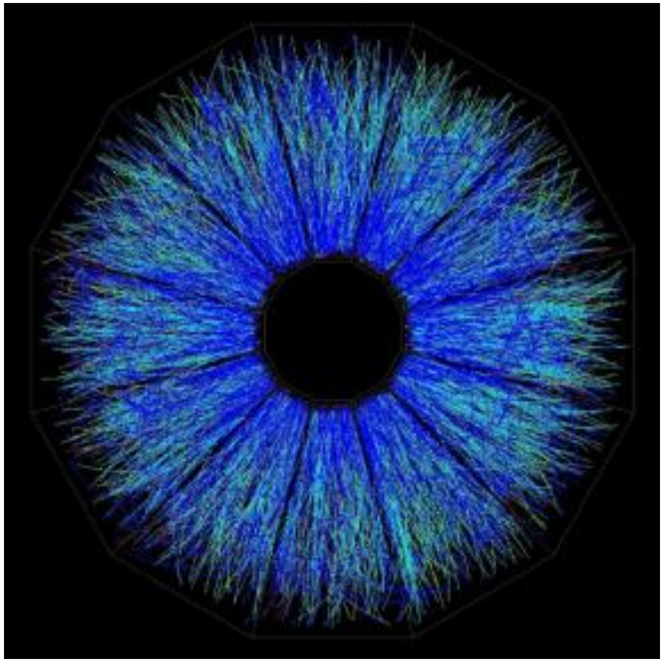
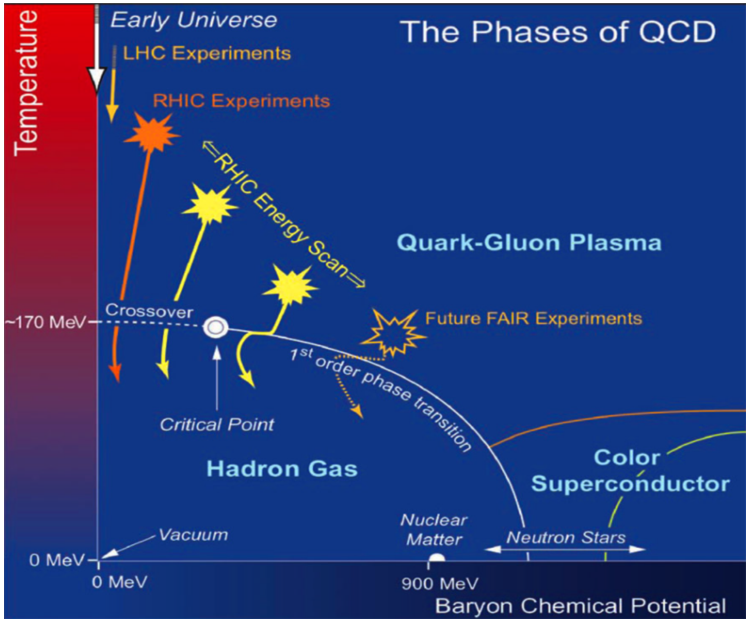
Strangeness and Hypernuclei with STAR

Zhangbu Xu

For the STAR Collaboration

1. Why strange is still interesting
2. Strangeness in RHIC Beam Energy Scan
3. Strangeness in Chiral Symmetry Restoration
4. Hypertriton
5. What is next? (ideas)



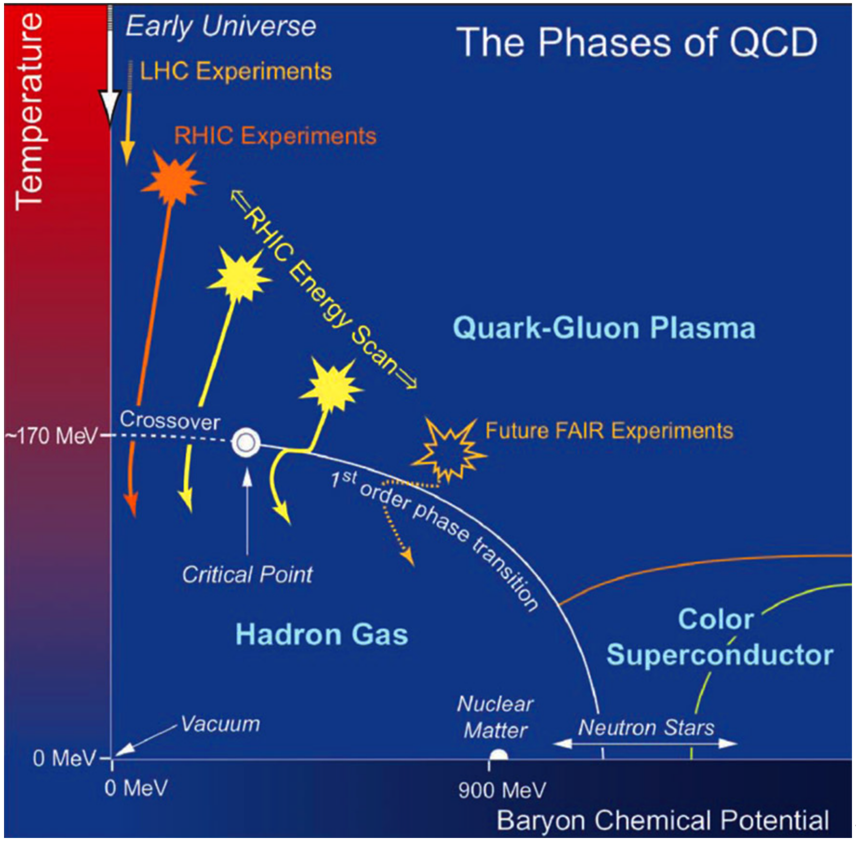


The International Workshop on the Future Potential of High Intensity Accelerator for Particle and Nuclear Physics 2016

BROOKHAVEN NATIONAL LABORATORY

Beam Energy Scan Phase I (2010-2014)

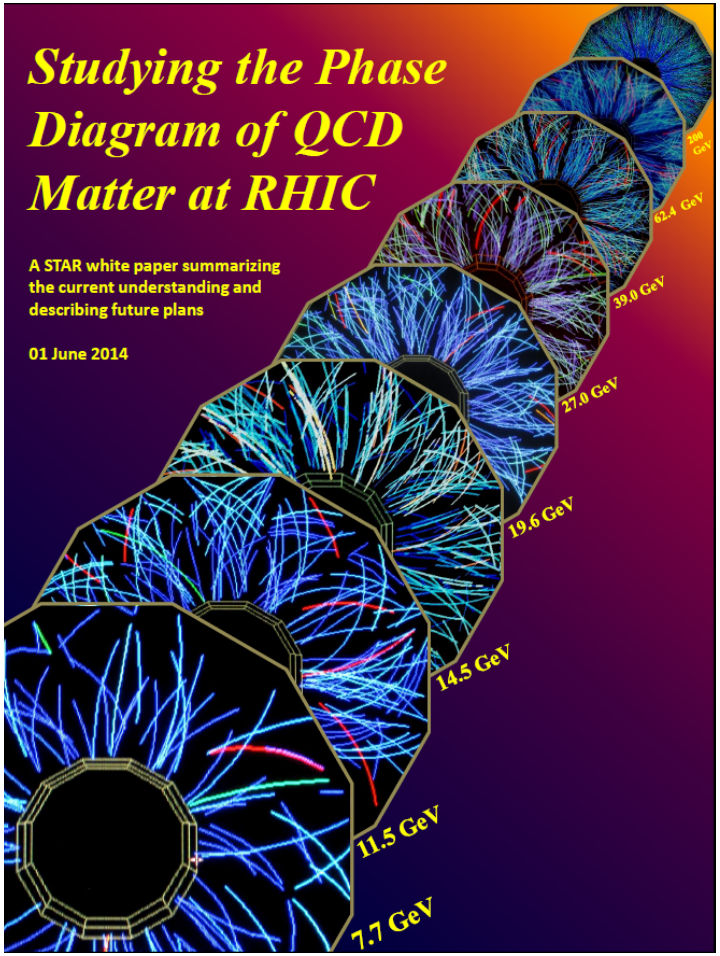
STAR 2005 Whitepaper: Nucl. Phys. A **757** (2005) 102
Extend RHIC Au+Au measurements down toward SPS energy, search for possible indicators of a rapid transition in measured properties.
Chaired by S. Vigdor (IU)



NSAC LRP 2007

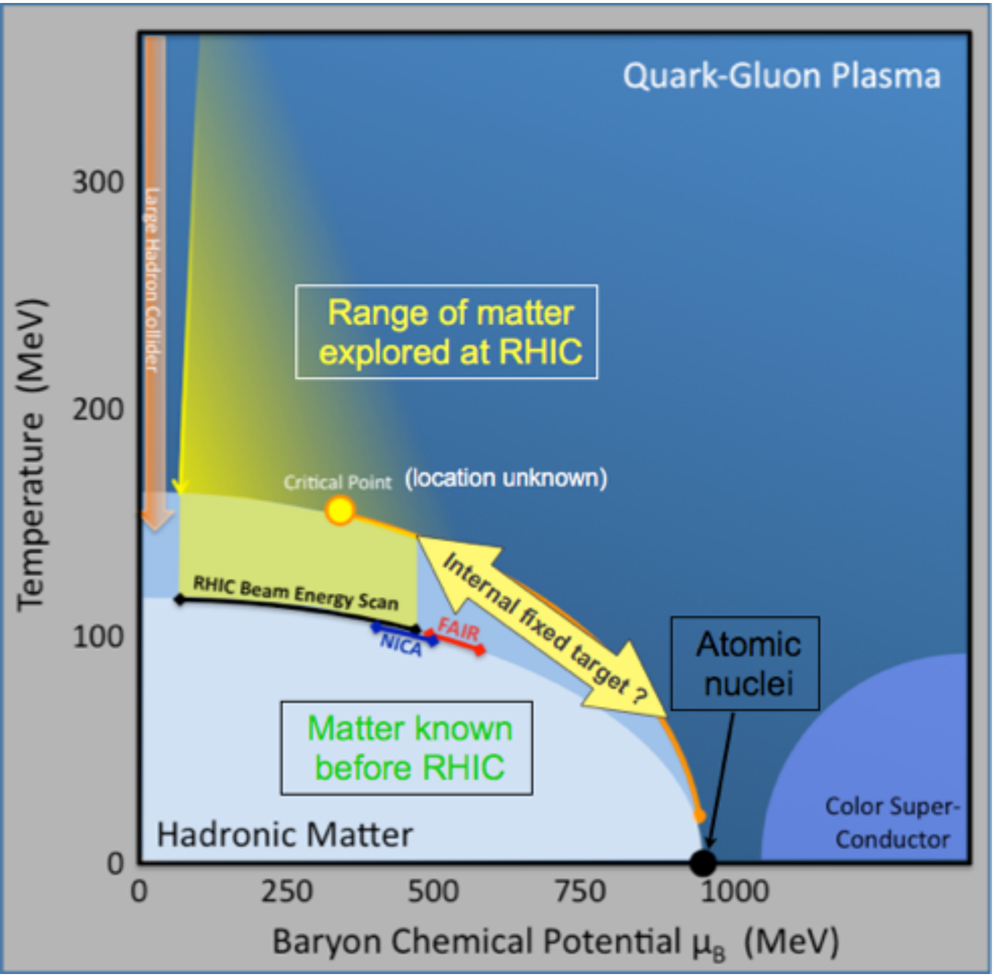
http://science.energy.gov/np/nsac/

2008 RHIC 3000events at 9.2GeV, Phys. Rev. C 81 (2010) 24911



2010: http://arxiv.org/pdf/1007.2613.pdf
2014: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Mapping the QCD Phase Diagram



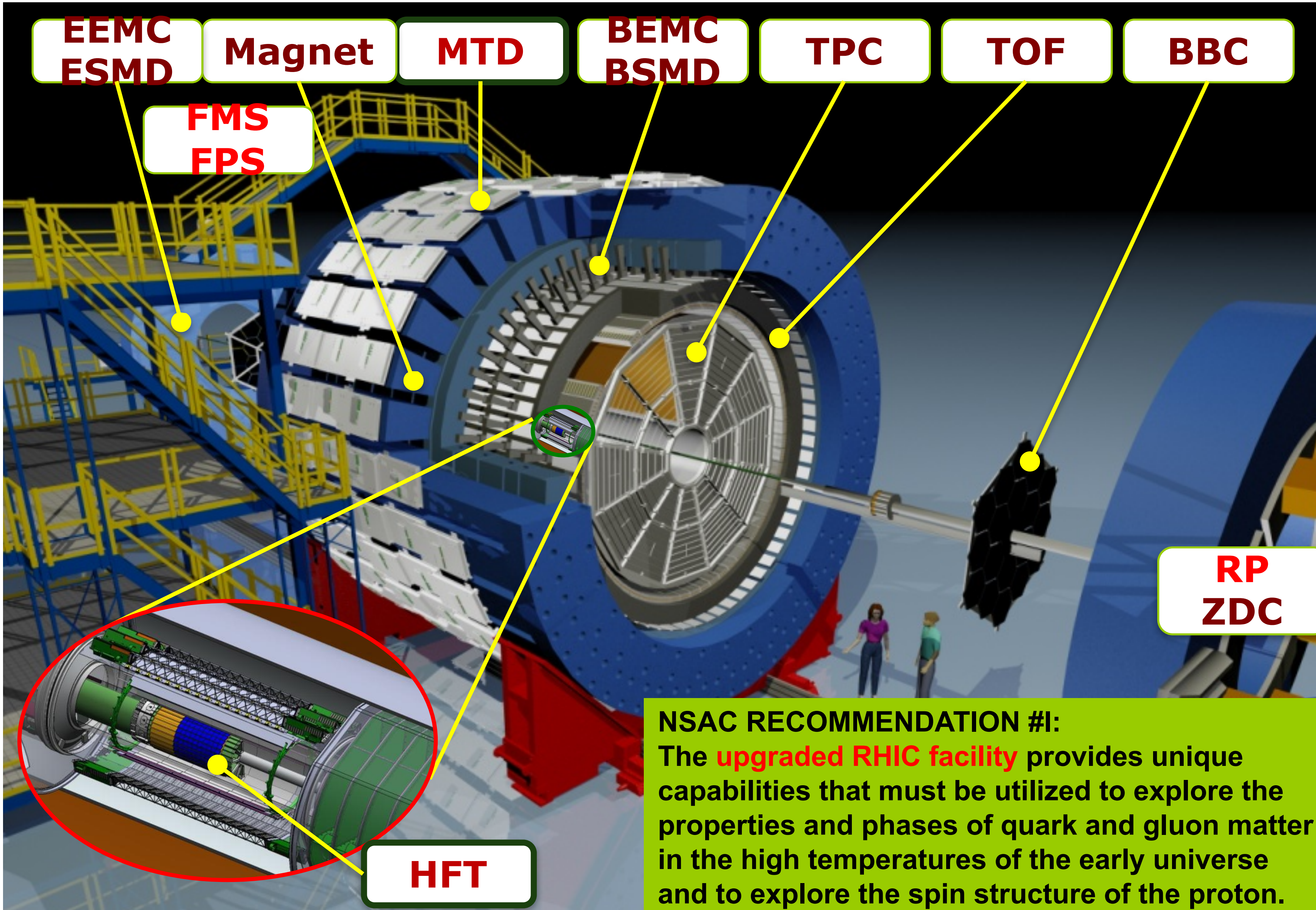
RHIC uniquely suited to map the QCD phase diagram at finite baryon density

1. Thermodynamics applicable
   - Chemical and thermal fit
   - Comparisons with LQCD
2. Change of Symmetry (degree of freedom)
   - Chiral symmetry restoration
   - Quark and gluon degree of freedom
   - Response to external field
3. Equation of State (soft)
4. Critical behavior
   - Critical exponent
   - Critical fluctuation

Hints of new behavior in first Beam Energy Scan
Beam Energy Scan Phase 2 (BES II):
from hints to quantitative understanding

STAR Detector System

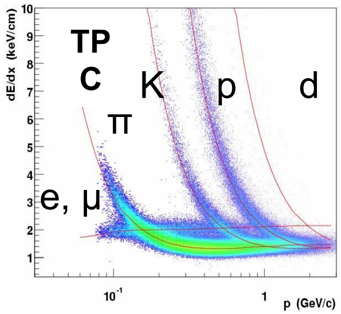
15 fully functioning detector systems

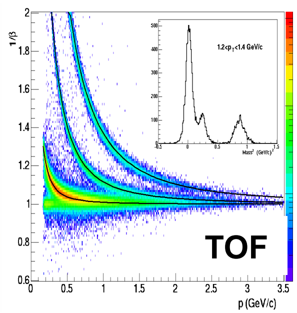


NSAC RECOMMENDATION #I:
The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.

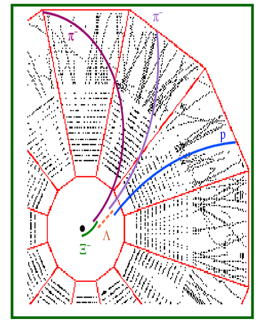
X10^3 increases in DAQ rate since 2000, most precise Silicon Detector (HFT 2014-16)

Particle Identification at STAR

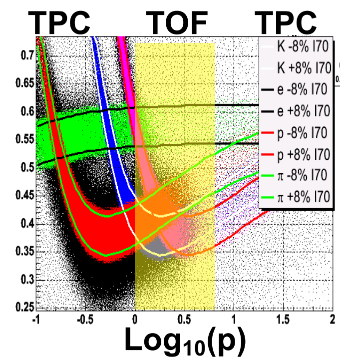


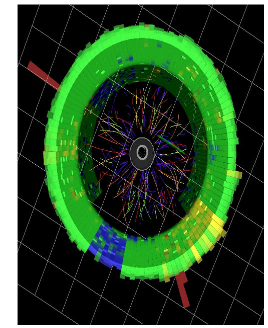


Charged hadrons

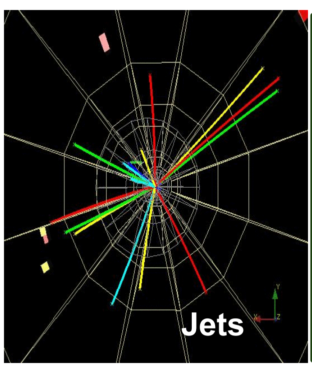


Hyperons & Hyper-nuclei

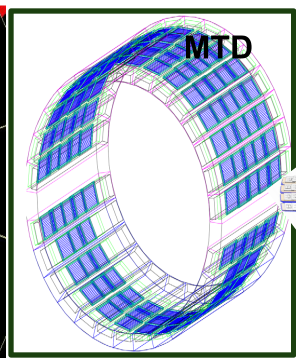




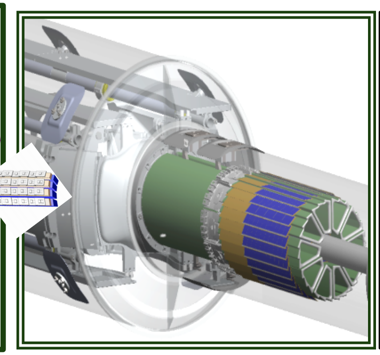
EM particles



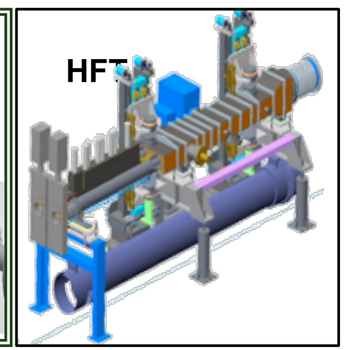
Jets & Correlations



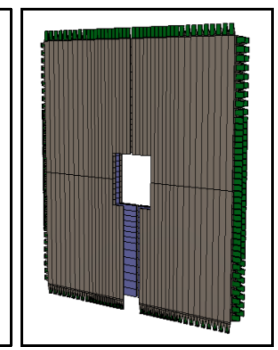
High p_T muons



Heavy-flavor hadrons



Forward protons

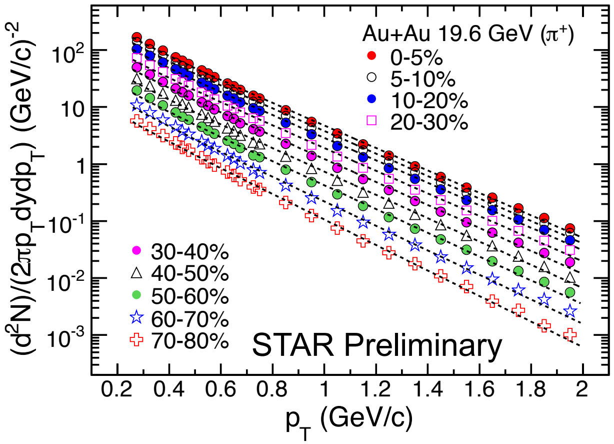


Forward photons

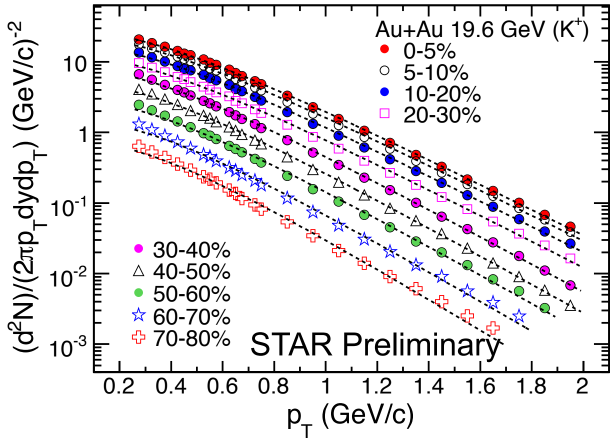
Multiple-fold correlations for identified particles!

Invariant Yield

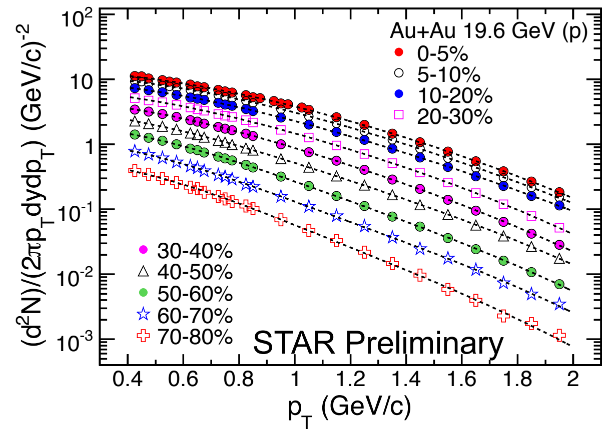
π^+



K^+



p



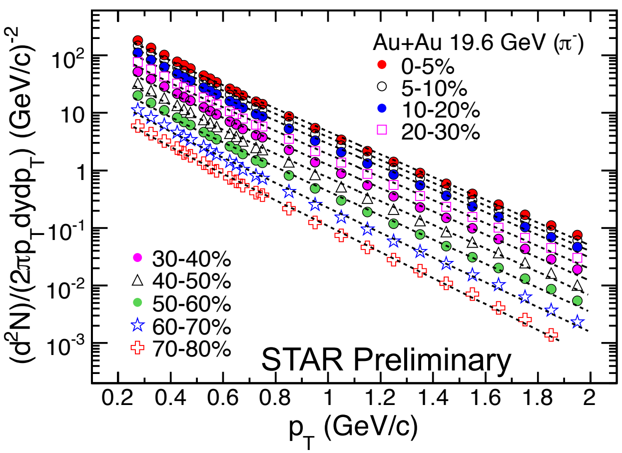
Pion curves:
Bose-Einstein fits

Au+Au 19.6 GeV

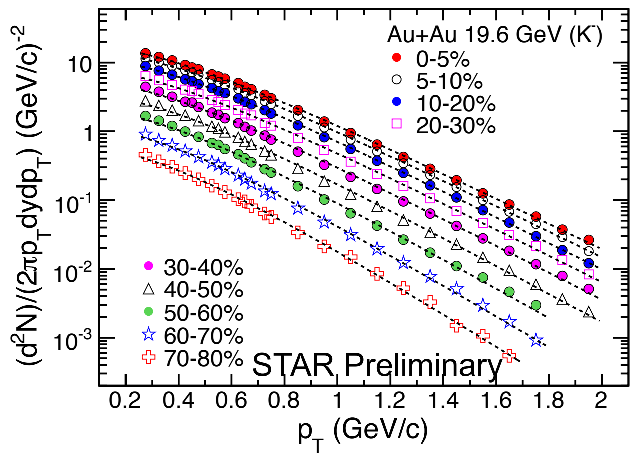
Kaon curves:
(m_T-m) exponential fits

proton curves:
Double exponential fits

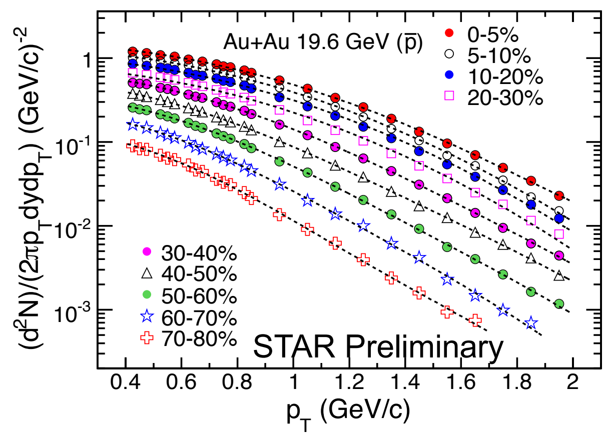
π^-



K^-

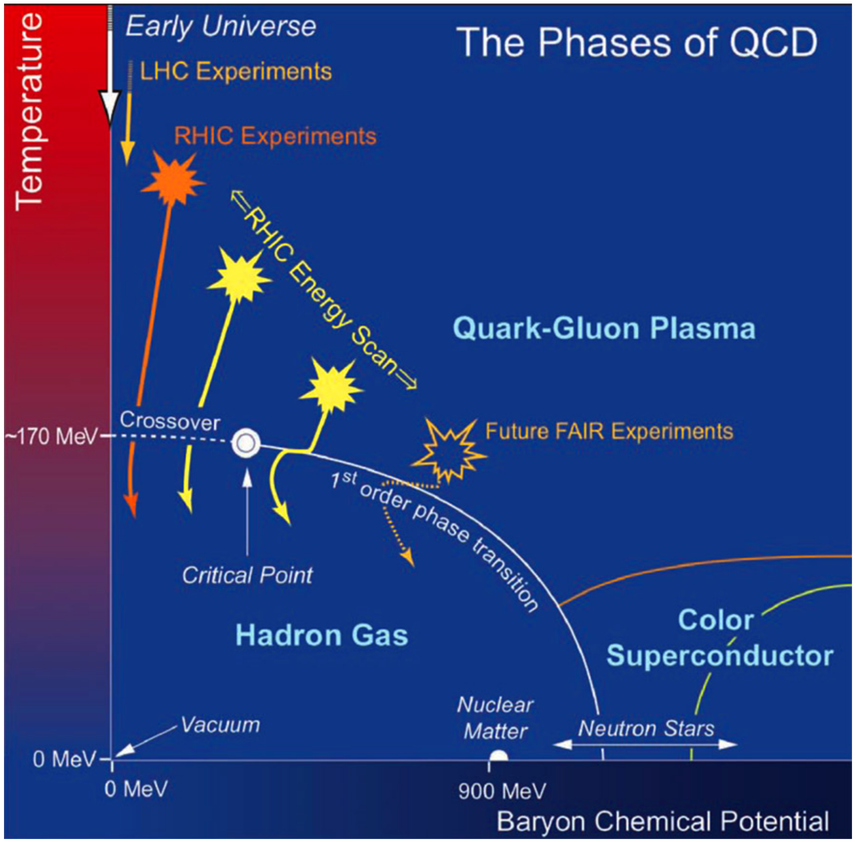


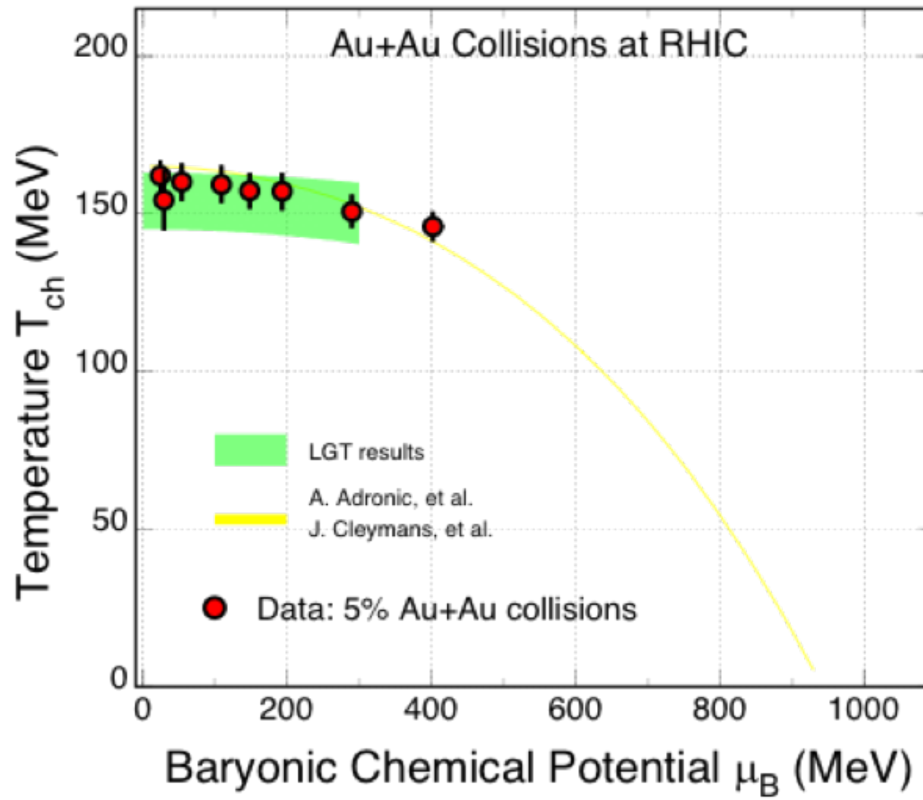
pbar



Spectra are characterized by dN/dy and $<p_T>$ or $<m_T>$

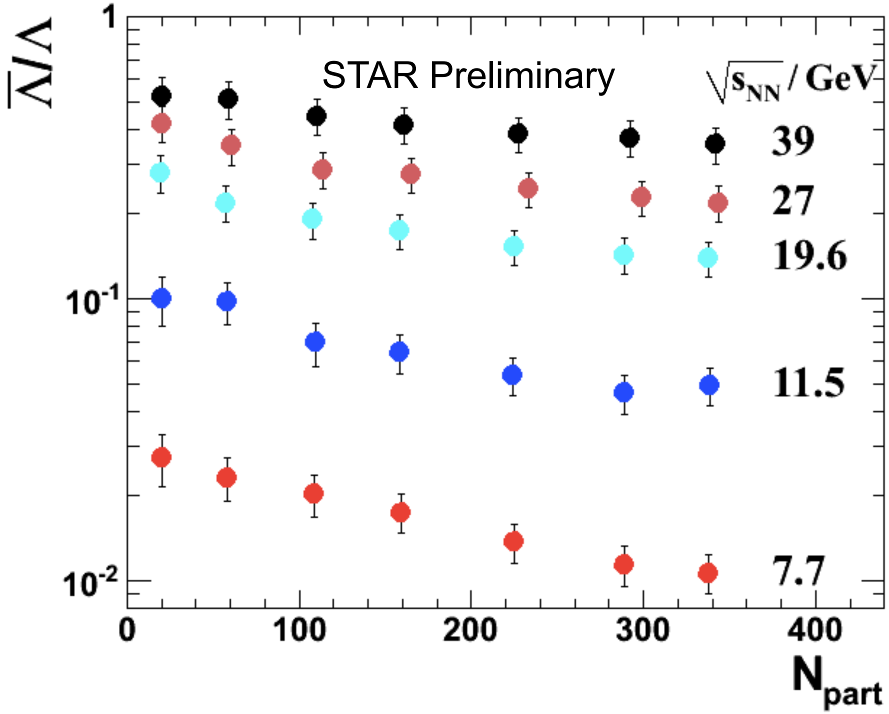
Putting data points on the phase diagram

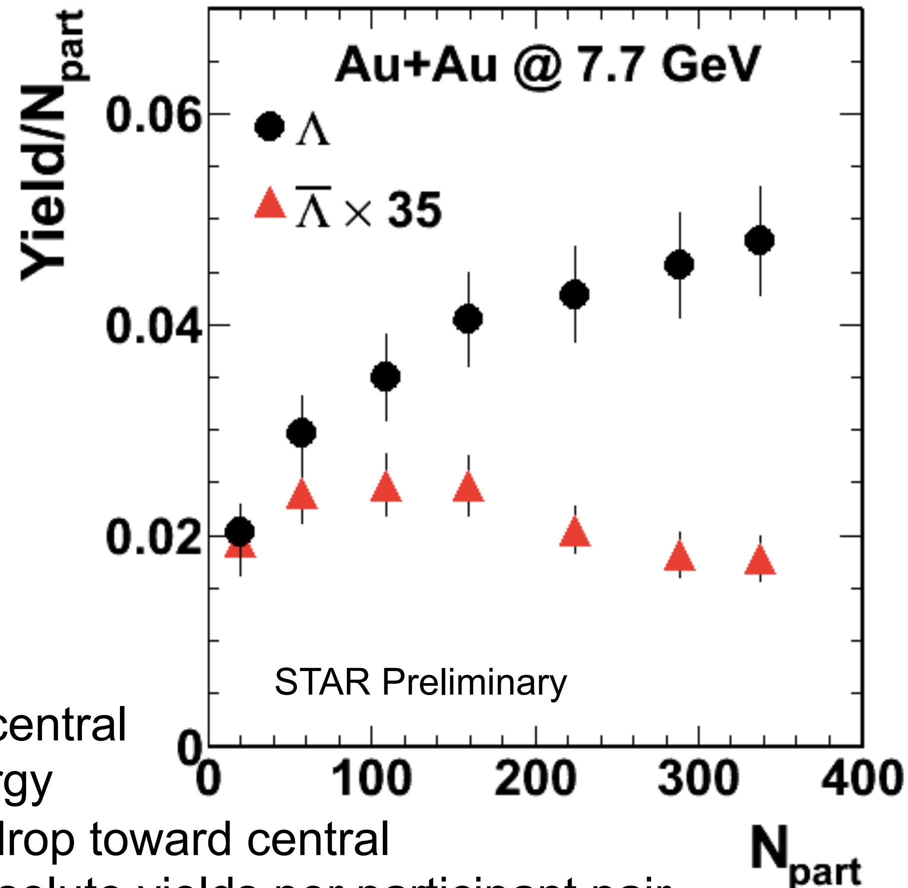




Chemical Freeze-out in Heavy-Ion collisions coincides with Lattice Phase Boundary

Stopping, Thermalization and Absorption





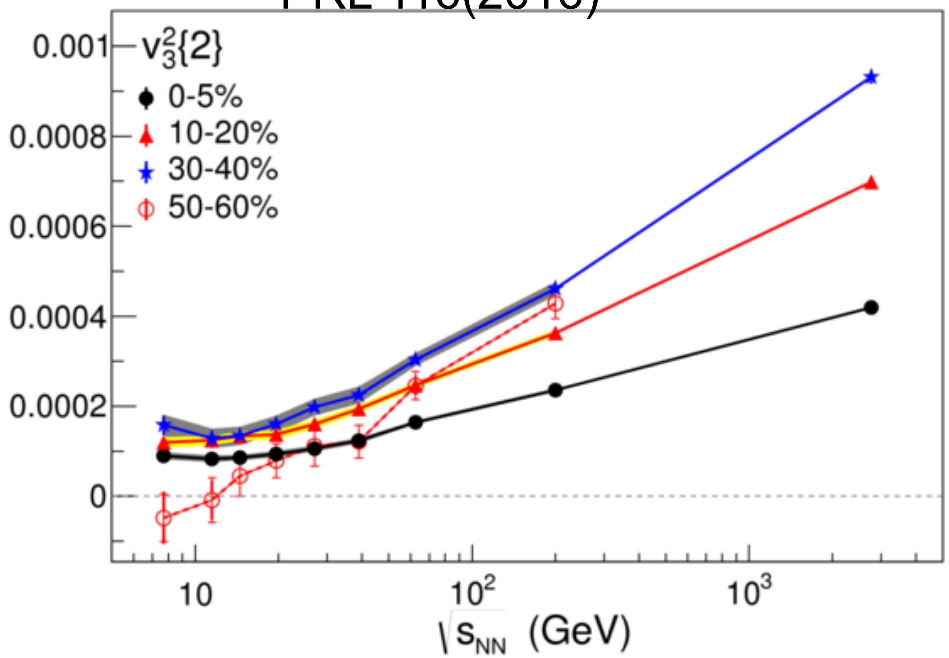
- Baryon stopping increases toward more central
- Stopping is more prominent at lower energy

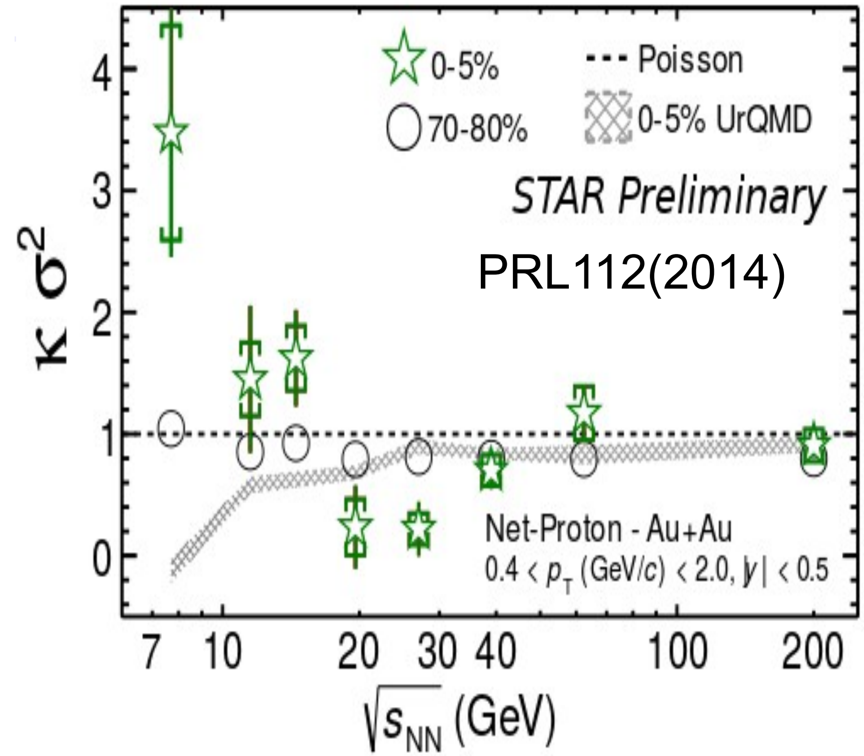
It is believed that Absorption drives Bbar/B drop toward central
However, very little change of antibaryon absolute yields per participant pair

Important to understand initial stopping and pair production vs final state
7.7GeV COM energy => Fixed target Energy **31GeV proton** beam
p, phi, Lambda, Xi, Omega (antiparticle) production in p+A

(STAR) Map QCD phase diagram (I)

PRL 116(2016)



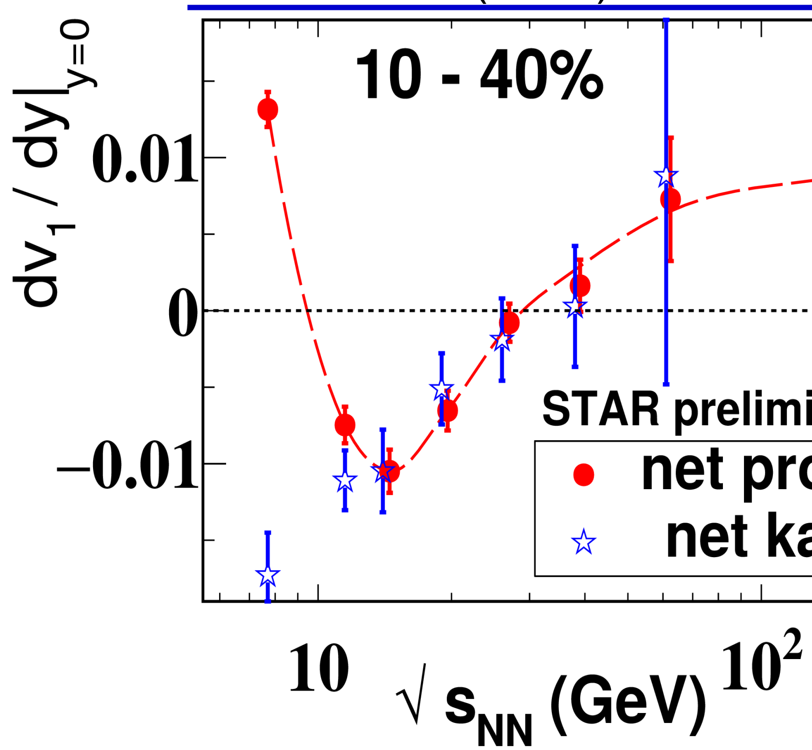


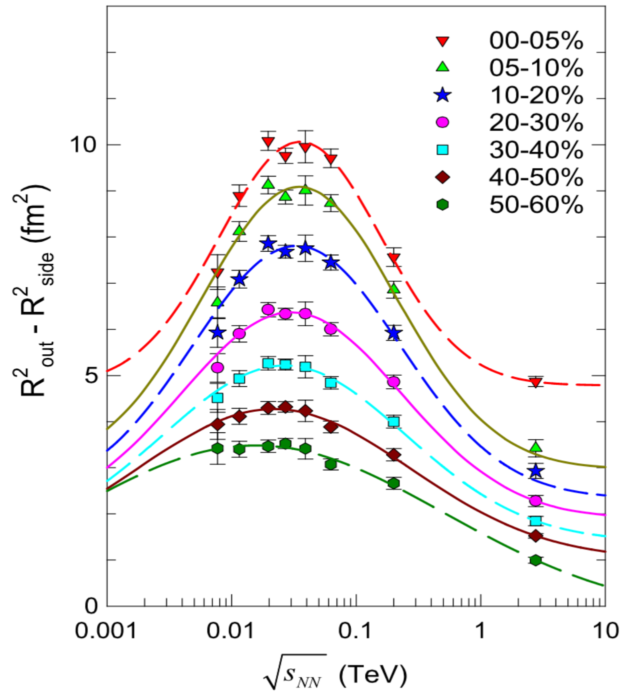
Beam Energy Scan Program:

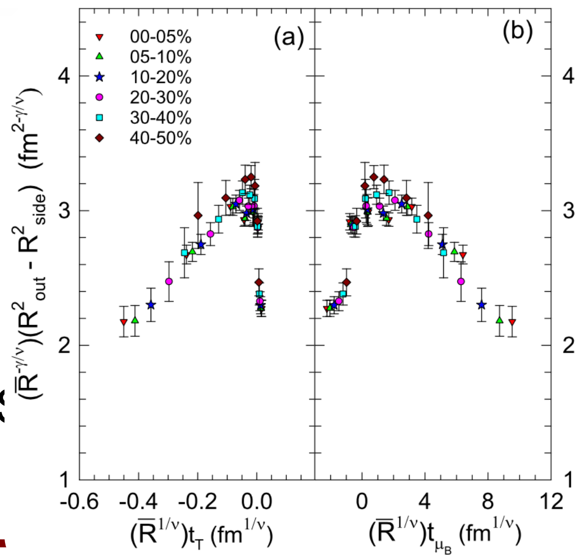
- Turn off QGP Signatures
  triangle flow (v_3) in peripheral at low energy consistent with zero
  Hadron suppression at high p_T
- Search for critical point
  net-proton Kurtosis possibly not Poissonian and grow with accepted rapidity window
- AND…

(STAR) Map QCD phase diagram (II)

PRL112(2014)







R. Lacey, PRL **114**, 142301 (April 2015)
STAR, PRC92(2015)

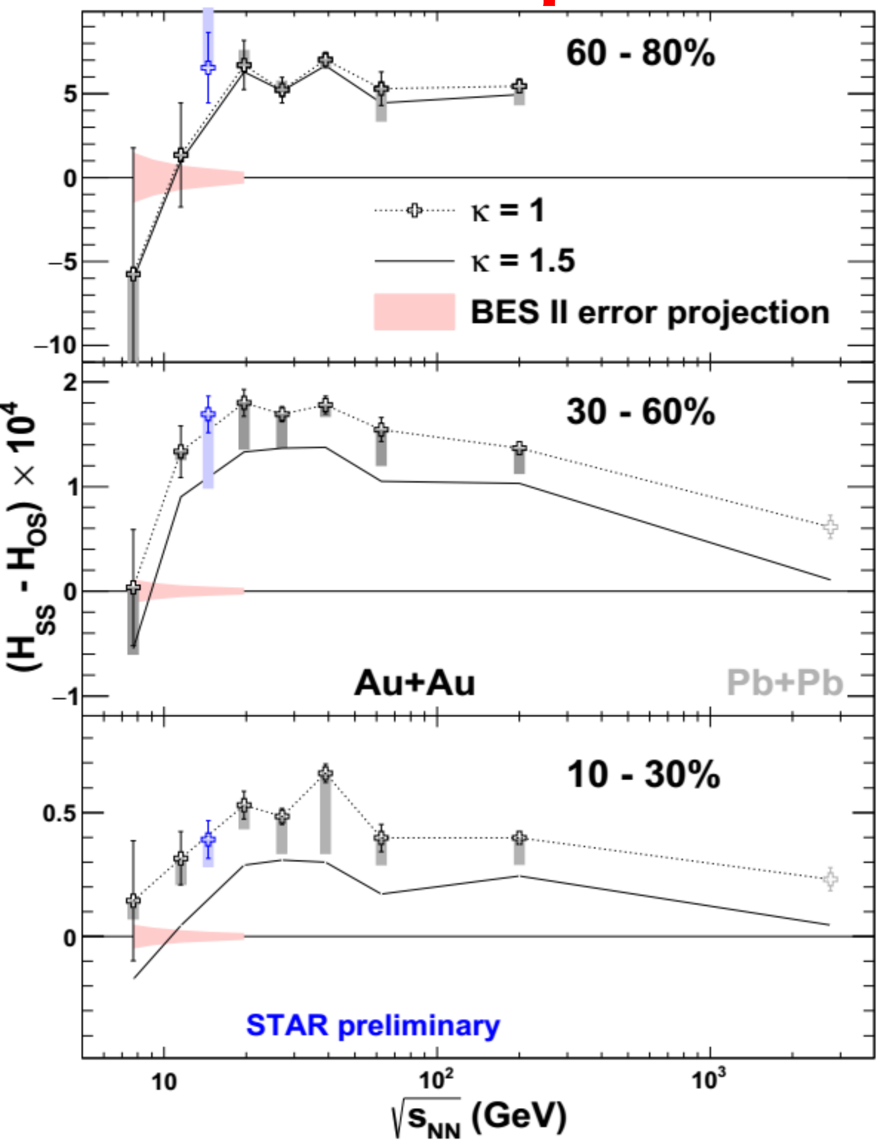
Beam Energy Scan Program:

- …

- Search for first-order phase transition
  - minimum net-proton v1 slope from interplay between baryon stopping and soft EOS
  - Finite Size (HBT) Scaling shows Criticality compressibility, speed of sound?

QCD phase transition is a chiral phase transition

PRL113(2014)



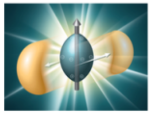
1. Charge separation (14.5GeV)
2. Bulk charge dependence of $\pi^{\pm}$ v_2
3. Low-mass dilepton excess
4. Global polarization of hyperons

Editors' Suggestion

Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions

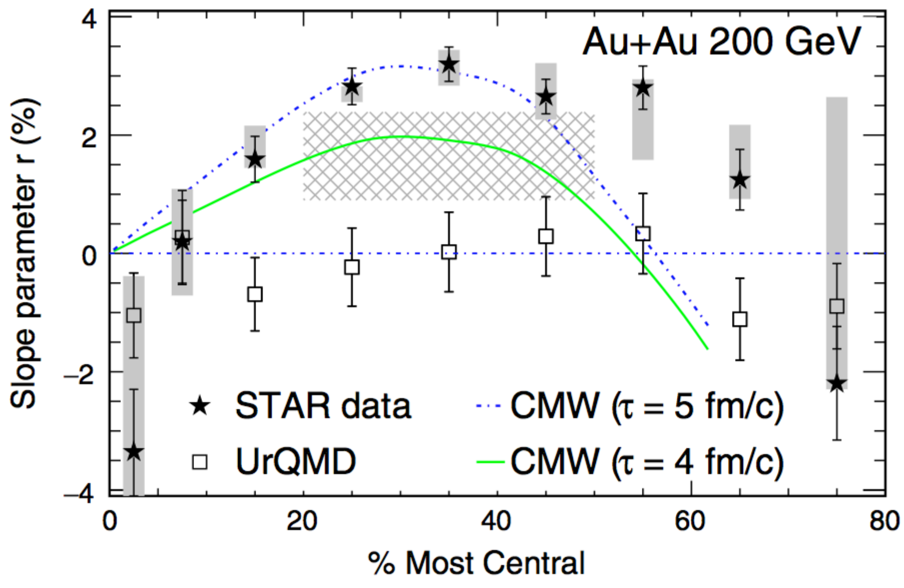
L. Adamczyk *et al.* (STAR Collaboration)

Phys. Rev. Lett. **114**, 252302 (2015) – Published 26 June 2015

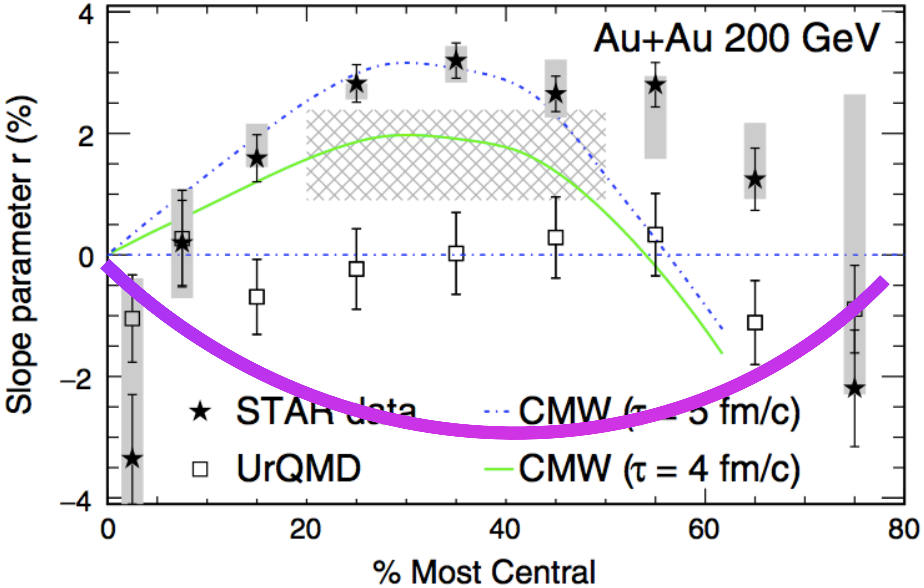


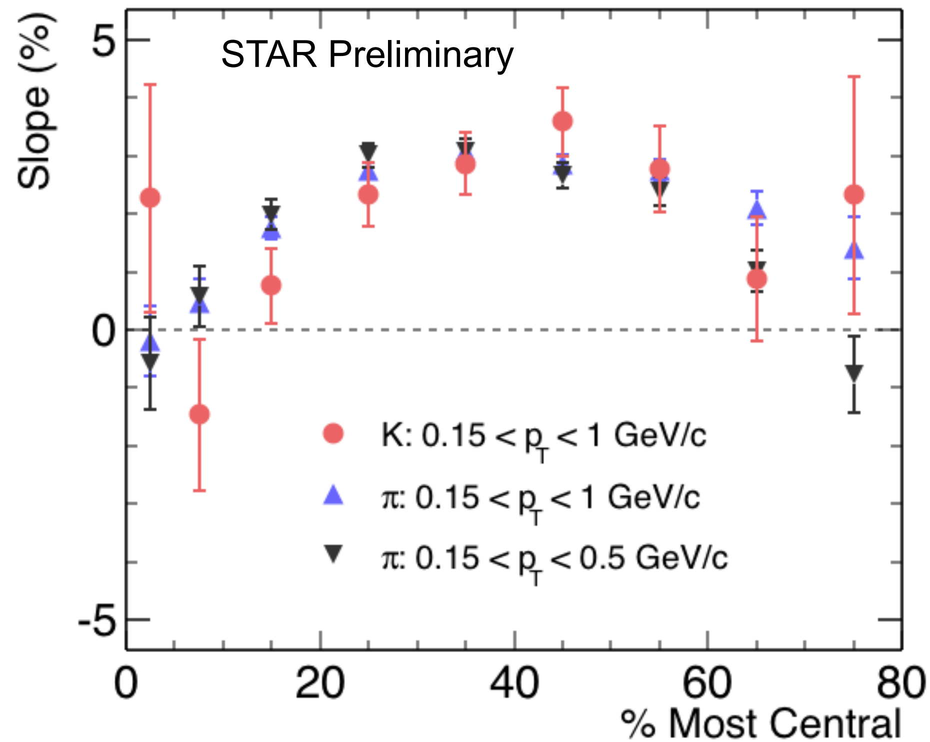
A possible signature of chiral symmetry restoration, in the form of a chiral magnetic wave in the quark-gluon plasma, has been observed in heavy-ion collisions at RHIC.

Show Abstract +



Strangeness distinguish models





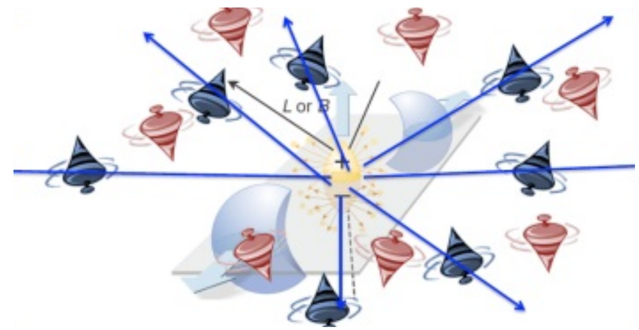
"… We demonstrate that the STAR results can be understood within the **standard viscous hydrodynamics** without invoking the **CMW**…"

"… **the slope r for the kaons should be negative**, in contrast to the pion case, and the magnitude is expected to be larger… Note that in these predictions are integrated over $0 < pT < \infty$. In order to properly test them, a wider pT coverage is necessary…"

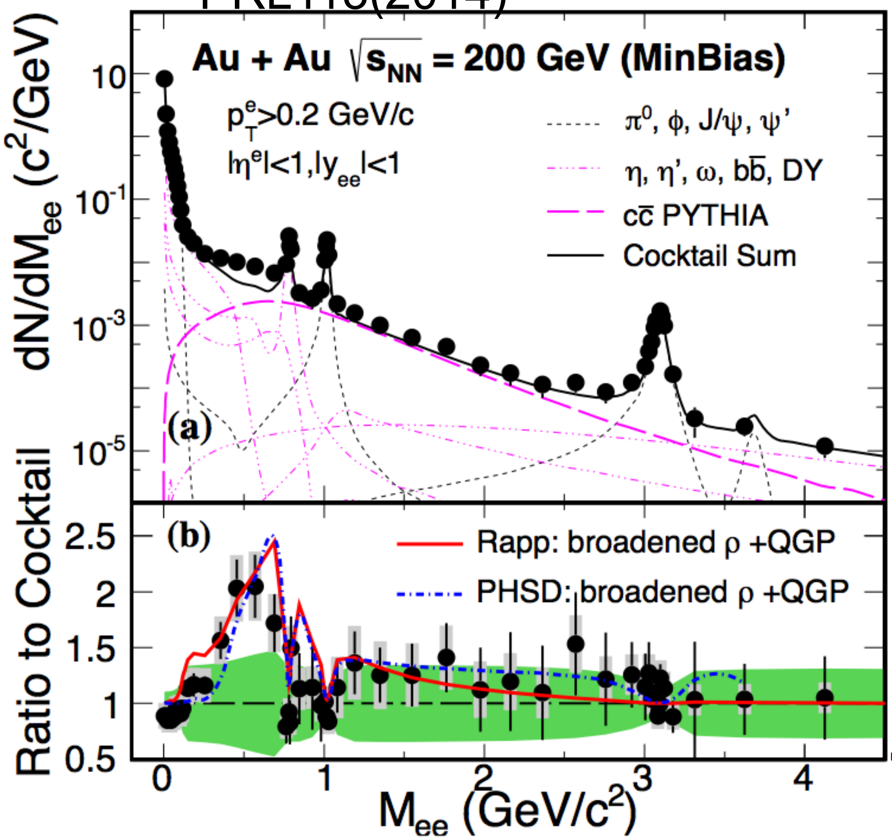
— Y. Hatta et al. Nuclear Physics A 947 (2016) 155

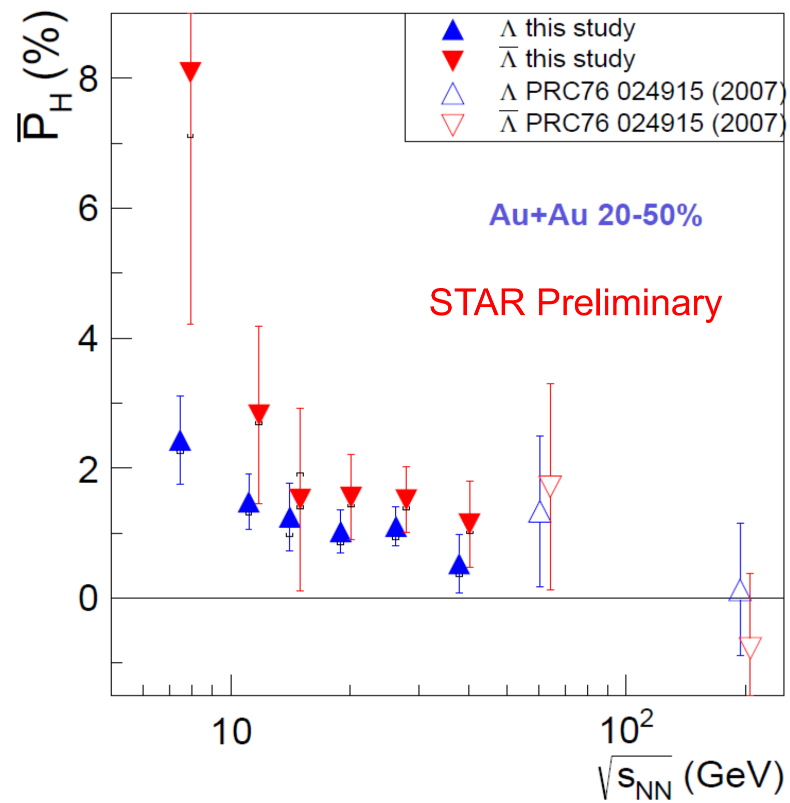
QCD phase transition is a chiral phase transition

1. Charge separation (14.5GeV)
2. Bulk charge dependence of $\pi^{\pm}$ v_2
3. Low-mass dilepton excess
4. Global polarization of hyperons



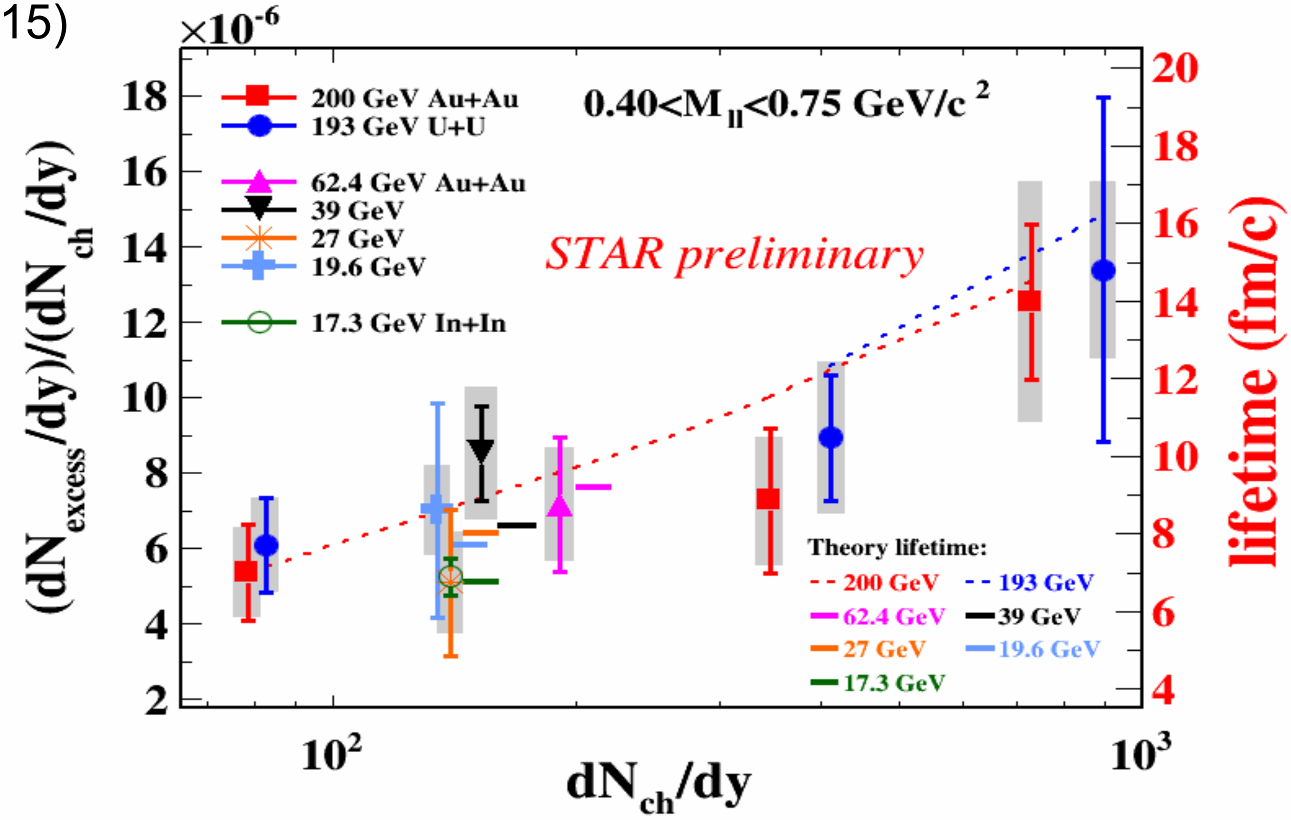
PRL113(2014)





Penetrating Probes

PLB750(2015)

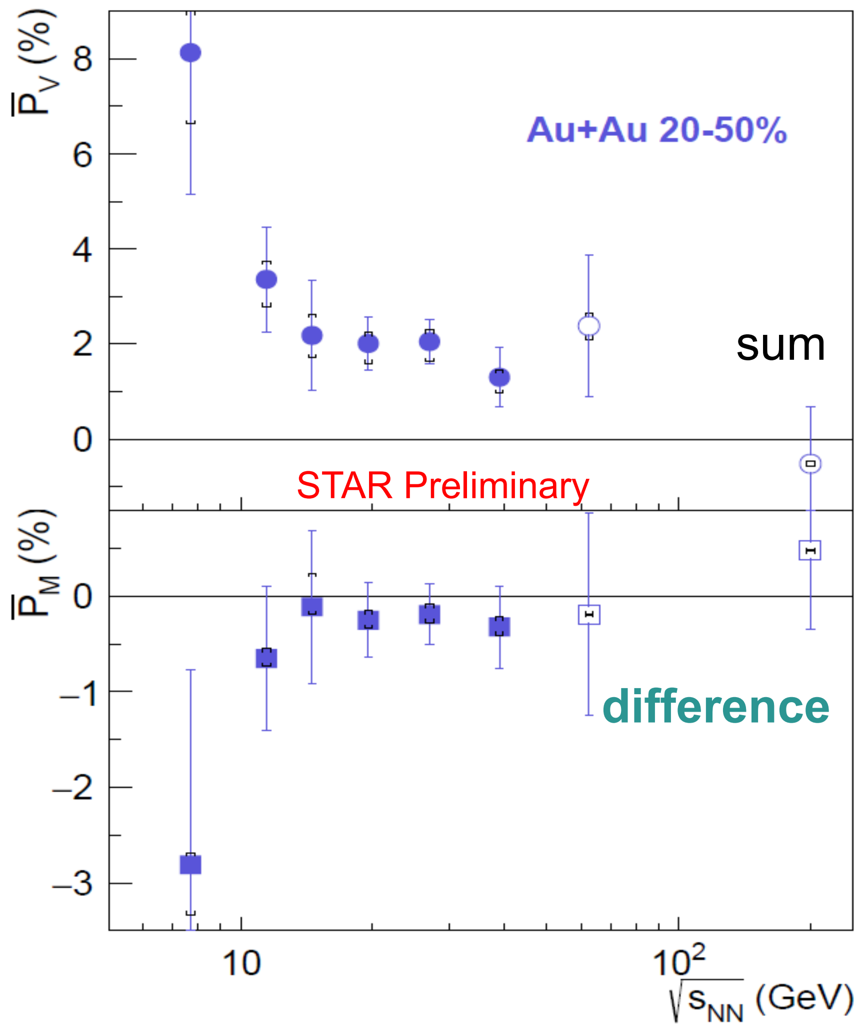


Low-mass di-electron production

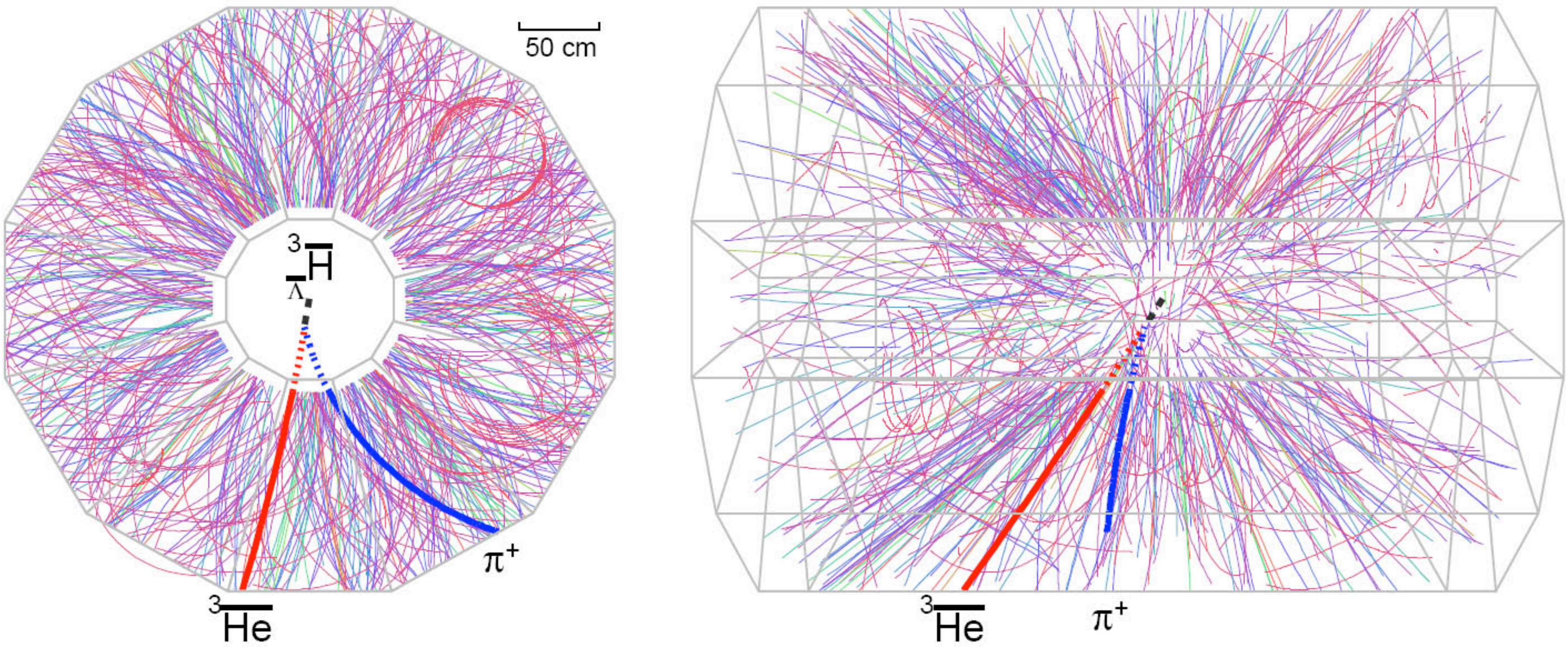
- Measured in many systems (Au+Au, U+U, p+p) and different energies (19.6, 27, 39, 62, 200 GeV)
- Quantifying how vector mesons evolve in the medium
- The yields probe timescale of collisions

QCD fluid responds to external field

- Positive Global Hyperon Polarization indicating a spin-orbit (Vortical) coupling
- Current data not able to distinguish Lambda/AntiLambda polarization difference,
- (potentially) Direct measure of Magnetic Field effect
- **Need >x10 more data**



Hypernuclei



- ★ A beautiful event in the STAR TPC that includes the production and decay of a antihypertriton candidate. (Data taken from Run4 Au+Au 200GeV MB collision)

The mesonic decay of hypertriton

Kamada et al., PRC 57, 1595(1998)

TABLE I. Partial and total mesonic and nonmesonic decay rates and corresponding lifetimes.

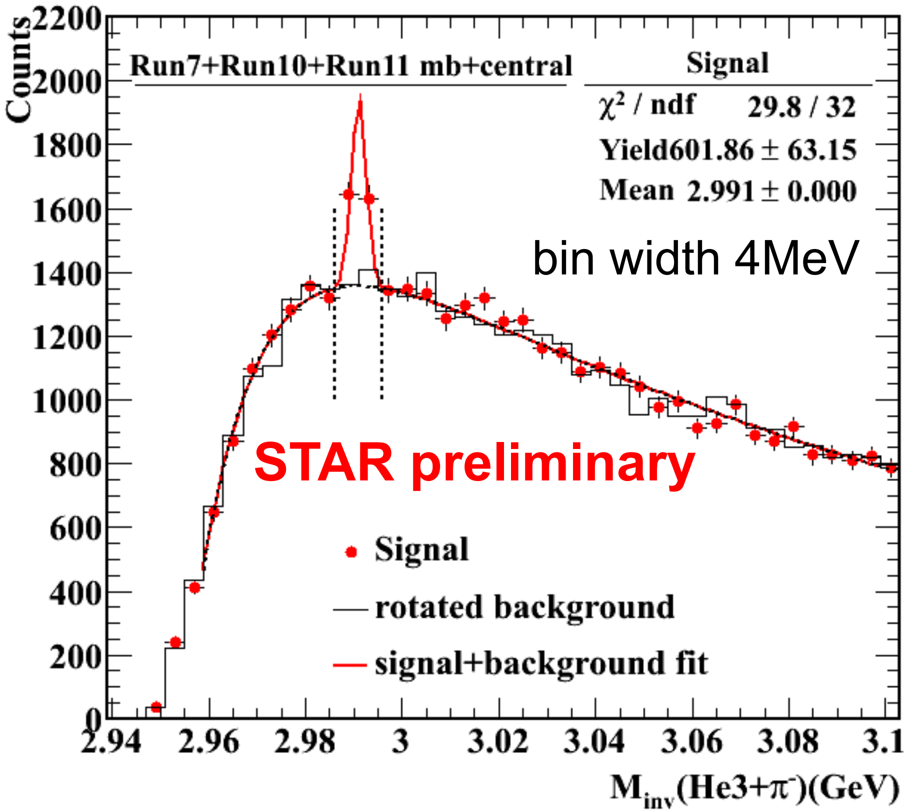
Channel	Γ [$\sec^{-1}$]	Γ/Γ_Λ	$\tau = \Gamma^{-1}$ [sec]
$^3He + \pi^-$ and $^3H + \pi^0$	0.146×10^{10}	0.384	0.684×10^{-9}
$d + p + \pi^-$ and $d + n + \pi^0$	0.235×10^{10}	0.619	0.425×10^{-9}
$p + p + n + \pi^-$ and $p + n + n + \pi^0$	0.368×10^{8}	0.0097	0.271×10^{-7}
All mesonic channels	0.385×10^{10}	1.01	0.260×10^{-9}
$d + n$	0.67×10^{7}	0.0018	0.15×10^{-6}
$p + n + n$	0.57×10^{8}	0.015	0.18×10^{-7}
All nonmesonic channels	0.64×10^{8}	0.017	0.16×10^{-7}
All channels	0.391×10^{10}	1.03	2.56×10^{-10}
Expt. [6]			$2.64\ {+0.92}\ {-0.54} \times 10^{-10}$
Expt. (averaged) [11]			$2.44\ {+0.26}\ {-0.22} \times 10^{-10}$

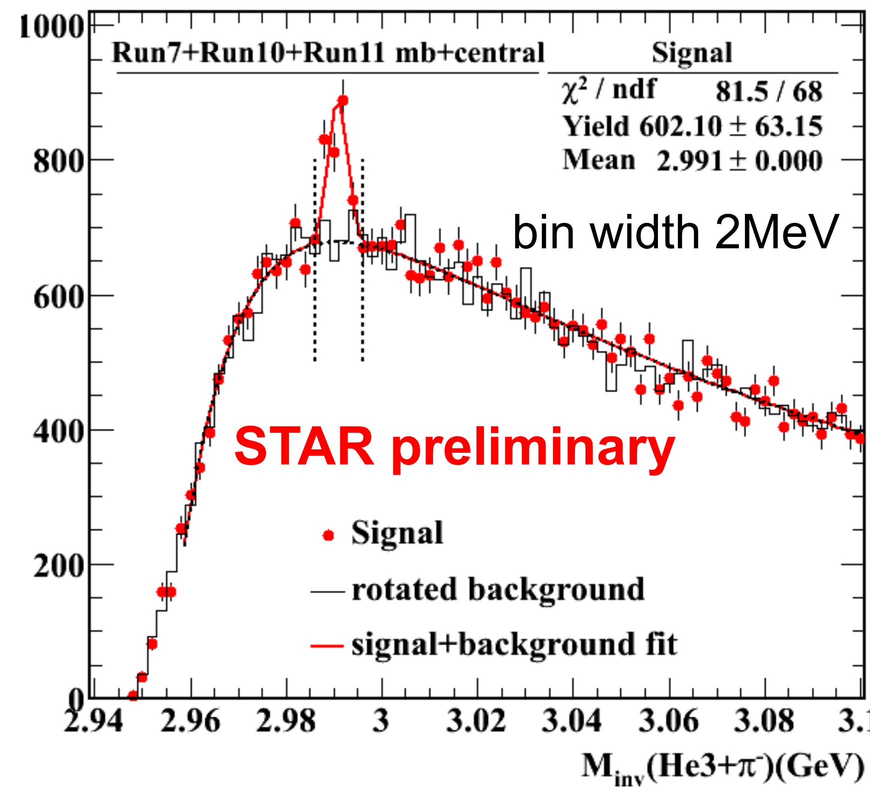
$$\frac{1}{\tau} = \sum_i \frac{1}{\tau_i}$$

- Decay Branching Ratios and lifetime are sensitive to binding energy and interaction length
- In experiment, the 2-body helium3 channel and the 3-body deuteron channel can both be measured in Heavy-ion collisions

The largest hypertriton sample

- Statistics: Run7+Run10+Run11 MB+Central, ~610M events

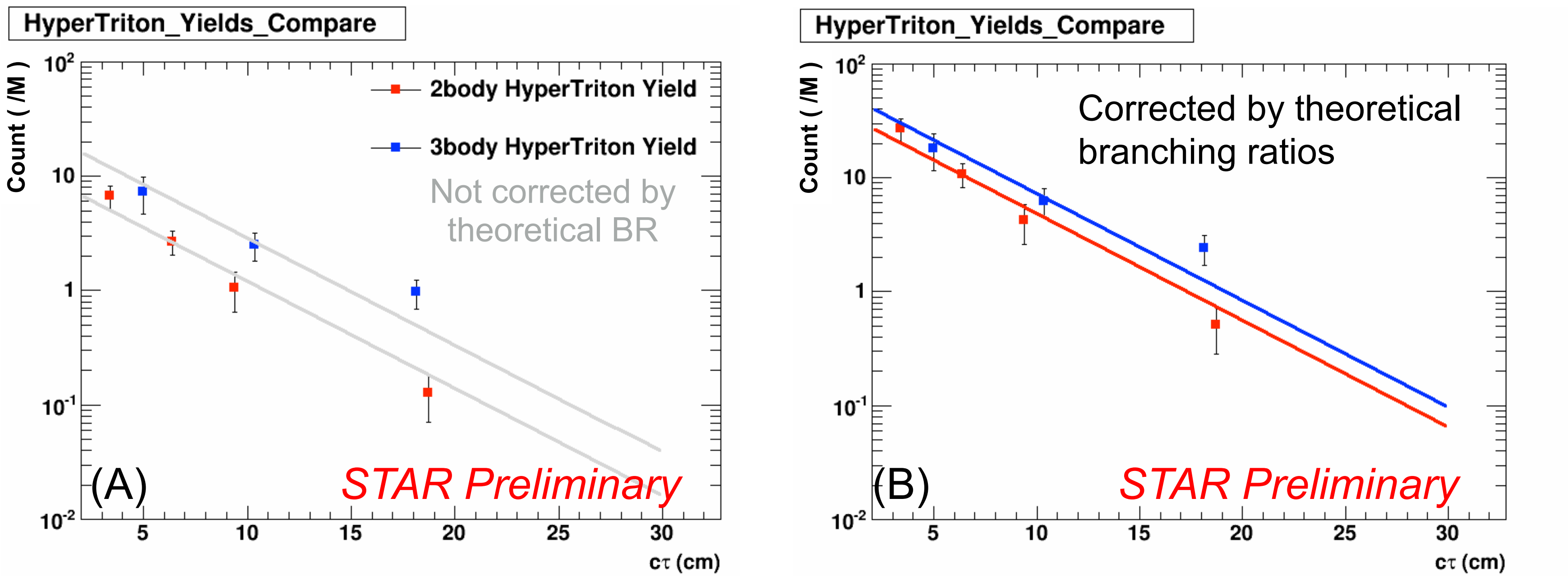




- Signal observed from the data (bin-by-bin counting [2.986,2.996]GeV): **602±63**, the largest hypertriton sample ever created
- Background estimation: rotated background

Measured Branching Ratio

Branching ratio can be calculated by decay law : $f(t) = N_0 Br e^{-\frac{t}{\tau}}$

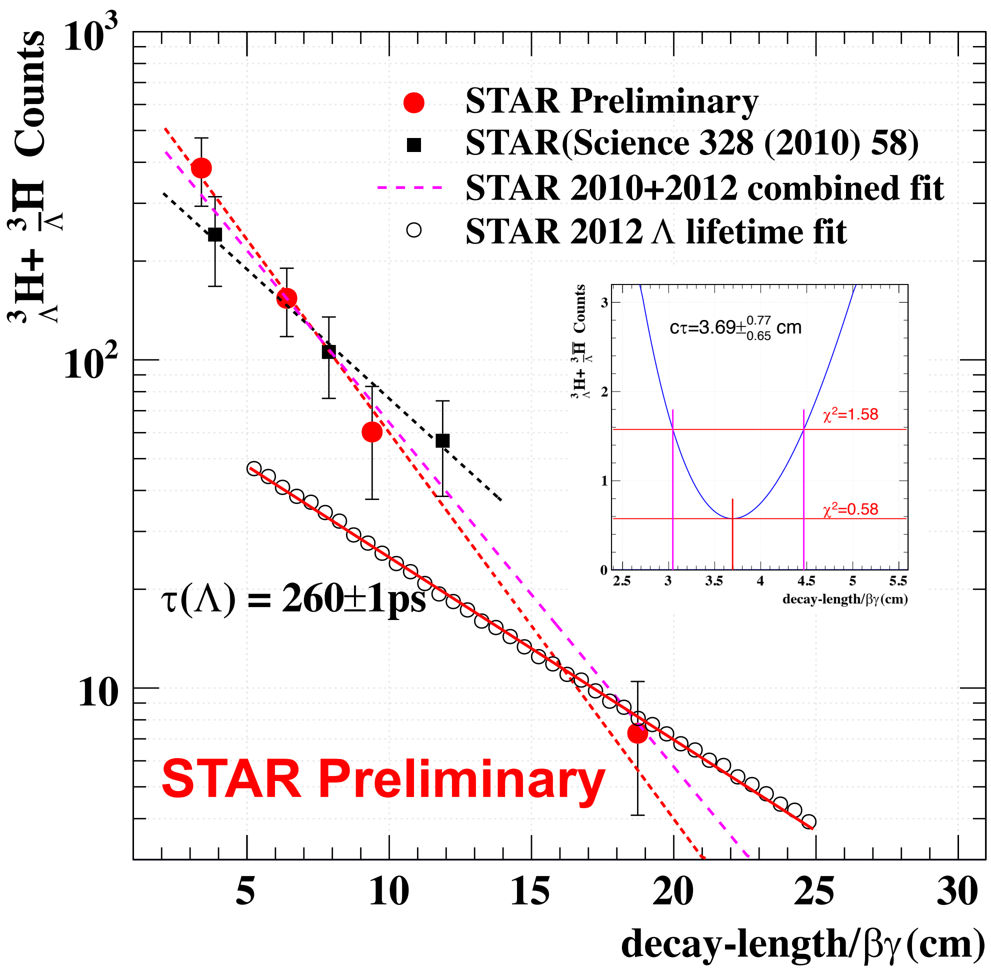


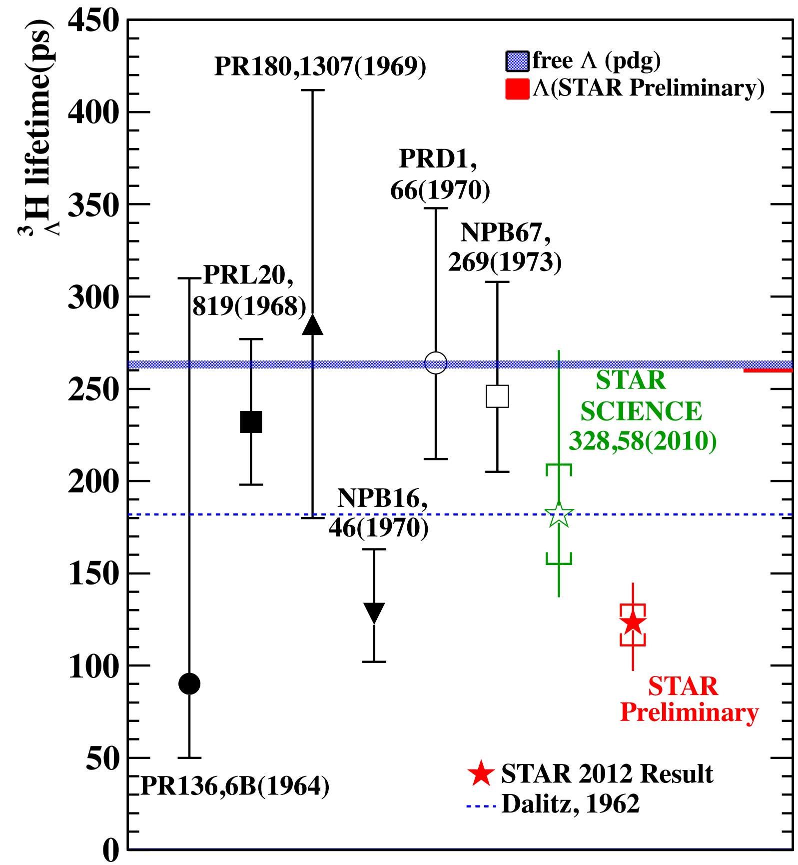
$$\frac{B.R.(d+p+\pi^-)}{B.R.(^3He+\pi^-)} = 2.41^{+0.39}_{-0.34}$$

Theoretical : $\left(\frac{40.15}{24.88} = 1.61\right)$

**Physical Review C.57.1595(1998)*

New hypertriton lifetime result





Y.H. Zhu for STAR Col., QM2012, USA
J.H. Chen for STAR Col., HYP2012, Spain

★ STAR 2012 preliminary result: $\tau = 123 \pm^{26}_{22} \pm 10\, ps$

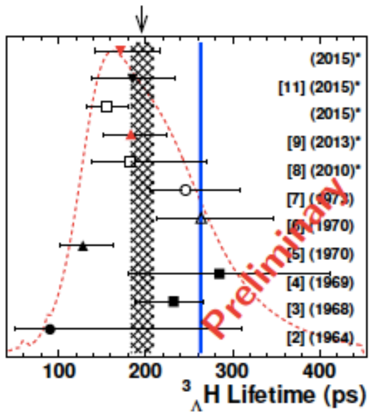
★ STAR 2010+2012 combined fit: $\tau = 138 \pm^{23}_{20}\, ps$

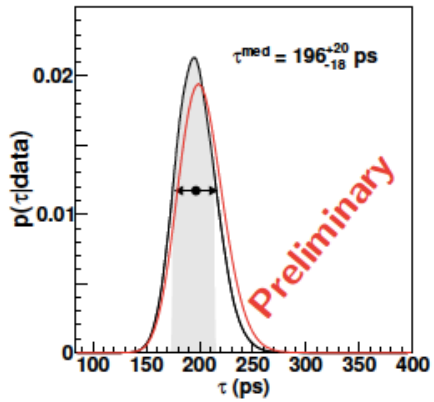
J.H. Chen, HYP2015

Implications from shorter lifetime

Lifetime of ${}^{3}_{\Lambda}H$ in 2015

Combination with the most recent available lifetime results:





- **Hypertriton lifetime seems to experimentally systematically lower than expectation**
- **Little data and understanding of the three-body system**

- PDG says need to rescale errors if $\chi^2 > 1$
  - initial χ^2=1.18, $197.5^{+12.4}_{-11.2}$ ps
  - scaled χ^2=0.98, $195.9^{+13.8}_{-12.5}$ ps
- Upper Limit at 95% : 223.9 ps & at 99% : 234.0 ps
- Bayesian :
  - $195.9^{+19.7}_{-18}$ ps & Upper Limit 95% : 229 ps
  - Bayes Factor : $B_{10} = 3.0$

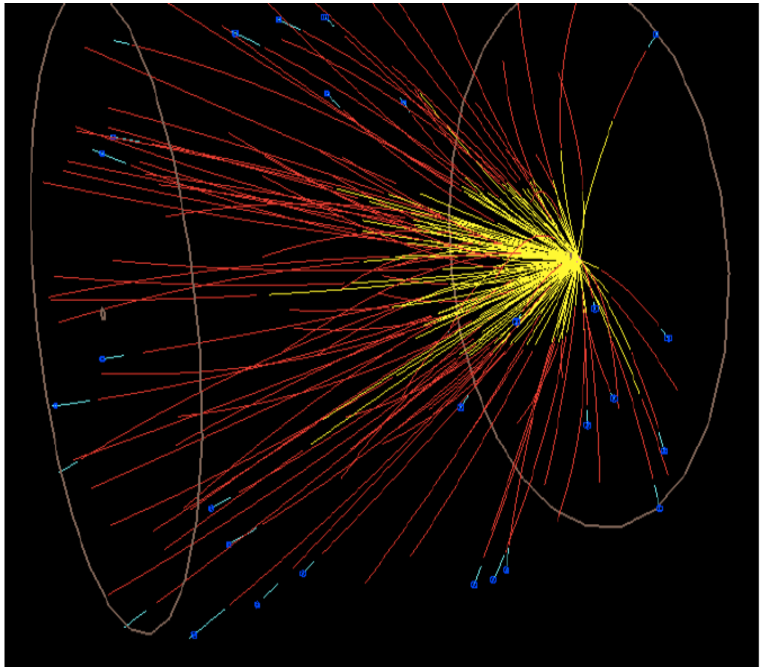
Theoretical value: 256ps
L lifetime: 261ps

C. Rappold GSI Status of hydrogen hypernuclear Lifetime 08/09/2015 12 / 14

Look into the future (-2020)

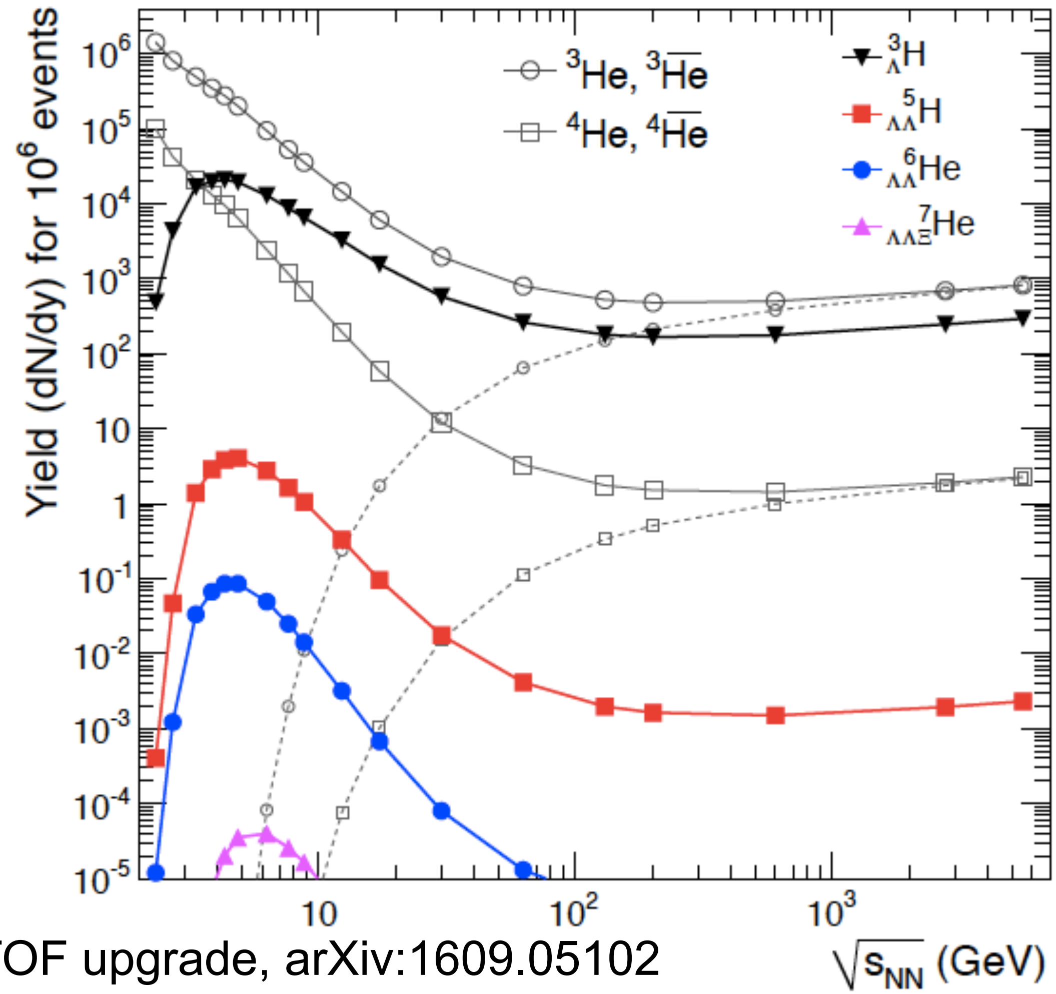
STAR BES-II
x10 more data at each energy

Fixed Target Program
access energies at the peak of
hypernucleus production
Rate >~1000Hz



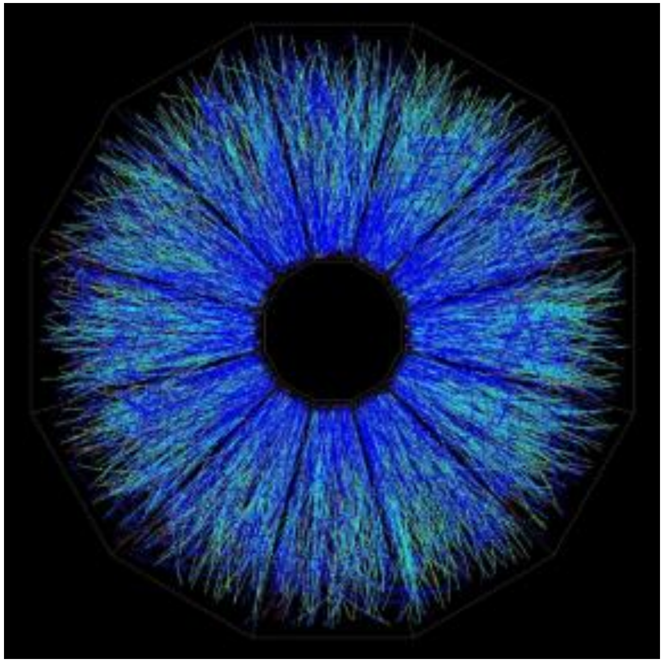
A. Andronic, et al. PLB (2011)

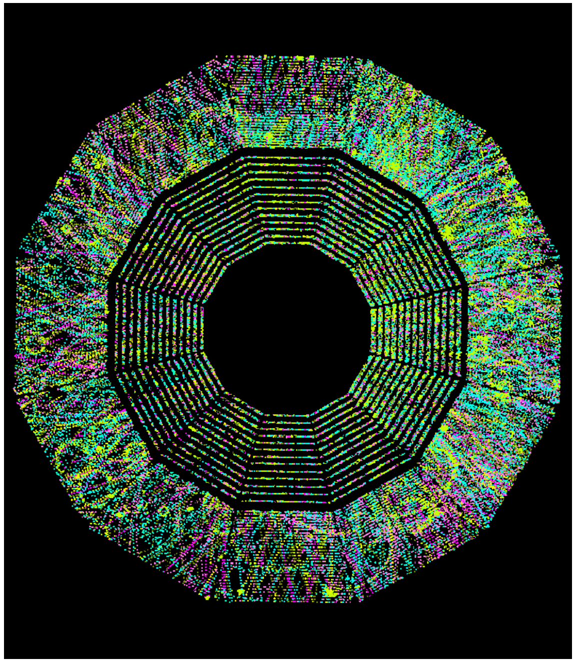
FAIR/[**BES** RHIC] LHC

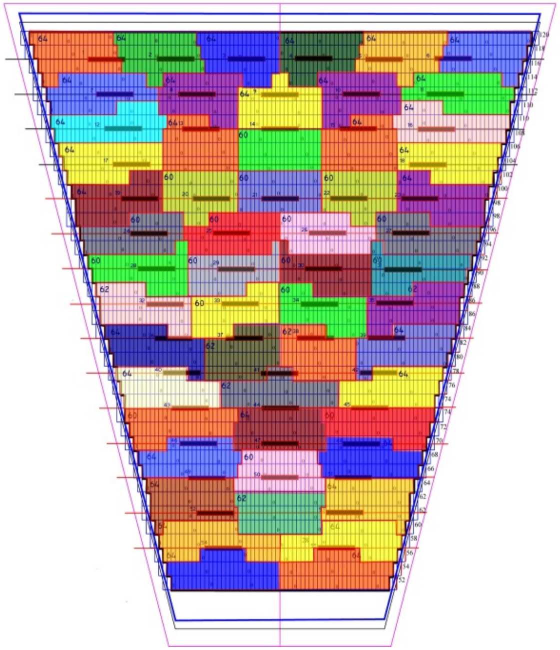


Physics Program for the STAR/CBM eTOF upgrade, arXiv:1609.05102

What is STAR iTPC upgrade?

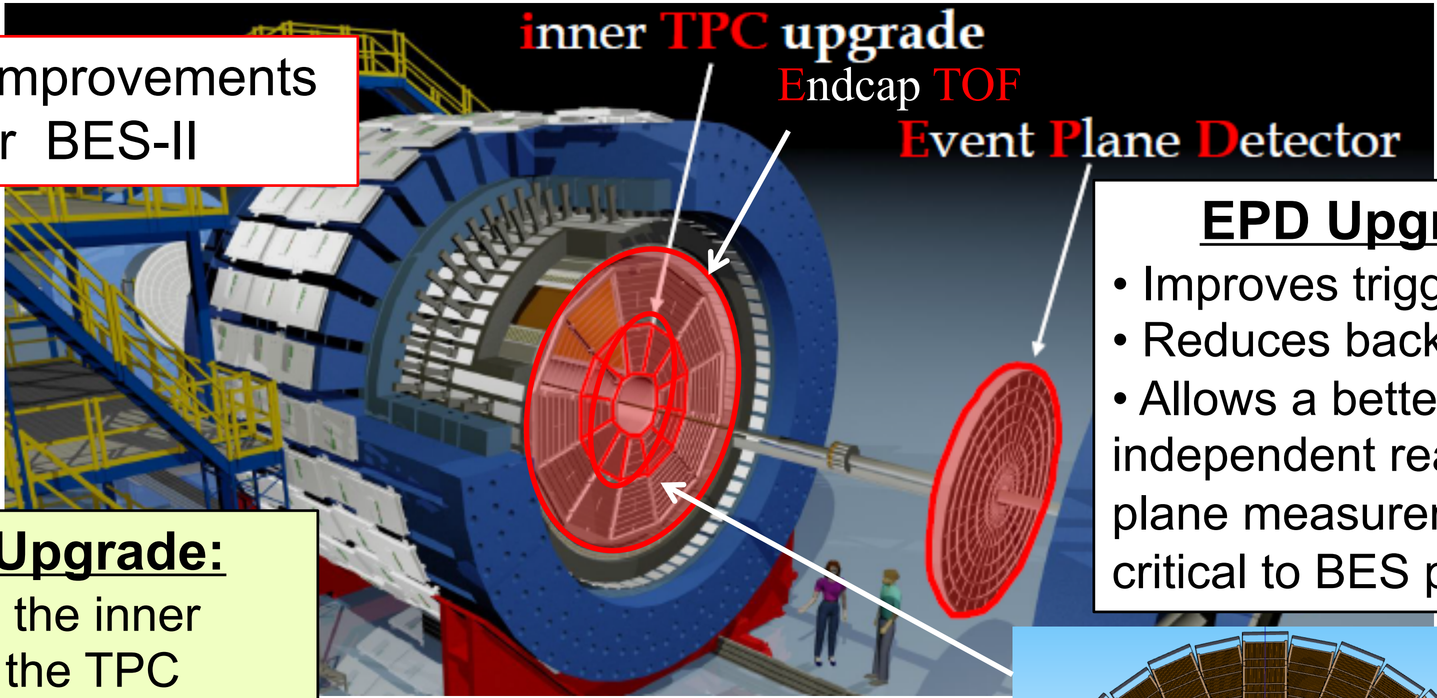






The STAR Upgrades and BES Phase II

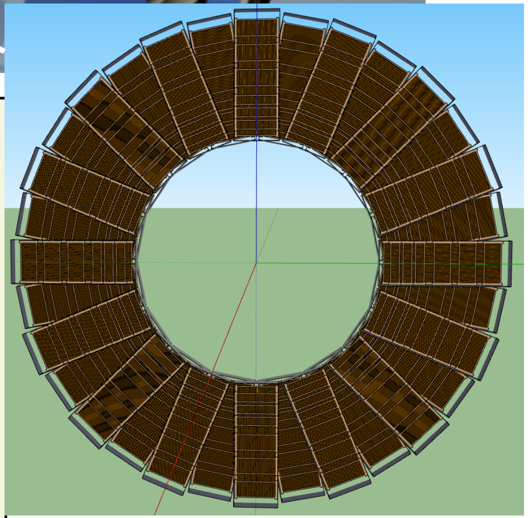
Major improvements for BES-II



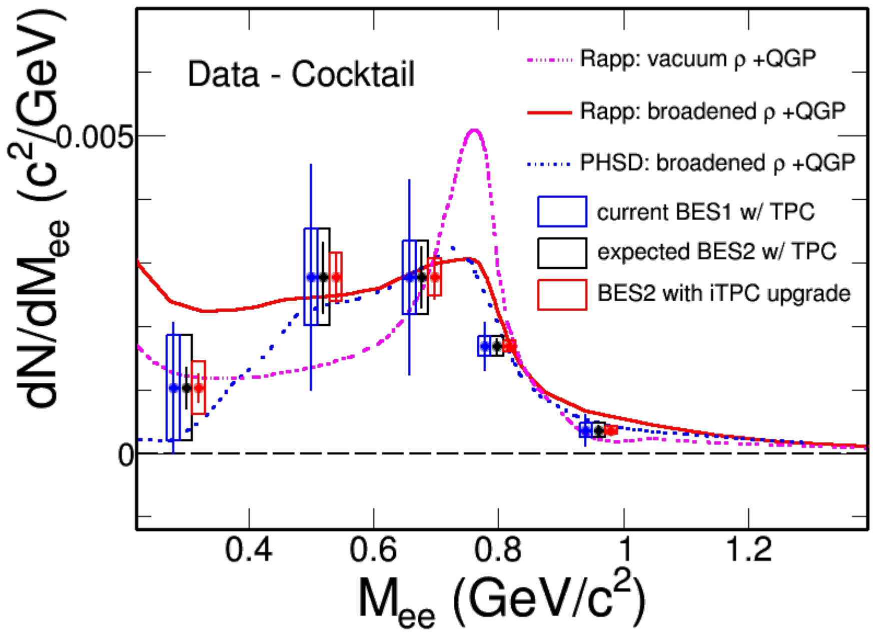
EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

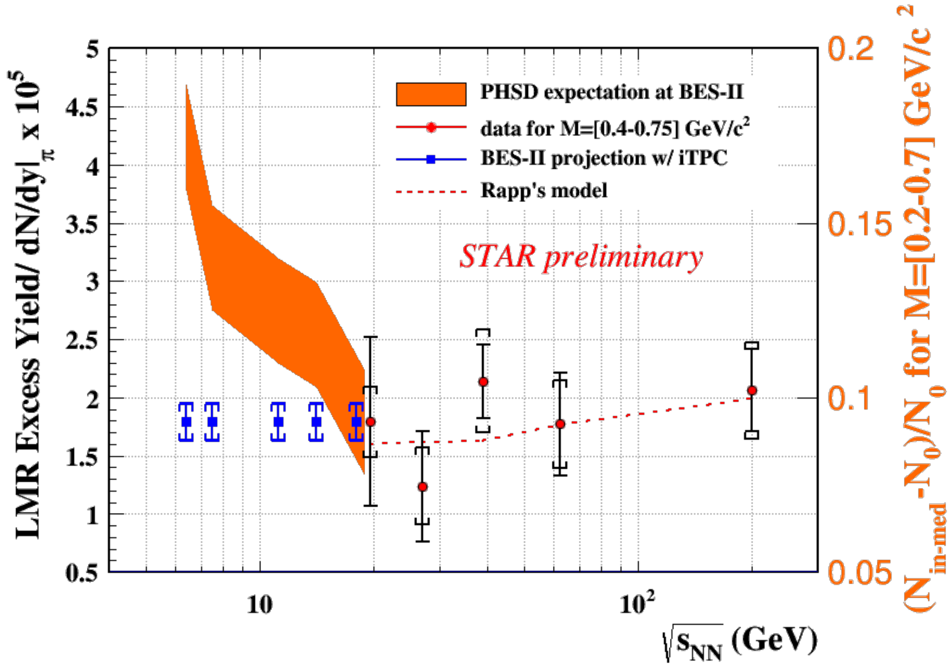
iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 0.9 to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR



Enhance Di-electron and strangeness measurements





- Systematically study di-electron continuum from $\sqrt{S_{NN}}$ = 7.7 – 19.6 GeV
- Inner Time Projection Chamber (iTPC) upgrade: reduce systematic and statistical uncertainties
- Distinguish models with different ρ-meson broadening mechanisms
- Study the total baryon density effect on LMR excess yield in BESII
- Strangeness production (usually low-pt pions) reconstruction efficiency improve by >x2

RHIC has been adaptable to science needs

2010-2013	2014	2015	2016	2017	2018	2019	2020		2022+
Au+Au p+p	Au+Au	p+p p+A	Au+Au d+Au	p+p Au+Au	Isobar Au+Au	Au+Au	Au+Au		Au+Au pp,pA
ΔG, QGP property	Charm flow	Ref. A_N	D_c, Λ_c Υ, Jets	Fc sign	CME, $\Lambda\uparrow$	Critical Point, Phase Transition			Jets, Υ forwardA_N
BES-I	200, 14.5	200	200- 19.6	500, 62.4	200, 27	BES-II 11-20	BES-II 7-11		200

BES-I

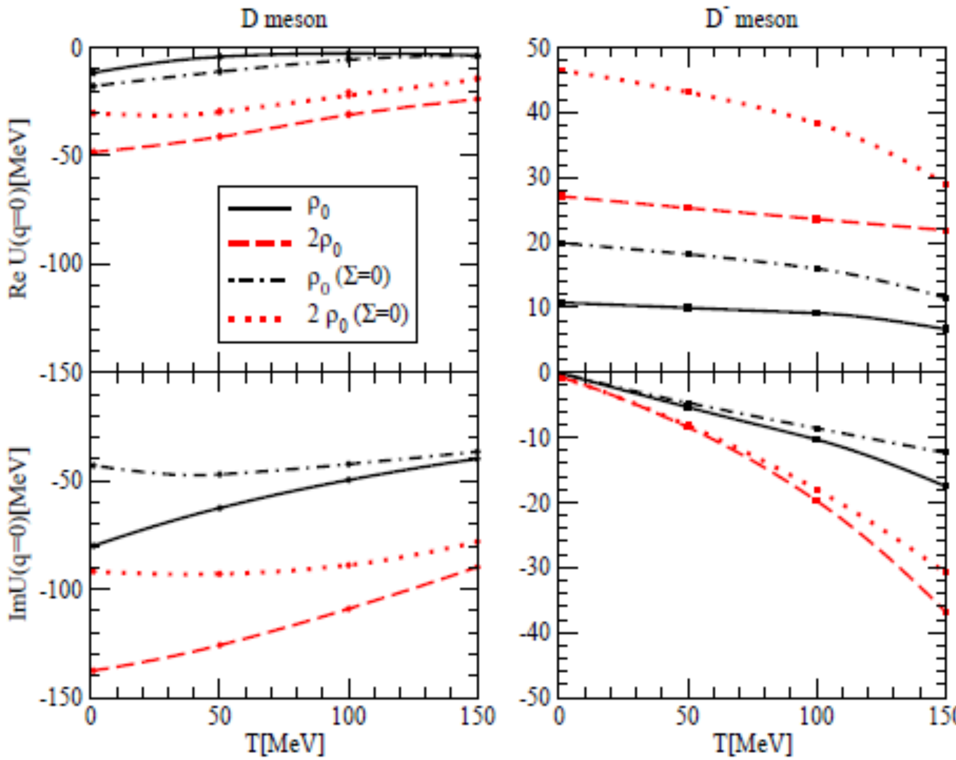
BES-II

Expand to include several programs:
p+A in run 15,
pp500 in run17,
Isobar (Zr, Ru-96) in run 18
BES-II more compelling, detector and machine upgrades in 2018
Future high-luminosity jets and Upsilon in 2020+
3+1D hydrodynamics and Unique Cold QCD (DY) portal to EIC

Discovery potential at EIC and JPARC

Heavy-flavor states

http://belle.kek.jp/belle/talks/moriondQCD10/pakhlov.ppt



Tolos 0905.1850

How about baryon states?

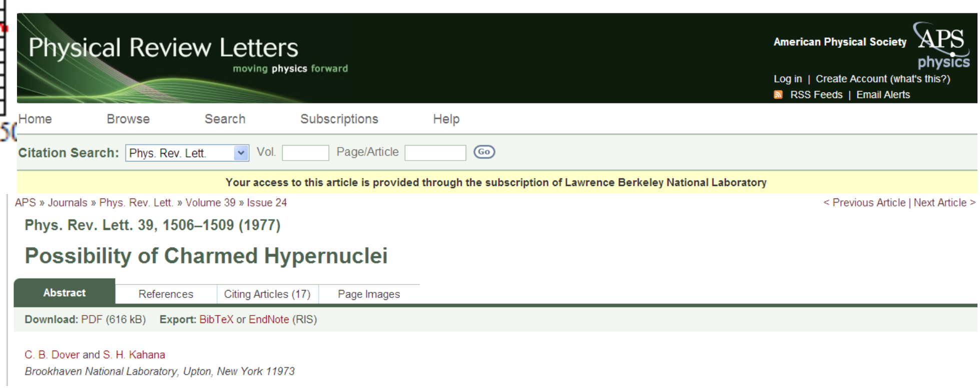
$D^-+p \rightarrow n+D^0$

$D^-+{}^4He$ stable

Heavy-flavor hypernuclei

- Predicted to exist (70's)
- Cannot be produced in pp, ep collisions
- EIC enough energy for charm and bottom hypernuclei
- High-Intensity p+A fixed target?
- Vertex detector at Fragmentation region

  Displace vertex: 3cm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C. B. Dover and S. H. Kahana
Brookhaven National Laboratory, Upton, New York 11973

Summary

- Strangeness and hypernuclei are still very exciting topics

- Strangeness is essential in determining
  - the data point locations in QCD phase diagram
  - Degree of thermalization from collisions to QGP
  - Final-state absorption of antibaryons
  - Chiral Magnetic Wave (test models)
  - Global Polarization and Vorticity of the QGP fluid

- Hypertriton is of particular interest:
  - Few-body Λ-N interaction and exotic particles
  - Lifetime measurements systematically low

- Looking forward to BES-II at RHIC, CBM, NICA and JPARC Programs