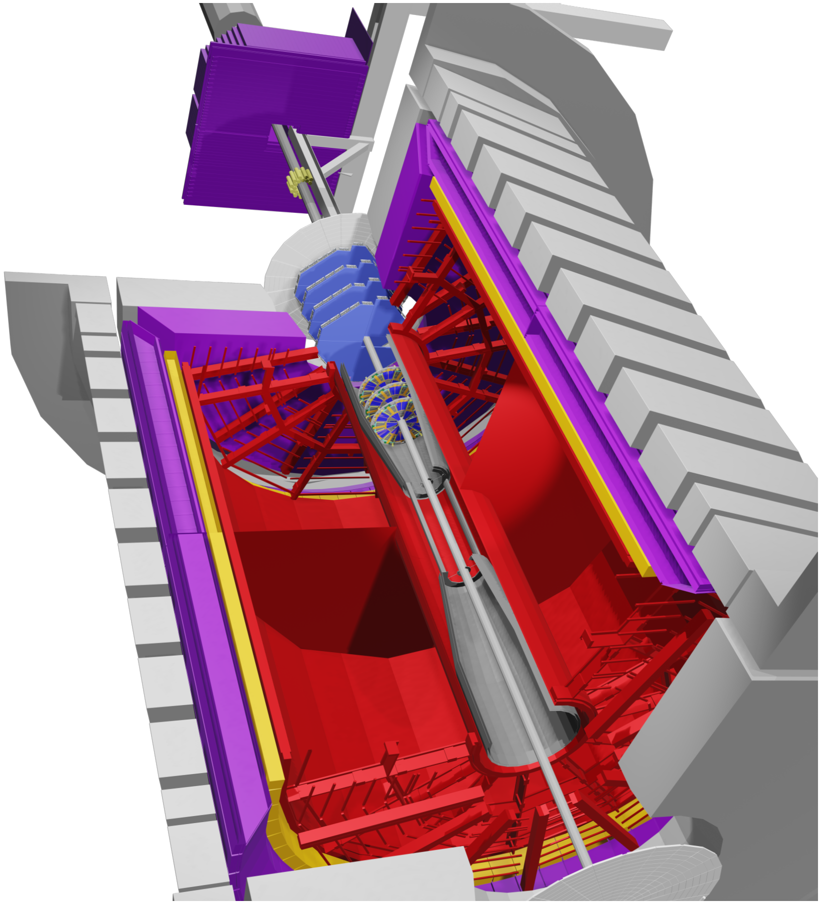
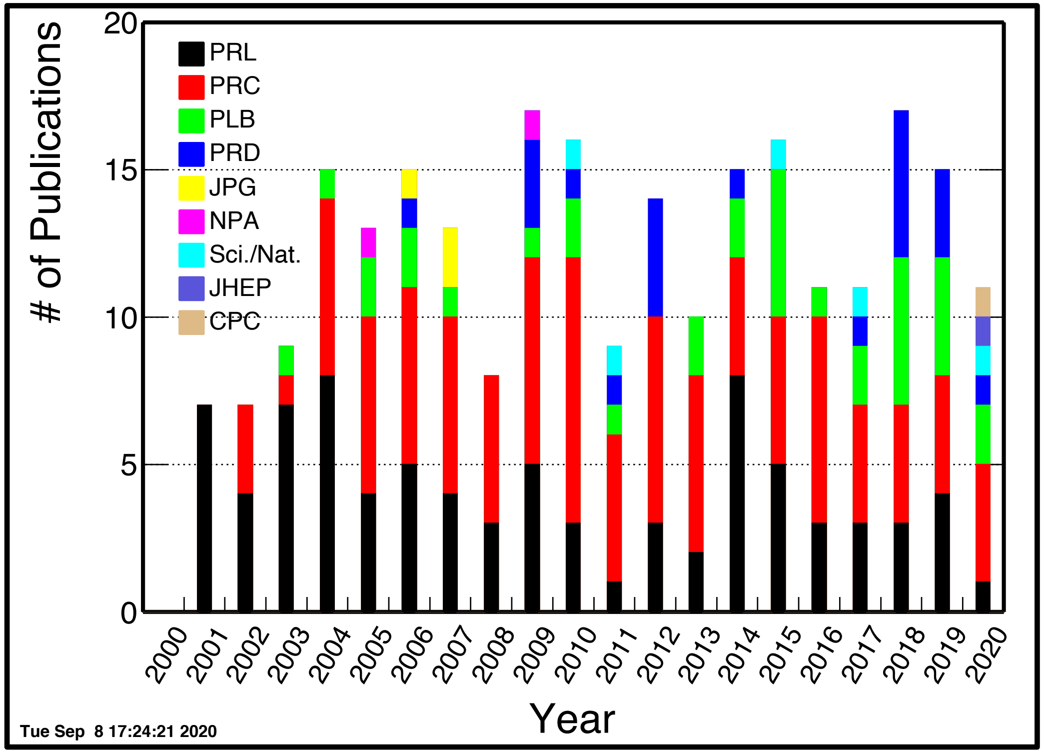
STAR's Run-21 and Run-22 Beam Use Request



Helen Caines - Yale - on behalf of the STAR Collaboration

Continue strong publication record



Many new results published and presented at conferences since 2019 PAC

QM19:

19+1 talks + 45 posters

Nuclear Physics A Young Scientist Award: James Daniel Brandenburg

2019: 15 published (4 PRL, 4 PLB, 4 PRC, 3 PRD)
2020: 11 published+accepted (1 PRL, 4 PRC, 2 PLB, 1 PRD, 1 Nature Physics, 1 JHEP, 1 CPC)

Journal review: 11

Collaboration review: 5; Active GPCs: 11+24

Executive summary

Run-21:

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
8.35	17.1	2.5 weeks	Au+Au	250 M	3
3.85	3 (FXT)	3 weeks	Au+Au	2 B	3

Table 2: Proposed Run-21 assuming 24-28 cryo-weeks, including an initial one week of cool-down, one week for CeC, a one week set-up time for each collider energy and 0.5 days for each FXT energy.

Run-22:

$\sqrt{s}$ (GeV)	Species	Polarization	Run Time	Sampled Luminosity	Priority
510	p+p	Transverse	16 weeks	400 pb^{-1}	1

Table 3: Proposed Run-22 assuming 20 cryo-weeks, including an initial one week of cool-down and a two weeks set-up time.

STAR's highest priorities are the **completion of the BES-II** and **transversely polarized p+p at 510 GeV** utilizing the Forward Upgrades

Executive summary II:

Second highest priority Run-21:

Au+Au $\sqrt{s_{NN}}$ = 3 GeV (FXT) 300 M minbias 3 days

- Net proton fluctuations, GCE vs GC, light hypernuclei production

Au+Au $\sqrt{s_{NN}}$ = 9.2, 11.5, 13.7 GeV (FXT) 50 M minbias 3 days

- Enhanced understanding of baryon stopping

Third highest priority Run-21:

O+O $\sqrt{s_{NN}}$ = 200 GeV 400(200) M minbias(central) 1 week

- Enhanced understanding of early conditions in small systems

Au+Au $\sqrt{s_{NN}}$ = 17.1 GeV 250 M minbias 2.5 weeks

- Probe for CP via non-monotonic behavior of higher order moments

Au+Au $\sqrt{s_{NN}}$ = 3 GeV (FXT) 2 B minbias 3 weeks

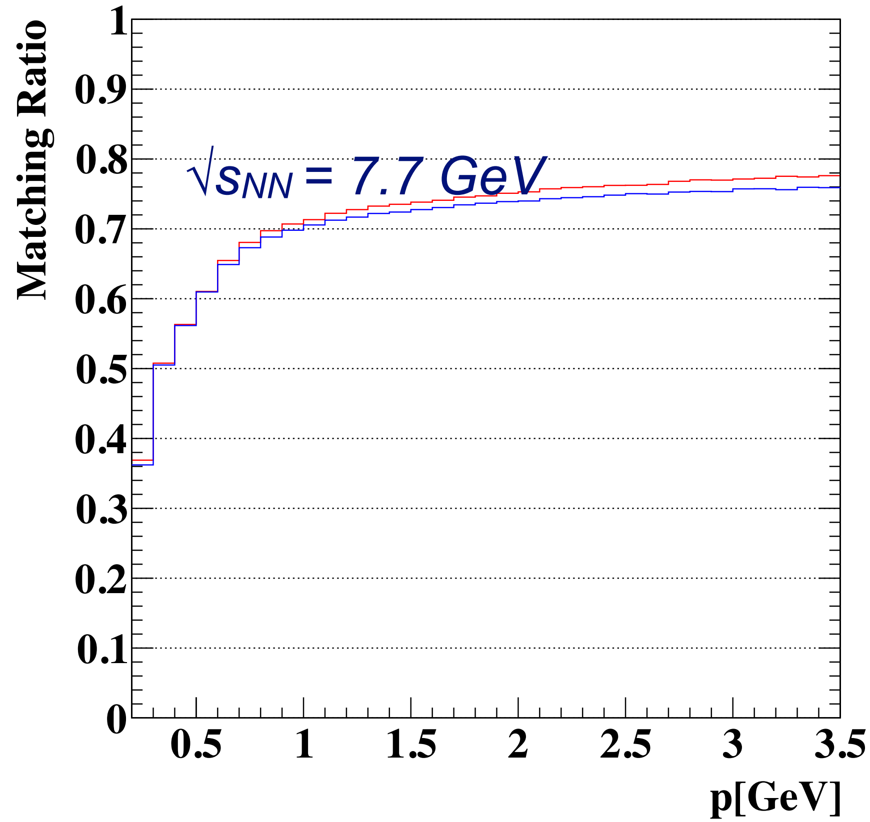
Higher order (>4) moments, ϕ flow, double-Λ hypernuclei

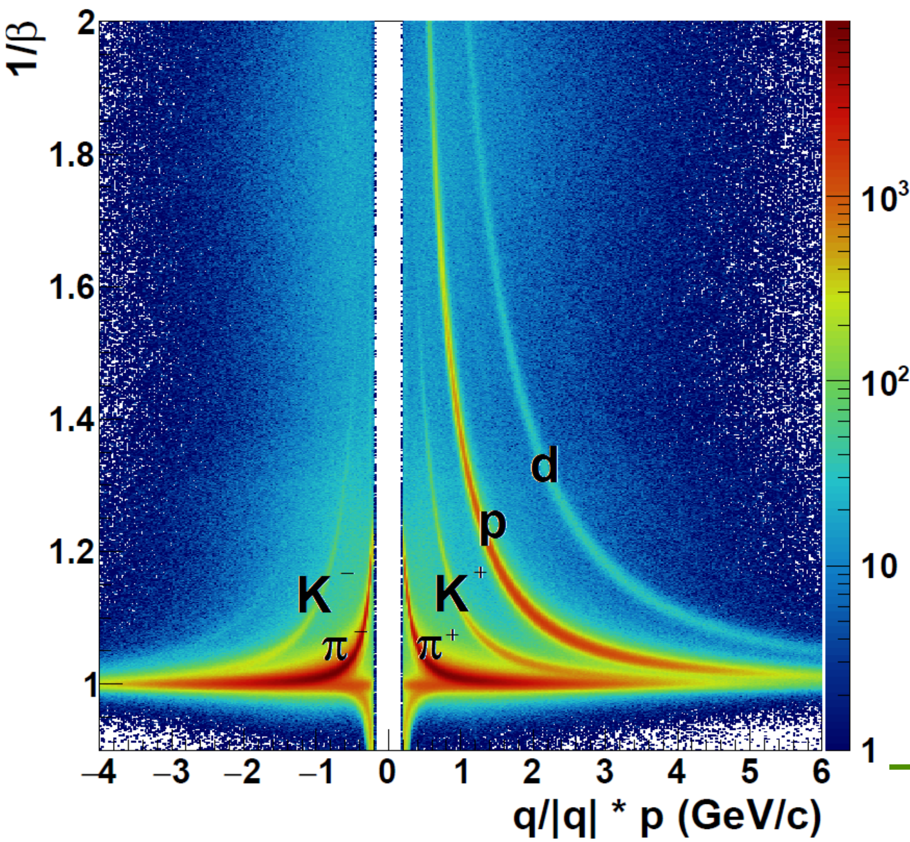
eToF update

Matching efficiency >70% above 1 GeV/c

Timing ~80ps

K/π separation up to p = 2.5 GeV/c





All FXT runs ~100 M events with eTOF

11.5 GeV 235 M events with eTOF

Mitigation work during last shut down led to successful eTOF performance in Run-20 and Run-20b

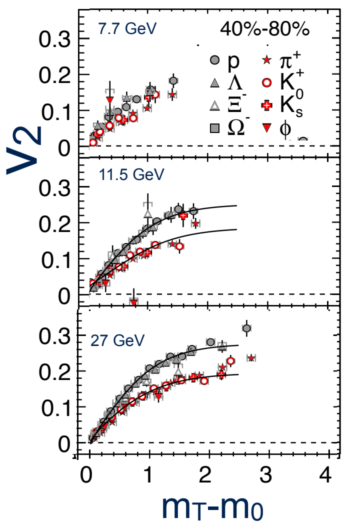
BES-II progress report

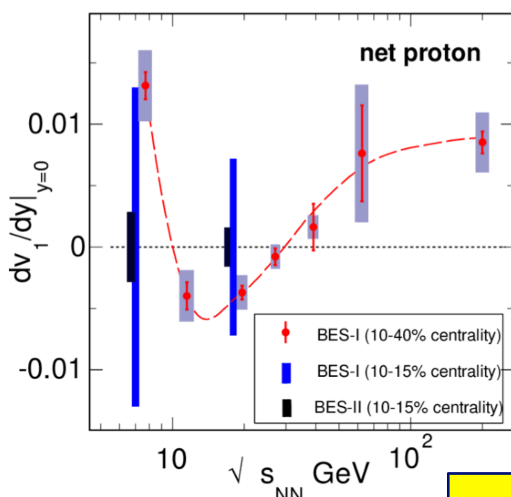
Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events Requested (Recorded)	Date Collected
13.5	27	156	24 days	(560 M)	Run-18
9.8	19.6	206	36 days	400 M (582 M)	Run-19
7.3	14.6	262	60 days	300 M (324 M)	Run-19
5.75	11.5	316	54 days	230 M (235 M)	Run-20
4.59	9.2	373	102 days	160 M (162 M)[1]	Run-20+20b
31.2	7.7 (FXT)	420	0.5+1.1 days	100 M (50 M+112 M)	Run-19+20
19.5	6.2 (FXT)	487	1.4 days	100 M (118 M)	Run-20
13.5	5.2 (FXT)	541	1.0 day	100 M (103 M)	Run-20
9.8	4.5 (FXT)	589	0.9 days	100 M (108 M)	Run-20
7.3	3.9 (FXT)	633	1.1 days	100 M (117 M)	Run-20
5.75	3.5 (FXT)	666	0.9 days	100 M (116 M)	Run-20
4.59	3.2 (FXT)	699	2.0 days	100 M (200 M)	Run-19
3.85	3.0 (FXT)	721	4.6 days	100 M (259 M)	Run-18
3.85	7.7	420	11-20 weeks	100 M	Run-21[2]

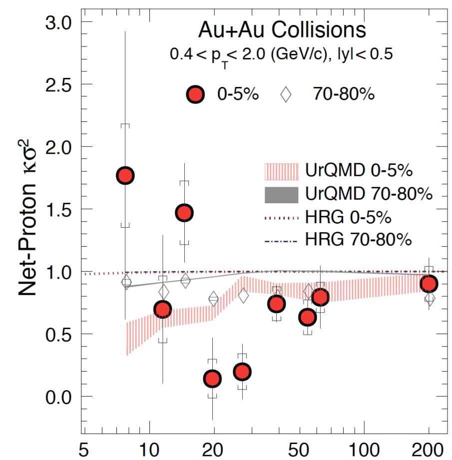
We have collected all originally proposed BES-II and FXT data except for $\sqrt{s_{NN}} = 7.7$ in collider mode

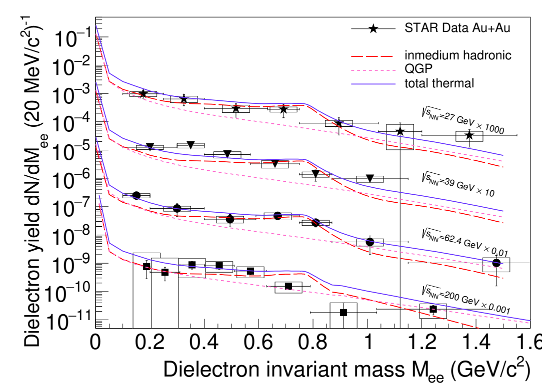
Case for collecting 7.7 GeV data

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**









Essential bridge between collider and FXT data

BES-I gave hints of features near 7.7 for several studies

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
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**

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

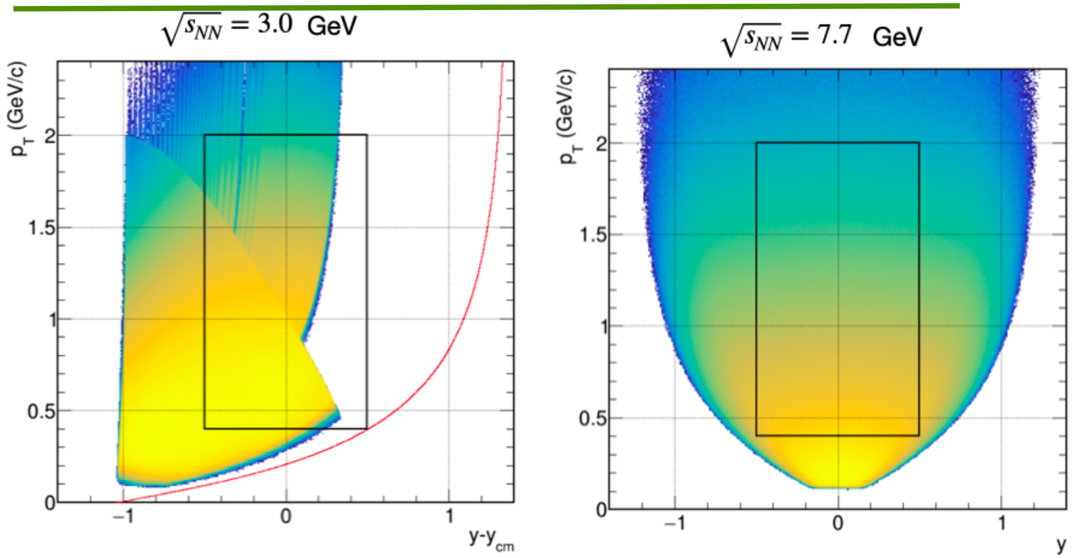
Rescaled running times in agreement with lower-middle end of projections

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

*Running with significant LEReC

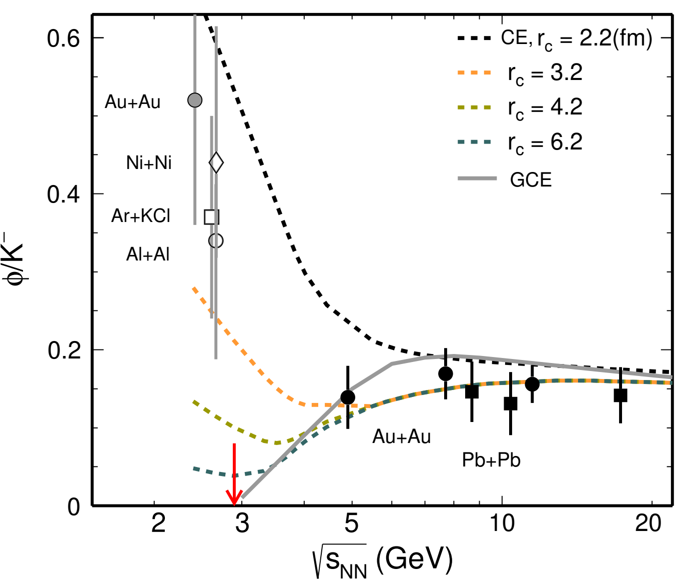
**Run-20b running

Case for Au+Au $\sqrt{s_{NN}}$ = 3 GeV (FXT)



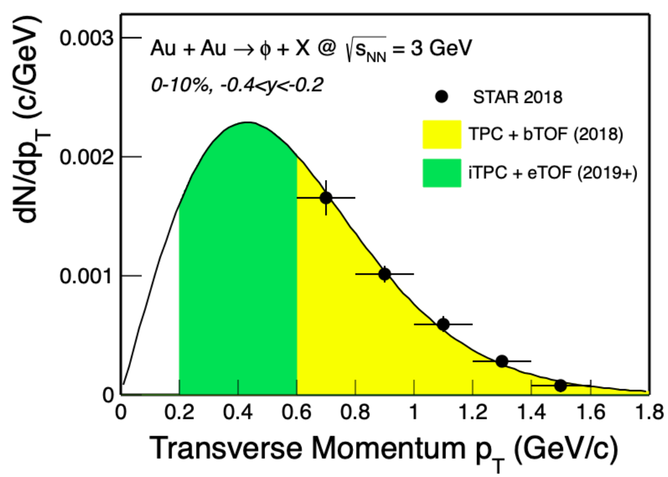
Net-proton fluctuations:

Run-21: iTPC and eTOF —> similar proton acceptance to 7.7 GeV collider data



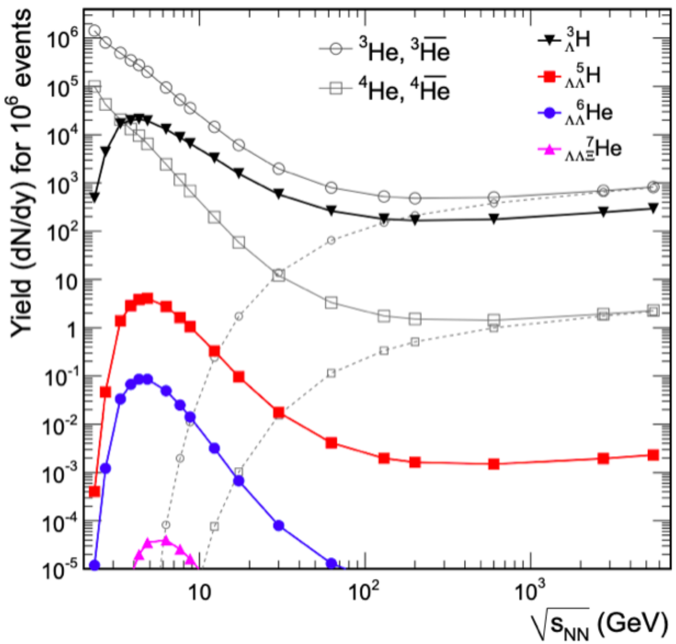
GCE or CE appropriate at low beam energy?

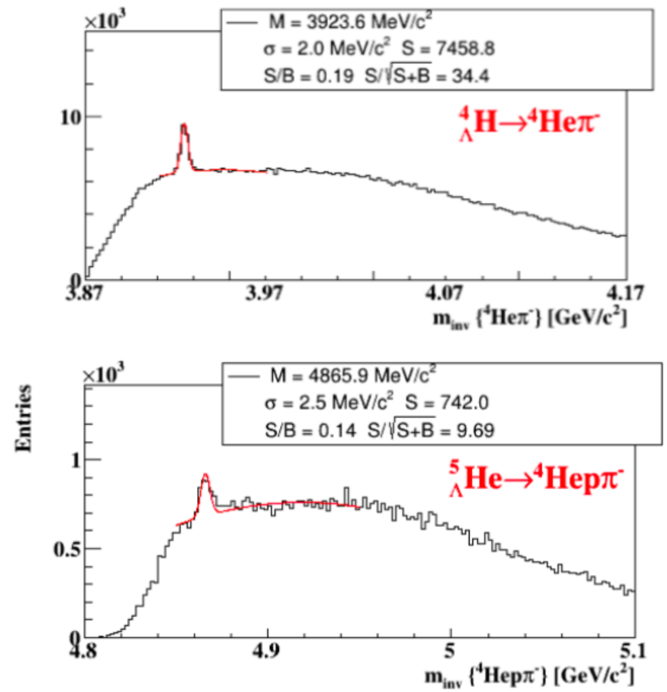
Sensitivity to r_c:



Run-21: iTPC and eTOF —> ~90% of ϕ yield measured at mid rapidity

Case for Au+Au $\sqrt{s_{NN}}$ = 3 GeV (FXT)





Run-21: iTPC and eTOF —>

Light hypernuclei lifetime, BE, yields and flow

If time permits propose to extend to 2B events - 3 weeks

Access to:

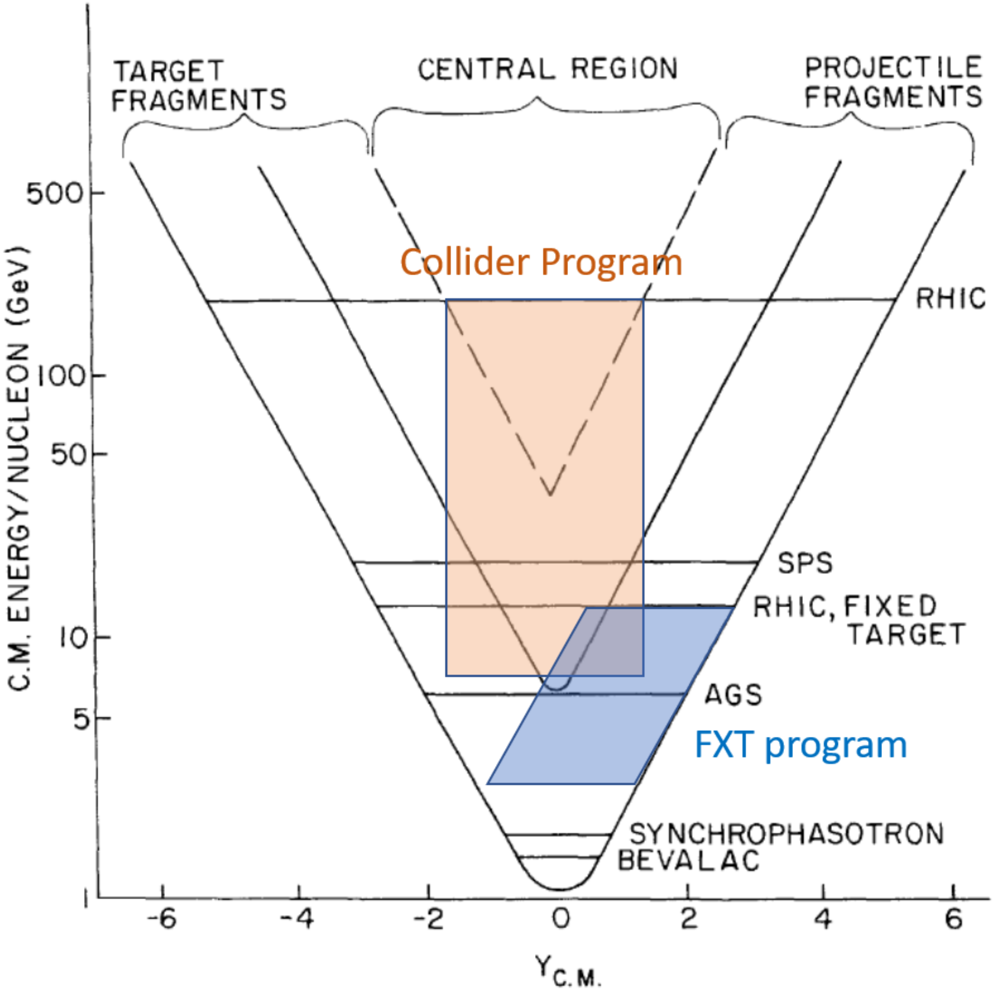
C_5, C_6

Centrality dependence of ϕ studies

Double-Λ hypernuclei

Propose to collect at least 300 M minbias events - 3 days of running

Case for Au+Au $\sqrt{s_{NN}}$ = 9.2, 11.5, 13.7 GeV (FXT)



y_{cm} = 2.28, 2.5 and 2.68 respectively

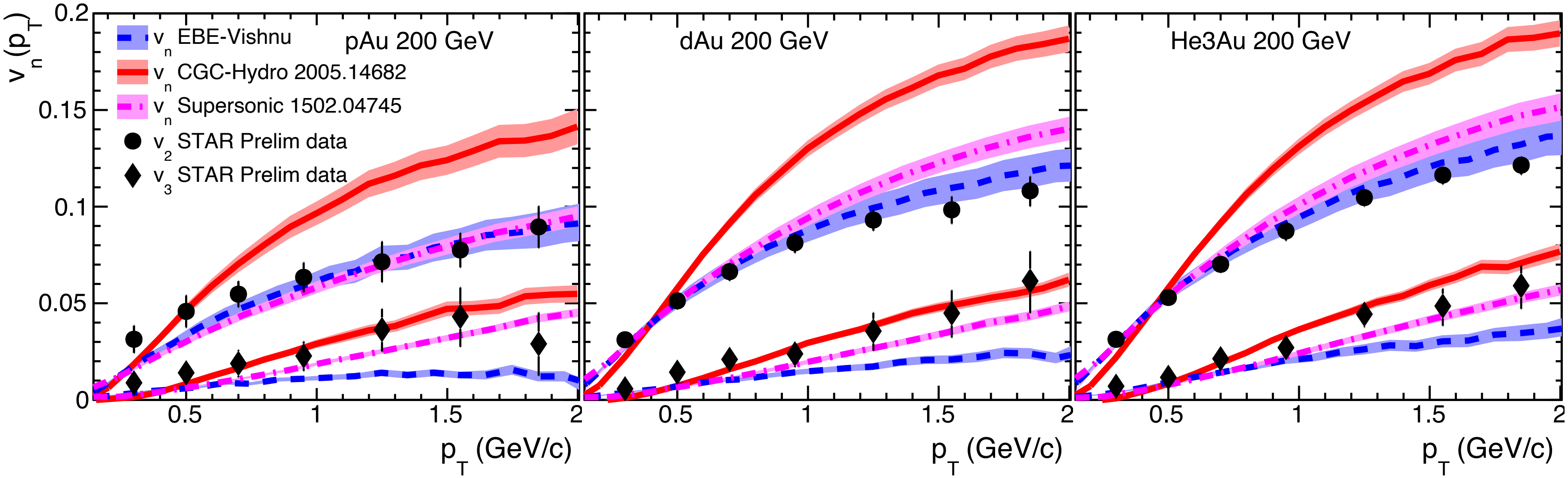
In combination with collider data near full rapidity coverage

High rapidity tails of dN/dy critical for constraining shear viscosity dependence on T and μ_B

Stall in rapidity shift of stopped protons - reveals softening of equation of state

Propose to collect 50 M minbias events at each energy
- 3 days of total running

Correlations in small systems



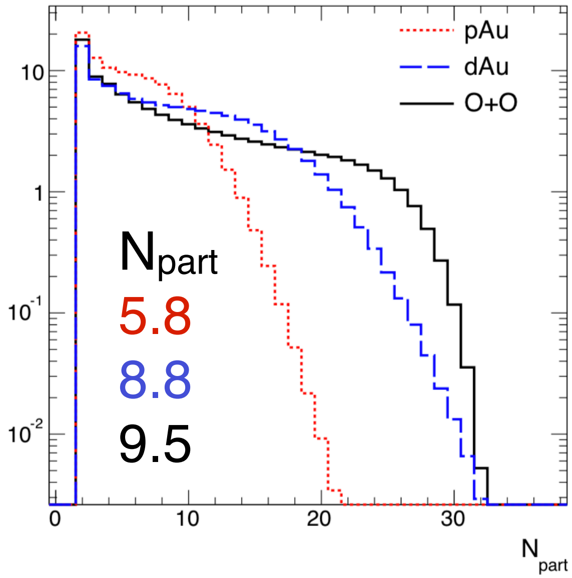
Models fail to describe all the current STAR data

Initial State Correlations or Final State Interactions in small systems?

If Final state: is collectivity fluid-like or off-equilibrium few scatterings?

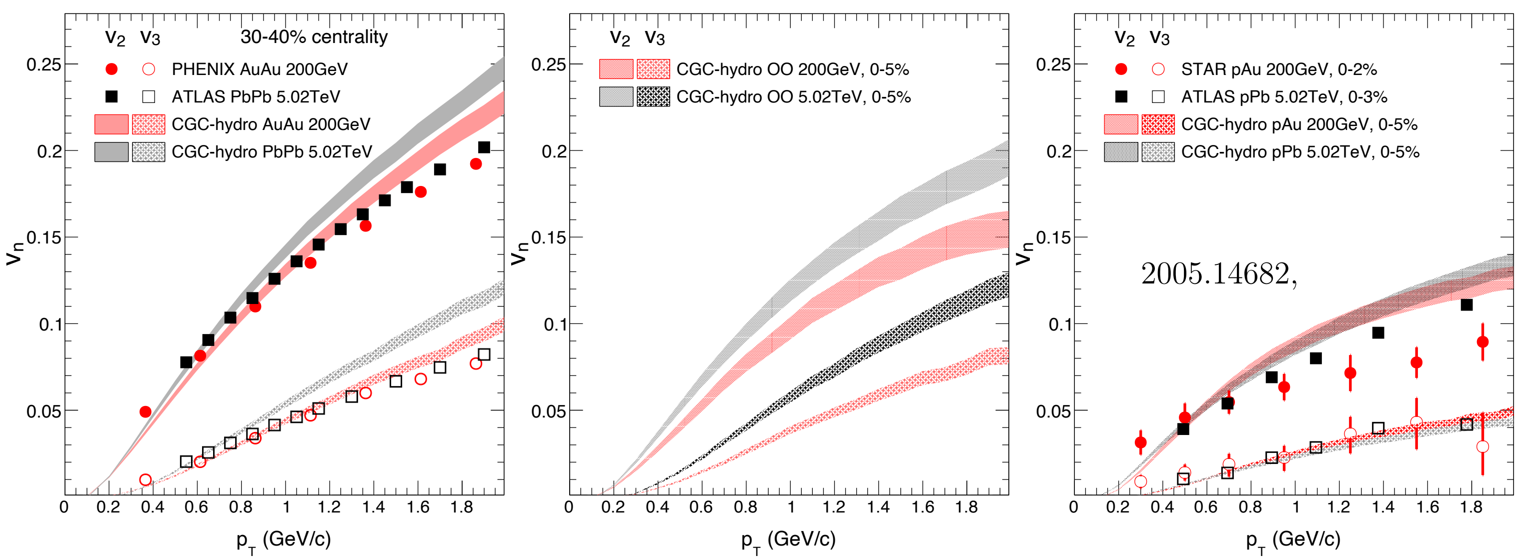
Case for O+O $\sqrt{s_{NN}}$ = 200 GeV

STAR

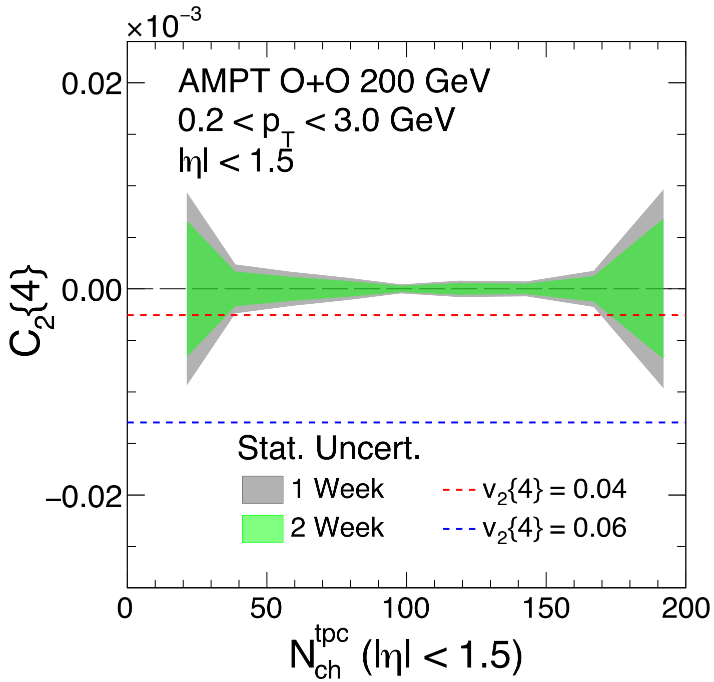


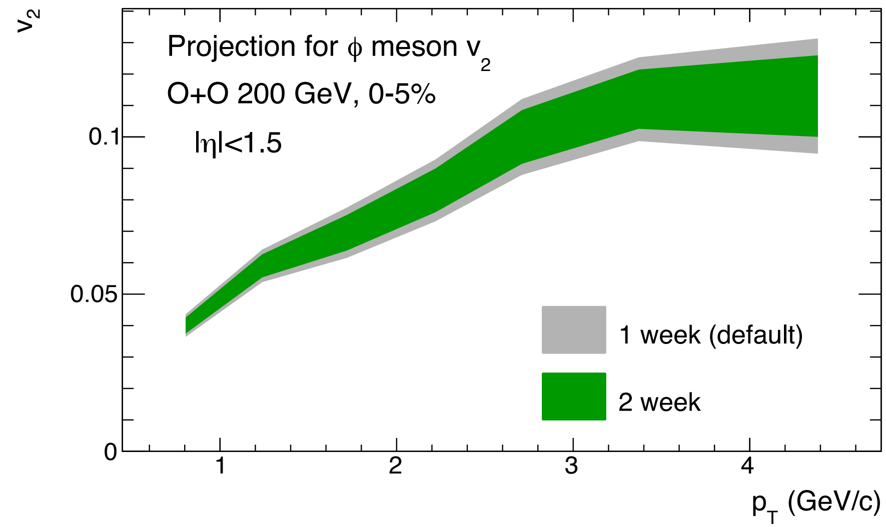
Why O+O:

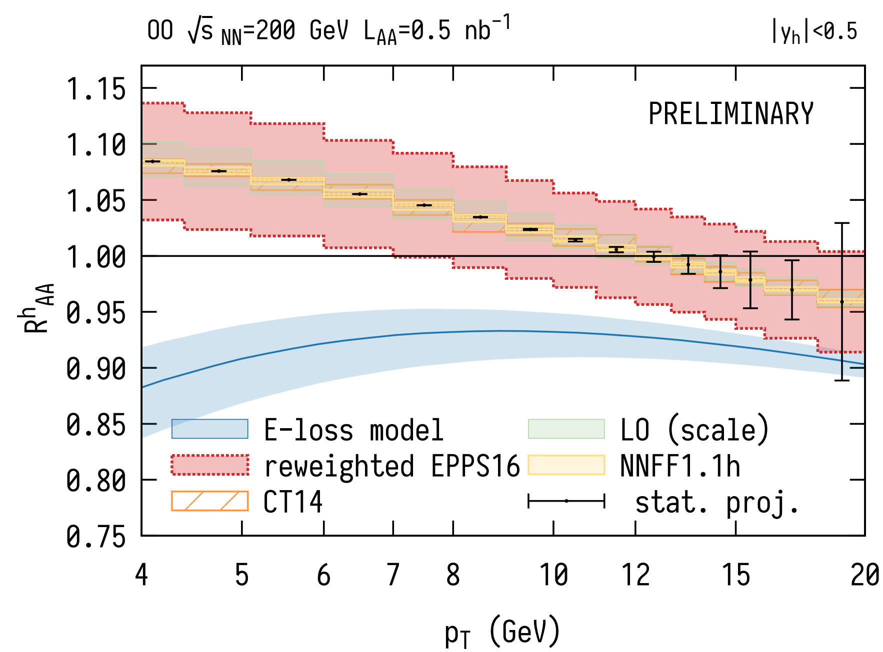
- Prediction of different $\sqrt{s_{NN}}$ dependence for symmetric and asymmetric systems
- Cu+Au, ^{3}He+Au results consistent with dominance of FSM, need system with small N_{part}~60
- Small symmetric system with similar N_{part} to p/d+Au but different nucleon/subnucleon fluctuations
- $v_n\{2k\}$ scales with N_{events} x N_p^k ;much less running than for smaller nuclei



Case for O+O $\sqrt{s_{NN}}$ = 200 GeV







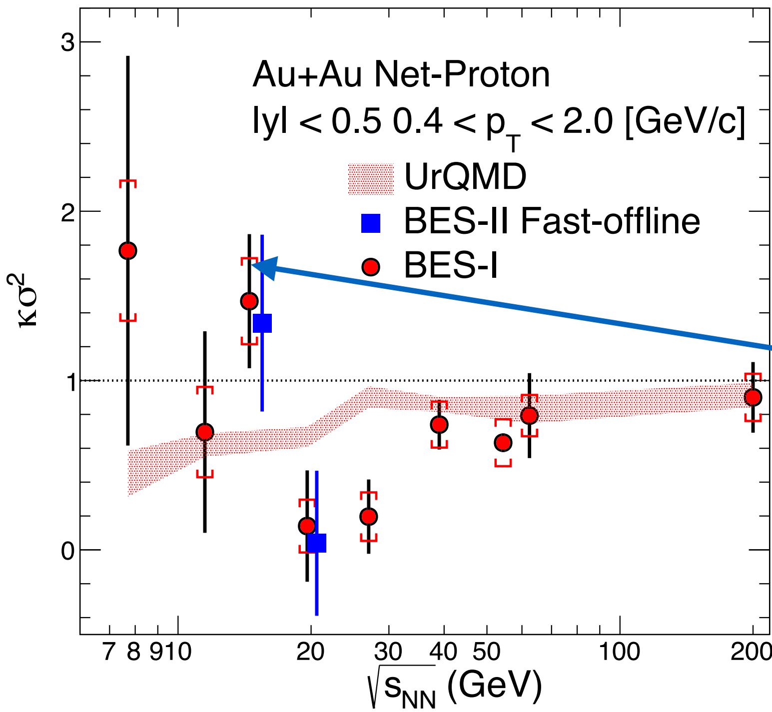
Multi-particle cumulants - event by event fluctuations of collectivity

π, K, p and ϕ flow with good precision - NCQ scaling?

R_{AA} - E_{loss} in small systems?

Propose to collect 400(200) M minbias(central) events
- 1 week of running

Case for Au+Au $\sqrt{s_{NN}}$ = 17.1 GeV



First order phase transition could also cause large increase in net-p kurtosis

Entering spinodal region (mixed phase)

Closer investigation of possible 2nd peak in non-monotonic energy dependence

17.1 GeV —> μ_B = 235 MeV

Equal spacing in μ_B

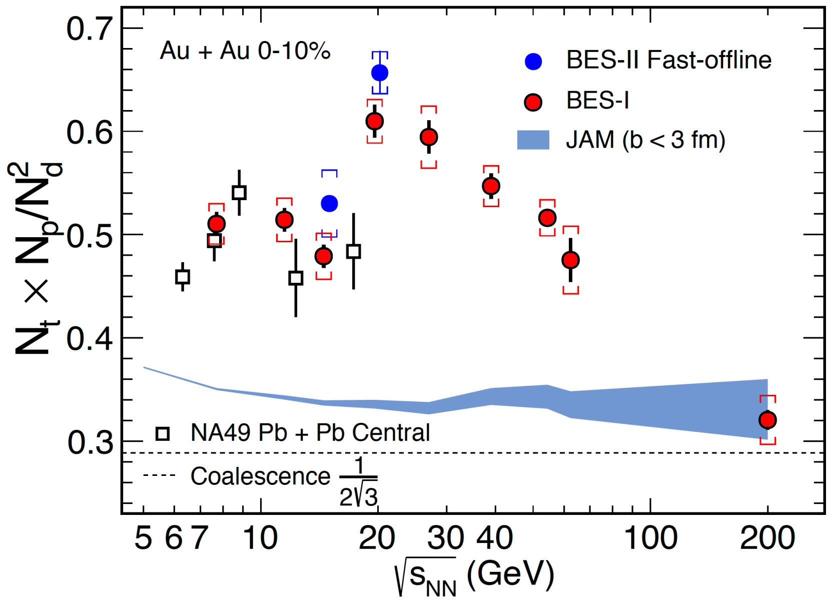
Table 10: Event statistics (in millions) needed in a Au+Au run at $\sqrt{s_{NN}} = 16.7$ GeV for fourth order net-proton fluctuations ($\kappa\sigma^2$) and neutron density fluctuation (Δn) measurements.

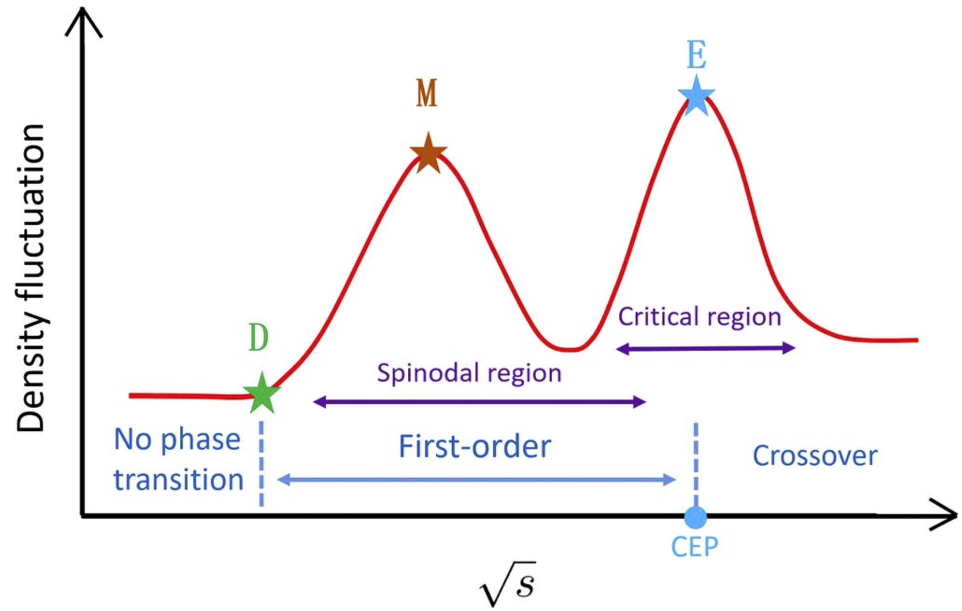
Triggers	Minimum Bias	Net-proton $\kappa\sigma^2$ (0-5% Cent.)	Δn (0-10% Cent.)
Number of events	250 M	6% error level	3.6% error level

Note: BES-II only ~5% of data

Case for Au+Au $\sqrt{s_{NN}}$ = 17.1 GeV

STAR





Ratio of light nuclei yields sensitive to neutron relative density fluctuations
Neutron relative density fluctuations increase near CP and/or 1st order PT

$$\Delta(n) = \langle(\delta n)^2\rangle / \langle n \rangle^2 = \frac{1}{g}\frac{N_t \times N_p}{N_d^2} - 1$$

Sudden drop below 19.6 GeV
- Consistent with NA49

Second peak?

Propose to collect 250 M minbias events
- 2.5 weeks of running

Note: BES-II only ~5% of data

Run-22: Transverse p+p 510 GeV

$\sqrt{s}$ (GeV)	Species	Polarization	Run Time	Sampled Luminosity	Priority
510	p+p	Transverse	16 weeks	400 pb^{-1}	1

Inaugural run with Forward Upgrades - See Elke's talk

Minimum of 16 weeks to collect at least 400 pb^{-1} for rare/non-rescaled triggers

Not to mention first p+p run with BES-II upgrade detectors

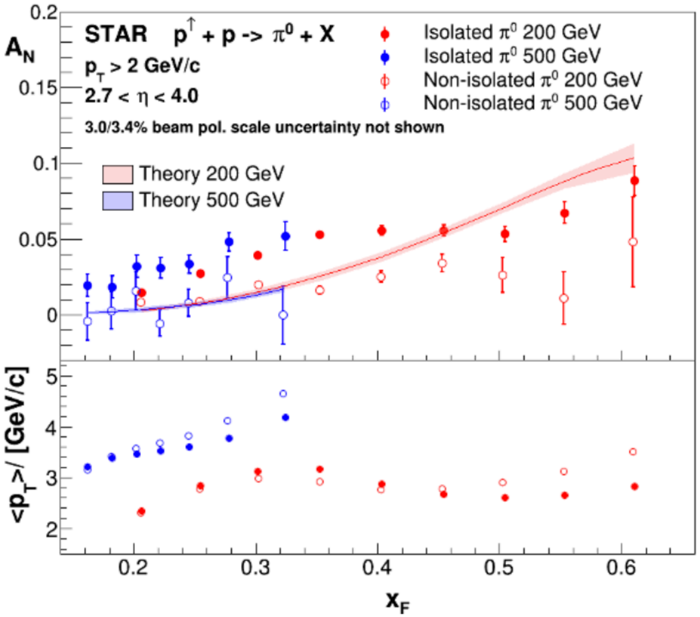
By going to 510 GeV and wide η range (up to η ~ 4.2) probe down to x ~$2x10^{-3}$ (gluons) and up to x~0.5 (valence quarks) regions possible

Transversely polarized beams:

Quark transversity (net transverse polarization of quarks in a transversely polarized proton) in the large x valence region

Current results statistics limited

Forward inclusive spin asymmetries



Transverse single spin asymmetries (TSSA) A_N largely independent of beam energy

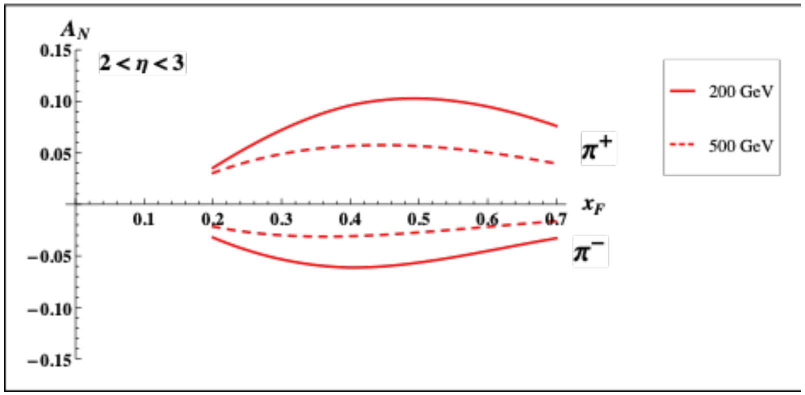
Caused by:

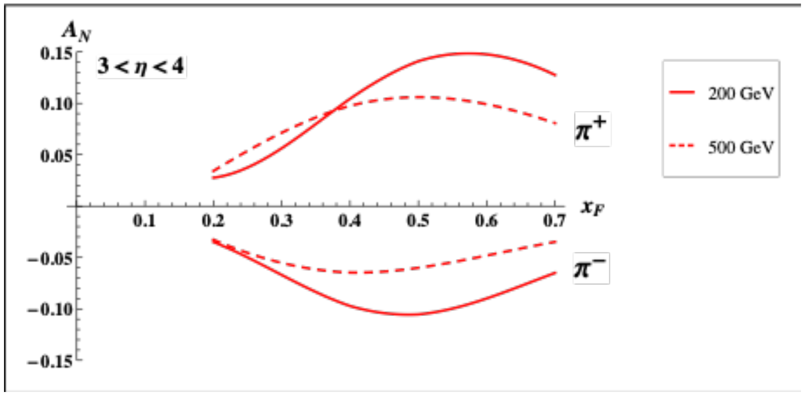
Spin dependent Initial state - Sivers or twist-3 analogue Efremov-Teryaev-Qiu-Sterman (ETQS)

and/or

Fragmentation of polarized quarks in Final state - Collins function or related twist-3 function H_{FU}

Predictions for forward region:

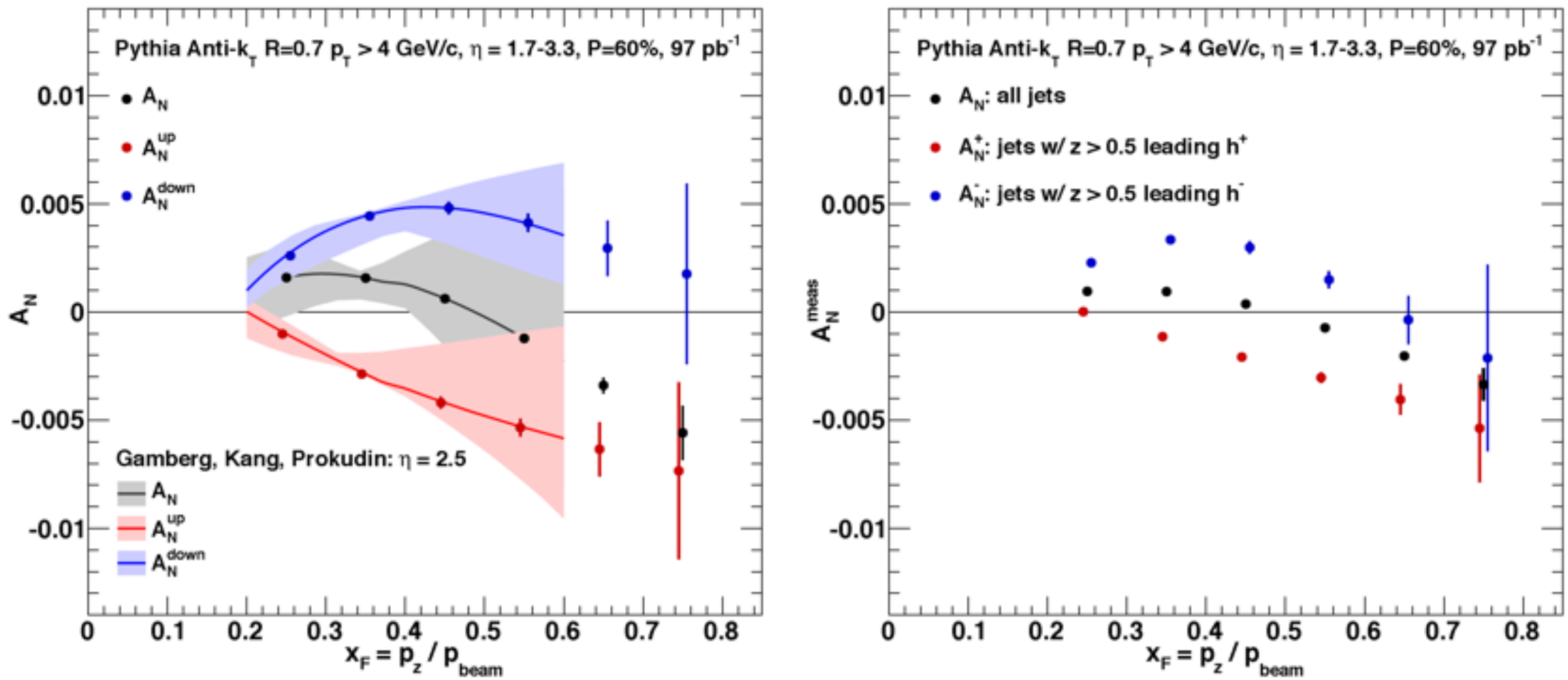




Constrain evolution of ETQS and test if H_{FU} drives the asymmetries

Sivers and ETQS

Forward jets and identification of leading charge sign now possible - tag u vs d vs gluons



Projections are at 200 GeV, 500 GeV will not cover quite the same x range but result in similar statistical precision and separation of jet charge

Projections only for 100 pb^{-1} - high precision measurement

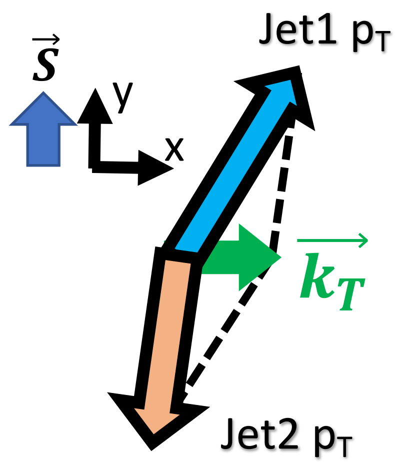
Small inclusive forward Sivers due to cancellation of u and d?

Novel probe of Sivers effect

Sivers: Correlation of initial state parton k_T with transverse spin of proton

$$\langle \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T) \rangle \neq 0$$

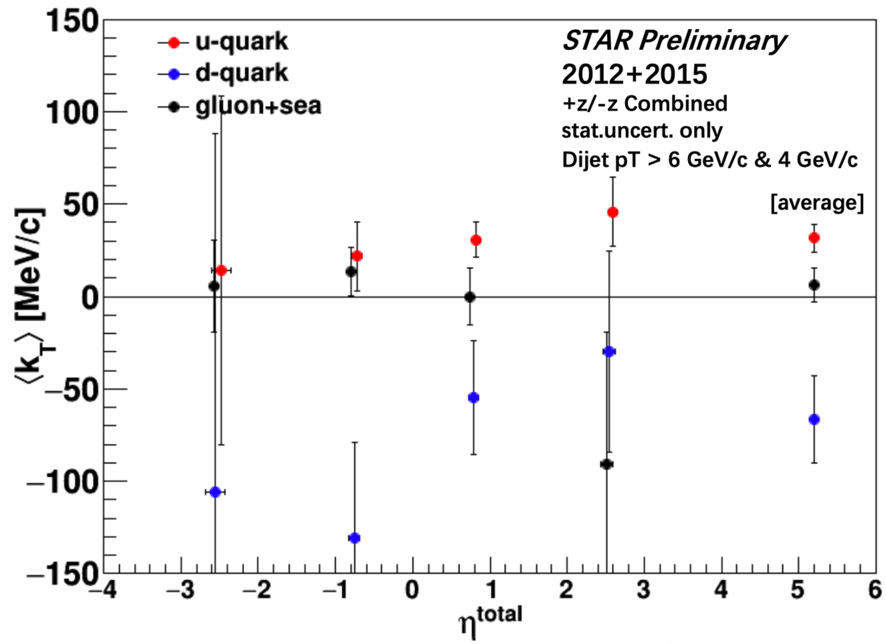
Parton k_T preference leads to spin-dependent tilt of dijet opening angle



510 GeV: Critical determination of x-dependence

200 GeV: Higher precision, extension to higher $|\eta^{total}|$

First measurements of non-zero dijet Sivers asymmetry



Jet charge tagging:

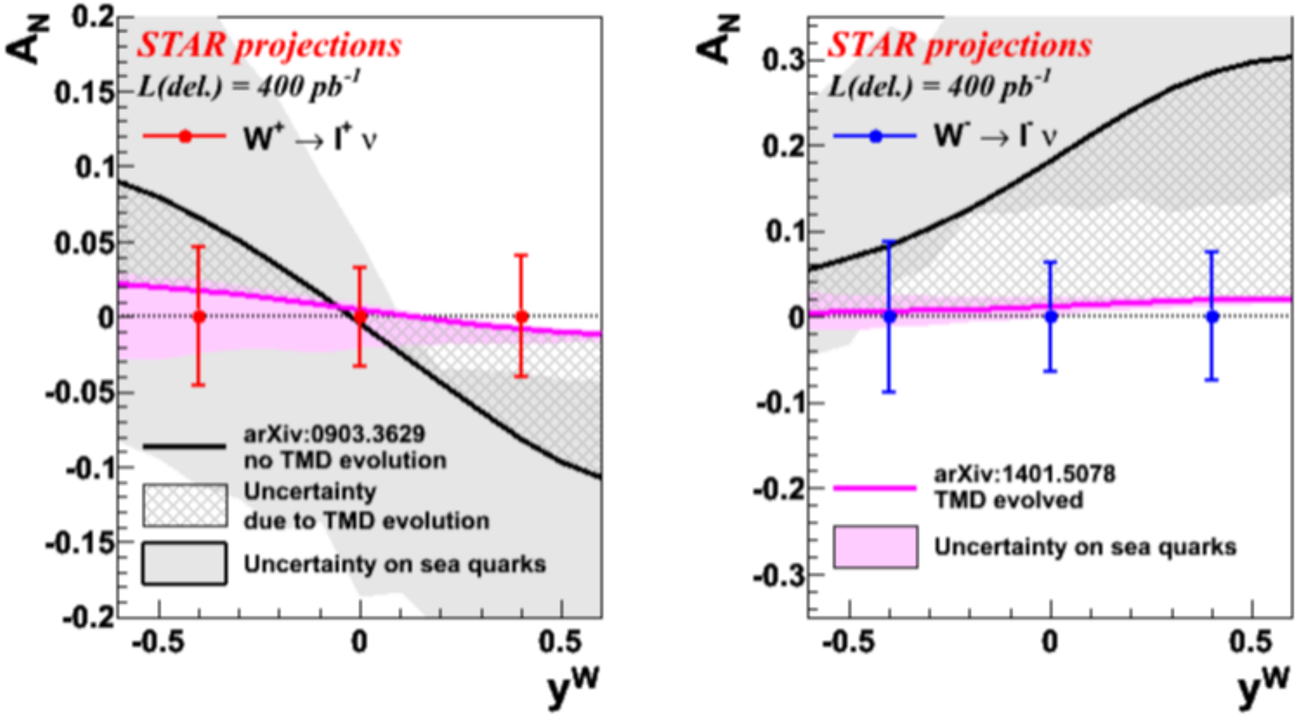
$\langle k_T^u \rangle \sim 32$ MeV/c

$\langle k_T^d \rangle \sim -67$ MeV/c

$\langle k_T^{g+sea} \rangle \sim 0$ MeV/c

Evolution and sign change of Sivers

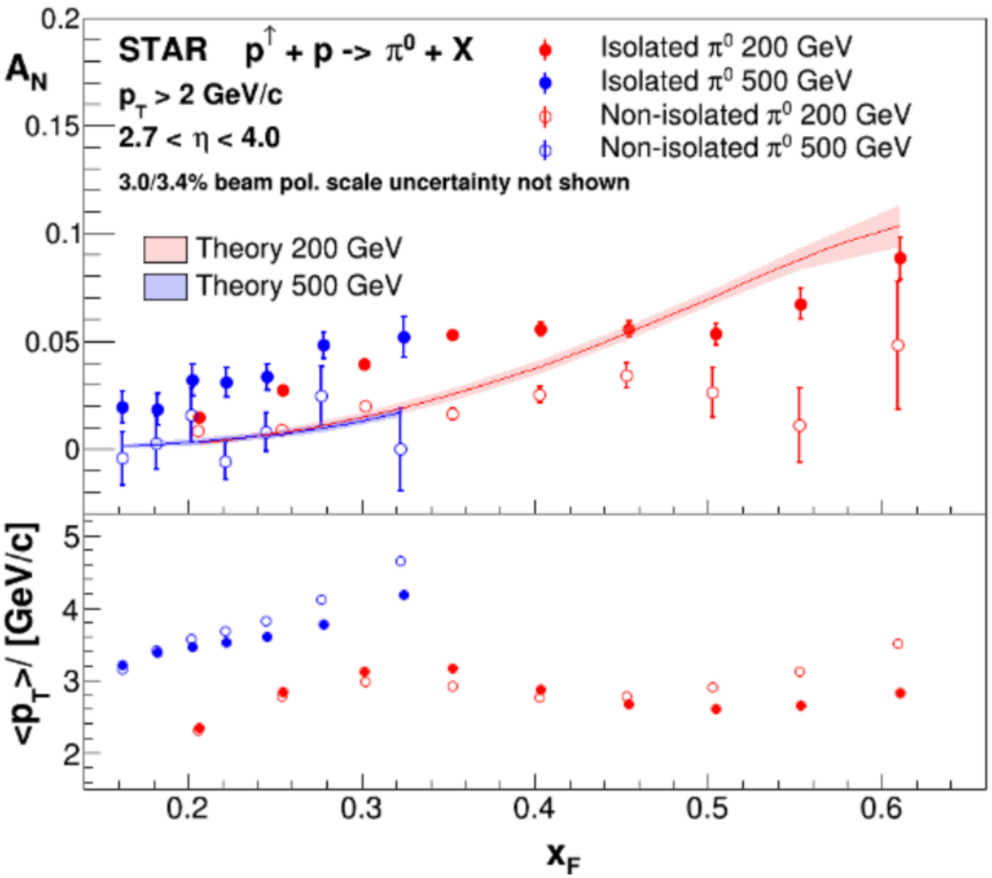
Weakly interacting W and Z - probe initial state and predicted sign change



Run-22: Factor 2 more statistics and extend measurements to larger y

Predictions suggest larger signals with increasing y - region currently unconstrained

Diffractive studies



A_N different for isolated and non-isolated π^0

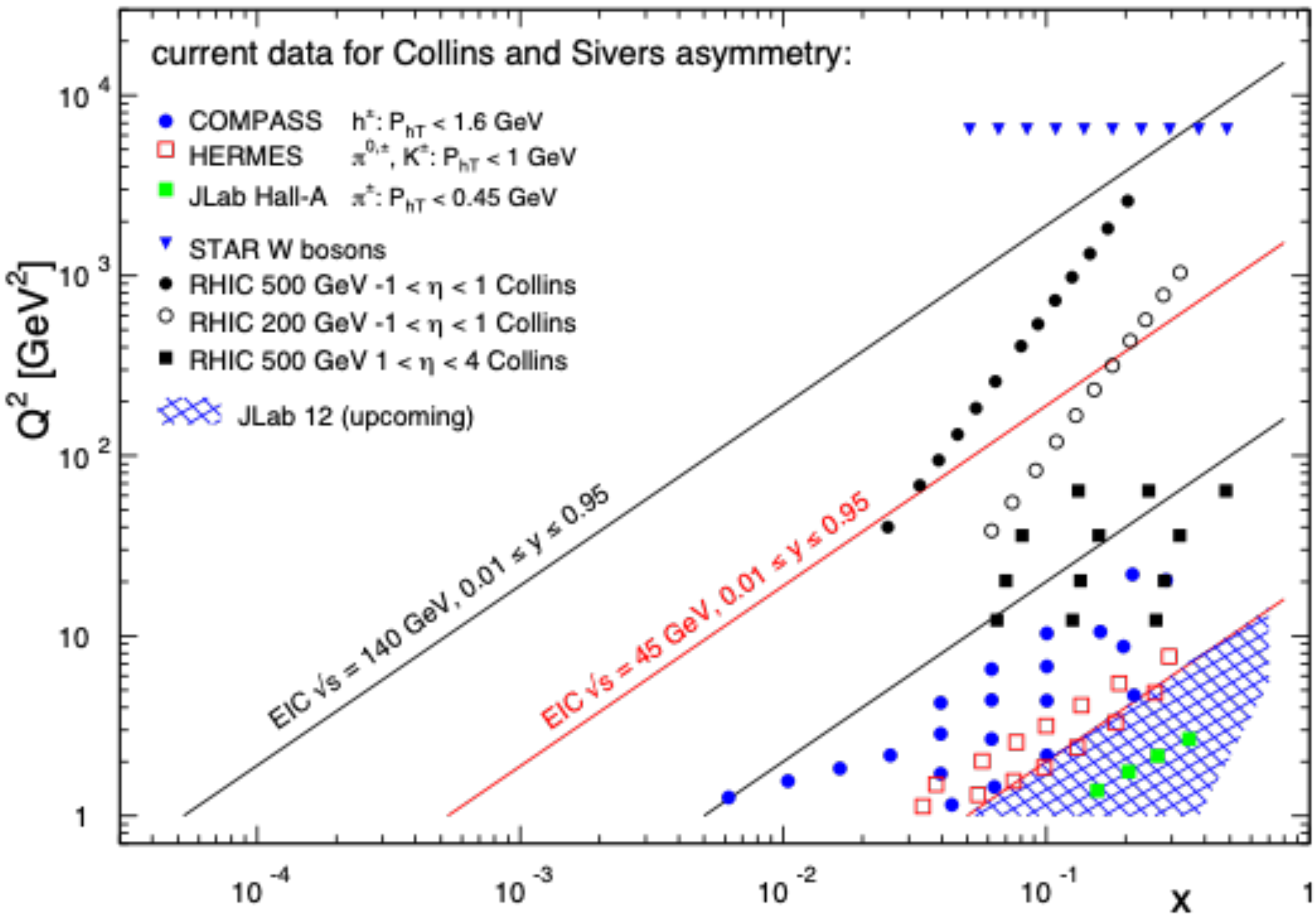
Model with initial and final state effect can only explain the non-isolated π^0 A_N

Origin of isolated pion?

Diffractive events tagged via proton in RP with/without rapidity gaps

Is observed large forward asymmetry due to diffractive events?
- new physics insights

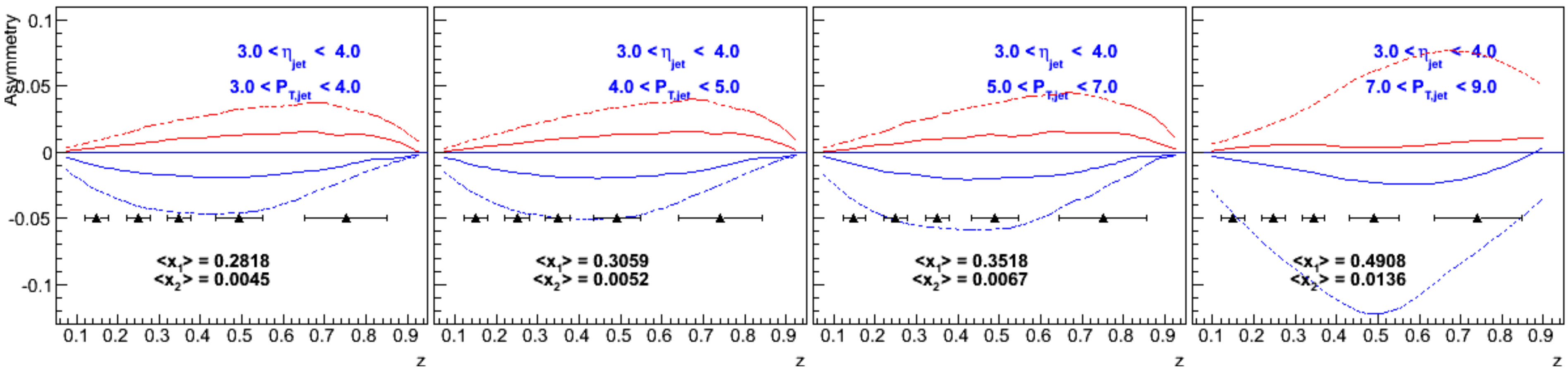
x-Q² coverage of STAR



Midrapidity + forward + $\sqrt{s}$ = 510 GeV + $\sqrt{s}$ = 200 GeV —> 0.005<x<0.5, overlap with EIC kinematics

Transversity, Collins, Interference FF

Collins asymmetry for hadrons in the forward region



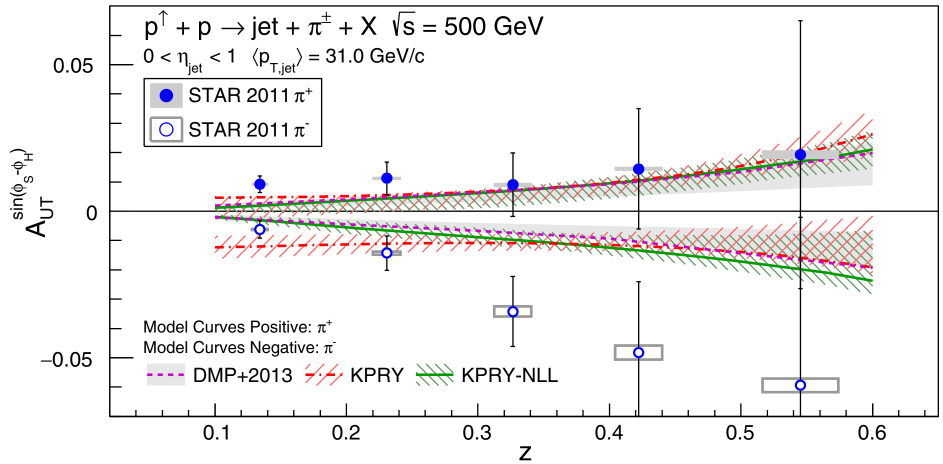
Key insight into tensor charge, 70% of contribution from x>0.1

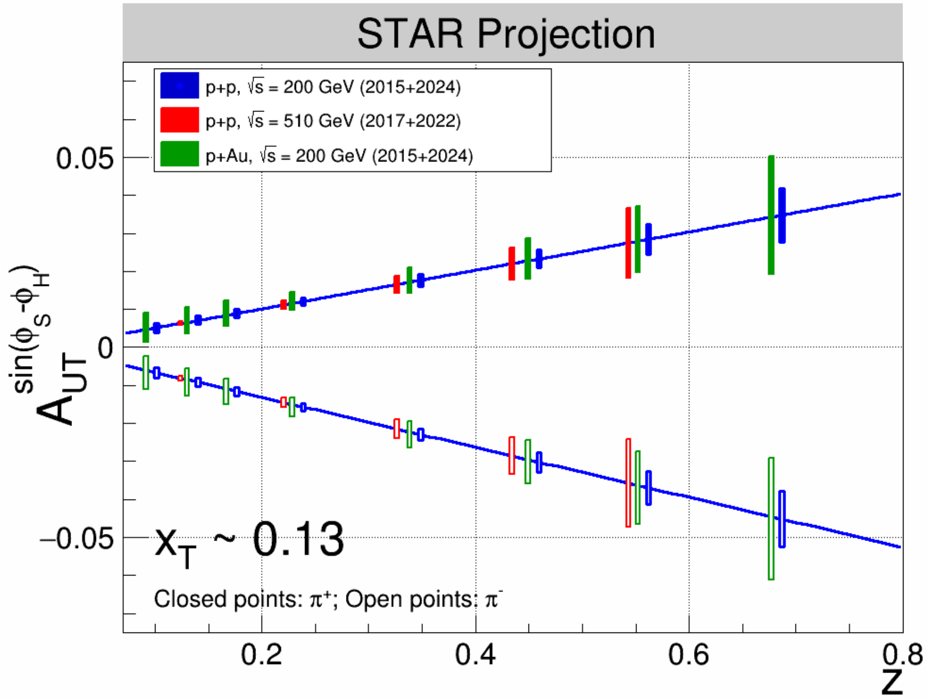
0.3 < x< 0.5 not probed before by SIDIS

Also perform high precision "Collins-like" asymmetry measurement to access the distribution of linearly polarized gluon down to x~0.005.

Collins at mid-rapidity

First observation of Collins effect in pp





Greatly enhanced statistics
Improved PID from iTPC

Precise multi-differential (p_T, η, z, j_T, Q^2) mid-rapidity Collins asymmetry measurements

IFFs serve as complementary transversity tool

Probe transversity and TMD factorization, universality, and evolution

Summary

Excellent performance from RHIC
BES-II upgrades performing at or above expectations
New Cold QCD program enabled by forward upgrades

STAR's highest priority requests
Run-21: completion of BES-II
Run-22: p+p 500 GeV

Run-21:

Assuming 7.7 GeV running goes well opportunistically take:

Au+Au at 3, 9.2, 11.5, 13.7 (FXT) - higher moments and baryon stopping
Au+Au at 17.1 GeV - location of CP
O+O at 200 GeV - initial conditions of small systems

Last chance to answer these critical HI questions

Run-22:

"Must-do" pp forward physics prior to the EIC

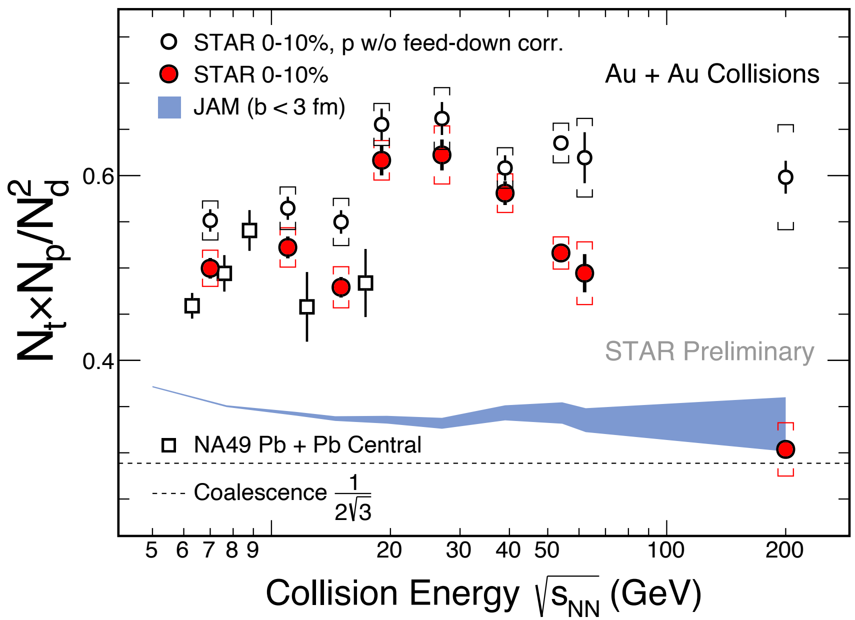
BACK UP

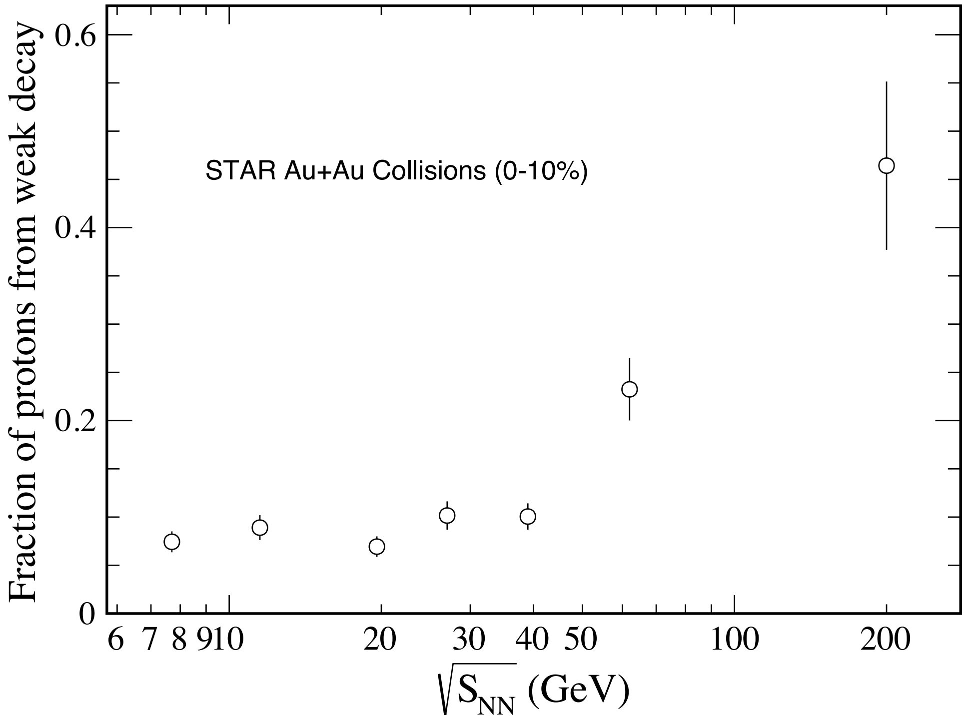
Event statistics requirements: FXT

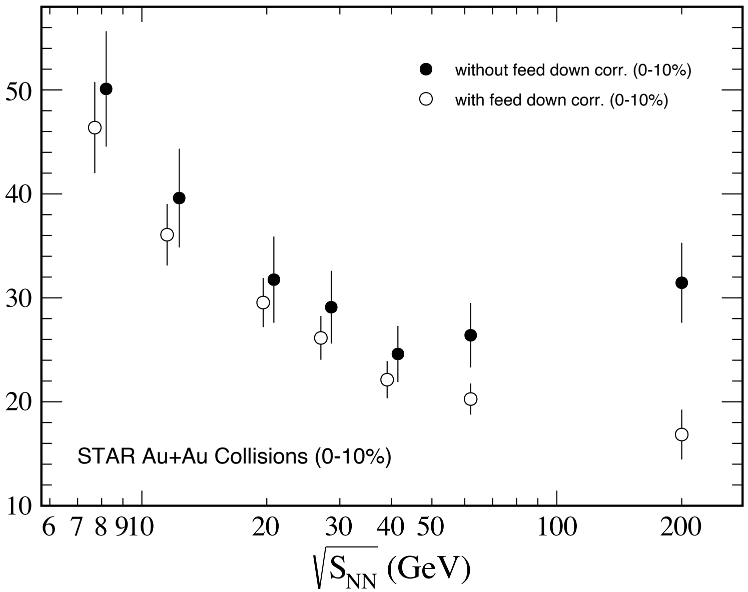
STAR

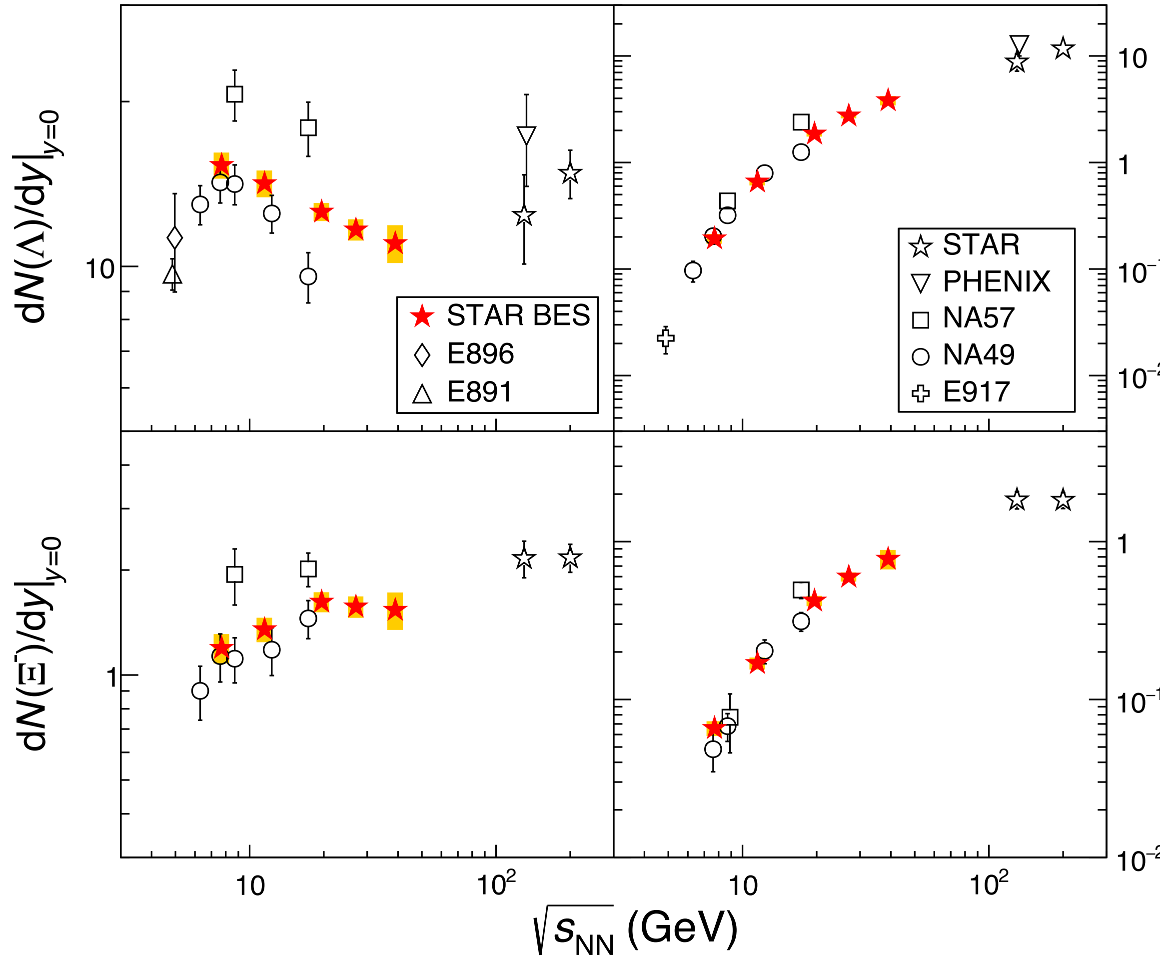
Table 8: Event statistics (in millions) needed in the fixed-target part of the BES-II program for various observables.

$\sqrt{s_{NN}}$ (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


STAR 0-10%, p w/o feed-down corr.
STAR 0-10%
JAM (b < 3 fm)
Au + Au Collisions
STAR Preliminary
NA49 Pb + Pb Central
Coalescence $\frac{1}{2\sqrt{3}}$
$N_t \times N_p / N_d^2$
0.6
0.4
5 6 7 8 9 20 30 40 50 100 200
Collision Energy $\sqrt{s_{NN}}$ (GeV)


STAR Au+Au Collisions (0-10%)
Fraction of protons from weak decay
0.6
0.4
0.2
0
6 7 8 910 20 30 40 50 100 200
$\sqrt{S_{NN}}$ (GeV)


without feed down corr. (0-10%)
with feed down corr. (0-10%)
STAR Au+Au Collisions (0-10%)
10
20
30
40
50
6 7 8 910 20 30 40 50 100 200
$\sqrt{S_{NN}}$ (GeV)


$dN(\Lambda)/dy|_{y=0}$
$dN(\Xi^-)/dy|_{y=0}$
STAR BES
E896
E891
STAR
PHENIX
NA57
NA49
E917
10
1
10^{-1}
10^{2}
$\sqrt{s_{NN}}$ (GeV)