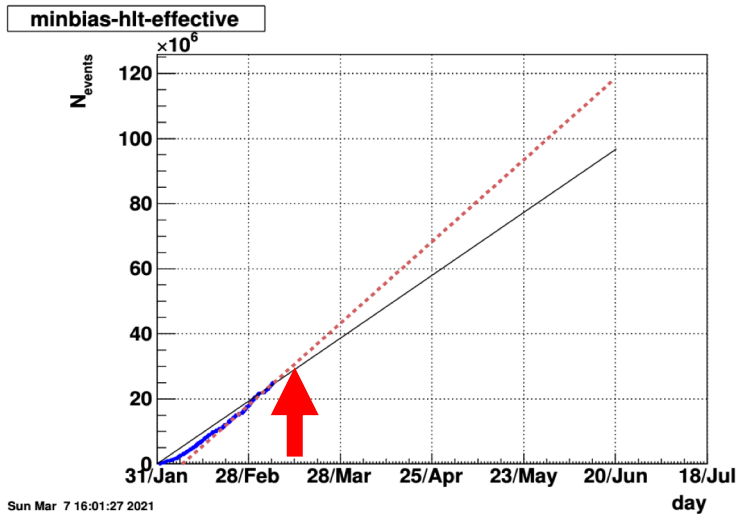
2019-2021 (BES-II @ STAR)

Alex Schmah



BES-II datasets : current run21 status and projection





STAR **Collected events up to Run20**

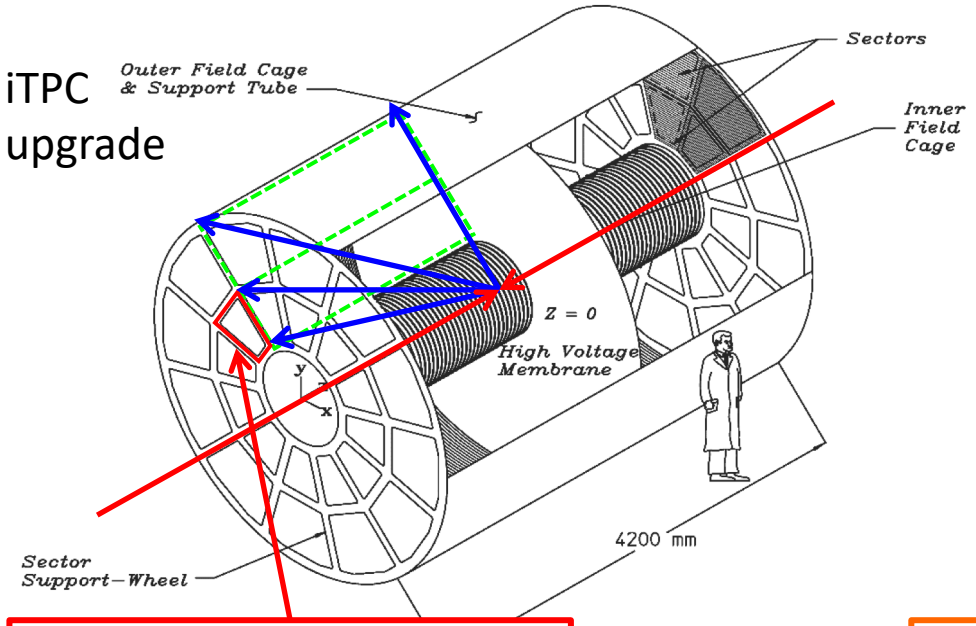
	Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events requested / collected ("Good")	
Run19	9.8	19.6	205	4.5 weeks	400M	582M
Run19	7.3	14.5	260	5.5 weeks	300M	324M
Run20	5.75	11.5	315	9.5 weeks	230M	235M
Run20	4.55	9.1	370	9.5 weeks	160M	162M
Run21	3.85	7.7	420	12 weeks	100M	3M
Run20	31.2	7.7 (FXT)	420	2 days	100M	51M 113M
Run20	19.5	6.2 (FXT)	487	2 days	100M	119M
Run20	13.5	5.2 (FXT)	541	2 days	100M	103M
Run20	9.8	4.5 (FXT)	589	2 days	100M	108M
Run20	7.3	3.9 (FXT)	633	2 days	100M	53M 114M
Run20	5.75	3.5 (FXT)	666	2 days	100M	114M
Run19	4.55	3.2 (FXT)	699	2 days	100M	201M
Run19	3.85	3.0 (FXT)	721	2 days	100M	3.7M+300M (run18)
Run20	26.5 GeV (during CeC)	7.2 (FXT)				315M

Ongoing Run21: Beam Use Requests

Single-Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Events (MinBias)	Priority
3.85	7.7	11-20 weeks	Au+Au	100 M	1
3.85	3 (FXT)	3 days	Au+Au	300 M	2
44.5	9.2 (FXT)	0.5 days	Au+Au	50 M	2
70	11.5 (FXT)	0.5 days	Au+Au	50 M	2
100	13.7 (FXT)	0.5 days	Au+Au	50 M	2
100	200	1 week	O+O	400 M 200 M (central)	3 a
8.35	17.1	2.5 weeks	Au+Au	250 M	3 b
3.85	3 (FXT)	3 weeks	Au+Au	2 B	3 c

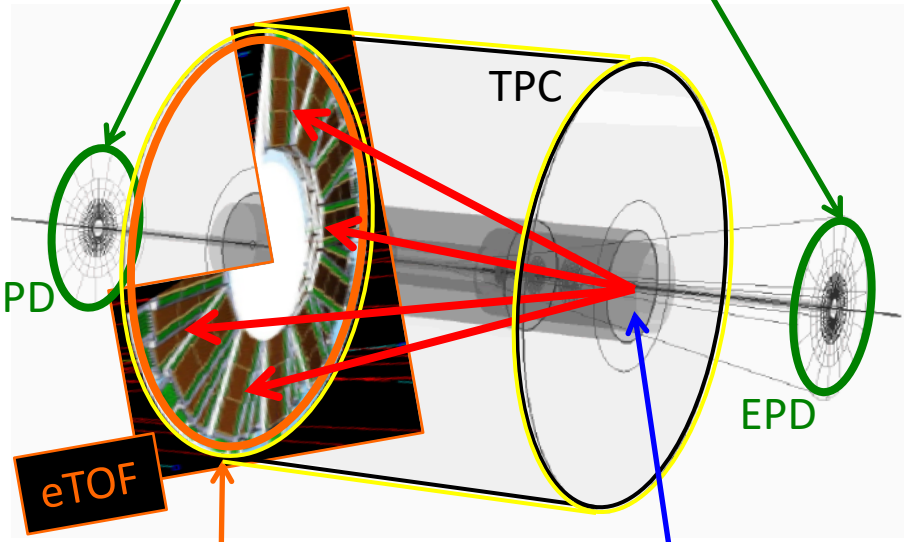
STAR detector upgrades for BES-II program

iTPC upgrade



TPC inner sector readout with more segmentation

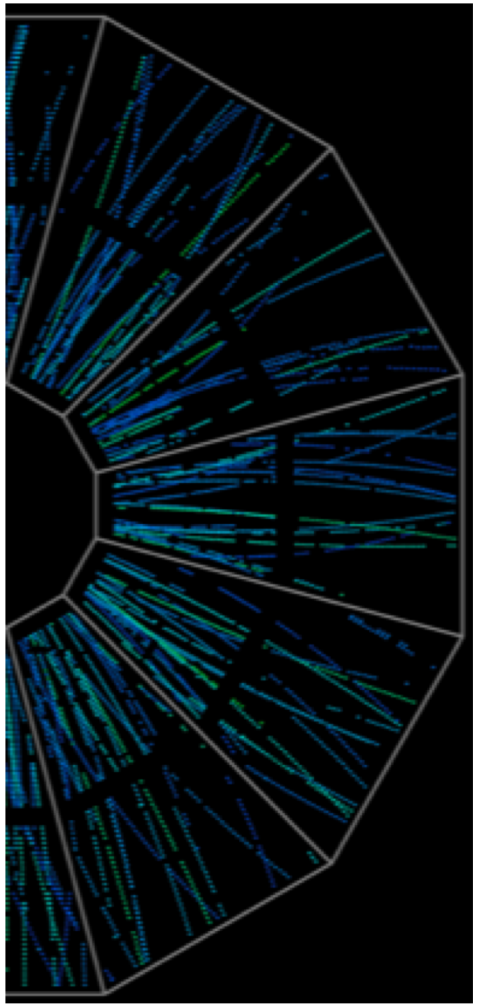
Event Plane Detector (EPD)

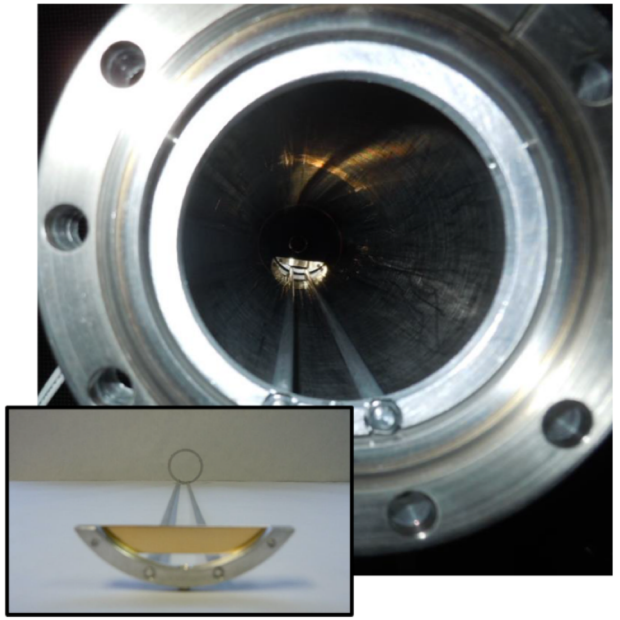


End-cap Time-of-Flight (eTOF) from FAIR-CBM

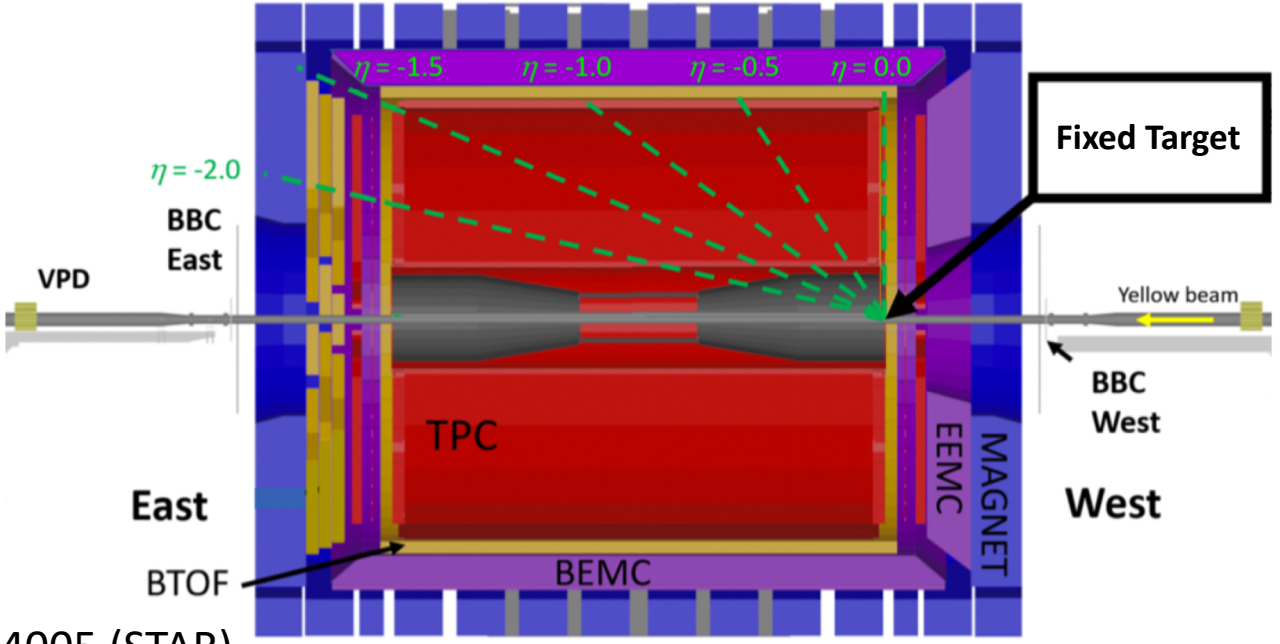
Fixed target mode

Inner TPC upgrades for wider rapidity coverage





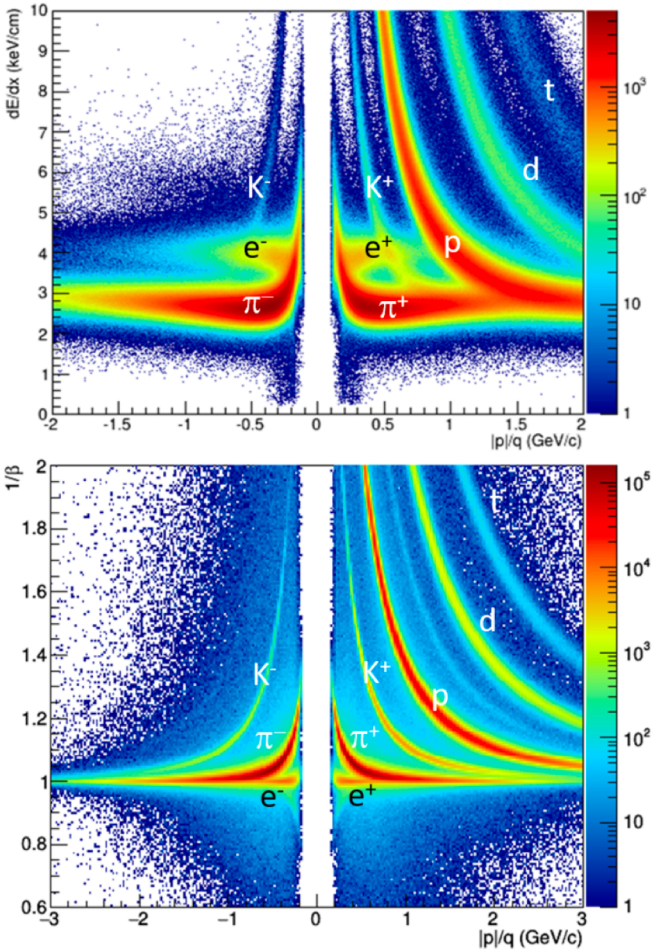
fixed target at z ~ 2m
inside the beam pipe for
lower CM energy collisions



arXiv:2007.14005 (STAR)

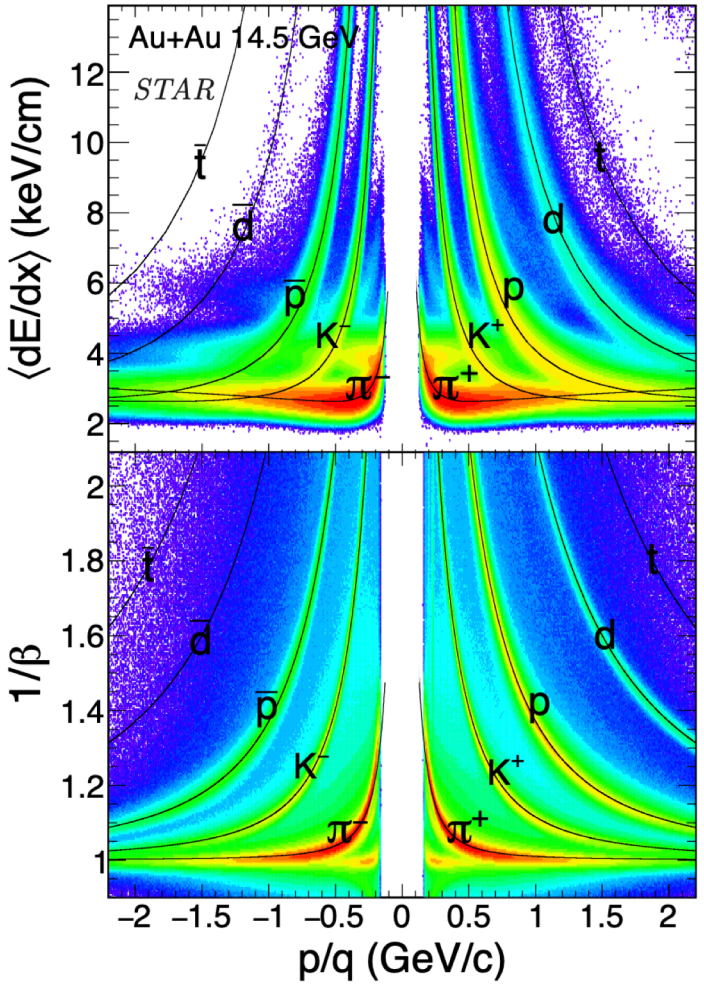
Particle identification via dE/dx(TPC), 1/β(TOF) and M_{inv} reconstruction

$\sqrt{s_{NN}}$=4.5GeV Fixed Target



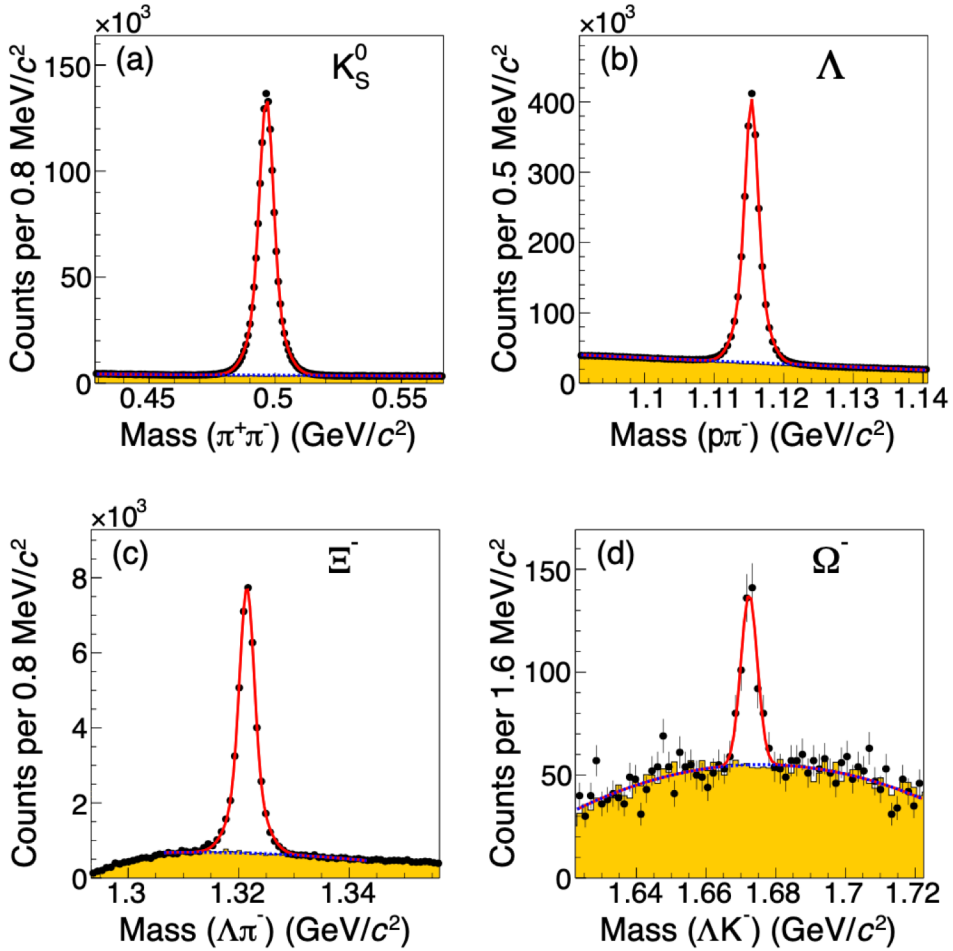
arXiv:2007.14005 (STAR)

$\sqrt{s_{NN}}$=14.5GeV Collider



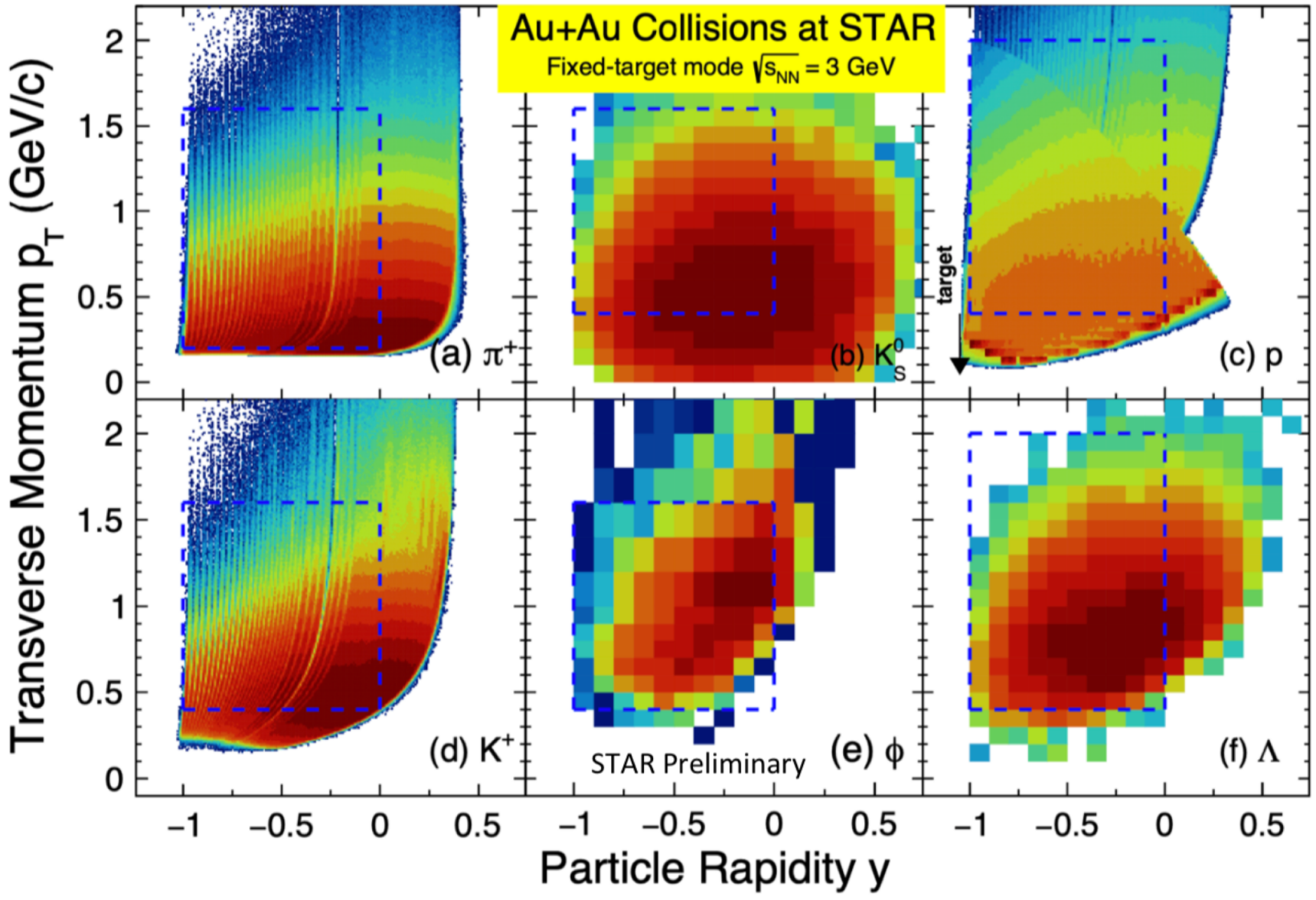
PRC **101** (2020) 24905 (STAR)

$\sqrt{s_{NN}}$=7.7GeV Collider



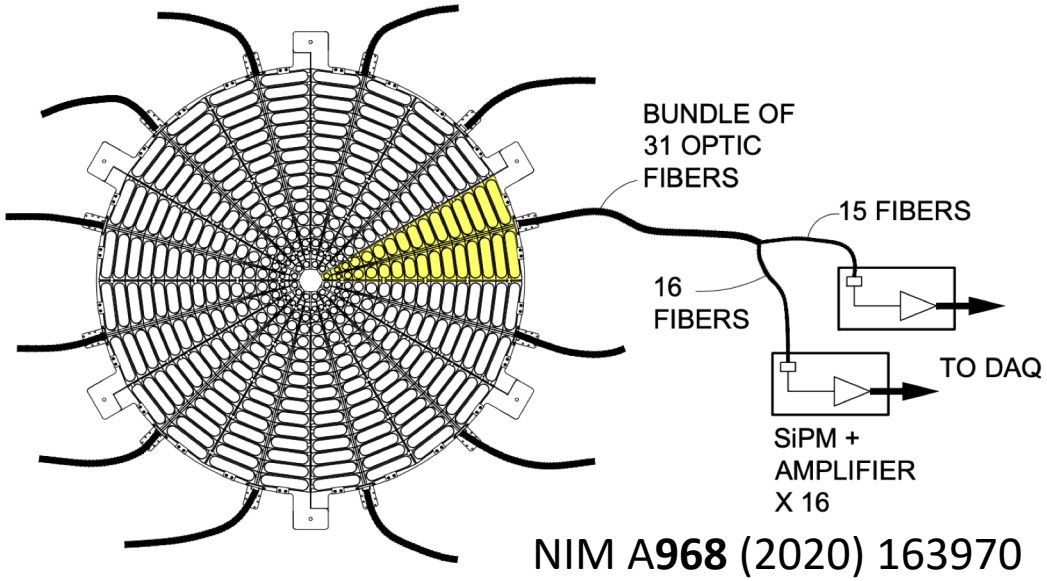
PRC **102** (2020) 34909 (STAR)

Identified particle p_T - rapidity acceptance at 3GeV in fixed-target mode

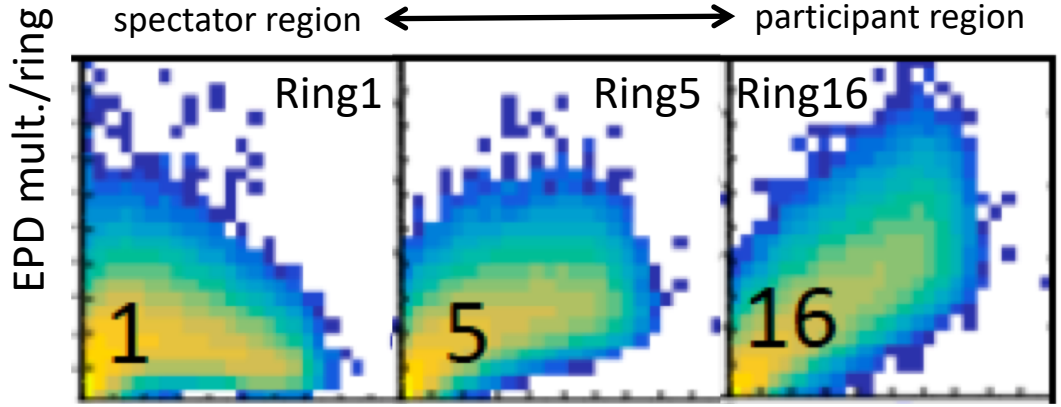


Event Plane Detector (EPD) $|\eta|$=2~5 in both forward and backward eta region for reaction plane, centrality and triggering

- improved accuracy for the event planes ($\Phi_{spec.}$, $\Phi_{part.}$)
- centrality and E.P. determined outside of mid-rapidity
- key information for the fluctuation, flow and correlation

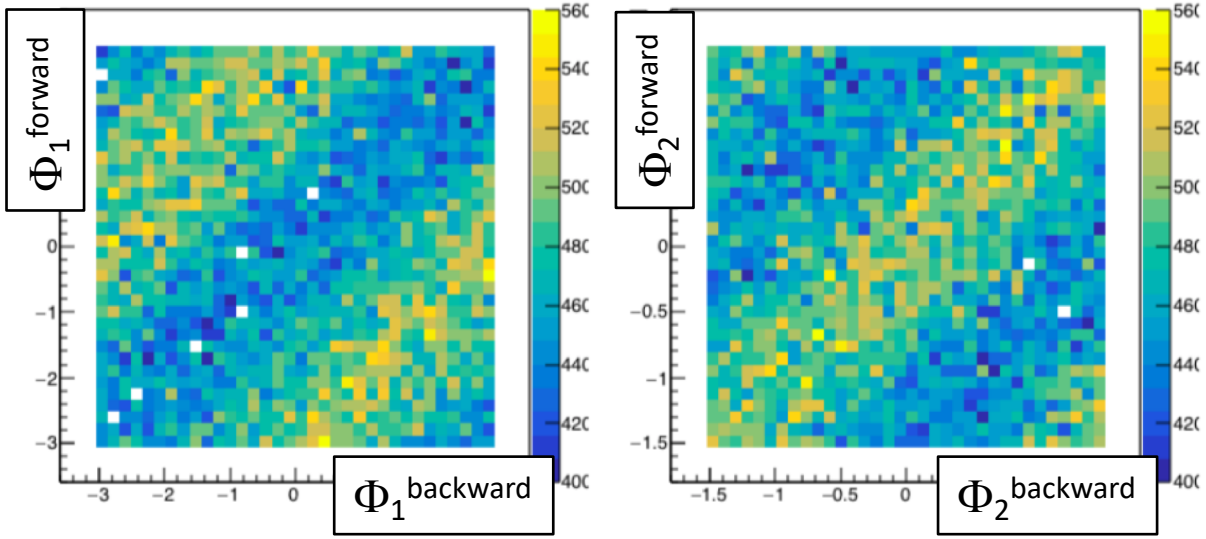


NIM A**968** (2020) 163970
J. Adams et. al.



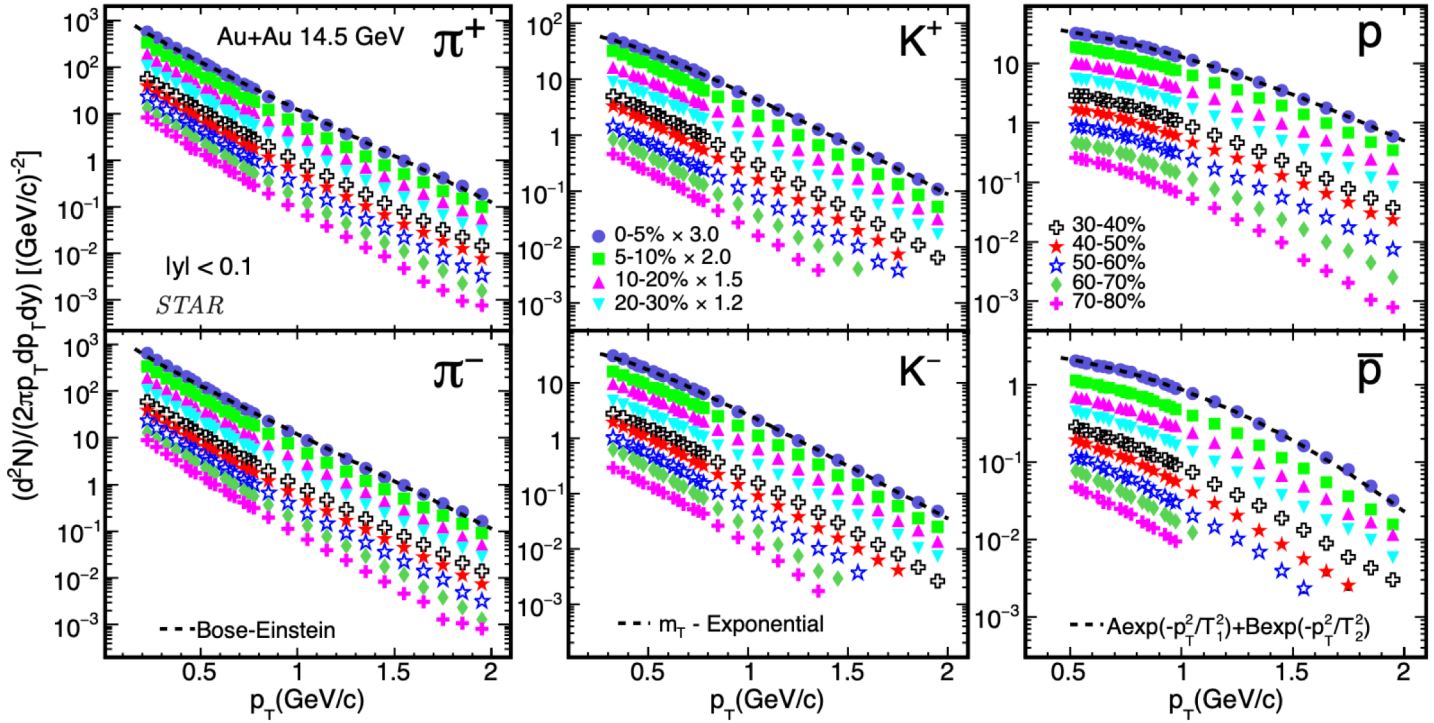
27GeV Au+Au TPC multiplicity

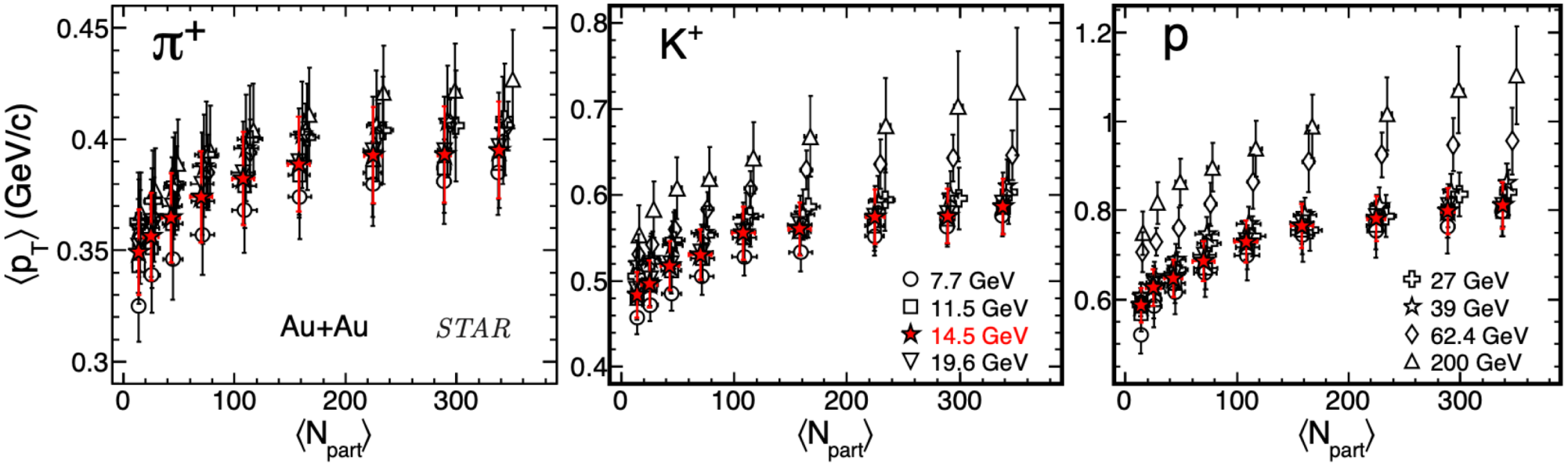
Forward-backward event-plane correlation



Identified hadron spectra for pions, kaons, proton and anti-proton

yields and shapes

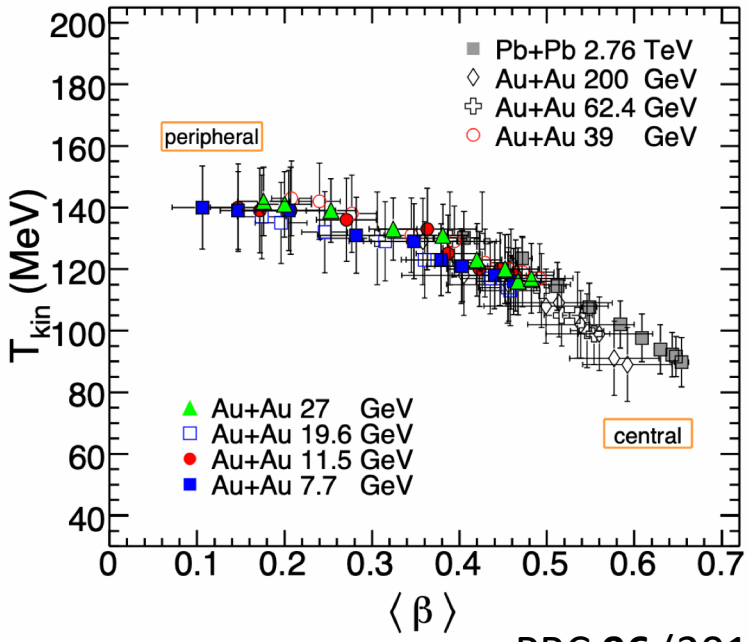




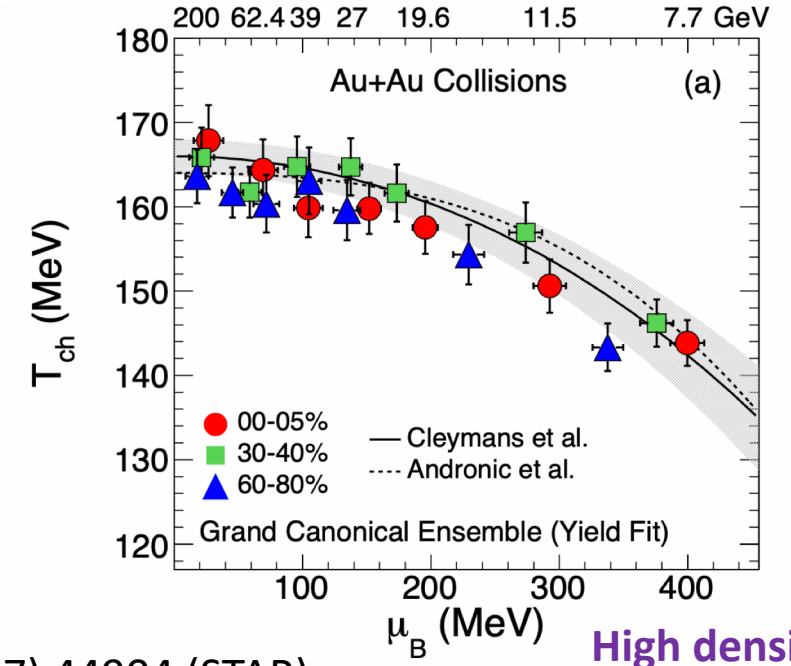
PRC **101** (2020) 24905 (STAR)

Kinetic and chemical freeze-out parameters via fitting based on thermal models

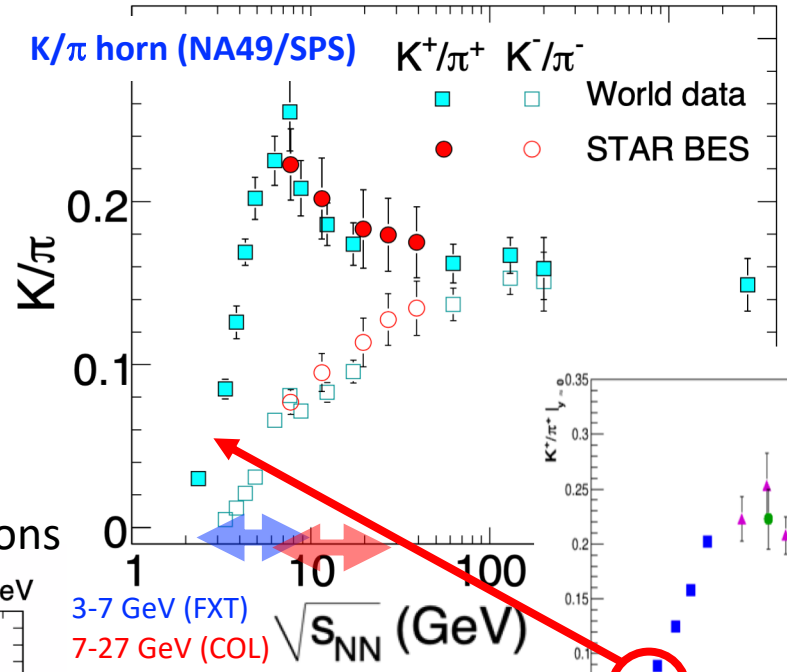
T_{kin} vs β_T at kinetic freeze-out with Blast wave model fitting

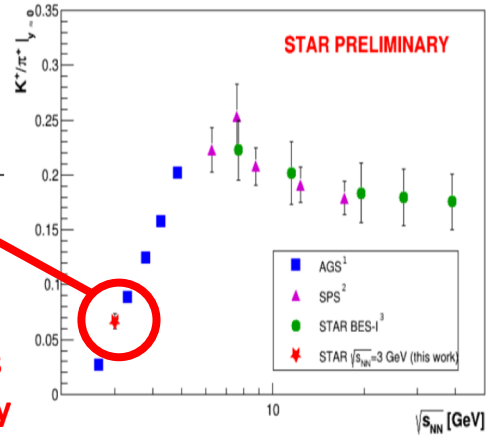


T_{ch} vs μ_B at chemical freeze-out by fitting yields and ratios of hadrons

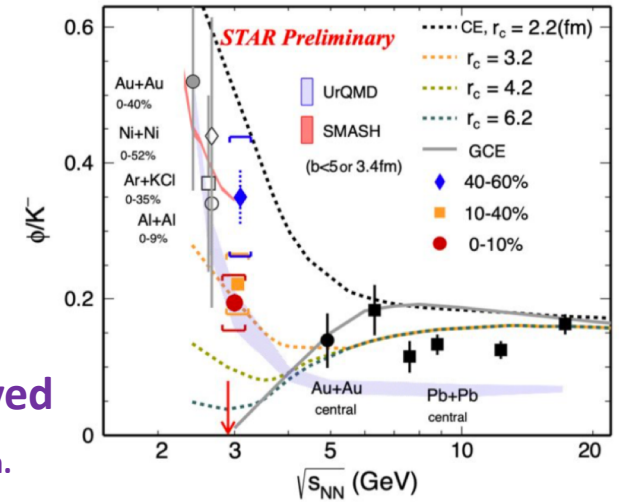


PRC **96** (2017) 44904 (STAR)





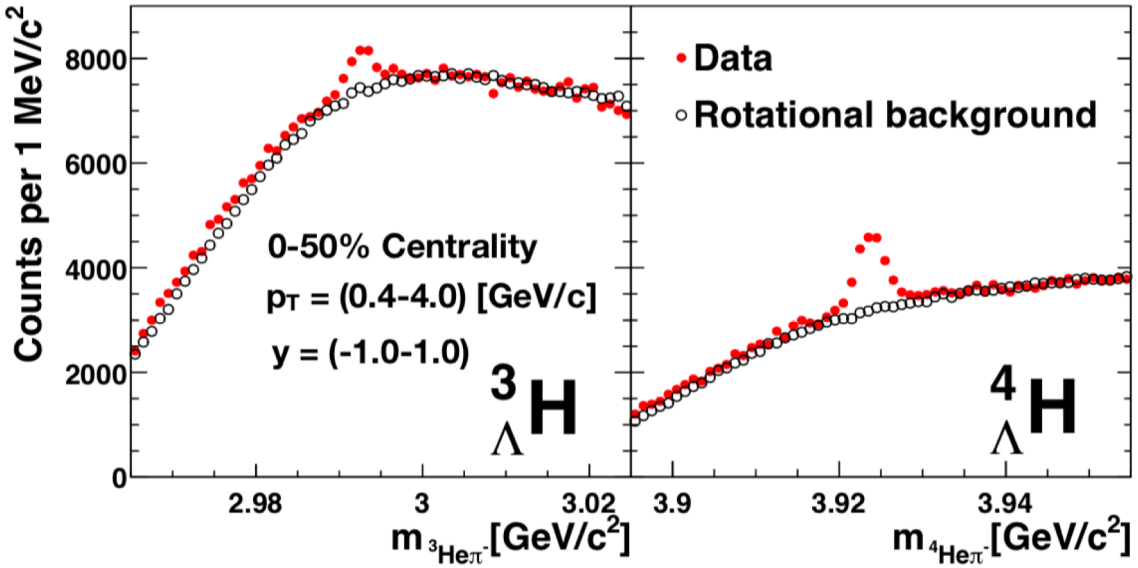
New data on various mesons at 3GeV FXT will be shown by Benjamin K.



High density is achieved with lowering E_{beam}.

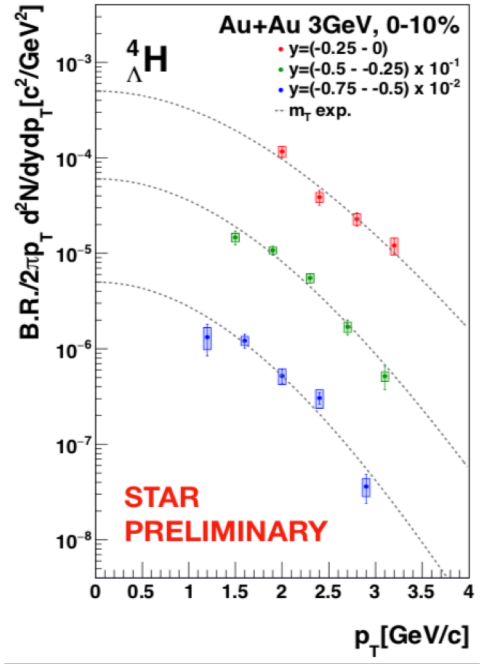
Hypernucleus life time, spectra and flow measurements at 3GeV FXT

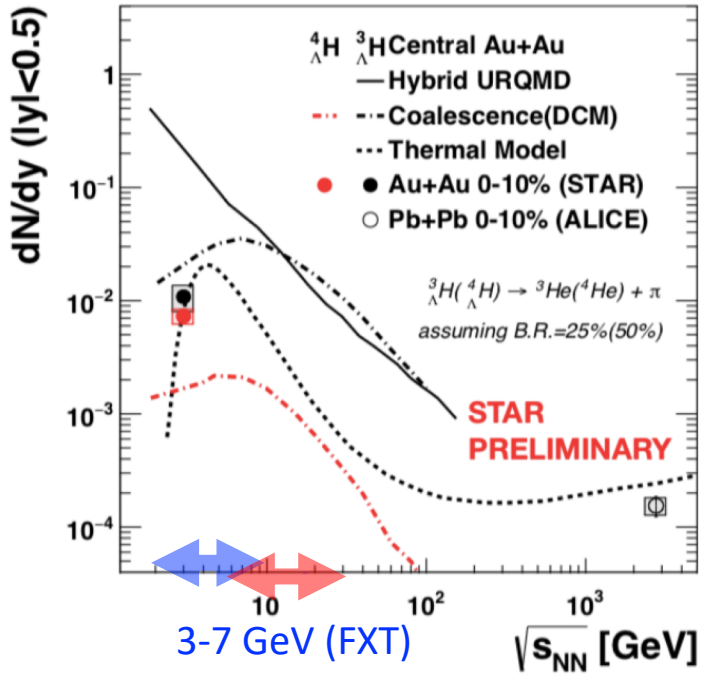
Hypernuclei ${}^{3}_{\Lambda}$H, (${}^{4}_{\Lambda}$H) are reconstructed via
2 and 3 body decays ^{3}He + π and p + d + π , (^{4}He + π)



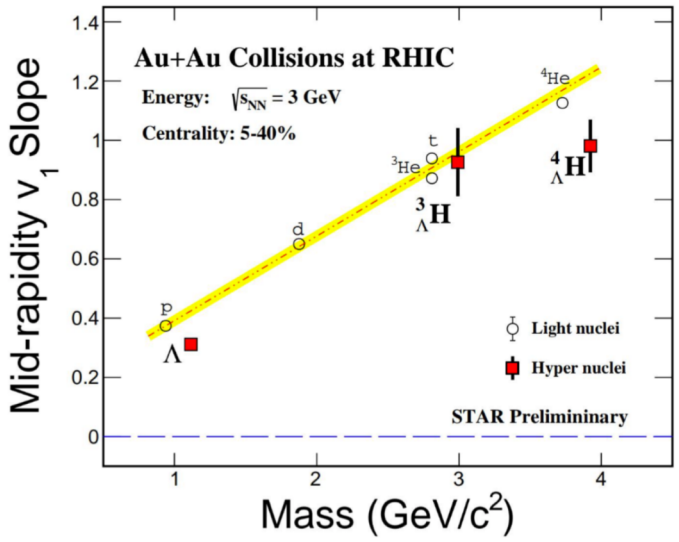
$$ {}^{3}_{\Lambda}\mathrm{H} : \tau = 232.1 \pm 29.2(\mathrm{stat}) \pm 36.7(\mathrm{syst})[\mathrm{ps}] $$
$$ {}^{4}_{\Lambda}\mathrm{H} : \tau = 218.3 \pm 7.5(\mathrm{stat}) \pm 11.8(\mathrm{syst})[\mathrm{ps}] $$

confirmed the previous measurements somewhat shorter than free Lambda





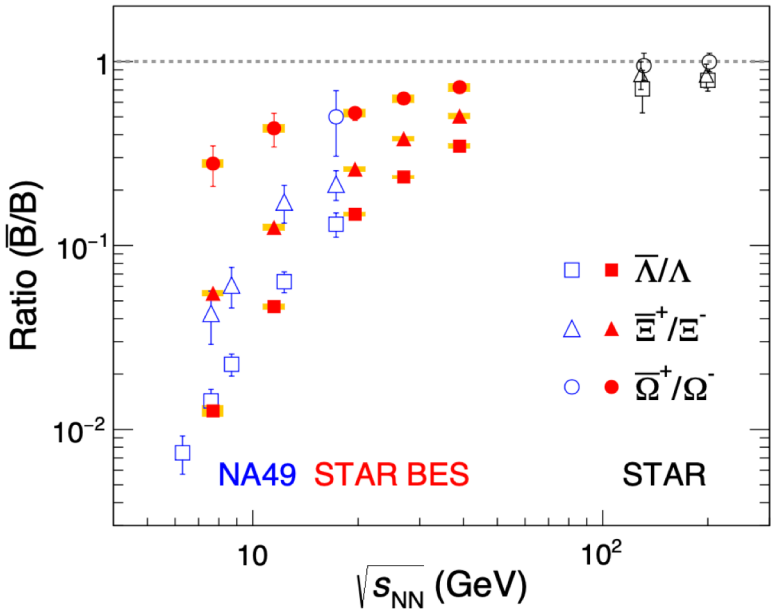
3-7 GeV (FXT)
7-27 GeV (COL)
BES-II in progress

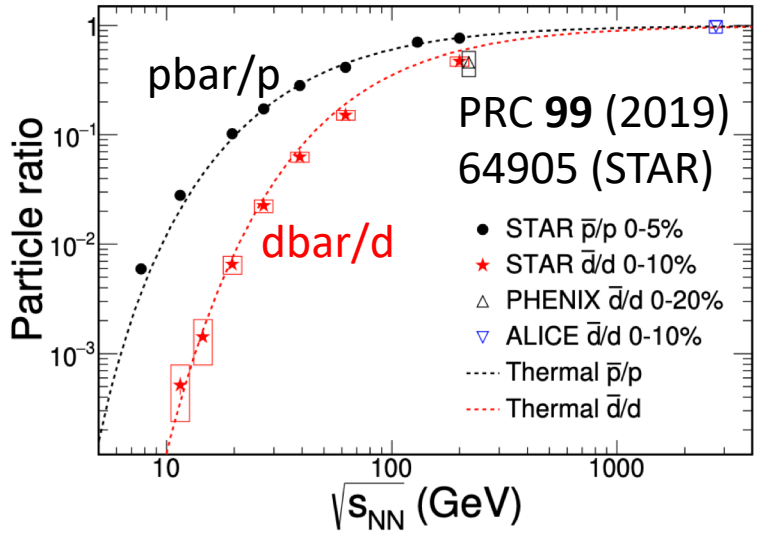


New data on hypernuclei life time, spectra and flow at 3GeV FXT will be shown by Yue-Hang L.

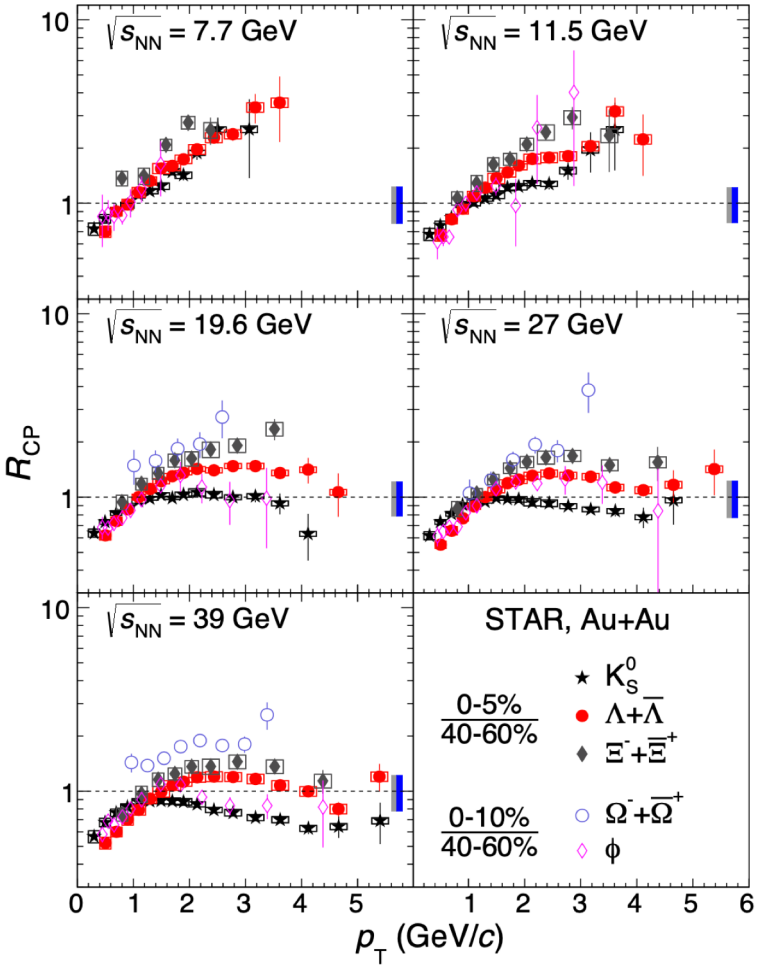
Nucleon/Baryon number scaling mostly holds also for the hypernuclei

Strangeness enhancement and jet quenching



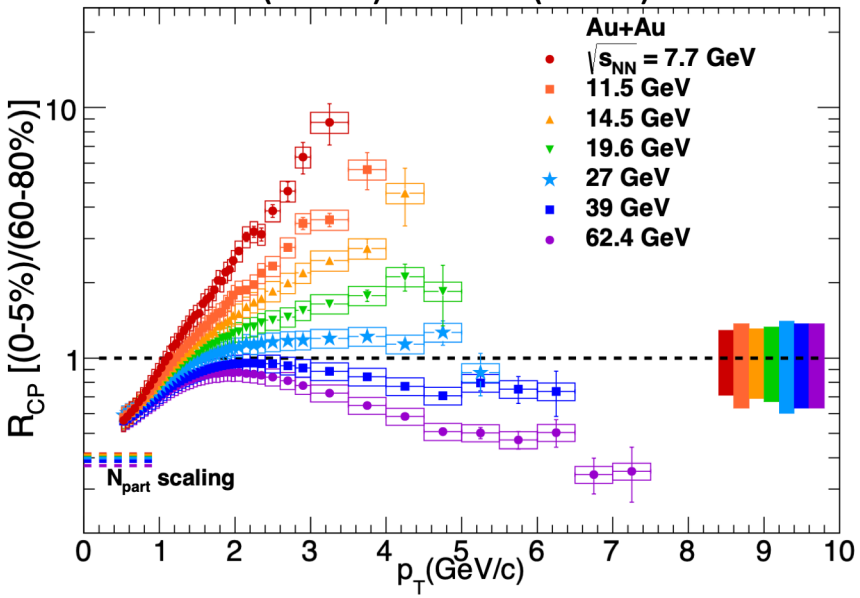


PRC **102** (2020) 34909 (STAR)

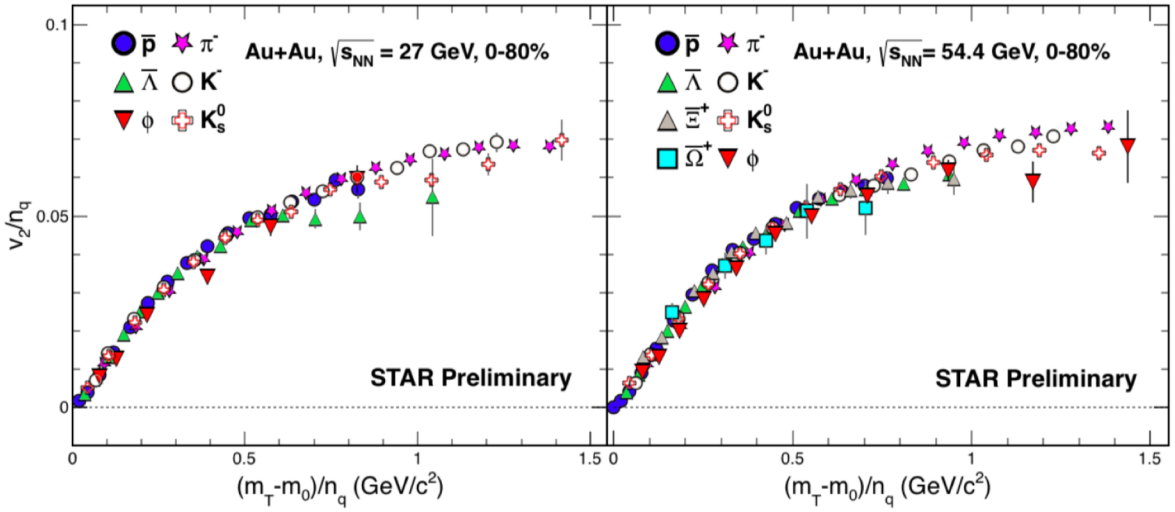


Nuclear modification factor R_{CP} (R_{AA}) of multi-strangeness hadrons and charged particles for different beam energies

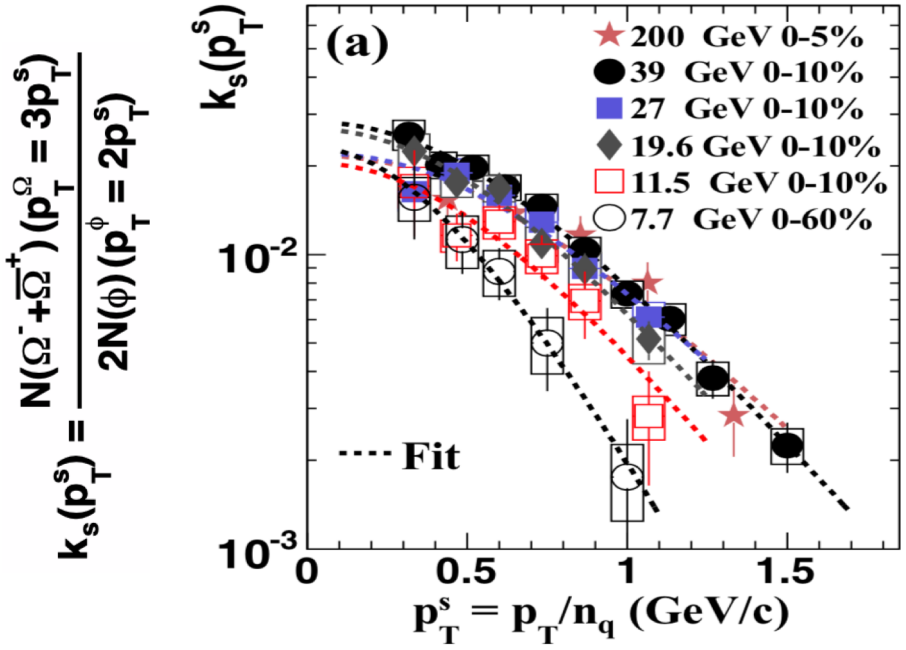
PRL **121** (2018) 32301 (STAR)

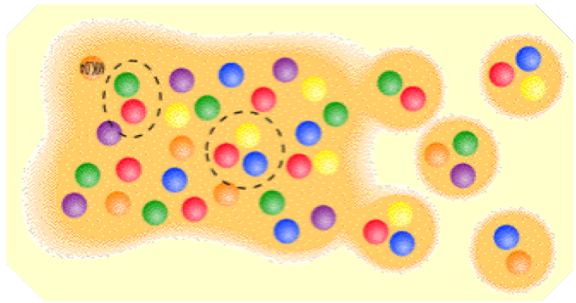


Extraction of strange quark p_T distribution based on quark coalescence picture

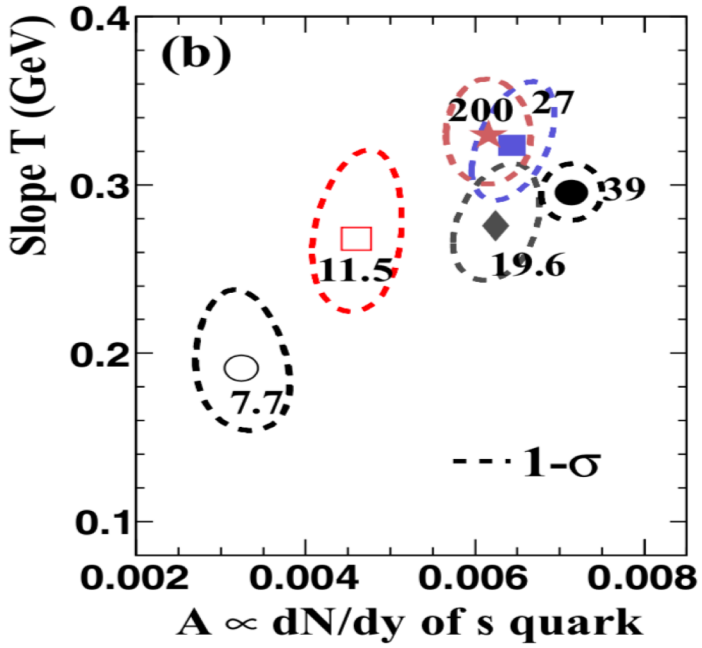


New data on ϕ v2 at 27 and 54 GeV will be shown by Prabhupada D.





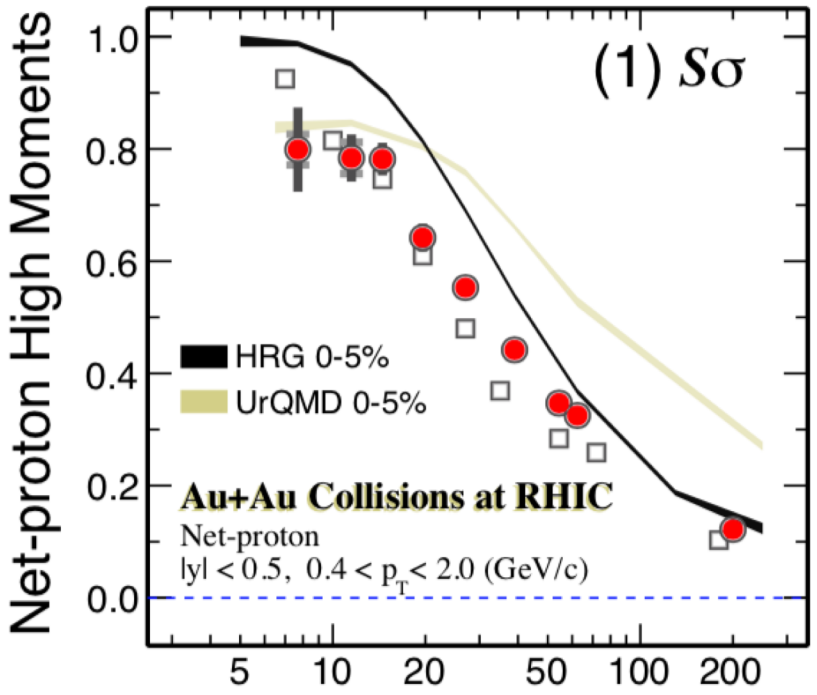
Quark coalescence behavior stays mostly unchanged at higher beam energy above ~20GeV.



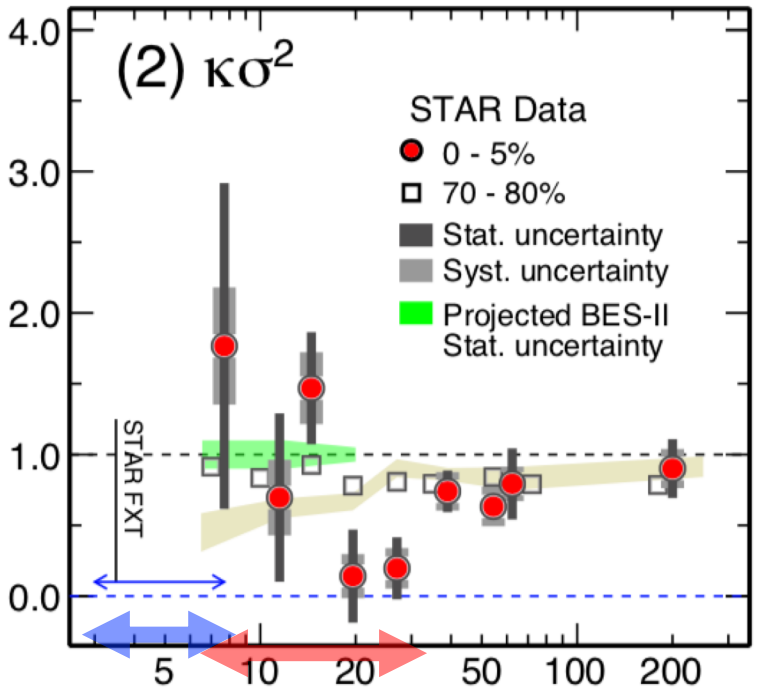
PRC **93** (2016) 21903 (STAR)

Higher order fluctuation of net-proton distribution as a proxy for the conserved net-Baryon fluctuation

Skewness



Kurtosis

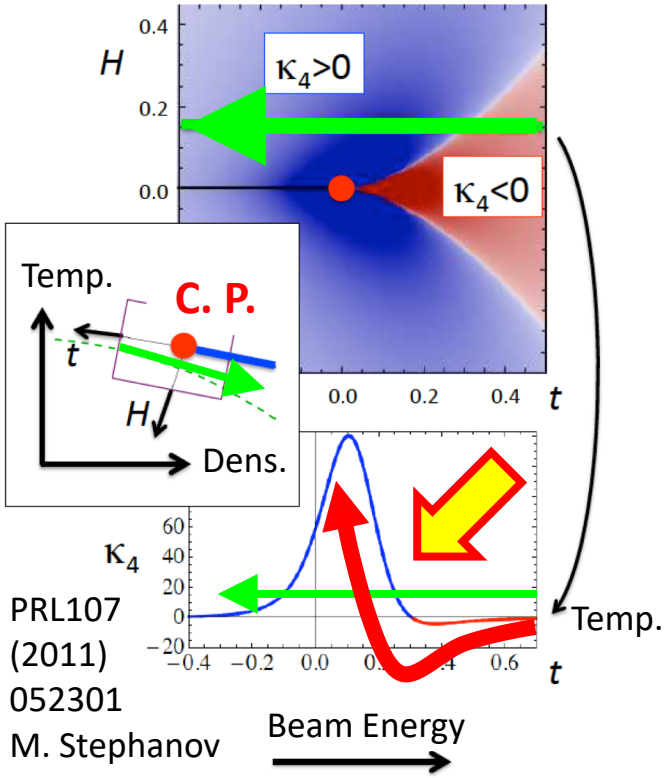


Collision Energy $\sqrt{s_{NN}}$ (GeV)

3-7 GeV (FXT)
7-27 GeV (COL)
BES-II in progress

PRL **126** (2021) 092301 (STAR)

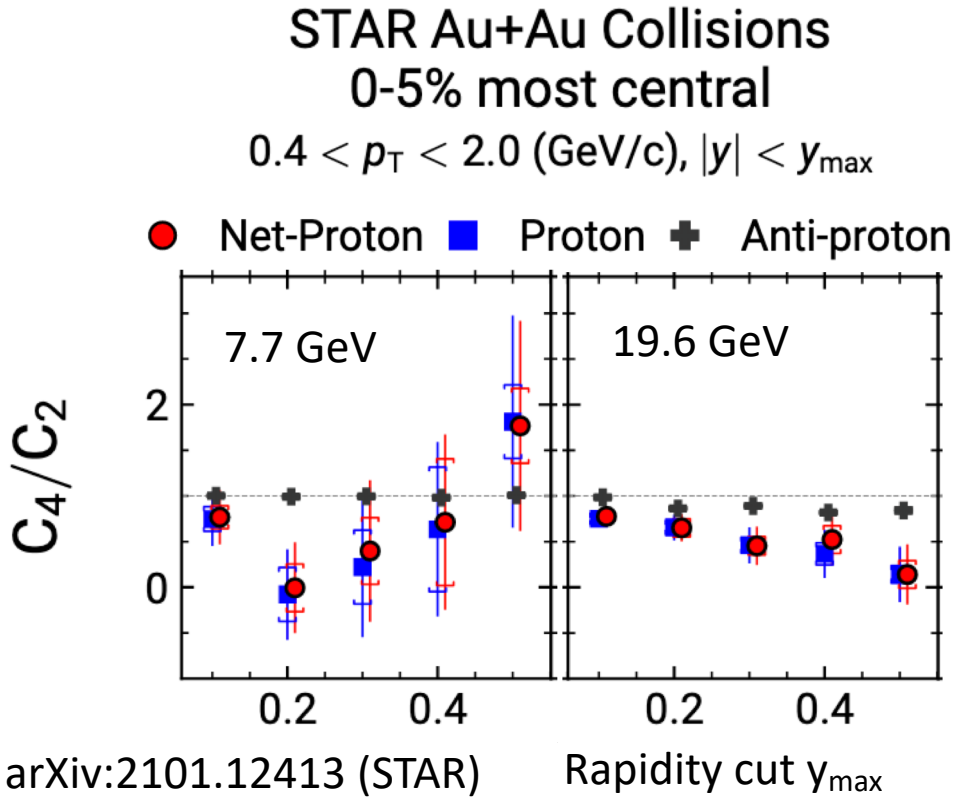
Higher order fluctuation (4th order κ_4)



PRL107 (2011) 052301
M. Stephanov

Beam Energy

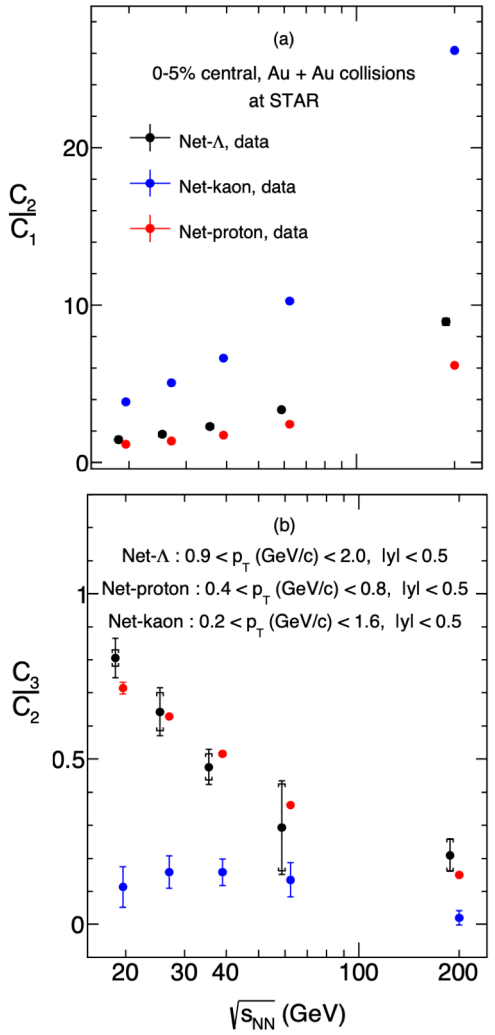
Higher order fluctuation of net-Lambda, net-proton and net-kaon distribution



arXiv:2101.12413 (STAR)

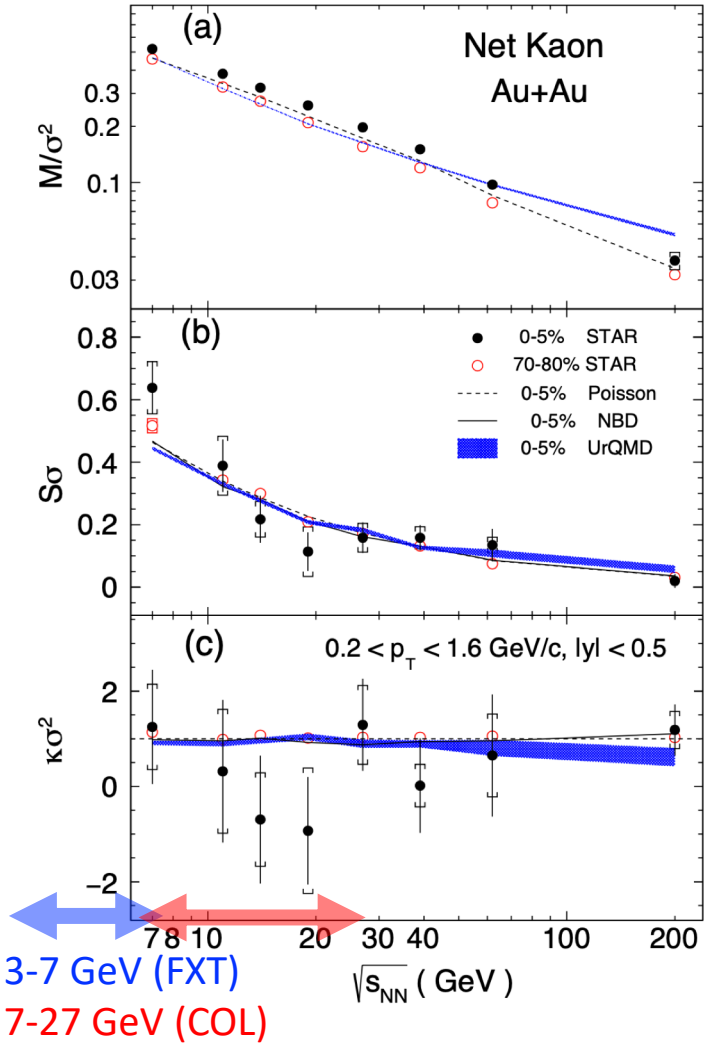
Larger |y| acceptance up to ~ 1 with iTPC in BES-II will be important

$2^{nd} - 3^{rd}$ order net-Lambda



PRC **102** (2020) 24903 (STAR)

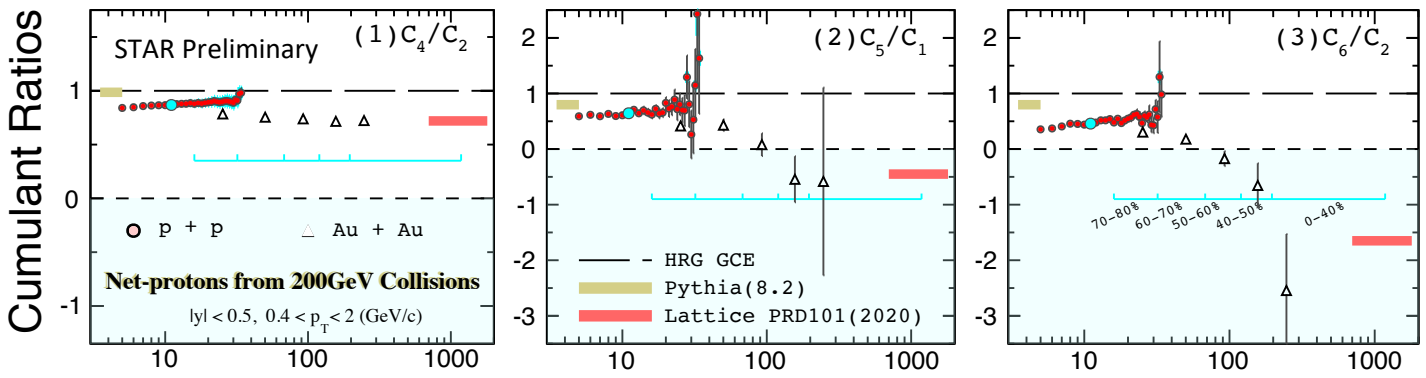
$2^{nd} - 4^{th}$ order net-kaon



PLB **785** (2018) 551 (STAR)

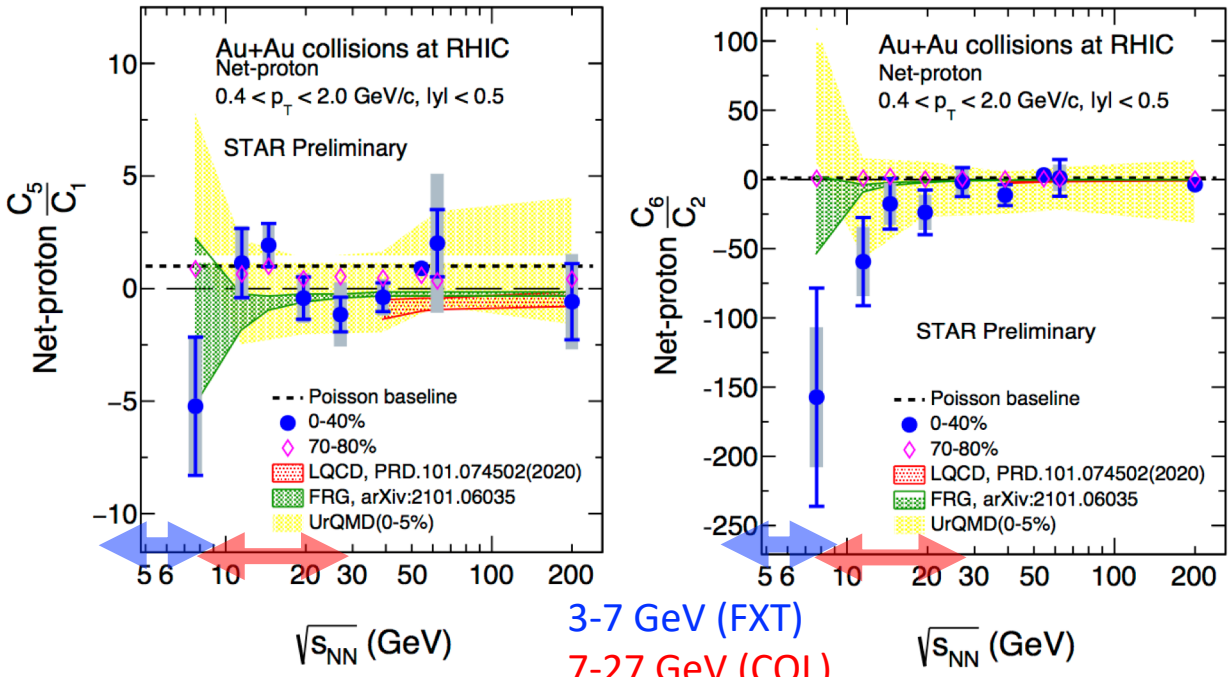
The 5th, 6th order fluctuation of net-proton including pp collisions

New data of net-p cumulants at 200 GeV pp collisions will be shown by Risa N.



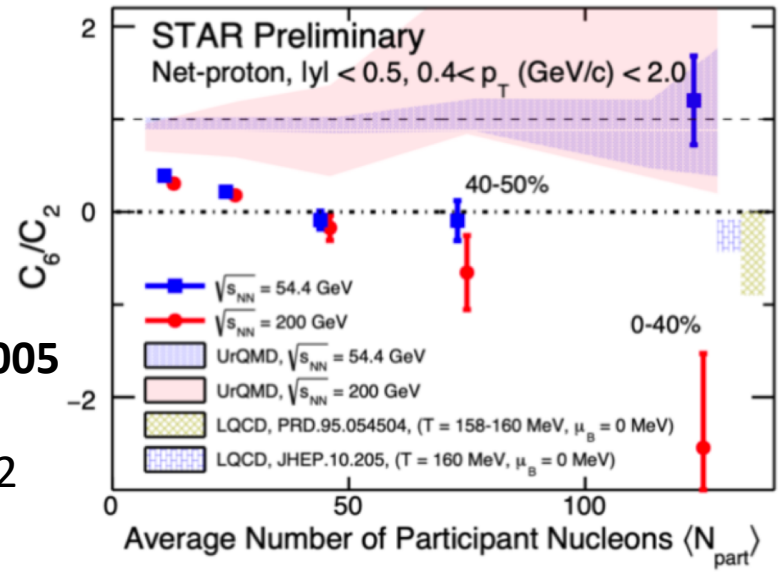
arXiv:2101.12413 (STAR)

New data of net-proton C_5 , C_6 at BES-I will be shown by Ashish P.



3-7 GeV (FXT)
7-27 GeV (COL)

negative c6 could be taken as an indication of cross-over transition at small μ_B

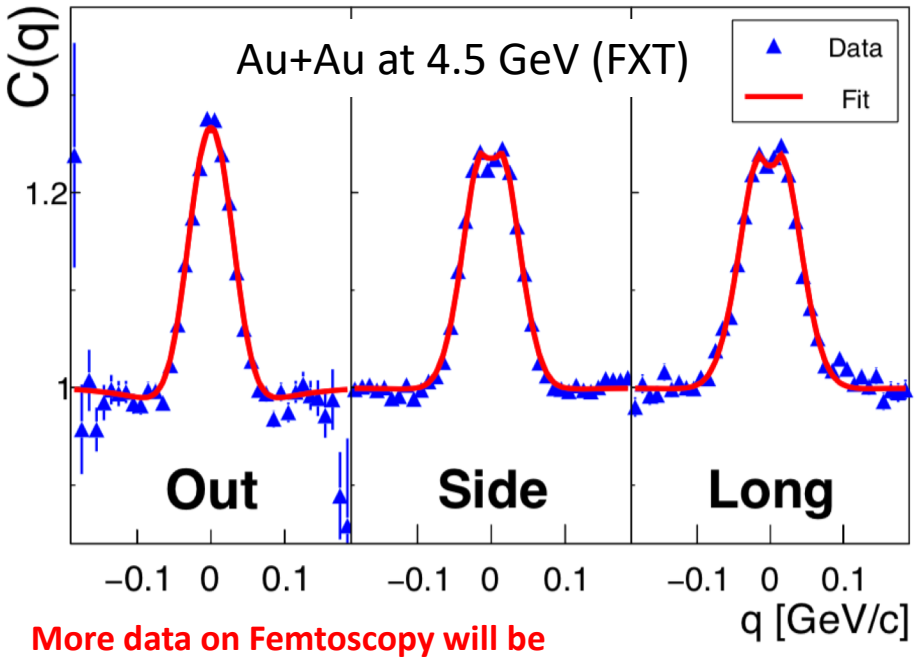


NPA **1005** (2021) 121882 (STAR)

Two-particle HBT interferometry to measure the space and temporal extent of freeze-out volume

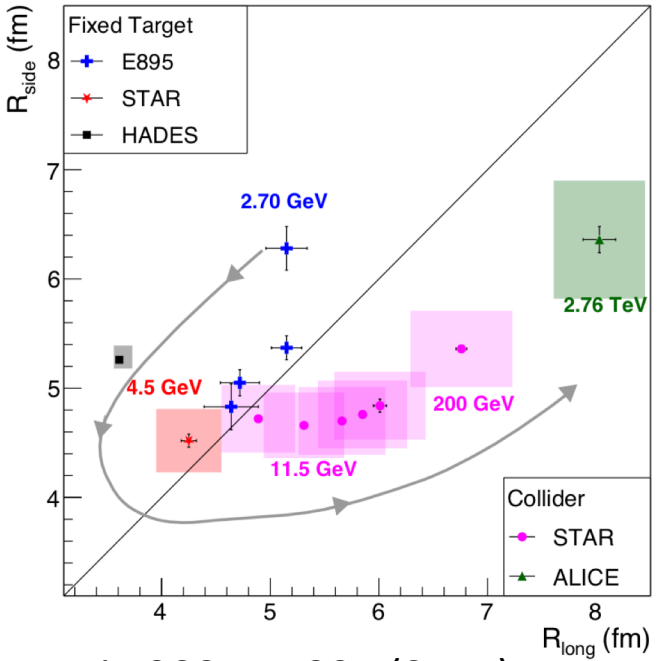
from fixed target mode (4.5 GeV) up to collider mode (200 GeV)

3-dimensional correlation functions

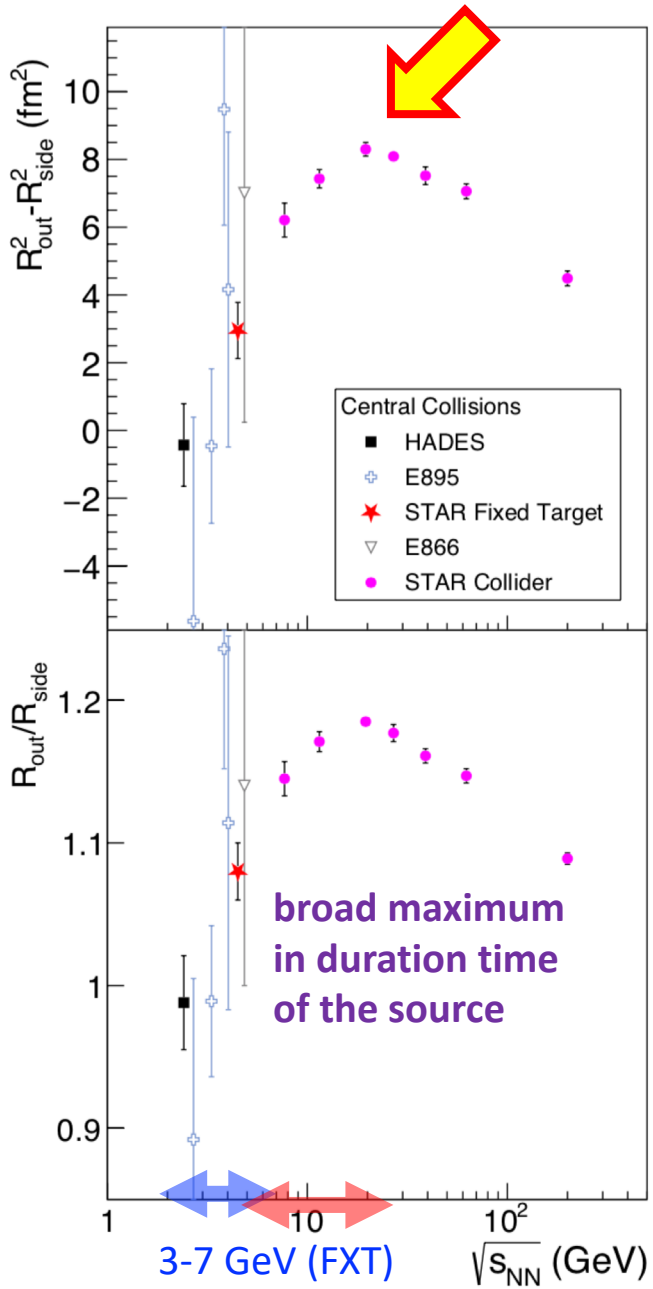


More data on Femtoscopy will be shown and discussed by Hanna Z.

correlation between transverse and longitudinal size



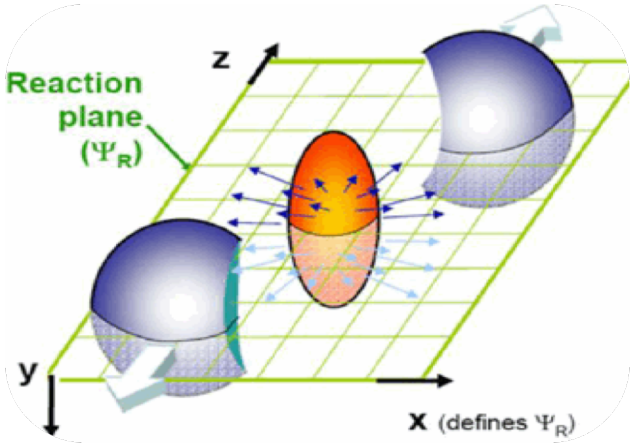
arXiv:2007.14005 (STAR)
(accepted in PRC) for 4.5 GeV

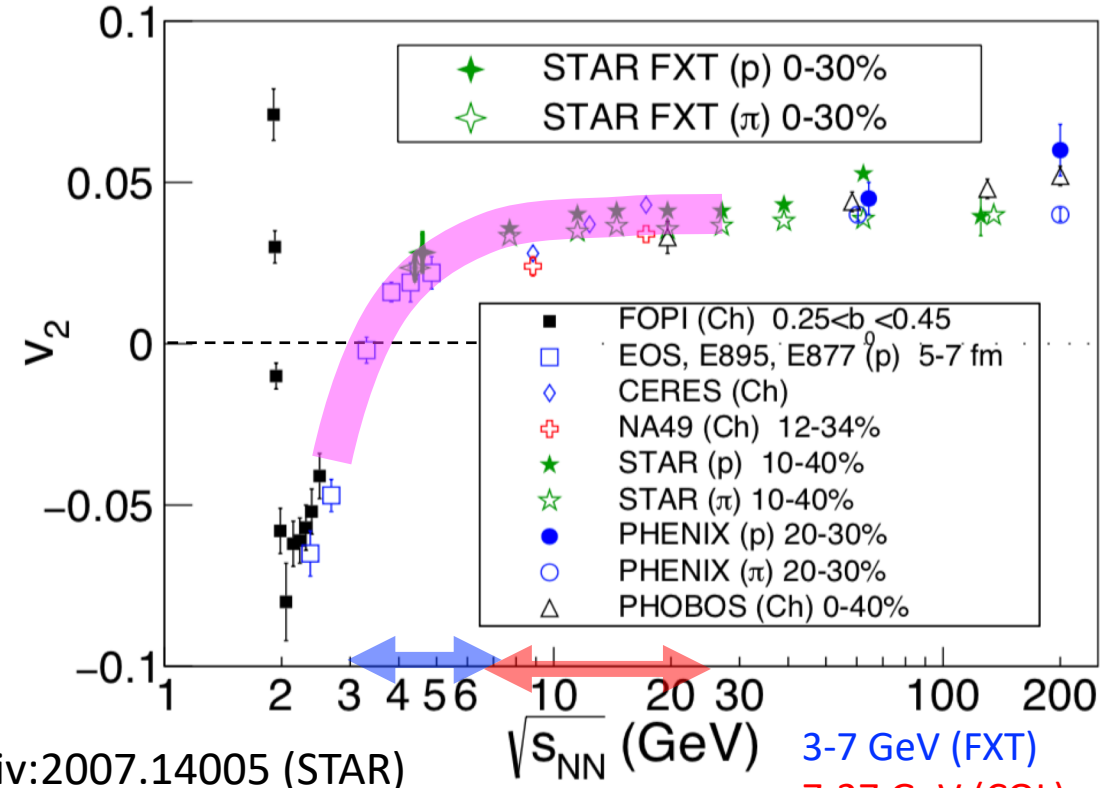


3-7 GeV (FXT)
7-27 GeV (COL)

Energy and eta dependences of elliptic emission/flow v_2

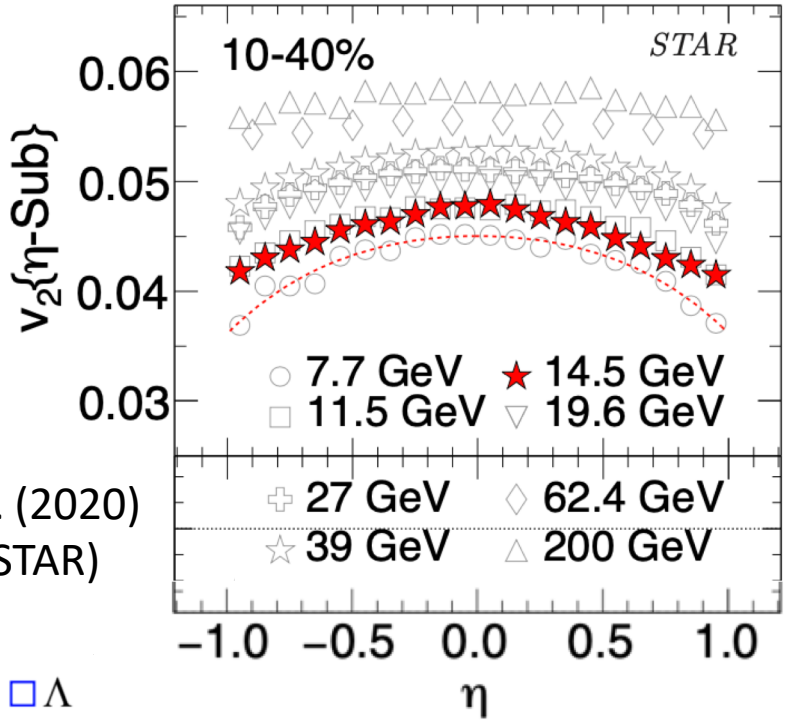
from squeeze-out (v_2<0) to in-plane elliptic expansion (v_2>0)



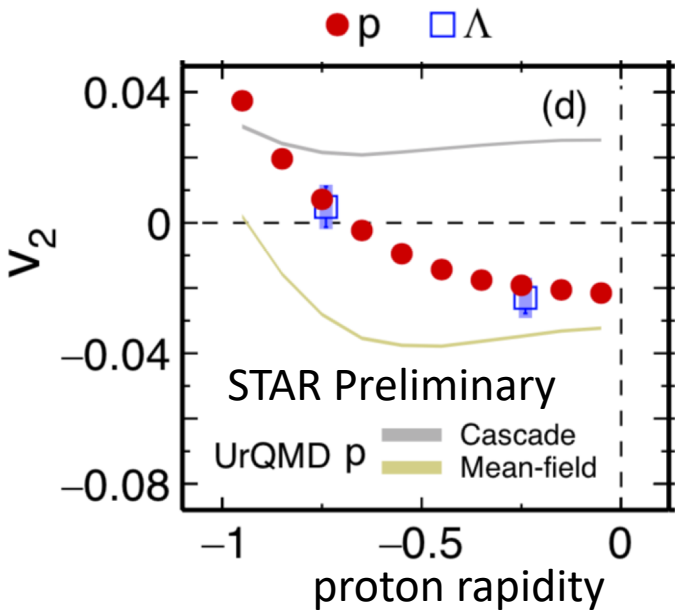


arXiv:2007.14005 (STAR)
(accepted in PRC) for 4.5 GeV

3-7 GeV (FXT)
7-27 GeV (COL)
BES-II in progress



PRC **101** (2020)
24905 (STAR)

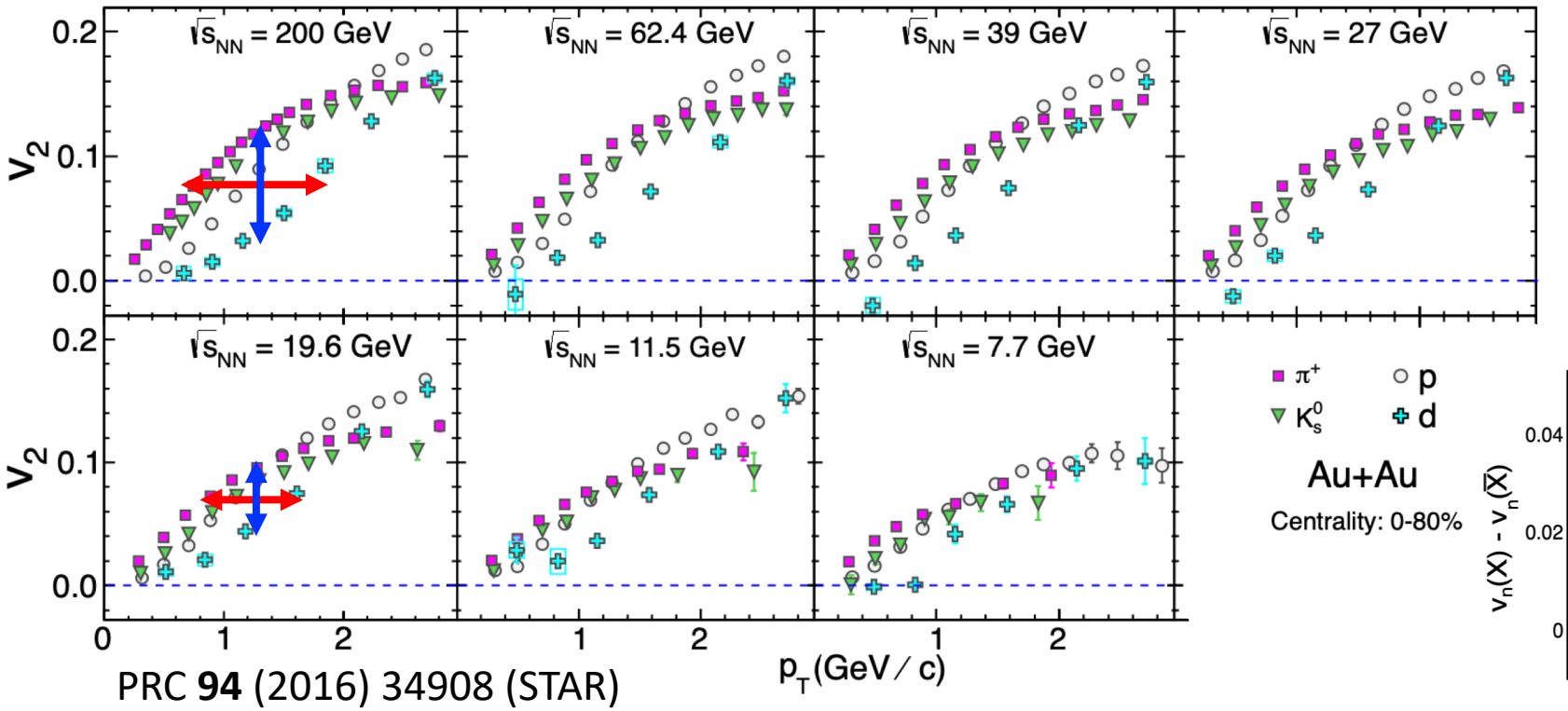


New data on PIDed hadron v1/v2 at 3GeV FXT will be shown by Shaowei L.

$\sqrt{s_{NN}}$ = 3 GeV
Au+Au Collision 10-40%
$0.4 < p_T < 2.0$ GeV/c

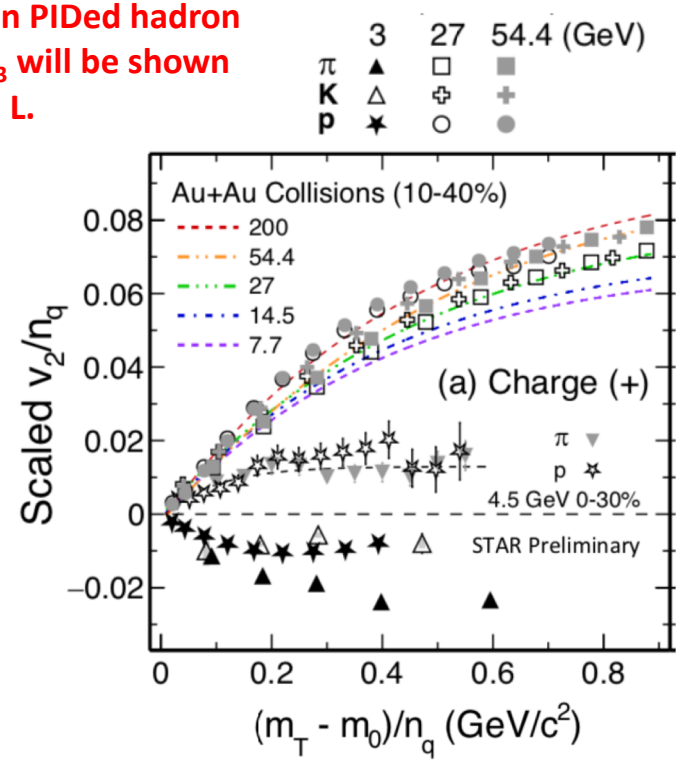
Elliptic and triangular flow of identified hadrons

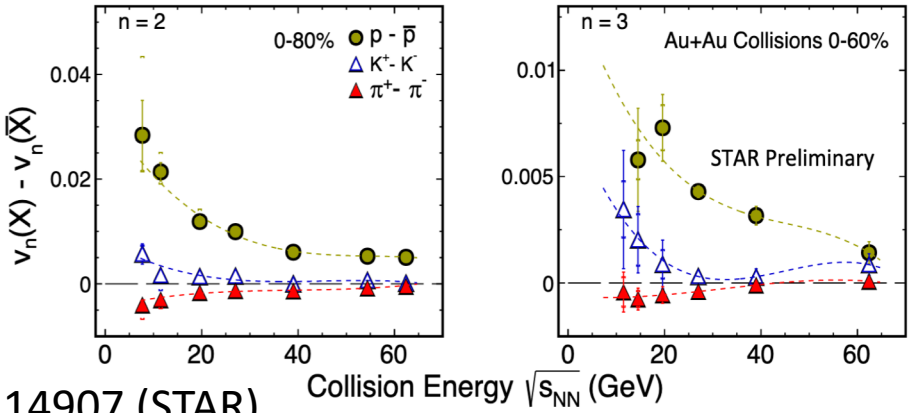
- particle mass dependence and number of quark scaling
- beam energy dependence and particle/anti-particle differences
- clear evolution of **radial** and **elliptic** expansion with beam energy



PRC **94** (2016) 34908 (STAR)

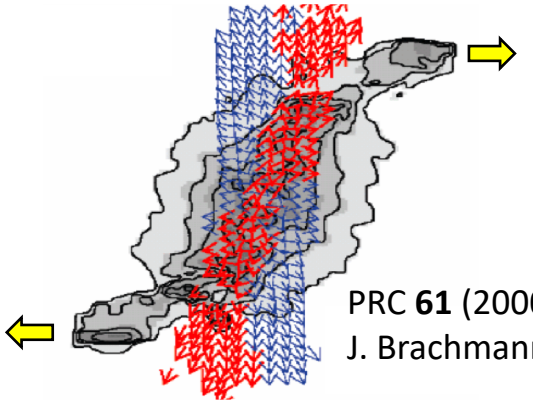
New data on PIDed hadron v_1, v_2 and v_3 will be shown by Shaowei L.



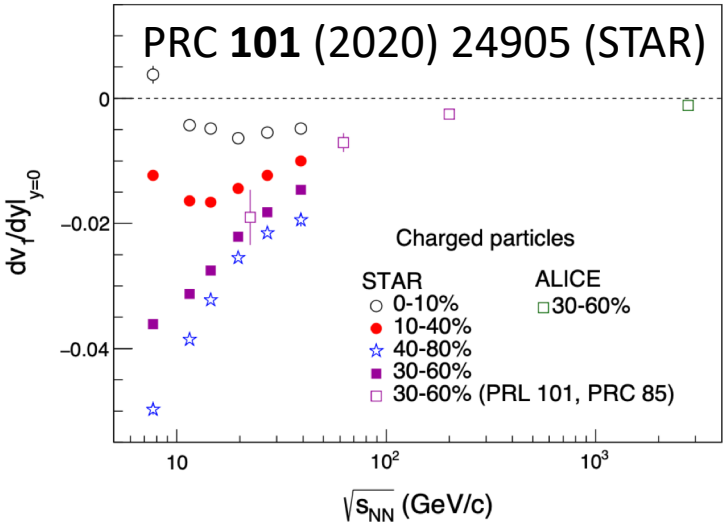


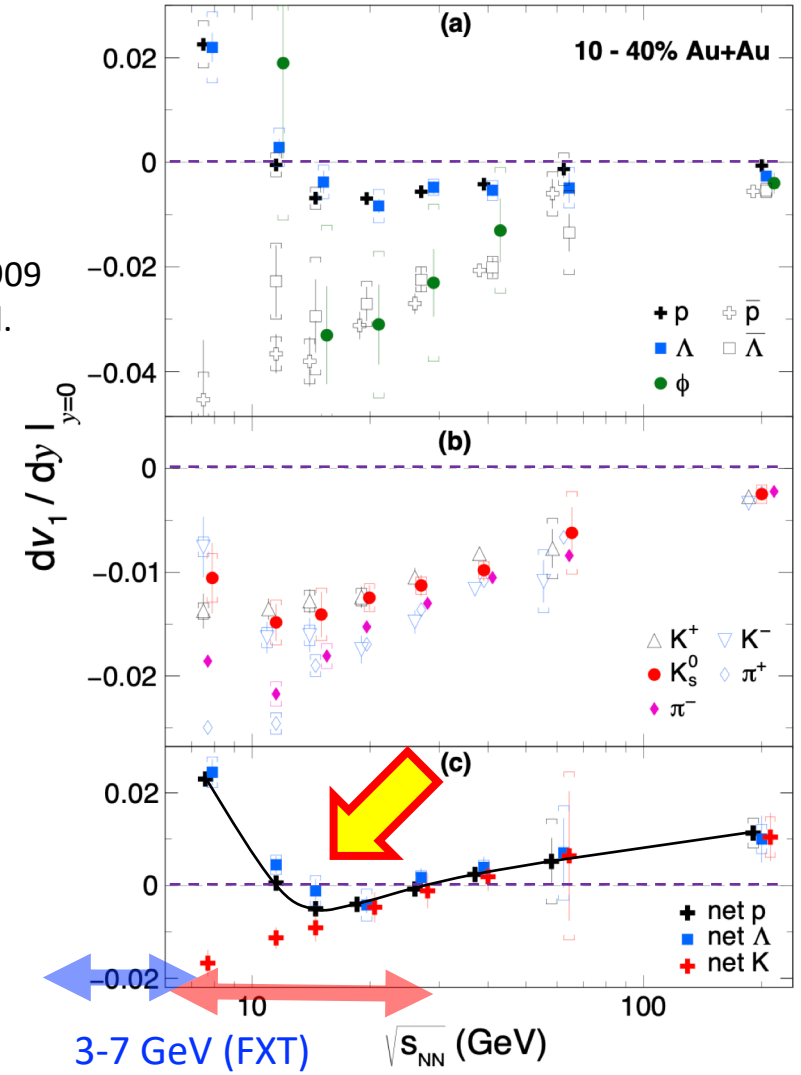
PRC **93** (2016) 14907 (STAR)

Directed flow of net-baryon and quark coalescence



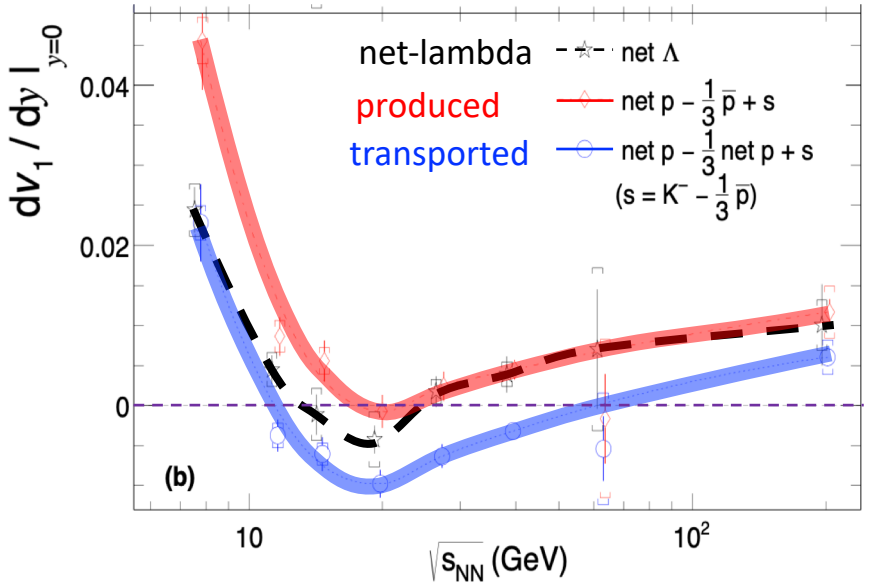
PRC **61** (2000) 24909
J. Brachmann et al.





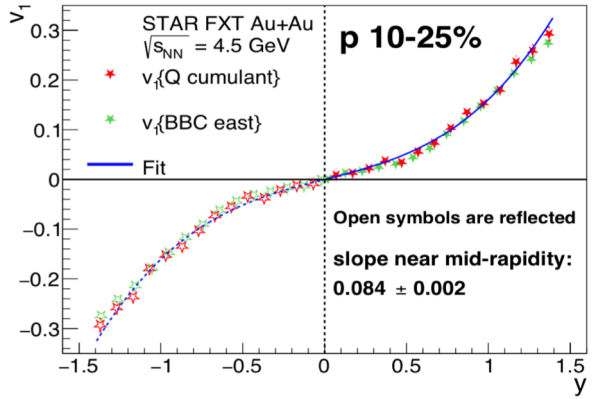
3-7 GeV (FXT)
7-27 GeV (COL)
BES-II in progress

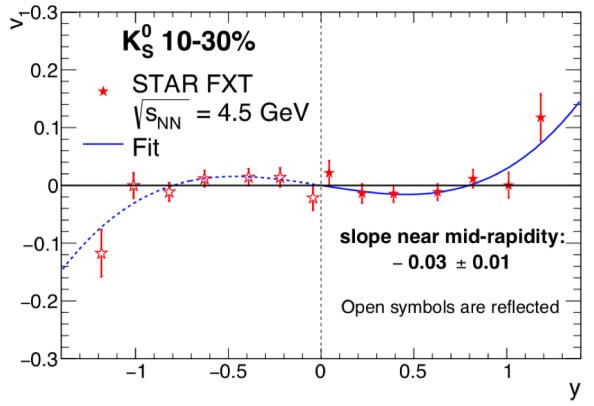
- net-baryon (p, Λ) **negative minimum v_1** as a signal of 1st order phase transition
- coalescence of **produced** or **transported** quark flow
- significant centrality dependence

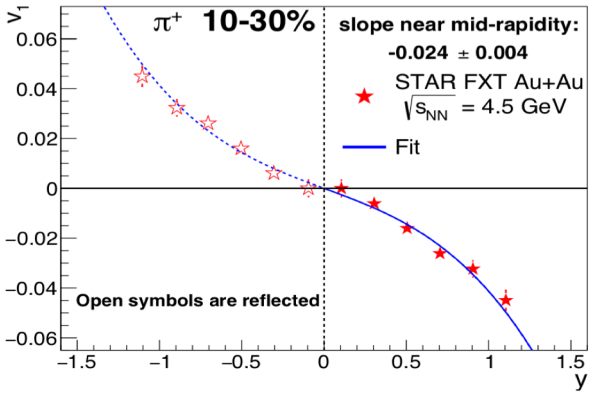


PRL **120** (2018) 62301 (STAR)

Directed flow of identified hadrons including fixed target mode



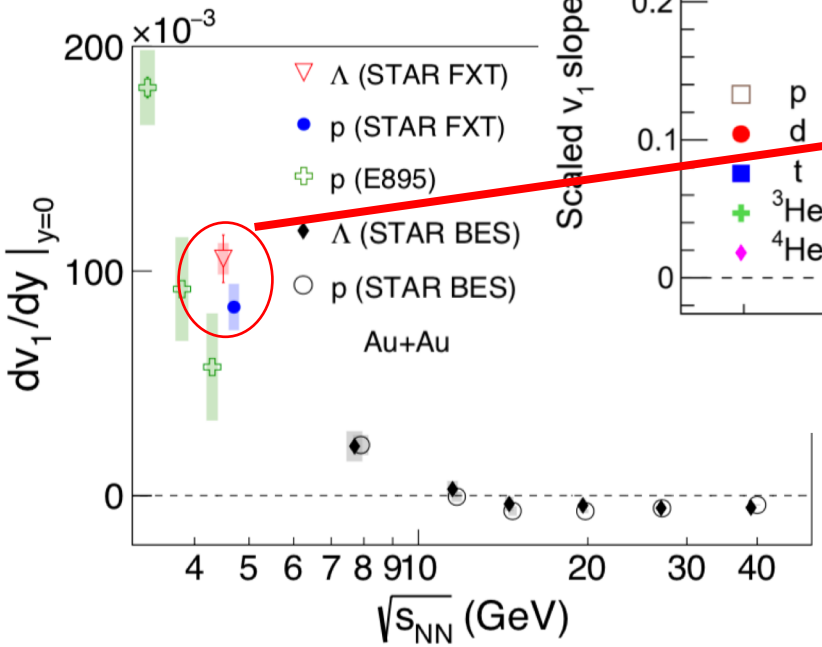


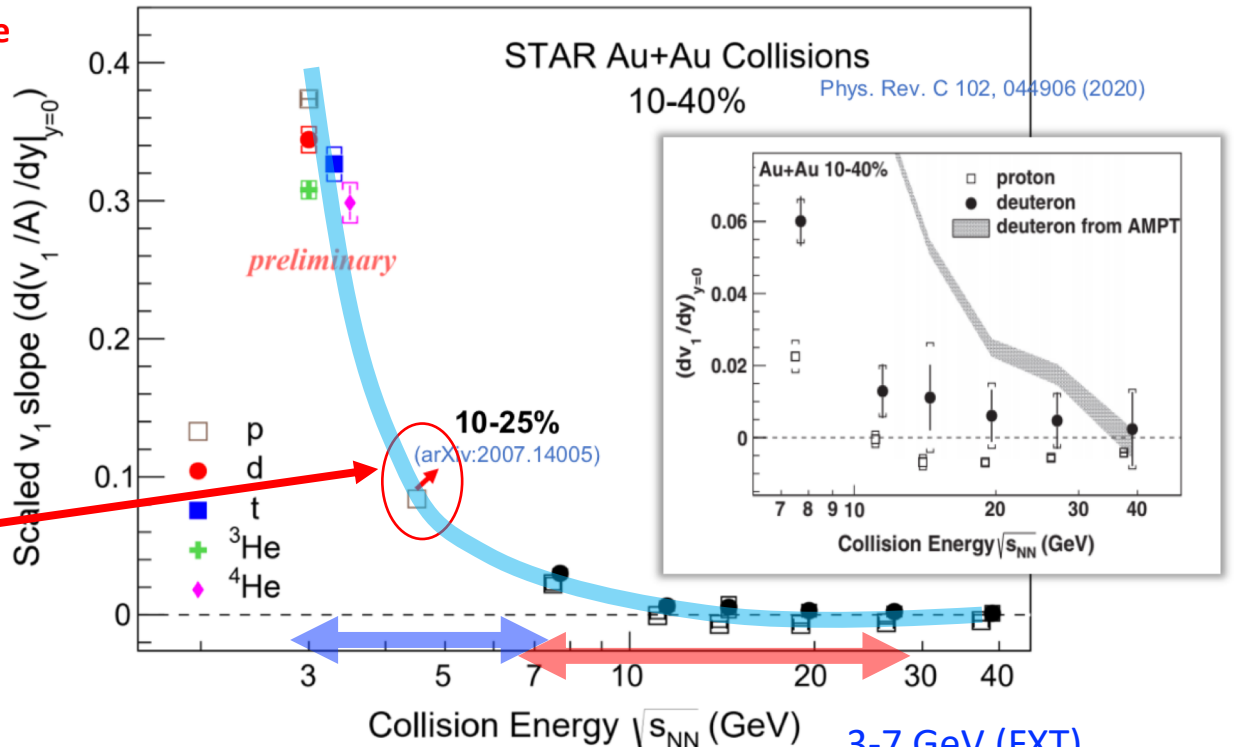


New data on light nuclei v1/v2 at 3GeV FXT will be shown by Xionghong H.

nucleon coalescence holds well for v_1 of p, d, t, ^{3}He, ^{4}He including hypernuclei $^3_\Lambda$H, $^4_\Lambda$H (see p.12)

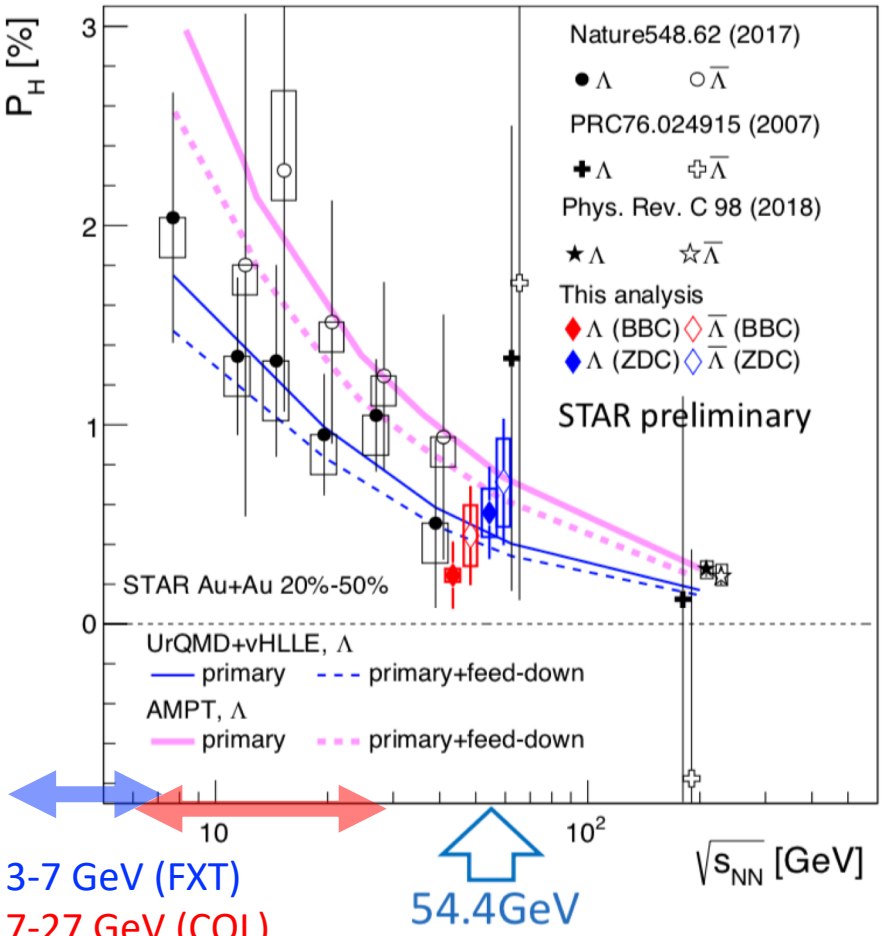
arXiv:2007.14005 (STAR)
(accepted in PRC) for 4.5 GeV





3-7 GeV (FXT)
7-27 GeV (COL)
BES-II in progress

Global polarization via Λ, Ξ

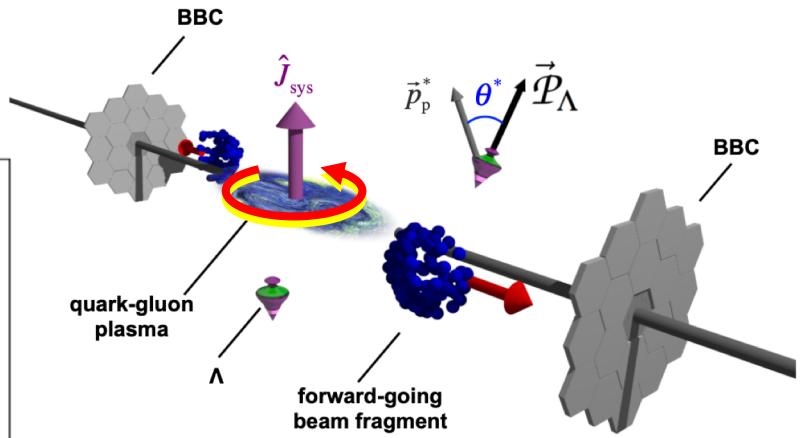


3-7 GeV (FXT)

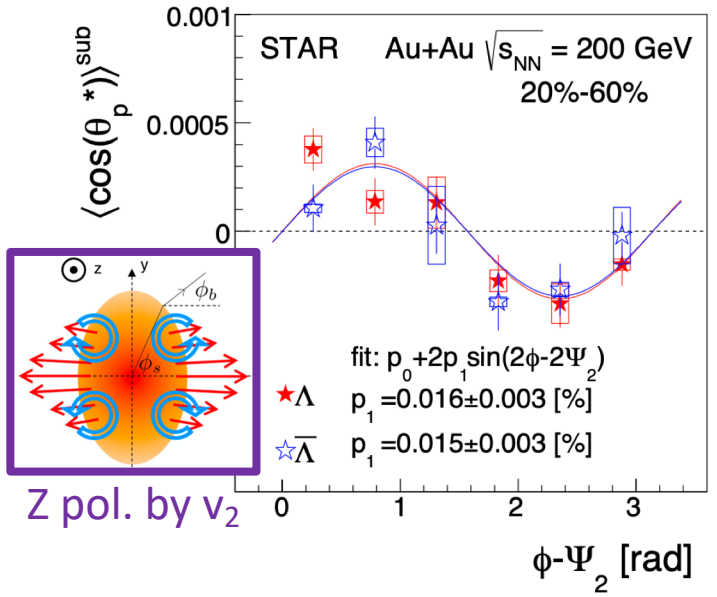
7-27 GeV (COL)

BES-II in progress

Nature **548** (2017) 62 (STAR)

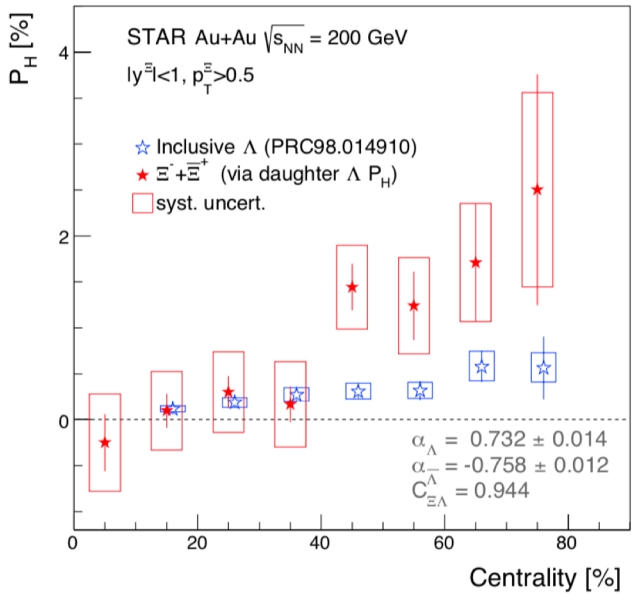


PRL **123** (2019) 132301 (STAR)

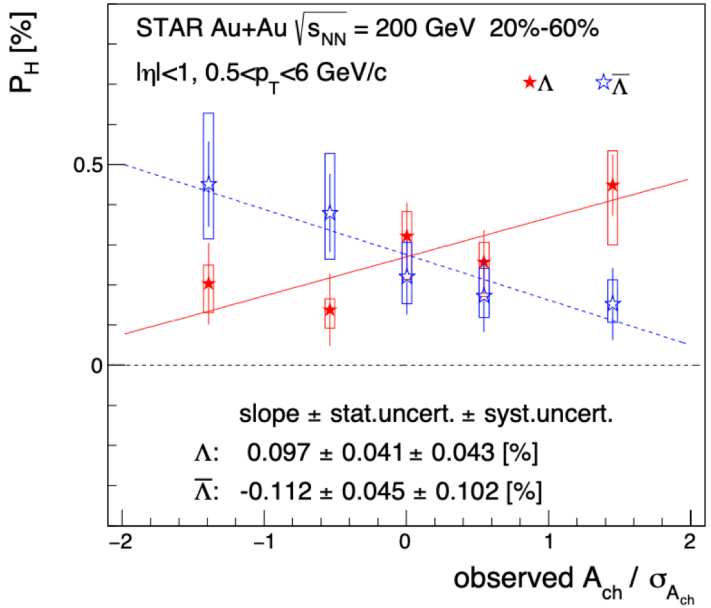


Z pol. by v_2

arXiv:2012.13601



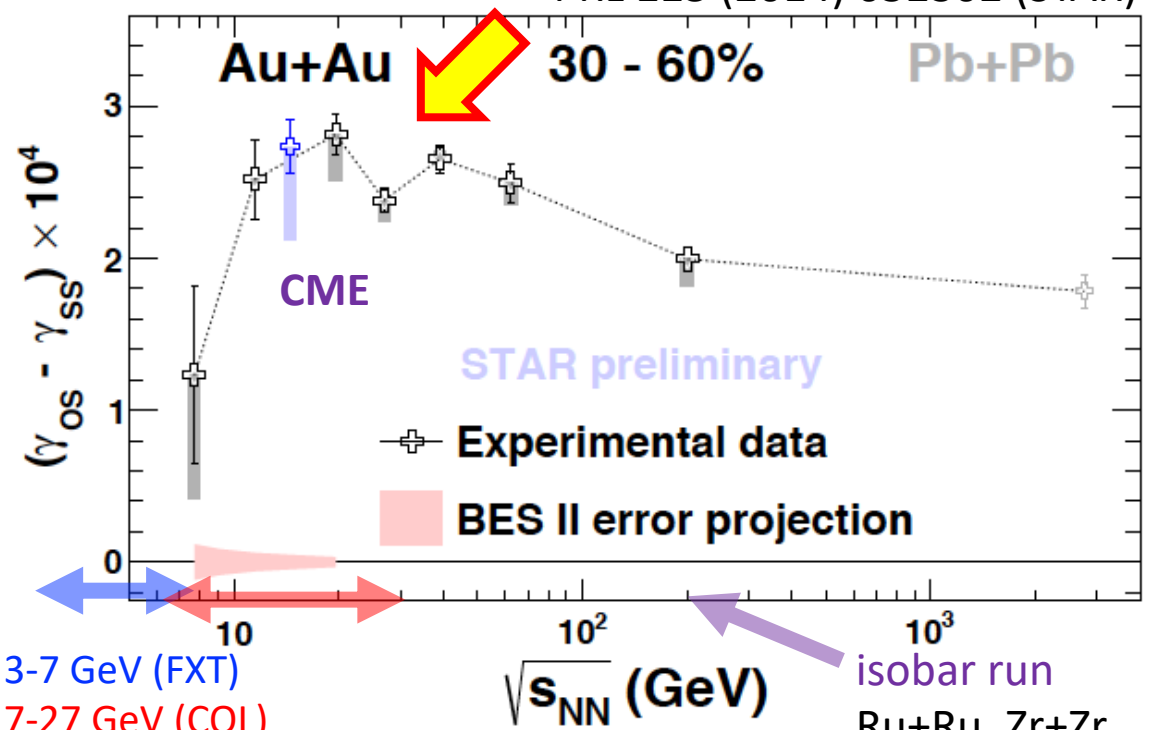
PRC **98** (2018) 14910 (STAR)



Chiral Magnetic Effect/Wave (CME/CMW)

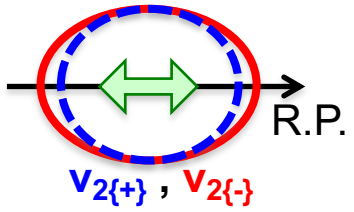
initial strong B-field perpendicular to reaction plane
- charge dipole asymmetry along B-field (CME)
- charge quadruple asymmetry along B-field (CMW)

PRL **113** (2014) 052302 (STAR)

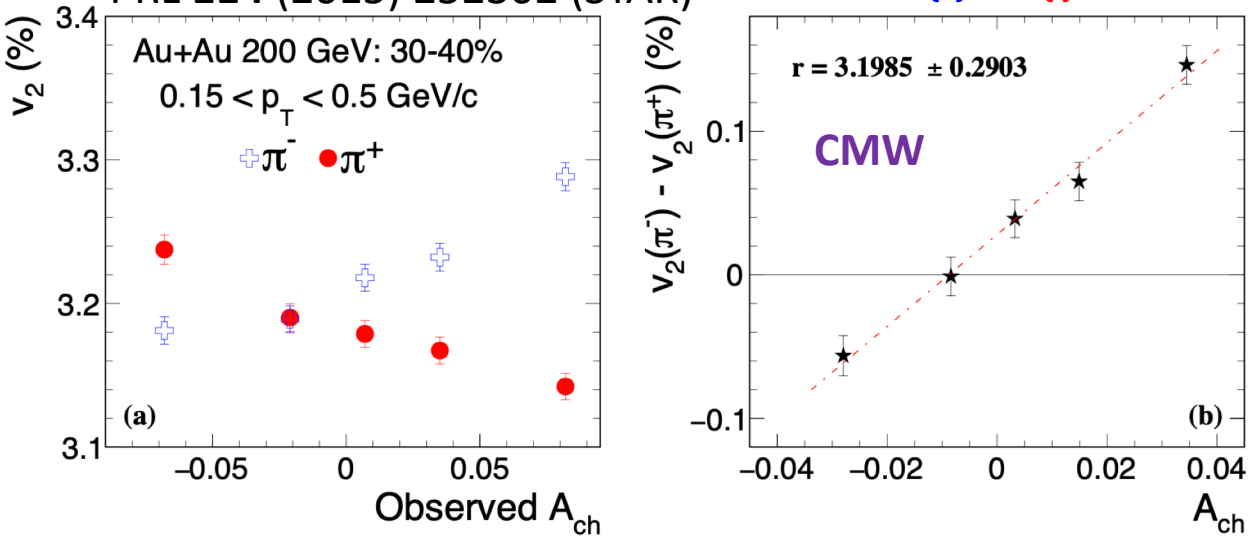


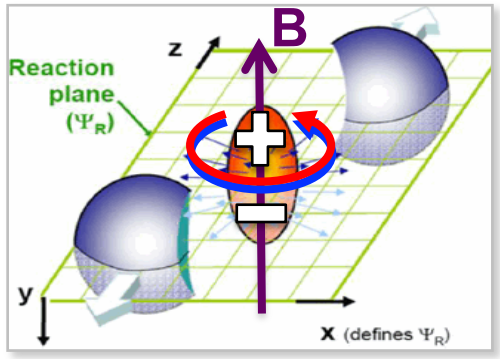
3-7 GeV (FXT)
7-27 GeV (COL)
BES-II in progress

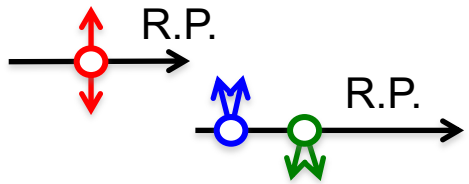
isobar run
Ru+Ru, Zr+Zr



PRL **114** (2015) 252302 (STAR)

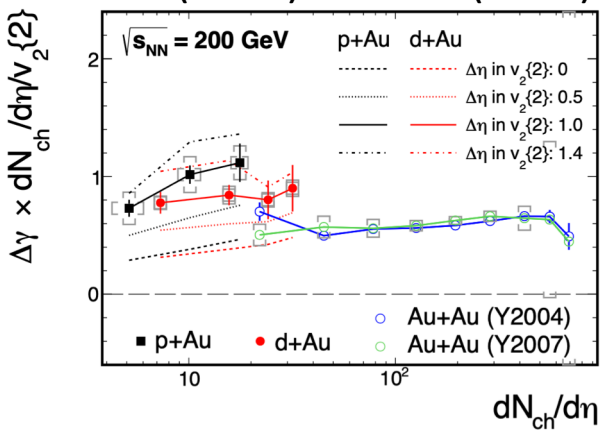




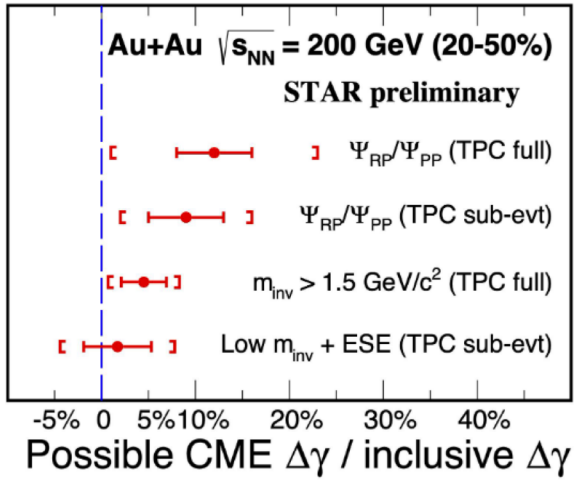


Various ways to find and to confirm CME

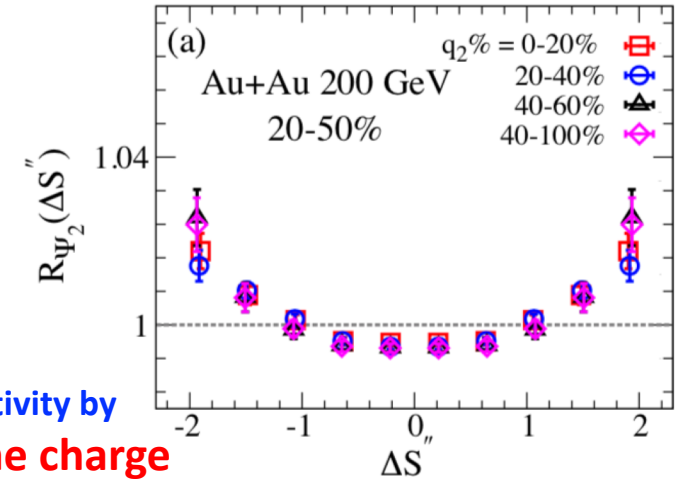
PLB **798** (2019) 134975 (STAR)



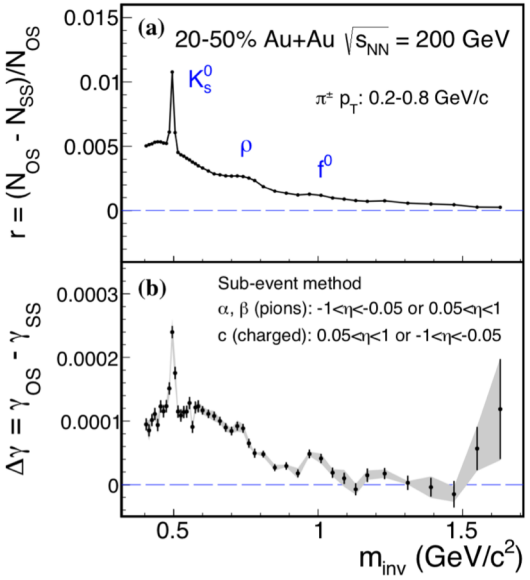
NPA **982** (2019) 535 (STAR)



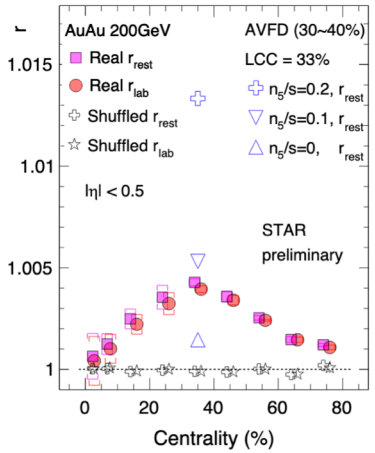
arXiv:2006.04251 (STAR)

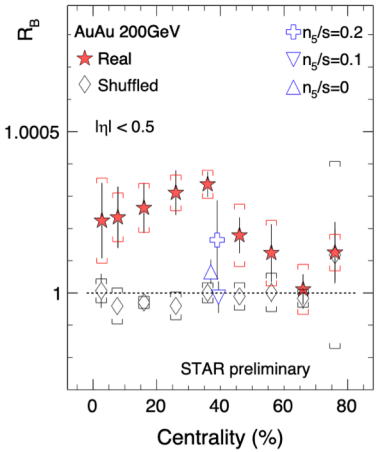


arXiv:2006.05035 (STAR)

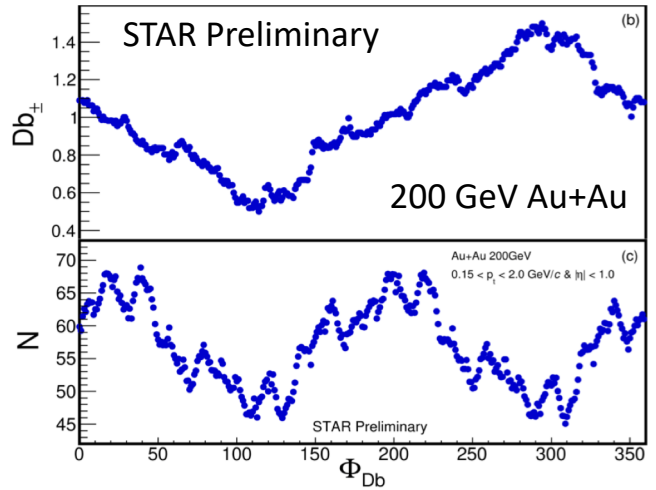


to increase sensitivity by
differentiating the Δγ measurements (total pair integration)





to increase sensitivity by
integrating the charge information event-by-event



Sensitivity comparison underway

Isobar blind analysis ongoing

Summary

- **Freeze-out** and **coalescence** measurements
- **Fluctuation** and **correlation** measurements
- **Elliptic** and **directed flow** measurements
- **Vorticity** and **chiral magnetic** measurements

Our challenges continue to look for the Critical point and the 1st order phase transition.

8 more talks from the STAR collaboration

(Mon) Prabhupada Dixit : Yield and flow of strange- and multi-strange hadrons
(Mon) Shaowei Lan : Anisotropic flow measurements of identified particle
(Tue) Benjamin Kimelman : Meson production in Au+Au collisions at 3 GeV FXT
(Tue) Hanna Zbroszczyk : STAR results on femtoscopy at the BES program
(Wed) Ashish Pandav : Beam energy dependence of net-proton c5 and c6
(Wed) Risa Nishitani : Higher order cumulants of net-proton in pp at 200 GeV
(Fri) Xionghong He : Light nuclei production and flow in Au+Au collisions at 3 GeV FXT
(Fri) Yue-Hang Leung : Hyper-nuclei lifetime, yield and directed flow at 3 GeV FXT

Many thanks to BNL/RHIC/STAR and Tsukuba group

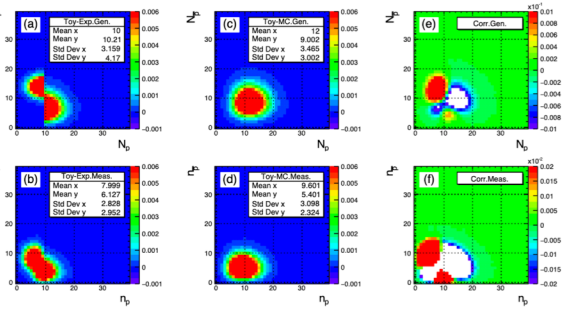
backup slides in the following

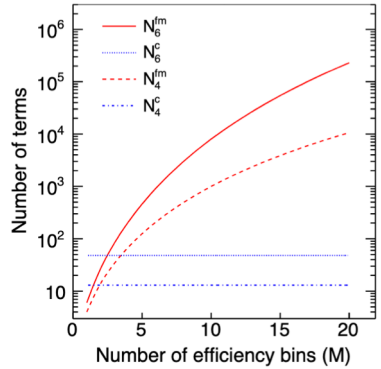
Technical improvements in fluctuation analysis

PRC 95 (2017) 064912

More efficient formulas for efficiency correction of cumulants and effect of using averaged efficiency

Toshihiro Nonaka,[1] Masakiyo Kitazawa,[2,3] and ShinIchi Esumi[1]

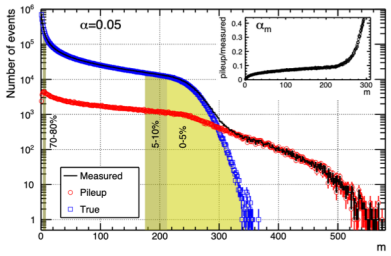




NIN A984 (2020) 164632

Pileup corrections on higher-order cumulants

Toshihiro Nonaka,[1,*] Masakiyo Kitazawa,[2,3,†] and ShinIchi Esumi[1,‡]



NIN A987 (2020) 164802

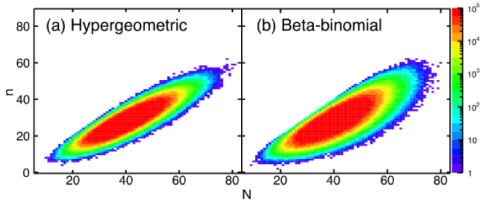
Reconstructing particle number distributions with convoluting volume fluctuations

ShinIchi Esumi,[1,*] Kana Nakagawa,[1] and Toshihiro Nonaka[1,2,†]

NIM A906 (2018) 10-17

A general procedure for detector-response correction of higher order cumulants

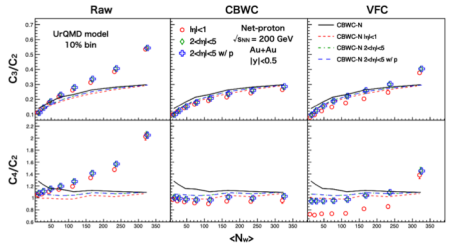
Toshihiro Nonaka,[1,2,*] Masakiyo Kitazawa,[3,4,†] and ShinIchi Esumi[2,‡]

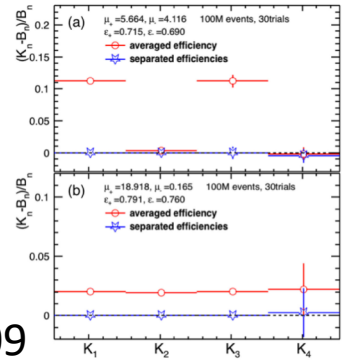


PRC 100 (2019) 044904

Volume fluctuation and multiplicity correlation on higher-order cumulants

Tetsuro Sugiura,[1,*] Toshihiro Nonaka,[2,†] and ShinIchi Esumi[1,‡]





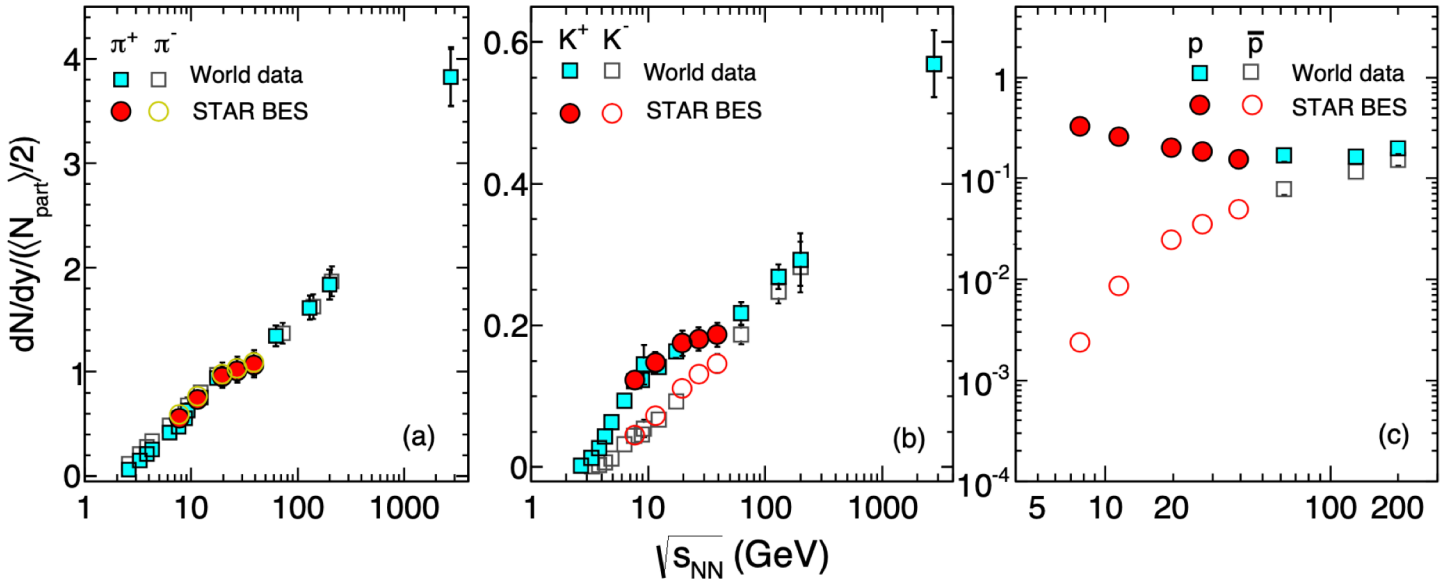
PRC 94 (2016) 034909

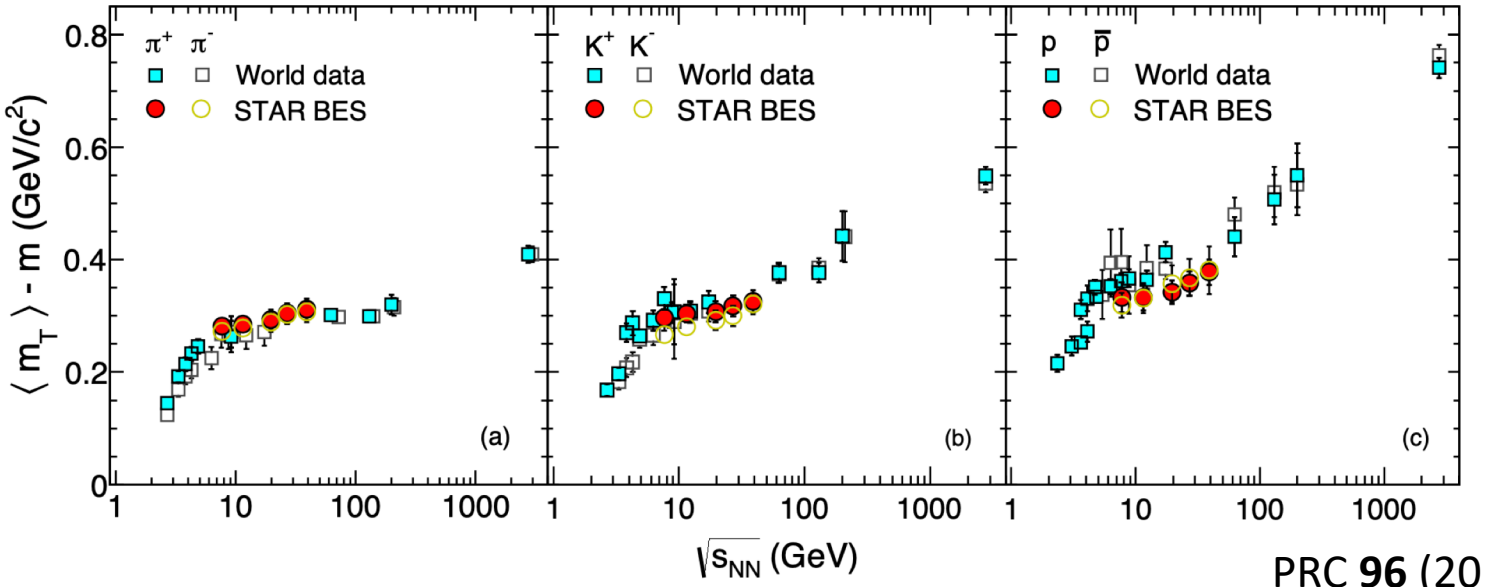
Importance of separated efficiencies between positively and negatively charged particles for cumulant calculations

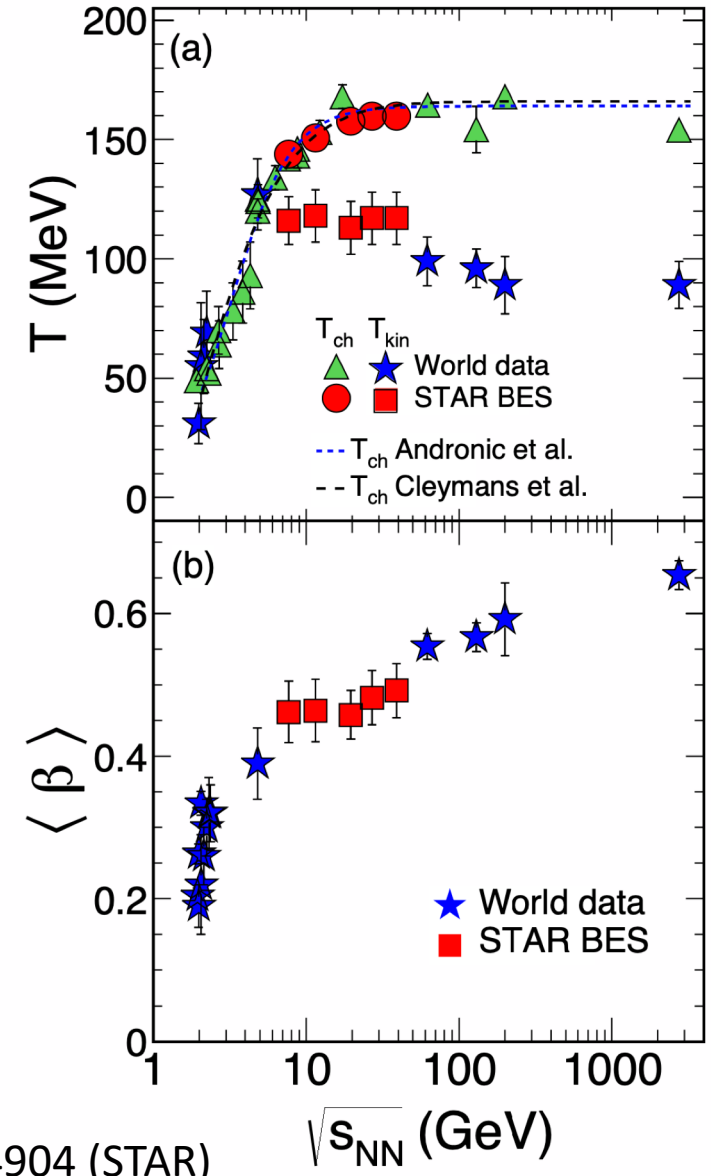
Toshihiro Nonaka,[1,*] Tetsuro Sugiura,[1,†] ShinIchi Esumi,[1] Hiroshi Masui,[1] and Xiaofeng Luo[2]

T. Nonaka (Tsukuba, CCNU), M. Kitazawa (Osaka)

Beam energy dependence of yield, shape and freeze-out parameters



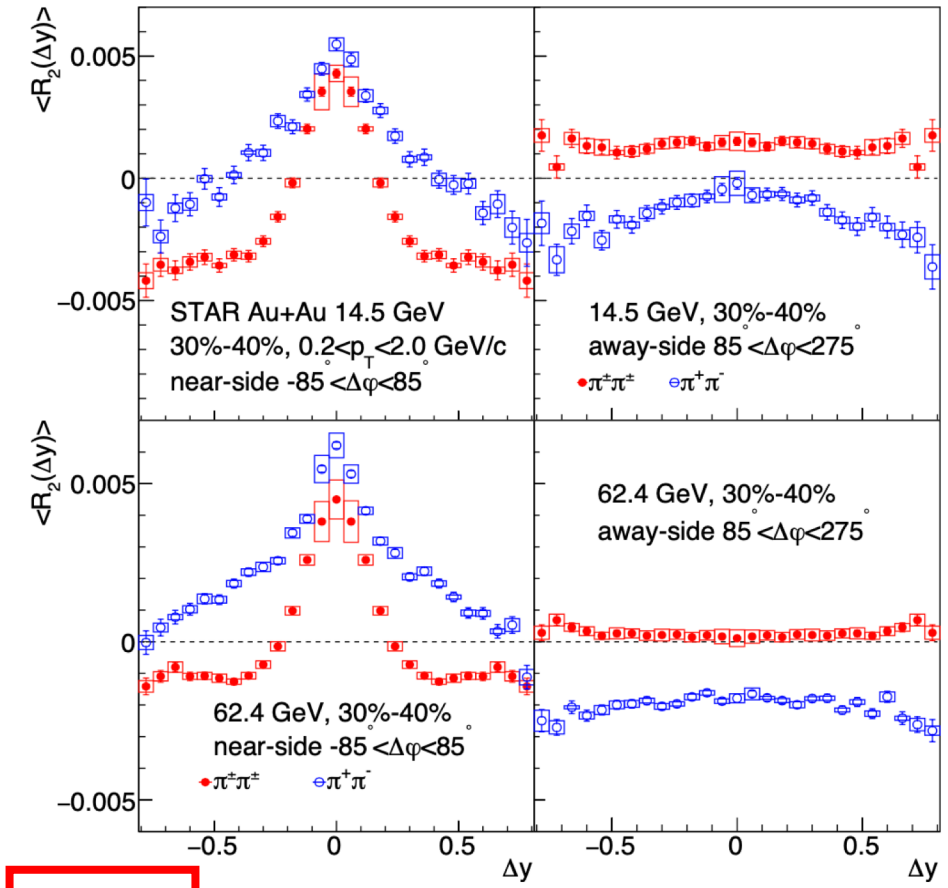




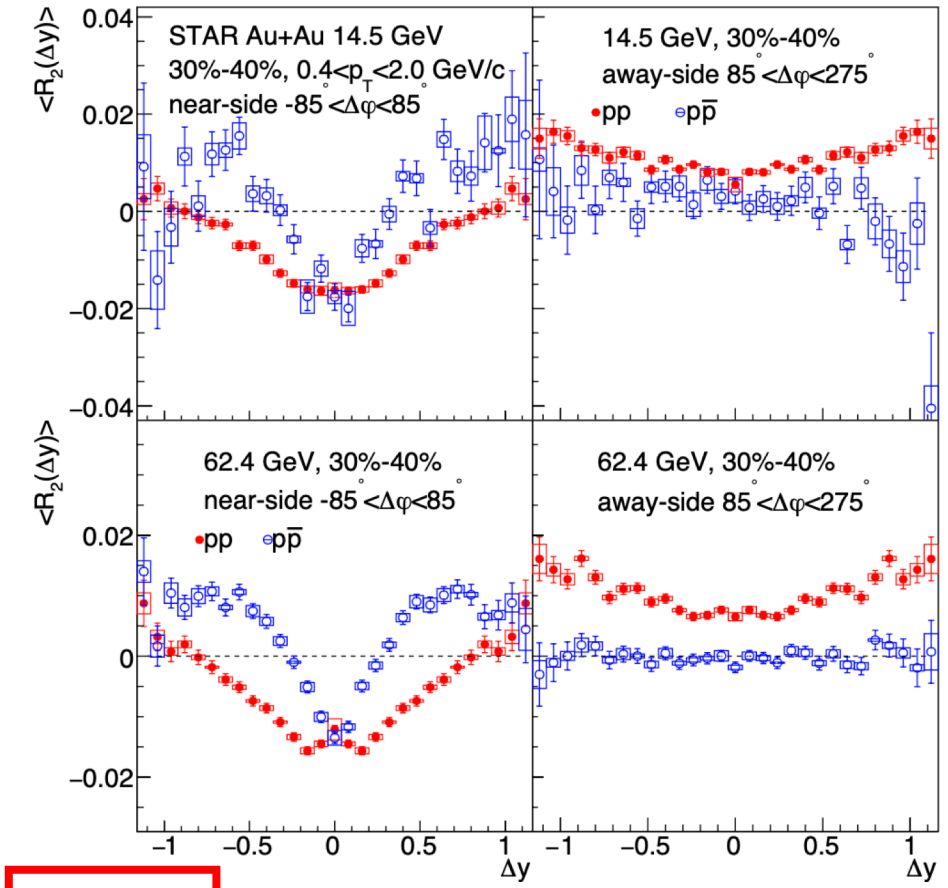
PRC **96** (2017) 44904 (STAR)

Two-particle Δy correlation between pions or protons

positive (π–π) and **negative** (p–p) Δy correlation, especially in near-side Δϕ



(a) pions

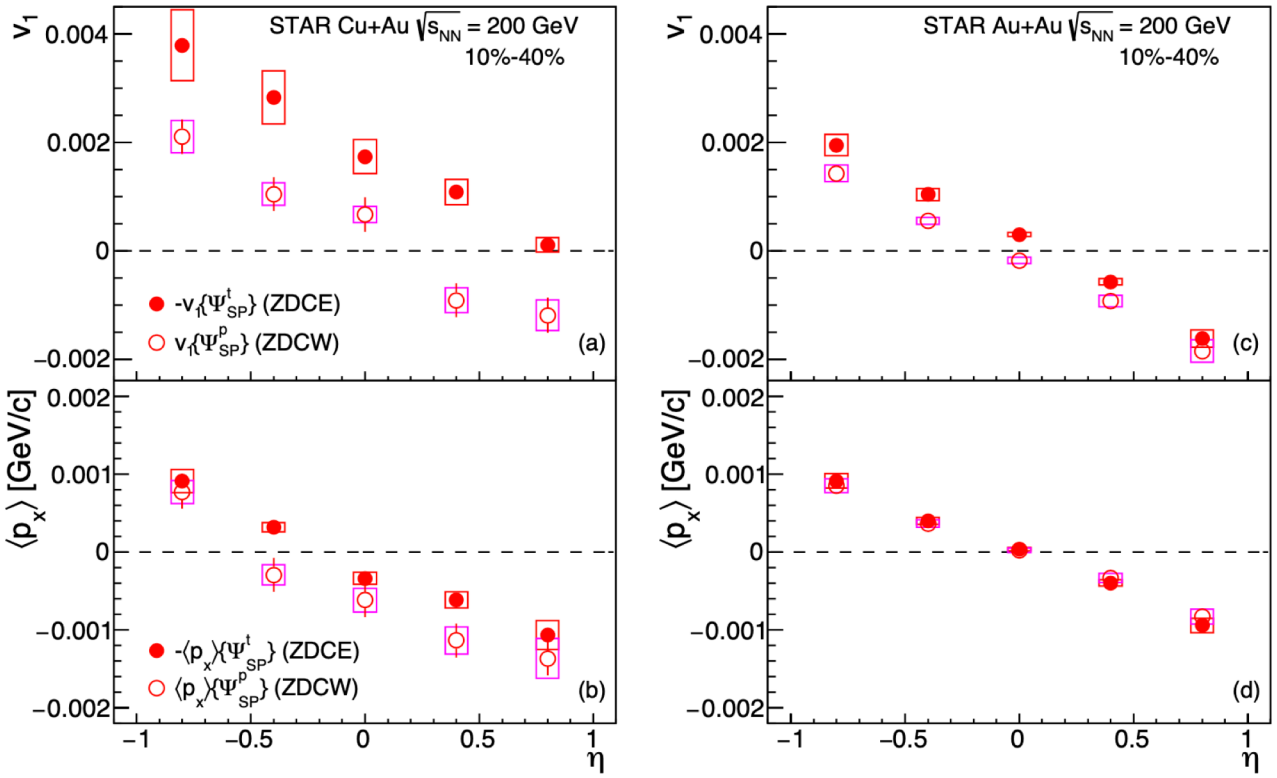


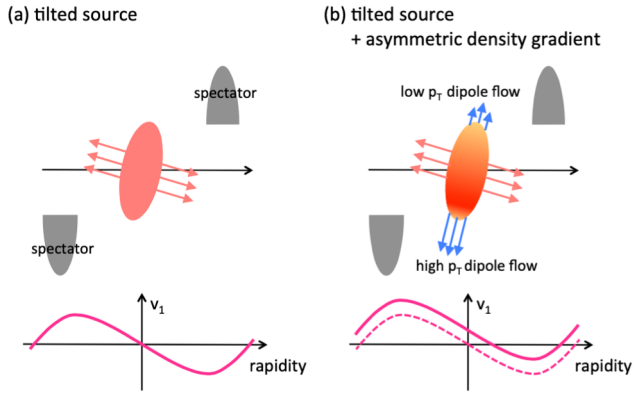
(b) protons

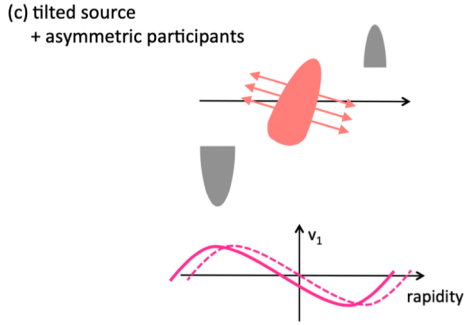
PRC **101** (2020) 14916 (STAR)

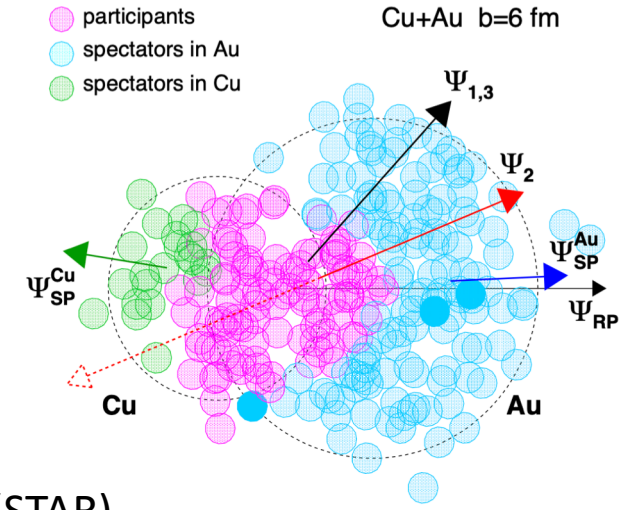
Directed flow in asymmetric system

Directed flow comparison between CuAu and AuAu









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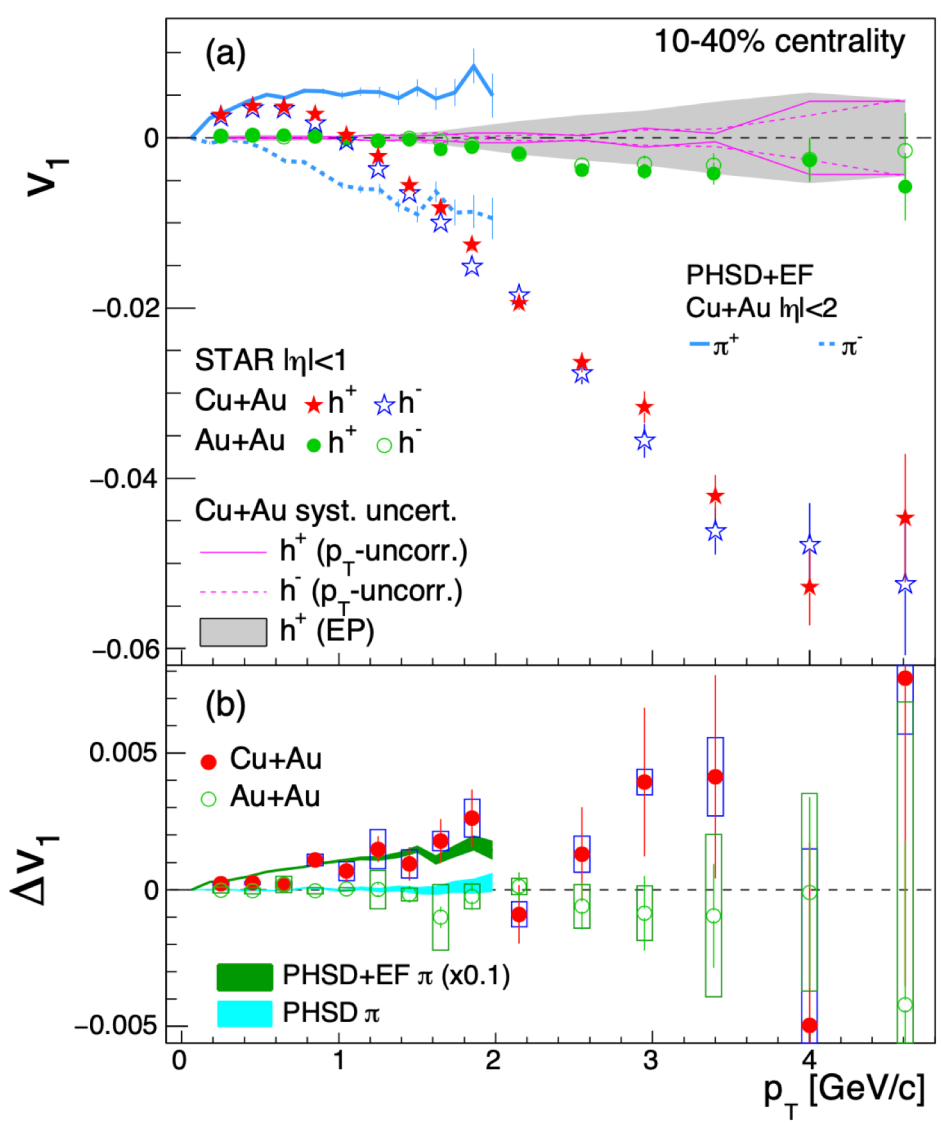
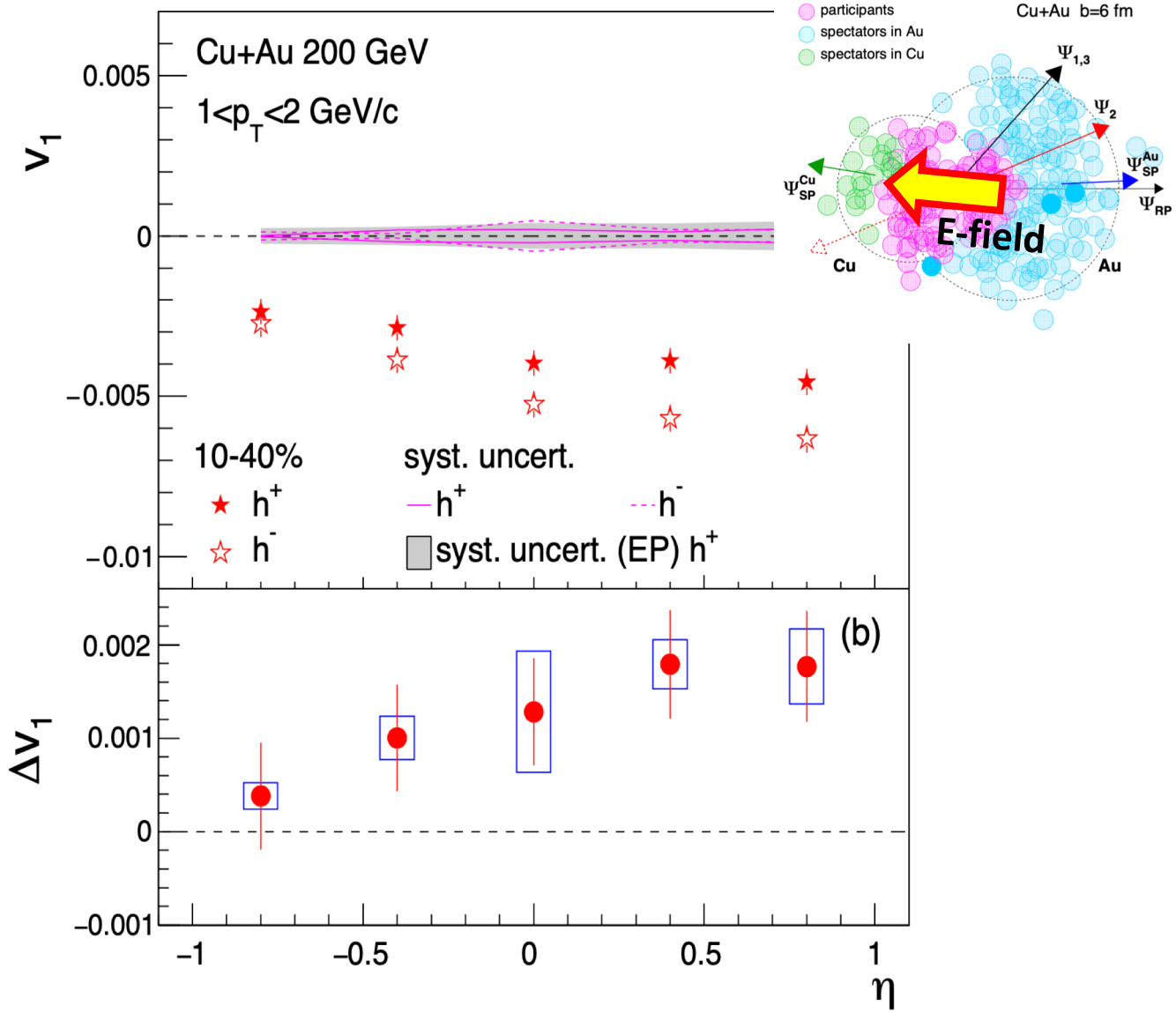
Charge asymmetry in directed flow at Cu+Au to probe E-field in the system





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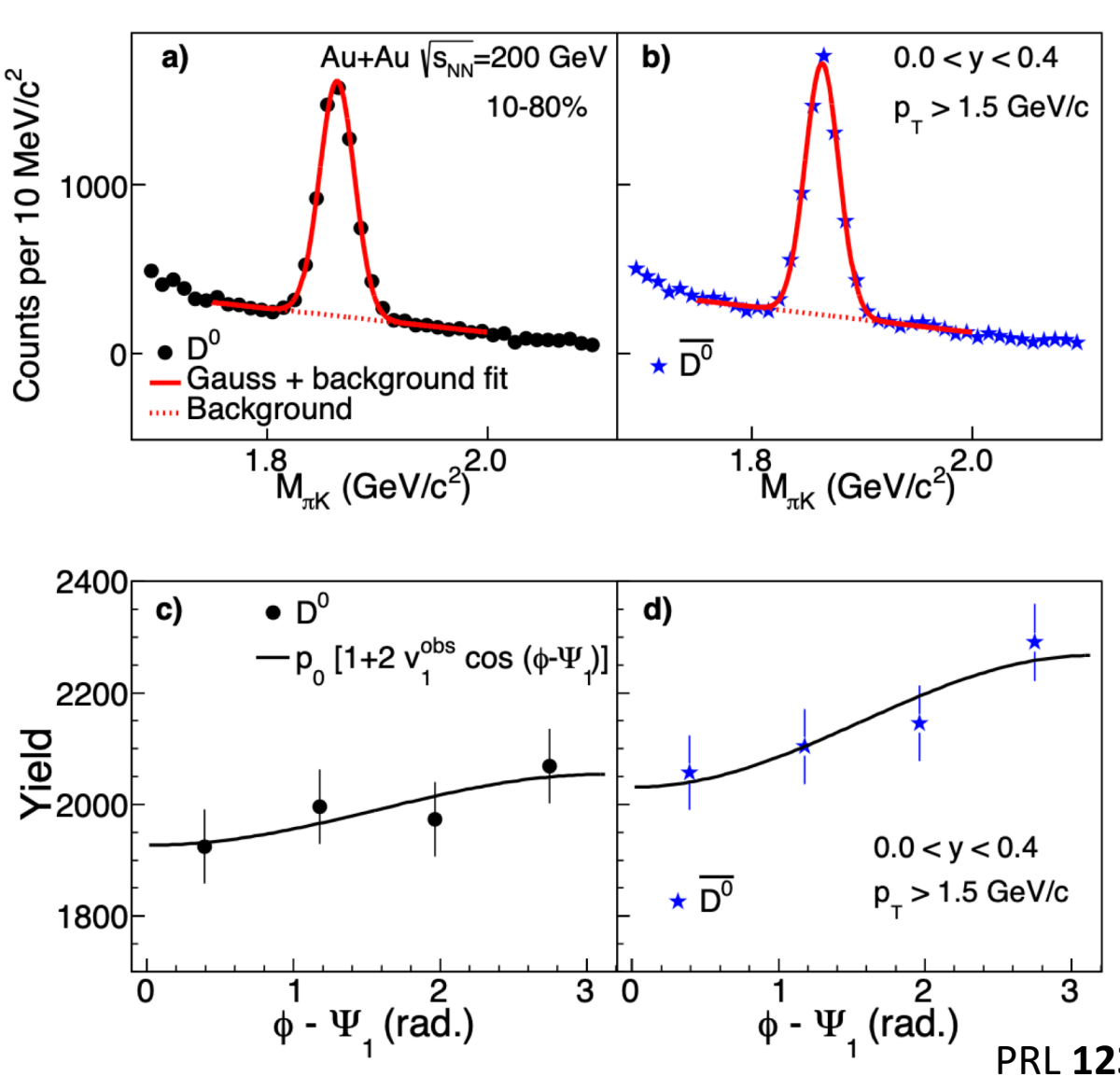
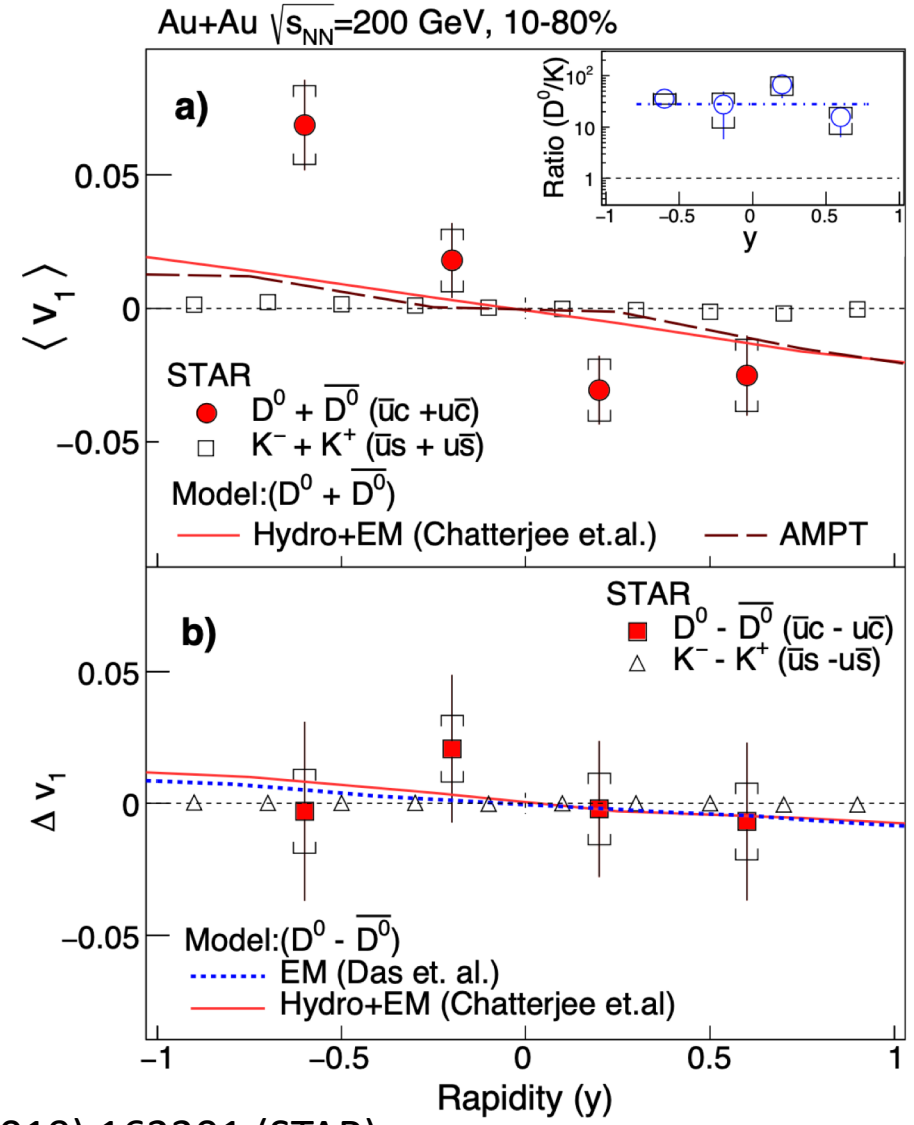
Directed flow of heavy quark

initial E-field or geometrical slope
High pT v1 and HBT w.r.t. Psi1





PRL **123** (2019) 162301 (STAR)