pA Physics – From Fermi Lab Bubble Chamber Data to Future STAR Upgrade at RHIC

Huan Zhong Huang
黃煥中
Department of Physics and Astronomy
University of California at Los Angeles

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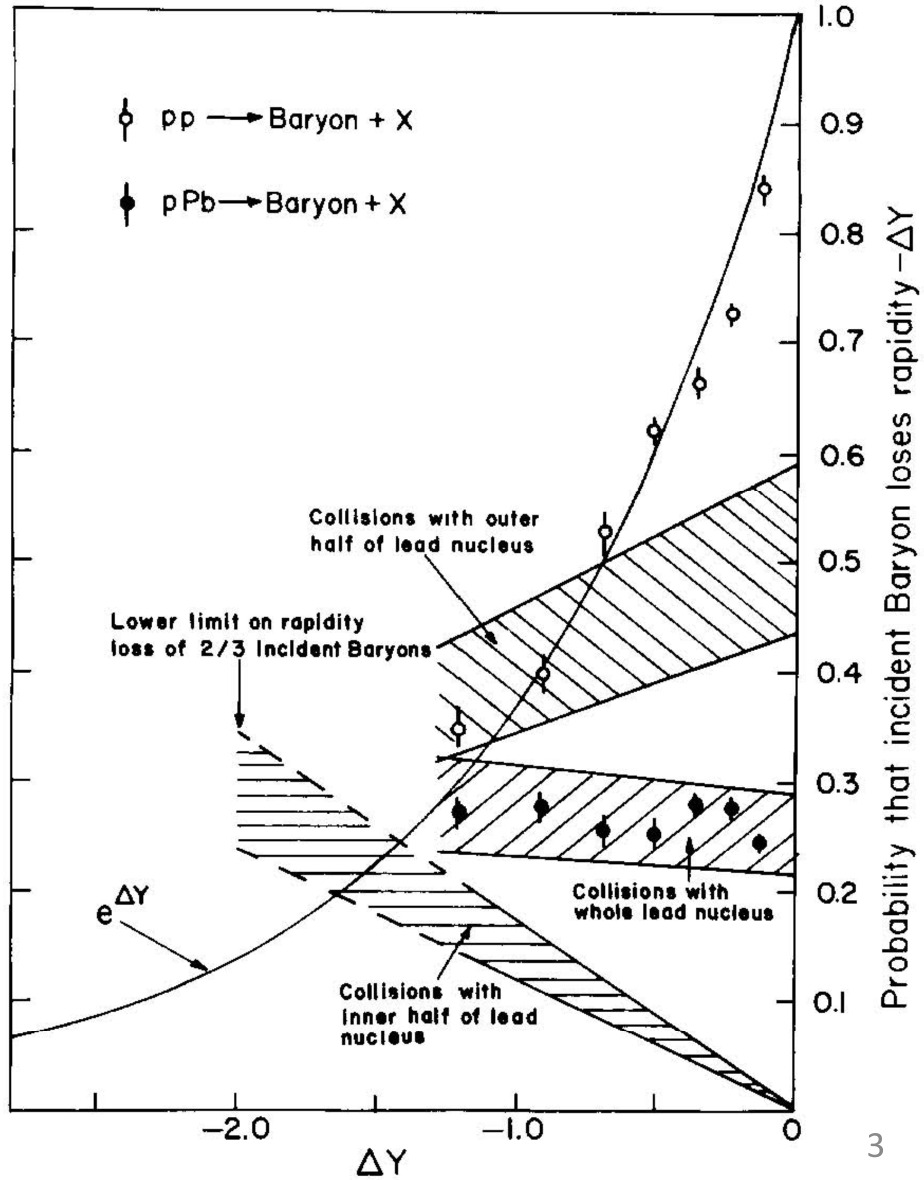
Outline

- Proton Energy Loss and Proton Fragmentation
- Gluon Junction and Mid-rapidity Hyperons
- Paradigm Shift – Parton Saturations in Nuclei
- STAR Scientific Program and Future Upgrades

Nuclear Stopping Power

Is there sufficient energy deposition at mid-rapidity in A+A collisions to create the Quark-Gluon Plasma at high temperature and energy density?

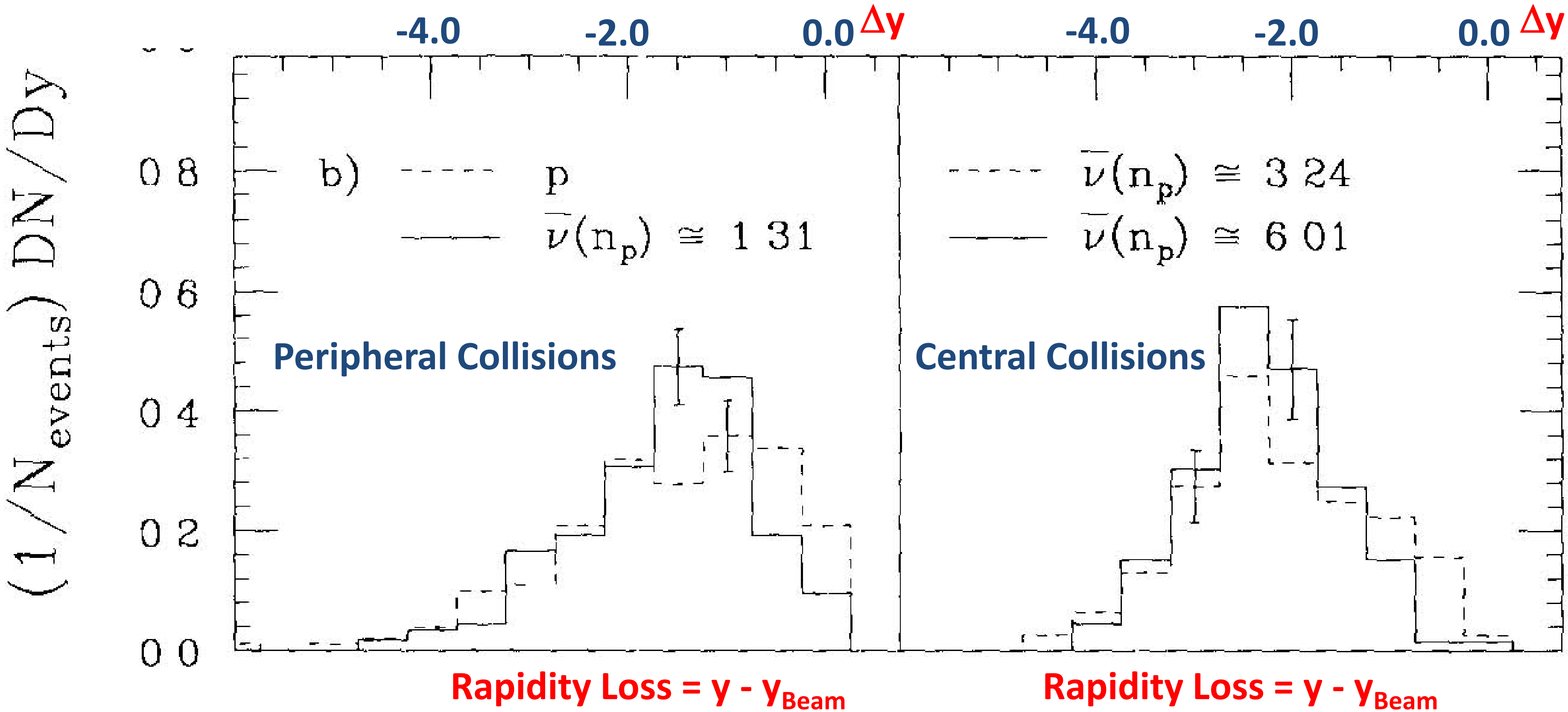


W. Busza and A. S. Goldhaber Phys. Lett. B 139, 235 (1984)

Leading Particle Rapidity Distribution

FermiLab 30-in bubble chamber hybrid spectrometer:

p + Mg/Ag/Au collisions, a few hundred events !



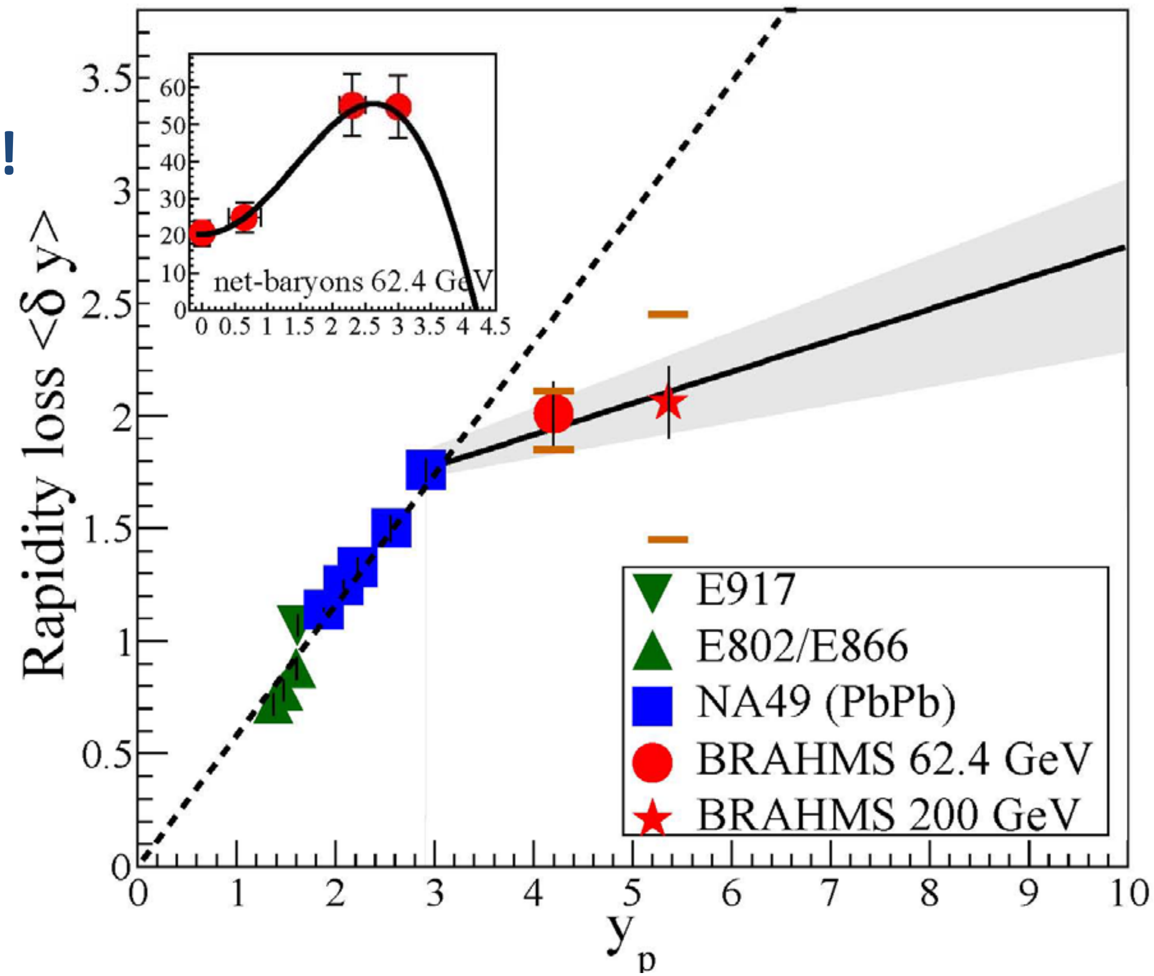
1) There is a proton rapidity loss of ~ 2 units in central p+A collisions
2) No particle identification – leading charged particles assumed proton
3) Major uncertainties – leading neutron events, and statistical

The Busza-Goldhaber Expectation !!

The average rapidity loss ~ 2 units from central pA collisions !

Recent data from BHRAMS are consistent with the B-G expectation !

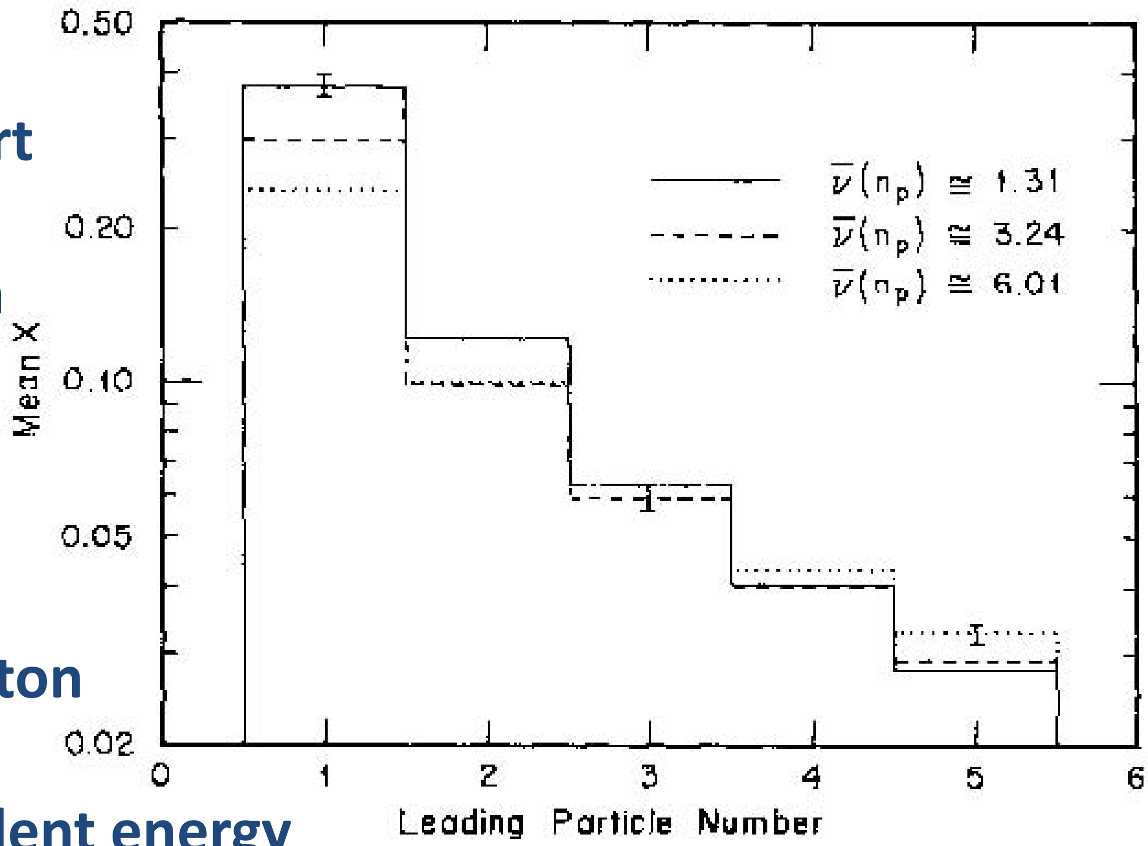
RHIC – BHRAMS PLB 677, 267 (2009)



Proton rapidity loss versus energy deposition at mid-rapidity

Proton rapidity loss
- baryon number transport

A few leading particles can carry away a significant fraction of beam energy!



Physical picture –
valence quarks in the proton
-- leading particles
-- carry away ~50% incident energy
gluons in the proton -- multi-particle production
still unknown – neutrons and neutral pions

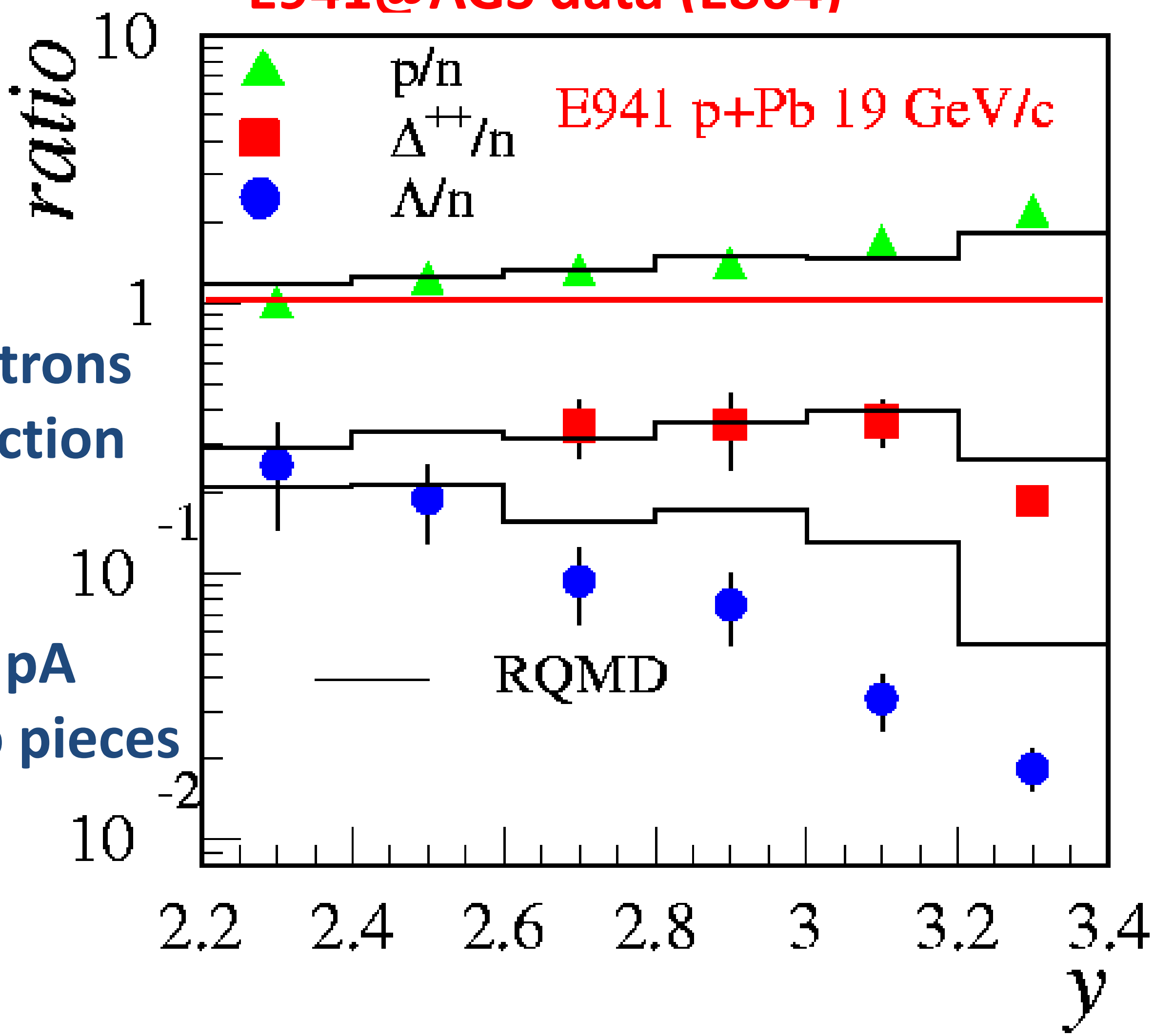
Proton Fragmentation and Hyperon Production

Inclusive pA
pAu→p+X
pAu→n+X

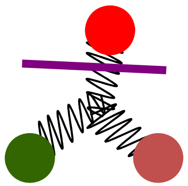
Fragmentation to neutrons
-- significant cross section

Baryons very brittle !
-- filter out gluons in pA
proton breaking to pieces

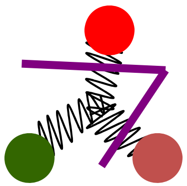
E941@AGS data (E864)



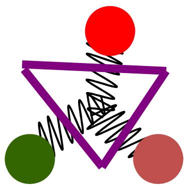
Proton Fragmentation Phenomenology



Diquark-quark fragmentation function



Three-quark fragmentation function
(hardly constrained, may be important is n/p ~ 1)



Gluon Junction fragmentation
(no unambiguous experimental result)

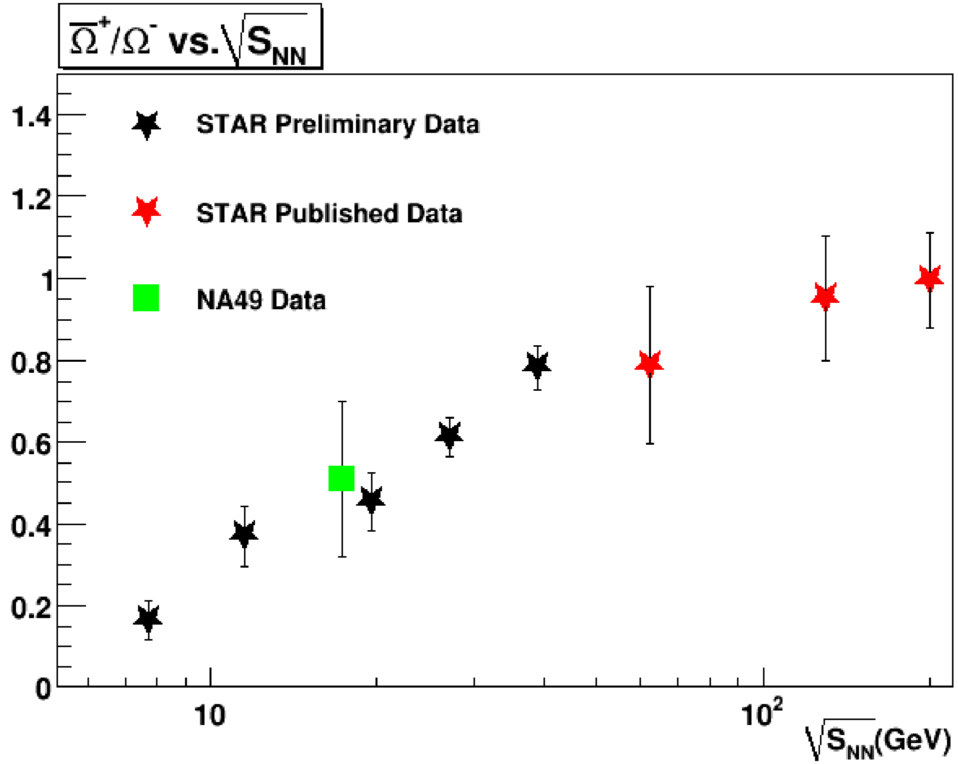
Kharzeev [PLB 378 (1996) 238] – gluon junction carries baryon #
Gyulassy et al: gluon junction – effective baryon # transport process

Constraining – these fragmentation functions/gluon junction
-- exclusive measurements of all leading particles in pA
(including neutral leading particles)
-- baryon # transport to hyperons

Ratio of anti-Omega/Omega

S quarks are pair-produced:

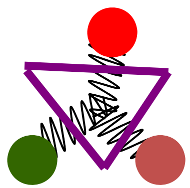
- why are there NET baryon numbers in Ω?
- What dynamical process responsible for the baryon number transport?



Note the anti-Lambda/Lambda ratio is much smaller where u/d quarks can carry the net quark number from baryon number stopping !

Baryon Number Transport to Omega

Direct Transport Through Gluon Junctions …



$\Omega + K + K + K + (X)$

Indirect Transport Through Pair Production Modified by
Baryon Chemical Potential …

$\Omega\ \bar{\Omega}$ and Ω K

$\Xi\ \ \bar{\Xi}$ and ΞK

$\Lambda\ \ \bar{\Lambda}$ and ΛK

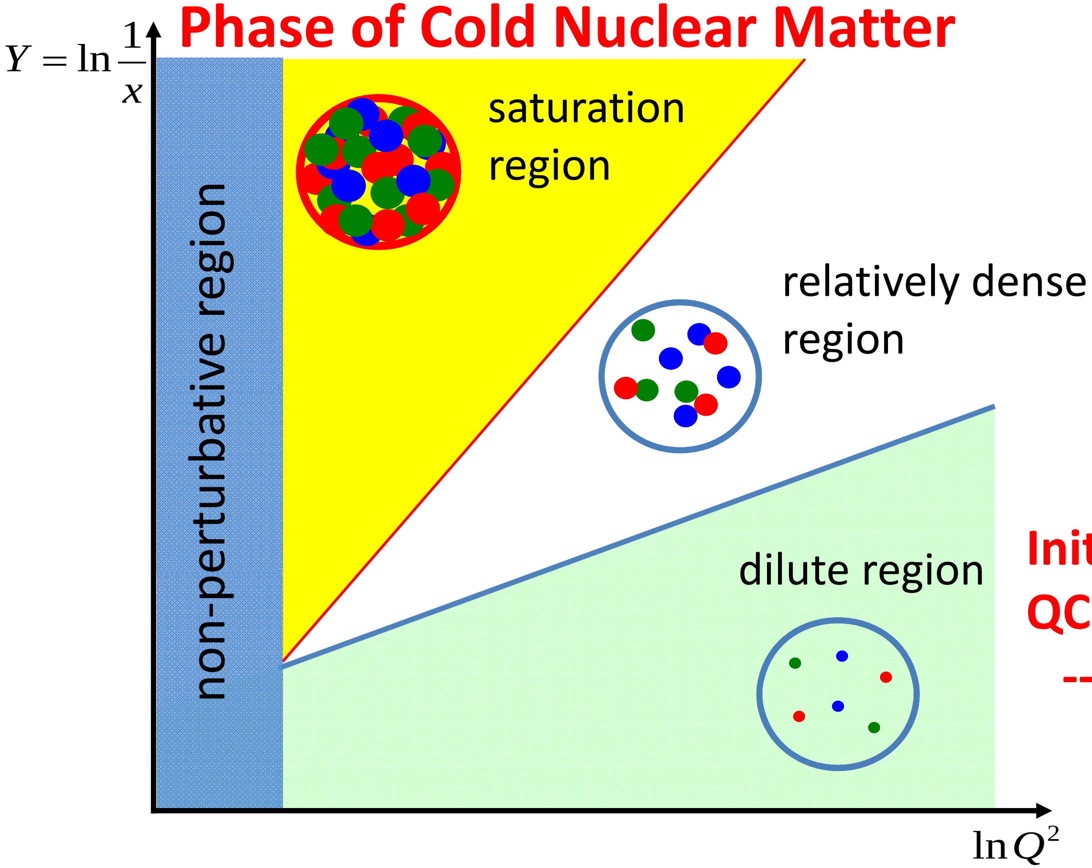
Net Baryon Density Increases the
Associated Production and
Transfers net baryon number
to multiply-strange baryons !

Event-by-Event STAR Hyperon Correlations
STAR Future Upgrade – iTPC, Forward Upgrade

Paradigm Shift: Gluon Saturation in Nuclei

pA dynamics in the forward proton semi-sphere sensitive to details of the gluons in the nuclei

Phase of Cold Nuclear Matter



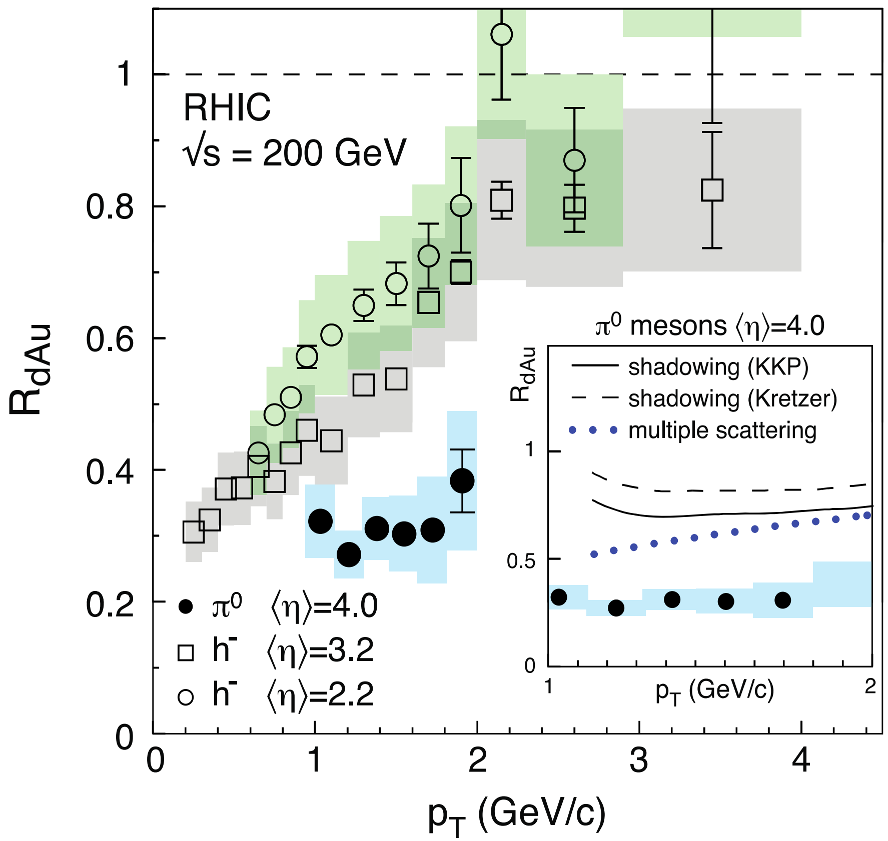
Forward direction kinematics favors parton scatterings of large x partons from p off small x partons from A !

Initial conditions for AA
QCD in high density non-linear regime -- Color Glass Condensate

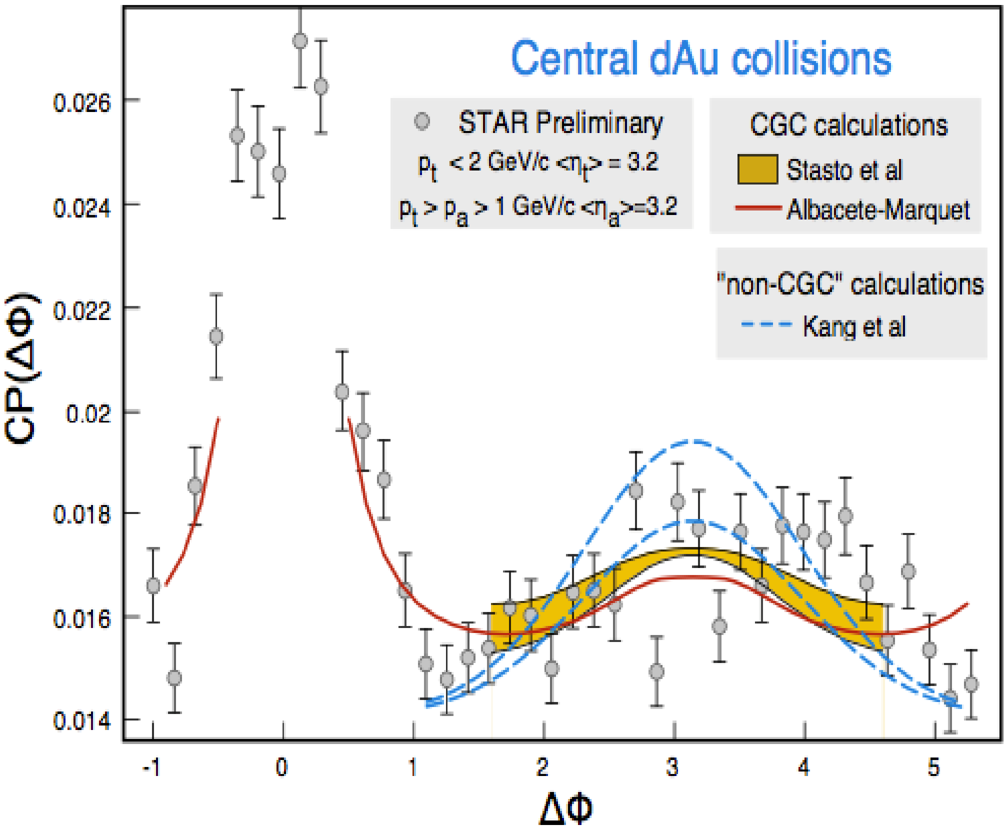
The quantum nature of the partons must manifest through saturations ! At what Q_S and x scales and to what extent?

Intriguing Hints @ RHIC d+Au Collisions

Suppression at forward direction



Broadening of away-side peak In $\pi^0\pi^0$ correlations

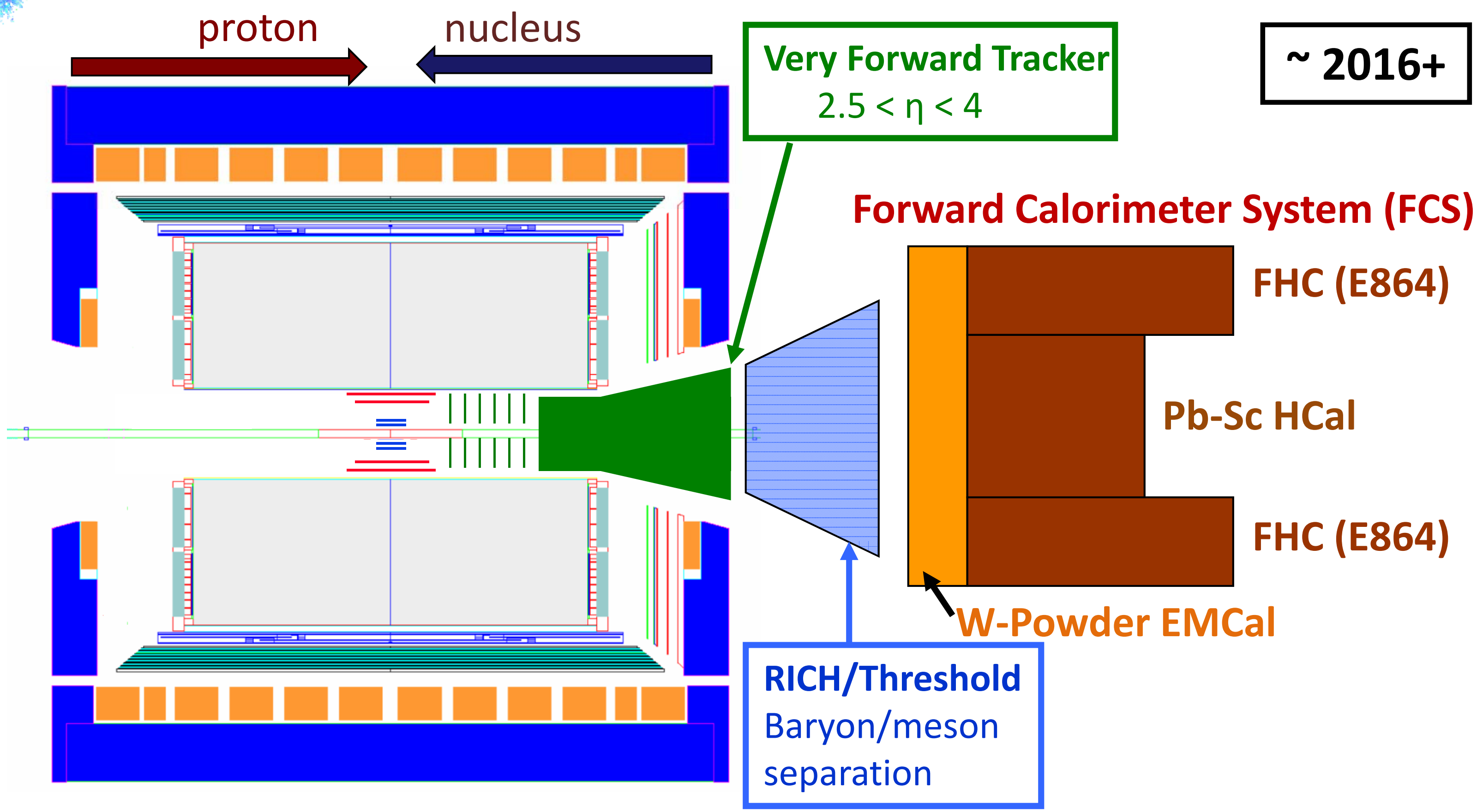


Next: full azimuthal coverage for photon, hadron and jet @ forward

h-h, γ-jet and jet-jet correlations!

systematic scan of A in p(d)+A collisions !

STAR forward instrumentation upgrade



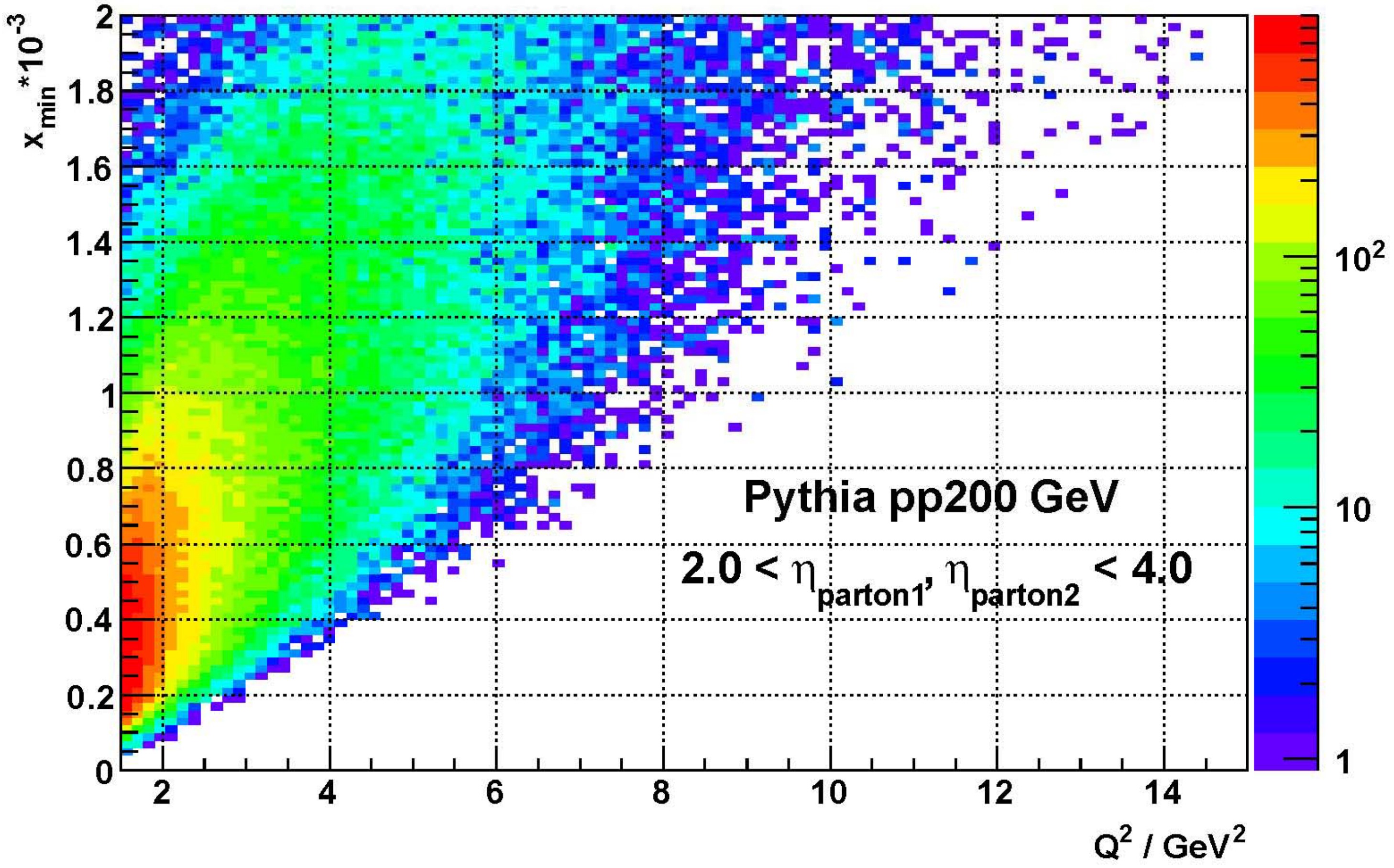
- Forward instrumentation optimized for **p+A** and **transverse spin** physics
  - Charged-particle tracking
  - *e*/*h* and γ/π^0 discrimination
  - Possibly Baryon/meson separation

STAR Forward Upgrade

Physics Focuses:

- Forward photon/electron/jet/leading hadron
- p+p -- transverse spin dynamics
  - (transversity function and Collins frag.
    QCD twist-3 processes)
- pp/pA -- Drell-Yan, jet-h, h-h, gamma-h correlations
  - (initial conditions and CGC)
- AA – Correlations over large rapidity range
  - (forward and mid-rapidity v_2 correlation,
    and possible heavy quark decay NPE)

Accessible x-Q^2 phase space from h-h correlations in the forward direction



STAR Plan for the Forward Upgrades

1) The Forward Calorimeter System (FCS) benefited from an EIC detector R&D project for constructing W-powder EMC modules. Current R&D effort focuses on compact read-out scheme and mechanical properties. We plan to build a full-scale prototype FCS module.
2) The Very Forward Tracker (VFT) detector is under consideration, combination of silicon and gas pad chambers. Details of the design <– AA requirements
3) RICH detector in STAR forward direction has not been demonstrated. Threshold Cerenkov detector is also under consideration. This detector will not be included in the initial phase of the upgrade project.
4) Schedule: Develop CD documents and Proposals aiming at VFT/FCS construction starting 2015+

Electron Ion Collider – Nuclear Parton Structure

eRHIC is better suited for full explorations of the spin structure of the proton and the nuclear parton distribution functions !

2020+
eRHIC essential for the future of RHIC community !

STAR Upgrade Path Towards eSTAR

Future eSTAR Option -- Detector R&D:

- EMC – Compact W-powder SPACAL
  (STAR Forward Upgrade, essential for eSTAR)
- Crystals – PWO and BSO testing
- ETTIE – electron PID and tracking in the forward
- Simulations

STAR will be ready with a detector coverage to explore eA physics during the initial phase of the eRHIC development !

RHIC – a Dedicated QCD Facility

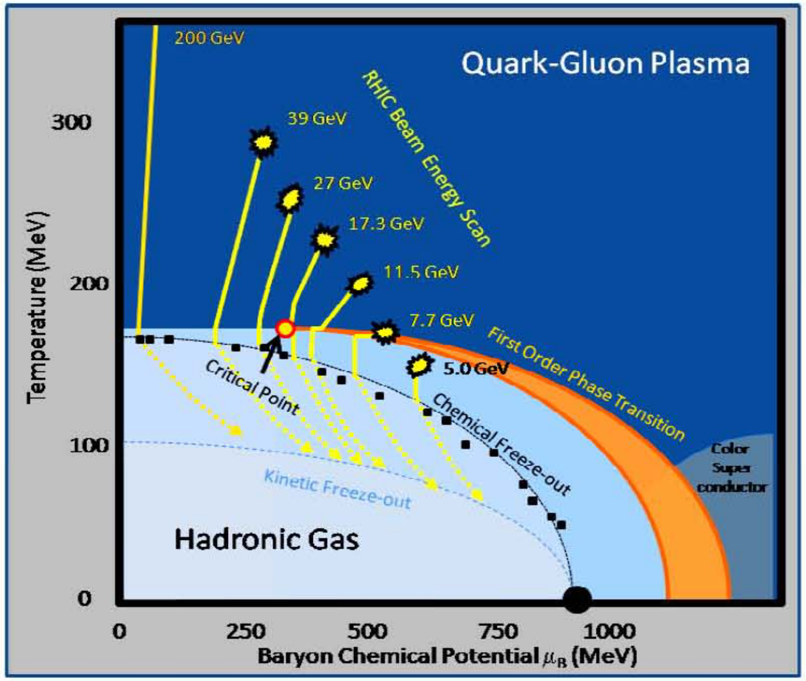
QCD – Fundamental Corner Stone of the Standard Model !!
-Dynamics of QCD in bulk matter, vacuum structure and hadrons?
Condensed Matter Physics with Underlying QCD Interactions !

We are beyond the QGP discovery phase already !
LHC -- Energy/Temperature Frontier
RHIC – New Horizons in QCD Phase Structure, Vacuum Excitation, Initial State Color Charge Dynamics, Hadron Structure and Exotics

RHIC continues to explore new QCD horizons with planned detector upgrades and vigorous scientific programs in the coming decade !

Very Exciting Scientific Program and Detector Upgrades for the coming decade

Hot QCD Matter



1: Properties of the sQGP

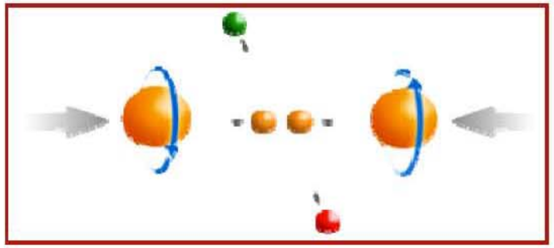
2: Mechanism of energy loss: weak or strong coupling?

3: Is there a critical point, and if so, where?

4: Novel symmetry properties

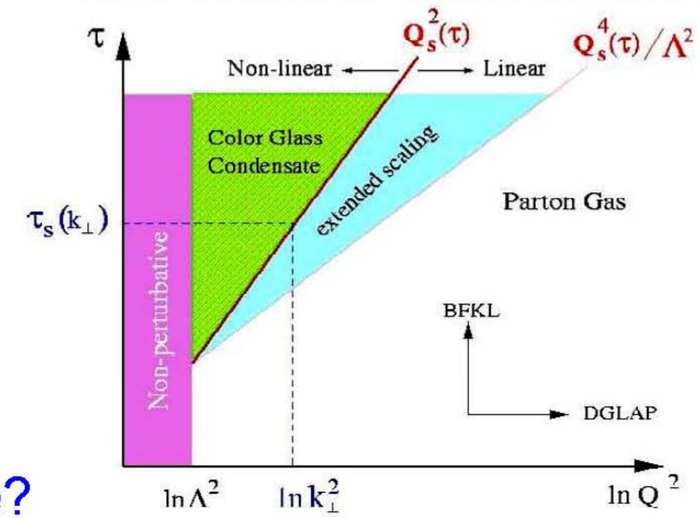
5: Exotic particles

Partonic structure



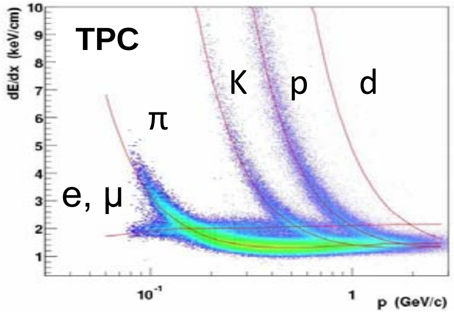
6: Spin structure of the nucleon

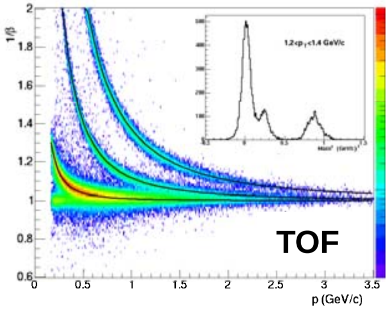
7: How to go beyond leading twist and collinear factorization?



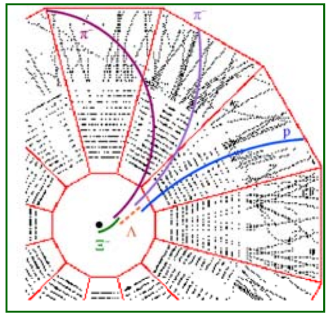
8: What are the properties of cold nuclear matter?

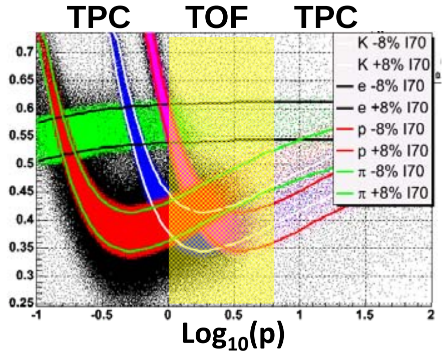
Particle Identification at STAR



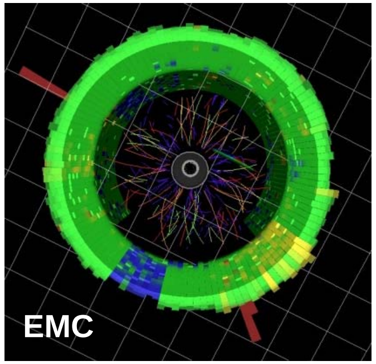


Charged hadrons

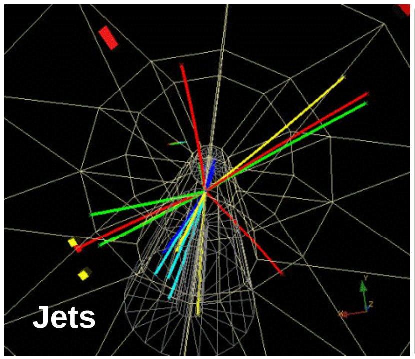




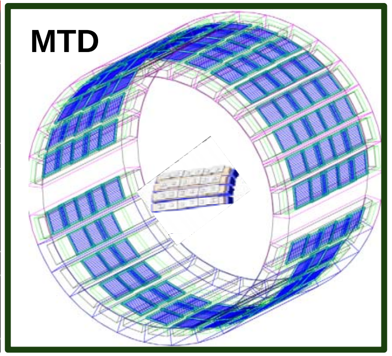
Hyperons & Hyper-nuclei



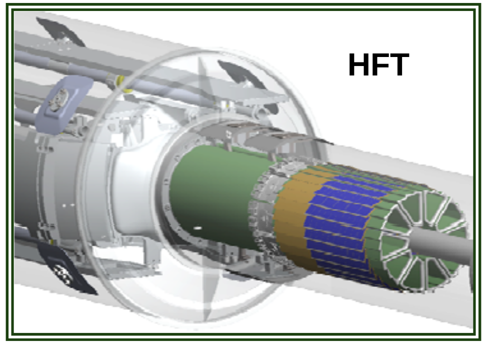
Neutral particles



Jets & Correlations



High p_T muons



Heavy-flavor hadrons

Multiple-fold correlations among the identified particles!

Nearly perfect coverage at mid-rapidity

Forward upgrade → giant leap towards perfection for pp,pA,AA &eA

Outlook

(A+A Program)

1) QCD Phase Boundary and Possible Critical Point
2) sQGP Properties
3) Chiral Symmetry and Di-lepton Probes
4) QCD Vacuum Excitation, Symmetry and Exotics

(Spin Program)

p+A Program

1) Phase of Cold Nuclear Matter –
   Gluon Saturation at Low x Region
2) Initial Conditions of AA

Towards eA Program

1) R&D Efforts
2) Day-1 Physics Capability @eRHIC

Backup

STAR Vision for BES II Program

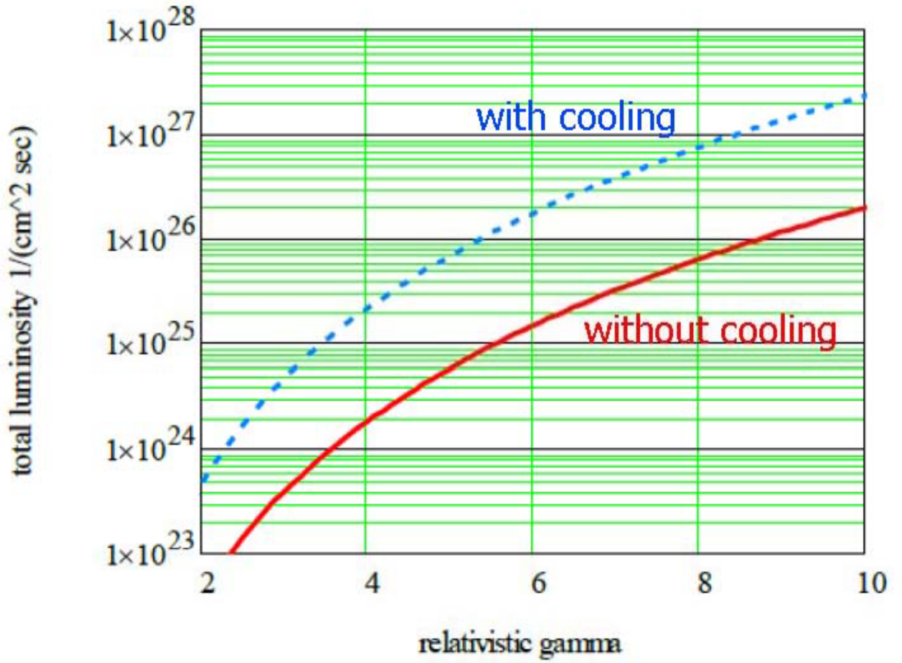
Likely beam energies below 25 GeV with improved statistics particularly for the lower end of the beam energies !

-- need electron cooling from CAD to be more efficient

-- match iTPC upgrade schedule for better detector coverage

Electron cooling necessary !!
Use RF Gun Cooler OR
Use Fermi Lab Pelletron ?

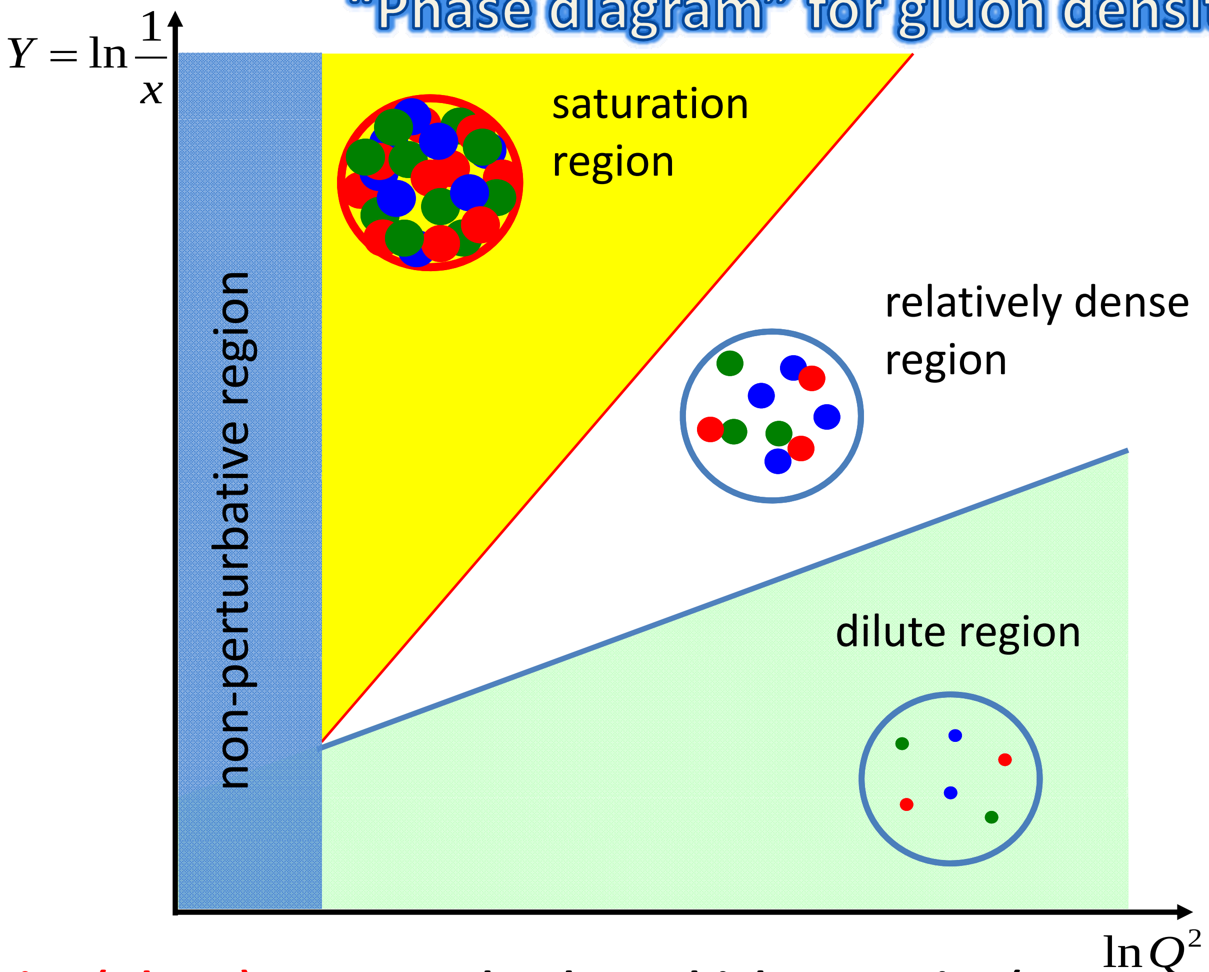
A. Fedotov – RHIC-AGS User Meeting 2012



RHIC CAD installation of the e-cooling device ~ 4 years !

BES-II takes data in 2016 +

"Phase diagram" for gluon density



Dilute region (x large): **pQCD works, the multiple scattering (power corrections) are not important**

Relatively dense region (x relatively small): **multiple scattering starts to become important, any additional scattering is power suppressed by** Q_s^2 / Q^2

Saturation region (x extremely small): **all the additional scattering becomes equally important, all power terms** $(Q_s^2 / Q^2)^n$ **have to be resummed**

STAR Detectors *Fast and Full azimuthal particle identification*