Revisiting the AGS Heavy Ion Program and Looking Forward to the Fixed-Target Program at STAR

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University of California, Davis

Abstract

In the 1980's and 90's the AGS initiated a heavy-ion beam program with both silicon and gold beams. A suite of dedicated experiments established the systematics for production of light charged particles, strangeness, light nuclei, and anti-particles, as well as systematics for flow and femtoscopy. Those experiments established the design of the RHIC detectors and trained the personnel who would become leaders in the RHIC program. Recently, there has been renewed interest in the energy region covered by the AGS heavy-ion program. New facilities are being built Germany and Russia and proposed in Japan and China. And a conclusion of the first beam energy scan at RHIC was that it would be necessary to revisit the AGS energy range by installing a fixed-target within the STAR experiment. This talk will review key results from the AGS heavy-ion program, and compare those to results from the STAR fixed-target test runs, and outline the proposed physics program.

Outline

- The AGS heavy-ion program
  - History and overview of AGS heavy-ion program
  - Particle spectra and yields
  - Collective Behavior
  - HBT
- The fixed-target program at STAR
  - History and overview
  - Review of test run results
  - Preview of 2018 – first physics run at 3.0 GeV
  - Plans for runs in 2019, 2020, and 2021
- Perspective and Conclusions

Alternating Gradient Synchrotron

- The first proton accelerator utilizing strong-focusing principle
- July 29, 1960: First beam, 33 GeV
- Three Nobel Prizes:
  - 1962: L. Lederman, M. Schwartz and J. Steinberger

    muon neutrino

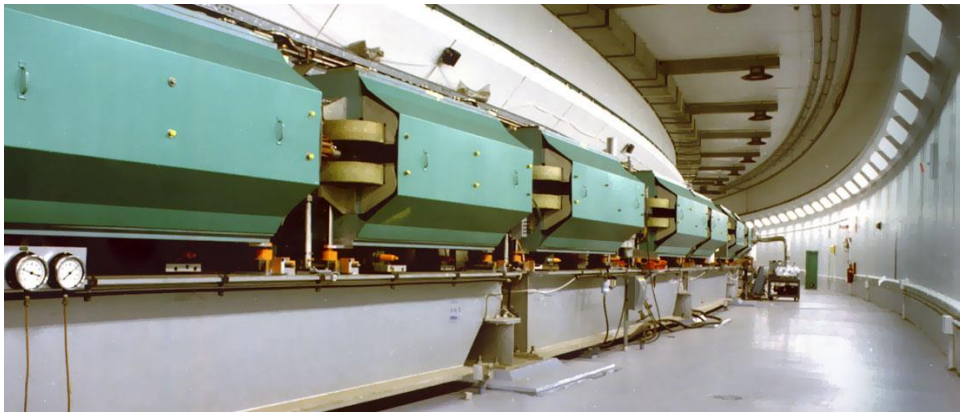
    1988 Nobel Prize
  - 1964: J. Cronin and V. Fitch

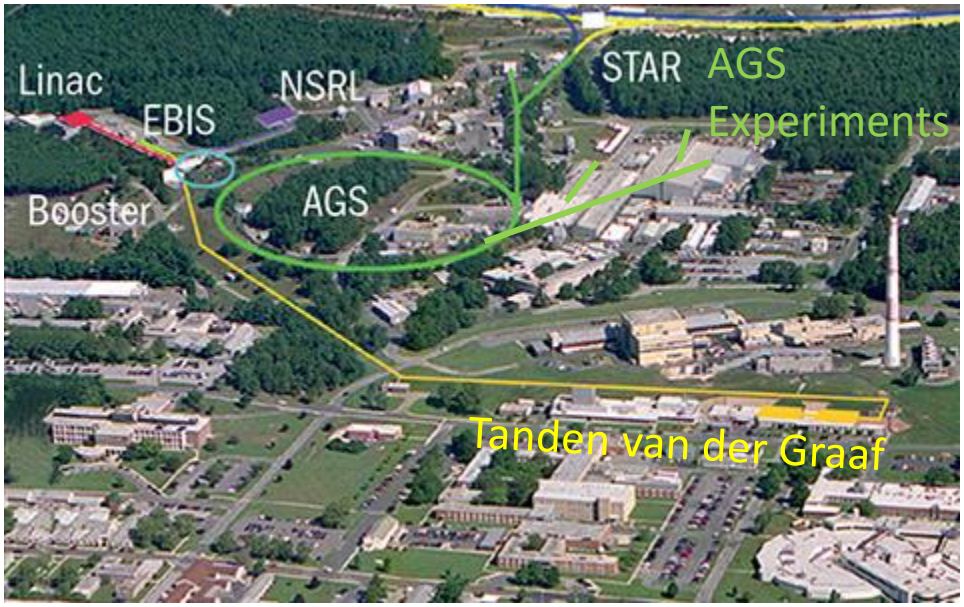
    CP violation in Kaon decay

    1980 Nobel Prize
  - 1974: S. C.C. Ting

    discovery of J/ψ

    1976 Nobel Prize
- 1988-92: Silicon beams at 14.6 AGeV/c
- 1993-96: Gold beams, 2.8-11.7 AGeV/c
- 1999-present: Injector for RHIC

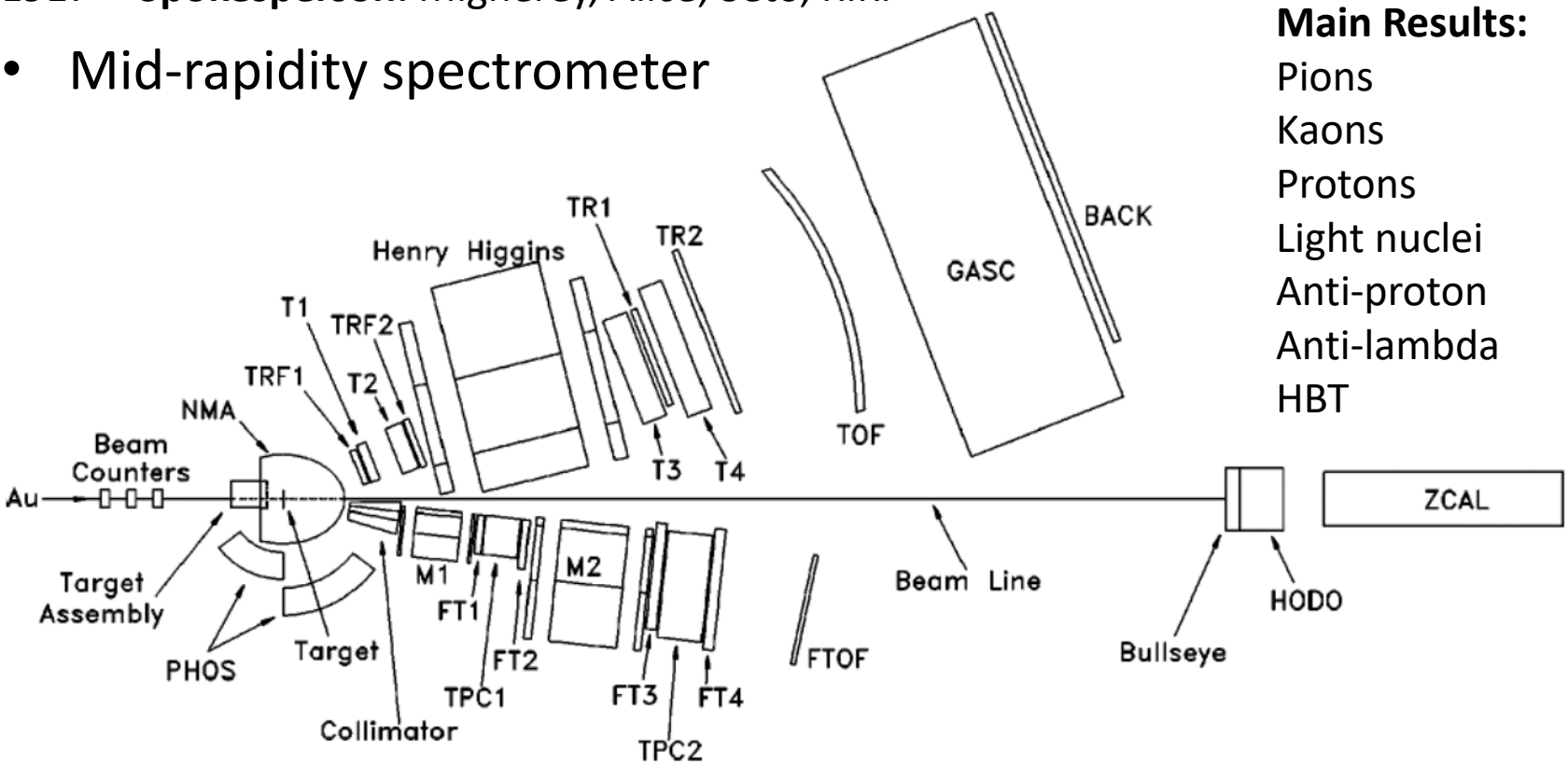




E802/E859/E866/E917 Experiment

E802 – **Spokesperson:** Chellis Chasman, Shoji Nagamiya
E859 -- **Spokesperson:** Ledoux, Robert J.; Remsberg, Louis P.; Zajc, William A.
E866 -- **Spokesperson**: Chasman, Chellis; Hamagaki, Hideki; Steadman, Steve G.
E917 -- **Spokesperson:** Mignerey, Alice; Seto, R.K.

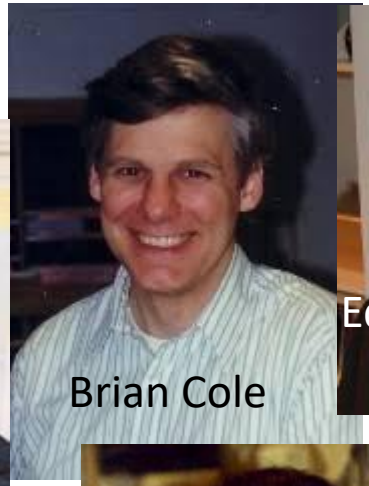
- Mid-rapidity spectrometer



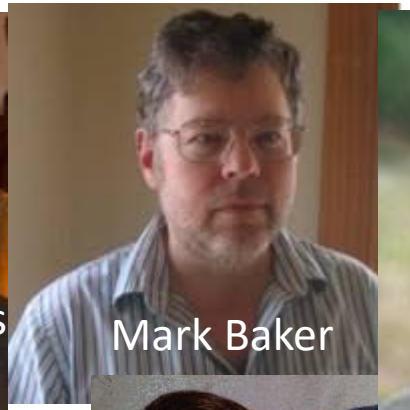
Main Results:
Pions
Kaons
Protons
Light nuclei
Anti-proton
Anti-lambda
HBT

E802/E866/E917


Huan Huang


Brian Cole


Edmundo Garcia-Solis


Mark Baker


Vince Cianciolo


Ron Soltz


Eleanor Judd


Fuqiang Wang


Jack Engelage


Dave Morrison


James Dunlop


Tapan Nayak


Alan Wuosmaa

JH Lee
Robert Pak

E810/E891 Experiment

E810 – **Spokesperson:** Lindenbaum, S.J.; Platner, E.D.
E891 – **Spokesperson:** Platner, E.D.

- Time Projection Chamber

Main Results:
K^0s (Si+Au)
Lambda (Si+Au)

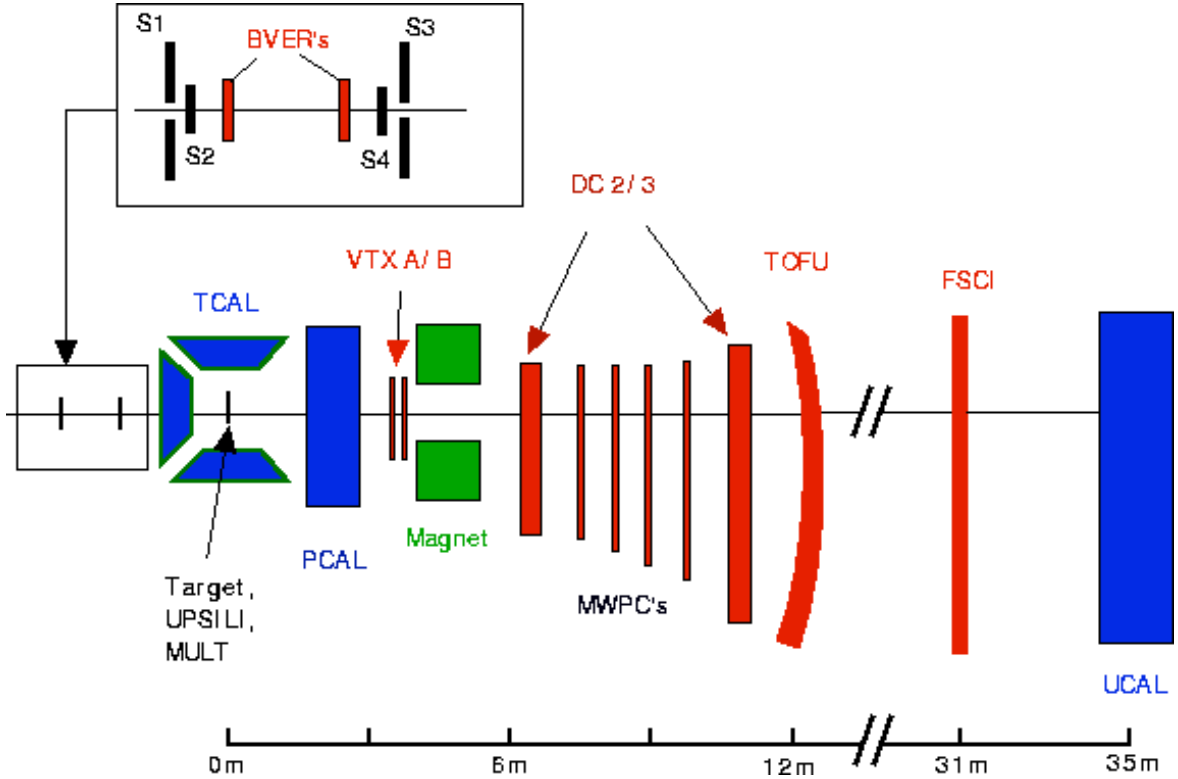
E810 – Tim Hallman (PhD 82 Johns Hopkins)

E814/E877 Experimental Setup

E814 – **Spokesperson:** Braun-Munzinger, Peter
E877 – **Spokesperson:** Braun-Munzinger, Peter

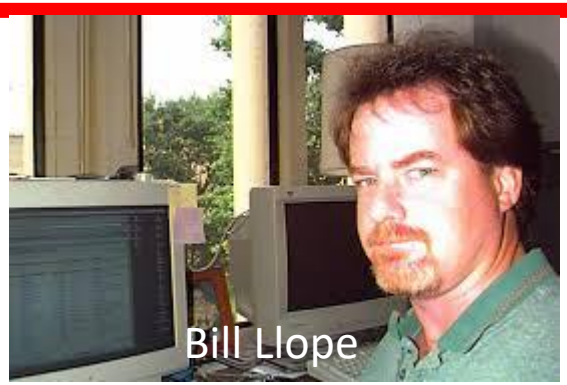
- Forward spectrometer
- TOF & Calorimetry

Main Results:
Pions
Protons
Light nuclei
Lambda
Anti-lambda
Directed flow
Elliptic flow
HBT



E814/E877


Sergey Panitkin


Bill Llope


Claude Pruneau


Nu Xu


Gabor David


Norbert Herrmann


Rena Bellwied


Victoria Greene

ShinIchi Esumi

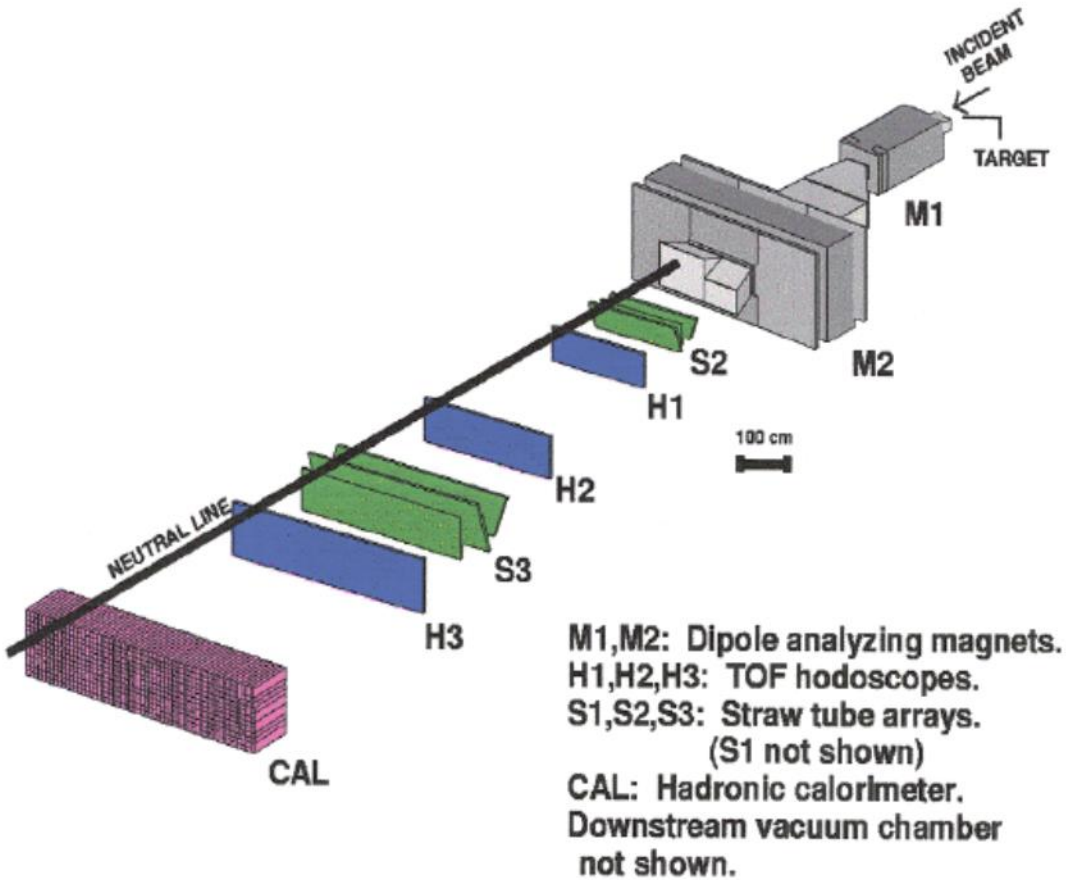
E864 Experiment

E864 – **Spokesperson:** Majka, Richard D.; Sandweiss, Jack
E941 – **Spokesperson:** Huan Huang

- Forward spectrometer
- TOF & Calorimetry

Main Results:
Protons
Light nuclei
Anti-proton
Anti-deuteron

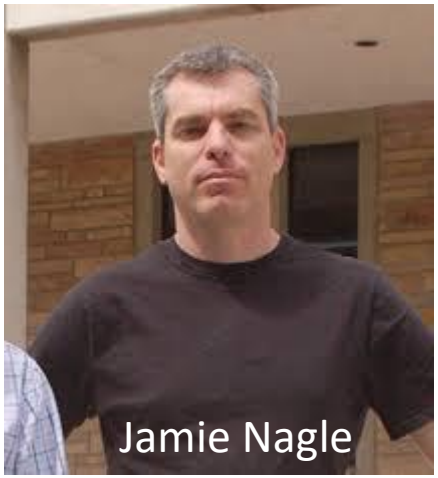
Found no strangelets

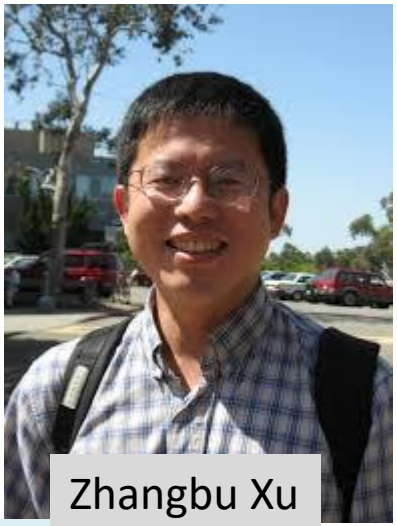


E864


John Lajoie

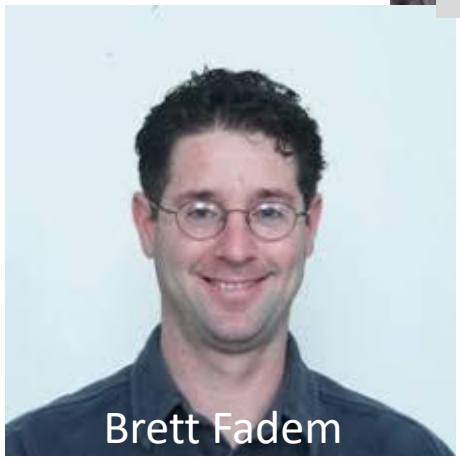

Ken Barrish


Jamie Nagle


Zhangbu Xu


Gene Van Buren

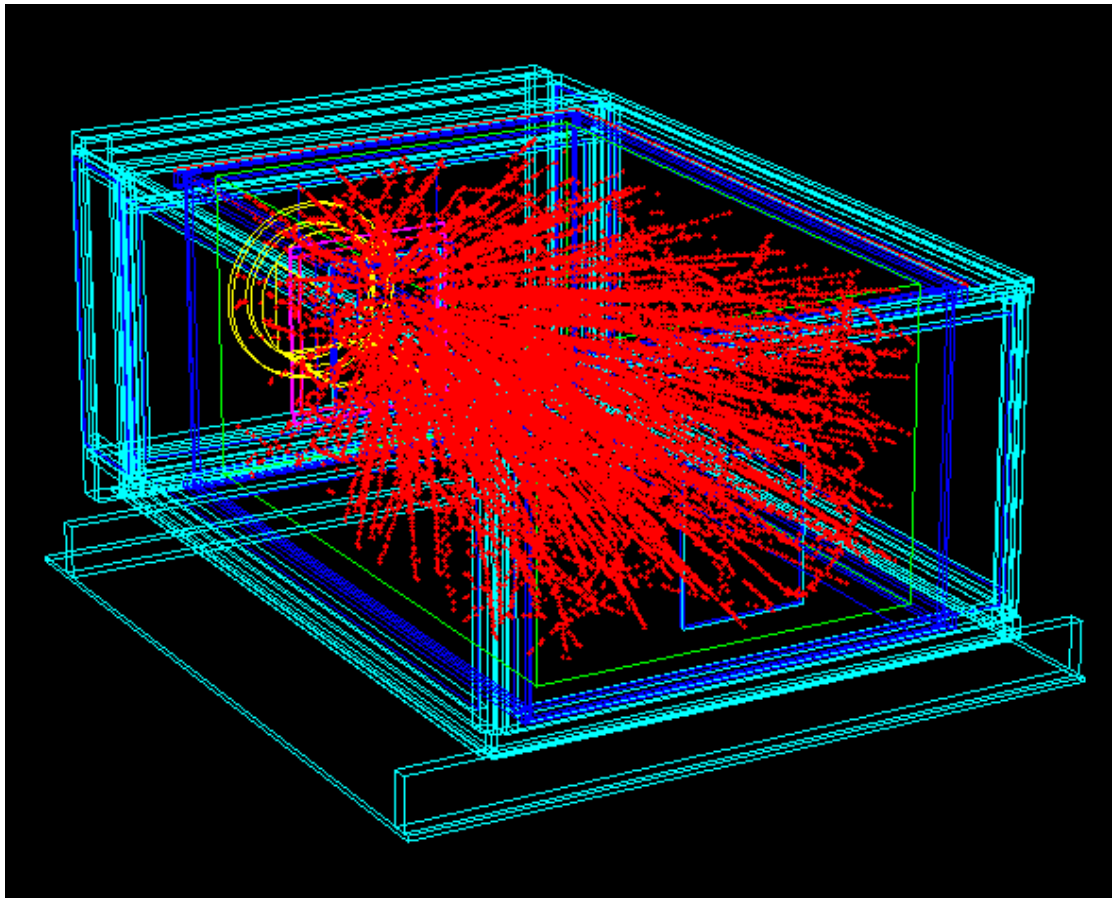

Evan Finch


Brett Fadem

E895/E910 Experiment

E895 – **Spokesperson**: Gulshan Rai
E910 -- **Spokesperson:** Cole, Brian A.

- Time Projection Chamber



Main Results:
Pions
Protons
Lambdas
Directed flow
Elliptic flow
HBT

E895/E910


Chris Pinkenburg


Mike Heffner


Mike Lisa


Jerome Lauret


Maskia Mioduszewski

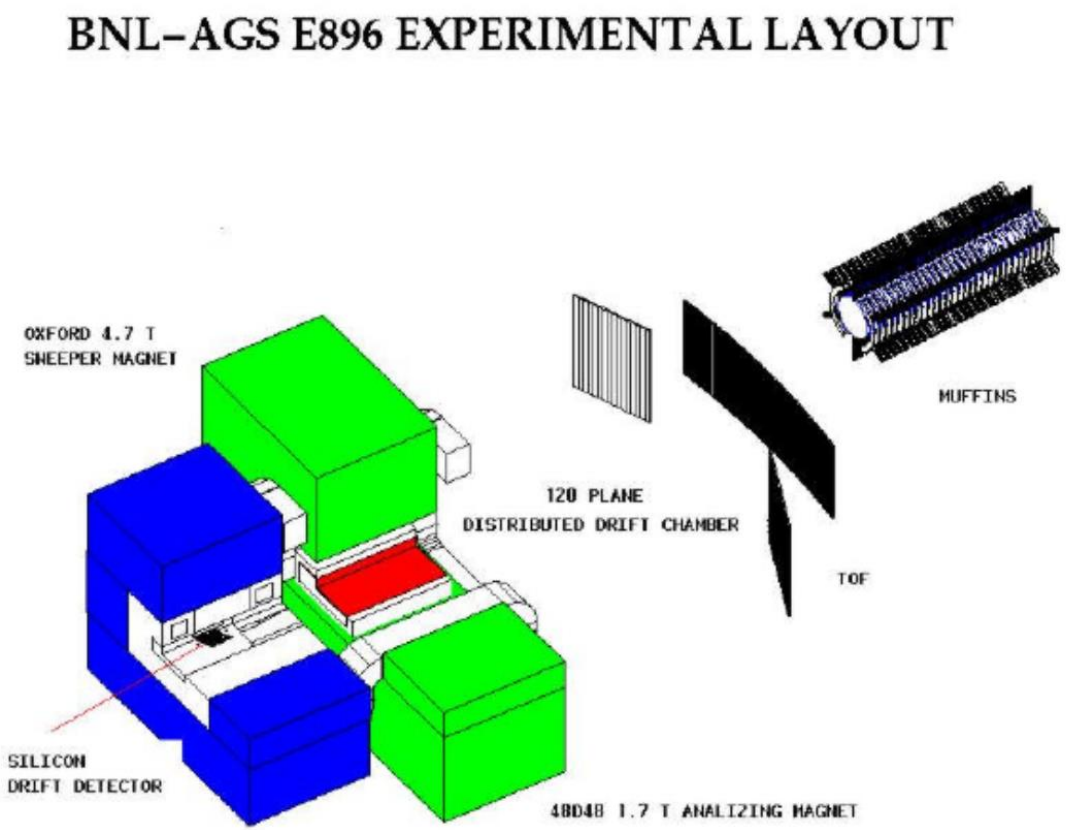

Jenn Klay


Richard Witt

E896 Experiment

E896 -- Spokesperson: Crawford, Henry J.; Hallman, Tim J

Helen Caines



AGS Results: pion, kaon, proton spectra

Spectra – pions:

- E895_PRC68(2003)054905 – π^+ and π^- spectra and dN/dy at 2, 4, 6, 8 AGeV
- E802_PRC57(1998)R466 – π^+ and π^- spectra and dN/dy at 10.5 AGeV
- E877_PRC62(2000)024901 -- π^+ and π^- high rapidity spectra and dN/dy at 10.5 AGeV
- E917_PLB476(2000)1 – π^+ mid-rapidity spectra at 2, 4, 6, 8 AGeV

Spectra – Kaons:

- E866_PLB490(2000)53 – K^+ and K^- mid-rapidity spectra at 2, 4, 6, 8, 10.5 AGeV
- E866_NPA630(1998)571c – K^+ and K^- dN/dy at 10.5 AGeV

➔ Need Charged kaon dN/dy for AGS scan energies

Spectra – Protons:

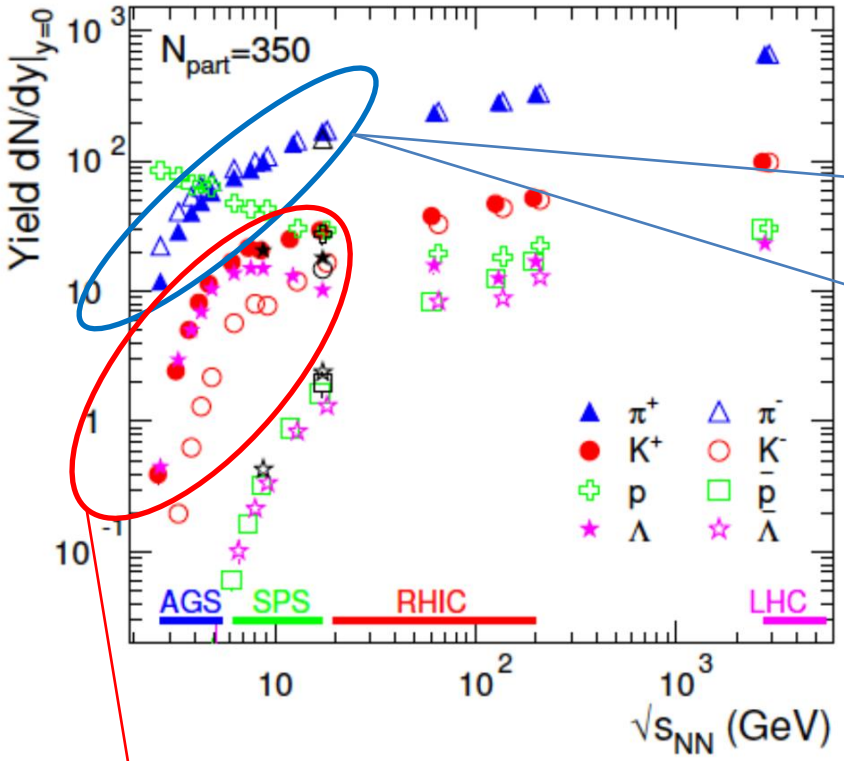
- E895_PRL88(2002)102301 – proton spectra and dN/dy at 2, 4, 6, 8 AGeV
- E917_PRL86(2001)1970 – proton spectra and dN/dy at 6, 8, 10.5 AGev

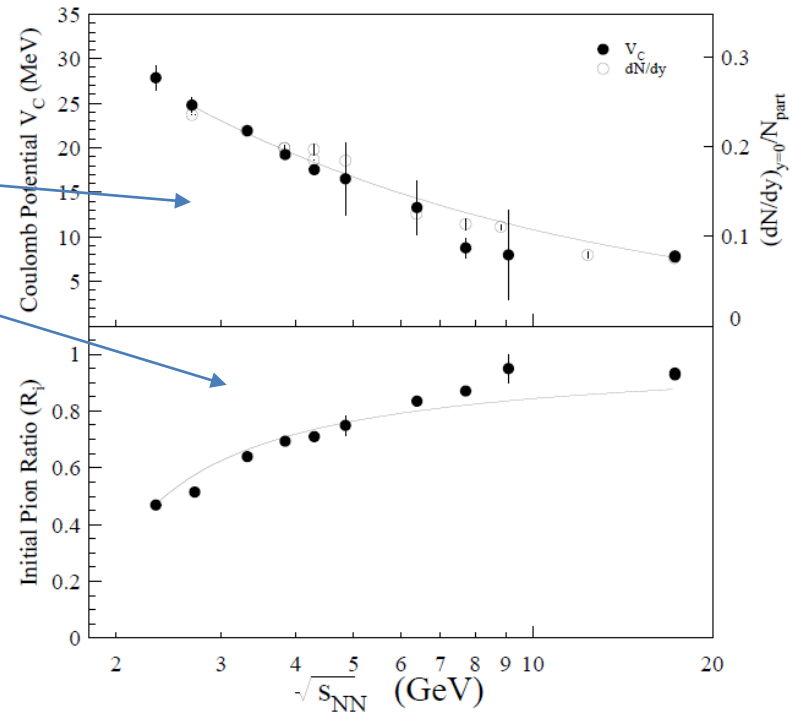
} Some issues

- E802_PRC57(1998)R466 – proton spectra and dN/dy at 10.5 AGeV
- E802_PRC60(1999)064901 – proton spectra and dN/dy at 10.5 AGeV
- E877_PRC56(1997)3254 – forward rapidity proton spectra at 10.5 AGeV
- E877_PRC62(2000)024901 – forward rapidity proton spectra at 10.5 AGeV

AGS Results: pion and kaon spectra

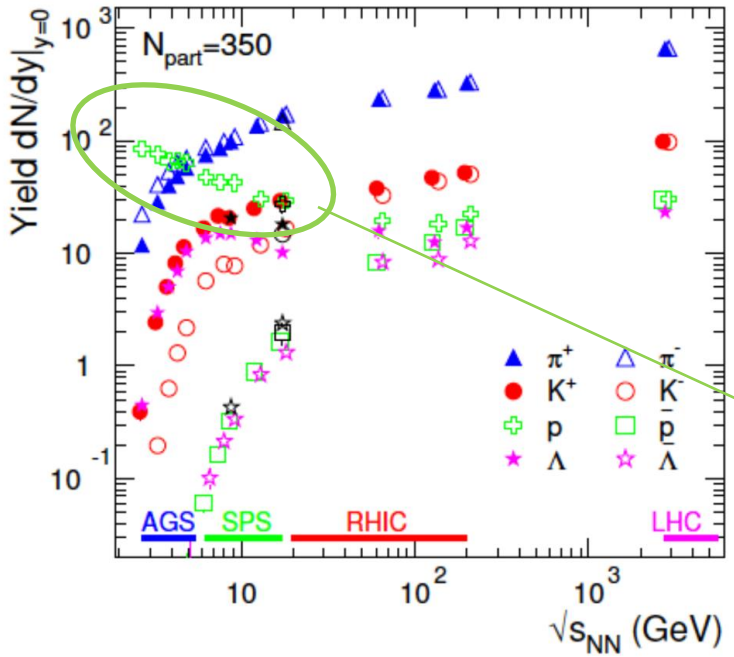
- pion ratio comes from initial n:p ratio as low p_T pions are produced primarily through the Δ channel ➔ accounted for by μ_Q is statistical models related to stopping
- Pion ratios provide another way to 'image' the size of the source

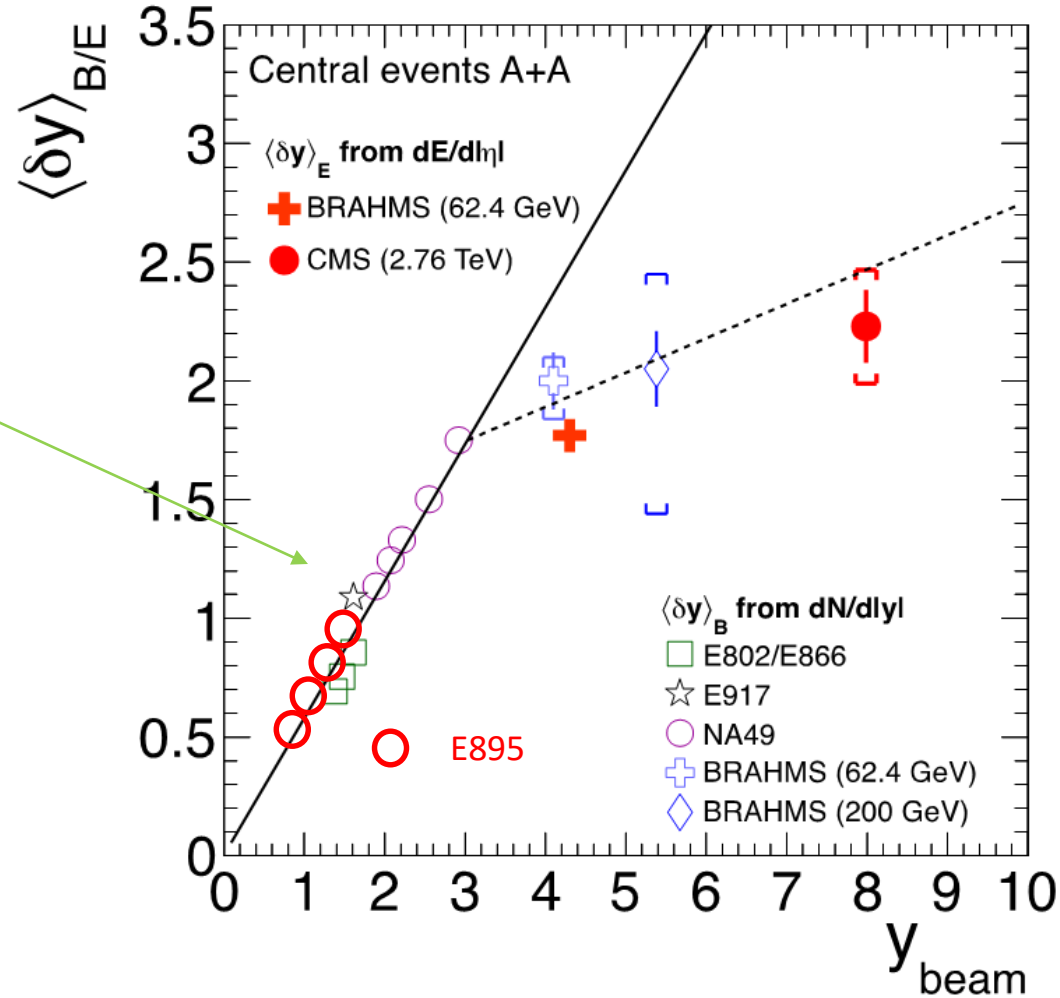




- Kaon ratios come from associated production, which feeds K^+ only

AGS Results: proton spectra





Evolution of stopping, a drop in stopping would indicate a development of transparency

AGS Results: anti-protons and light nuclei

Spectra – Other:

- E864_PRC60(2000)064903 – neutron spectra and dN/dy at 10.5 AGeV
- E864_PRC61(2000)064908 – p, d, t, ^{3}He, ^{4}He spectra and yields at 10.5 AGeV
- E864_PRL85(2000)2685 – anti-deuteron yields at 10.5 AGeV
- E864_PRL79(1997)3351 – anti-proton yields at 10.5 AGeV
- E917_PRL(2001)242301 – anti-proton spectra at 10.5 AGeV
- E802_PRL81(1998)2650 – anti-proton spectra t 10.5 AGeV
- E814_PRC61(2000)044906 – deuteron spectra at 10.5 AGeV
- E802_PRC60(1990)064901 – deuteron spectra and dN/dy at 10.5 AGeV
- E814_PRC61(2000)044906 – t and ^{3}He yields at 10.5 AGeV

Need to map these out across the AGS energy scan range

AGS Results: Strangeness (V^0's)

V^0s – Kaons:

- No spectra or yields

V^0s – Lambdas:

- E877_PRC63(2001)014902 – Λ spectra and dN/dy at 10.5 AGeV
- E895_PRL91(2003)202301 – Λ yields at 6 AGeV

V^0s – Anti-Lambdas:

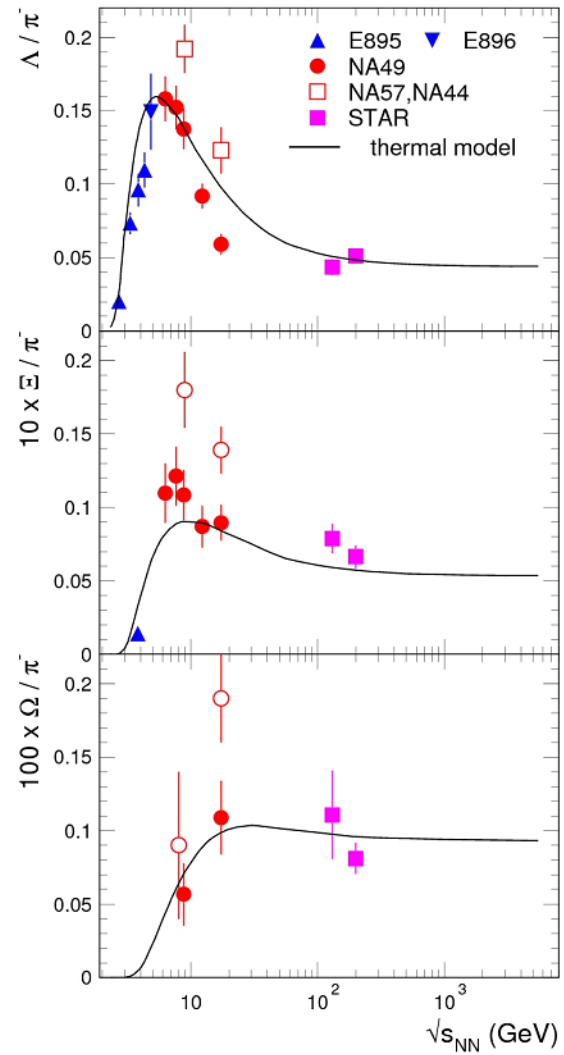
- E917_PRL(2001)242301 – mid-rapidity yield at 10.5 AGeV

V^0s – Phi:

- E917_PRC69(2004)054901 – ϕ mid-rapidity spectra t 10.5 AGeV

V^0s – Cascades:

- E895_PRL91(2003)202301 – Ξ^- yields at 6 AGeV



Need energy scan results to identify the turn on of multi-strange baryons

AGS Results: Directed Flow

Directed Flow – pions:

- E877_PRC56(1997)3254 – π^+ and π^- at 10.5 AGeV ← Need energy scan

Influenced by shadowing and Coulomb

Directed Flow – Kaons:

- E895_PRL85(2000)940 – K^0_S at 6 AGeV ← Need charged kaons

Influenced by shadowing

Directed Flow – Protons:

- E895_PRL84(2000)5488 – at 2, 4, 6, 8 AGeV
- E877_PRC56(1997)3254 – at 10.5 AGeV

No anticipated minimum →

Directed Flow – Anti-protons:

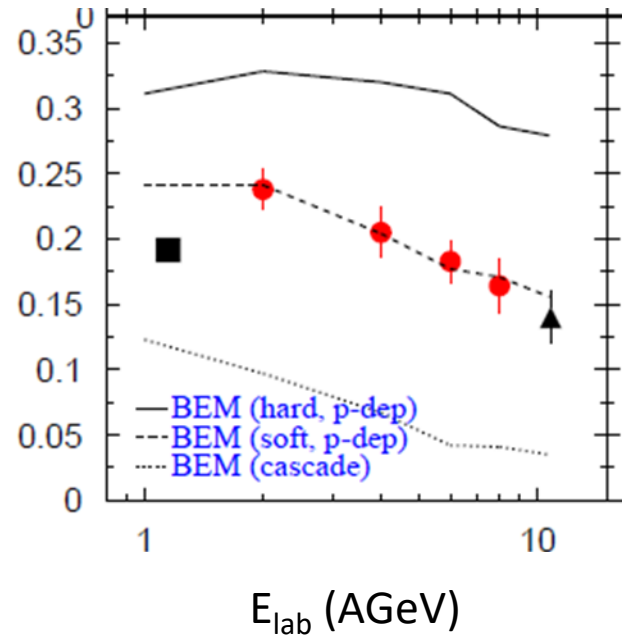
- E877_PLB485(2000)319 – at 10.5 AGeV

← Need energy scan

Directed Flow – Lambdas:

- E895_PRL86(2001)2533 – at 2, 4, 6 AGeV
- E877_PRC63(2001)014902 – at 10.5 AGeV

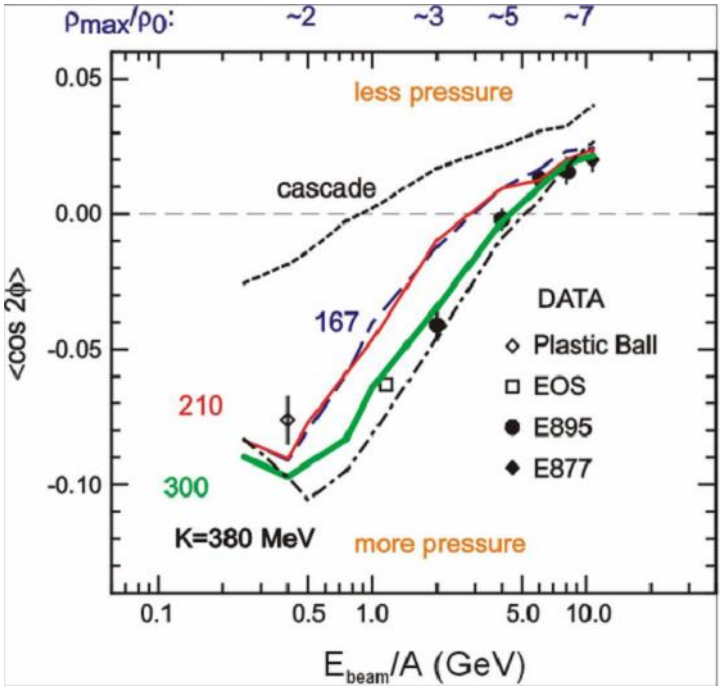
Follow protons



AGS Results: Elliptic Flow

Elliptic Flow – Protons:

- E895_PRL83(1999)1295 – at 2, 4, 6, 8 AGeV
- E877_PRC56(1997)3254 – at 10.5 AGeV
- E895_PRC66(2002)021901 – at 2, 4, 6 AGeV with centrality cuts



- Crossover from squeeze-out to in-plane at 4 AGeV
- Relevance to the change of stiffness of EoS?

Need other particle species

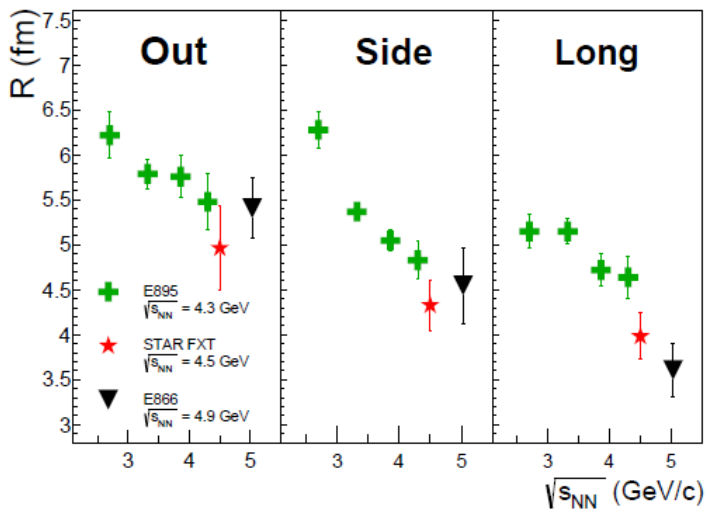
AGS Results: HBT

HBT – Pions:

- E895_PRL84(2000)2798 – R_{out}, R_{side}, R_{long} at 2, 4, 6, 8 AGeV
- E802_PRC66(2002)054096 – R_{out}, R_{side}, R_{long} at 10.5 AGeV
- E877_PRL78(1997)2916 – R_{out}, R_{side}, R_{long} at 10.5 AGeV

HBT – protons:

- E814_PRC60(1999)054905 – correlation functions for protons



Across the AGS energy range, the source radii are falling

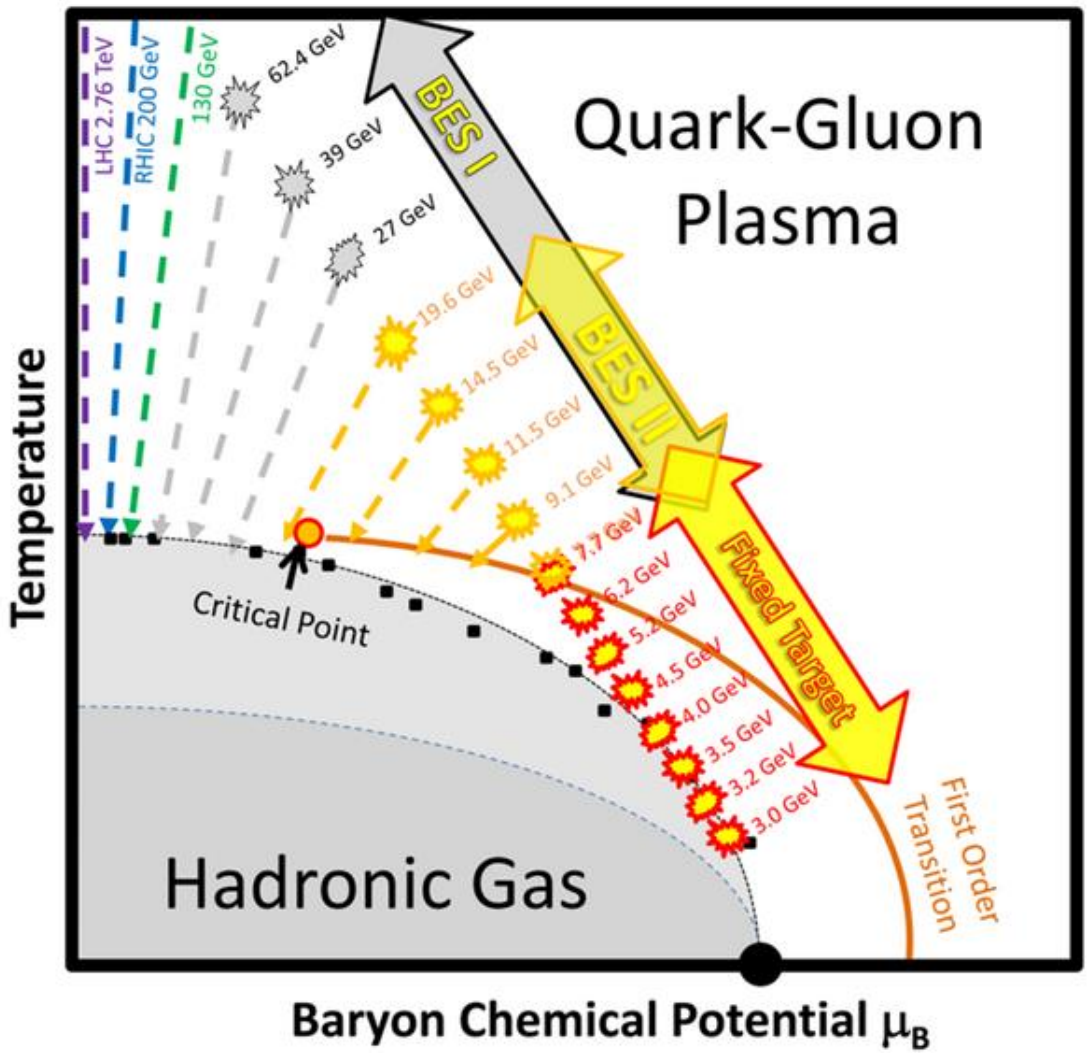
- Need to do negative pion positive pions separately
- Need to get the "tilt" angle
- Need more pp HBT

Fixed-Target Program

The Fixed-Target Program will extend the reach of the RHIC BES to higher μ_B.

Goals:

1) Search for evidence of the first entrance into the mixed phase
2) Control measurements for BES collider program searches for Onset of Deconfinement
3) Control measurements for Critical Point searches



History of Low Energy Running at RHIC

RHIC Runs at or Below Nominal Injection Energy:

1. Au+Au 19.6 GeV 2001	100 k events
2. Cu+Cu 22.4 GeV 2005	250 k events
3. Au+Au 9.0 GeV 2007	0 events
4. Au+Au 9.2 GeV 2008	7 k events
5. Au+Au 7.7 GeV 2010	4 M events
6. Au+Au 11.5 GeV 2010	12 M events
7. Au+Au 5.5 GeV 2010	0 events
8. Au+Au 19.6 GeV 2011	36 M events
9. Au+Au 5.0 GeV 2011	1 event
10. Au+Au 14.5 GeV 2014	20 M events

We learned that background was a serious concern

We conclude that RHIC can not achieve a useful collider event rate at 5.0 GeV

STAR and RHIC recognized the importance to run at energies down to and below 7.7 GeV

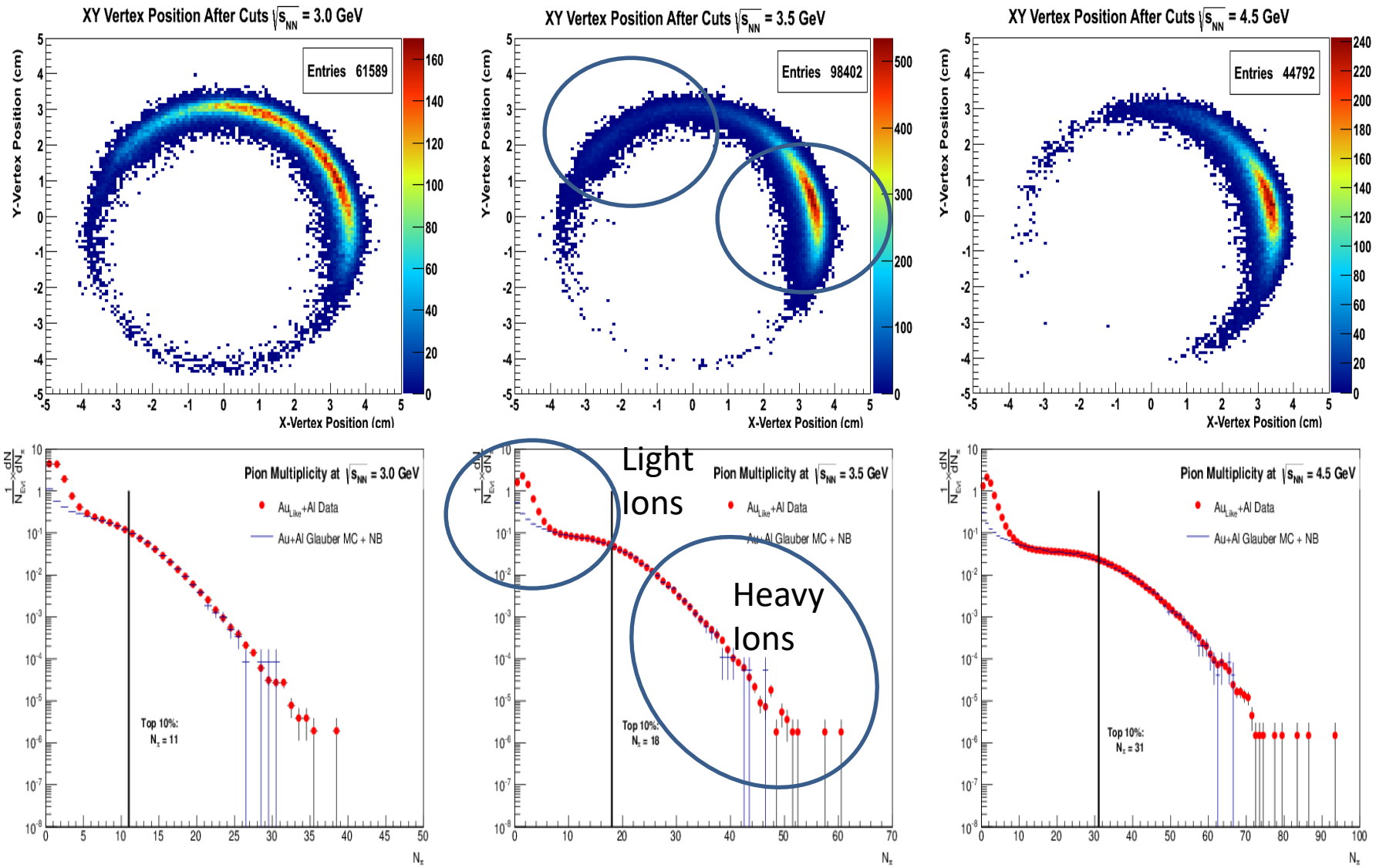
Studies using Beam Halo Background

2010 - 2014

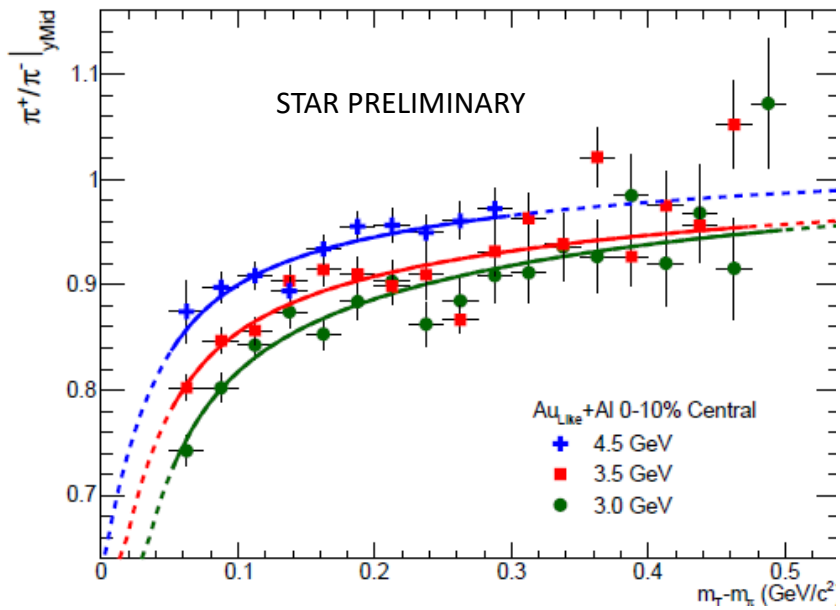
Goals:

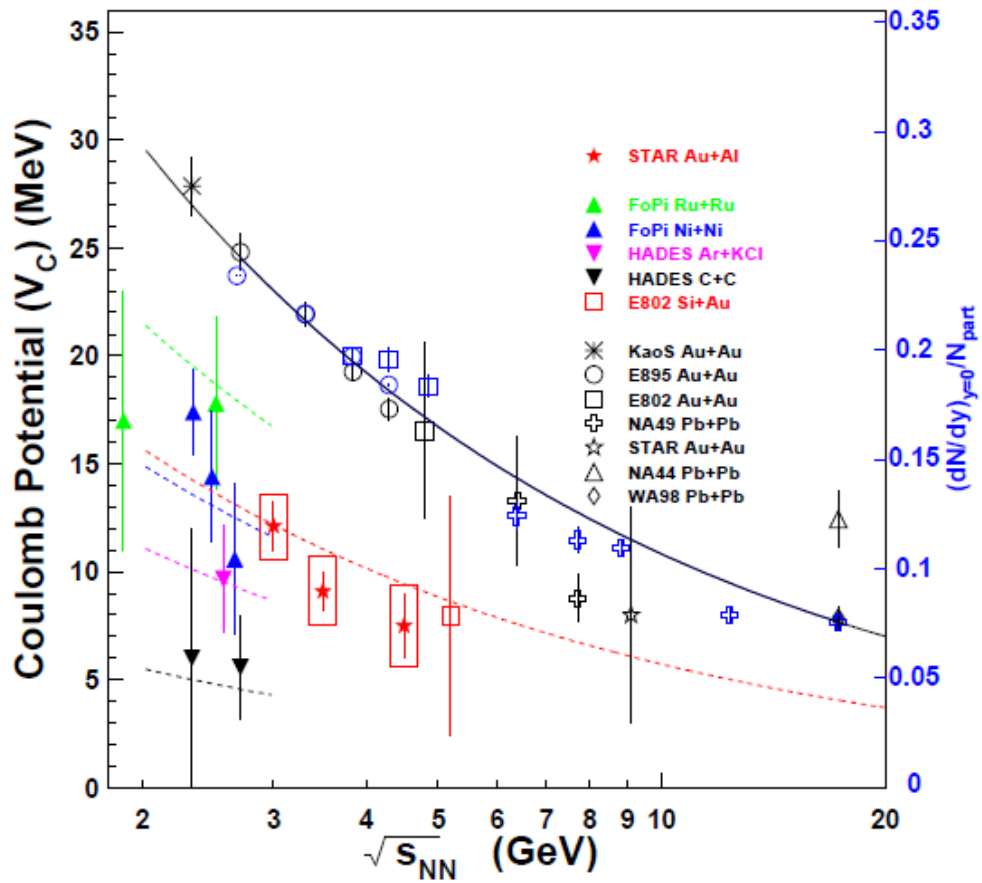
- Understand the Beam Halo Background
- Determine the applicability of STAR for fixed-target
- First of FXT results ➔ Au+Al

Beam Halo on Al Vacuum Pipe



Pion Ratio Analysis





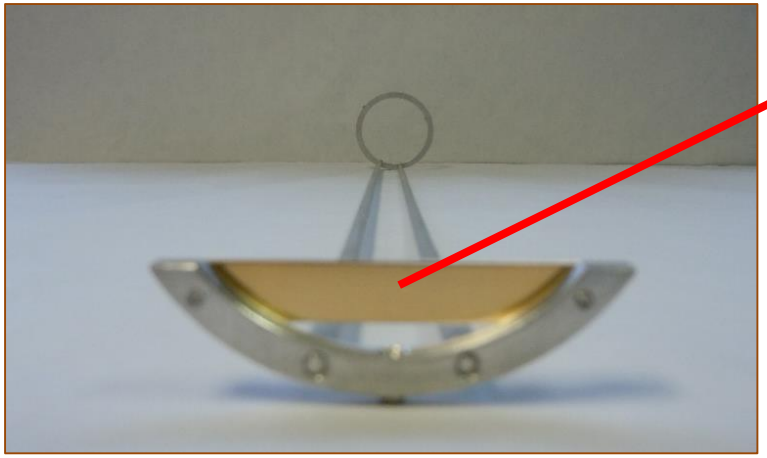
We conclude that there are gold nuclei in the beam halo

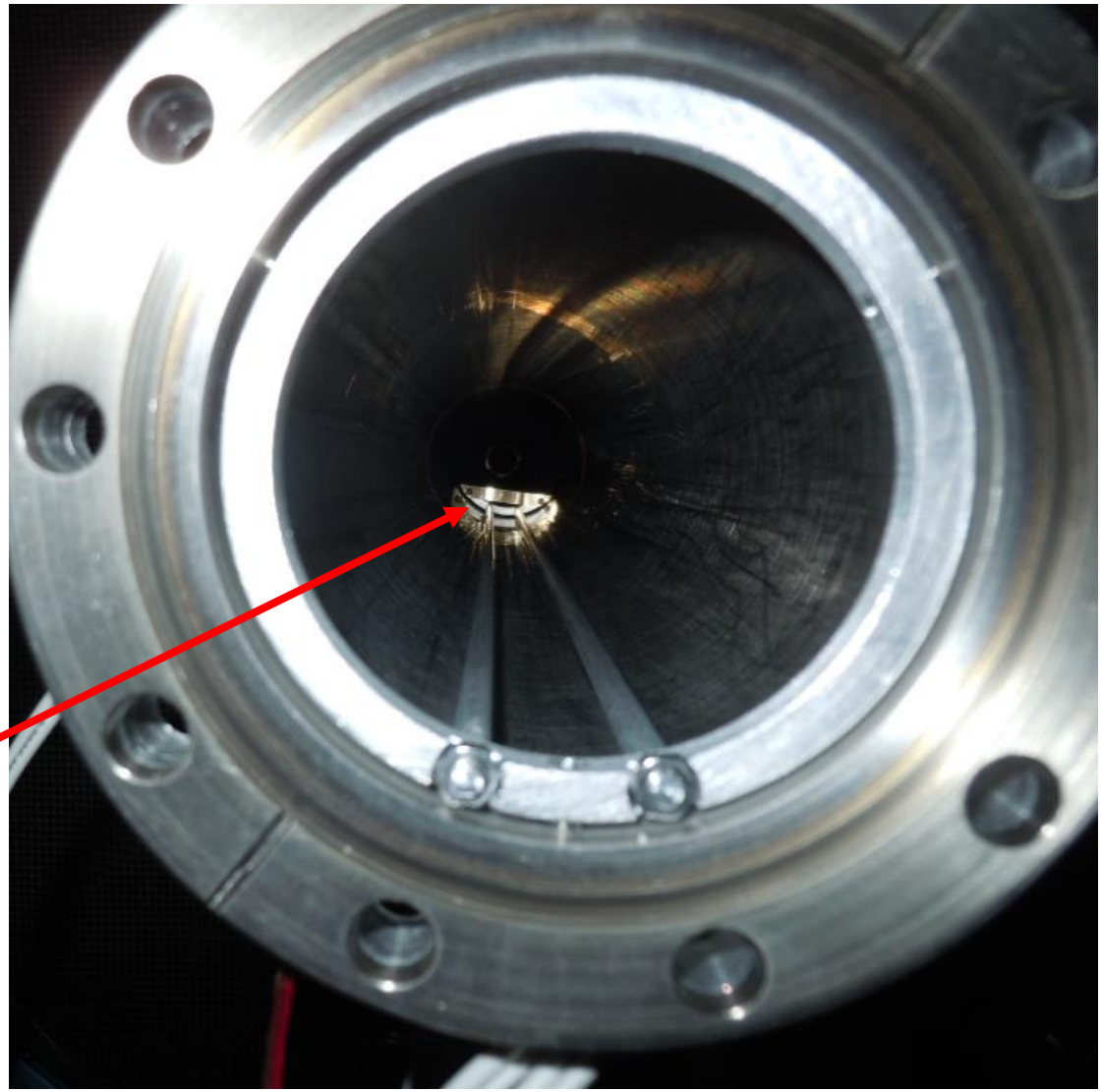
Target Design 2014 and 2015

The success of the beam pipe studies motivated installing an internal gold target

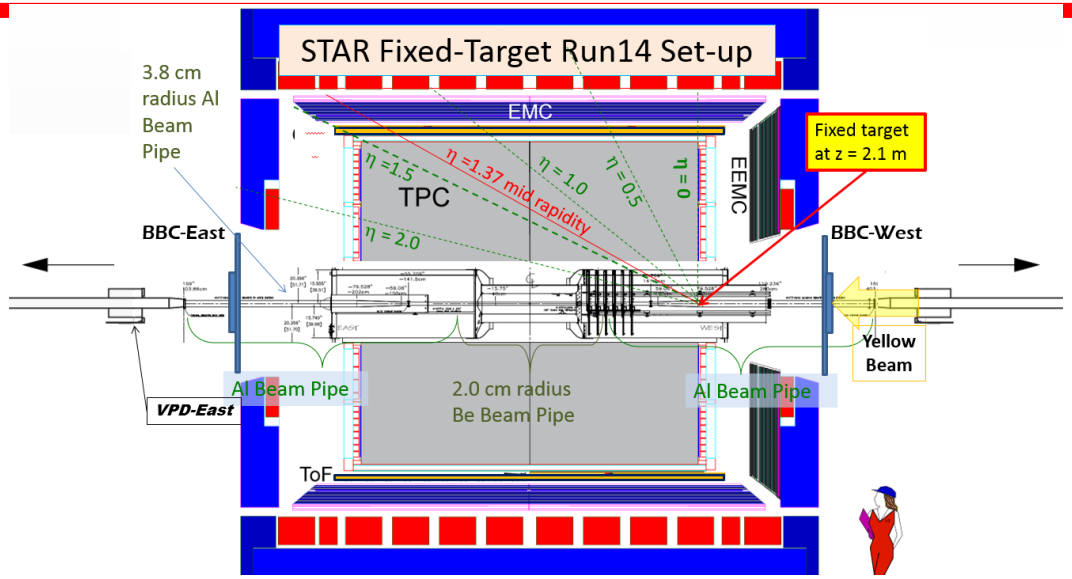
Target design:

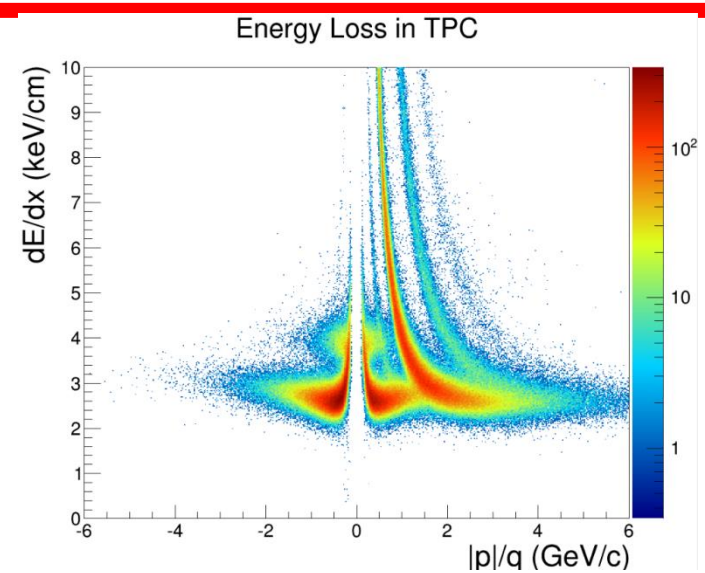
Gold foil
1 mm Thick (4%)
~1 cm High
~4 cm Wide
~2 cm below beam axis
210 cm from IR



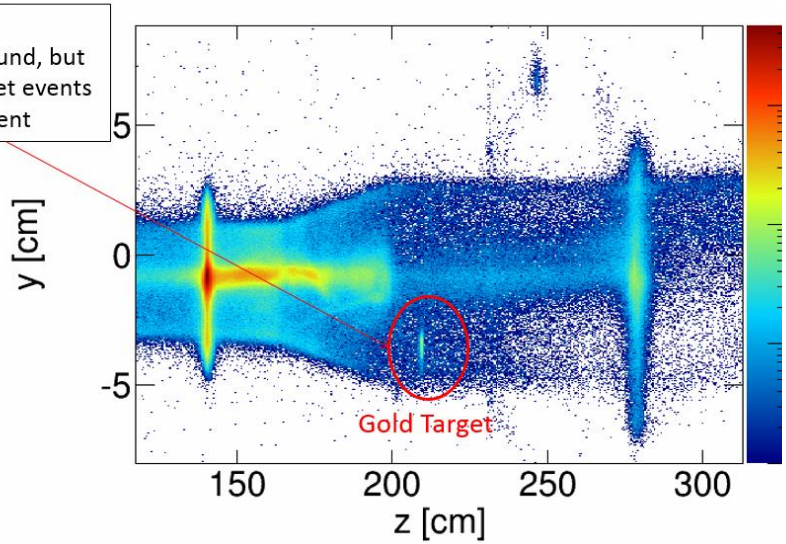


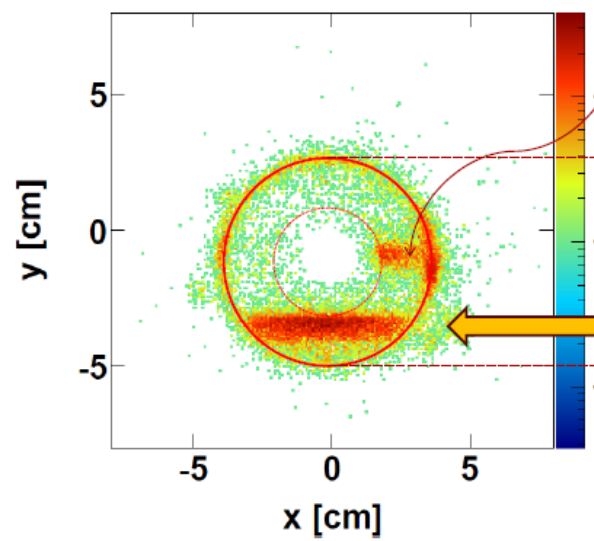
2014 ➔ $\sqrt{s_{NN}}$=3.9 GeV Au halo + Au target



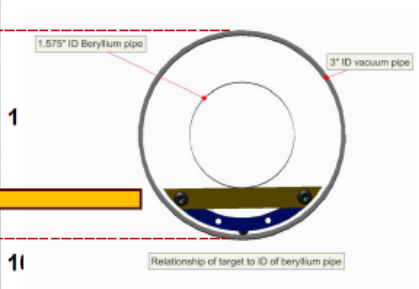


Lots of background, but the target events are evident





The most intense beam halo is deflected by the dipole magnets in the positive *x* direction. These are Au_{Halo}+$Al_{Beampipe}$ background



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 :

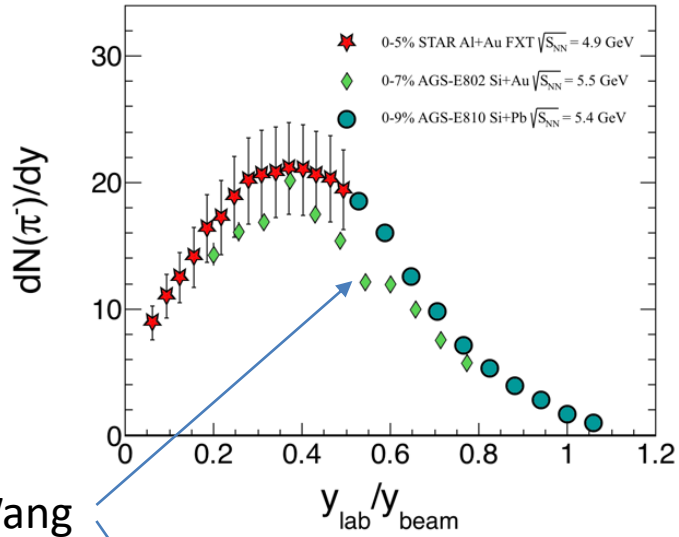
➔ 4 PhD Theses (Kathryn Meehan, Yang Wu, Usman Ashraf, Todd Kinghorn)

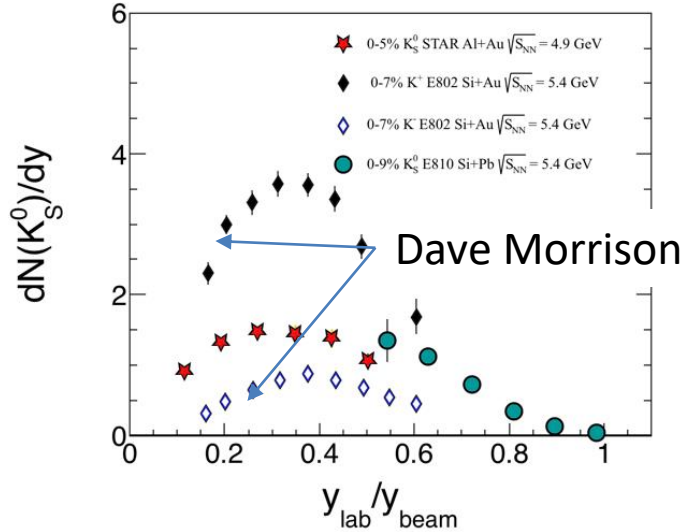
➔ 1 MS Thesis (Lukasz Kozyra)

➔ 1 Postdoctoral project (David Tlusty)

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

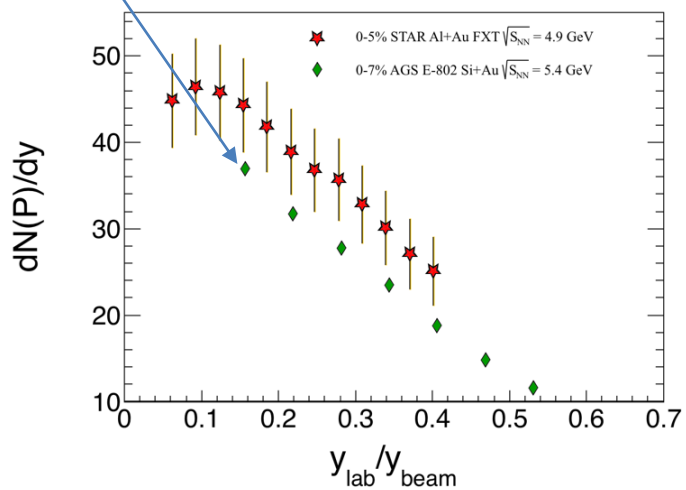
- Compare to AGS Si+Au results
- Yields and consistent

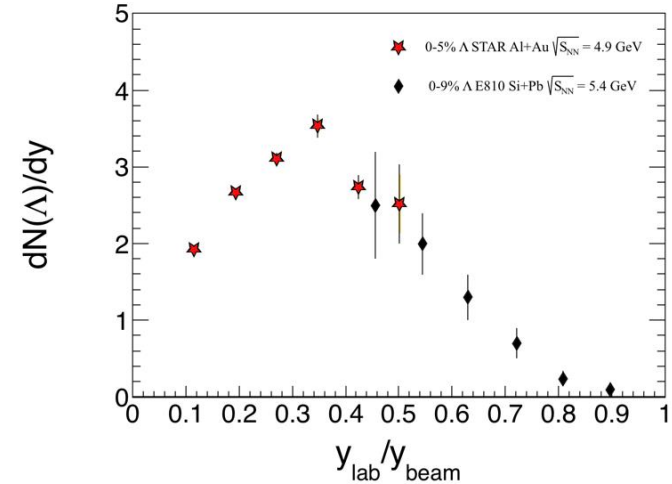




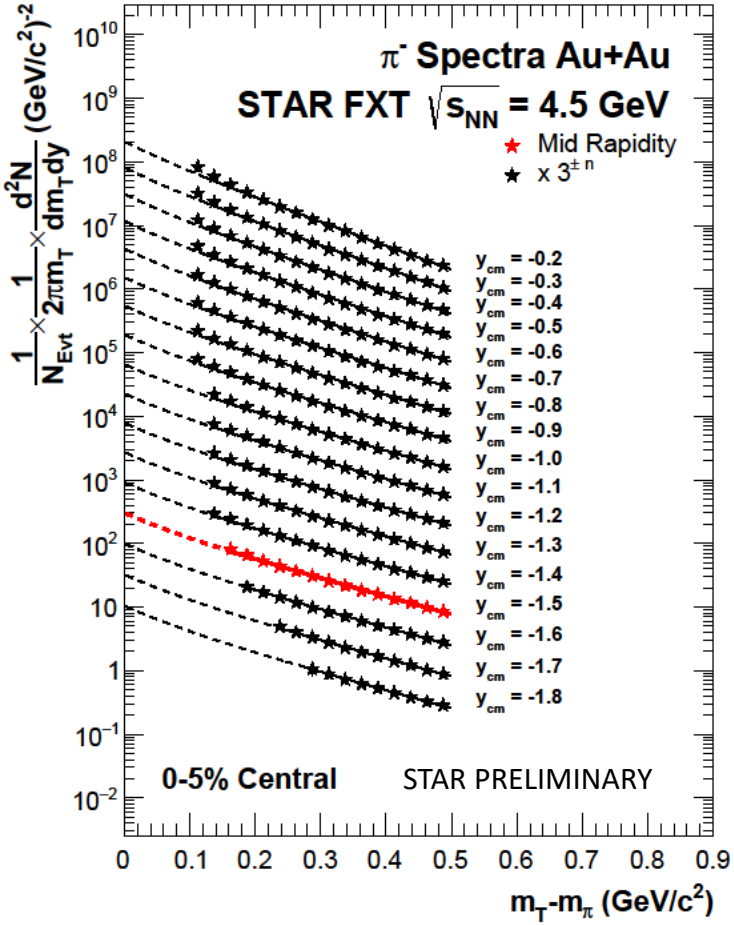
Dave Morrison

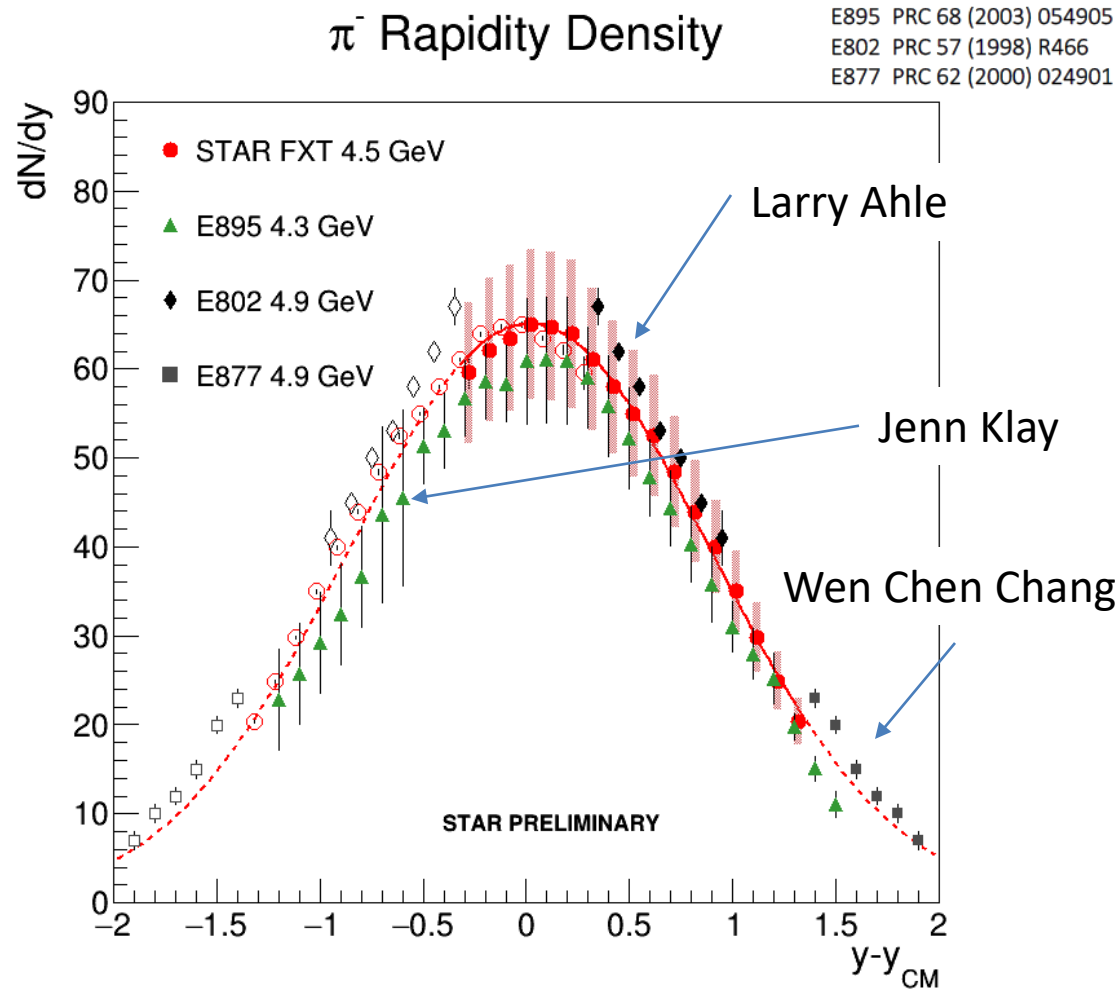
Fuqiang Wang





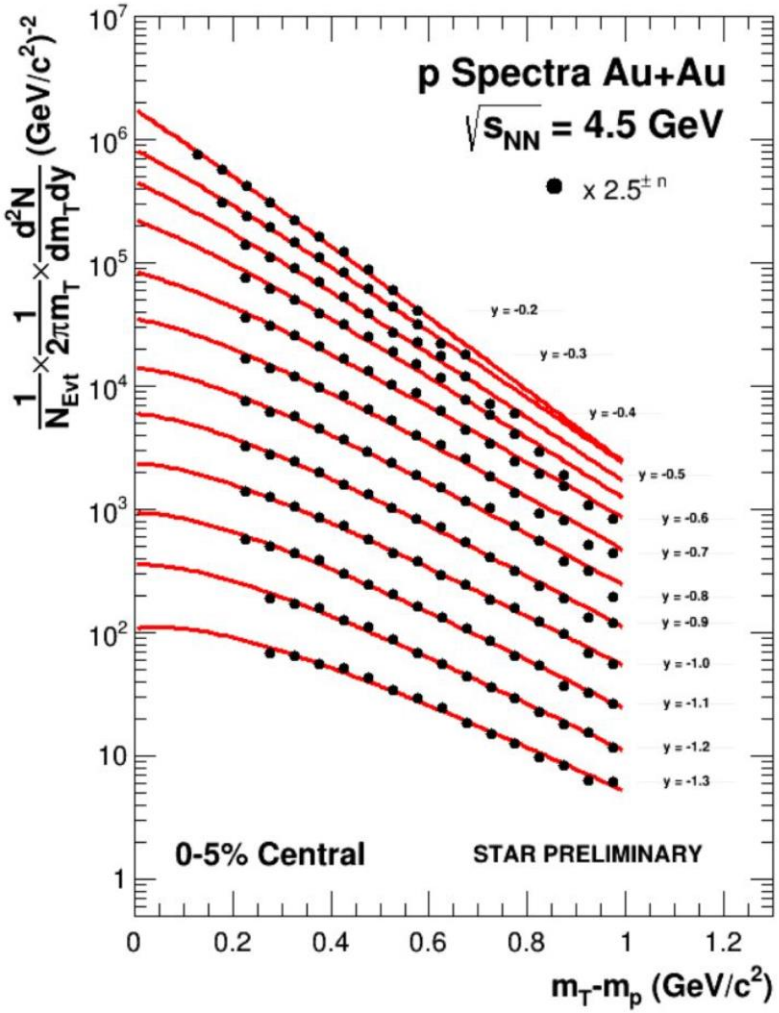
FXT Results: pion spectra

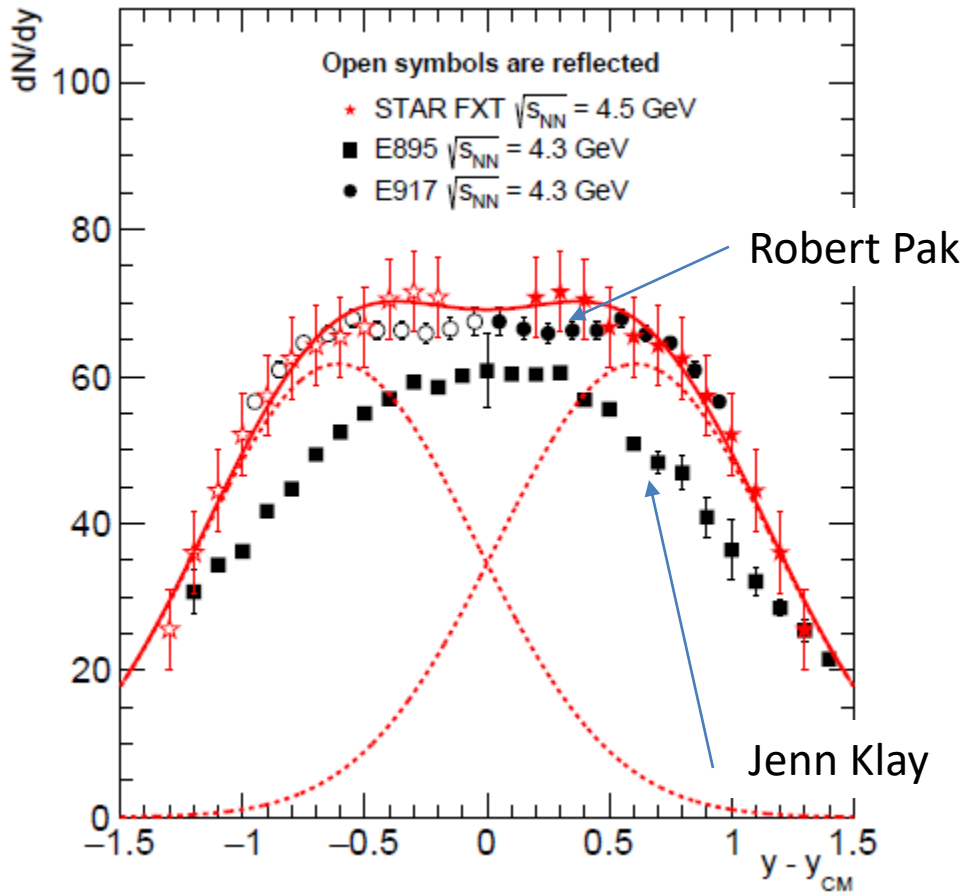




Consistent with AGS results

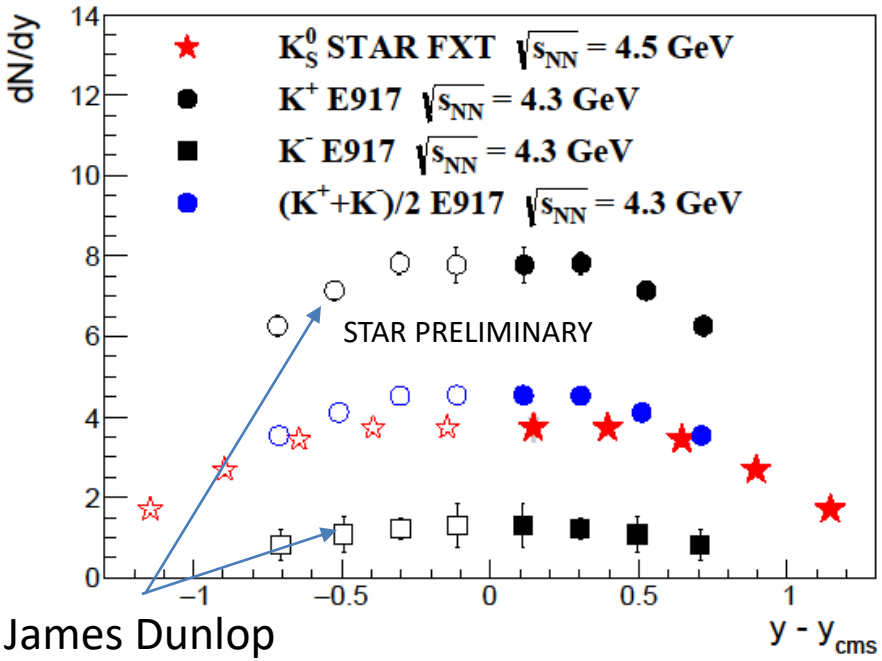
FXT Results: proton spectra



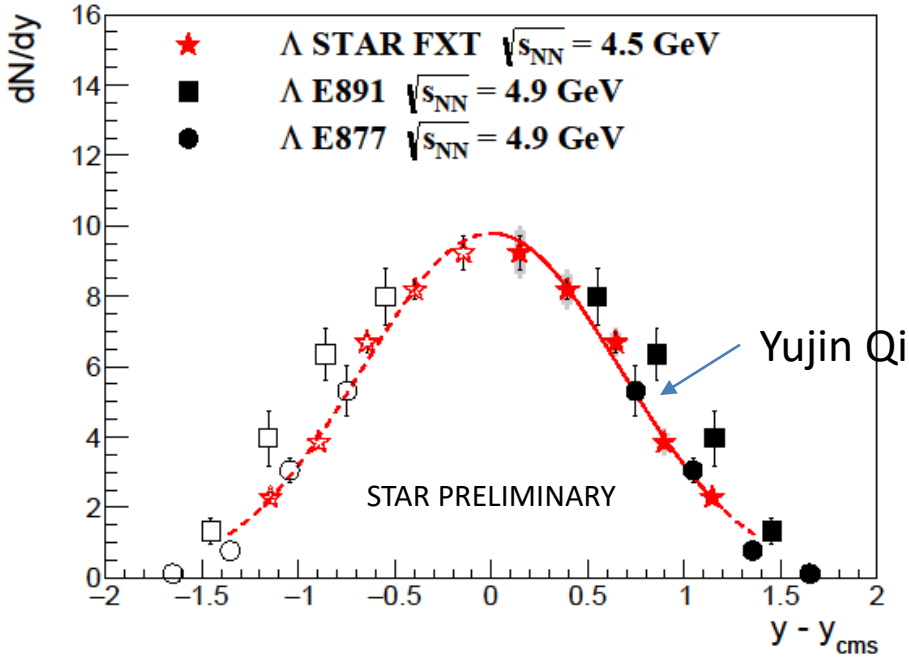


Consistent with AGS results (*)

FXT Results: V^0 yields



James Dunlop

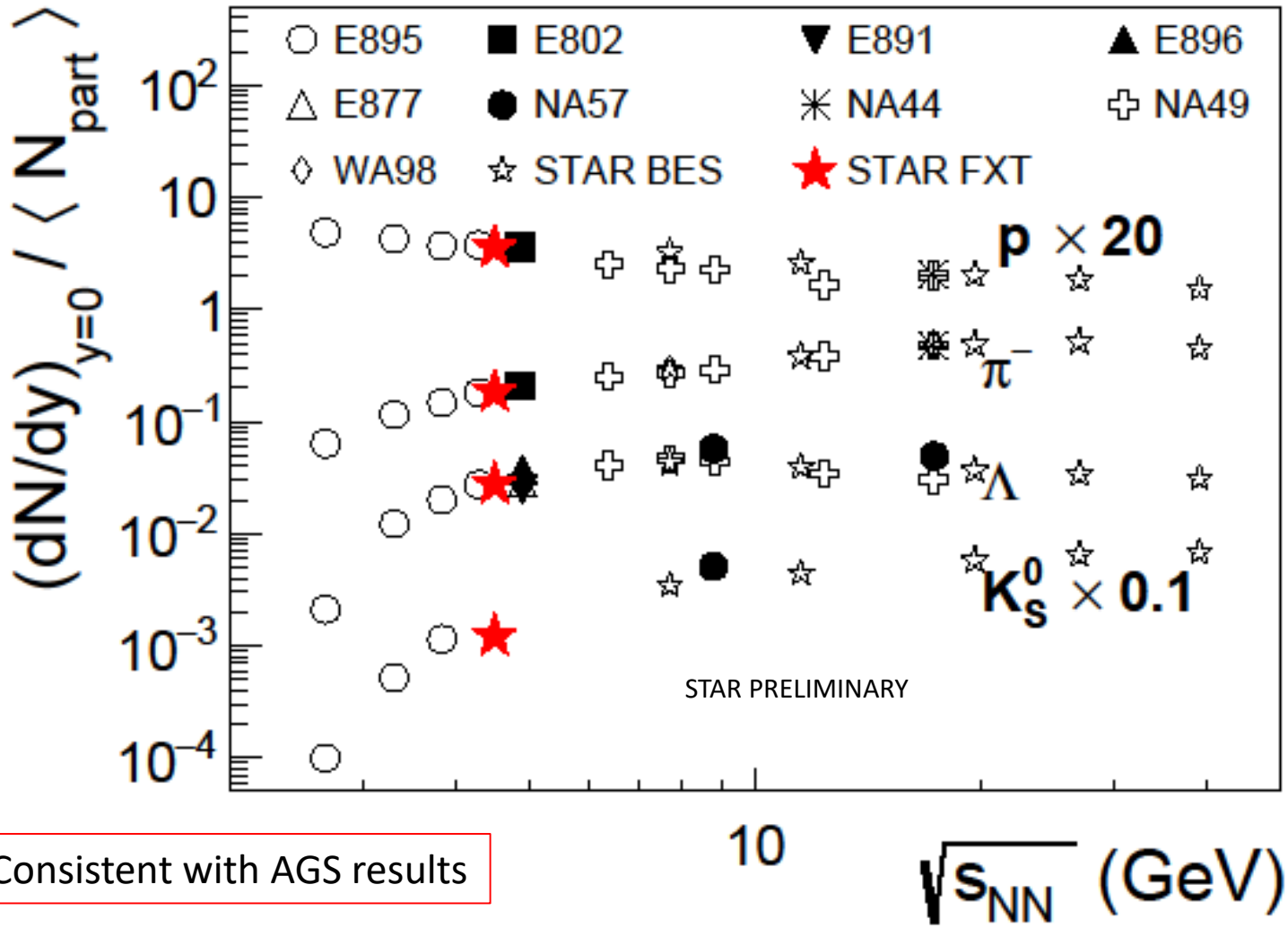


Yujin Qi

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

Consistent with AGS results

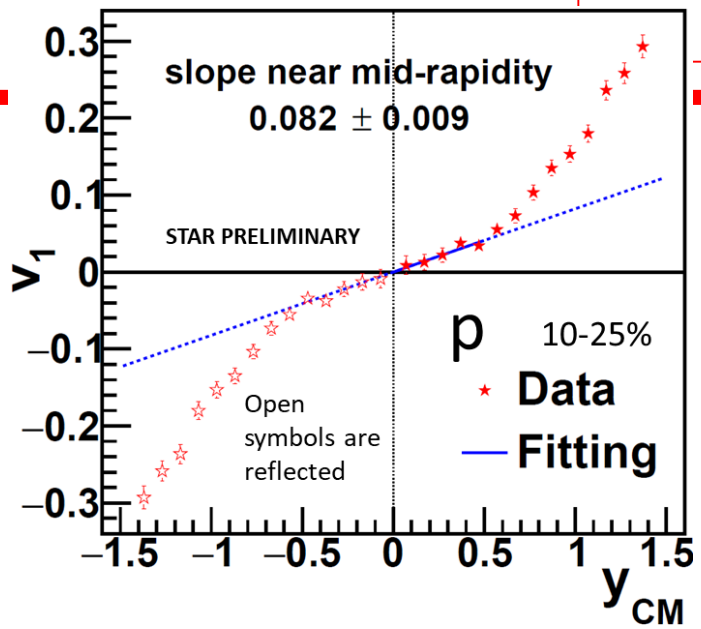
FXT Results: spectra overview

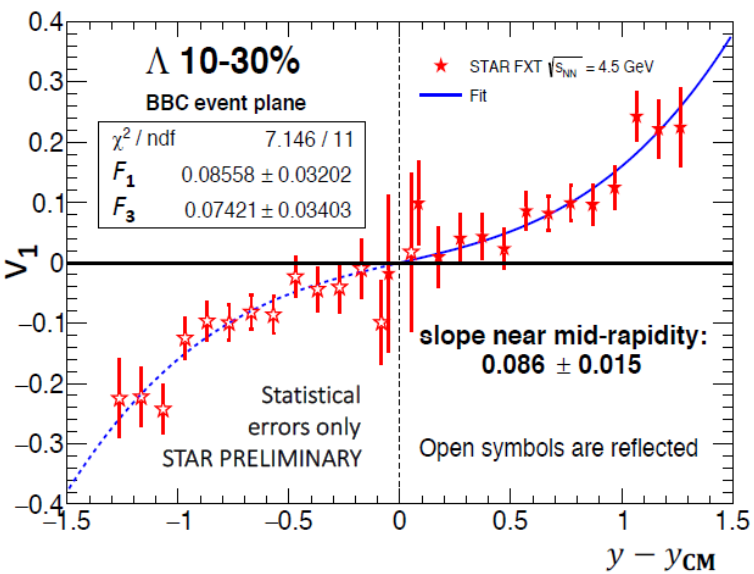


E896 PRL 88 (2002) 062301
NA44 PRC 66 (2002) 044907
NA49 JPG 30 (2004) S701
NA49 PRL 93 (2004) 022302
NA57 JPG:NPP 32 (2006) 2065
WA98 PRC 67 (2003) 014906
E895 RPC 68 (2003) 054905
E895 NPA 698 (2002) 495c
E917 PLB 476 (2000) 1
E802 NPA 610 (1996) 139c
E877 PRC 63 (2001) 014902
E891 PLB 382 (1996) 35

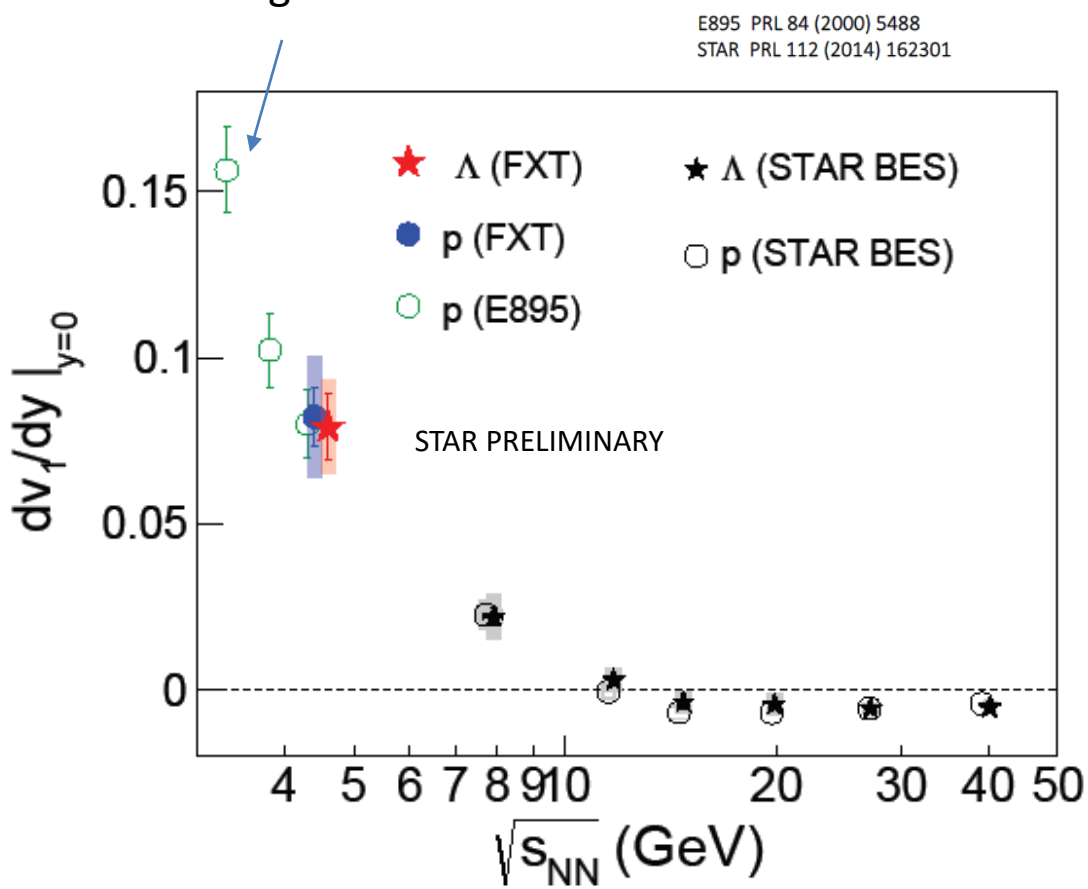
Consistent with AGS results

FXT Results: baryon directed flow



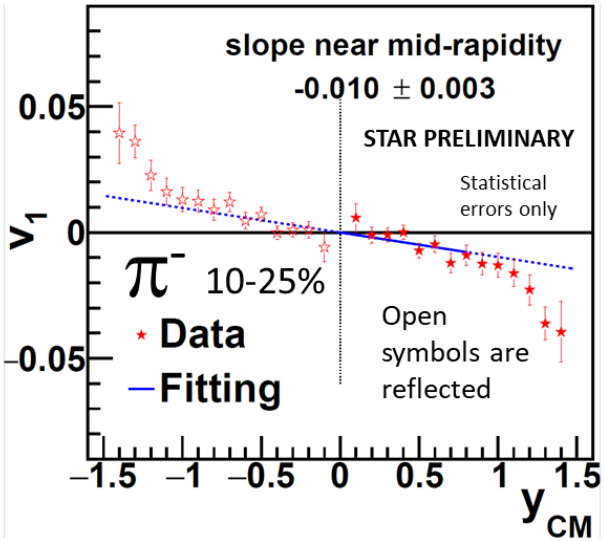


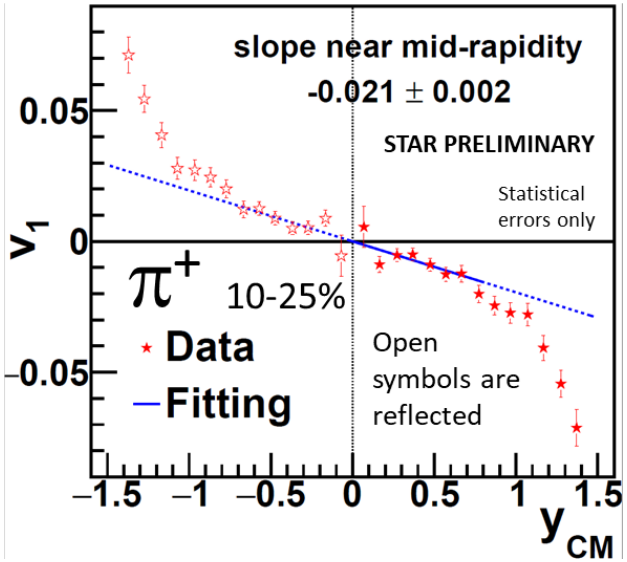
Heng Liu

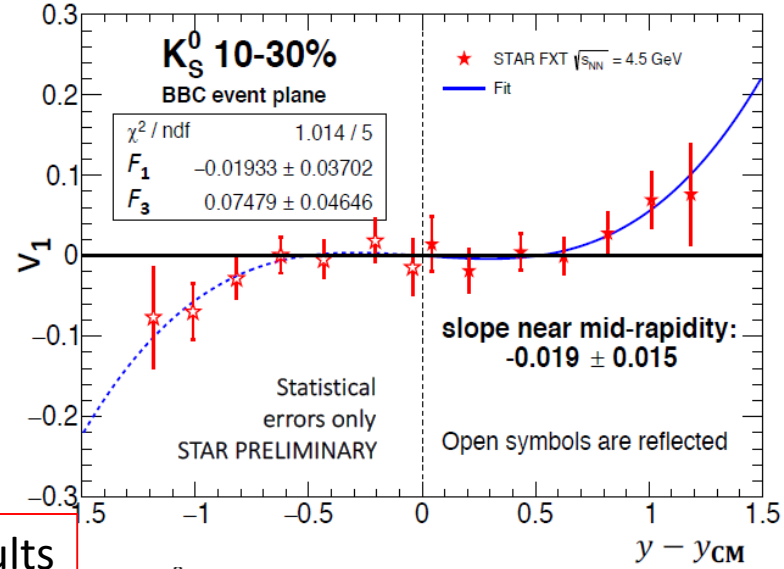


Consistent with proton results (*)

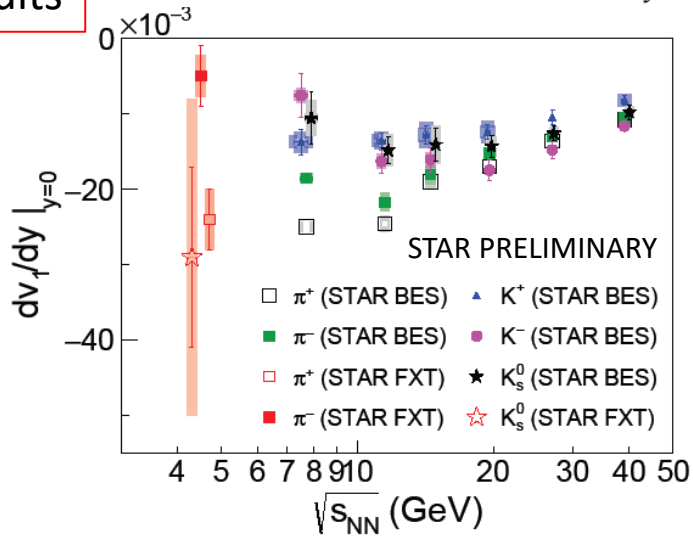
FXT Results: meson directed flow







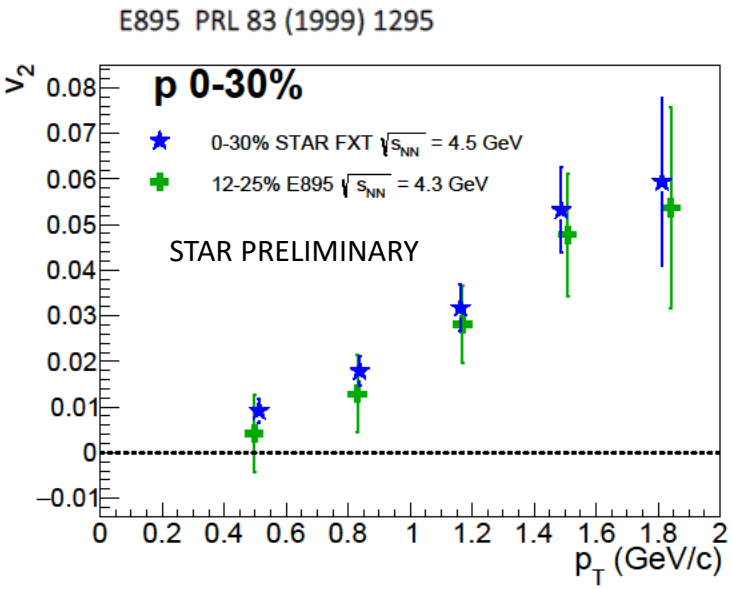
No AGS results



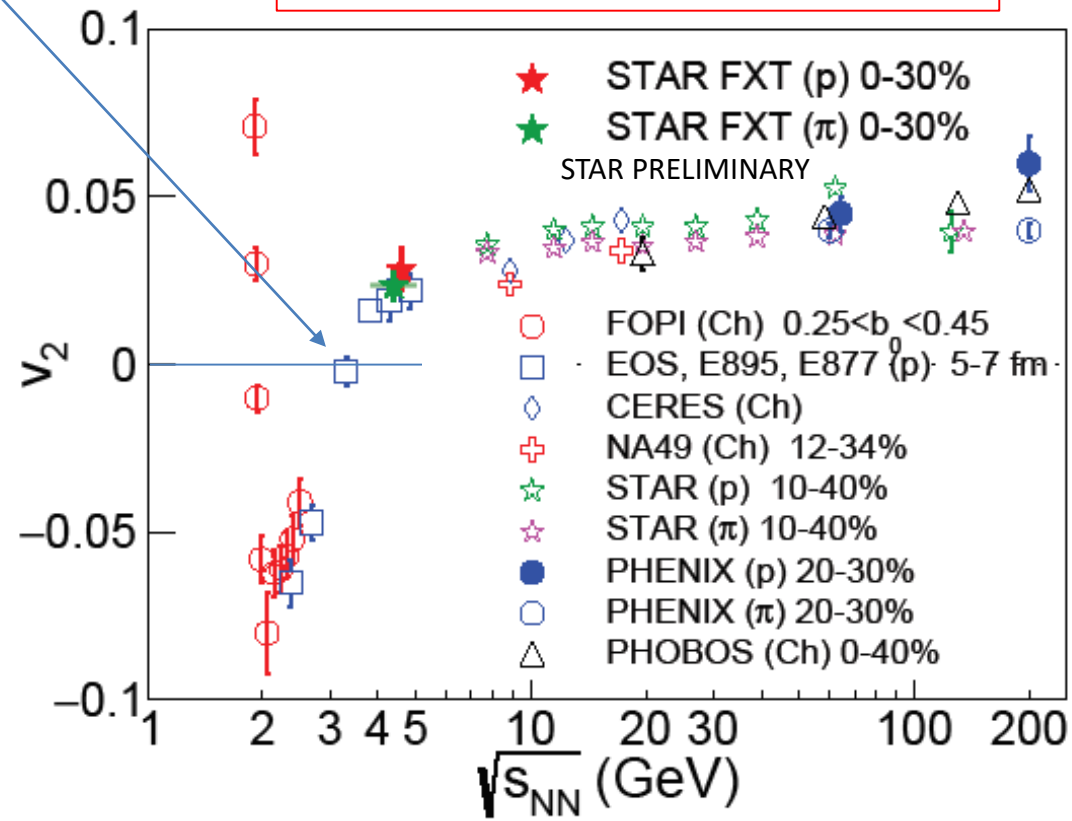
FXT Results: proton elliptic flow

Chris Pinkenberg

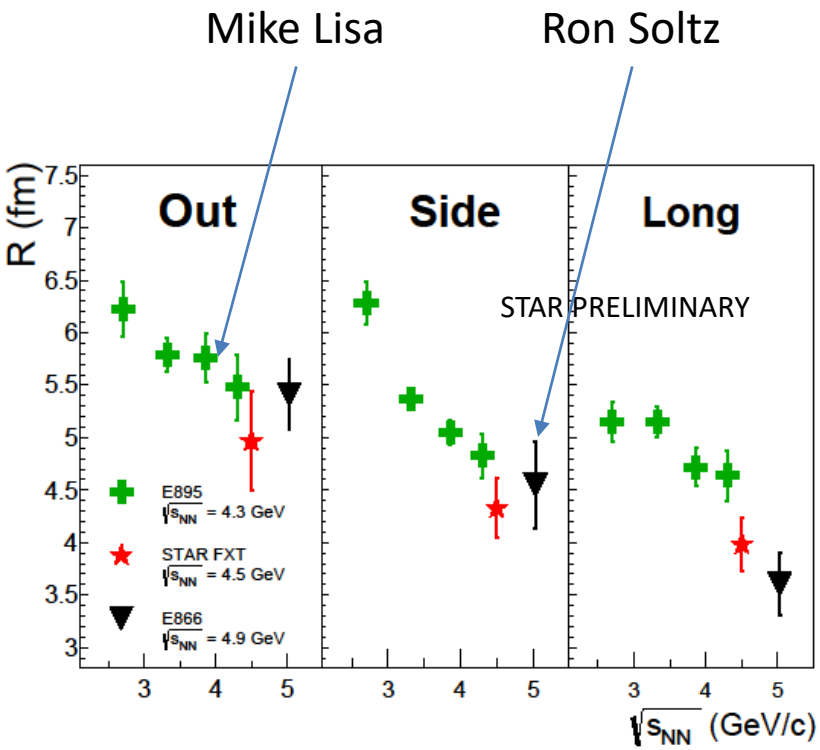
Consistent with AGS proton results
No AGS pion results



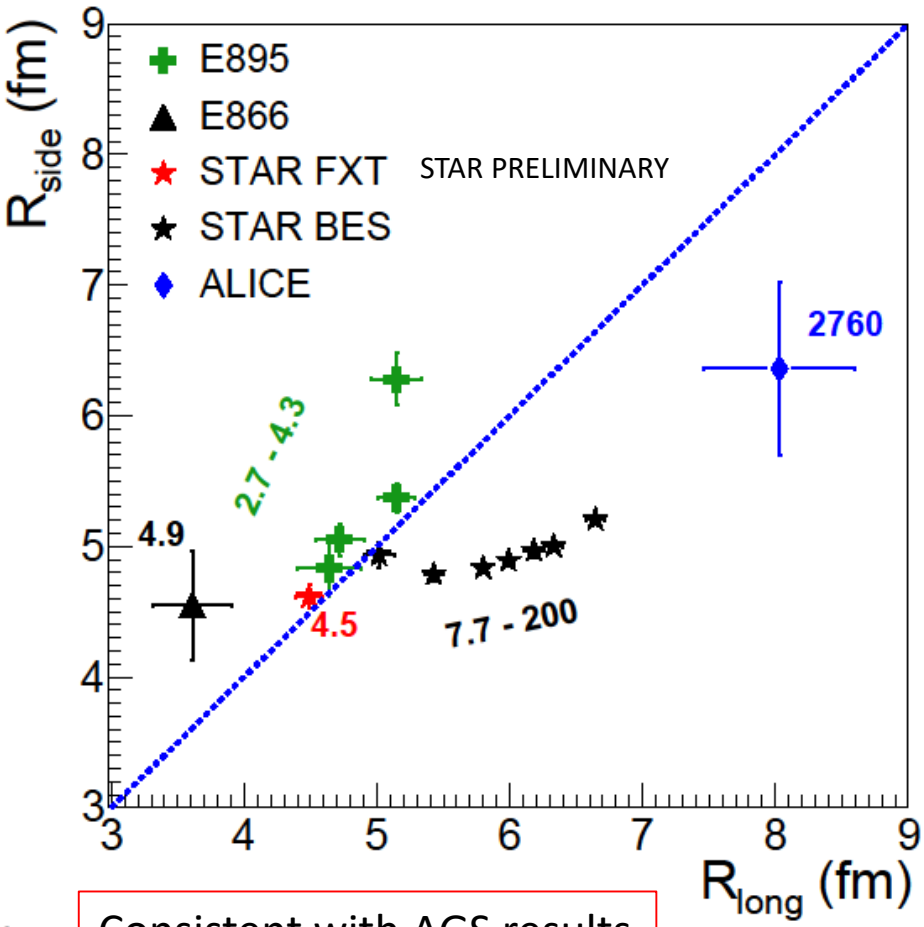
Consistent with AGS results



FXT Results: HBT



Consistent with AGS results



Consistent with AGS results

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

2018 ➔ 3.85 GeV Au+Au ($\sqrt{s_{NN}}$ = 3.0 GeV) Data Set

Data taking started: Thursday 31 May 2018 03:19 EDT with Run 19151029

Data taking completed: Monday 04 June 2018 07:48 EDT with Run 19155021

Total hours of beam: 60

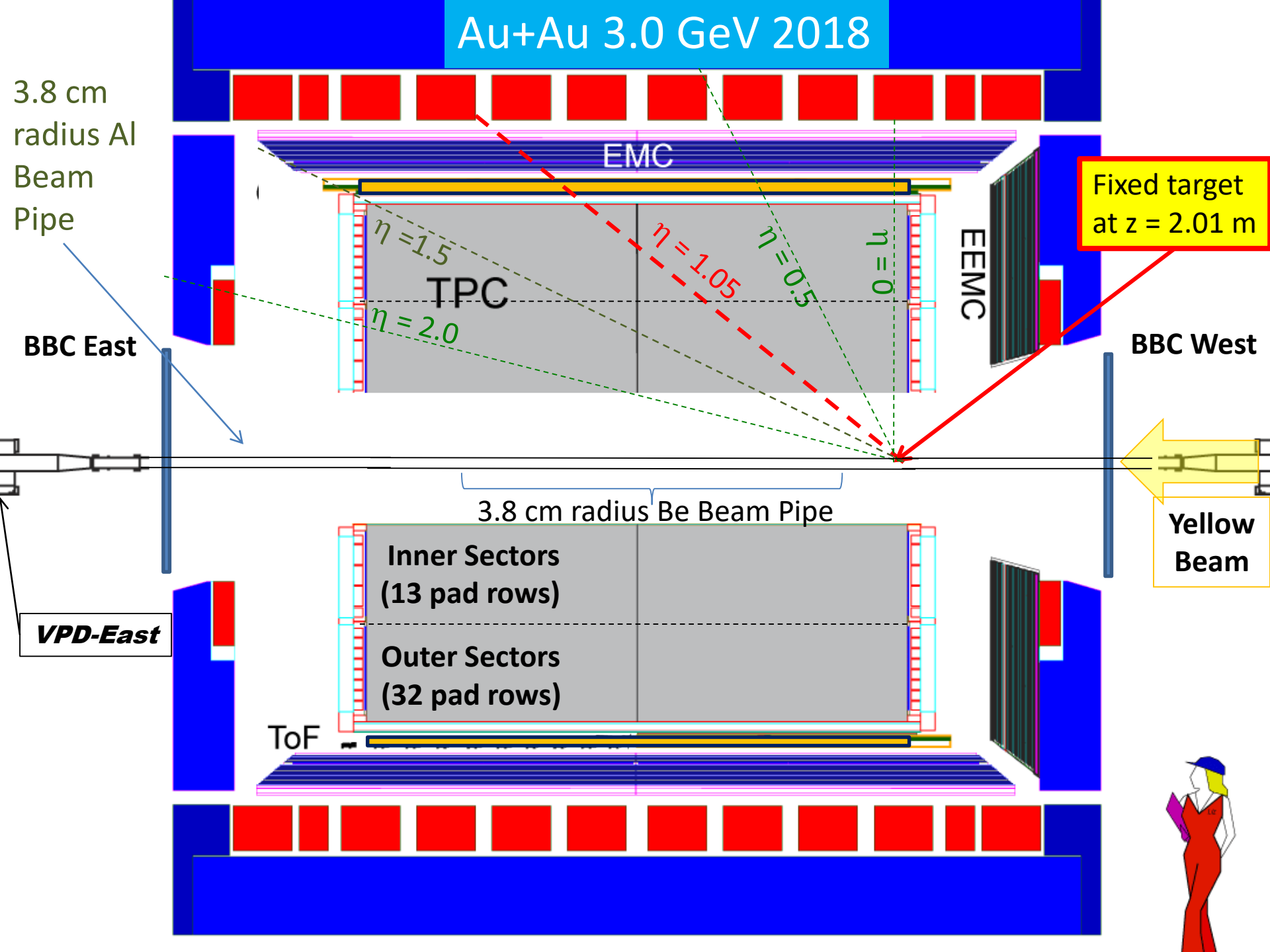
Total physics triggers: 340 Million

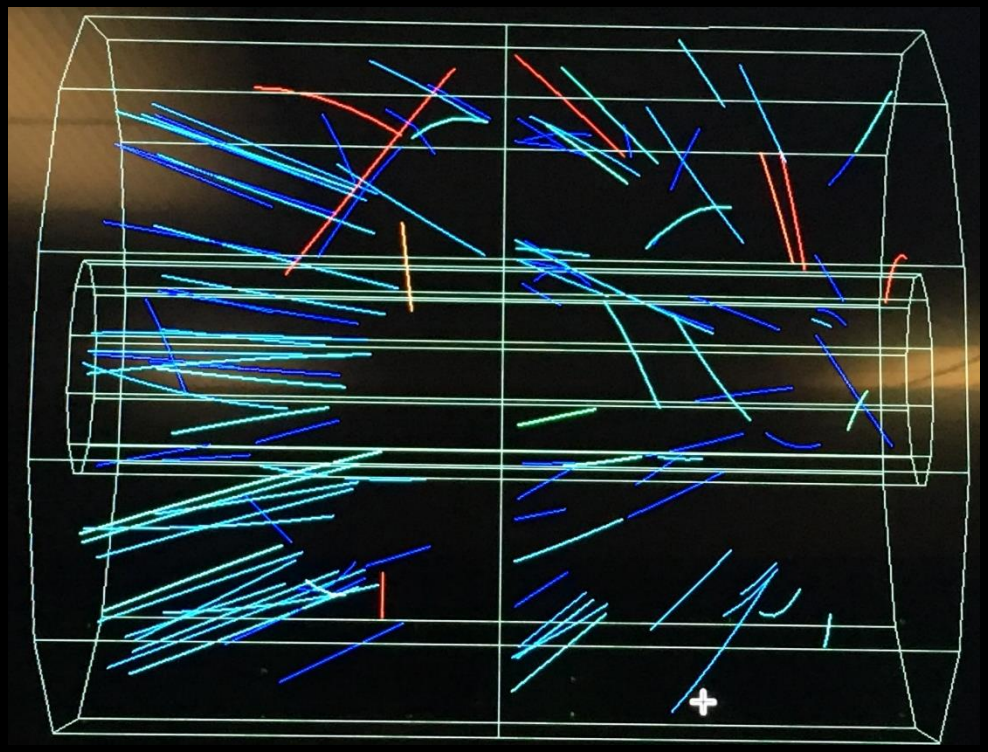
Total good events: 309 Million

Tigger efficiency: 91%

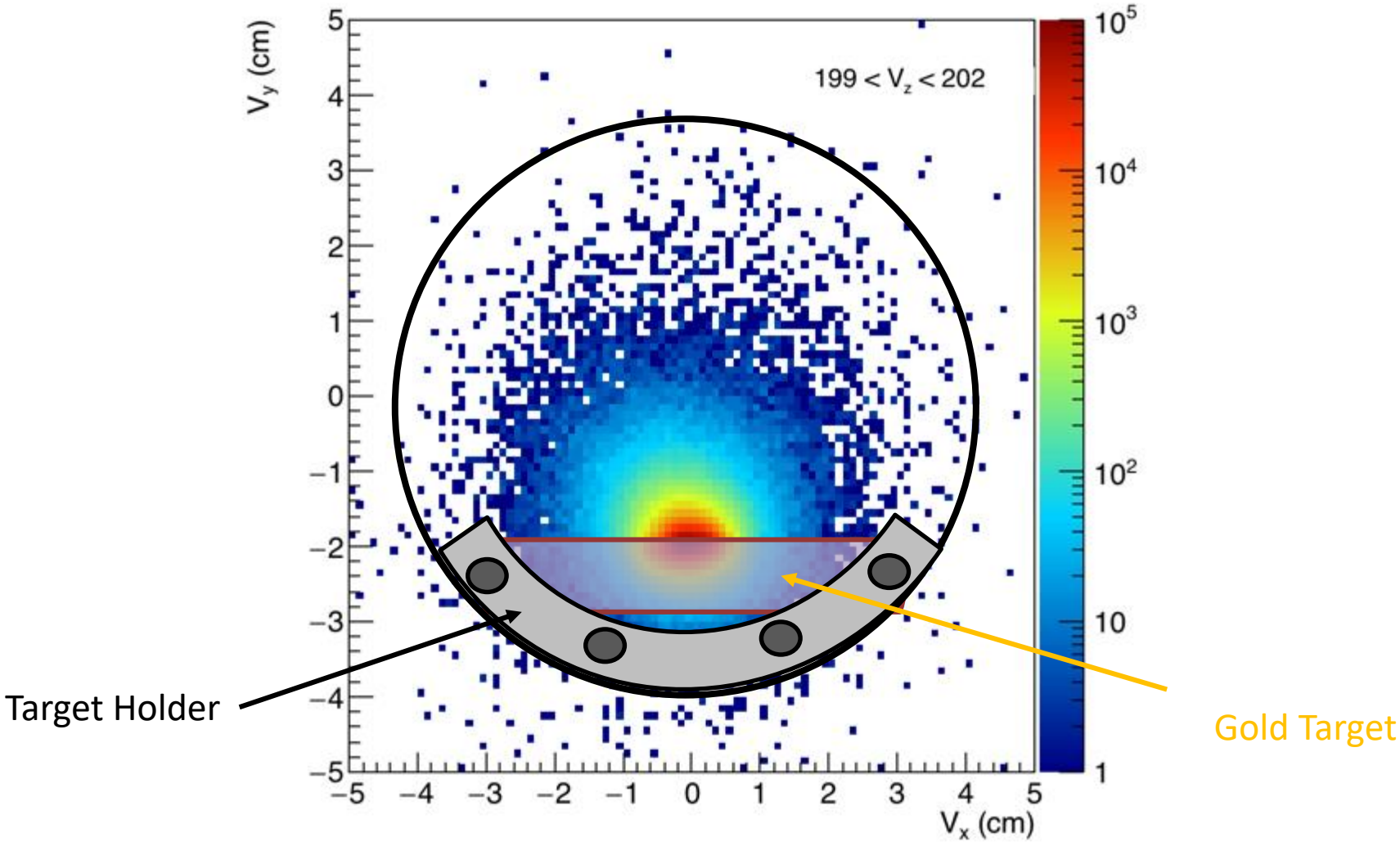
First FXT Physics Run
Result should be available soon

(*Also, we took 7.2 GeV Au+Au FXT data for 72 hours, for a total of 237 M triggers*)


Au+Au 3.0 GeV 2018
3.8 cm radius Al Beam Pipe
EMC
η =1.5
η = 1.05
η = 0.5
η = 0
TPC
η = 2.0
EEMC
Fixed target at z = 2.01 m
BBC East
BBC West
3.8 cm radius Be Beam Pipe
Yellow Beam
Inner Sectors (13 pad rows)
Outer Sectors (32 pad rows)
VPD-East
ToF



Well centered beam spot; no background



Physics Goals of the FXT Program

The Onset of Deconfinement:

- High p_T suppression
- N_{CQ} 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:

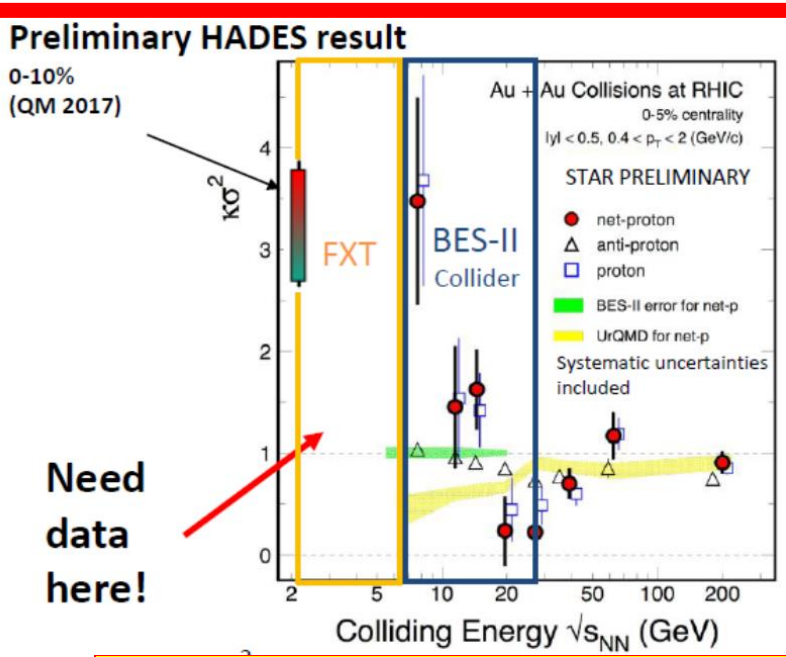
- Higher moments
- Particle Ratio Fluctuations

Chirality:

- Dilepton studies

No measurements in this energy range

Hypernuclei: ➔ Lifetime of the hypertriton



What a STAR FXT Program will not do:

- Omega's
- Charm
- Doublely Hyper nuclei
- p+p scan
- p+A scan
- peripheral collisions
- > 200 Million event per energy
- > two weeks of beam time

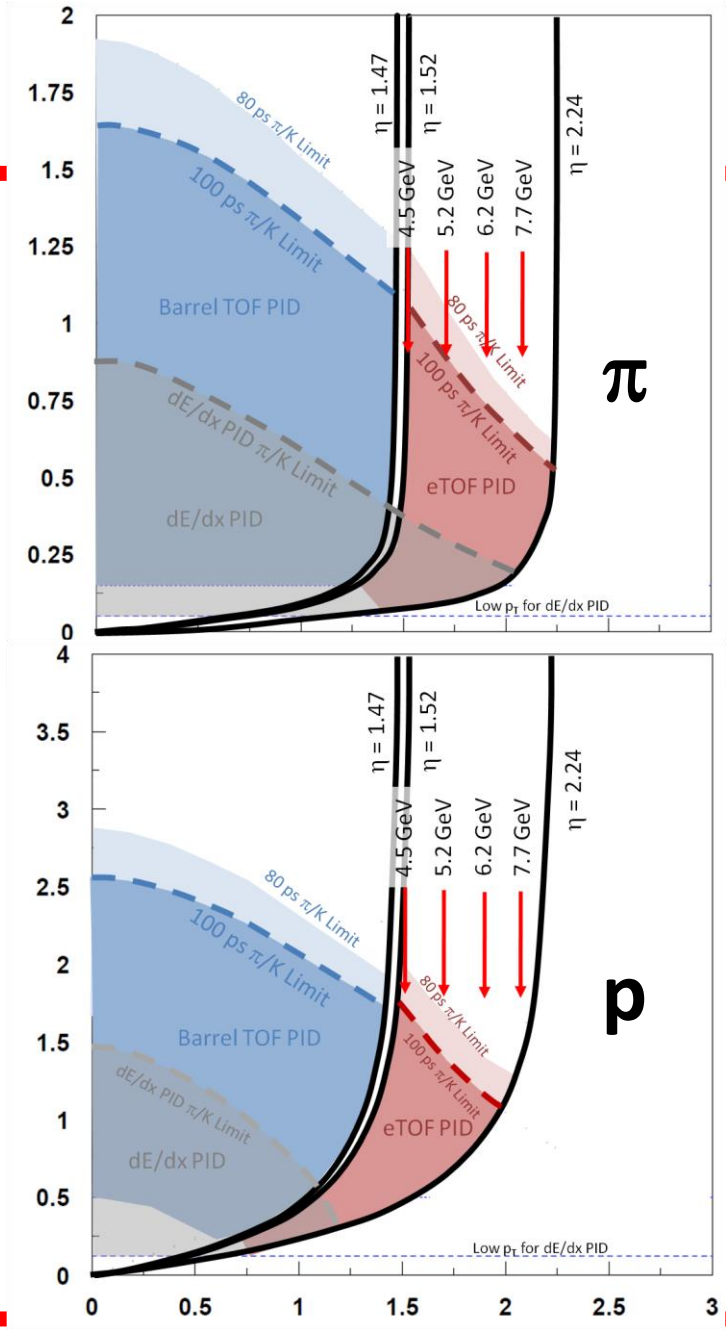
Plans for the Future 2019-2021

- Full FXT proposal was included in the May 2018 Beam Use Request
- Approved to run three energies in 2019
- Additional energies will be scheduled in 2020 and 2021

FXT Program

Collider Energy	Fixed-Target Energy	Single beam AGeV	Center-of-mass Rapidity	μ_B (MeV)	Year to complete
62.4	7.7	30.3	2.10	420	2019
39	6.2	18.6	1.87	487	2021?
27	5.2	12.6	1.68	541	2021?
19.6	4.5	8.9	1.52	589	2019
14.5	3.9	6.3	1.37	633	2019
11.5	3.5	4.8	1.25	666	2020
9.1	3.2	3.6	1.13	699	2020
7.7	3.0	2.9	1.05	721	2018

- Data rate is DAQ limited
- Would need 100 Million Events at each energy to make the sensitivity of BES-II
- Roughly one to two days per energy



Comparison of Facilities

Facilty	RHIC BESII	SPS	NICA	SIS-100 SIS-300	J-PARC HI
Exp.:	STAR +FXT	NA61	MPD + BM@N	CBM	JHITS
Start:	2019-20 2018	2009	2020 2017	2022	2025
Energy: $\sqrt{s_{NN}}$ (GeV)	7.7– 19.6 3.0-7.7	4.9-17.3	2.7 - 11 2.0-3.5	2.7-8.2	2.0-6.2
Rate: At 8 GeV	100 HZ 2000 Hz	100 HZ	<10 kHz	<10 MHZ	100 MHZ
Physics:	CP&OD	CP&OD	OD&DHM	OD&DHM	OD&DHM
	Collider Fixed Target	Fixed Target Lighter ion collisions	Collider Fixed Target	Fixed Target	Fixed Target

CP = Critical Point
OD = Onset of Deconfinement
DHM = Dense Hadronic Matter

Conclusions

- AGS Program provided extensive results at the top energy, but left many observables unmeasured across the energy scan.

- FXT program will allow for comprehensive measurements below 7.7 GeV

- Acceptance and physics have been demonstrated in test runs and other studies