STAR Heavy-Ion Program in 2015+

Zhangbu Xu
(for the STAR Collaboration)

- Key Questions in Heavy-Ion Program
  - Properties of sQGP and its thermalization
  - QCD critical point and 1st phase transition line
  - Detailed Mechanism of jet quenching
  - Novel symmetries in QCD
  - New (exotic) particles
  - Initial state of gluonic matter in nuclear collisions
- Identify Key Measurements
- Upgrades relevant to 2015+

HAVEN
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Charges from ALD and Priority

Three Stages of RHIC's Future

Short-term (2011-2016): ***ongoing upgrades to RHIC $\mathcal{L}$, PHENIX & STAR fuel well-defined program addressing key open questions:***

- ***How perfect is the near-perfect liquid?***
- ***Is the nature of QCD vacuum transformed at RHIC T? (e.g., are LPV "bubbles" real effect? Chiral symmetry restored?)***
- ***Is there a critical endpoint in QCD phase diagram?***
- ***How is force between q and $\overline{q}$ modified in QGP?***
- ***How do partons lose energy in traversing QGP?***
- ***Does the QGP respond collectively to the lost energy?***
- ***How do nucleons get their spin from q, g constituents?***
- ***...***

Issue: ***Define complementarity to LHC HI clearly & compellingly!***

Medium-term (2017-2022): ***PHENIX, STAR Decadal Plans aimed at pursuing compelling long-term questions in A+A, d(p)+A, and $\vec{p}+\vec{p}$ that require further detector upgrades***

Issues: ***Why are RHIC HI collisions still needed? Can national NP budget support operations at CEBAF, RHIC and FRIB, plus construction of EIC? What is optimal strategy for RHIC going into next NP Long Range Plan?***

I am herein charging the PHENIX and STAR Collaborations with generating new decadal plans that lay out your proposed science goals and detector upgrade paths for the period 2011-2020.
--- Steve Vigdor

Collaboration Priority:

2012---2016 (HFT+MTD+…)
AA, AB, pp (Dunlop's talk)
2017—~2018 (Forward Upgrades):
pA and polarized pp (He3)
~2019 preparation for eRHIC
~2020+:
eSTAR (workshop tomorrow)

Are we done with HI by ~2016+:

If eRHIC starts **2023+**
or evidence of critical point
or new discoveries in next 5 years
demand further experiments
My talk➔

How to answer these questions

- Hot QCD matter: high luminosity RHIC II (fb^{-1} equivalent)
  - Heavy Flavor Tracker: precision charm and beauty
  - Muon Tagging Detector (MTD): e+μ and μ+μ at mid-rapidity
  - Trigger and DAQ upgrades to make full use of luminosity
- Phase structure of QCD matter: possible Phase II BES
- Near-term upgrades for p+p collisions
  - Forward GEM Tracker: flavor-separated anti-quark polarizations
  - Forward Hadron Calorimeter: strange quark polarization
  - Roman Pots phase II: search for glueballs
- Cold QCD matter and nuclear spin: high precision p+p and p+A, followed by e+p and e+A
  - Major upgrade of capabilities in forward direction
  - Devote the time to explore p+A, not d+A
  - Existing mid-rapidity detectors well suited for portions of the initial e+p and e+A program, but must extend detection capability to larger rapidities

Summary of the plan

	Near term (Runs 11-13)	Mid-decade (Runs 14-16)	Long term (Runs 17–)
Colliding systems	*p*+*p*, A+A	*p*+*p*, A+A	*p*+*p*, *p*+A, A+A, *e*+*p*, *e*+A
Upgrades	FGT, FHC, RP, DAQ10K, Trigger	HFT, MTD, Trigger	Forward Instrum, eSTAR, Trigger
(1) Properties of sQGP	Y, $J/\psi \rightarrow ee$, m_{ee}, v_2	Y, $J/\psi \rightarrow \mu\mu$, Charm v_2, R_{CP}, corr, Λ_c/D ratio, μ-atoms	*p*+A comparison
(2) Mechanism of energy loss	Jets, γ-jet, NPE	Charm, Bottom	Jets in CNM, SIDIS, *c*/*b* in CNM
(3) QCD critical point	Fluctuations, correlations, particle ratios	Focused study of critical point region	
(4) Novel symmetries	Azimuthal corr, spectral function	*e*-μ corr, μ-μ corr	
(5) Exotic particles	Heavy anti-matter, glueballs		
(6) Proton spin structure	W A_L, jet and di-jet A_{LL}, intra-jet corr, (Λ+Λ) D_{LL}/D_{TT}		Λ D_{LL}/D_{TT}, polarized DIS & SIDIS
(7) QCD beyond collinear fact	Forward A_N		Drell-Yan, F-F corr, polarized SIDIS
(8) Properties of initial state			Charm corr, Drell-Yan, J/ψ, F-F corr, Λ, DIS, SIDIS

Detector Upgrade driven schedule: Measurements listed when they first become possible

Many will continue in future periods

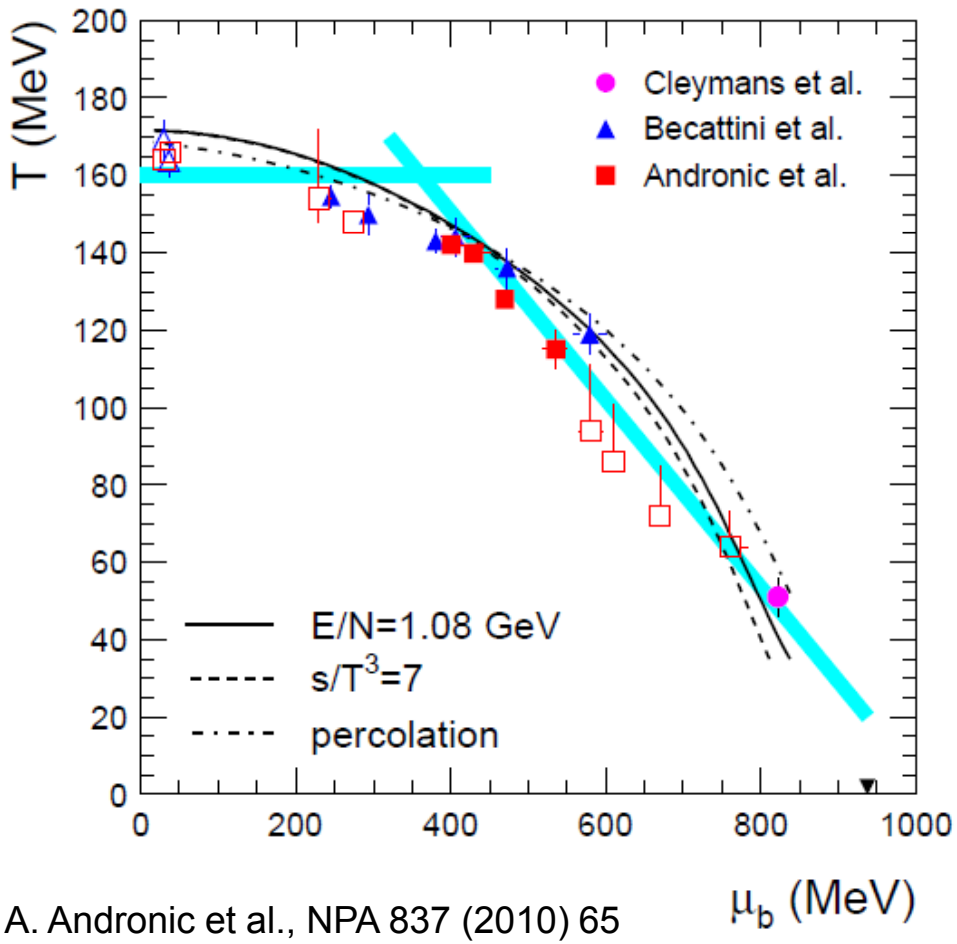
Properties of sQGP and Critical Point

- Chemical properties and Baryon density
  - Identified particle yields
  - Multibaryon states
- Acoustic Effect and η/s
  - Initial state fluctuation and viscous damping
  - v_n from different beam species
- Thermalization:
  - Charm hydrodynamic flow
  - Thermal leptons

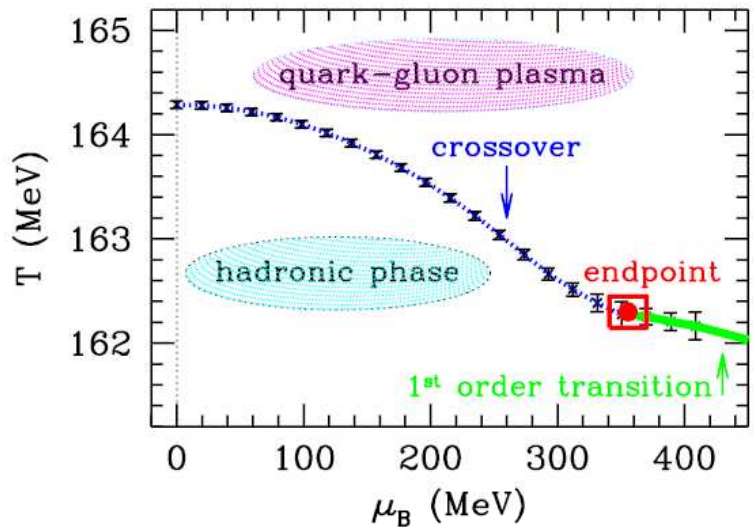
Thermodynamic properties of hot QCD state

A thermodynamic state is specified by a set of values of all the thermodynamic parameters necessary for the description of the system. --- statistical mechanics by K. Huang

Temperature (**T**), chemical potential (**μ**), pressure(**P**), **viscosity (η) …**

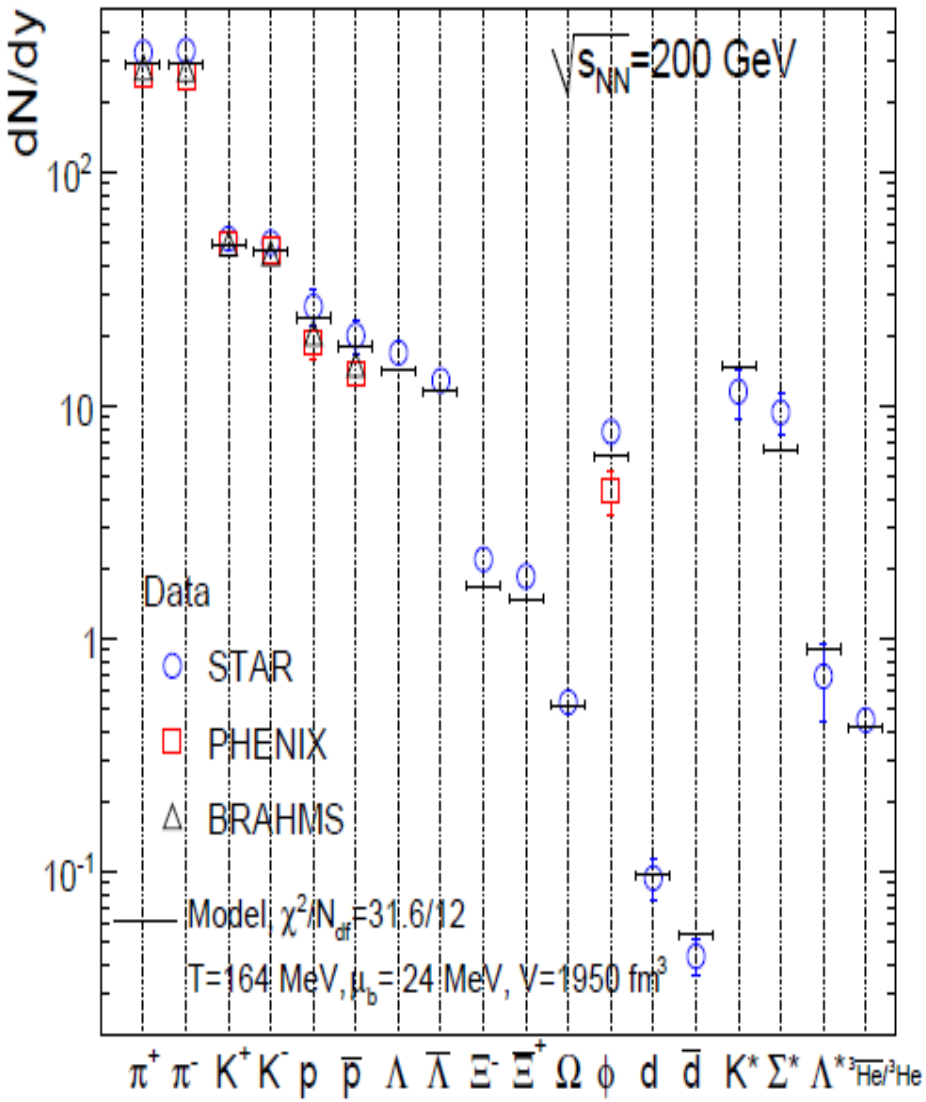


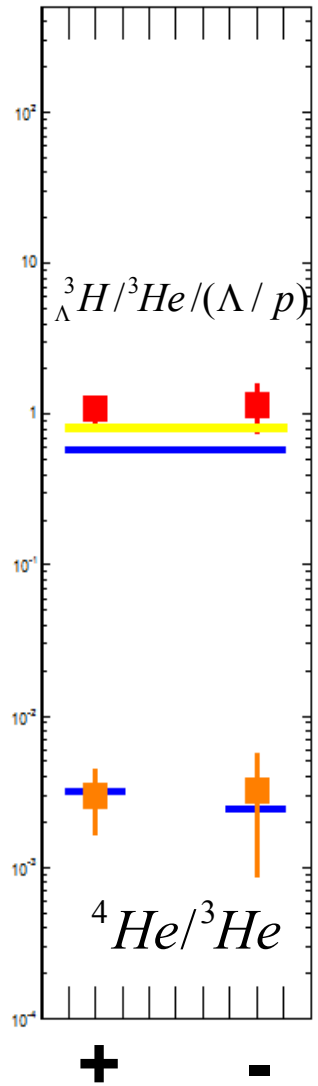
A. Andronic et al., NPA 837 (2010) 65

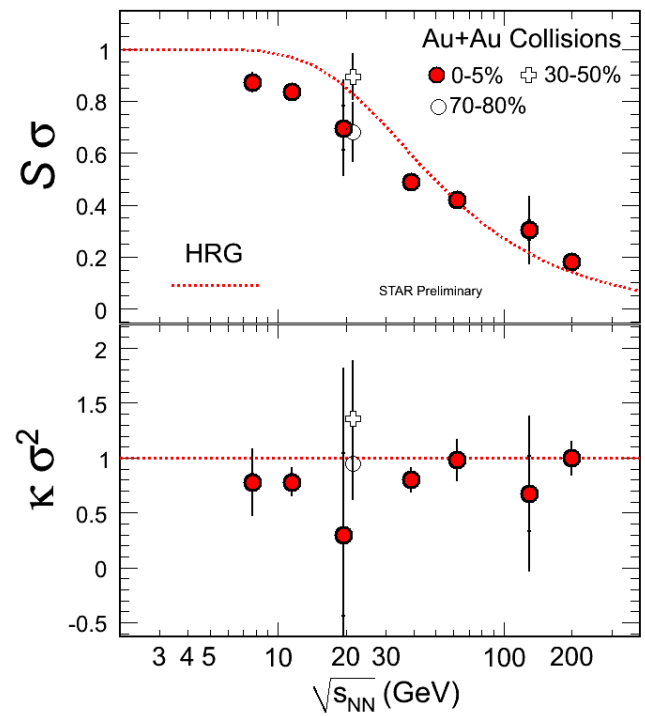


1. Chemical/thermal Equilibrium at certain stage of the evolution
2. At the predicted QCD phase boundary
3. persistent from SPS to RHIC
4. Temperature decreases at AGS and SIS

Predictable Production Rate







Why is it so predictable?
T=164MeV?

A. Andronic, P. Braun-Munzinger, J. Stachel, and H. Stocker, Phys Lett B697:203-207 2011

Predictability is a shock

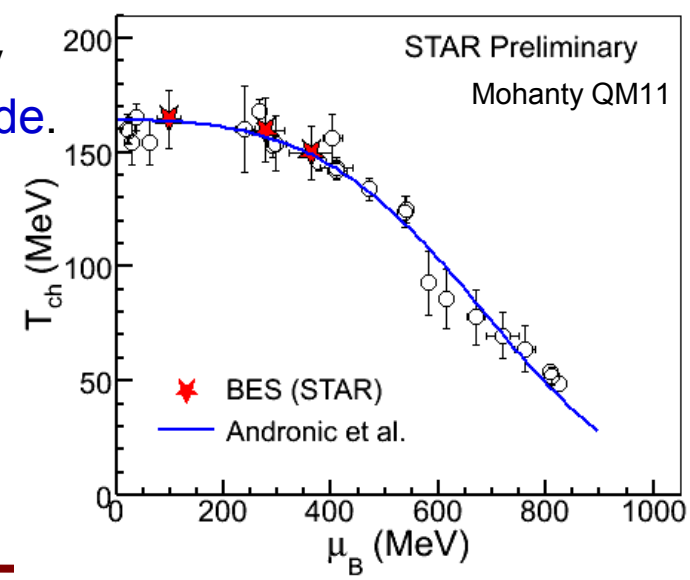
If I told you that:

1. create a state of matter at 4×10^{12} degrees out of a few thousands of particles
2. Matter and antimatter do not annihilate at energy density 100 times the normal nuclear density
3. Anti-nuclei and nuclei with weak binding energy carry information from the QGP phase transition (Temperature = 160MeV)
4. All particles maintain statistical equilibrium (no sign of annihilation but coalescence)
5. Models that assume thermal equilibrium correctly account for yields spanning 11 orders of magnitude. (1000 π, 10^{-8} ^{4}He) ± 0.00000000001

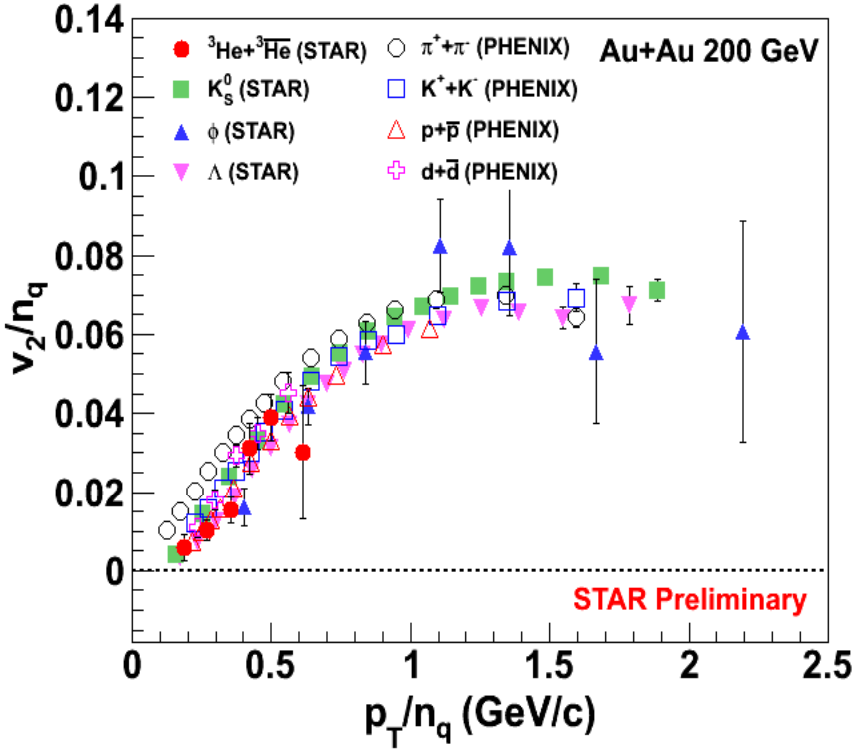
How many of you would say that "I expect that!"?

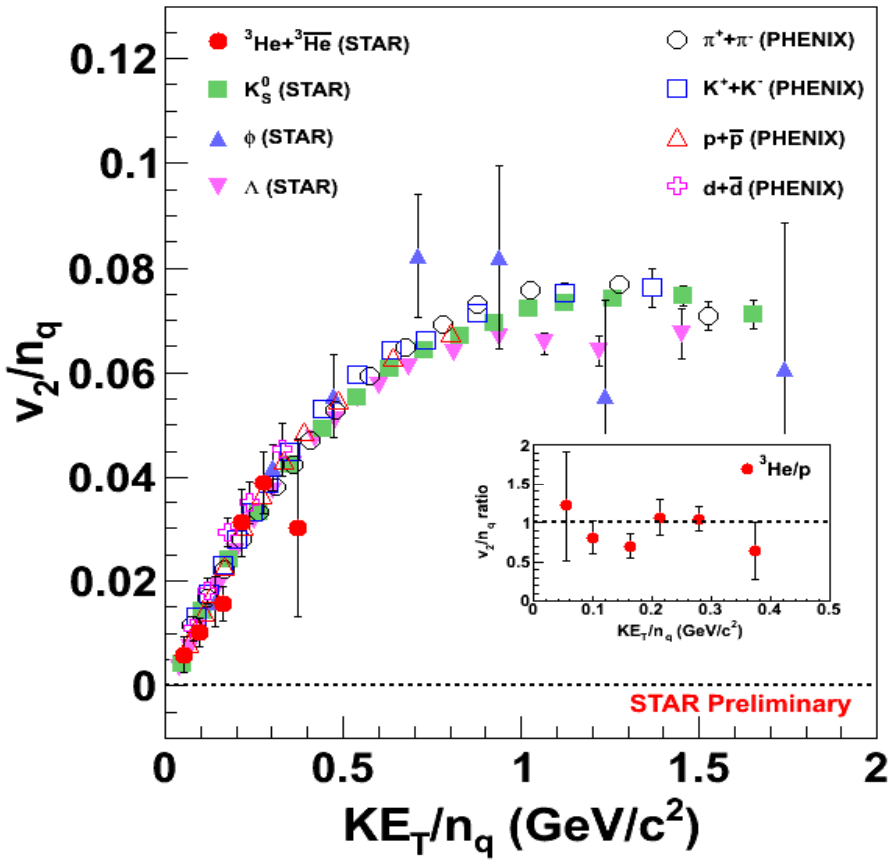
That is what we did when we found all these Heavy antimatter nuclei!

One of the major successes of RHIC program: convincing data on thermal system, hydrodynamics and phase diagram



NCQ Scaling





STAR, arXiv:0909.0566 [nucl-ex]

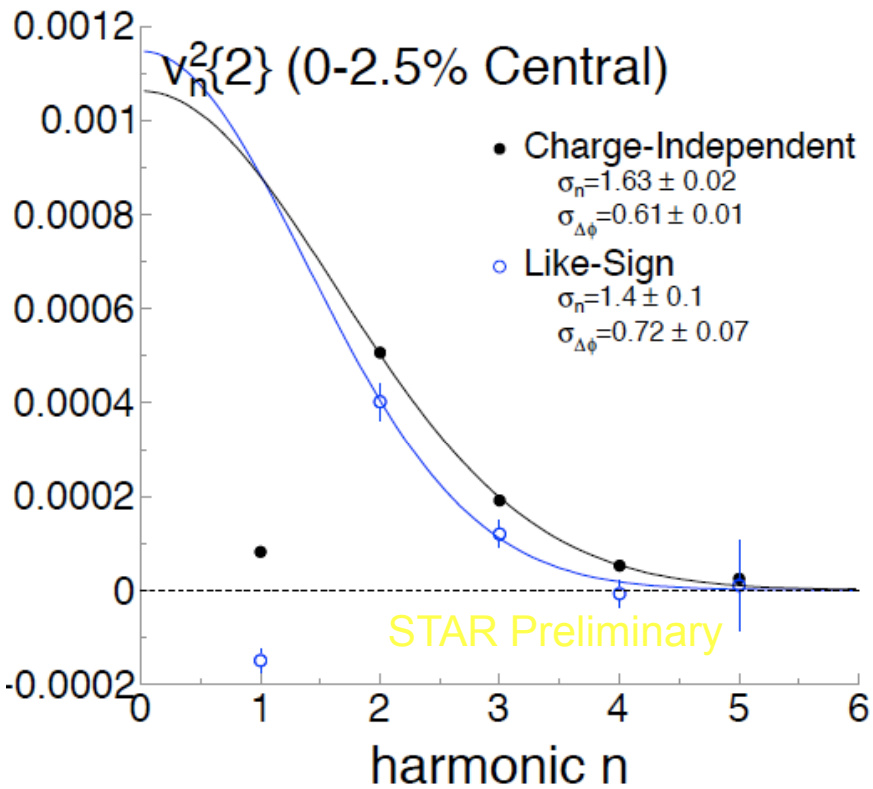
PHENIX, PRL 99, 052301 (2007)

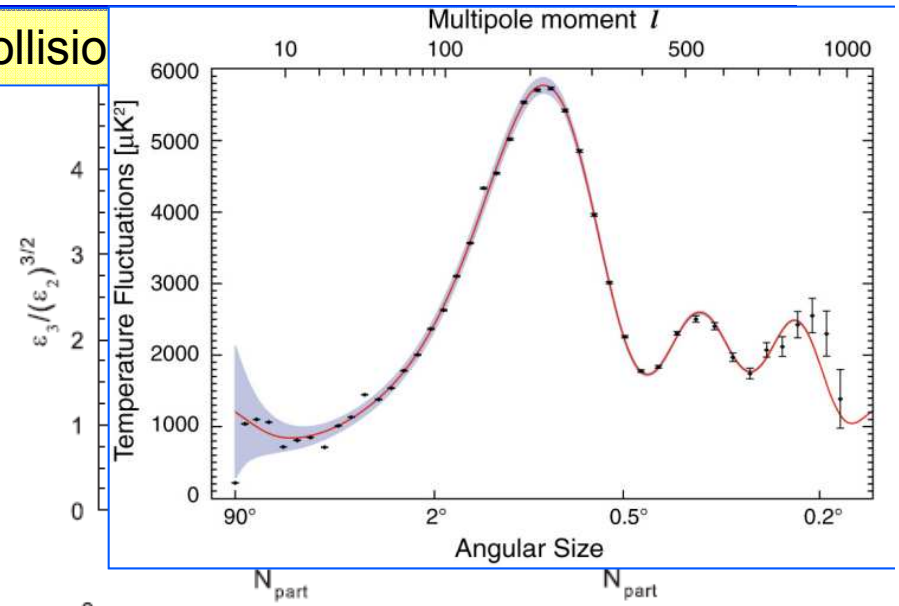
d(p+n) : $n_q = 2 \times 3$ $\quad$ ^{3}He(2p+n) : $n_q = 3 \times 3$

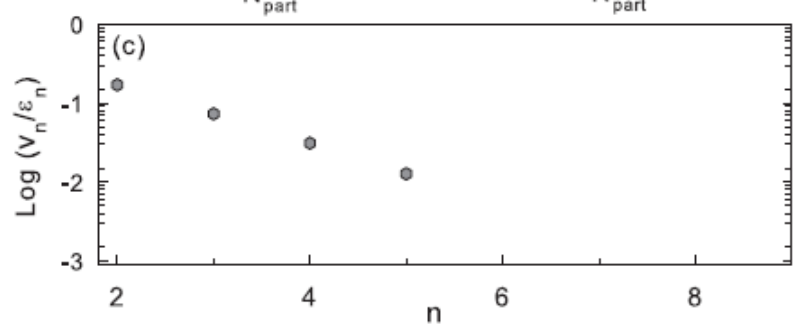
➢Number of constituent quark scaling holds well for v_2 of ^{3}He.

Fourier expansion (v_n): Power Spectrum?

This is the Power Spectrum of Heavy-Ion Collisio







look at $v_n^2\{2\}$ vs n to extract power spectrum in nearly symmetric collisions

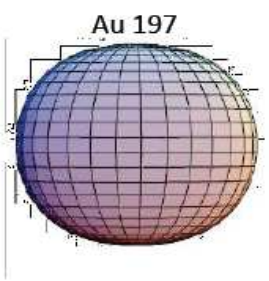
Width and falling slope vs n may be related to viscous and acoustic effects

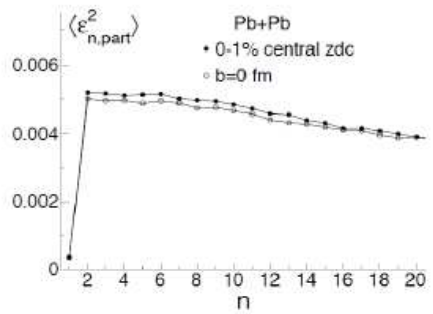
QM11, P. Sorensen, A. Mocsy, B. Bolliet, Y. Pandit, arXiv:1102.1403; R. Lacey et al. , arXiv:1105.3782

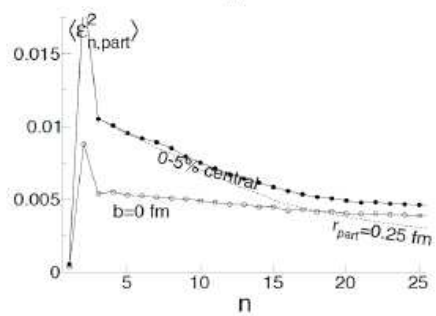
Decouple viscosity from fluctuation: Beam flexibility

In Progress

- Change initial conditions: Au+Au, Pb+Pb, Cu+Pb, U+U
- Quantify initial state fluctuation and viscosity



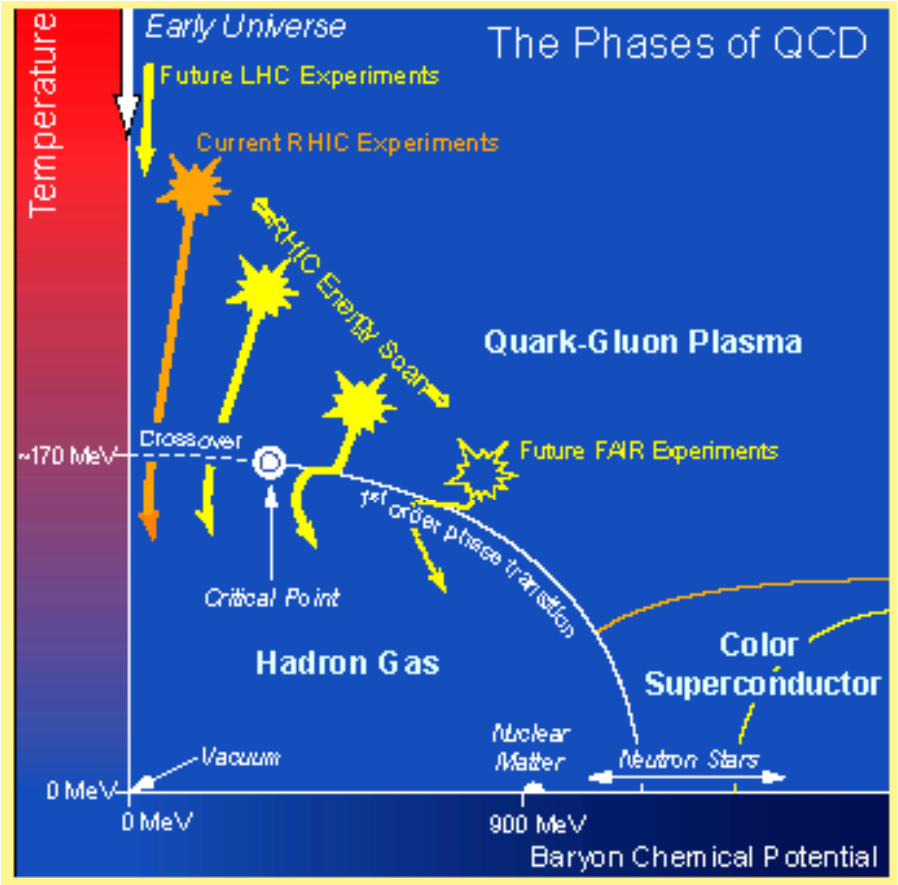




Program beyond 2015+

- Beyond phase I BES
- Mapping viscosity/s in (μ, T) phase diagram
- If critical point or 1st order phase transition line or softening EOS: bulk and shear viscosity
- PID v_n? (baryonic effect)
- Deviation from statistics
- pA program on initial state configuration

Where is the QCD critical point?



Phase II Expedition

- 39, 62, and 200 GeV collisions are qualitatively similar
- Even extends to LHC energies
- But **many changes** appear **at lower energies (11.5, 7.7)**
- Narrowing down the region of interest (19.6, 27) in run 11
- Future (2015+): **need detailed study of the key region**
  - Finer energy steps with higher statistics, beam species
  - Quantify the properties

- A **landmark on the QCD phase diagram**

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sQGP properties and phase diagram

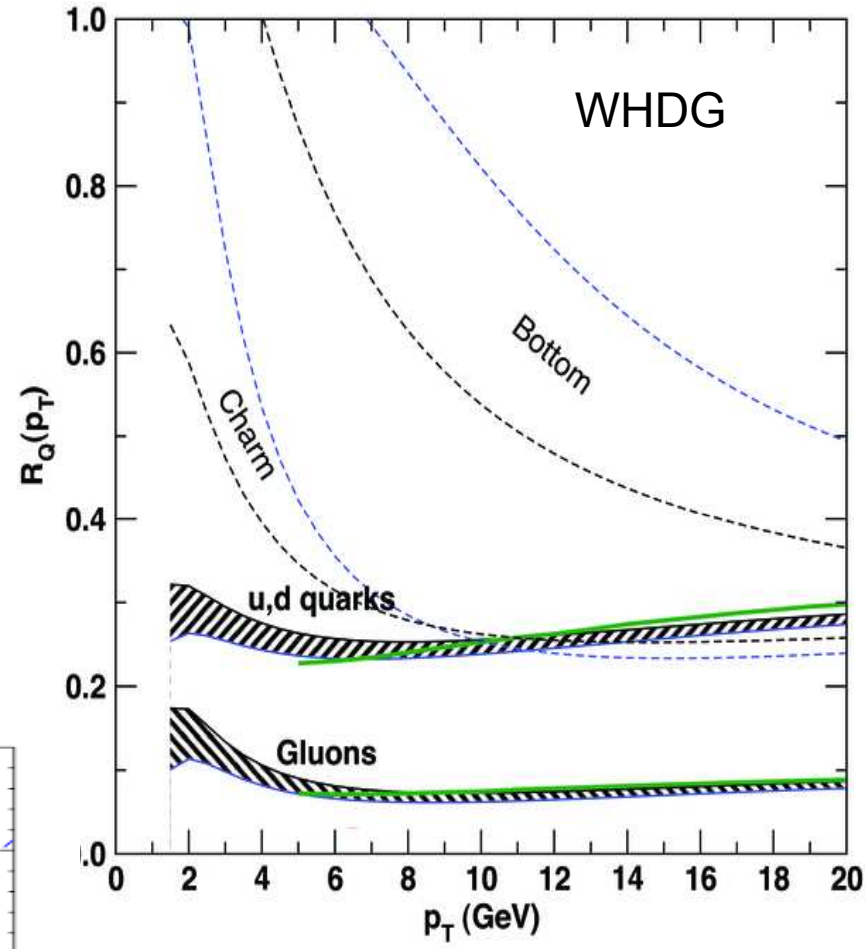
- Charm hydrodynamic flow
- v_n with different beam species at top energy
- More particles to test thermal model (~x100)

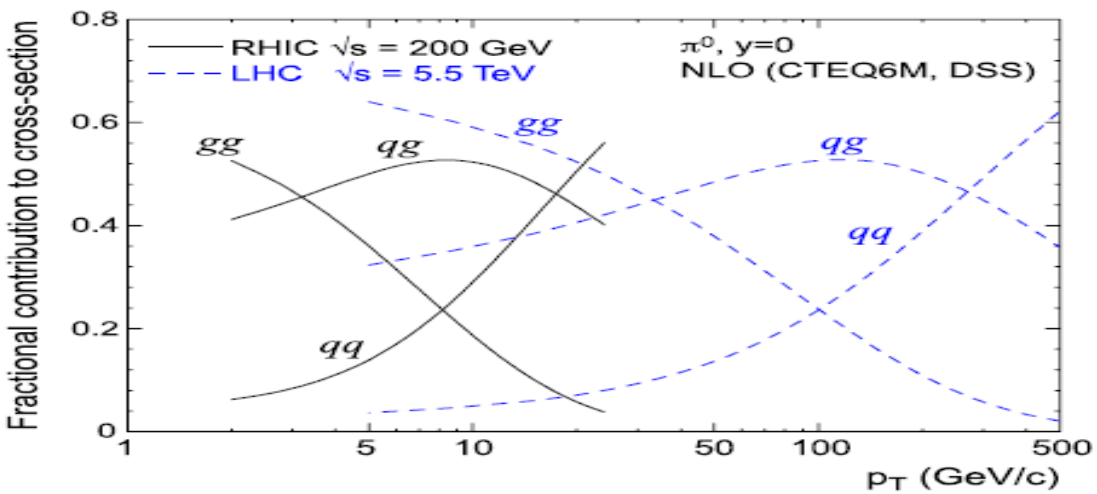
Beyond 2017

- Charmed correlation with HFT (fast readout)
- Phase II BES for precision viscosity (η/s) in phase diagram(μ,T) plane?
- pA program to understand the initial-state gluon configuration

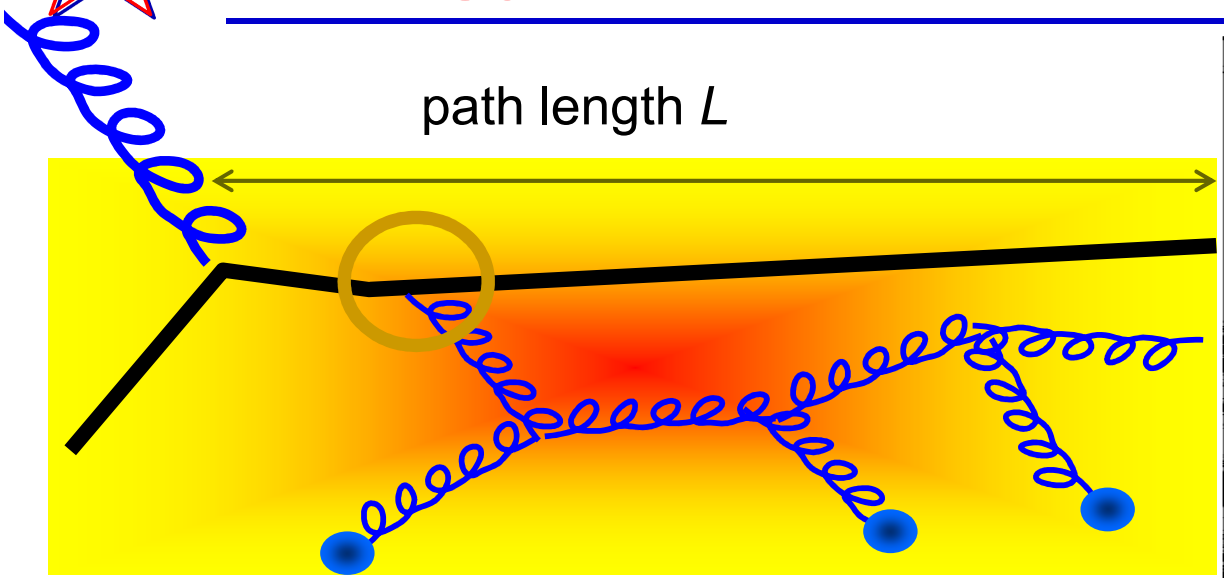
Mechanism of jet energy loss

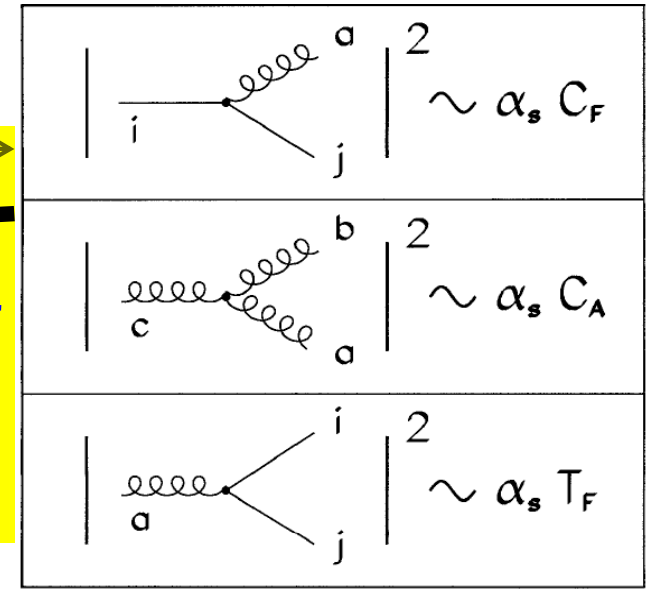
- Quark vs gluon:
  color factor
- heavy vs light quarks:
  deadcone effect
- Heavy-quarks in medium
  resonant states?
- RHIC advantage:
  Leading hadron PID at
  [10,20]GeV/c





Energy Loss and fundamental QCD





One mechanism of energy loss :
Medium induced gluon radiation

$$\frac{\Delta E_g}{\Delta E_q} \sim 9/4 \Rightarrow C$$

$$\langle \Delta E \rangle \sim \alpha_s \; C \; \langle \hat{q} \rangle L^2$$

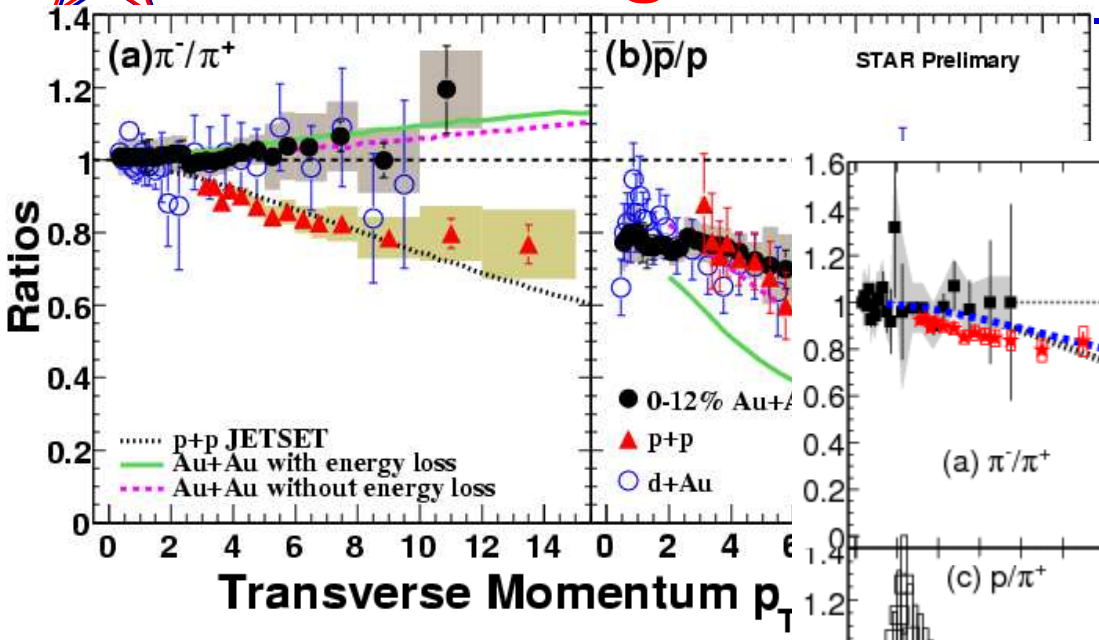
<q>: energy density, RHIC/LHC
L: anisotropy, Cu+Pb
C: quark vs gluon

Experimentally observable (of E_{loss}) related to basic ingredient of QCD - Gauge Group through Color Factors
Or extracting an effective Color Factor

R. Baier et al., NPB 483 (1997) 291 M. Gyulassy et al., PRL 85 (2000) 5535 S. Wicks et al, nucl-th/0512076

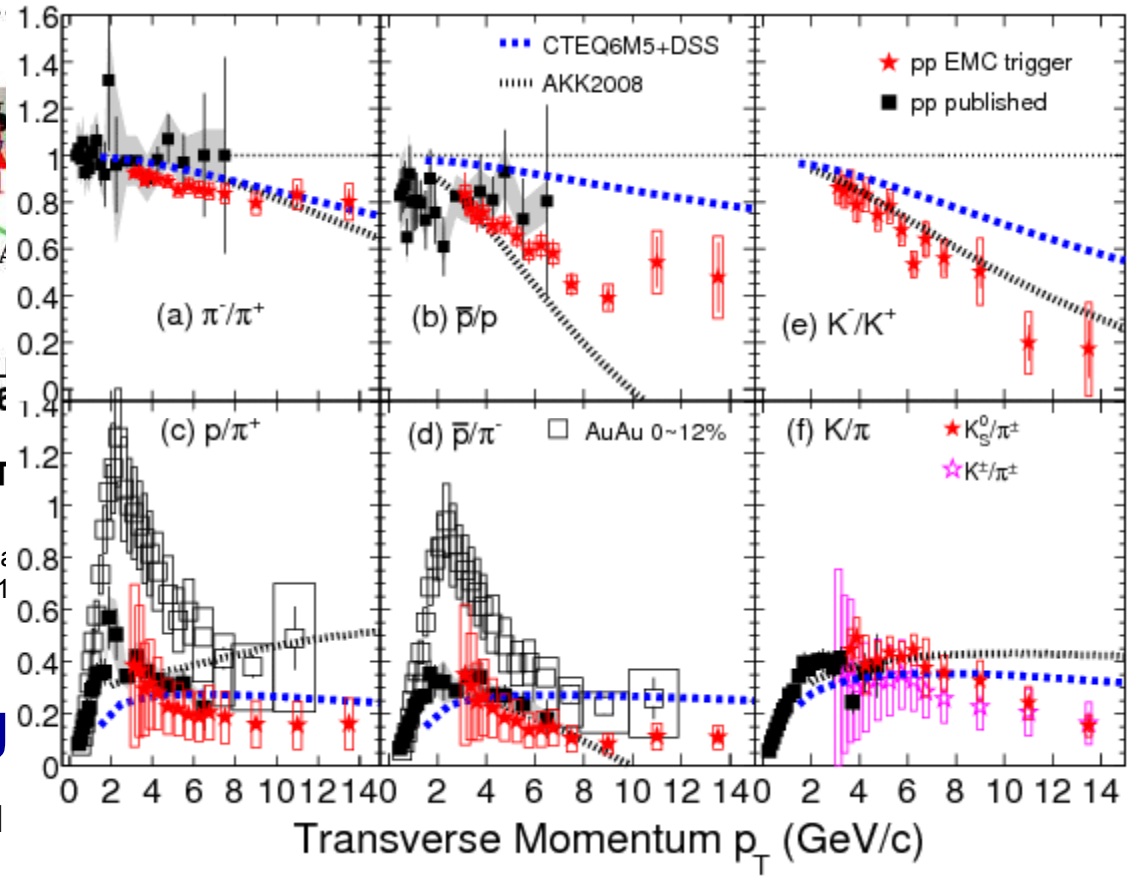
Quark vs gluon from hadron suppression

STAR, B. Mohanty
STAR, P. Fachini
STAR. Yichun Xu



PRL 97, 152301 (2006)
STAR Preliminary

Curves: X-N. Wang et a
PRC70(2004) 031901

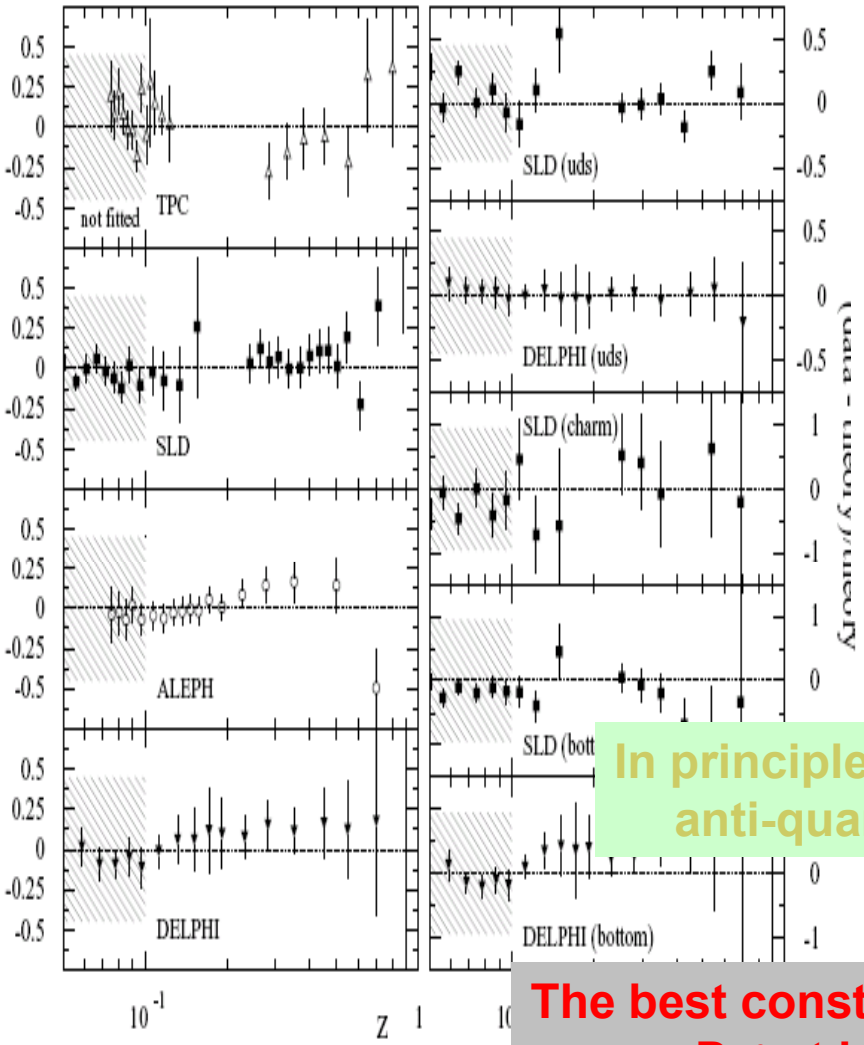


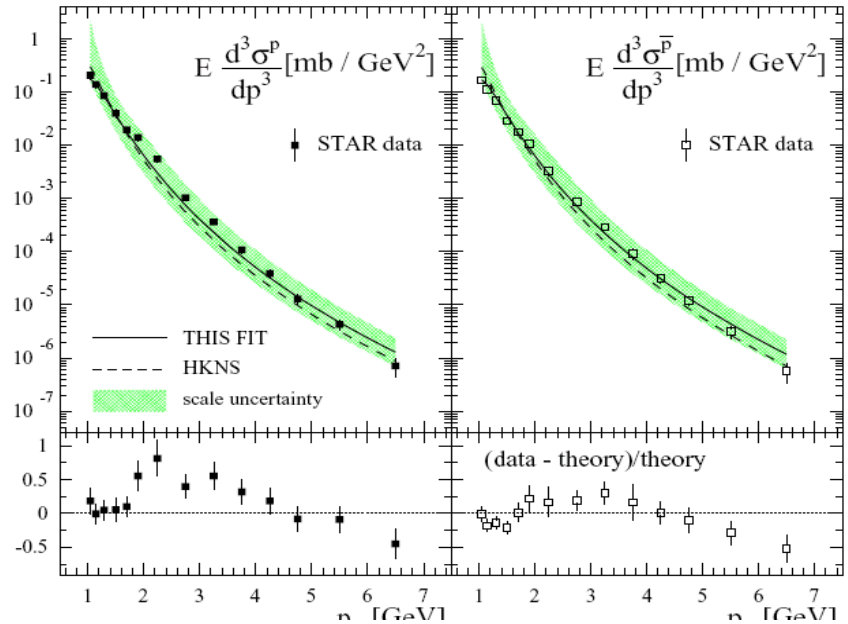
No sign of stronger g

X.N. Wang and X.F. Guo, N
T. Renk and K. Eskola, PRC
W. Liu, C.M. Ko, B.W. Zhang, nucl-th/0607047

Need good understanding of how quarks and gluons turn into hadrons

Global Fit on Fragmentation Function





The second key ingredient in our global analysis are the single-inclusive hadron production data from proton-proton collisions at BNL-RHIC taken by STAR [10] at

In principle, allow to separate quark-to-proton and anti-quark-to-proton fragmentation functions

and anti-quark-to-proton fragmentation functions in the fit. However, at the presently accessible range of transverse momenta p_T and at mid-rapidities the production

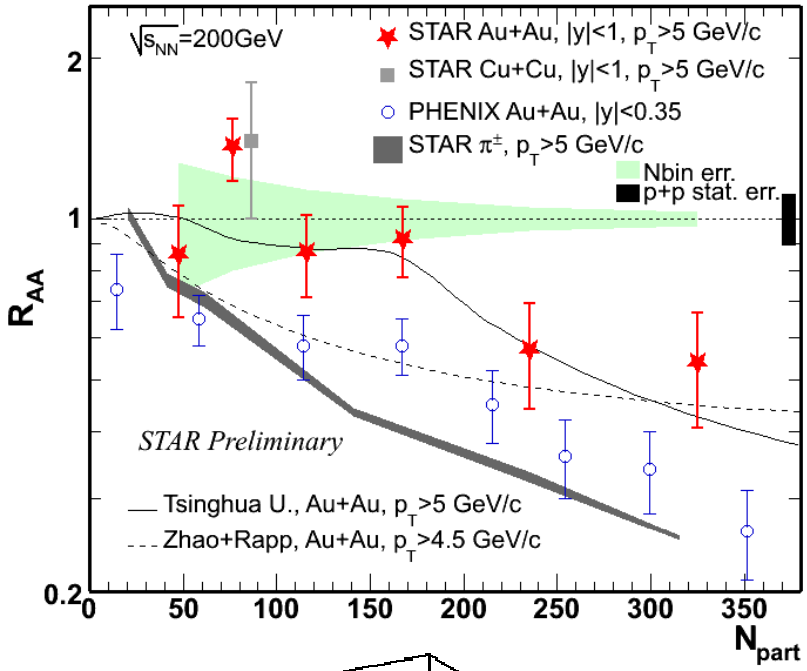
The best constraint on the gluon fragmentation function D_g^p at large values of z currently available.

tion D_g^p at large values of z currently available. Figure

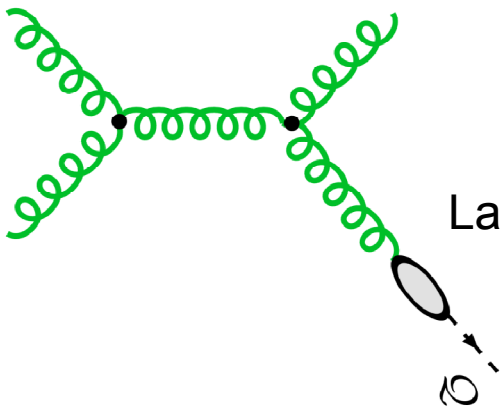
Daniel de Florian, Rodolfo Sassot and Marco Stratmann
arXiv: 0707.1506 [hep-ph]; Phys.Rev.D76:074033,2007.

DSS Fragmentation Functions –provided by W. Vogelsang

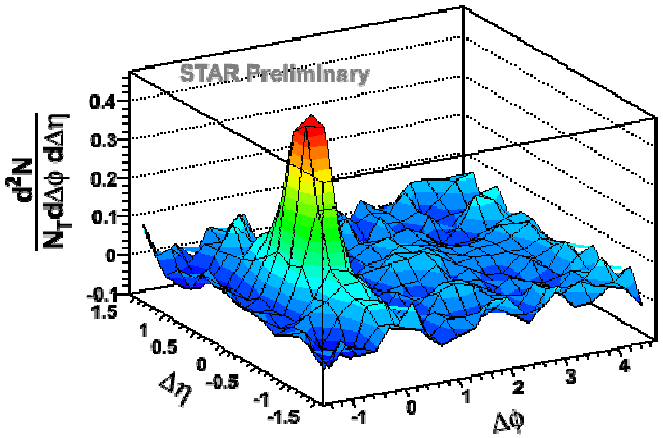
Tag Gluon/quark jet at RHIC

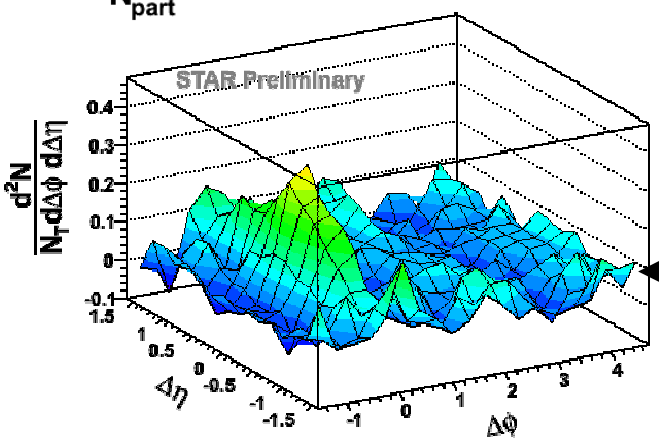


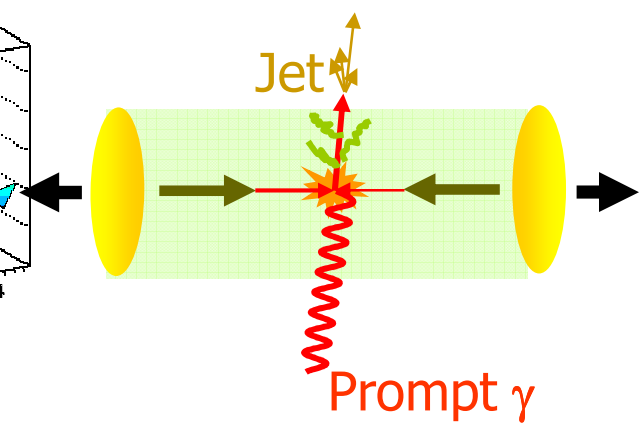
None of these at ideal kinematics for LHC



Can we use high-pt J/Ψ to tag gluon?

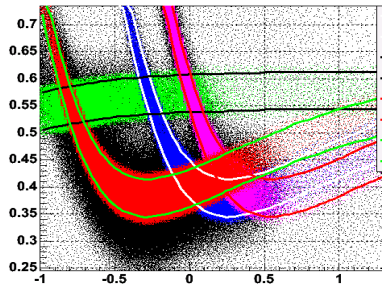






QM11: leading pion jet ←→ leading (p+K) jet

Turn PID Jet into a program



In Progress

- Large data volume with DAQ1000 (DAQ10K/Trigger)
- Install GEM Monitoring of TPC Tracking (GMT) surrounding TPC for space-charge and drift velocity monitoring
- Cosmic Ray triggers mixed in normal data taking: dE/dx, alignment
- Pile-up Protect events with ±45μs TPC drift time dE/dx, momentum resolution

Program in 2015+

- PID Fragmentation Function at high z (<10%?)
- MTD and EMC triggers on J/Psi, rate and IAA feasibility
- **Possible detector upgrades:** Complementary PID at 10<pt<20 GeV/c -2<η<-1

Exotic particles and rare decays

RHIC: a very flexible machine

C.M. Energy (GeV)	collision species
500	Polarized p+p
200	Polarized p+p, Au+Au, d+Au, Cu+Cu
130	Au+Au
62.4	Polarized p+p, Au+Au, Cu+Cu
39	Au+Au
19--22	Au+Au, Cu+Cu
11	Au+Au
7.7	Au+Au
9.2	Au+Au test
200	U+U (2010--2011)

RHIC: a high-rate machine

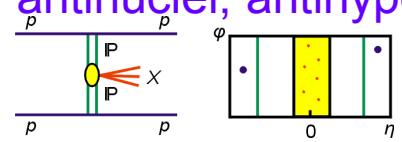
Annual Au+Au collisions to tape:
STAR: ~1 billion; PHENIX: ~10 billion

Luminosity p+p Equivalent: fb^{-1}

Annual particles to tape: $>10^{12}$

RHIC: new and rare particle factory

- Antimatter: antinuclei, antihypernuclei
- Glueball:



- Dibaryons: $[\Xi^0\ \Xi^-] \rightarrow \Xi^- + \Lambda$
- Strangelet: PRC **76** (2007) 011901
- Muonic atoms: π–μ, K-μ, p-μ, antimatter
- Rare Decays: $\eta \rightarrow e^+e^-, \Sigma^+ \rightarrow pl^+l^-$

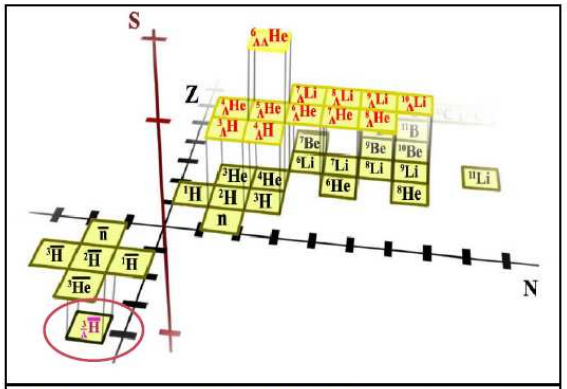
New Antimatter Detected at RHIC's STAR Detector

New Antimatter Detected at RHIC's STAR Detector

Discovery of the heaviest known antinucleus and first antinucleus with an anti-strange quark, from gold nuclei collisions at RHIC.

- Opens further exploration of fundamental symmetries and understanding the dominance of matter over antimatter in the universe
- Has implications for our understanding of the structure of collapsed stars
- Discovery extends 3-D chart of the nuclides and suggests even heavier antinuclei exist.

Results highlighted at the American Physical Society Meeting, Feb 13-16, 2010; Over 500 related news articles published worldwide.



The STAR collaboration observed the first antimatter hypernucleus: antihypertriton. This nucleus contains an antiproton, an antineutron, and an antilambda hyperon, which is made up of an up quark, a down quark, and a strange quark. The discovery extends our knowledge of the nuclear terrain, represented by a three-dimensional graph with axes Z, the number of protons in a nucleus; N, the number of neutrons; and S, the degree of strangeness. Each axis has positive and negative sections, representing particles and antiparticles. This latest result extends the nuclear terrain below the N–Z plane for the first time.

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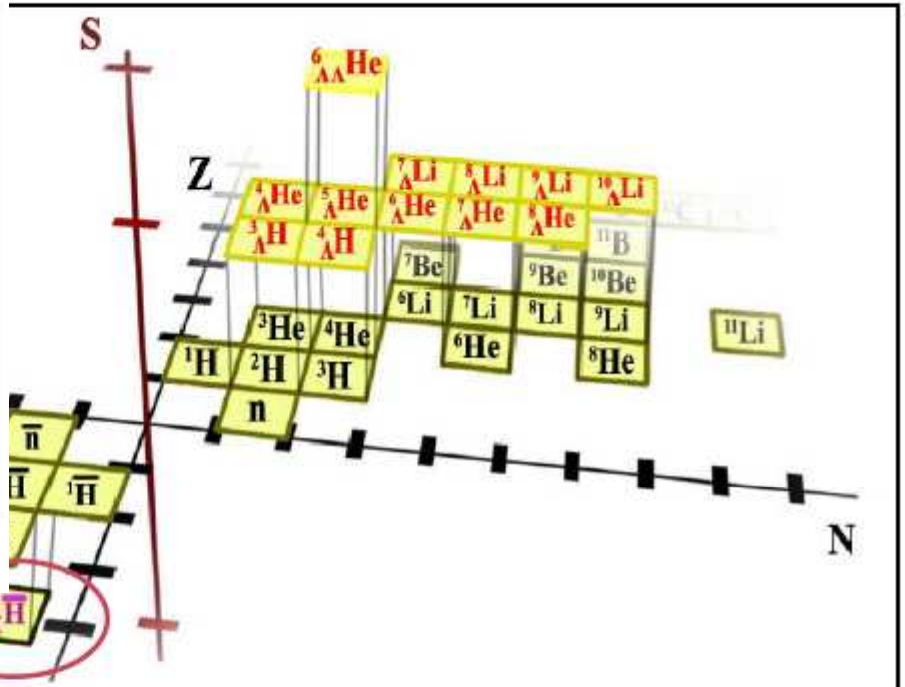

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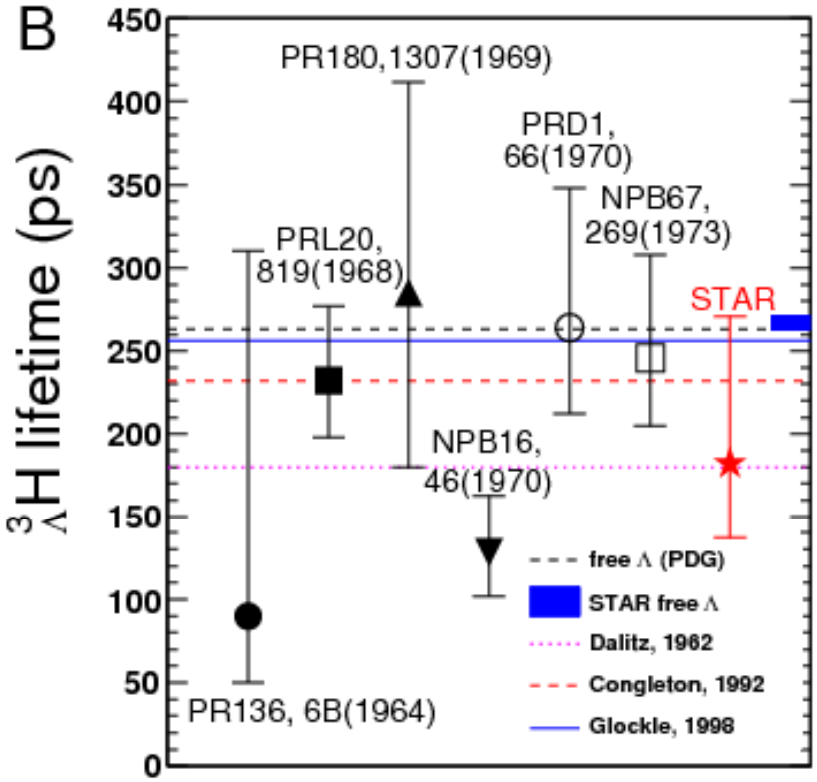
quark, and a strange quark. The discovery extends our knowledge
resented by a three-dimensional graph with axes Z, the number of
e number of neutrons; and S, the degree of strangeness. Each axis
sections, representing particles and antiparticles. This latest result
n below the N–Z plane for the first time.

U.S. DEPARTMENT OF ENERGY | Office of Science

46

Car: RHIC
Engine: QGP
Fuel: Jet Quenching, Flow
Design: Perfect Liquid
Wheels: Antimatter/new particles

Hypernucleus and Dibaryon



Science AAAS

Observation of an Antimatter Hypernucleus
The STAR Collaboration, *et al.*
Science **328**, 58 (2010);
DOI: 10.1126/science.1183980

World data

Precision measurement;
Rate can be very well predicted,
If we don't find, it doesn't exist!

Heavy Ion Collisions versus Kaon Beam Facility

Hyperon-hyperon interaction:

kaon beam facility – difficult to go beyond
- Λ-Λ
- Ξ-N systems

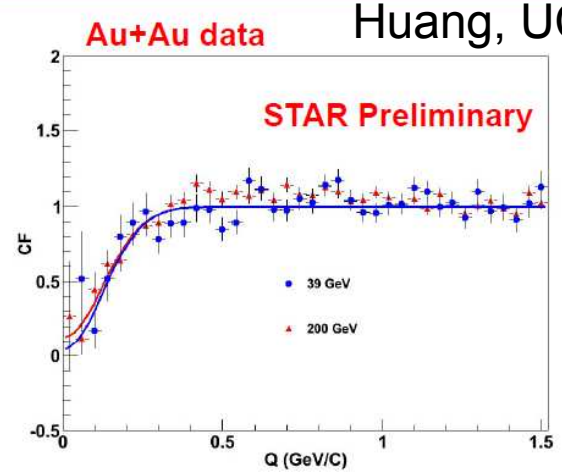
@RHIC
- Ξ-Λ
- Ξ-Ξ
- Ξ-Ω
- Ω-Ω systems possible candidates

- $[\Sigma^+ p] \rightarrow p + p$,
- $[\Xi^0 p] \rightarrow p + \Lambda$,
- $[\Xi^0 \Lambda] \rightarrow p + \Xi^-, \Lambda + \Lambda$
- $[\Xi^0 \Xi^-] \rightarrow \Xi^- + \Lambda$,

J. Schaffner-Bielich et al (H-H); G. Miller (Ξ-Ξ); Z.Y. Zhang et al (Ω-Ω)

STAR Has Tens of Thousand ΛΛ Pairs

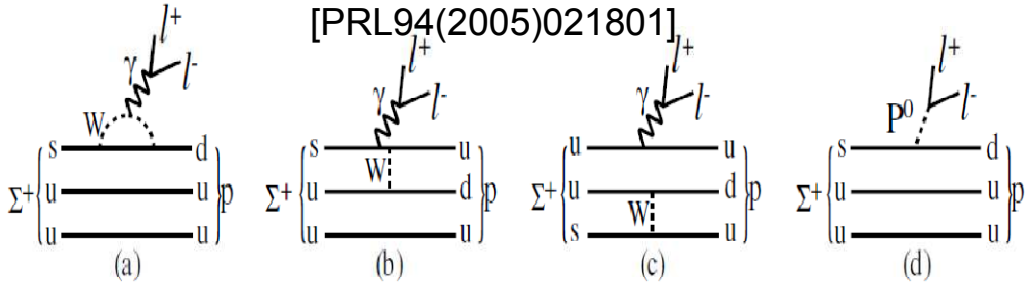
Huang, UCLA

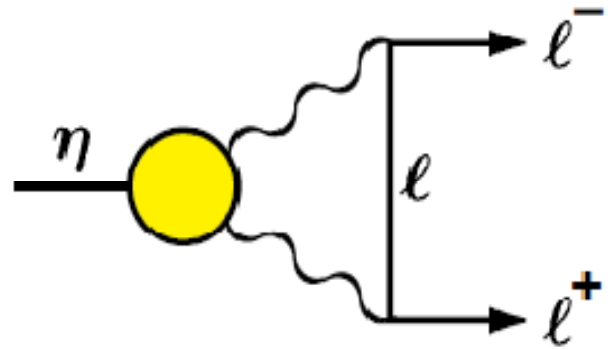


Is there a true depletion of Λ-Λ pairs near threshold?

Rare Decay $\eta \rightarrow e^+e^-$: an example

[PRL94(2005)021801]

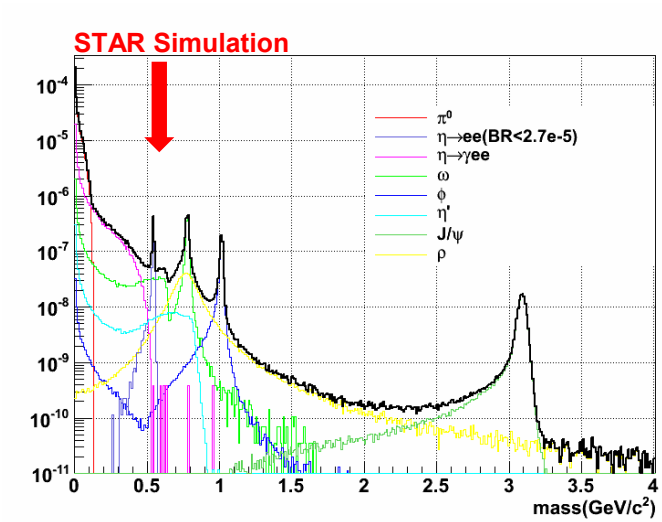


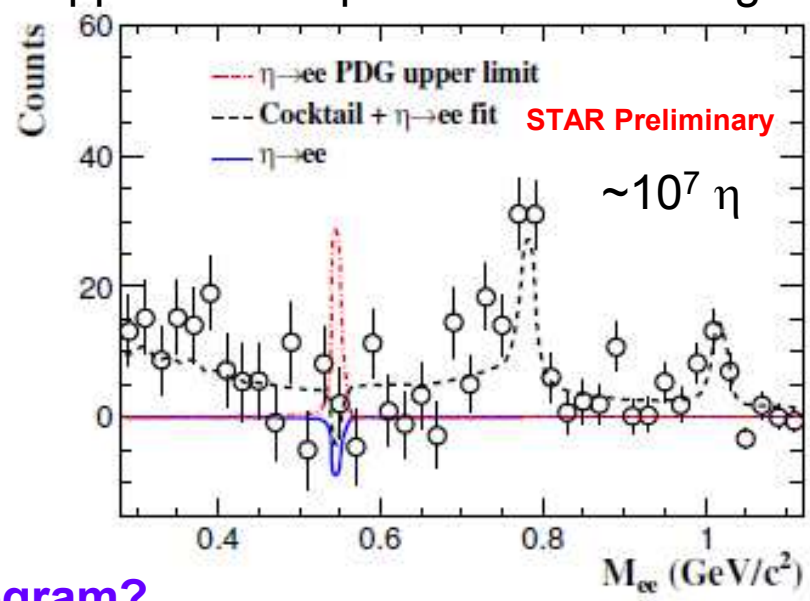


Physics beyond standard model enhances rare decay rate (10^{-9} to $10^{-8,-7}$)
RHIC: ideal for such search;
$>10^{11}$ η annual yield;
Clean Low-pt electron identification

$\eta \rightarrow e^+e^-$ PDG BR $<2.7\times10^{-5}$

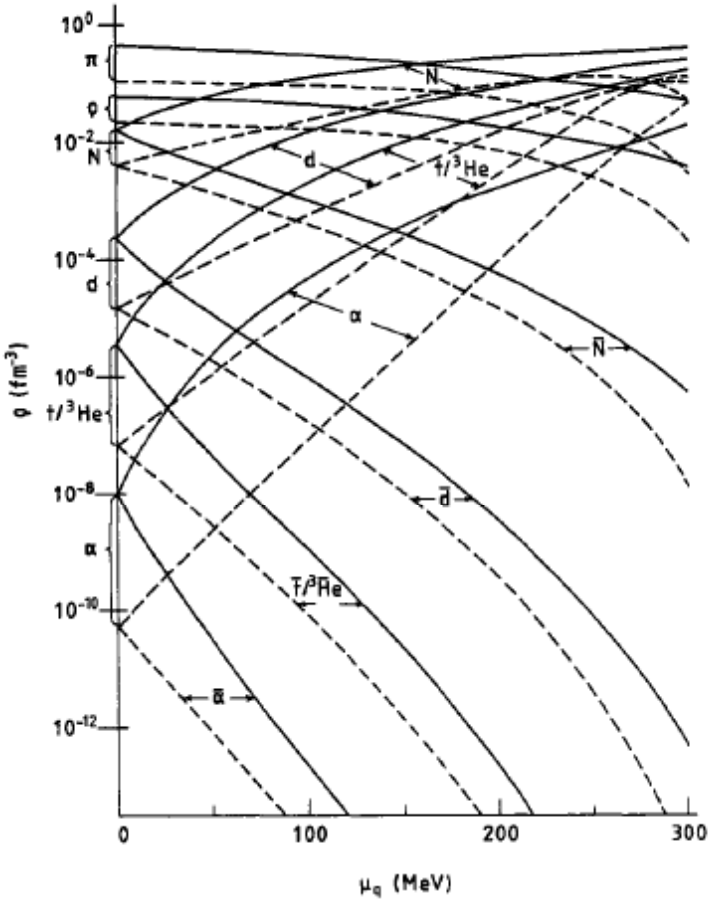
Run9 pp data with partial TOF coverage

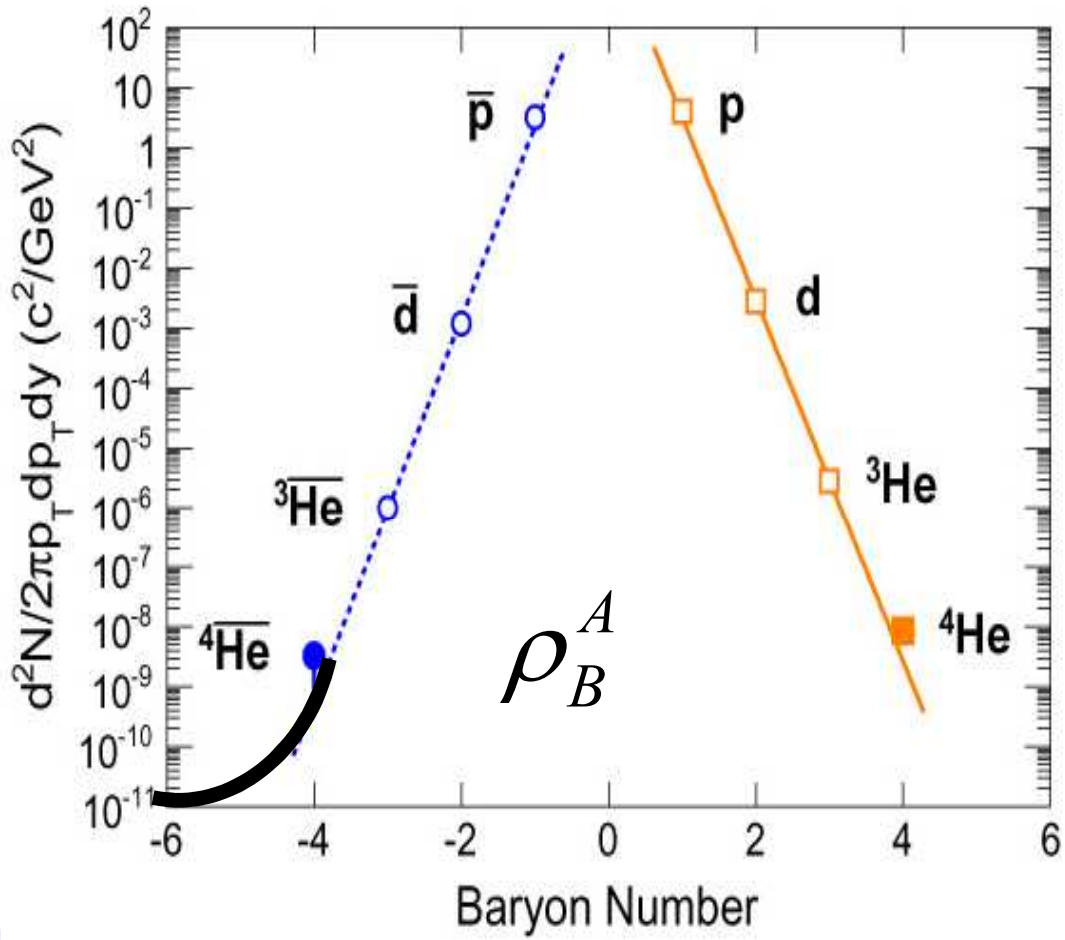




Isn't that an exciting program?

Even Heavier Antimatter





- Formation of antimatter clusters in the hadronisation phase transition: U. Heinz et al. JPG: 12 (1986) 1237
- Pull $\bar{\alpha}$ from vacuum (Dirac Sea): W. Greiner, IJMPE 5 (1995) 1

LETTER nature

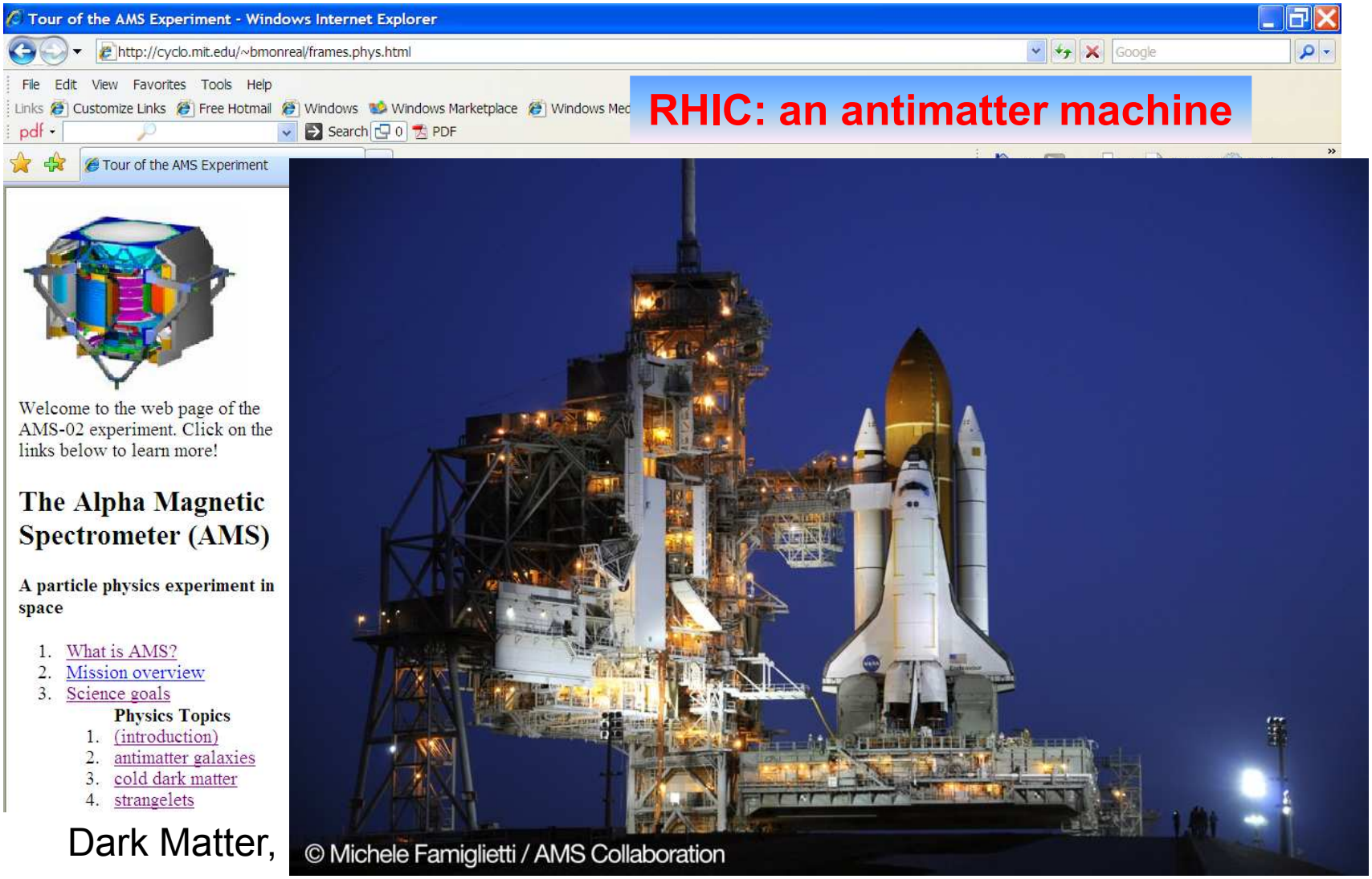
doi:10.1038/nature10079

Observation of the antimatter helium-4 nucleus

The STAR Collaboration*

Antinuclei in nature (new physics)

To appreciate just how rare nature produces antimatter (strange antimatter)



RHIC: an antimatter machine

Dark Matter,

User Facility on exotic and rare processes

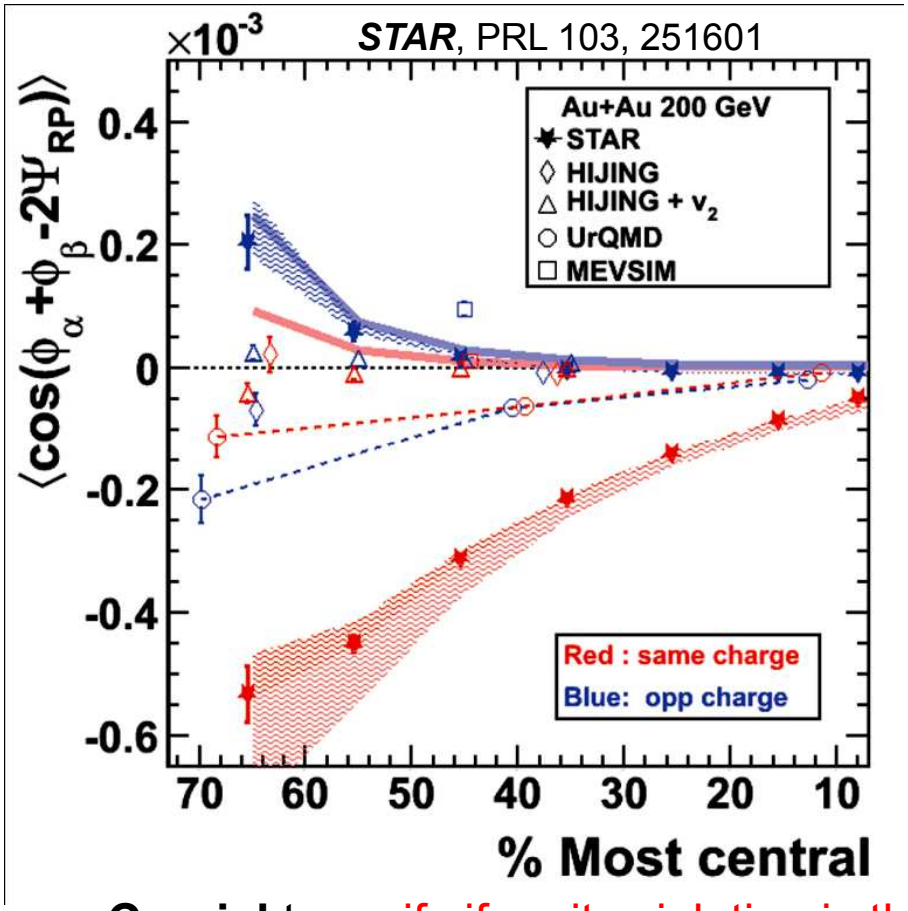
- Antimatter:
  low-energy atom;
  Astrophysics:
  CERN, AMS
- Hypernuclei, dibaryon:
  nuclear structures
  Strangeness
  Pomeron/Odderon
- Rare decays:
  e^+e^- collider;
  precise physics

- **A program appealing to other communities?**
- How do we get other communities involved?

Relevant upgrades:
DAQ10K, High-level Trigger,
TOF, HFT, MTD, RP II

Novel Symmetries

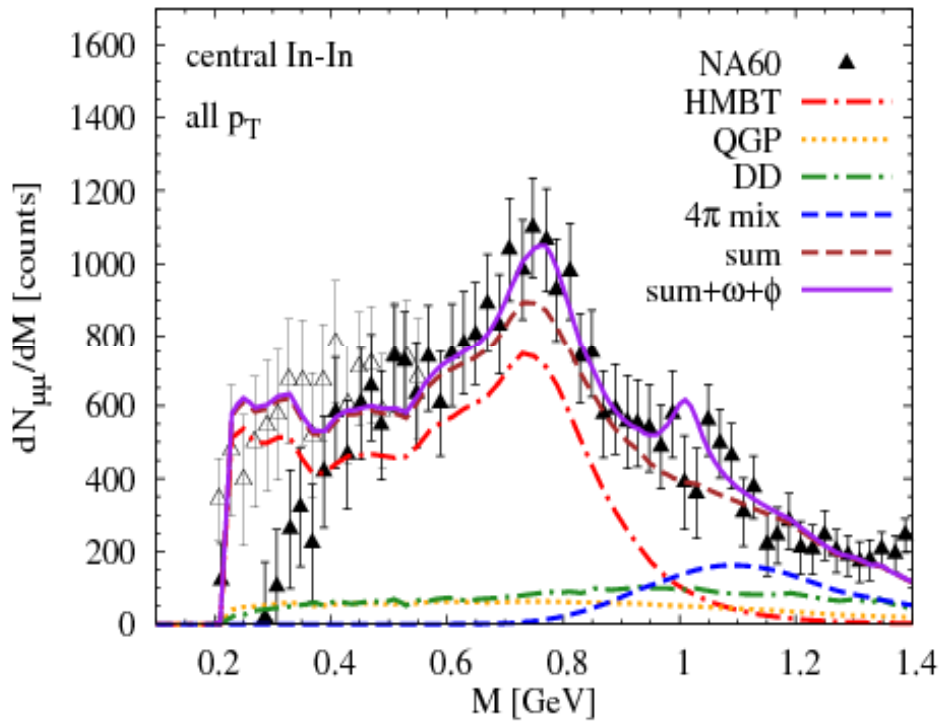
Local Parity Violation



Crucial to verify if parity violation is the **correct explanation**

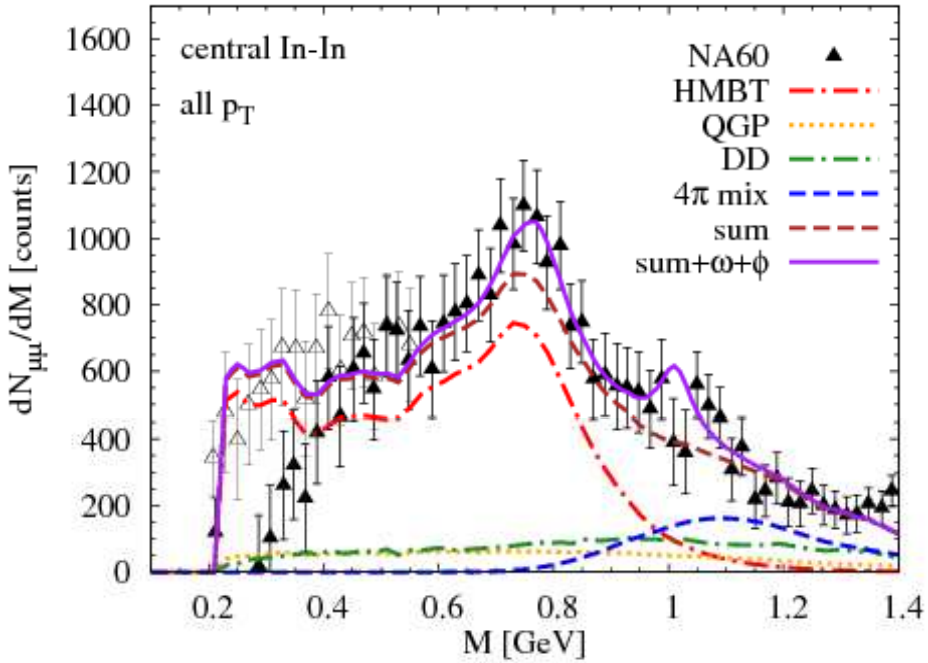
U+U collisions: collisions with **more v_2** and **less B field** than Au+Au

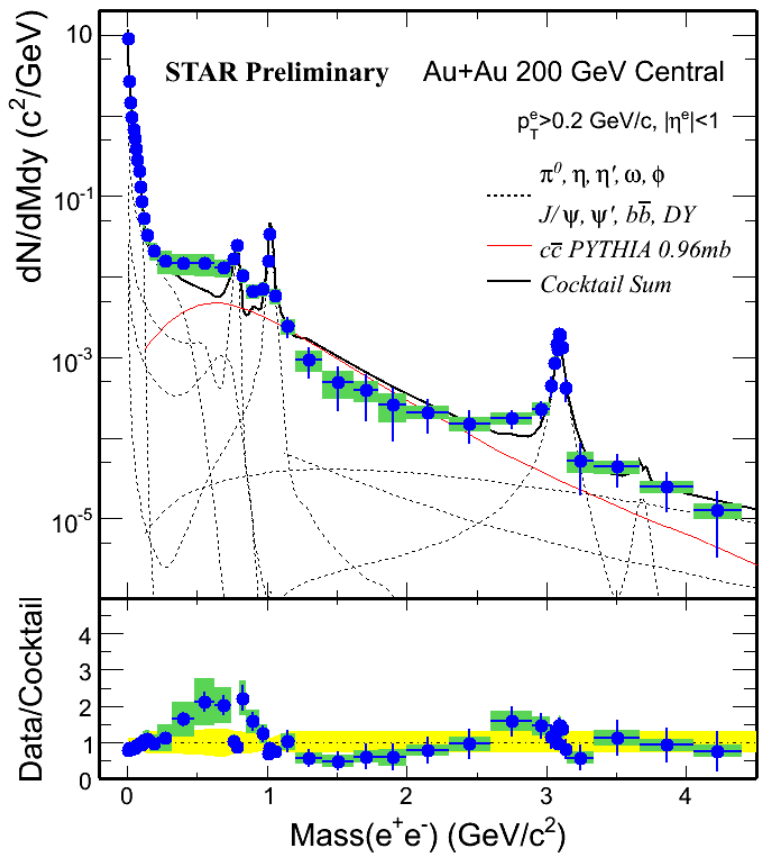
Chiral Symmetry



In-medium Vector-Meson and χ symmetry

NA60, PRL96(2006)162301





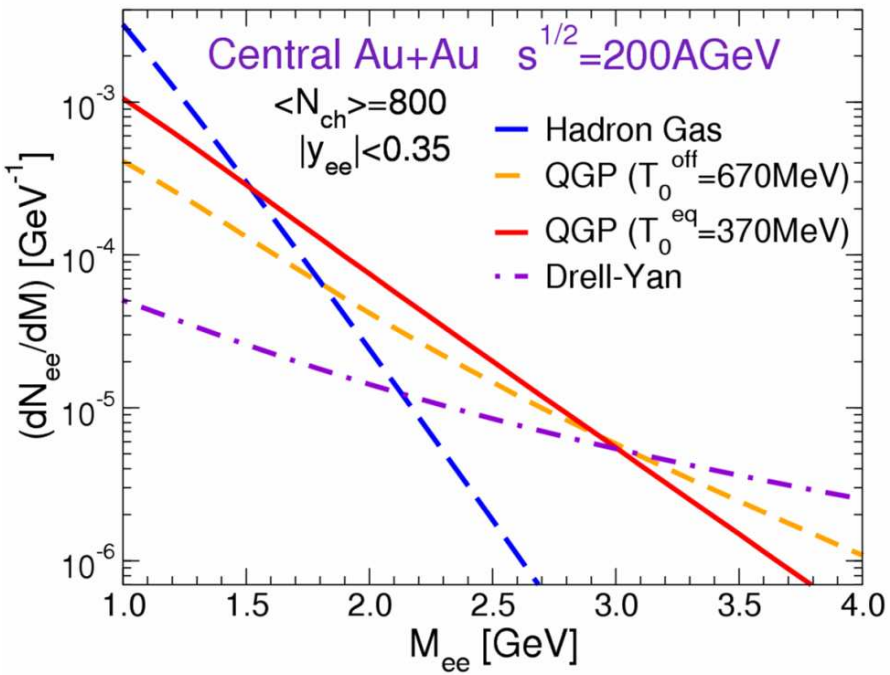
Model with in-medium vector-meson mass broadening describes dimuon spectral function in NA60 at SPS

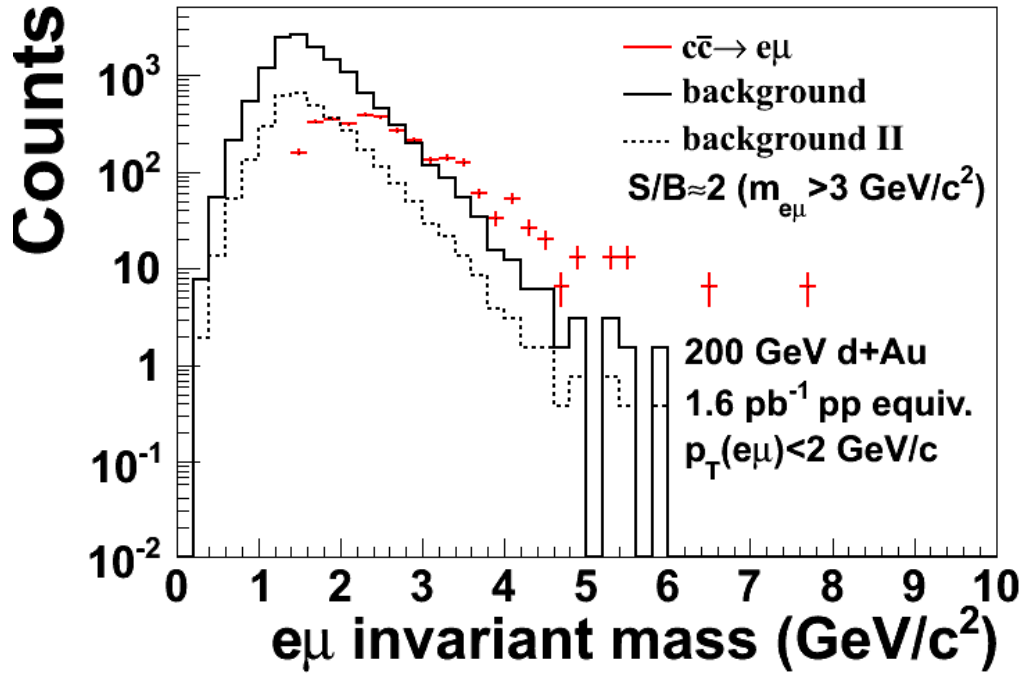
R Rapp et al. Phys.Rept.462(2008)176

Enhancement at around M=0.5GeV observed by RHIC not described by the model extrapolating from SPS

PHENIX PRC 81(2010)034911

Measure Irreducible background





In addition to the dimuon measurements

$e\mu$ correlation simulation with Muon Telescope Detector at STAR from ccbar:

S/B=2 (M_{eu}>3 GeV/c2 and $p_T(e\mu)$<2 GeV/c)

S/B=8 with electron pairing and tof association

L. Ruan et al., Journal of Physics G: Nucl. Part. Phys. 36 (2009) 095001

Catching thermal leptons: QED for QCD

RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 48, NUMBER 9 1 NOVEMBER 1993

Production of muon-meson atoms in ultrarelativistic heavy-ion collisions

Gordon Baym,* Gerald Friedman, R. J. Hughes, and Barbara V. Jacak
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 9 November 1992)

Ultrarelativistic heavy-ion collisions should produce hydrogen-atom-like Coulomb bound states of muons and mesons. Such atoms could provide a convenient way to measure the muon momentum distribution. We estimate the production rate of pion-muon atoms expected from heavy-ion colliders.

PACS number(s): 25.75.+r, 13.85.Rm, 24.60.Ky, 36.10.−k

Soft leptons produced in the early evolution of an ultrarelativistic heavy-ion collision are a potentially important probe of the collision volume. It is difficult to measure the spectrum of directly produced soft leptons because of the large number of charged particles created in the collision and the need to separate the directly produced leptons from those arising from hadronic decays. However, it has been suggested [1] that the detection of muon-meson atoms, consisting of a muon electromagnetically bound to a π or K meson, provides a method to study the soft lepton spectrum. With magnetic analysis, such neutral atoms can be readily separated from the large flux of charged particles [2]. On the other hand, π-π and K-K atoms annihilate long before detection, and muons produced by most weak hadronic decays are not captured by directly produced mesons to form atoms because they are generally made too late in the evolution of the collision. Pion-muon atoms provide a sample of muons of transverse momentum below 1 GeV/c, a momentum range otherwise experimentally inaccessible due to contamination by muons from hadronic decays and difficulties in particle identification. Measurements in this range are capable of probing thermal electromagnetic emission processes in an initial plasma with a temperature ~200 MeV.

$m_{\rm red}=(m_1^{-1}+m_2^{-1})^{-1}$ is the reduced mass for the relative motion of the constituents (of masses m_1 and m_2). A π-μ atom is $\approx$450 fm in radius, and a K-μ atom $\approx$250 fm. Consequently, atom formation occurs well after freeze-out through coalescence of particles sufficiently close in phase space, and is sensitive only to the particle distributions at freeze-out.

Other atoms such as K-μ, π-π, and K-π will be produced in heavy-ion collisions in addition to π-μ. As probes of the muon spectrum, K-μ atoms are less effective than π-μ atoms, because K-μ atoms primarily include muons only of small transverse momenta. To form a K-μ atom, the kaon must have a transverse momentum larger than that of the muon by a factor m_K/m_μ, and thus the transverse-momentum fraction of the muons is $\approx\frac{1}{6}$ that of K-μ atom. On the other hand, the constituents of π-μ atoms have comparable masses and thus are formed from mesons of comparable transverse momenta. π-π and K-π atoms are of less interest as they contain no leptons. We calculate here only the production rate for π-μ atoms, although the calculation is readily extended to other types of atoms.

In a hydrogenic atom, the relative velocity $v_{\rm rel}$ of the two constituents is $\alpha c/n$, the Bohr velocity, where n is the principal quantum number (=1 in the ground state)

PHYSICAL REVIEW C VOLUME 59, NUMBER 5 MAY 1999

Hydrogenlike atoms from ultrarelativistic nuclear collisions

Joseph Kapusta* and Agnes Mocsy†
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455
(Received 3 December 1998)

The number of hydrogenlike atoms produced when heavy nuclei collide is estimated for central collisions at the Relativistic Heavy Ion Collider using the sudden approximation of Baym *et al.* As first suggested by Schwartz, a simultaneous measurement of the hydrogen and hadron spectra will allow an inference of the electron or muon spectra at low momentum where a direct experimental measurement is not feasible. [S0556-2813(99)03605-5]

PACS number(s): 25.75.−q

VOLUME 48, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1982

Measurement of the Rate of Formation of Pi-Mu Atoms in K_L^0 Decay

S. H. Aronson, R. H. Bernstein, G. J. Bock, R. D. Cousins, Jr.,[a] J. F. Greenhalgh,[b] D. Hedin,[c] M. Schwartz, T. K. Shea, G. B. Thomson,[d] B. Winstein
Brookhaven National Laboratory, Upton, New York 11973, and University of Chicago, Chicago, Illinois 60637, and Stanford University, Stanford, California 94305, and University of Wisconsin, Madison, Wisconsin 53706
(Received 5 February 1982)

Hydrogenlike atoms consisting of a pion and a muon can be formed in $K_L^0\to\pi\mu\nu$ decays. In an intense, high-energy K_L^0 beam, 320 pi-mu atoms were detected and simultaneously the K_L^0 flux was monitored by recording ordinary $K_L^0\to\pi\mu\nu$ decays. The first measurement is reported of the branching ratio $R=\Gamma(K_L^0\to\text{pi-mu atom}+\nu)/\Gamma(K_L^0\to\pi\mu\nu)=(3.88\pm0.41)\times10^{-7}$, using a subset of 155 atoms. This ratio may be sensitive to anomalous interactions between the pion and the muon. In the absence of such interactions, theory predicts $R=(4.43\pm0.12)\times10^{-7}$.

PACS numbers: 13.20.Eb, 13.60.-r, 14.40.Aq, 36.10.-k

$$\frac{dN_{\rm atom}}{dy\,d^2p_{\perp,\rm atom}}=8\pi^2\zeta(3)\alpha^3 m_{\rm red}^2\frac{dN_h}{dy\,d^2p_{\perp,h}}\frac{dN_l}{dy\,d^2p_{\perp,l}}. \quad (1)$$

- Exciting possible new discoveries:
  K-μ atoms;
  antimatter mounic hydogen: $\bar{p}$-μ^+
- Direct measure of single lepton spectrum from thermal radiation

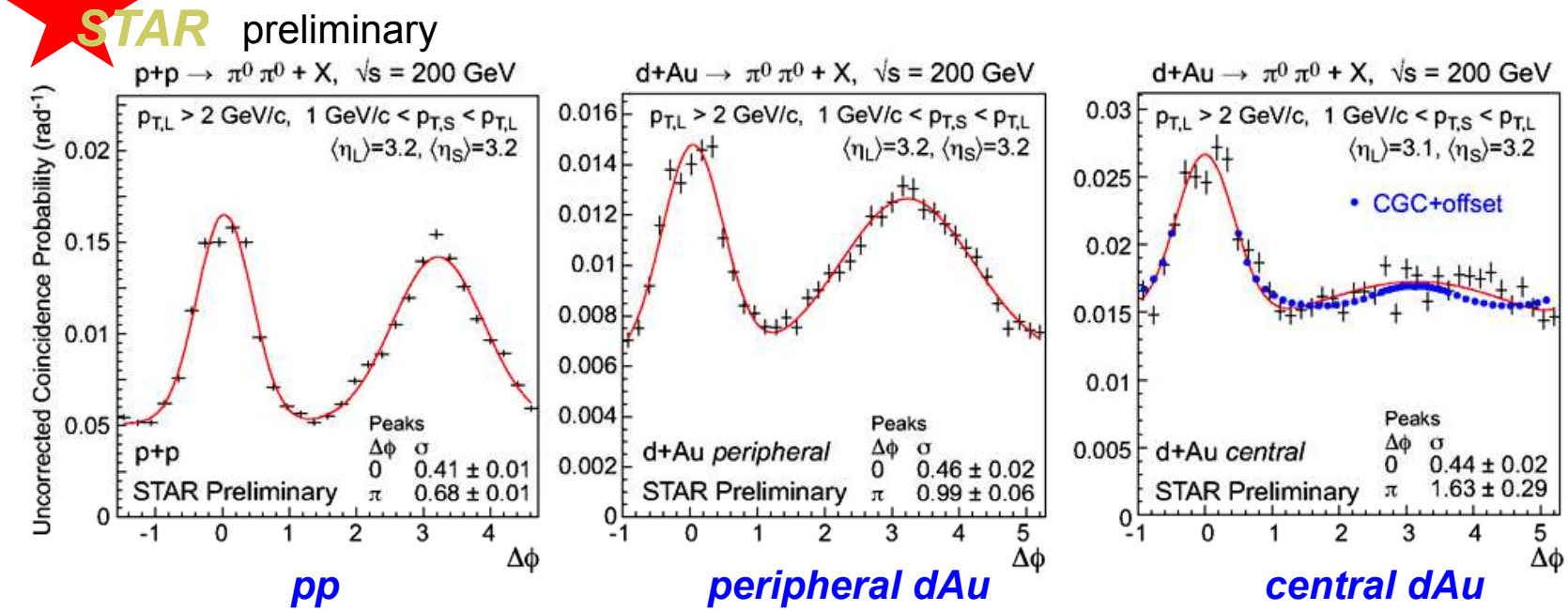
Understanding Symmetry and DOF

- STAR at RHIC is the best detector to study LPV and Chiral symmetry restoration:
  - flexible machine to change conditions beam species (magnetic field), BES (turn on/off QGP)
  - Large Acceptance (good for both LPV and chiral symmetry)
  - Excellent lepton PID (both electrons and muons at midrapidity, who else has that!)
- Since the beginning of physics, symmetry considerations have provided us with an extremely powerful and useful tool in our effort to understand nature. Gradually they have **become the backbone of our theoretical formulation of physical laws**.

  — Tsung-Dao Lee
  Particle Physics and an Introduction to Field Theory (1981), 177

- LPV:
  - beam energy: deconfinement, chiral symmetry
  - Beam species: magnetic field
- Medium effect on vector mesons (chiral symmetry, resonant states):
  - beam energy;
  - Spectra and v_2 vs M_{l+l-}
- HFT+MTD upgrade 2017-
  - First glimpse of dilepton spectra around ρ_0 and $1<M<3$GeV
  - Atoms as a tool?
- Beyond 2017
  - Phase II BES?
  - **Detailed studies of DOF**

Cold QCD matter – the initial state at RHIC

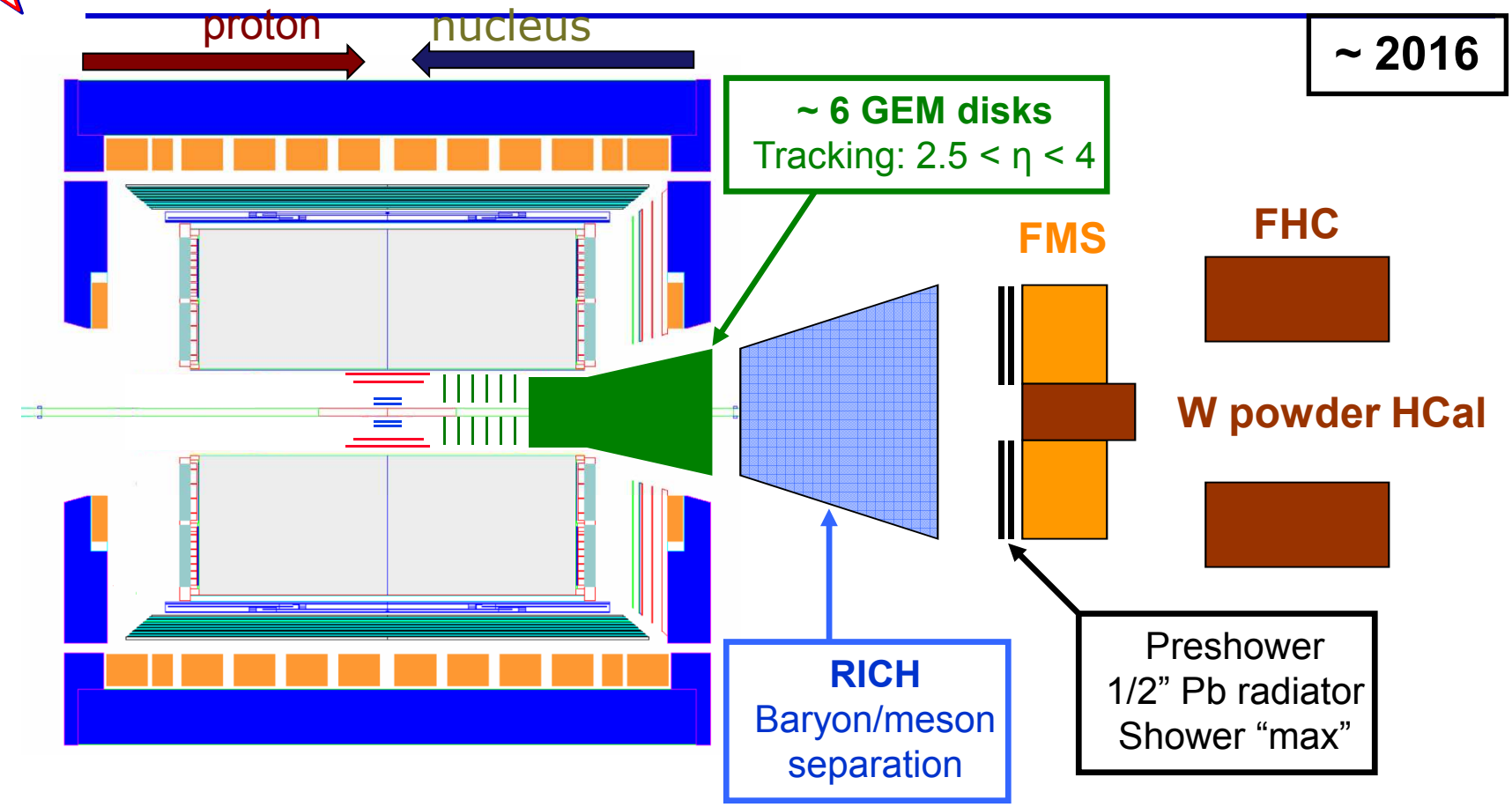


- RHIC may provide **unique access to the onset of saturation**
- Future questions for **p+A**
  - What is the gluon density in the (x,Q^2) range relevant at RHIC?
  - What role does saturation of gluon densities play at RHIC?
  - What is Q_s at RHIC, and how does it scale with A and x?
  - What is the impact parameter dependence of the gluon density?

Some planned p+A measurements

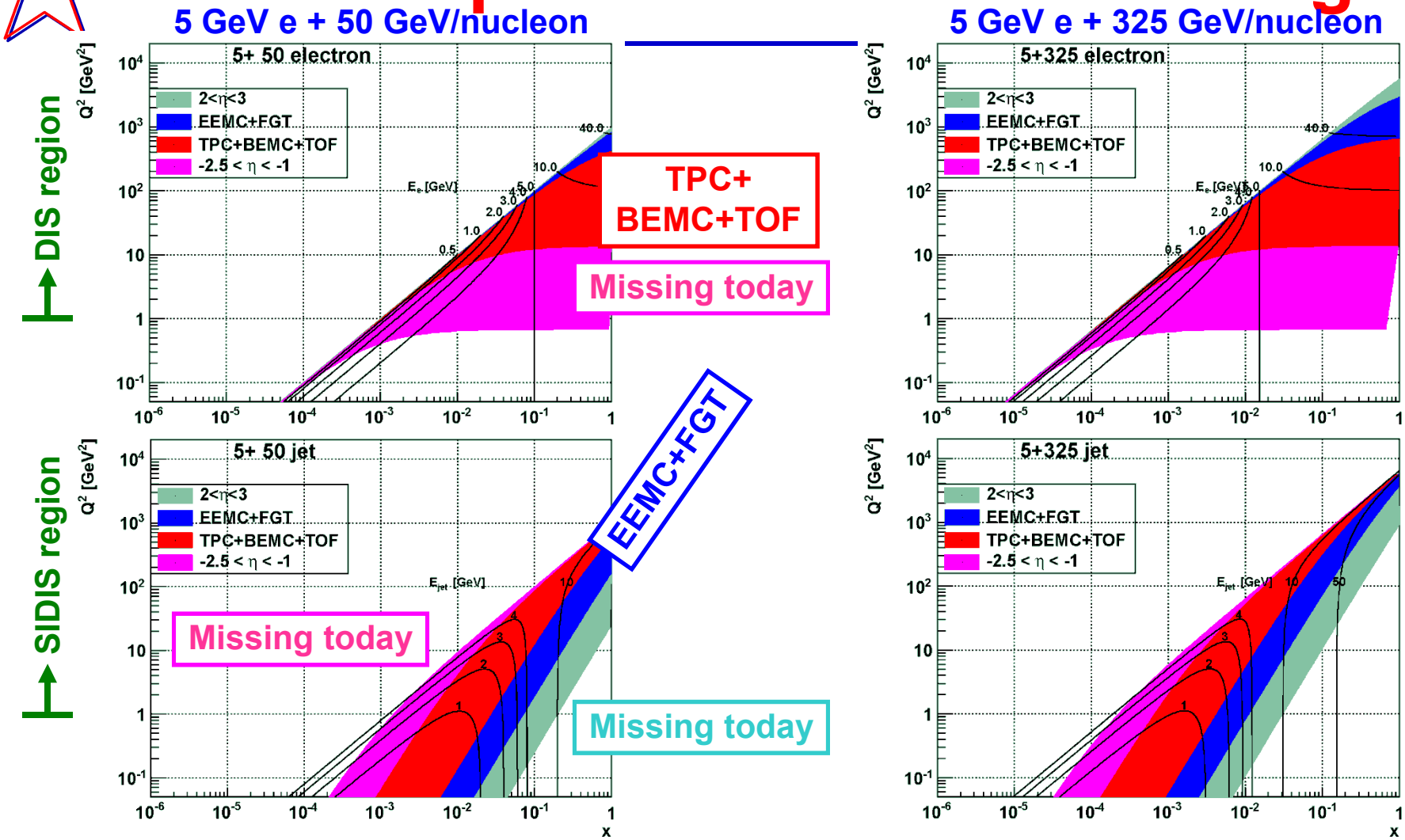
- Nuclear modifications of the gluon PDF
  - Correlated charm production
- Gluon saturation
  - Forward-forward correlations (extension of existing π^0-π^0)
    - *h*-*h* } Easier to measure
    - π^0-π^0
    - γ-*h* } Easier to interpret
    - γ-π^0
  - Drell-Yan
    - Able to reconstruct x_1, x_2, Q^2 event-by-event
    - Can be compared directly to nuclear DIS
    - True 2 → 1 provides model-independent access to $x_2 < 0.001$
  - Λ polarization
  - Baryon production at large x_F
- What more might we learn by scattering *polarized* protons off nuclei?
- Forward-forward correlations, Drell-Yan, and Λs are also very powerful tools to unravel the dynamics of forward transverse spin asymmetries – Collins vs Sivers effects, TMDs or Twist-3, …

Forward Instrumentation Upgrades



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

eRHIC phase 1: kinematic range



- "Forward" (**-2.5 <~ η < -1**) **electron acceptance essential** to span deep-inelastic (DIS) regime
- Both **backward** and **forward** **hadron coverage valuable** for semi-inclusive deep-inelastic (SIDIS) scattering

STAR → eSTAR

Optimizing ***STAR*** for e+p and e+A collisions from 5+50 to 5+325 GeV

- **Inclusive scattering over the entire deep-inelastic region**
  - **Key measurements**
    - **F_L in e+p and e+A: direct measure of gluon densities in nucleons and nuclei**
    - **g_1 in e+p and e+^{3}He: nucleon spin structure**
    - **F_2^A/F_2^d: parton distributions in nuclei (including gluons via Q^2 evolution)**
  - **Need electron detection, ID, and triggering over -2.5 <~ η < -1**
    - **Combined mini-TPC/threshold gas Cherekov detector**
- **Semi-inclusive deep-inelastic scattering over a broad (x,Q^2) domain**
  - **Key measurements**
    - **Flavor-separated helicity distributions, including strangeness**
    - **Collins, Sivers, Boer-Mulders, and other transverse spin distributions**
    - **Flavor-separated parton distributions in nuclei, including strangeness**
    - **Parton energy loss in cold nuclear matter**
  - **Need hadron detection and identification beyond the TPC/EEMC**
    - **Extend TOF to cover -2 < η < -1**
    - **GEM disks (from forward instrumentation upgrade) plus hadronic calorimetry in the region 2 < η < 3**
- **Deeply-virtual Compton scattering**
  - **Key measurement**
    - **GPDs**
  - **Need forward proton and expanded photon detection**
    - **Roman pots (also valuable for spectator proton tagging in e+^{3}He)**
    - **EM calorimetry for -4 < η < -1**

Evolving from *STAR* into *eSTAR*

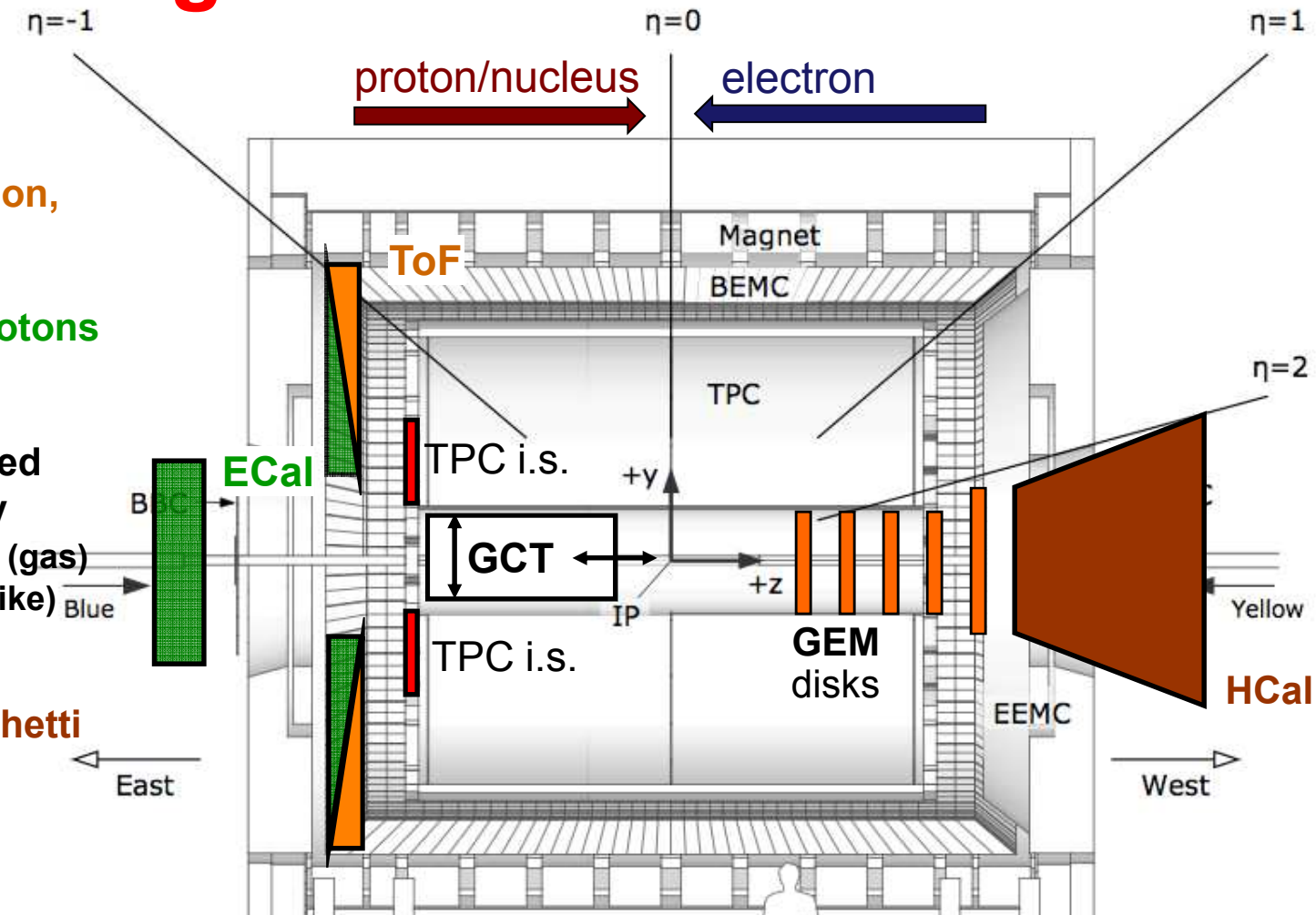
ToF: π , *K* identification, t_0, electron

ECal: electrons and photons

GCT: a compact tracker with enhanced electron capability

Combine high-threshold (gas) Cherenkov with TPC(-like) tracking

HCal: W powder, spaghetti cal



Simulations ahead:
eSTAR task force formed

EIC Generic Detector R&D Panel:

GCT: LOI toward multi-institution R&D effort

HCal: R&D proposal

STAR Forward Instrumentation R&D Projects

Development of a new detector technology for fiber sampling calorimeters for EIC and STAR.

H. Z. Huang, J. Dunkelberger, G. Igo, S. Trentalange, O. Tsai
University of California at Los Angeles

C. Gagliardi
Texas A&M University

S. Heppelmann
Pennsylvania State University

O.Tsai (UCLA) May 9, 2011

An Endcap TOF + PID
$-2<\eta<-1$, electron E<~5GeV
TOF+TPC+EMC (shower), hadron PID
Rice+UT+BNL+UCLA (USA)
USTC+Tsinghua (China)
Ongoing discussion,
proposal for second EIC R&D call?

Letter of Intent for Detector R&D Towards an EIC Detector

TK Hemmick for the EIC Tracking R&D Group

- Brookhaven National Laboratory
- Florida Institute of Technology
- Iowa State University
- Lawrence Berkeley National Laboratory
- Massachusetts Institute of Technology
- Riken Research Center at BNL
- Stony Brook University
- University of Virginia
- Yale University

Roman Pot Phase II
Important for ep, pHe3, pA
BNL+CU+ODU+SINS+WUT

FSC+FMS+RICH+GEM
$2<\eta<4$, DY+hadron jets
PS+BNL+TUAM+UCLA+IU+KU?

Conclusions

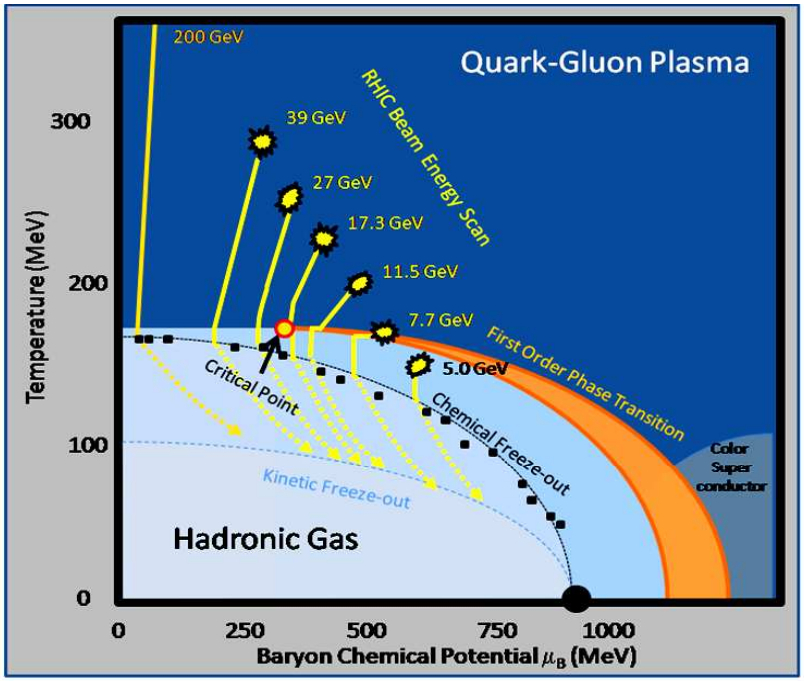
- Properties of sQGP and thermalization
- Mapping and quantifying matter properties in QCD phase diagram
- Mechanism of jet quenching
- Validate and quantify the fundamental difference of gluon and quark jet energy loss
- Novel symmetry
- Understanding the possible symmetries and DOF
- Search for exotic particles
- User facility for hypernuclei, multibaryon states, rare decays
- Properties of cold gluonic matter
- Nuclear structure function, Initial condition, CGC, jet energy loss in nuclei

STAR(--2016)➔pSTAR(2017-18)➔eSTAR(2020)

Backup slides

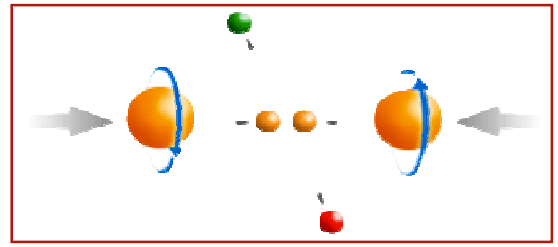
RHIC: eight key unanswered questions

Hot QCD Matter

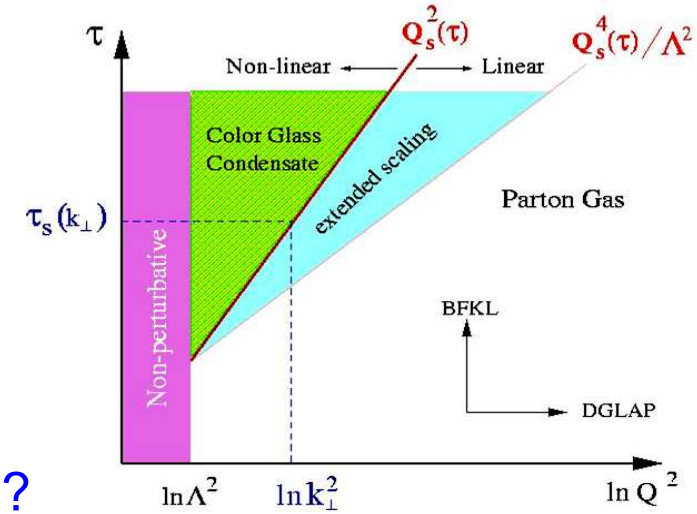


1: Properties of the sQGP
2: Mechanism of energy loss:
weak or strong coupling?
3: Is there a critical point, and if so, where?
4: Novel symmetry properties
5: Exotic particles

Partonic structure

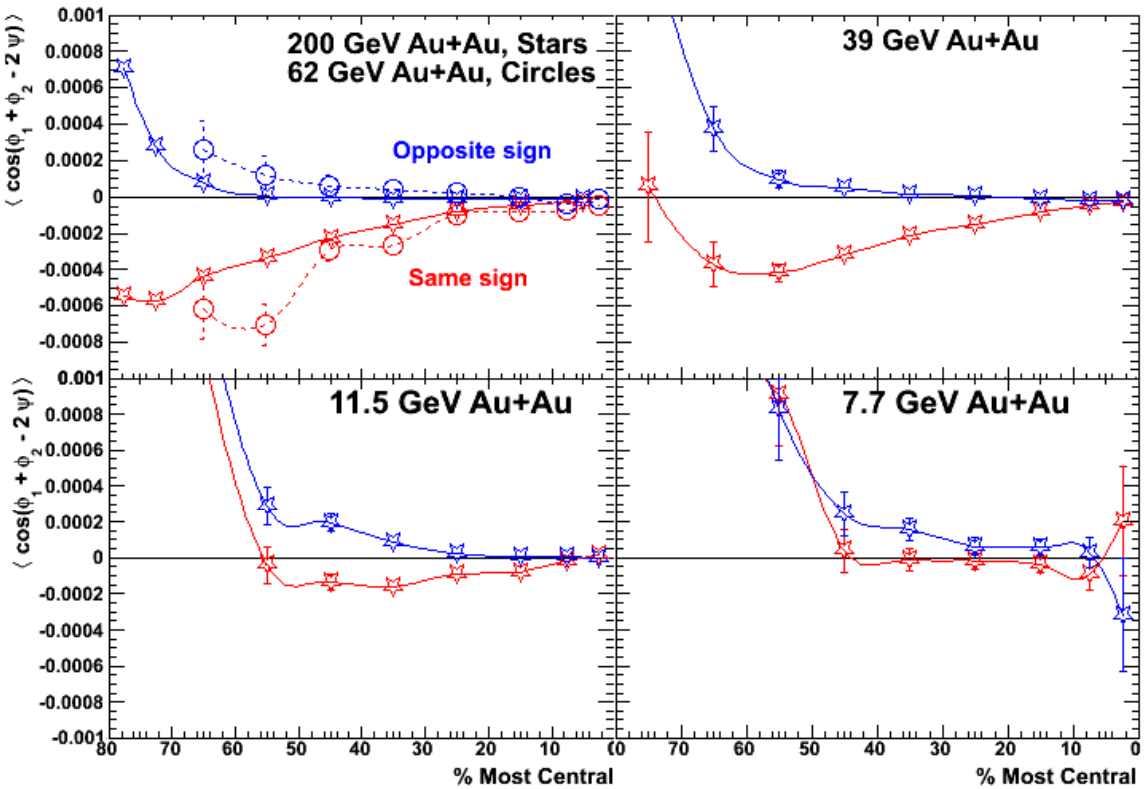


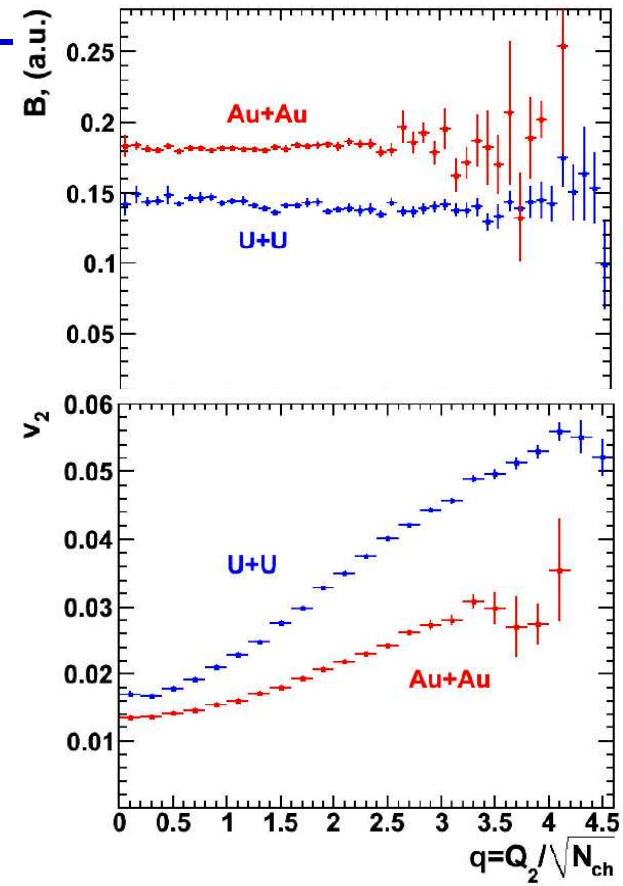
6: Spin structure of the nucleon
7: How to go beyond leading twist and collinear factorization?



8: What are the properties of cold nuclear matter?

Novel symmetries: local strong parity violation





- Transitions between domains with different topological charge may induce parity violation in the dense matter
  - Similar transitions (at much higher energies) might have produced the matter-antimatter asymmetry in the early universe
- Magnetic field in A+A plays a key role: **chiral magnetic effect**
- **Crucial** to verify if parity violation is the **correct explanation**
  - **U+U collisions:** collisions with **more v_2** and **less B field** than Au+Au

Discover antimatter Unstable Nuclei

NEXT:

Discover antimatter Unstable Nuclei:

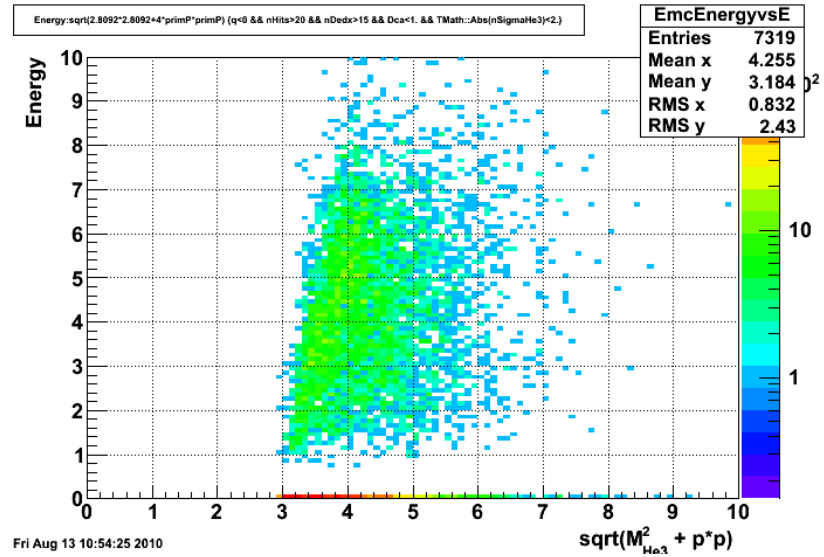
$^{4}Li \rightarrow {}^{3}He + p$

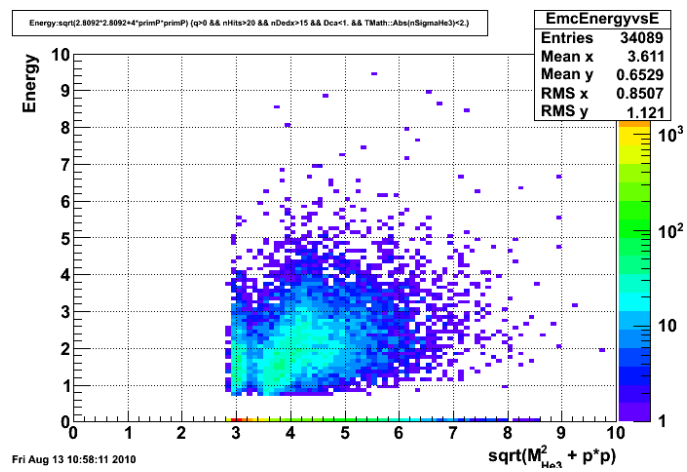
$^{4}He^{*} \rightarrow d + d,\ t + p$

$^{5}Li \rightarrow {}^{4}He + p$

${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi$ (x100)

- Clear energy excess:
  EMC energy vs TPC Energy
  He3bar (top panel) He3 (bottom panel)
  Run10, He3bar efficiency with Et>2.5GeV is 62%

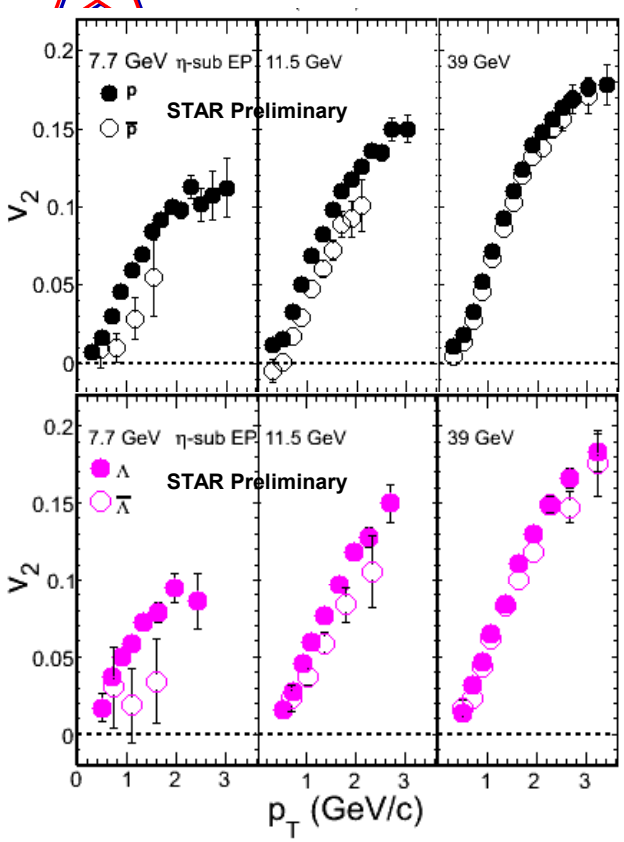


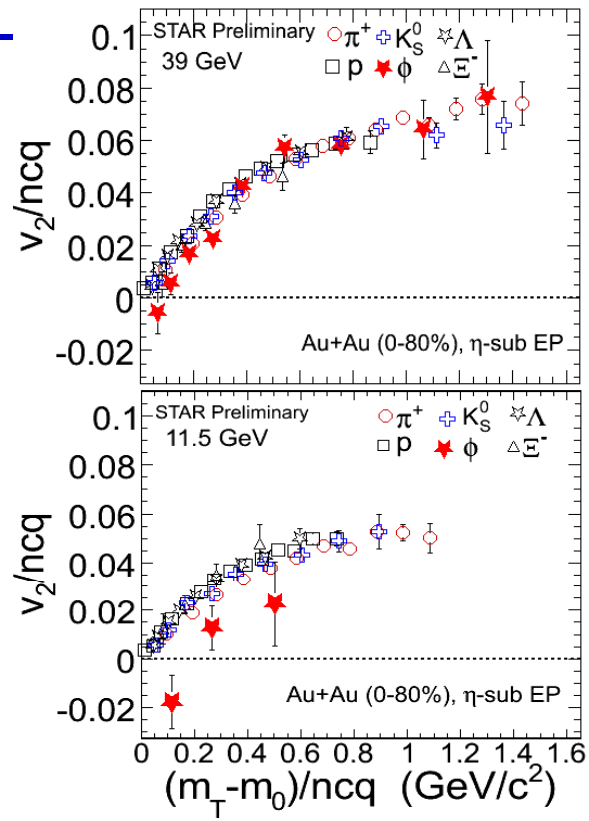


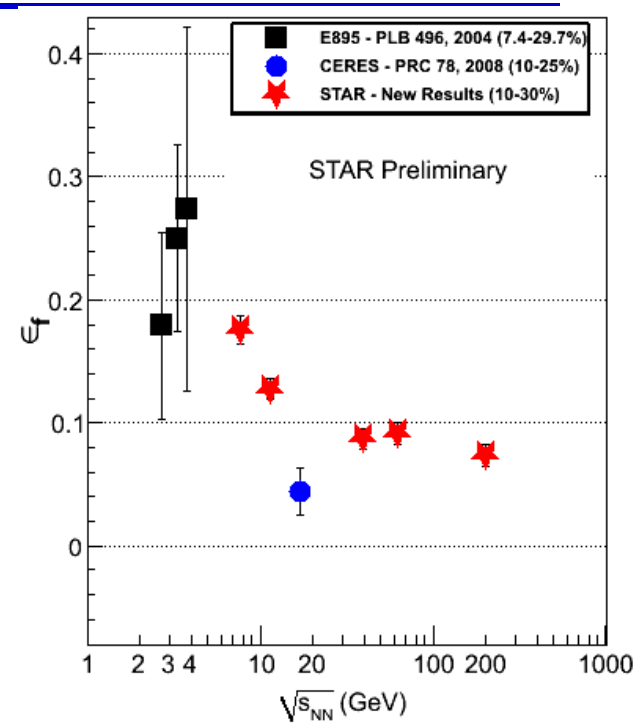
Proposed Trigger:

- L0 EMC HT>1.8 or 2.5GeV
- L0 decision on TPC sector readout
- Read events at high rate with 1--2 TPC sectors (DAQ10K)
- Full RHIC II luminosity
- Two order of magnitude enhancement

Phase II Expedition







- 39, 62, and 200 GeV collisions are qualitatively similar
- Even extends to LHC energies
- But **many changes** appear **at lower energies (11.5, 7.7)**
- Narrowing down the region of interest (19.6, 27) in run 11
- Future (2015+): **need detailed study of the key region**
  - Finer energy steps with higher statistics, beam species

Summary

Successful RHIC BES Program from Collider/Accelerator and experimental side

New observations:

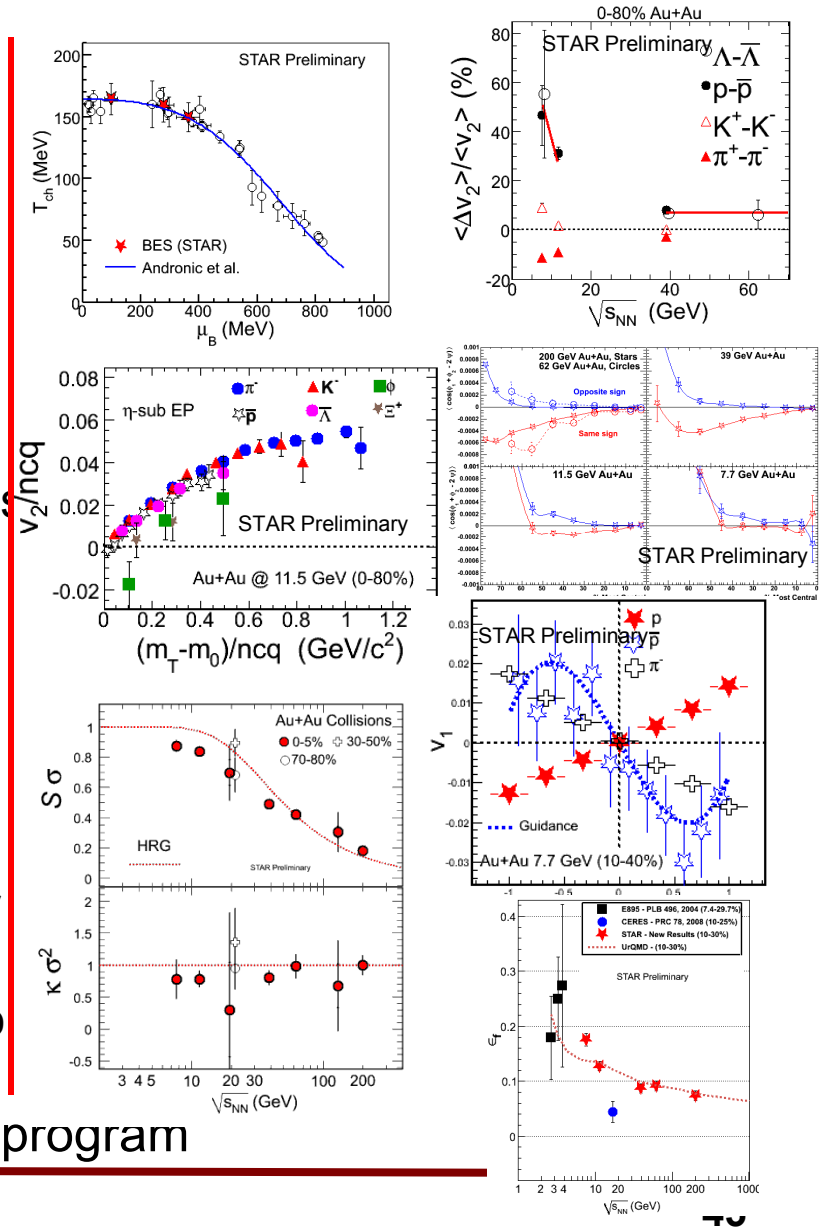
- Identified hadron production & freeze-out parameters reveals high net-baryon density at these energies. Effect on several observables seen.

- Hadronic interactions at low energy. Small ϕ meson v_2 at 11.5 GeV. Disappearance of dynamical charge correlations

- Interesting trends for observables related to softening of EOS. Non-monotonic variation of freeze-out eccentricity. Change in sign of proton v_1 with energy and centrality.

- Large acceptance & excellent PID allows for fluctuations measurements. Deviations from HRG and Poisson statistics. Is being used to study structure of the QCD phase diagram.

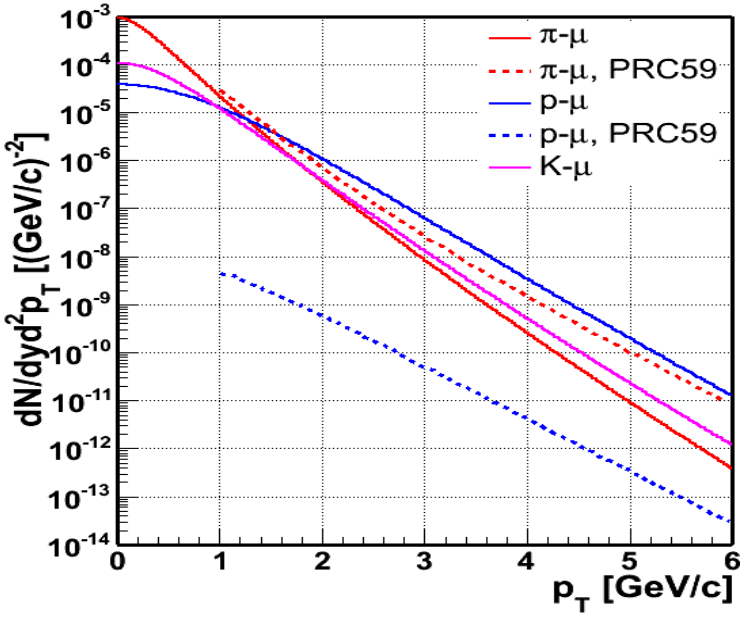
Need to complete the first phase of BES program

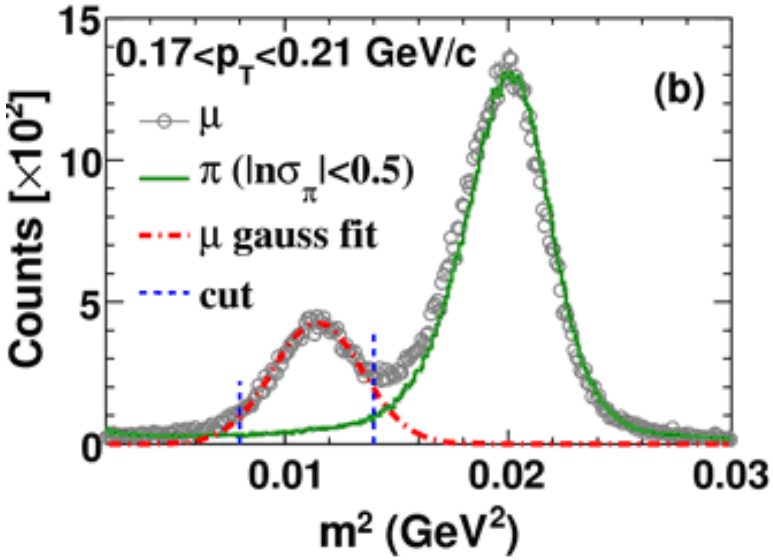


Rate Estimates

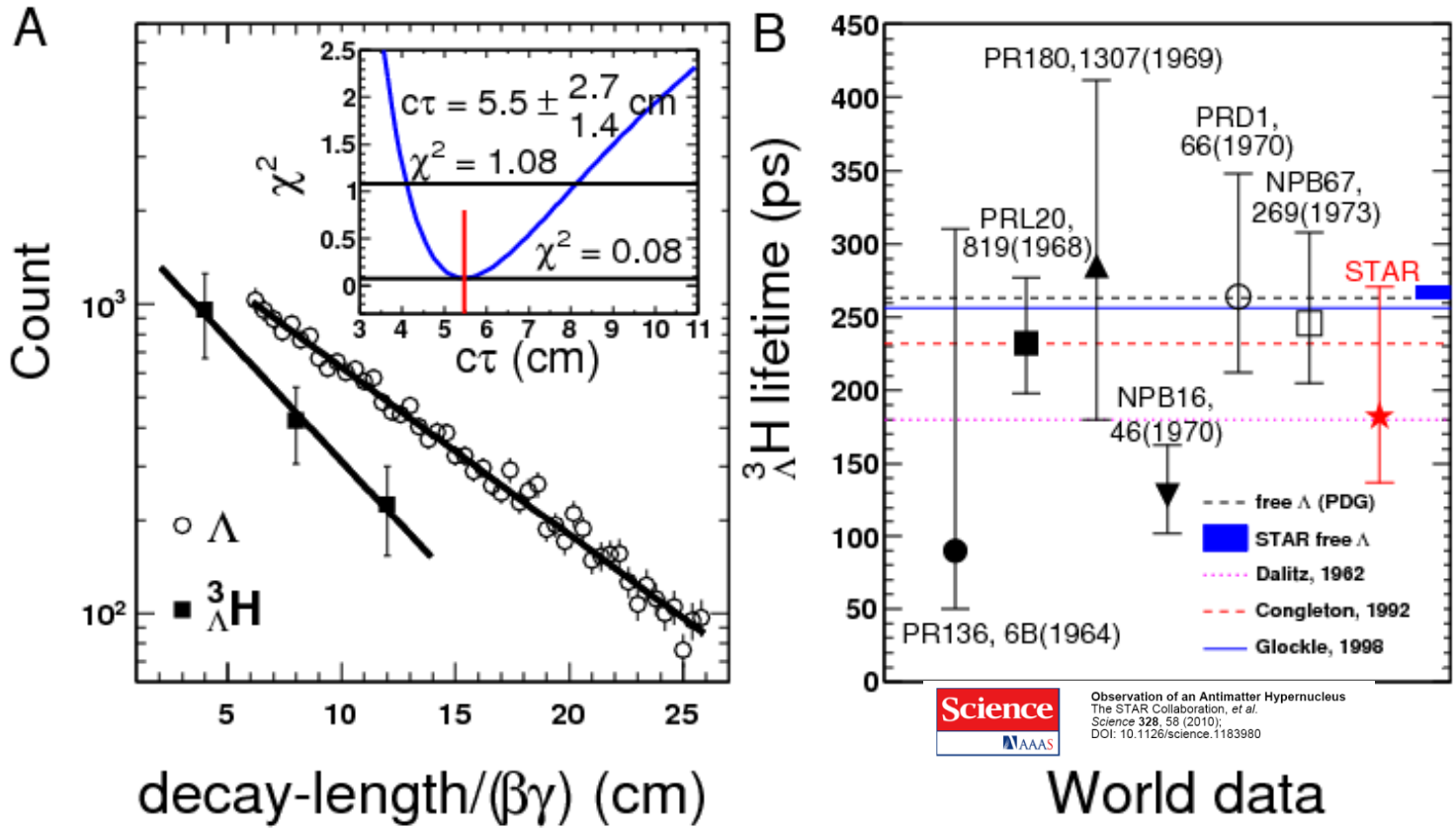
- Muon PID using TOF/TPC/MTD
- the antimatter muonic hydrogen: >1000 candidates in 500M central events
- MTD trigger for π-μ high-pt atoms with single TPC sector readout

Atom	μ pt (GeV/c)	Hadron pt	Atom pt	dN/dy
π–μ	[0.17,0.3]	[0.22,0.4]	[0.39,0.7]	3e-4
K-μ	[0.17,0.3]	[0.8,1.4]	[0.97,1.7]	3e-5
p-μ	[0.17,0.3]	[1.5,2.7]	[1.7,3.0]	1e-5
π–μ	>1.5	>2	>3.5	1e-8





Lifetime of a hypertriton



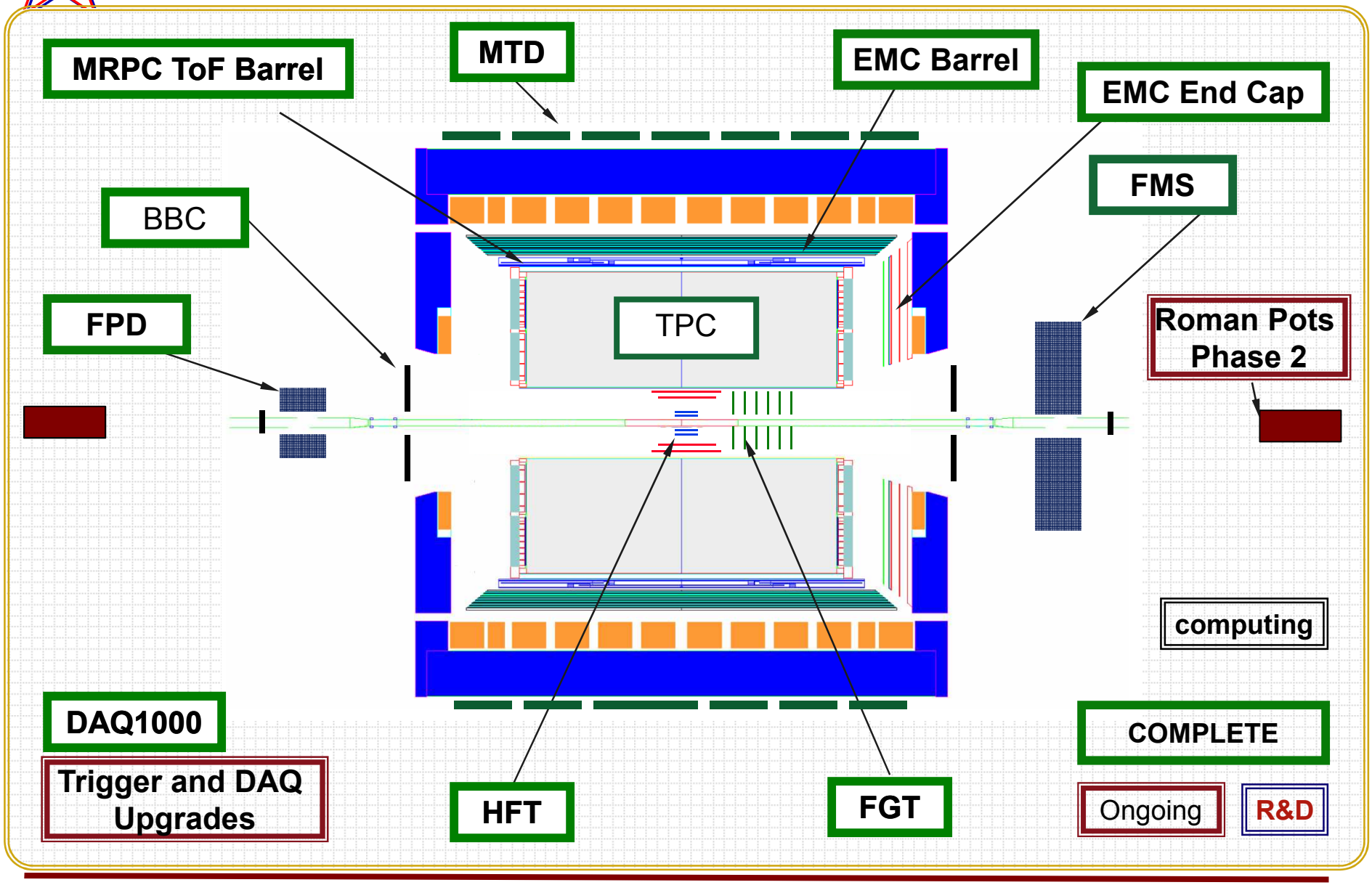
- Lifetime related to binding energy
- Theory input: the Λ is lightly bound in the hypertriton

[1] R. H. Dalitz, *Nuclear Interactions of the Hyperons* (Oxford Uni. Press, London, 1965).

[2] R.H. Dalitz and G. Rajasekharan, Phys. Letts. 1, 58 (1962).

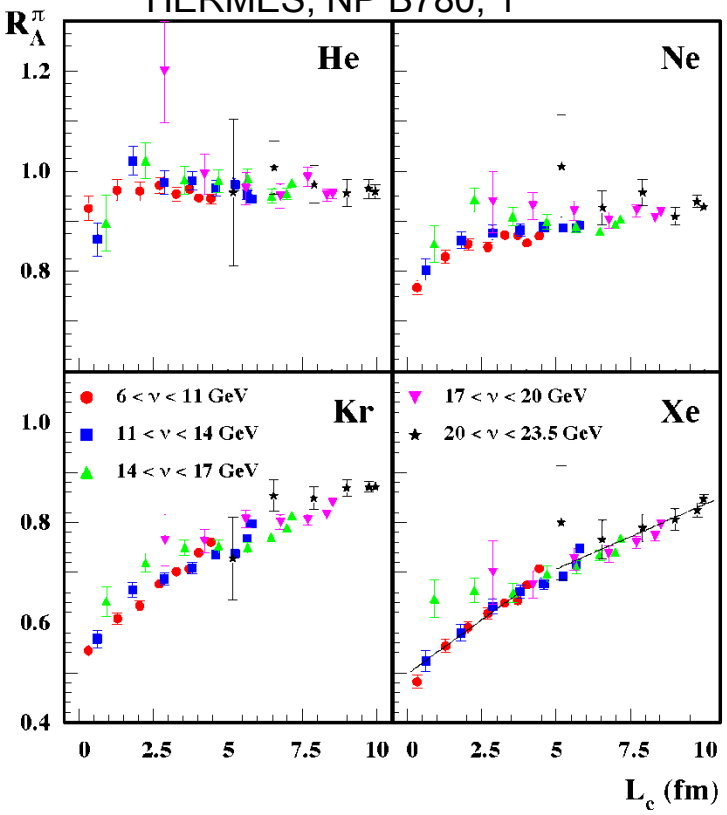
[3] H. Kamada, W. Glockle at al., Phys. Rev. C 57, 1595(1998).

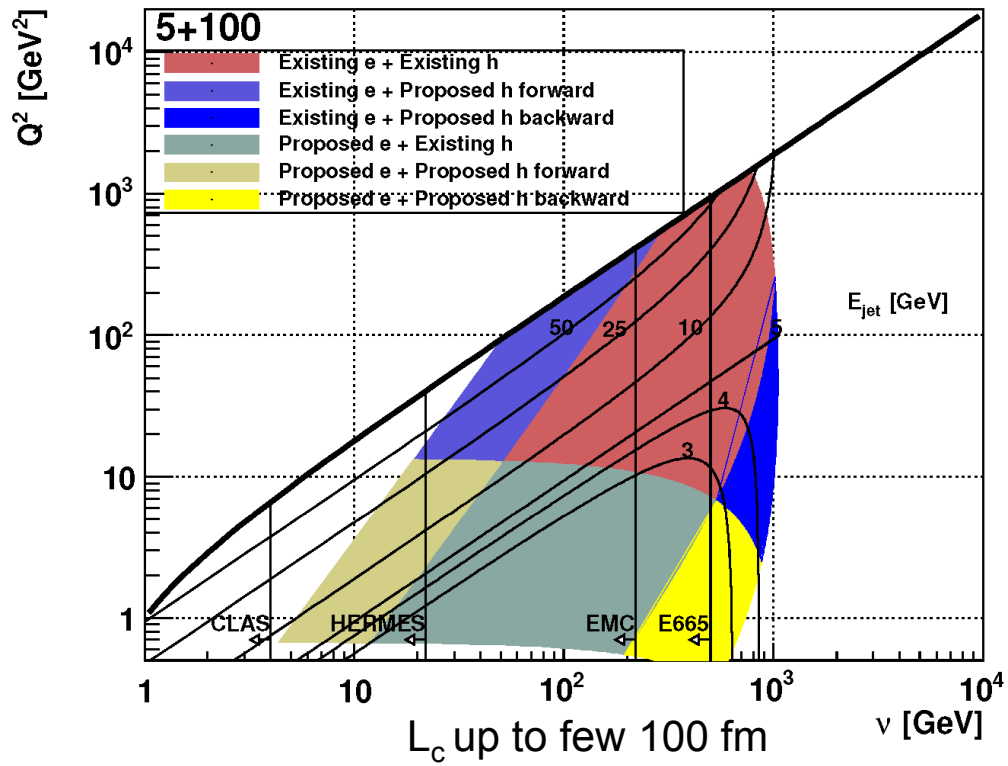
STAR Experiment



Parton energy loss in cold QCD matter

HERMES, NP B780, 1





- Complementary tool to investigate partonic energy loss
- HERMES: hadrons can form partially inside the medium
  - Mixture of hadronic absorption and partonic energy loss
- eRHIC: light quark hadrons form well outside the medium
- Heavy quarks: unexplored to date. Low β → short formation time