STAR Fixed-Target Results from $\sqrt{S_{NN}} = 4.5$ GeV Au+Au and $\sqrt{S_{NN}} = 4.9$ GeV Al+Au Collisions

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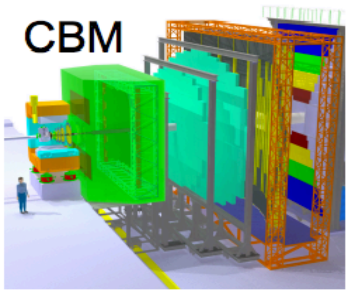
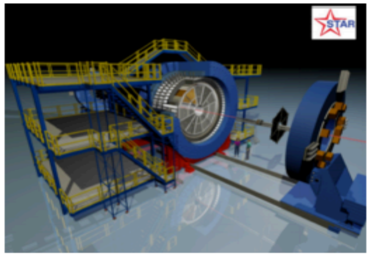


CBM-STAR Joint Meeting

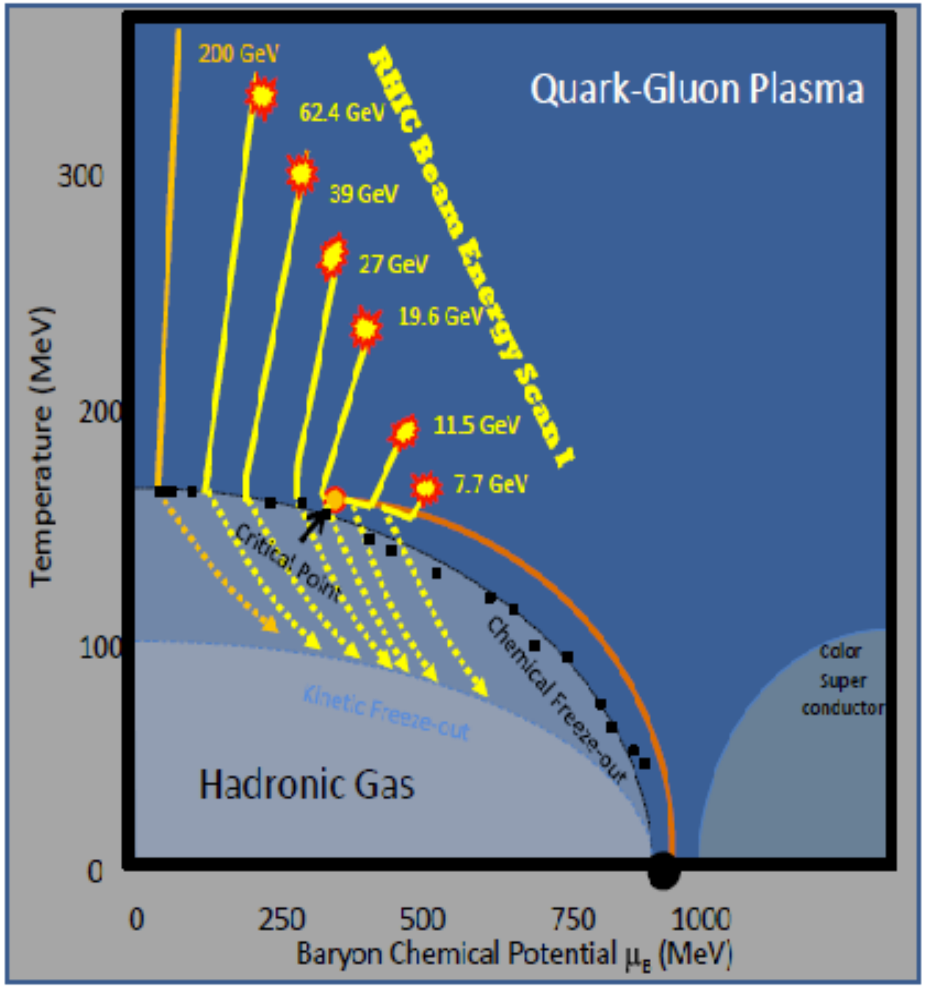
[https://indico.gsi.de/event/6116/]
Central China Normal University
Wuhan, China
September 23, 2017



Outline

- Goals of the BES-I Program
- Physics Motivation of FXT program.
- Introduction to the Fixed-Target (FXT) Program
- Results from Au+Au FXT Collisions at $\sqrt{S_{NN}} = 4.5$ GeV
- Results from Al+Au FXT Collisions at $\sqrt{S_{NN}} = 4.9$ GeV
- Future upgrades and the FXT program
- Summary

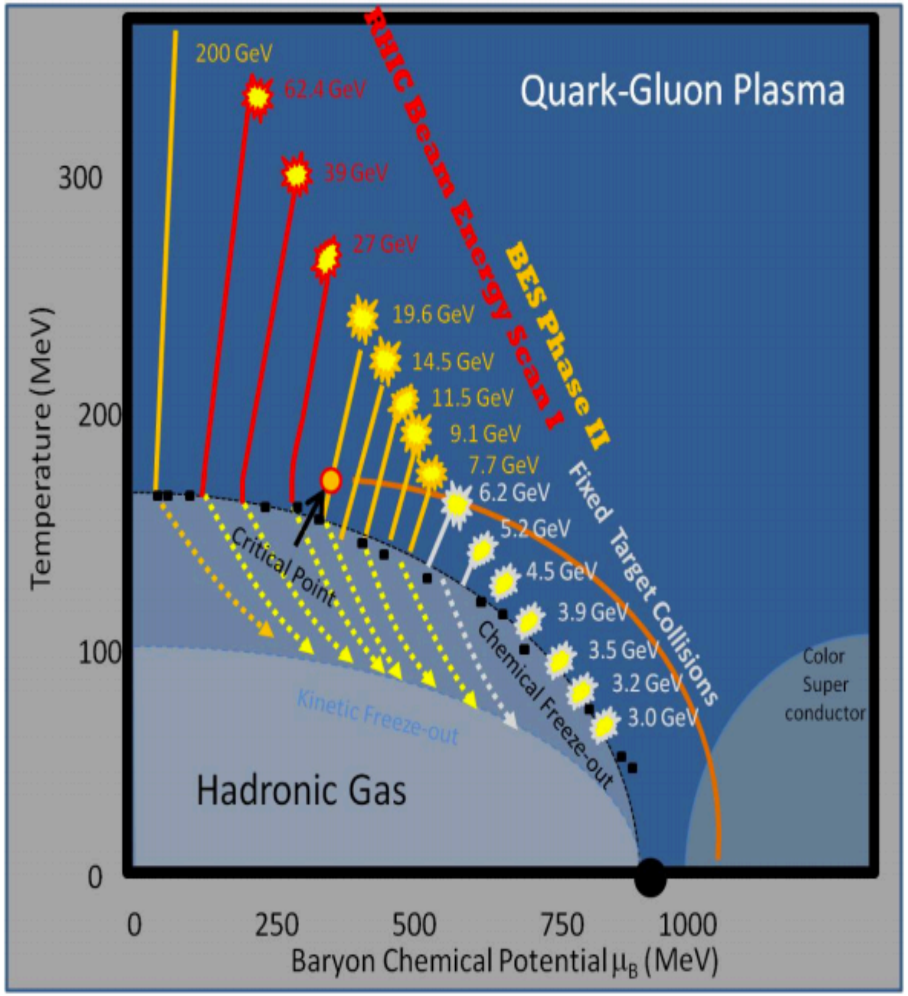
Goals of the BES Program



STAR: arXiv:1007.2613

- BES phase I at RHIC
  - Study the **onset of de-confinement** and **phase boundary**
  - Search for the **QCD critical point**
  - Turn-off of QGP signals
  - Softening of the equation of state
  - Find evidence of the possible first-order phase transition
- Systematic study of Au+Au collisions at 7.7, 11.5, 14.5, 19.6, 27, 39 GeV (BES Phase-I)

Motivation for the Fixed-Target Program

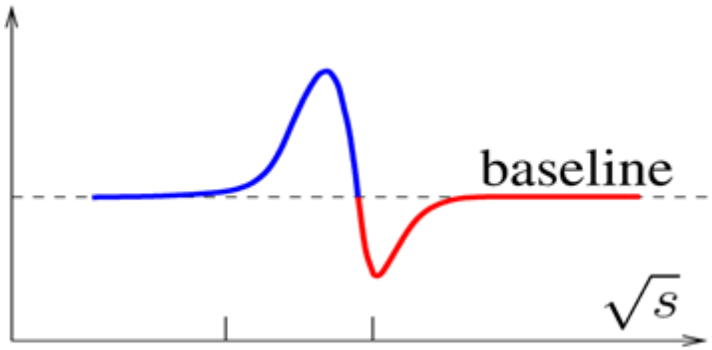


- ❑ NA49 has reported that the onset of deconfinement may occur at 7 GeV, the low end of BES range.
- ❑ How to achieve low energy?
  - ➢ By installing a target inside the beam pipe and using RHIC beam as a projectile.
  - ➢ It can extend the μ_B range from 400 MeV to about 720 MeV
  - ➢ Provide control measurements for searches of the critical point and onset of deconfinement

Need to probe lower energies!

Control Measurements for CEP Signatures

Peak behavior predicted in critical region:

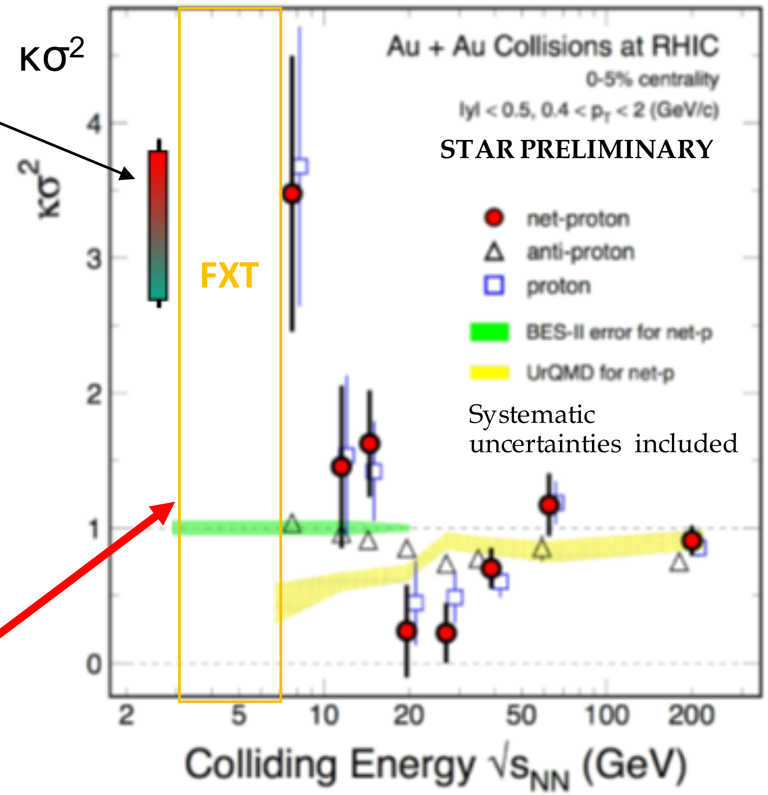


M. Stephanov. J. Physics G.: Nucl. Part. Phys. *38* (2011) 124147

Preliminary HADES result, Quark Matter 2017
0-10%
(QM 2017)

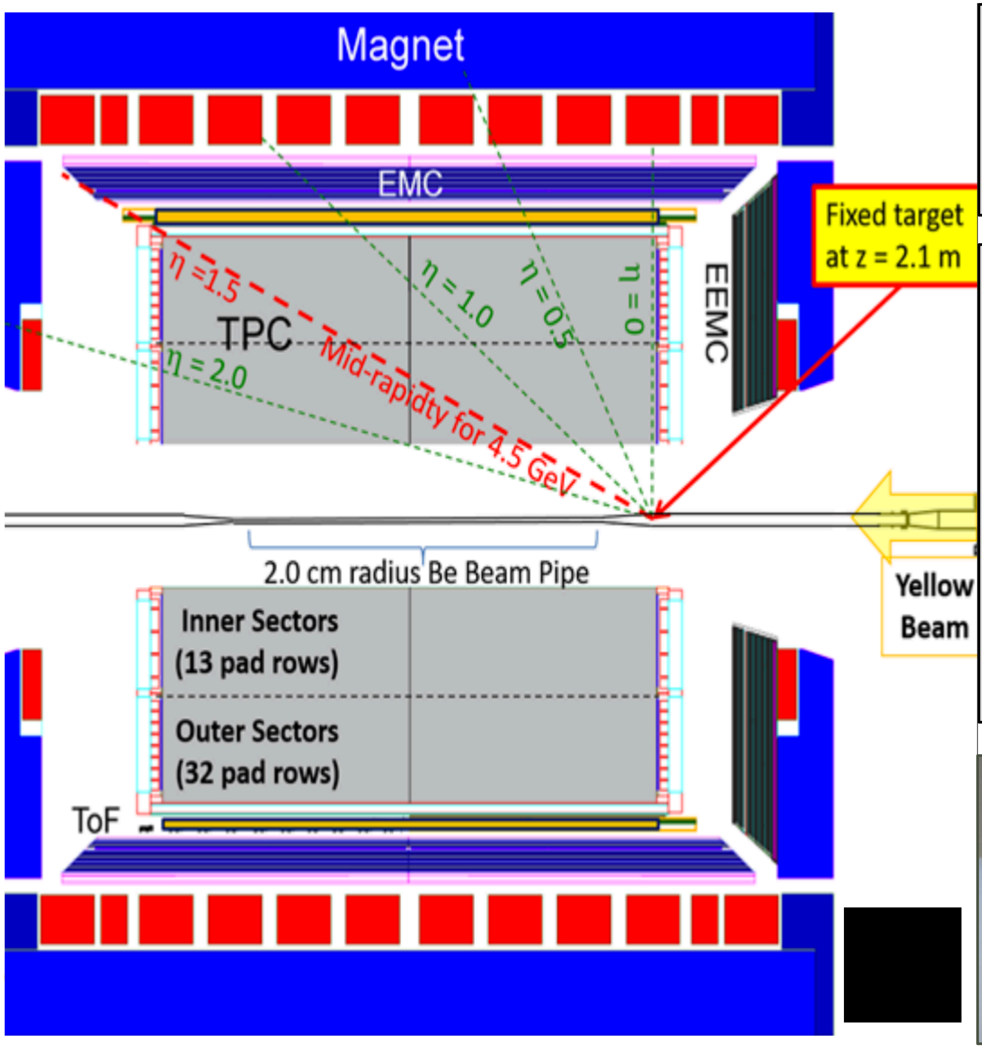
$\kappa\sigma^2$

Need data here!



→ FXT measurements needed to determine shape of $\kappa\sigma^2$ observable at lower energies

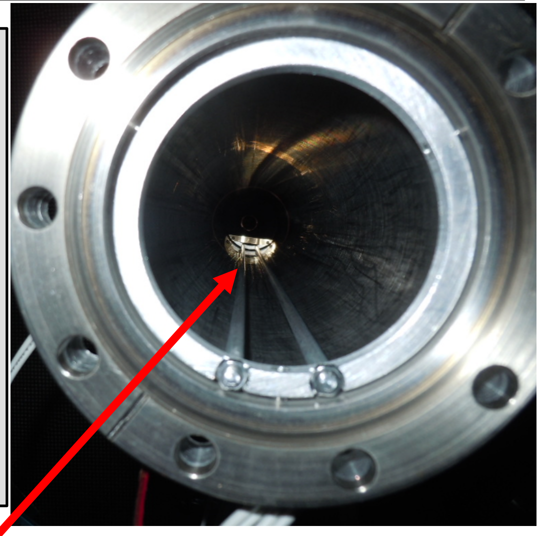
Fixed-Target Geometry

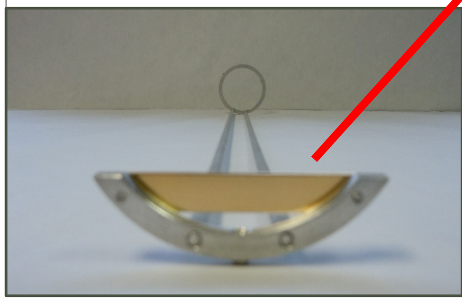


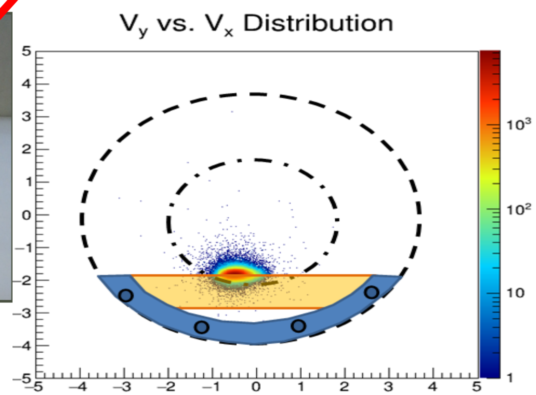
→target is outside of the STAR TPC at ~211 cm

→Gold foil is 1mm thick with about a 4% interaction probability

→1.3M Au+Au events with top 30% centrality trigger

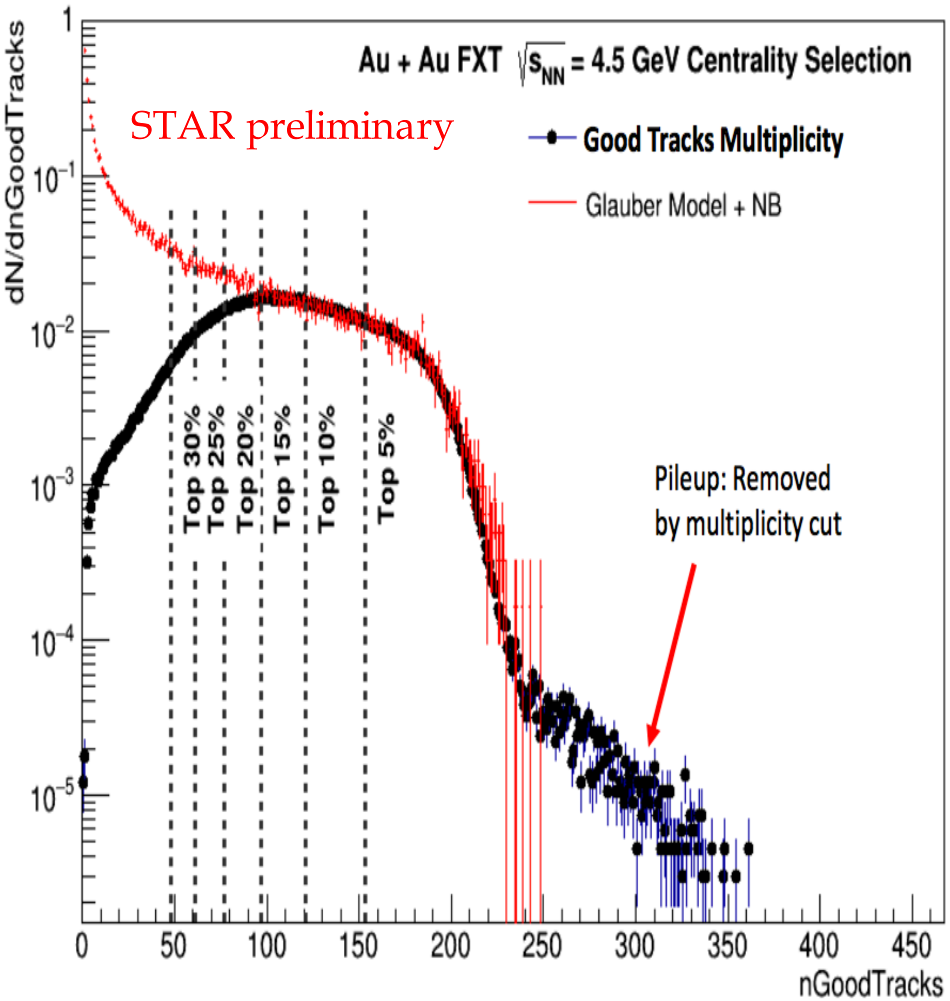






Results from FXT Au+Au Collisions at $\sqrt{S_{NN}}$ = 4.5 GeV

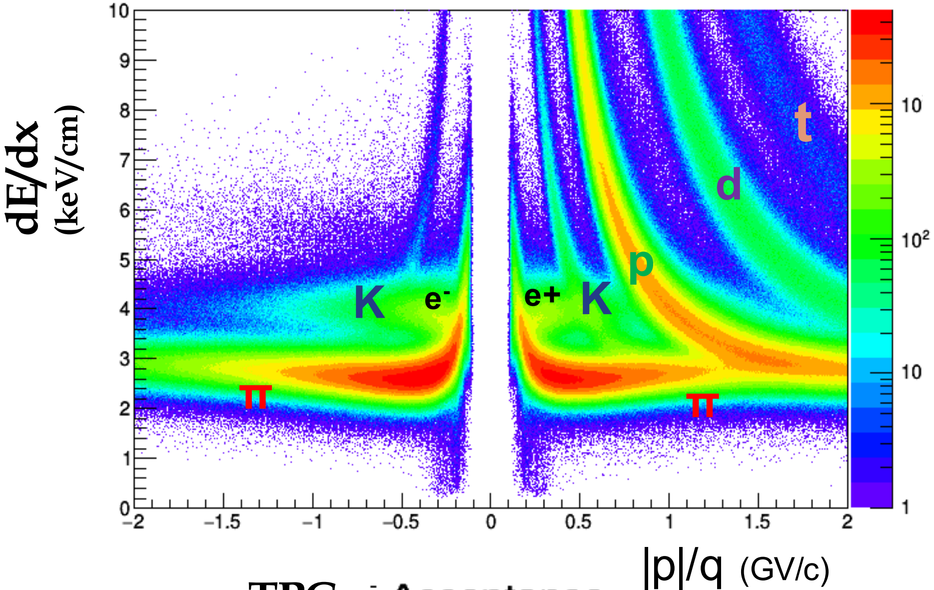
Centrality Determination for Au+Au Collisions at $\sqrt{S_{NN}}$ = 4.5 GeV



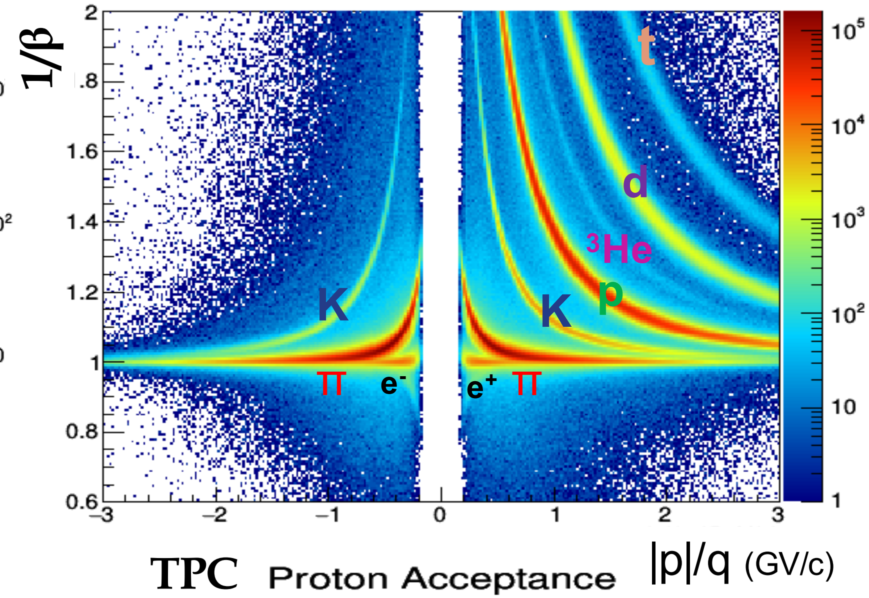
- nGoodTracks are those tracks which pass through basic QA cuts.
- Pileup has been removed by multiplicity cut.
- 15%-30% centralities are biased toward the more central collisions. This biasing is minimal for more central events.

FXT PID & Acceptance

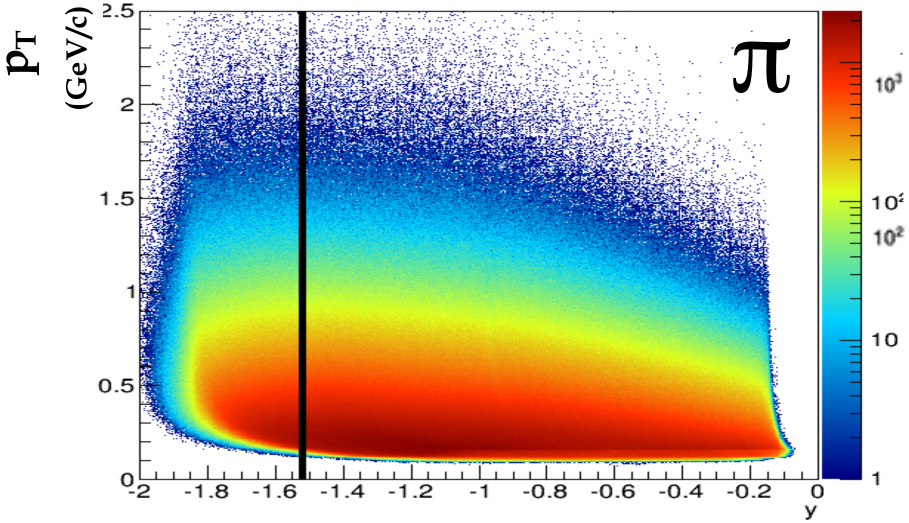
PID with **TPC**



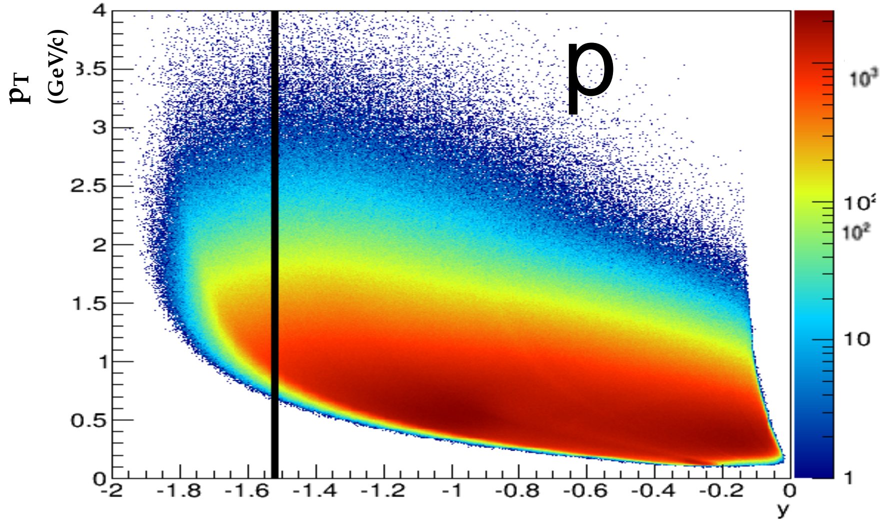
Time-of-Flight



TPC π^- Acceptance

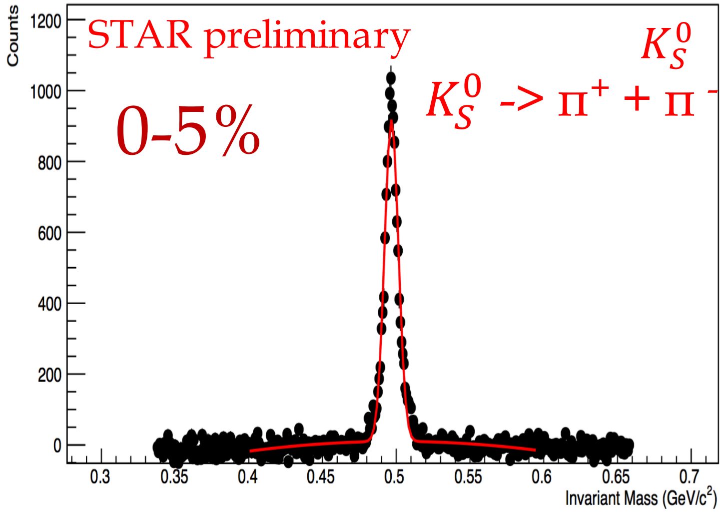


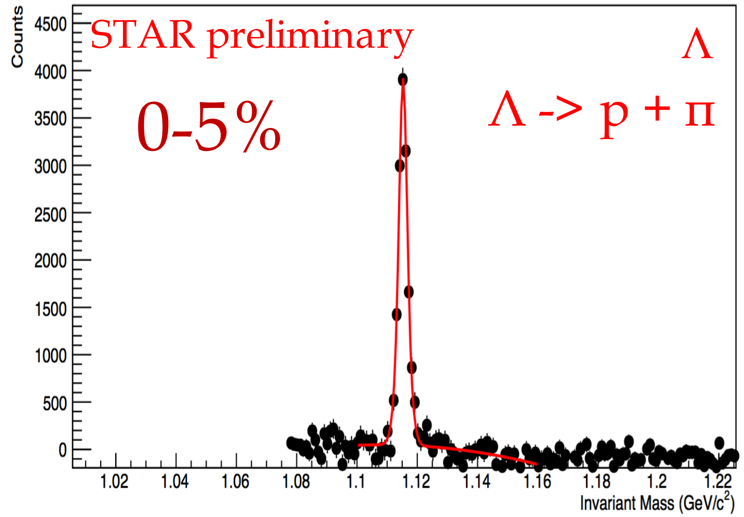
TPC Proton Acceptance



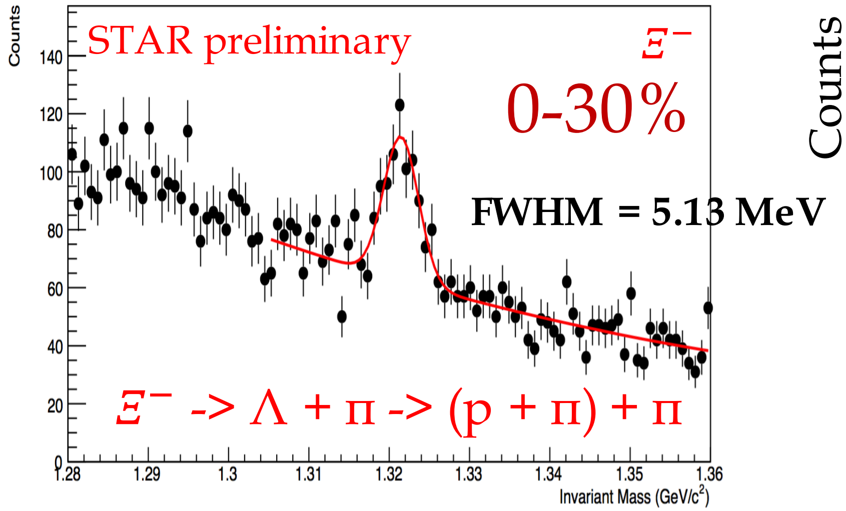
- In STAR, the acceptance for particles and anti-particles is the same. This is not normally true for an experiment with a dipole magnet.

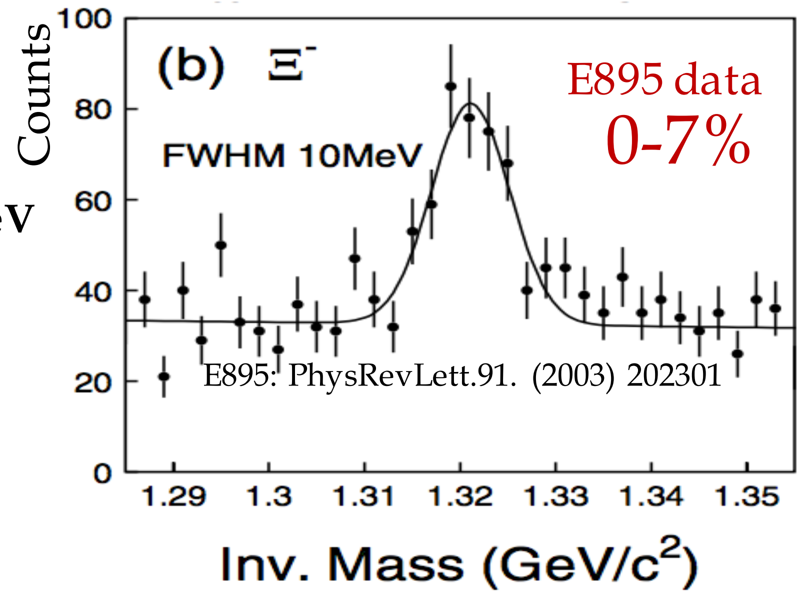
Particle Reconstruction in Au+Au at $\sqrt{S_{NN}}$ = 4.5 GeV



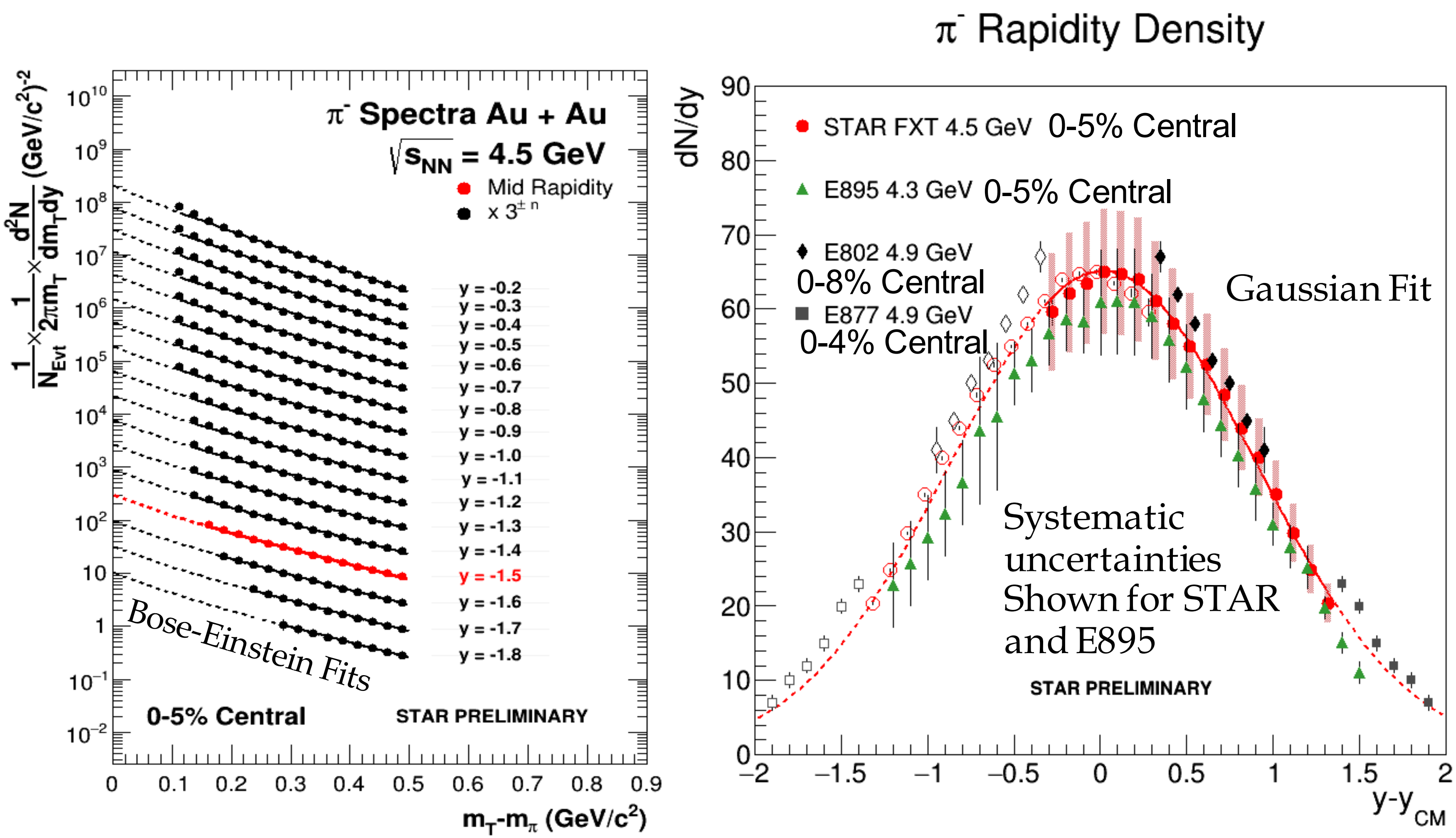


π ,K, p are identified by dE/dx in TPC. Secondary vertex reconstruction.





Pion Spectra and dN/dy Distribution



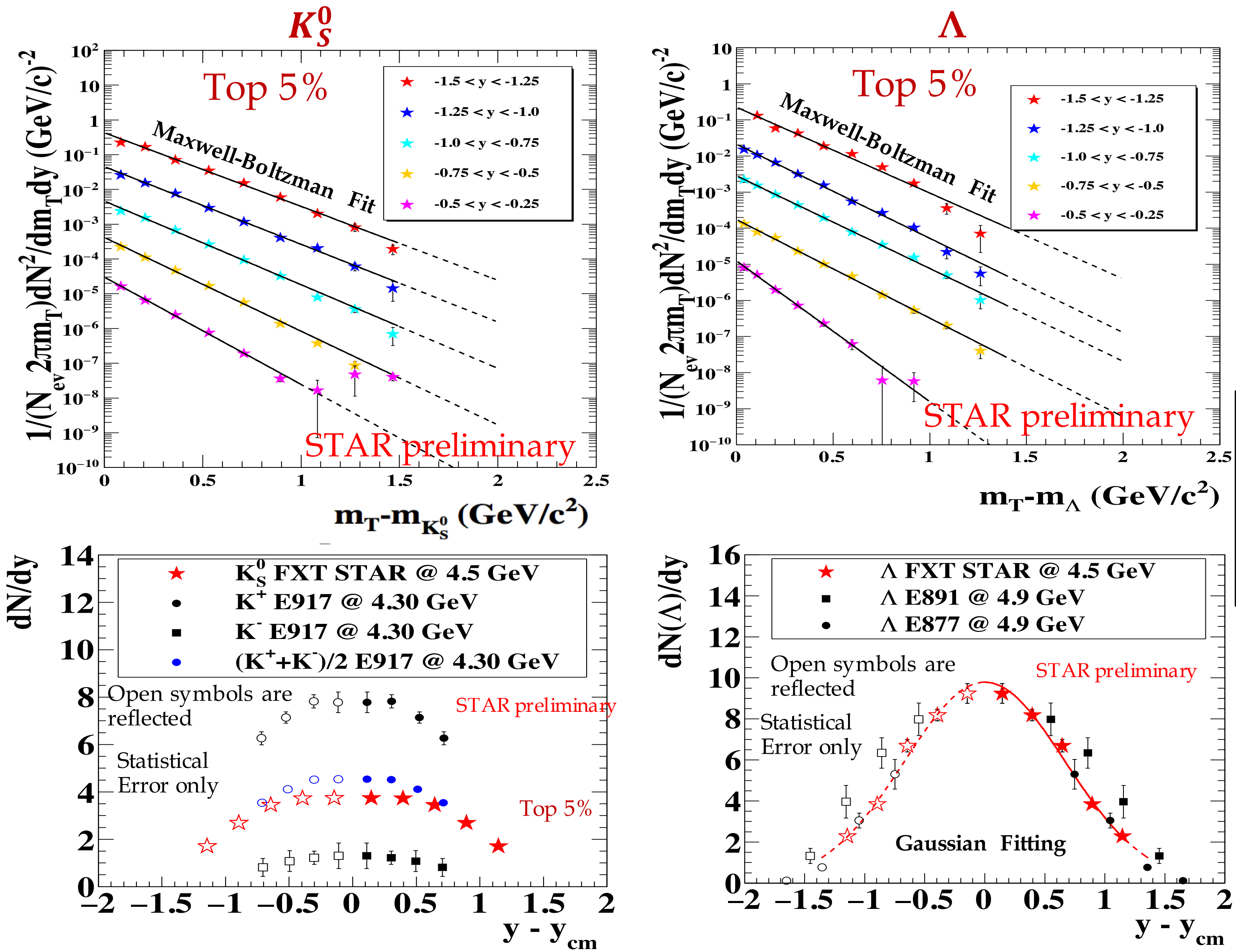
- Amplitudes and widths of the rapidity densities are consistent with results from the AGS experiments

E802: Phys. Rev. C 57 (1998) R466

E877: Phys. Rev. C 62 (2000) 024901

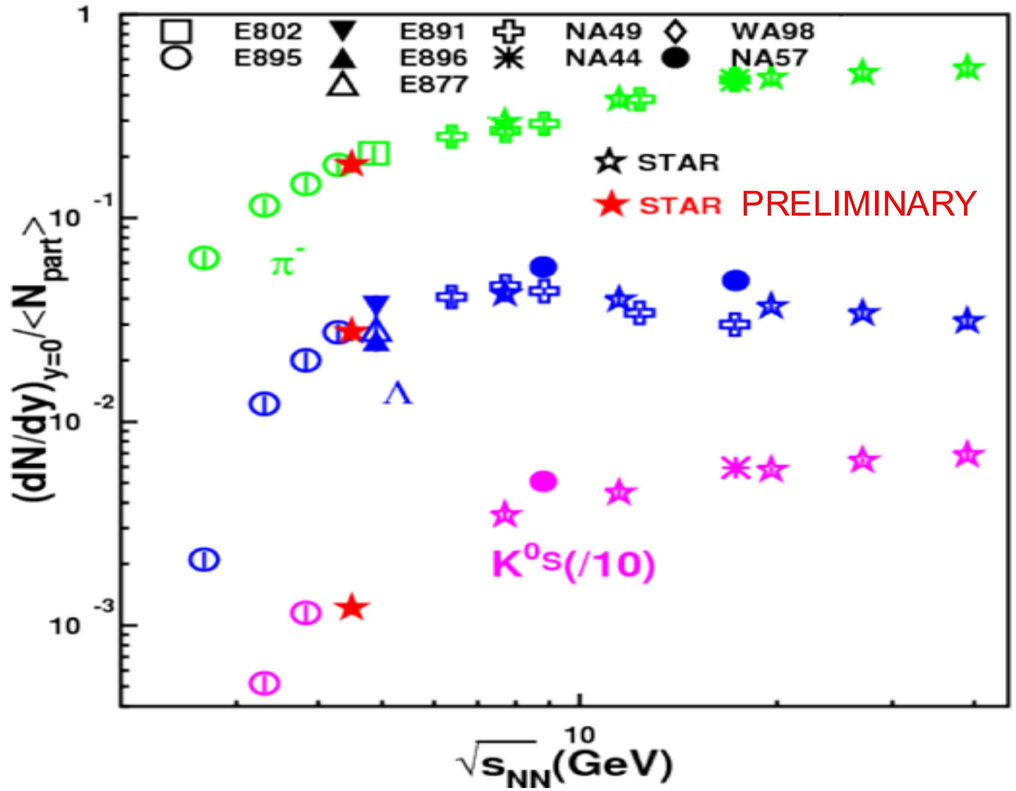
E895: Phys. Rev. C 68 (2003) 054905

m_T-m_0 and dN/dy spectra of K_S^0 and Λ in Au+Au at $\sqrt{s_{NN}}$ = 4.5 GeV



Amplitudes and widths of rapidity density, dN/dy, are in a good agreement with AGS experiments.

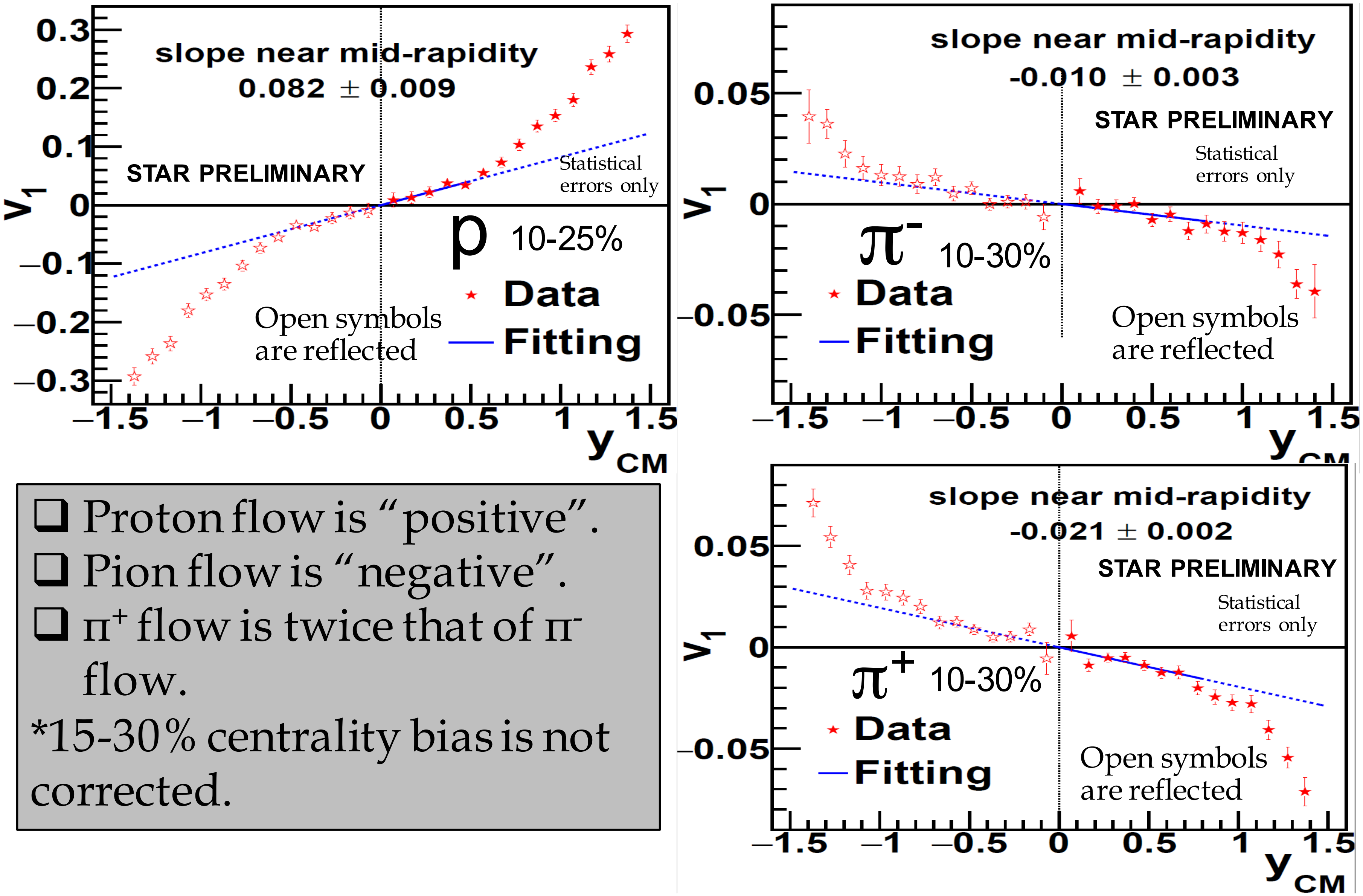
Particle Yield comparison in Au+Au at $\sqrt{S_{NN}}$ = 4.5 GeV with different experiments



- E895: Phys. Rev. C 68 (2003) 054905
- E895: NPA 698 (2002) 495c
- E802: NPA 610 (1996) 139c
- E877: Phys. Rev. C 63 (2001) 014902
- E891: PLB 382 (1996) 35 E896: Phys. Rev. Lett. 88, 062301
- NA44: Phys. Rev. C 66 (2002) 044907
- NA49: JPG 30 (2004) S701
- NA49: Phys. Rev. Lett. 93 (2004) 022302
- Phys. Rev. Lett. 93 (2004) 022302
- NA57: JPG:NPP32 (2006) 2065
- WA98: Phys. Rev. C 67 (2003) 014906

- ❑ The excitation function of integrated yield, dN/dy, at mid-rapidity, scaled by the average number of participants.
- ❑ K_S^0 points are scaled by factor of 10.
- ❑ STAR data are in a good agreement with various AGS and CERN experiments.

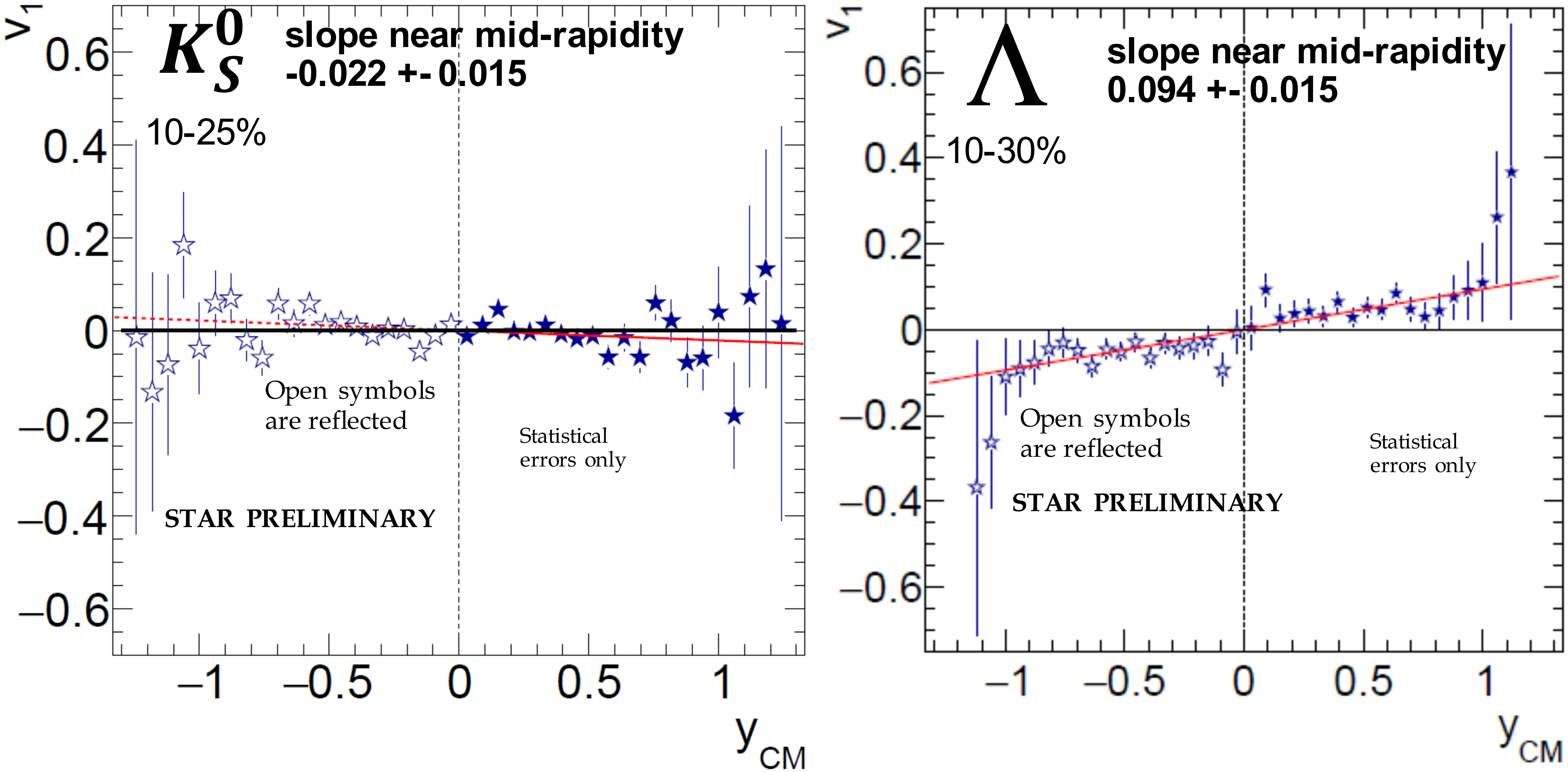
Directed flow of protons and pions in Au+Au Collisions at $\sqrt{s_{NN}}$ = 4.5 GeV



- ❑ Proton flow is "positive".
- ❑ Pion flow is "negative".
- ❑ π^+ flow is twice that of π^- flow.

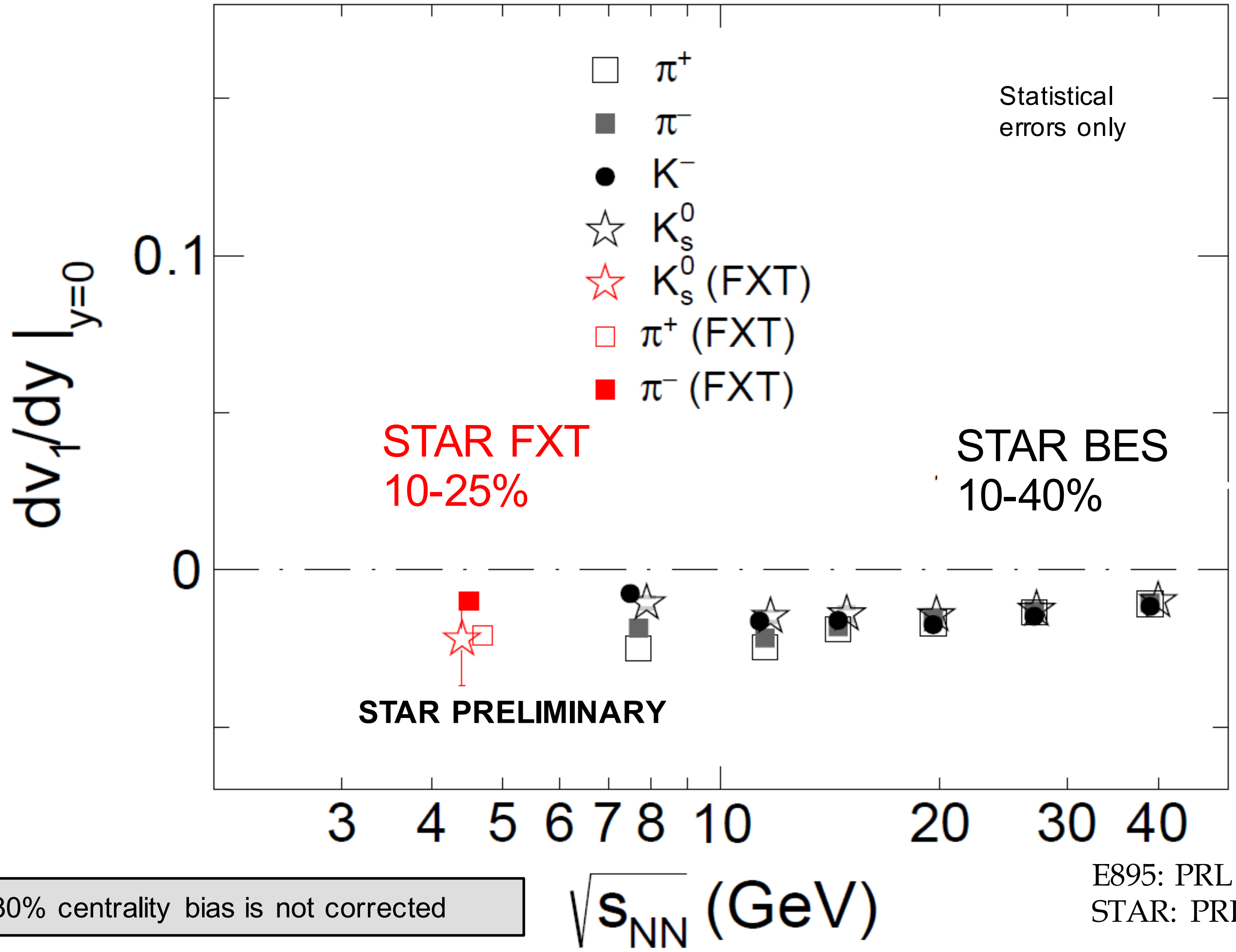
*15-30% centrality bias is not corrected.

Directed flow of K_S^0 and Λ in Au+Au Collisions at $\sqrt{s_{NN}}$ = 4.5 GeV



- ❑ $dv_1/dy\,|_{y=0}$ of K_S^0 (mesons) is negative.
- ❑ $dv_1/dy\,|_{y=0}$ of Λ (baryons) is positive.
- ❑ *15-30% centrality bias is not corrected.

Directed Flow Comparison Across Experiments and Energies

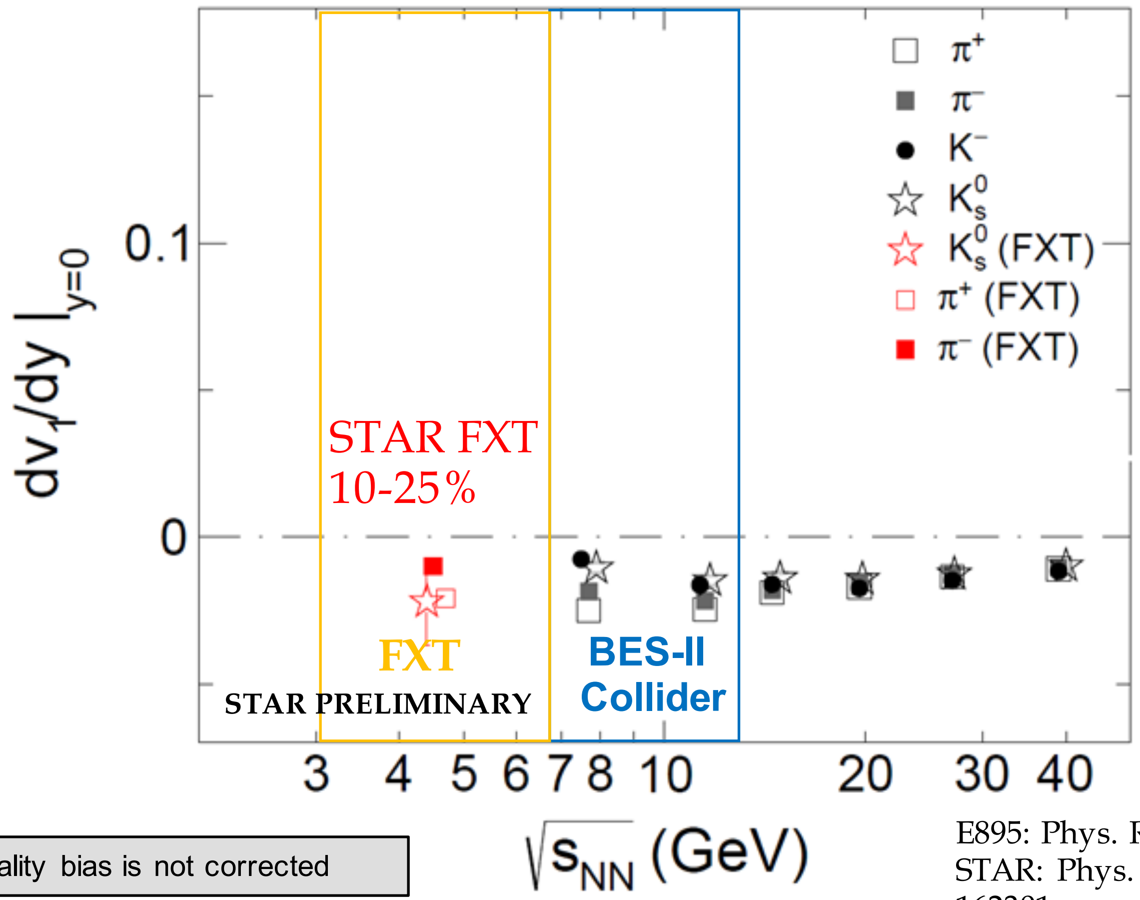


*15-30% centrality bias is not corrected

E895: PRL 84 (2000) 5488
STAR: PRL **112** (2014) 162301

- First π results shown for this $\sqrt{s_{NN}}$ = 4.5 GeV.
- The mesons continue the trend of negative flow seen at higher energies.

Directed Flow Comparison Across Experiments and Energies

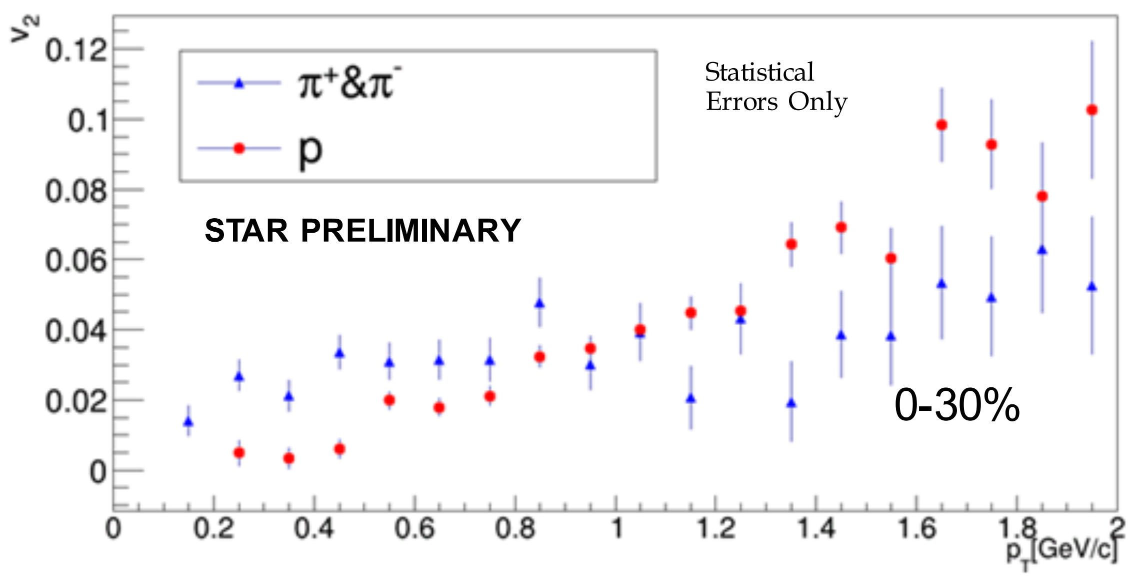


*15-30% centrality bias is not corrected

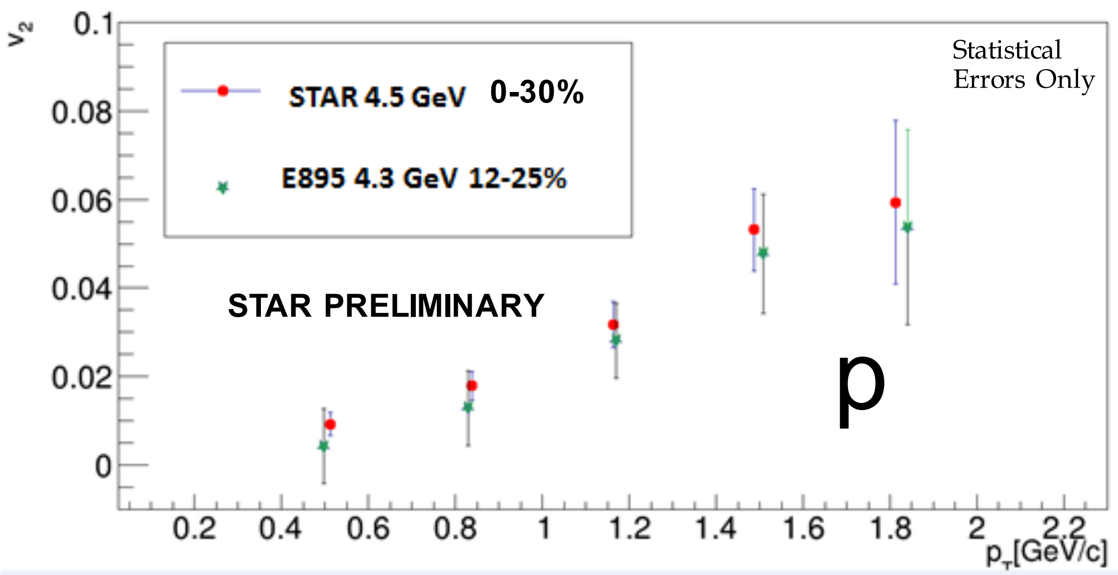
E895: Phys. Rev. Lett. 84 (2000) 5488
STAR: Phys. Rev. Lett. **112** (2014) 162301

- ❑ First π results shown for this energy range.
- ❑ The mesons continue the trend of negative flow seen at higher energies.
- ❑ Protons and Lambdas are consistent with positive flow indicative of compression.

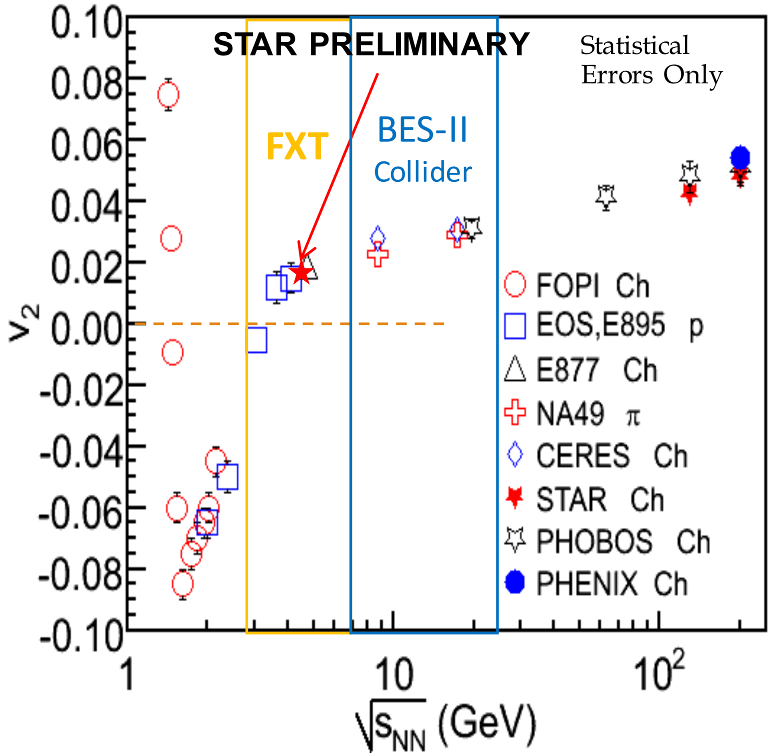
Elliptic Flow of Pions and Protons



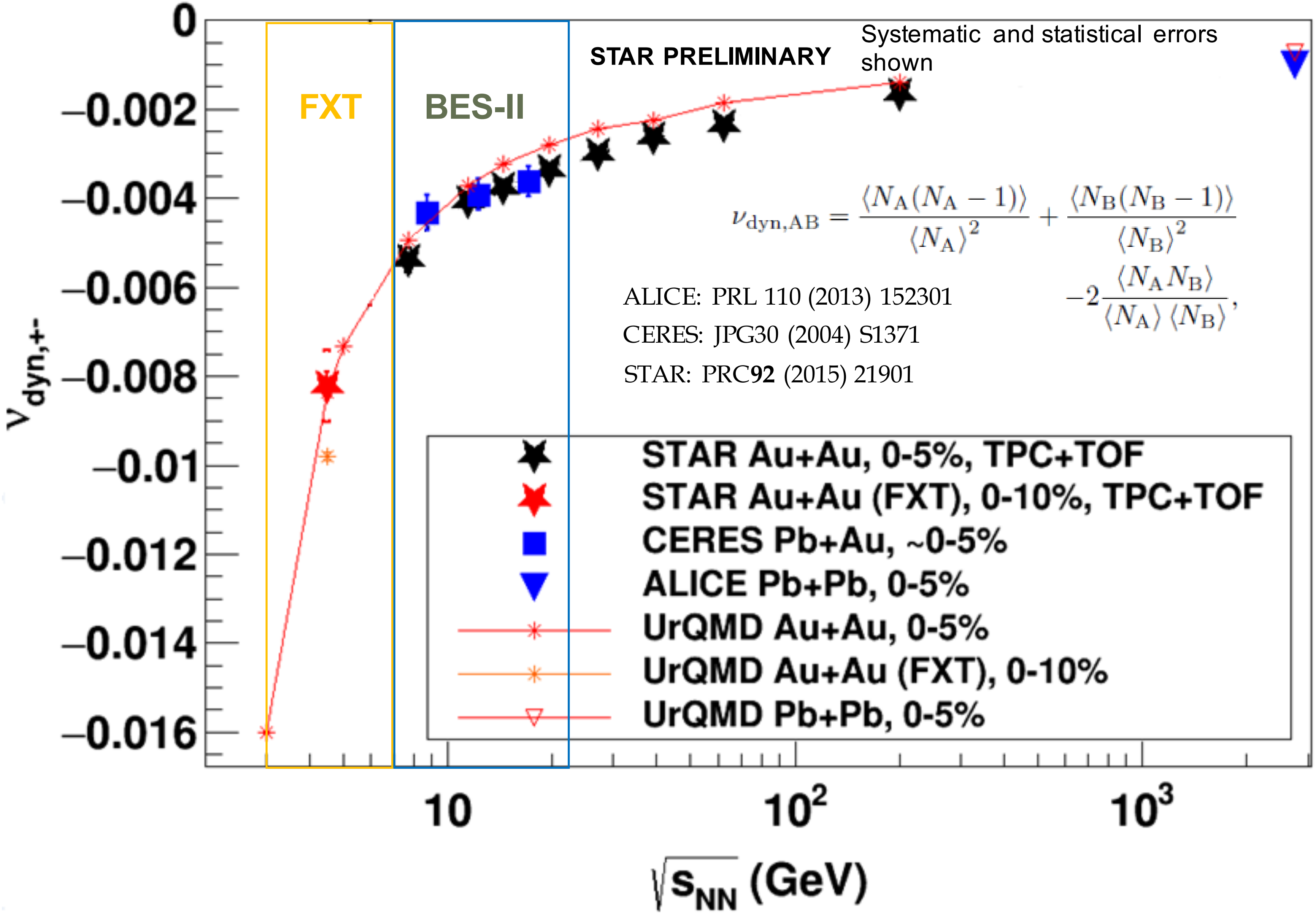
E895: Phys. Rev. Lett. 83 (1999) 1295



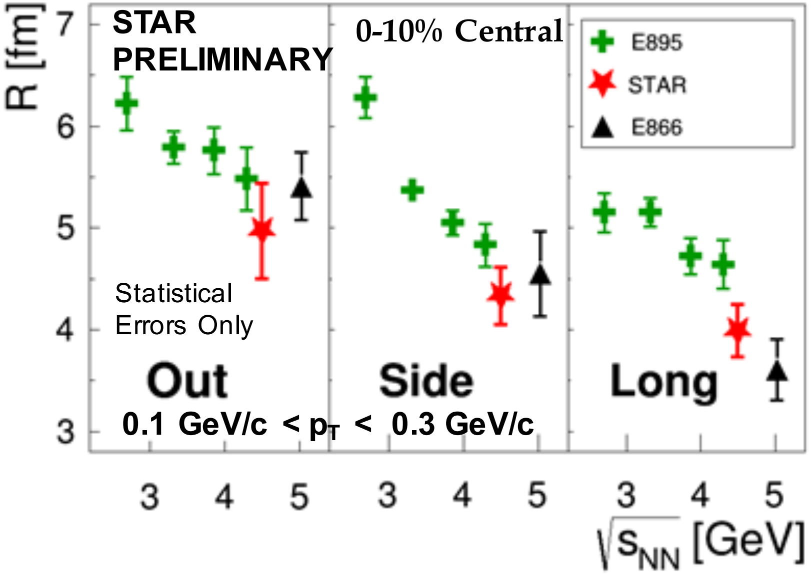
- ❑ First measurement of pion elliptic flow for this energy range.
- ❑ Proton v_2 shows good agreement with E895.
- ❑ *15-30% centrality bias is not corrected.



Dynamical Relative Charge Number Fluctuations



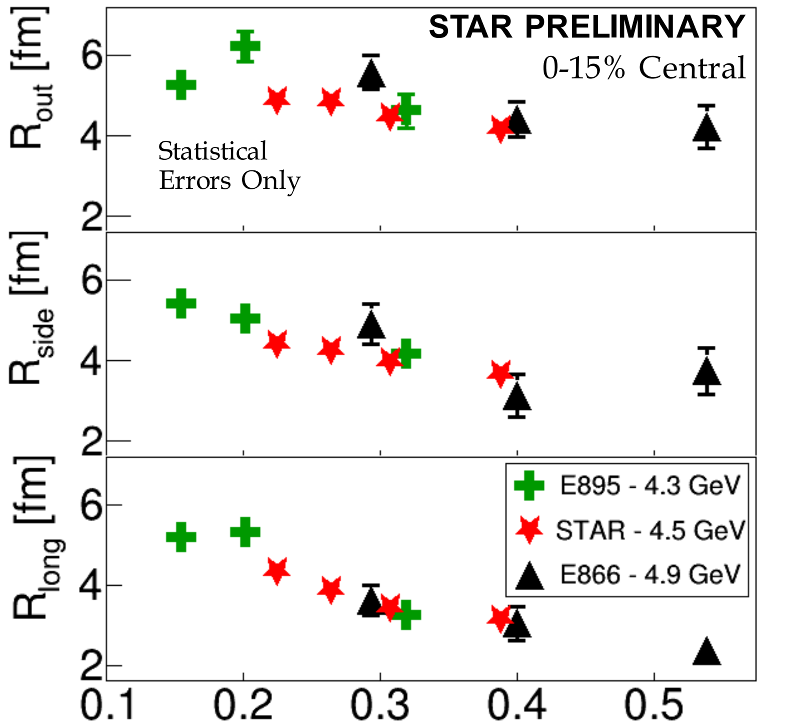
- FXT measurement continues the decreasing trend towards lower energies and is in a good agreement with UrQMD.

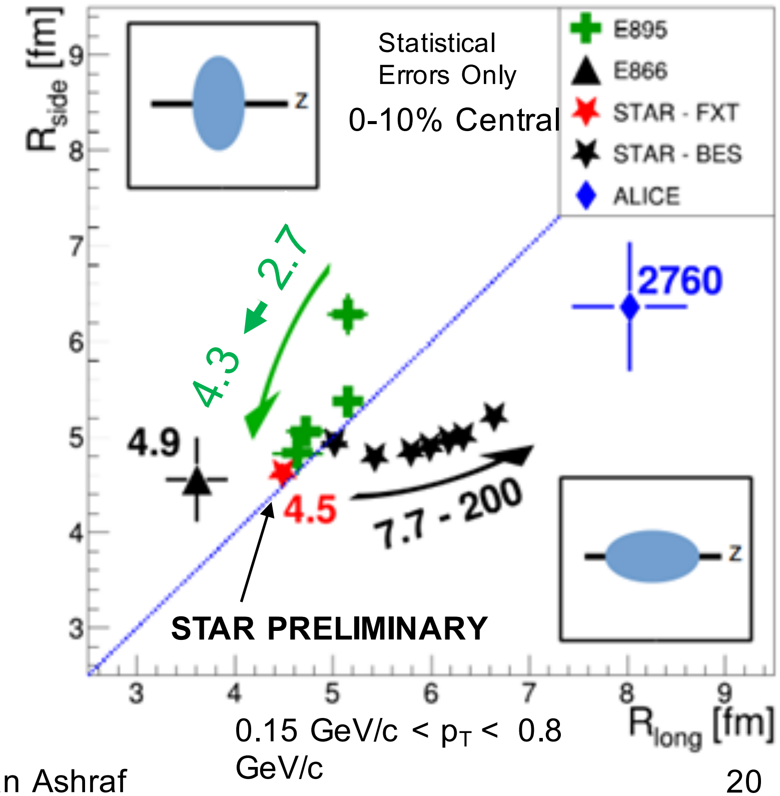


Pion HBT Results

- Consistent with results from AGS experiments.
- In the FXT regime, as the collision energy rises, compression reduces the source size and increases the baryon density.
- The BES collider regime shows increased longitudinal expansion.

E866: Phys. Rev. C 66 (2002) 054096 ALICE: Phys. Lett. B 696 (2011) 328
E895: Phys. Rev. Lett. 84 (2000) 2798 STAR BES: Phys. Rev. C **92** (2015) 14904





E895: Phys. Rev. Lett. 84 (2000) 2798
E866: Phys. Rev. C 66 (2002) 054096

Conclusions from First FXT Run at $\sqrt{s_{NN}}$ = 4.5 GeV

- First pion dv_1/dy results obtained for this energy range. They continue the trend of negative flow for mesons.

- First pion v_2 results obtained for this energy.

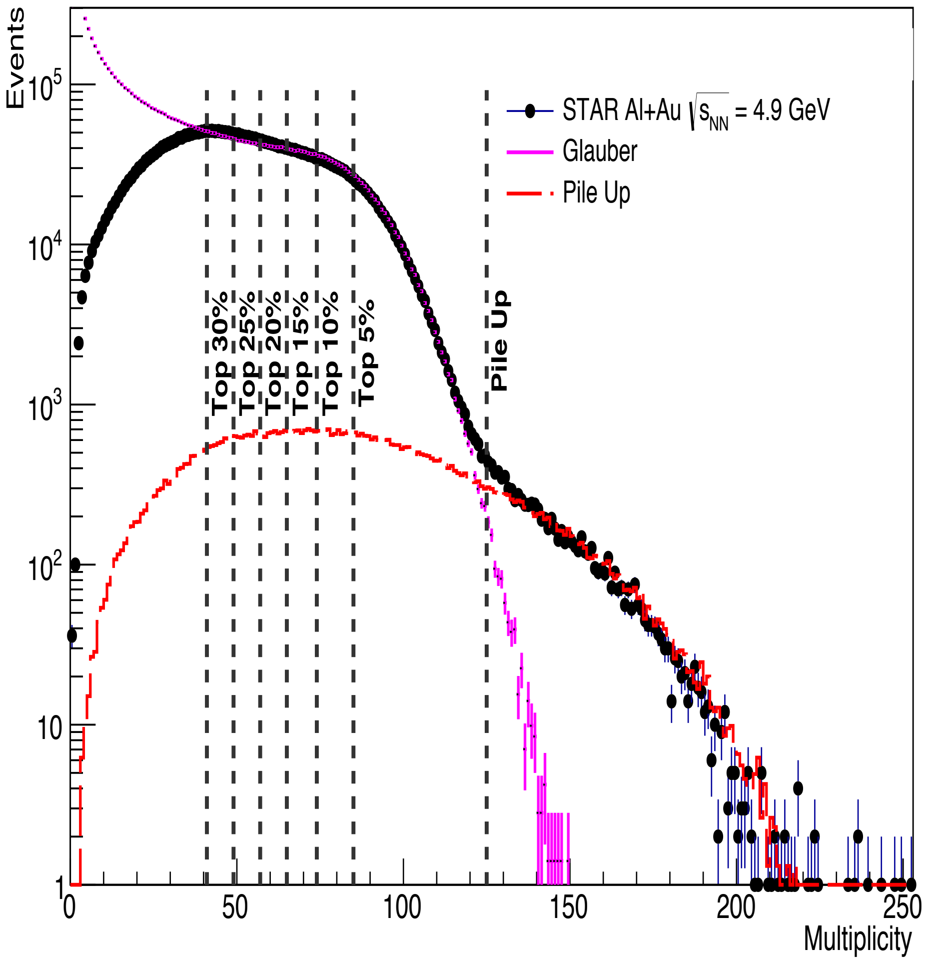
- First ν_{dyn} result obtained for this energy range.

- Spectra and yields, HBT radii, proton dv_1/dy, and proton v_2 results are consistent with results from AGS experiments.

→ STAR operates well in FXT mode!

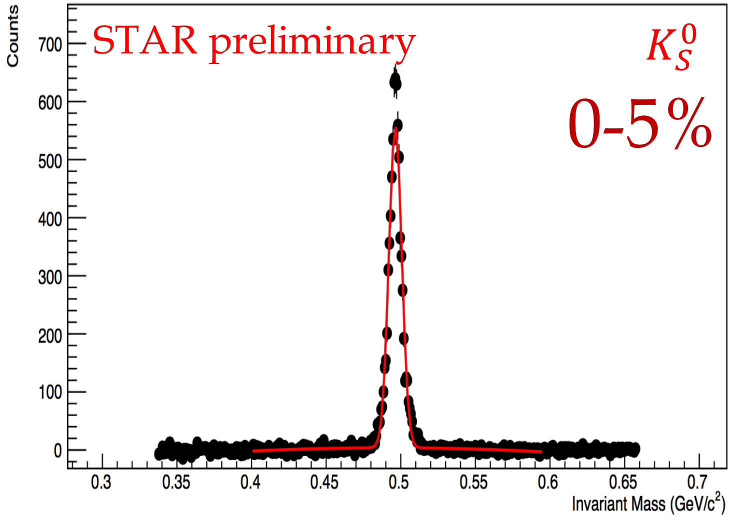
Results from FXT Al+Au Collisions at $\sqrt{S_{NN}}$ = 4.9 GeV

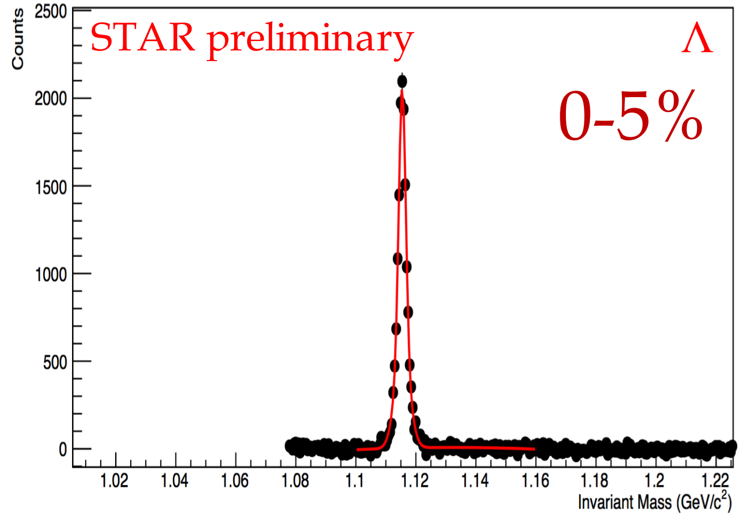
Centrality Determination for Al+Au at $\sqrt{S_{NN}}$ = 4.9 GeV



- ❑ 3.4 M Al+Au events collected with the top 30% centrality.
- ❑ It is not a beam pipe study.
- ❑ Pileup has been removed by multiplicity cut.

Particle Reconstruction in Al+Au at $\sqrt{S_{NN}}$ = 4.9 GeV



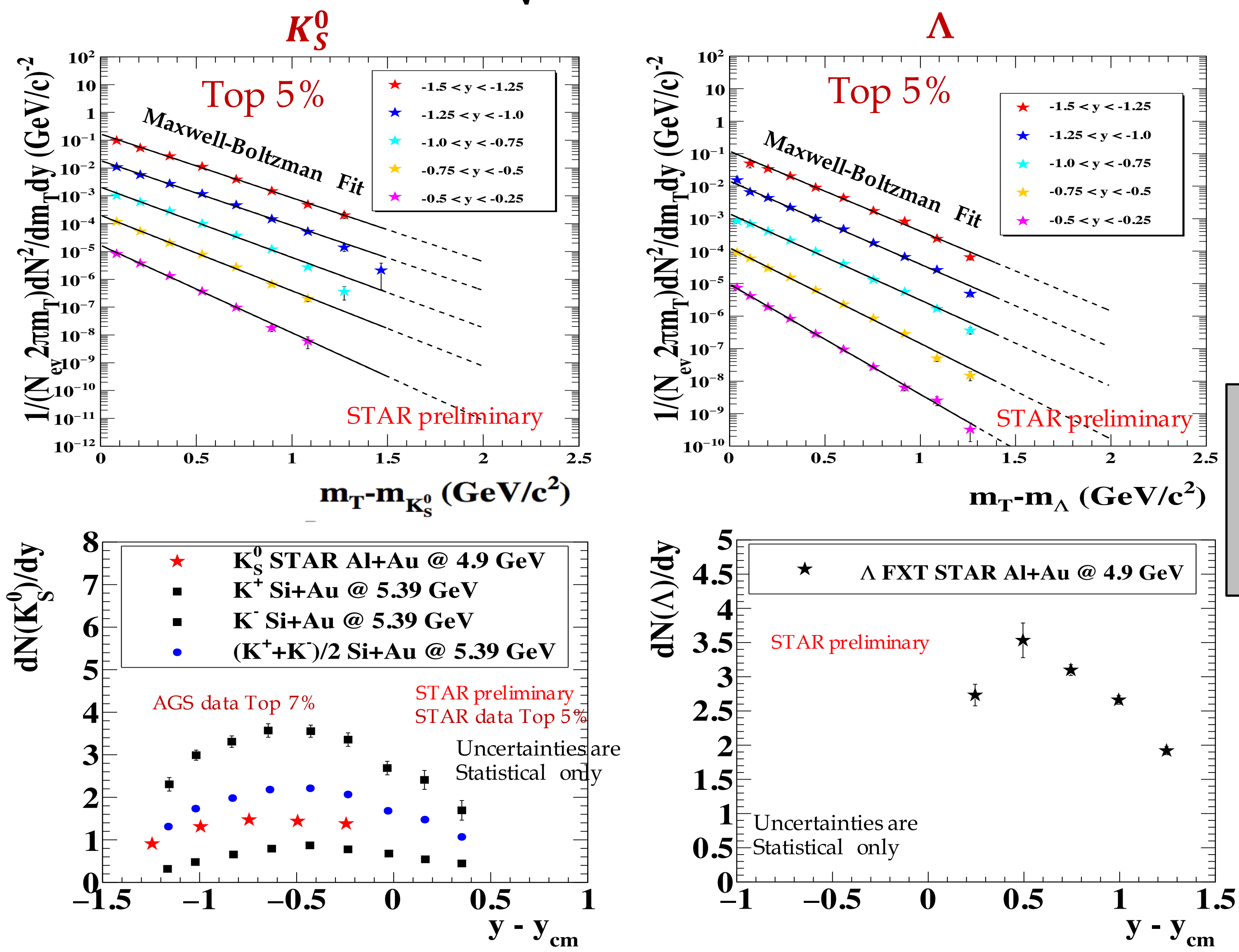


Al+Au at $\sqrt{S_{NN}}$ = 4.9 GeV, 0-5%

→ $K^0_S \rightarrow \pi^+ + \pi^-$
→ $\Lambda \rightarrow p + \pi^-$

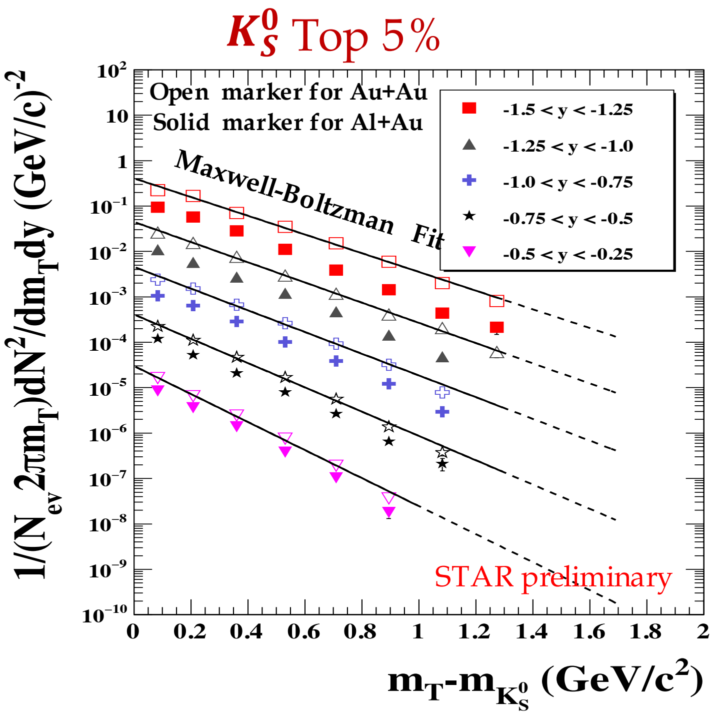
- ❑ π ,K, p are identified with TPC dE/dx
- ❑ Secondary vertex reconstruction

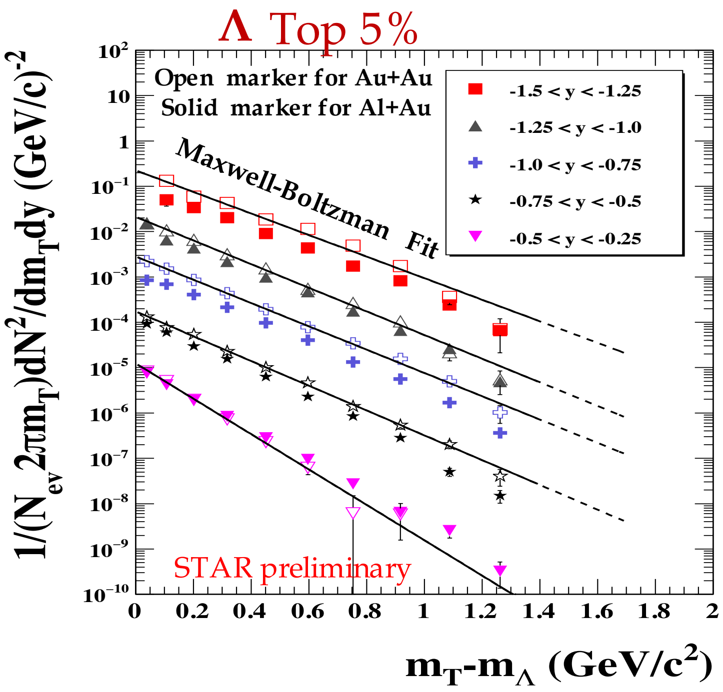
m_T-m_0 and dN/dy spectra of K_S^0 and Λ in Al+Au at $\sqrt{s_{NN}}$ = 4.9 GeV



Amplitudes and widths of rapidity density, dN/dy, are In a good agreement with AGS experiments.

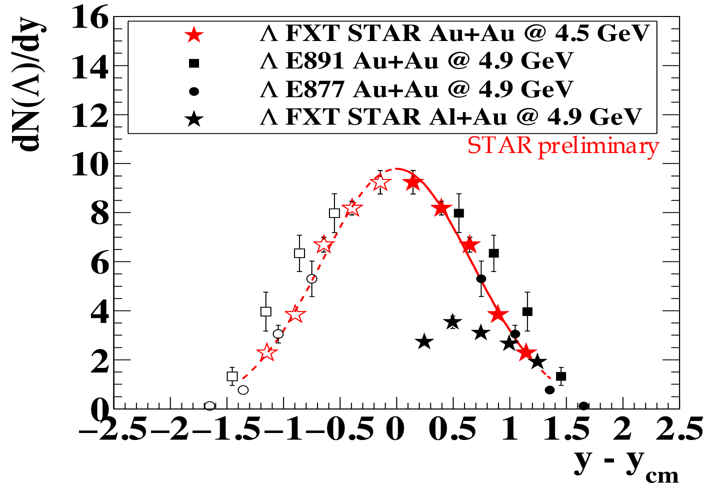
Comparison of m_T-m_0 spectra and dN/dy with Au+Au and Al+Au



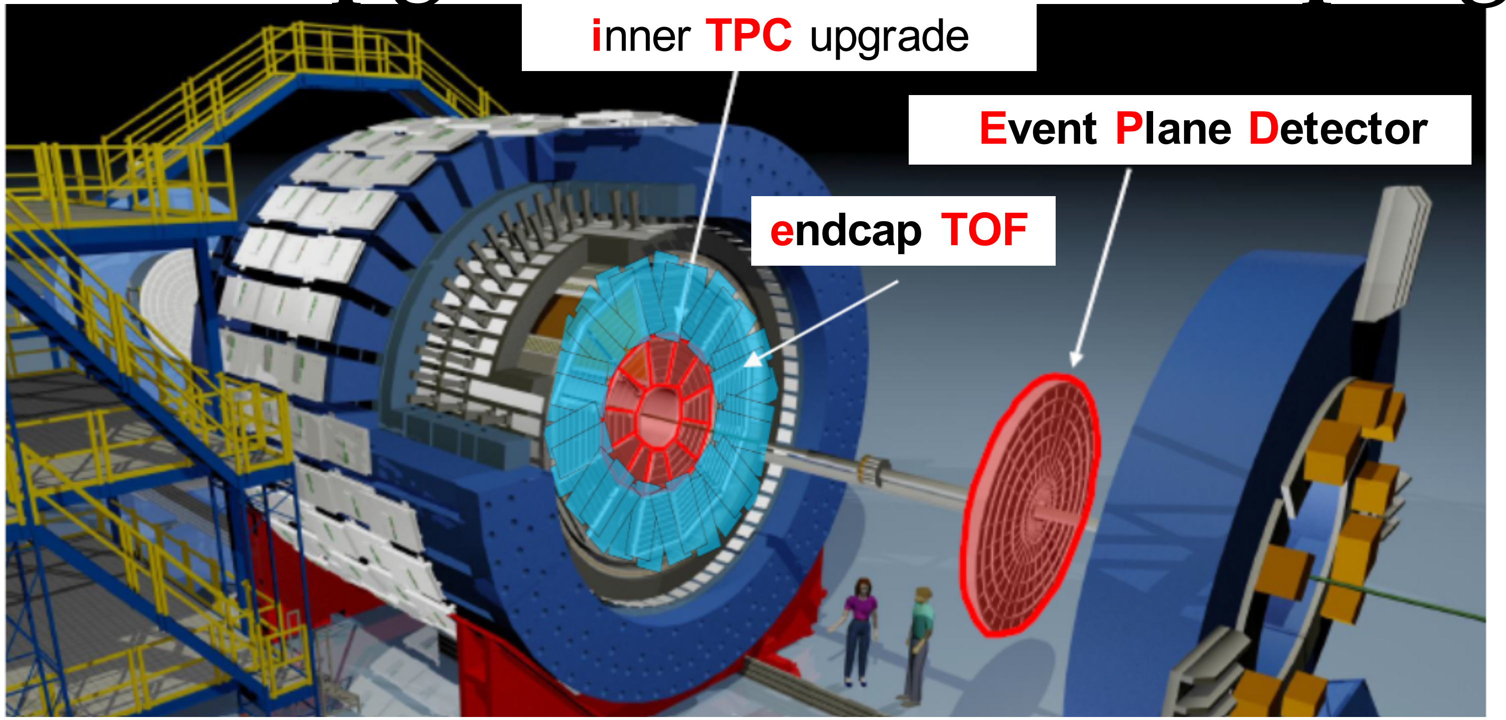


- m_T-m_0 Spectra and dN/dy in **Different rapidity bins for FXT Au+Au collisions at $\sqrt{S_{NN}}$ = 4.5 GeV and Al+Au collisions at $\sqrt{S_{NN}}$ = 4.9 GeV.**
- Errors are statistical only.

→ Solid line fit to data and dashed line is extrapolation with fitting function.



The STAR Upgrades and the FXT program



iTPC Upgrade:

- ✓ Improved dE/dx resolution
- ✓ Better momentum resolution
- ✓ Extends η coverage from 1.0 to 1.5
- ✓ p_T >60 MeV/c
- ✓ Ready in 2019

Star Note 0644 : Technical Design Report for the iTPC Upgrade

EndCap TOF Upgrade:

- ✓ Mid-rapidity coverage is critical
- ✓ Needed for PID at mid-rapidity
- ✓ **$-1.6<\eta<-1.1$**
- ✓ Allows higher energy range of FXT program
- ✓ Ready in 2019

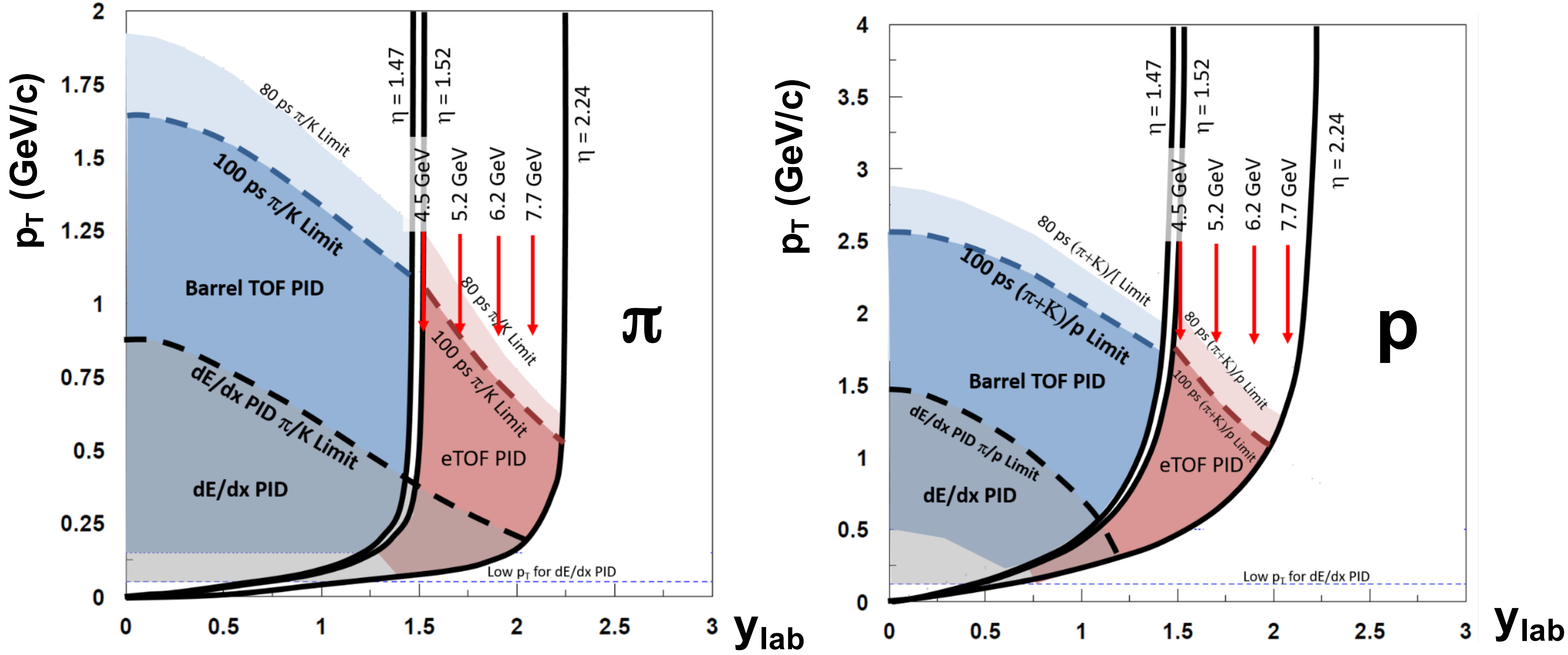
https://arxiv.org/pdf/1609.05102.pdf

EPD Upgrade:

- ✓ Better trigger
- ✓ Reduces background
- ✓ Improves event plane resolution
- ✓ **$2.1<|\eta|<5.1$**
- ✓ Ready in 2018

Star Note 0666 : An Event Plane Detector for STAR

FXT Energy Reach With Upgrades



Current Acceptance

Acceptance with upgrades

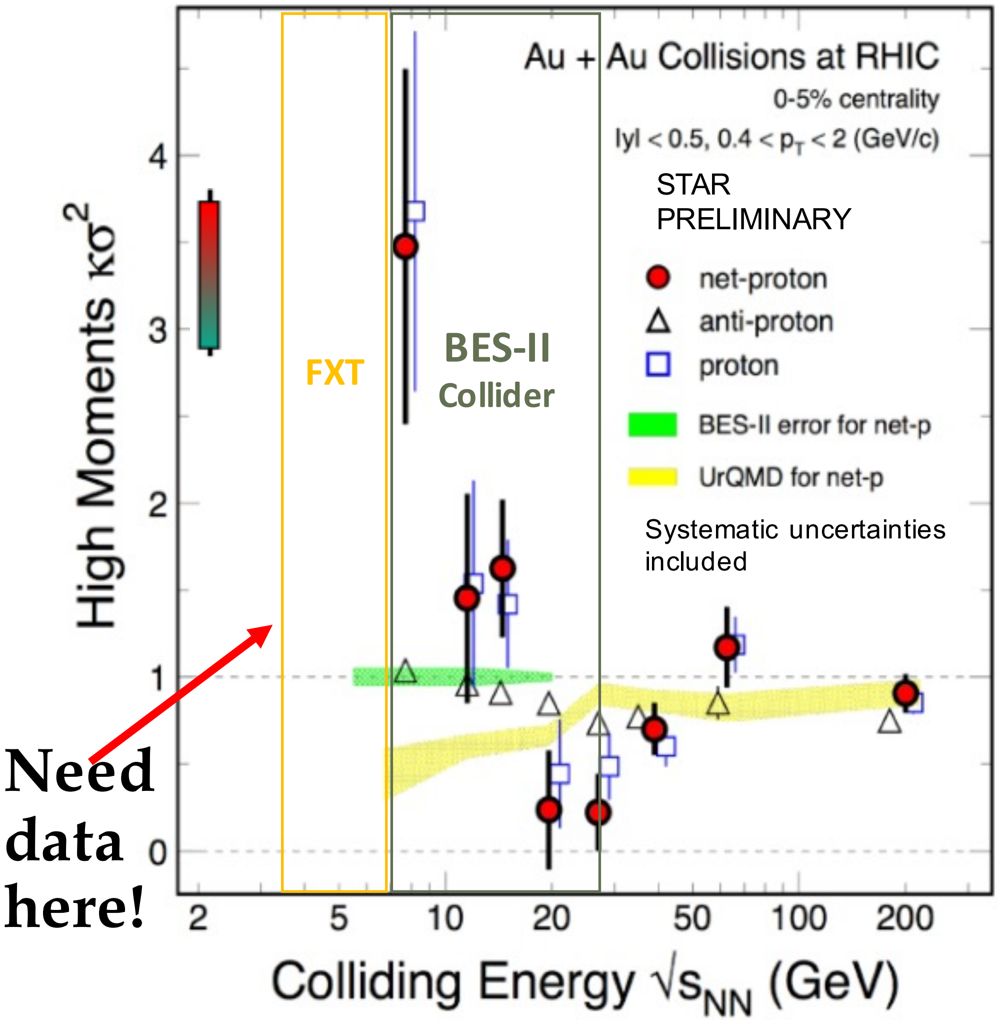
Current Acceptance

Acceptance with upgrades

- Detector upgrades required to extend STAR FXT up to 7.7 GeV, an overlap energy with the collider mode.

Outlook: FXT Program in Run 18

Preliminary HADES result, Quark Matter 2017
0-10%
(QM 2017)



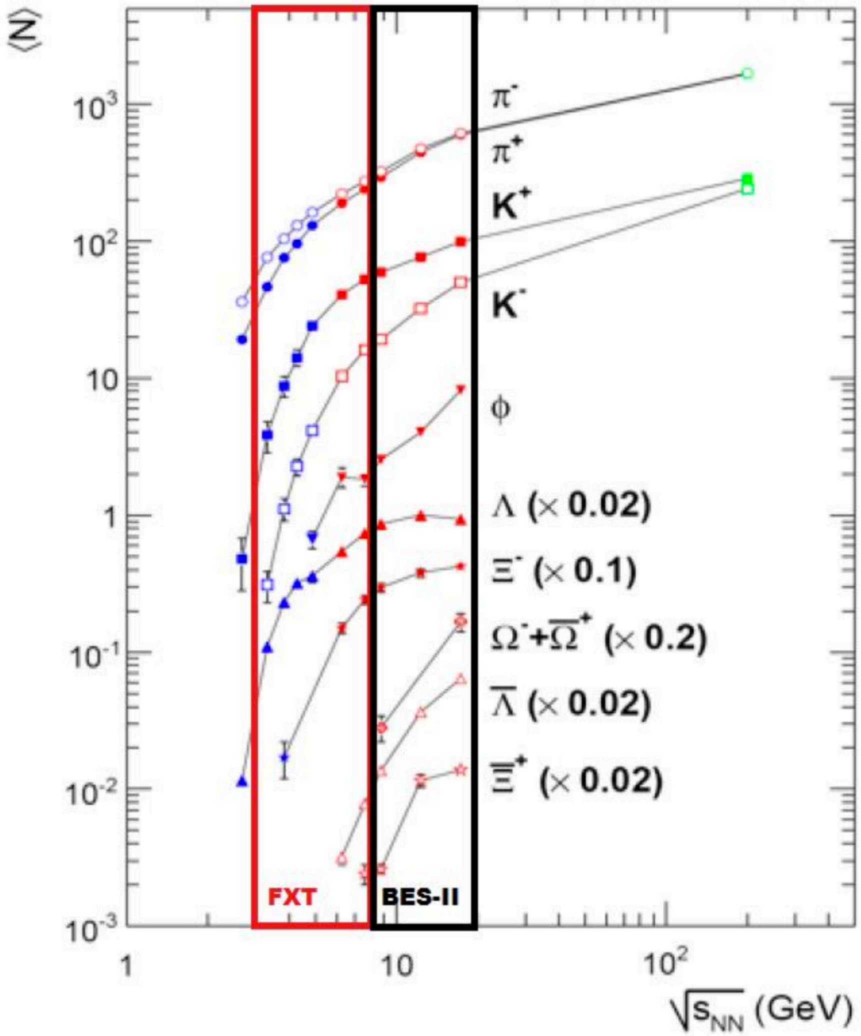
- ❑ 100 M (~2 days) events of Au + Au collisions at $\sqrt{s_{\mathrm{NN}}} = 3.0$ GeV .
- ❑ The Event Plane Detector will be ready and available for flow analyses.
- ❑ Can obtain a fluctuation measurement at energies below BES-I.

Outlook: FXT Program in Run 19

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Number Events
5.75	3.5	2 days	Au+Au	100M MB
7.3	3.9	2 days	Au+Au	100M MB
9.8	4.5	2 days	Au+Au	100M MB
13.5	5.2	2 days	Au+Au	100M MB
19.5	6.2	2 days	Au+Au	100M MB
31.2	7.7	2 days	Au+Au	100M MB

- iTPC and eTOF upgrades will be available.
- Would need 100 million events at each energy, 2 days per energy (3.5 GeV – 7.7 GeV).
- Data rate is limited by DAQ.
- Data at 7.7 GeV would provide an overlap energy with the collider mode.

Strange Particles in FXT and BES-II



C. Blume, J. Phys. G31, S57 (2005).

- Clear signals for K_S^0, Λ and Ξ^- are observed in Au+Au at 4.5 GeV FXT test run
- Clear signals for K_S^0 and Λ are observed in Al+Au at 4.9 GeV FXT test run.
- Have not seen $\overline{\Lambda}$ and **Ω**, due to low statistics.
- After upgrade we need ~100M events for each energy and hoping to see the $\overline{\Lambda}$, **Ω** and Ξ^- .

Summary

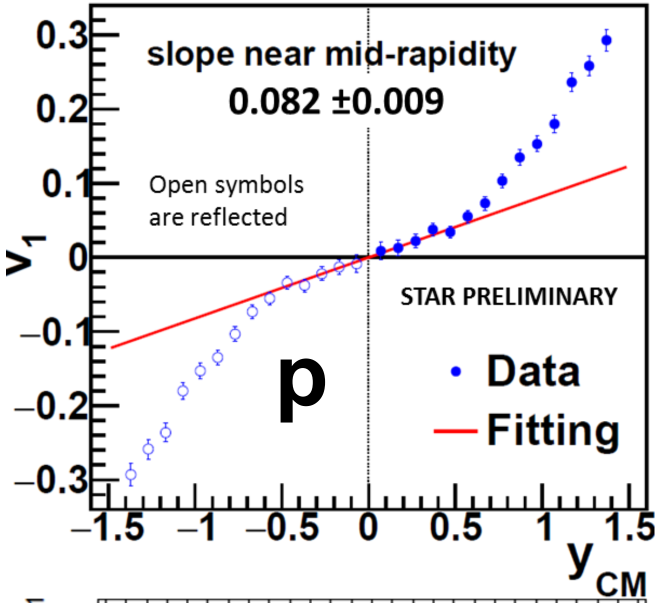
- First FXT run results demonstrate STAR has a capability to run in the fixed-target as well as in the collider mode.
- Higher statistics FXT run in 2018 will allow a kurtosis measurements at 3 GeV.
- Installation of EPD in 2018 will allow to improve flow measurements.
- The FXT program will extend the energy range of the RHIC BES-II down to $\sqrt{s_{NN}}$ = 3.0 GeV (μ_B=720 MeV).
- With detector upgrades the FXT program can be extended up to 7.7 GeV, where it overlaps with the collider mode.
- This will also allow more comprehensive and refined measurements.

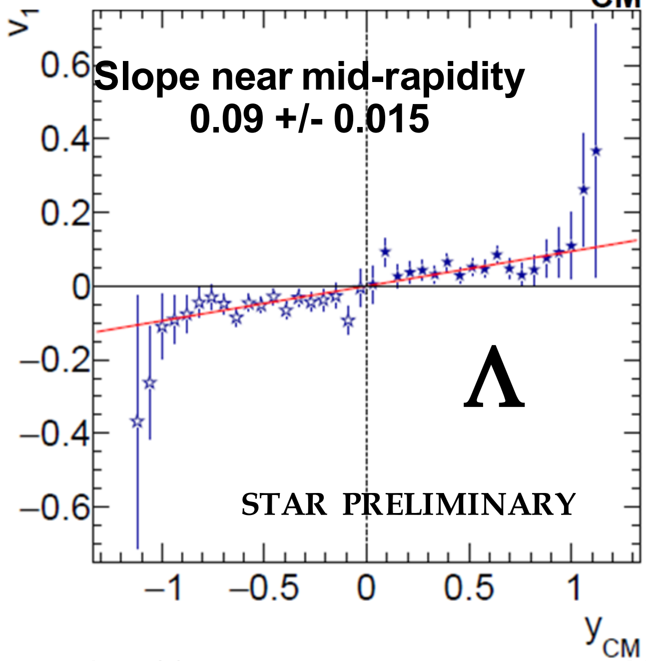
Thank You!

Back Up

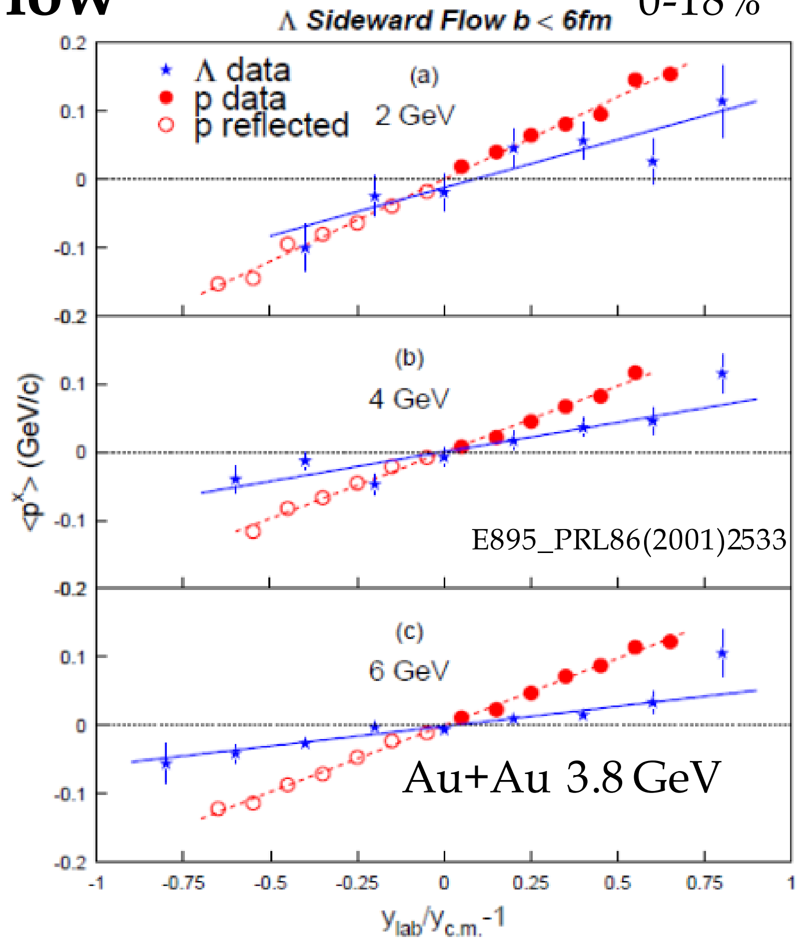
Comparison to E895 Λ Flow

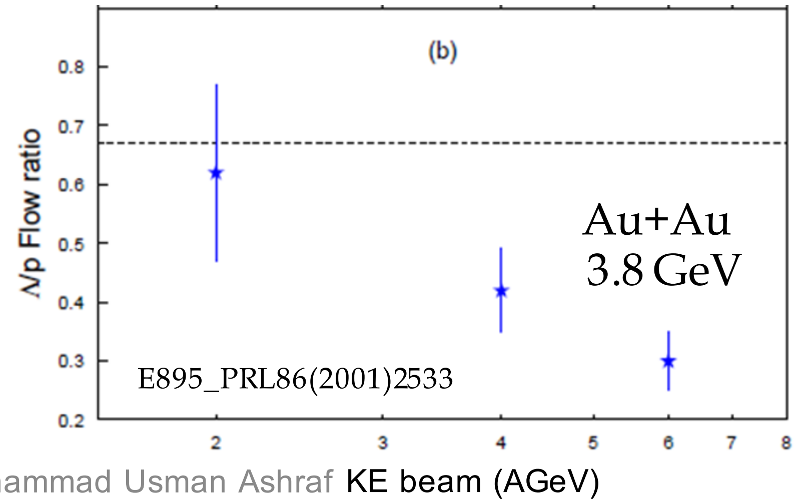
Au+Au 4.5 GeV 10-25%





0-18%





Differences:

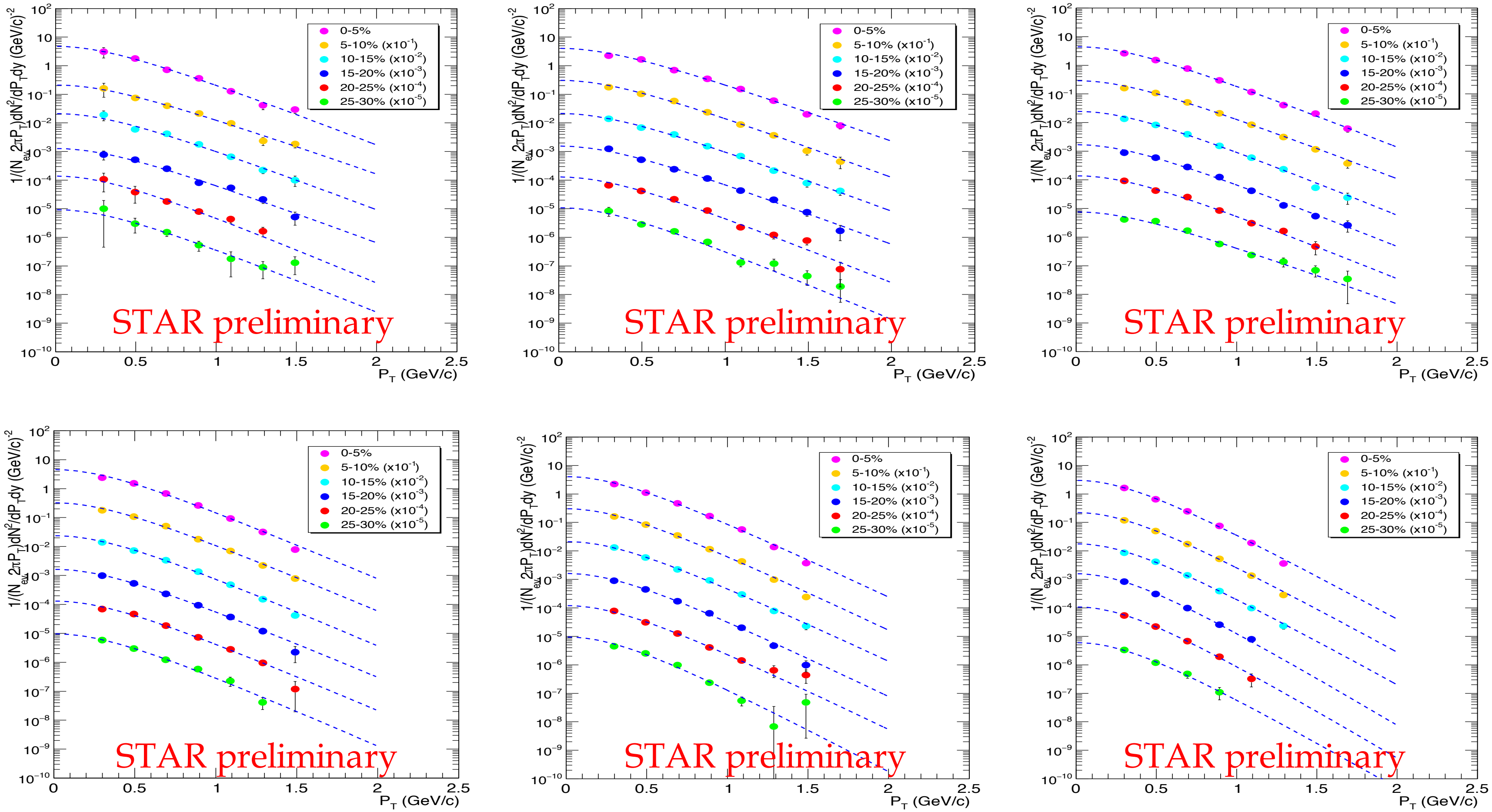
E895 -- $\langle p^x \rangle$
STAR-FXT – v_1

E895 – 0-18%
STAR-FXT 10-25%

E895 *trend*:
Λ/p flow ratio at 4.5 GeV ➔ 0.2

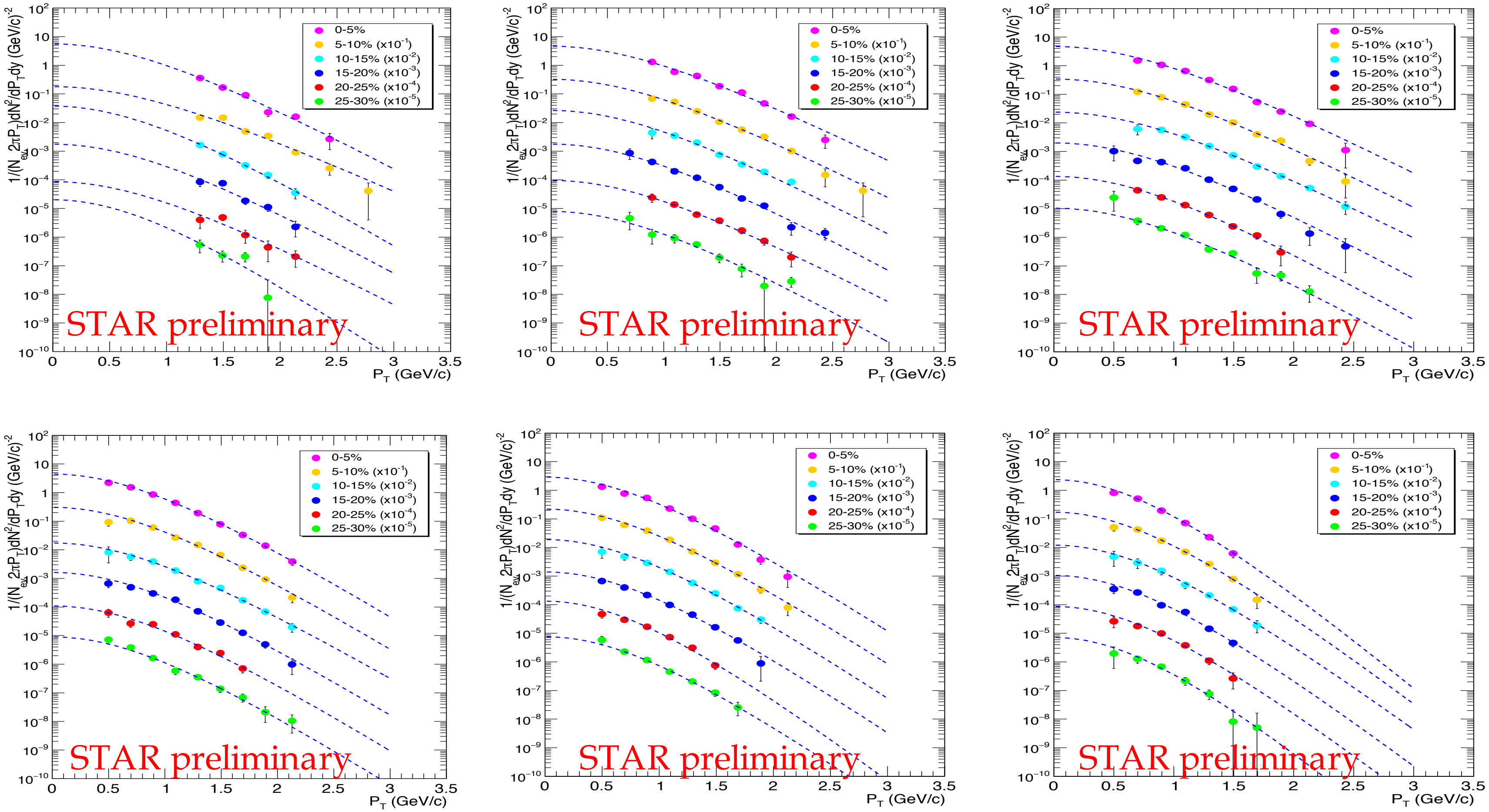
STAR FXT:
Λ/p flow ratio at 4.5 GeV ➔ 1.1

p_T spectra of K_S^0 in Au+Au at $\sqrt{S_{NN}}$ = 4.5 GeV



- ➢ K_S^0 Spectra in **Different rapidity bins for FXT Au+Au at $\sqrt{S_{NN}}$ = 4.5 GeV.**
- ➢ Statistical errors only.
- ➢ 15-30% trigger is biased towards the most central.
  → Spectra are extrapolated to high p_T with Stefan-Boltzmann fitting function.

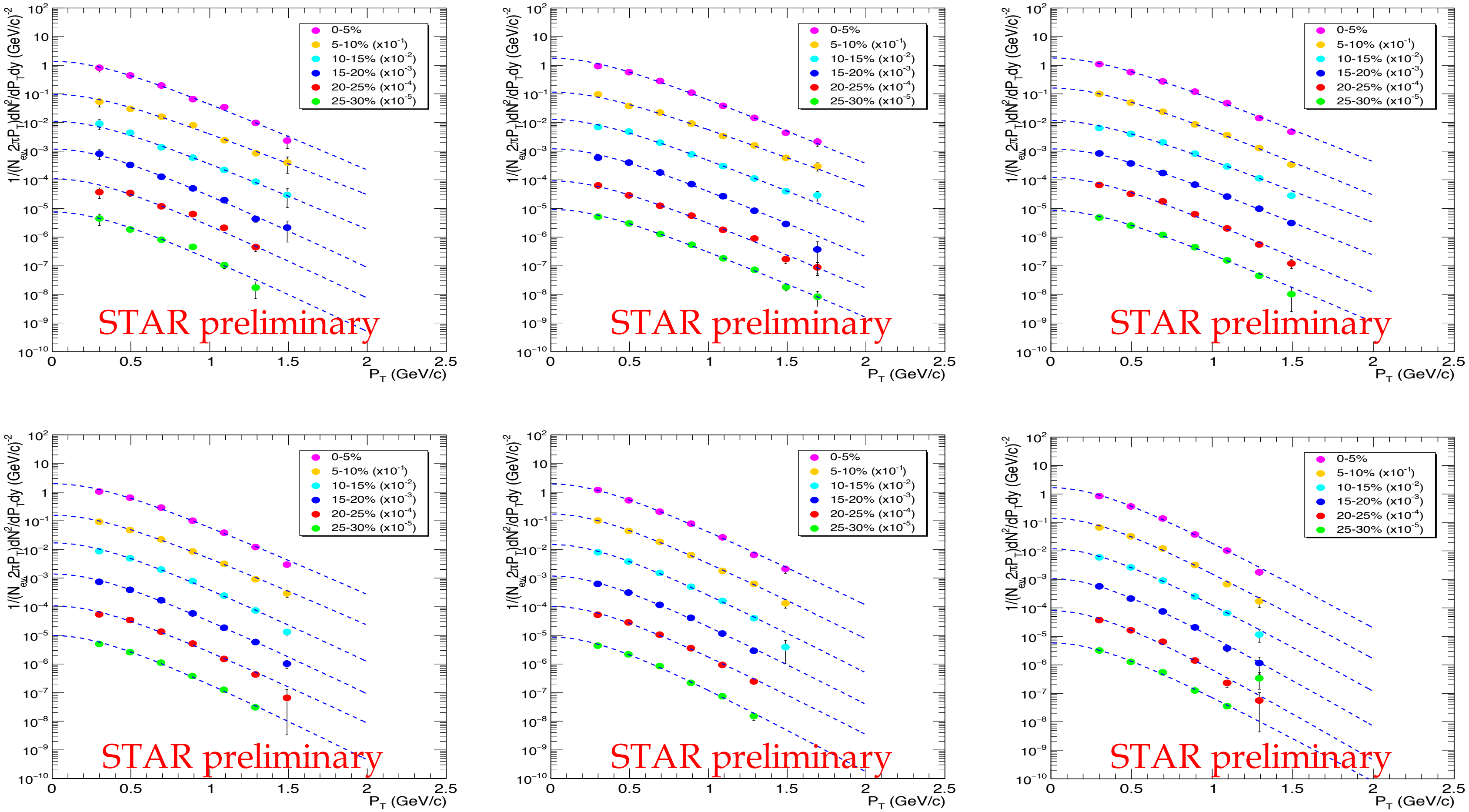
p_T spectra of Λ in Au+Au at $\sqrt{S_{NN}}$ = 4.5 GeV



- Λ Spectra in **Different rapidity bins for FXT Au+Au at $\sqrt{S_{NN}}$ = 4.5 GeV.**
- Statistical errors only.
- 15-30% trigger is biased towards the most central.

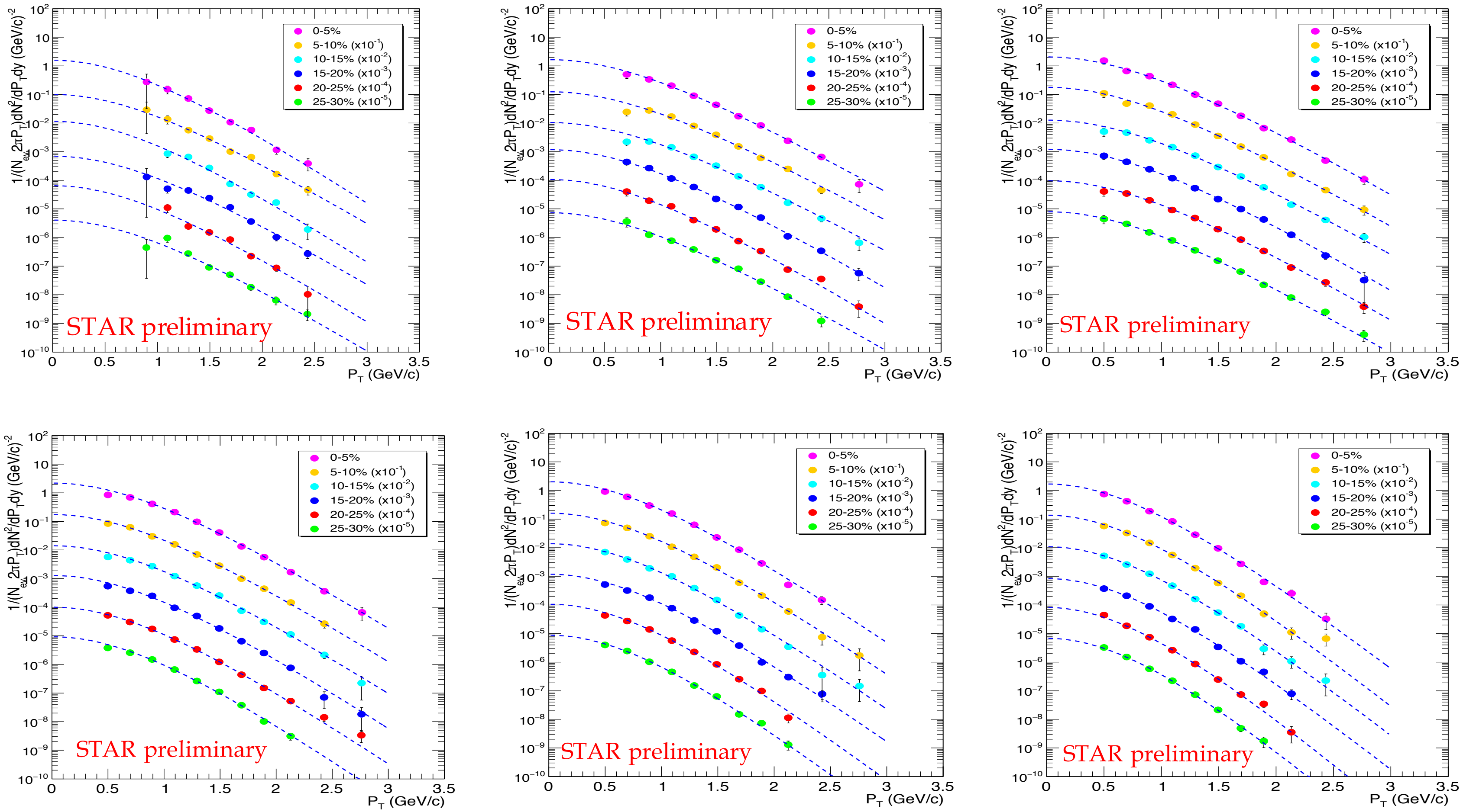
→ Spectra are extrapolated to high p_T with Stefan-Boltzmann fitting function.

p_T spectra of K_S^0 in Al+Au at $\sqrt{S_{NN}}$ = 4.9 GeV



- ➢ K_S^0 Spectra in **Different rapidity bins for FXT Al+Au at $\sqrt{S_{NN}}$ = 4.9 GeV.**
- ➢ Statistical errors only.
- → Spectra are extrapolated to high p_T with Stefan-Boltzmann fitting function.

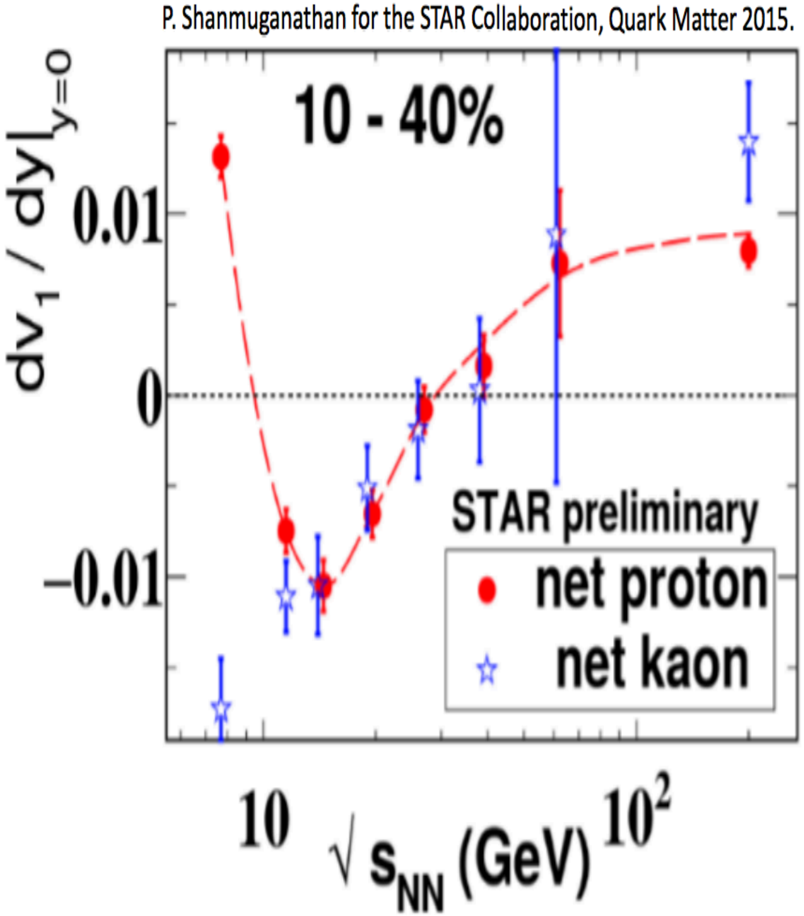
p_T spectra of Λ in Al+Au at $\sqrt{S_{NN}}$ = 4.9 GeV



- Λ Spectra in **Different rapidity bins for FXT Al+Au at $\sqrt{S_{NN}}$ = 4.9 GeV.**
- Statistical errors only.

→ Spectra are extrapolated to high p_T with Stefan-Boltzmann fitting function.

Net-Proton Directed Flow Slope at Mid-rapidity



- ❑ A minimum is observed in the mid-rapidity slope of net proton directed flow.
- ❑ The energy range of this minimum is $\sqrt{S_{NN}}$ **= 10-20 GeV.**
- ❑ According to prediction of hydrodynamic models, this minimum resembles the "softest point".

Relation between centrality bins and <npart>

Centrality	# of Events	<Npart> +/- stat +/- sys
0-5%	~267k	335.9 +/- 0.51 +/- 0.97
5-10%	~287k	285.9 +/- 0.56 +/- 0.88
10-15%	~259k	242.4 +/- 0.53 +/- 0.37
15-20%	~204k	203.9 +/- 0.48 +/- 0.85
20-25%	~126k	170.3 +/- 0.44 +/- 0.46
25-30%	~69k	142.2 +/- 0.43 +/- 0.50

Trigger efficiencies and pileup for each centrality bin.

Centrality	PileUp	Efficiency
0-5%	*6.014710%*	*96.871020%*
5-10%	*2.179419%*	*95.604648%*
10-15%	*1.815579%*	*98.653689%*
15-20%	*1.578787%*	*96.707016%*
20-25%	*1.367026%*	*92.393202%*
25-30%	*1.149513%*	*95.157688%*