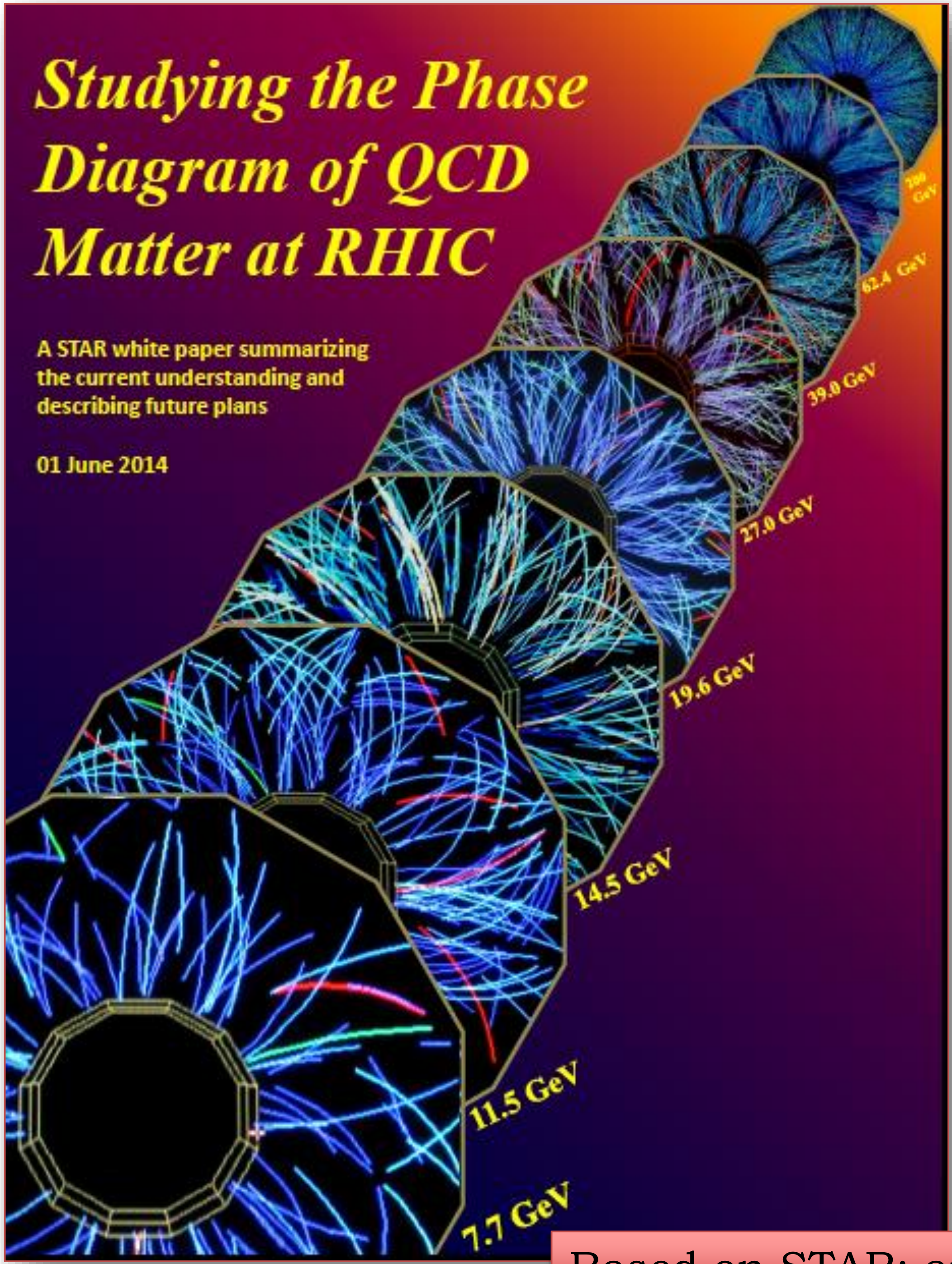
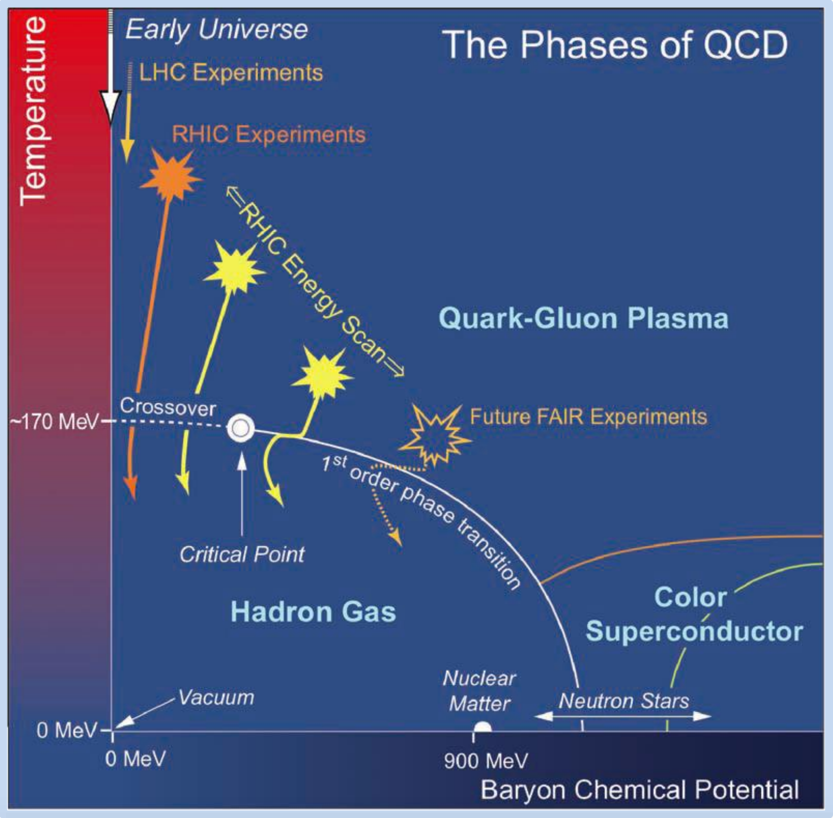


Particle Production in Heavy Ion Collisions at RHIC

Bedanga Mohanty
NISER
(For STAR Collaboration)

Based on STAR: arXiv: 1701.07065

Goals of Heavy-Ion Collision

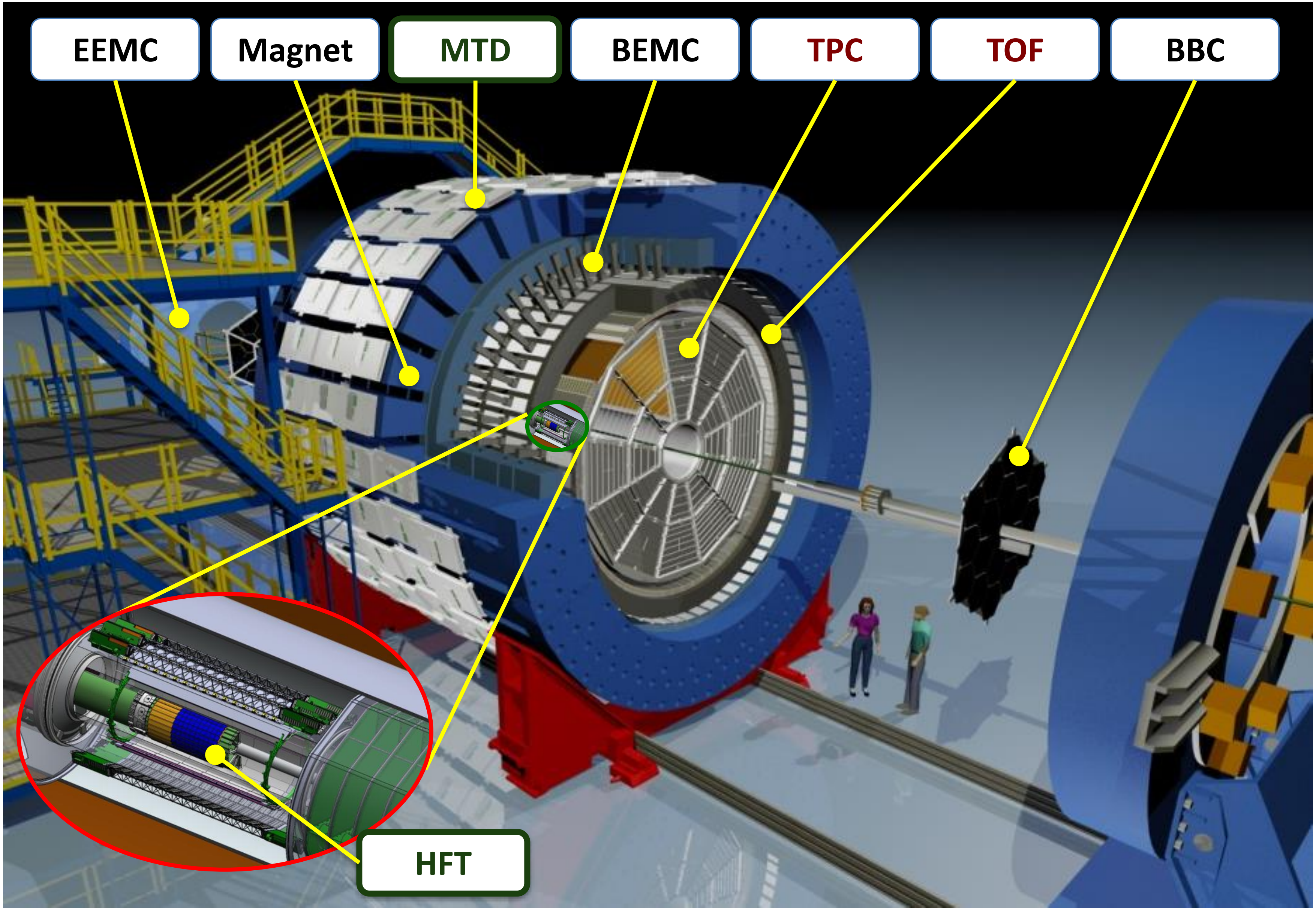


Find out the phase structure of QCD phase diagram experimentally

In this talk we will focus on the freeze-out dynamics in heavy-ion collisions

Beam Energy (in GeV)	Baryon Chemical Potential (in MeV)	Year of Data Taking	Event Statistics (Millions)	Beam Time (Weeks)
200	20	2010	350	11
62.4	70	2010	67	1.5
39	115	2010	130	2.0
27	155	2011	70	1.0
19.6	205	2011	36	1.5
14.5	260	2014	20	3.0
11.5	315	2010	12	2.0
7.7	420	2010	4	4.0

STAR Detector System



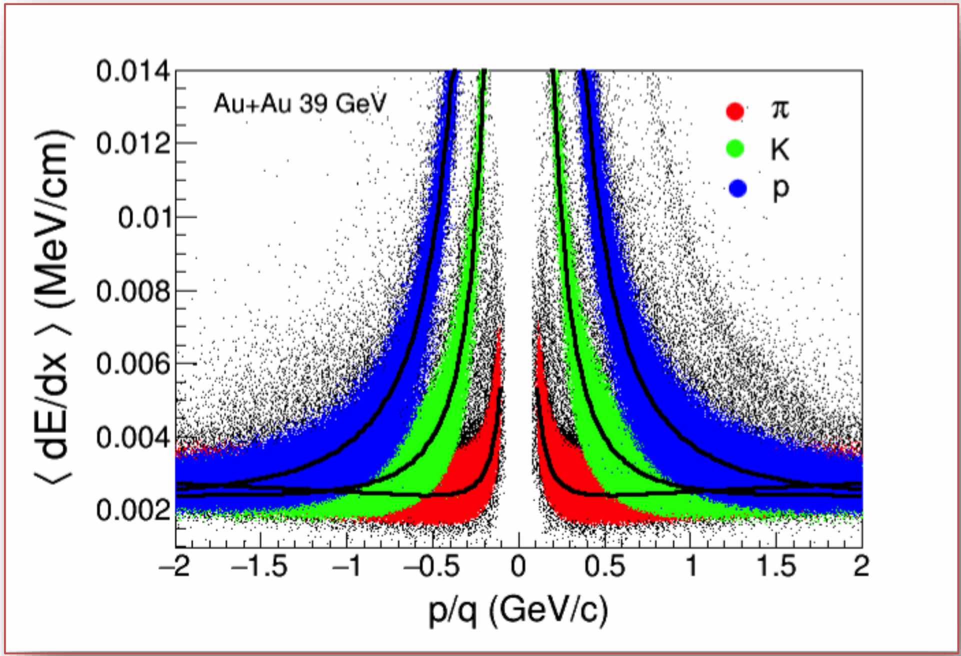
STAR: arXiv: 1701.07065

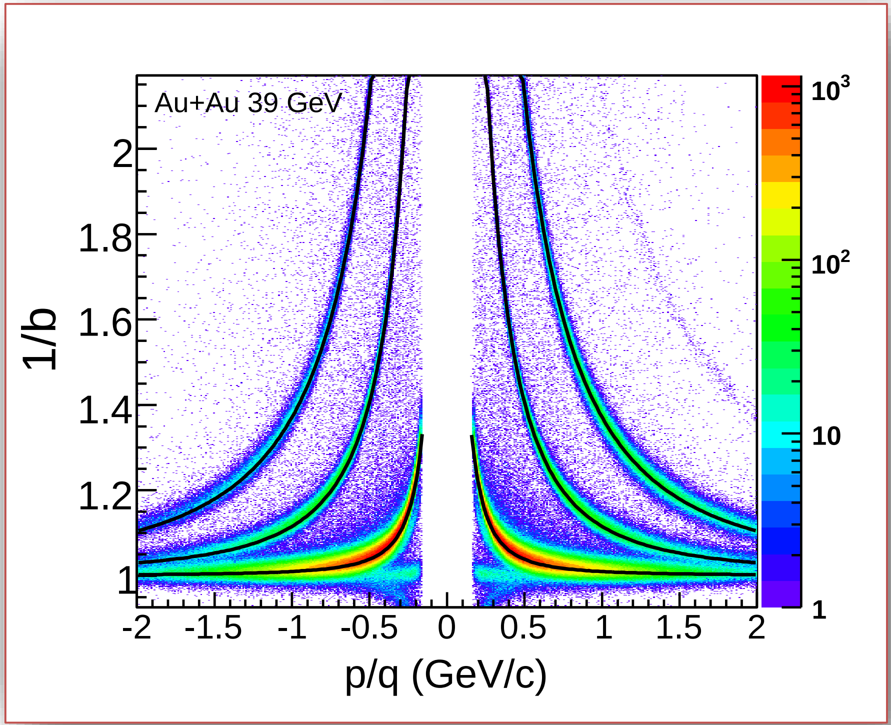
Particle Identification

Charged particles: π, K, p

Momentum $p = \gamma \beta m$

$m = [\, p\,(1 - \beta^2)^{1/2}\,] / \beta$





Ionization energy loss:

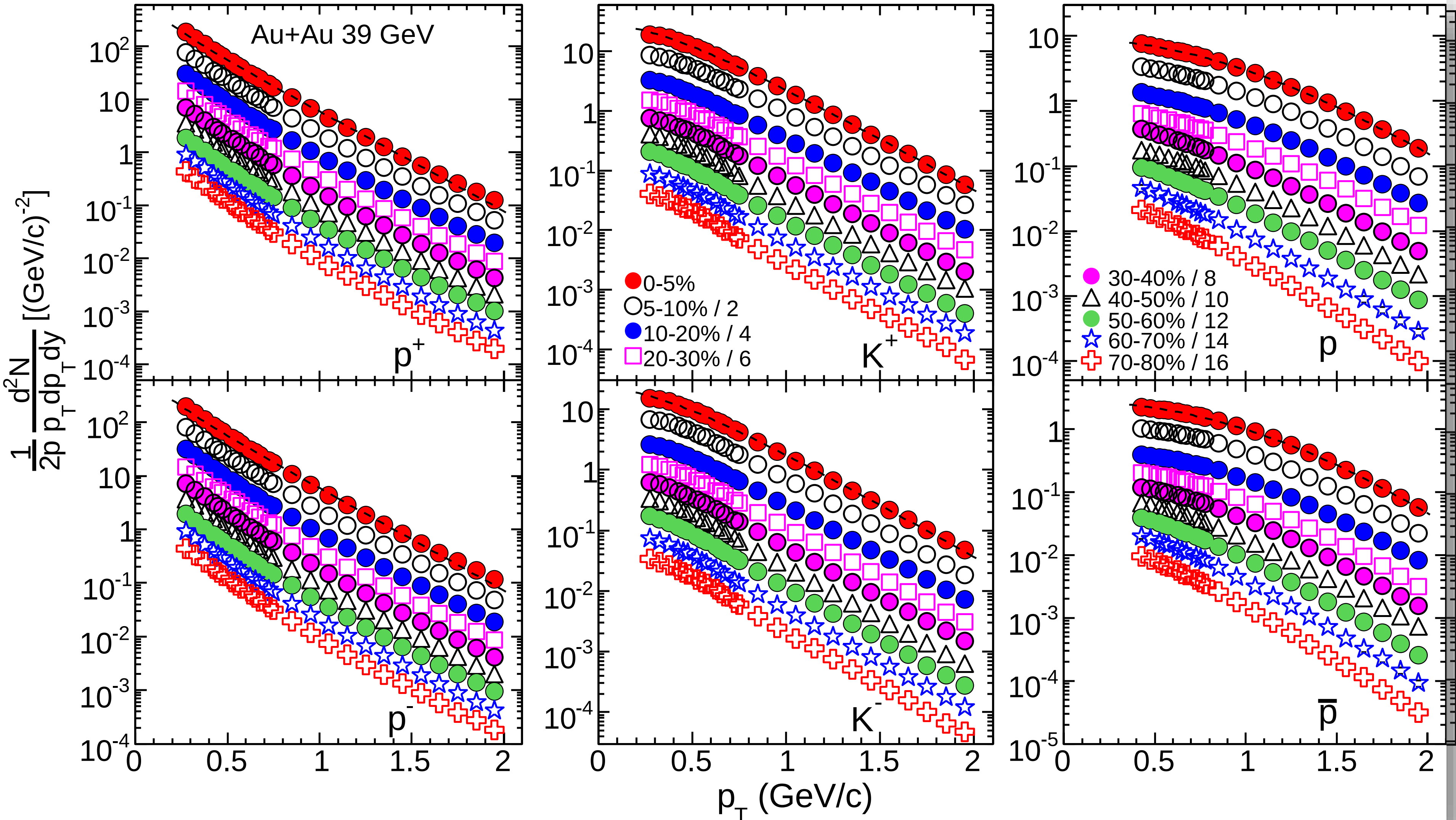
$- < dE/dx > \sim A / \beta^2$
$= A\,(1 + \mathbf{m^2} / p^2)$

Time of flight:

$< \tau > = L / \beta$
$= L\,(1 + \mathbf{m^2} / p^2)^{1/2}$

STAR: arXiv: 1701.07065

Invariant Yields



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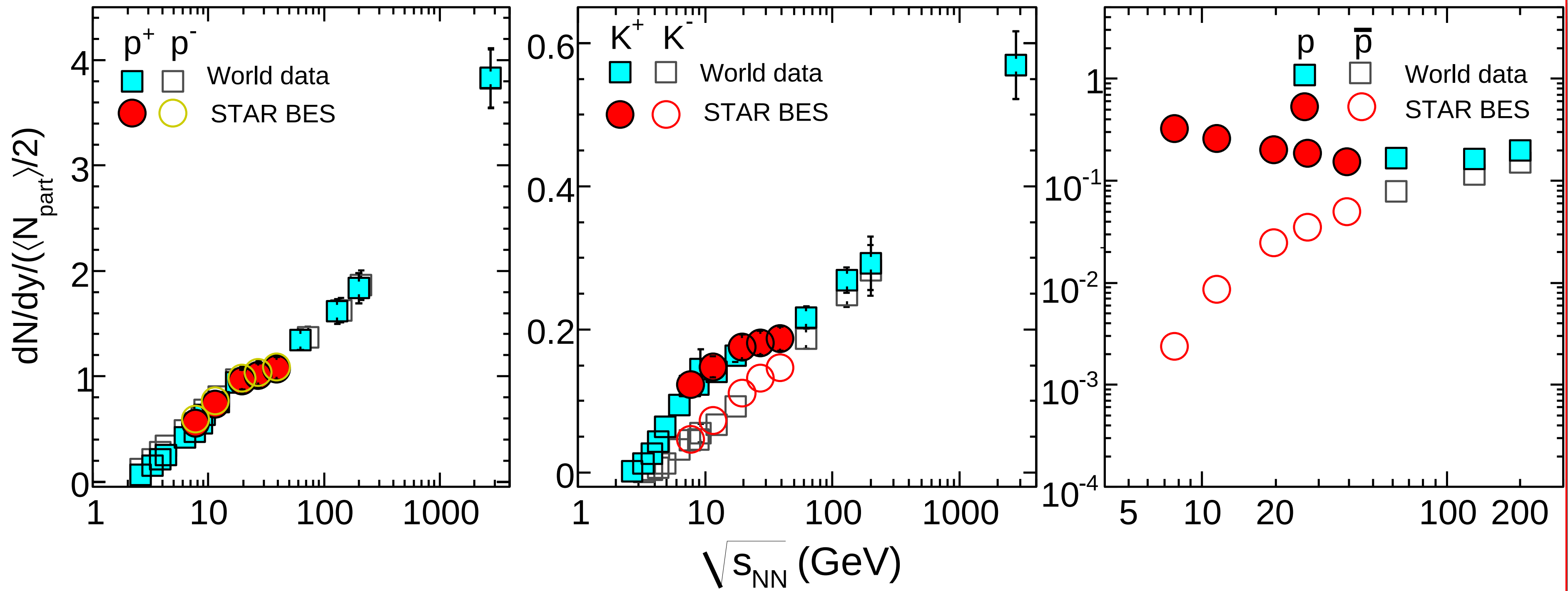
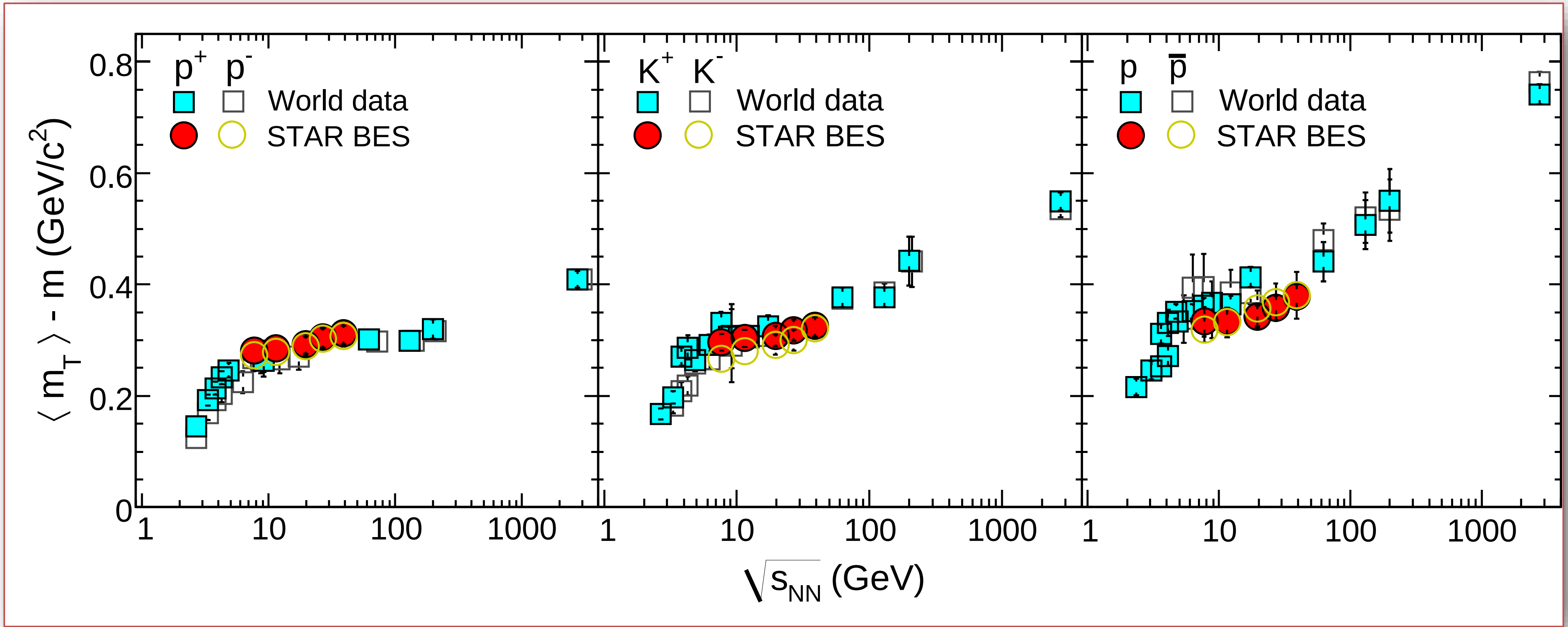
Yields



✓ Yields of hadrons per participating nucleon pair at mid rapidity in central heavy-ion collisions as a function of collision energy

STAR: arXiv: 1701.07065 and references therein

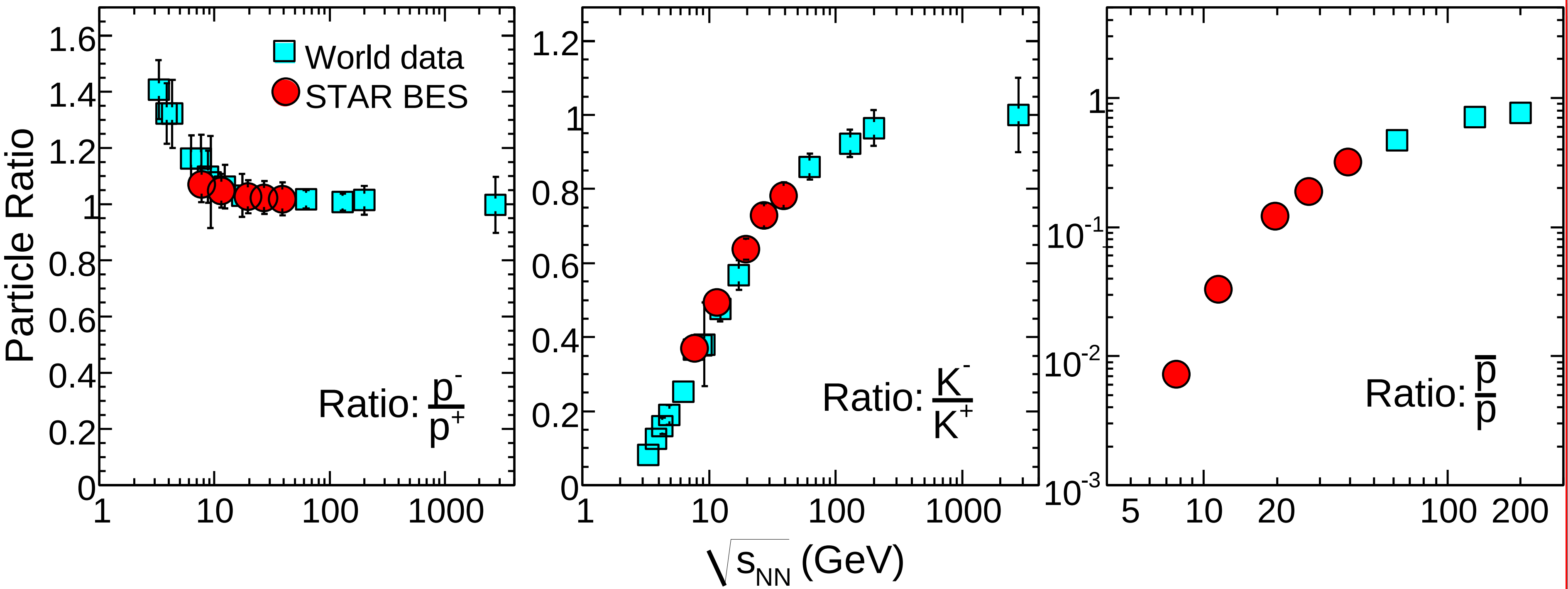
Transverse Mass



✓ Average transverse mass of hadrons at mid rapidity in central heavy-ion collisions as a function of collision energy

STAR: arXiv: 1701.07065 and references therein

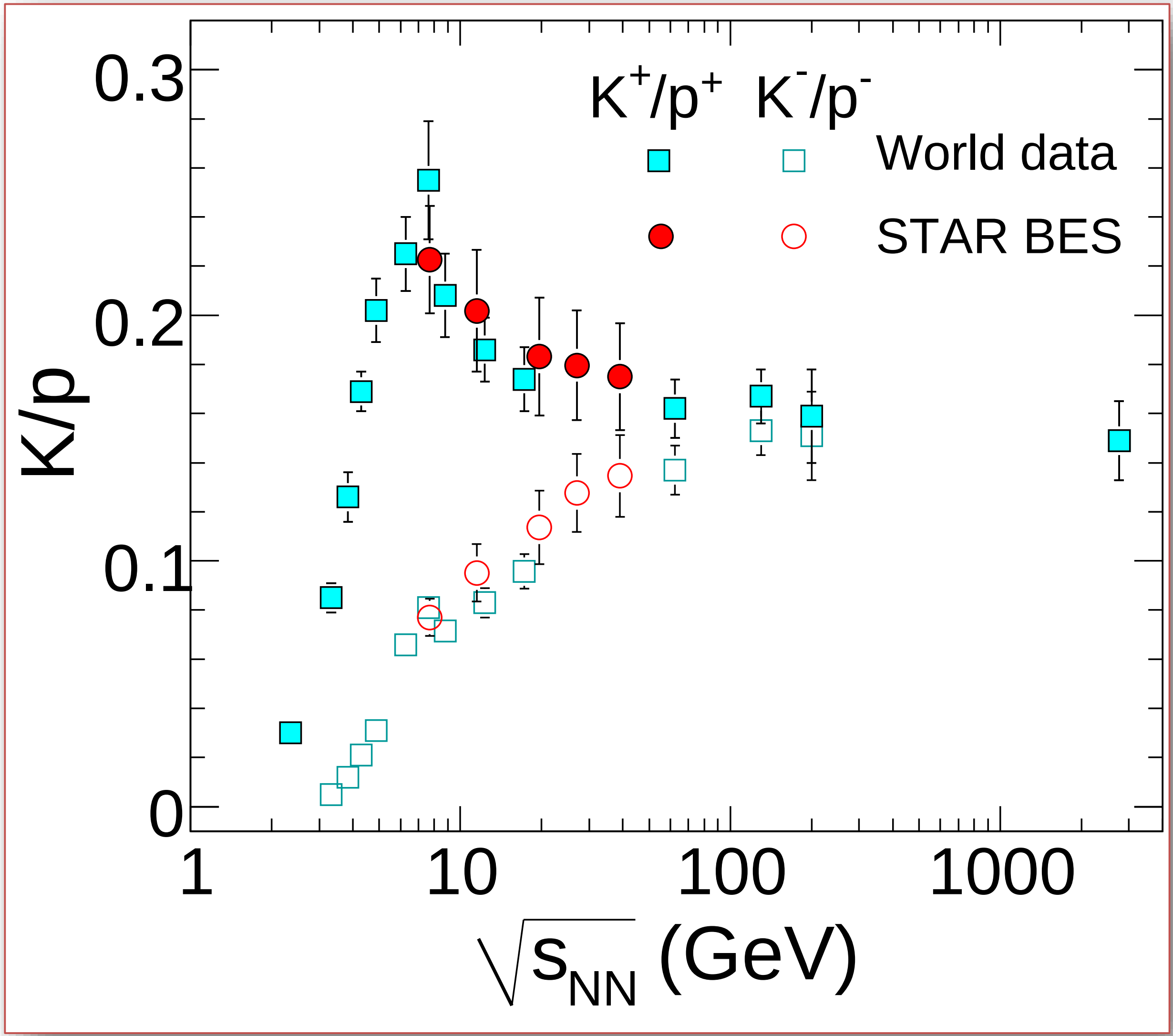
Particle Ratios



✓ Anti-particle to particle ratio at mid rapidity in central heavy-ion collisions as a function of collision energy

STAR: arXiv: 1701.07065

Particle Ratios



✓ Energy dependence of Kaon to pion ratio at mid-rapidity in central heavy-ion collisions

STAR: arXiv: 1701.07065 and reference therein

Freeze-out Dynamics

- ✓ Chemical Freeze-out
- ✓ Kinetic Freeze-out

Tests of thermal statistical models

Chemical Freeze-out Dynamics

Definition:
Inelastic collisions ceases
Chemical composition or
Particle ratios get fixed

Statistical Thermal Model

$$\ln Z^{GC}(T, V, \{\mu_i\}) = \sum_{\text{species i}} \frac{g_i V}{(2\pi)^3} \int d^3p \ln(1 \pm e^{-\beta(E_i - \mu_i)})^{\pm 1}$$

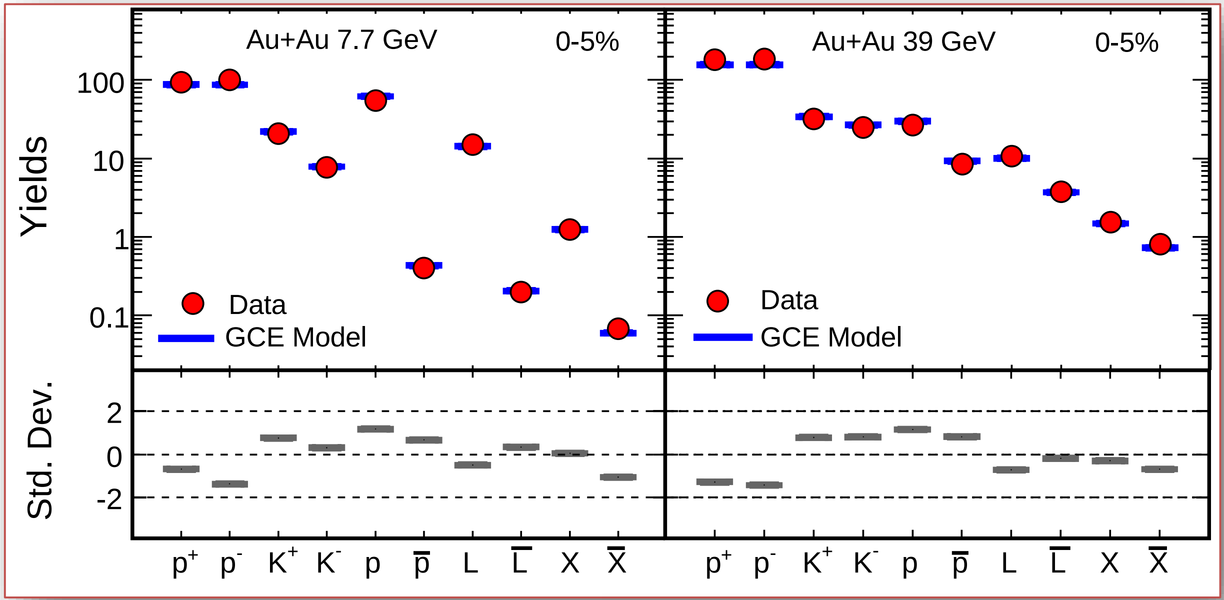
Particle Abundances: Grand Canonical Ensemble

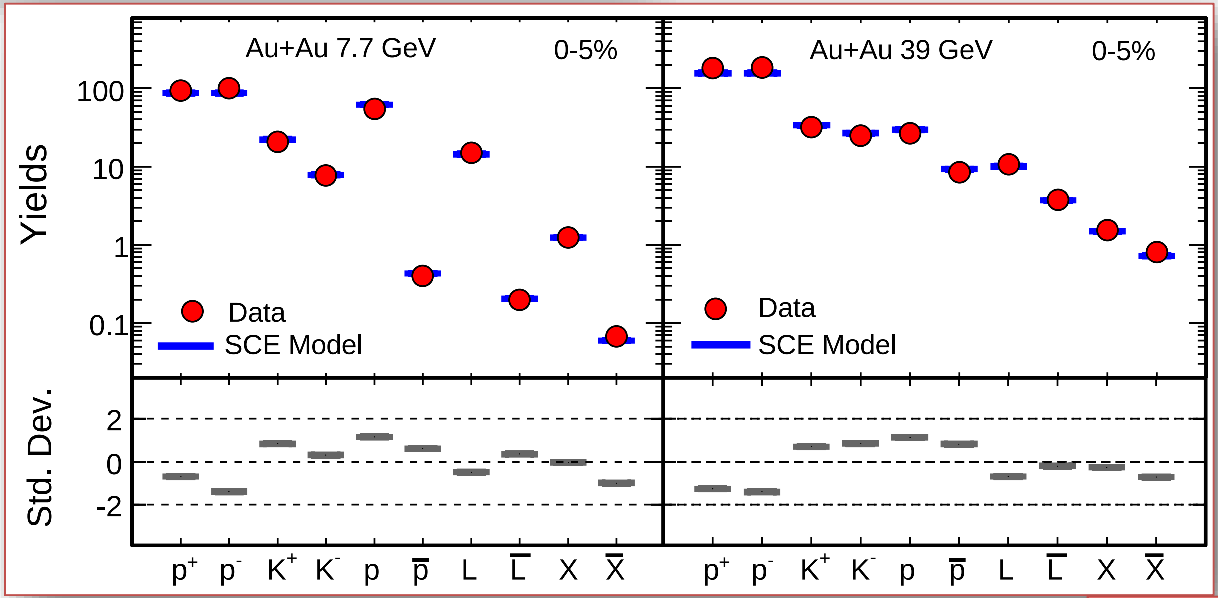
$$N_i^{GC} = T\frac{\partial \ln Z^{GC}}{\partial \mu_i} = \frac{g_i V}{2\pi^2} \sum_{k=1}^{\infty} (\mp 1)^{k+1} \frac{m_i^2 T}{k} K_2\left(\frac{k m_i}{T}\right) \times e^{\beta k \mu_i}$$

Model Features:
- ❑ Assumes non-interacting hadrons and resonances
- ❑ Assumes thermodynamically equilibrium system
- ❑ Ensembles : Grand Canonical - average conservation of B, S, and Q
  Strangeness Canonical - exact conservation of S
  Canonical - exact conservation of B, S, and Q

Dynamics Characterized by:
Temperature T_{ch} and baryon chemical potential μ_B

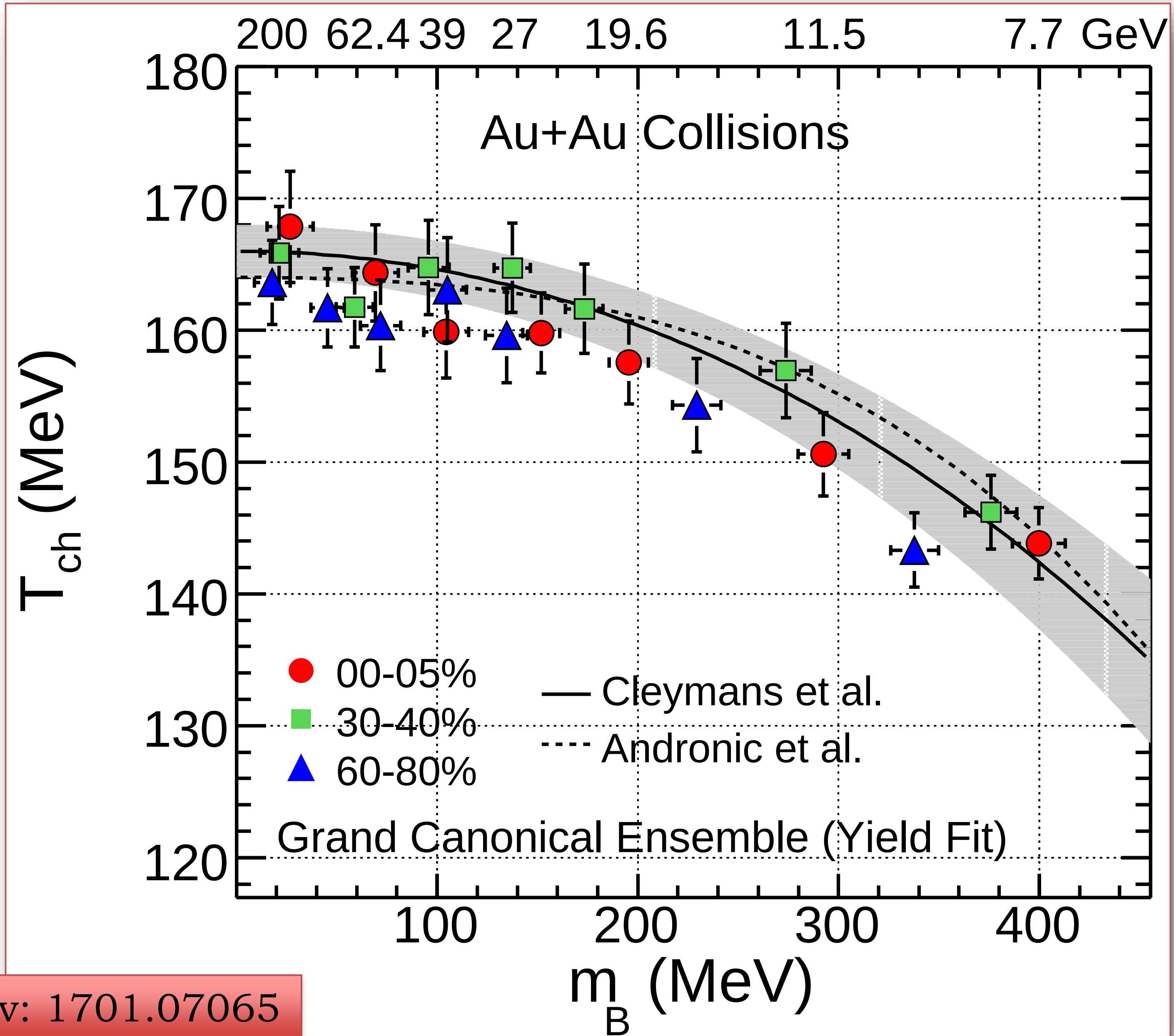
Chemical Freeze-out:Data vs. Model





STAR: arXiv: 1701.07065

Chemical Freeze-out: T vs. μ_B



STAR: arXiv: 1701.07065

Kinetic Freeze-out Dynamics

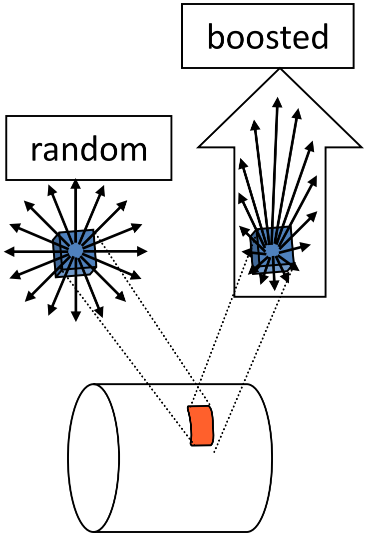
Definition:
Elastic collisions ceases
Momentum distribution
of particles get fixed

Blast Wave Model

$$E\frac{d^3N}{dp^3} \propto \int_\sigma e^{-(u^\mu p_\mu)/T_{fo}}\, p\, d\sigma_\mu$$

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

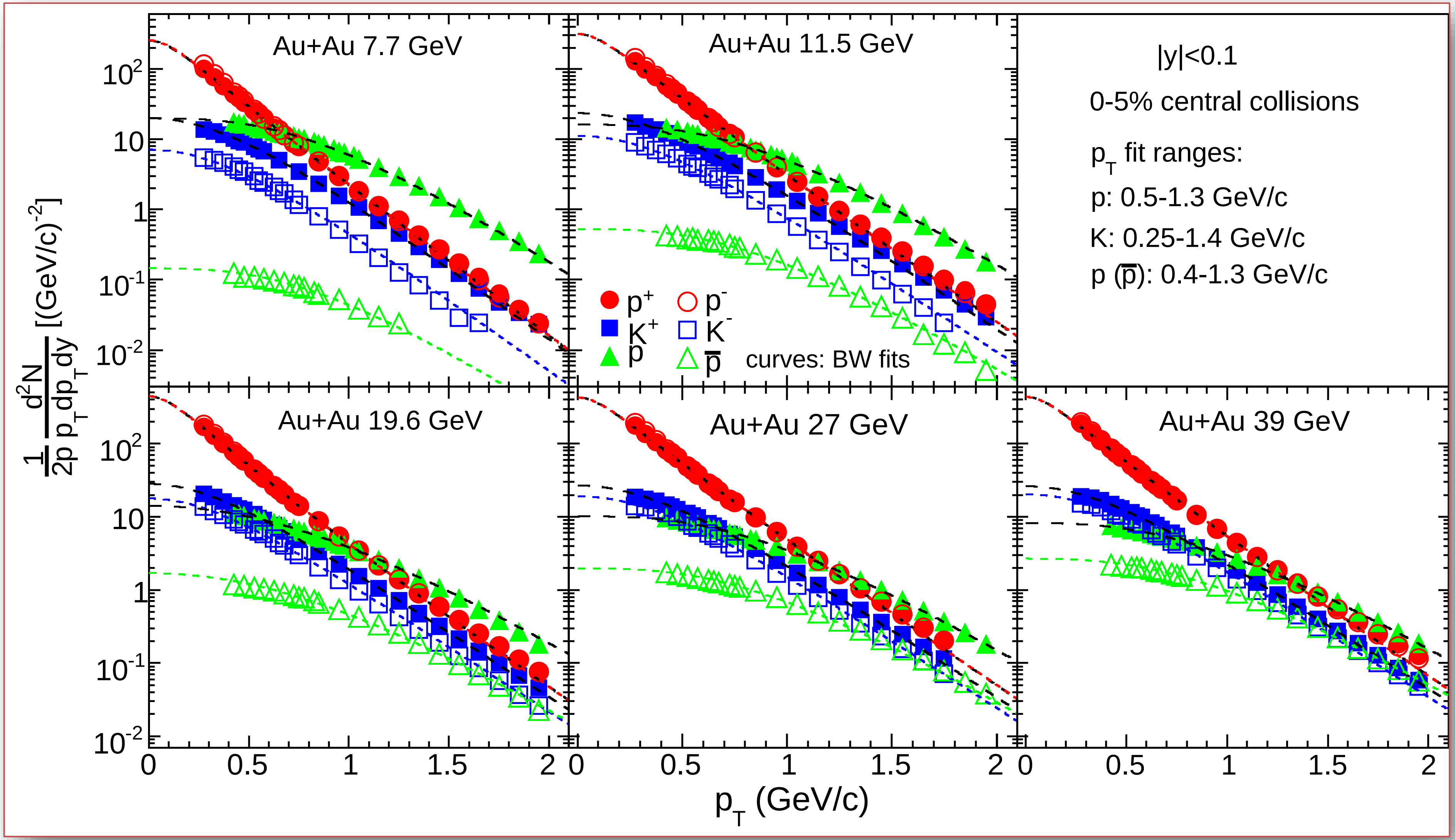
$\rho = \tanh^{-1}\beta_T$ $\quad$ $\beta_T = \beta_S\left(\frac{r}{R}\right)^{\alpha}$ $\quad$ $\alpha = 0.5,\ 1,\ 2$



Source is **assumed** to be:
- Locally thermally equilibrated
- Boosted in radial direction

Dynamics Characterized by:
Thermal temperature T_{fo} and velocity parameter $\langle\beta_T\rangle$

Kinetic Freeze-out: BW Model



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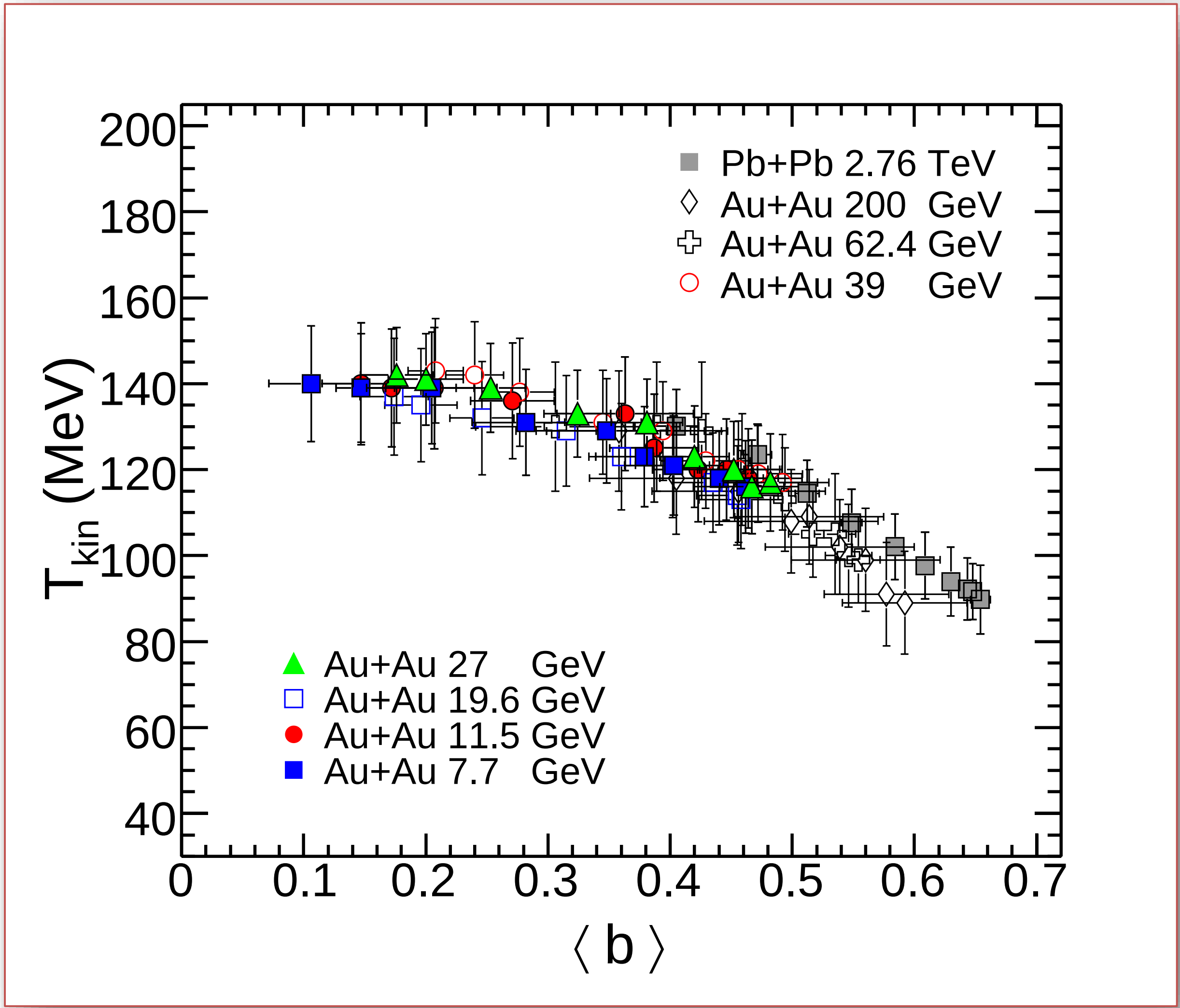
Kinetic Freeze-out: Parameters

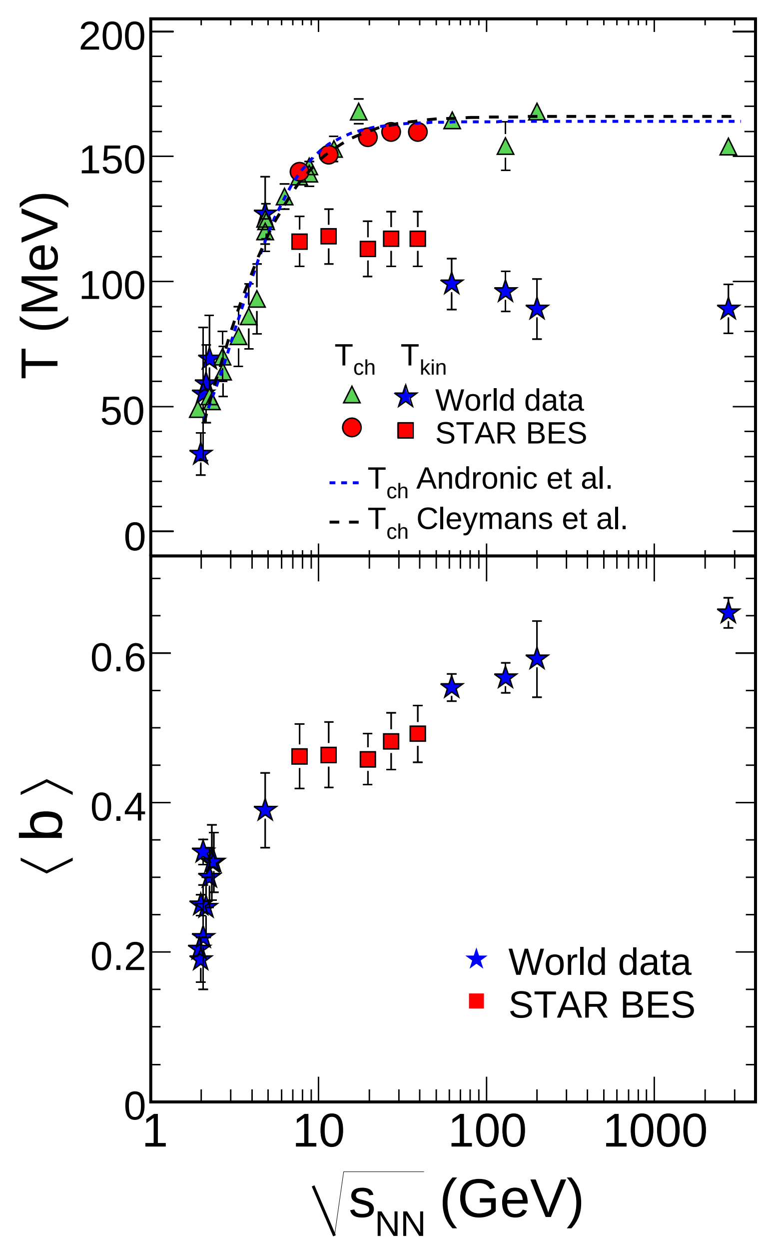
ALICE:
Phys.Rev. C88 (2013) 044910



- ✓ **Anti-correlations:** T_{fo} vs. $\langle \beta_T \rangle$
- ✓ More collectivity in central collisions vs. peripheral collisions
- ✓ Lower temperature at higher energies and central collisions

STAR: arXiv: 1701.07065

Summary : Freeze-out Dynamics



- ✓ Collectivity increases with beam energy for central collisions
- ✓ Chemical Freeze-out temperature increases and then saturates with beam energy
- ✓ Kinetic Freeze-out temperature decreases with beam energy for central collisions
- ✓ Gap between chemical and kinetic freeze-out temperatures increases with beam energy

Suggests system interacts for longer duration in higher energy collisions

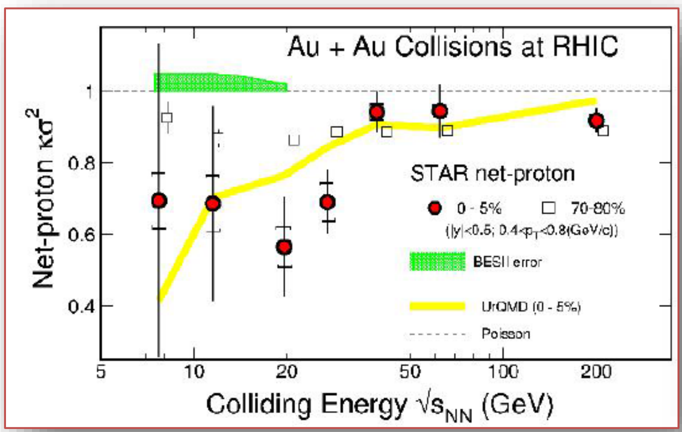
STAR: arXiv: 1701.07065

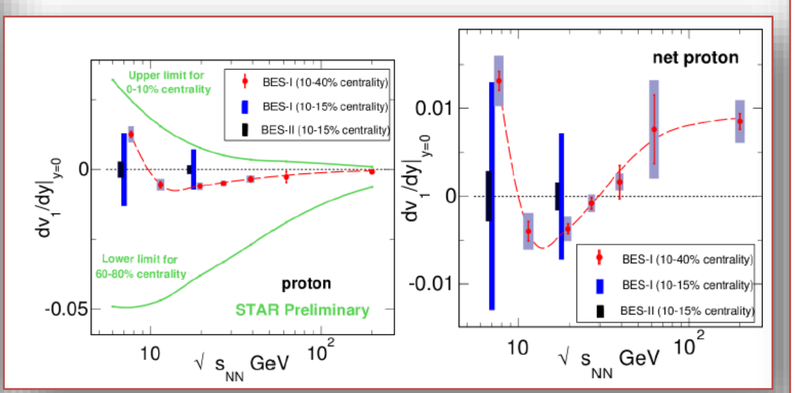
RHIC-BES Phase-II Detector Upgrades

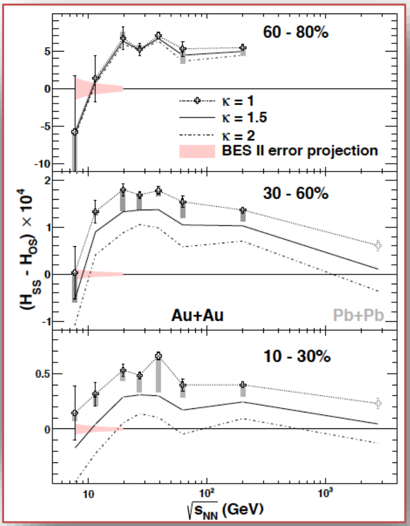
Better acceptance for the STAR TPC in rapidity and p_T (low momentum and $|\eta| < 1.5$)

Centrality determination and Event Plane determination: EPD - $2 < |\eta| < 4$

Trigger performance ~ factor of 10 improvement expected







SN0598 : Studying the Phase Diagram of QCD Matter at RHIC : https://drupal.star.bnl.gov/STAR/files/BES_WPII_ver6.9_Cover.pdf

RHIC-BES Phase-II

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	–		160	125	92
Elliptic Flow (ϕ mesons)	100	150	200	200	400
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	50	75	100	100	200
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	80	100	120	200	400
Dileptons	100	160	230	300	400
Required Number of Events	**100**	**160**	**230**	**300**	**400**

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% Central Collisions	420	370	315	260	205
BES-I (Million Events)	4	–	12	20	36
BES-I Event Rate (Million Events/Day)	0.25	0.6	1.7	2.4	4.5
BES-I Int. Luminosity (1×10^{25}/cm^2 s)	0.13	0.5	1.5	2.1	4.0
e-Cooling Luminosity Improvement Factor	4	4	4	8	15(4)
BES Phase-II (Million Events)	100	160	230	300	400
Required Beam Time (Weeks)	14	9.5	5.0	2.5	4.0+

RHIC – Fixed Target Program

Collider Energy	Fixed-Target Energy	Single beam AGeV	Center-of-mass Rapidity	μ_B (MeV)
62.4	7.7	30.3	2.10	420
39	6.2	18.6	1.87	487
27	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	721
5.0	2.5	1.6	0.82	774

D. Cebra: INT Program INT-16-3: Exploring the QCD Phase Diagram through Energy Scans