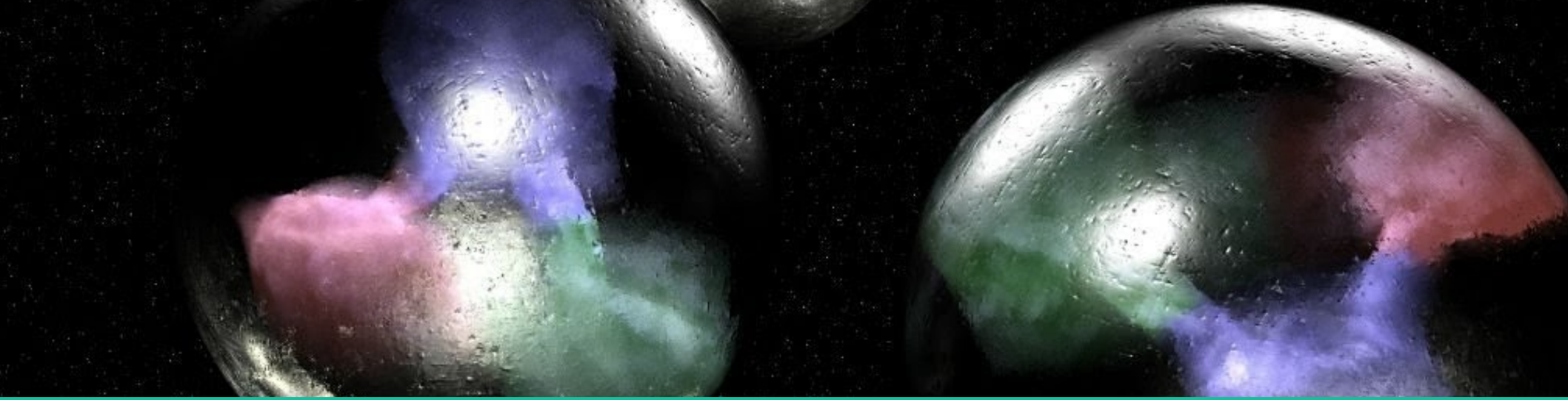


Particle Production in Au+Au Collisions at Beam Energy Scan II Energies at RHIC

Matthew Harasty

For the STAR Collaboration

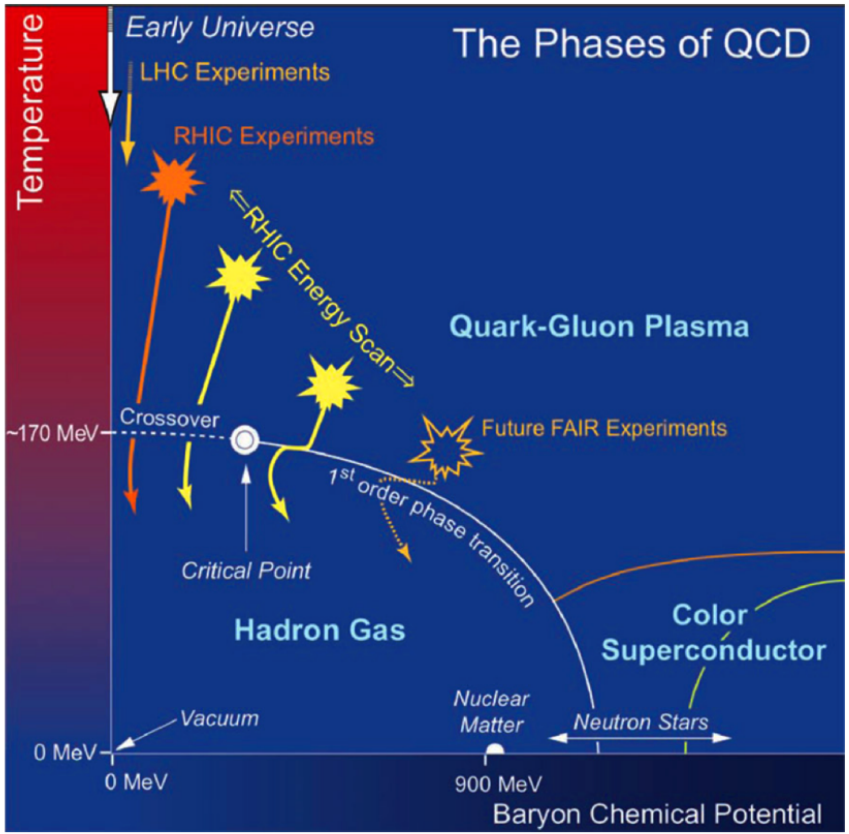
5 September 2023
Quark Matter (Houston, TX)

UC DAVIS
UNIVERSITY OF CALIFORNIA

Supported in part by:

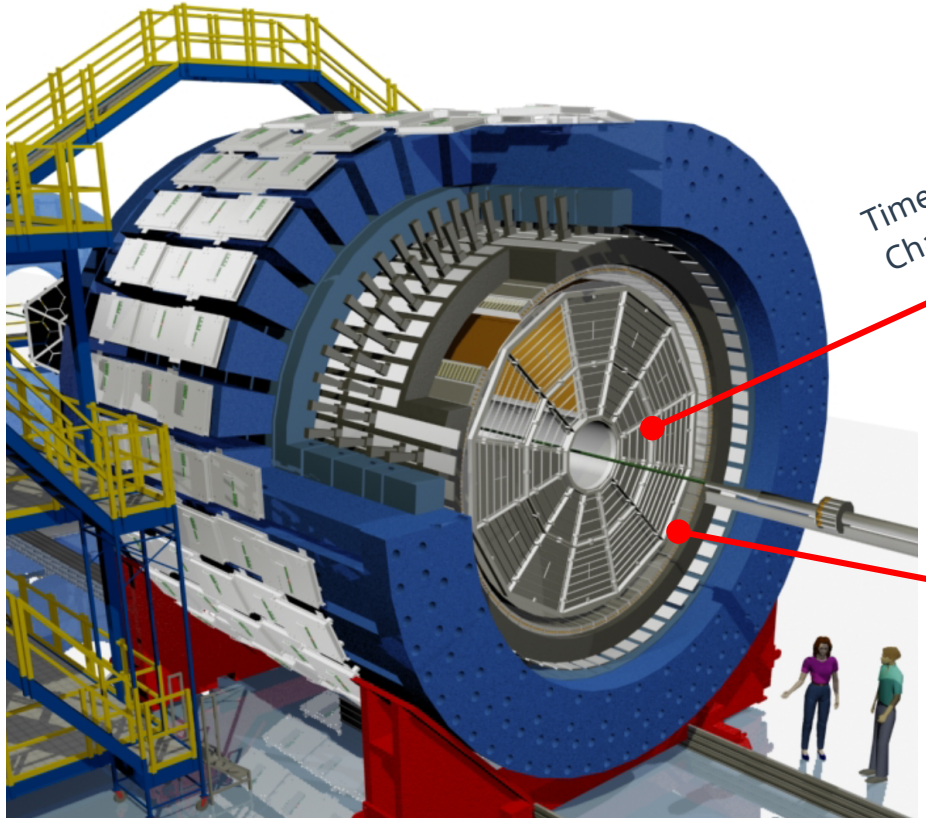
Why Measure Light Hadrons?

- **Measure $\pi^{\pm}$, $K^{\pm}$, p, & $\bar{p}$ across p_T and rapidity**
  - Kinetic & Chemical Freeze-out
  - Baryon and Strangeness Chemical Potentials
  - Associated Production of K^{+}
  - Baryon Stopping
  - Collective Radial Flow with Blast-Wave Model
- **Beam Energy Scan II (BES-II)**
  - $\sqrt{s_{NN}}$ = 7.7, 9.2, 11.5, **14.6**, 17.3, **19.6**, **27**, **54.4** GeV
  - BES-I Published Mid-Rapidity Measurements
  - Where are we on the QCD phase diagram at kinetic & chemical freeze-out?



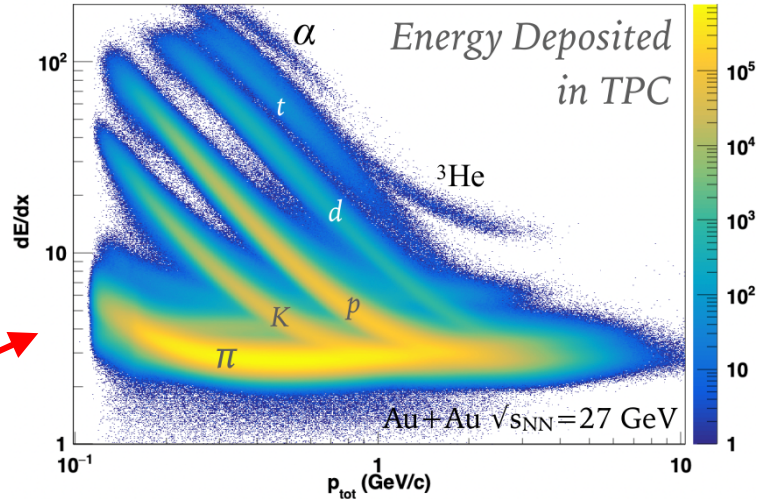
Particle Identification in STAR

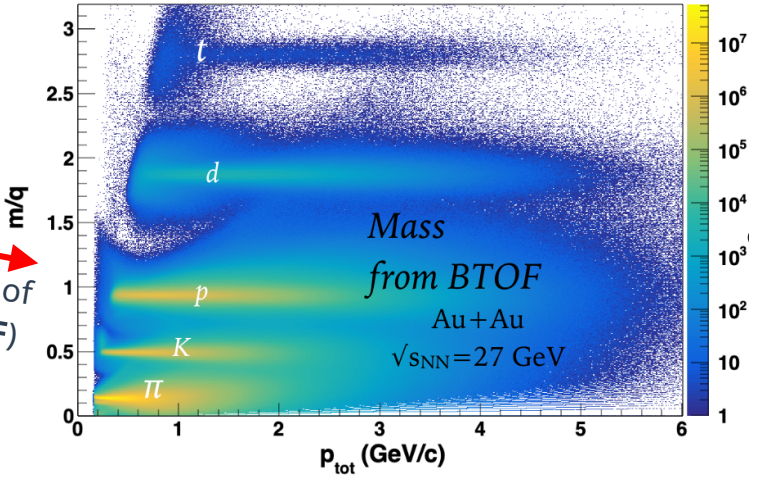
Solenoidal Tracker At RHIC (STAR)



Time Projection Chamber (**TPC**)

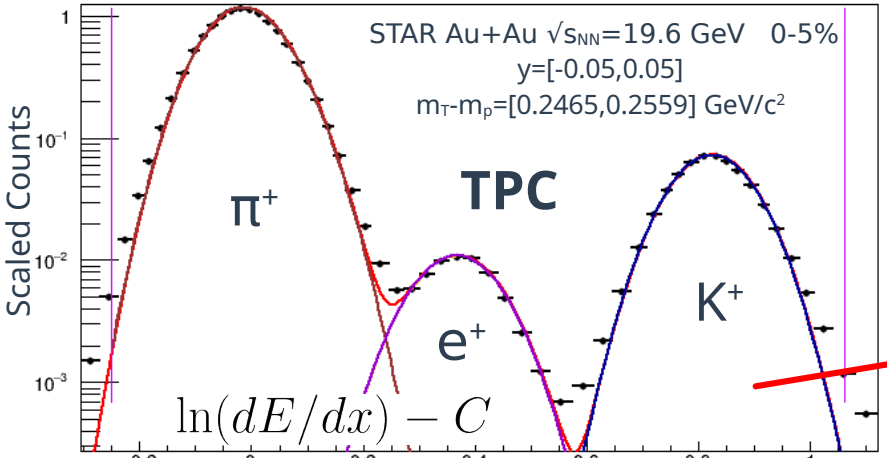
Barrel Time of Flight (**BTOF**)

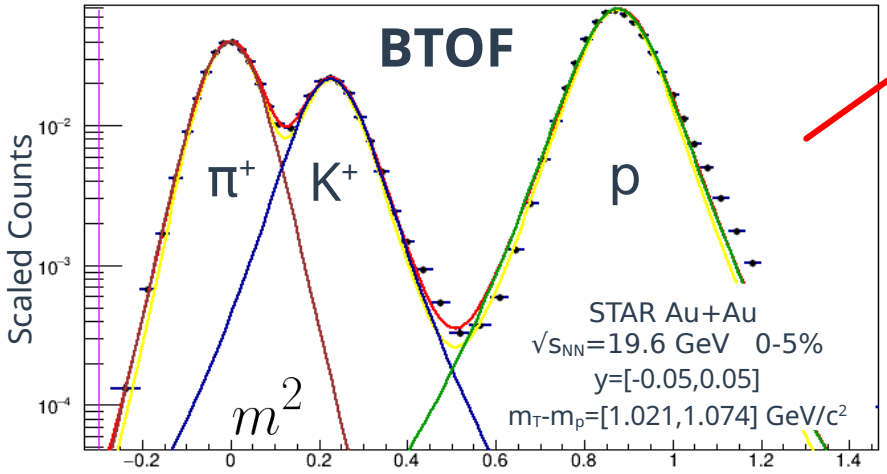


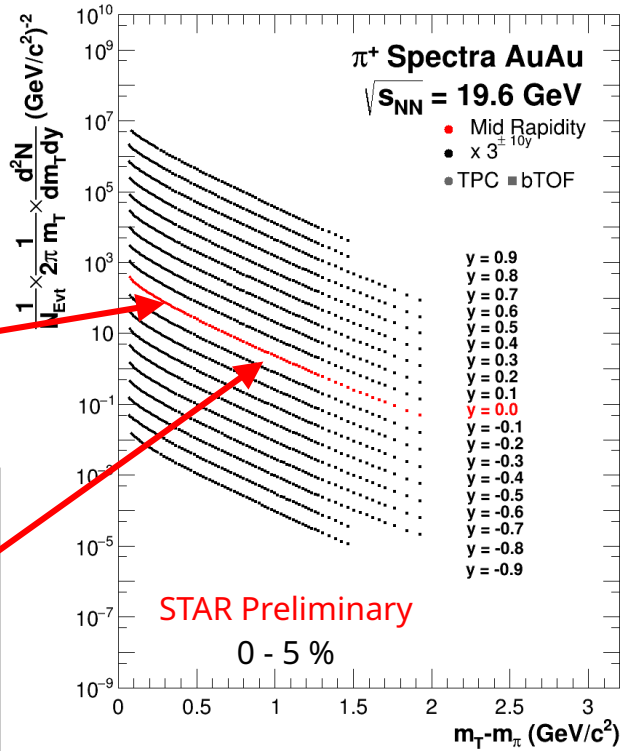


Yield Extraction

- Gaussian Fits of ln(dE/dx) from TPC
- Student-T Fits of m^2 from BTOF



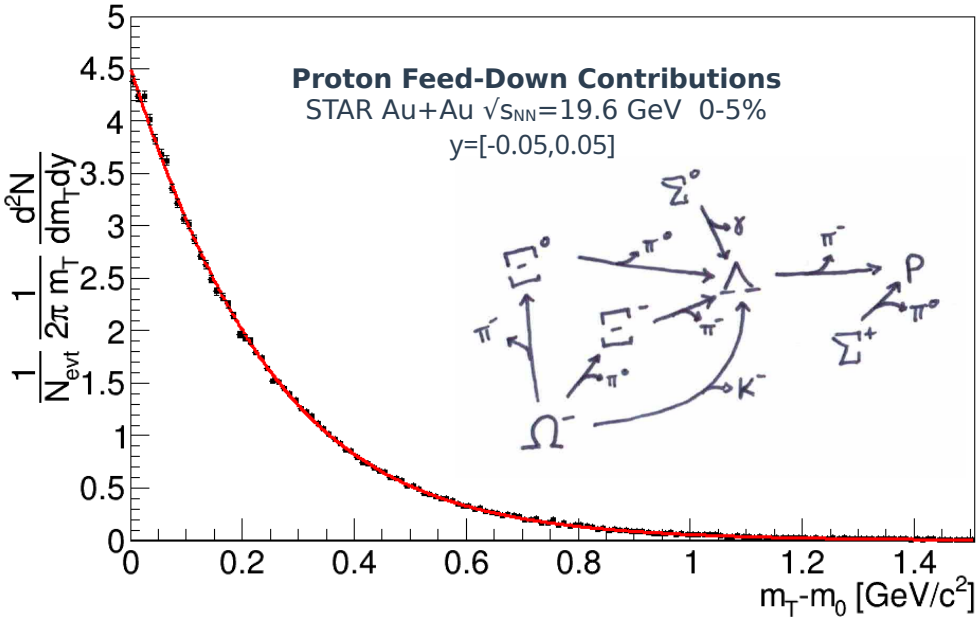


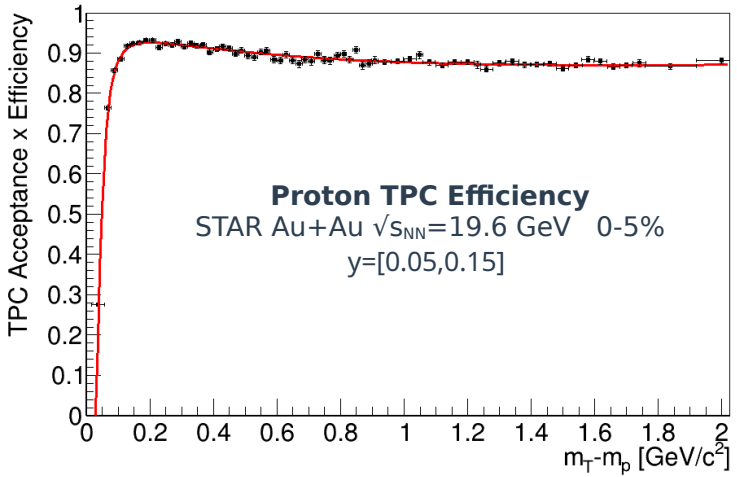


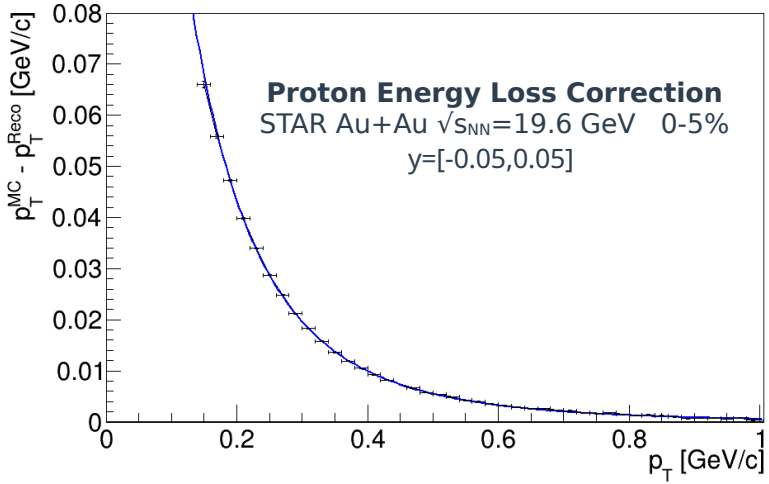
$$m_T - m = \sqrt{p_T^2 + m^2} - m$$

Corrections to the Spectra

- Feed-Down Decays
  - 15% for protons at y = 0, $\sqrt{s_{NN}}$ = 19.6 GeV
- Acceptance & Efficiency
- Energy Loss

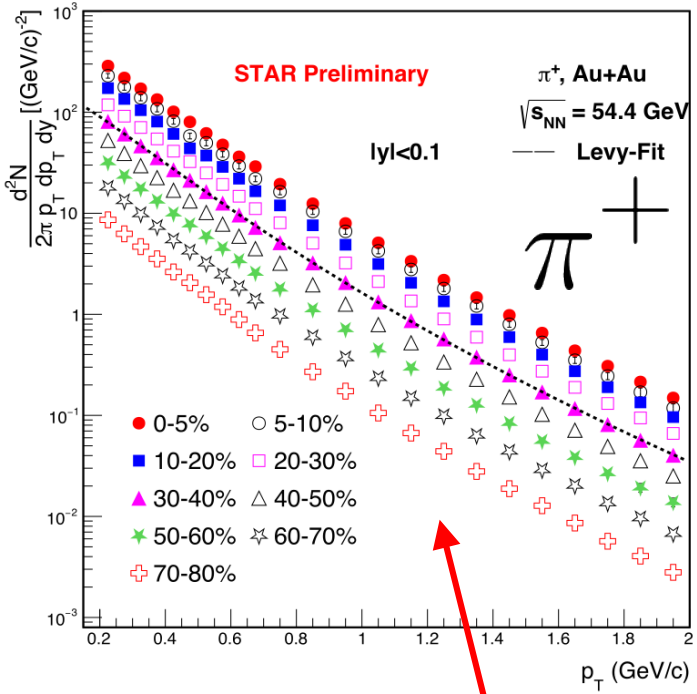


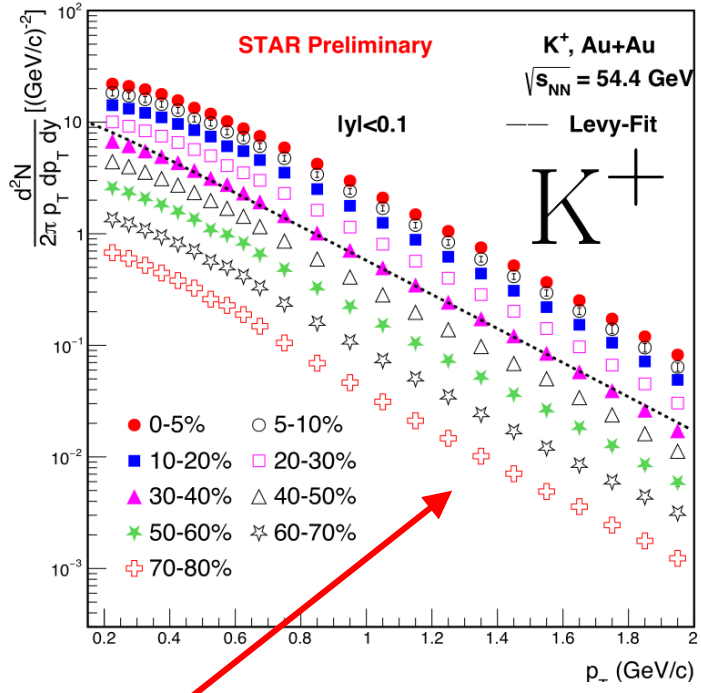


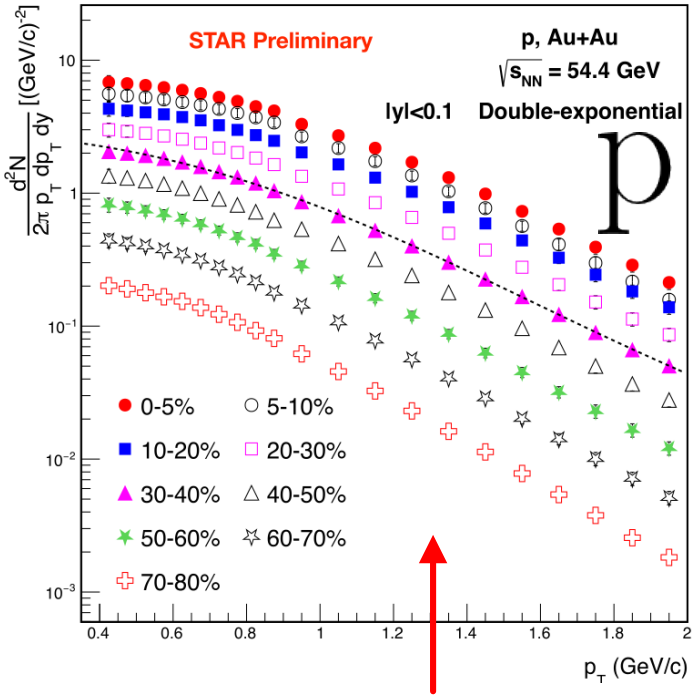


Mid-Rapidity Yields at 54.4 GeV

Work of Krishan Gopal





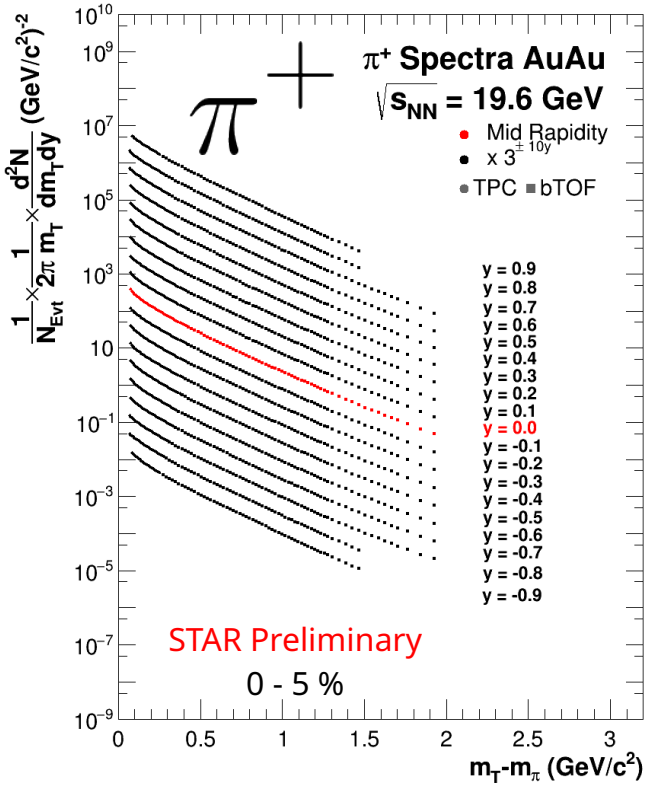


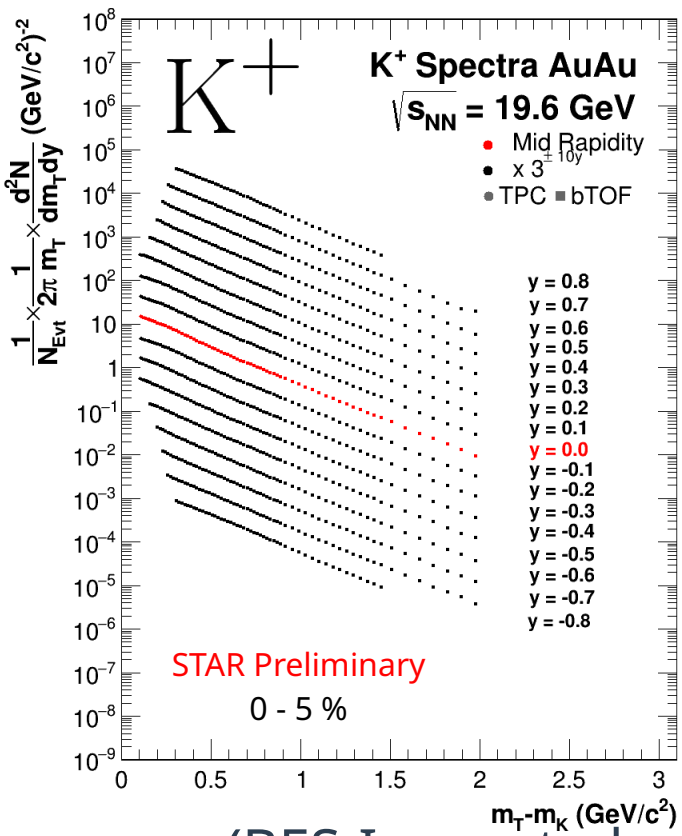
Levy function : $\frac{d^2N}{dydp_T} = \frac{(n-1)(n-2)}{nT[nT+m(n-2)]} \times \frac{dN}{dy} \times p_T \times \left(1+\frac{m_T-m}{nT}\right)^{-n}$

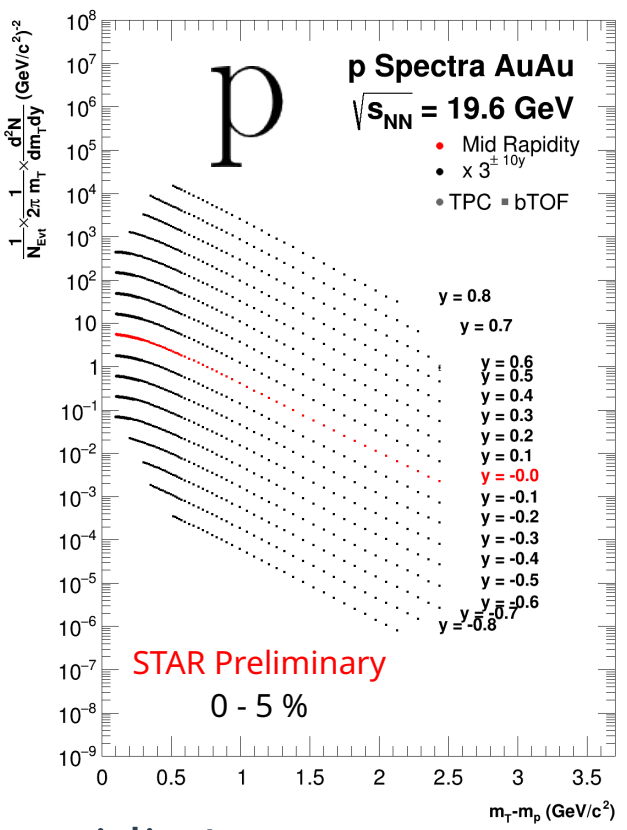
Double exponential : $A_1 e^{-p_T^2/T_1^2} + A_2 e^{-p_T^2/T_2^2}$

- Centrality dependence of yields at y = [-0.1,0.1]

Rapidity Dependent Spectra



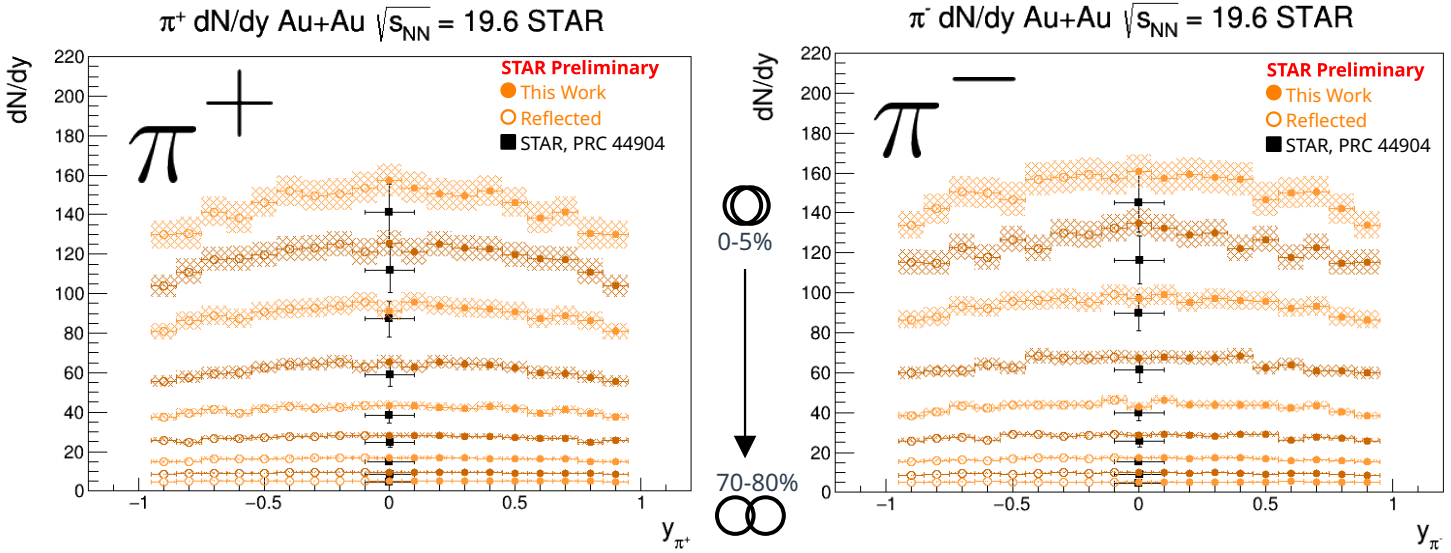




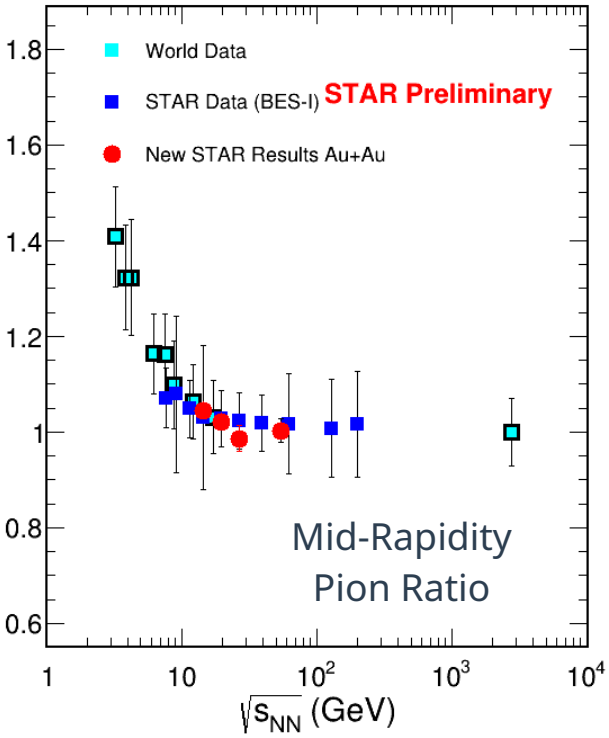
- Wide Rapidity Coverage (BES-I reported mid-rapidity)
- Spectra fit at low pT to extract dN/dy

Pion Production

- Pair production of pions
- π^- excess at low $\sqrt{s_{NN}}$ due to delta resonance
  - Neutron rich initial conditions



π^- / π^+

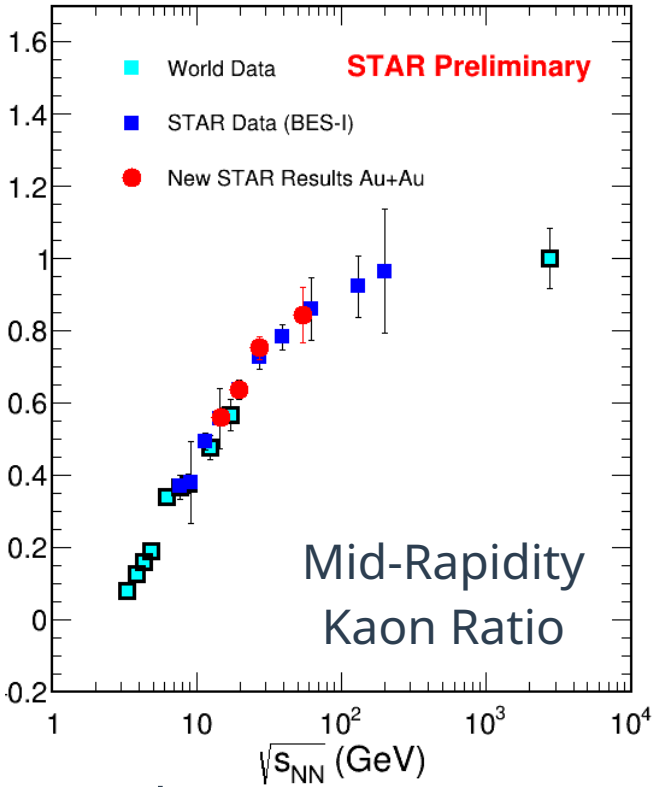


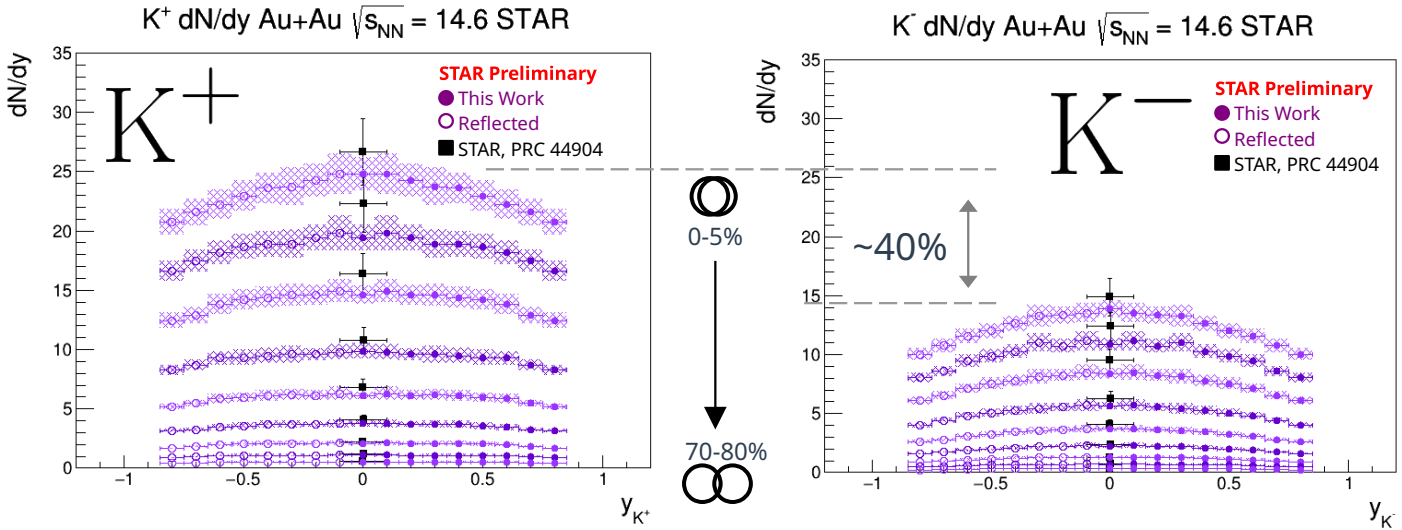
K+ and Associated Production

- Associated K+ production dominates over pair production at lower $\sqrt{s_{NN}}$

$$p + N \rightarrow \Lambda + K^+ + N$$
$$uud \qquad uds \quad u\bar{s}$$

$\frac{K^-}{K^+}$

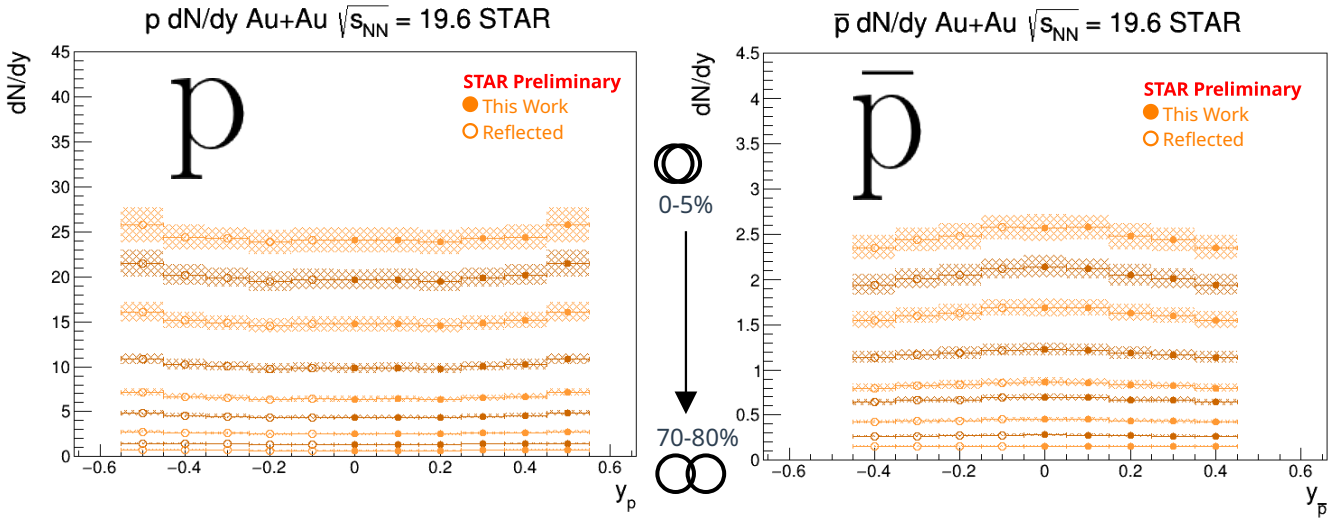


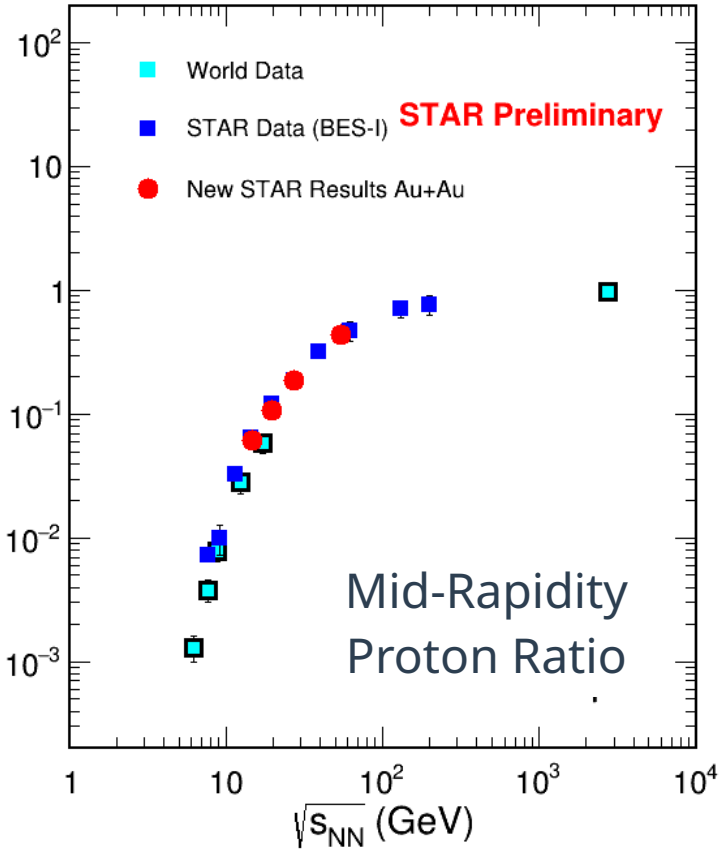


- Indicates non-zero μ_S
- Strangeness distillation

Baryon Stopping

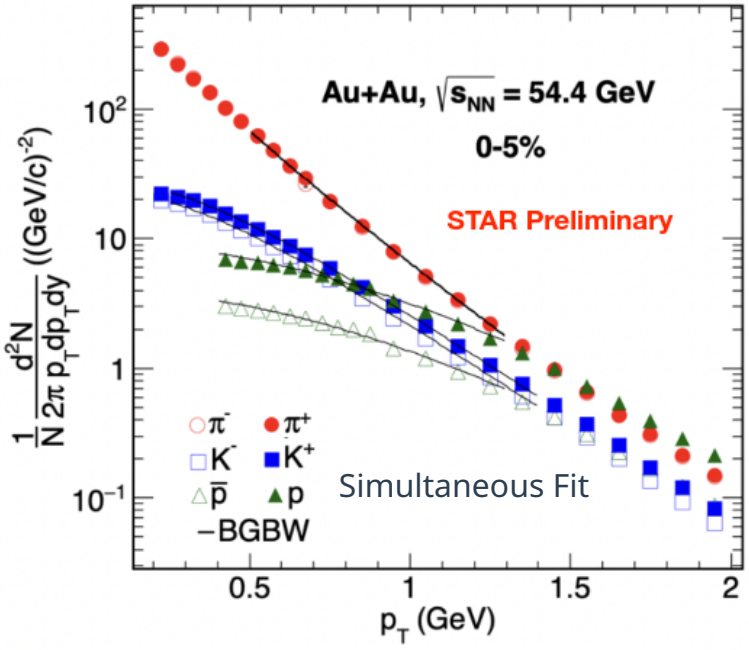
- **Participant protons slowed toward mid-rapidity**
  - Interactions with medium
  - y_{beam} = 2.75 (14.6 GeV) 3.04 (19.6 GeV)
- **$\bar{p}$/p ratio relates to baryon chemical potential**





Kinetic Freeze-out at 54.4 GeV

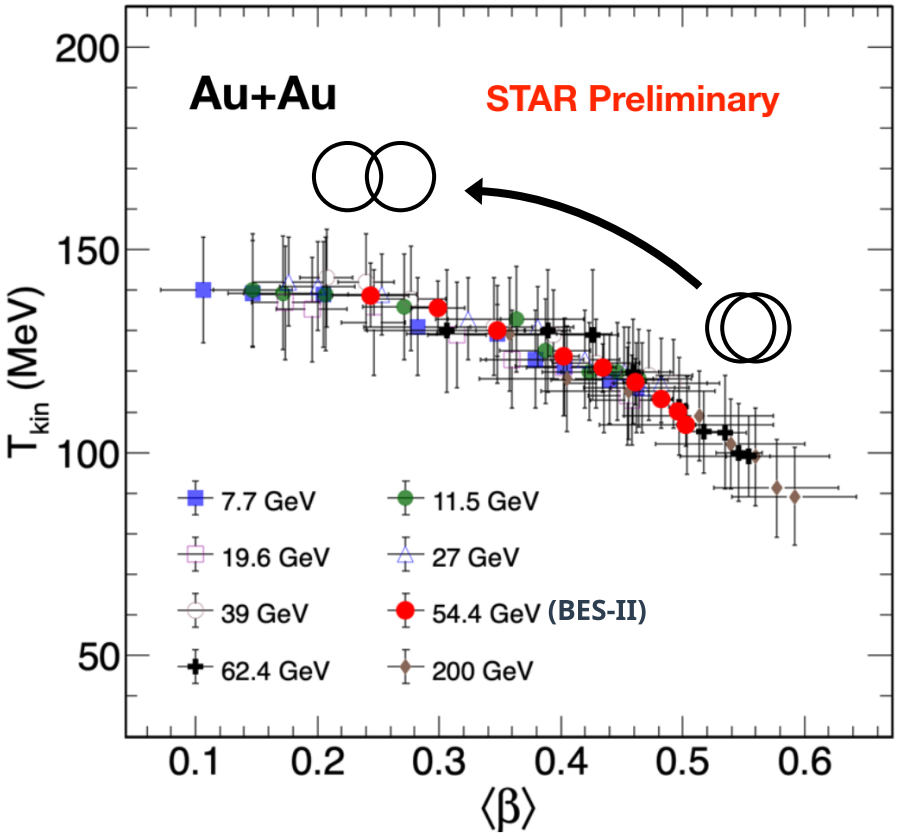
Work of Krishan Gopal



Blast-Wave Model : Hydrodynamic inspired model

$$\frac{dN}{p_T dp_T} \propto \int_0^R r\, dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

I_0, K_1: Modified Bessel functions
$\rho(r) = \tanh^{-1}\beta$
β = Transverse radial flow velocity
T_{kin}: Kinetic freeze-out temperature



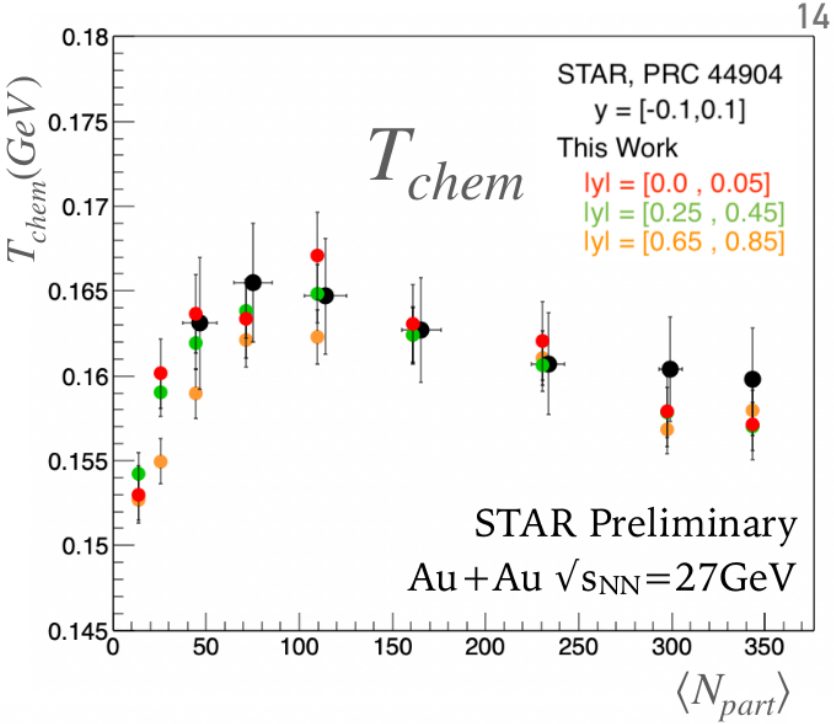
- T_{kin} and <β> show anti-correlated trend, similar to the other BES-I energies

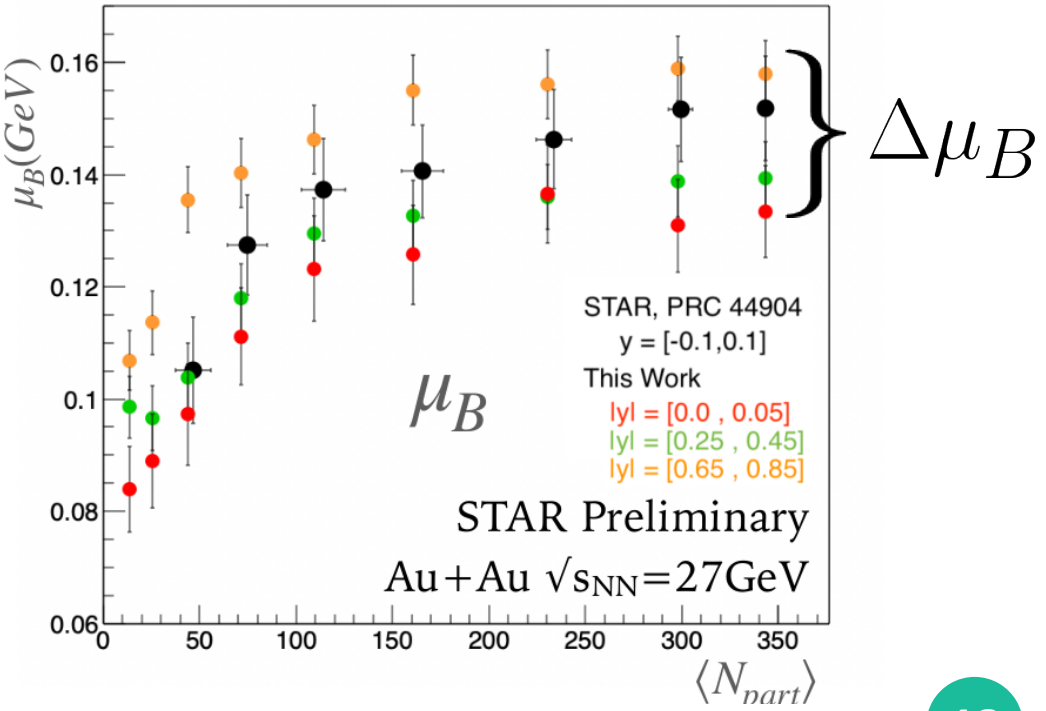
Chemical Freeze-Out at 27 GeV

- **Fits by THERMUS**
  - Chemical equilibrium model

➤ $\Delta\mu_B \sim 25$ MeV for $\Delta y = 1$

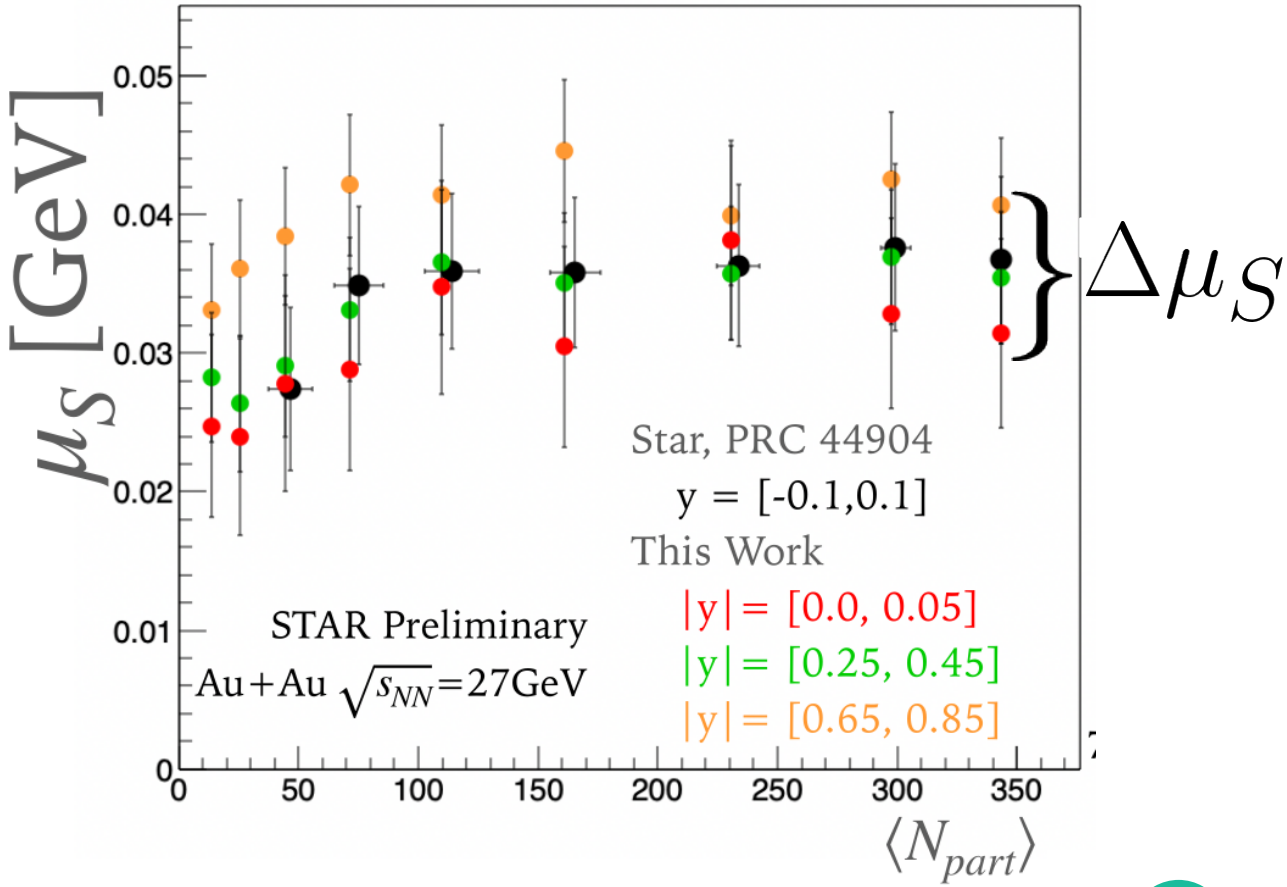
➤ New results were feed-down corrected, while the previous results were not.





Chemical Freeze-Out at 27 GeV

- **Fits by THERMUS**
  - Chemical equilibrium model
- **K+ associated production**
- **Differing Lambda and K+ dN/dy → $\Delta\mu_S \sim 10$ MeV for $\Delta y = 1$**

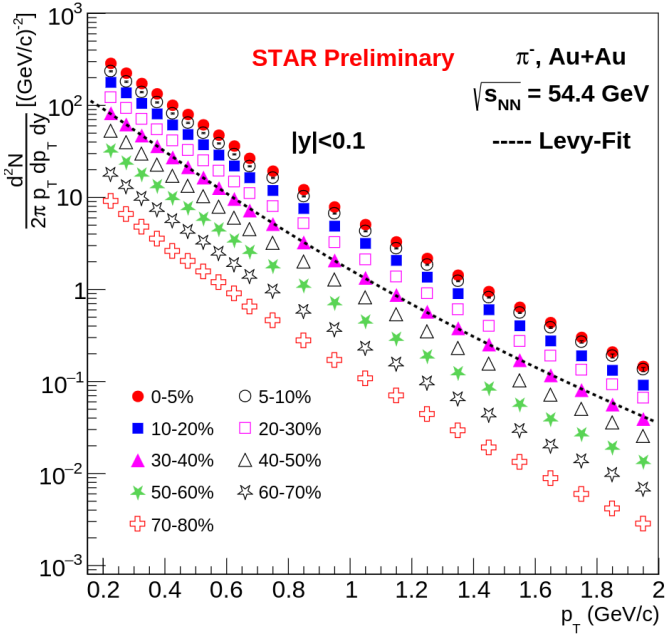


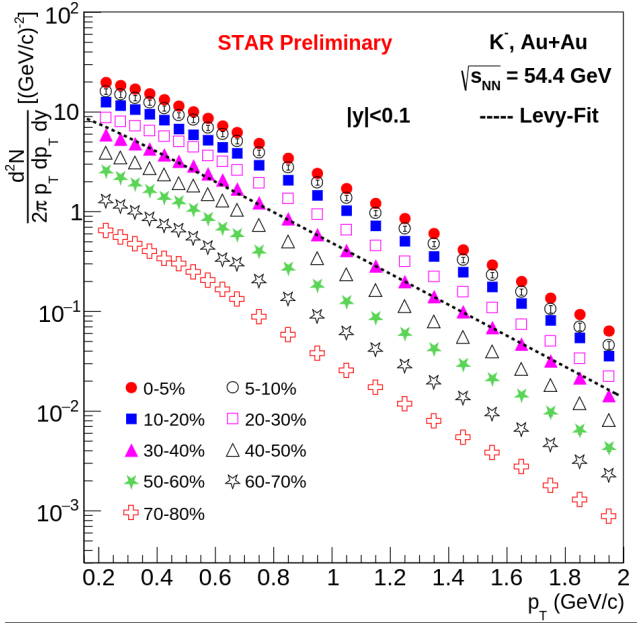
Conclusions

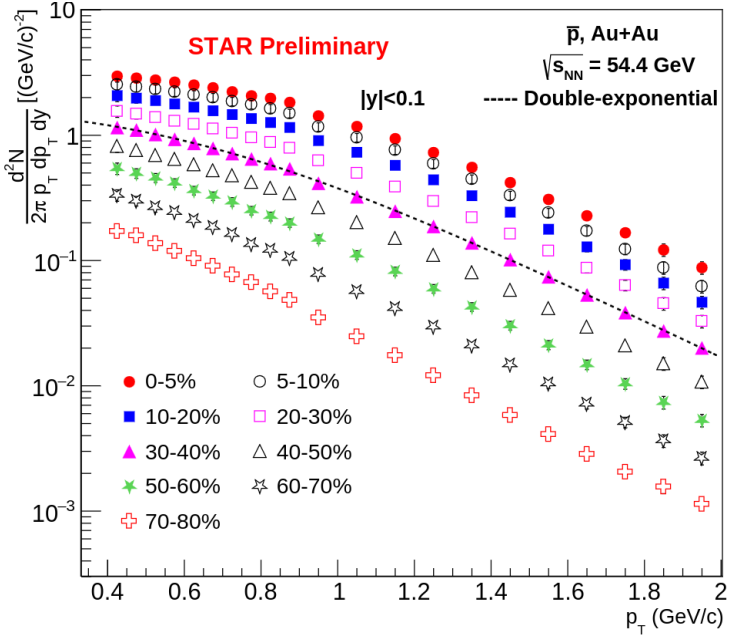
- **dN/dy of $\pi^{\pm}$, $K^{\pm}$, p, & $\bar{p}$ with p_T spectra**
  - $\sqrt{s_{NN}}$ = 14.6, 19.6, 27, 54.4 (mid-rapidity) GeV
  - Associated Production of K^+
    - 40% at $\sqrt{s_{NN}}$ = 14.6 GeV → 15% at $\sqrt{s_{NN}}$ = 54.4 GeV
  - Baryon and Strangeness Chemical Potentials ($\sqrt{s_{NN}}$ =27 GeV)
    - $\Delta\mu_B \sim 25$ MeV for $\Delta y = 1$ (baryon stopping)
    - $\Delta\mu_S \sim 10$ MeV for $\Delta y = 1$ (associated production)


Thank You!

Negative 54.4 GeV Spectra



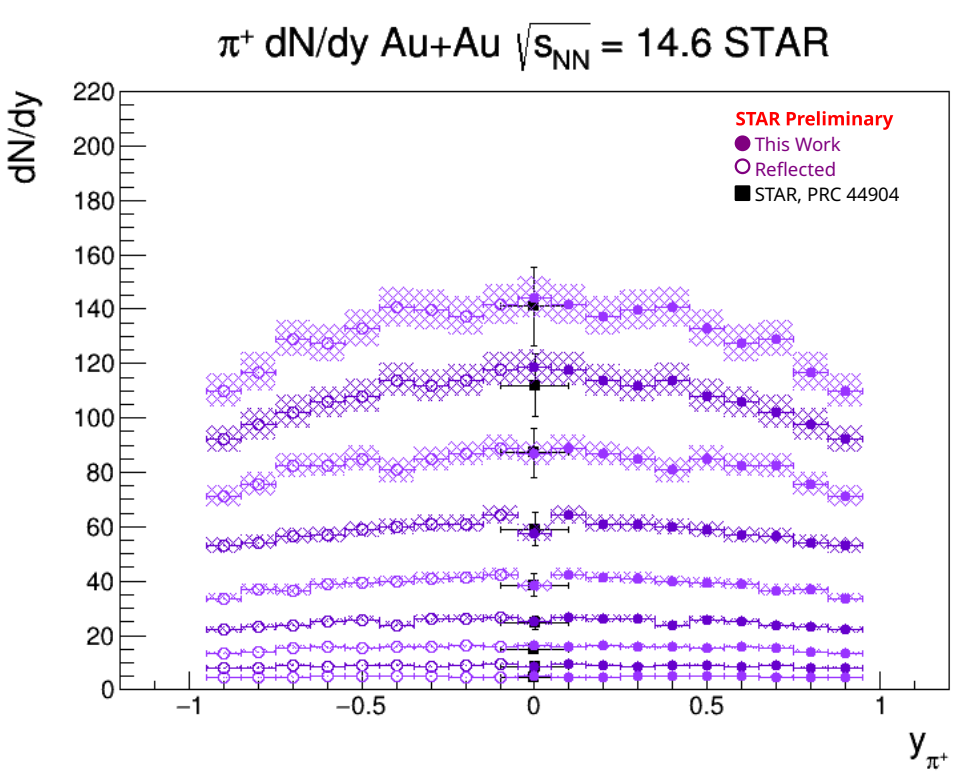


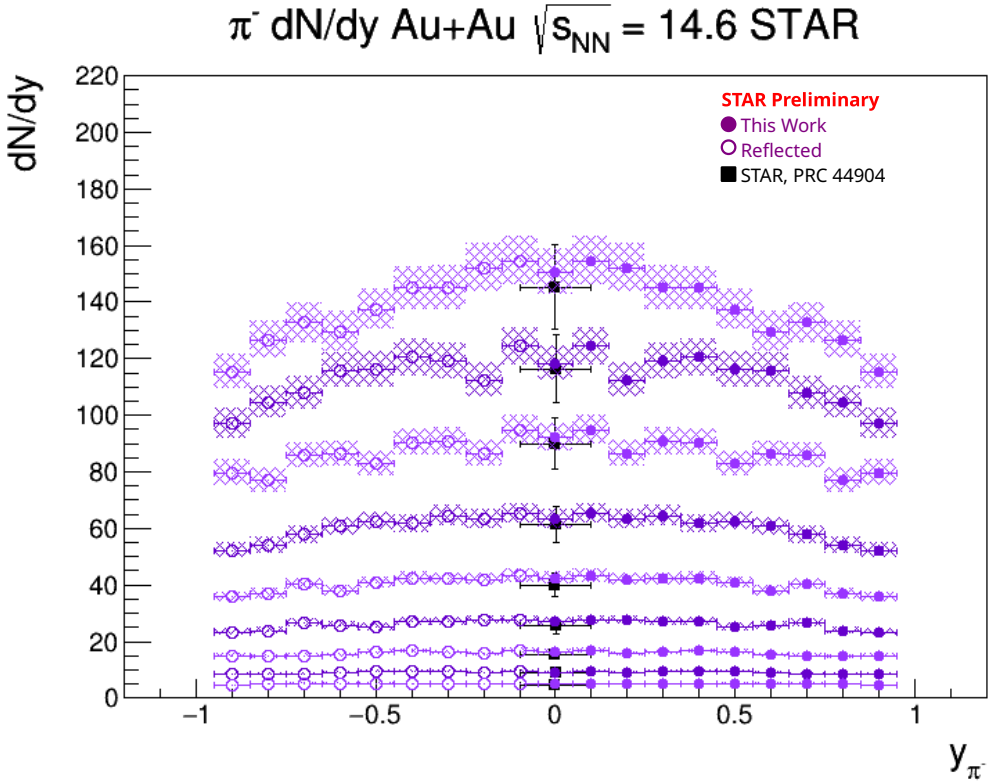


Levy function : $$\frac{d^2N}{dydp_T} = \frac{(n-1)(n-2)}{nT[nT+m(n-2)]} \times \frac{dN}{dy} \times p_T \times \left(1+\frac{m_T-m}{nT}\right)^{-n}$$

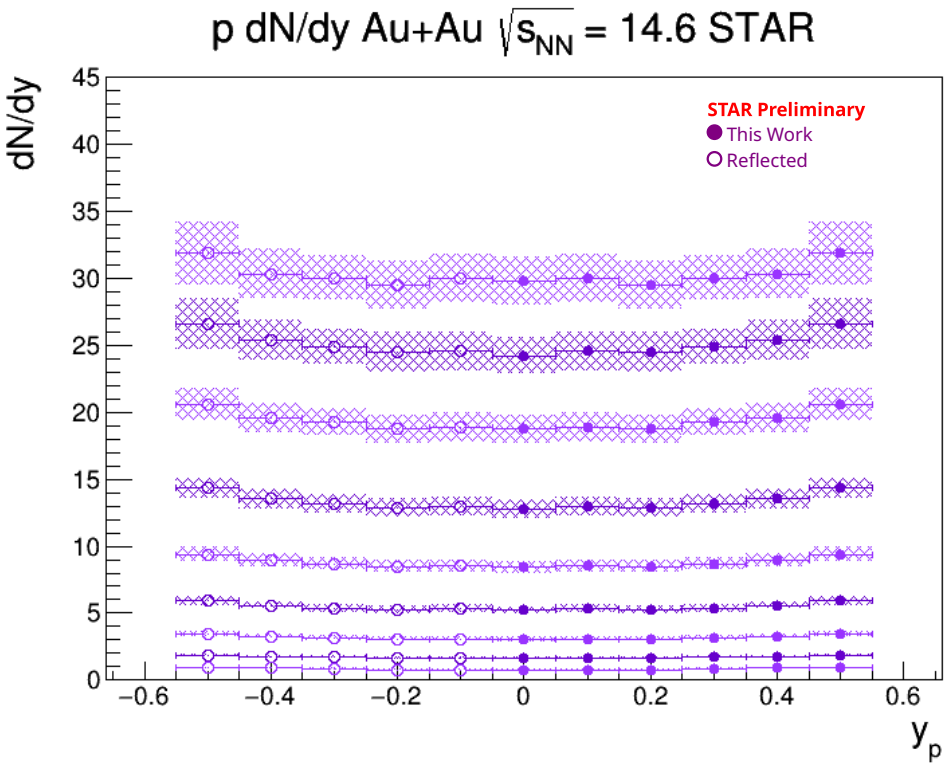
Double exponential : $A_1 e^{-p_T^2/T_1^2} + A_2 e^{-p_T^2/T_2^2}$

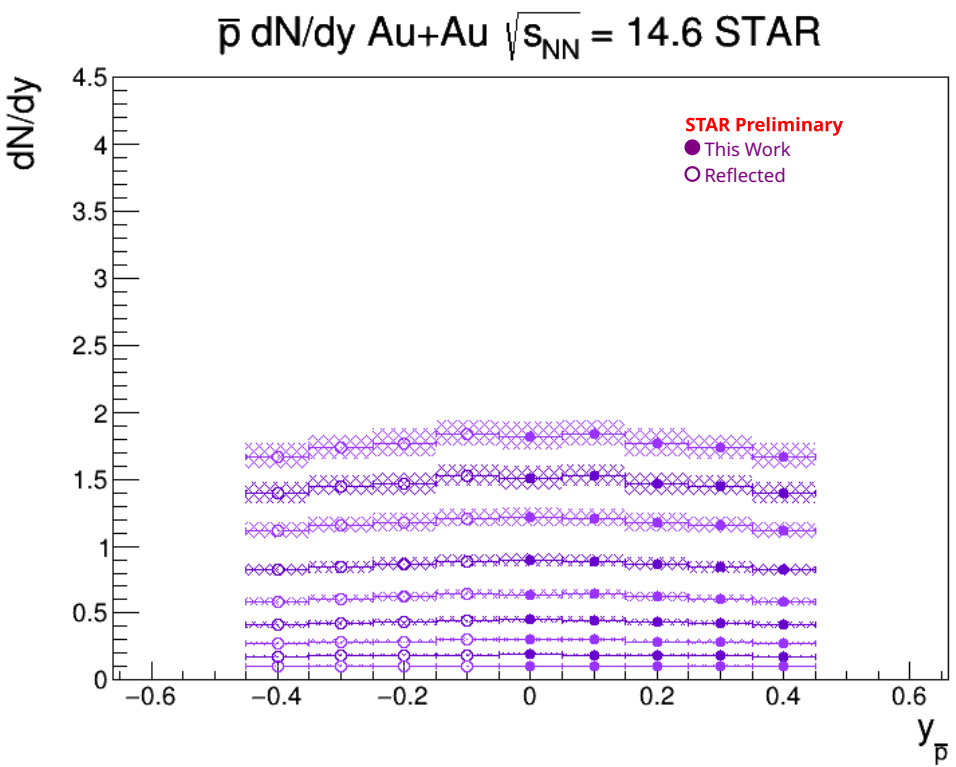
14.6 GeV Pion dN/dy



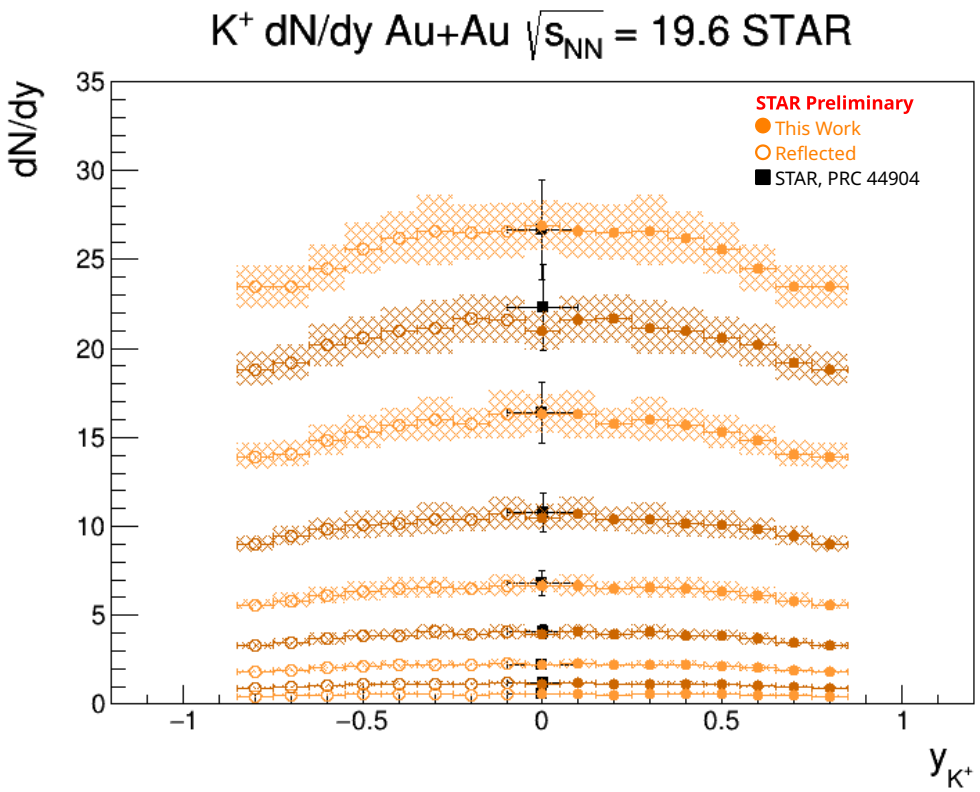


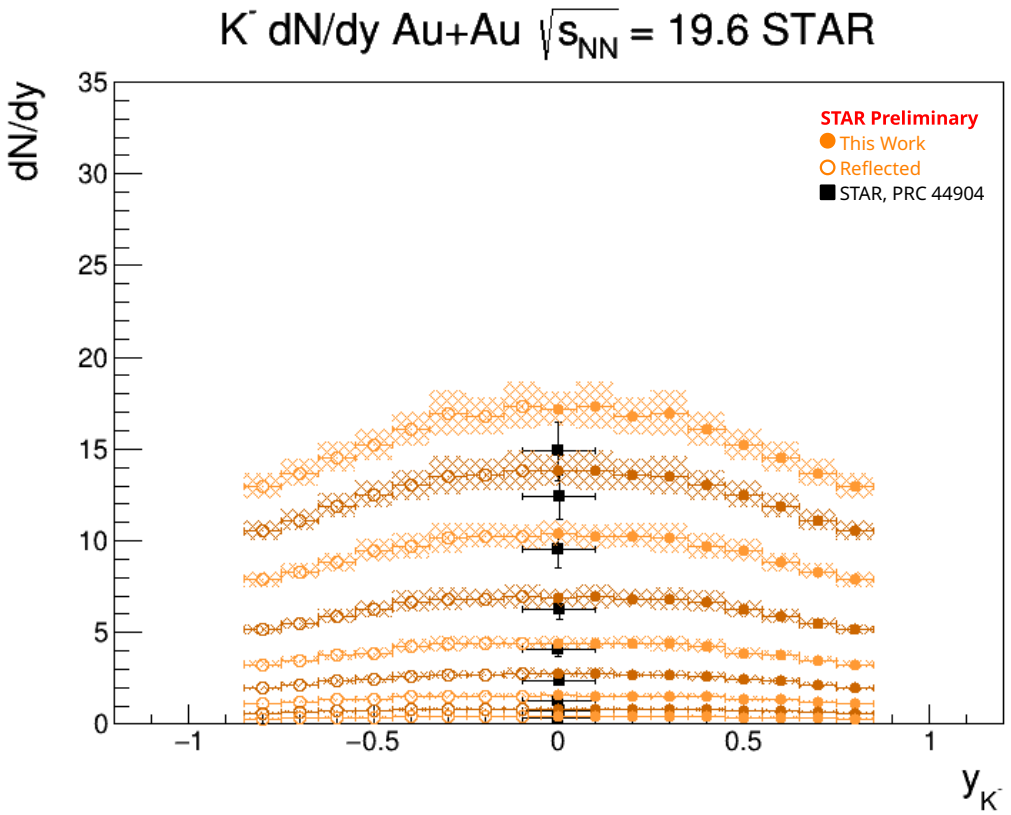
14.6 GeV Proton dN/dy



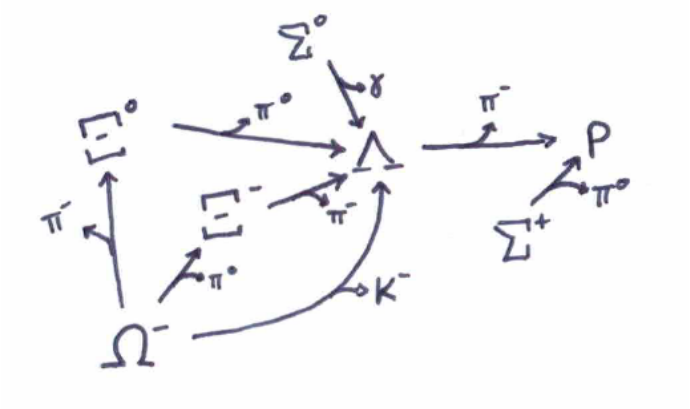


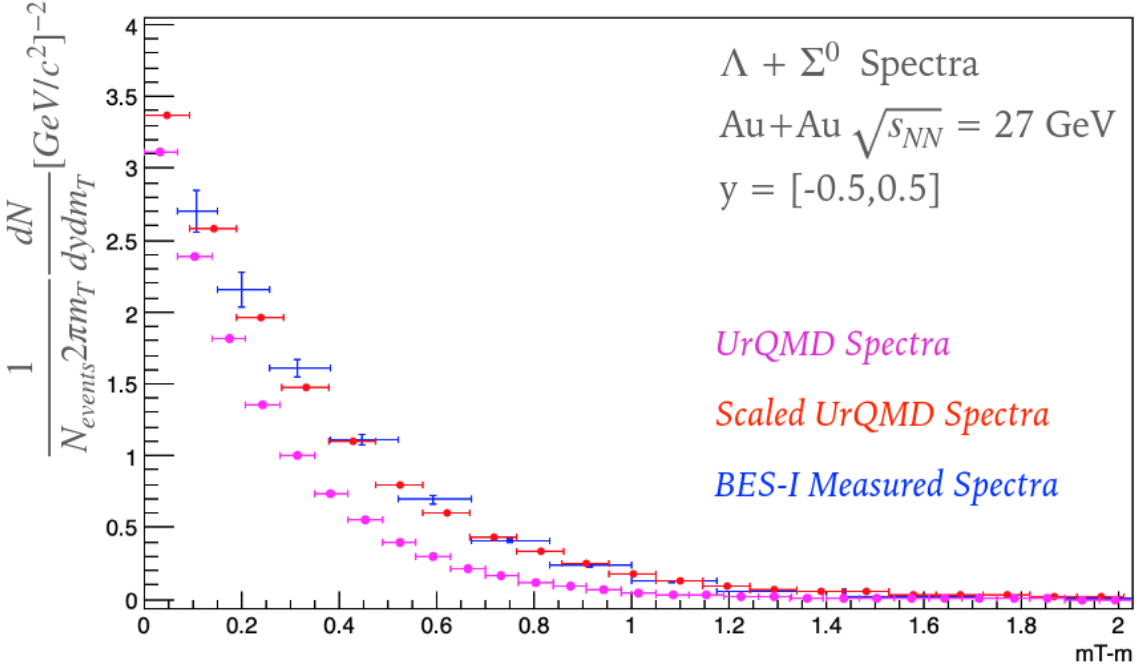
19.6 GeV Kaon dN/dy





HYBRID FEED-DOWN METHOD



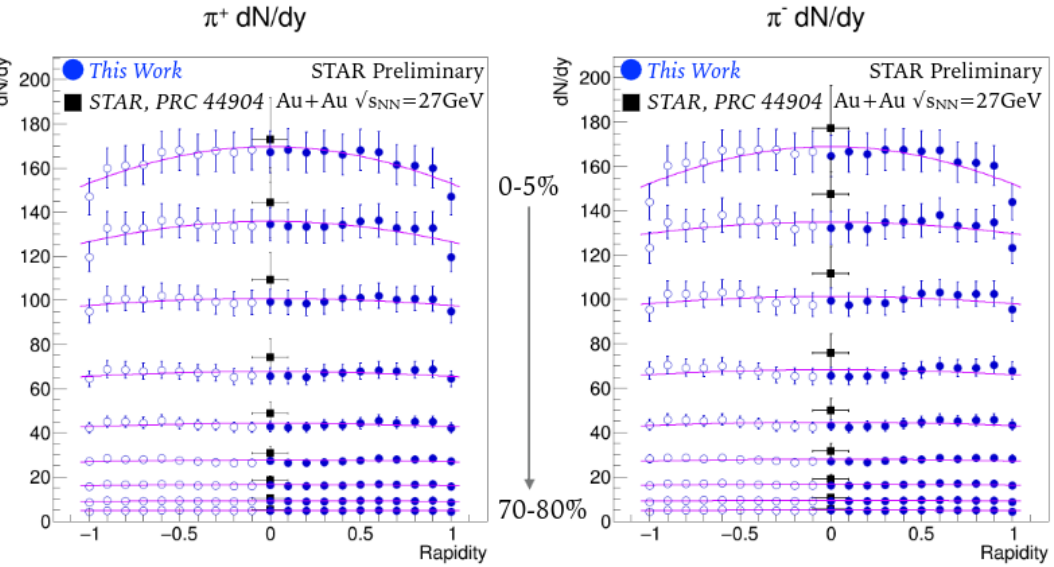


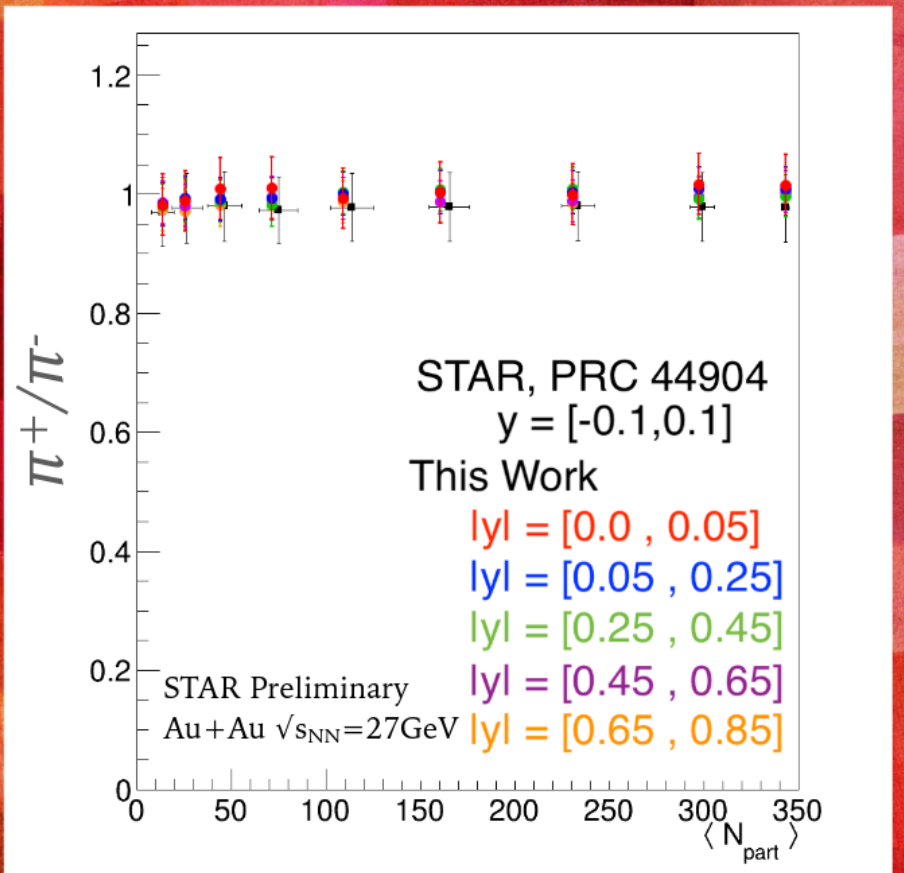
- Scale UrQMD strange spectra to mid-rapidity BES measurements
  - Many analyses need rapidity dependence and BES-I published mid-rapidity strangeness only
  - No measured coverage at low p_T
  - Scale and stretch parameters determined by χ^2 minimization
    - Scale : $d^2N/dm_T dy \rightarrow a \cdot d^2N/dm_T dy$
    - Stretch : $m_T - m_0 \rightarrow b \cdot (m_T - m_0)$
  - Ξ^- and Ξ^0 spectra assumed identical (Ξ^0 not measured)
  - Σ^+/Λ ratio conserved (Σ^+ not measured)

- Strange hadron production in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, and 39 GeV. *Phys. Rev. C 102 34909 (2020)*
  - Ξ^- and Ξ^0 decays into Λ were corrected by data-driven feed-down (23% at low p_T) assuming uncorrelated uncertainties.
  - Σ^0 considered prompt (included in Λ) and Ω^- considered insignificant to Λ production

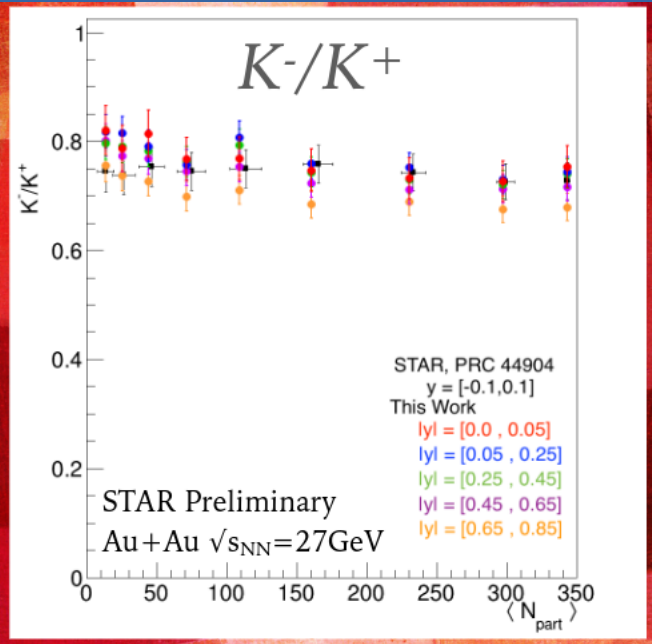
PION PRODUCTION

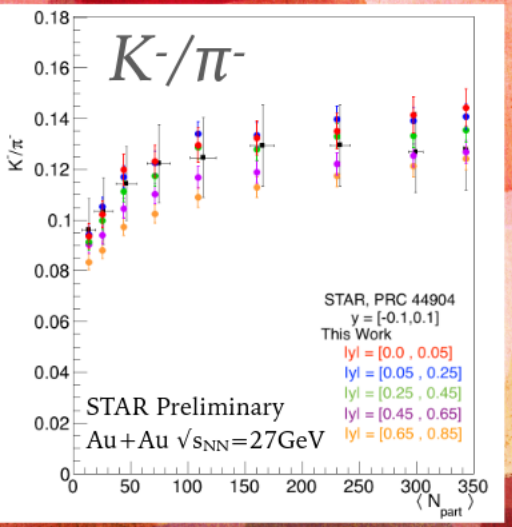
- Thermally produced
- Charge chemical potential (μ_Q)
- Little variation in ratio by centrality

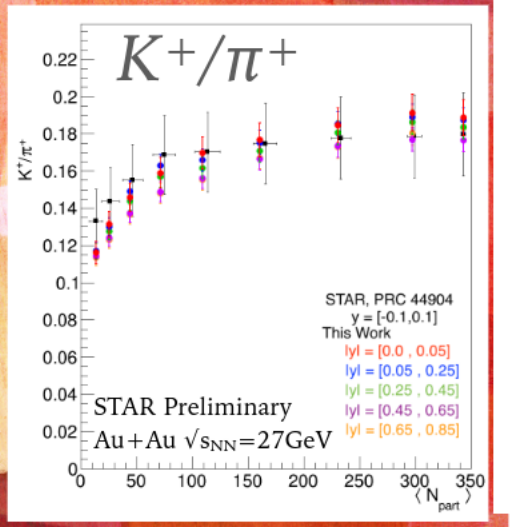




KAON PRODUCTION



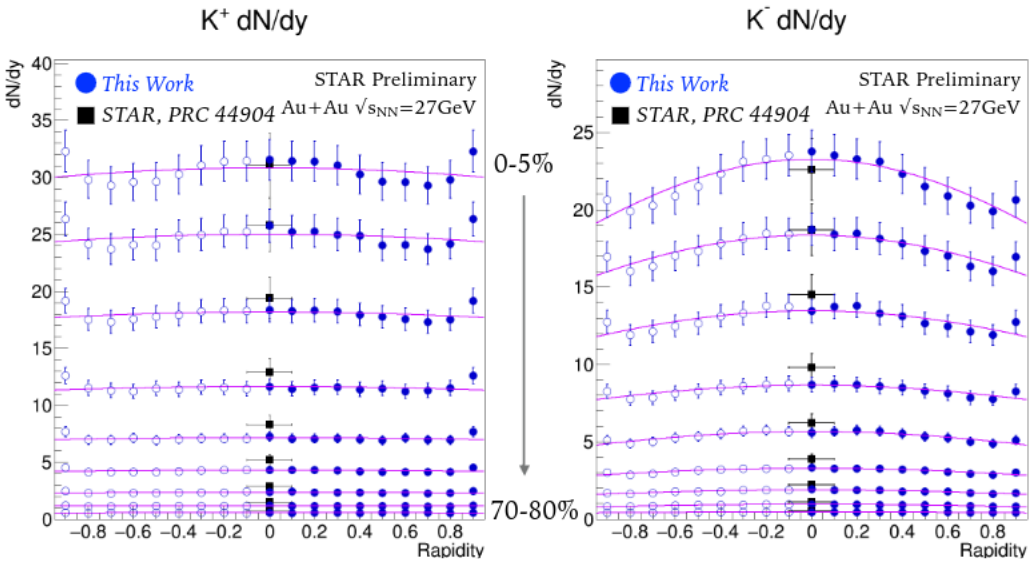




- Thermal production of K^+ and K^-
- ~1/3 of K^+: associated production

$$NN \rightarrow N\Lambda K^+$$

- Associated production increases with y
- Strangeness chemical potential (μ_S)



PROTON PRODUCTION

- Thermal and participant protons
- Baryon stopping
- Baryon chemical potential (μ_B)
- New results were feed-down corrected, while the previous results were not.