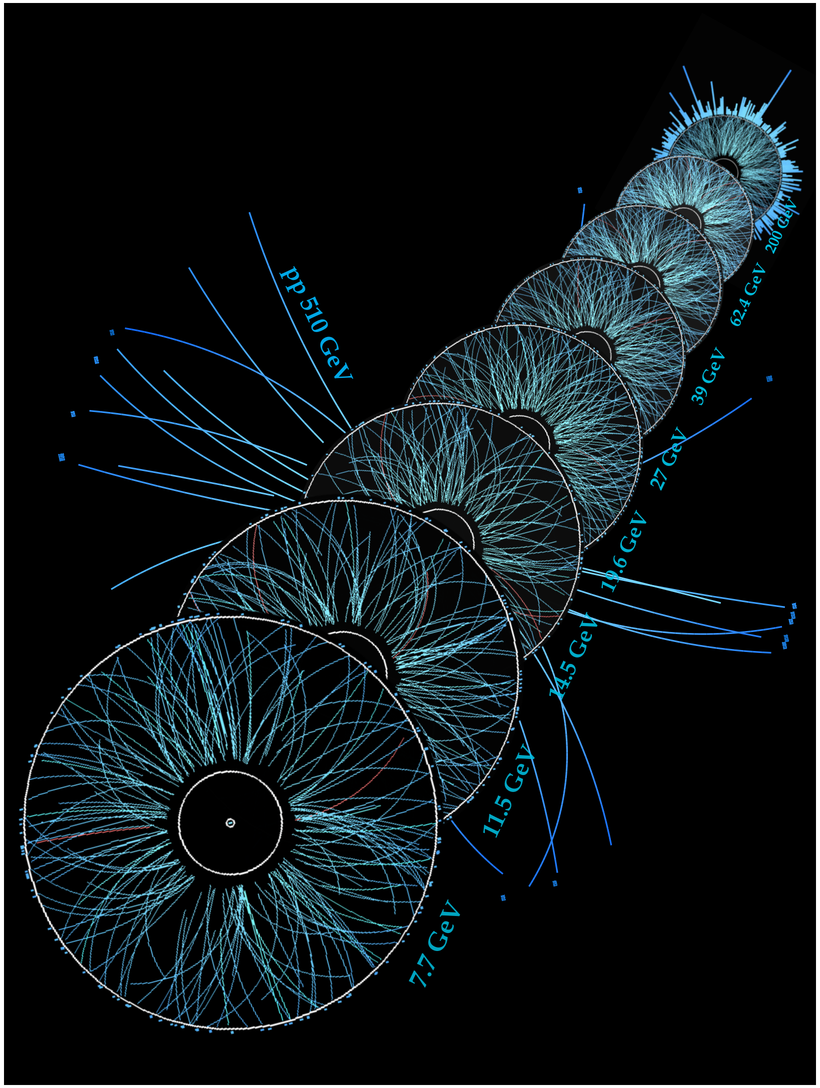
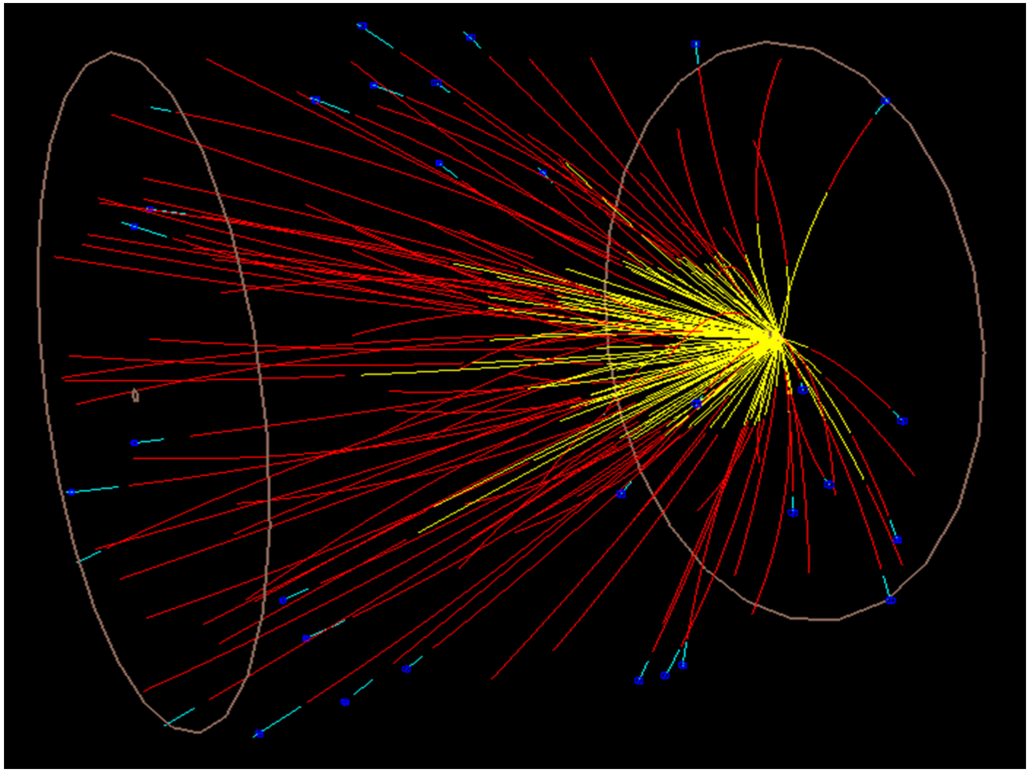
STAR BES-II Status and Analysis Plan





Helen Caines - Wright Lab, Yale - on behalf of the STAR Collaboration

Supported by the U.S. DEPARTMENT OF ENERGY | Office of Science

BES-I → BES-II

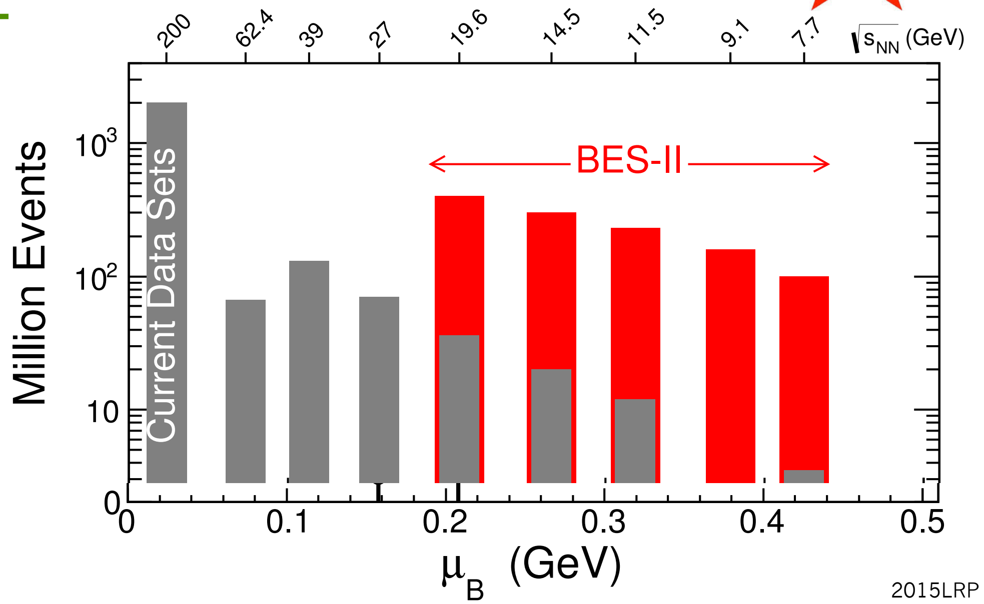
BES-I:
Hints that at low √s
QGP turns off
Ordered phase transition
Critical Point

BES-II:
Focus in on regions of interest

Need higher statistics

Need to maximize fraction particles measured

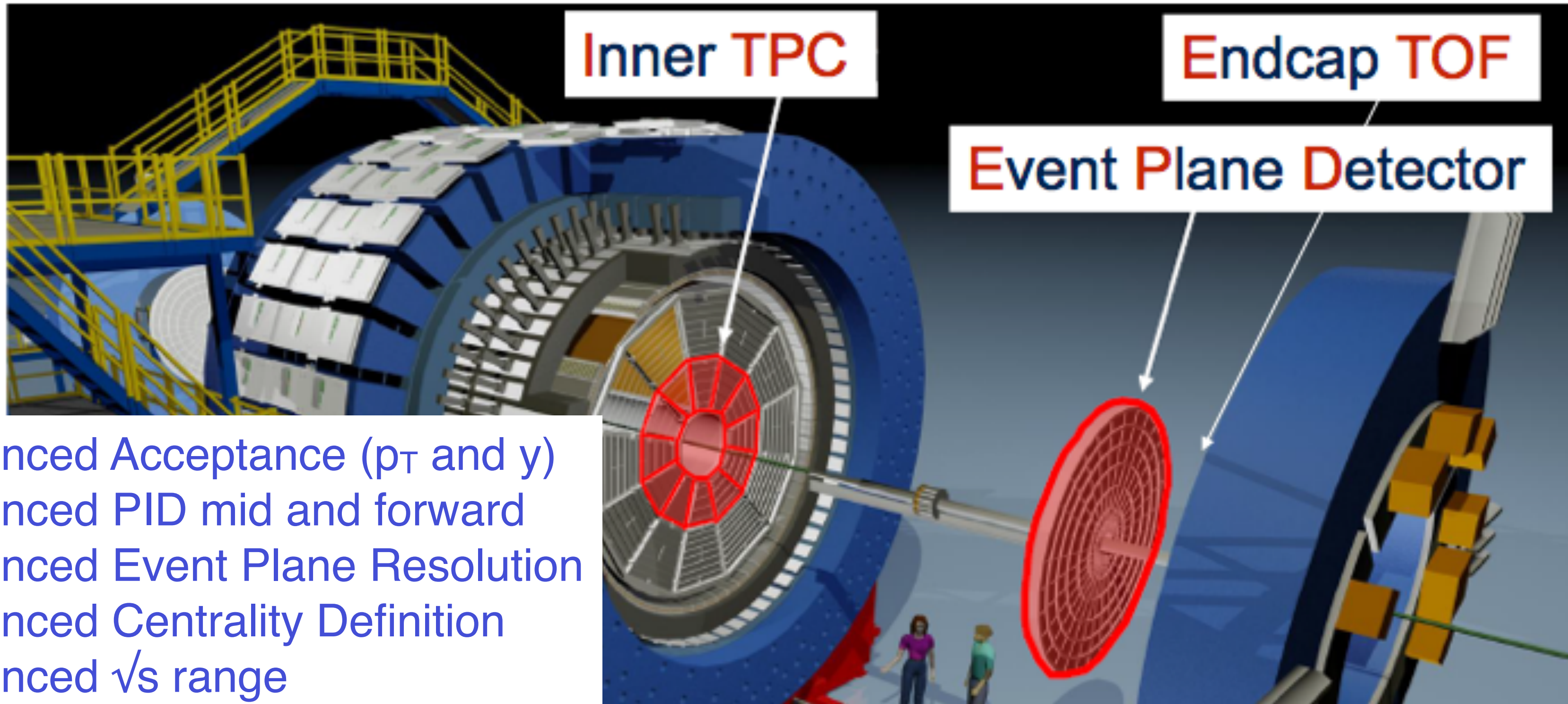
Need lower energies
- Fixed Target (FXT) program
- electron cooling of beam



BES-II approved by BNL PAC to take place over course of two (then three) RHIC running periods
➔ Project listed as a top US NP priority in LRP 2015

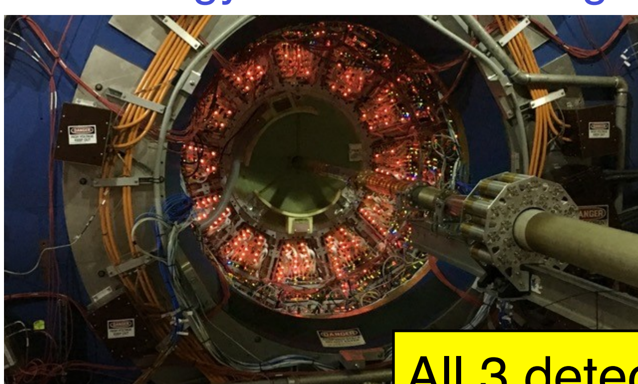
Turn trends and features into definitive conclusions

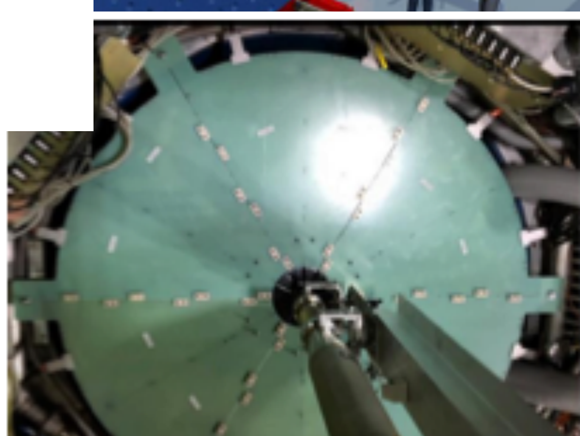
The BES-II Upgrades



Enhanced Acceptance (p_T and y)
Enhanced PID mid and forward
Enhanced Event Plane Resolution
Enhanced Centrality Definition
Enhanced $\sqrt{s}$ range

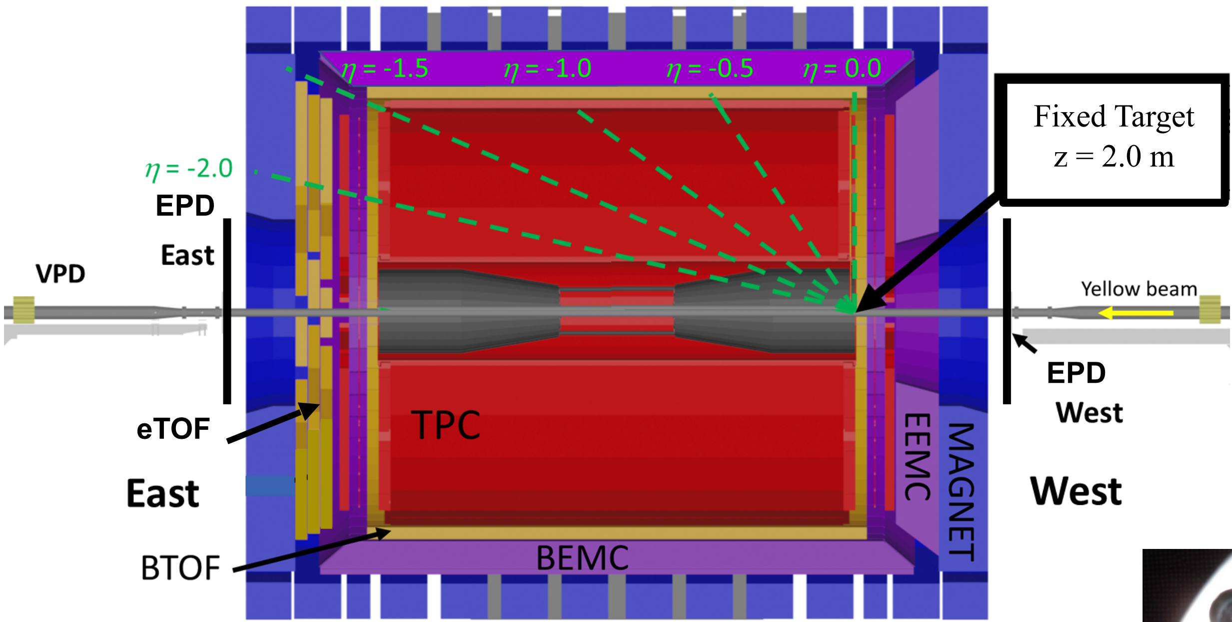
Low Energy Electron Cooling

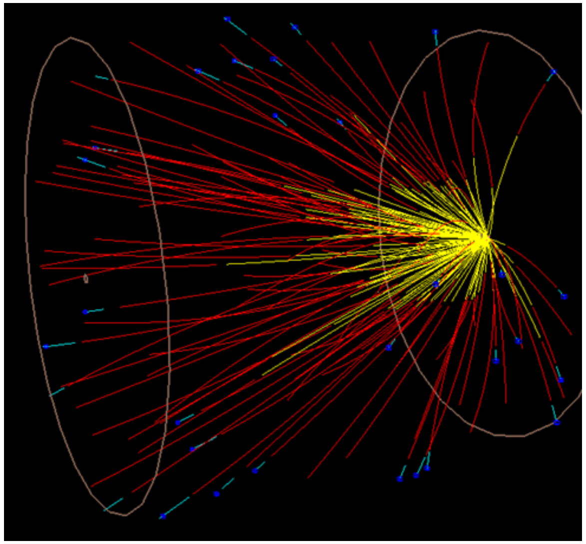




All 3 detectors fully installed prior to start of BES-II

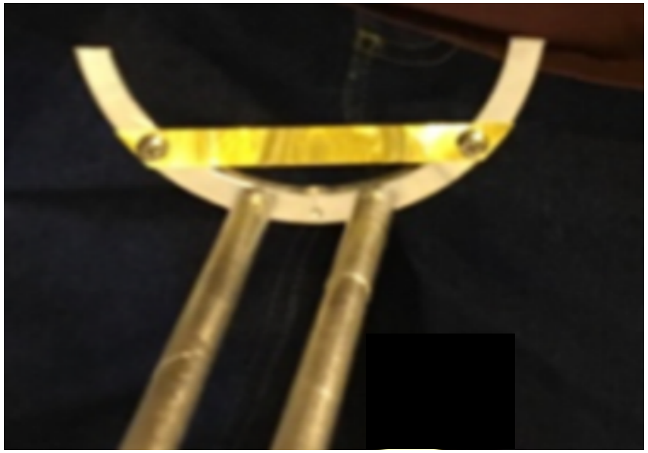
The fixed-target (FXT) setup

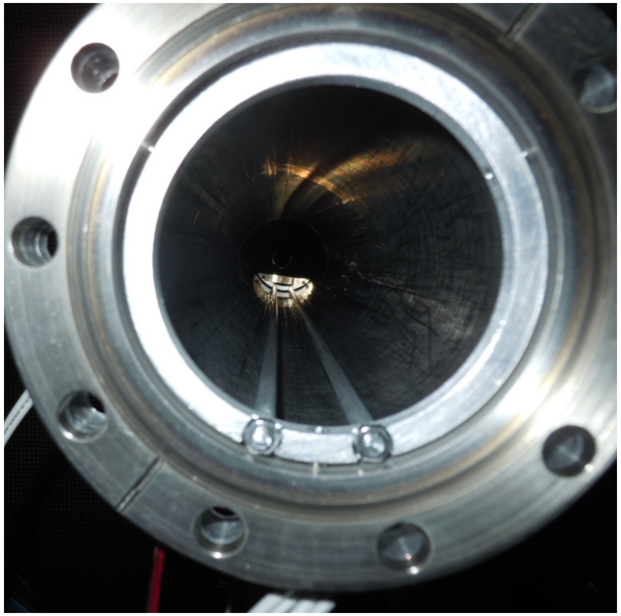




Gold Target:

- 250 µm foil
- 2 cm below nominal beam axis
- 2 m from center of STAR





Mid-rapidity for 3.0 GeV is y = 1.049

Original planning for the BES-II

Berndt Mueller's (ALD) proposed charge

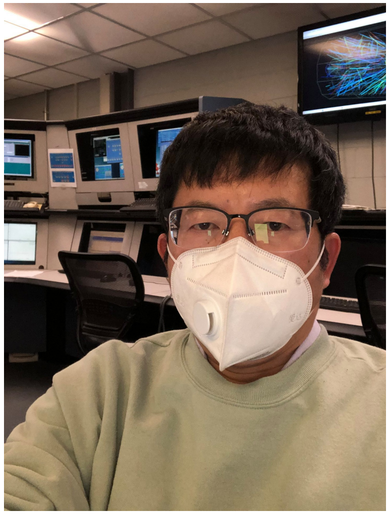
We anticipate the 2019 RHIC run to constitute the first year of a two-year high statistics beam energy scan.

The 2017 PAC assigned highest priority to proposed Au+Au runs at 11.5, 14.5, and 19.6 GeV, interleaved by brief fixed target runs at the same beam energies, as well as dedicated fixed target runs corresponding to CM energies of 7.7, 6.2, and 5.2 GeV. The PAC tentatively recommended Au+Au runs in the collider mode at 9.1 and 7.7 GeV during the 2020 RHIC campaign.

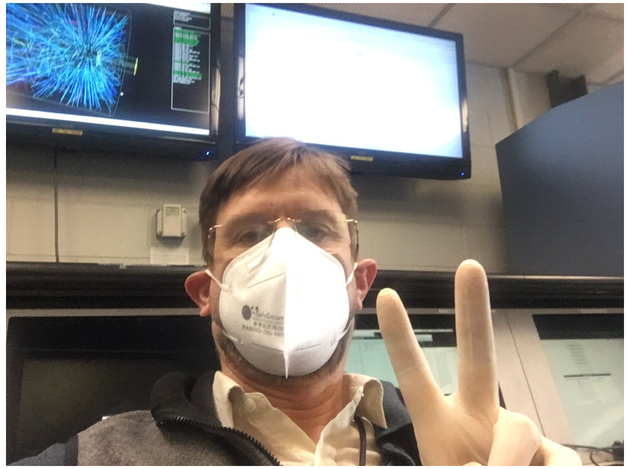
STAR should not simply take these tentative recommendations as a given, but reconsider and justify the prioritized set of beam energies and the requested accumulated statistics at each energy, assuming either 24 cryo-week runs or 20 cryo-week runs in each of the years 2019 and 2020

Helen Caines - Collab. meeting, LBNL Jan 2018 2

Then the pandemic hit



Zhangbu Xu (BNL)

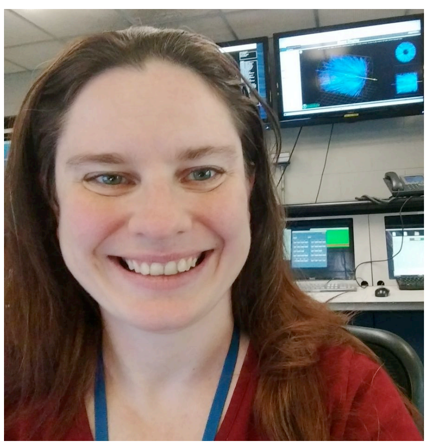


Dan Cebra (UC Davis)

Run-19 went very well

Run-20 halted in March

- lots of new safety protocols in place
- shift crew reduced and some remote
- minimal-to-no face-to-face interactions



Rosi Reed (Lehigh)

Liz Mogavero (BNL)

Were able to restart in the June - all planned data collected

Run-21 undertaken with similar restrictions as Run-20b

$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	$y_{center\ of\ mass}$	μ_B (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	0	230	14	256 M (250 M)	Run-21
14.6	7.3	C	0	262	60	324 M (310 M)	Run-19
13.7	100	FXT	2.69	276	0.5	52 M (50 M)	Run-21
11.5	5.75	C	0	316	54	235 M (230 M)	Run-20
11.5	70	FXT	2.51	316	0.5	50 M (50 M)	Run-21
9.2	4.59	C	0	372	102	162 M (160 M)	Run-20+20b
9.2	44.5	FXT	2.28	372	0.5	50 M (50 M)	Run-21
7.7	3.85	C	0	420	90	100 M (100 M)	Run-21
7.7	31.2	FXT	2.10	420	0.5+1.0+ scattered	50 M + 112 M + 100 M (100 M)	Run-19+20+21
7.2	26.5	FXT	2.02	443	2+Parasitic with CEC	155 M + 317 M	Run-18+20
6.2	19.5	FXT	1.87	487	1.4	118 M (100 M)	Run-20
5.2	13.5	FXT	1.68	541	1.0	103 M (100 M)	Run-20
4.5	9.8	FXT	1.52	589	0.9	108 M (100 M)	Run-20
3.9	7.3	FXT	1.37	633	1.1	117 M (100 M)	Run-20
3.5	5.75	FXT	1.25	666	0.9	116 M (100 M)	Run-20
3.2	4.59	FXT	1.13	699	2.0	200 M (200 M)	Run-19
3.0	3.85	FXT	1.05	721	4.6	259 M -> 2B(100 M -> 2B)	Run-18+21

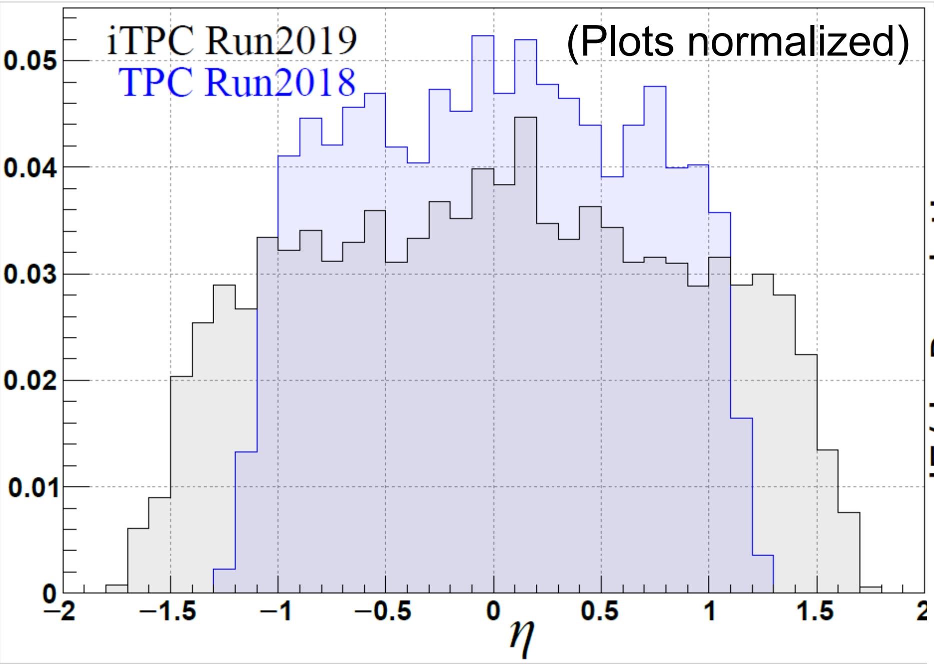
iTPC: Enhanced acceptance

Successfully integrated into data-taking since day 1 of BES-II

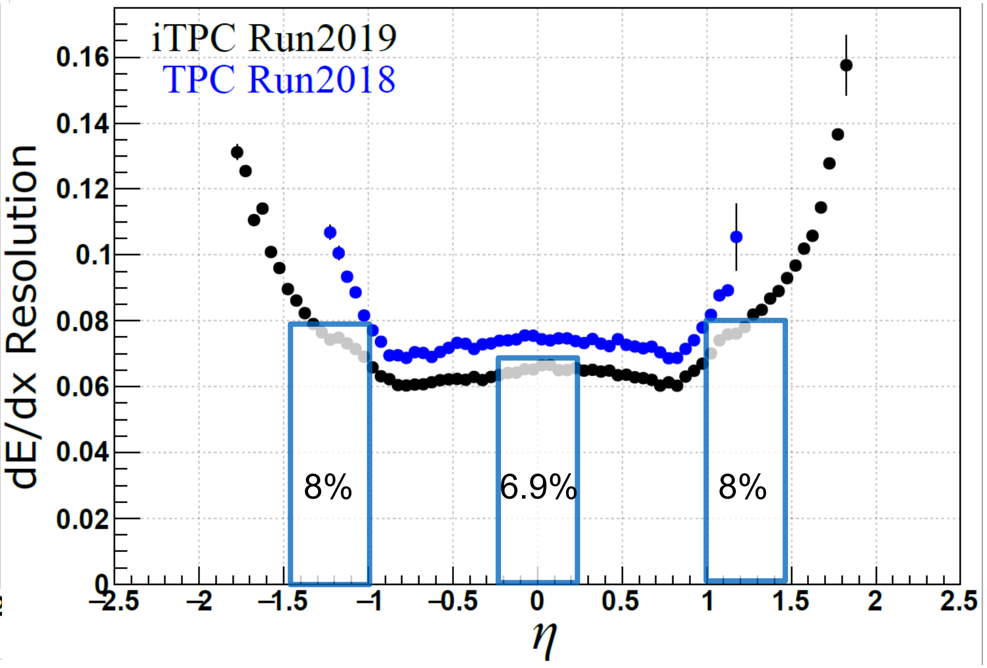
Projected detector performance criteria met

Demonstrated improvement:

Increased pseudorapidity coverage



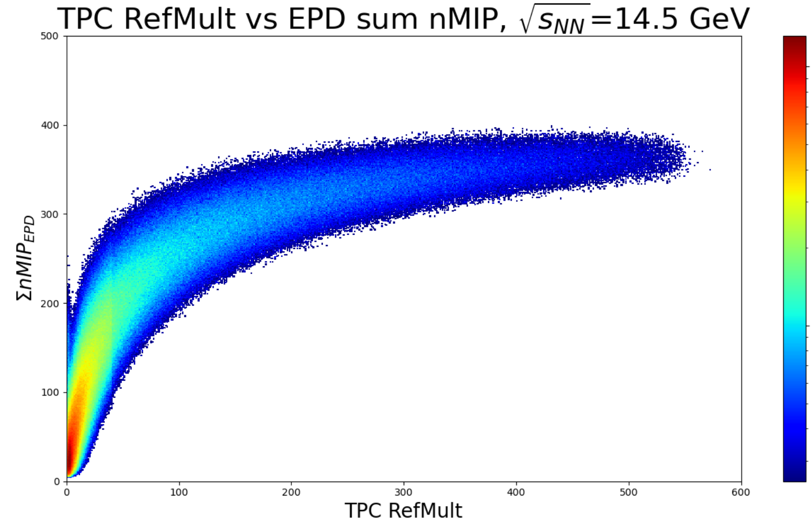
Improved dE/dx resolution

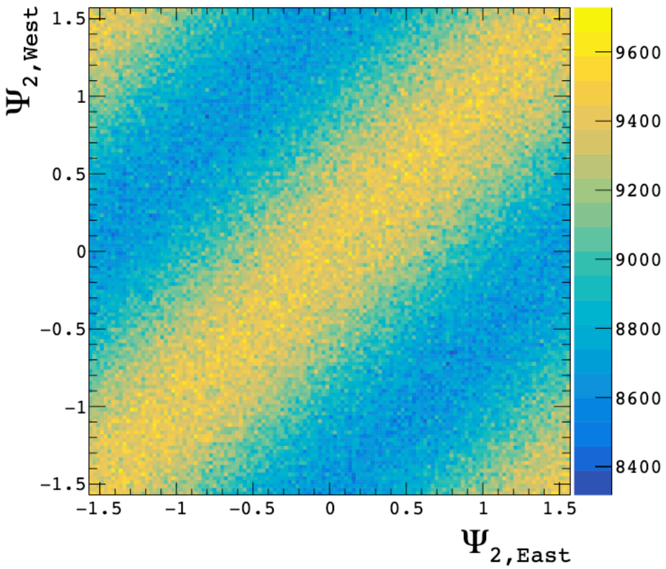


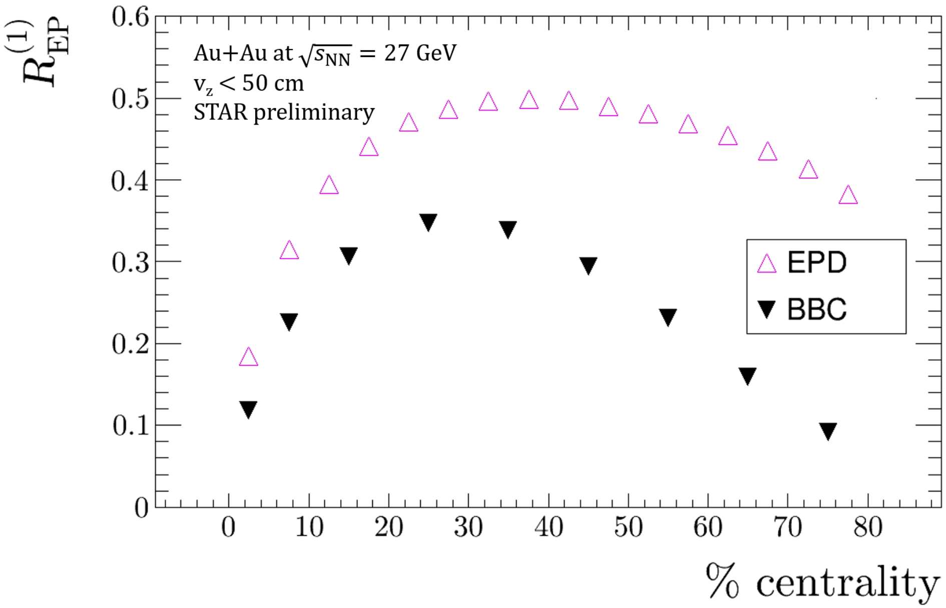
EPD: Enhanced event plane resolution

All tiles operational from Run-18 (pre-BES-II)
2.1 < |η| < 5.1

BES-II: Main trigger detector
Greater acceptance than VPD or ZDC
Better timing resolution than BBC
(0.75 ns)







Event plane (and centrality) outside of iTPC acceptance

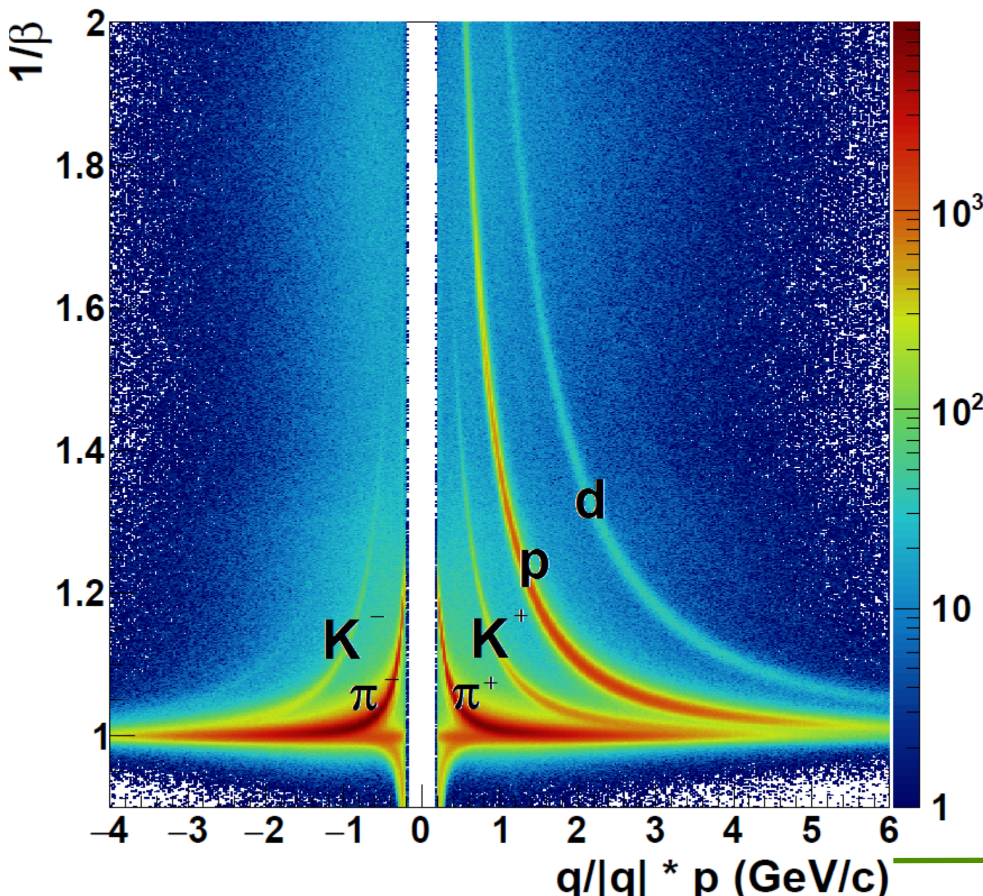
NIMA **968** (2020) 163970

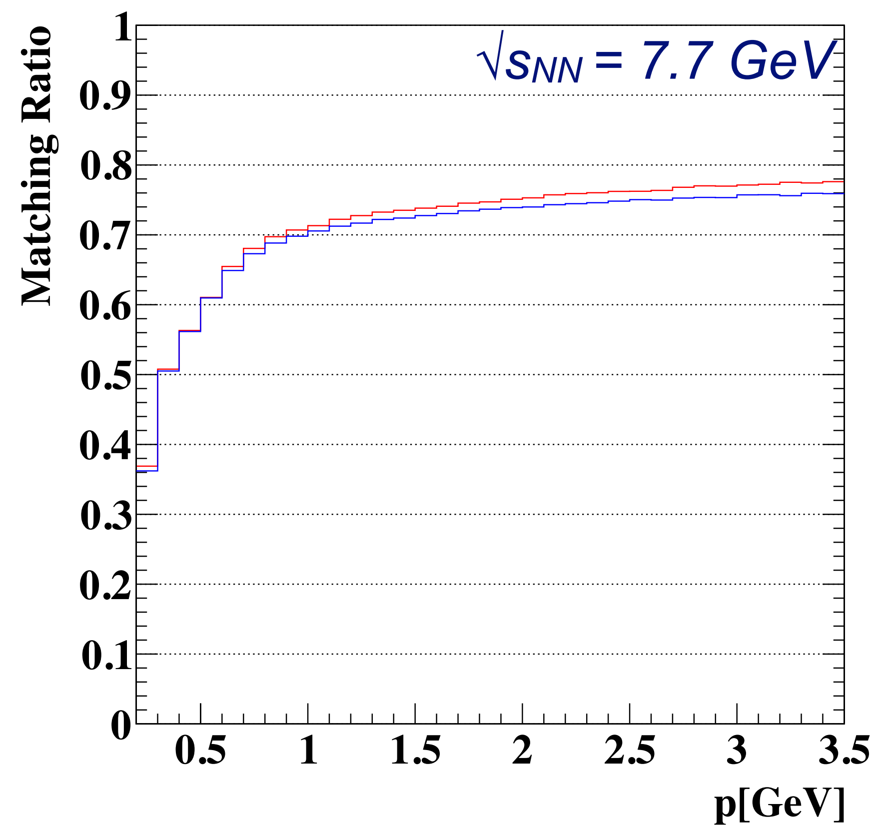
eToF - Joint STAR-CBM initiative

Matching efficiency >70% above 1 GeV/c

Timing ~80ps

K/π separation up to p = 2.5 GeV/c



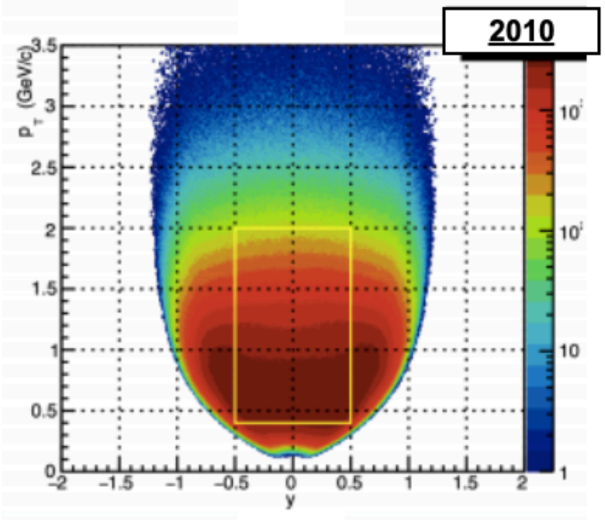


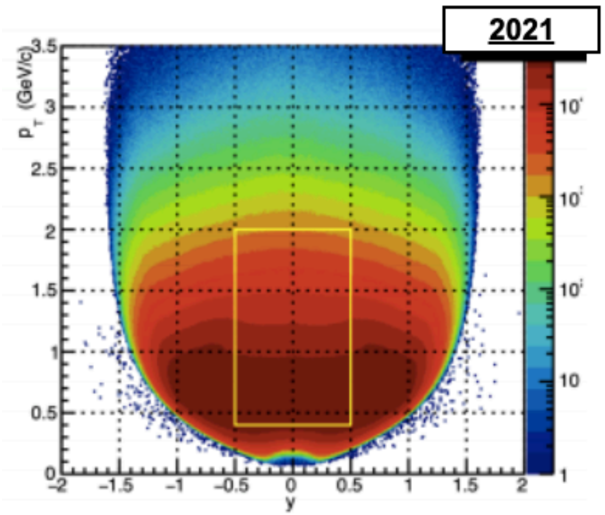
Critical for fixed-target data

Proton acceptance comparisons

Improved acceptance from iTPC!

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



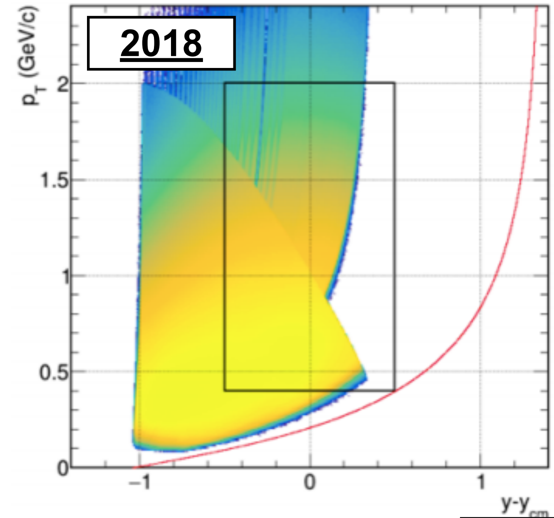


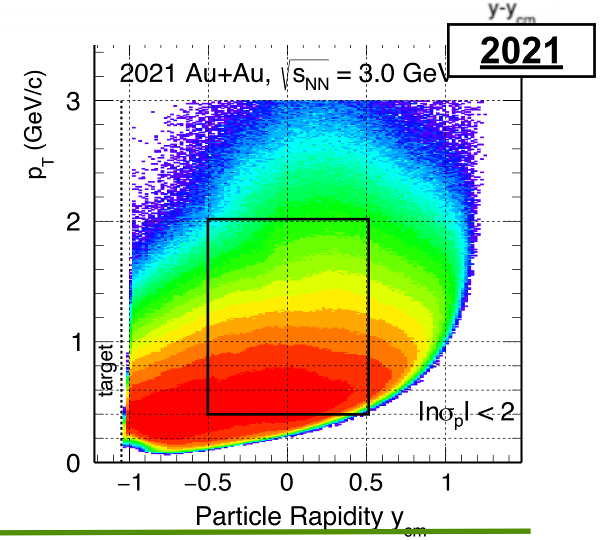
Real data!

Extended and similar acceptance for collider and FXT running in BES-II

Essential for proton fluctuations analyses

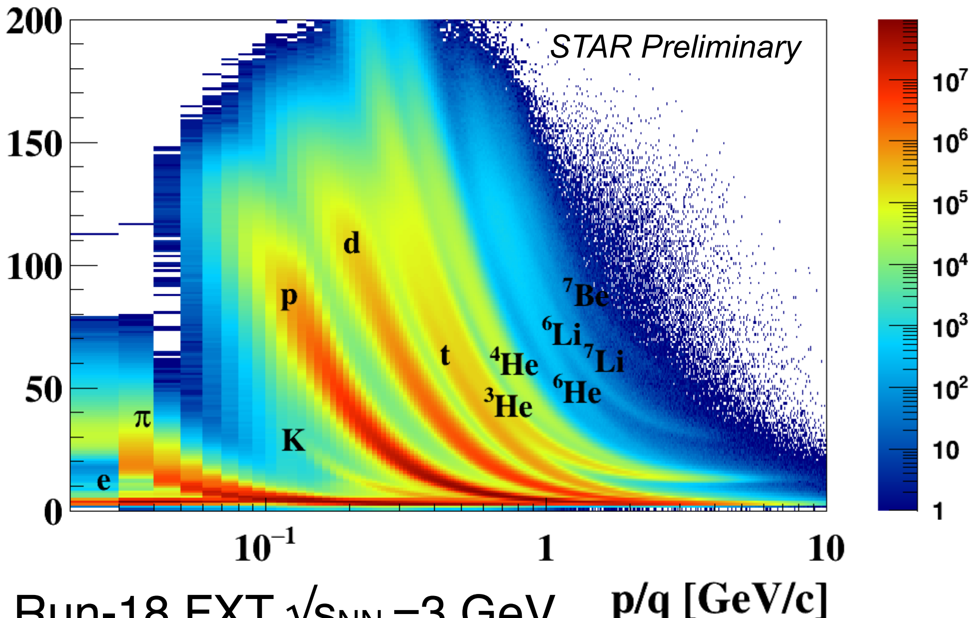
$\sqrt{s_{NN}}$ = 3 GeV FXT





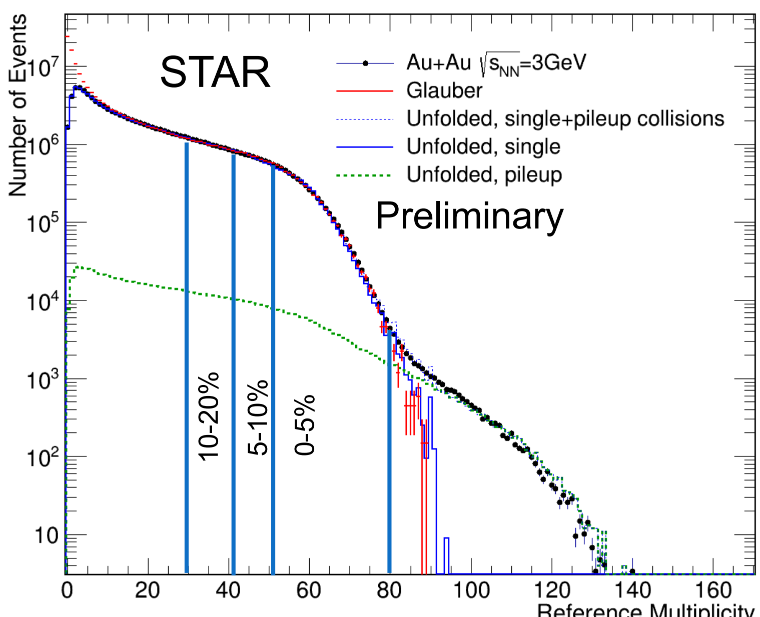
Data quality appears excellent

Heavy fragments up to ^{7}Be



Run-18 FXT $\sqrt{s_{NN}}$ =3 GeV

Tracks, on average, longer in FXT mode
→ enhanced dE/dx and 1/β resolutions



Techniques implemented to identify and reject "pile up" (present in FXT data mostly):

Enables accurate centrality definitions

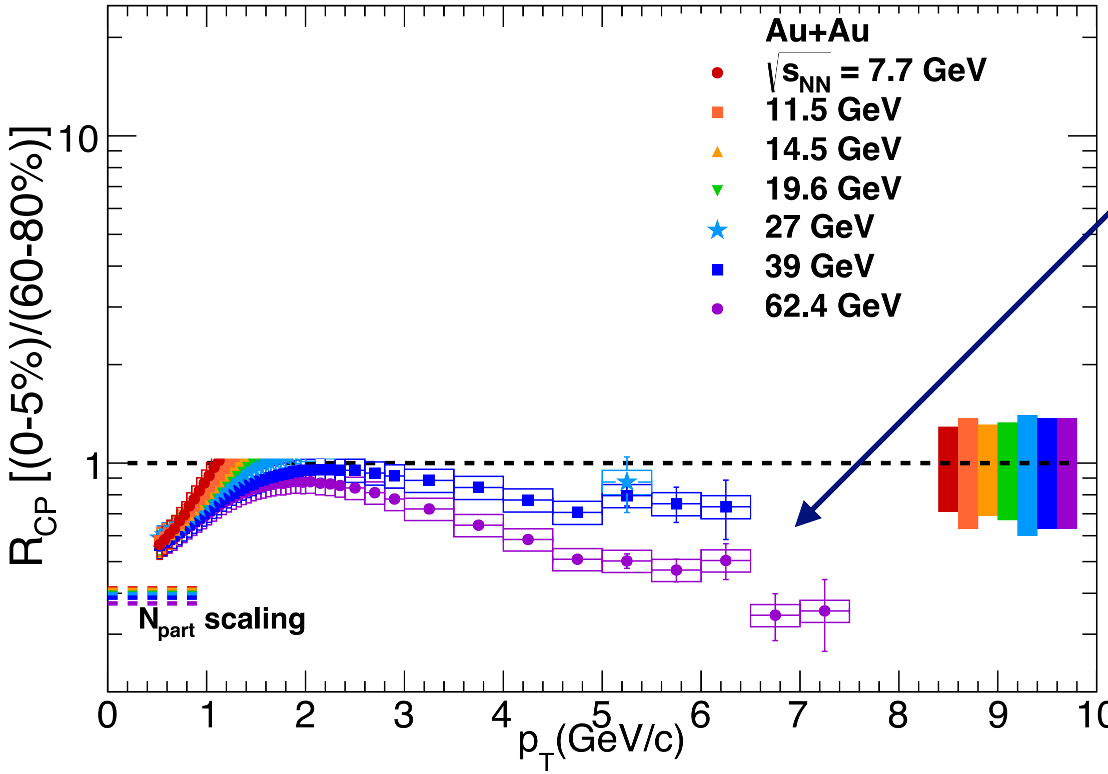
Dominance of QGP signal

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

Average number of p-p collisions in A-A collision

Compare to scaled p-p at same collision energy



At higher beam energies - clear signs of "jet quenching" in the medium

PRL **121** (2018) 32301

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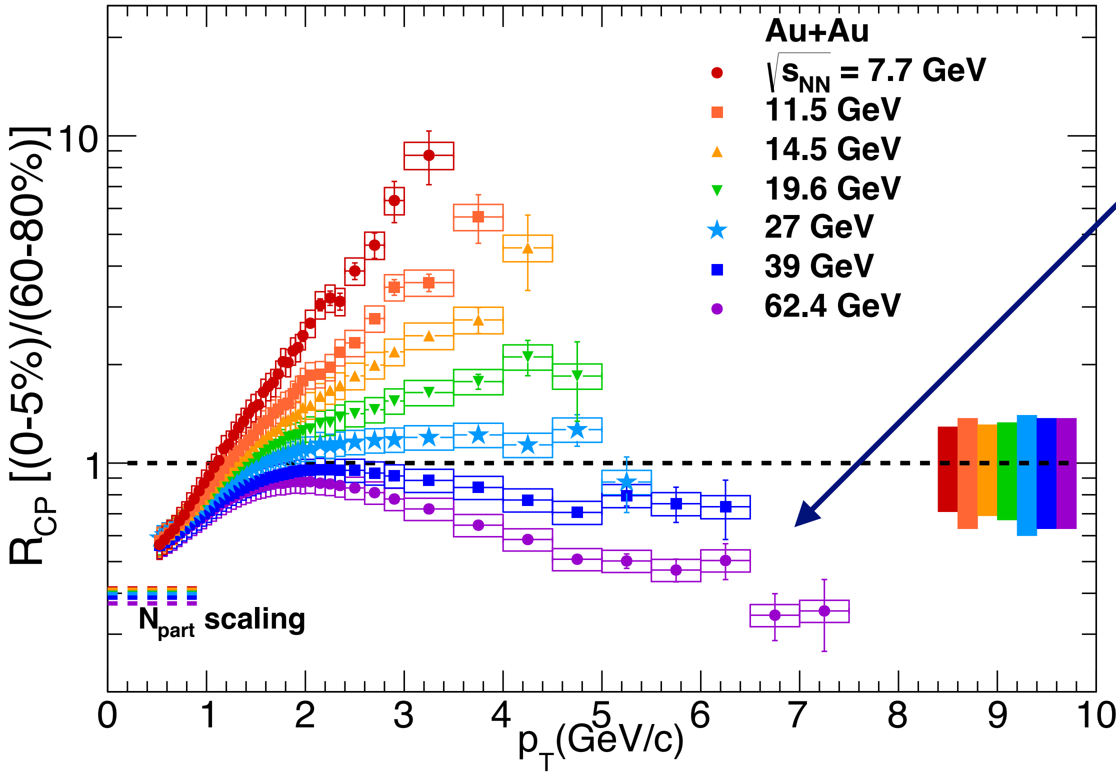


At higher beam energies - clear signs of "jet quenching" in the medium

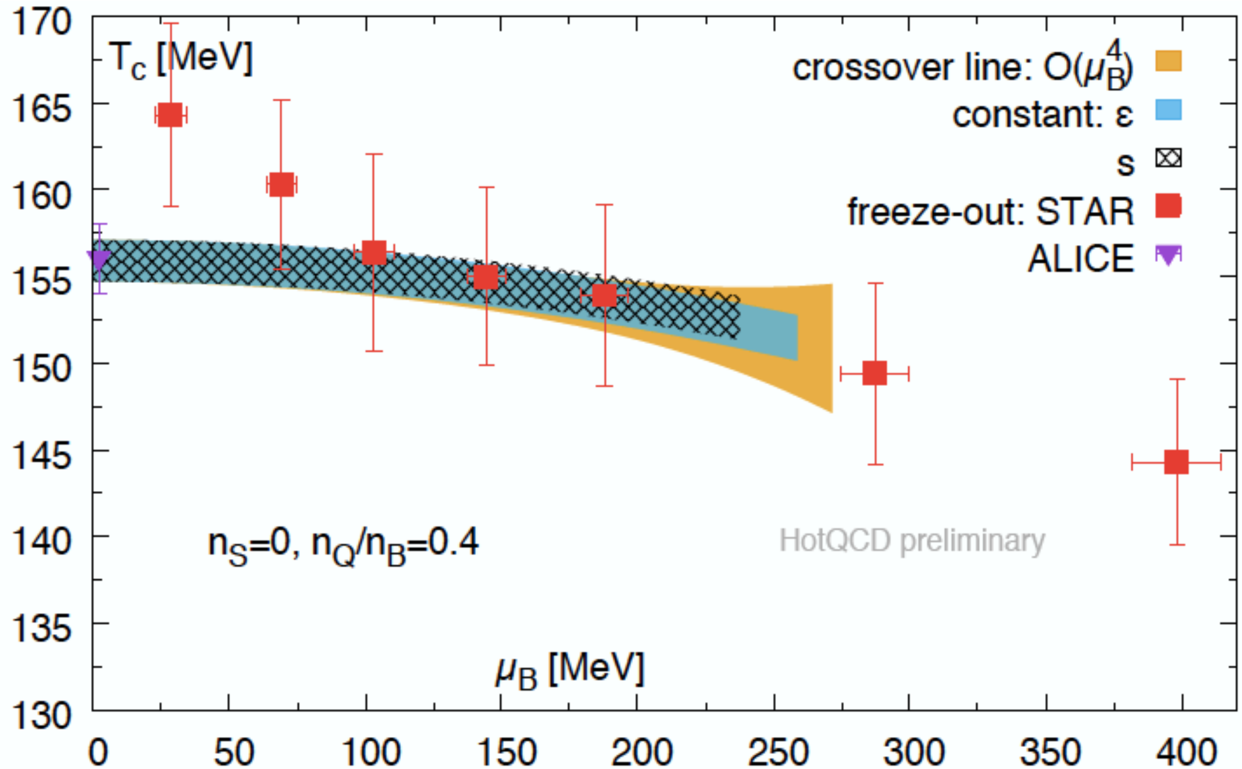
"Standard" QGP signal only dominates above $\sqrt{s_{NN}}$ ~ 20 GeV

Less jets, radial flow and other effects dominant at lower beam energies

BES-II: Precision to disentangle?

PRL **121** (2018) 32301

Precision mapping of phase diagram



Theory: Cross-over starts at
T_0 = 156.5 (1.5) MeV
$\varepsilon_0 \sim 1$ GeV/fm^3

Significant systematic errors from BES-I data

Now have BES-II and ~140 M top energy data with iTPC from Run-19

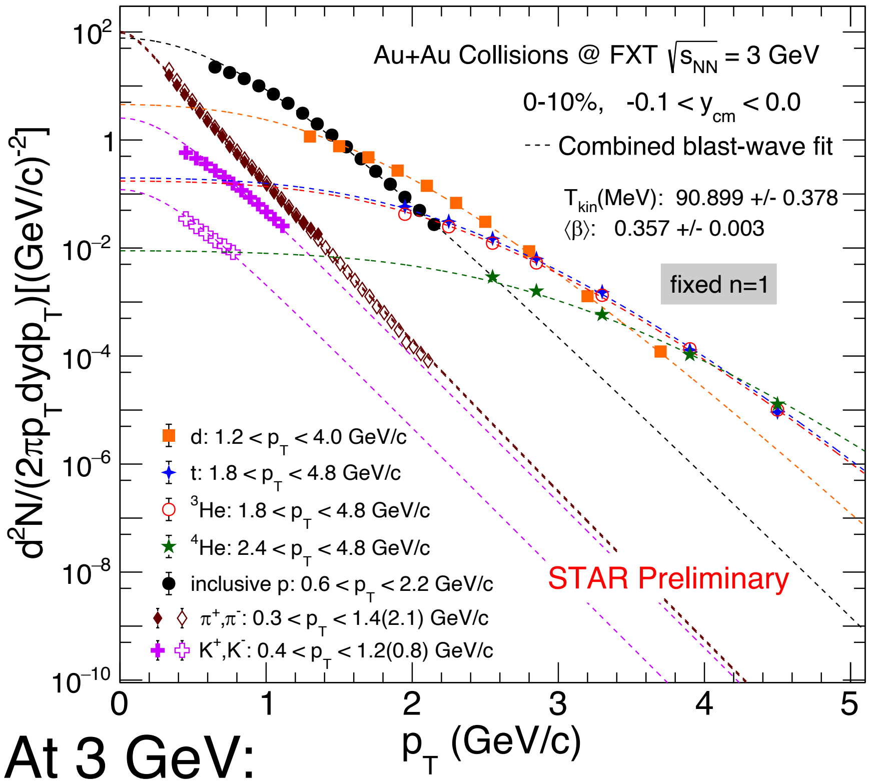
Reduce chemical fit uncertainty

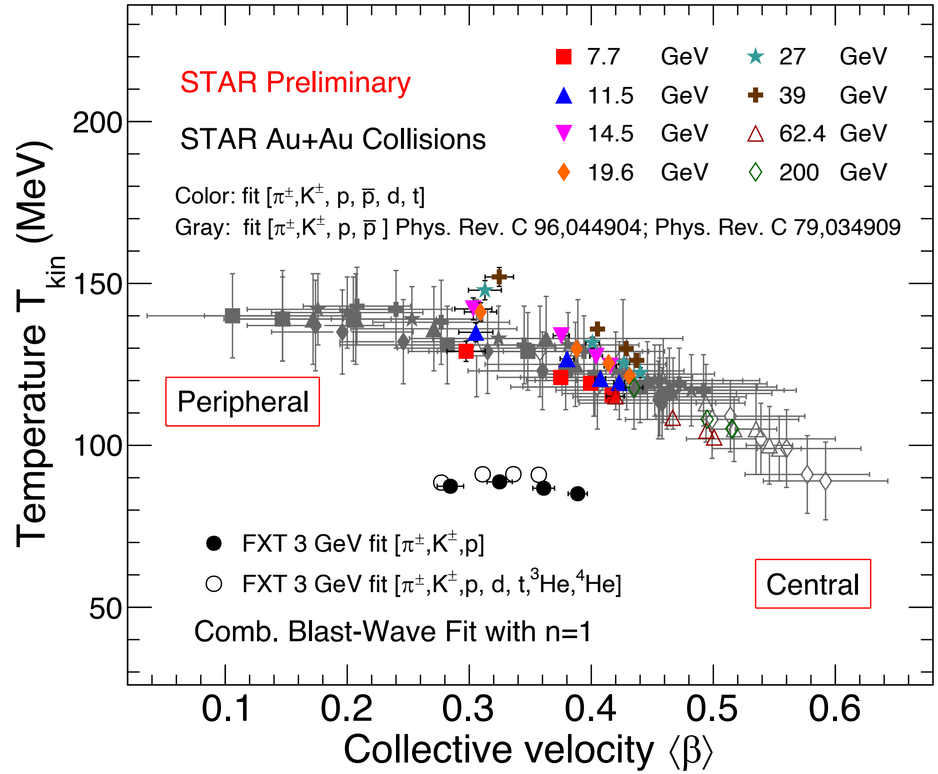
- smaller extrapolation, higher efficiency

Test Flow models at low p_T (<0.5 GeV/c) with heavy particles

PRC **101** (2020) 24905
PRC **102** (2020) 34909
Patrick Steinbrecher QM18

Light nuclei and blast-wave fitting





At 3 GeV:

Light nuclei p_T and rapidity distributions have been extracted

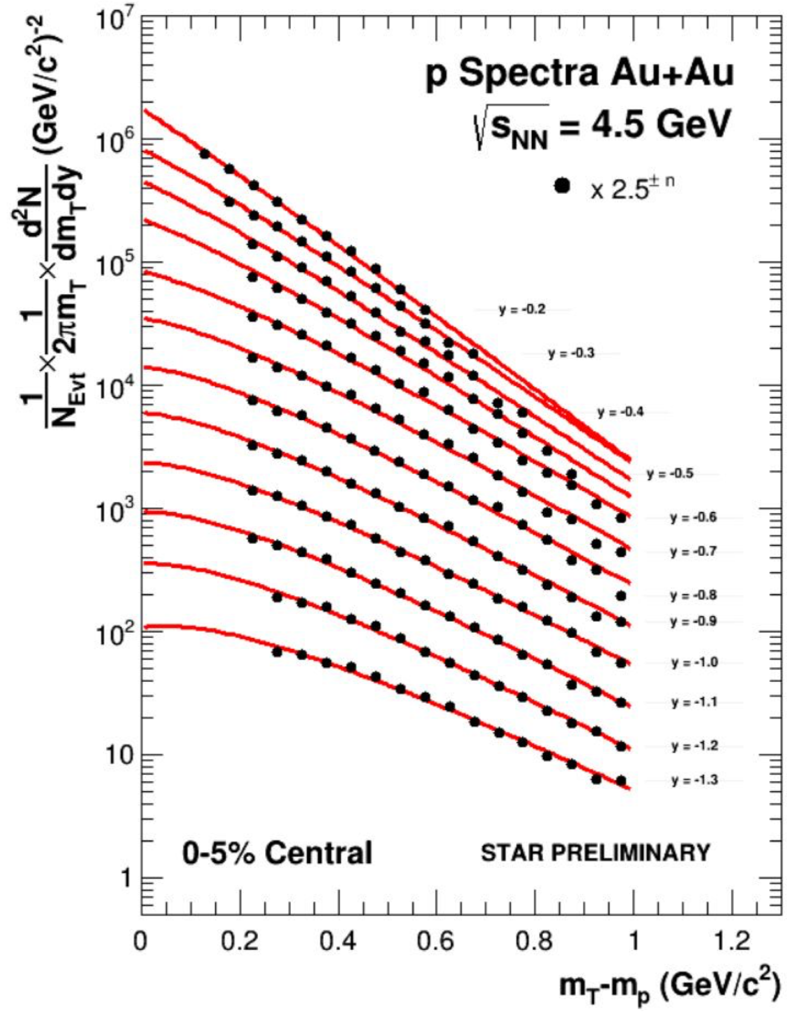
Mid-rapidity blast-wave fits:

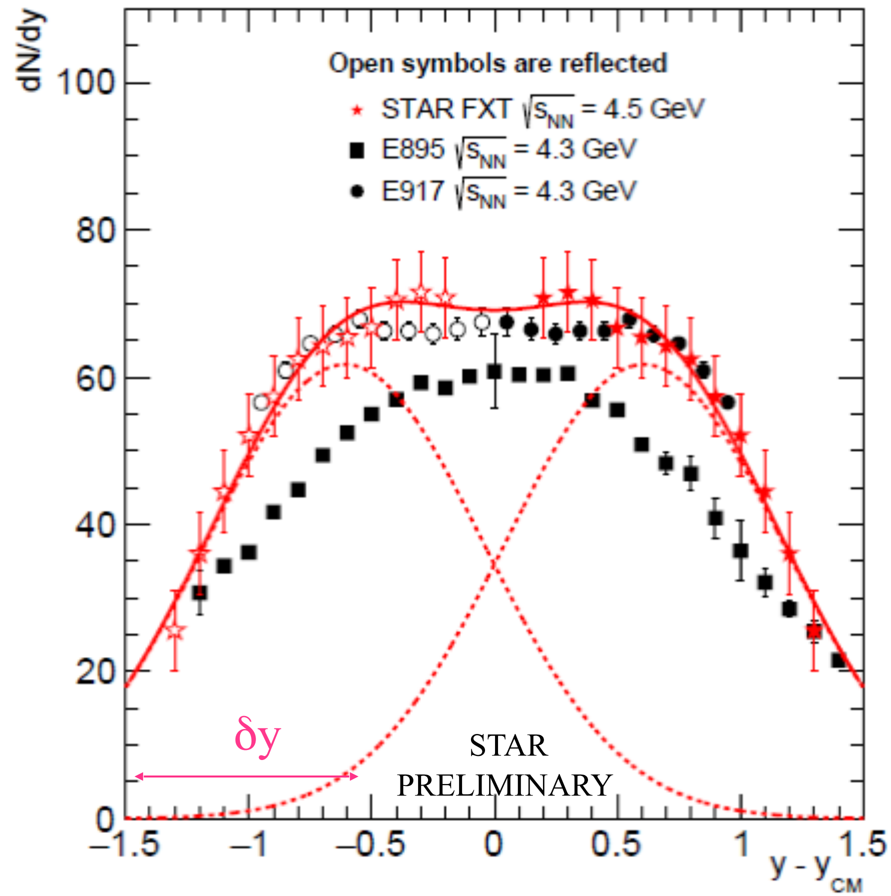
- Light nuclei prefer slightly higher T_{kin}, lower β
- Combined fit to all particles successful

Different trend compared to higher $\sqrt{s_{NN}}$ - different EoS at 3 GeV?

BES-II : Is transition smooth?

Beyond mid-rapidity p_T spectra





Better consistency with AGS E917 measurements

Plan to report rapidity distributions from BES-II data

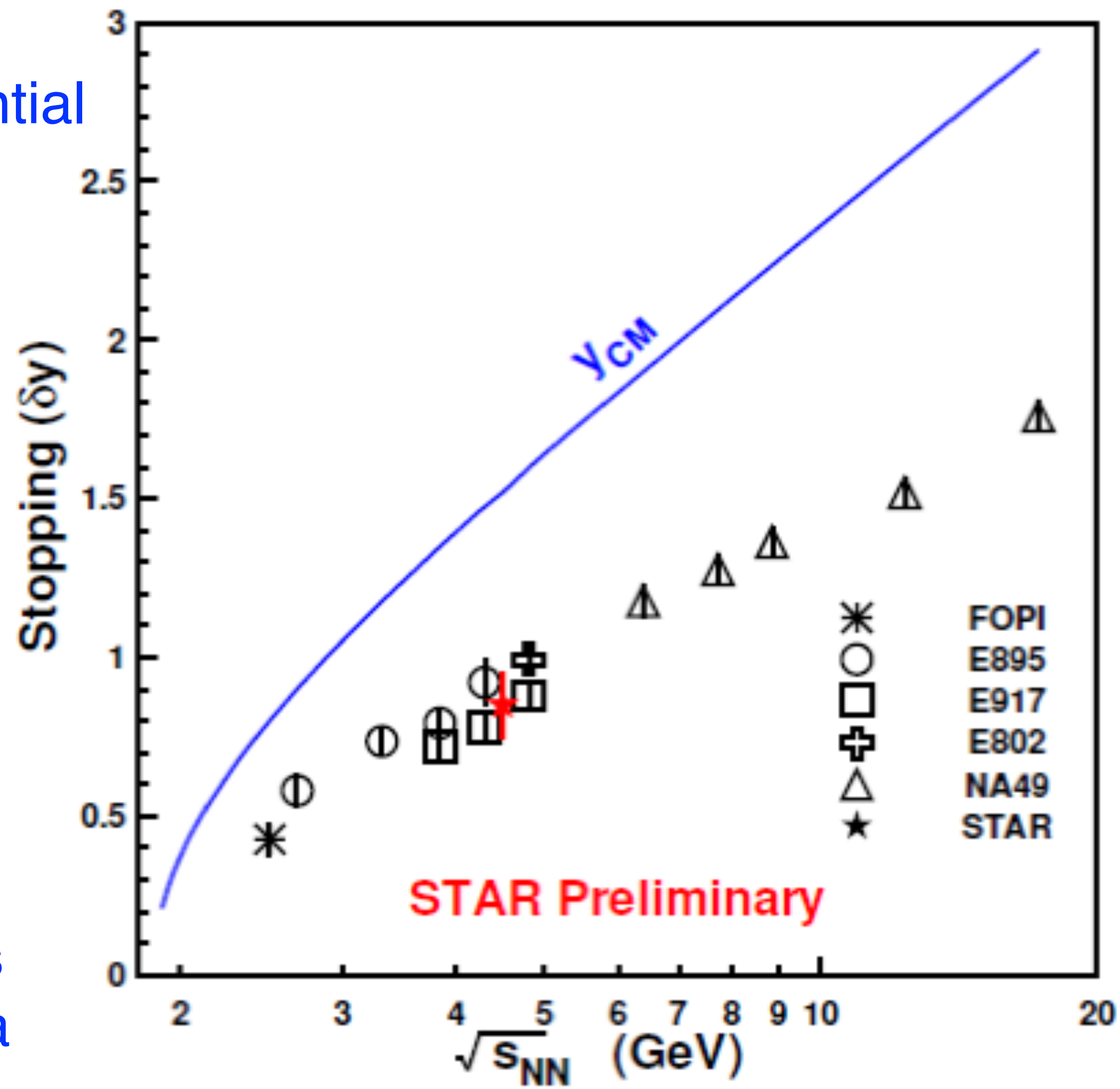
Baryon stopping systematics

Amount of stopping determines chemical potential

May also reveal first order phase transition and softening of the EoS

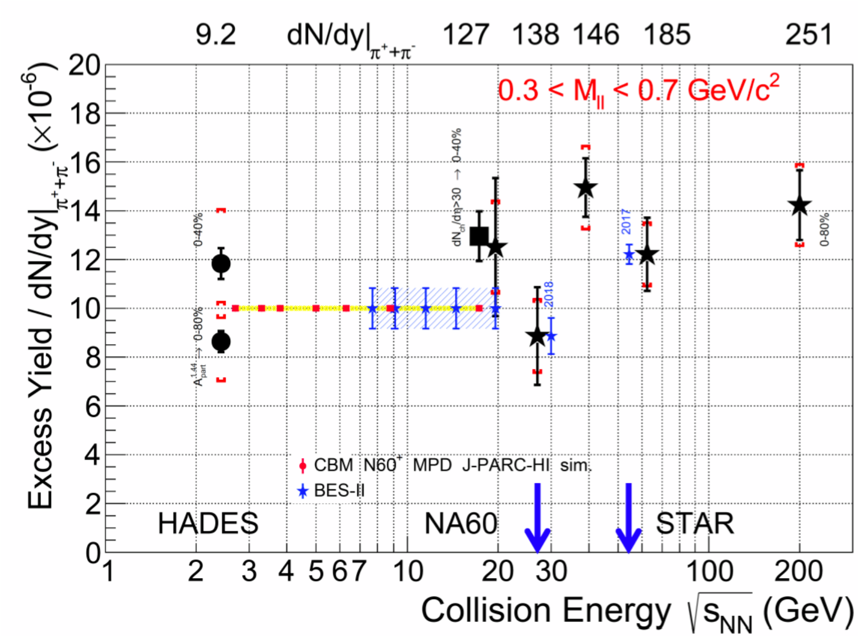
Signal is a “wiggle” in the amount of stopping

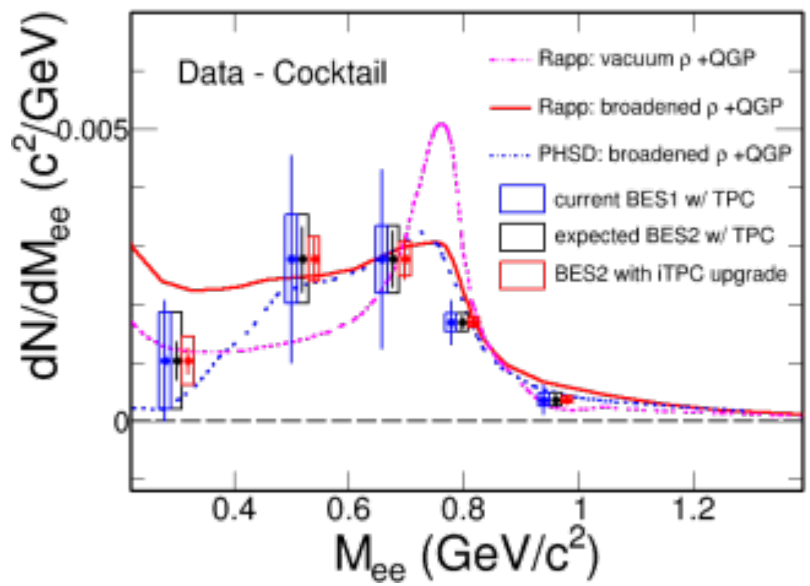
Precision measurements possible with BES-II data



Y. Ivanov, PRC87, 064904 (2013)

Change in total baryon number





Low Mass Region:

iTPC: Significant reduction in sys. and stat. uncertainties

Disentangle total baryon density effects

ρ-meson broadening:

different predictions for di-electron continuum (Rapp vs PHSD)

iTPC: Significant reduction in sys. and stat. uncertainties

Enables to distinguish between models for $\sqrt{s_{NN}}$ =7.7-19.6 GeV

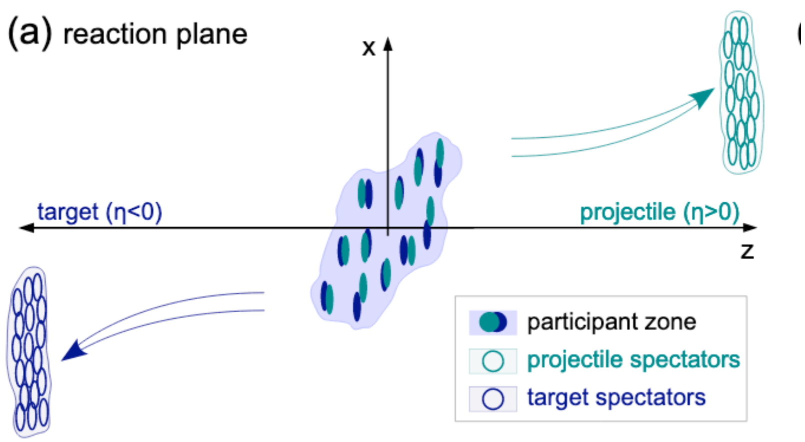
Softest point in equation of state?

Directed flow, v_1 - attributed to collective sidewards deflection of particles

$$v_1 = \langle\cos(\phi-\Psi)\rangle$$

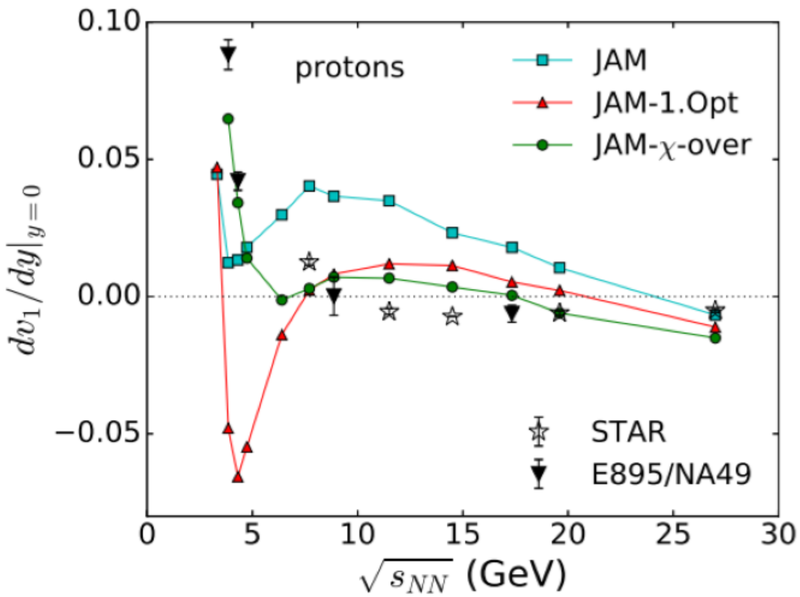
Symmetry of collision requires

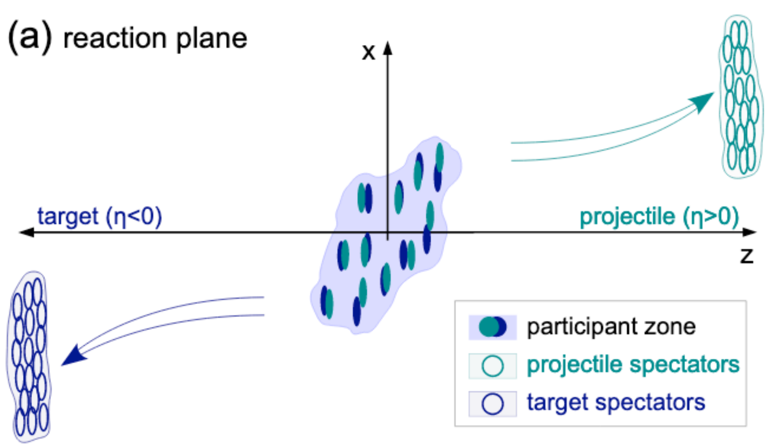
$$v_1(\eta) = -v_1(-\eta)$$



ALICE: PRL **111** (2013) 232302

Softest point in equation of state?





Directed flow, v_1 - attributed to collective sidewards deflection of particles

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JAM 1.Opt: First order phase transition
strong "wiggle"

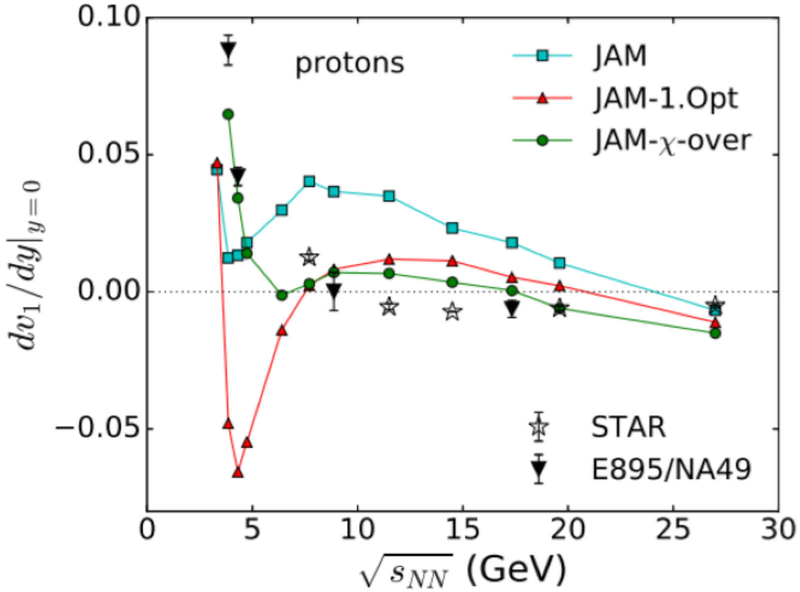
JAM X-over - Cross over
weaker "wiggle"

JAM - No transition
no "wiggle"

Calculations predict minimum in slope of directed flow of baryons in presence of 1st order phase transition

Y.Nara et al. PLB 769 (2017) 543
ALICE: PRL **111** (2013) 232302

Softest point in equation of state?



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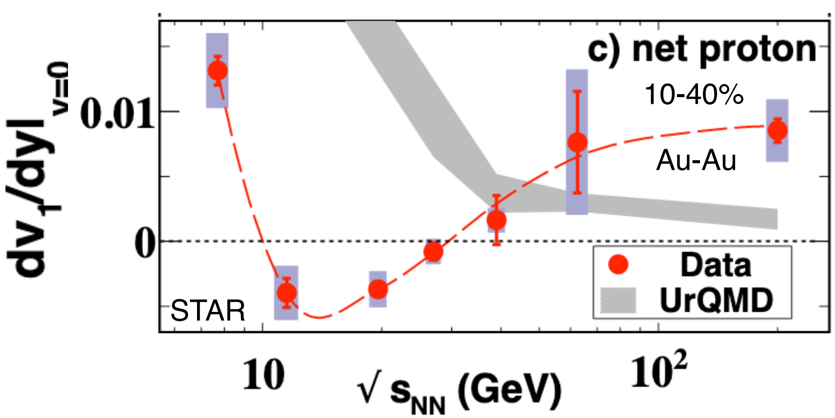


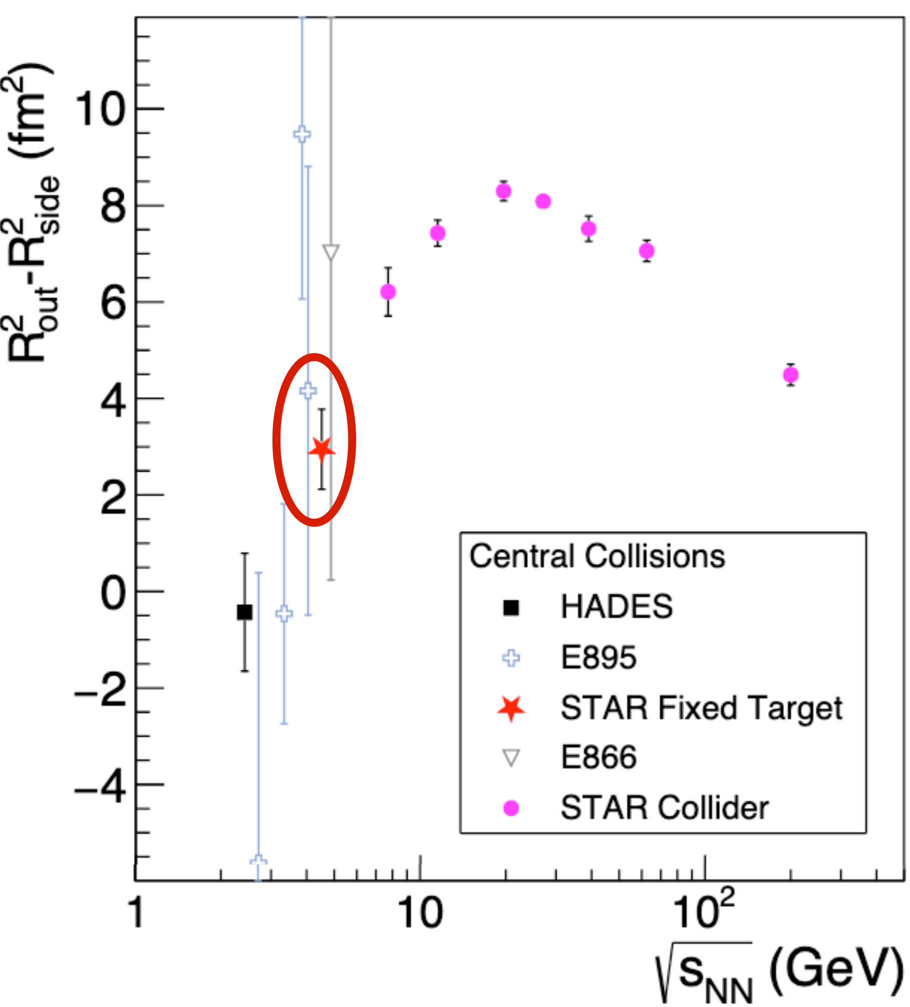
Calculations predict minimum in slope of directed flow of baryons in presence of 1st order phase transition

Net-proton isolates transported baryons : Double sign change in dv_1/dy around $\sqrt{s}$ ~15 GeV

PRL **112** (2014) 162301
Y.Nara et al. PLB 769 (2017) 543
ALICE: PRL **111** (2013) 232302

Evolution through phase transition?

Publication of first FXT data - 4.5 GeV



Interferometry:

R_{long} - Longitudinal size

R_{side} - Transverse size

R_{out} - Transverse size + emission duration

STAR data in combination with HADES results reveal long-sought peak in R^2_{out}/ R^2_{side} beam energy dependence

- Such a peak may occur if system evolves through 1st order phase transition

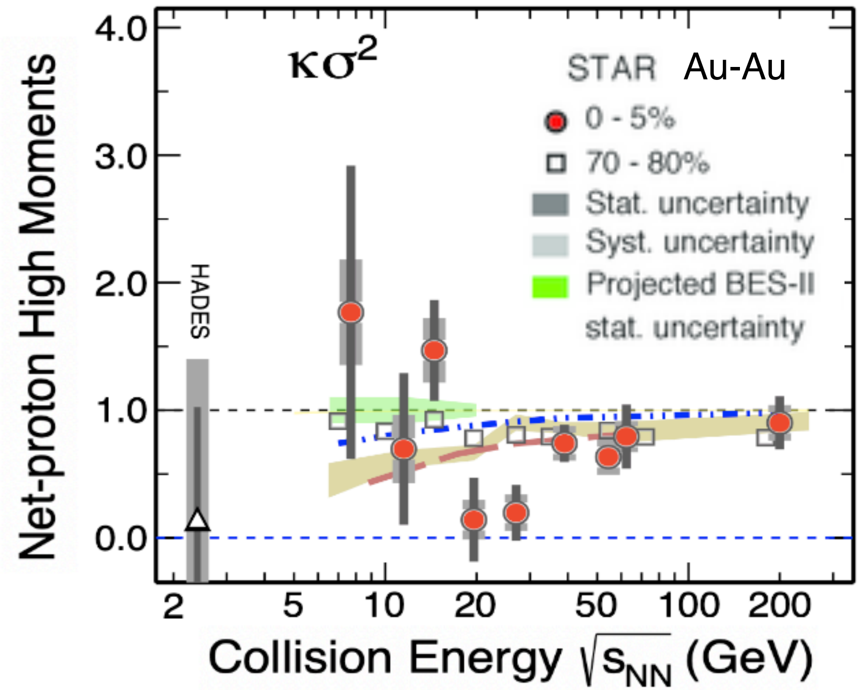
The magnitude and width of structure **may** allow an estimate of latent heat of QCD deconfinement transition

- more theory input needed

PRC 92 014904 (2015)

PRC 103 34908 (2021)

Hints of critical fluctuations

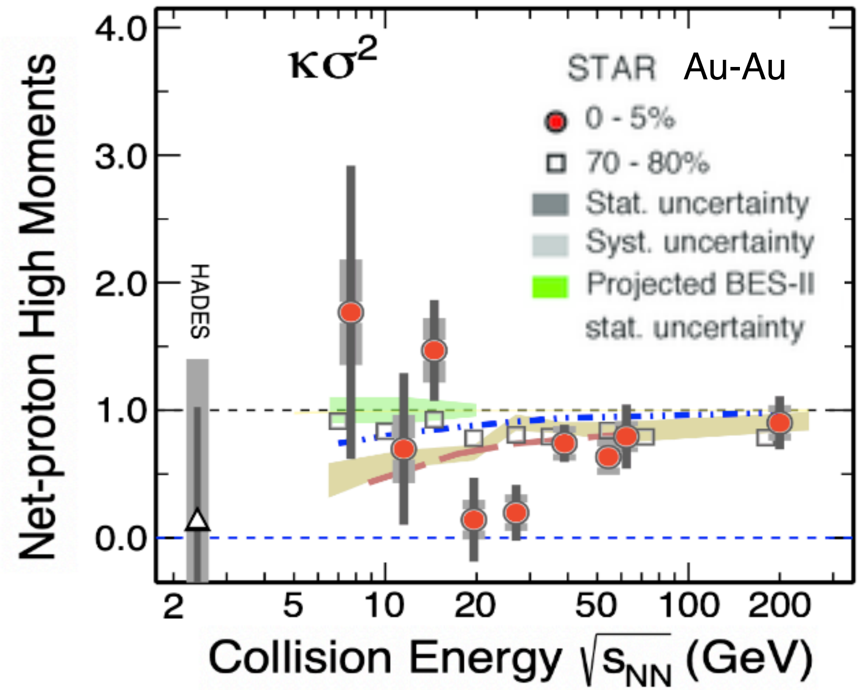


κ/σ^2

BES-I: results published in PRL with details in PRC

PRL **126** (2021) 92301
PRC **104** (2021) 24902
arXiv:2105.14698

Hints of critical fluctuations

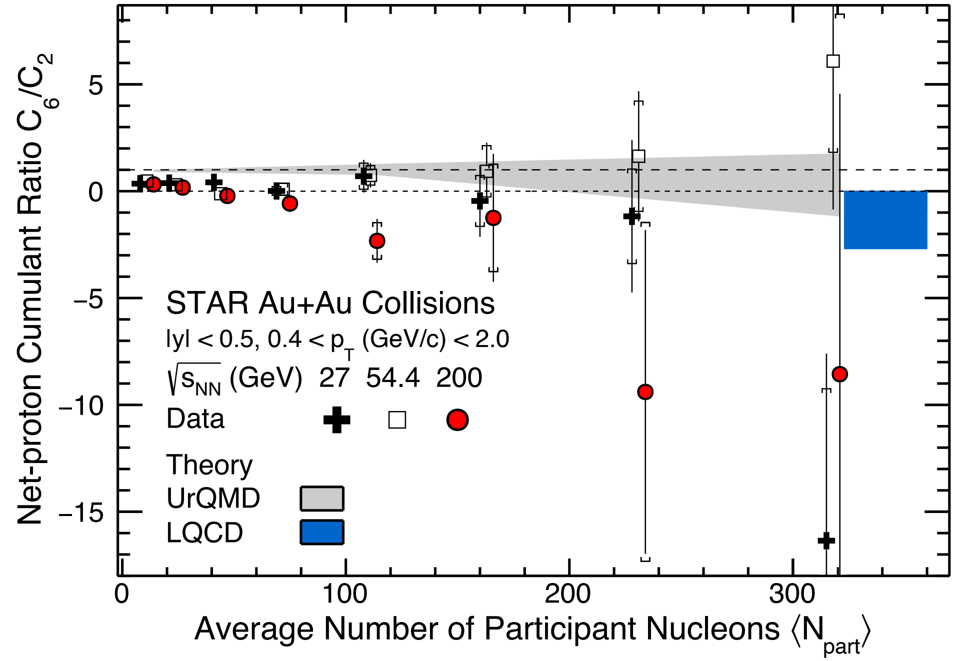


First measurement of net-proton C_6/C_2 at RHIC

27 & 54.5: Consistent with zero
200: Negative in more central collisions

κ/σ^2

BES-I: results published in PRL with details in PRC



Suggestive of smooth cross-over at top RHIC energies

PRL **126** (2021) 92301
PRC **104** (2021) 24902
arXiv:2105.14698

BES-II: Critical fluctuations

Current data: Suggestive of non-trivial √s dependence of net-proton cumulant ratios. Limited rapidity width range

iTPC:

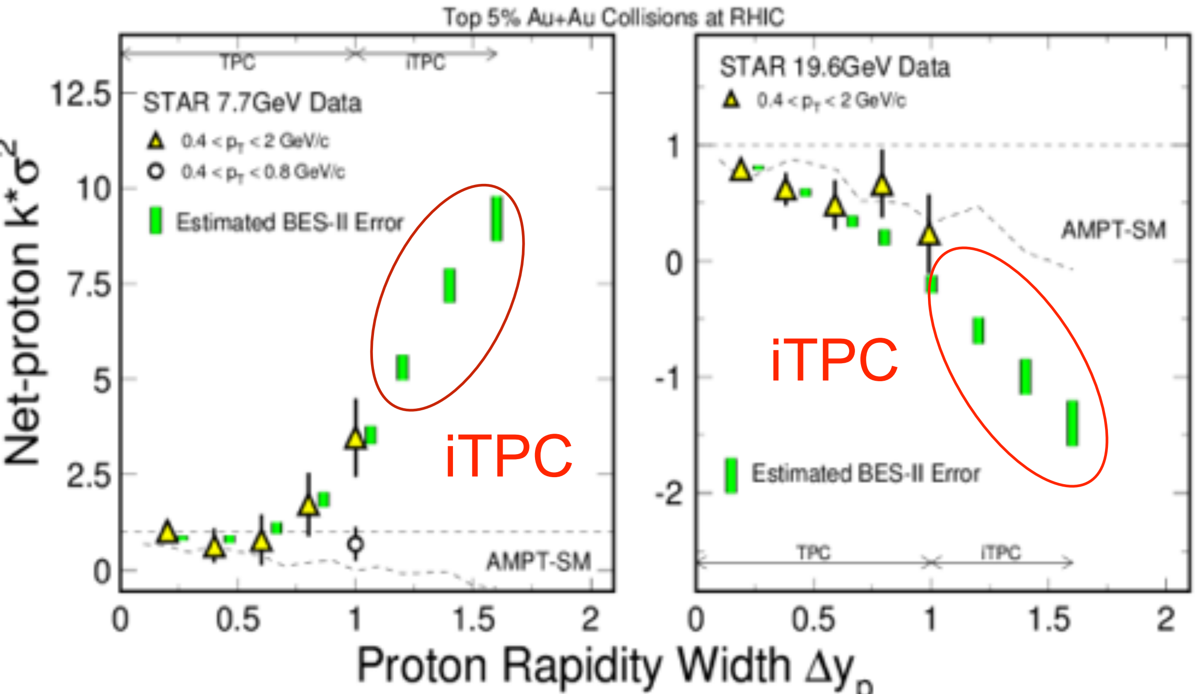
Increase Δy_p acceptance

$\Delta y_p > \Delta y$ correlation

EPD:

Improved centrality selection

Use all TPC for measurement



Establish true nature of correlation

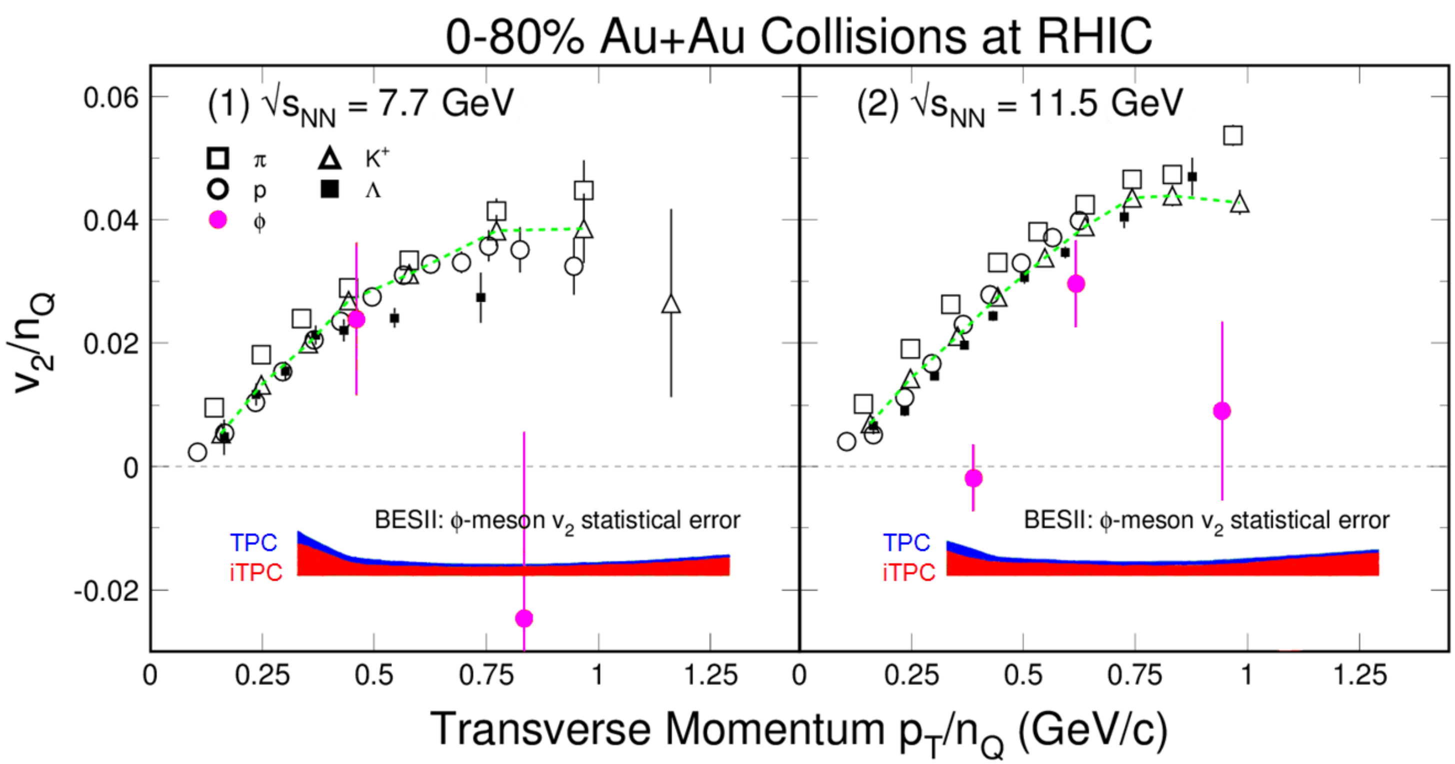
BES-II: Plan to only release final results

Access to net-kaon also possible

BES-II: Quark coalescence via flow

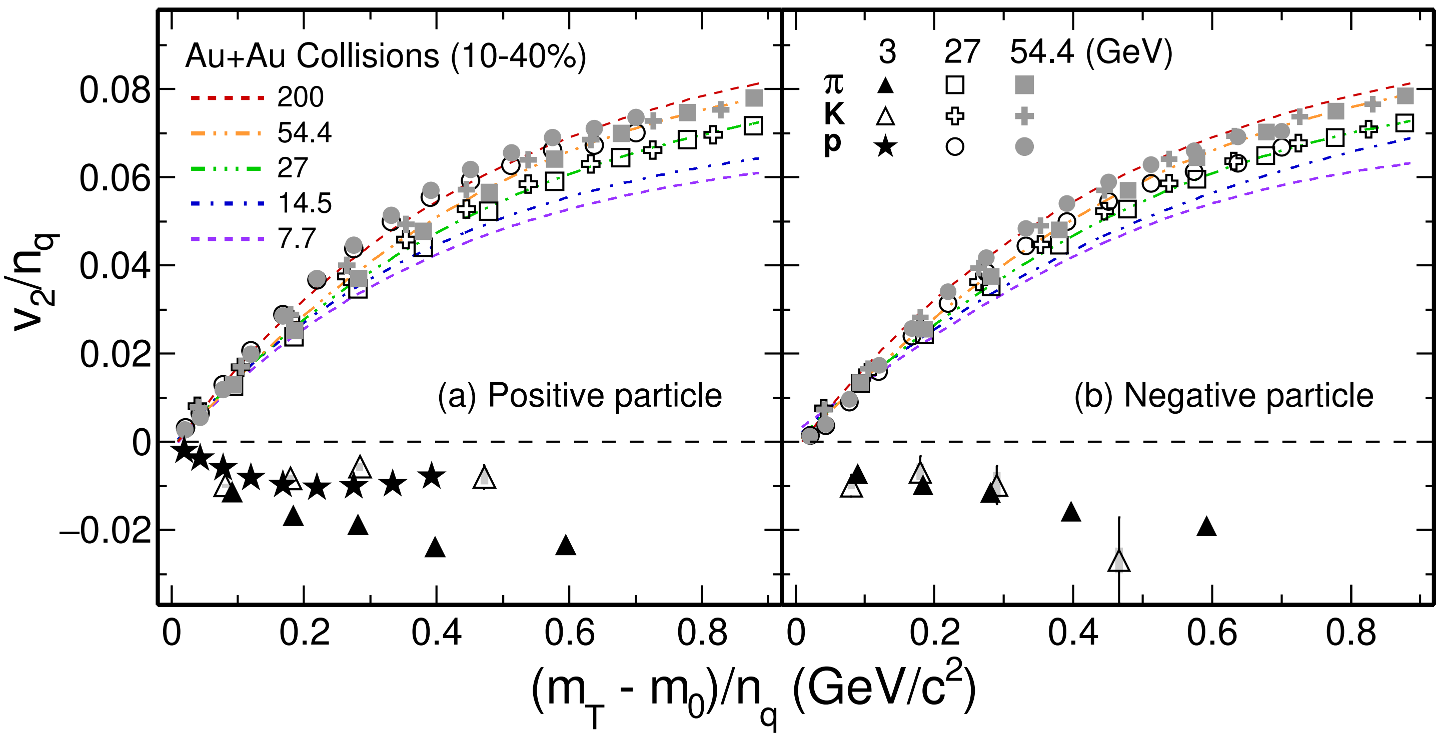
How much collective motion from quark phase vs hadronic phase?

Use ϕ as probe - very small hadronic scattering cross-section



BES-II: Precision measurement of the ϕ (and other) flow

Disappearance of partonic collectivity



3 GeV 2018 data - First order EP from EPD

NCQ scaling not observed at $\sqrt{s_{NN}}$ = 3 GeV

Particles and antiparticles no longer consistent with single-particle NCQ scaling as collision energy decreases

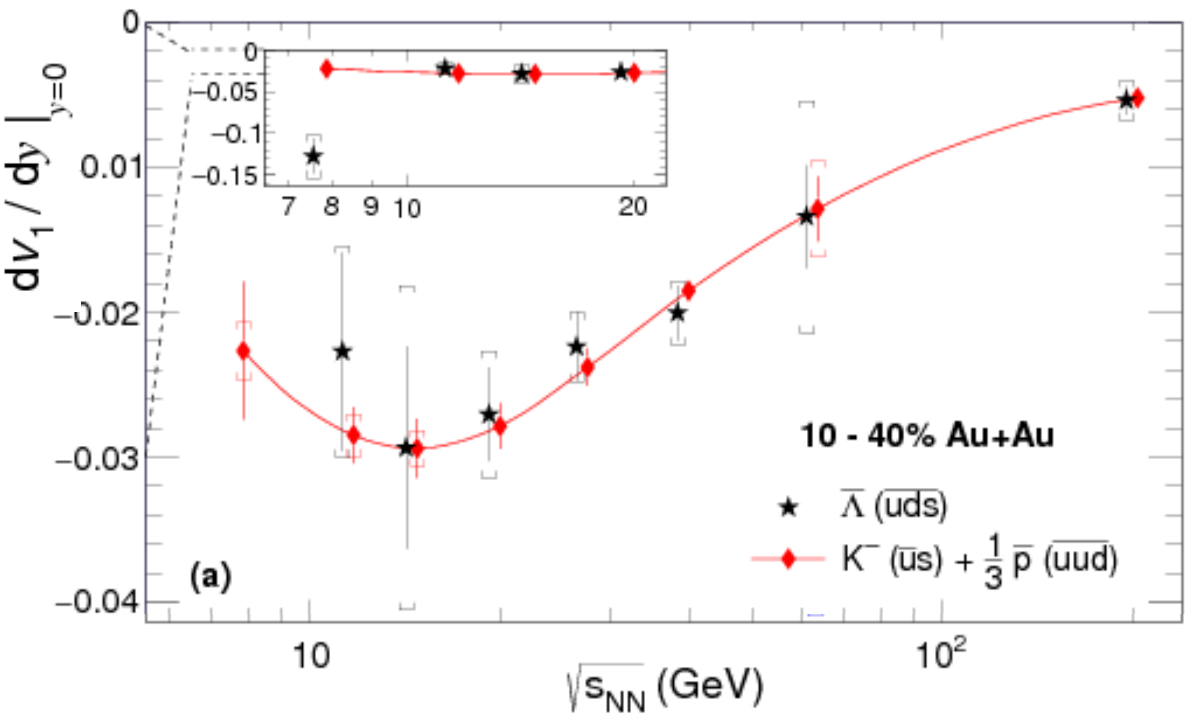
mixing of transported and produced quarks changing

arXiv:2108.00908

Particle production via coalescence

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 $(v_1)_s = (v_1)_{\bar{s}}$

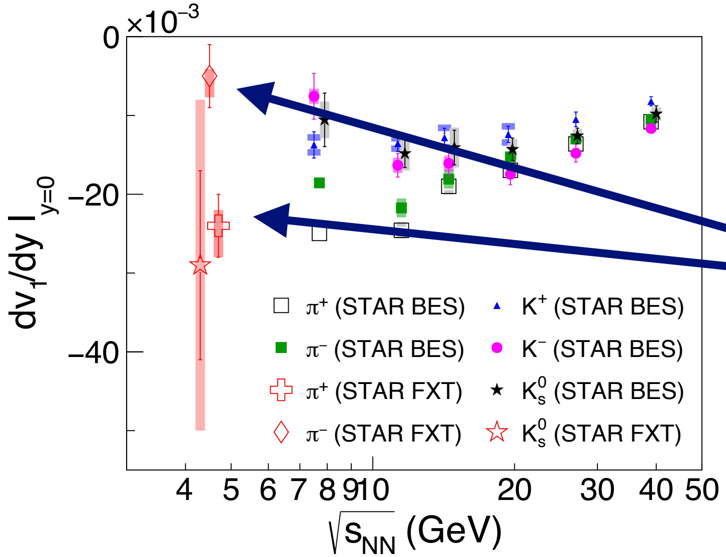


anti-Λ measured and predicted from quark values deduced from K and p

Quark coalescence sum run fails for 7.7 GeV - At least one assumption incorrect

PRL **120** (2018) 62301

(pre)BES-II: Flow



~1.3M 0-30% - x10 more from BES-II

First π v_1 and v_2 results

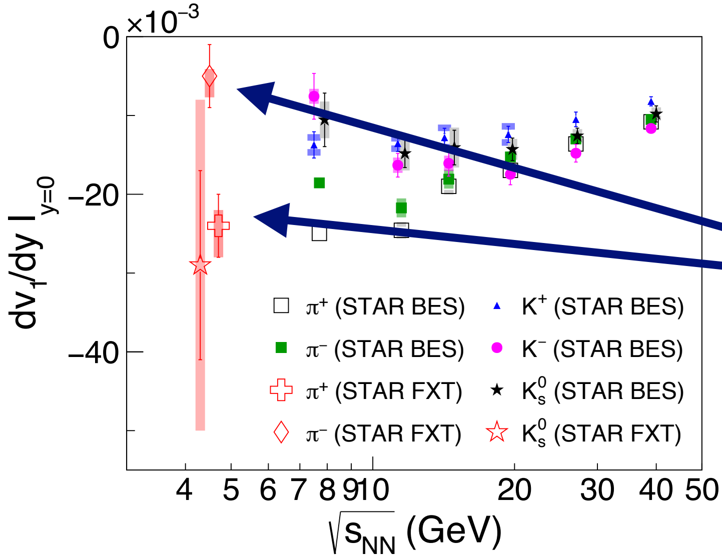
Difference in v_1 slope for π^+ and π^-

Isospin and/or Coloumb dynamics becoming prominent

Similar observation reported by FOPI at lower energies (arXiv:nucl-ex/0610025)

E895 PRL 83 (1999) 1295
PRC 103 34908 (2021)

(pre)BES-II: Flow



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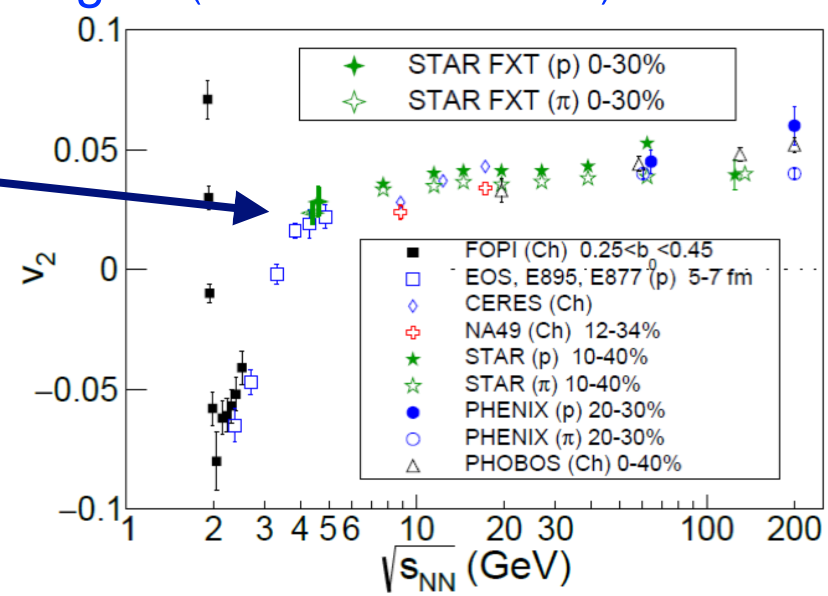
Publication of first FXT data - 4.5 GeV

π and p in-plane elliptic flow



E895 PRL 83 (1999) 1295
PRC 103 34908 (2021)

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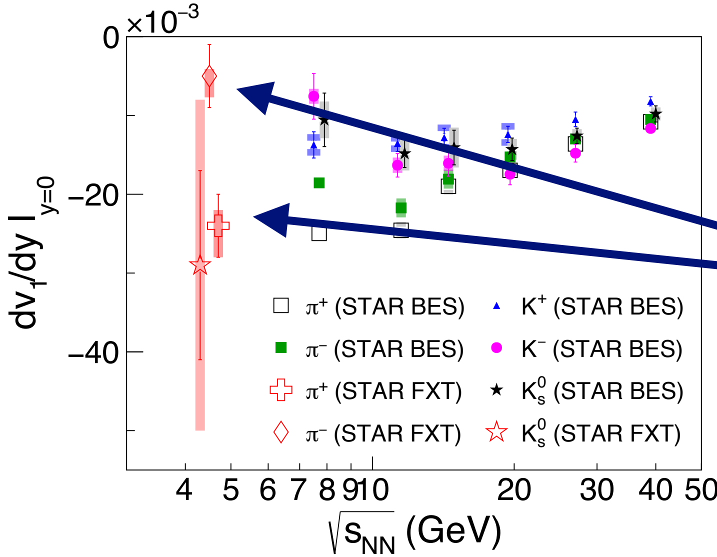

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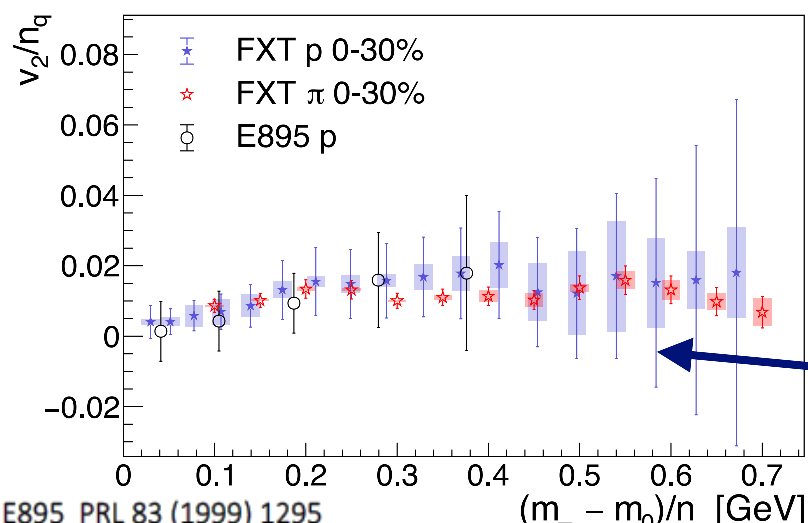
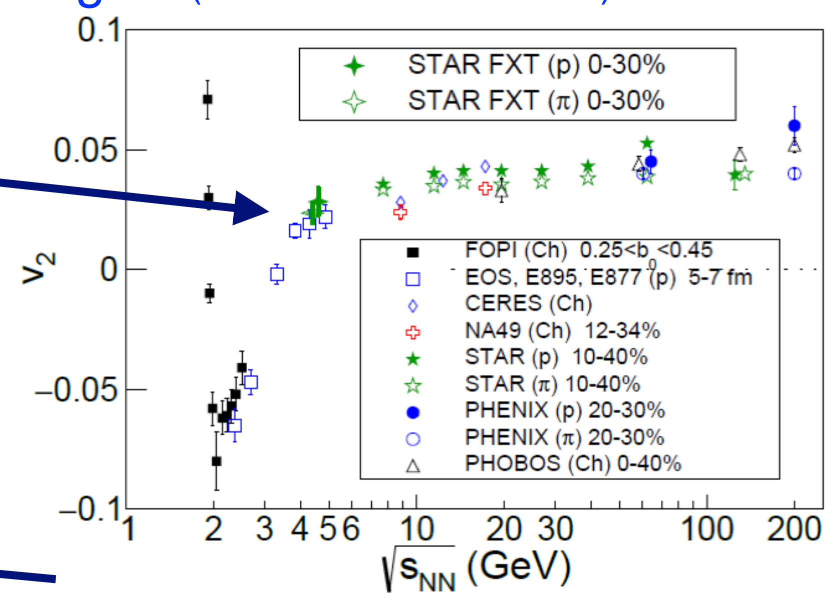
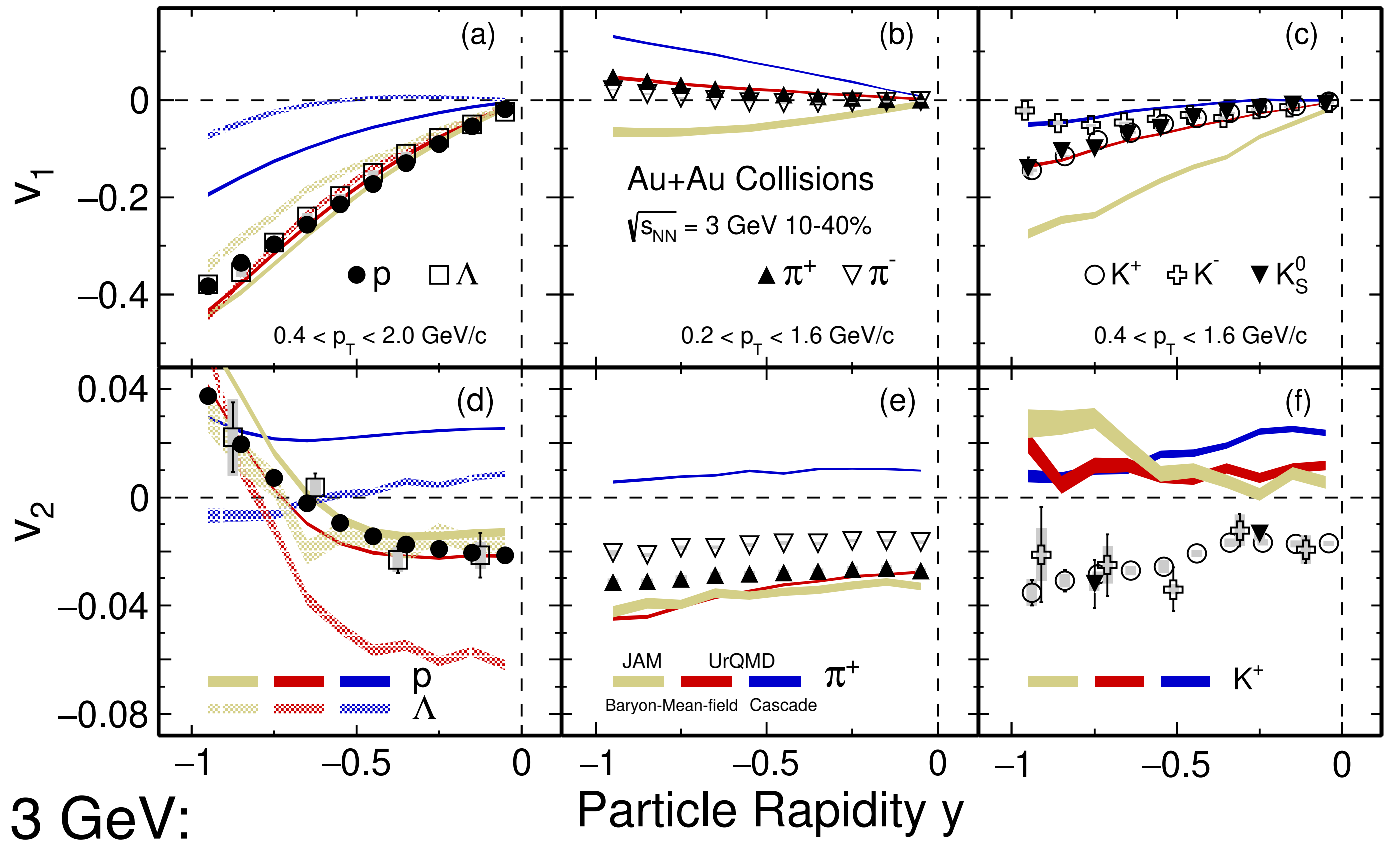




Hint of NCQ scaling: large errors

E895 PRL 83 (1999) 1295
PRC 103 34908 (2021)

Dominance of baryonic scatterings



FXT 3 GeV:

v_2 out-of-plane for

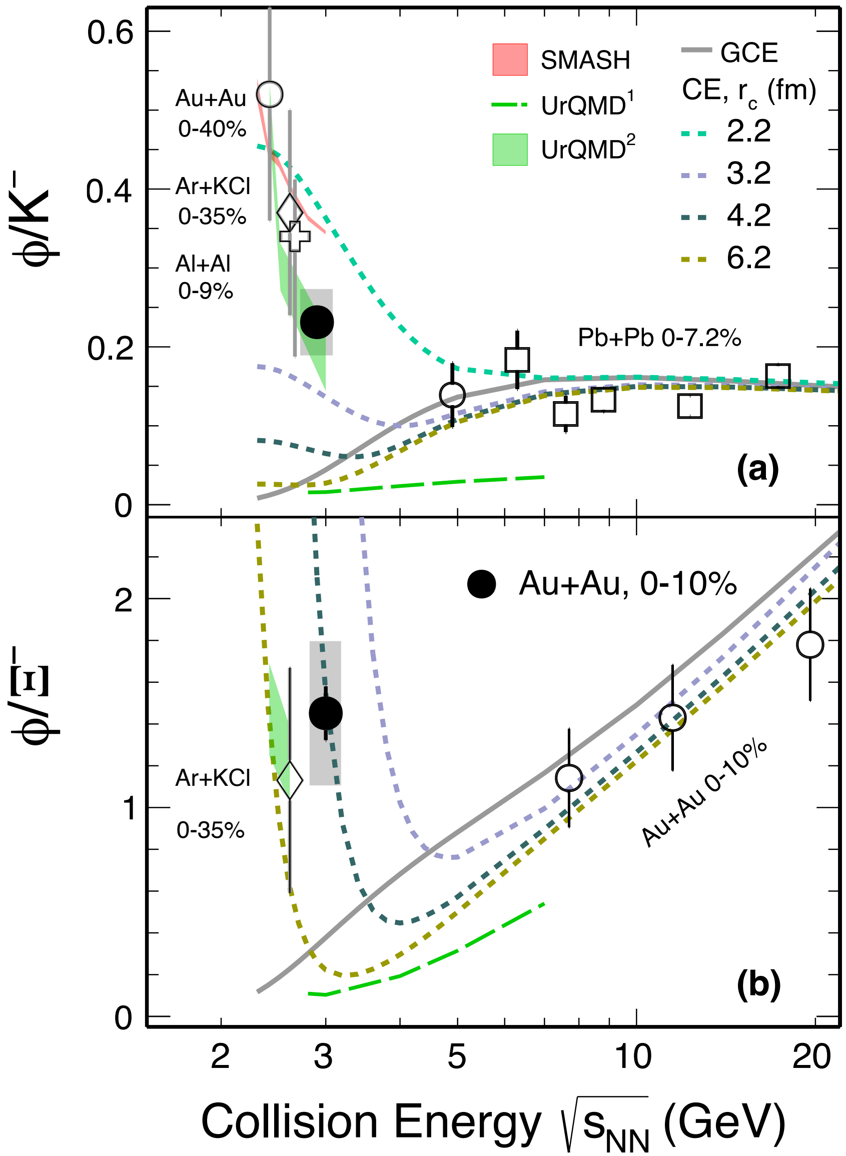
Models including baryon mean-fields needed to describe data

Kaons not well described

Baryonic not partonic interactions dominate

arXiv:2108.00908

Probing (grand)canonical production



First multi-dimensional ϕ and Ξ measurements at $\sqrt{s_{NN}}$ = 3 GeV

p_T and rapidity spectra reported

Collision energy:

- below threshold for Ξ
- very close to threshold for ϕ

Local treatment of strangeness conservation crucial at lower $\sqrt{s_{NN}}$

Small strangeness correlation radius preferred, $r_C \leq 4.2$ fm

CE cannot simultaneously describe ϕ/K– and ϕ/Ξ– ratios (also noted by HADES)

STAR: arXiv:2108.00924

Polarization seen even at 3 GeV

3FD:

Approximate agreement

UrQMD:

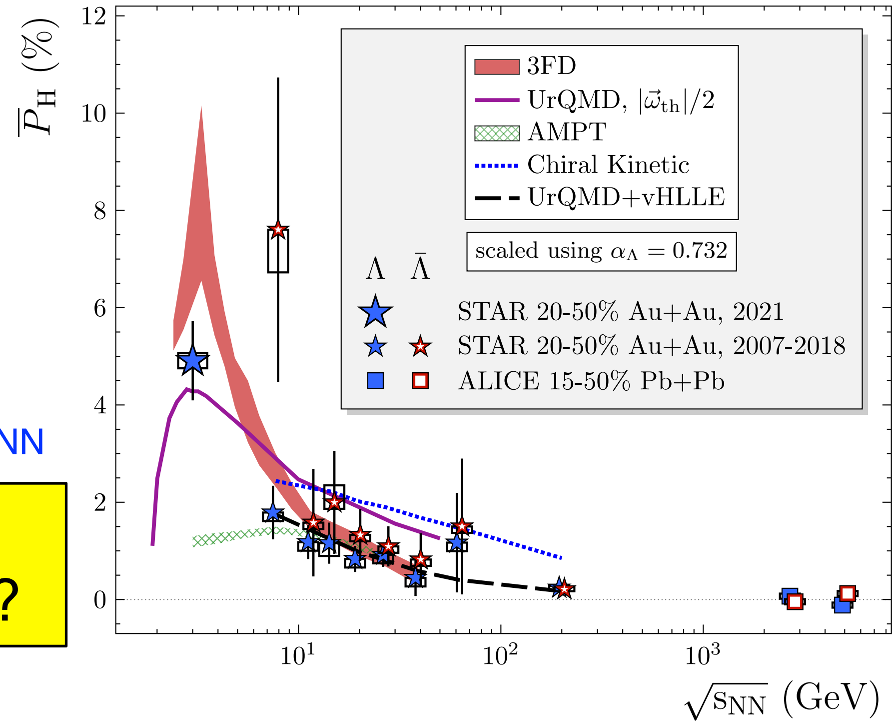
Approximate agreement at low $\sqrt{s_{NN}}$

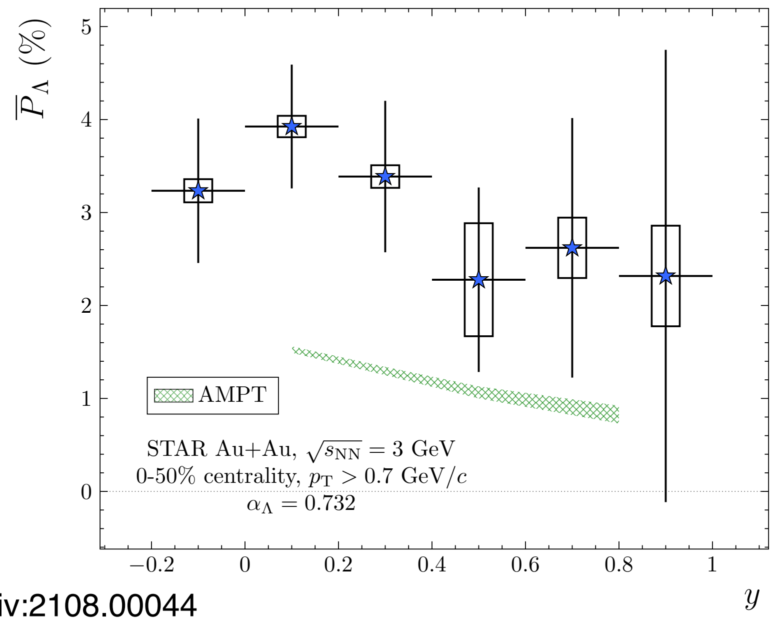
Over-estimates higher $\sqrt{s_{NN}}$

AMPT:

Dramatic underprediction at low $\sqrt{s_{NN}}$

Formation of vortical flow not dependent on presence of QGP?





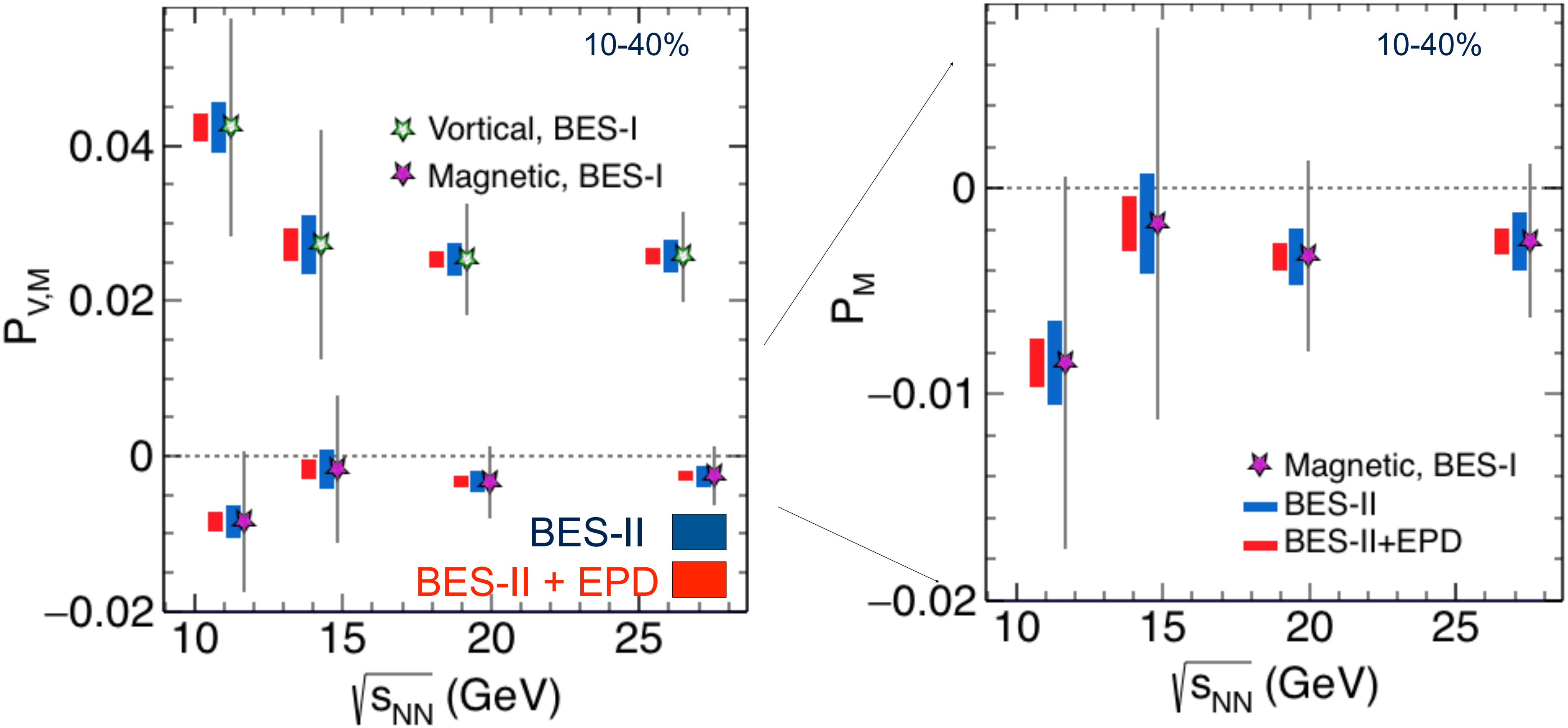
arXiv:2108.00044

No statistically significant dependence observed

- Measurements out to beam rapidity

Forward upgrade should yield interesting results

Access to initial B-field



Vortical + Magnetic Contributions:

Current data barely stat. significant

EPD:

Improved EP resolution

BES-II: >3σ effect

Unique measurement of B field

Hypernuclei lifetime

Hypernuclei - probe hyperon-nuclei interaction
Lifetimes, Binding energies, branching ratios

Lifetimes from 3 GeV data

Λ:

265.0 ± 2.2 ps
(PDG 263.1± 2.0 ps)

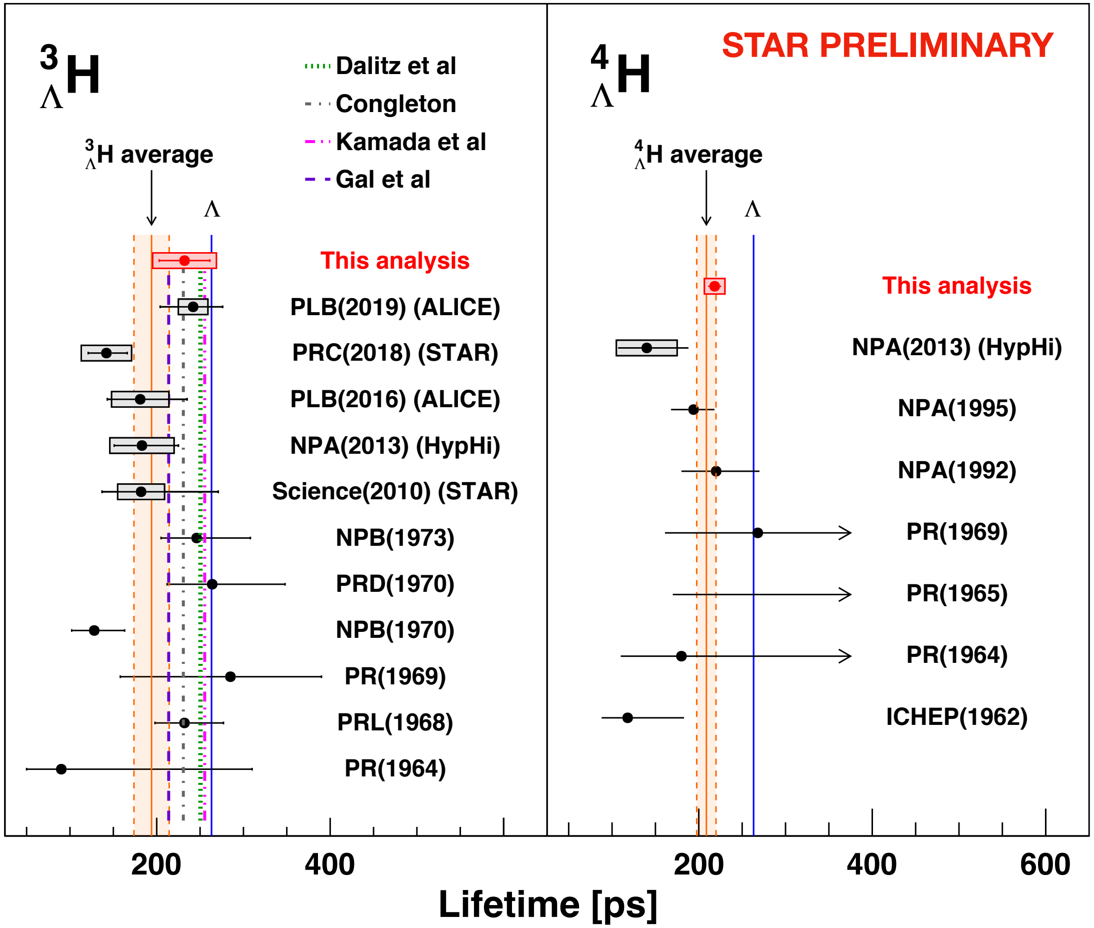
$^3_\Lambda$H:

Consistency with previous results

$^4_\Lambda$H:

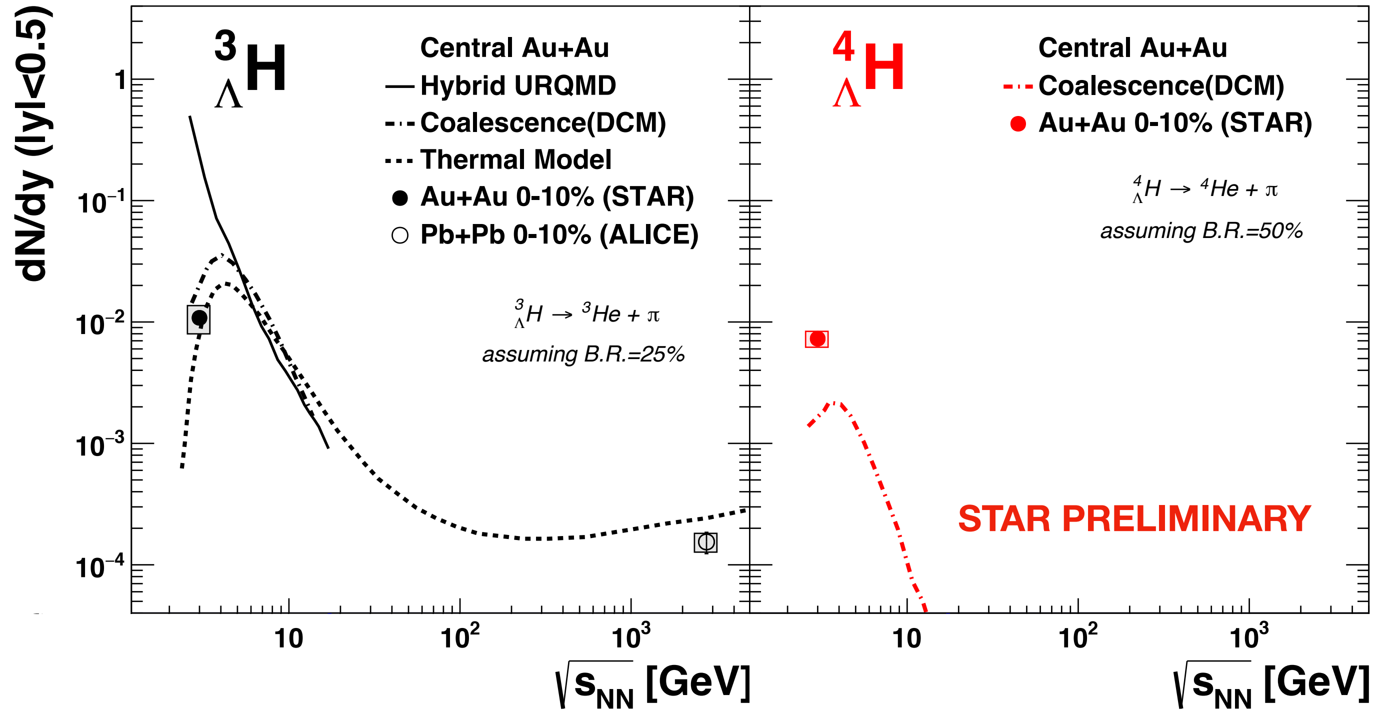
Most precise measurement to date

Consistency with previous results



Hypernuclei yields

Significant increase in production of hypernuclei expected



Canonical ensemble thermal model (GSI-Heidelberg) describes $^{3}_{\Lambda}H$

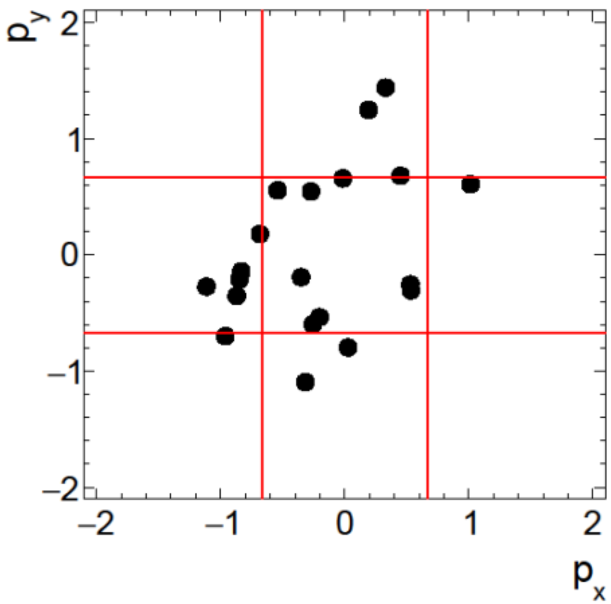
Coalescence describes $^{3}_{\Lambda}H$ but not $^{4}_{\Lambda}H$

BES-II: more energies, heavier hypernuclei, S=2 hypernuclei, and differential results to come

Charged particle intermittency

Intermittency analysis in p_T space - measure scaled factorial moments

Probes local **density fluctuations** and long range correlations near CP



$F_q(M)$ - scaled factorial moment

n_i - particle multiplicity in i^{th} cell

M^D - number of equal-size cells in which D-dimensional space is partitioned

q - order of moment

$$F_q(M) = \frac{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i(n_i - 1)\ldots(n_i - q + 1) >}{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i >^q}$$

$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M)$$

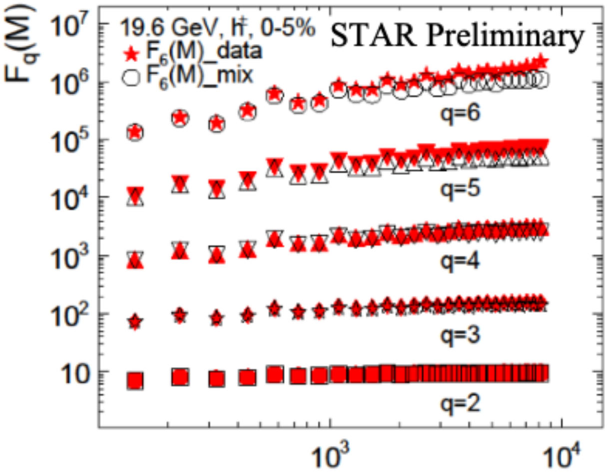
$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$$

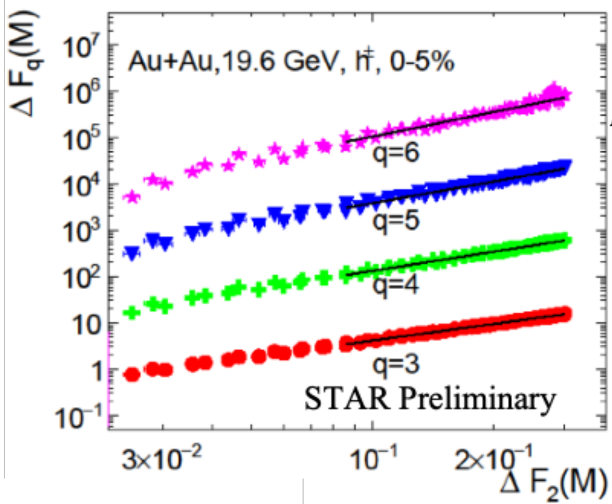
$$\beta_q \propto (q-1)^{\nu}$$

ν specifies scaling behavior

Energy dependence of ν could be used to search for signature of CP

Charged particle intermittency





$$F_q(M) = \frac{\left\langle \frac{1}{M^D} \sum_{i=1}^{M^D} n_i(n_i-1)\ldots(n_i-q+1) \right\rangle}{\left\langle \frac{1}{M^D} \sum_{i=1}^{M^D} n_i \right\rangle^q}$$

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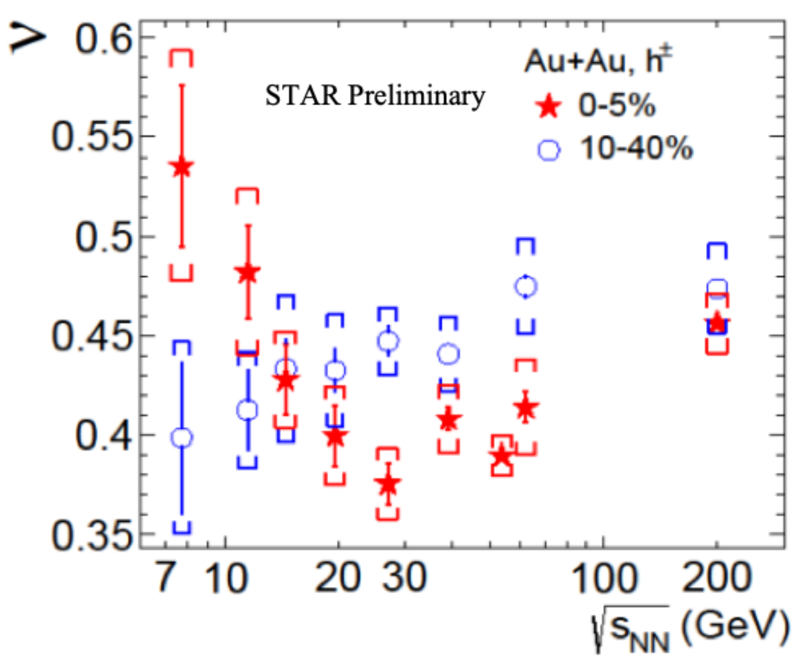


Scaling exponent exhibits a non-monotonic energy dependence in central Au+Au collisions minimum around = 20-30 GeV.

More theory input needed

BES-II: higher statistics enable centrality study

Summary

Excellent performance from RHIC and STAR

All requested BES-II data collected and more - 17 unique energies from 3-200 GeV with some overlapping Collider and FXT energies

BES-II upgrades performing at or above expectations

Precision analyses ongoing with very well understood detector

- first results submitted

New ideas developed since original proposal: vorticity, hypernuclei..

Last chance to answer these critical HI questions at RHIC

Next steps

Run-22-25 - pp at 500 GeV, Au-Au, pp and p+Au at 200 GeV

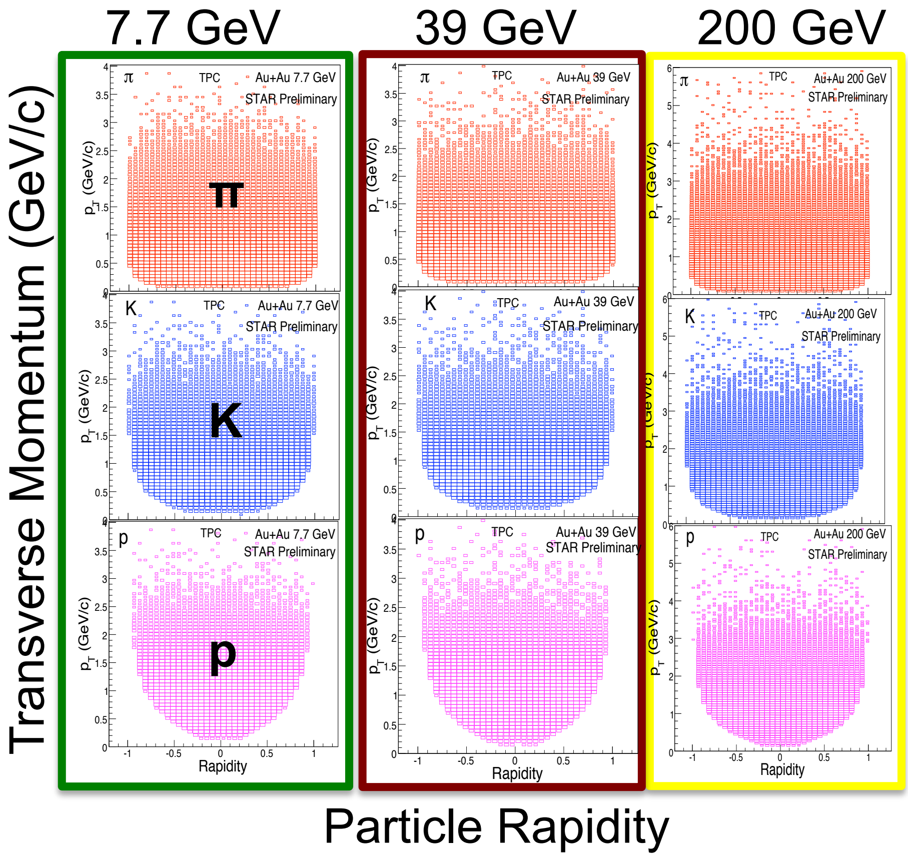
Exciting physics program enabled by BES-II and Forward Upgrades collection of RHIC legacy data prior to EIC

BACK UP

First Beam Energy Scan (BES-I)

Au+Au Collisions

$\sqrt{s_{NN}}$ (GeV)	Events ($X10^6$)	Year	*μ_B (MeV)	*T_{CH} (MeV)
200	238	2010	25	166
62.4	46	2010	73	165
54.4	1200	2017	83	165
39	86	2010	112	164
27	30	2011	156	162
19.6	15	2011	206	160
14.5	13	2014	264	156
11.5	7	2010	315	152
7.7	3	2010	420	140



Designed to have roughly equal μ_B step sizes from $\sqrt{s_{NN}}$ = 200 - 7 GeV

Collider mode of operation + STAR detector design - uniform acceptance around mid-rapidity

Projecting 7.7 GeV run time

Collision Energy (GeV)	7.7	9.2	11.5	14.6	17.1	19.6	27
Performance in BES-I	2010	NA	2010	2014	NA	2011	2011
Good Events (M)	4.3	NA	11.7	12.6	NA	36	70
Days running	19	NA	10	21	NA	9	8
Data Hours per day	11	NA	12	10	NA	9	10
Fill Length (min)	10	NA	20	60	NA	30	60
Good Event Rate (Hz)	7	NA	30	23	NA	100	190
Max DAQ Rate (Hz)	80	NA	140	1000	NA	500	1200
Performance in BES-II (**achieved**)	2021	2020	2020	2019	2021	2019	2018
Required Number of Events	100	160	230	300	250	400	NA
Achieved Number of Events	2.9	**162**	**235**	**324**	TBD	**582**	**560**
fill length (min)	20-45	**45**	**25**	**45**	50	**60**	**120**
Good Event Rate (Hz)	16-24	**33**	**80**	**170**	265	**400**	**620**
Max DAQ rate (Hz)	400	**700**	**550**	**800**	1300	**1800**	**2200**
Data Hours per day	12-15	**13**	**13**	**9**	15	**10**	**9**
Projected number of weeks	11-20	8.5-14	7.6-10	5.5	2.5	4.5	NA
weeks to reach goals	TBD	**14.6***	****8.9**	**8.6***	TBD	**5.1***	**4.0**

Below injection energy luminosity scales well with γ^3

Rescaled running times in agreement with lower-middle end of projections

7.7 GeV projections 11-20 (~28-CAD) weeks optimistic/pessimistic assumptions

*Running with significant LEReC

**Run-20b running

Projecting 7.7 GeV run time

Collision Energy (GeV)	7.7	9.2	11.5	14.6	17.1	19.6	27
Performance in BES-I	2010	NA	2010				
Good Events (M)	4.3	NA	11.7				
Days running	19	NA	10				
Data Hours per day	11	NA	12				
Fill Length (min)	10	NA	20				
Good Event Rate (Hz)	7	NA	30				
Max DAQ Rate (Hz)	80	NA	140				
Performance in BES-II (**achieved**)	2021	2020	2020	2019	2021	2019	2018
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weeks to reach goals	TBD	**14.6****	**8.9**	**8.6***	TBD	**5.1***	**4.0**

Run-20b 7.7 GeV running over holiday weekend reached a good event rate average of 16 Hz and up to 16 hours/day of data taking!!

Below injection energy luminosity scales well with γ^3

Rescaled running times in agreement with lower-middle end of projections

7.7 GeV projections 11-20 (~28-CAD) weeks optimistic/pessimistic assumptions

*Running with significant LEReC
**Run-20b running

Event statistics requirements: Collider

Table 7: Event statistics (in millions) needed in the collider part of the BES-II program for various observables. This table updates estimates originally documented in STAR Note 598.

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	-	-	160	125	92
Elliptic Flow (ϕ mesons)	80	120	160	160	320
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	20	30	35	45	50
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	70	85	100	170	340
Dileptons	100	160	230	300	400
$>5\sigma$ Magnetic Field Significance	50	80	110	150	200
Required Number of Events	100	160	230	300	400

Typically factor 20 more than for BES-I

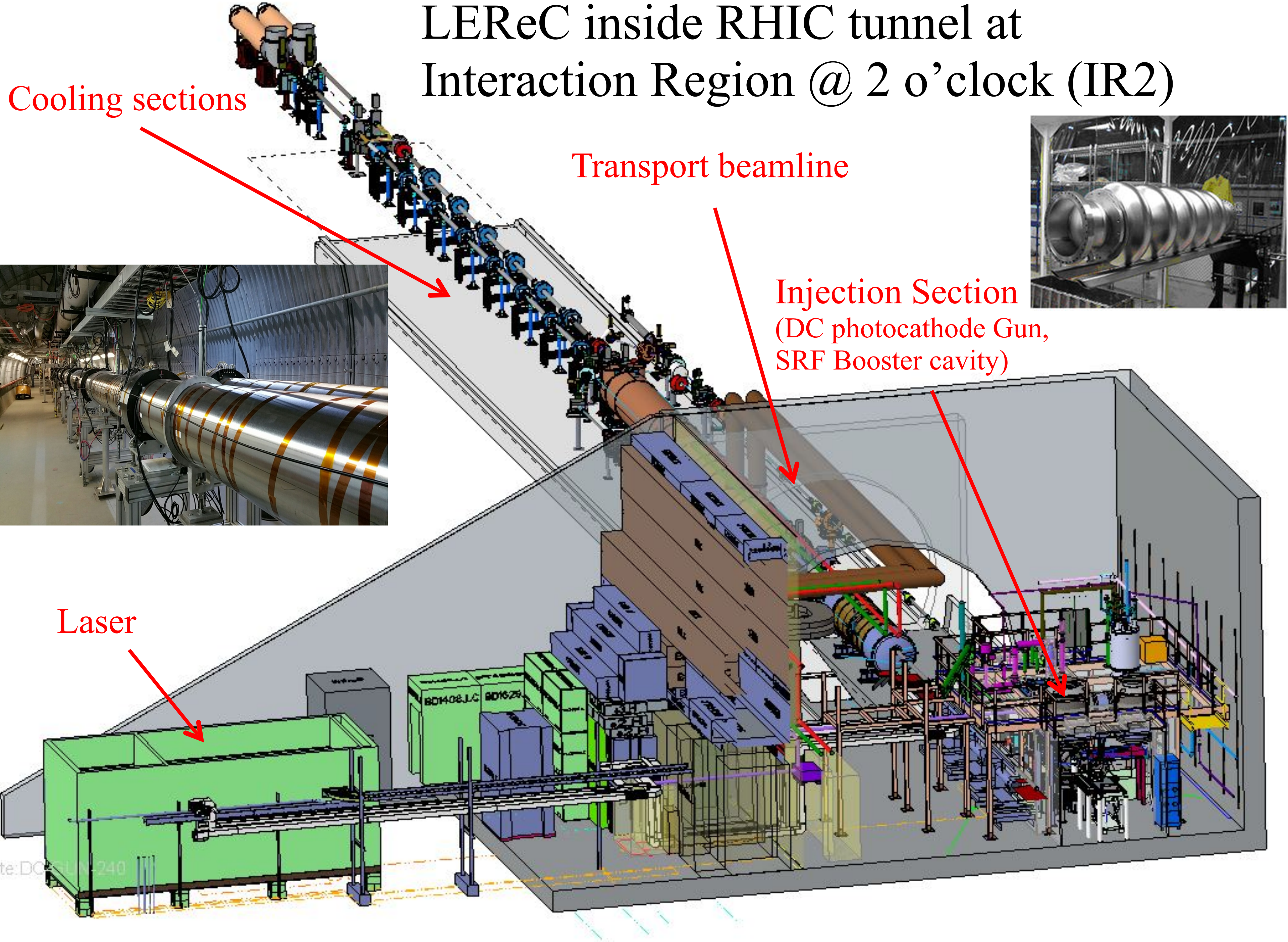
Event statistics requirements: FXT

Table 8: Event statistics (in millions) needed in the fixed-target part of the BES-II program for various observables.

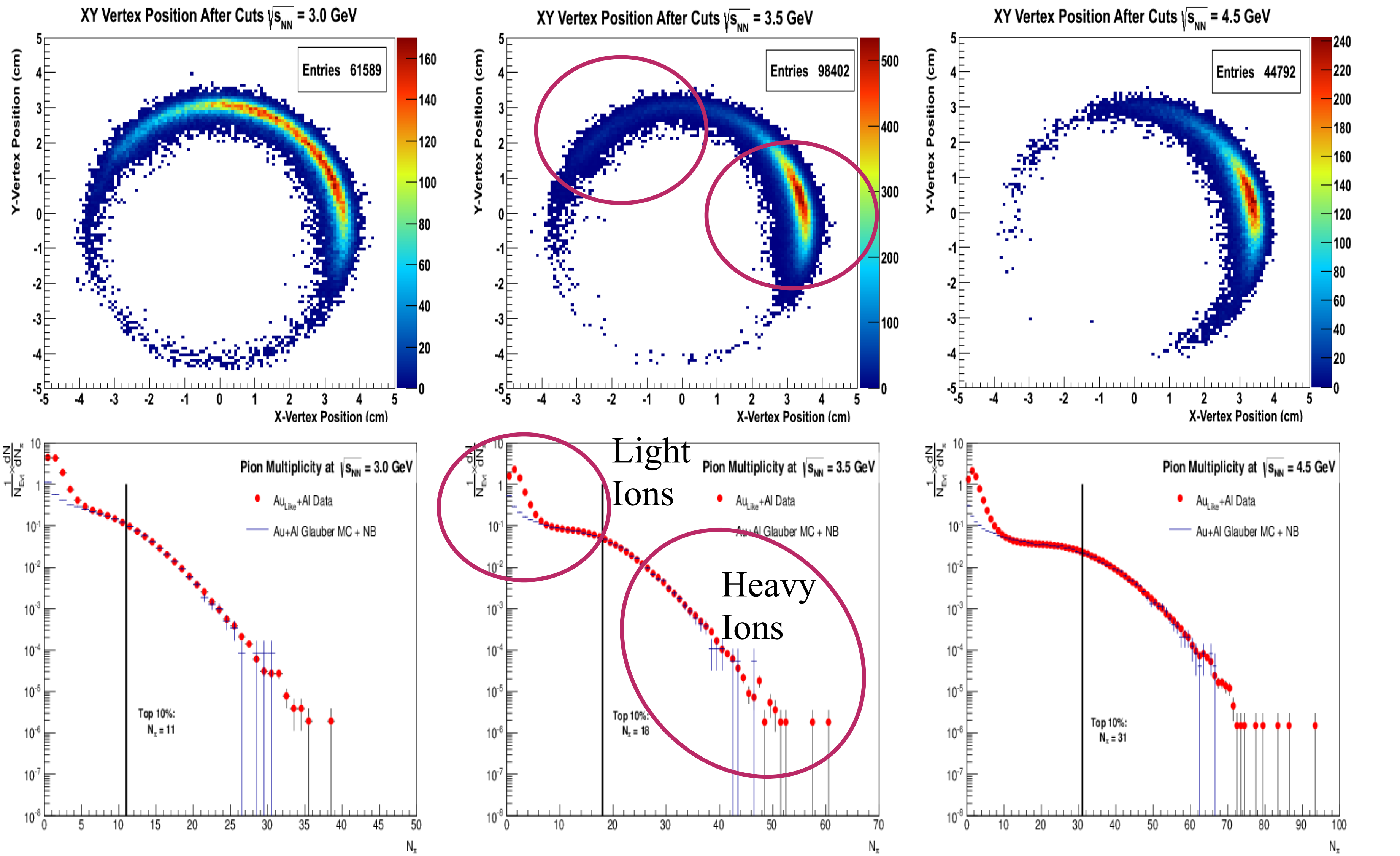
$\sqrt{s_{NN}}$ (GeV)	3.0	3.2	3.5	3.9	4.5	5.2	6.2	7.7
Single Beam Energy (GeV)	3.85	4.55	5.75	7.3	9.8	13.5	19.5	31.2
μ_B (MeV)	721	699	666	633	589	541	487	420
Rapidity y_{CM}	1.06	1.13	1.25	1.37	1.52	1.68	1.87	2.10
Observables								
Elliptic Flow (kaons)	300	150	80	40	20	40	60	80
Chiral Magnetic Effect	70	60	50	50	50	70	80	100
Directed Flow (protons)	20	30	35	45	50	60	70	90
Femtoscopy (tilt angle)	60	50	40	50	65	70	80	100
Net-Proton Kurtosis	36	50	75	125	200	400	950	NA
Multi-strange baryons	300	100	60	40	25	30	50	100
Hypertritons	200	100	80	50	50	60	70	100
Requested Number of Events	300	100	100	100	100	100	100	100

Beam E_T (GeV)	Beam E_k (AGeV)	Beam p_Z (GeV/c)	Rapidity y_{Beam}	$\sqrt{s_{NN}}$ (GeV)	Rapidity y_{CM}	Ch. Pot. μ_B (GeV)
3.85	2.92	3.73	2.10	3.0	1.05	721
4.59	3.66	4.50	2.28	3.2	1.13	699
5.75	4.82	5.67	2.51	3.5	1.25	666
7.3	6.4	7.25	2.75	3.9	1.37	633
9.8	8.9	9.44	3.04	4.5	1.52	589
13.5	12.6	13.5	3.37	5.2	1.68	541
19.5	18.6	19.5	3.73	6.2	1.87	487
26.5	25.6	26.5	4.04	7.2	2.02	443
31.2	30.3	31.2	4.20	7.7	2.10	420
44.5	43.6	44.5	4.56	9.2	2.28	372
70	69.1	70	5.01	11.5	2.51	316
100	99.1	100	5.37	13.7	2.69	276

LEReC inside RHIC tunnel at Interaction Region @ 2 o'clock (IR2)



Beam Halo on Al Vacuum Pipe



BES-II: Directed Flow Improvements

STAR

Current data: Double sign change of v_1

Precision measurement of dv_1/dy as function of centrality

iTPC+ eTOF:

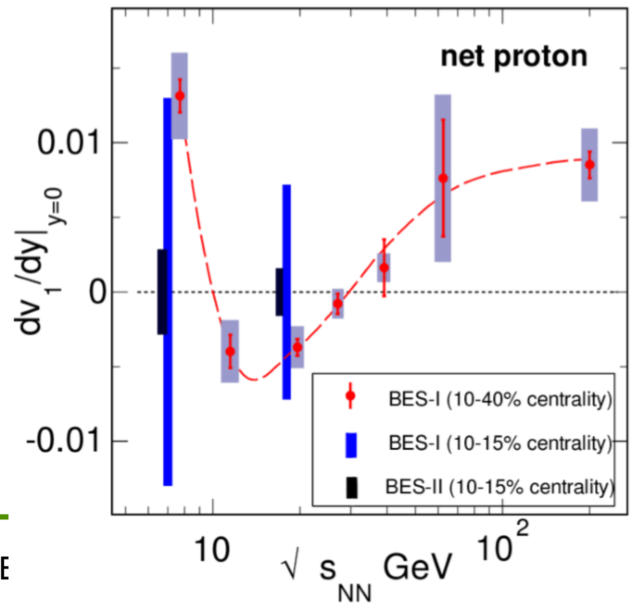
Enhanced coverage at forward y

Signal larger - role of baryon stopping

EPD:

Enhanced 1st order EP resolution

Reduced systematics



BES-II: Directed Flow Improvements

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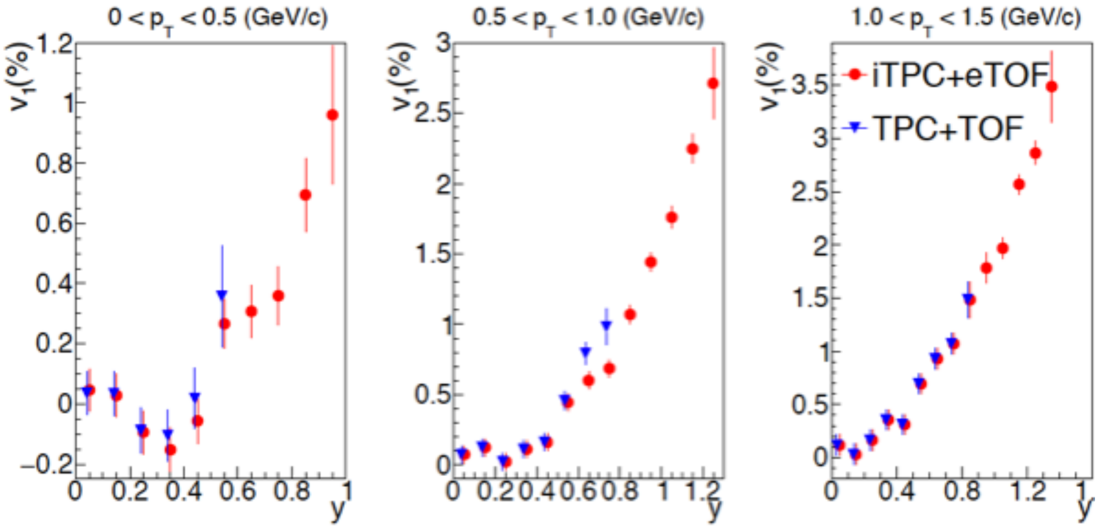
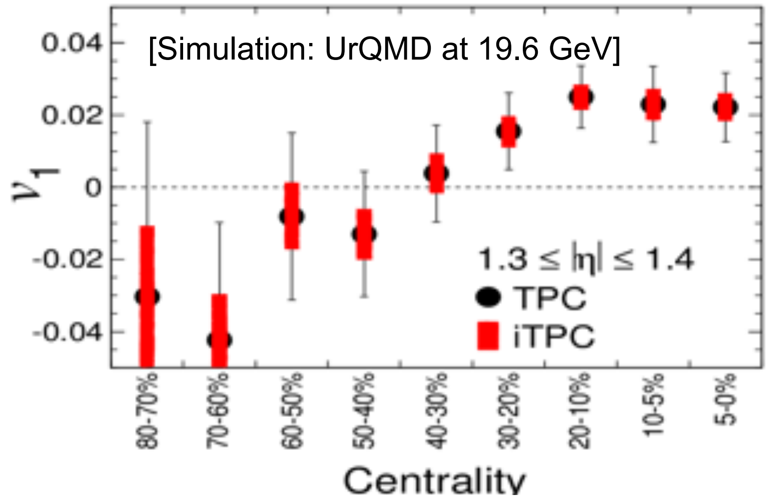
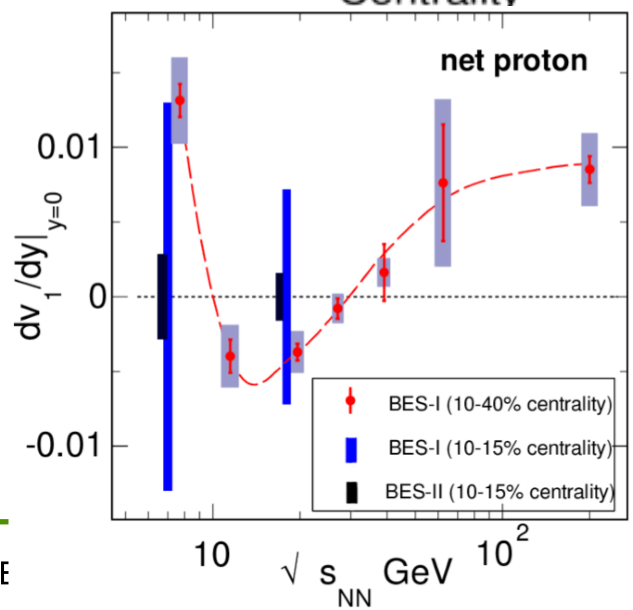
Precision measurement of dv_1/dy as function of centrality







iTPC+ eTOF:

Enhanced coverage at forward y

Signal larger - role of baryon stopping

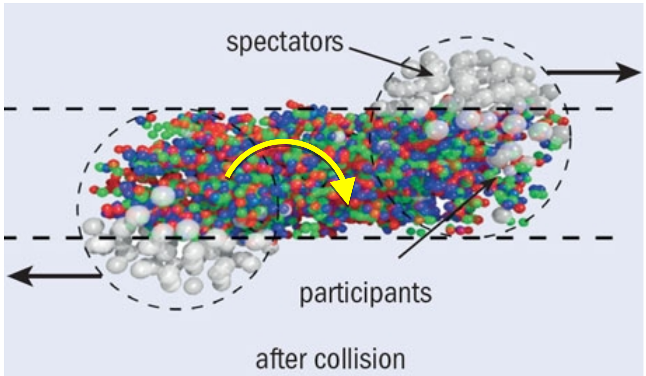
EPD:

Enhanced 1st order EP resolution

Reduced systematics

The spinning QGP

|J| ~ 1000 $\hbar$ in peripheral collisions

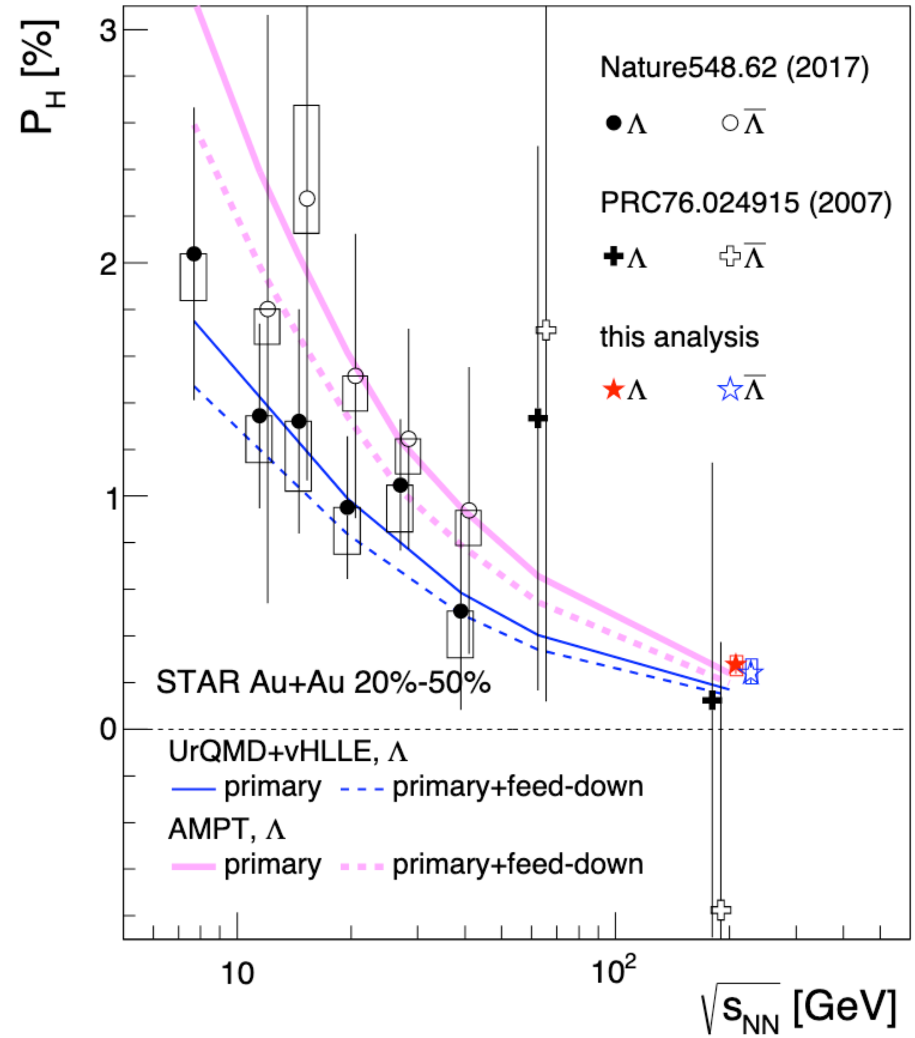


Sheer forces in fluid lead to vorticity

Spin-orbit coupling: polarization along direction of vorticity & J

$$\omega = k_B T \left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\overline{\Lambda}'} \right) / \hbar,$$

$\sqrt{s_{NN}}$-averaged $\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$



Expected strong B-field coupled to magnetic moment of particles
Affects particle and anti-particle differently

$$P_{EM} = \frac{1}{2}(P_\Lambda - P_{\bar{\Lambda}})$$

Nature 548 (2018) 62
PRC **98** (2018) 14910