Dedicated to the 90th anniversary of Academician A.M. Baldin

Recent STAR Heavy Ion Results

M.Tokarev
JINR, Dubna, Russia

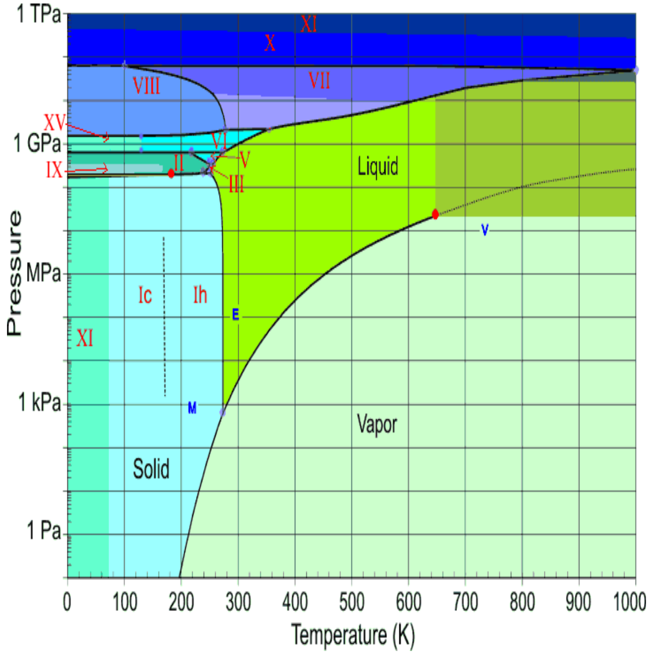
for the STAR Collaboration

Outline:

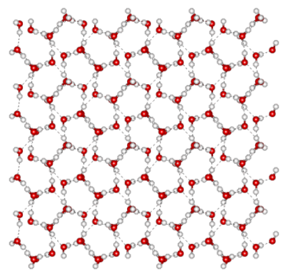
- Introduction
- STAR detector system
- Recent results from HIC at STAR
- Summary and Outlook

Phase Diagram of Matter

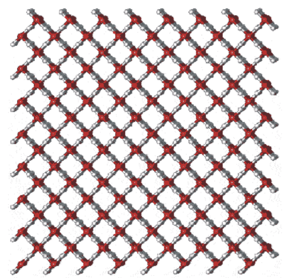
The phase diagram
of the water is established



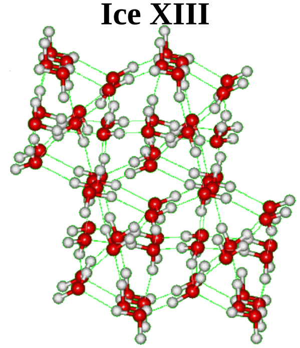
Ice III



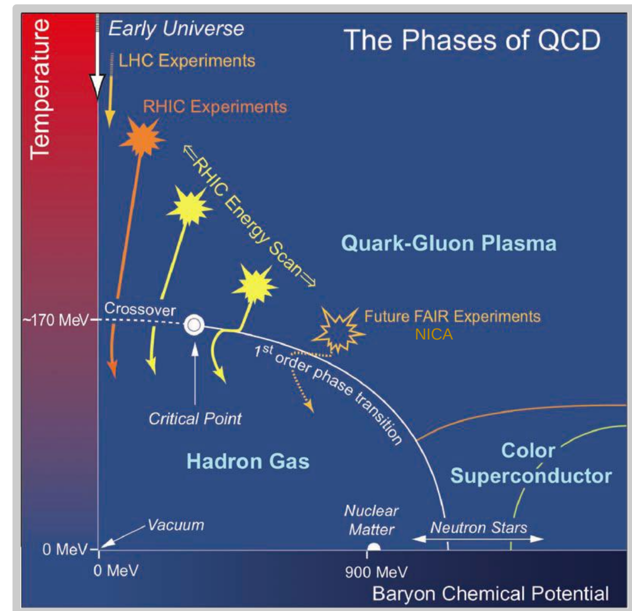
Ice X



Ice XIII



The phase diagram
of the nuclear matter is under study



- Phases (ice I-XV, liquid, vapor)
- Phase boundaries
- Phase transitions
- Triple Point (16)
- Critical Point (2)

- Phases
- Phase boundaries
- Phase transitions
- Triple Point
- Critical Point

The Relativistic Heavy Ion Collider

Commissioning 1999

- 3.83 km circumference
- Two separated rings
  120 bunches/ring
  106 ns bunch crossing time
- A+A, p+A, p+p
- Maximum Beam Energy :
  500 GeV for p+p
  200A GeV for Au+Au
- Luminosity
  Au+Au: 2 x 10^{26} cm^{-2} s^{-1}
  p+p : 2 x 10^{32} cm^{-2} s^{-1}
- Beam polarizations
  P=70%

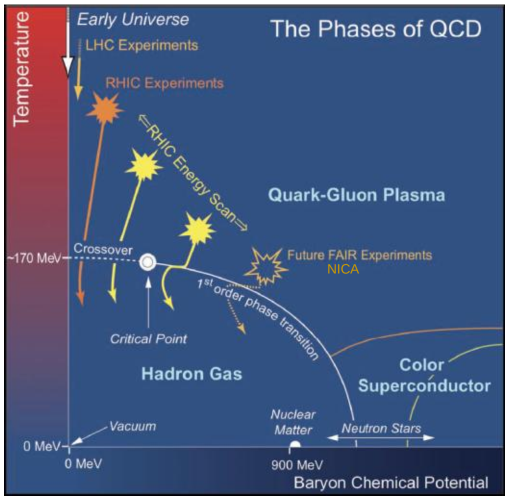
Nucleus-nucleus collisions (AuAu, CuCu, dAu, CuAu, UU, … $\sqrt{s_{NN}}$ =7.7-200 GeV)

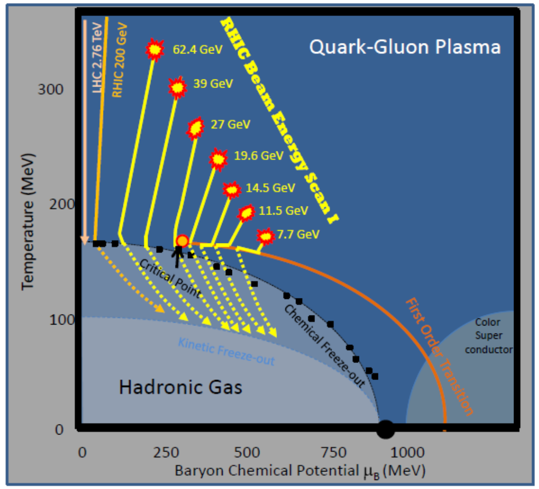
Polarized proton-proton collisions $\sqrt{s}$ =62.4,200,510 GeV

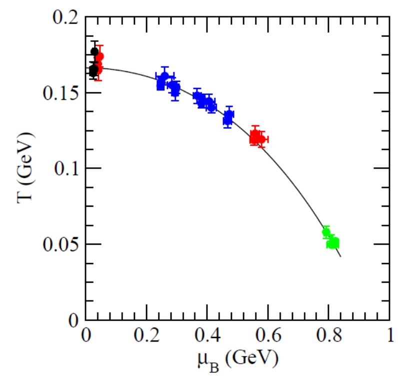
RHIC is uniquely suited to map the QCD phase diagram at finite baryon density

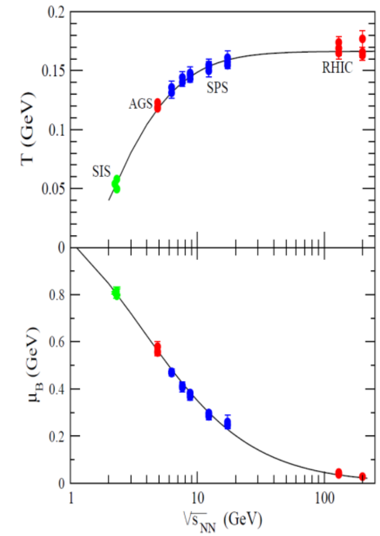
Explore the QCD phase diagram

Vary collision energy to change temperature and baryon chemical potential









- Search for turn-off of signatures of sQGP.
- Search for 1st order phase transition from partonic to hadronic phase.
- Search for possible critical point.

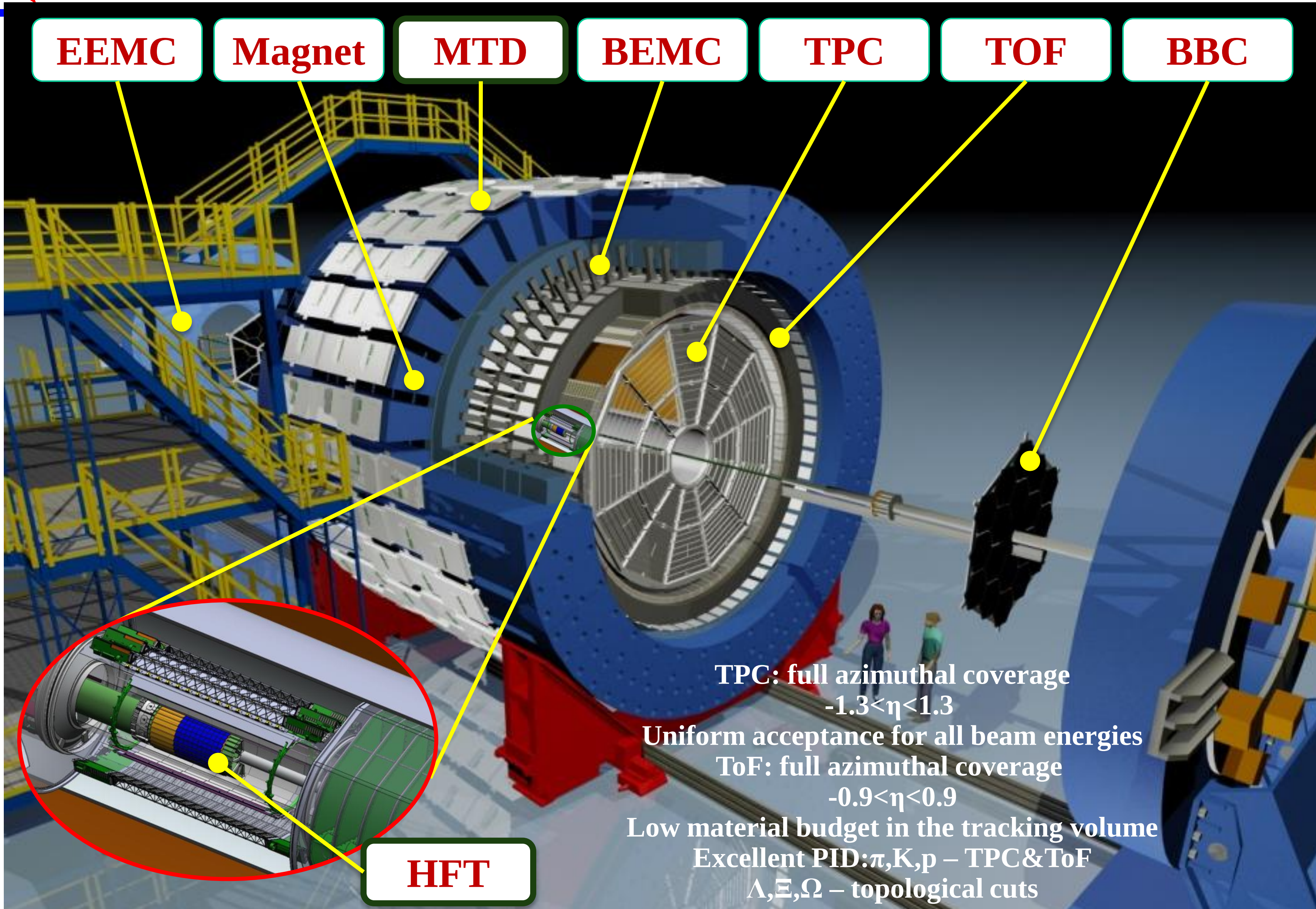
Resonance gas model with free particle dispersion relations for all constituents: mesonic, baryonic and resonance degrees of freedom.

STAR white paper
"Studying the Phase Diagram of QCD Matter at RHIC"
STAR Note SN0493, Phys. Rev. C 81, 024911 (2010)

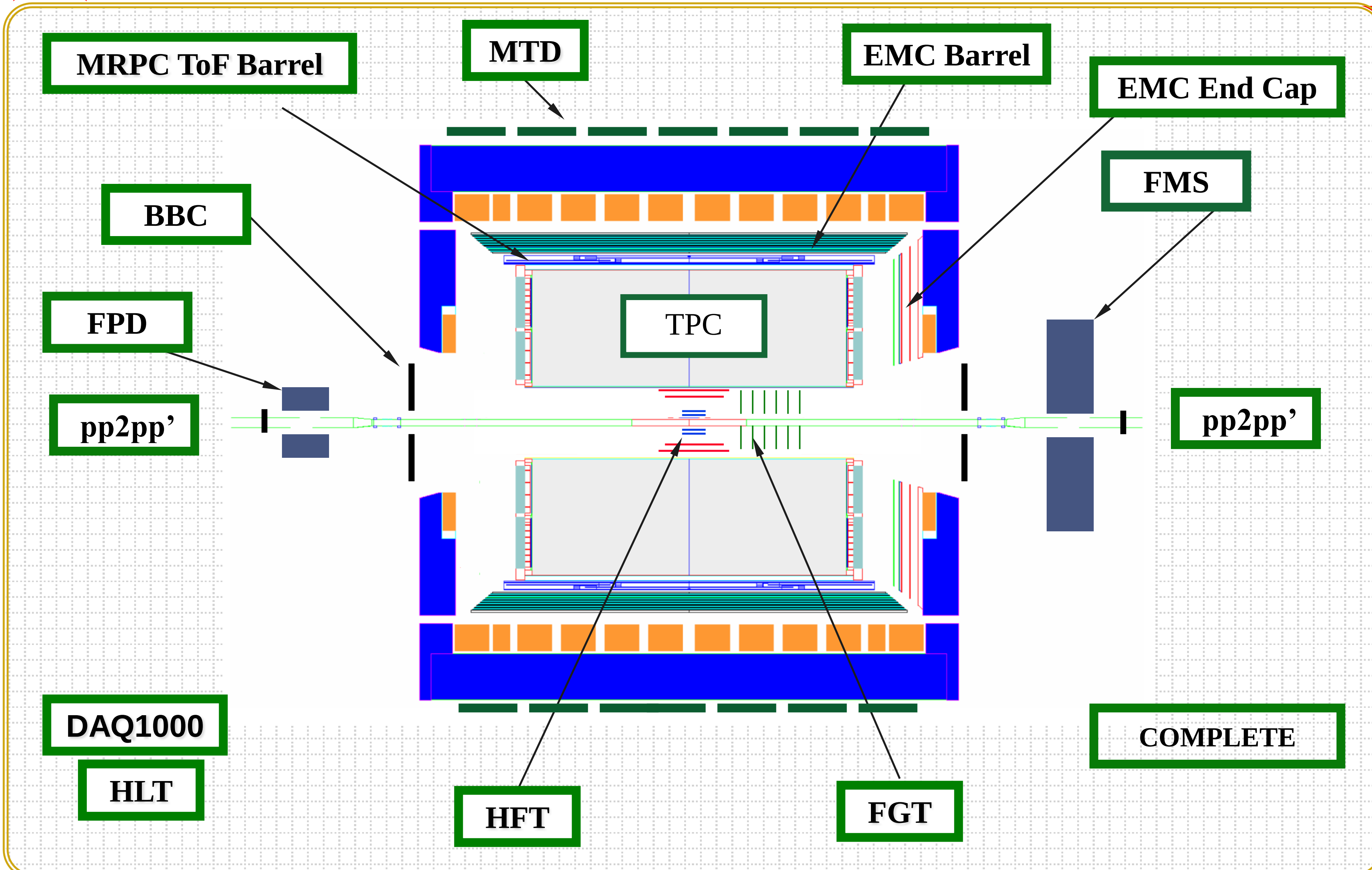
J. Cleymans et al.
Phys. Rev. C73, 034905

STAR detector at RHIC

The Solenoidal Tracker At RHIC (STAR)

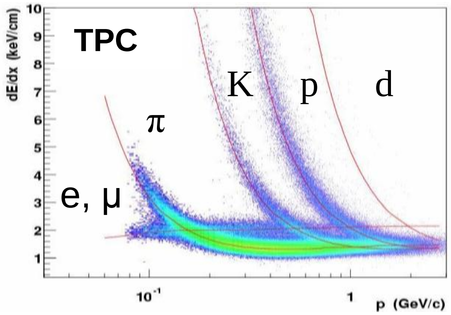


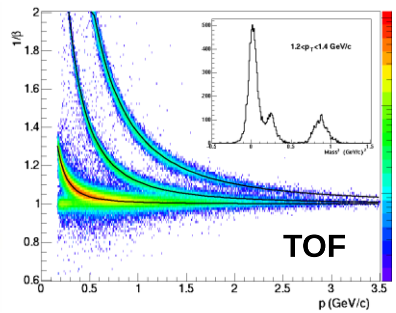
STAR Detector



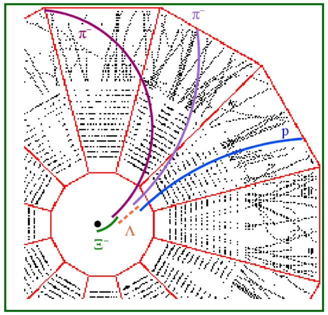
STAR

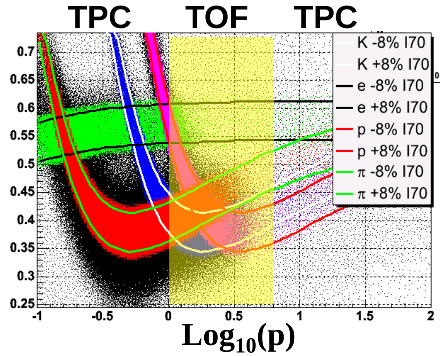
Particle Identification at STAR



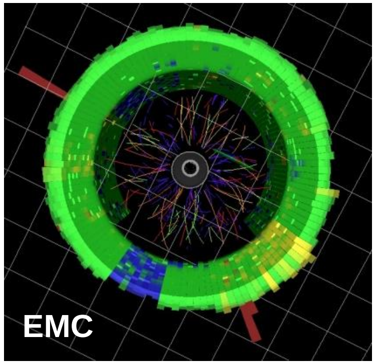


Charged hadrons

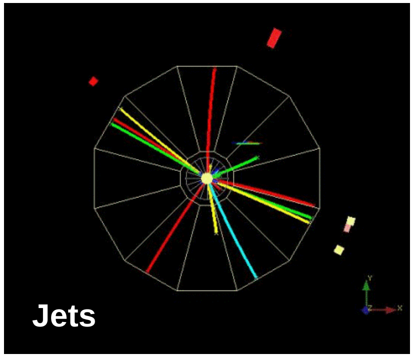




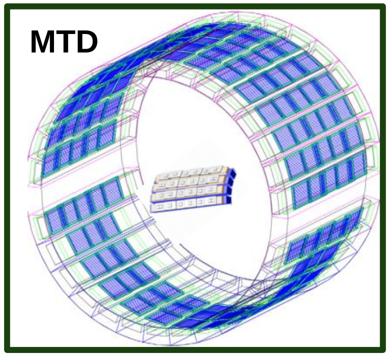
Hyperons & Hyper-nuclei



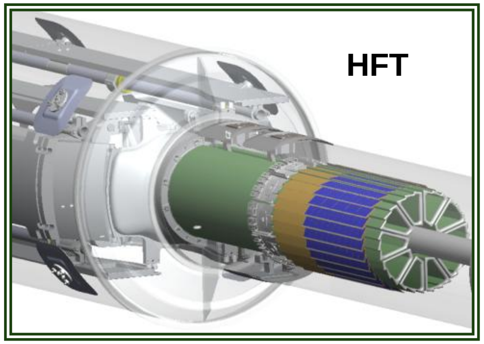
Neutral particles



Jets & Correlations



High p_T muons



Heavy-flavor hadrons

Wide acceptance and excellent particle identification

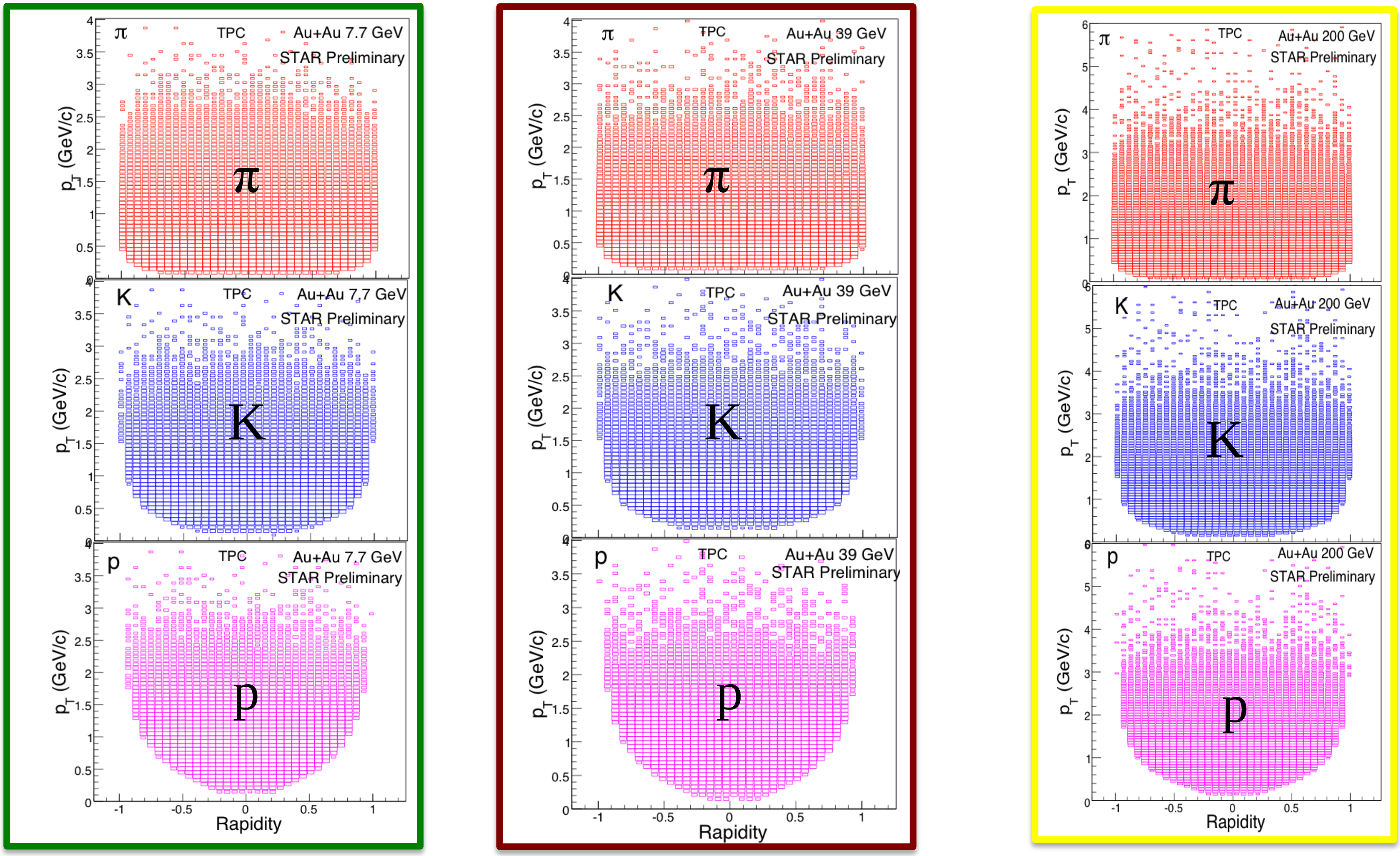
Multi-fold correlations for identified particles

Identified Particle Acceptance at STAR

Au+Au 7.7 GeV

Au+Au 39 GeV

Au+Au 200 GeV

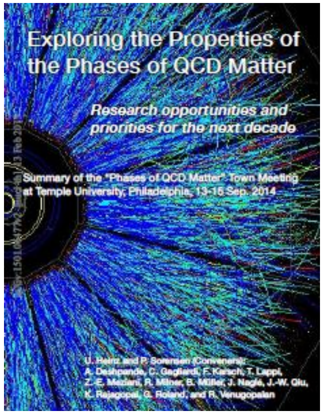


Homogeneous acceptance for all energies

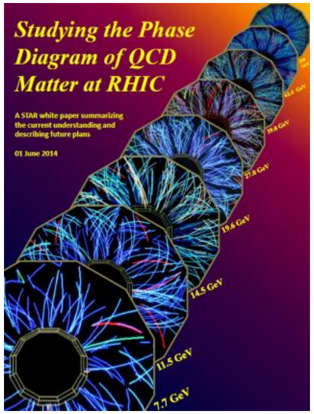
Phase structure of QCD matter
is experimentally studied at SPS, RHIC and LHC

Dense, strongly-coupled matter and an almost perfect liquid with partonic collectivity has been created in HIC at RHIC.

STAR, PHENIX, PHOBOS, BRAHMS - White papers - Nucl. Phys. A757 (2005)



Experimental results from the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) support the hypothesis that a strongly-coupled nuclear medium with partonic degrees of freedom, namely the Quark-Gluon Plasma (QGP), is created in heavy-ion collisions at high energy.



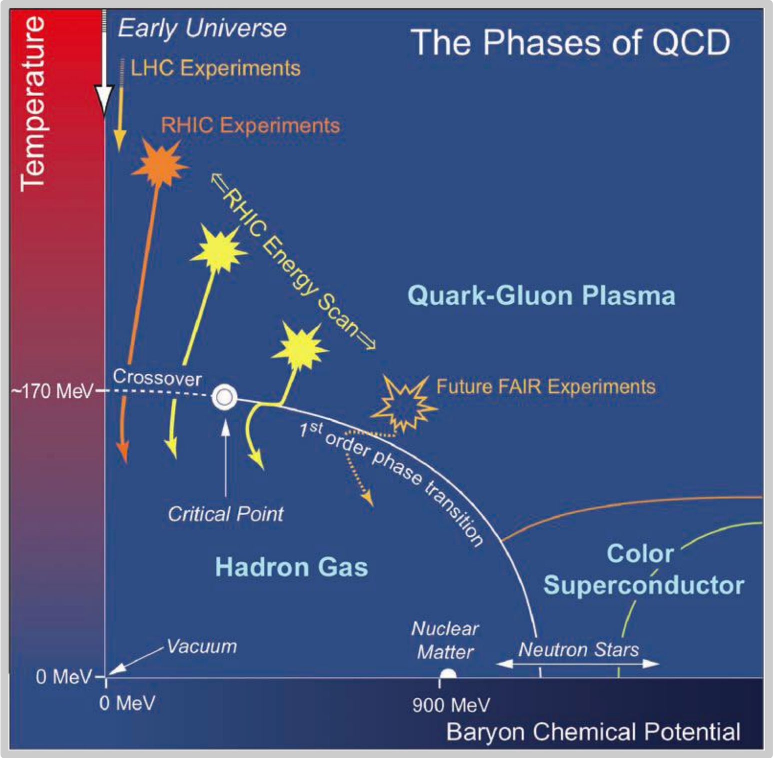
"Exploring the Properties of the Phases of QCD Matter" – arXive:1501.06477
"The Hot QCD White Paper: Exploring the Phases of QCD at RHIC and the LHC" – arXiv:1502.02730

Nuclear matter at RHIC

Extreme conditions reached in heavy ion collisions:

- high multiplicity density ($dN_{ch}/d\eta \approx 700$)
- high energy density ($\varepsilon_{Bj} \approx$4-5 GeV/fm^3)
- various types of particles (π,K,…, Ω,…)
- light (anti)nuclei, (anti)hypernuclei (d,t, He,..)

STAR Beam Energy Scan-I at RHIC



Systematic Study QCD Phase Structure

- Onset of sQGP
- Phase boundary and critical point
- Chrial symmetry restoration

Observables:

1st order phase transition
(1) Azimuthally sensitive HBT
(2) Directed flow v_1

Partonic vs. hadronic dof
(3) R_{AA}: nucl. mod. factor
(4) Charge separation
(5) v_2 - NCQ scaling

Critical point, correl. length
(6) Fluctuations

Chiral symmetry restoration
(7) Di-lepton production

BES-I: $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39 GeV

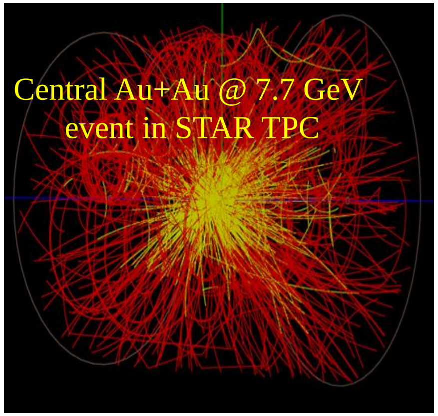
STAR Beam Energy Scan Phase I - completed !

Main focus of RHIC

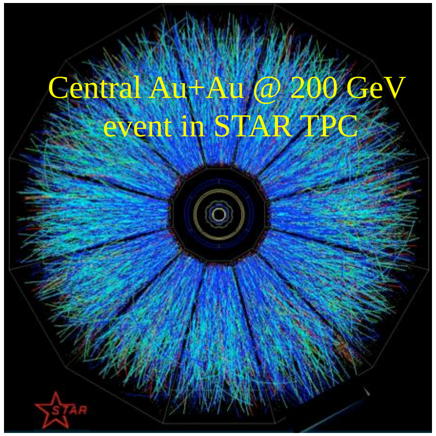
- signatures for a phase transition
- signatures for a critical point
- boundary of phase diagram

Almost equidistant steps in T_{ch}–μ_B plane

AuAu @ 7.7, 11.5, 14.5, 19.6, 27, 39 GeV + 62 & 200 GeV

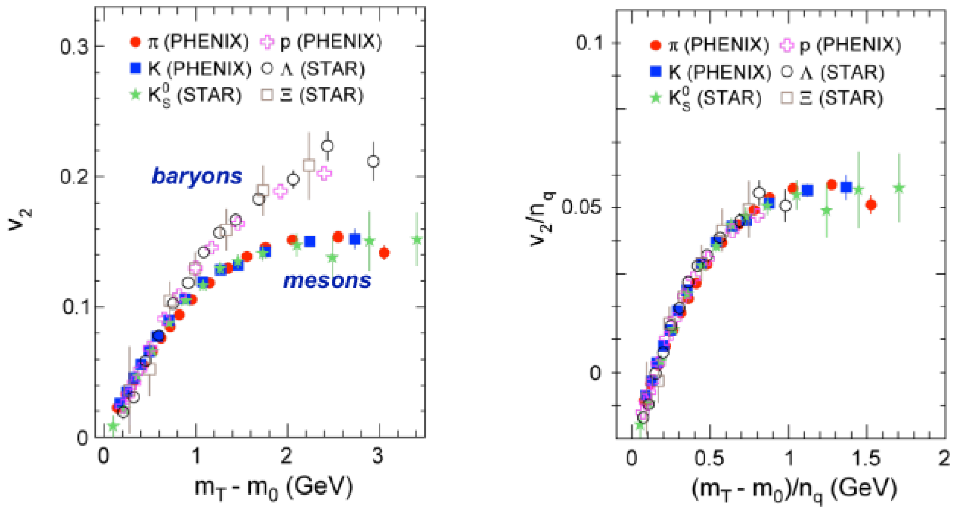


$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	T (MeV)	nEvents (M) MB
7.7	420	140	4
11.5	315	152	12
14.5	260	156	20
19.6	205	160	36
27	155	163	70
39	115	164	130
62.4	70	165	67
200	20	166	350



Flow of nuclear matter

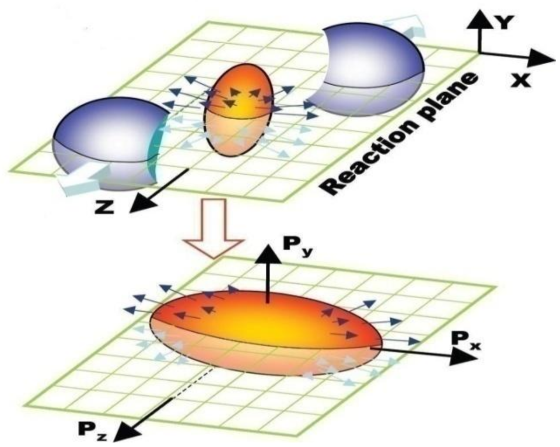
Collectivity of partonic degrees of freedom
Number-of-Constituent Quark Scaling



Quark coalescence in the strongly interacting medium of quarks and gluons formed in heavy-ion collisions

STAR: Phys.Rev.Lett. 95 (2005) 122301
PHENIX: Phys.Rev.Lett. 98 (2007) 162301

Directed (v_1) & Elliptic (v_2) flow in AuAu



Coordinate-Space Anisotropy

↓

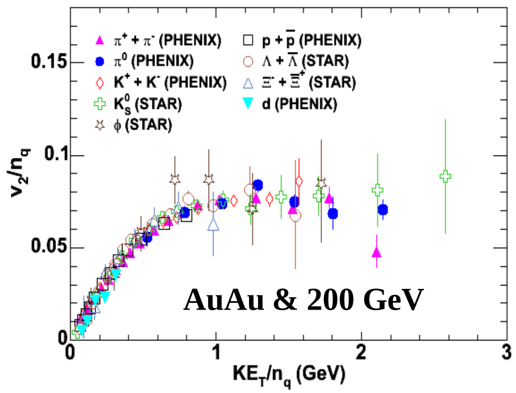
Momentum-Space Anisotropy

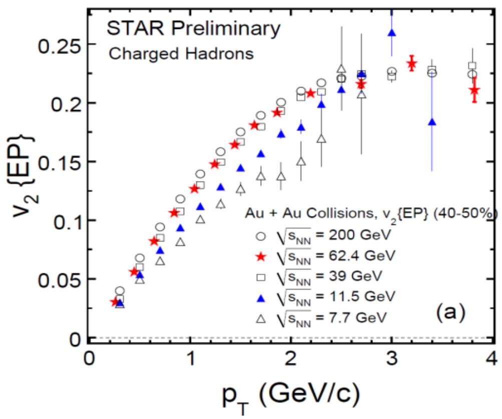
Fourier expansion of the momenta distribution

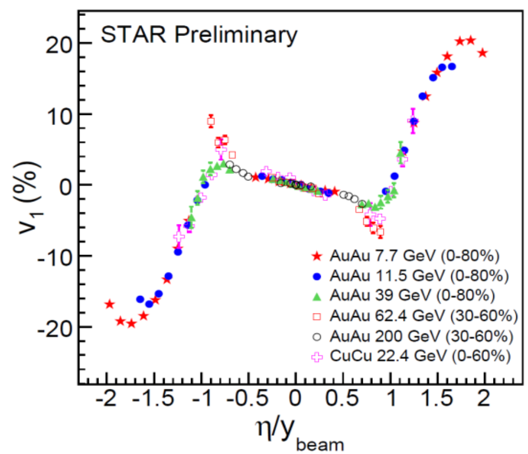
$$E\frac{d^3N}{dp^3} \propto \left(1+\sum_{n=1}^{\infty} 2v_n \cos n(\varphi-\Psi_r)\right)$$

$$v_n = \langle \cos n(\varphi-\Psi_r) \rangle$$

$$\varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$





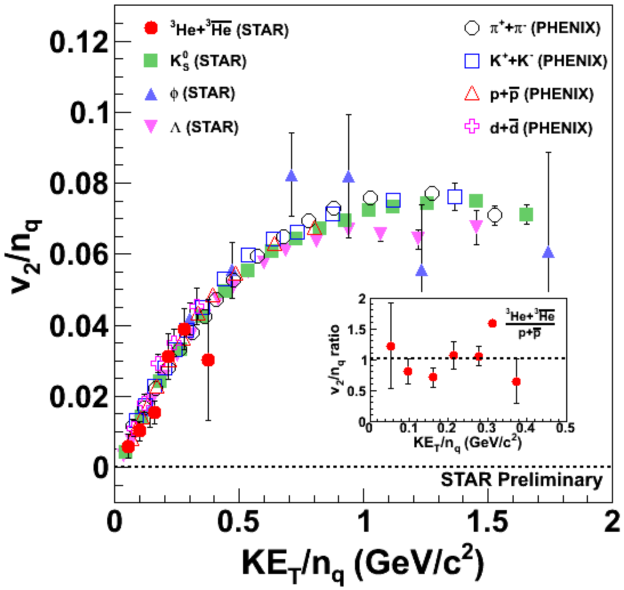


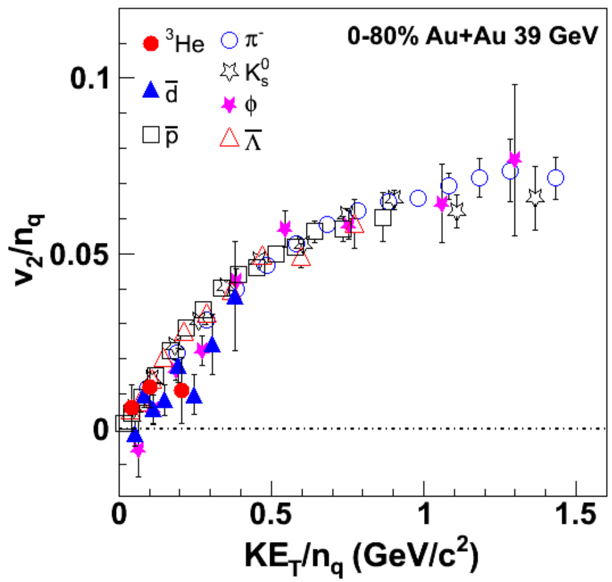
- v_1 (y) sensitive to baryon transport, space momentum correlations and QGP formation.
- v_2 provides the possibility to gain information about the degree of thermalization of the hot, dense medium.
- The breaking of v_2 number of quark scaling will indicate a transition from partonic to hadronic degrees of freedom.

L. Kumar (STAR), ICPAQGP 2010

NCQ scaling: Au+Au 200 & 39 GeV

Flow vs. energy, centrality, particle mass





v_2 of light nuclei scaled to the number of constituent quarks (NCQ) of their constituent nucleons, are consistent with NCQ scaled v_2 of baryons and mesons

NCQ scaling holds good for v_2 of light nuclei in Au+Au 39 GeV

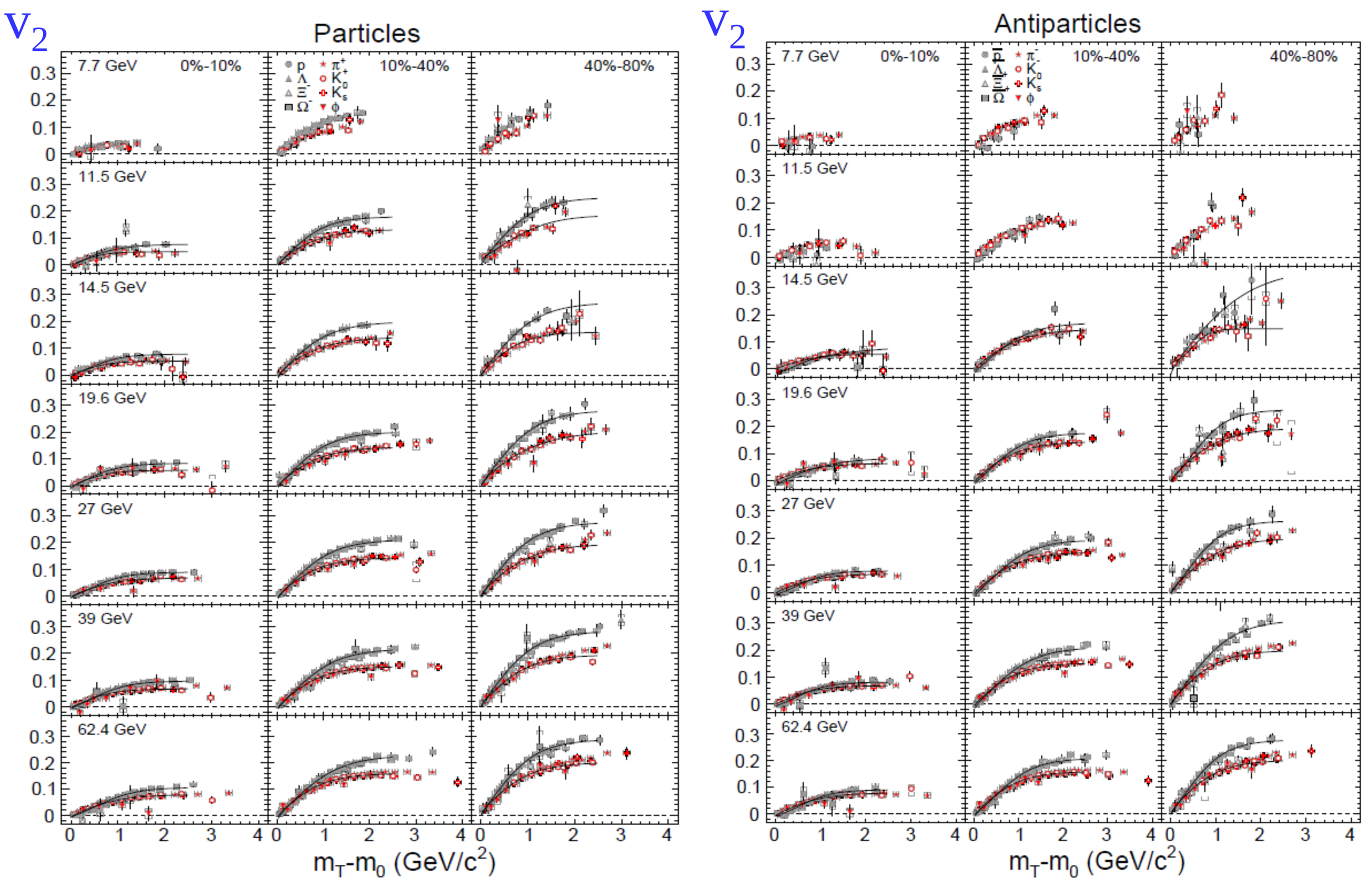
L.Kumar (STAR), ICPAQGP 2010 C.Jena (STAR), ICPAQGP 2010 A. Schmah (STAR), QM 2011

Elliptic flow of identied particles in Au+Au

$$\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4\,\text{GeV}$$

STAR
Phys. Rev. C93 (2016) 014907

$$\pi^-, \pi^+, K^-, K^+, K^0_S, p, \bar{p}, \varphi, \Lambda, \bar{\Lambda}, \Xi^-, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+$$



Dependence of v_2 on
- collision energy
- centrality
- transverse momentum

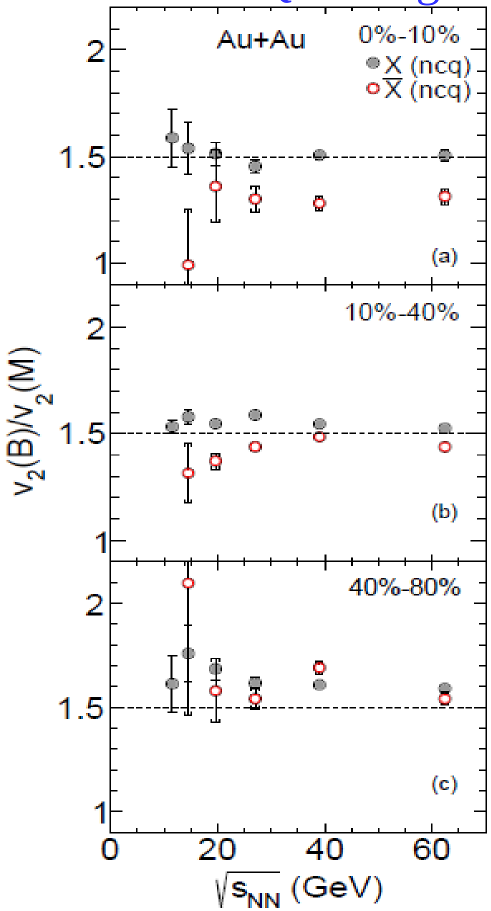
- type of particle
- (anti) particle
- barion-meson spliting
- NCQ scaling

Phys.Rev. C86, 054908 (2012)
Phys.Rev. C88, 014902 (2013)

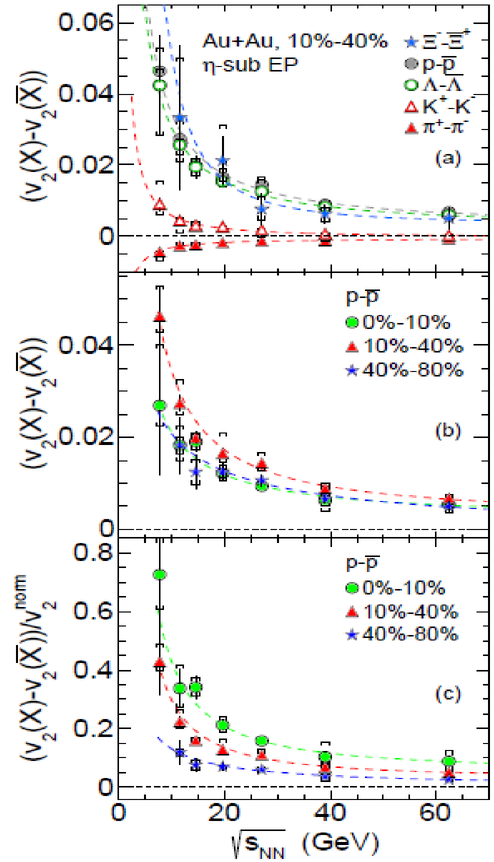
Parton collectivity of the nuclear flow.

NCQ scaling & baryon – meson splitting

NCQ scaling



Difference in v_2 between particle-antiparticle



- $v_2(B)/v_2(M)=3/2$ for perfect NCQ scaling
- Δv_2 increases with decrease in energy.
- Δv_2 relative to proton v_2 (at $p_T = 1.5$ GeV/c) shows a centrality dependence.

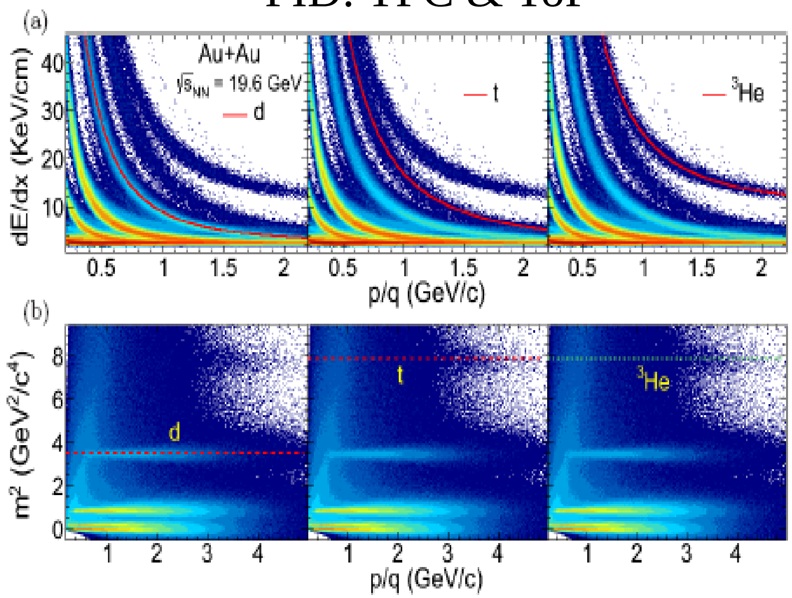
STAR
Phys. Rev. C 93 (2016) 014907
Phys. Rev. Lett. 110 (2013) 142301

Elliptic flow of light nuclei in Au+Au

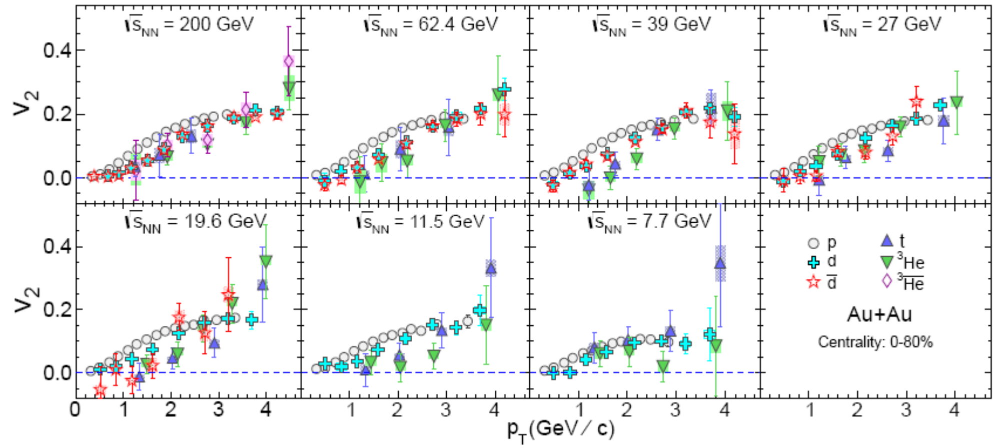
$\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, 62, 200 GeV @ | y|<1.

STAR Collaboration
nucl-ex1601.07052

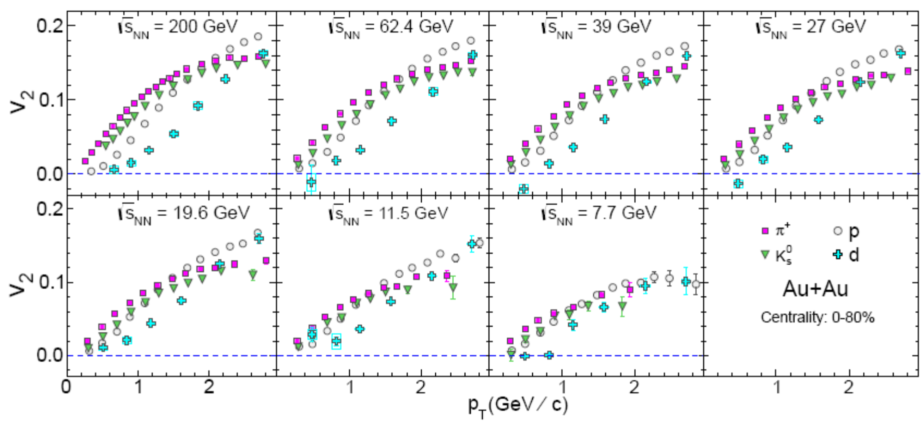
PID: TPC & ToF



$p, d, t, {}^3He$ & $\bar{d}, {}^3\overline{He}$



π, p, K_S^0, d

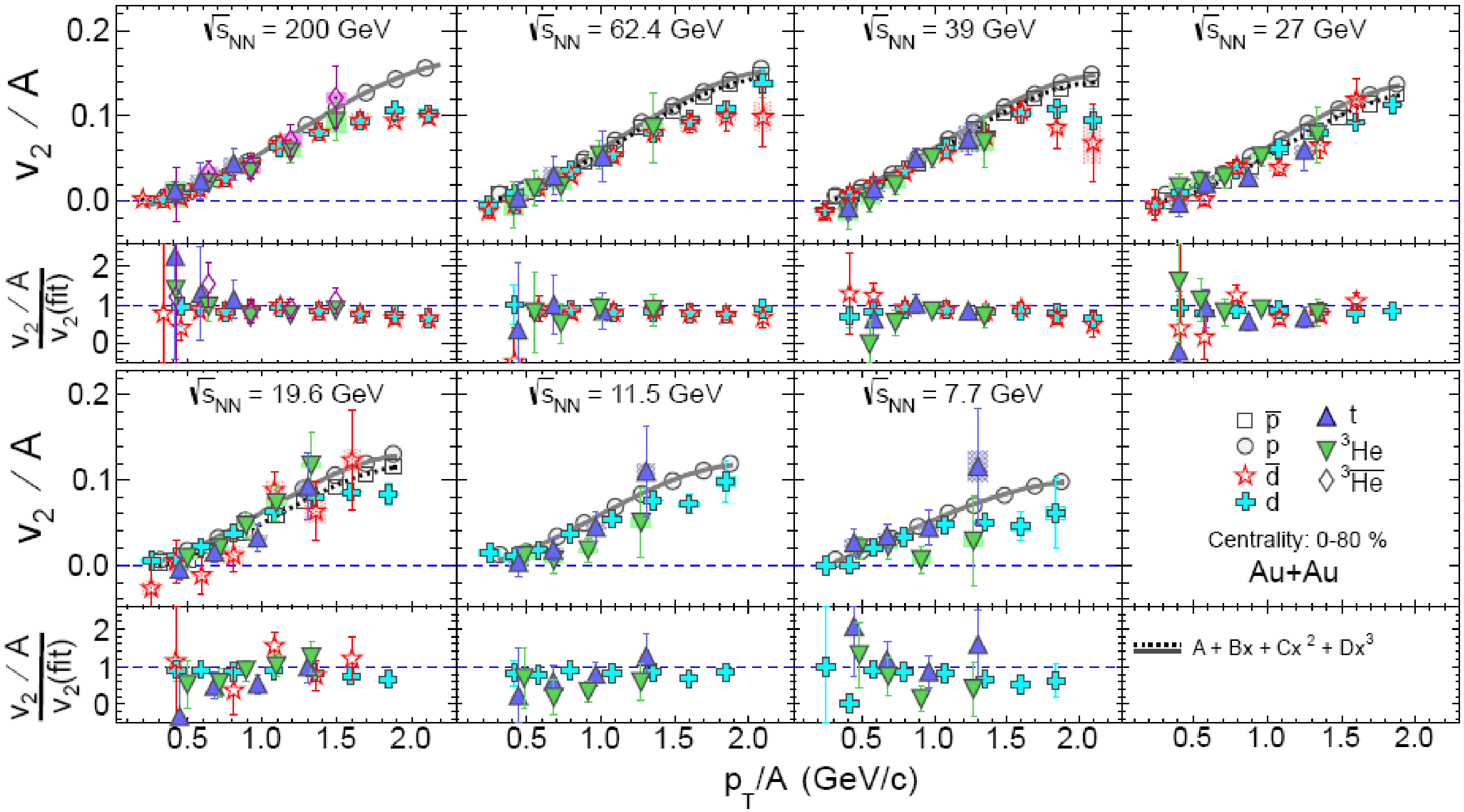


Mechanisms
of light (anti-)nuclei production
via coalescence, transport model,…
- Hadron & Quark DoF
- Quark Number Scaling

Atomic mass number scaling v_2/A

STAR Collaboration
nucl-ex1601.07052

$p, \bar{p}, d, \bar{d}, t, {}^3He, {}^3\overline{He}$ $\sqrt{s_{NN}} = 7.7 - 200\,GeV$



In the collision energy range the light-nuclei production favors the coalescence model.

- Monotonic rise with p_T
- Mass ordering at low p_T
- Reduction for more central collisions

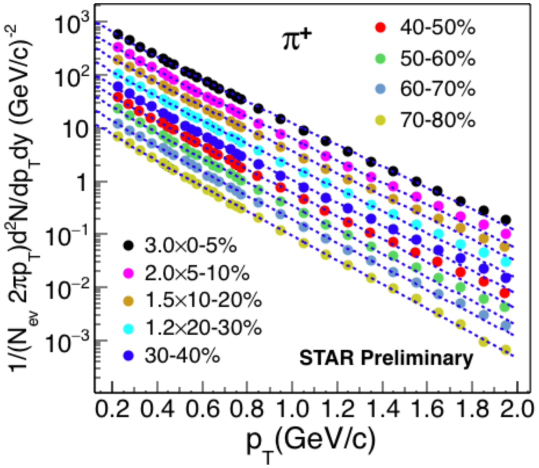
Spectra

probing QCD phase diagram
with identified particles: $\pi^{+/-}$, $K^{+/-}$ and $\bar{p}/p$
in STAR BES-I

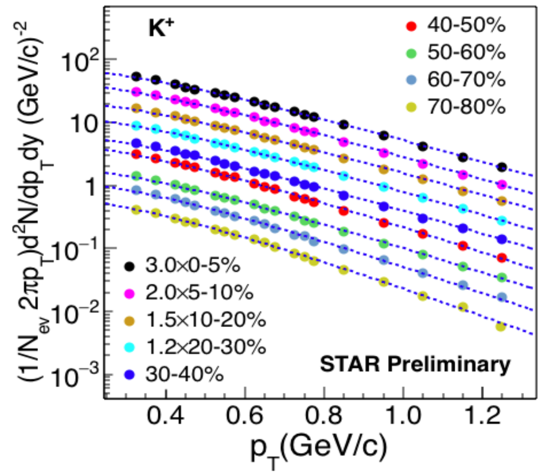
$\pi^{+/-}$, $K^{+/-}$ and $p/\bar{p}$ spectra in Au+Au

Au+Au @ 14.5 GeV

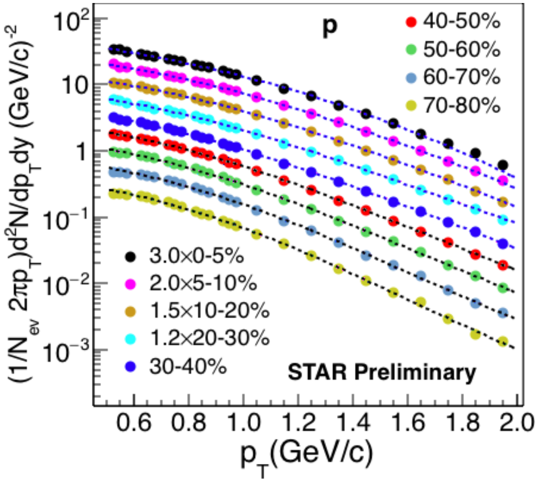
Bose-Einstein fit



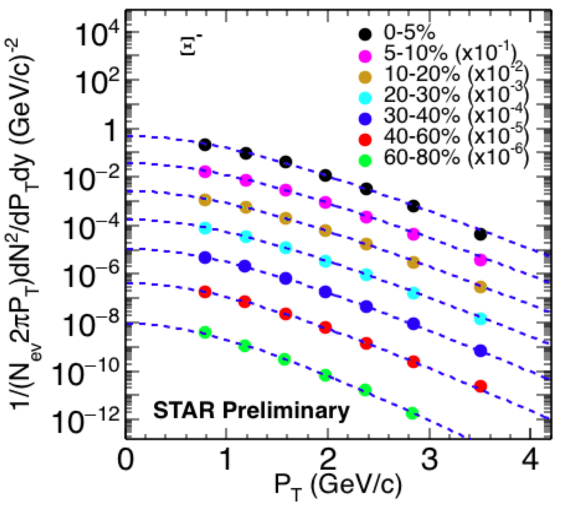
(m_T-m) Exponential fit



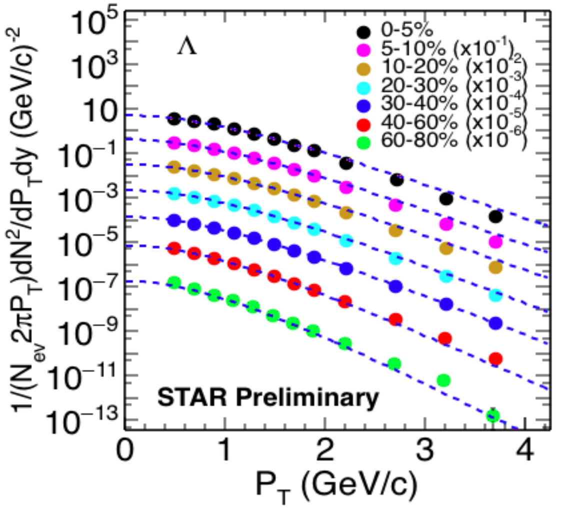
Double Exponential fit



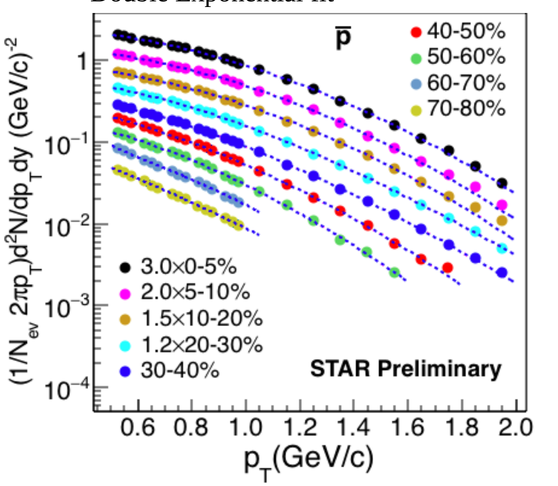
Boltzmann fit



Boltzmann fit



Double Exponential fit

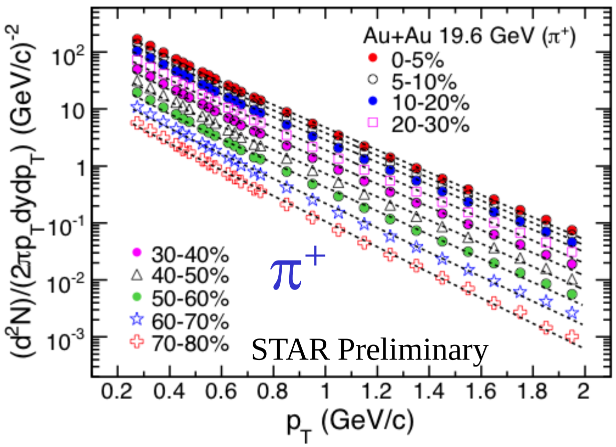


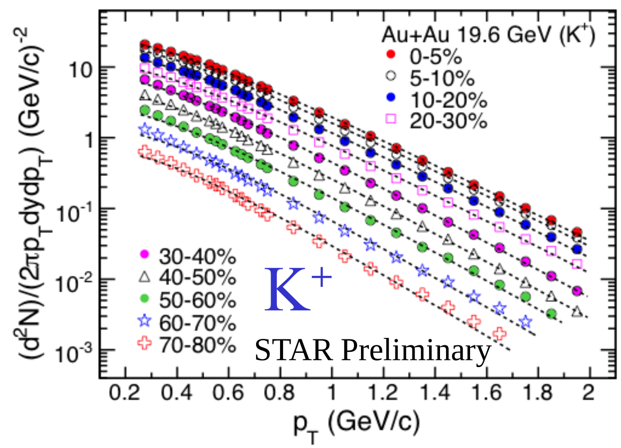
Vipul Bairathi
QM'15, Kobe, Japan, Sept. 27 – Oct. 3, 2015

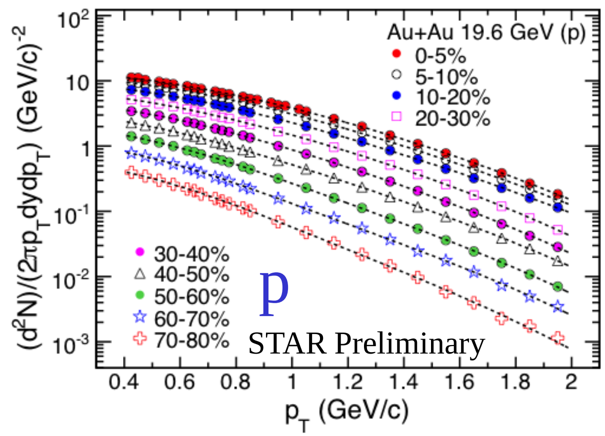
L. Kumar & STAR - ICPAQGP, 2010,India; CPOD2011;China; QM2014, Germany

$\pi^{+/-}$, $K^{+/-}$ and $p/\bar{p}$ spectra in Au+Au

Au+Au 19.6 GeV



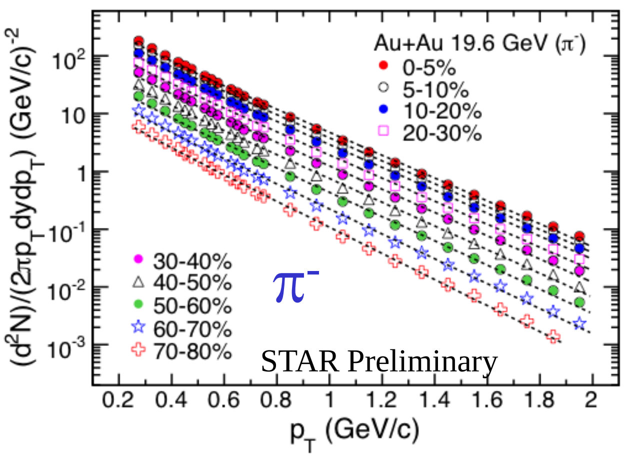


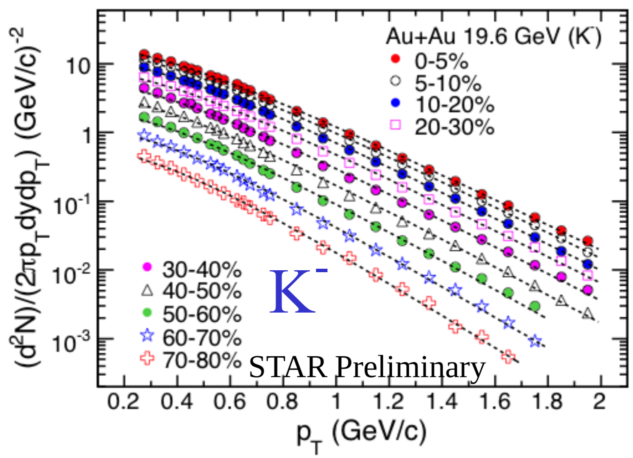


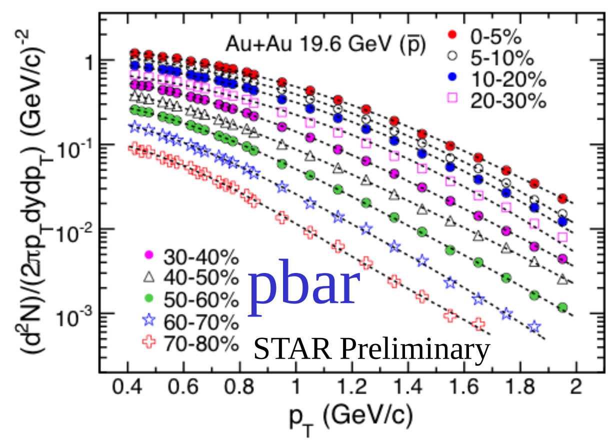
Pion curves:
Bose-Einstein fits

Kaon curves:
$(m_T$-$m)$ exponential fits

proton curves:
Double exponential fits







Spectra are characterized by dN/dy and $\langle p_T \rangle$ or $\langle m_T \rangle$

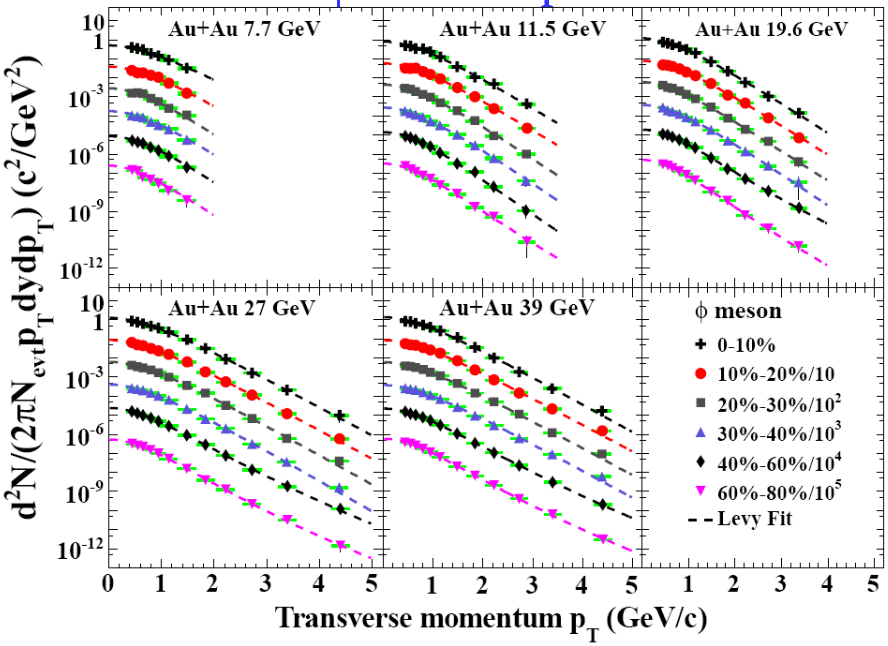
Spectra with strange probes

probing QCD phase diagram
with identified strange particles: φ, K_S^0, Λ, Ξ , Ω
in STAR BES-I

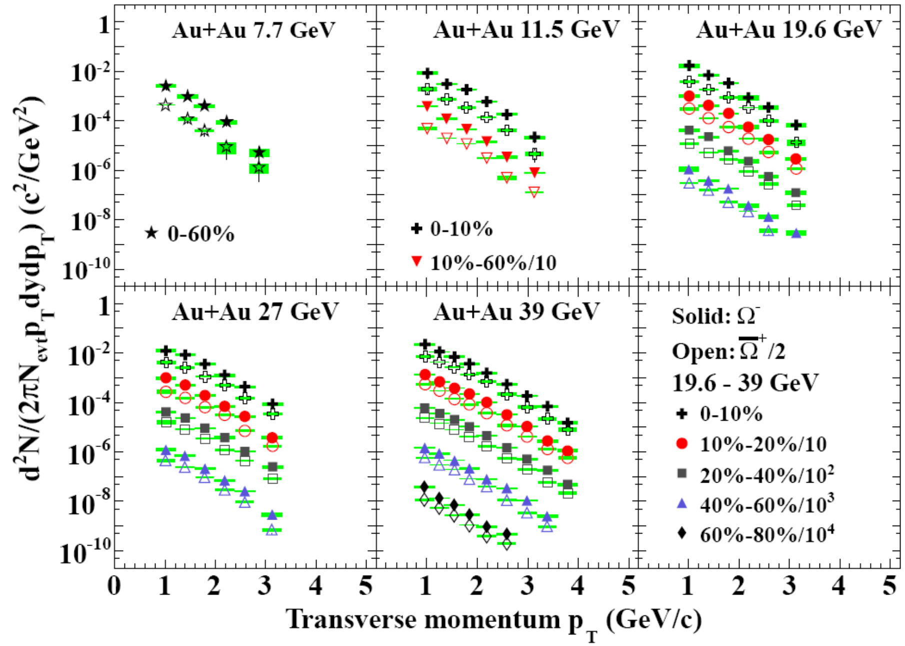
STAR Collaboration
Phys. Rev. C **93** (2016) 21903

AuAu @ 7.7-39 GeV, |y|<0.5

φ meson spectra



Ω hyperon spectra



Transverse momentum spectra are well described by the Levy function with parameters T & n

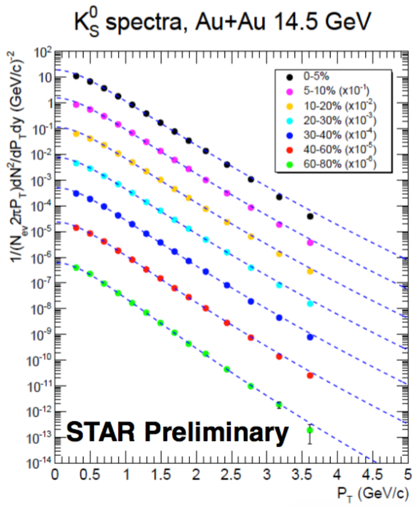
$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}=\frac{dN}{dy}\frac{(n-1)(n-2)}{2\pi nT(nT+m(n-2))}\left(1+\frac{\sqrt{p_T^2+m^2}-m}{nT}\right)^{-n}$$

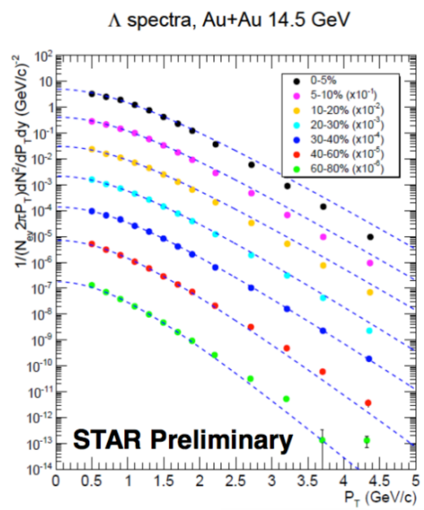
Coalescence formation

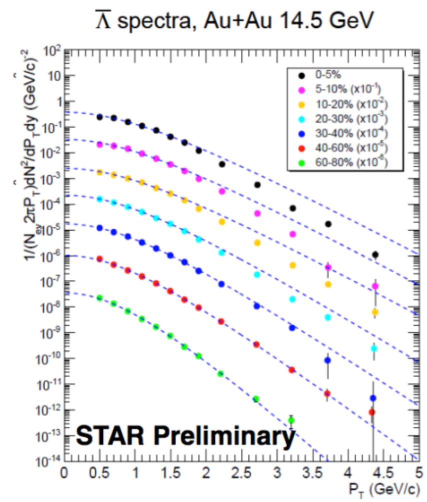
These hadrons are expected to provide information primarily from the partonic stage of the collision:

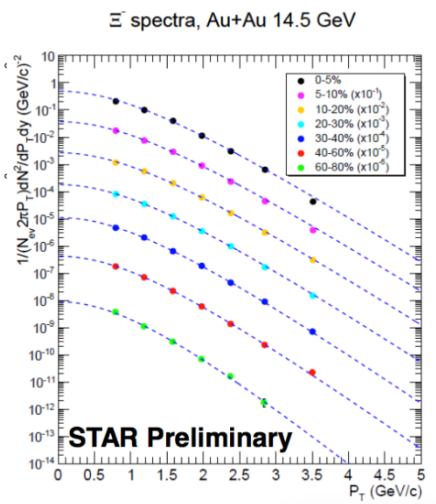
- relatively small hadronic cross section
- direct information from chemical freeze-out stage
- little or no distortion due to hadronic rescattering
- minimal distortion due to feed-down

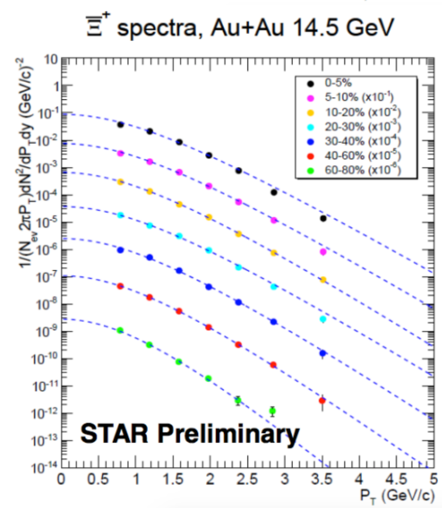
Spectra of K_S^0, Λ, Ξ particles & Au+Au, 14.5 GeV











√s=14.5 GeV

Λ spectra are weak decay

- feed-down corrected:
- statistical uncertainties

Spectra vs. collision energy, centrality, transverse momentum

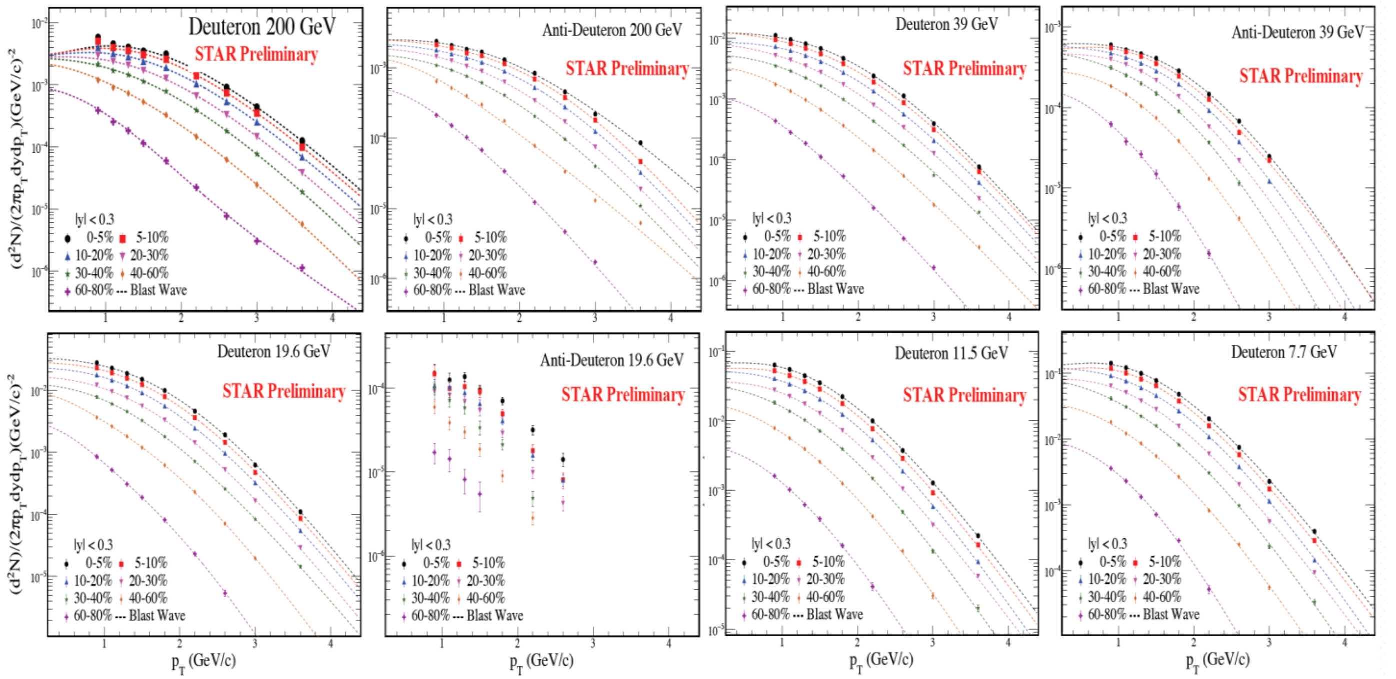
D.Brandenburg & STAR,
Deshaies, Guadeloupe, France,
Feb. 28 - Mar. 5, 2016

X.Zhu, CPOD 2011, China; F.Zhao, APS, DNP, 2011, USA

(Anti) d spectra in Au+Au at STAR & BES

N.Yu & STAR
QM2015

$$E_A \frac{d^3N_A}{d^3p_A} = B_A \left(\frac{d^3N_p}{d^3p_p}\right)^Z \left(\frac{d^3N_n}{d^3p_n}\right)^{A-Z} \approx B_A \left(\frac{d^3N_p}{d^3p_p}\right)^A$$



Systematic study of colliding energy, centrality, transverse momentum dependence of mid-rapidity deuteron and anti-deuteron production measured by the STAR experiment from Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, and 200 GeV.

The coalescence parameter B_2

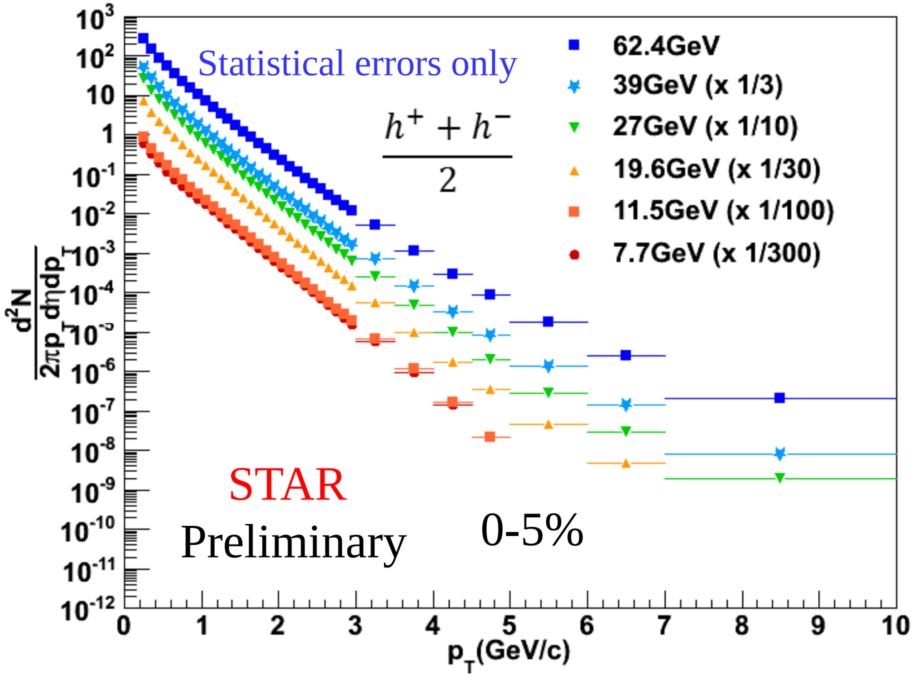
- measure of the phase space density for nucleons
- decreases as collision energy increases

Spectra with charged hadrons

probing QCD phase diagram
with unidentified particles
in STAR BES-I

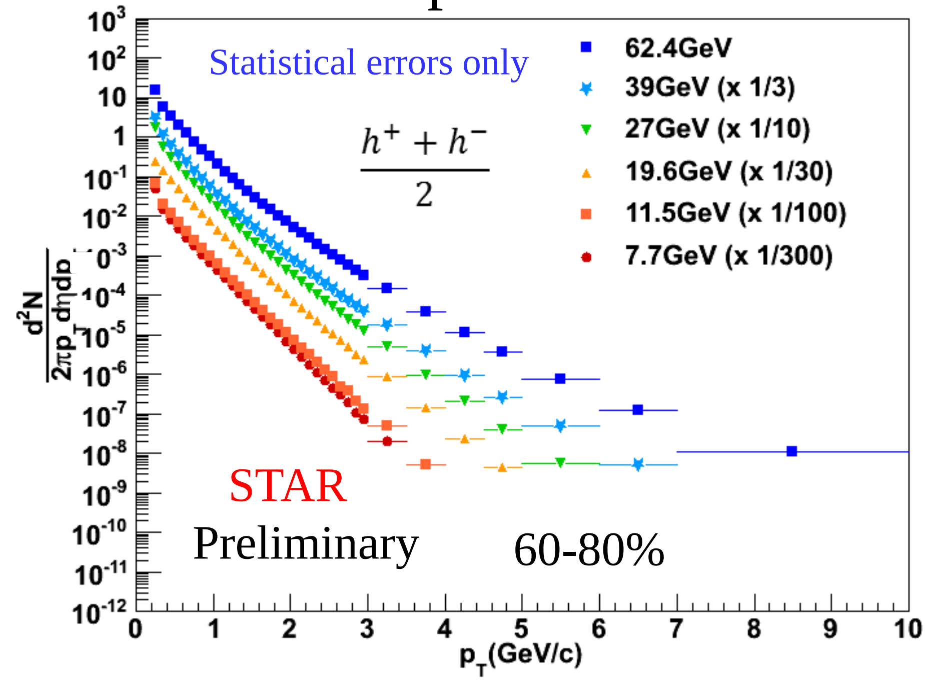
STAR Charged hadron spectra in Au+Au at 7.7-62.4 GeV

Central



Slopes are equal

Peripheral



Slopes are different

Peripheral spectra show stronger dependence on beam energy.

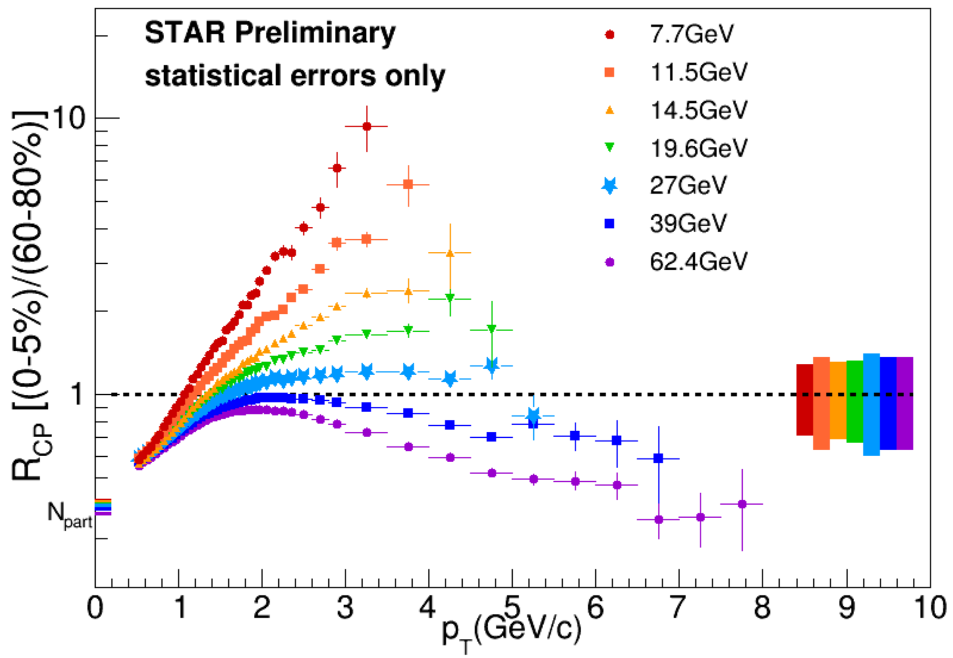
S.Horvat & STAR
PoS (CPOD 2013) 002

Nuclear modification factor R_{CP}

S.Horvat & STAR
nucl-ex:1601.01644

$$R_{CP} = \frac{(N_{Bin})_P}{(N_{Bin})_C} \cdot \frac{\left(\frac{d^2N}{2\pi p_T dp_T d\eta}\right)_C}{\left(\frac{d^2N}{2\pi p_T dp_T d\eta}\right)_P}$$

N_{Bin} ≡ number of binary collisions (Glauber MC model)

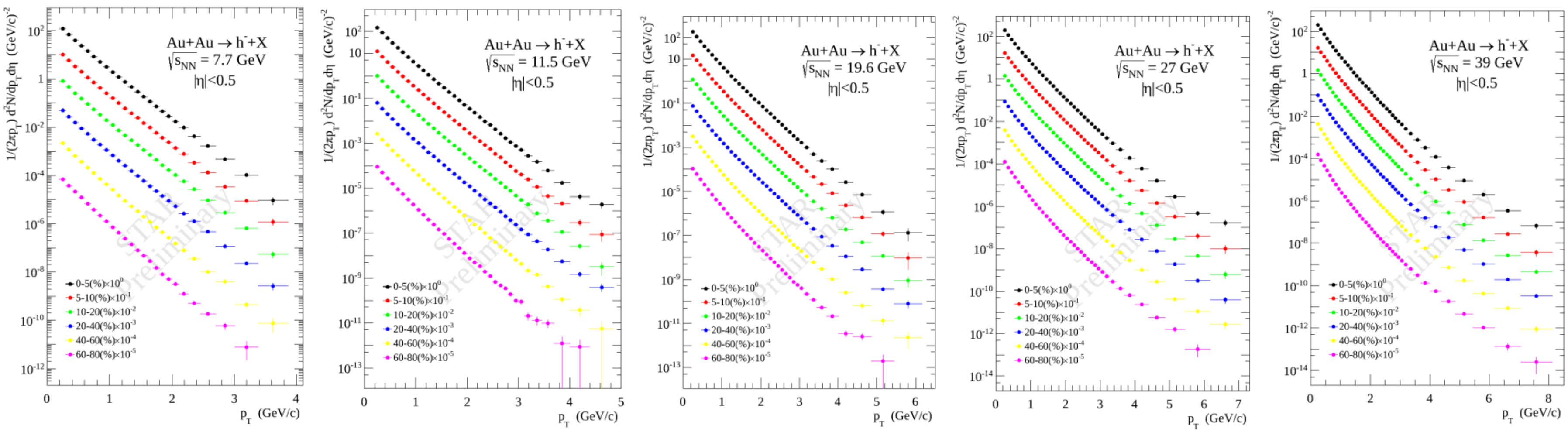


Smooth transition in the intermediate to high p_T range from suppression at $\sqrt{s_{NN}}$ = 39 GeV to strong enhancement at $\sqrt{s_{NN}}$ = 7.7 GeV.

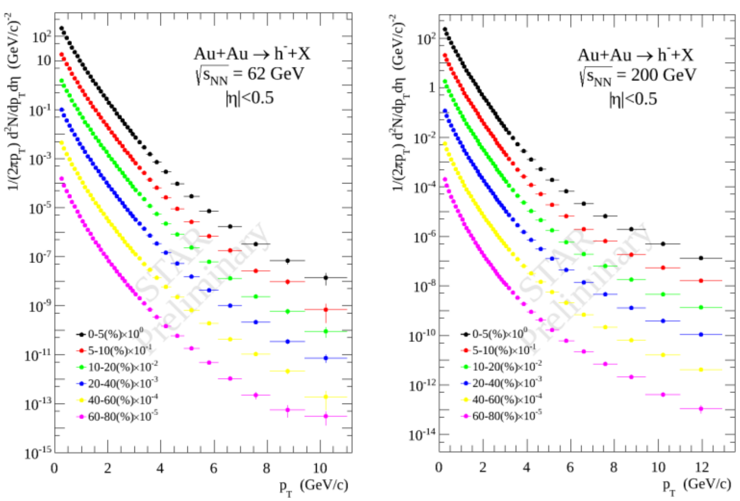
Transverse momentum h^- spectra in Au+Au

Int. J. Mod.Phys. (2015) 1560103

BES-I energies



Top RHIC energies



Wide kinematic and dynamical range of particle production:

- Beam energy $\sqrt{s_{NN}}$ = 7-200 GeV
- Centrality 80% - 5% ($dN_{ch}/d\eta|_0 \approx$10-600)
- Transverse momentum p_T = 0.2-12 GeV/c

Unprecedented conditions to search for new phenomena in nuclear matter produced in heavy ion collisions.

Search for scaling features at STAR

Probing the microscopic structure of hot QCD matter
at multiple length scales

Self-similarity of hadron production

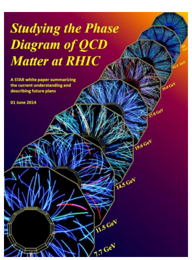
Int. J. Mod.Phys. (2015) 1560103

Phase transition and critical phenomena in usual matter (gas, liquid, solid)

"Scaling" and "Universality" are concepts developed to understanding critical phenomena. Scaling means that systems near the critical points exhibiting self-similar properties are invariant under transformation of a scale. According to universality, quite different systems behave in a remarkably similar fashion near the respective critical points. Critical exponents are defined only by symmetry of interactions and dimension of the space.

H.Stanley, G.Barenblatt,…

Phase transition and critical phenomena in nuclear matter



The idea is to vary the collision energy and look for the signatures of QCD phase boundary and QCD critical point i.e. to span the phase diagram from the top RHIC energy (lower μ_B) to the lowest possible energy (higher μ_B). To look for the phase boundary, we would study the established signatures of QGP at 200 GeV as a function of beam energy. Turn-off of these signatures at particular energy would suggest the crossing of phase boundary. Similarly, near critical point, there would be enhanced fluctuations in multiplicity distributions of conserved quantities (net-charge, net-baryon).

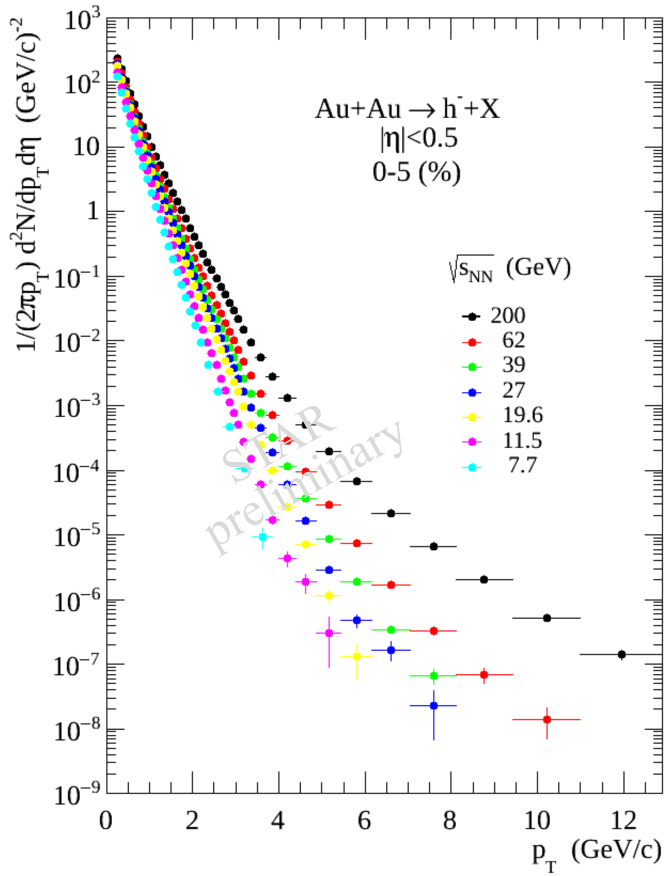
STAR collaboration

Transverse momentum spectra in Au+Au

Dimensional dynamical function
versus
dimensional measurables

Ed^3N/dp^3 & $P_{1,2}, M_{1,2}, p, m, dN/d\eta$

- Energy dependence of spectra
- Centrality dependence of spectra
- Exponential behavior of spectra at low p_T and energy $\sqrt{s_{NN}}$
- Power behavior of spectra at high p_T and energy $\sqrt{s_{NN}}$
- Difference of yields at various energies strongly increases with p_T



The study of critical phenomena in nuclear matter
in terms of dimensionless variables

Int. J. Mod.Phys. (2015) 1560103

Self-similarity in Au+Au collisions

Self-similarity parameter

$$z = z_0 \Omega^{-1}$$

$$z_0 = \frac{s_{\perp}^{1/2}}{(dN_{ch}/d\eta|_0)^c m_N}$$

$$\Omega = (1-x_1)^{\delta_{A_1}}(1-x_2)^{\delta_{A_2}}(1-y_a)^{\varepsilon}(1-y_b)^{\varepsilon}$$

- $dN_{ch}/d\eta|_0$ - multiplicity density
- c - "specific heat" of bulk matter
- δ_A - nucleus fractal dimension
- ε - fragmentation fractal dimension

Dimension of fragmentation

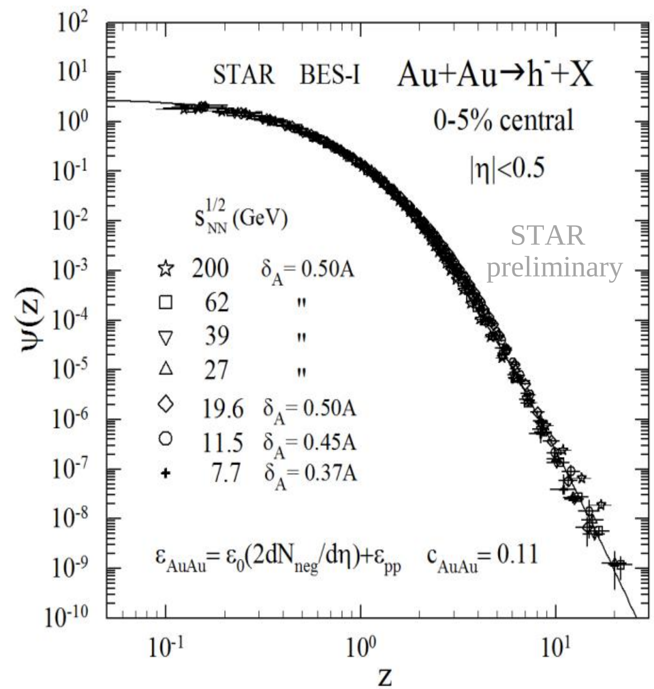
$$\varepsilon_{AA} = \varepsilon_0 (dN/d\eta) + \varepsilon_{pp}$$

Scaling function

$$\Psi(z) = \frac{\pi}{(dN/d\eta)\cdot \sigma_{inel}} \cdot J^{-1} \cdot E\frac{d^3\sigma}{dp^3}$$

M.T. & I.Zborovsky
PRD75,094008(2007)
IJMPA24,1417(2009)

"Collapse" of data points onto a single curve



- Energy independence of $\Psi(z)$
- Centrality independence of $\Psi(z)$
- Dependence of ε_{AA} on multiplicity
- Power law at low- and high-z regions

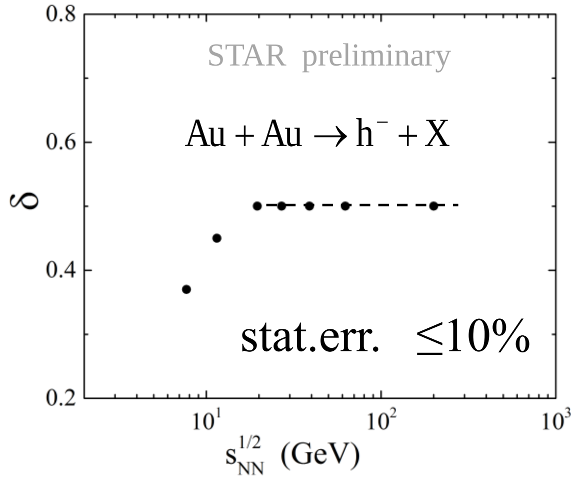
Indication on energy dependence of δ for $\sqrt{s_{NN}} < 19.6$ GeV

Model parameters: δ_A, ε_{AA}, c

Parameters δ_A, ε_{AA}, c are determined from the requirement of scaling behavior of Ψ as a function of self-similarity parameter z

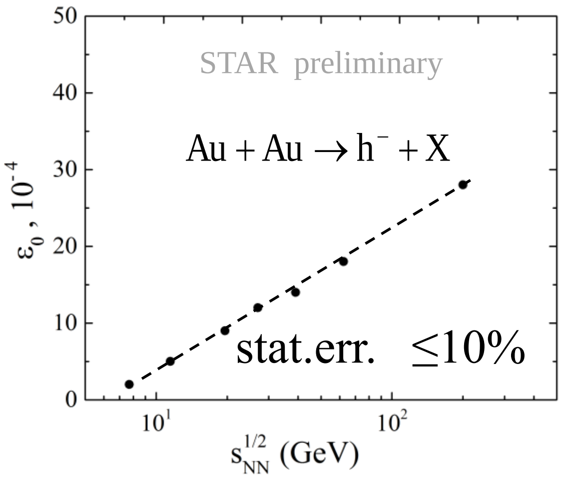
Nucleus fractal dimension

$$\delta_A = A \cdot \delta$$



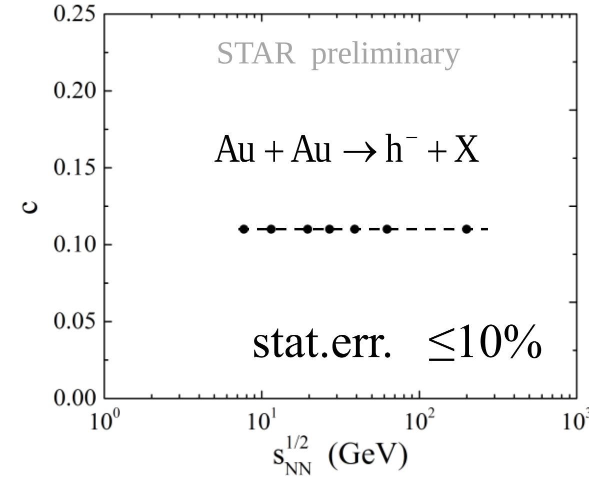
Fragmentation dimension

$$\varepsilon_{AA} = \varepsilon_0 (dN/d\eta) + \varepsilon_{pp}$$



"Specific heat"

c



- δ decreases with energy for $\sqrt{s_{NN}} \leq 20$ GeV
- δ is independent of energy for $\sqrt{s_{NN}} \geq 20$ GeV
- ε_{AA} increases with energy
- c is independent of energy

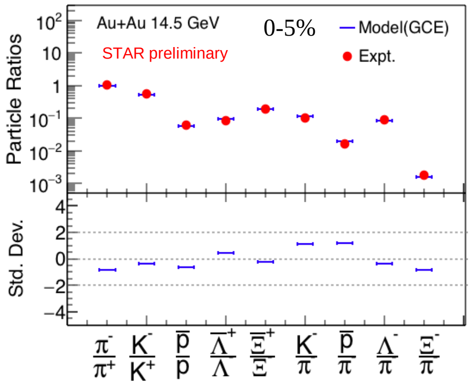
Search for discontinuity and correlations of the model parameters.

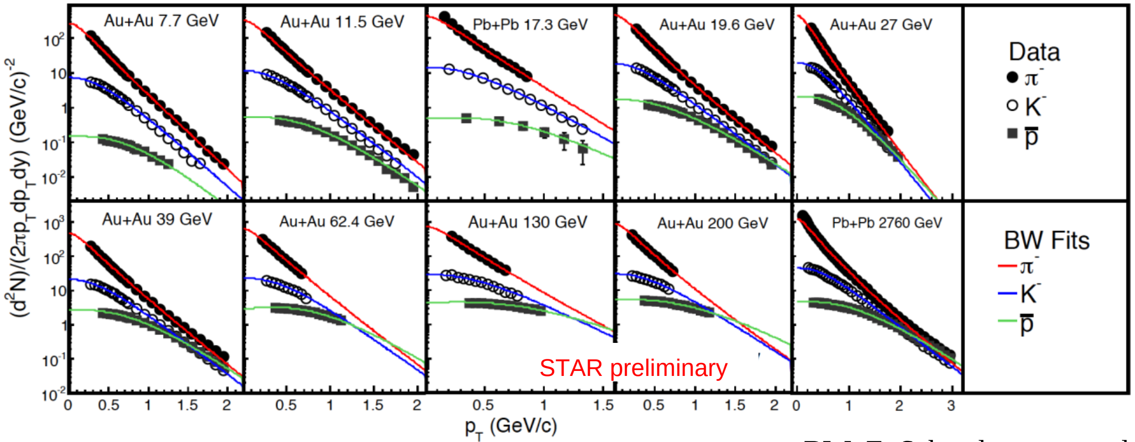
Phase diagram of nuclear matter

Particle yields and particle ratios allow to extract
within the statistical equilibrium and blast wave models
the chemical and kinetic freeze-out thermodynamic parameters

T_{ch} vs. μ_B

T_{kin} vs. β





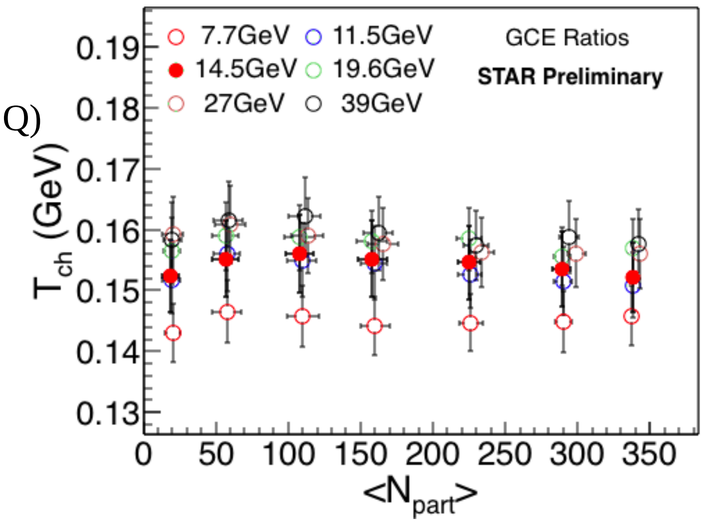
BW: E. Schnedermann et al., Phys.Rev. C 48 (1993) 2462.

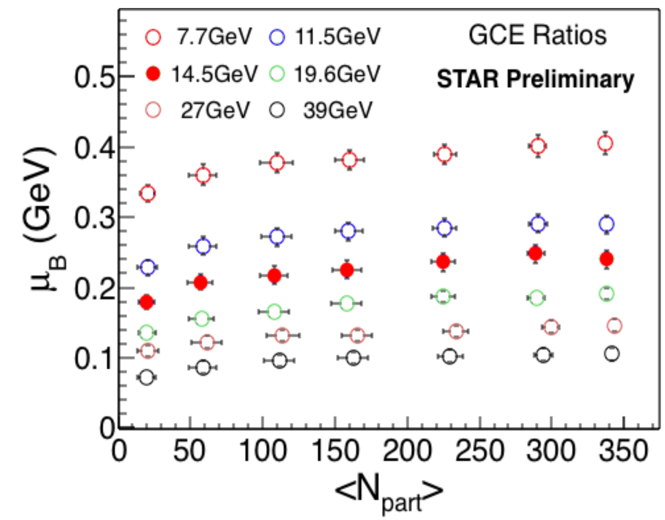
Chemical Freeze out & BES I

BES I results for Au+Au & 7.7,11.5,14.5,19.6,27,39 GeV

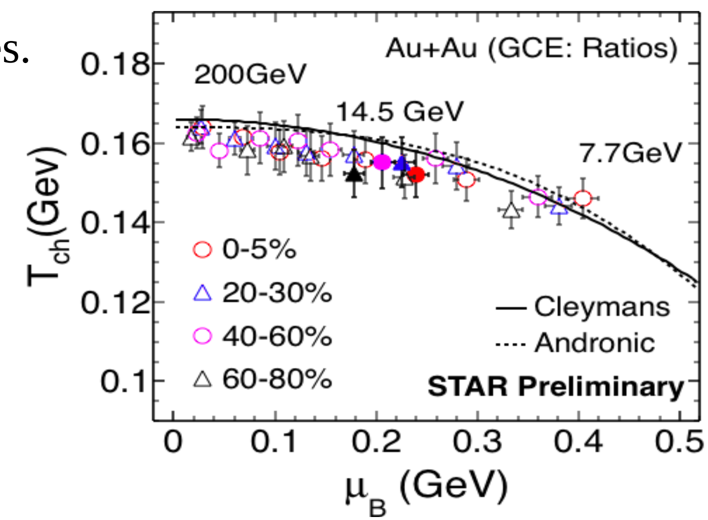
- Statistical thermal model
- Quantum numbers (B, S, Q) are conserved on average

S. Wheaton & Cleymans, Comput. Phys. Commun., 180, 84-109 (2009)





- Particles used in fit : π, K, p, Λ, Ξ and their anti-particles.
- T_{ch} increases as collision energy increases.
- μ_B decreases with increase in collision energy.
- Centrality dependence of μ_B is observed.



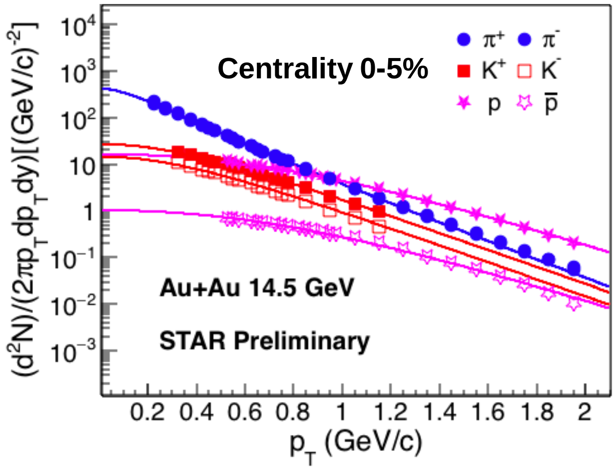
Vipul Bairathi & STAR
QM'15, Kobe, Japan, Sept. 27 – Oct. 3, 2015
Lokesh Kumar & STAR
QM'12, Nucl.Phys. A904-905 (2013) 256C
J.Cleymans et al. Phys. Rev. C 73 (2006) 034905
A. Andronic et al. Nucl. Phys. A 834 (2010) 237C

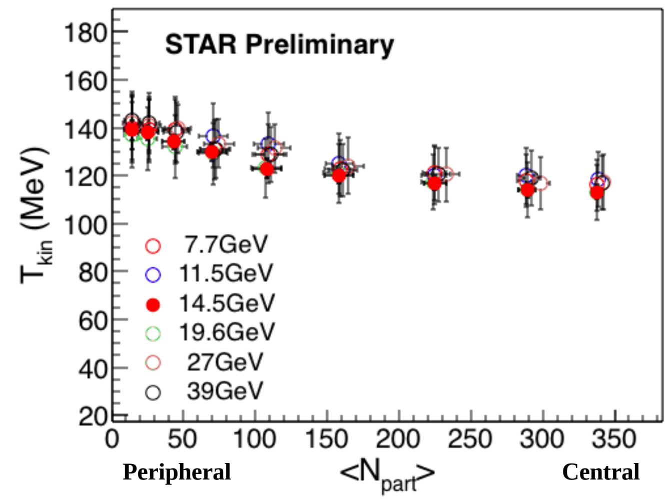
Kinetic Freeze out & BES I

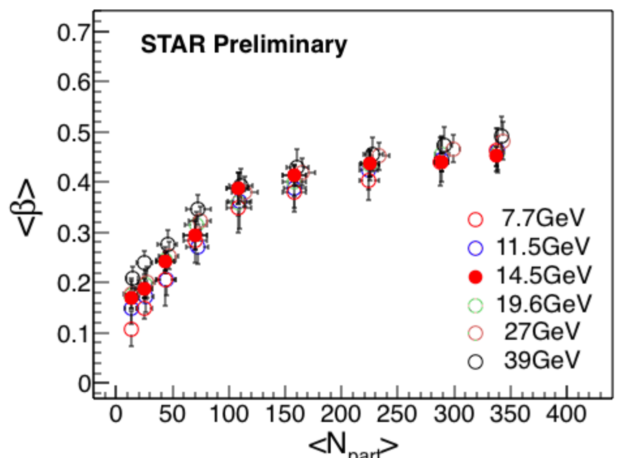
BES I results for Au+Au & 7.7,11.5,14.5,19.6,27,39 GeV

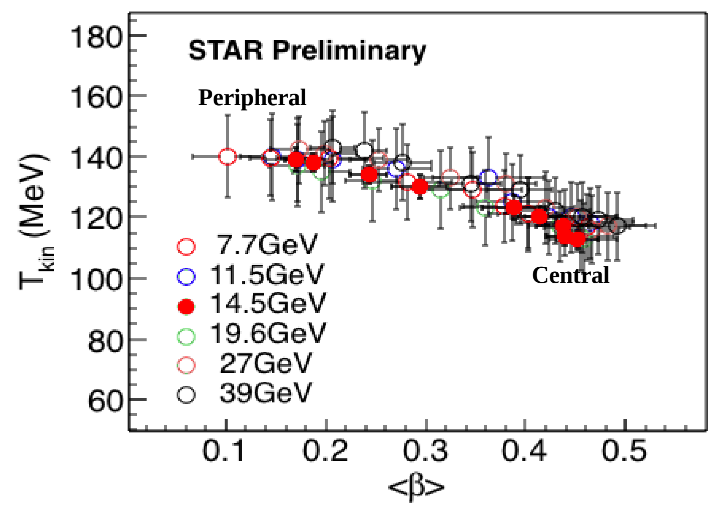
- Hydro based model
- Local thermalization of particles at a kinetic freeze-out temperature and moving with a common radial flow velocity

E. Schnedermann, J. Sollfrank,U.W.Heinz Phys. Rev. C 48, 2462 (1993)







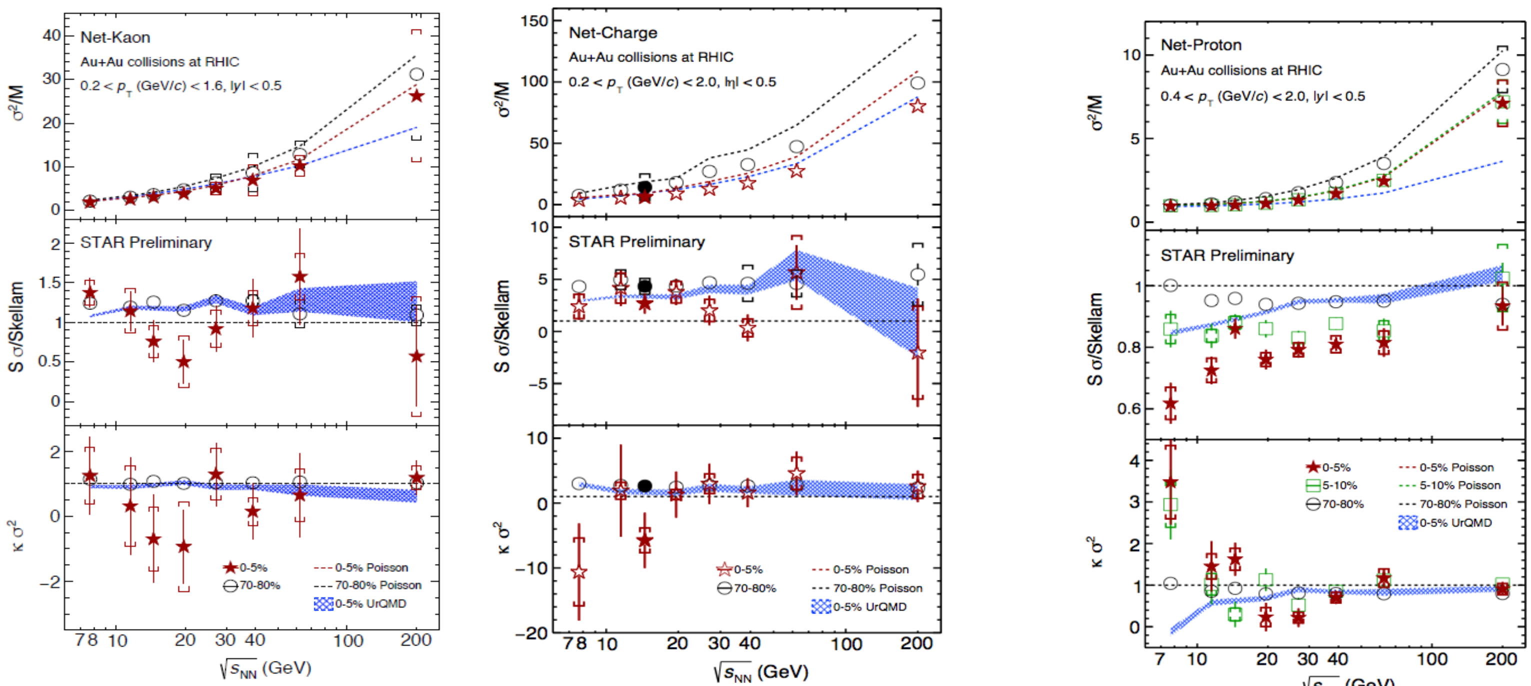


- <β> decreases from central to peripheral collisions.
- T_{kin} increases from central to peripheral collisions.
- An anti-correlation observed between T_{kin} and <β>.

Vipul Bairathi & STAR
QM'15, Kobe, Japan, Sept. 27 – Oct. 3, 2015

Sophisticated STAR BES-I data analysis

BES I results for Au+Au & 7.7,11.5,14.5,19.6,27,39,62.4, 200 GeV



The values of net-Kaon's and net-Charge's $\kappa\sigma^2$ and $S\sigma$/Skellam are consistent with Poisson distributions within errors.

Non-monotonic behavior seen in net-Proton $\kappa\sigma^2$ in 0-5% and 5-10% central collisions.

Y.Pandit & STAR
ICHEP'16,Chicago,USA
PRL 112, 32302(2014)

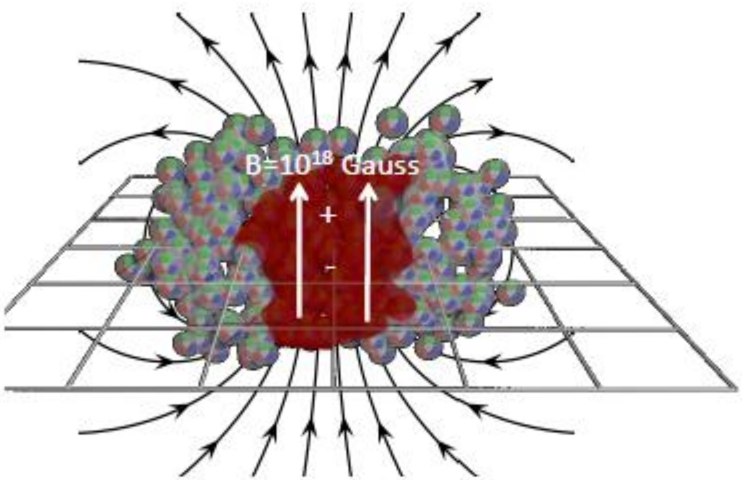
Need more precise measurement below 20 GeV with finer steps in μ_B and increased rapidity acceptance

Chiral Magnetic Effect

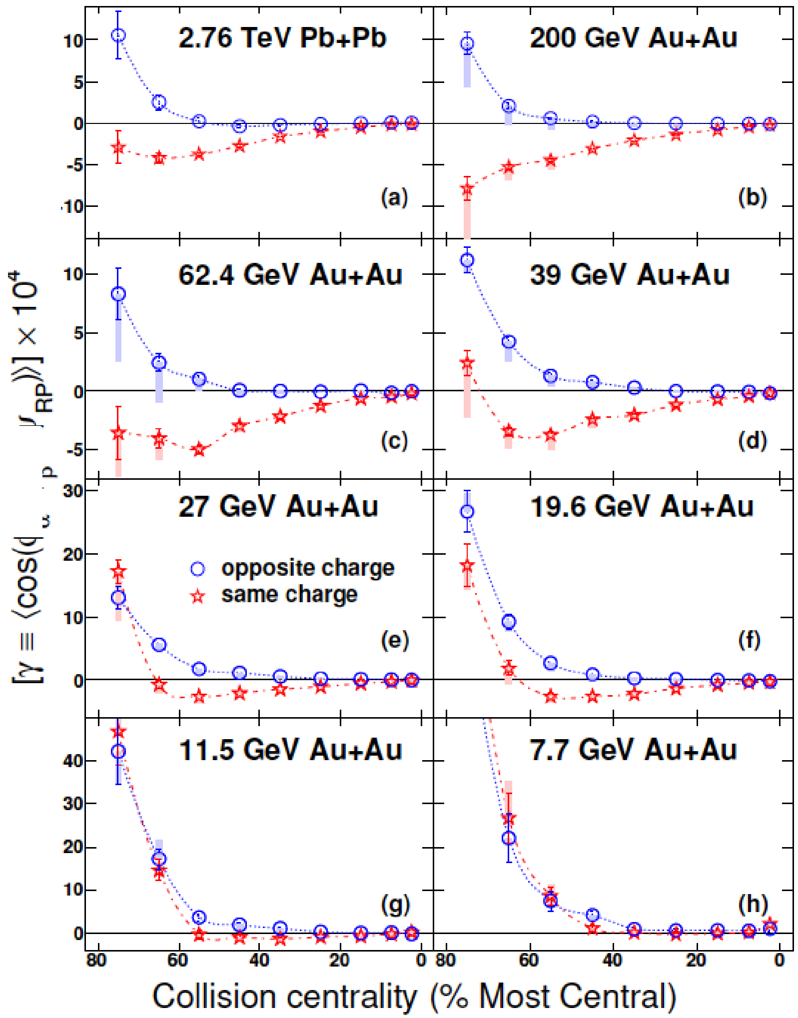
Three Effects:

1. Chiral Magnetic Effect
2. Chiral Magnetic Wave
3. Chiral Vortical Effect

Chiral anomaly creates differences in the number of left handed and right handed quarks. Leads to charge separation along the magnetic field lines.



STAR, Phys. Rev. Lett. 113 (2014) 52302



Daniel Cebra & STAR
34th Reimei Workshop J-PARC, Tokai, Japan,2016

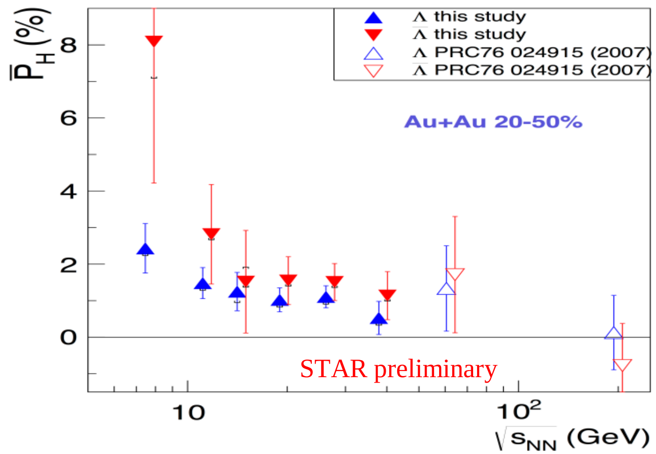
STAR "Spinning" QGP – Global hyperon polarization

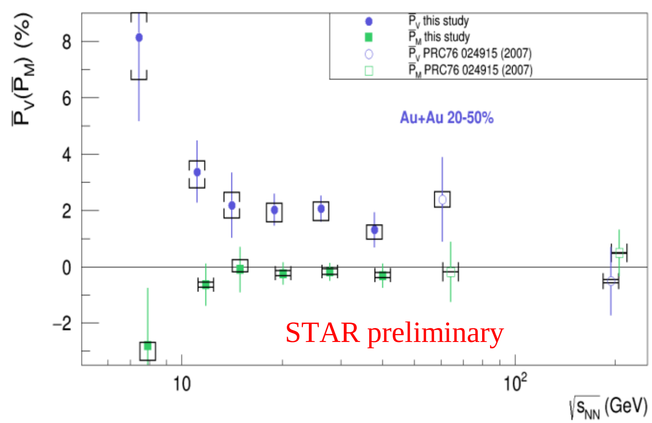
Hydro: from laminar to turbulent flow ?

- Lambdas reveal their polarization through decay topology.
- Polarization expected through "vortical alignment with the event angular momentum vector.
- Polarization expected magnetic alignment with the event magnetic field
- These effects can be disentangled looking at Λ and anti-Λ
- Goal is a definitive measurement of the magnetic alignment effect

$$P_{Vortical} = (P_{\Lambda} + P_{\bar{\Lambda}})/2$$

$$P_{Magnetic} = (P_{\Lambda} - P_{\bar{\Lambda}})/2$$





Non-central Au+Au collisions

Fluid vorticity may generate global polarization of emitted particles

$$\vec{\omega} = \nabla \times \vec{v}$$

Viscosity dissipates vorcity to fluid at larger scale

- Global polarization is positive for Λ and anti-Λ
- Corrections for feed-down from $\Sigma^0, \Xi^0, \Xi^-, \Omega^-$ decays

J.Bunce et al., PRL 36 (1976)1113

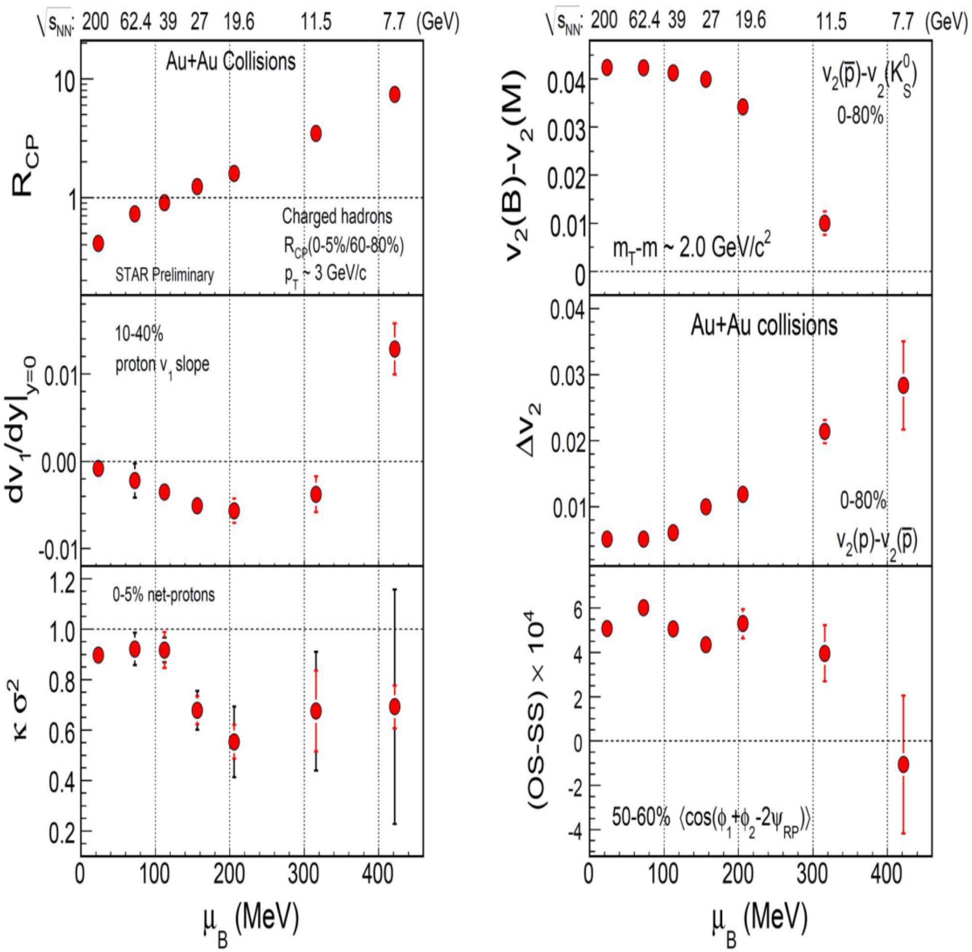
Mike Lisa & STAR, SQM'16, Berkeley, 2016

Selected results from Au+Au collisions in the BES phase I program at RHIC

A reduction in the partonic energy loss.

Non-monotonic variation with respect to μ_B. Sensitivity to possible first-order phase transition effects.

To clarify whether the trend follows a monotonic or non-monotonic variation with a minimum.



A difference between the v_2 of baryons and mesons at intermediate p_T is the key to the experimental observation of NCQ scaling and partonic collectivity at top RHIC energy.

The difference in v_2 between baryons and antibaryons are consistent with the finding that hadronic interactions dominate at lower beam energies..

The difference of dynamical charge correlations between same-sign and opposite-sign charges. One of the possible explanations is the Chiral Magnetic Effect.

STAR BES-I White paper
Rosi Reed & STAR,
RHIC/AGS Users Meeting, 2016

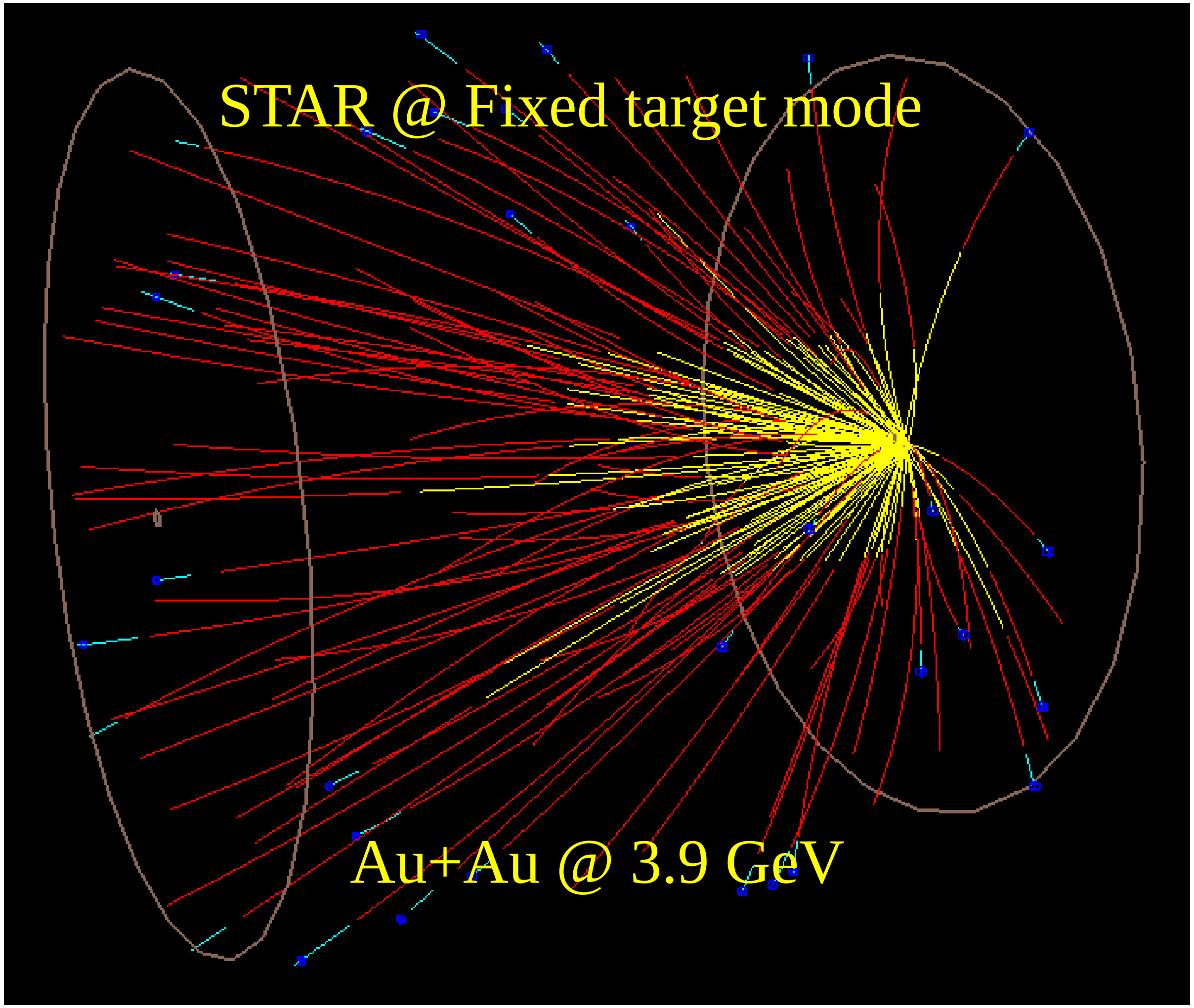
Fixed target program at STAR

probing QCD phase diagram
with identified particles over a range $\sqrt{s_{NN}}$ = 3.0 to 7.7 GeV

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

Goals:

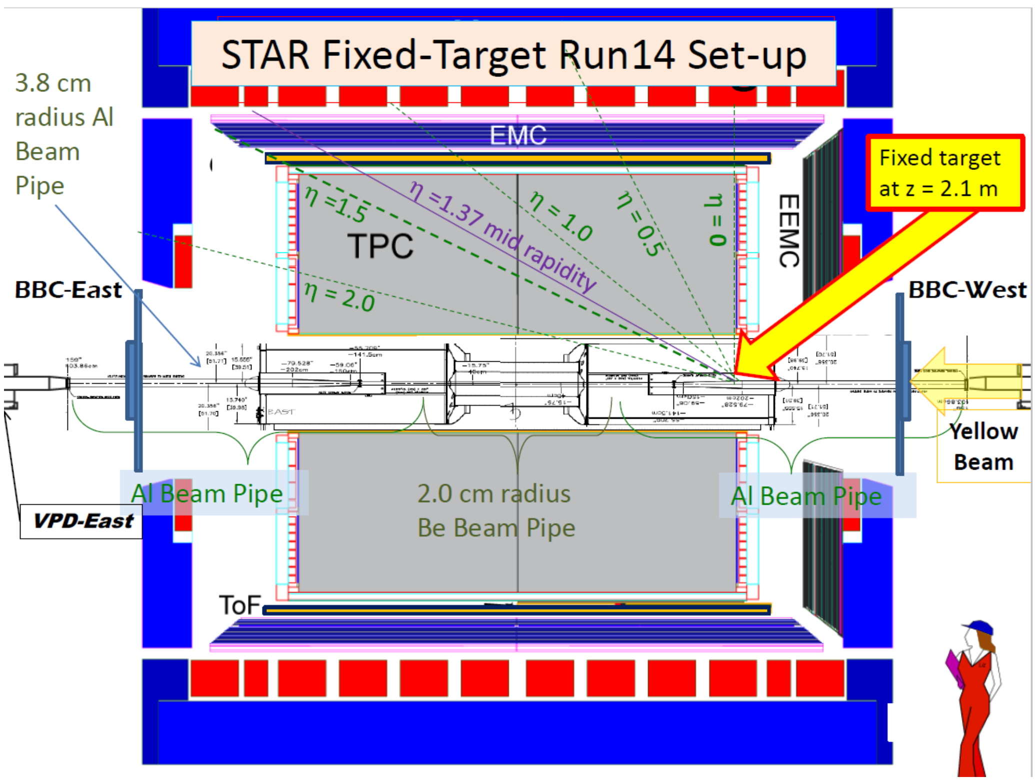
- Search for evidence of the first entrance into the mixed phase.
- Control measurements for BES collider program searches for Onset of Deconfinement.
- Control measurements for Critical Point searches.

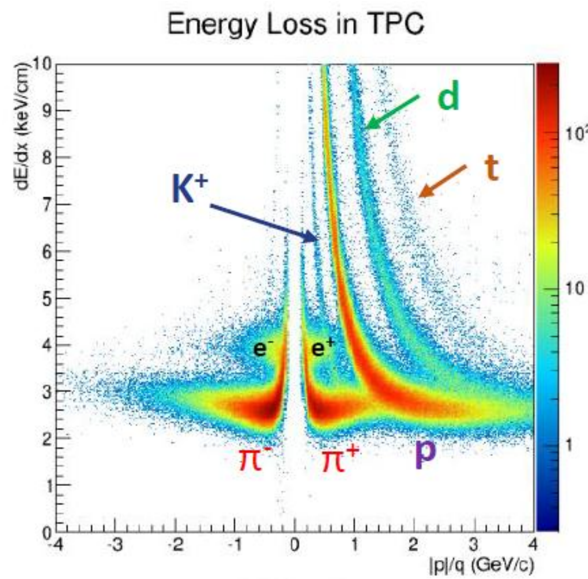

STAR @ Fixed target mode
Au+Au @ 3.9 GeV

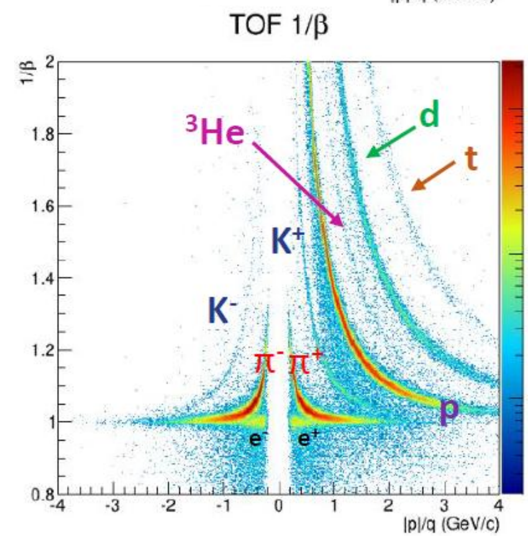
Fixed Target Mode & Au+Au @ 3.9 GeV

K.Meehan & STAR
RHIC & AGS Users Meeting 2016

Test run 16

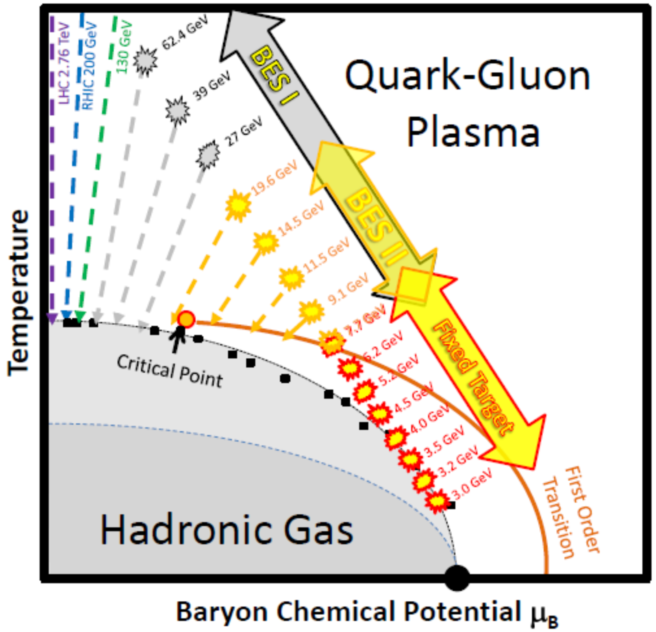






Excellent PID with TPC & TOF
for fixed target events

The Fixed-Target Experiment at STAR



Collider energy (GeV)	Fixed-Target energy (GeV)	Center-of-mass rapidity	Single Beam Energy (GeV	Chemical potential μ_B (MeV (collider mode)	Chemical potential μ_B (MeV) (FT mode)
19.6	4.47	1.52	8.87	205	589
17.2	4.21	1.46	7.67	230	608
14.5	3.90	1.37	6.32	250	633
13.0	3.72	1.32	5.57	288	649
11.5	3.53	1.25	4.82	315	666
9.1	3.19	1.13	3.62	370	699
7.7	2.98	1.05	2.92	420	721

BES Phase II

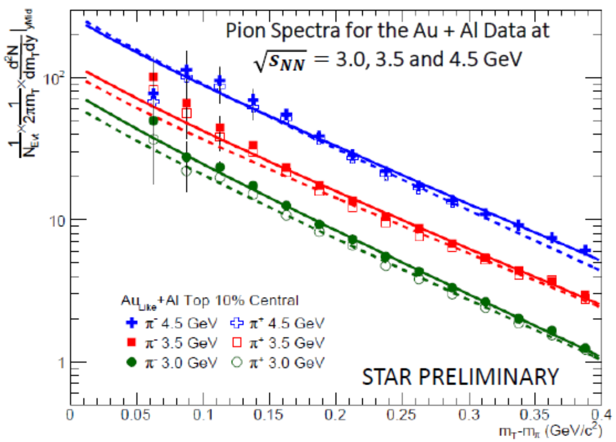
- BES program is designed to study the phase diagram of QCD matter.
- Need to access the lower energy range to study all region of the phase diagram.
- Fixed Target program along with key upgrades allows us to scan from $\sqrt{s_{NN}}$ 19.6 to 3.0 GeV (200-720 MeV in μ_B)

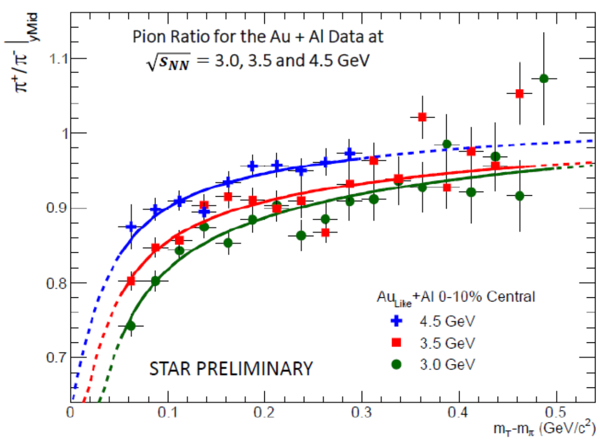
D.Cebra, K.Meehan , Rosi Reed & STAR, RHIC & AGS Users Meeting 2016

D.Sebra & STAR, 34th Reimei Workshop J-PARC, Tokai, Japan, 2016

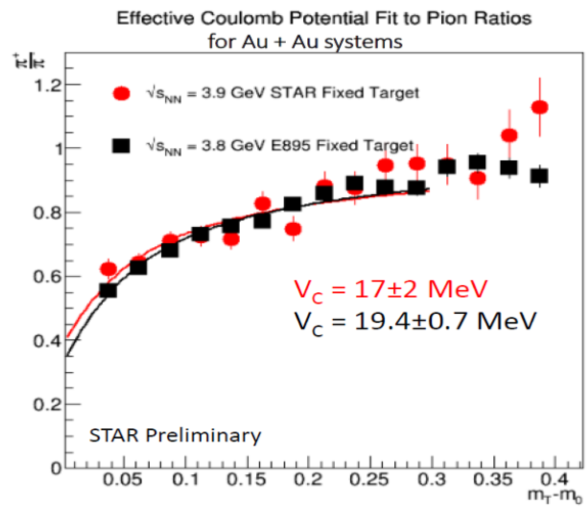
Energy scan at low energy: Fixed target mode

Au+Al Beam Pipe Studies





Au+Au Beam FT Studies



STAR results for spectra and Coulomb potential are consistent with AGS previous experiments.

K.Meehan & STAR
RHIC & AGS Users Meeting, 2016

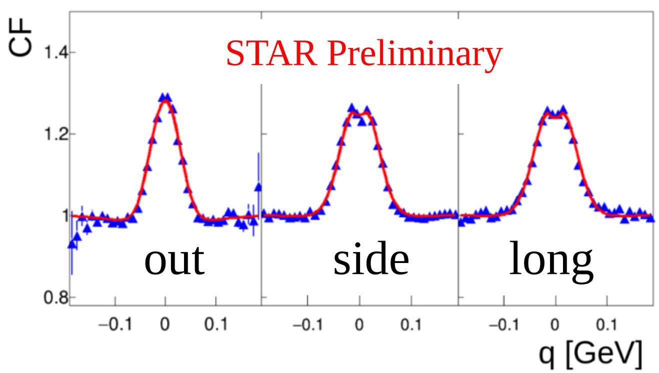
J. Klay et al.(E895 Collaboration), Phys. Rev. C 68,054905 (2003)

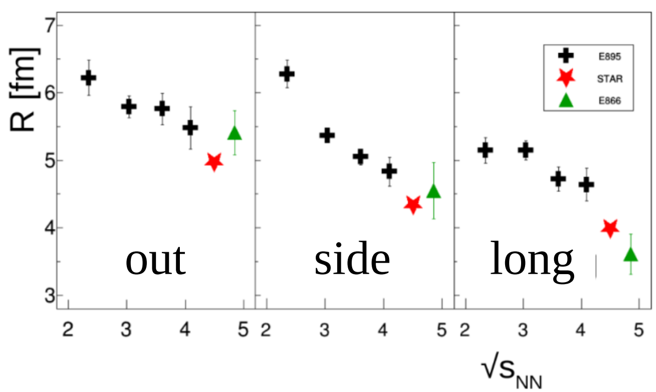
Fixed Target Mode & Au+Au @ 4.5 GeV

HBT correlations

$$CF(q) = N((1-\lambda)+\lambda K(q)G)$$

$$G \equiv e^{-\left(R_{out}^2 q_{out}^2 + R_{side}^2 q_{side}^2 + R_{long}^2 q_{long}^2 + 2R_{os}^2 q_{out} q_{side}\right)}$$





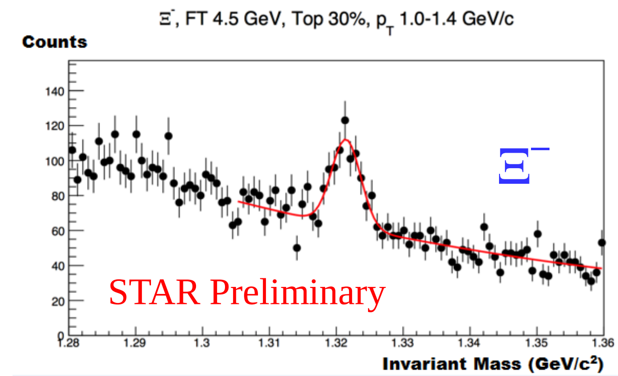
AGS & RHIC comparison

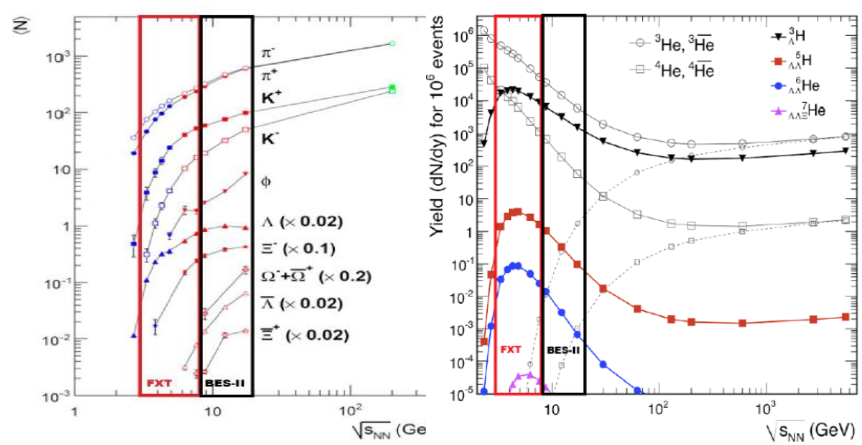
K.Meehan & STAR

RHIC & AGS Users Meeting , 2016

Test run 2015

Hyperons & Hypernuclei





STAR FXT could improve world hypertriton lifetime measurement

Spectra with heavy flavor probes

probing QCD phase diagram
with identified charm particles: D^0, J/ψ
in STAR with new detectors HFT and MTD

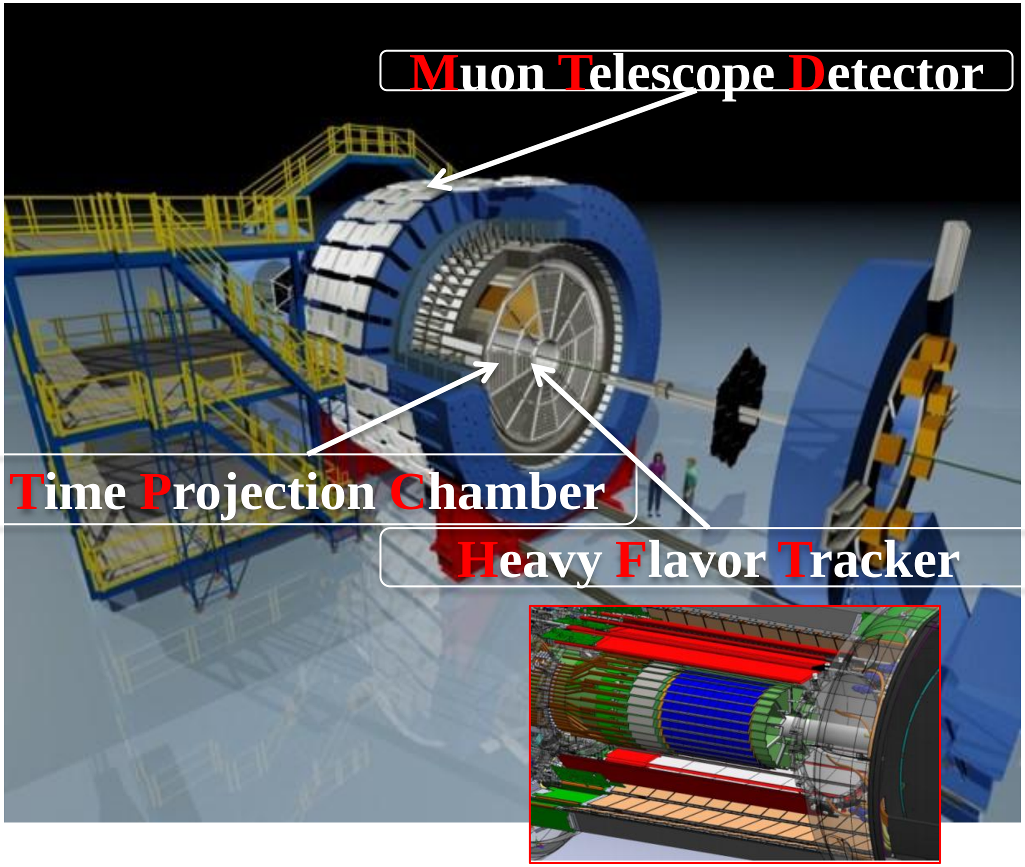
Talks by

Pavol Federič
"Heavy flavor measurements at the STAR experiment"

Pavla Federičová
"J/ψ production at the STAR experiment"

The Solenoidal Tracker At RHIC

Mid-rapidity detector: $|\eta| < 1$, $0 < \varphi < 2\pi$



TPC, HFT, MTD

- **TPC**: precise momentum, energy loss
- **HFT**: topological reconstruction of D
  - σ_{DCA} < 50 μm for kaon at 750 MeV/c
  - 1^{st} layer of PXL <0.4%X_0
  - Take data: 2014-2016
- **MTD**: trigger on and identify muons
  - Precise timing measurement (σ~100 ps)
  - Fully installed in 2014

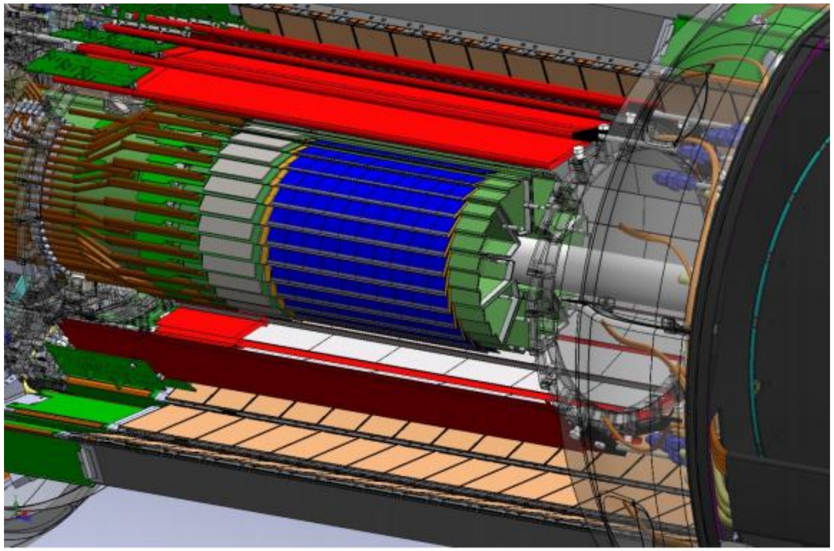
Topological reconstruction with HFT

- Greatly reduced combinatorial background (4 orders of magnitude)
- Highly improved S/√(B+S) (~8-18)

STAR Collaboration
Rongrong Ma, RHIC&AGS Users' Meeting, 2016
Michael Lomnitz, Heavy Flavor Workshop, BNL,Upton,2016
Hao Qiu, ICHEP'16,Chicago,USA,2016

Heavy Flavor Tracker at STAR

Acceptance coverage:
$-1 < \eta < 1\ ,\ \ 0 < \varphi < 2\pi$

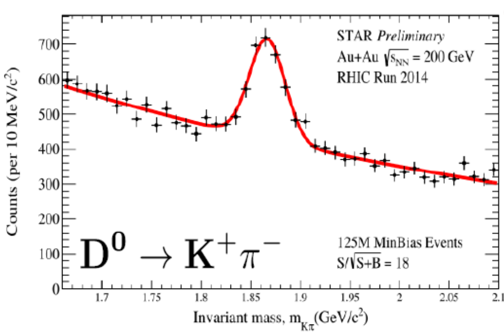


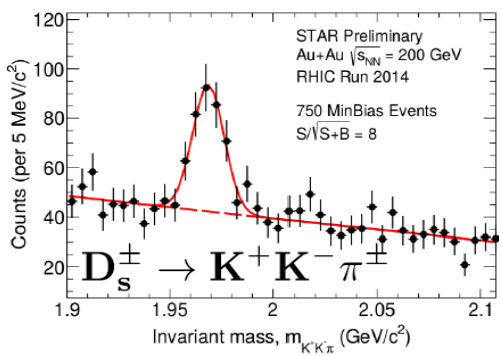
TPC – Time Projection Chamber (main tracking detector in STAR)

HFT – Heavy Flavor Tracker

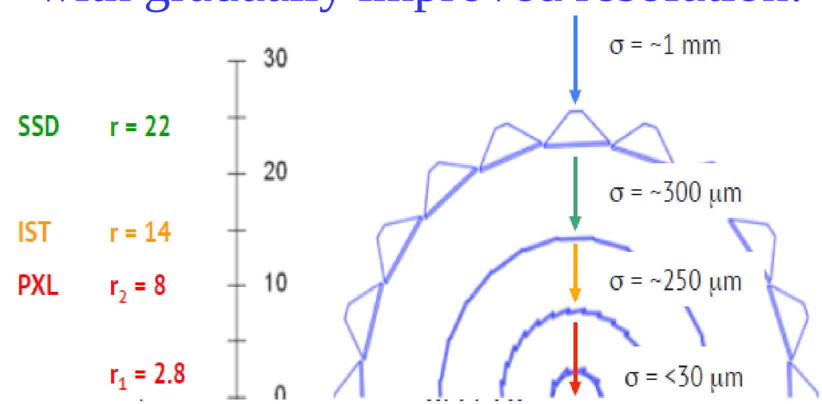
- SSD – Silicon Strip Detector
- IST – Intermediate SiliconTracker
- PXL – Pixel Detector

Excellent long-lived hadron and electron identification
Secondary vertex reconstruction with HFT → Full kinematic reconstruction of charmed hadron





Tracking inwards with gradually improved resolution:



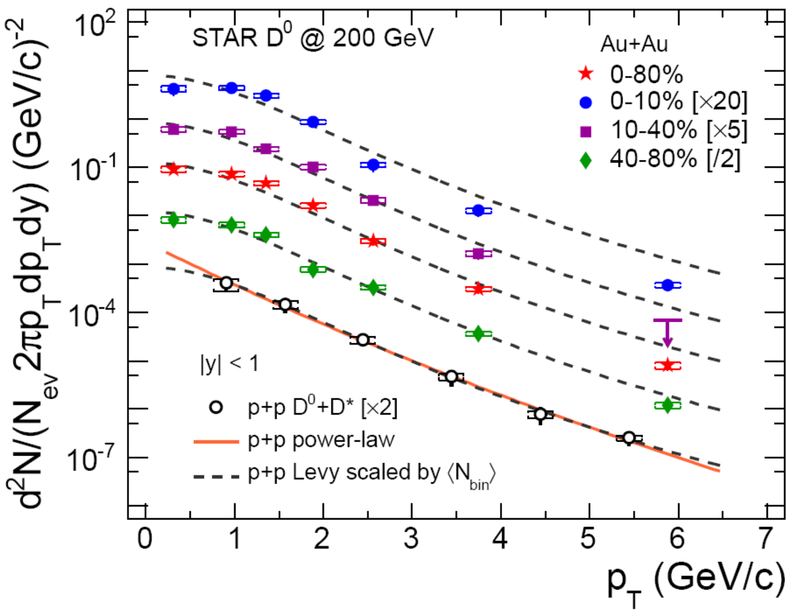
STAR Collaboration
Michael Lomnitz, Heavy Flavor Workshop, BNL,Upton,2016
Hao Qiu, ICHEP’16,Chicago,USA,2016

D^0 meson nuclear modification in Au+Au

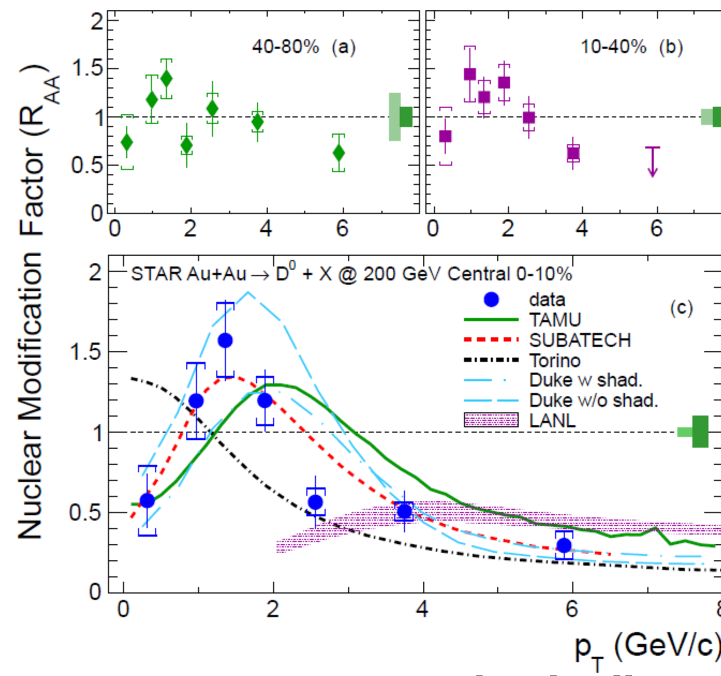
STAR Colabotration
PRL **113** (2014) 142301

$$D^0 \rightarrow K^- + \pi^+$$

Spectra TPC & ToF



R_{AA} vs. pT & centality



- No suppression in peripheral collisions
- A clear suppression in central collisions

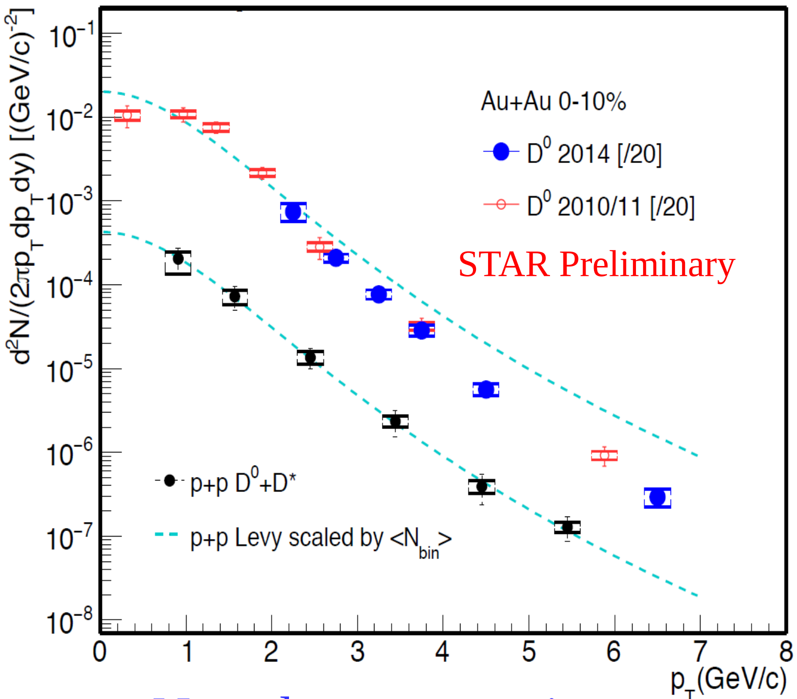
Strong charm-medium interactions and hadronization via coalescence at intermediate p_T.

Significant energy loss of charm quarks in the hot and dense medium for transverse momenta p_T > 3 GeV/c.

Spectra & R_{AA} for $D^0 \rightarrow K^- + \pi^+$

Au+Au @ 200 GeV

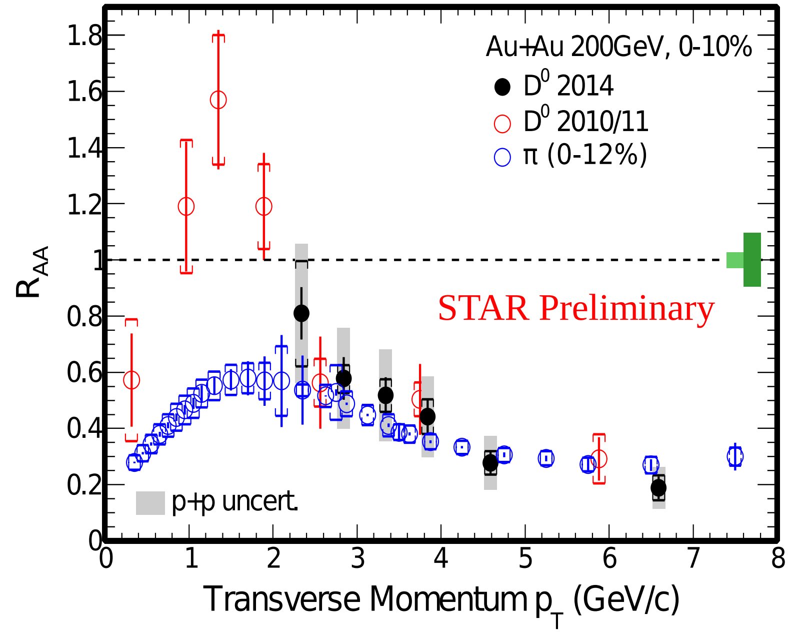
TPC & ToF & HFT



New data are consistent with published results, with improved statistical precision.

STAR Collaboration
Michael Lomnitz, Heavy Flavor Workshop, BNL,Upton,2016
Hao Qiu, ICHEP'16,Chicago,USA,2016
STAR: PRL 113 (2014) 142301; PLB 655 (2007) 104

R_{AA} – significant suppression



- $R_{AA} > 1$ for $p_T \sim 1.5$ GeV/c

Charm coalescence with the flowing medium

- $R_{AA} \ll 1$ for $p_T > 2.5$ GeV/c

Strong charm-medium interaction leading to sizable energy loss

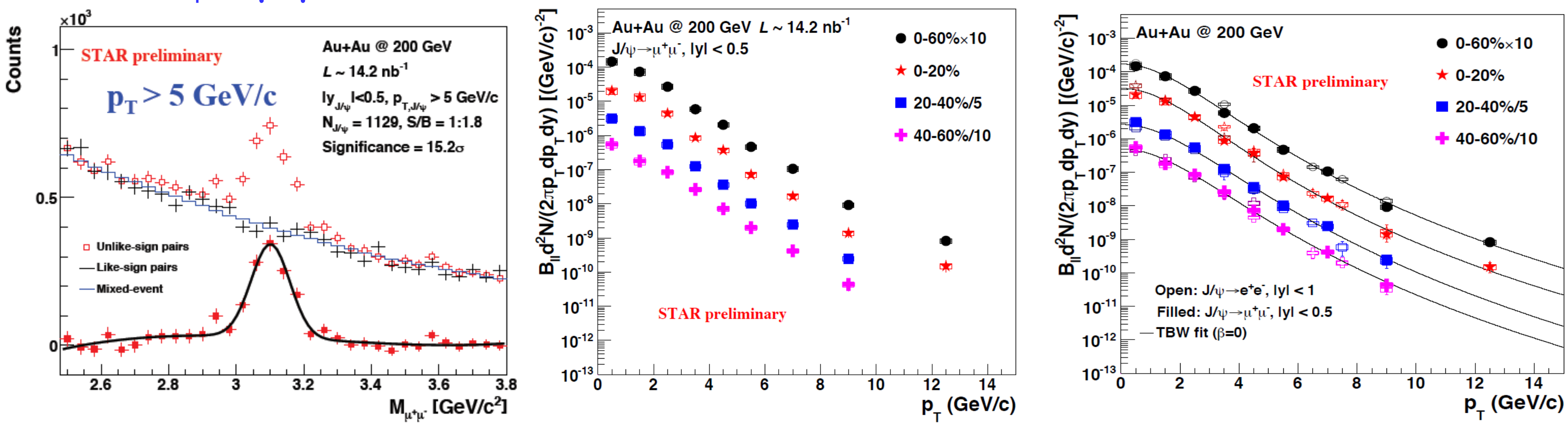
- Similar suppression as pions at high p_T

Invariant yield of J/ψ in Au+Au at 200 GeV

TPC & ToF & MTD

Full statistics from 2014 Au+Au 200 GeV run

$J/\psi \to \mu^+\mu^-$



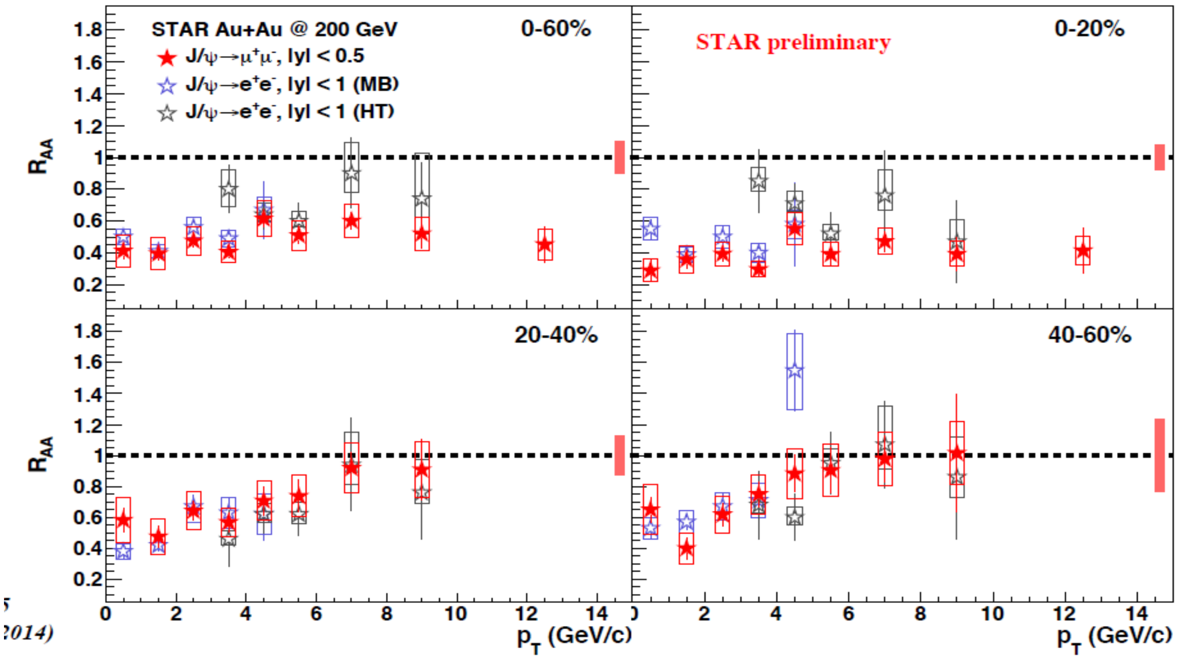
- First mid-rapidity measurement of J/ψ yield in Au+Au collisions via di-muon channel for $0 < p_T < 15$ GeV/c.
- Consistent with the di-electron results.
- Tsallis Blast Wave fits to di-electron results assuming zero velocity for J/ψ.

TakahitoTodoroki & STAR
SQM 2016, Berkeley, USA,
June 27 - July 1, 2016

STAR Collaboration
Phys. Lett. B722 (2013) 55
Phys. Rev. C90 (2014) 024906

J/ψ meson nuclear modification in AuAu @ 200 GeV

$$R_{AA}(p_T) = \frac{\sigma_{in}^{pp}}{< N_{coll}^{AA} >} \cdot \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta}$$

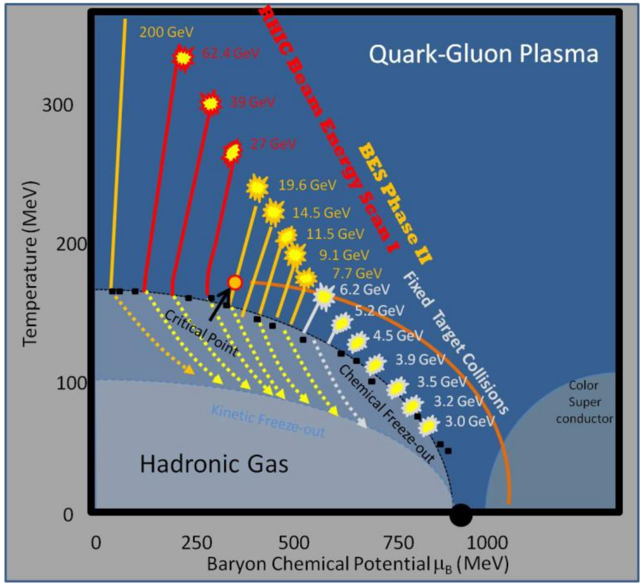


- R_{AA} vs. p_T is consistent with di-electron channel results for the entire p_T range within uncertainties in all centralities.
- Strong suppression at low p_T.
- Less suppression at higher p_T.

TakahitoTodoroki & STAR
SQM 2016, Berkeley, USA,
June 27 - July 1, 2016

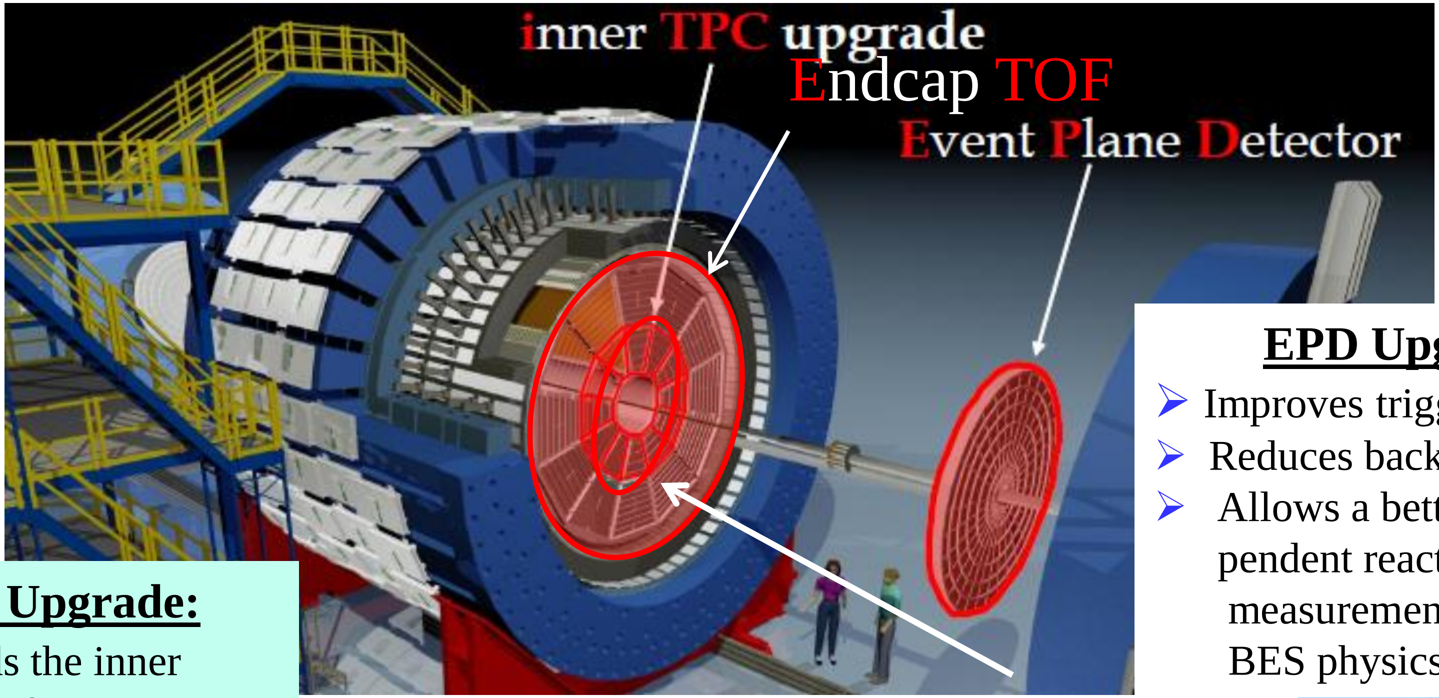
STAR Collaboration
Phys. Lett. B722 (2013) 55
Phys. Rev. C90 (2014) 024906

The STAR Upgrades and BES Phase II



Collider mode	Fixed target mode
$7.7 < \sqrt{s}_{NN} < 20$ GeV	$3 < \sqrt{s}_{NN} < 7.7$ GeV
$300 < \mu_B < 420$ MeV	$420 < \mu_B < 750$ MeV

New Detectors for BES Phase II



iTPC Upgrade:

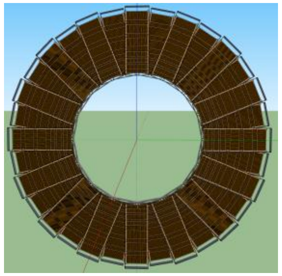
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:

- Rapidity coverage is critical
- PID at $\eta = 0.9$ to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR

EPD Upgrade:

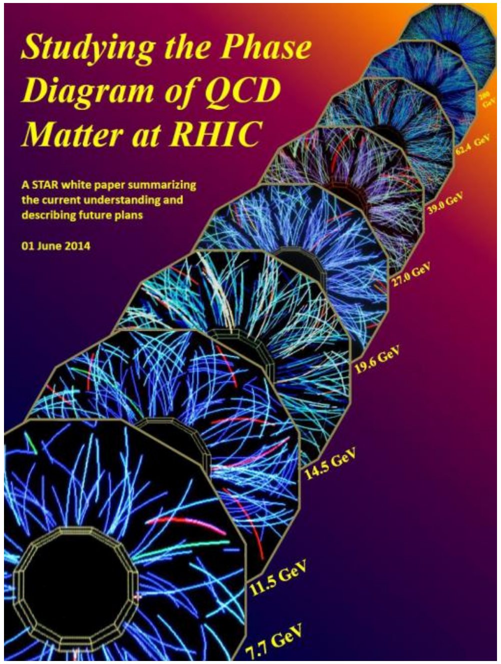
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics



Major improvements for BES-II.

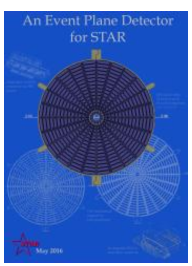
A.Schmah & STAR
SQM2016, Berkeley, USA

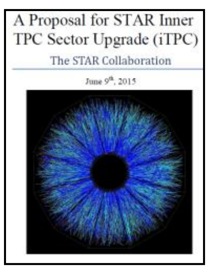
Beam Energy Scan II (2019-2020)

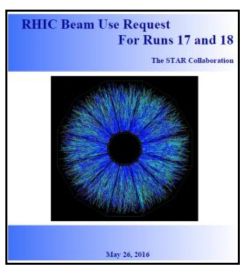


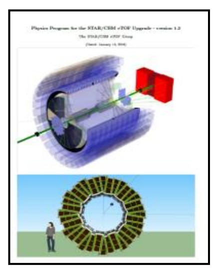
STAR upgrade for BES II

- Select the most important energy range
  5 to 20 GeV
- Improve significance
  Long runs, higher luminosity (eCooling)
- Refine the signals
  Detector improvements (iTPC,eToF,EPD)
- Extend Range
  Fixed Target Opportunity
- Concurrent Theory Initiative
  Beam Energy Scan Theory Collaboration









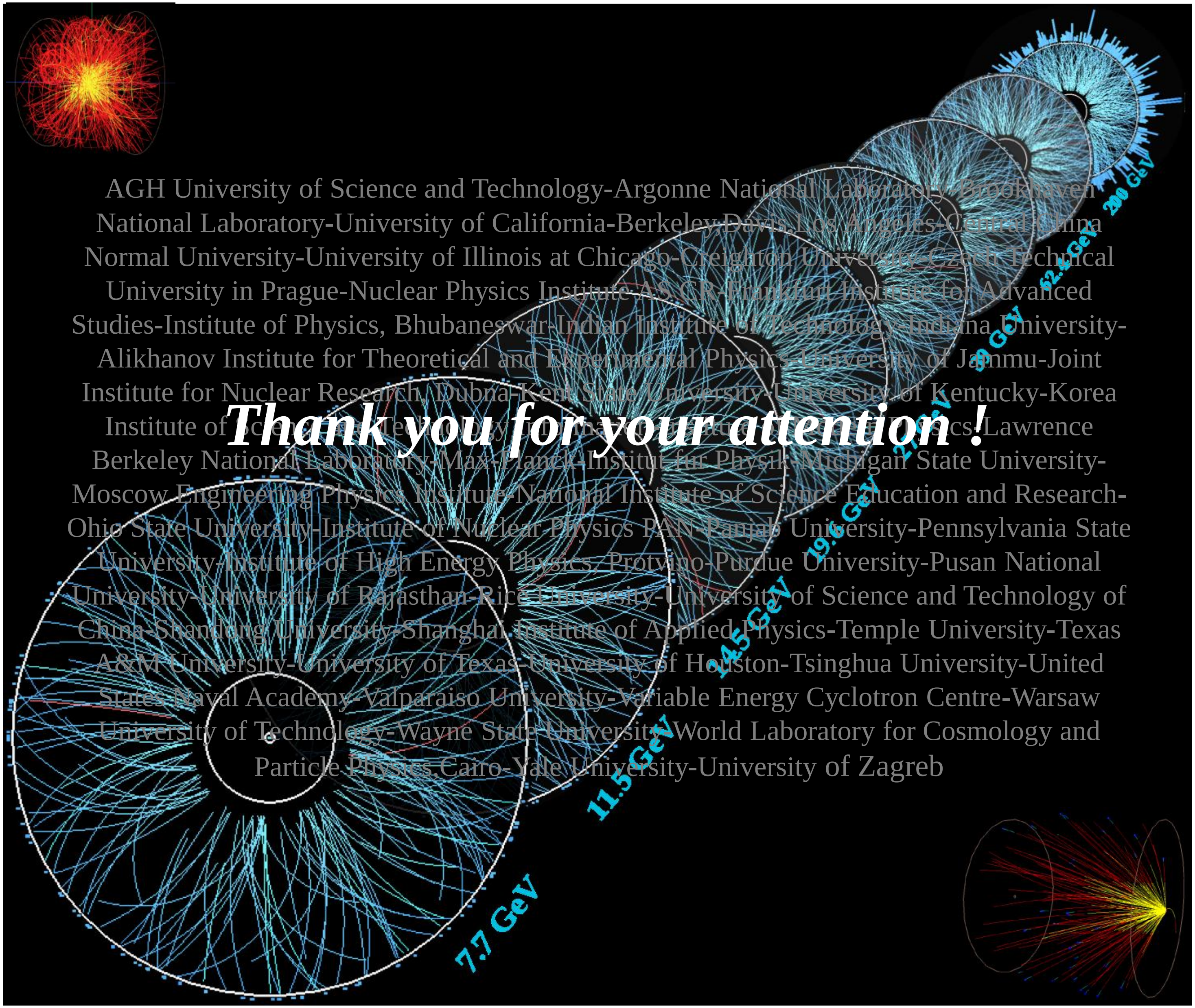
$\sqrt{s_{NN}}$ (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV)	420	370	315	250	205
BES I (MEvts)	4.3	---	11.7	24	36
Rate(MEvts/day)	0.25		1.7	2.4	4.5
BES I $\mathcal{L}$ (1×10^{25}/cm²sec)	0.13		1.5	2.1	4.0
BES II (MEvts)	100	160	230	300	400
eCooling (Factor)	4	4	4	3	3
Beam Time (weeks)	**12**	**9.5**	**5.0**	**5.5**	**4.5**

BES-II whitepaper: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598
iTPC proposal: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
Event-Plane Proposal-May. 2016
eTOF Proposal-January, 2016

D.Cebra & STAR Collaboration
RHIC & AGS Users Meeting 2016

Conclusions

- Some of STAR results from RHIC Beam Energy Scan-I were reviewed.
- The wide range of collision energy ($\sqrt{s_{NN}}$ =*7-200 GeV*), centrality, various probes (*π,p,K,J/ψ,e,μ,Λ,Ξ,Ω, d,..*) allows us to scan the phase diagram of nuclear matter over a wide range of T and μ_B .
- The obtained data are basis for verification of different theoretical models, transition scenarios and properties of nuclear matter (*the hydro of ideal liquid, NCQ scaling, jet quenching, the spinning QGP etc.)*
- The collider and fixed target modes with new detector systems (*HFT, MTD, iTPC, EPD, eTOF*) significantly improve the capabilities of STAR for BES II to detect key features of QCD phase diagram.



AGH University of Science and Technology-Argonne National Laboratory-Brookhaven National Laboratory-University of California-Berkeley-Davis-Los Angeles-Central China Normal University-University of Illinois at Chicago-Creighton University-Czech Technical University in Prague-Nuclear Physics Institute AS CR-Frankfurt Institute for Advanced Studies-Institute of Physics, Bhubaneswar-Indian Institute of Technology-Indiana University-Alikhanov Institute for Theoretical and Experimental Physics-University of Jammu-Joint Institute for Nuclear Research, Dubna-Kent State University-University of Kentucky-Korea Institute of Science and Technology Information-Institute of Modern Physics-Lawrence Berkeley National Laboratory-Max-Planck-Institut fur Physik-Michigan State University-Moscow Engineering Physics Institute-National Institute of Science Education and Research-Ohio State University-Institute of Nuclear Physics PAN-Panjab University-Pennsylvania State University-Institute of High Energy Physics, Protvino-Purdue University-Pusan National University-University of Rajasthan-Rice University-University of Science and Technology of China-Shandong University-Shanghai Institute of Applied Physics-Temple University-Texas A&M University-University of Texas-University of Houston-Tsinghua University-United States Naval Academy-Valparaiso University-Variable Energy Cyclotron Centre-Warsaw University of Technology-Wayne State University-World Laboratory for Cosmology and Particle Physics,Cairo-Yale University-University of Zagreb

Thank you for your attention !

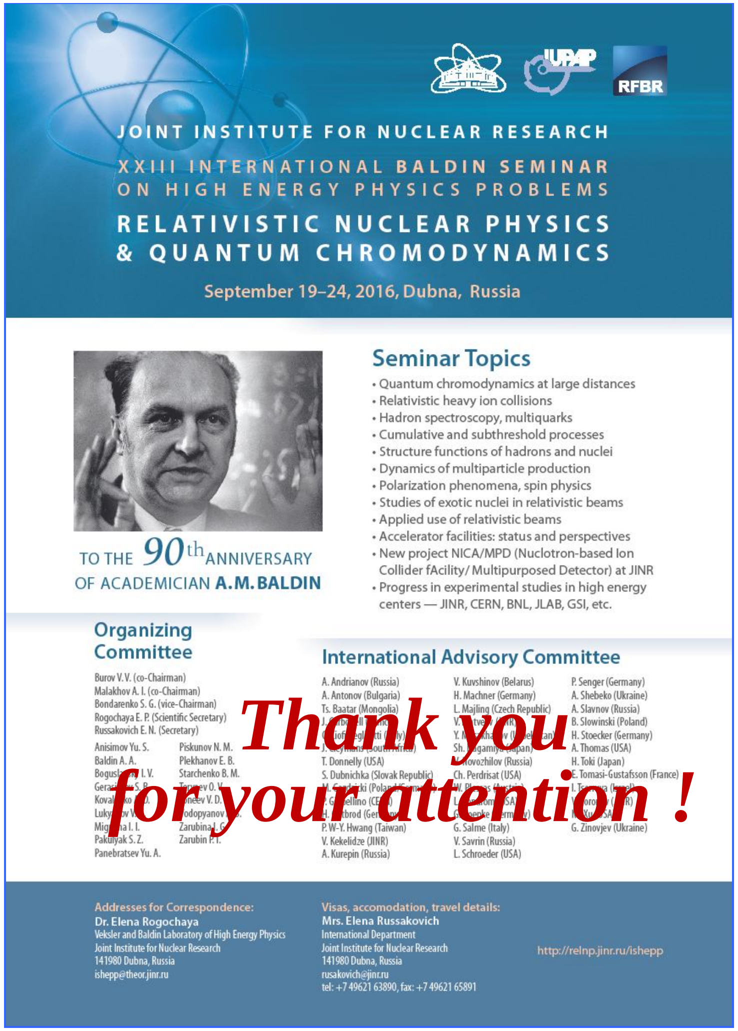
Back-up slides

Devoted to the 90th anniversary of Academician A.M. Baldin

XXIII International Baldin Seminar on High Energy Physics Problems

Relativistic Nuclear Physics & Quantum Chromodynamics

September 19 - 24, 2016, Dubna, Russia



Thank you for your attention !