Prospects for Measurements of Production Cross Sections of Light Nuclei at RHIC

Opportunity for 2023-25

Light Fragment Yields from C, Al, and Fe on C, Al, and Fe Targets with Beam Energies from 5 to 50 GeV

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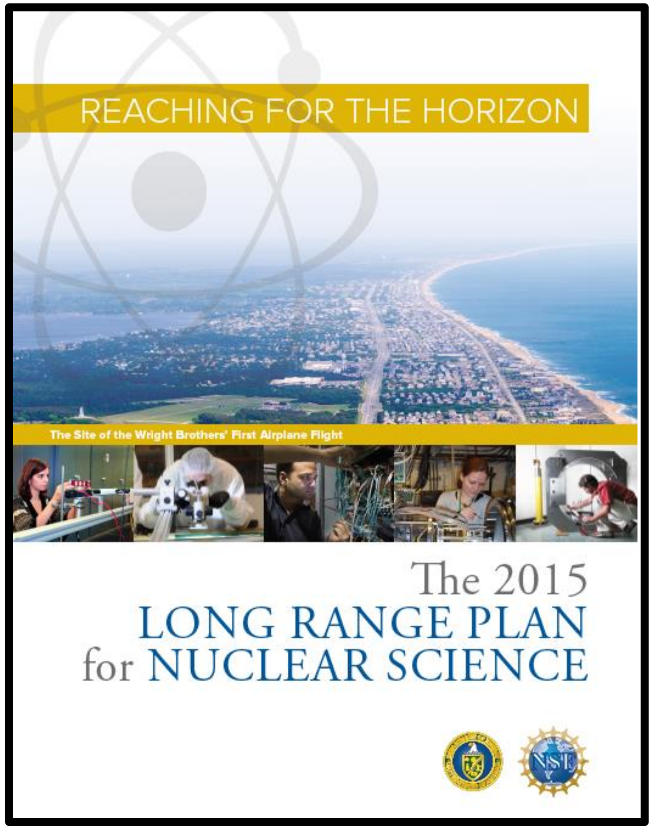
Supported in part by:

The Key Science Questions for Nuclear Science

Page 3, even before recommendations



1. How did visible matter come into being and how does it evolve?
2. How does subatomic matter organize itself and what phenomena emerge?
3. Are the fundamental interactions that are basic to the structure of matter fully understood?
4. **How can the knowledge and technical progress provided by nuclear physics best be used to benefit society?**

Science Communities Other Than Nuclear Physics Also Do Long Range Planning

- **The *International Biophysics Collaboration* (IBC) considers studies relevant to space radiation protection, ion therapy, and other biophysics applications.**

- **Within IBC, a *Cross Section Working Group* was formed to assess and prioritize the needs for new measurements.**

- **The working group identified measurements of light nucleus production from heavy ion induced reactions (Z = 2-26) on targets of interest (C, Al, Fe) as a key decadal need.** https://doi.org/10.3389/fphy.2020.565954

> measurement gaps for space radiation. The highest priority measurement recommendations were double differential cross sections for the following ion[2] reactions,
>
> $$\mathrm{He, C, O, Si, Fe + H, C, O, Al, Fe} \longrightarrow {}^{1,2,3}\mathrm{H}, {}^{3,4}\mathrm{He} + \mathrm{X}, \qquad (1)$$

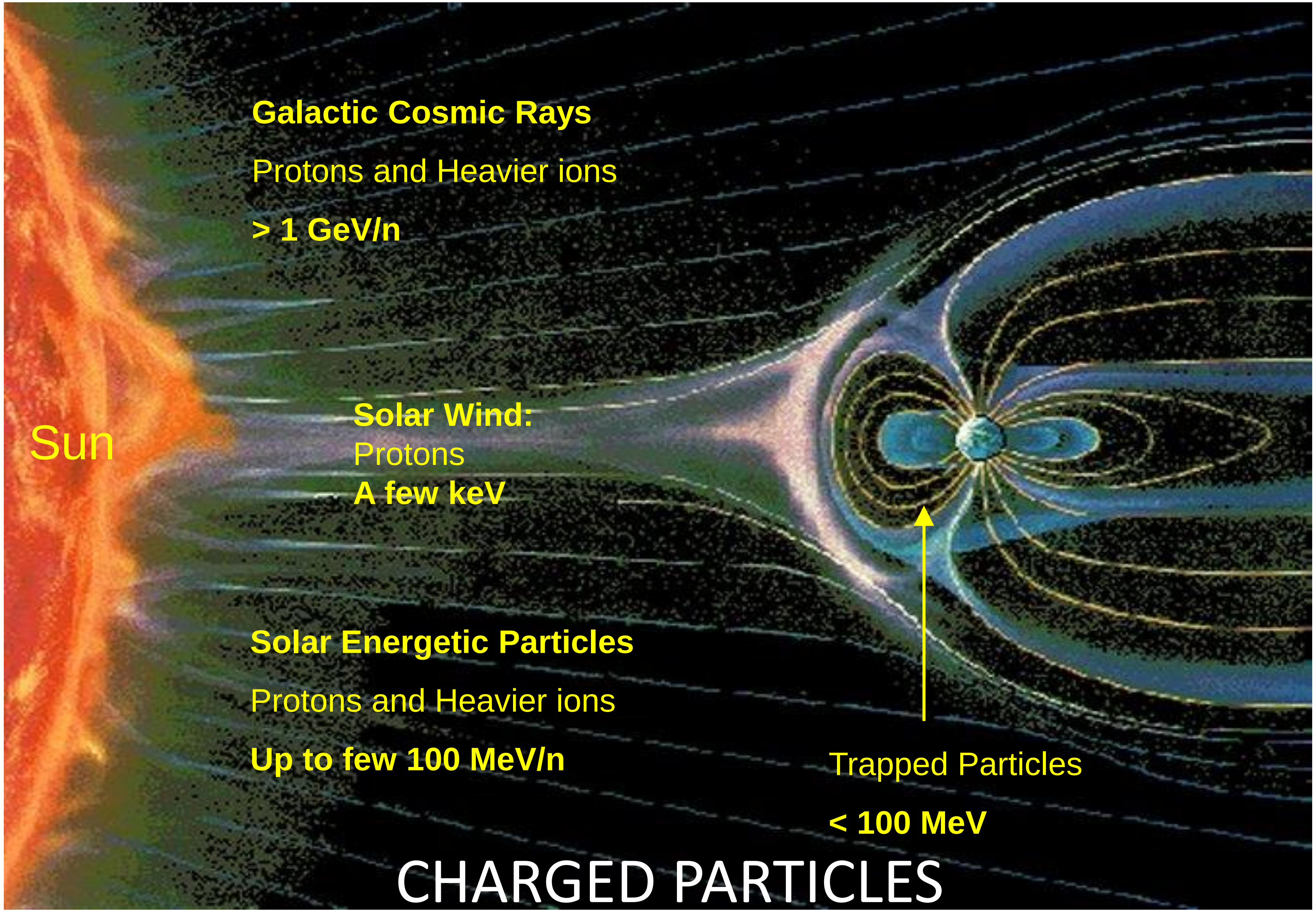
What is "Space Radiation"?

Space Radiation = energetic charged particles.

Solar Wind:
Protons from 0.5 to 10 keV

Solar Energetic Particles
Protons and ions up to 1 GeV/n

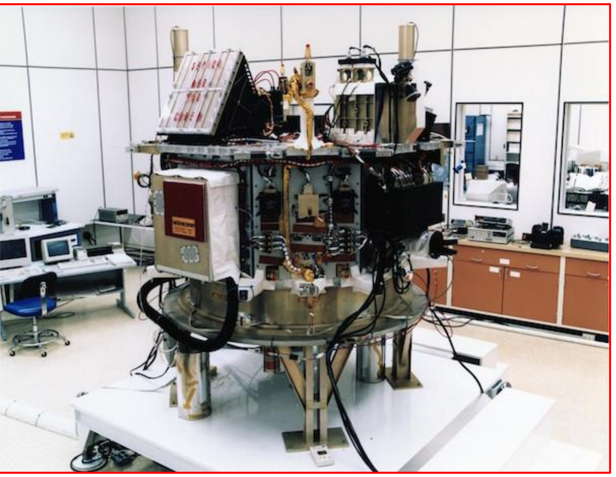
Galactic Cosmic Rays (GCR)
- high energy protons
- highly energy ions
- not effectively shielded (break up into lighter, more penetrating pieces)
- abundances and energies quite well known
- MAIN PROBLEM: biological effects poorly understood but known to be most significant space radiation hazard



What Do We Know About Galactic Cosmic Rays?

The GCR environment is well known from Space Station, Satellite, Balloon, and Voyager I measurements.

Advanced Composition Explorer



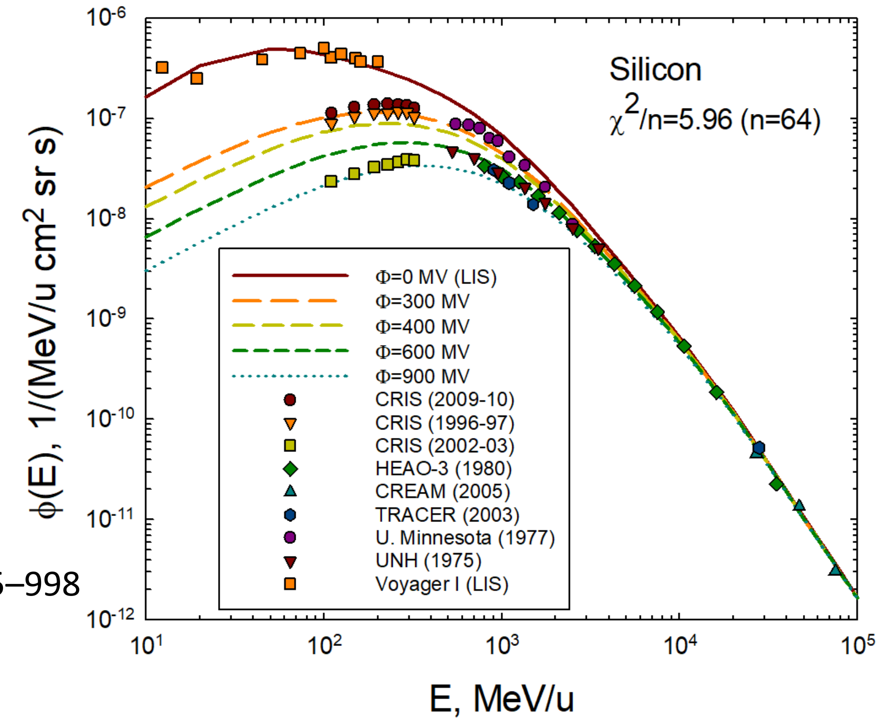
Alpha Magnetic Spectrometer

The energy spectrum:

100 MeV/n to 100 GeV/n

Cucinotta et al.

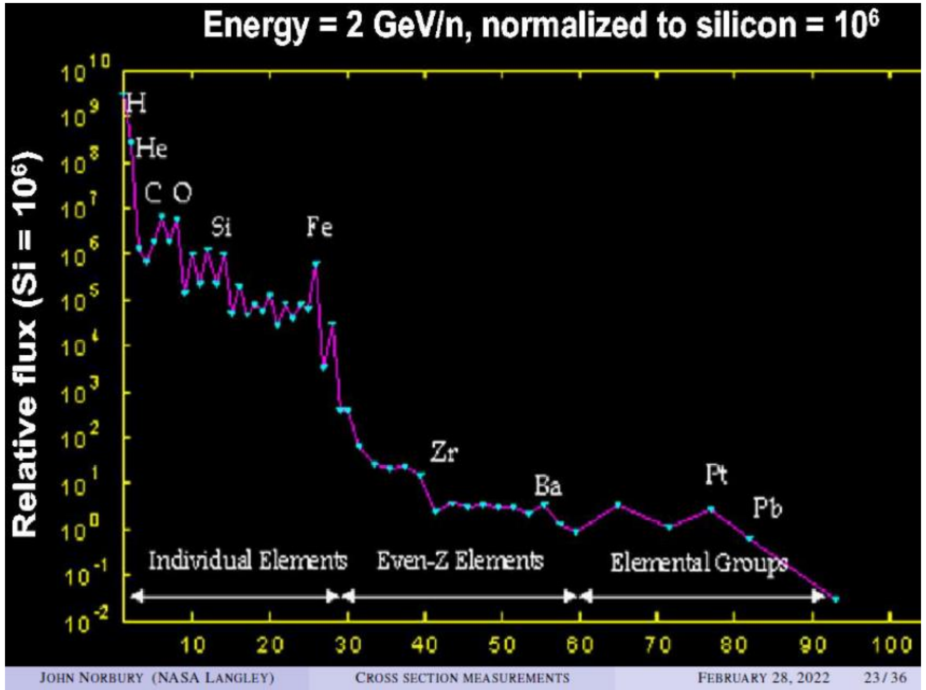
Int J Radiat Biol. 2019 Jul; 95(7): 985–998



Species abundances:

Peaks for H, He, C, O, Si, Fe

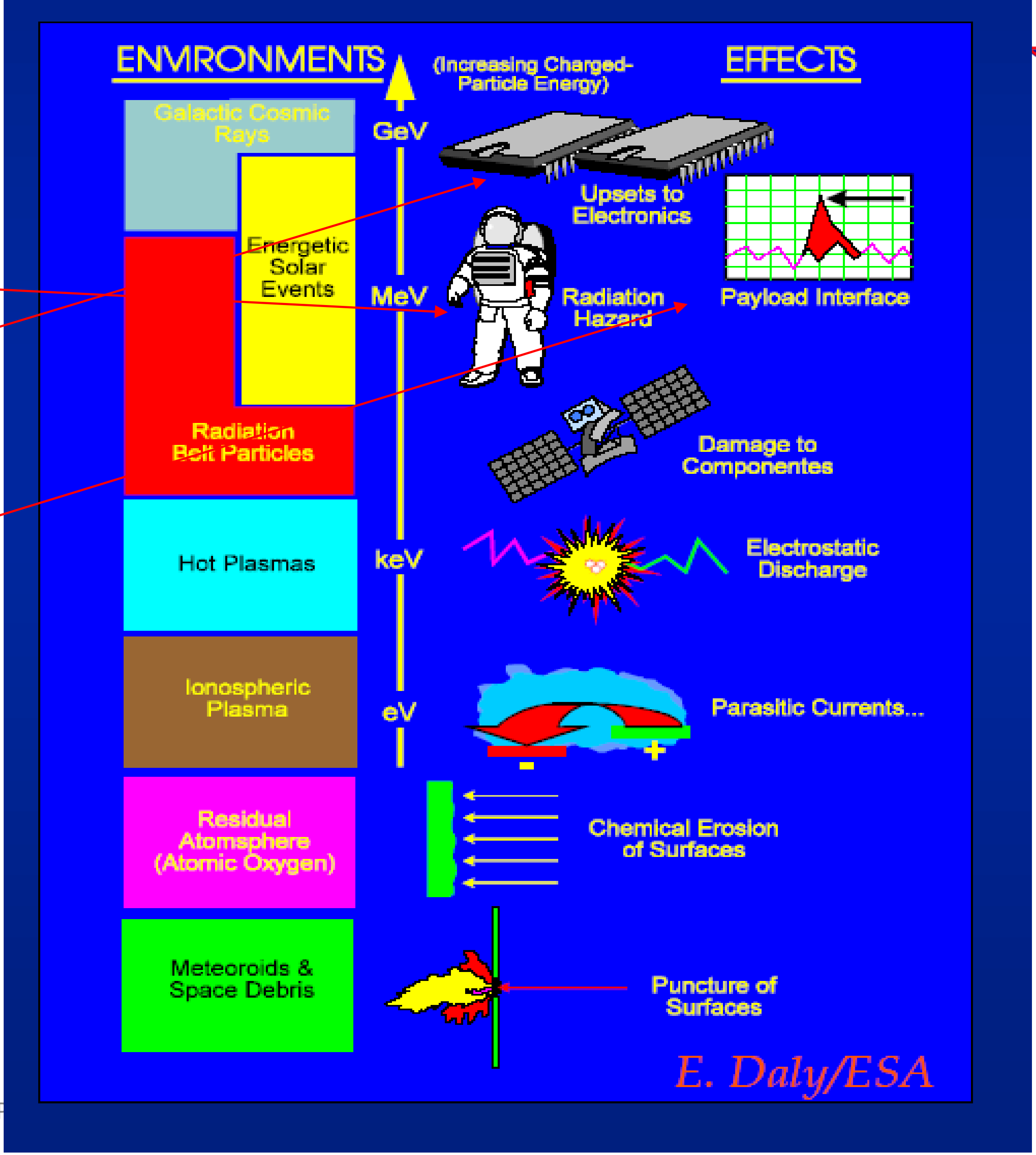
H. S. Ahn et al 2010 ApJ 715 1400



Space Radiation Effects

- Radiation effects on astronauts
  - Total Ionizing Dose (TID)
- Single Event Effects (SEE)
- Radiation induced noise in scientific sensors/detectors

Artemis launch
November 14th



Current Facilities for Space Radiation Protection Measurements

Domestic Facilities

Facility	Energy
NSRL	Up to 1.5 GeV/n
TAMU K500 and K50	15-40 MeV/n
LBNL 88 Inch	10-20 MeV/n
MSU Linac Stage 1	5-40 MeV/n
ARUNA – 10 Universities	< 11 MeV/n

NASA notes several key gaps in domestic program:

- Capacity
- **High Energy Range**
- Large Beam Spot

European Facilities

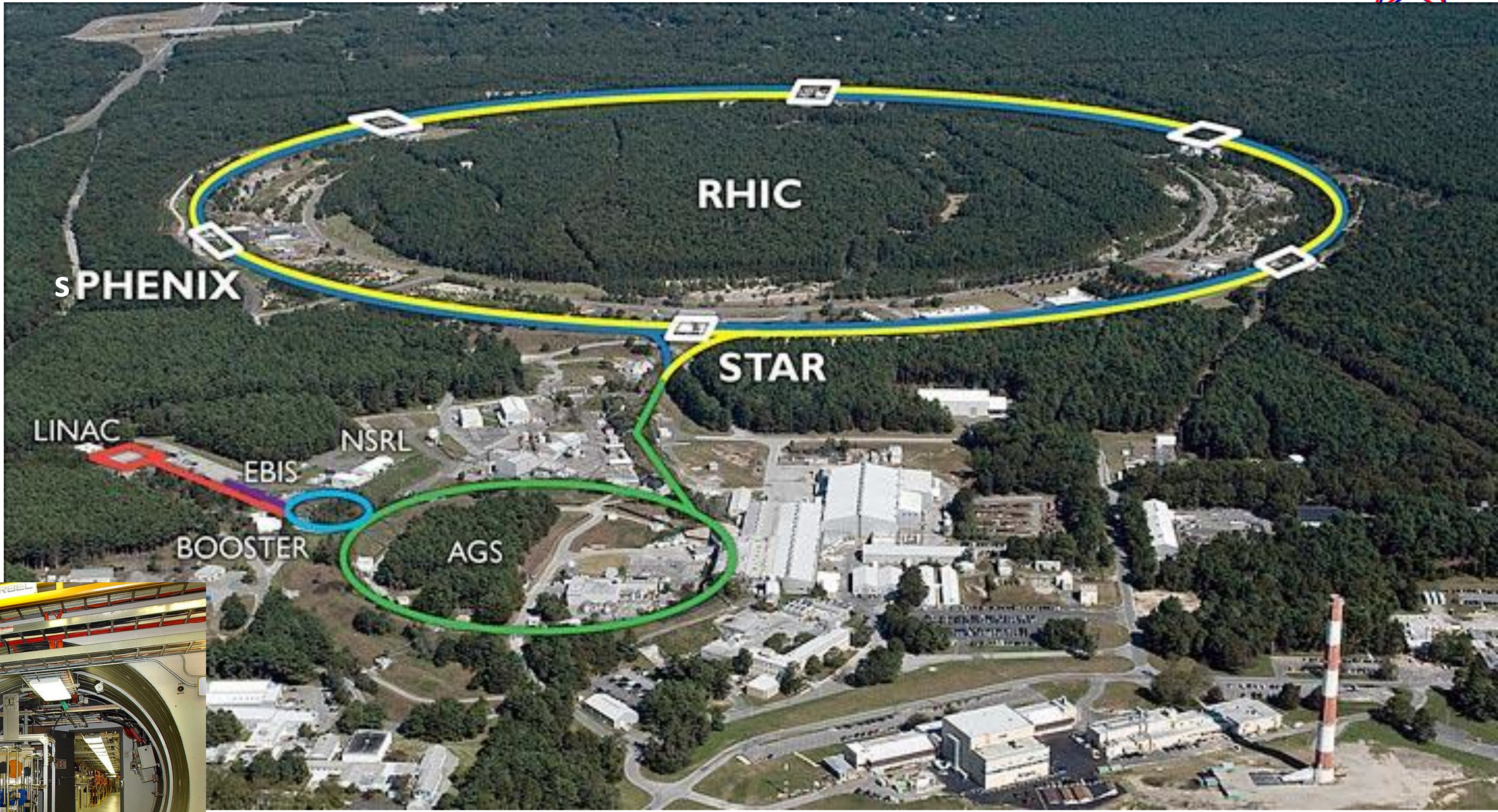
Facilities	Energy (MeV/nucleon)	Range of heavy species (Xe) in silicon
CERN	6-160 GeV/nucleon	meters
GSI SIS18	50 MeV/n to 1-1.5 GeV/n	2.4 mm to 7.8 cm
GANIL G4	27 to 60MeV/n	50 µm to 685 µm
KVI CART	30 MeV/n	333 µm
RADEF	22 MeV/n , 16.3 MeV/n, 9.3 MeV/n	255 µm 155 µm 92 µm
UCL HIF	8-10 MeV/n	73 µm
LNS	10-80 MeV/n	1 mm

Space Radiation Protection at BNL: NSRL

Ion Sources:
- LINAC
- EBIS
- Tandems

Synchrotrons:
- Booster
- AGS
- RHIC

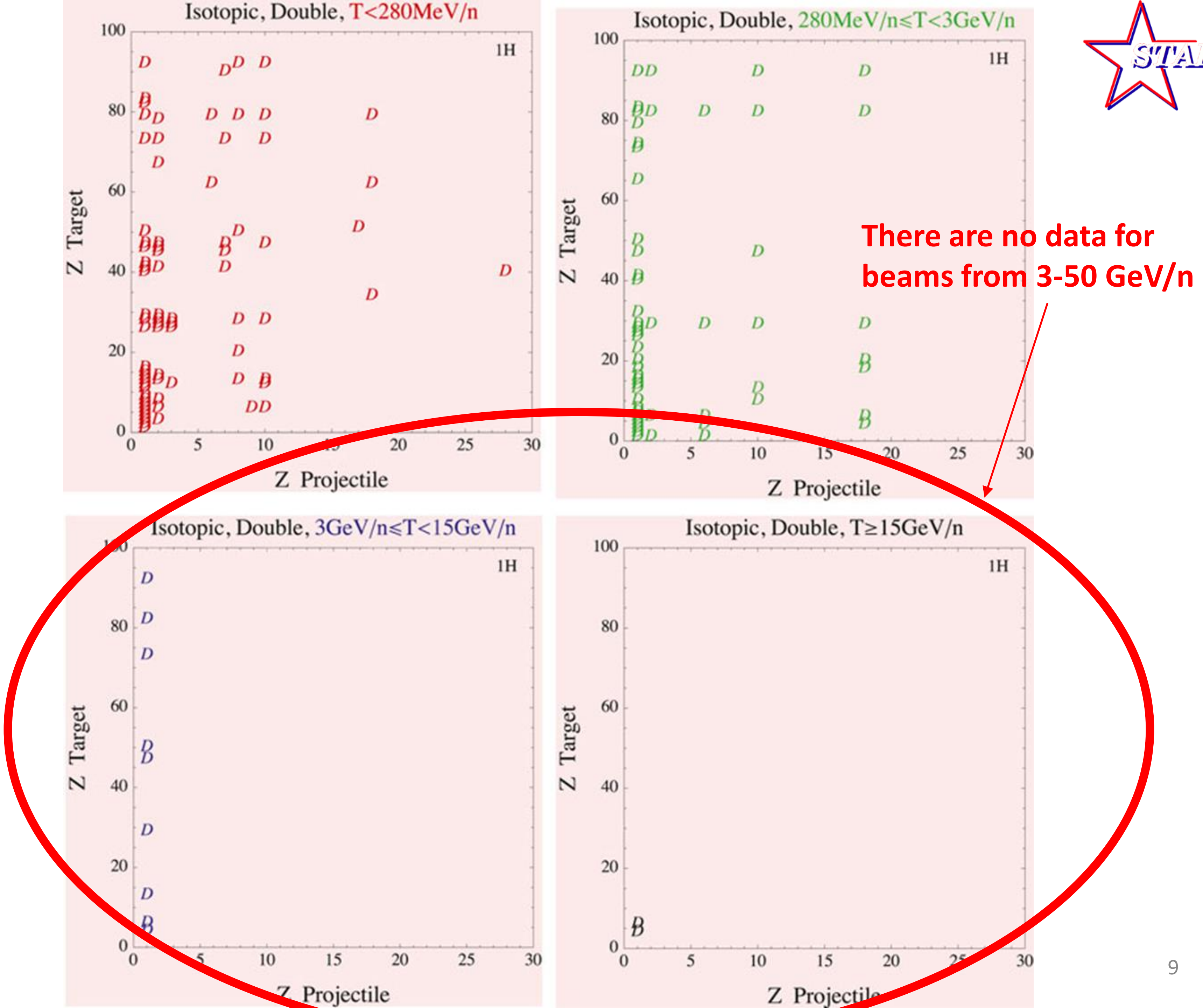
Experimental Areas
- NSRL
- RHIC IP6 (STAR)
- RHIC IP8 (sPHENIX)



NSRL ➔Species up to iron, energies up to 1.5 GeV/n

Existing Proton Double Differential Measurements

- Double differential cross section measurements are required to calculate the energy deposited in thick targets
- There are many facilities that reach a few hundred MeV/n (cyclotrons, ion therapy machines)
- There are a few that reach a few GeV/n:
  - BNL - NSRL
  - GSI – SIS18
  - Dubna – Nuclotron
- Currently no ion projectile data for energies above 3 GeV/n



Summary of the Motivation:

- Cosmic rays are a serious concern to astronauts, electronics, and spacecraft.
- The cosmic ray flux is composed of nuclei (protons, He, and nuclei up to Fe).
- The damage is proportional to Z^2, therefore the component due to ions is important.
- Damage from secondary production of p, d, t, ^{3}He, and ^{4}He is also significant.
- Extensive double differential measurements for light fragments production have been made for projectile energies below 3 GeV/n. (At facilities like NSRL).
- No data exist for projectile energies from 3-50 GeV/n. *Energy range dominated by Galactic Cosmic Rays (GCR).*
- The Space Radiation Protection community has identified this high energy regime as an area of need. https://doi.org/10.3389/fphy.2020.565954

➔ Can the Hot QCD community address this need?

- STAR has excellent light fragment capabilities.
- RHIC can deliver the ion beam species (C, Al, Fe) and energies (3-50 GeV/n) of need to the Space Radiation Protection community.
- STAR can install the targets of interest (C, Al, Fe).

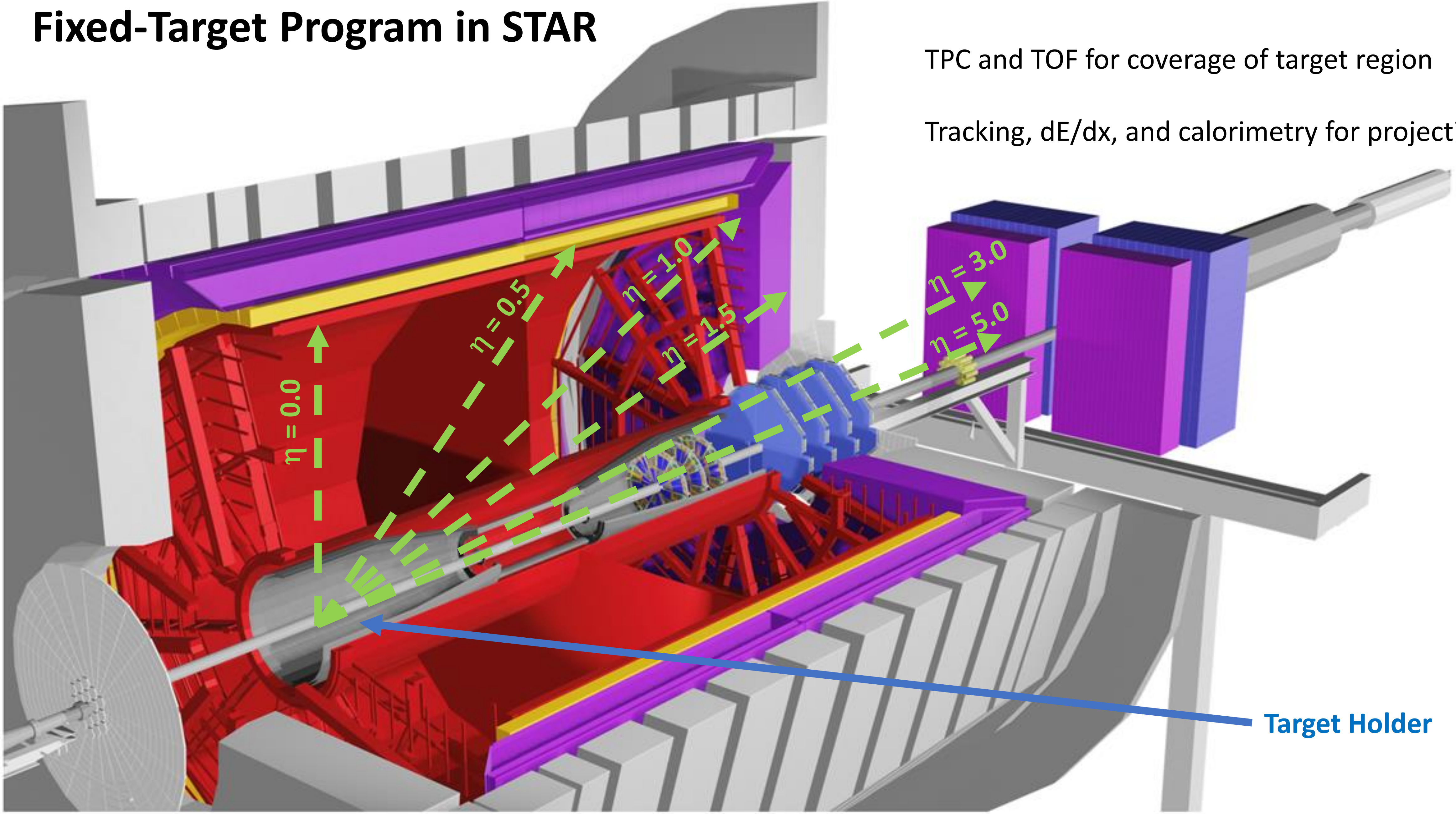
What is needed, and can RHIC/STAR meet that need?

- Double differential cross sections ($dN/dEd\Omega$) for light nuclei (p, d, t, h, α)
- Particle multiplicities
- Particularly interested in projectile fragmentation
- Need good PID (TOF)
- Targets of interest (C = astronaut, Si = electronics, Al = spacecraft)
- Beams of interest: He, C, O, Si, Fe

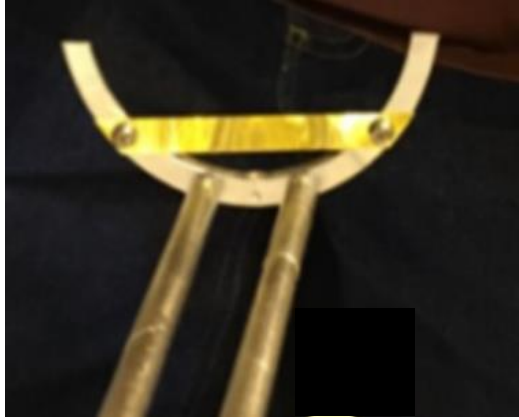
Fixed-Target Program in STAR

TPC and TOF for coverage of target region

Tracking, dE/dx, and calorimetry for projectile

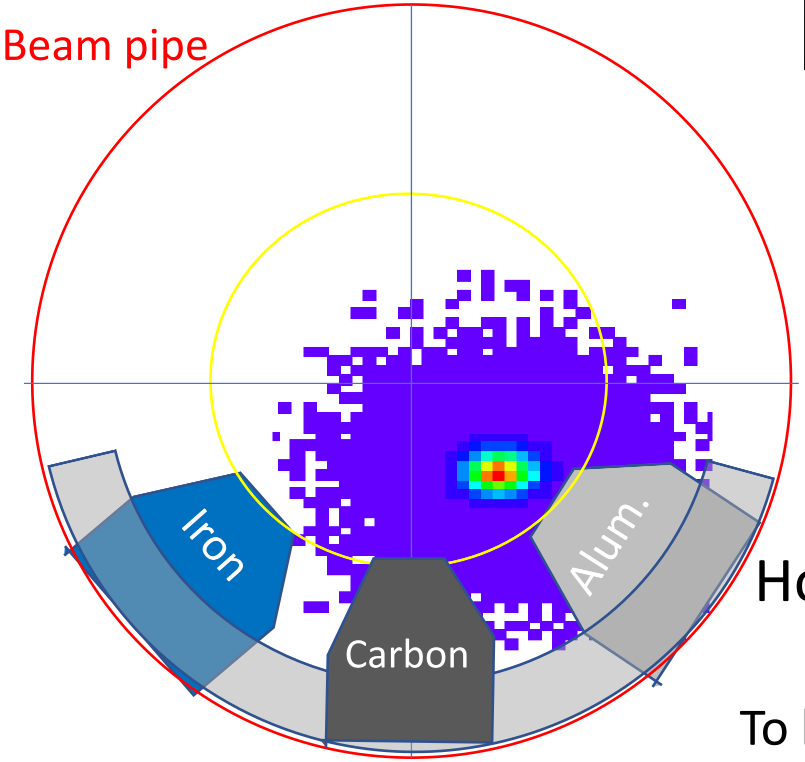


Considerations for Targets/Holder



Current gold target

- Need to avoid limiting horizontal plane
- Beam may be up to one cm in size.
  We measured σ_{xy} = 2 mm.
- Need to know in real time which target is being hit.
  Resolution in HLT is OK.
- Need to be able to resolve hits offline



Holder Scenario

To hit Carbon down 2 cm
To hit Iron, down, then left
To hit Al, down, then right

Thicknesses of targets

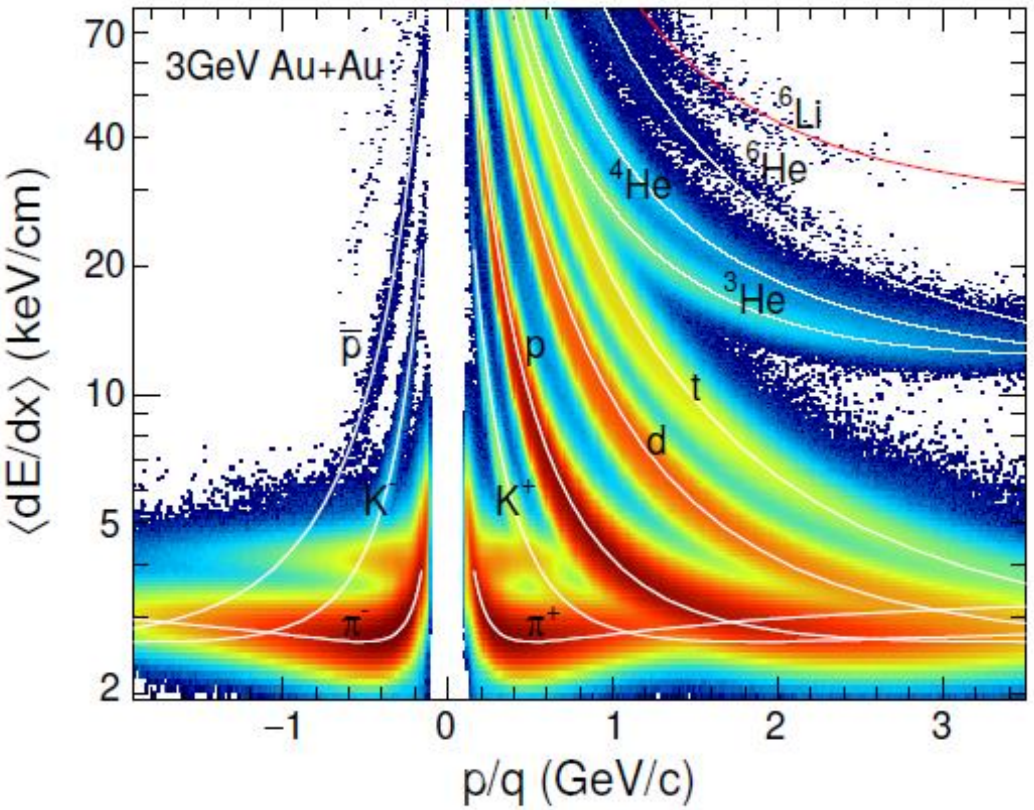
Carbon ➔ **1.0 mm**
Aluminum ➔ **1.5 mm**
Iron ➔ **0.8 mm**

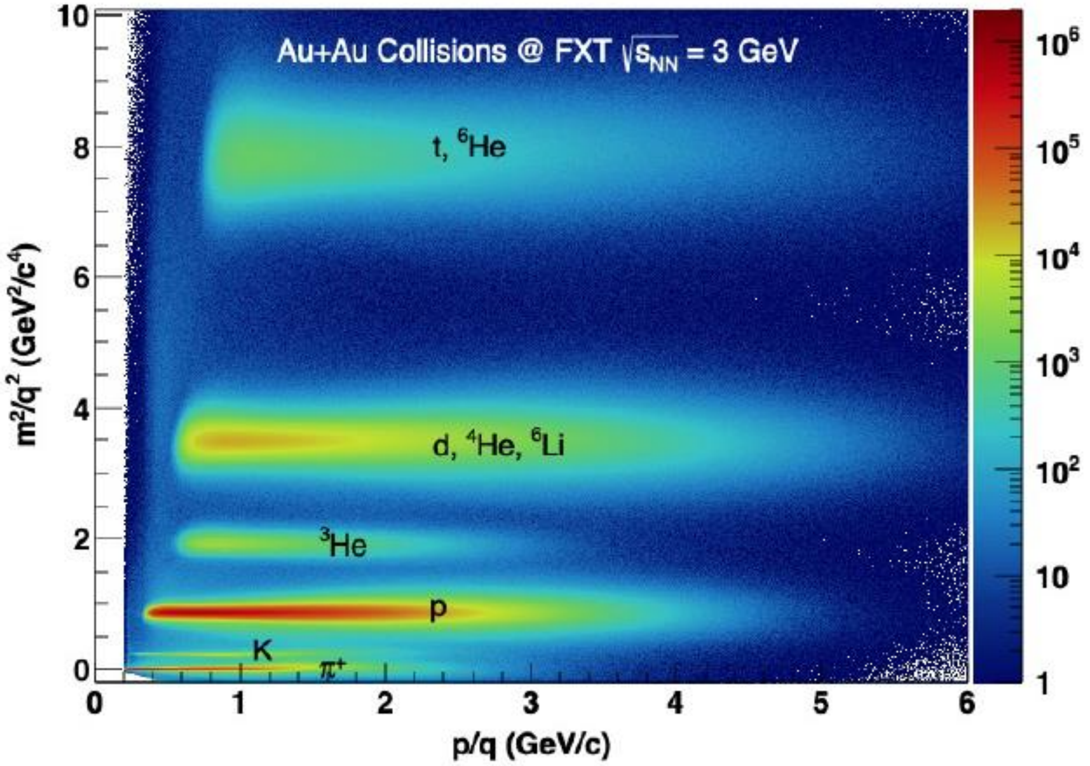
Gold ➔ **0.25 mm**

STAR Has Completed a Au+Au Fixed-target Program; Energies from 3-100 GeV/n

Very good light fragment particle identification ➔ dE/dx and time-of-flight

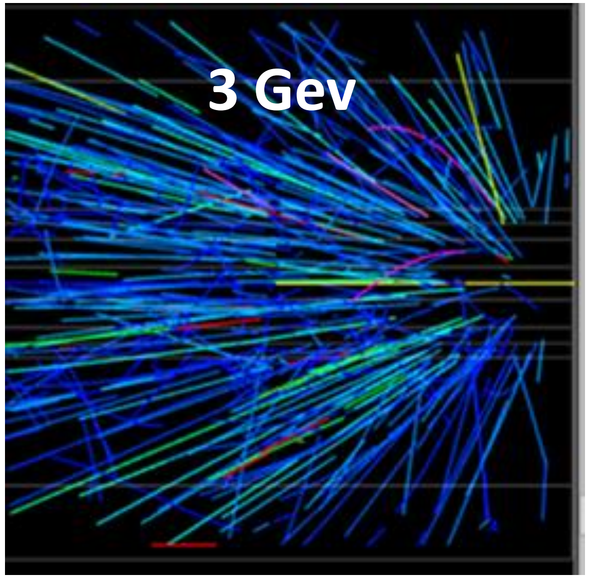
3GeV Au+Au Collisions at RHIC

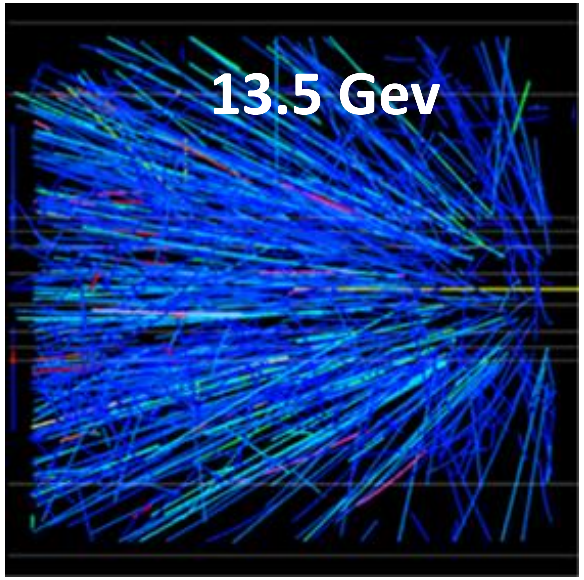


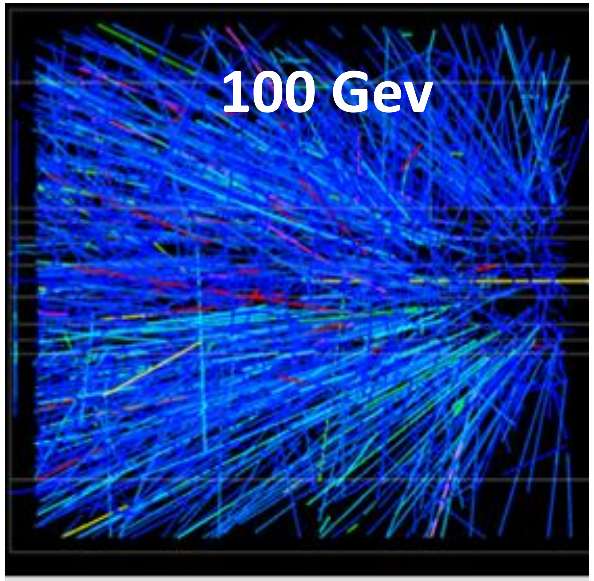


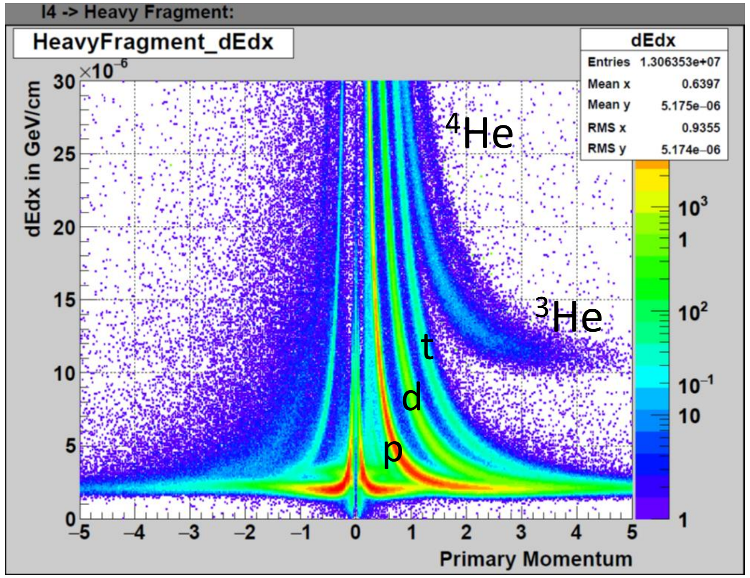
Performance with Beam Energy

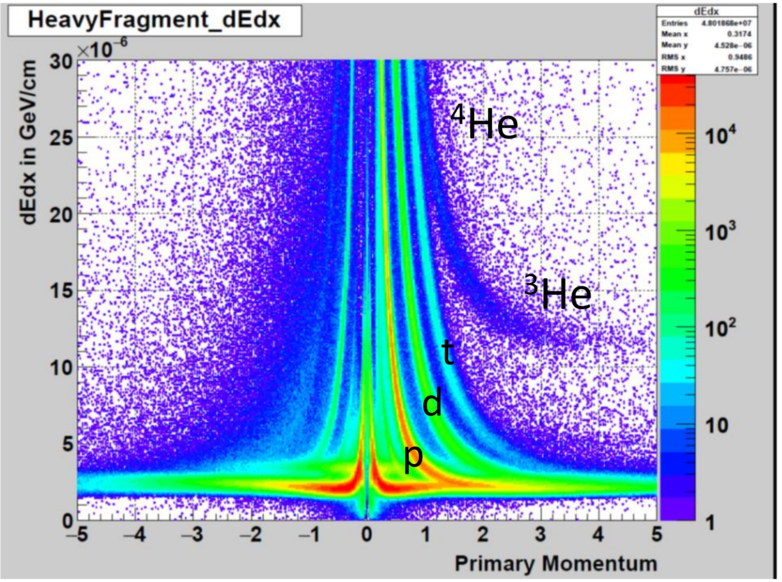
Fewer tracks, more helium nuclei

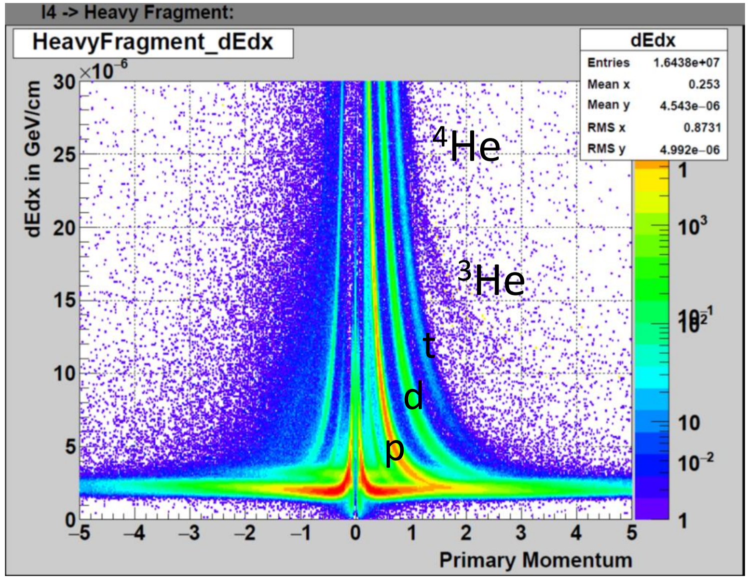












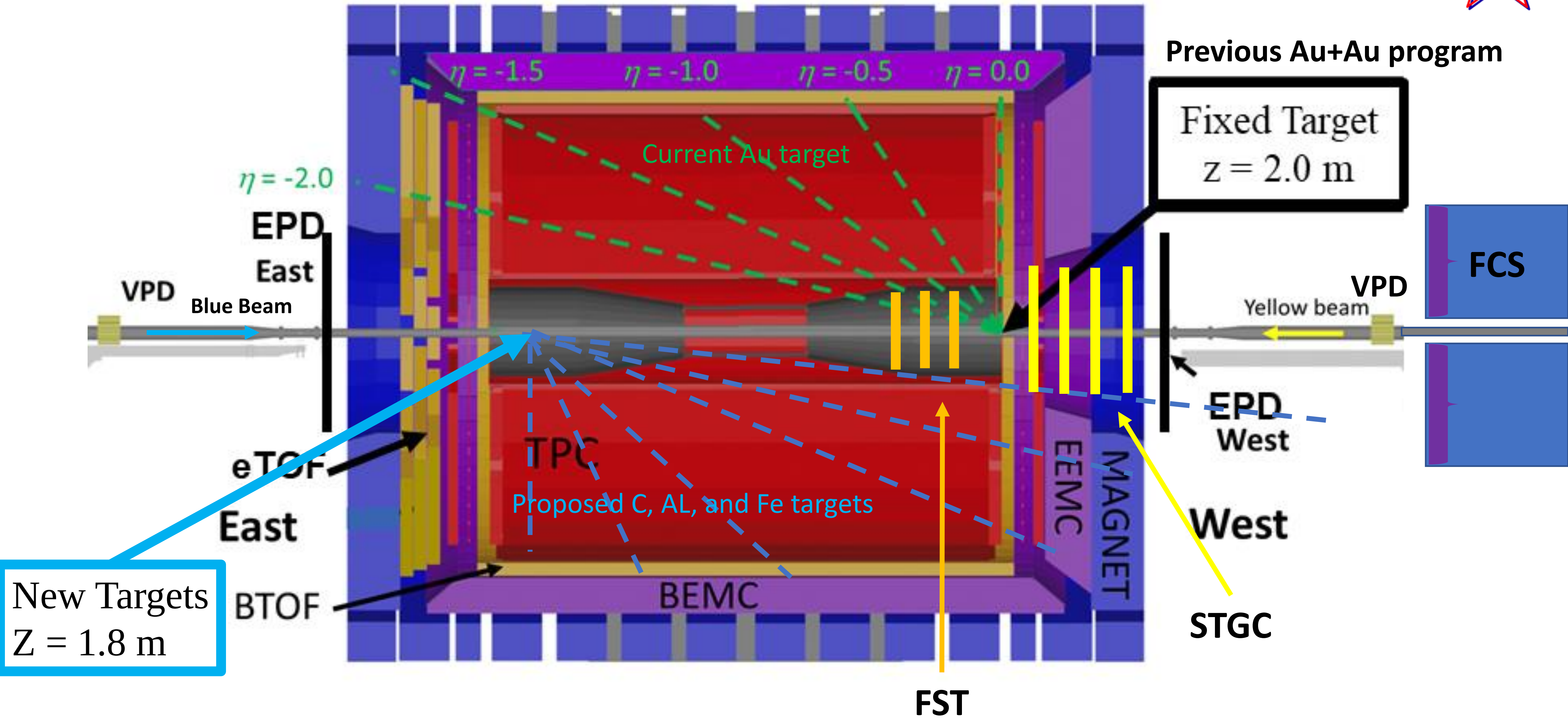
More tracks, fewer helium nuclei

Conclusions:

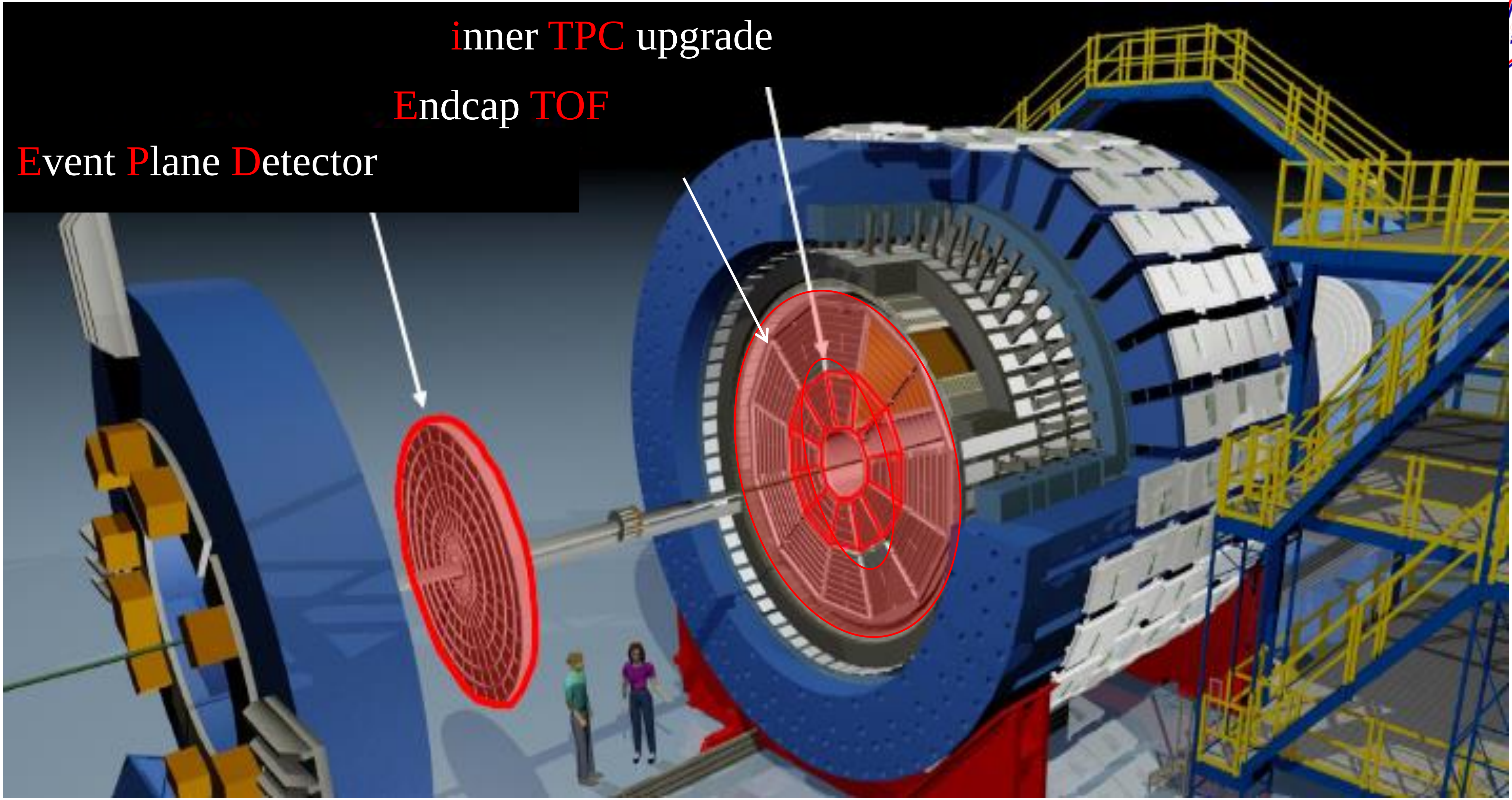
- Nuclear data are needed for Space Radiation Protection.
- There are several facilities and an active program covering energies up to 1.5 GeV/n.
- Light fragment cross section data for projectiles in the energy range 3-50 GeV are needed.
- Data from the STAR/RHIC FXT program could address the high energy needs for Space Radiation Protection.
- STAR is evaluating the accuracy to which cross sections can be measured.

The RHIC/STAR has developed techniques, facilities, and a knowledge base such that measurements could be made that would benefit society by addressing a key identified need of the Space Radiation Protection community. Timely acquisition of relevant data sets would reduce the risk to astronauts, spacecraft, and equipment.

BACKUP



Projectile fragmentation measurements with Forward Upgrade



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

Proposal (In STAR BUR 2023-25):

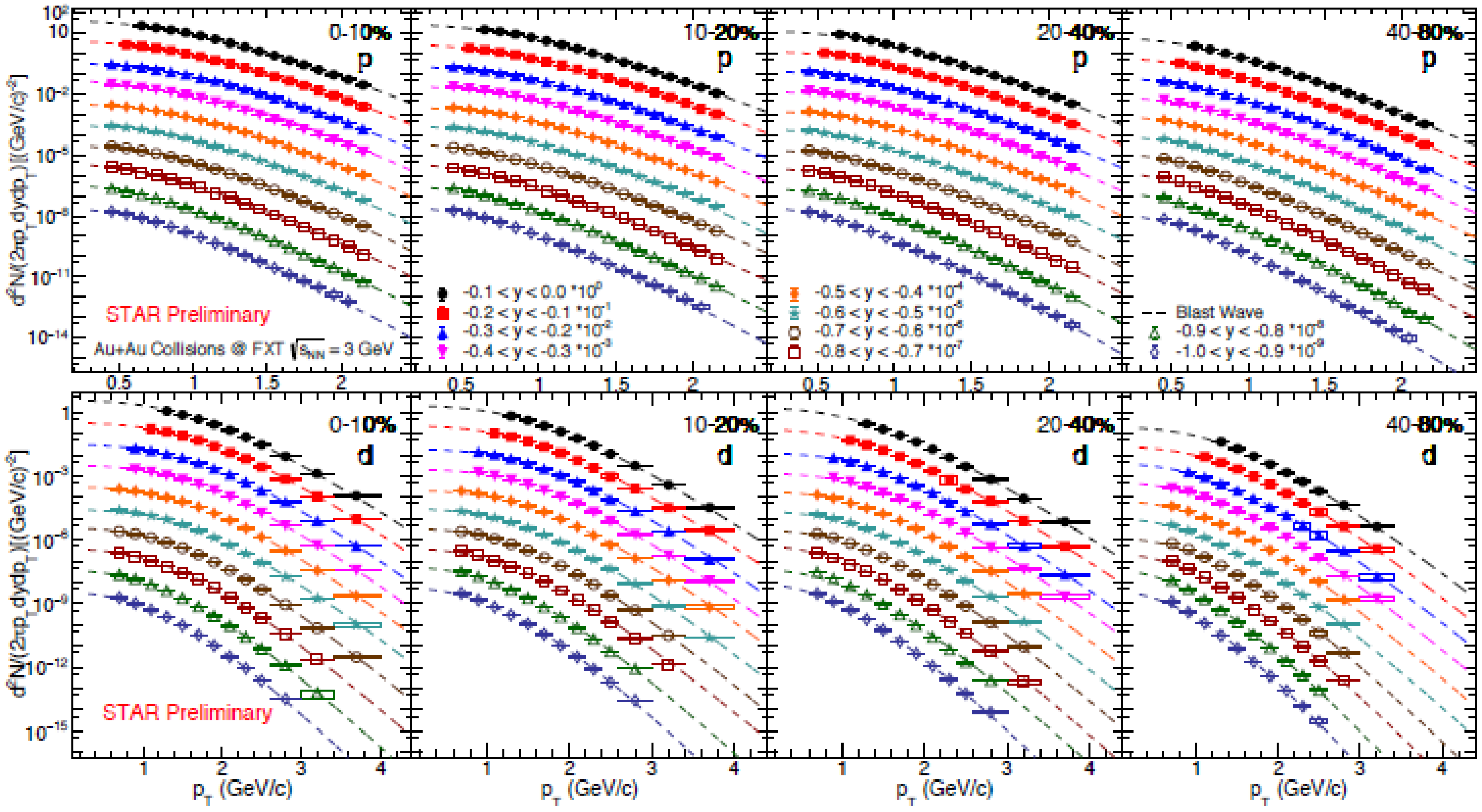
- Replace the current gold target with a target frame holding Carbon, Aluminum, and Iron Targets

- Take data for two weeks using Carbon, Aluminum, and Iron beams at 3 energies each (5-50 GeV).

From 2023-25 BUR

Beam	Energy	Targets	Time
Machine Setup			1 day
Carbon	5 GeV	C, Al, Fe	2 days
Carbon	20 GeV	C, Al, Fe	2 days
Carbon	50 GeV	C, Al, Fe	2 days
Total			1 week
Machine Setup			1 day
Aluminum	5 GeV	C, Al, Fe	2 days
Aluminum	20 GeV	C, Al, Fe	2 days
Aluminum	50 GeV	C, Al, Fe	2 days
Total			1 week
Machine Setup			1 day
Iron	5 GeV	C, Al, Fe	2 days
Iron	20 GeV	C, Al, Fe	2 days
Iron	50 GeV	C, Al, Fe	2 days
Total			1 week
Grand Total			3 weeks

Modified to two weeks

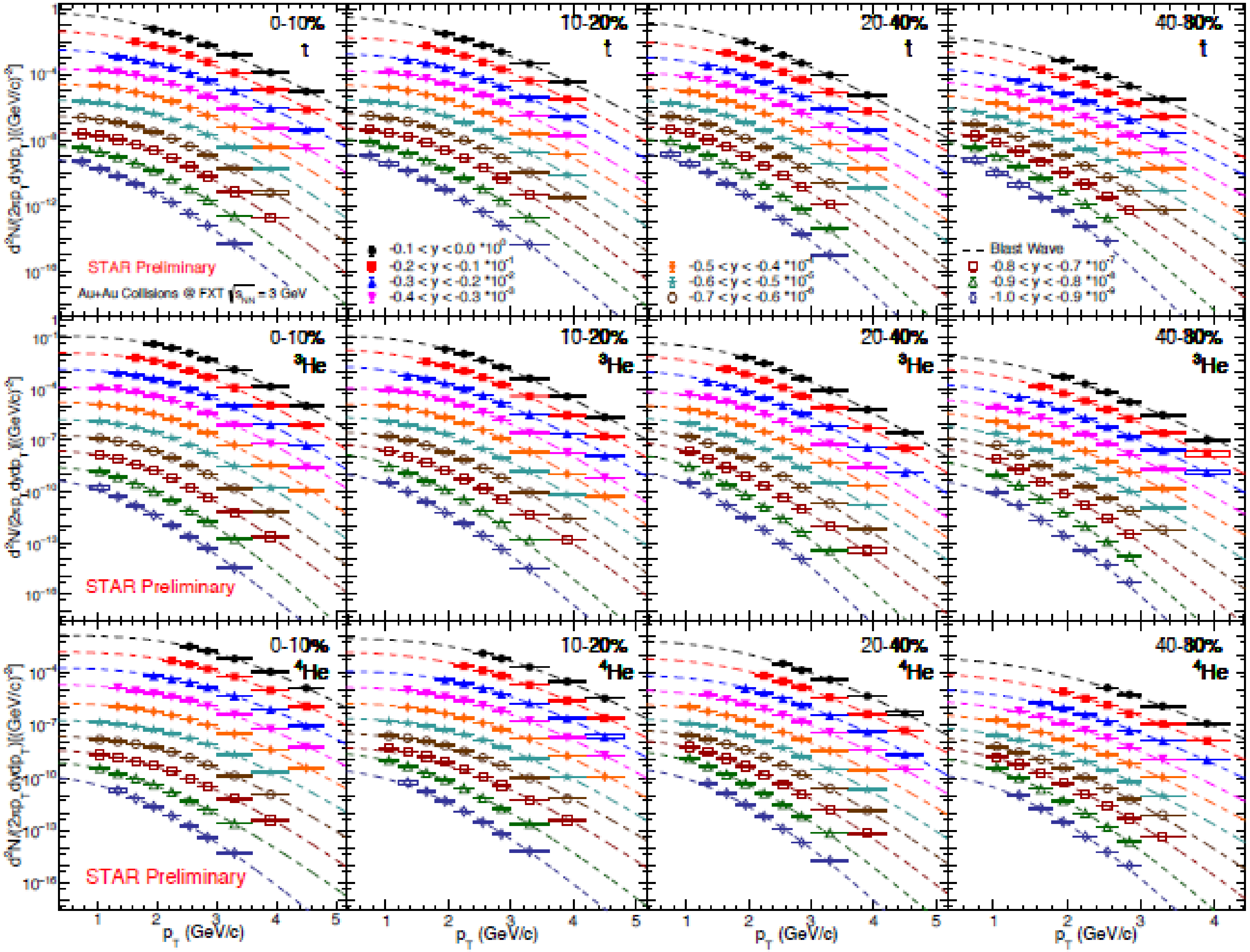


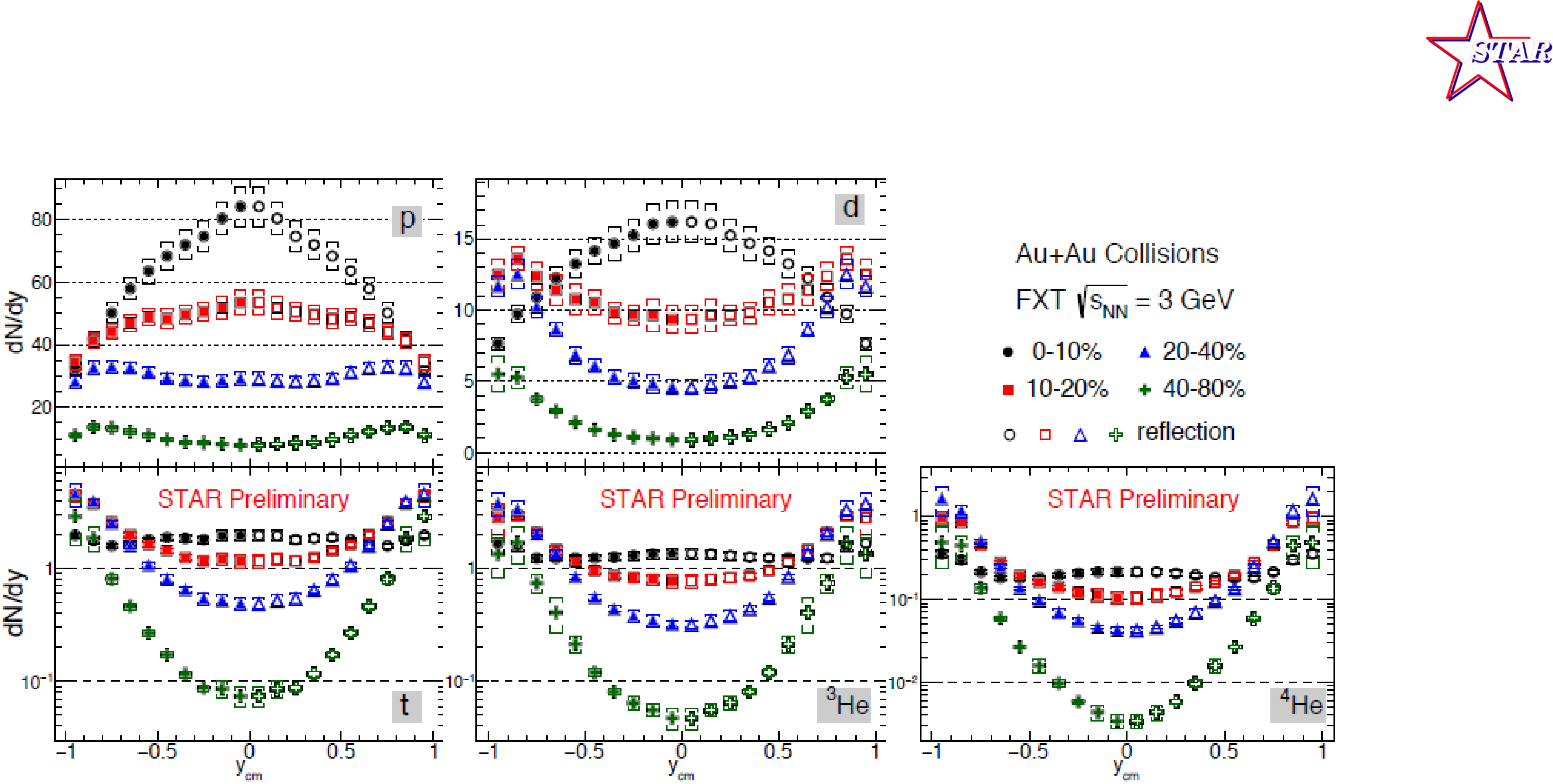
0-10%
10-20%
20-40%
40-80%
p
d
STAR Preliminary
Au+Au Collisions @ FXT $\sqrt{s_{NN}}$ = 3 GeV
-0.1 < y < 0.0 *10^0
-0.2 < y < -0.1 *10^-1
-0.3 < y < -0.2 *10^-2
-0.4 < y < -0.3 *10^-3
-0.5 < y < -0.4 *10^-4
-0.6 < y < -0.5 *10^-5
-0.7 < y < -0.6 *10^-6
-0.8 < y < -0.7 *10^-7
Blast Wave
-0.9 < y < -0.8 *10^-8
-1.0 < y < -0.9 *10^-9
$d^2N/(2\pi p_T dy dp_T)$ [(GeV/c)^-2]
p_T (GeV/c)

Triton

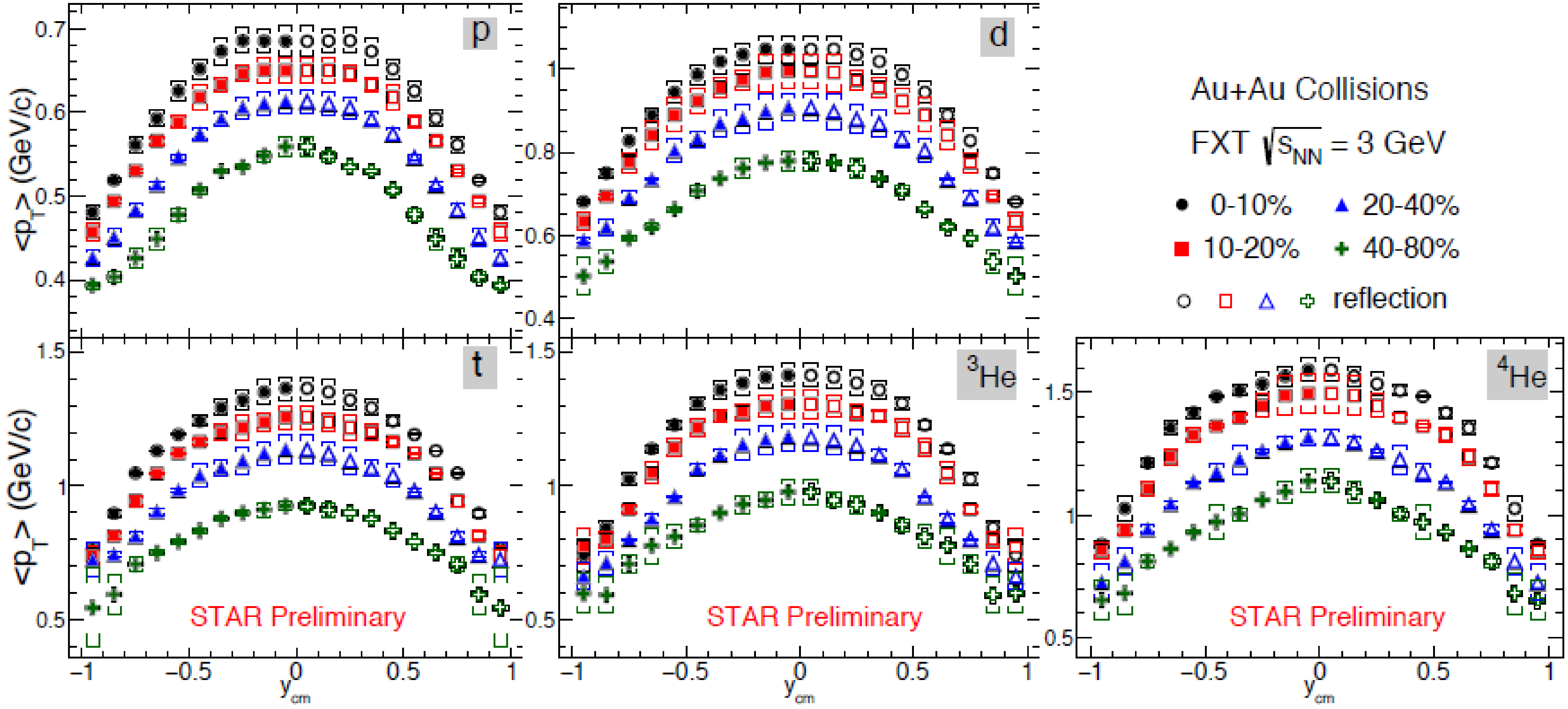
^{3}He

^{4}He





STAR
p
d
t
^{3}He
^{4}He
dN/dy
y_{cm}
STAR Preliminary
Au+Au Collisions
FXT $\sqrt{s_{NN}}$ = 3 GeV
0-10%
20-40%
10-20%
40-80%
reflection


p
d
t
^{3}He
^{4}He
$\langle p_T \rangle$ (GeV/c)
y_{cm}
Au+Au Collisions
FXT $\sqrt{s_{NN}}$ = 3 GeV
0-10%
20-40%
10-20%
40-80%
reflection
STAR Preliminary
STAR Preliminary
STAR Preliminary

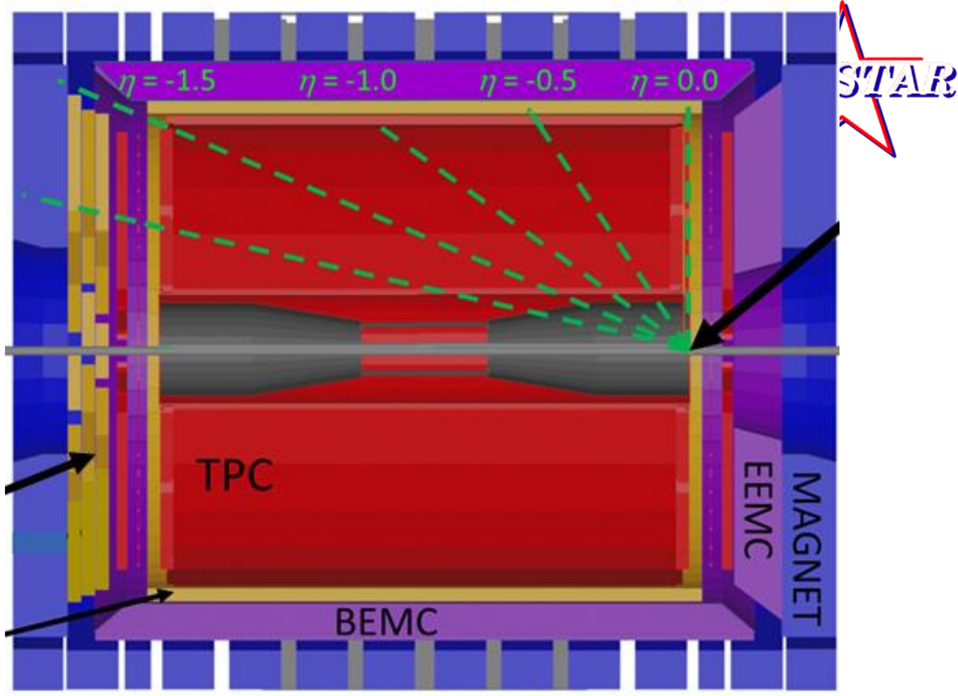
Acceptance for the FXT Program

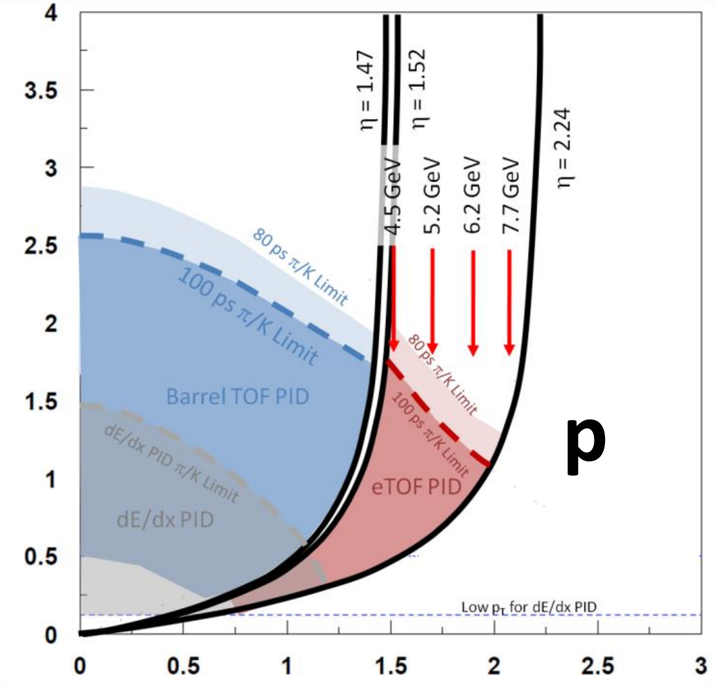
From 2018-2021, RHIC/STAR has beam running a fixed-target program performing an energy scan of gold beams on a gold target.

Note on energies: There a few different units to use to describe the collision energy.

Note that acceptance is dependent on the collision energy

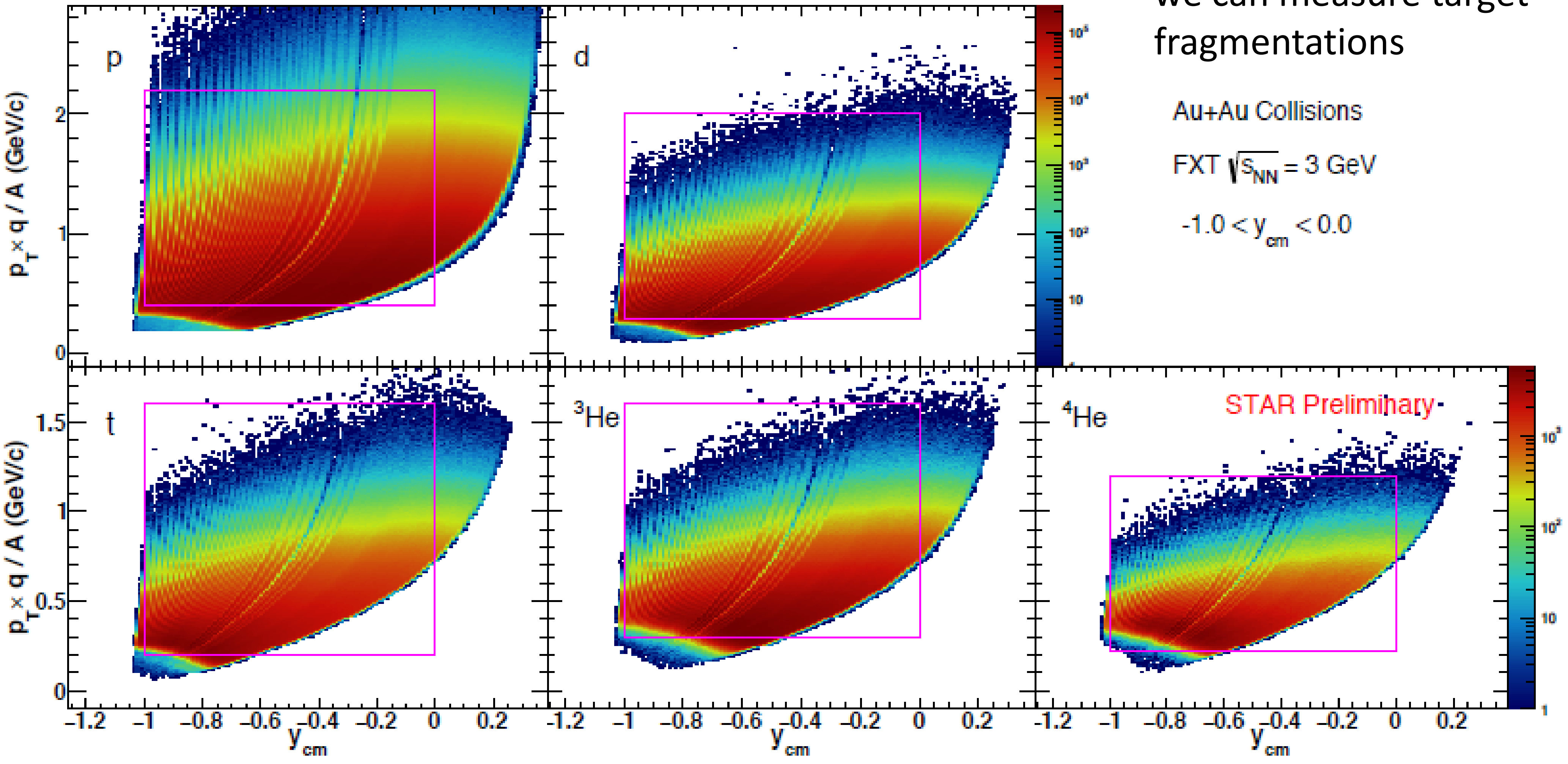
FXT Energy $\sqrt{s_{NN}}$	Single Beam E_T (GeV)	Single beam E_k (AGeV)	Center-of-mass Rapidity	Chemical Potential μ_B (MeV)	Year of Data Taking
3.0	3.85	**2.9**	1.05	721	2018
3.2	4.59	**3.6**	1.13	699	2019
3.5	5.75	**4.8**	1.25	666	2020
3.9	7.3	**6.3**	1.37	633	2020
4.5	9.8	**8.9**	1.52	589	2020
5.2	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

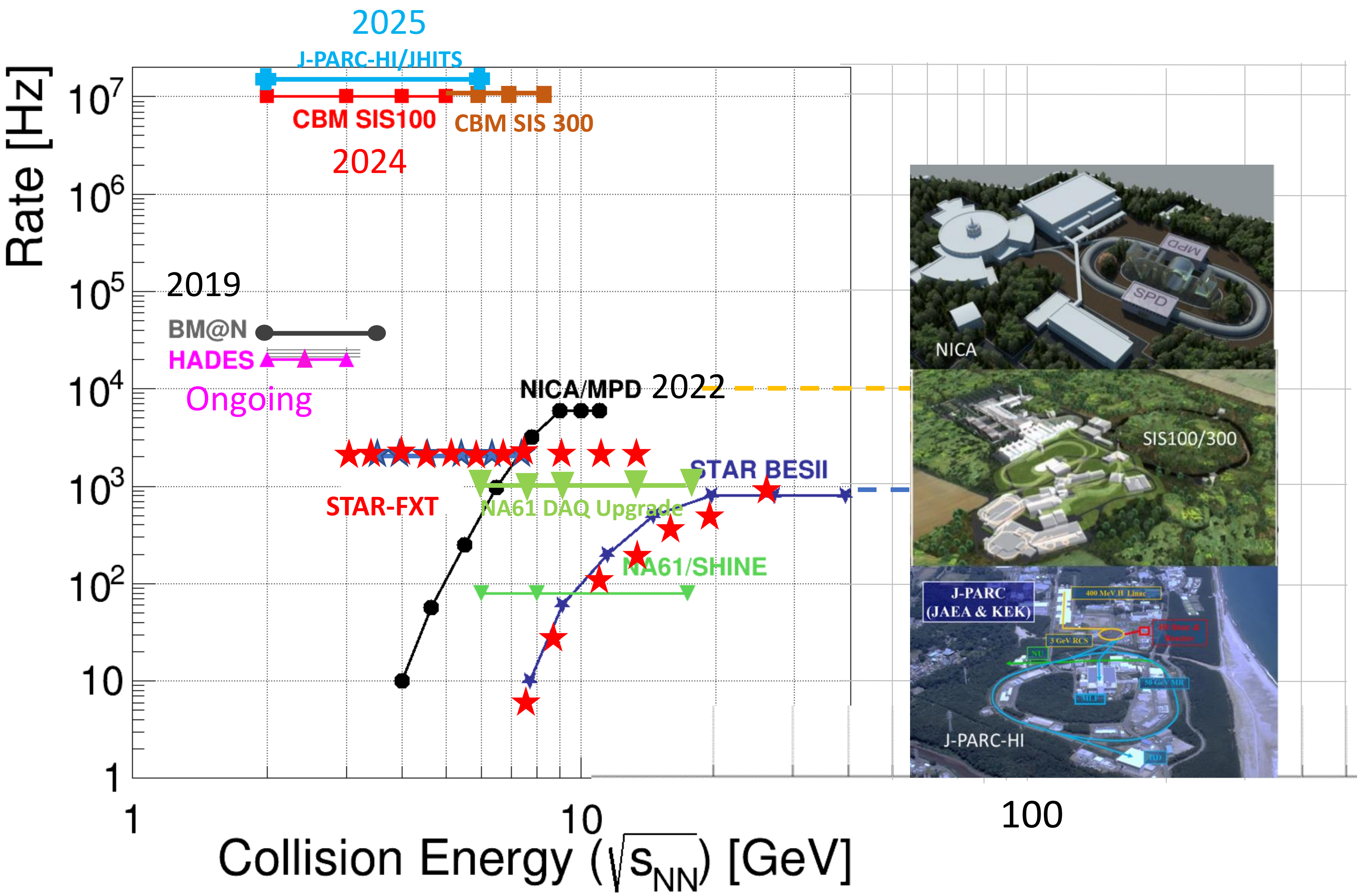




STAR light fragment acceptance

TPC has no forward acceptance for projectile fragmentation ➔ consider using inverse kinematics, we can measure target fragmentations





SPS up to 160 GeV

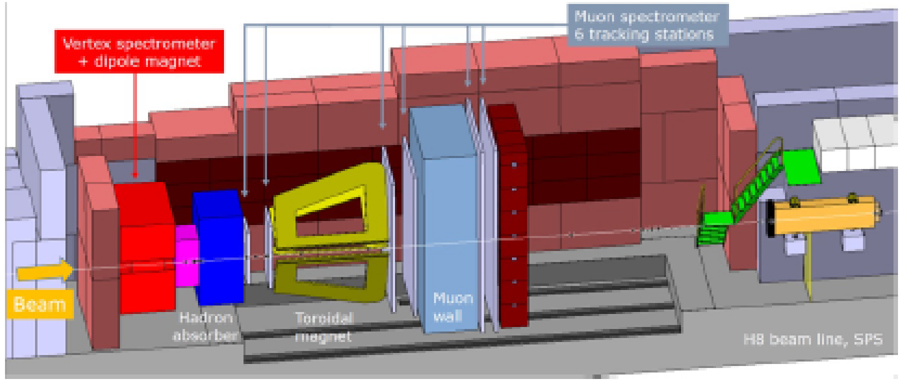
NICA/MPD is a Collider exp.
NICA single beam of about 10 GeV

Nuclotron reaches up to 3.5 GeV

JPARC up to about 18 GeV

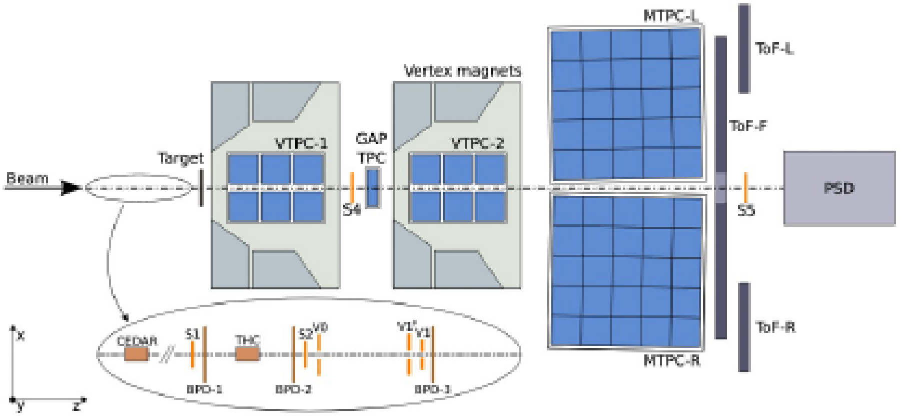
NA60+ and NA61 Experiments at SPS

NA60+ (2029)



1) High rate (10^6 Hz Pb beam) di-muon spectrometer for energy scan $6 \leq \sqrt{s_{NN}} \leq 17.3$ GeV
2) **Key Physics:** (i) Temperature; (ii) Onset of deconfinement; (iii) QCD transport coefficient

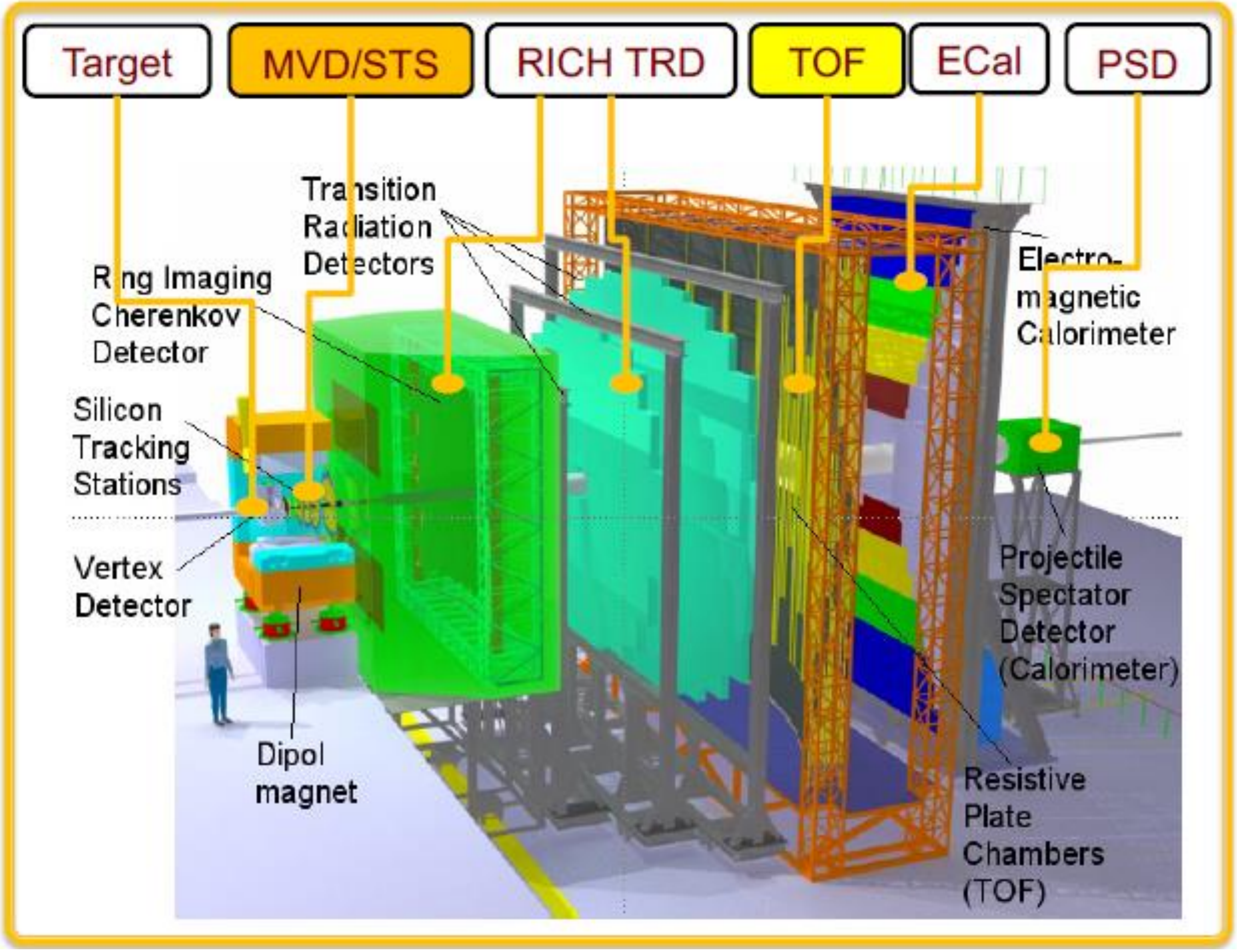
NA61 (2008 - 2027)



1) Study hadronic production in p-p, p-A and A-A collisions over $5.1 \leq \sqrt{s_{NN}} \leq 17.3$ GeV
2) **Key Physics:** (i) QCD CP; (ii) Onset of deconfinement

Pb+Pb, Xe+La, Ar+Sc, Be+Be, p+Pb, p+p

CBM Experiment at FAIR

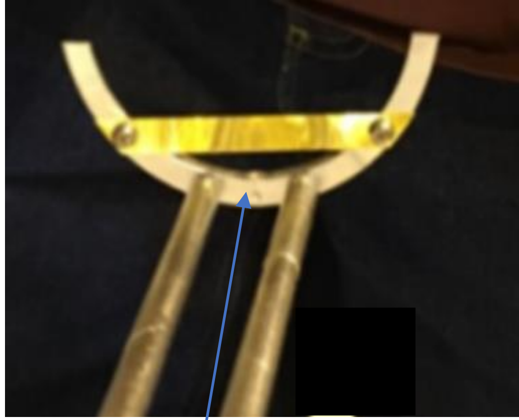


- FAIR: The brightest accelerator complex;
- Precision measurements at high baryon density region:
  (i) Dileptons (e, μ);
  (ii) High order correlations;
  (iii) Flavor production (s, c) and hyper-nuclei

CBM: BES-III experiment

($2.5 \leq \sqrt{s_{NN}} \leq 4.9$ GeV)

Considerations for Targets/Holder



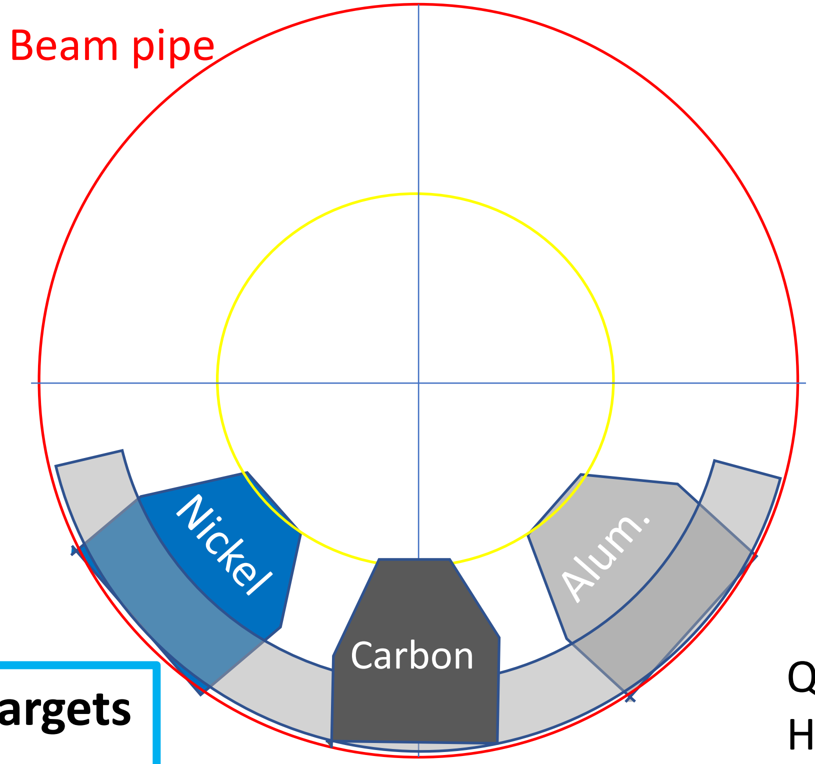
Current gold target

Target Foils:

Carbon 2.0 X 2.0 cm 734$

Nickel 5.0 X 5.0 cm 300$

Alum. 2.5 X 2.5 cm 338$



Carbon

Thicknesses of targets

Carbon → **1.0 mm**
Aluminum → **1.5 mm**
Iron → **0.8 mm**

Gold → **0.25 mm**

Questions:
How far apart are these screw holes?

Other modifications:
Rods need to be 20 cm longer.