Insights from the STAR Fixed-Target Program

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For the STAR Collaboration

QCD Phase Diagram

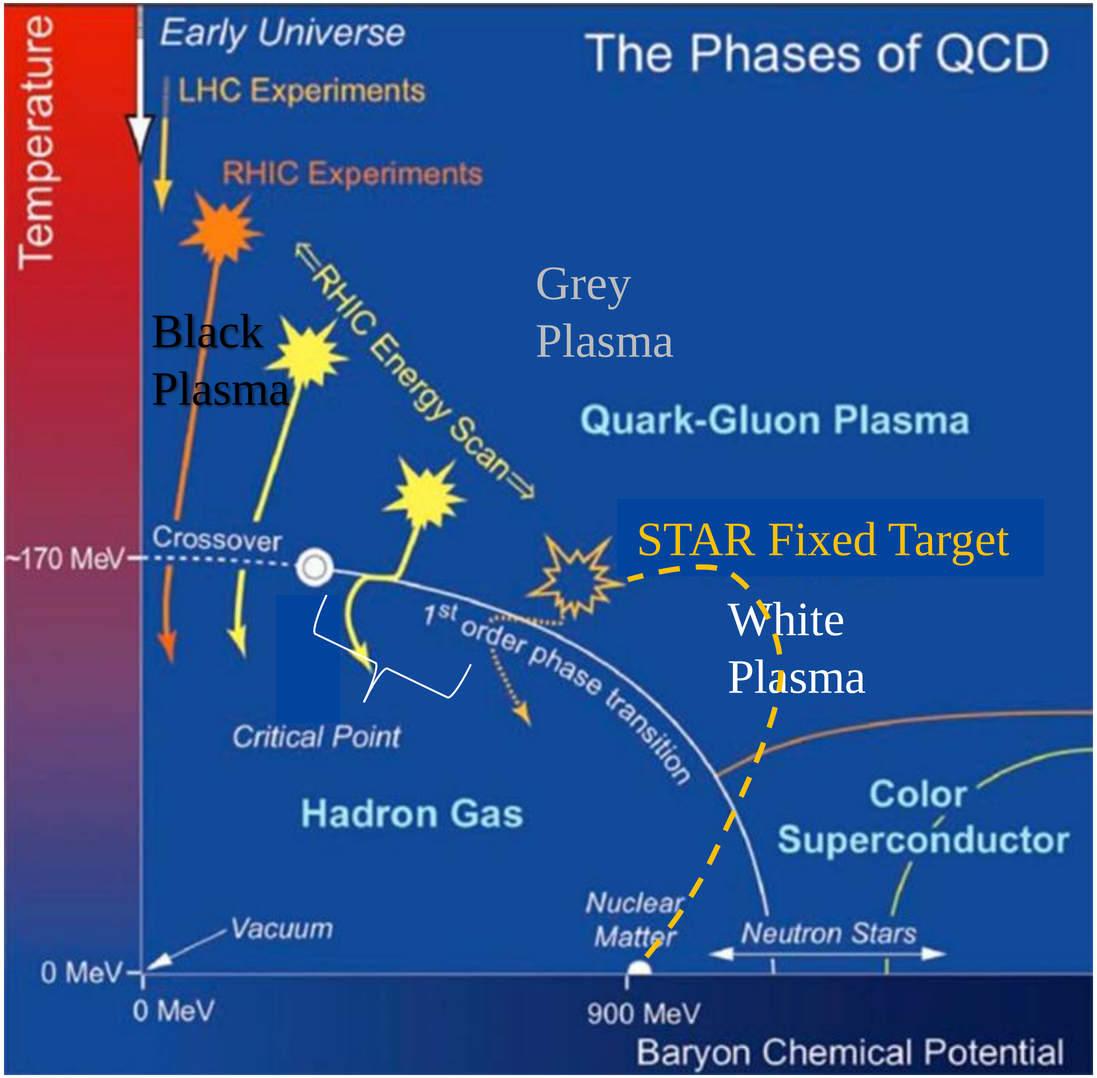
All QCD matter is colorless

Low μ_B, equal numbers of quarks and anti-quarks ➔ QGP cools to pion gas

➔ *Black Plasma* (equal color and anti-color)

High μ_B, more quarks than anti-quarks ➔ QGP cools to baryon-rich gas

➔ *White Plasma* (equal numbers of red, green, and blue quarks)



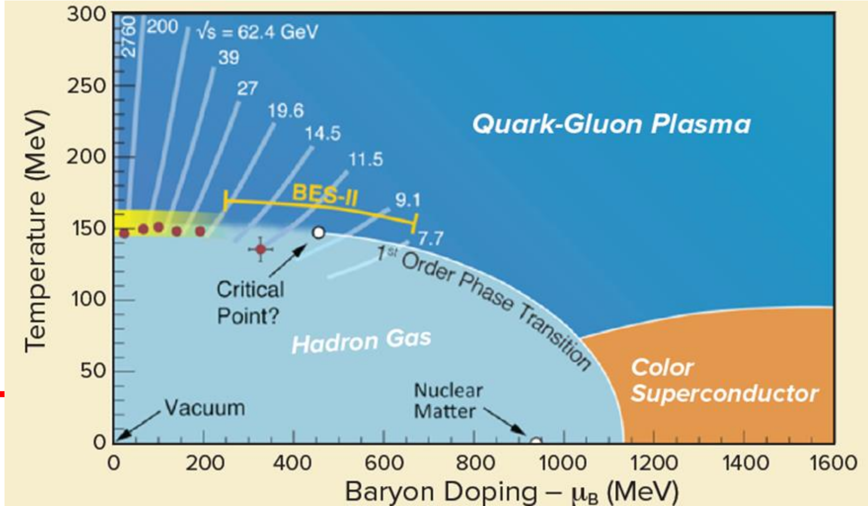
BES Phase I – What Did We Learn

• Signatures consistent with a parton dominated regime either disappear, lose significance, or lose sufficient reach at the low energy region of the scan.

•There are indicators pointing towards a softening of the equation of state which can be interpreted as evidence for a first order phase transition.

• The higher moment fluctuation is sensitive to critical phenomena, but these analyses place stringent demands on the statistics.

• Dilepton mass spectra show a broadening consistent with models including hadron gas and quark-gluon plasma components

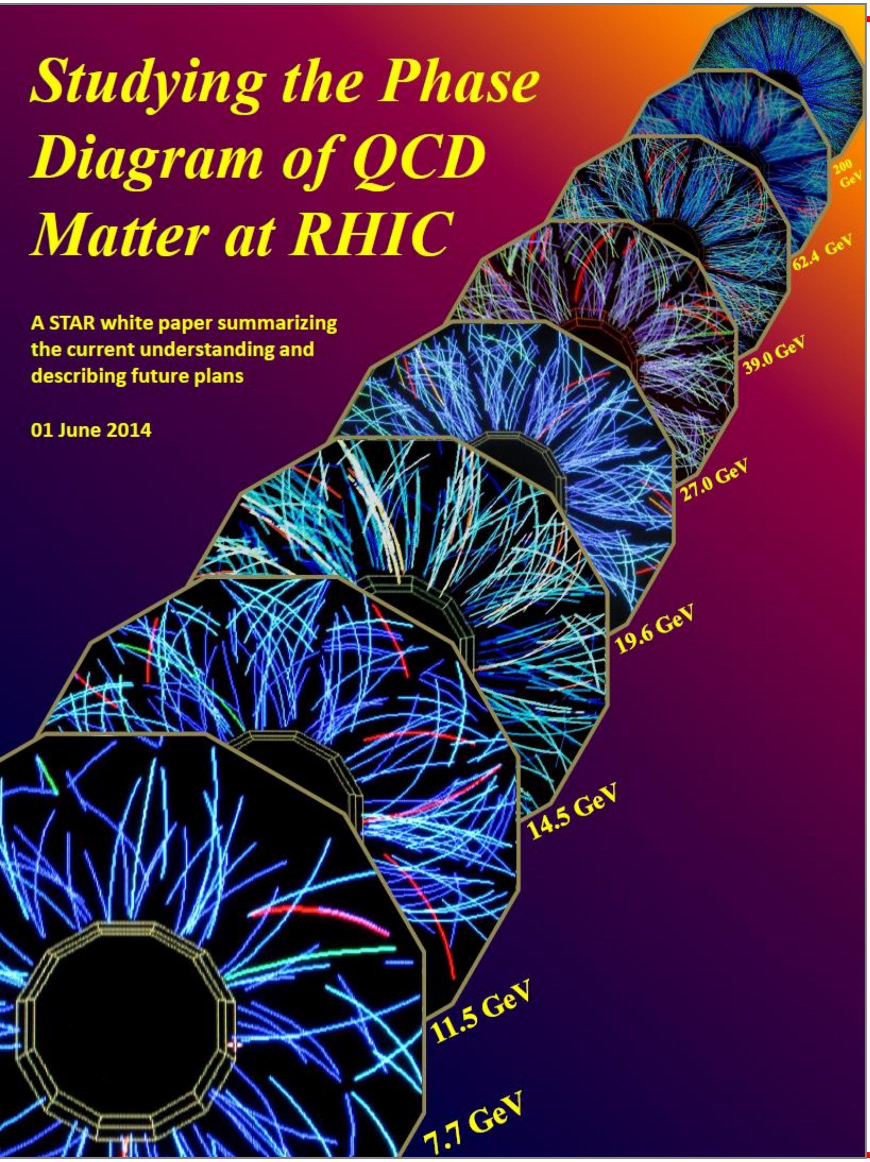


Continuous P.T. above 19.6 GeV

Critical Point below 19.6 GeV

1st Order P.T. below BES range

➔ Listed as one of the highest priority goals in 2015 NSAC Report



Beam Energy Scan II (2018-2021)

Select the most important energy range
➔ 3 to 30 GeV (**➔ Add fixed-target program**)

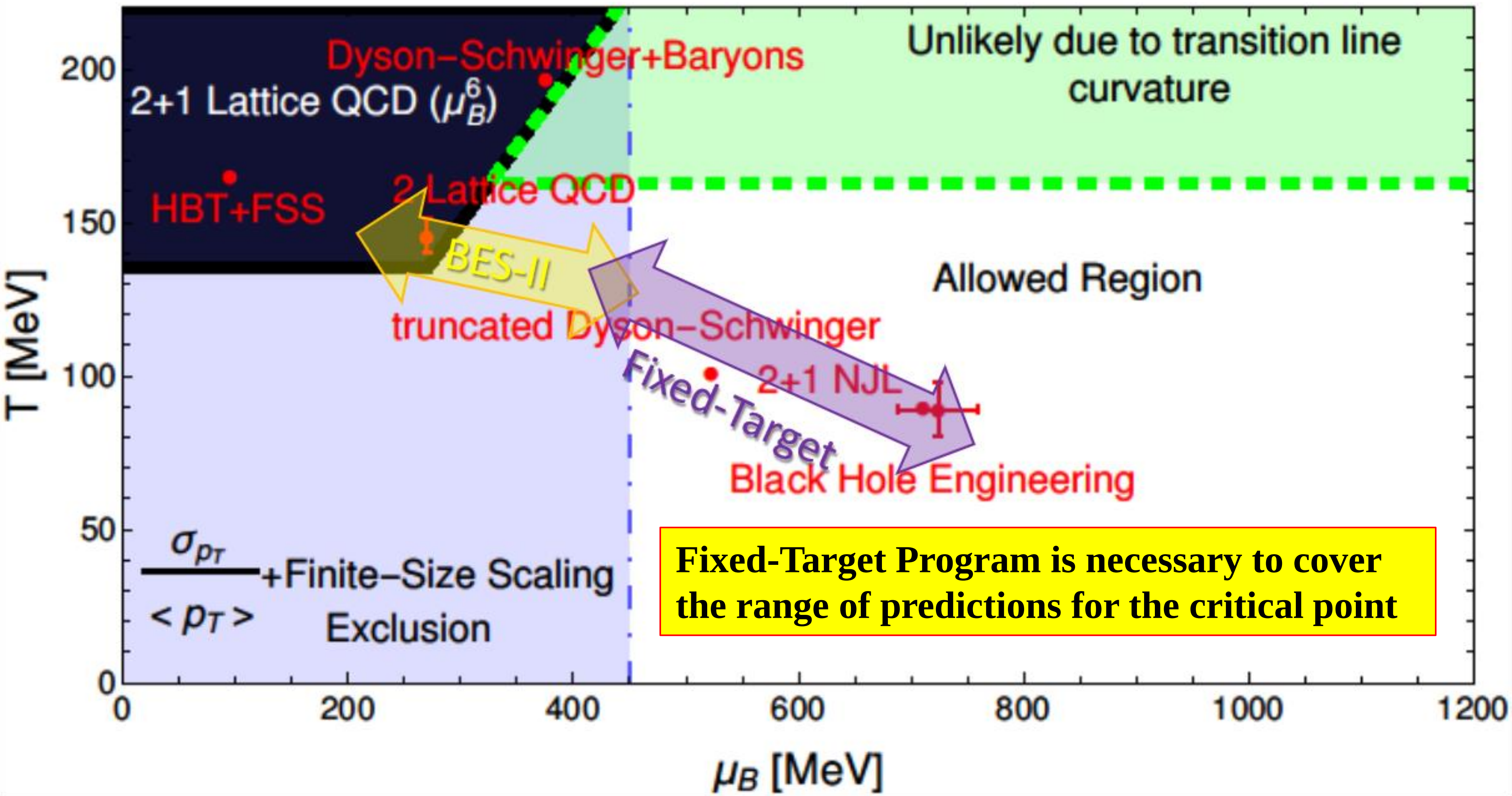
Improve significance
➔Long runs, higher luminosity (**➔ electron cooling**)

Refine the signals
➔ Detector improvements (**➔ iTPC, eTOF, EPD**)

➔ Project listed as a top US NP priority in LRP 2015

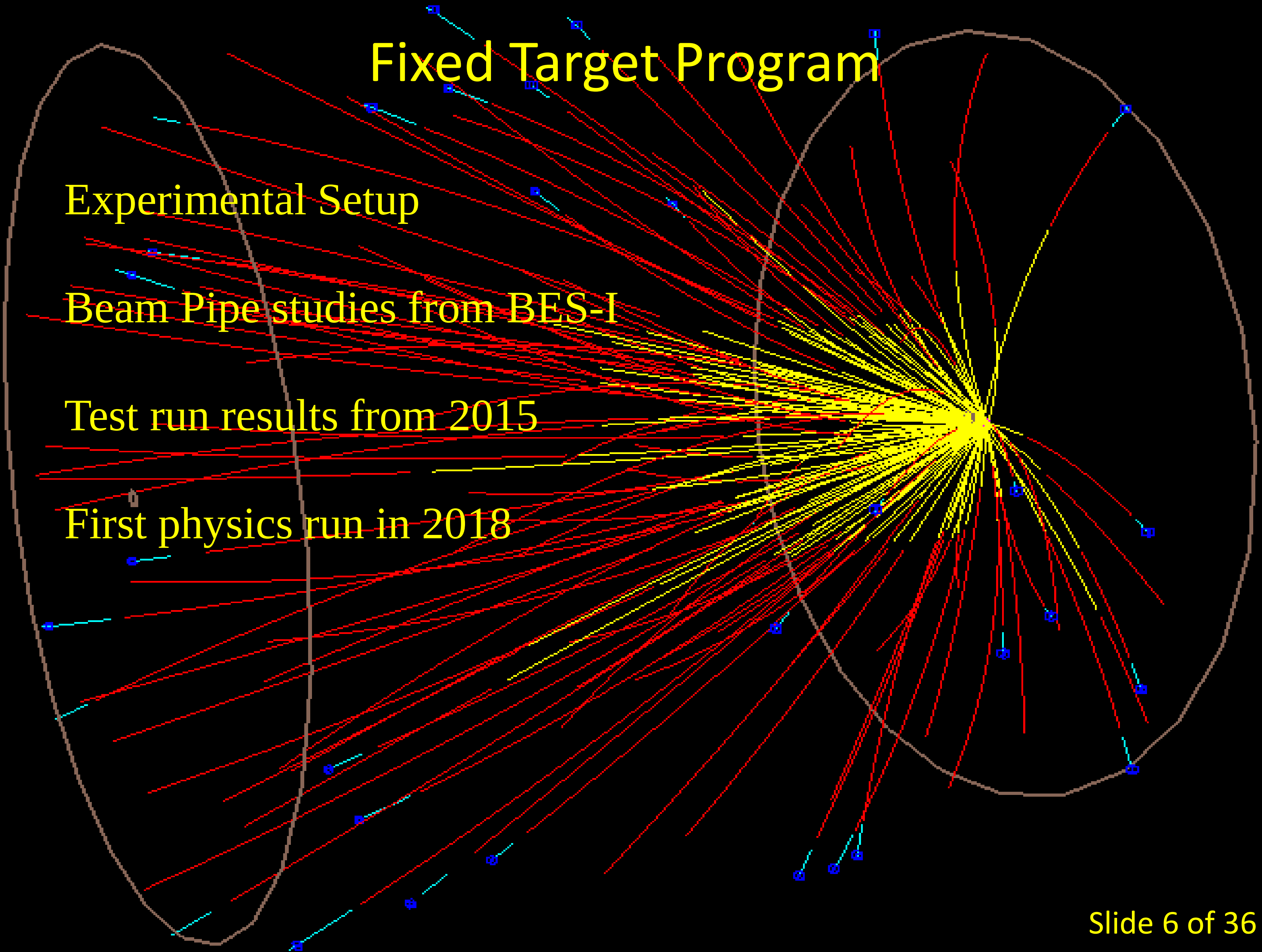
Example: Where do we Expect a Critical Point?

There are quite a range of theory predictions



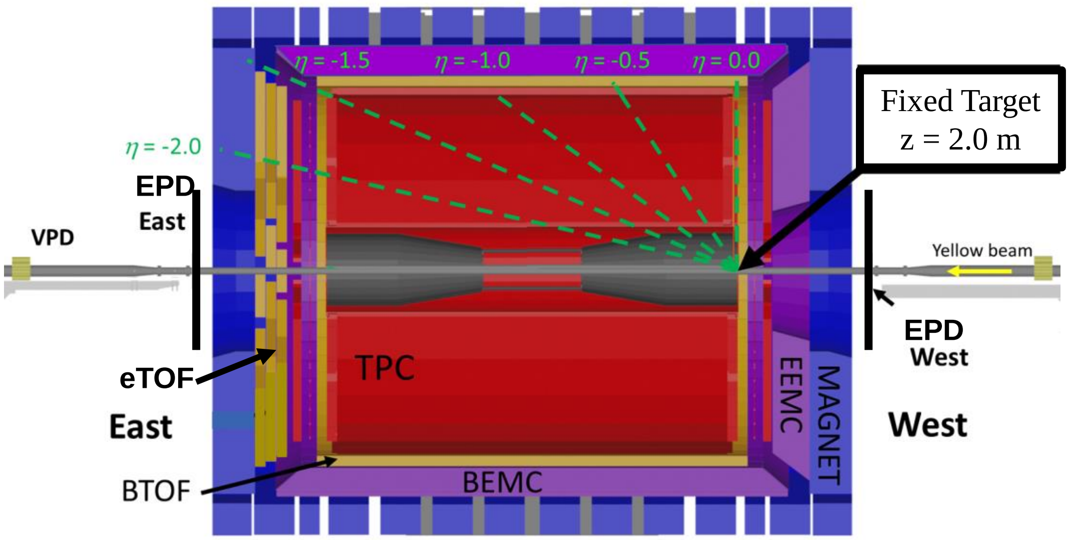
Fixed-Target Program is necessary to cover the range of predictions for the critical point

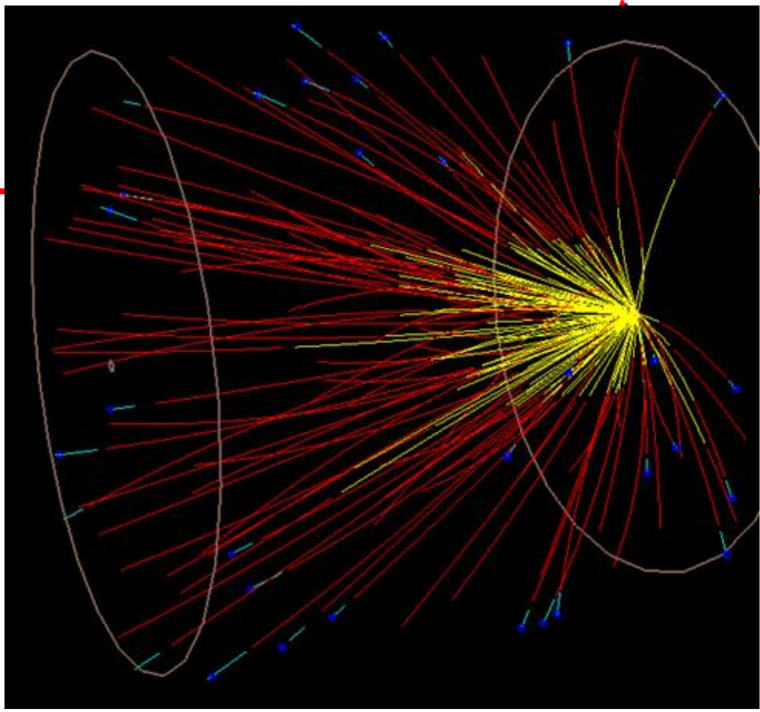
Fixed Target Program



- Experimental Setup
- Beam Pipe studies from BES-I
- Test run results from 2015
- First physics run in 2018

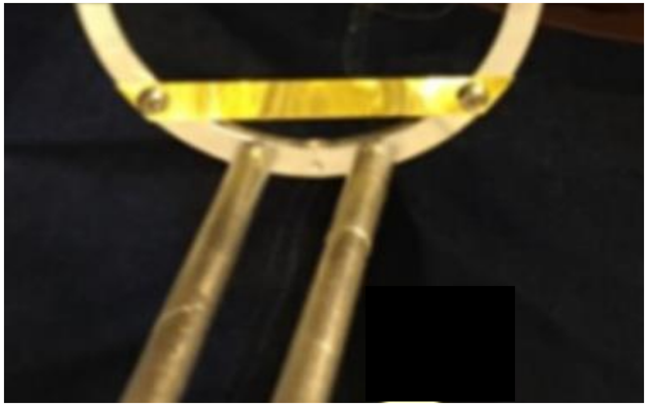
Fixed-Target Program Exp. Setup

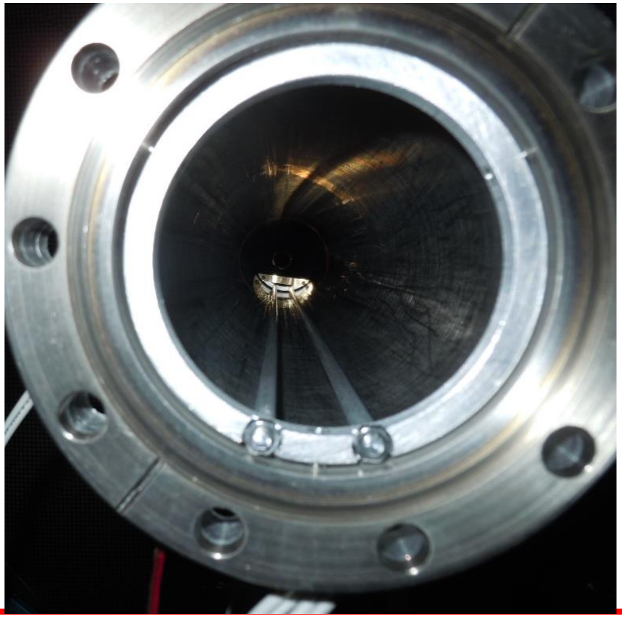




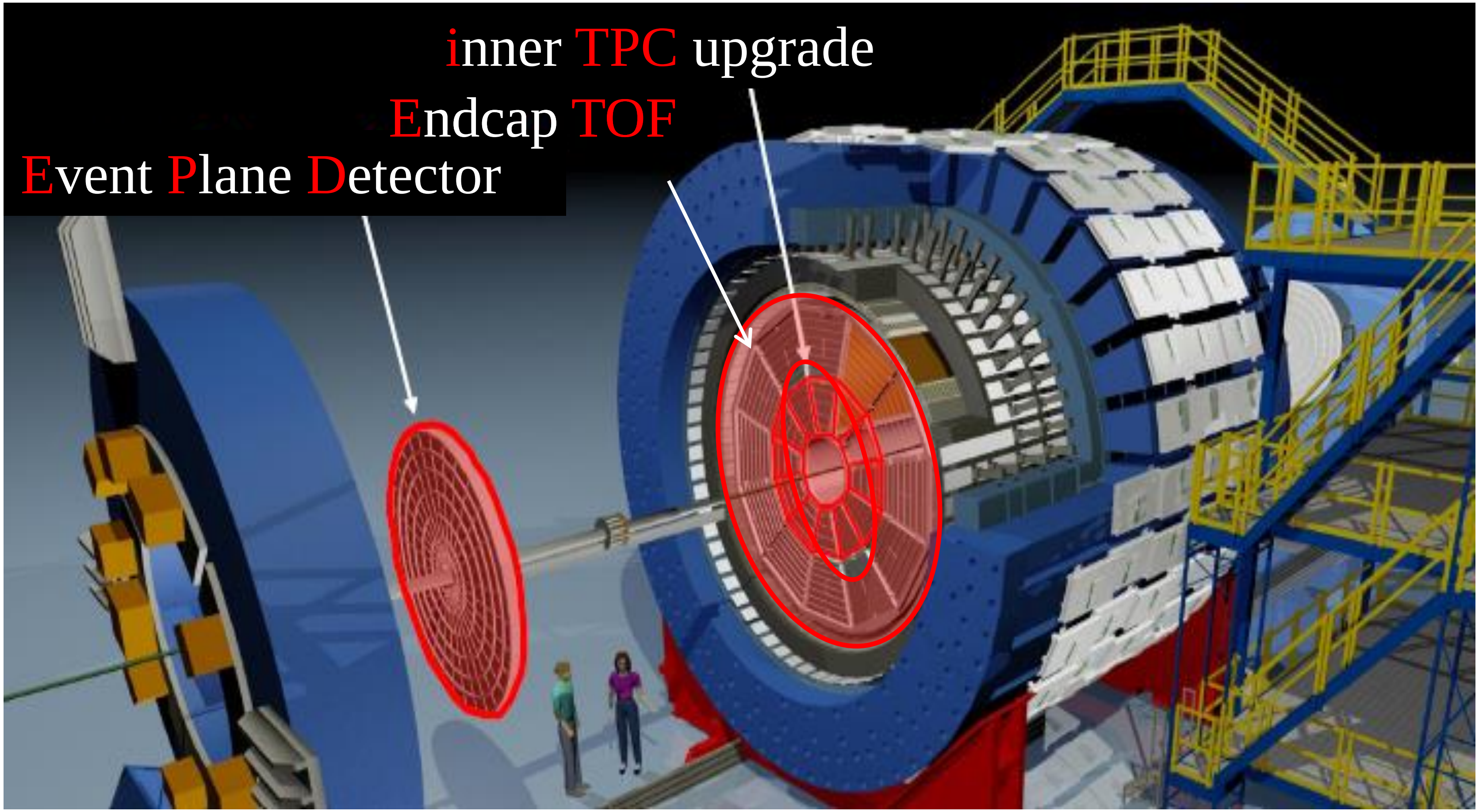
Gold Target:

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





The Upgrades are Important for the FXT Program



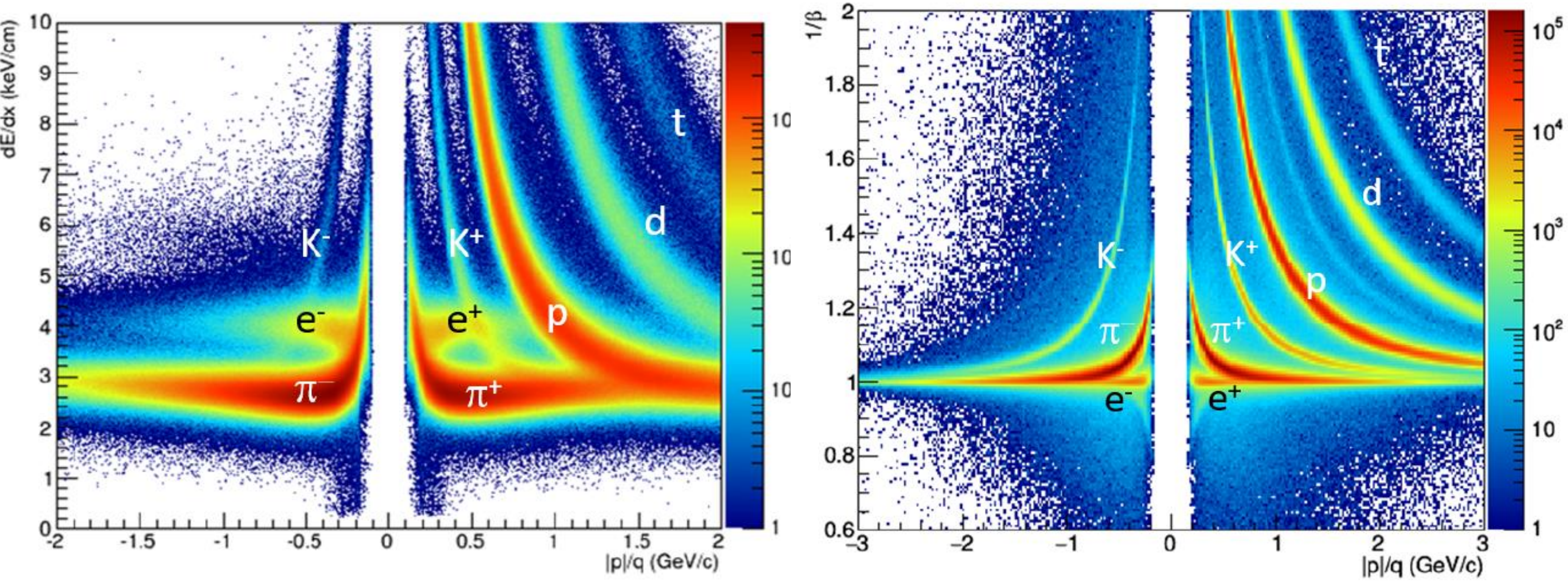
Detects Particles in the $0 < \eta < 2$ range

π, K, p, d, t, h, α through dE/dx and TOF

K^0_s, Λ, Ξ, Ω, ϕ, ${}^3_\Lambda H$, ${}^4_\Lambda H$ through invariant mass

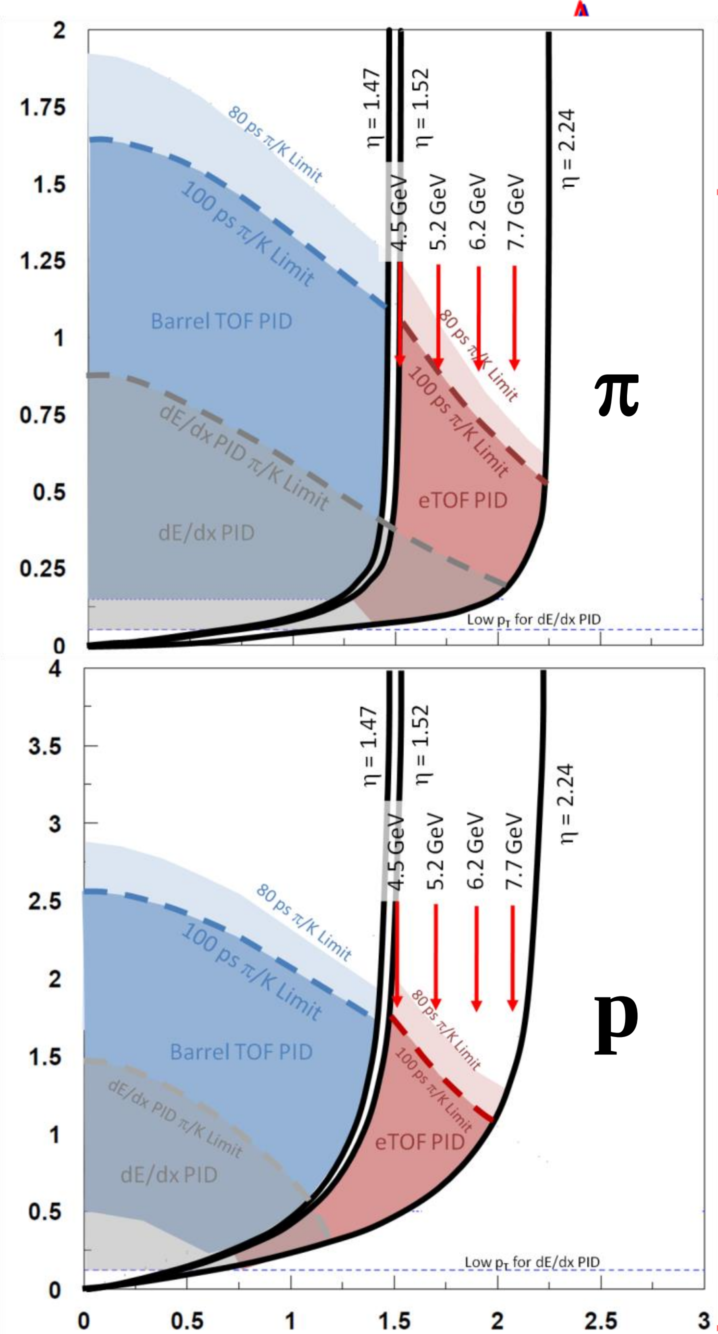
Particle Identification

Because the tracks are longer, on average, for FXT events than for collider events, the resolutions for both dE/dx and 1/β are better in FXT mode than collider mode.



Acceptance for the FXT Program

FXT Energy $\sqrt{s_{NN}}$	Single Beam E_T (GeV)	Single beam E_k (AGeV)	Center-of-mass Rapidity	Chemical Potential μ_B (MeV)	Year of Data Taking
3.0	3.85	2.9	1.05	721	2018
3.2	4.59	3.6	1.13	699	2019
3.5	5.75	4.8	1.25	666	2020
3.9	7.3	6.3	1.37	633	2020
4.5	9.8	8.9	1.52	589	2020
5.2	13.5	12.6	1.68	541	2020
6.2	19.5	18.6	1.87	487	2020
7.2	26.5	25.6	2.02	443	2018
7.7	31.2	30.3	2.10	420	2020
9.1	44.5	43.6	2.28	372	2021
11.5	70	69.1	2.51	316	2021
13.7	100	99.1	2.69	276	2021



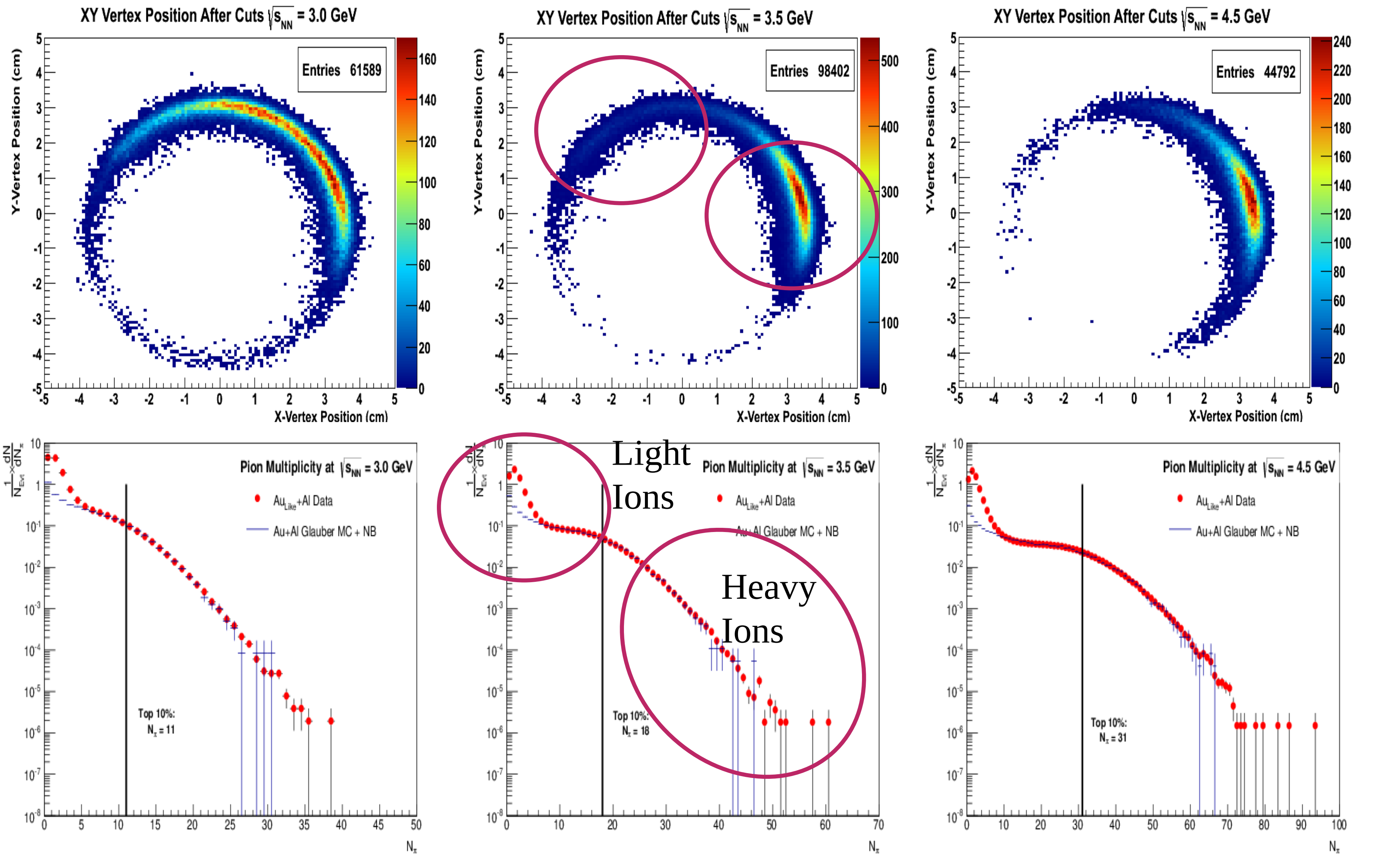
Studies using Beam Halo Background

2010 - 2014

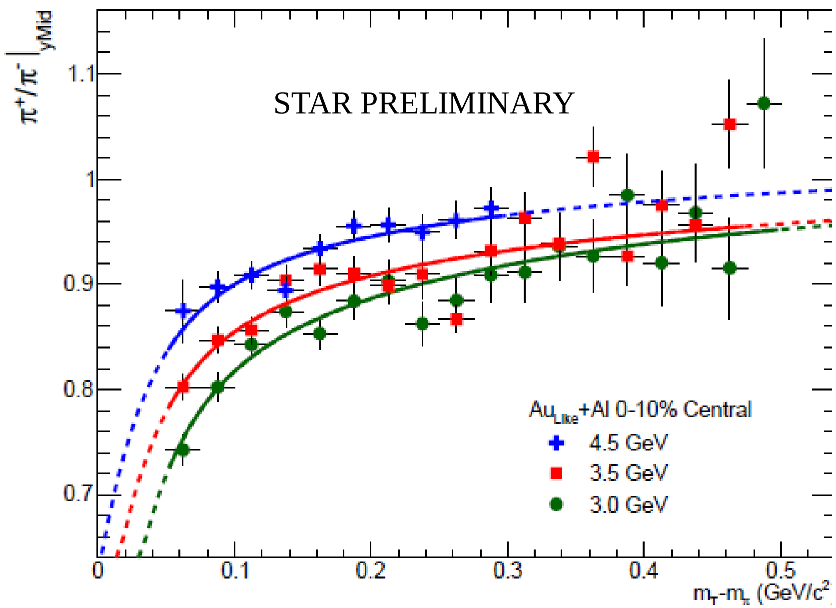
Goals:

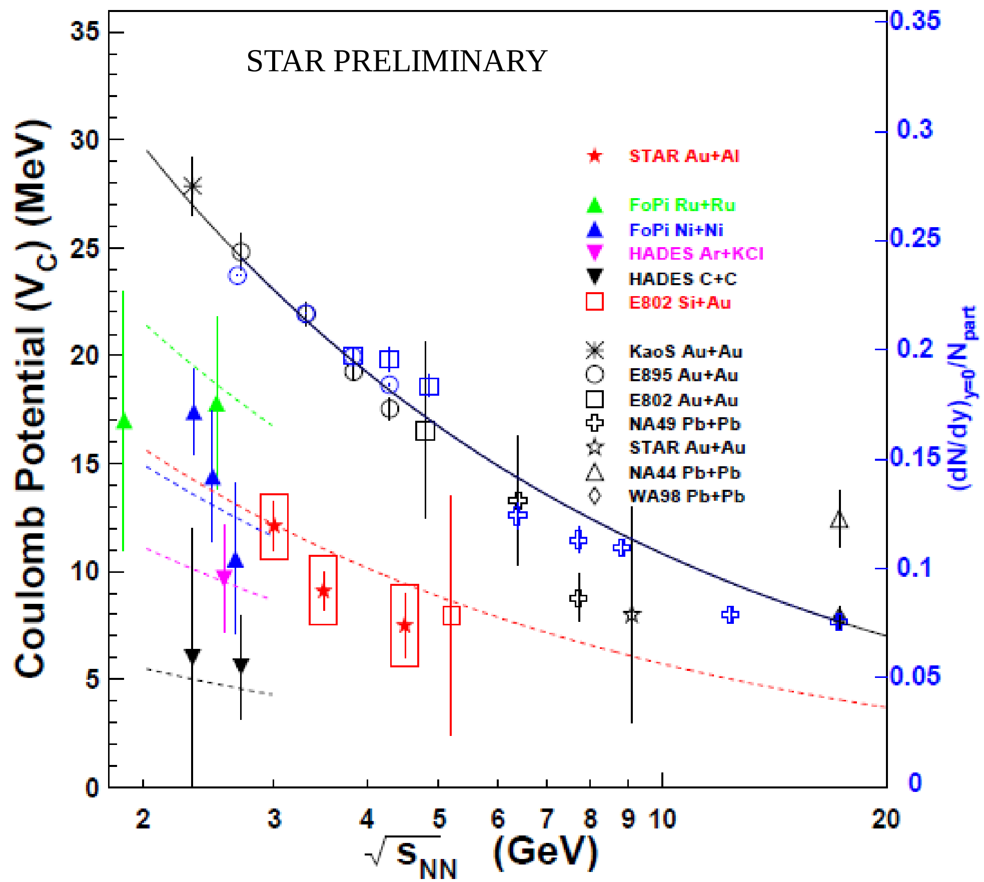
- Understand the Beam Halo Background
- Determine the applicability of STAR for fixed-target
- First of FXT results ➔ Au+Al

Beam Halo on Al Vacuum Pipe



Pion Ratio Analysis





We conclude that there are gold nuclei in the beam halo ➔ Au + Al at $\sqrt{s_{NN}}$ = 3.0, 3.5, and 4.5 GeV

➔ Provided the motivation to install a gold target

Direct Beam Test Runs 2015

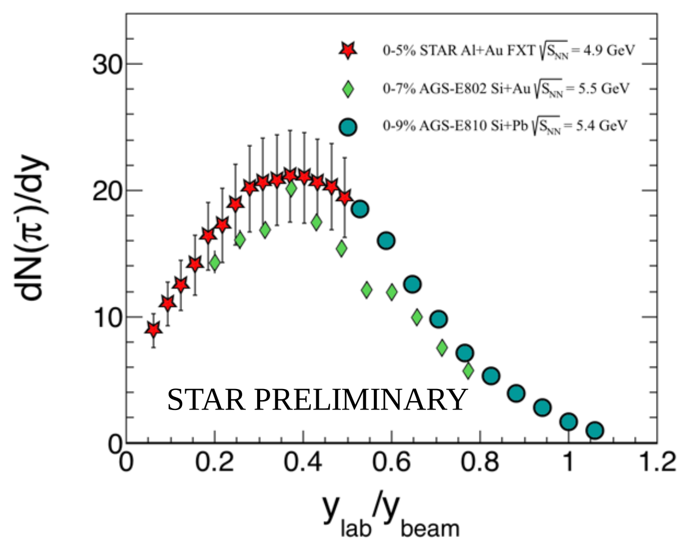
Goals:

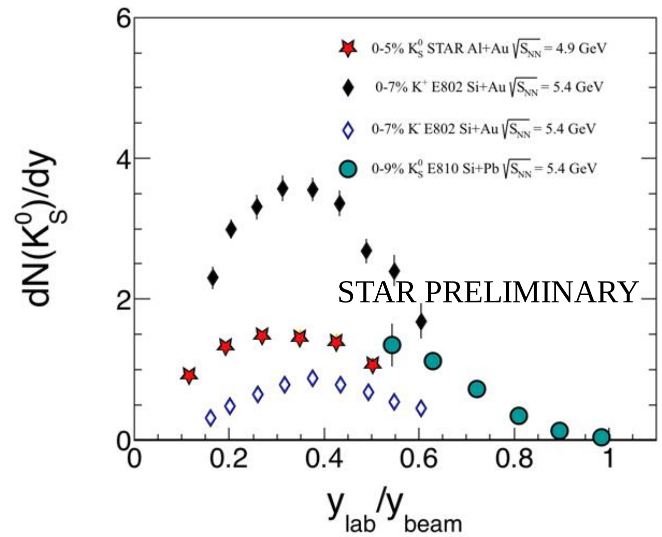
- Check the conclusion that there are gold ions in the halo
- Determine if the direct beam is a better conduct of operations
- Acquire enough data for significant feasibility studies
- Physics analyses ➔ Reproduction of AGS results

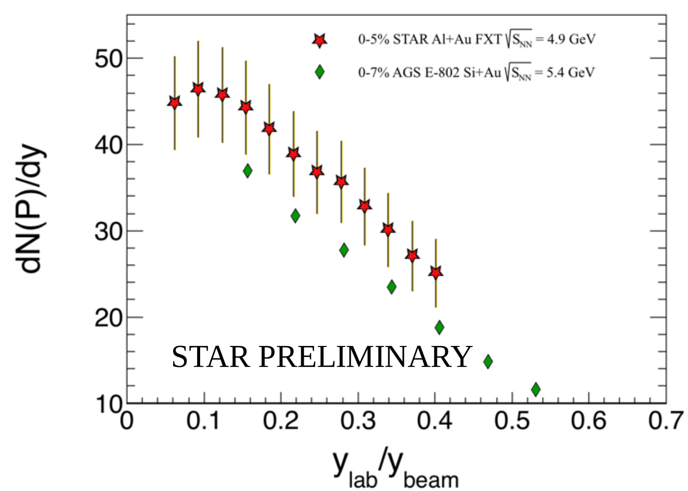
Two test runs, one using gold beam the other using aluminum beam :
➔ 4 PhD Theses (Kathryn Meehan, Yang Wu, Usman Ashraf, Todd Kinghorn)
➔ 1 MS Thesis (Lukasz Kozyra)
➔ 1 Postdoctoral project (David Tlusty)

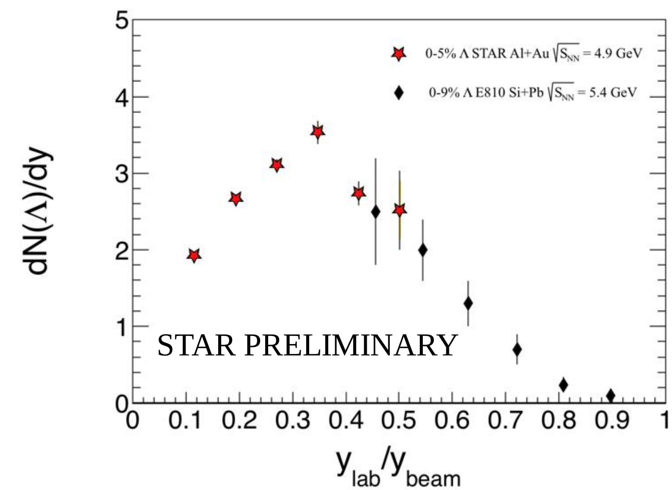
FXT Results: $\sqrt{s_{NN}}$ = 4.9 GeV Al+Au

- Compare to AGS Si+Au results
- Yields are consistent

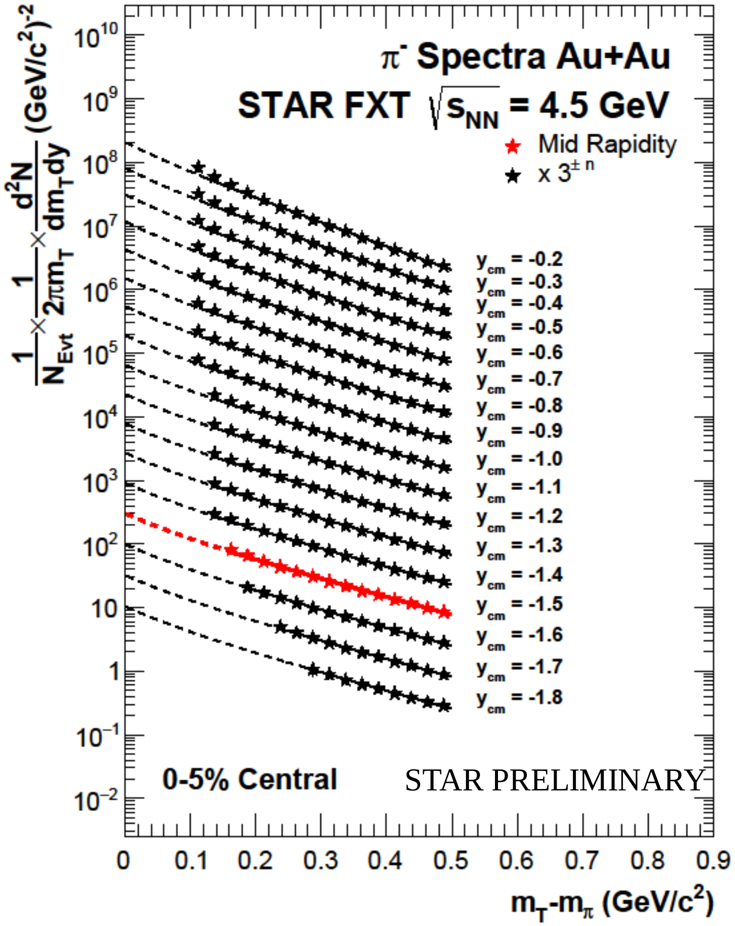


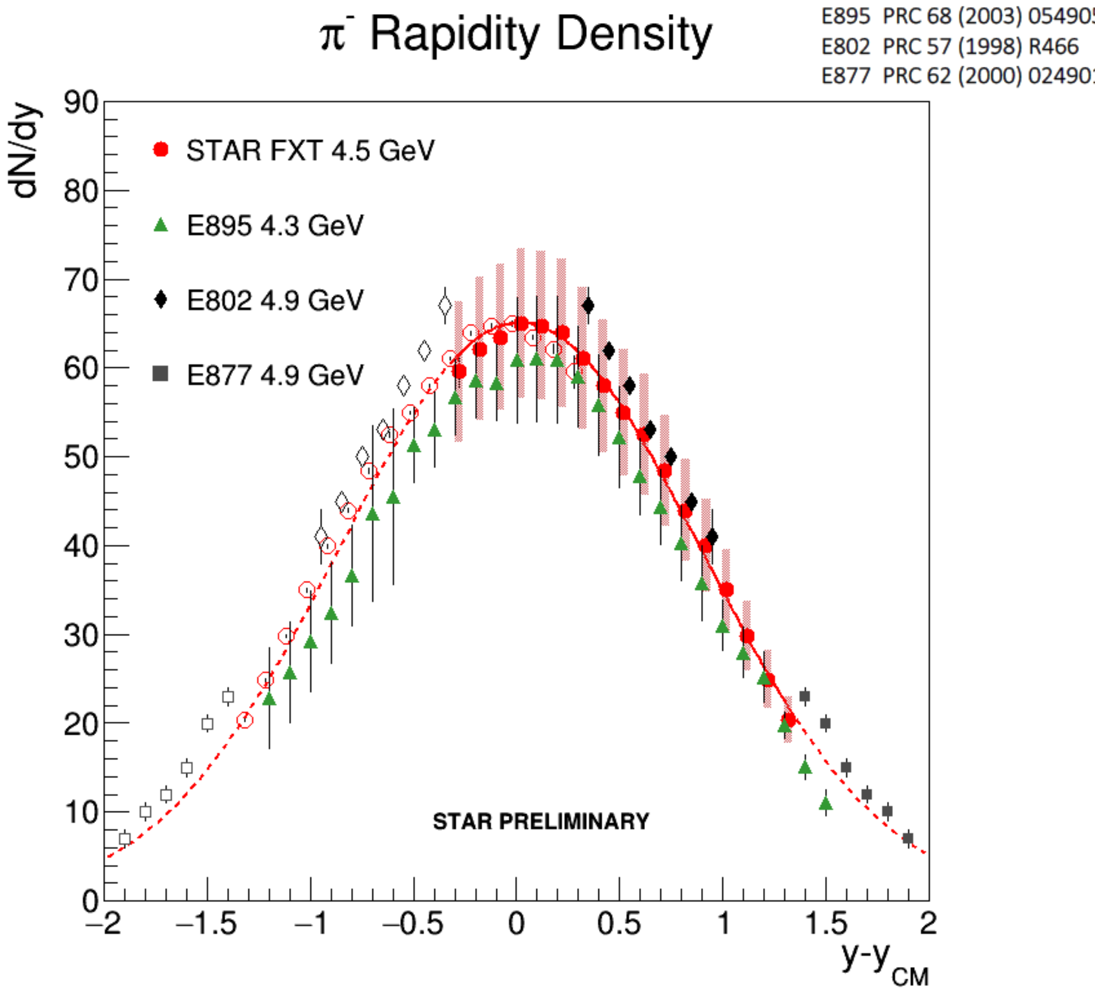






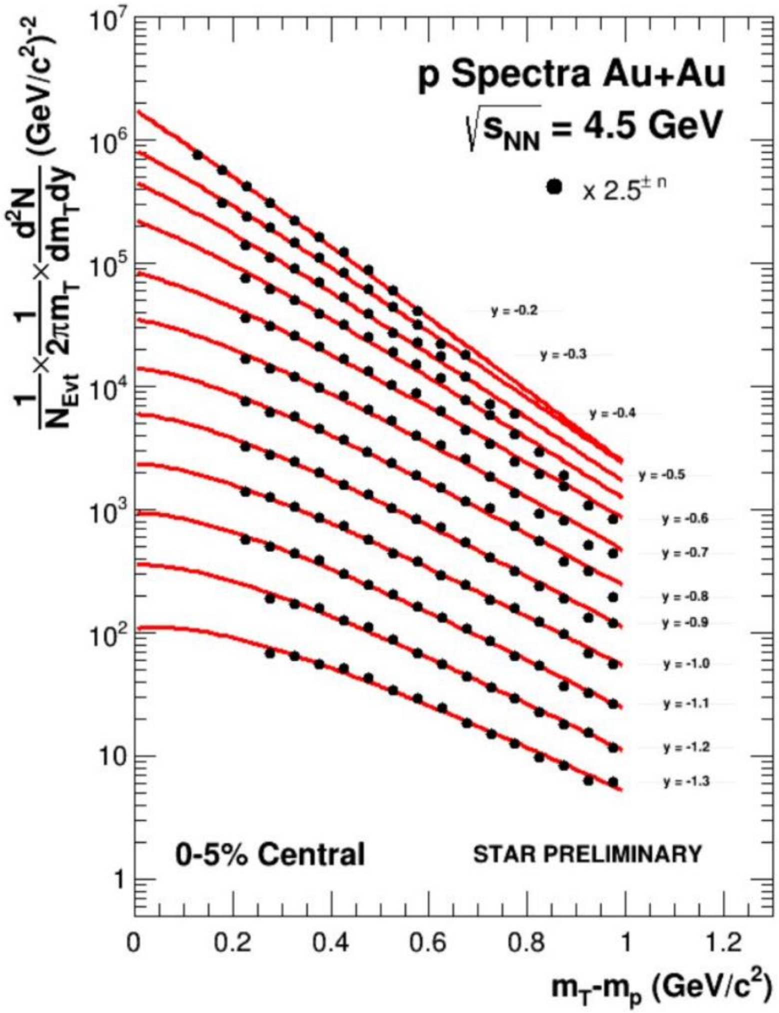
$\sqrt{s_{NN}}$ = 4.5 GeV Au+Au : pion spectra

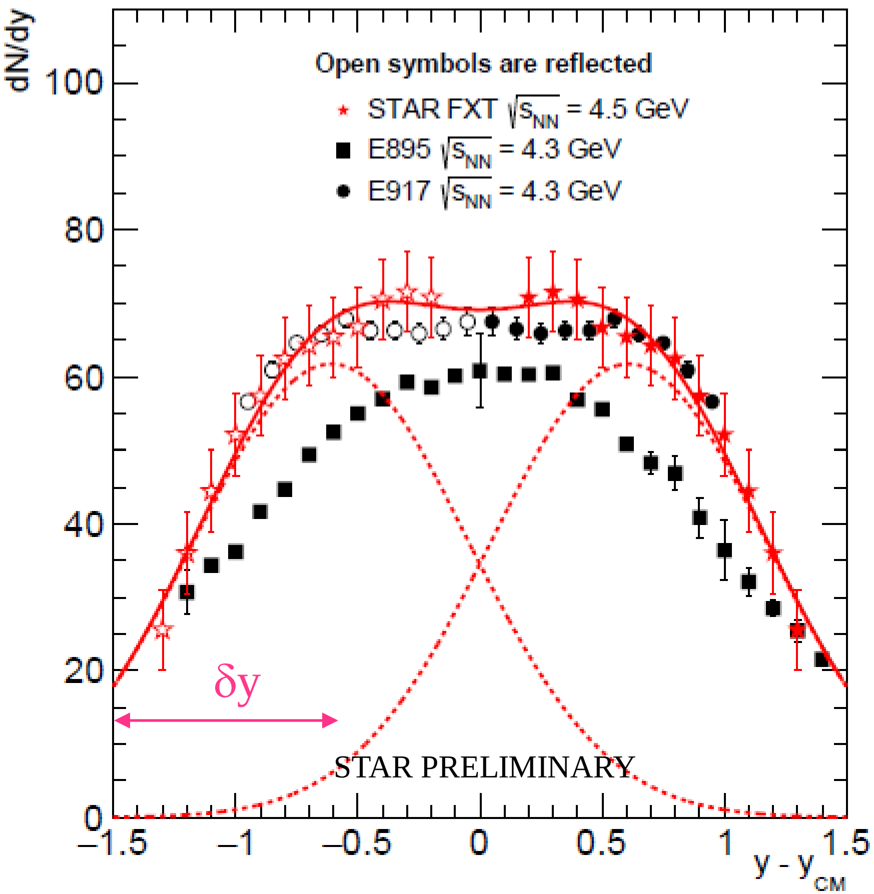




Consistent with AGS results

$\sqrt{s_{NN}}$ = 4.5 GeV Au+Au : proton spectra





Consistent with AGS results (*)

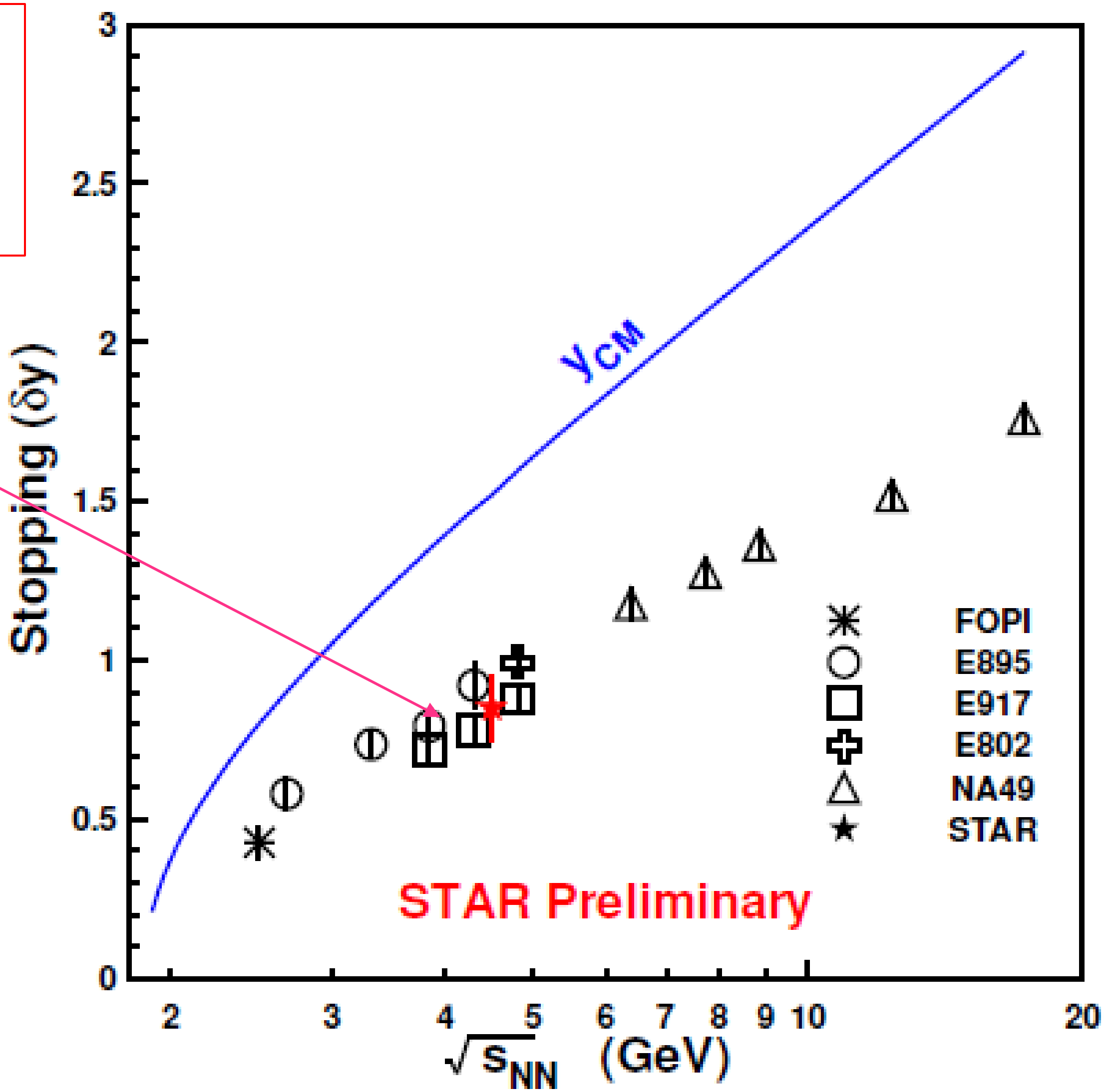
Systematics of Stopping

"Stopping" is key to determining the μ_B, but may also be a signature of a first order phase transition.

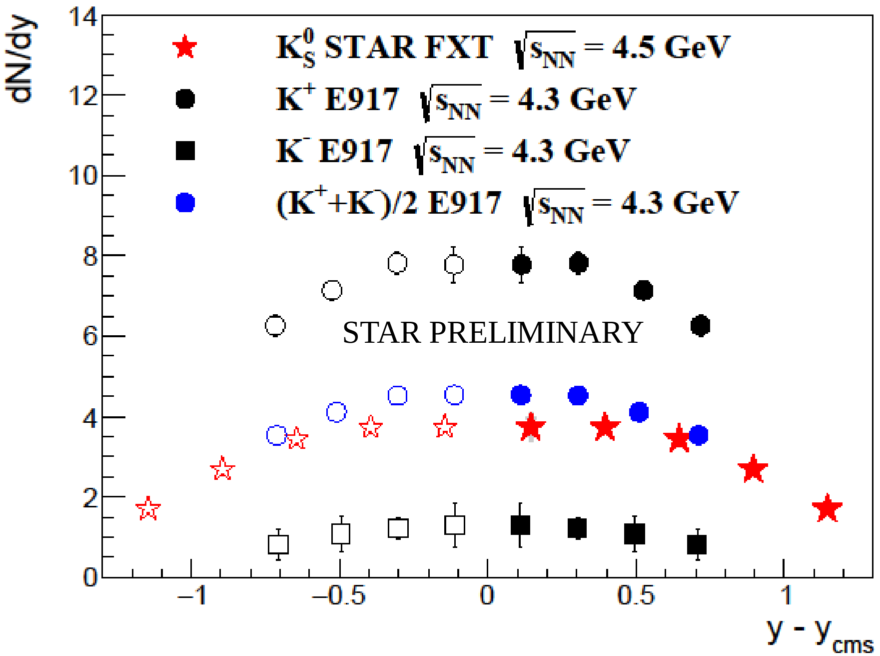
Y. Ivanov, PRC87, 064904 (2013)

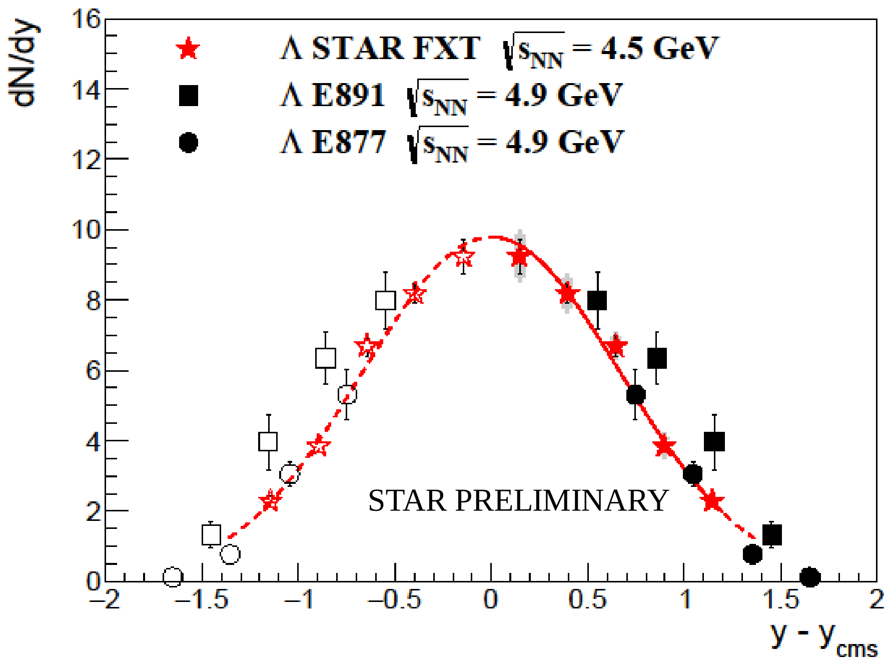
Maybe evidence of a softening of the equation of state

More precise measurements are needed



$\sqrt{s_{NN}}$ = 4.5 GeV Au+Au : V^0 yields

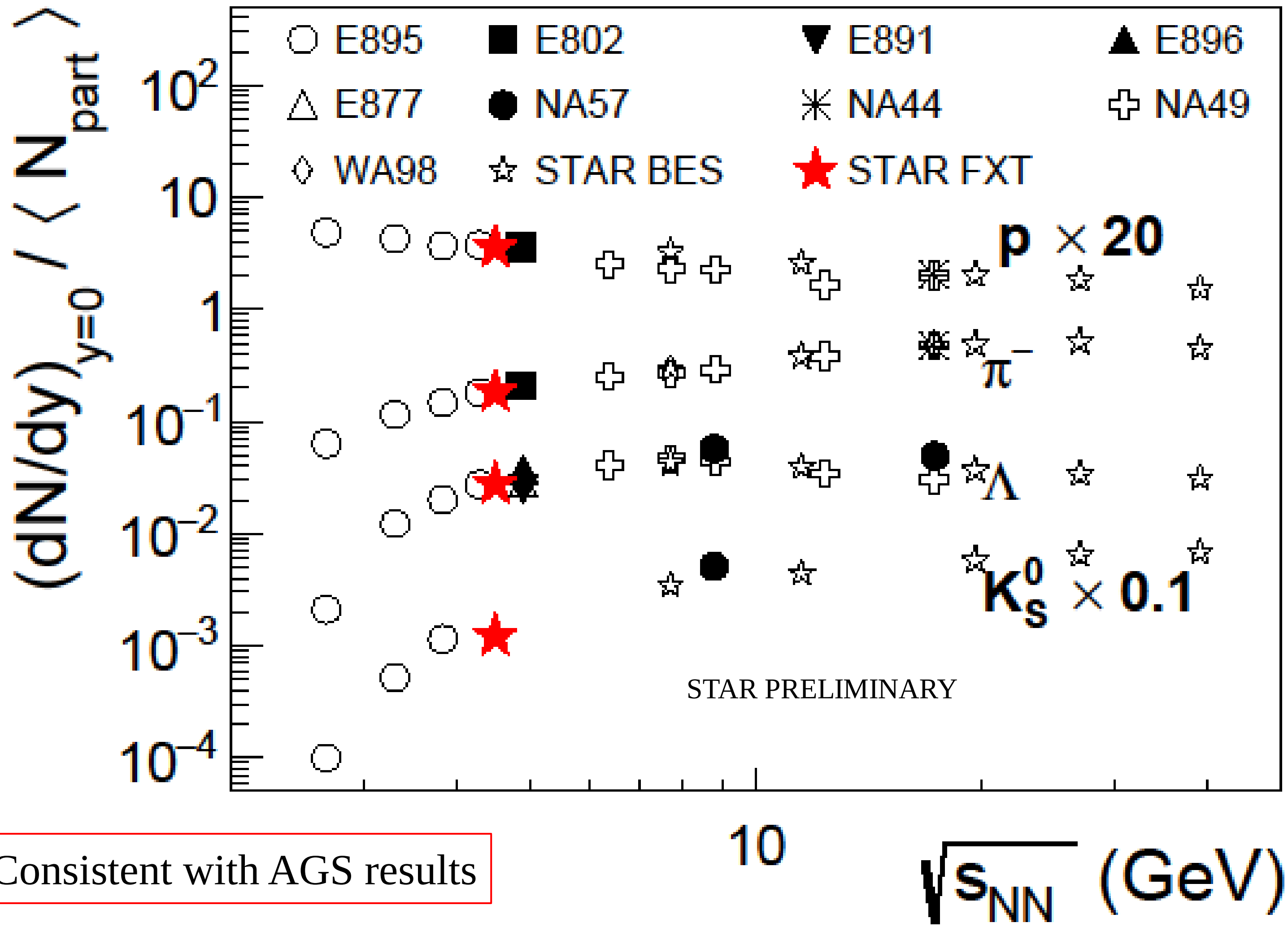




No AGS K^0_S results at this energy
But similar to K^+/K^- average

Consistent with AGS results

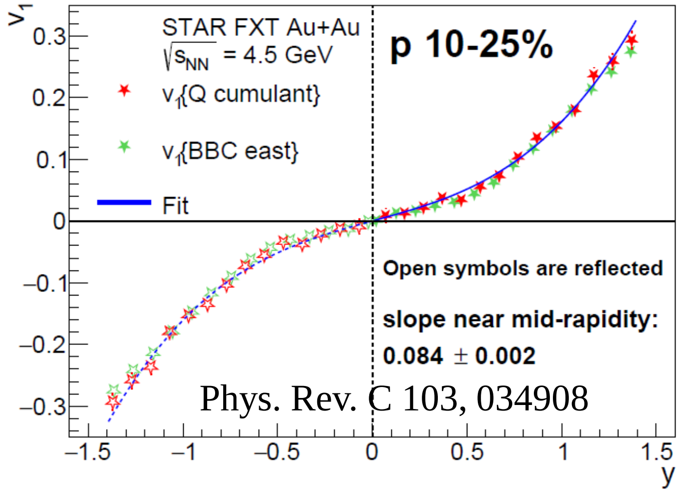
$\sqrt{s_{NN}}$ = 4.5 GeV Au+Au : spectra overview

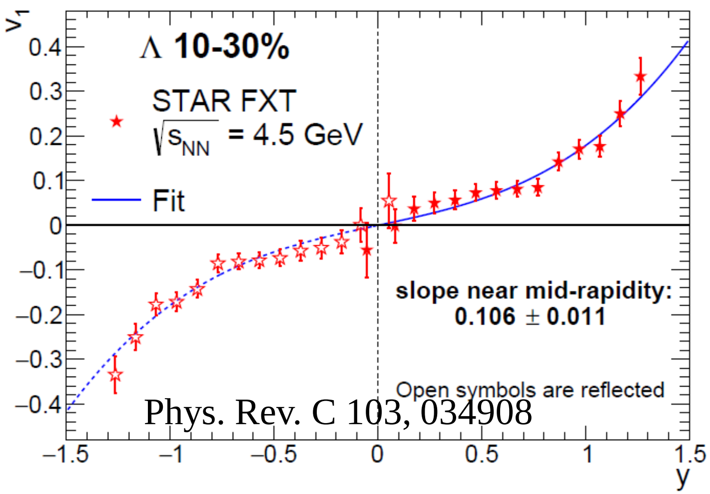


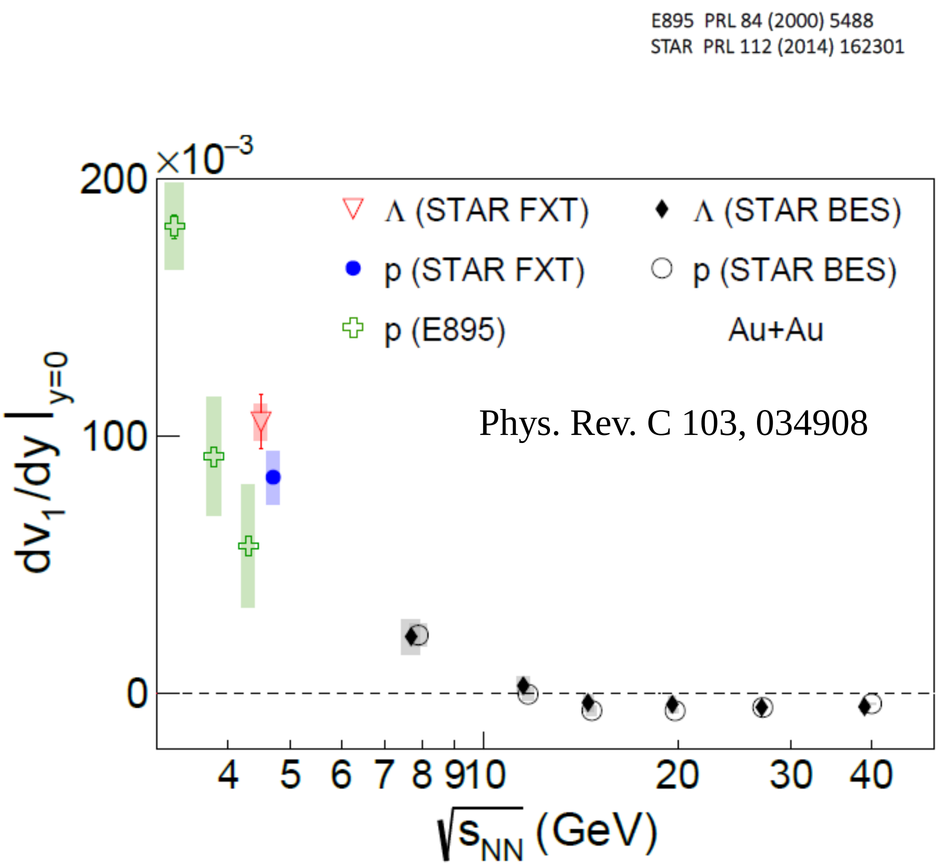
E896 PRL 88 (2002) 062301
NA44 PRC 66 (2002) 044907
NA49 JPG 30 (2004) S701
NA49 PRL 93 (2004) 022302
NA57 JPG:NPP 32 (2006) 2065
WA98 PRC 67 (2003) 014906
E895 RPC 68 (2003) 054905
E895 NPA 698 (2002) 495c
E917 PLB 476 (2000) 1
E802 NPA 610 (1996) 139c
E877 PRC 63 (2001) 014902
E891 PLB 382 (1996) 35

Consistent with AGS results

$\sqrt{s_{NN}}$ = 4.5 GeV Au+Au : baryon directed flow

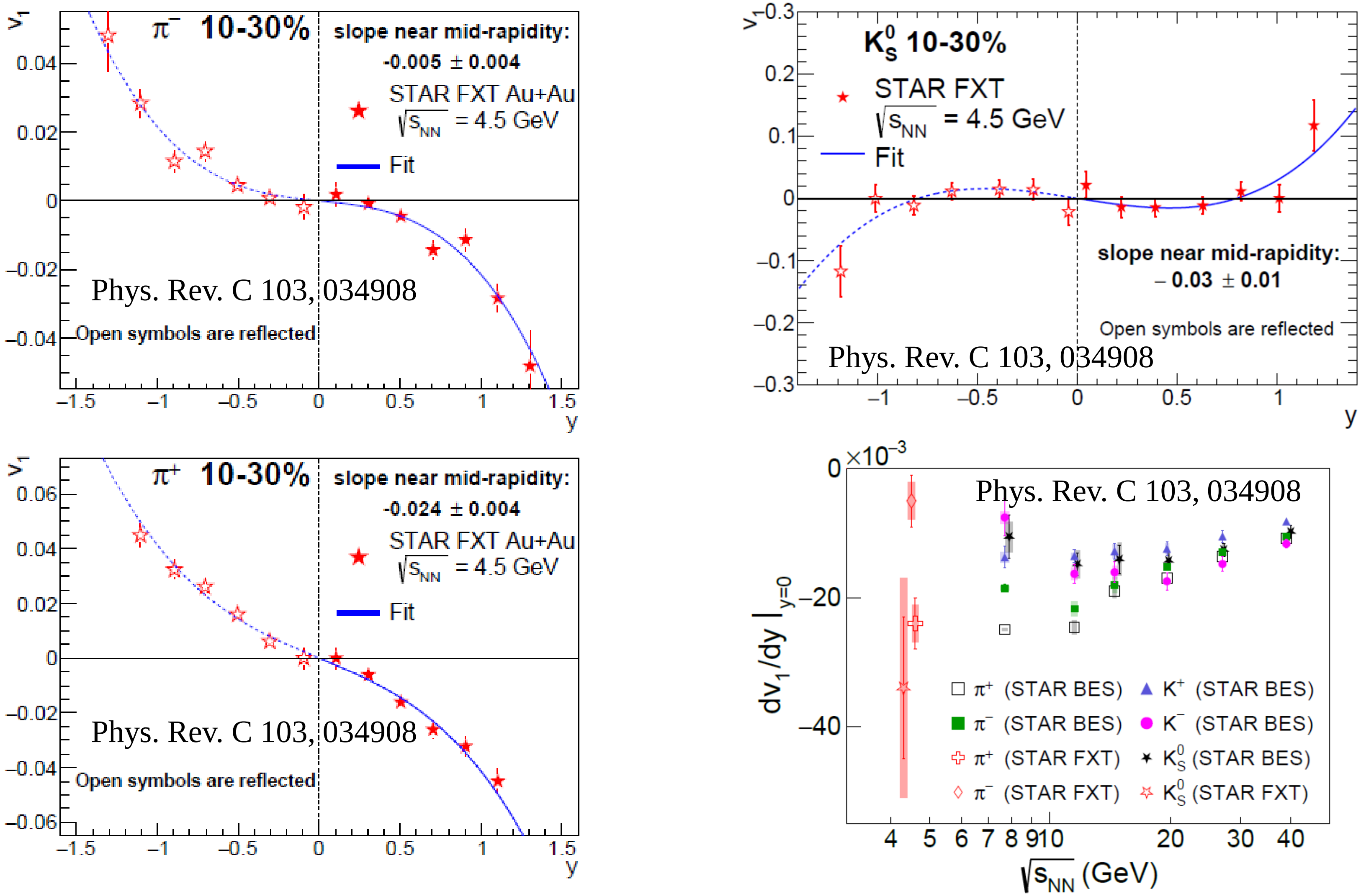






Consistent with proton results (*)

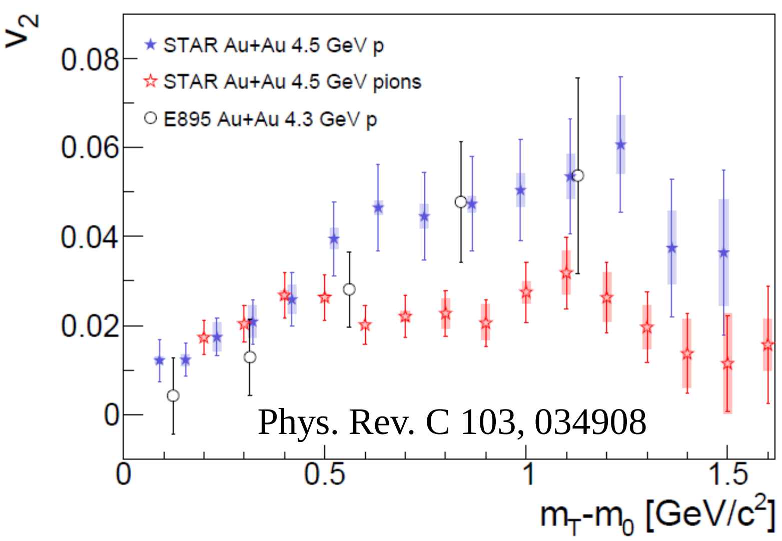
$\sqrt{s_{NN}}$ = 4.5 GeV Au+Au : meson directed flow

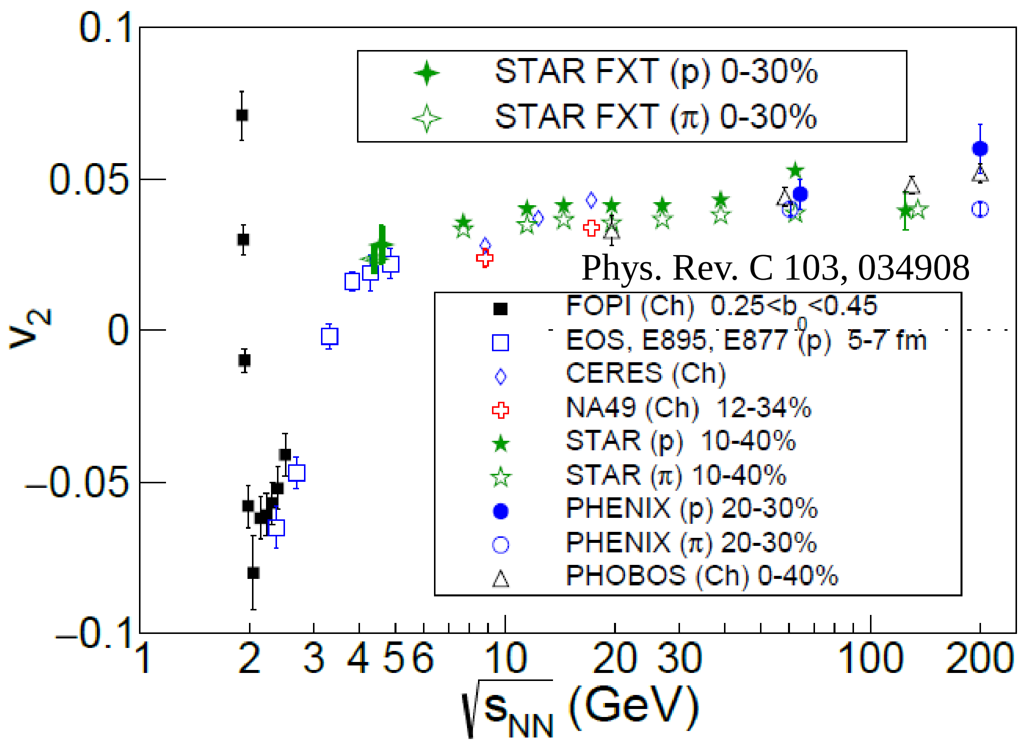


$\sqrt{s_{NN}}$ = 4.5 GeV Au+Au : p and π elliptic flow

Consistent with AGS proton results
No AGS pion results

E895 PRL 83 (1999) 1295

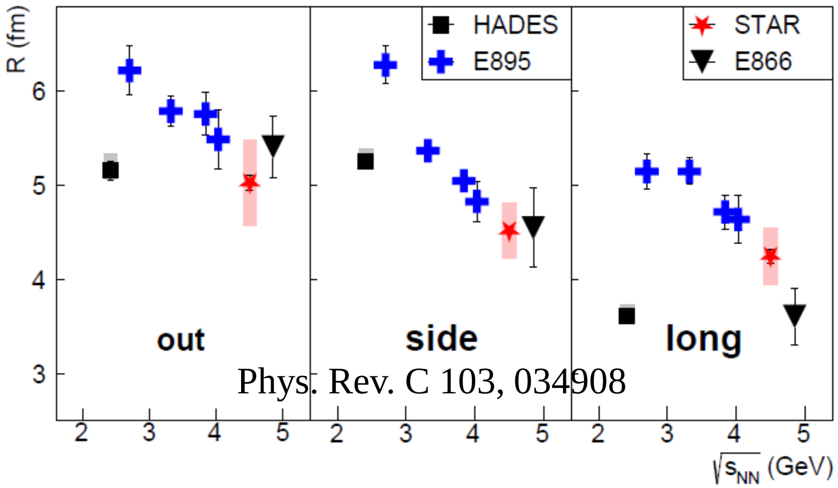




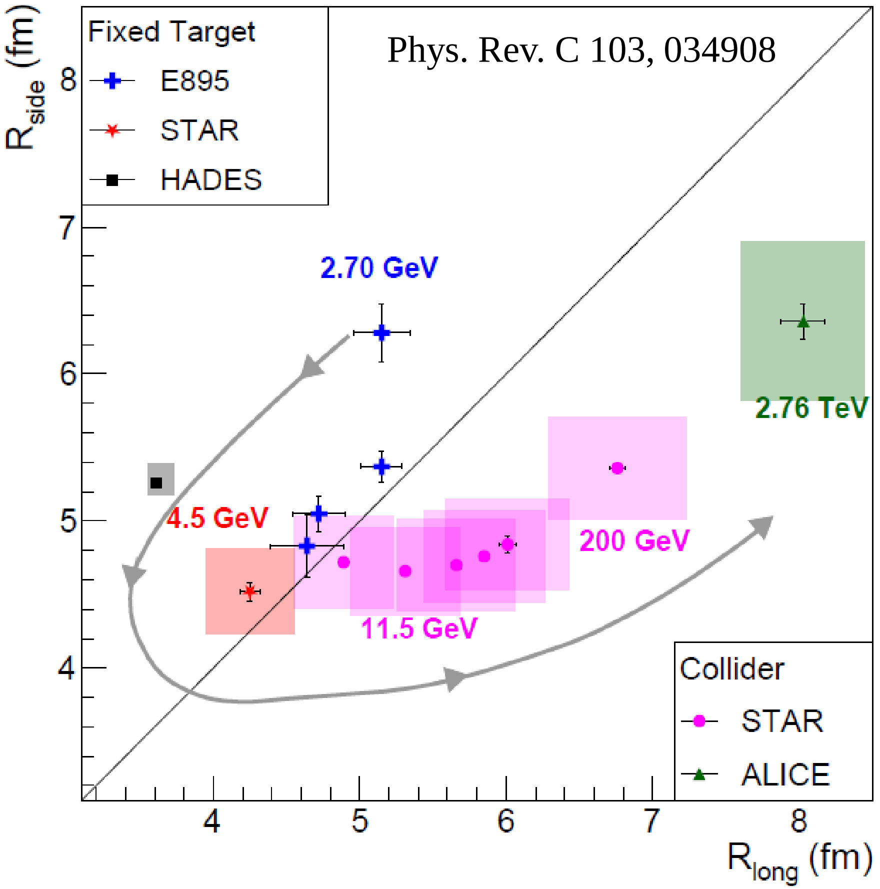
Consistent with AGS results

Protons and pions exhibit in-plane elliptic flow

$\sqrt{s_{NN}}$ = 4.5 GeV Au+Au : HBT



Phys. Rev. C 103, 034908



Consistent with AGS results

E866 PRC 66 (2002) 054096
E895 PRL 84 (2000) 2798
ALICE PRB 696 (2011) 328
STAR PRC 92 (2015) 14904

Minimum size seen at 4.5 GeV
Consistent with softening

FXT Physics Program 2018-2021

Physics Goals

The Onset of Deconfinement:

- High p_T suppression
- NCQ scaling of elliptic flow
- LPV through three particle correlators (CME)
- Balance functions
- Strangeness enhancement

Compressibility ➔ First Order Phase Transition

- Directed flow
- Tilt angle of the HBT source
- The volume of the HBT source
- The width of the pion rapidity distributions (Dale)
- The zero crossing of the elliptic flow (~6 AGeV)
- Volume measures from Coulomb potential

Criticality:

- Higher moments
- Particle ratio fluctuations

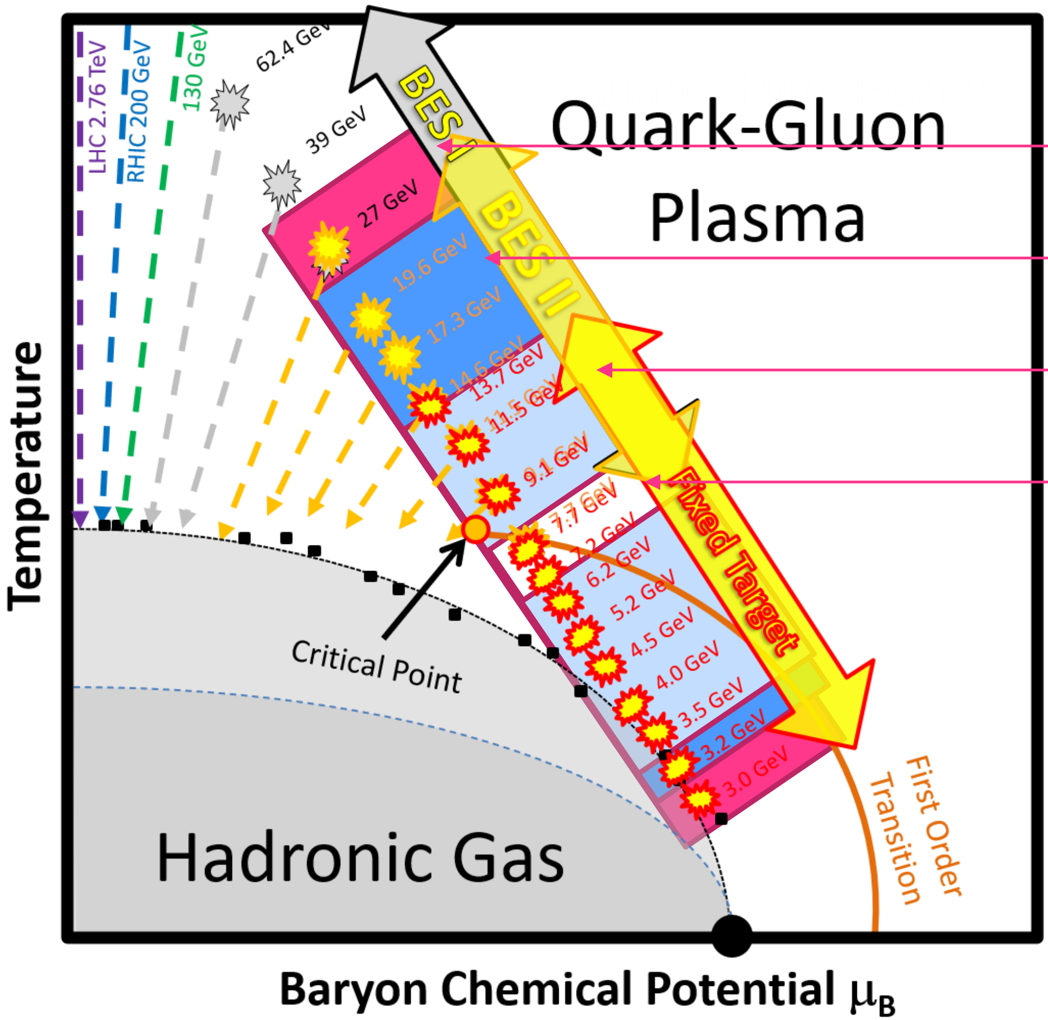
Chirality:

- Dilepton studies

Hypernuclei:

Lifetime of the hypertriton

BES-II and FXT -- Mapping the QCD Phase Diagram



Go from easiest to hardest

Run 18 -- 27 GeV, FXT 3.0, 7.2 GeV
Beams are accelerated

Run 19 – 19.6, 14.6, FXT 3.2 GeV
No acceleration in RHIC

Run 20 – 11.5, 9.2, many FXT
Needs cooling at 9.2 GeV

Run 21 – 7.7, 17.3 GeV Collider and FXT 3.0, 7.2, 9.1, 11.5, 13.7 GeV

The BES-II collider program maps the approach to the transition from the QGP side of the QCD phase diagram.

The FXT program maps the baryon-rich side of the phase diagram

How are we doing so far?

Worked out the FXT conduct of operations

2018	Start	Stop	Good	Target
27 GeV	May 10th	June 17th	555 M	700 M
3.0 FXT	May 30th	June 4th	258 M	100 M
7.2 FXT	June 11th	June 12th	155 M	none

Held off most of the FXT program due to damage to the eTOF

2019	Start	Stop	Good	Target
19.6 GeV	Feb 25th	April 3rd	582 M	400 M
14.6 GeV	April 4th	June 3rd	324 M	310 M
3.9 FXT	June 18th	June 18th	52.7 M	50 M
3.2 FXT	June 28th	July 2nd	200.6 M	200 M
7.7 FXT	July 8th	July 9th	50.6 M	50 M
200 GeV	July 11th	July 12th	138 M	140 M

2020	Start	Finish	HLTgood	Target
11.5 GeV	Dec 10th	Feb 24th	235 M	230 M
7.7 FXT	Jan 28th	Jan 29th	112.5 M	100 M
4.5 FXT	Jan29th	Feb 1st	108 M	100 M
6.2 FXT	Feb 1st	Feb 2nd	118 M	100 M
5.2 FXT	Feb 2nd	Feb 3rd	103 M	100 M
3.9 FXT	Feb 4th	Feb 5th	117 M	100 M
3.5 FXT	Feb 13th	Feb 14th	115.6 M	100 M
9.2 GeV	Feb 24th	Sep 1st	161.8 M	160 M
7.2 FXT	Sep 12th	Sep 14th	317 M	None

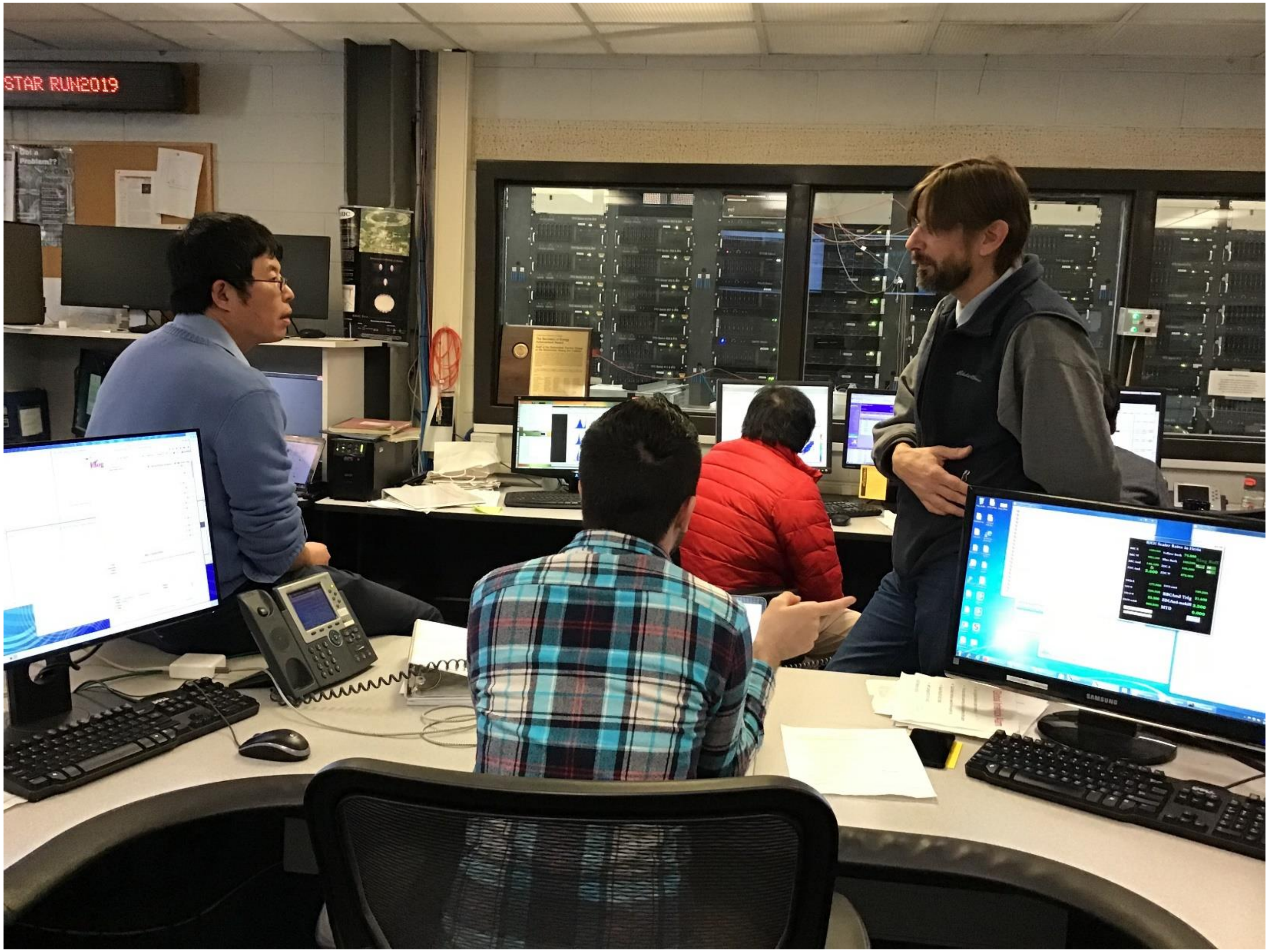
Completed the bulk of the physics program. Roughly one day for each energy

2021	Start	Stop	Good	Target
7.7 GeV	Jan 31st	~ May 1st	~100 M	100 M
3.0 FXT		3 weeks		2.0 B
9.2 FXT		1 day		50 M
11.5 FXT		1 day		50 M
13.7 FXT		1 day		50 M
7.2 FXT		TBA		None
17.3 GeV		3 weeks		250 M

Added more overlap energies to study stopping

Long run for hypernuclei and higher momements

2018 FXT Preliminary Results

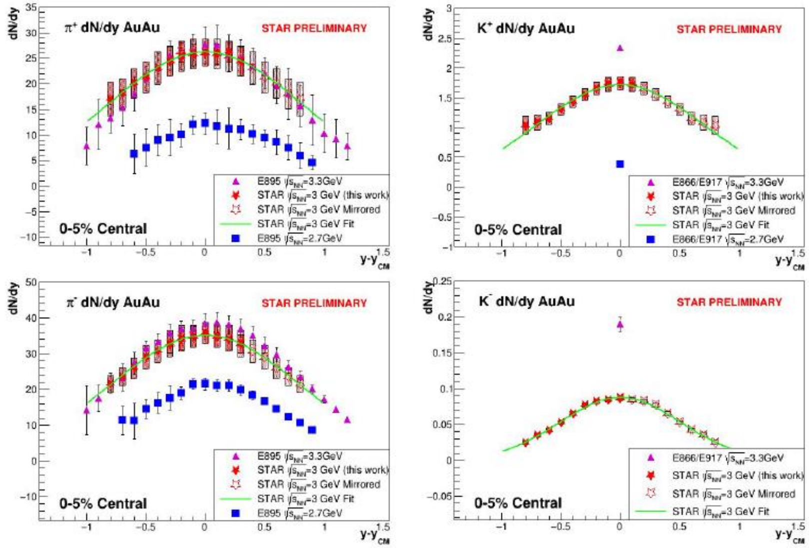


Particle Production at $\sqrt{s_{NN}}$ = 3.0 GeV

Spectra and rapidity densities have been measured for:

- π^+
- π^-
- K^+
- K^-
- ϕ
- p
- d
- t
- h
- α
- ${}^{3}_{\Lambda}H$
- ${}^{4}_{\Lambda}H$

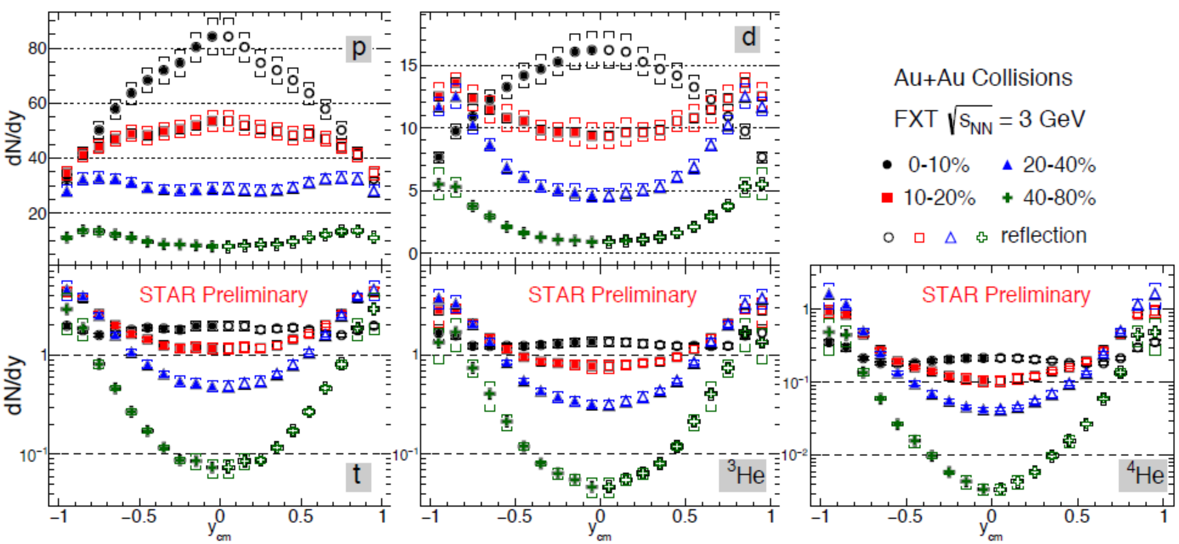
To come: K^0_S and Λ

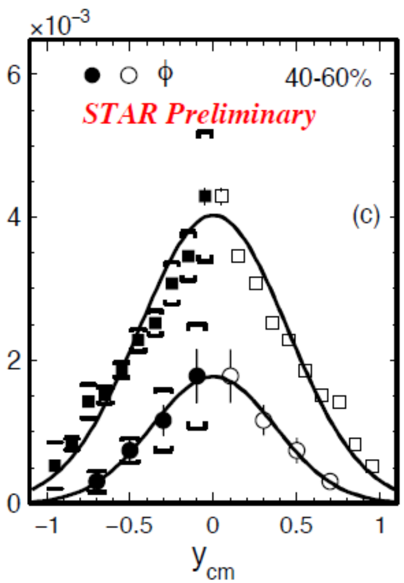


For more details see the the following talks

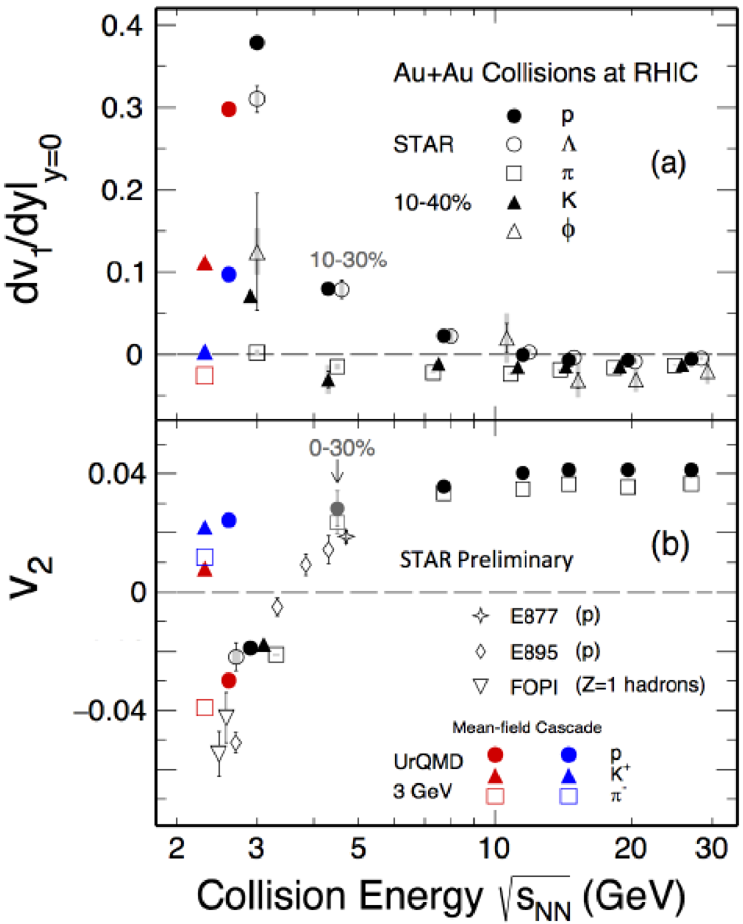
- L15 – 03 Guannan Xie – Phi production
- L15 – 08 Hui Lui – Light nucleus production
- L15 – 09 Yue Hang Leung -- Hypernuclei

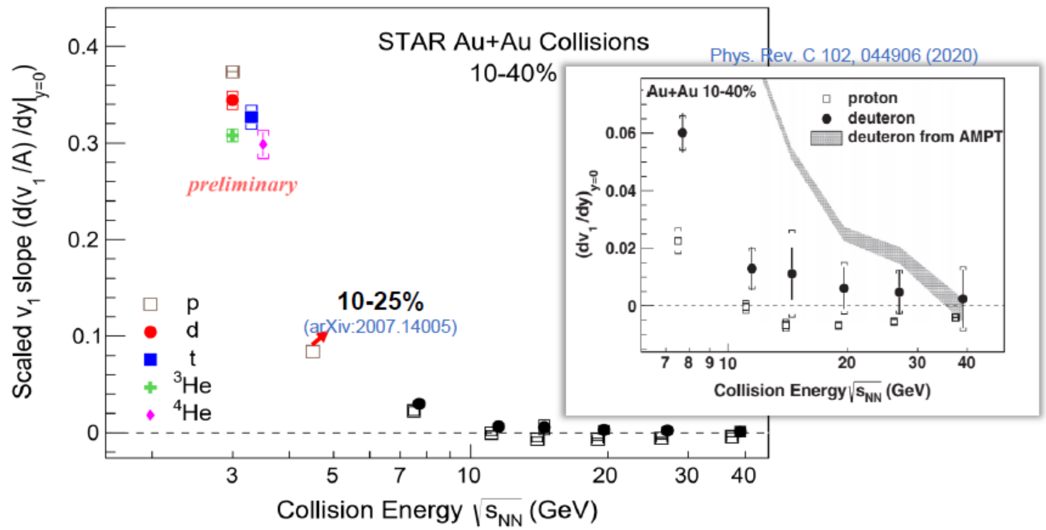
Note the importance of Δ's and associated production of Λ's

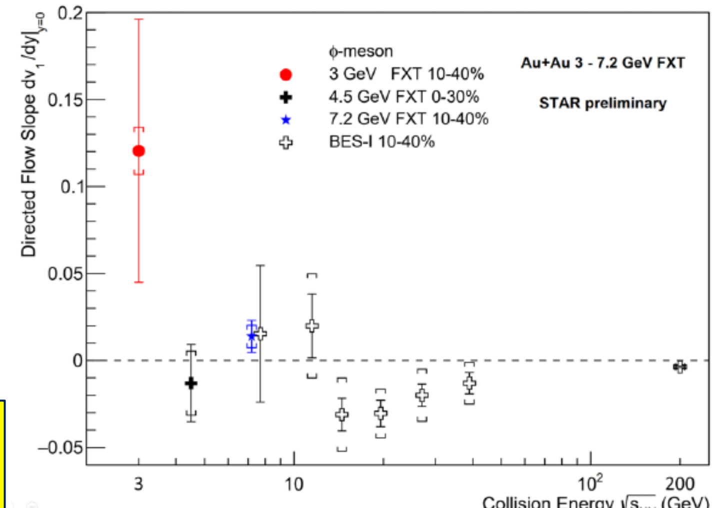




Flow results at $\sqrt{s_{NN}} = 3.0$ GeV



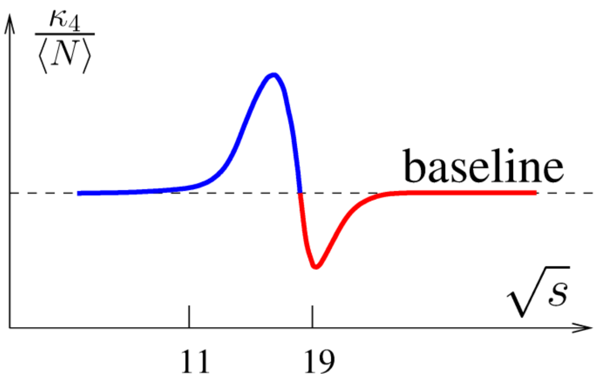


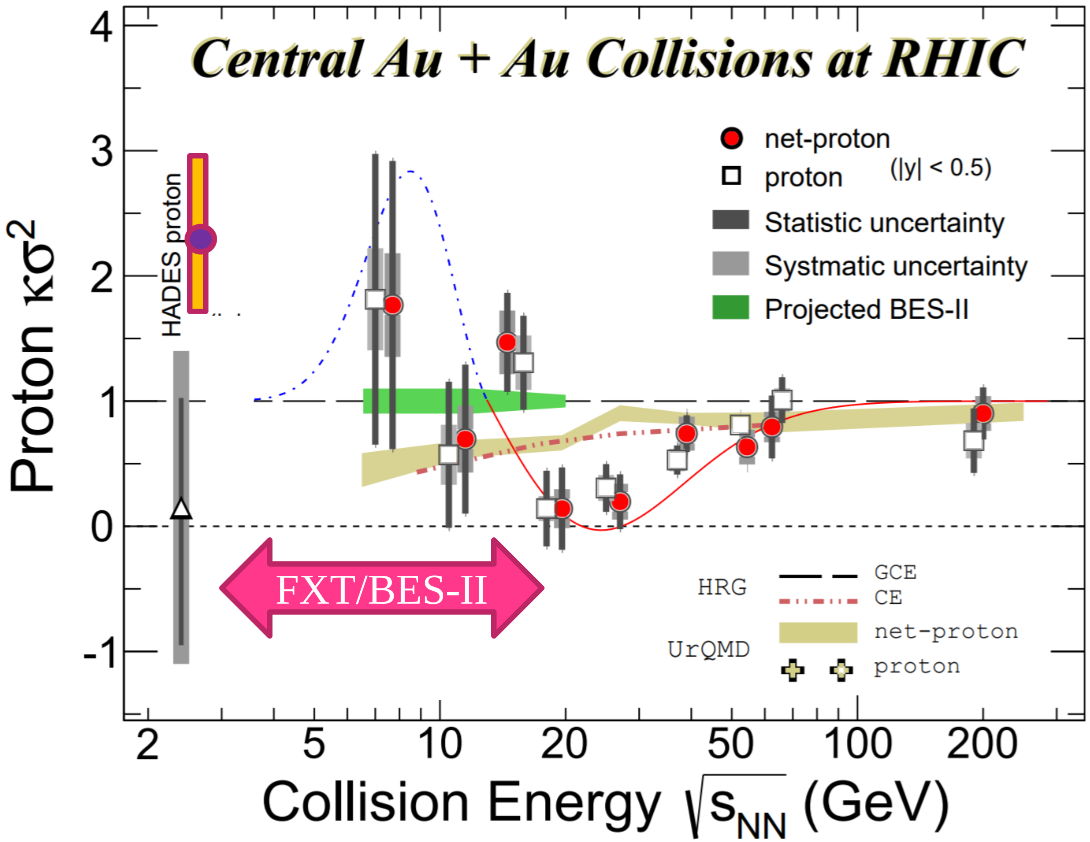


For more details see the the following talks

- L15 – 02 Sooraj Radhakrishnan – v_1 and v_2 of π, K , p
- L15 – 04 Ding Chcn – Flow of ϕ mesons
- L15 – 07 Xionghong He – v_1 and v_2 of light nuclei

Proton Fluctuations – $\kappa\sigma^2$





Preliminary HADES results was high

Their new final result is credible

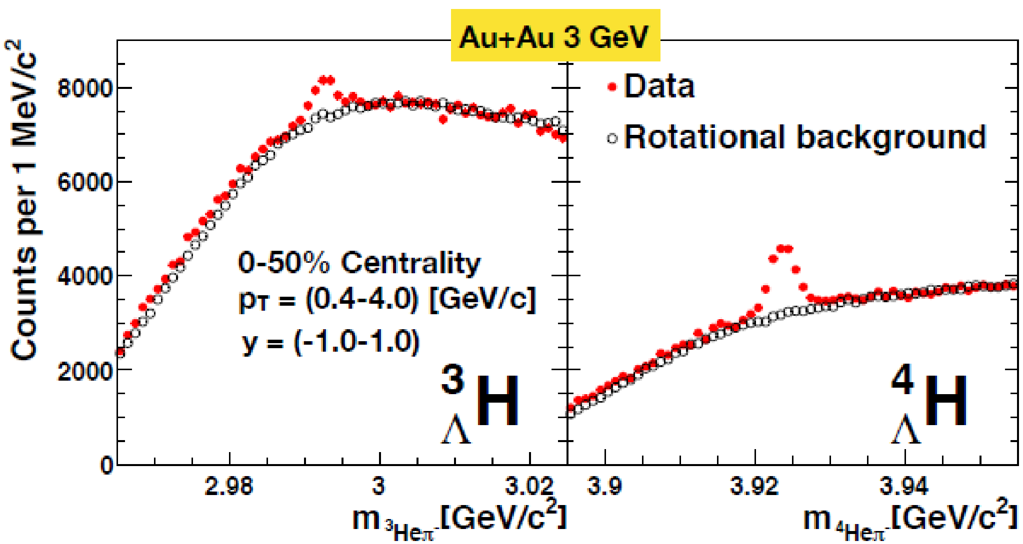
STAR has decided not to release preliminary results for this observable

For more details see the the following talks
- K15 – 05 Yu Zhang – Higher order cumulants
- K15 – 06 Jonathan Cap – Lambda Fluctuations

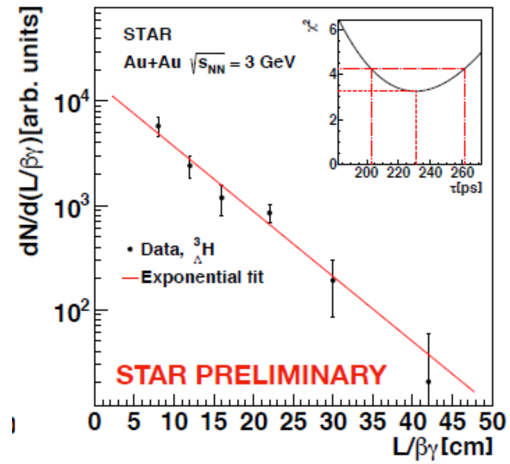
Hyper-nuclei $\sqrt{s_{NN}}$ = 3.0 GeV

Does being bound within a nucleus stabilize or de-stabilize a hyperon?

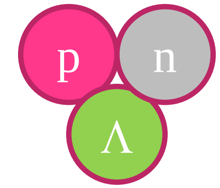
➔ A hyperon is a baryon which includes a strange quark



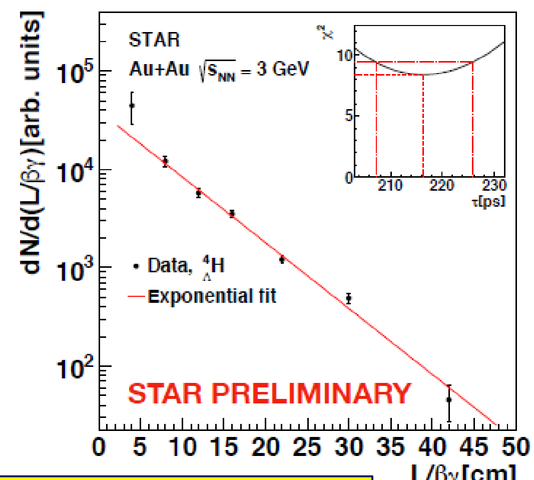
$^{3}_{\Lambda}H$



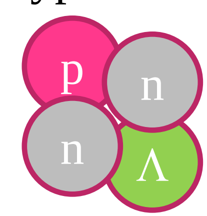
Hyper-triton



$^{4}_{\Lambda}H$



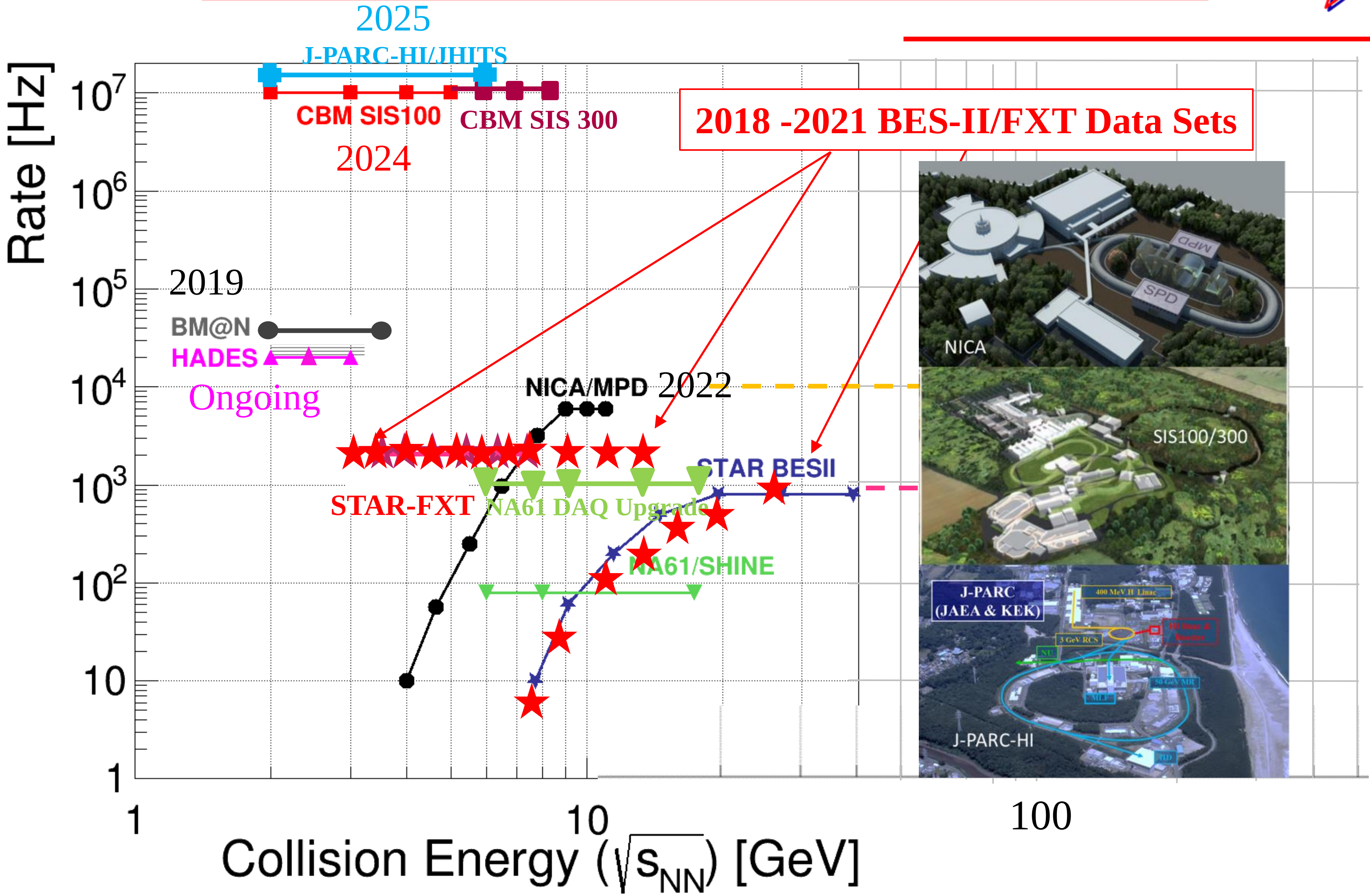
Hyper-^{4}H



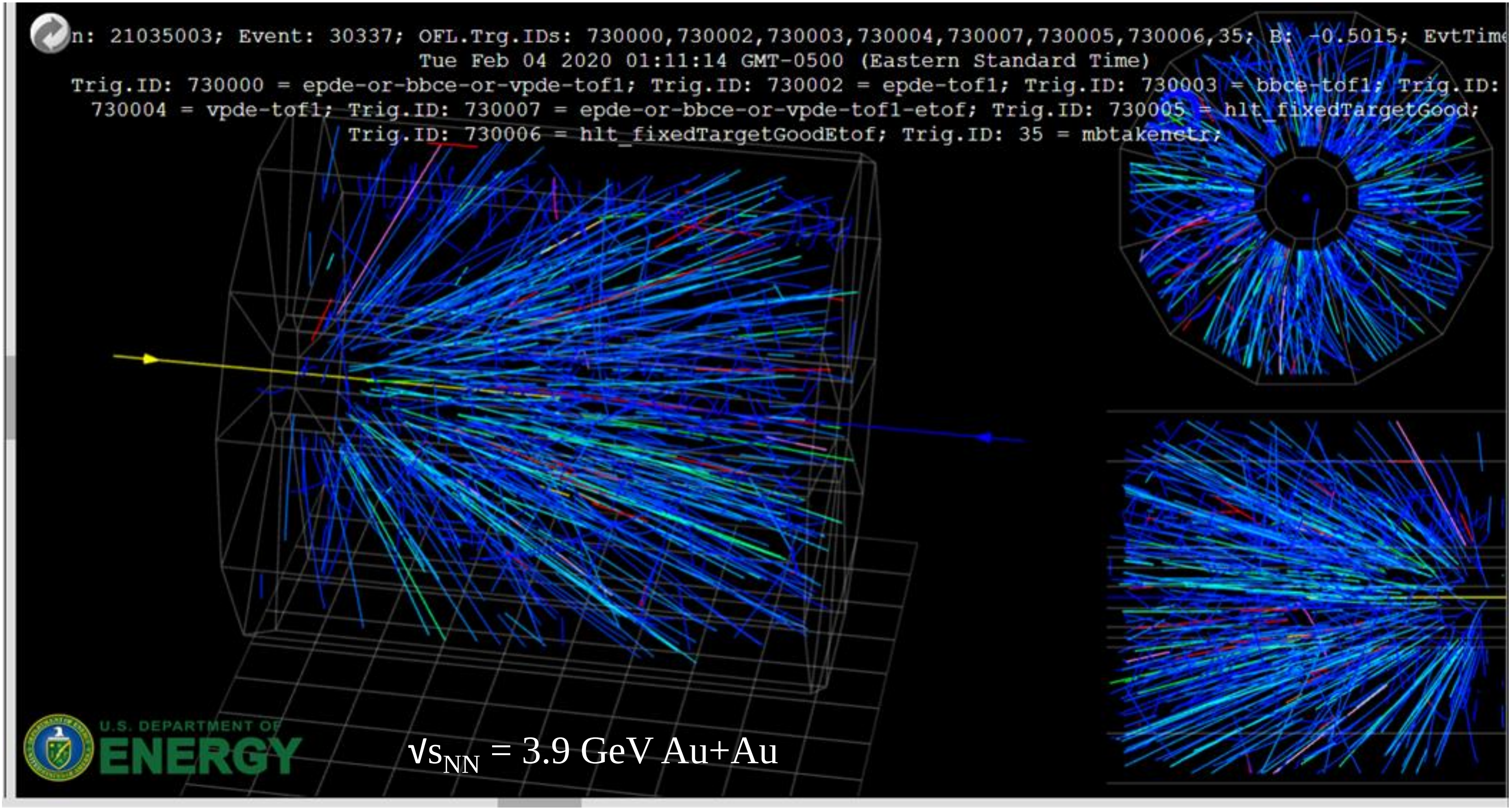
For more details see the the following talks

- L15 – 09 Yue Hang Leung -- Hypernuclei

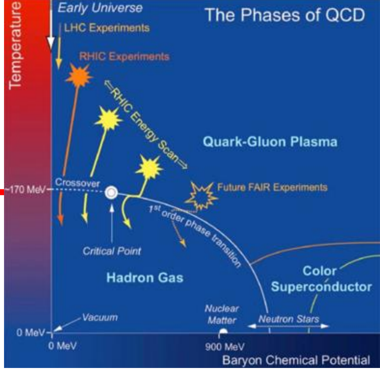
We Have Competition for this Physics



Online Event Display – FXT Event



$\sqrt{s_{NN}}$ = 3.9 GeV Au+Au



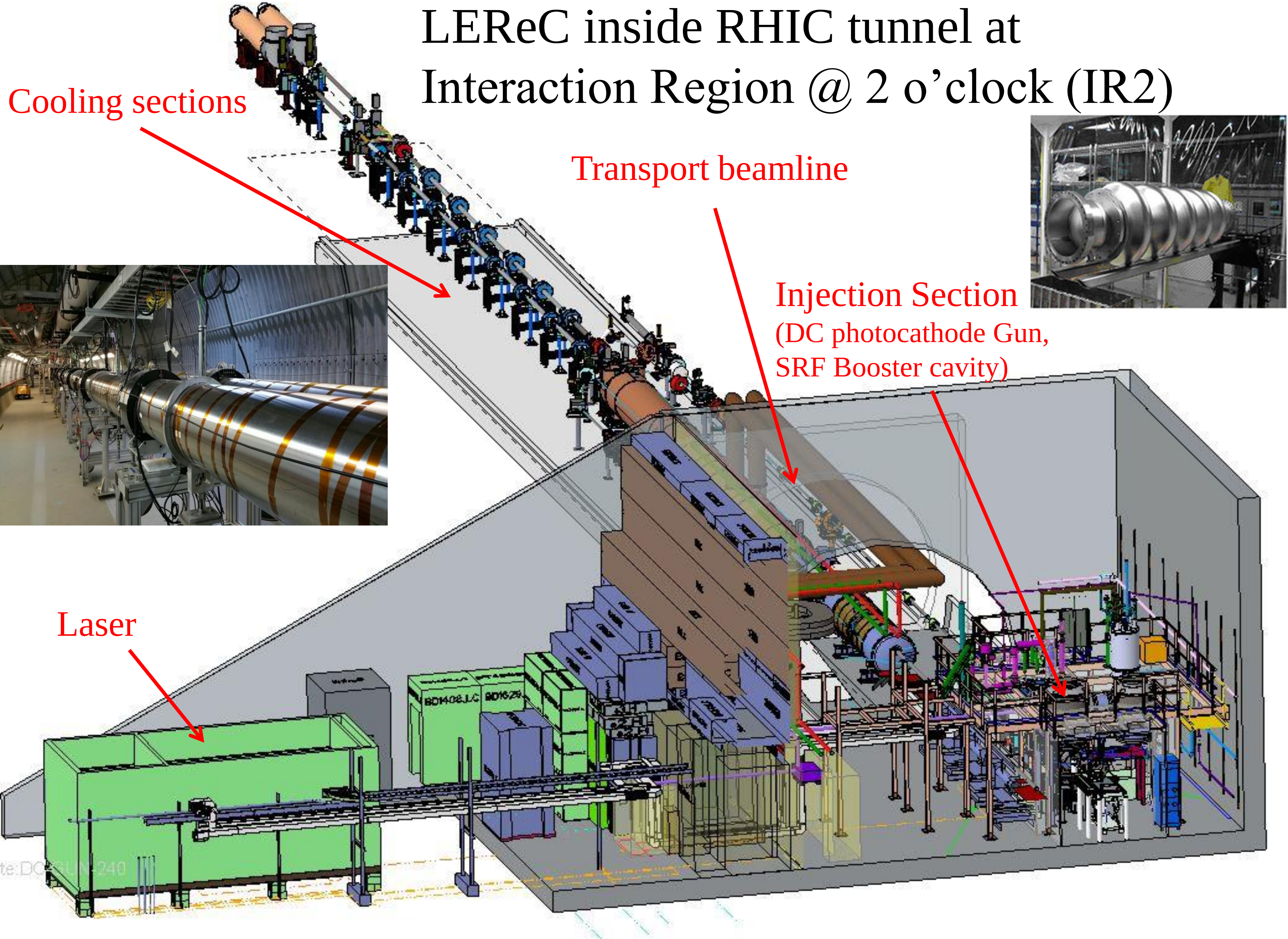
Conclusions

- Understanding the phase diagram of QCD matter is a top national strategic goal for Nuclear Physics
- The key energy range is $\sqrt{s_{NN}}$ = 3 – 30 GeV. ➔ **The FXT program is needed to cover the low end of that range.**
- A fast and efficient conduct of operations has been developed for FXT running.
- Extensive data sets have been acquired at nine energies, data for three more energies will be acquired this year.
- QGP to hadron gas transition:
  - **Continuous for energies above 19.6 GeV**
  - **Searches for a softening of the equation of state are underway**
  - **Searches for critical behavior are underway**

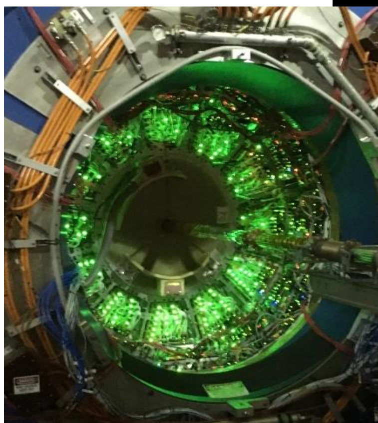
BACKUPS

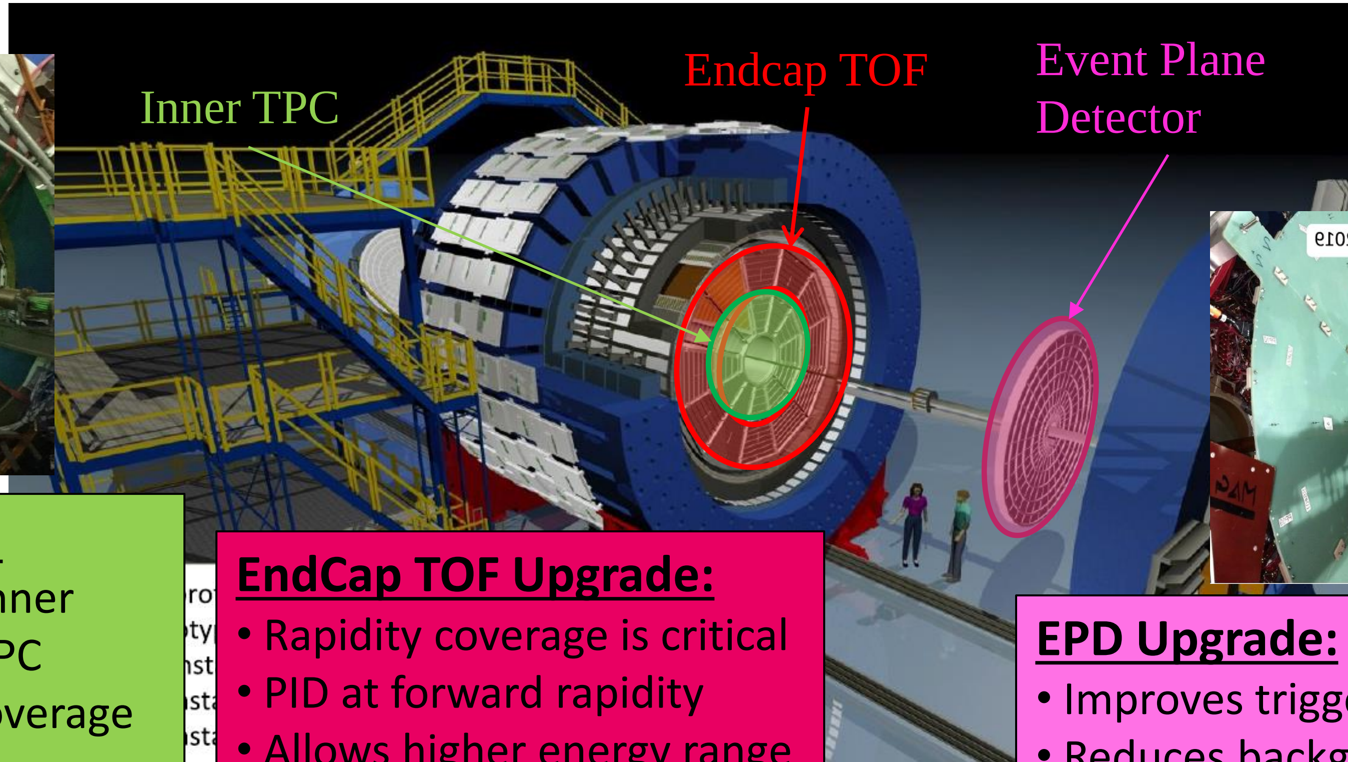
Beam E_T (GeV)	Beam E_k (AGeV)	Beam p_Z (GeV/c)	Rapidity y_{Beam}	$\sqrt{s_{NN}}$ (GeV)	Rapidity y_{CM}	Ch. Pot. μ_B (GeV)
3.85	2.92	3.73	2.10	3.0	1.05	721
4.59	3.66	4.50	2.28	3.2	1.13	699
5.75	4.82	5.67	2.51	3.5	1.25	666
7.3	6.4	7.25	2.75	3.9	1.37	633
9.8	8.9	9.44	3.04	4.5	1.52	589
13.5	12.6	13.5	3.37	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

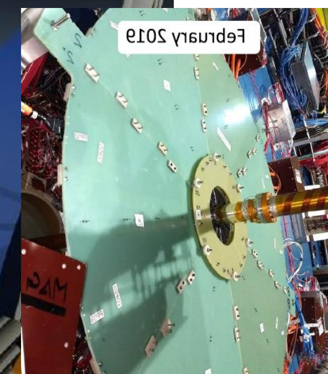
LEReC inside RHIC tunnel at Interaction Region @ 2 o'clock (IR2)



The STAR Detector Upgrades → BES-II





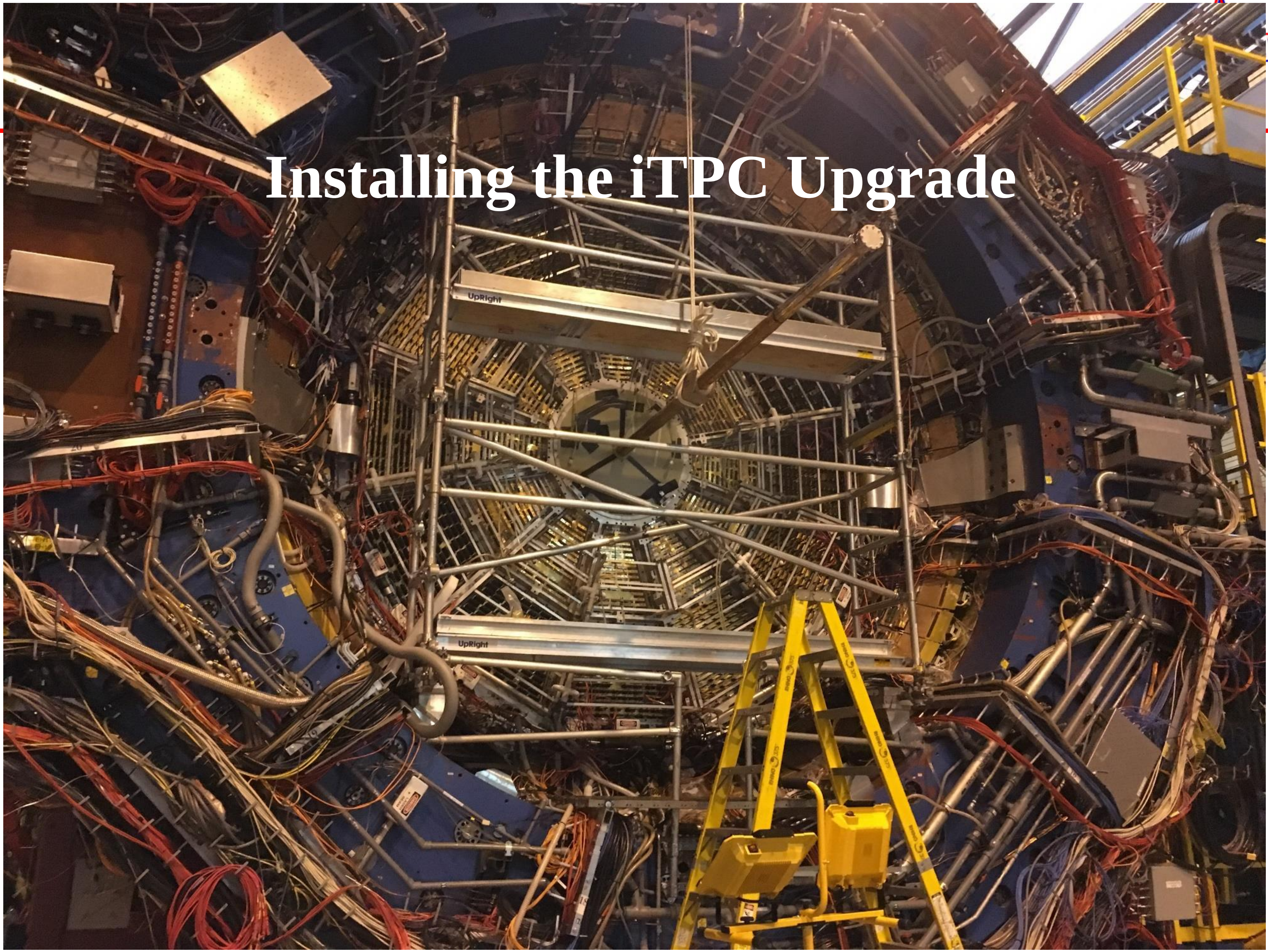


iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage to 1.5 (2.2 for FXT)
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c
- Ready in 2019

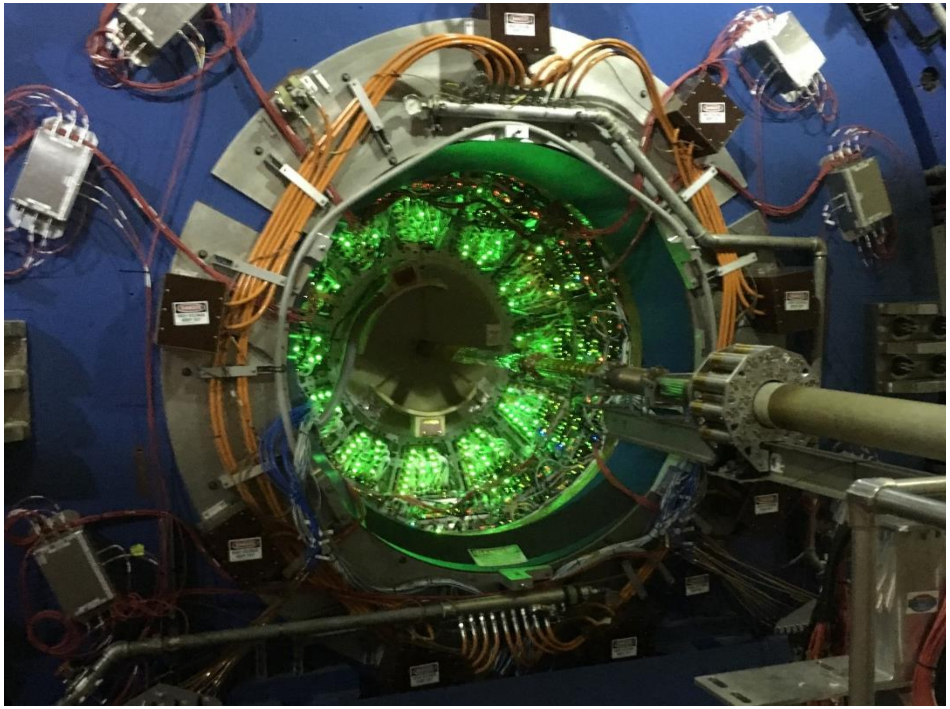
EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at forward rapidity
- Allows higher energy range of FXT program
- CBM/FAIR
- Ready 2019

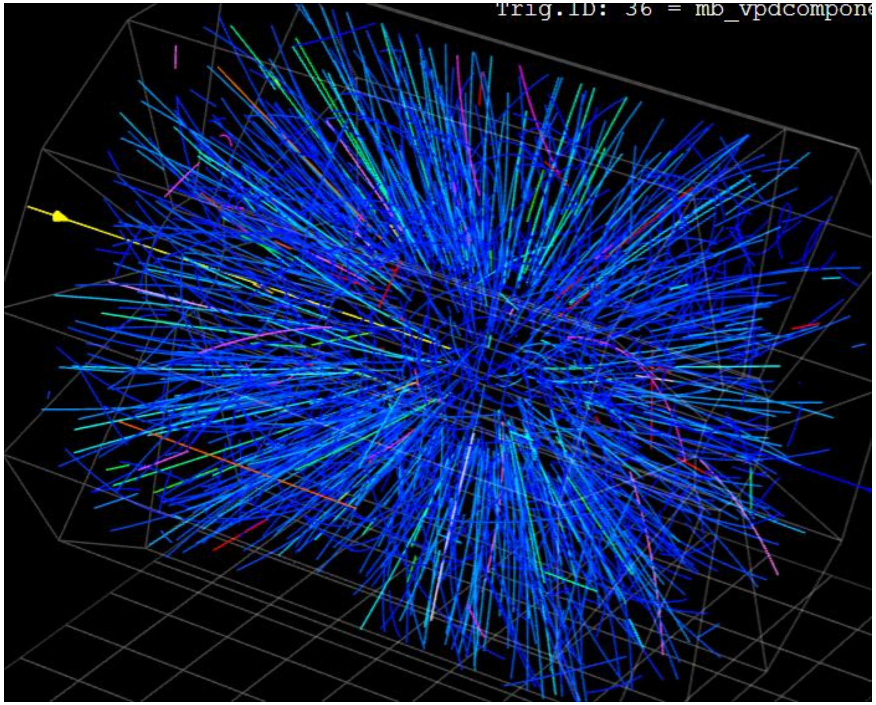
EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES and FXT
- Ready 2018

Installing the iTPC Upgrade



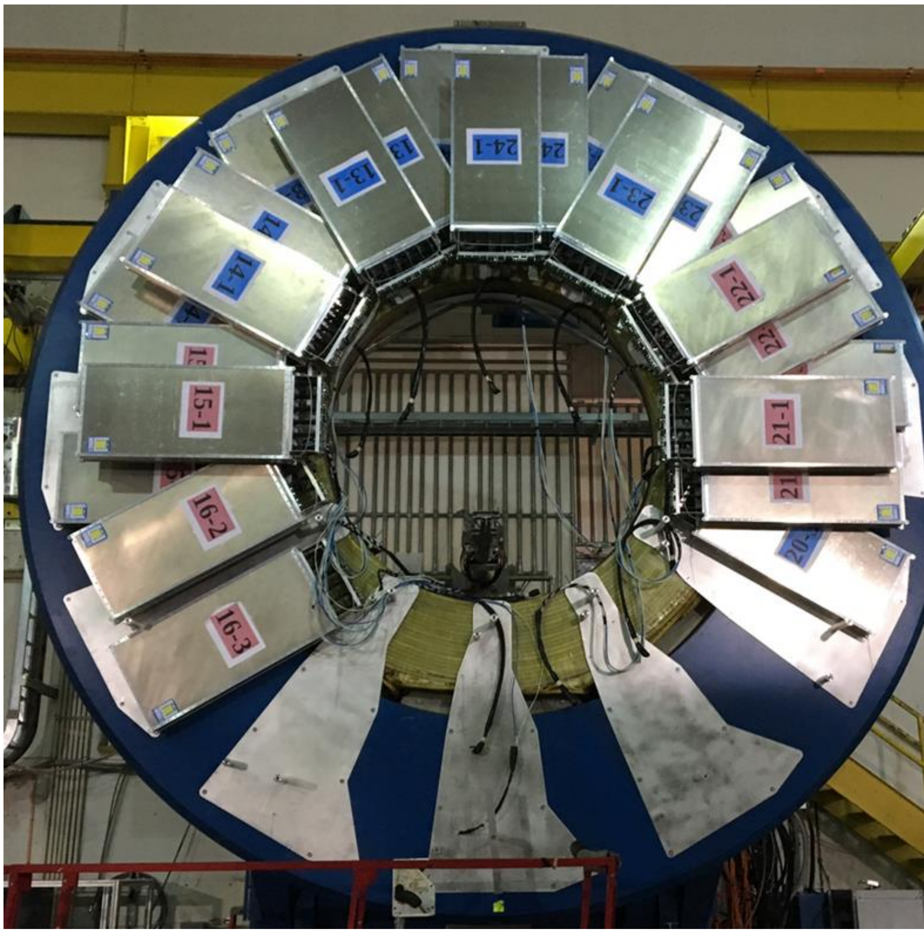
iTPC Upgrade – Current Performance

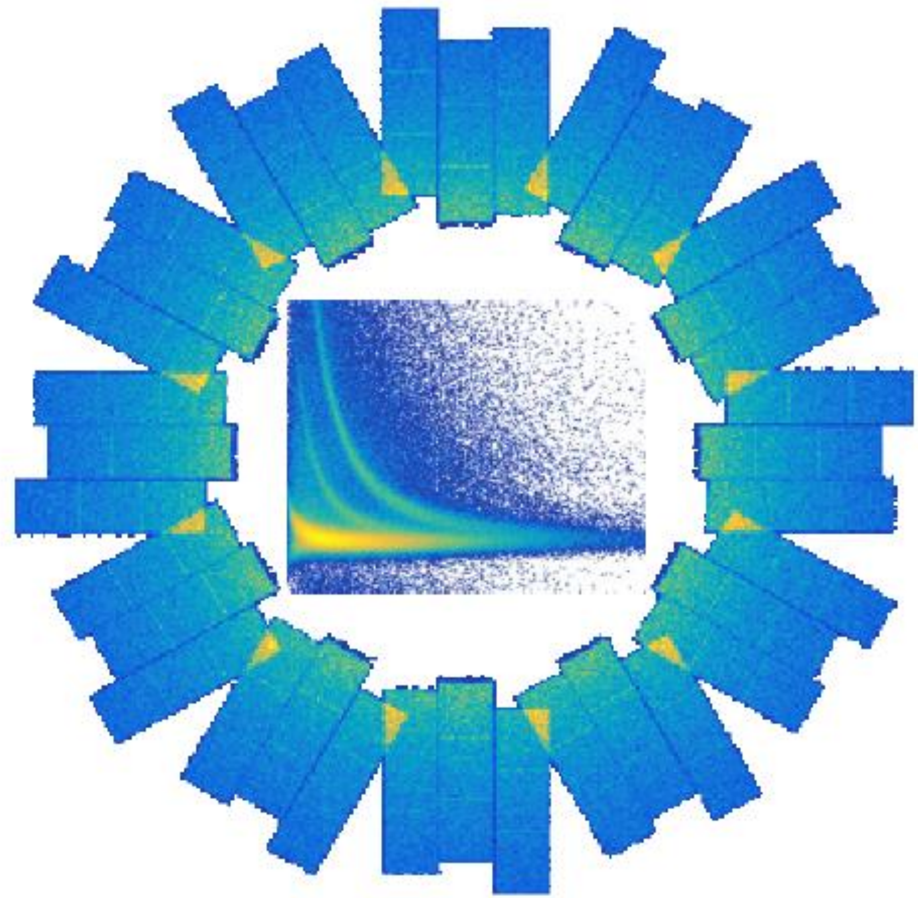




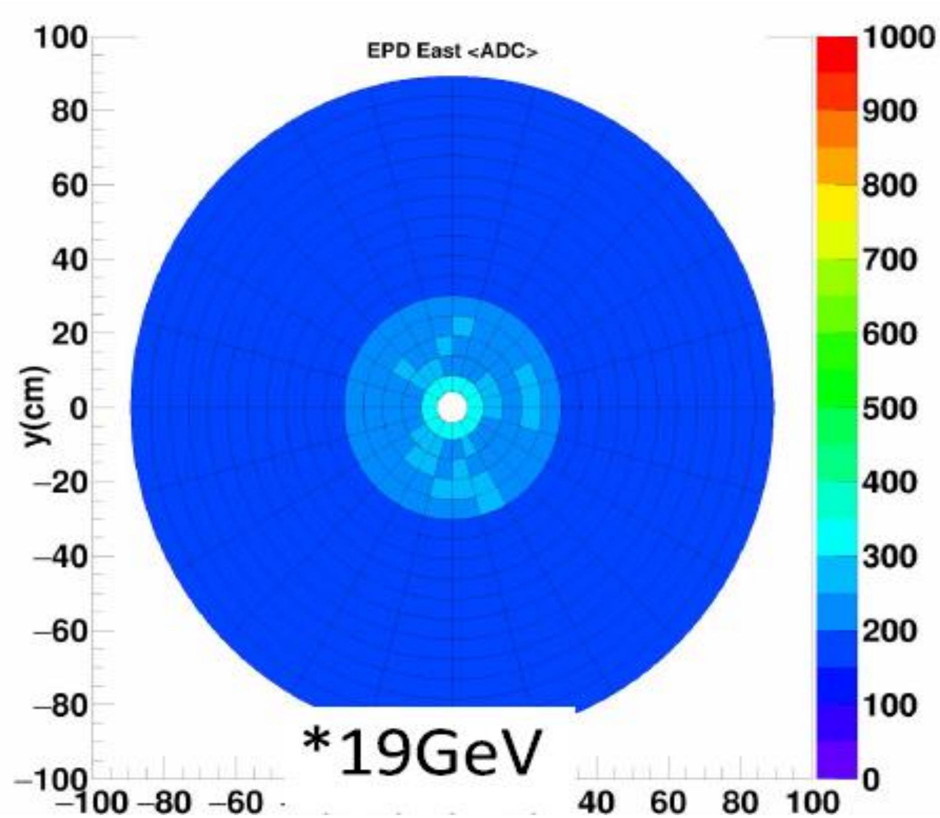
eTOF Upgrade – Current Performance

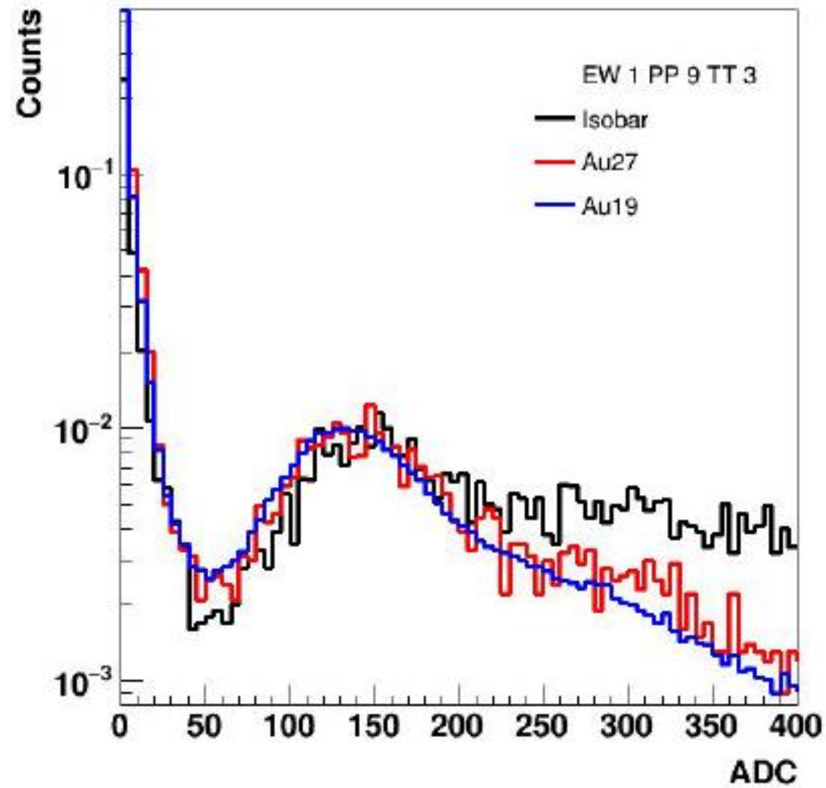
System time resolution → 85 ps
Individual counter time resolution → 65 ps





EPD Upgrade – Current Performance





Talks at this meeting presenting FXT results:

- K15 – 02 Zach Sweger – Centrality Determination
- K15 – 05 Yu Zhang – Higher order cumulants
- K15 – 06 Jonathan Cap – Lambda Fluctuations
- L15 – 02 Sooraj Radhakrishnan – v_1 and v_2 of π, K , p
- L15 – 03 Guannan Xie – Phi production
- L15 – 04 Ding Chcn – Flow of ϕ mesons
- L15 – 07 Xionghong He – v_1 and v_2 of light nuclei
- L15 – 08 Hui Lui – Light nucleus production
- L15 – 09 Yue Hang Leung -- Hypernuclei