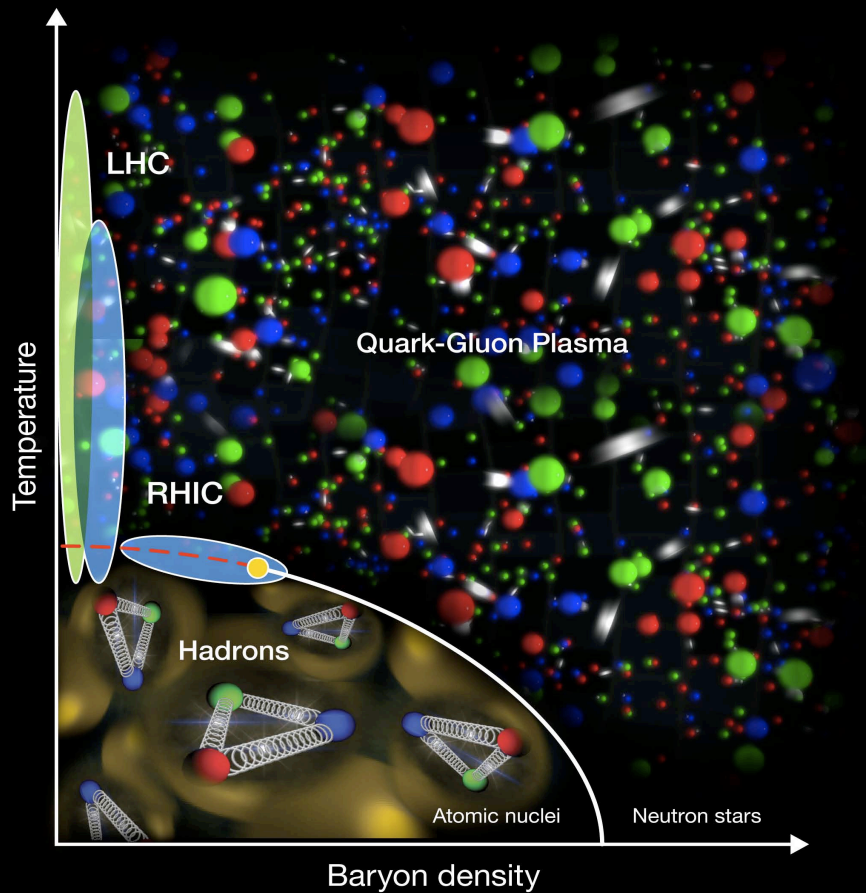




Probing QCD Phase Diagram with Heavy-Ion Collision Experiments

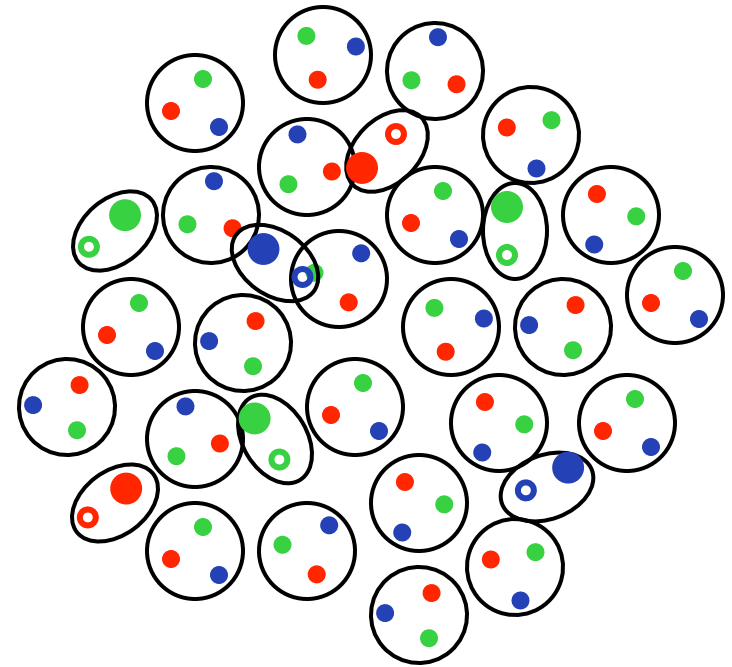
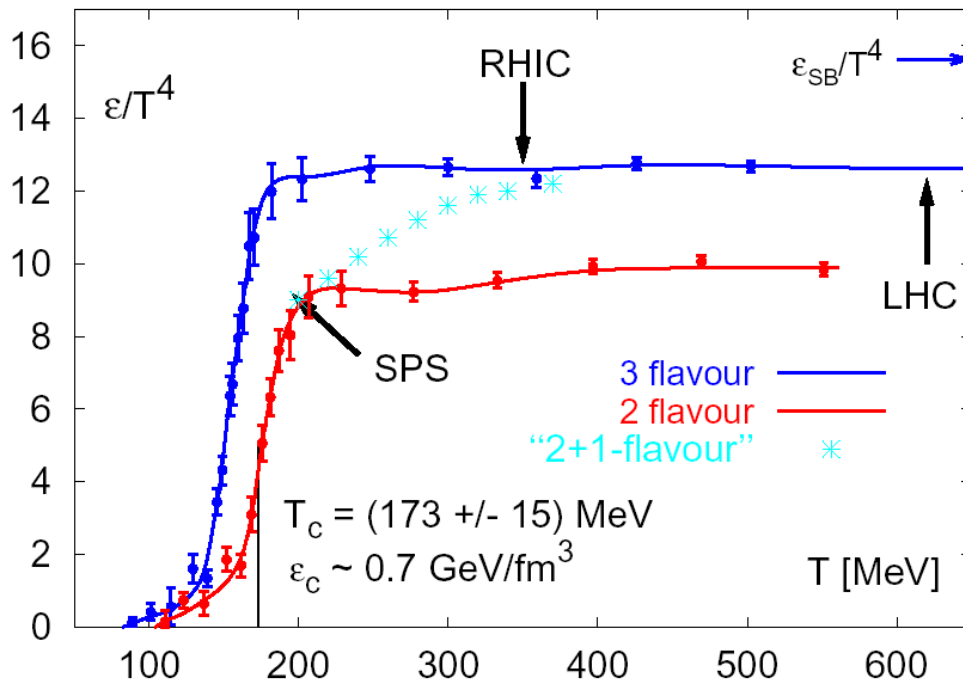
Grazyna Odyniec

Lawrence Berkeley National Laboratory

Theory: Generating a deconfined state

Present understanding of Quantum Chromodynamics (QCD)

- heating
 - compression
- *deconfined color matter*

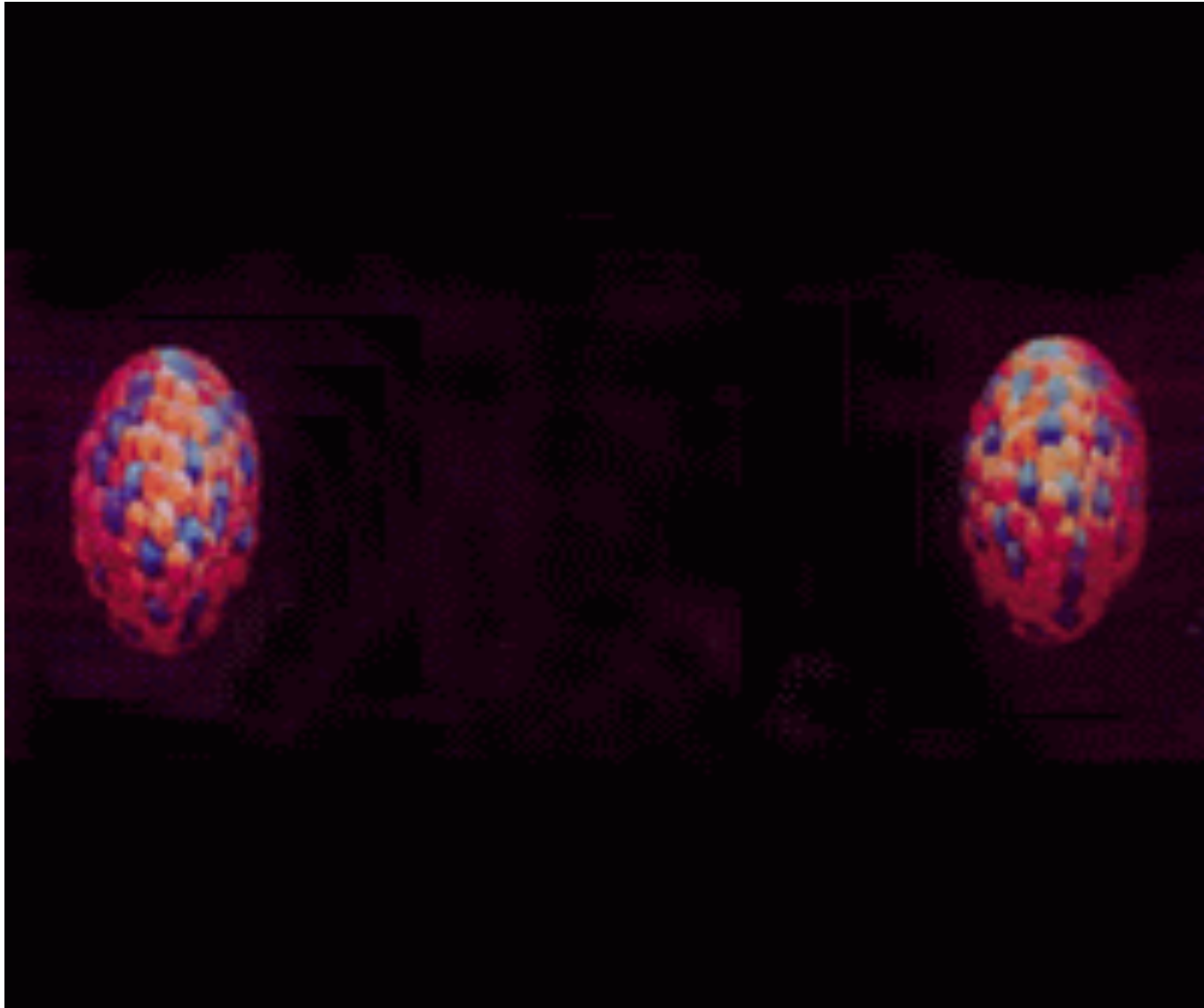


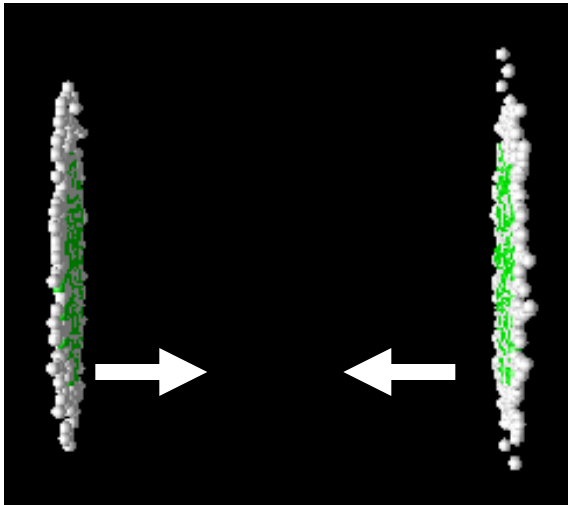
Quark Gluon Plasma
(deconfined)

practical question:

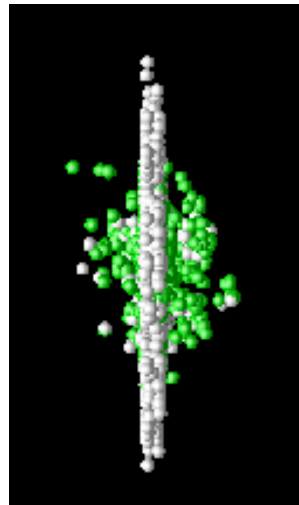
- How do we do it ?
 - high-energy nuclear collisions
 - RHIC
- Accelerators function a bit like time machines, they take us to the early stages of the Universe when matter was extraordinary hot and dense*

Heavy Ion Collisions

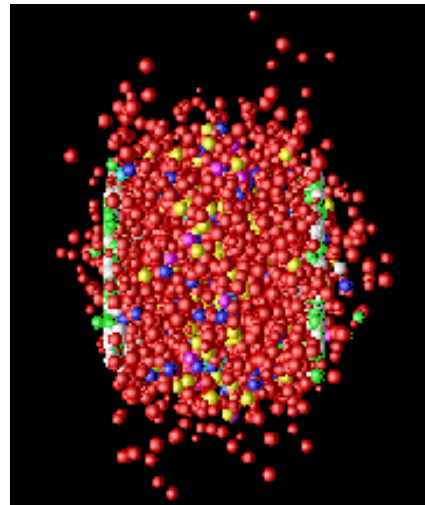




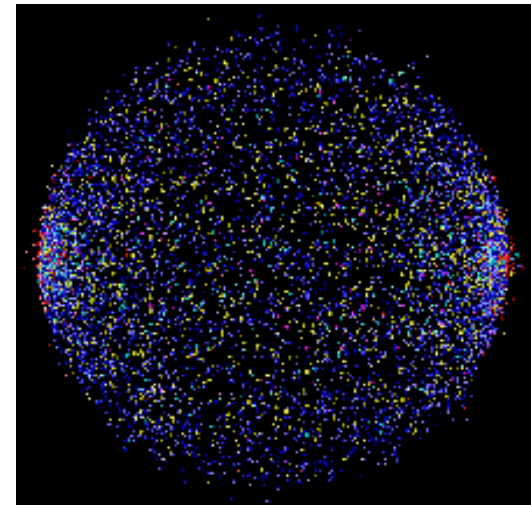
Approach



Collision



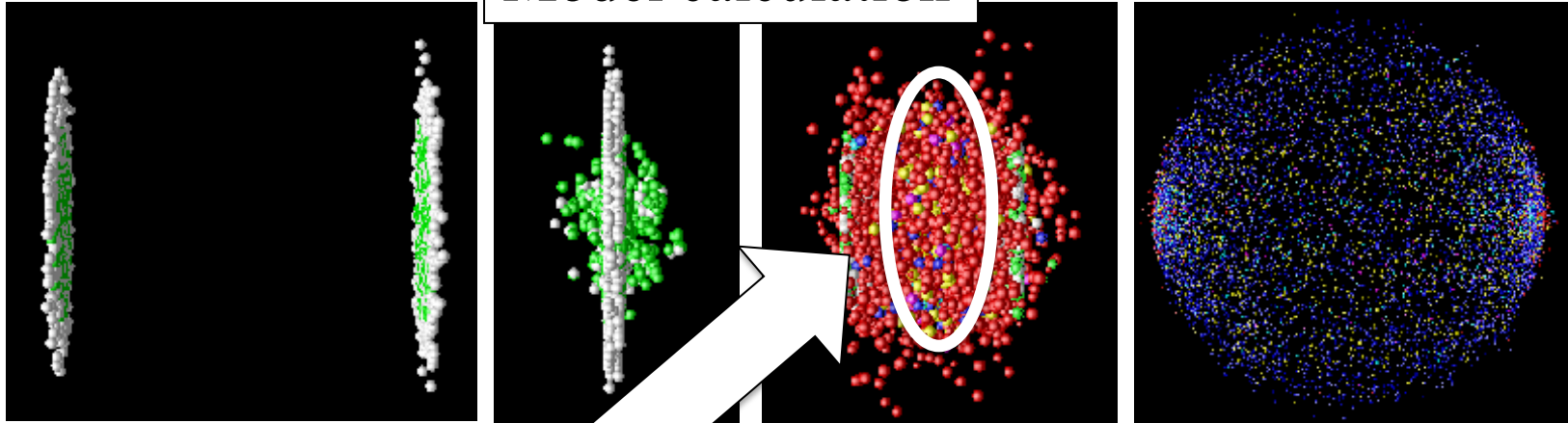
Particle Shower



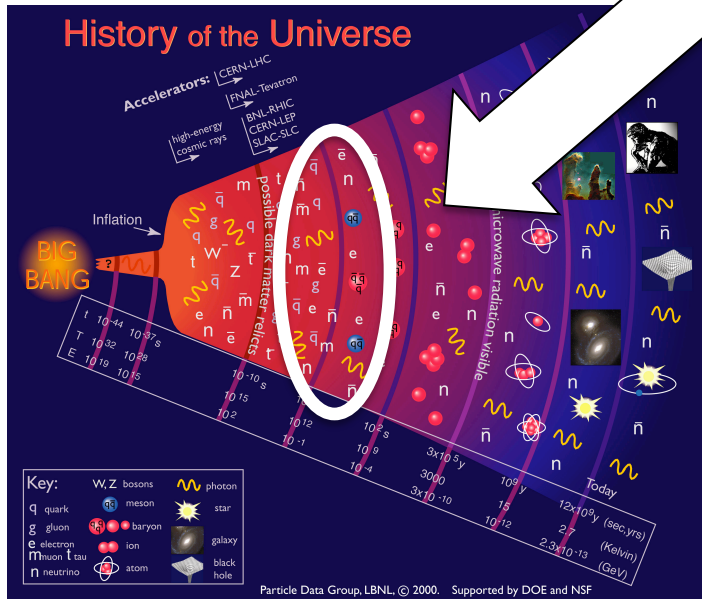
Collision time $\sim 10^{-22}$ seconds

Hot QCD and high energy collisions of heavy nuclei

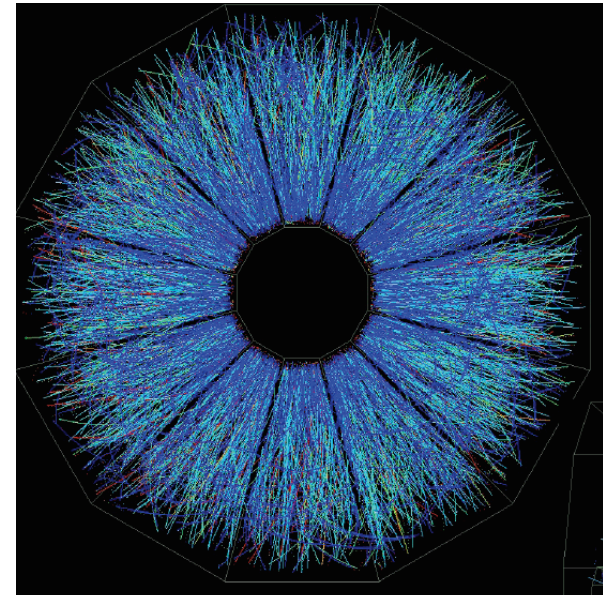
Model calculation



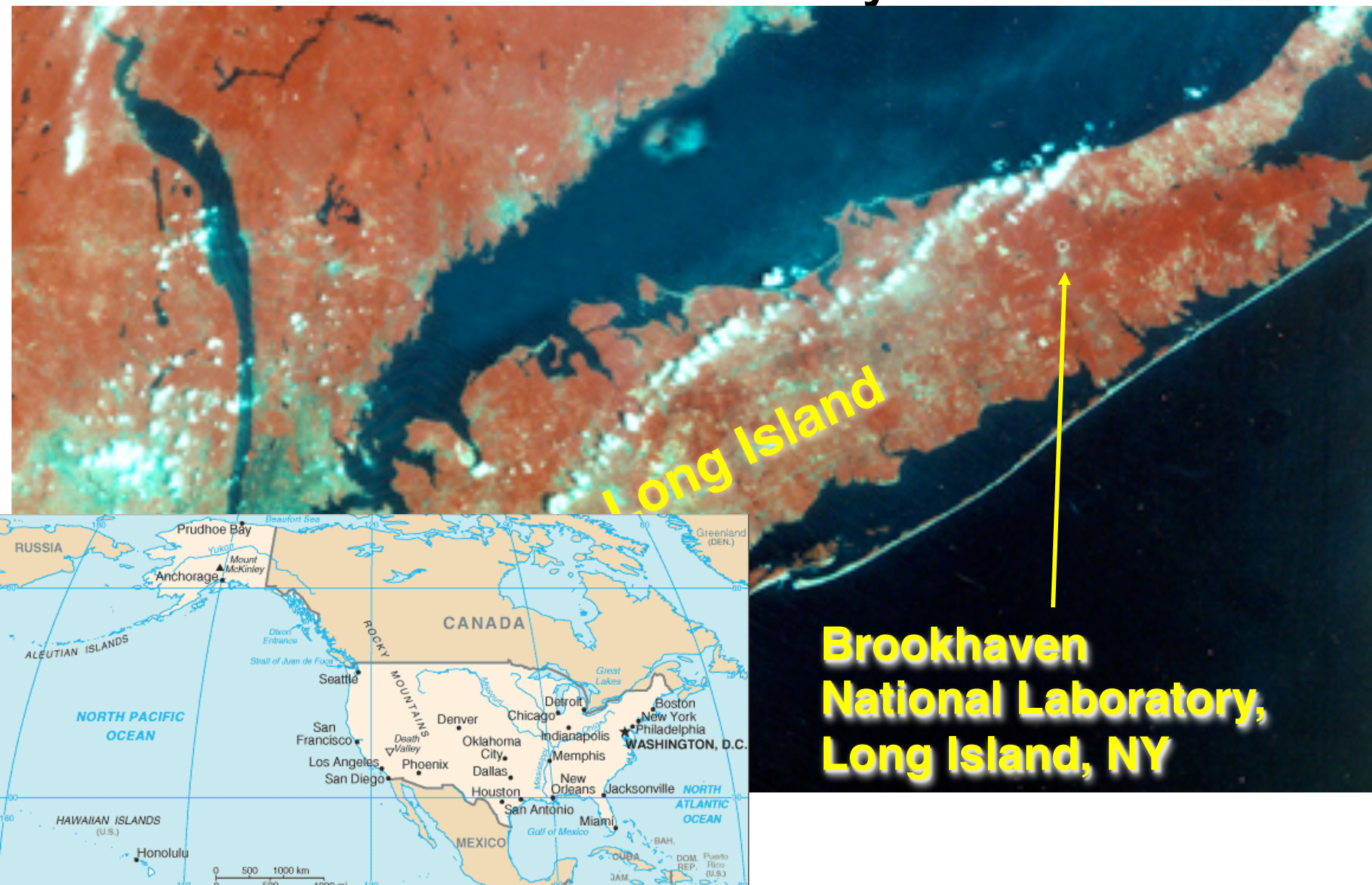
History of the Universe



Au+Au @ 200 GeV, STAR:

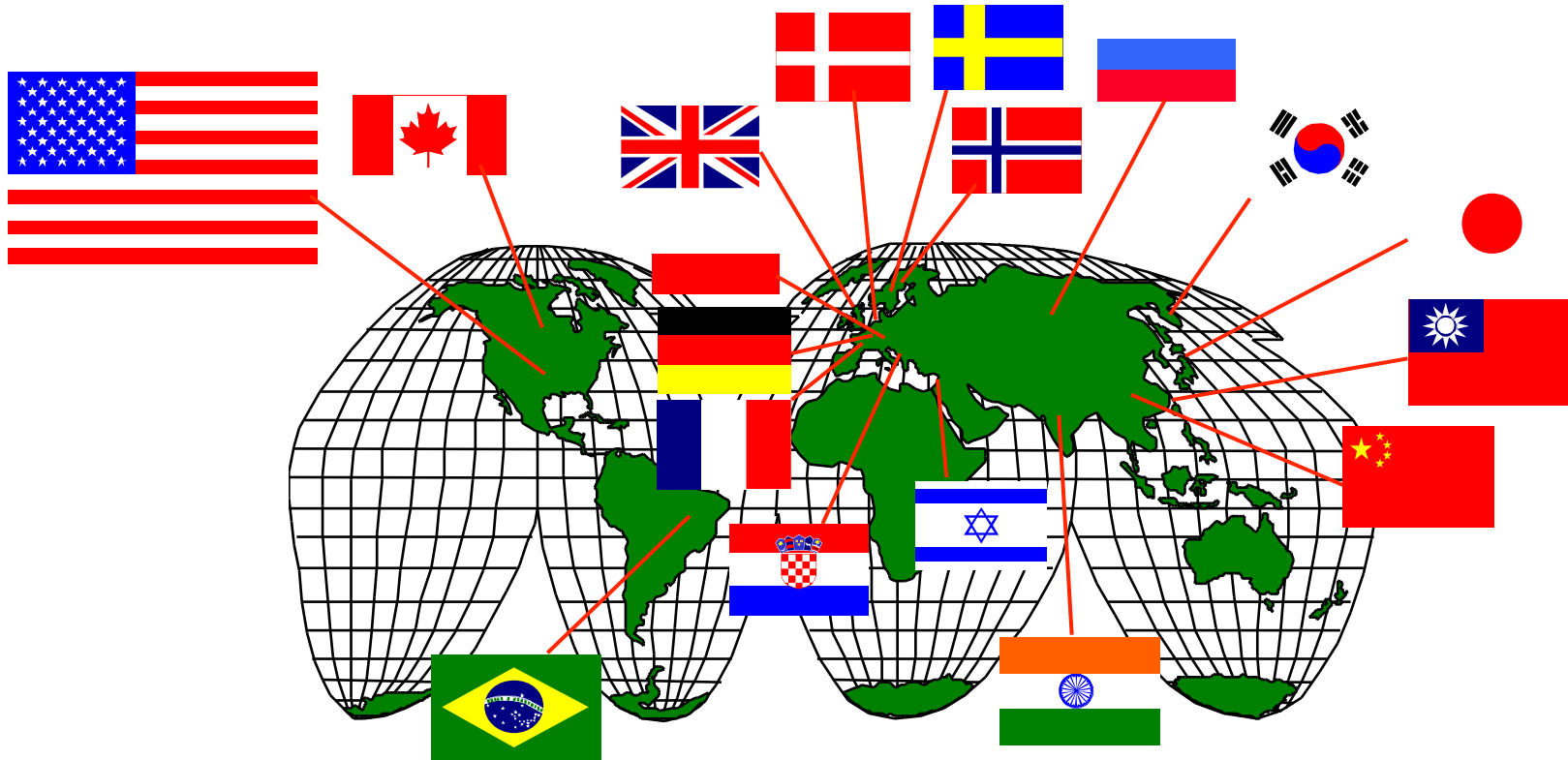


RHIC: Relativistic Heavy Ion Collider



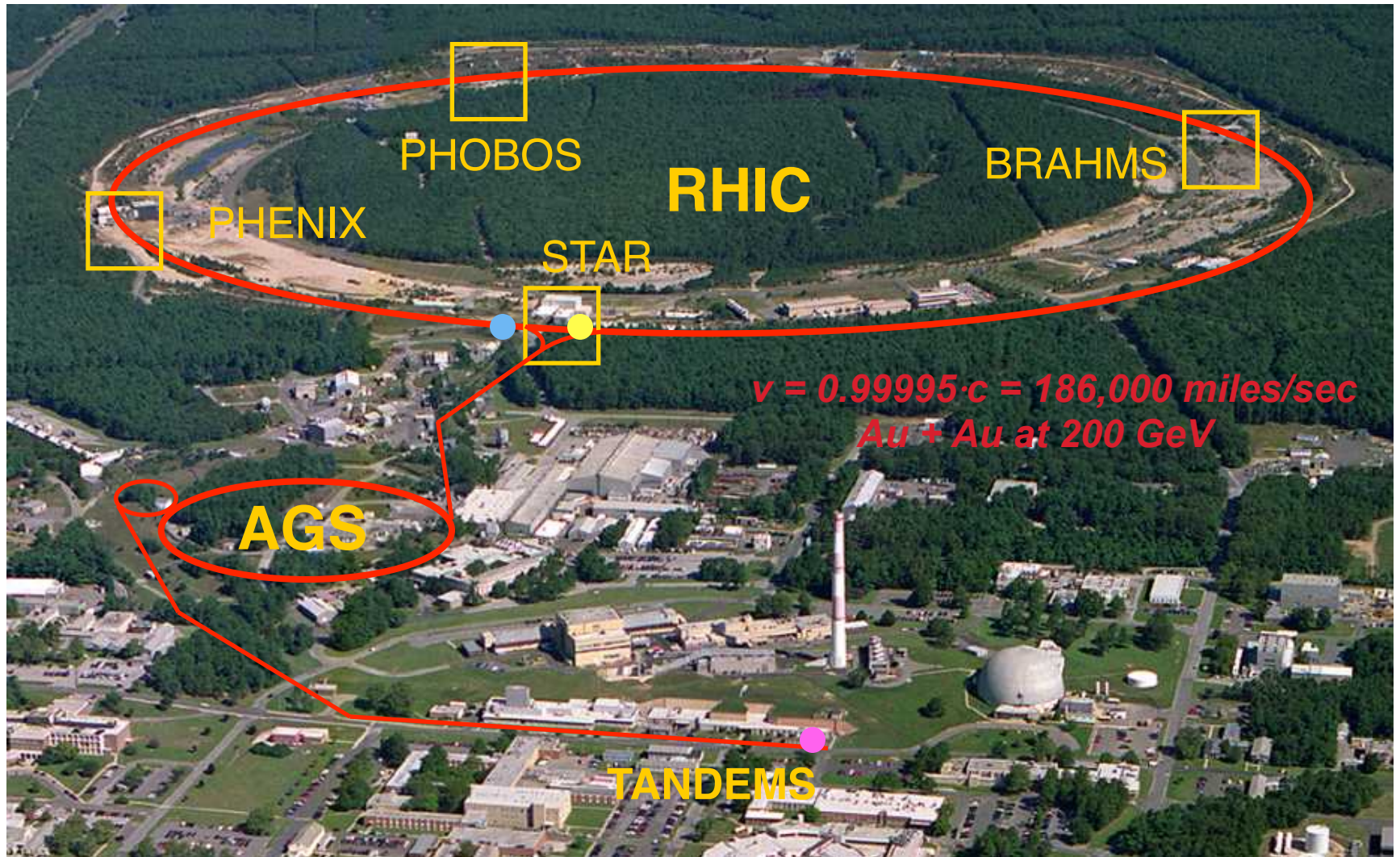
Who's Involved in RHIC?

People from around the world

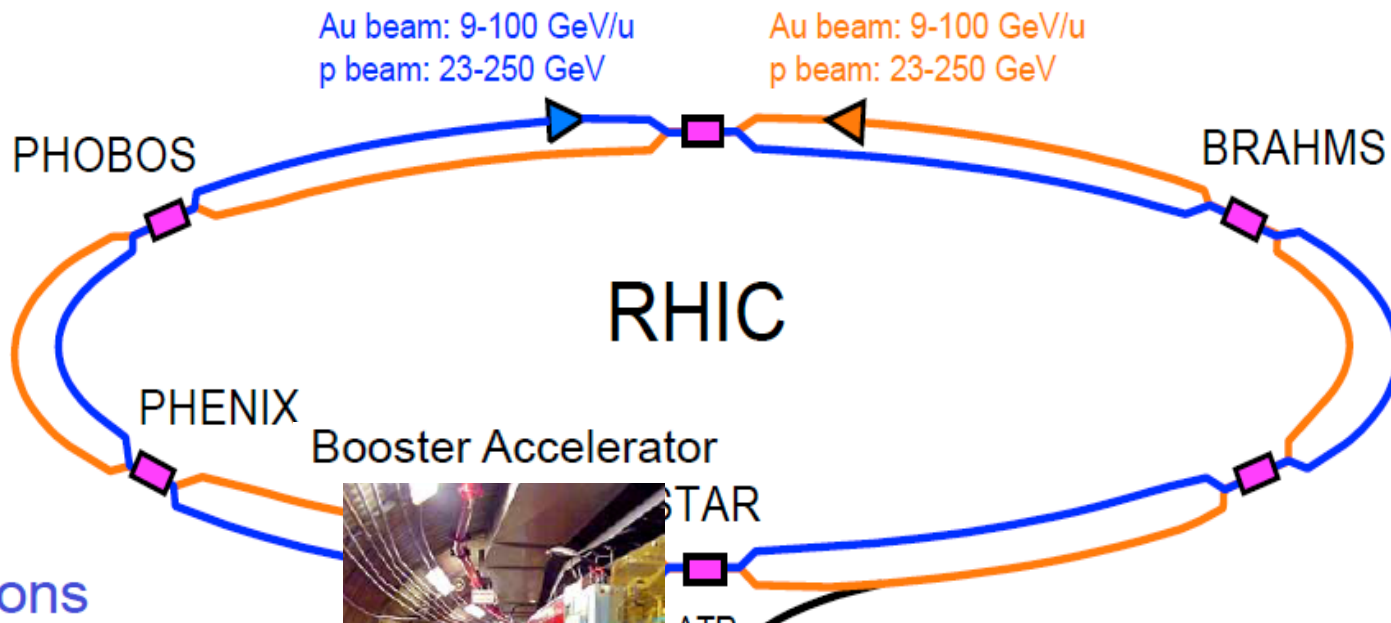


Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY

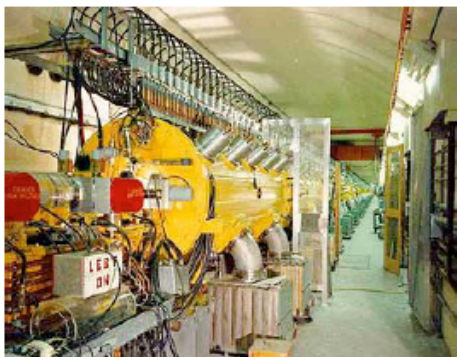


Animation M. Lisa

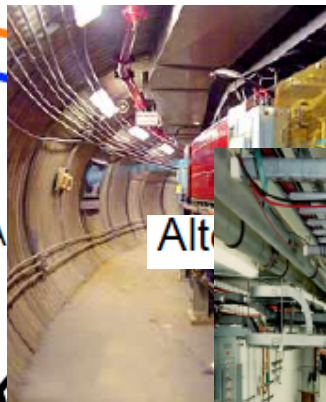


Protons

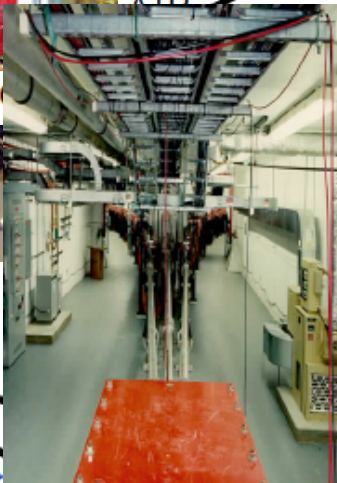
200 MeV Linear Accelerator



BA



Alt

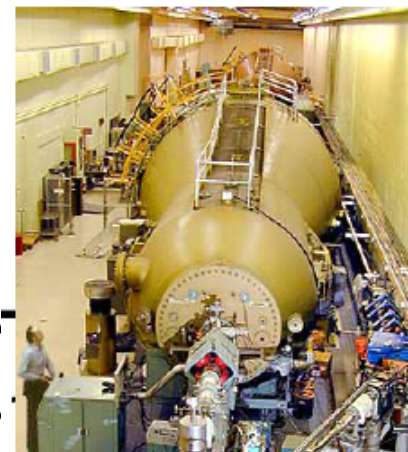


Synchrotron



Ions

Tandem Van de Graaff



Au beam: 1 MeV/u, Q=+32

HITL

Pulsed Sputter
Ion Source

RHIC: Relativistic Heavy Ion Collider
ATR: Ags-To-Rhic transfer line
AGS: Alternating Gradient Synchrotron
HITL: Heavy Ion Transfer Line

RHIC requires a complex of machines

Ions

Tandem Van de Graaff



Au: $Q=+32$,
1 MeV/u

Booster Accelerator



Au: $Q=+77$,
95 MeV/u

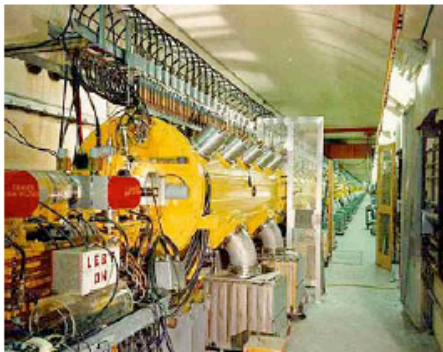
Alternating Gradient
Synchrotron



Au: $Q=+79$,
8.9 GeV/u

Protons

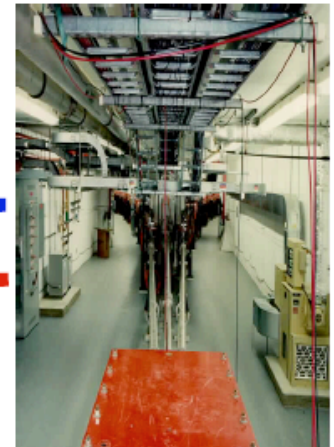
200 MeV Linear Accelerator



RHIC: Injection arcs to
blue and yellow rings

RHIC

Au: $Q=+79$, 9-100 GeV/u



Brief “summary” of RHIC

- Flexible **dedicated HI** machine
- Complex chain of machines: Van de Graff, Booster, AGS, RHIC
- Any A on any A
- $\sqrt{s}_{\text{max}} = Z/A \times 500 \text{ GeV}$
- Exceeds design luminosity by factor 4-6
- Luminosity limited by intra-beam scattering
- Can run at lower energies $\sqrt{S} = 5\text{-}50 \text{ GeV}$
 - Beam Energy Scan – most exciting of all !

How RHIC is different ?

- It's dedicated to high energy **Heavy Ion Physics**

Heavy ions run 20-30 weeks/year

- It's a collider

Detector systematics independent of $\sqrt{s}$

- It's high energy

Access to perturbative phenomena, calculable processes

- Its detectors are comprehensive

All final state species measure with a suite of detectors that have significant overlap for comparisons

some RHIC facts worth knowing

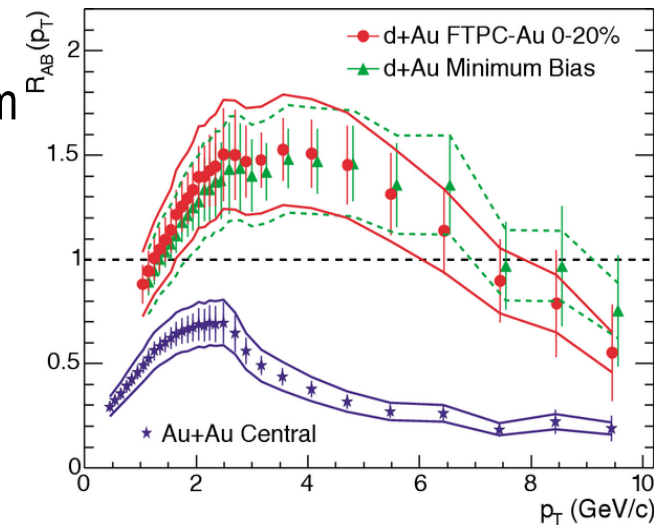
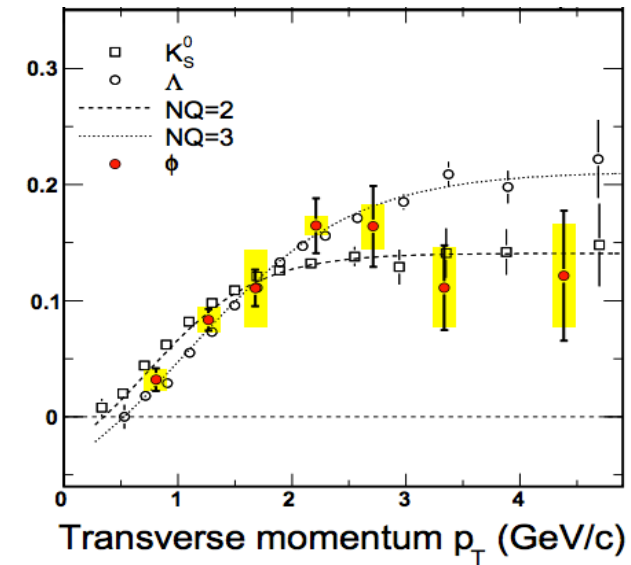
- RHIC 's two rings made of 1740 **super-conducting magnets** are cooled by liquid helium to -269°C
- RHIC contains **seven tons of helium**
- The refrigerator to cool the helium needs a **power of 15 MW** (as much as 15000 homes !)
- Over 20 years for Au beams, less than one gram of gold is used

Fast forward: RHIC top discoveries

- Partonic collectivity
 - Strong collective flow even for multistrange (ϕ , Ω) & D
 - Flow driven by Number-of-Constituent-Quark (NCQ) in hadrons
- Jet quenching
 - energy loss of high p_t partons in hot and dense medium
 - medium response

→ **Formation of strongly-coupled
Quark Gluon Plasma (sQGP)**

not wQGP – surprise , surprise !!!

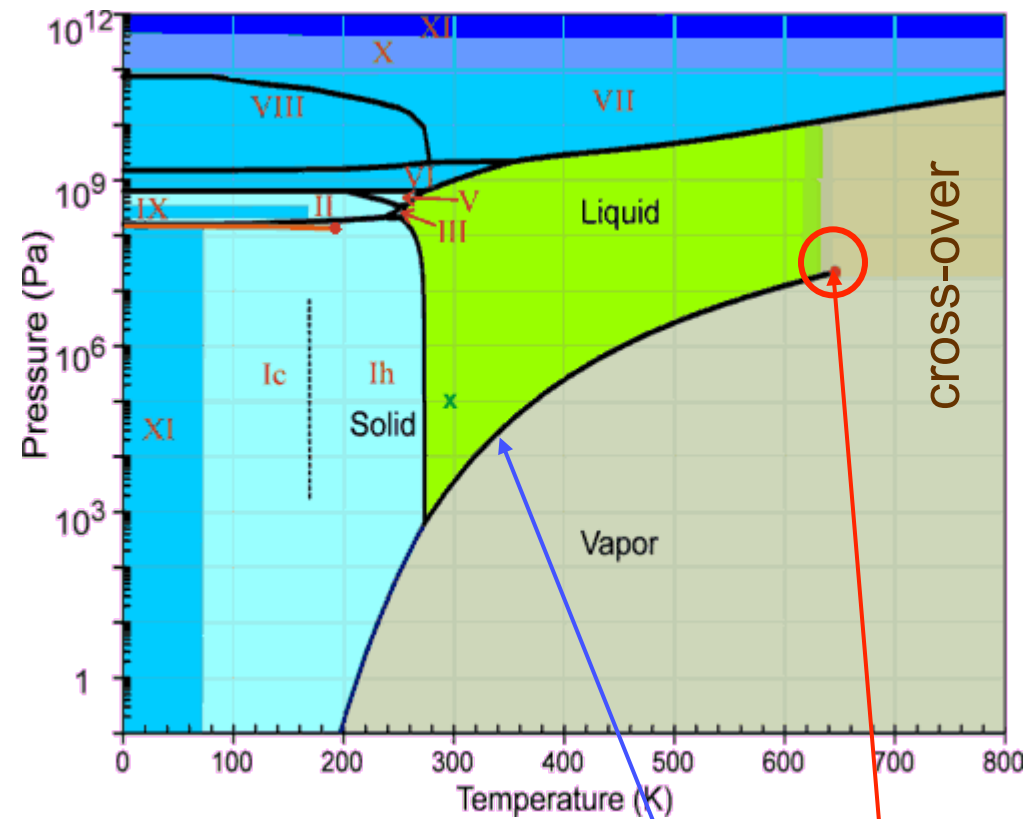
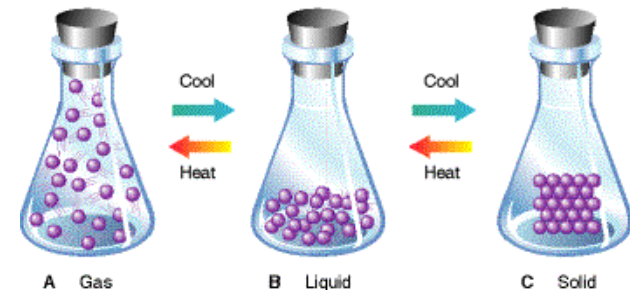


The “situation”

- Now:
sQGP produced in A+A at RHIC at top energies
(hot and dense matter with partonic dof)
- Problem:
we still don't know much about sQGP
- Future:
properties of sQGP (wQGP) – RHIC, LHC, ...?
boundary between hadronic and partonic phases ?
(where is a phase transition ?)
Critical Point ?

➔ **Exploration of QCD phase diagram**

Phases of matter: water



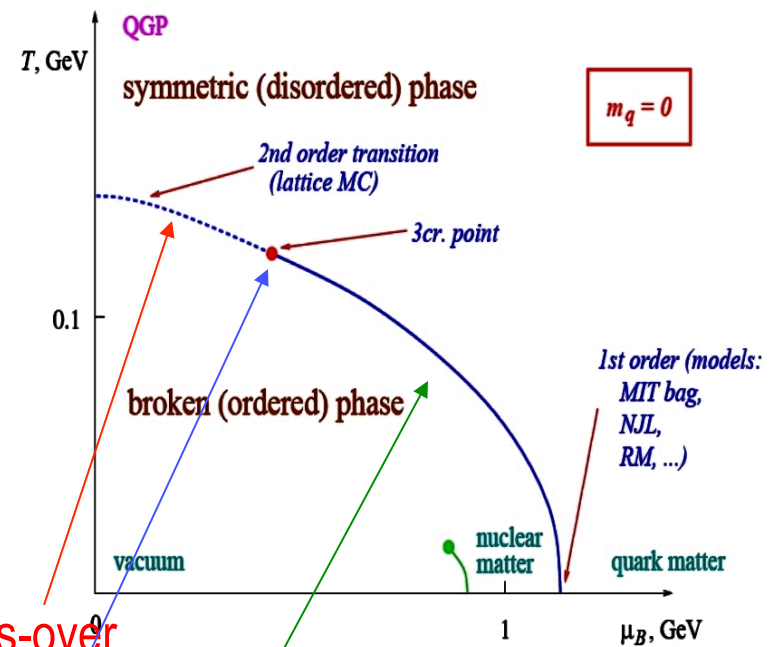
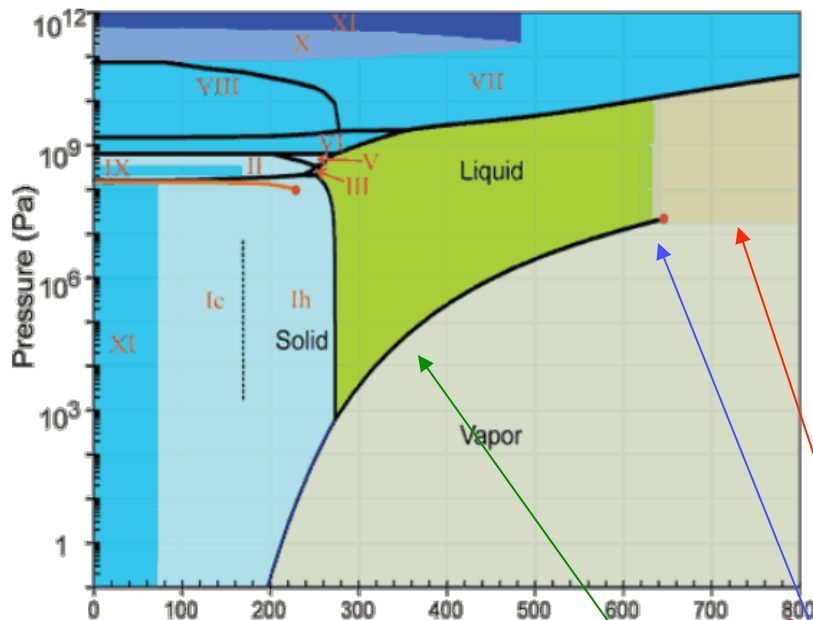
1st order phase
transition

CP

QCD Phase Diagram

WATER: the phase diagram of water is well established (non-relativistic particles)

QCD: The phase diagram of strongly interacting matter is **under study** (relativistic particles)



Cross-over

CP

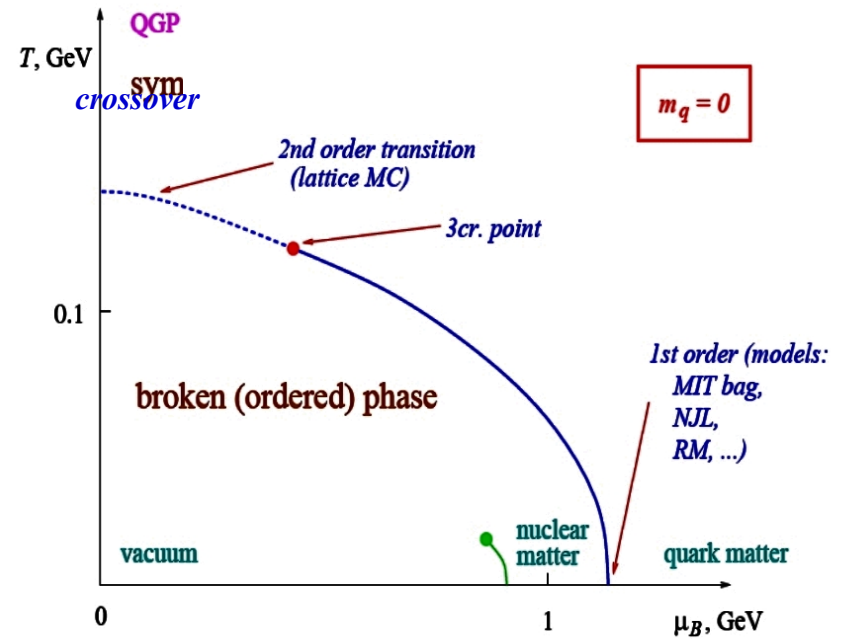
1st order phase transition

QCD phase diagram - Theory

M. Stephanov, hep-ph/0402115v1 (March 2006)

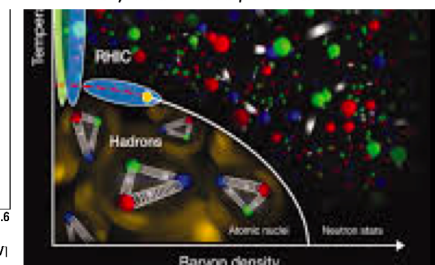
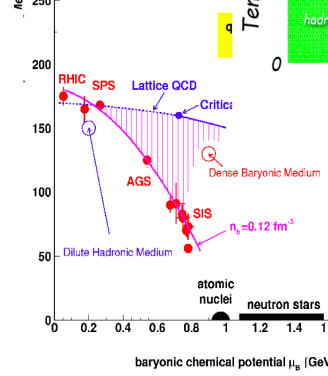
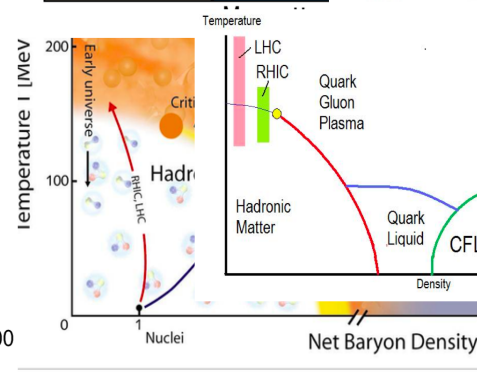
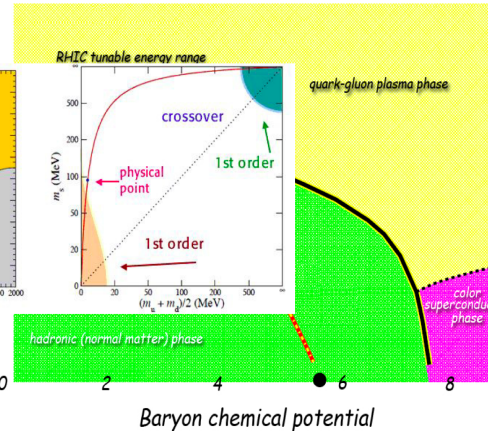
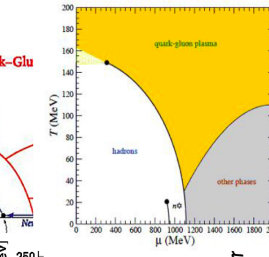
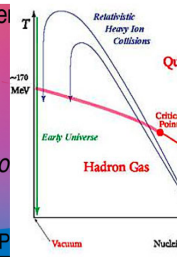
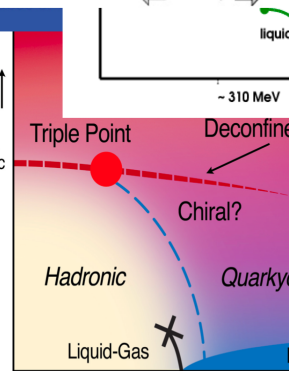
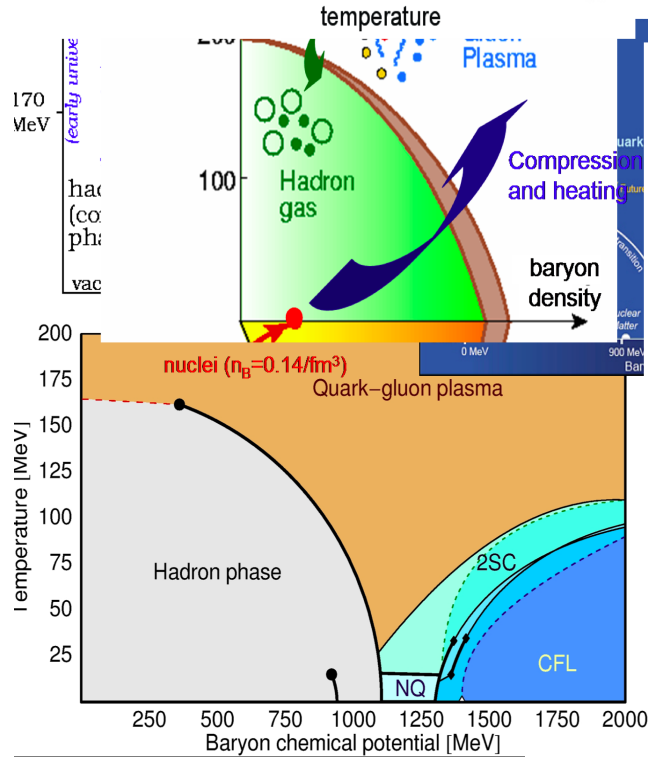
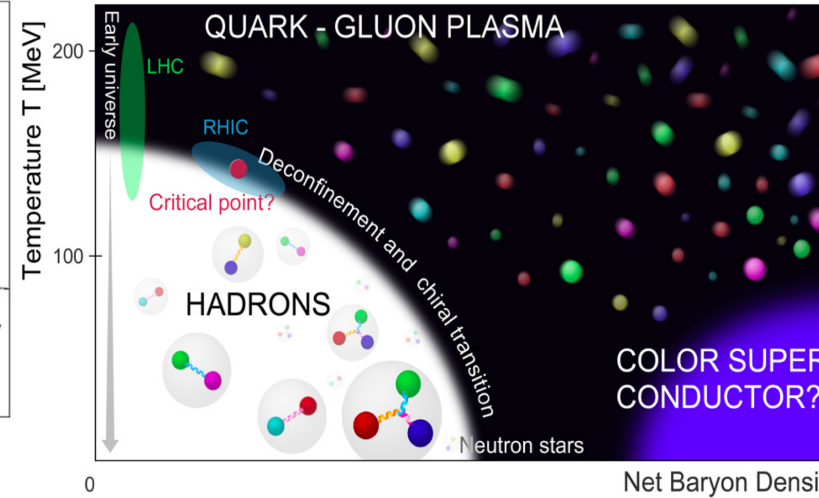
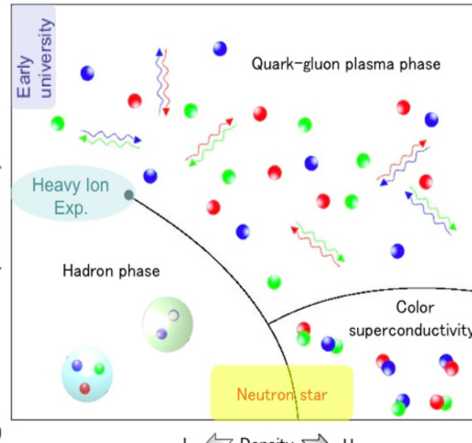
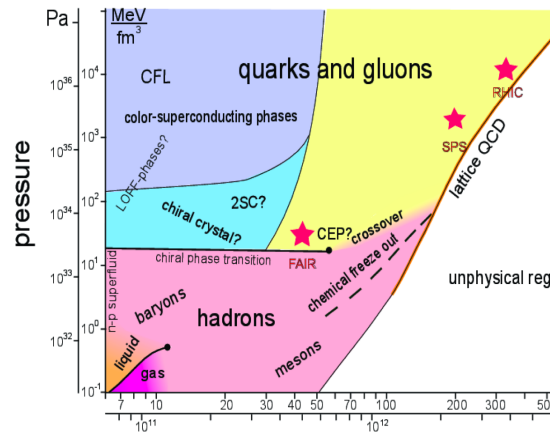
Theory at the “edges” is believed to be well understood:

1. Lattice QCD finds a smooth crossover at large T and $\mu_B \sim 0$
2. Various models find a strong 1-st order transition at large μ_B



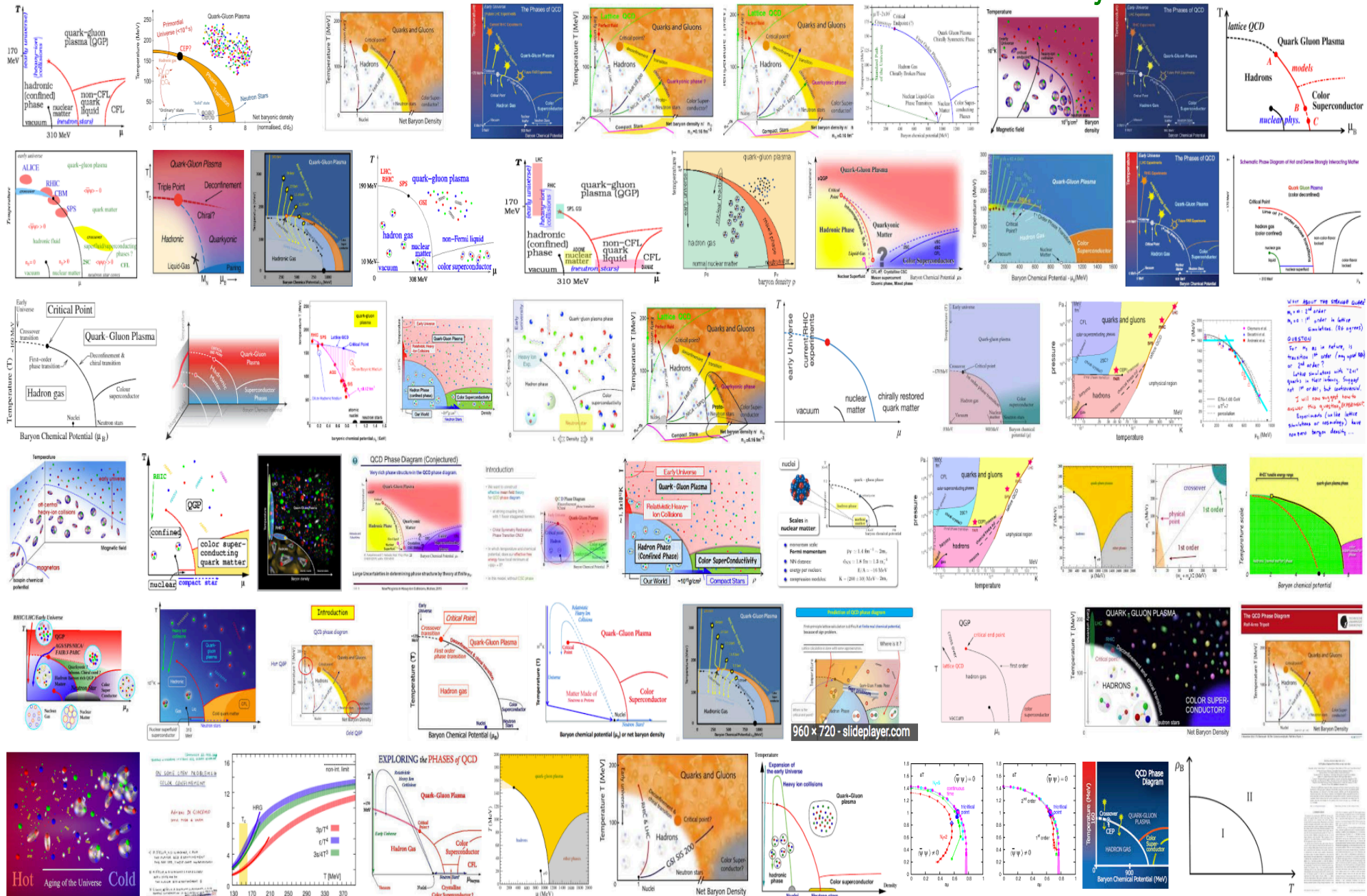
So, **there must be a critical point**, but where?

Very many



even more ...

B.Zajc – QM 2017

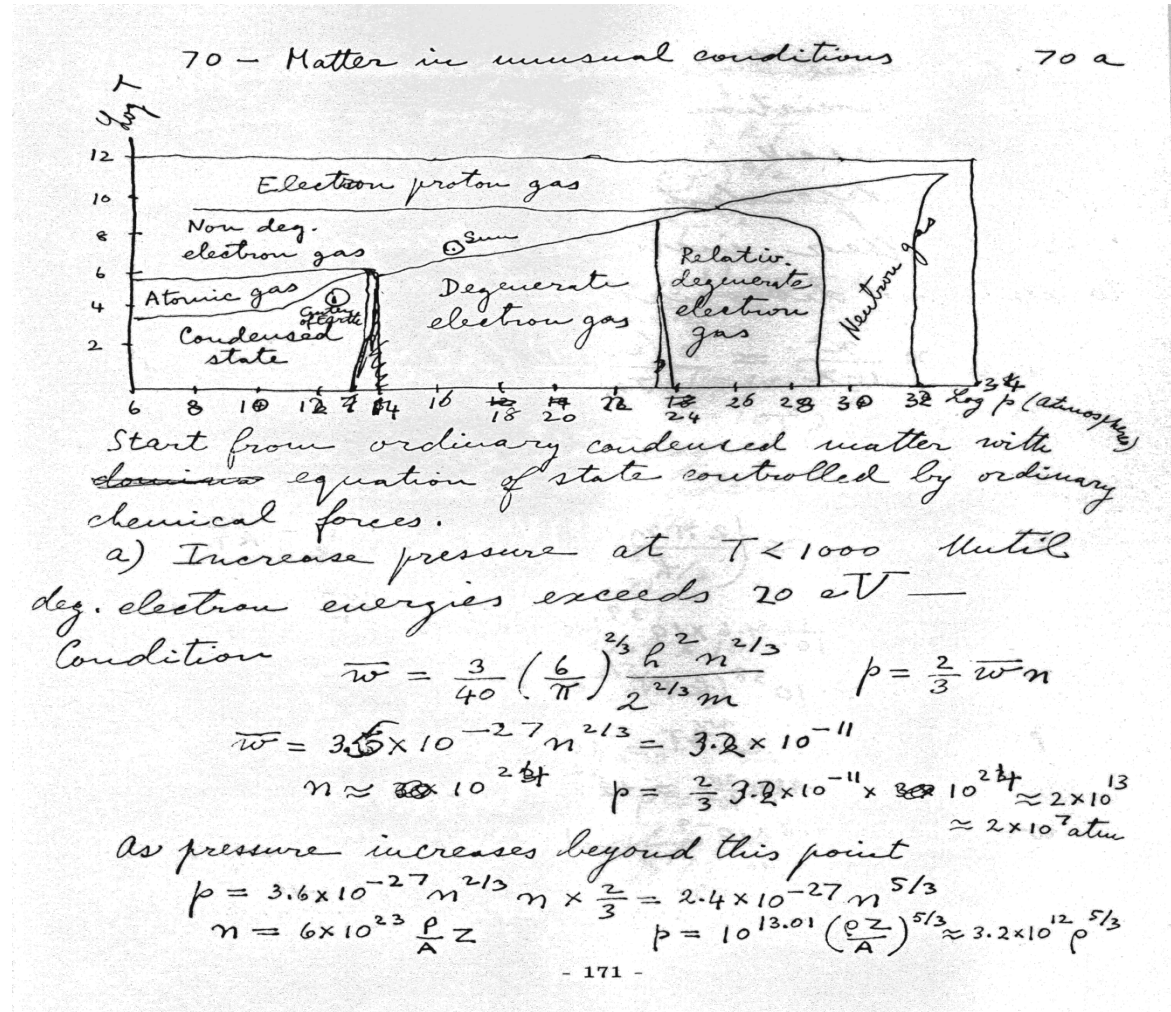


Concept of phase diagram not new at all !

E. Fermi: "Notes on Thermodynamics and Statistics" (1953)

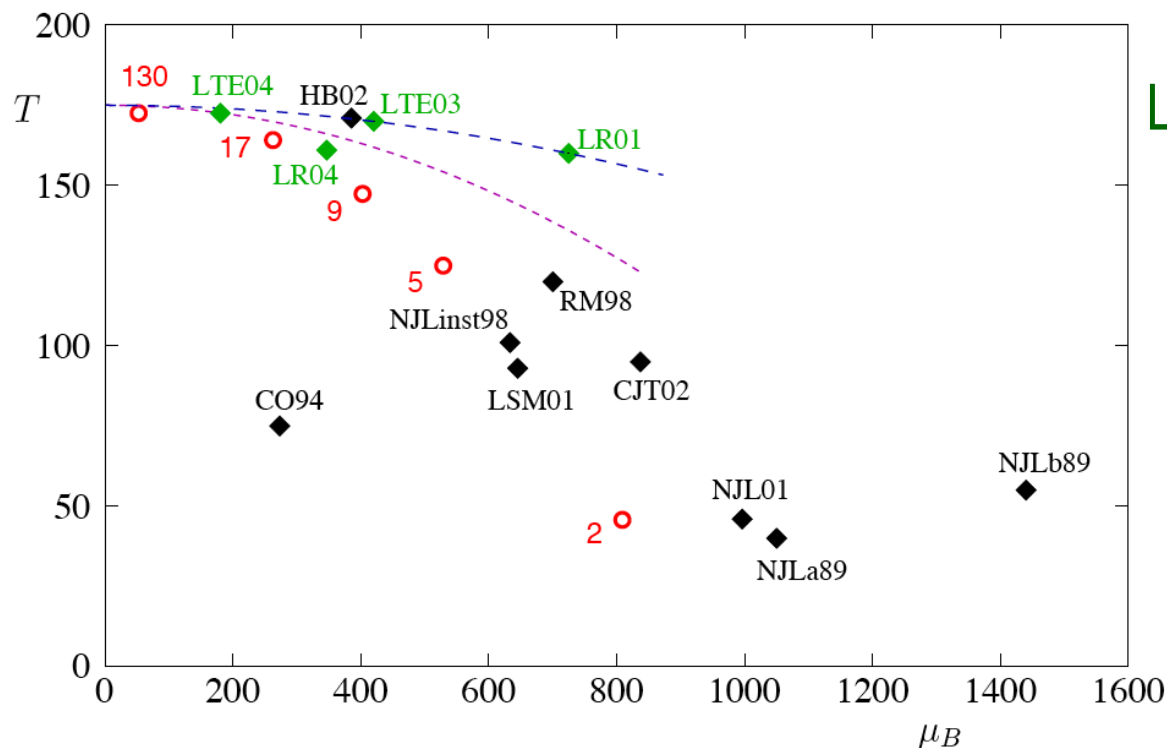


E. Fermi



Theory:

hep-lat/0701002v1



Lattice - green points !

$\mu_B < 500$

Lattice at $\mu_B \neq 0$: serious problems, several methods on lattice, no agreement so far:

→ CP range: $160 < \mu_B < 500$ MeV

Latest (QM 2017): $T_c = 154(9)$ MeV and $\mu_B/T > 2$ (Lattice Gauge Theory increasingly accurate)

Given the significant theoretical difficulties, **experiment must lead the search !**

→ we are focusing in on the right region (BES@RHIC)

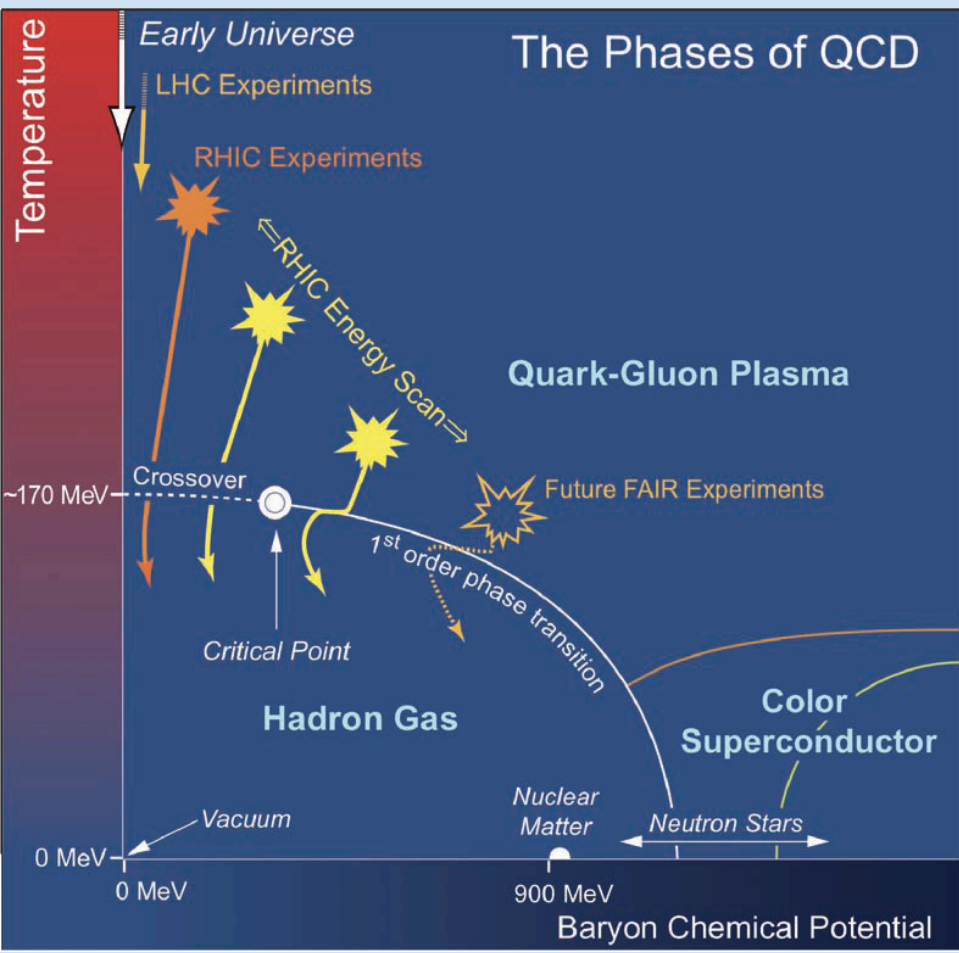
- How do we do it ?

how do we explore the QCD phase diagram ...

- high-energy nuclear collisions *
- steps in energy: RHIC @ $\sqrt{s_{NN}}$ of 5-50 GeV

*) Heavy ions the only experimental tool

QCD Phase Diagram



single most important graph of our field
- still highly speculative

We built RHIC to find QGP – and we did it !
(with unique and unexpected properties)

The main task now, besides study of properties of QGP, is to understand the structure of the QCD phase diagram:

- at high energies cross-over transition
(top RHIC energy, $\mu_B \sim 0$)
- at lower ($\mu_B > 0$) – 1st order phase transition ?
- CP ?

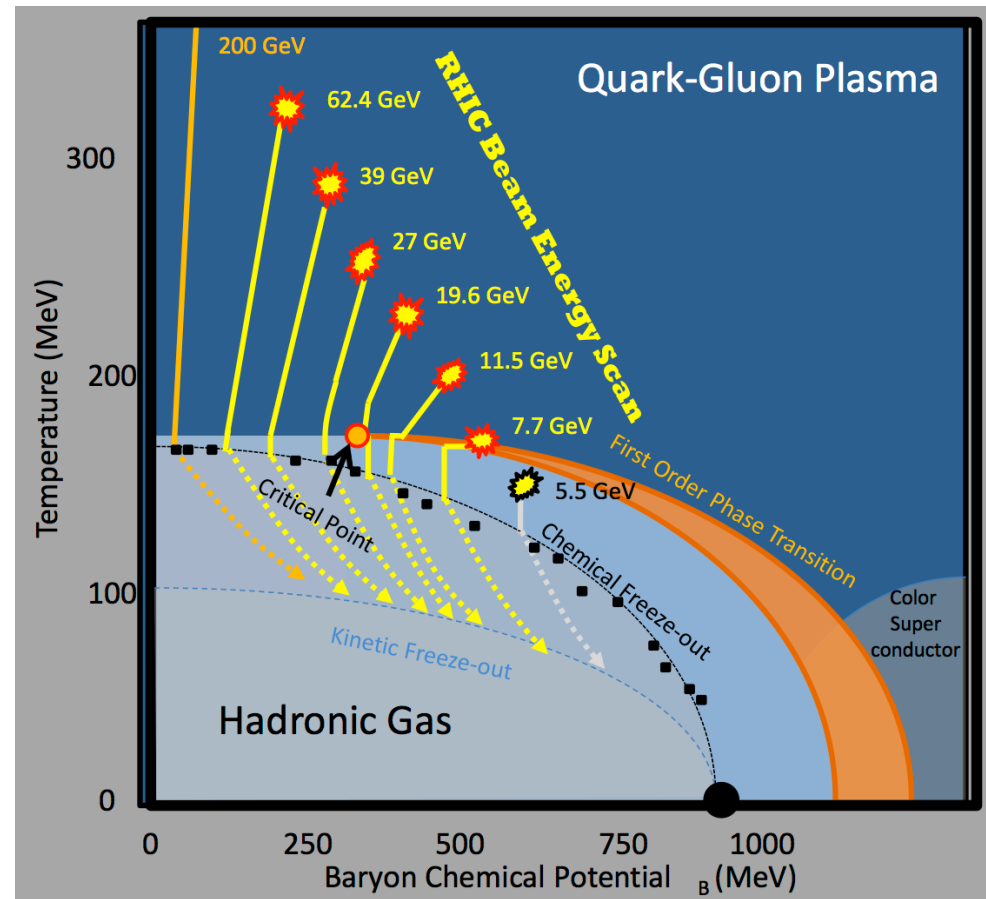


BES program at RHIC to map out
QCD matter phase diagram

BES Energies chosen to cover the interesting transition region dictated by the scale of the theory

arXiv:1007.2613

Beam Energy [GeV]	μ_B
39	112
27	156
19.6	206
15	256
11.5	316
7.7	421
5.5 (5)	522 (553)



by lowering energy we move towards larger μ_B

BES – Phase I

$\sqrt{s}$ (GeV)	Statistics (Millions)	Year
7.7	~4	2010
11.5	~12	2010
14.5	~20	2014
19.6	~36	2011
27	~70	2011
39	~130	2010
62.4	~67	2010
200	~350	2010

Search the QCD phase diagram for evidence of :

1. critical point fluctuations ?
2. signals of 1st order phase transition ?
3. sQGP signatures turn off/on ?

→ theory feedback & further exploration

BES-I (2010 - 2014): $\sqrt{s_{NN}} = 7.7, 11.5, \mathbf{14.5}, 19.6, 27, 39\text{GeV}$
+ 62.4, 130 and 200 GeV

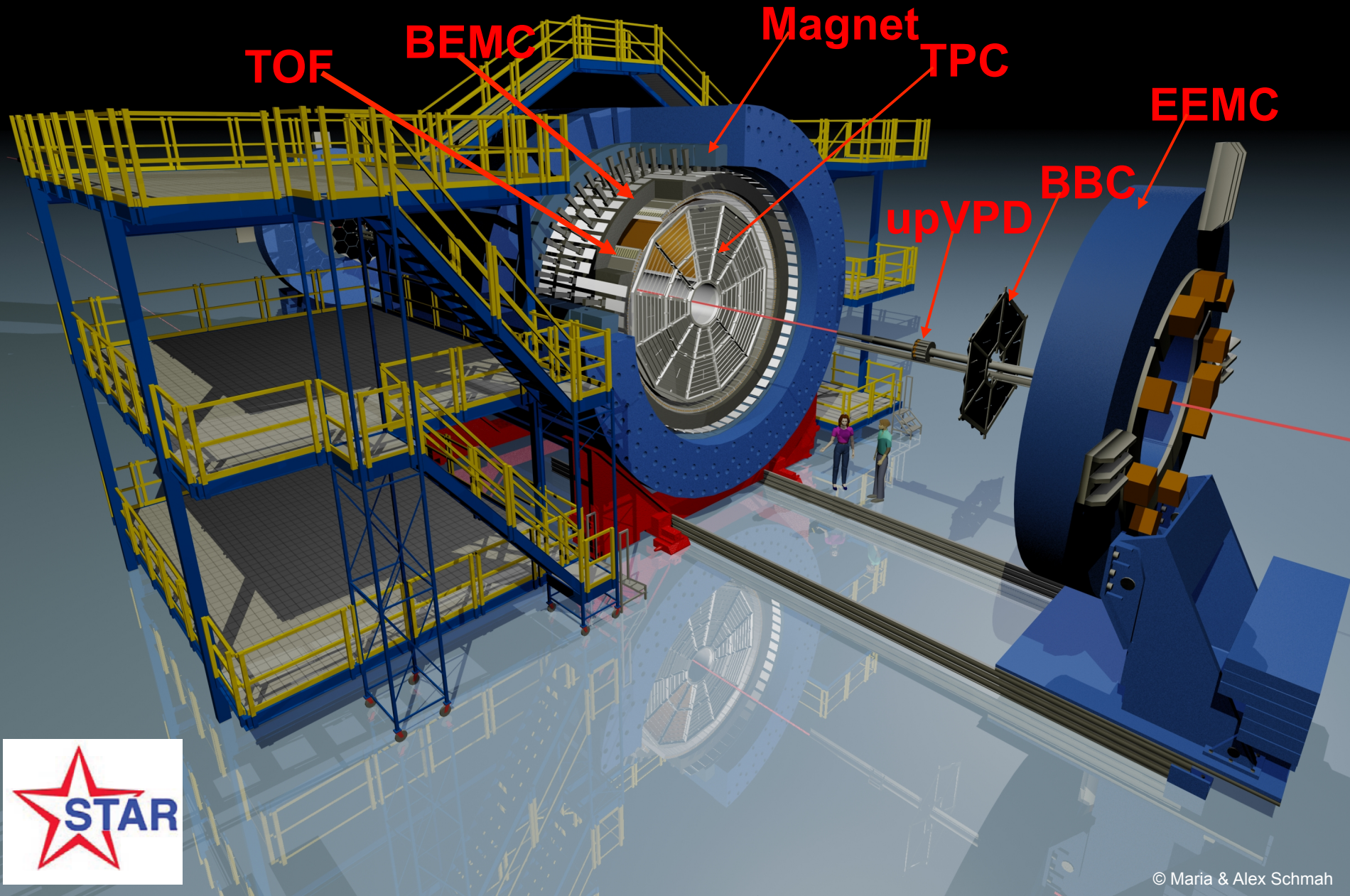
16 STAR papers published based on BES I (+ half-dozen is in preparation)

at RHIC



with STAR

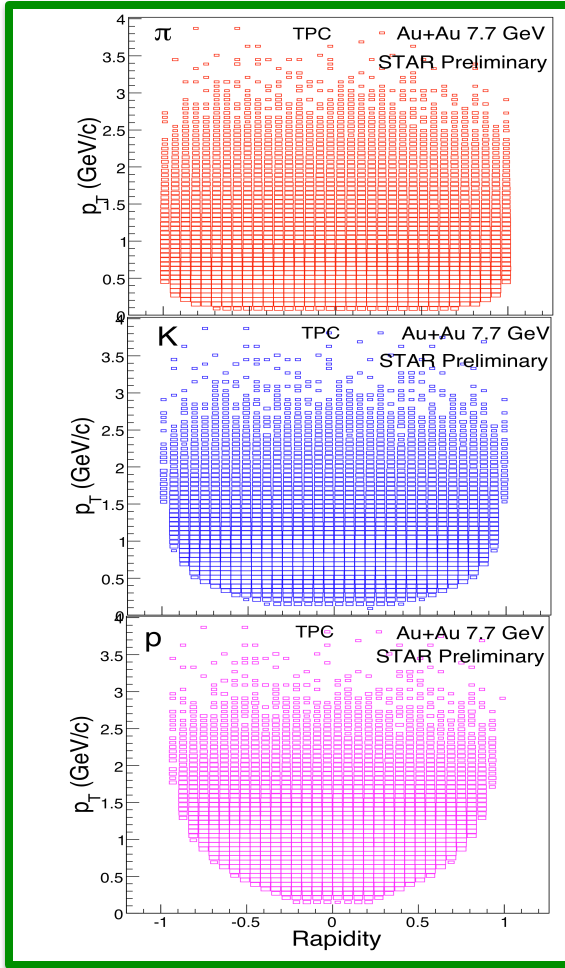
Solenoid Tracker At RHIC



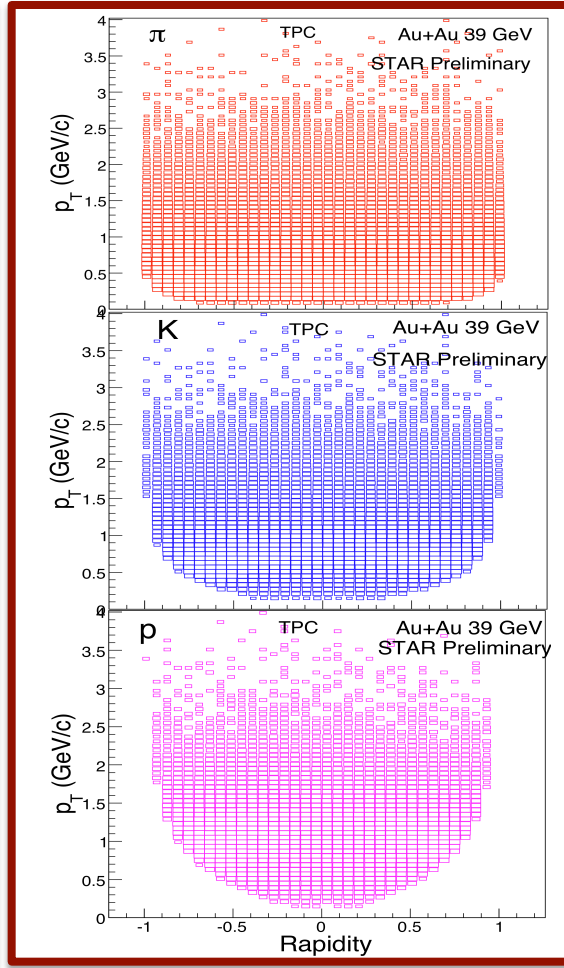
Collider geometry !

Identified particle acceptance at STAR

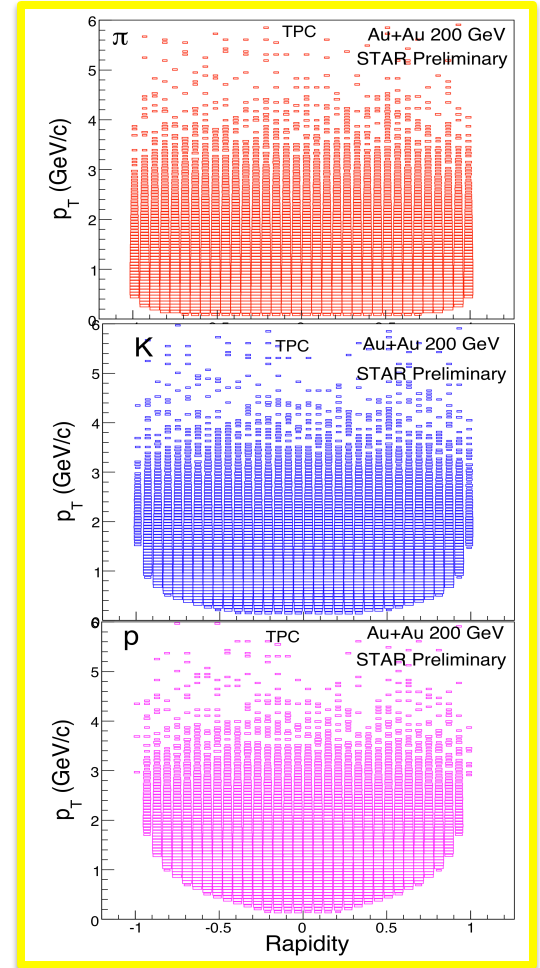
Au+Au at 7.7 GeV



Au+Au at 39 GeV



Au+Au at 200 GeV

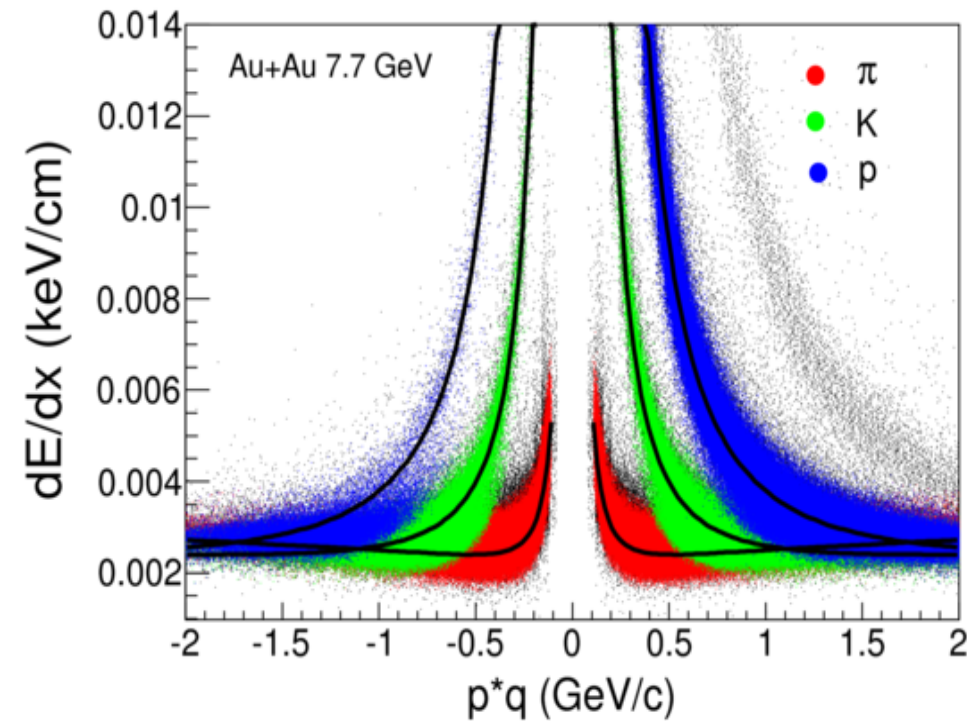


At collider geometry - similar acceptance for all particles and energies

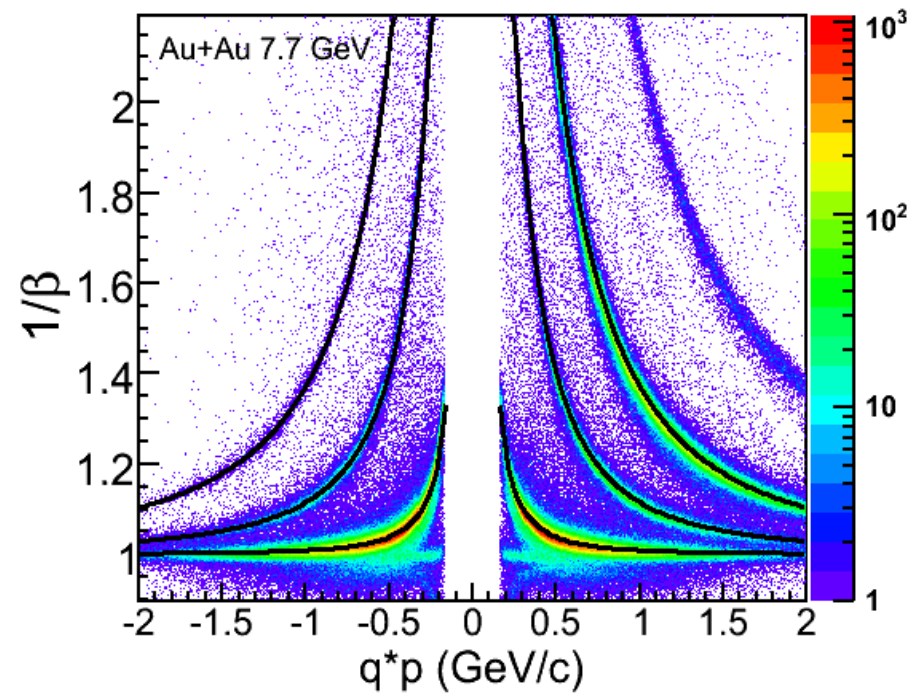
Excellent PID

STAR Performance in Run 10 - particle Identification at 7.7 GeV

TPC PID

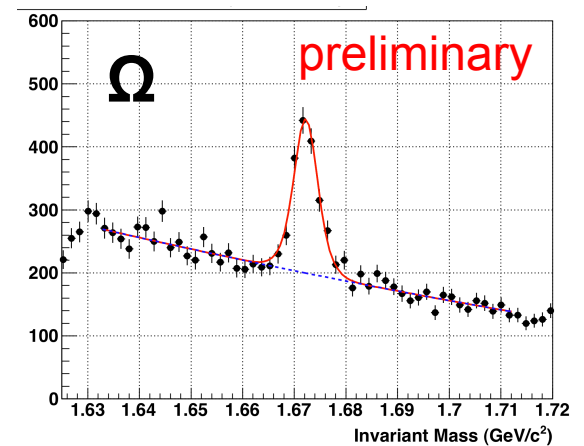
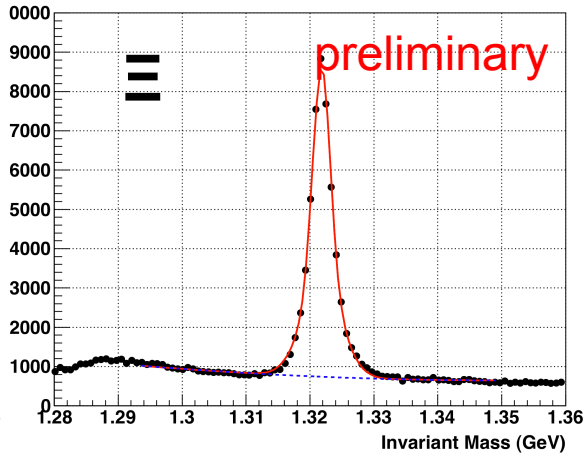
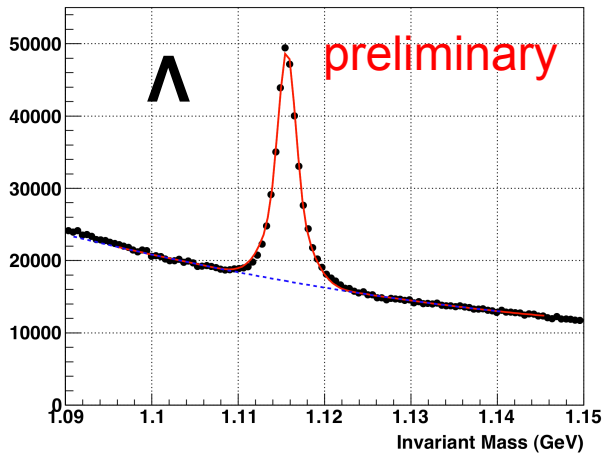
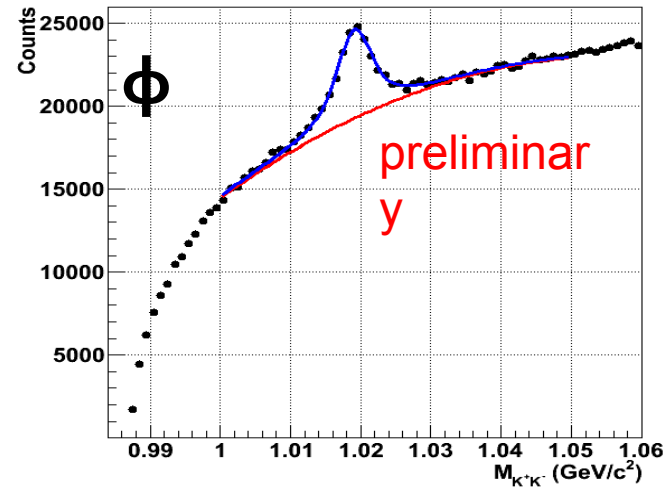
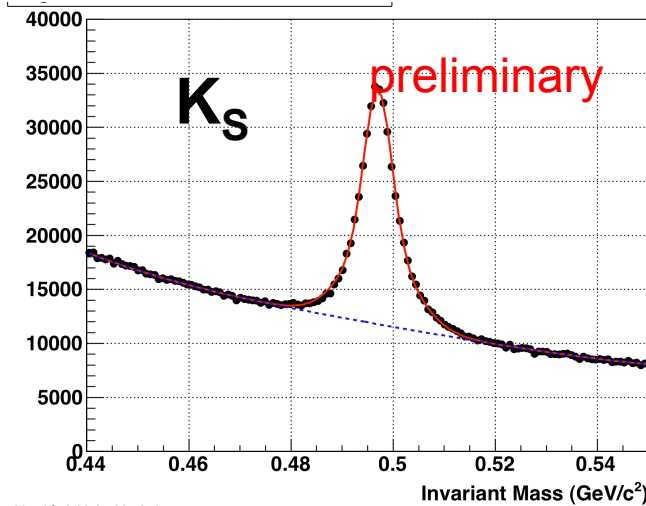


TPC+TOF PID

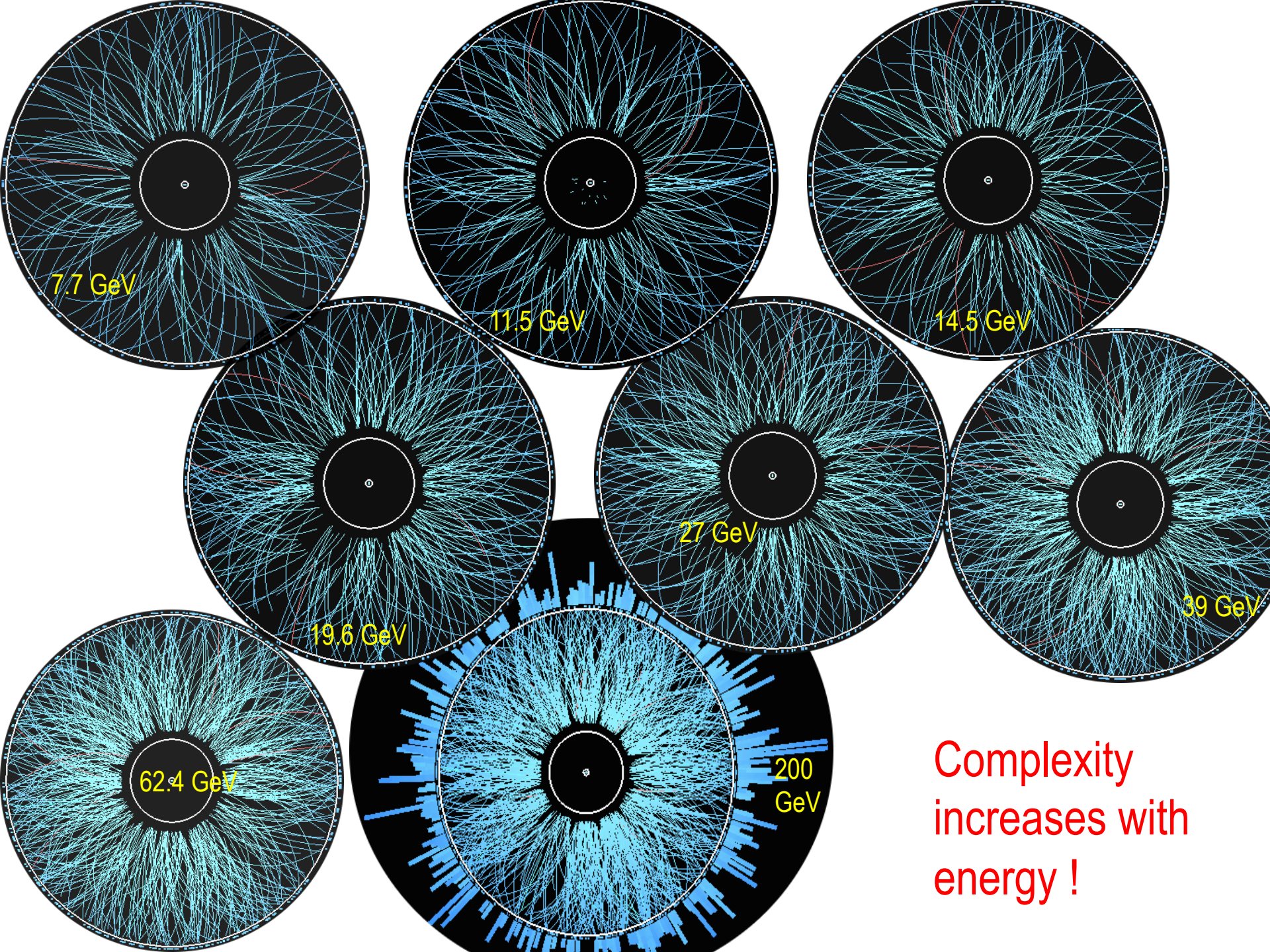


Topological particle identification

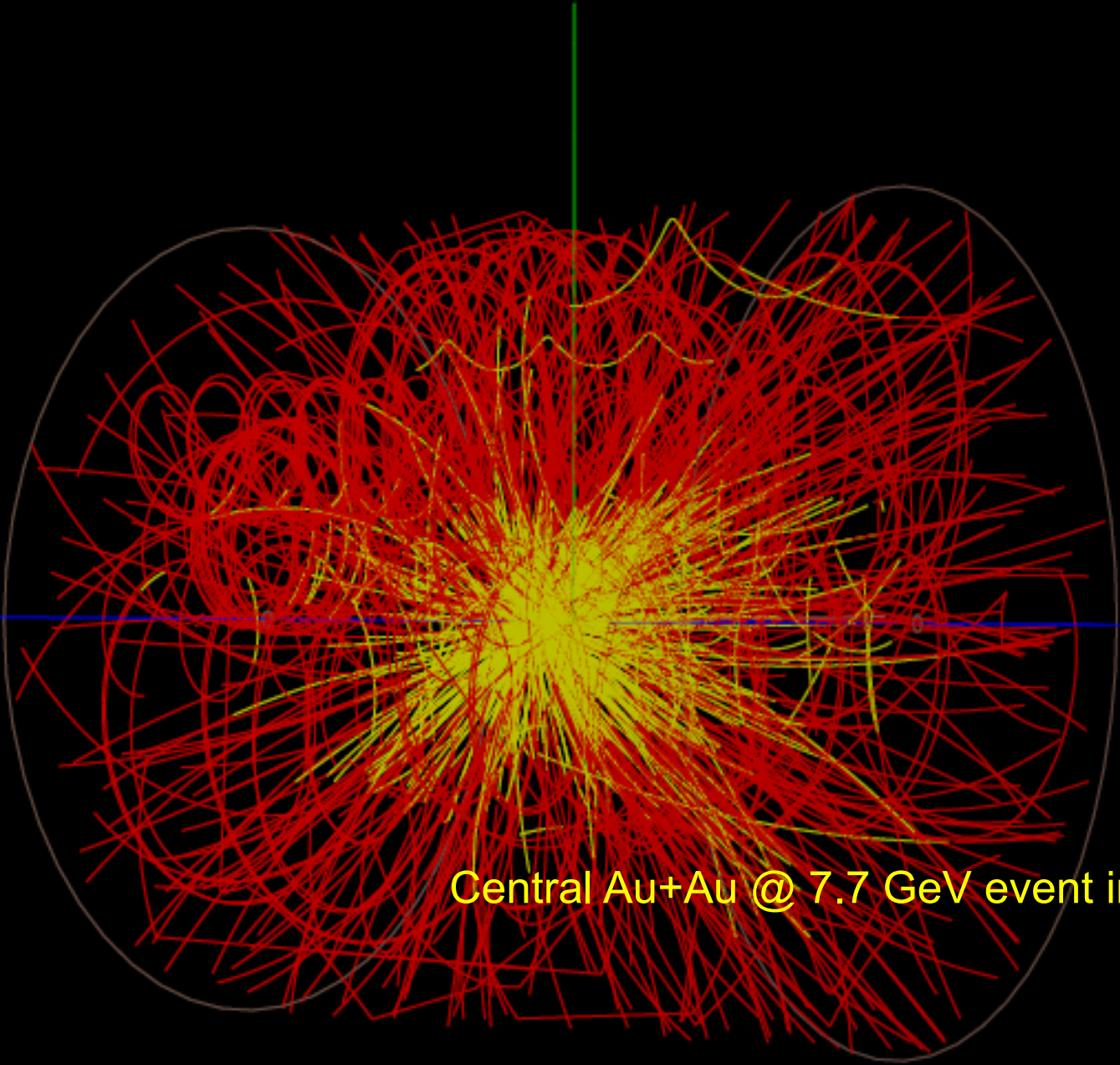
$\sqrt{s_{NN}} = 39$ GeV Au + Au collisions in STAR



Invariant Mass (GeV)



Complexity
increases with
energy !



A visualization of a central Au+Au collision event in the STAR TPC. The event is represented by a dense, chaotic network of red lines radiating from a central yellow-orange core, all contained within a large, faint grey oval. A horizontal blue line and a vertical green line intersect at the center of the event, likely representing the beam axis and the plane of the detector's readout.

Central Au+Au @ 7.7 GeV event in STAR TPC

Strategy for STAR BES program

First:

Establish the thermodynamic conditions sampled at each energy

Later on:

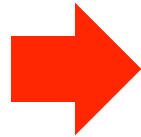
Carry on physics program at each energy

- 1) Probe for **first-order phase transition**
 - “softening” of EoS – reduced pressure as temperature is varied
 - manifest in dynamic observables
- 2) Probe for **critical point**
 - divergent correlation lengths
 - manifest in fluctuation measures
- 3) Look for QGP signals to “**turn off**” as energy is lowered

Where we are on the phase diagram ?

Au+Au at freeze-out: T and μ_B

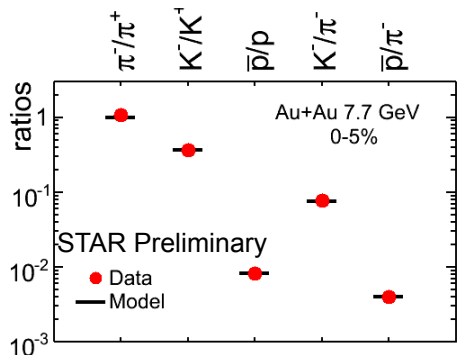
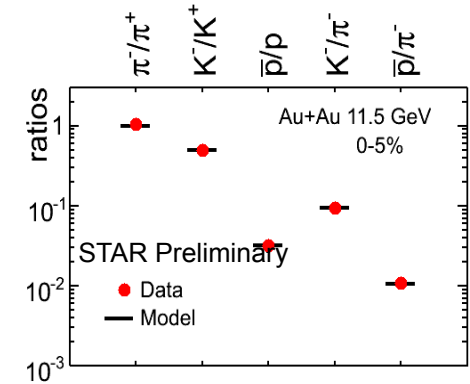
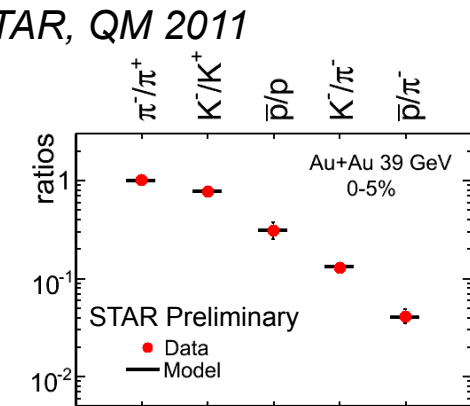
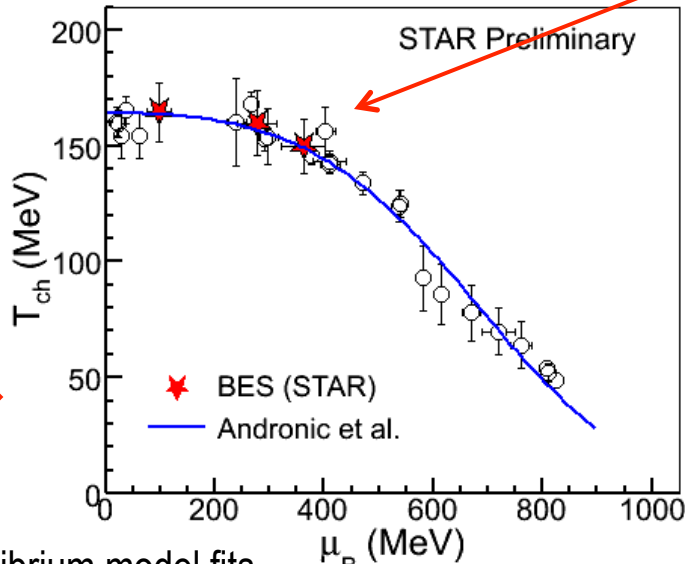
$\sqrt{s_{NN}} = 39, 11.5 \text{ and } 7.7 \text{ GeV}$



Thermal equilibrium model fits
Phys.Rev.C 79, 034909 (2009)
Phys.Lett. B344, 43 (1995)

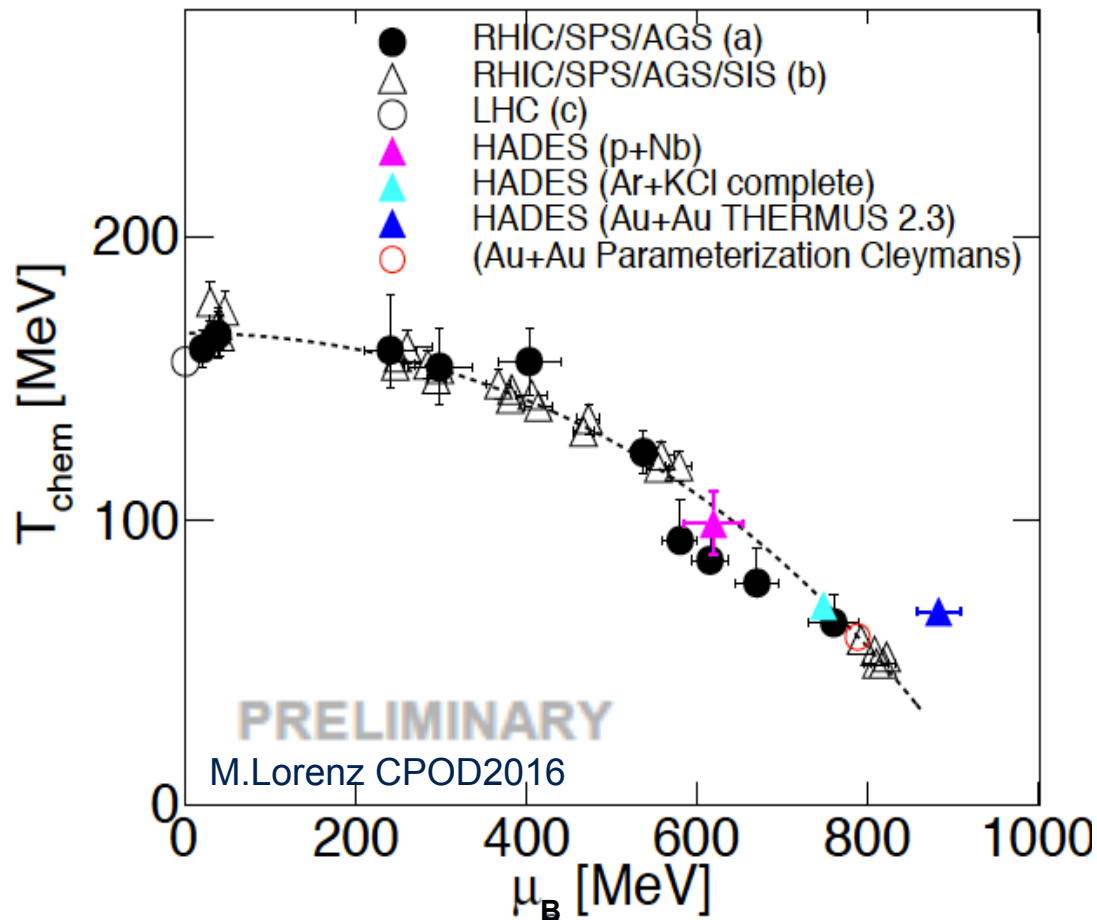
Extended μ_B range covered by RHIC :
 $20 \rightarrow \sim 400 \text{ MeV}$ ($\sqrt{s_{NN}} = 7.7 \text{ GeV}$)

Caveat: $\sqrt{s_{NN}} \leftrightarrow \mu_B$ correspondence somewhat model & centrality-dependent



No longer in equilibrium ?

QM 2017



Hades data above universal curve at lower energies

Role of resonances: at low energies baryonic resonances required in models (HADES)

BES goals and (some of) observables

- disappearance of QGP signatures (partonic vs. hadronic dof) :
 - NCQ scaling, v_2
 - R_{cp} (R_{AA}) – nuclear modification factor
 - charge separation
- 1st order phase transition:
 - directed flow v_1
 - azimuthally sensitive HBT
- critical point:
 - fluctuations
- chiral symmetry restoration (?) -> spectral function change
 - di-lepton production

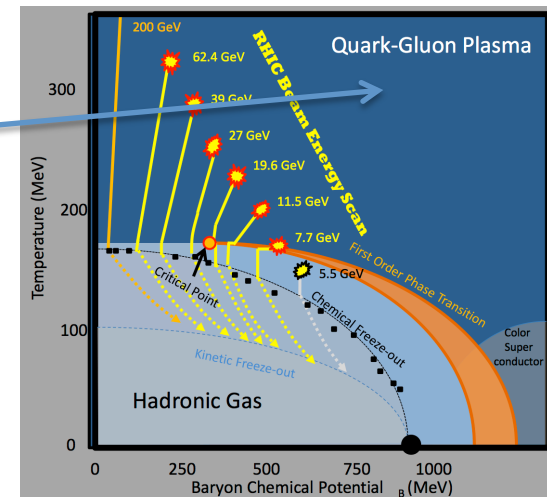
<http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493>, *arXiv:1007.2613*

<http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598>, *BES II White Paper, 2014*

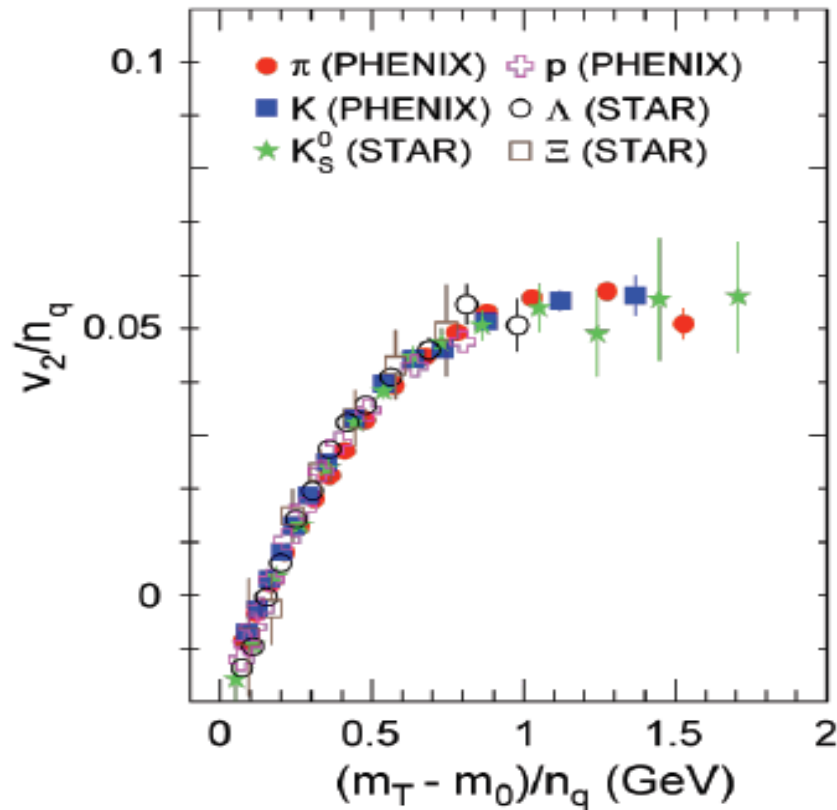
the easiest one ...

disappearance of signals of
partonic degrees of freedom
seen at 200 GeV

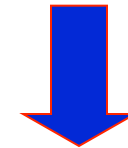
do QGP signatures (v_2 , R_{cp} , ...) turn-off ?



Disappearance of partonic degrees of freedom



Scaling flow parameters by quark content n_q (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons

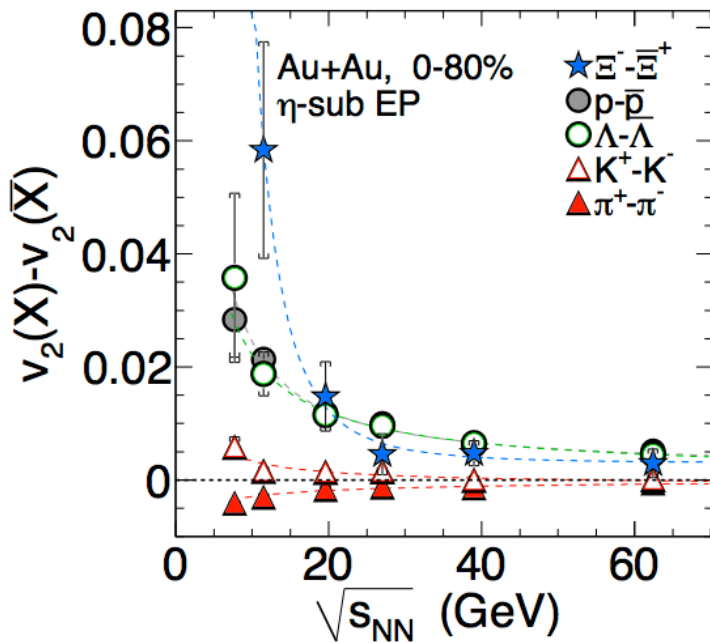
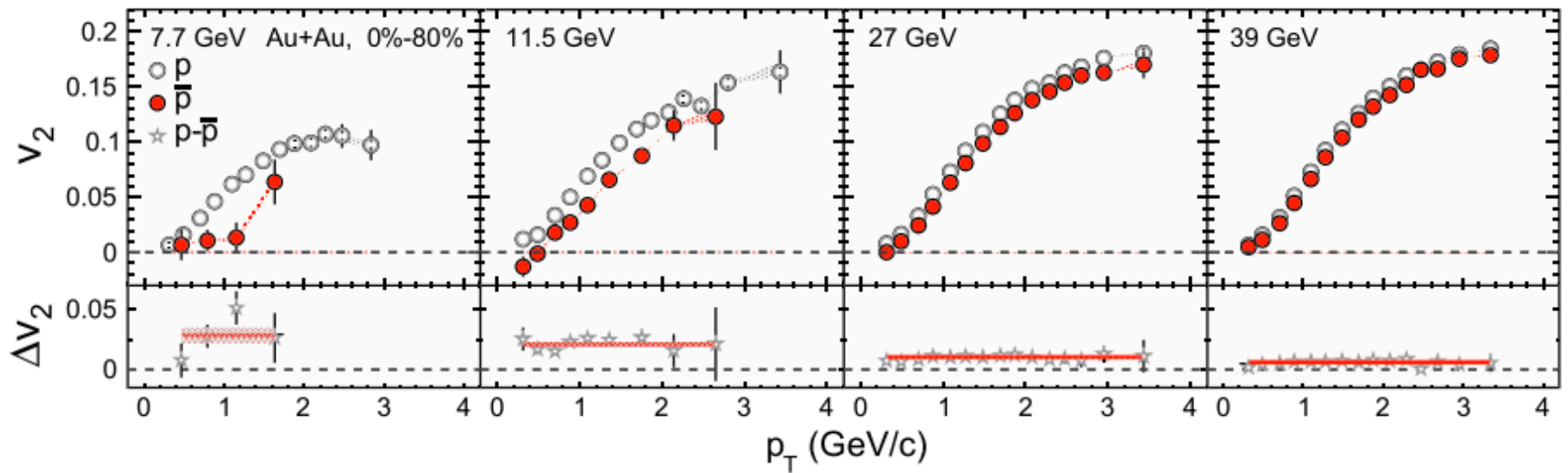


flow developed in pre-hadronic stage
DECONFINEMENT at RHIC

With lowering energy, disappearance of n_q scaling would suggest that we exit partonic dof world

BES I: v_2 difference between particle and anti-particle

STAR, PRL 110 (2013) 142301, PRC 88 (2013) 014902, PRC 93 (2016) 014907



Significant difference between baryon-antibaryon v_2 at $\sqrt{s_{NN}} \leq 11.5$ GeV

NCQ scaling between particles and anti-particles is broken

→ consistent with hadronic interactions becoming dominant

→ Indication for a phase transition ??

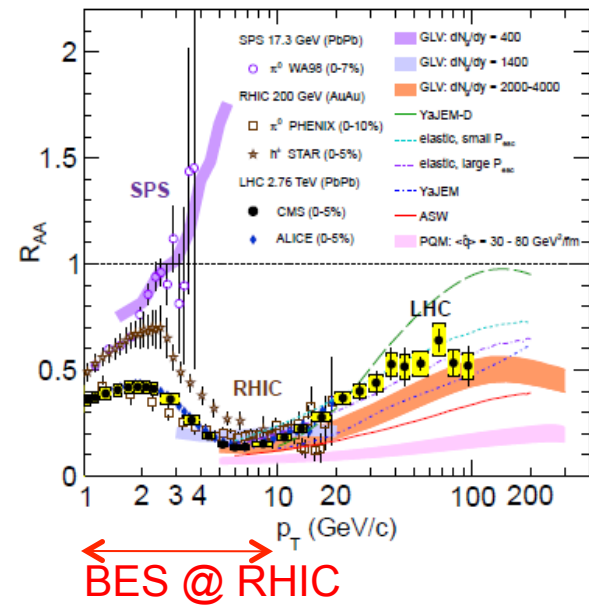
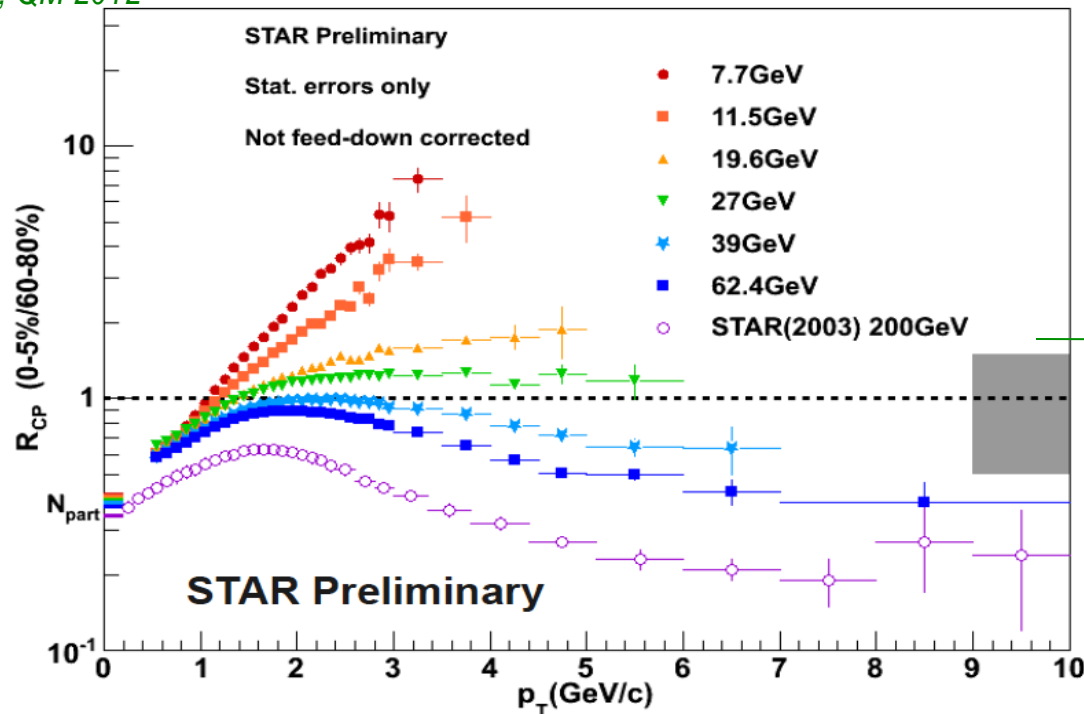
Note, that particle composition changes with energy !

Charged hadrons R_{cp}

Nuclear modification factor - measure of partonic energy loss in medium :

$$R_{CP} = \frac{d^2 N dp_T d\eta / \langle N_{bin} \rangle (central)}{d^2 N dp_T d\eta / \langle N_{bin} \rangle (peripheral)}$$

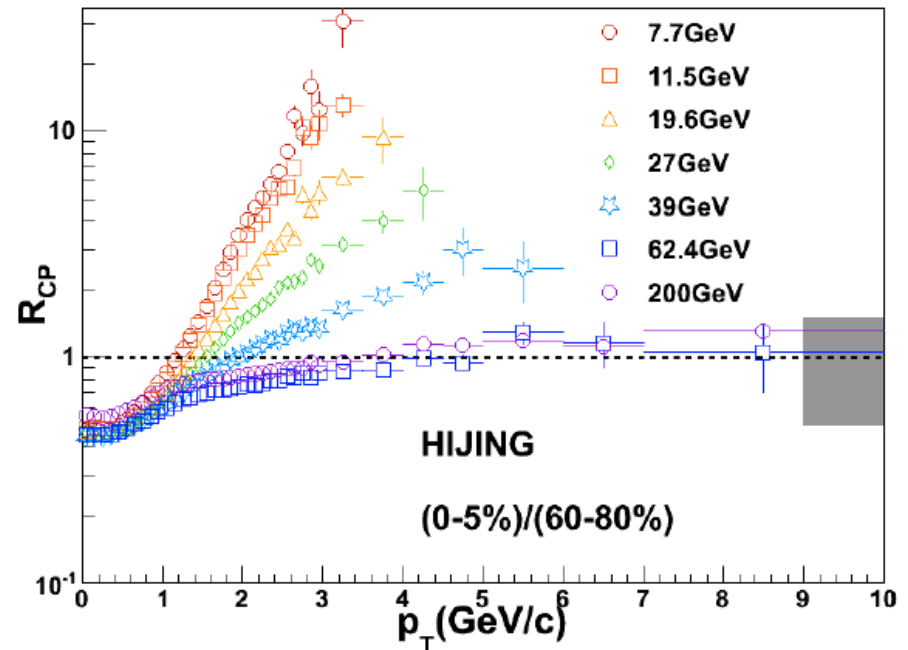
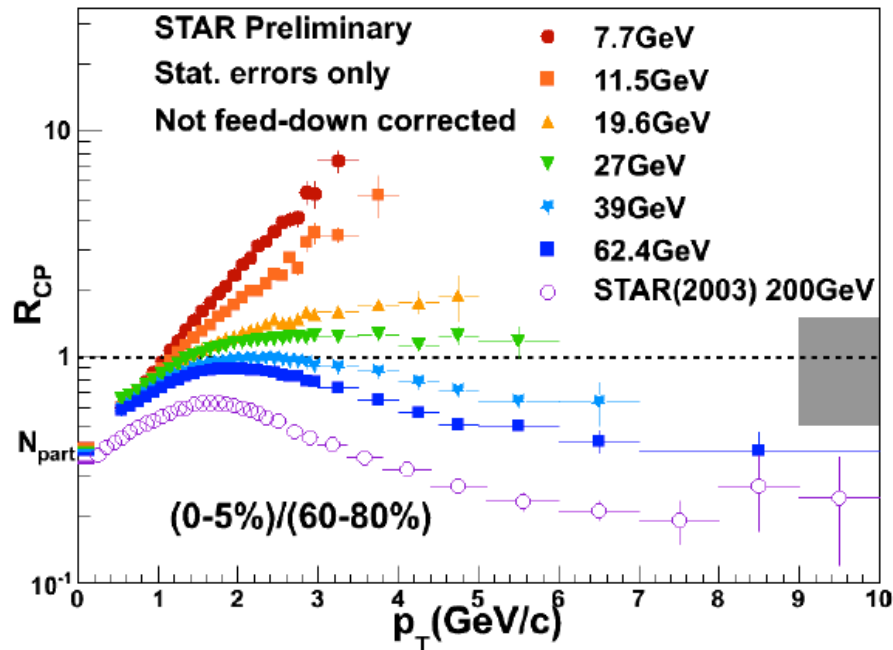
STAR, QM 2012



J.Adams et al., (STAR coll.)
PRL 91, 172302 (2003)

- High p_t suppression seen at 39, 62.5 and 200 GeV
- Signature “turn-off” between 27 and 39 GeV ?
 - clearly less suppression as energy is reduced
- but insufficient reach to search for evidence of high p_t suppression below 19.5 GeV

Charged hadrons R_{cp}

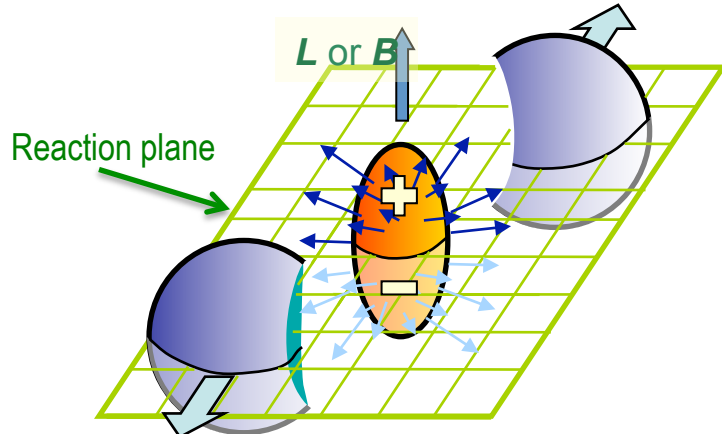


Similar behavior in HIJING with no partonic energy loss at low energies but with Cronin effect (though k_t broadening)

Hadronic interactions play a significant role at $\sqrt{s_{NN}} \leq 11.5$ GeV

Chiral Magnetic Effect (CME)

D.E. Kharzeev et al, NPA 803, 227 (2008)
K. Fukushima et al, PRD 78, 074033 (2008)

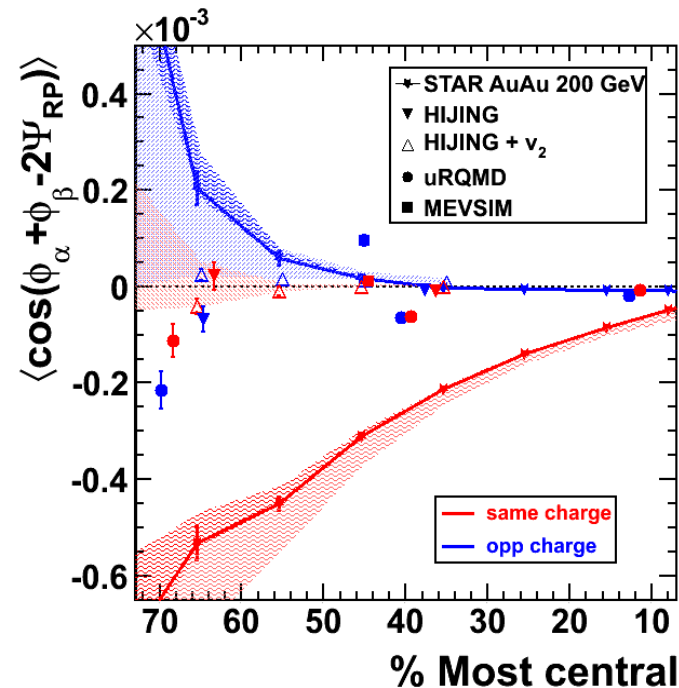


(1) interplay between the strong magnetic field produced in the non-central heavy-ion collisions and the deconfined state created in these collisions causes the separation of charges along the axis of the magnetic field, phenomenon is known as Chiral Magnetic Effect (CME)

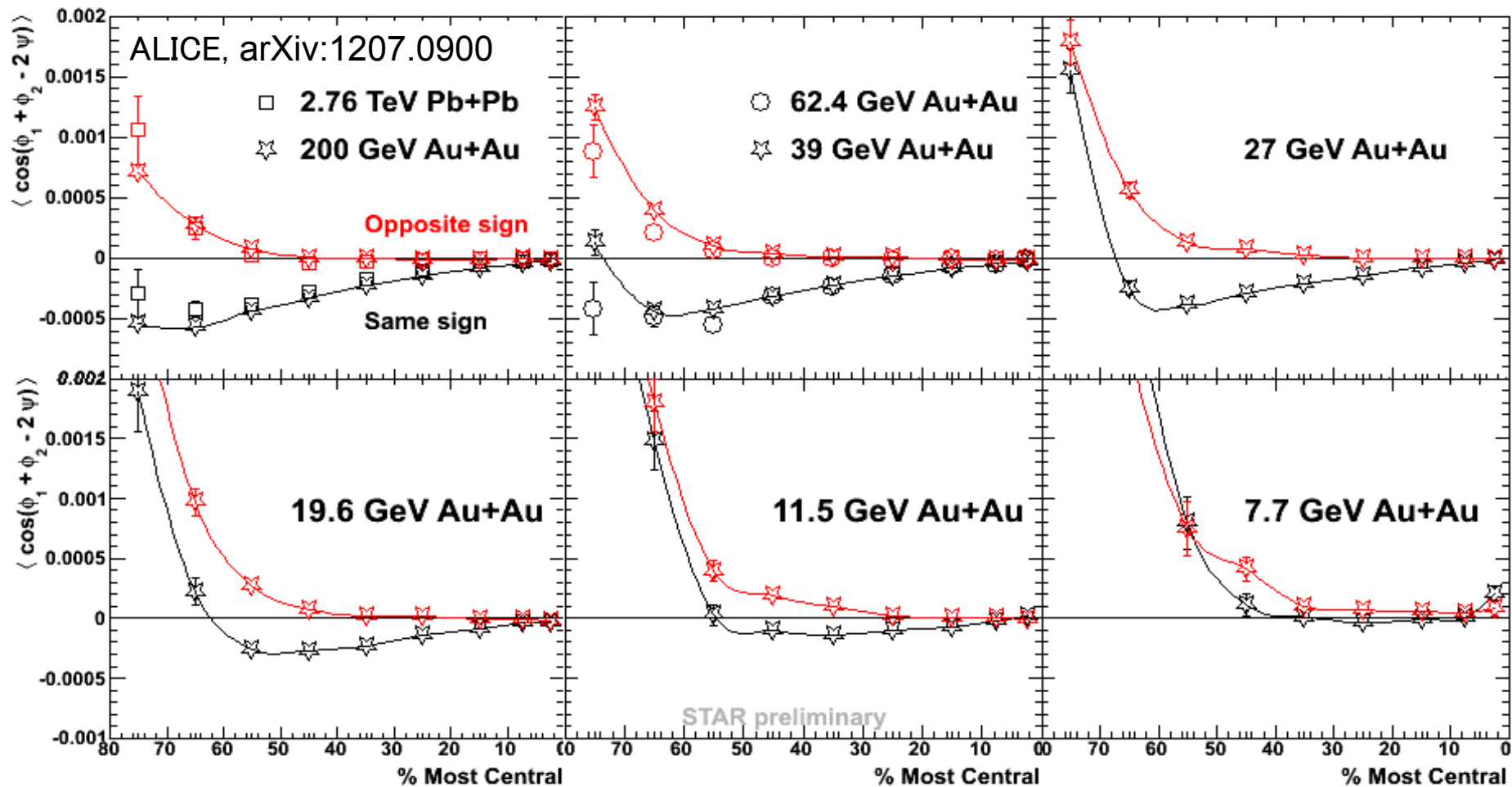
(2) Experimentally one would observe the separation of the charges in high-energy nuclear collisions.

(3) RHIC Beam Energy Scan program:

- test the model prediction
- the energy when the charge separation disappear => phase boundary



Dynamical charge correlation signal vs. $\sqrt{s_{NN}}$



Splitting between same and opposite-sign charges decreases with decreasing $\sqrt{s_{NN}}$ and disappears below $\sqrt{s_{NN}} = 11.5$ GeV

Lesson learned ...

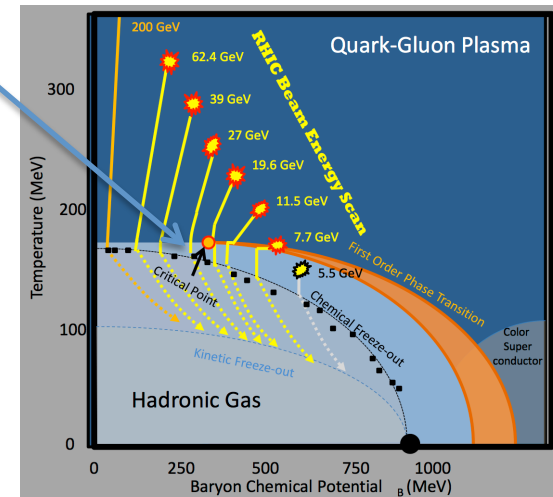
These observations:

- baryon/meson grouping for *antiparticles* starts to collapse at 11.5 GeV
- disappearance of high p_t suppression
- disappearance of charge separation
- break down of N_q scaling between particles and *antiparticles*
- local parity violation decreases with decrease of $\sqrt{s_{NN}}$
- ...

indicate that hadronic interactions become dominant at lower beam energies

the most anticipated ...

Critical Point

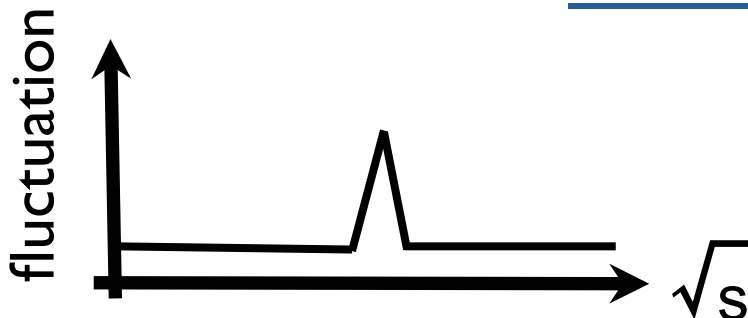


CP: Why fluctuations and correlations ?

Theory:

predictions that the behavior of fluctuations/ correlations in deconfined phase are different than that in hadron gas → search for discontinuities in fluctuations and correlations as function of $\sqrt{s}_{NN}$

Fluctuations maximized at Critical Point



more sensitive : - Higher Moments

Thermodynamics: Divergence of susceptibilities for conserved quantities (B,Q,S) at critical point.

Lattice QCD: Spikes for both χ_B and χ_S @CP

Berdnikov, Rajagopal, PRD61, 105017 (00)

Stephanov, Rajagopal, Shuryak, PRD 60, 114028 (99)

Hatta, Stephanov, PRL. 91, 102003 (03)

Gavai and Gupta, Phys. Rev. D 78, 114503 (2008);

Gupta, arXiv:0909.4630 [nucl-ex].

Observable: high moments of conserved quantities are related to susceptibilities

$$\chi_2^X = \frac{1}{VT^3} \langle N_X^2 \rangle$$
$$\chi_4^X = \frac{1}{VT^3} (\langle N_X^4 \rangle - 3\langle N_X^2 \rangle^2)$$

- *connection to lattice calculations!*

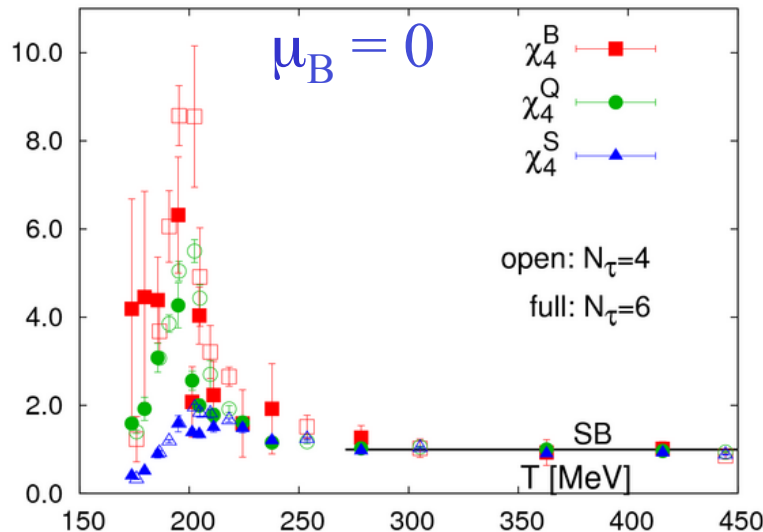
Cheng et al., PRD 79, 074505 (2009)

Karsh and Redlich, Phys.Lett.B 695, 136 (2011)

Caveats: dynamical effects in collisions may influence fluctuation measurements

(finite time and size, critical slowing,...)

M.Cheng et al., arXiv:0811.1006



Theoretical Aspects of High Moments Method

(I) Link between susceptibilities (from Lattice QCD) and products of higher moments of experimentally measurable multiplicity distribution :

arXiv: 0811.1006

arXiv:1001.3796

$$\chi_j^X = \frac{1}{VT^3} \frac{\partial \ln Z}{\partial \mu_X^j}$$

$$\chi_2^X = \frac{1}{VT^3} \frac{\partial \ln Z}{\partial \mu_X^2} = \frac{1}{VT^3} \langle \delta N_X^2 \rangle$$

$$\chi_4^X = \frac{1}{VT^3} \frac{\partial \ln Z}{\partial \mu_X^4} = \frac{1}{VT^3} (\langle \delta N_X^4 \rangle - 3 \langle \delta N_X^2 \rangle^2)$$

$$\frac{\chi_B^4}{\chi_B^2} = (\kappa \sigma^2)_B \text{ volume}$$

$$\frac{\chi_B^3}{\chi_B^2} = (S \sigma)_B \text{ cancels out !}$$

(II) High fluctuations near Critical Point : QCD Based Model Calculation:

High moments sensitive to high power of the correlation length.

$$\langle (\delta N)^2 \rangle \approx \xi^2, \langle (\delta N)^3 \rangle \approx \xi^{4.5}, \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2 \approx \xi^7$$

Non-Gaussian fluctuation will increase !

M. A. Stephanov, *Phys. Rev. Lett.* 102, 032301 (2009)

(III) Net-proton number fluctuations can reflect baryon number fluctuations

Digression: Skewness and Kurtosis

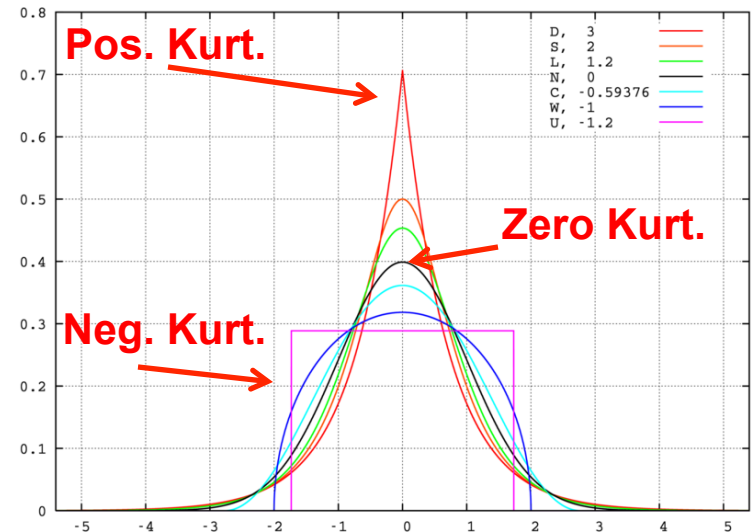
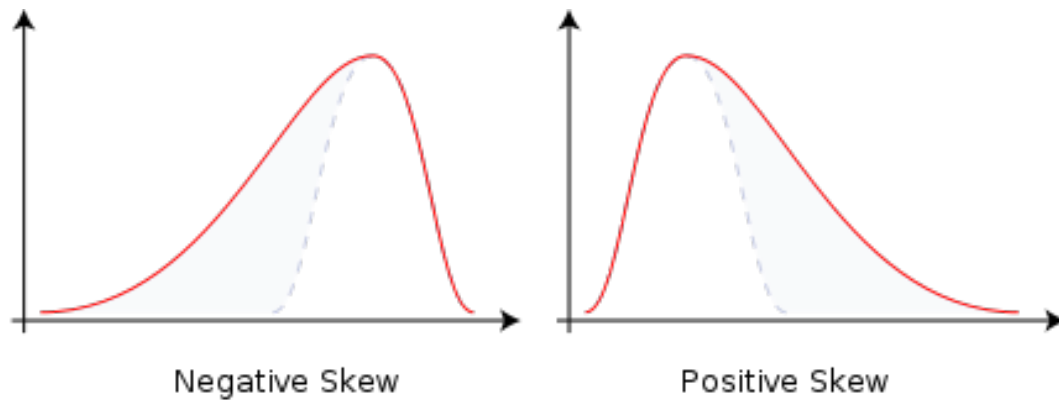
Mean: $M = \langle N \rangle$

St. Deviation: $\sigma = \sqrt{\langle (N - \langle N \rangle)^2 \rangle}$

Skewness: $s = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$

Kurtosis: $\kappa = \frac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} - 3$

N: Event by Event Multiplicity Distribution



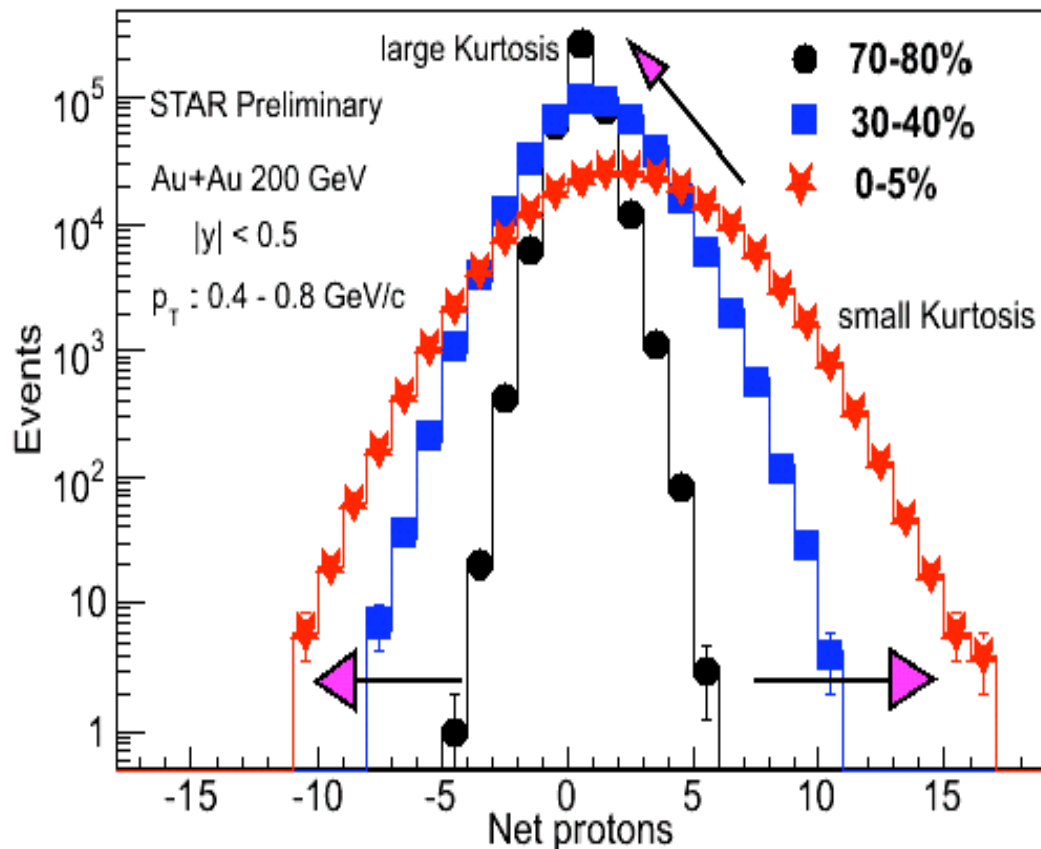
Skewness describes the **asymmetry** of the distribution

Kurtosis describes the **peakness** of the distribution

End of digression

How to measure ?

event by event net-baryon number is difficult
but net-proton distributions is measurable



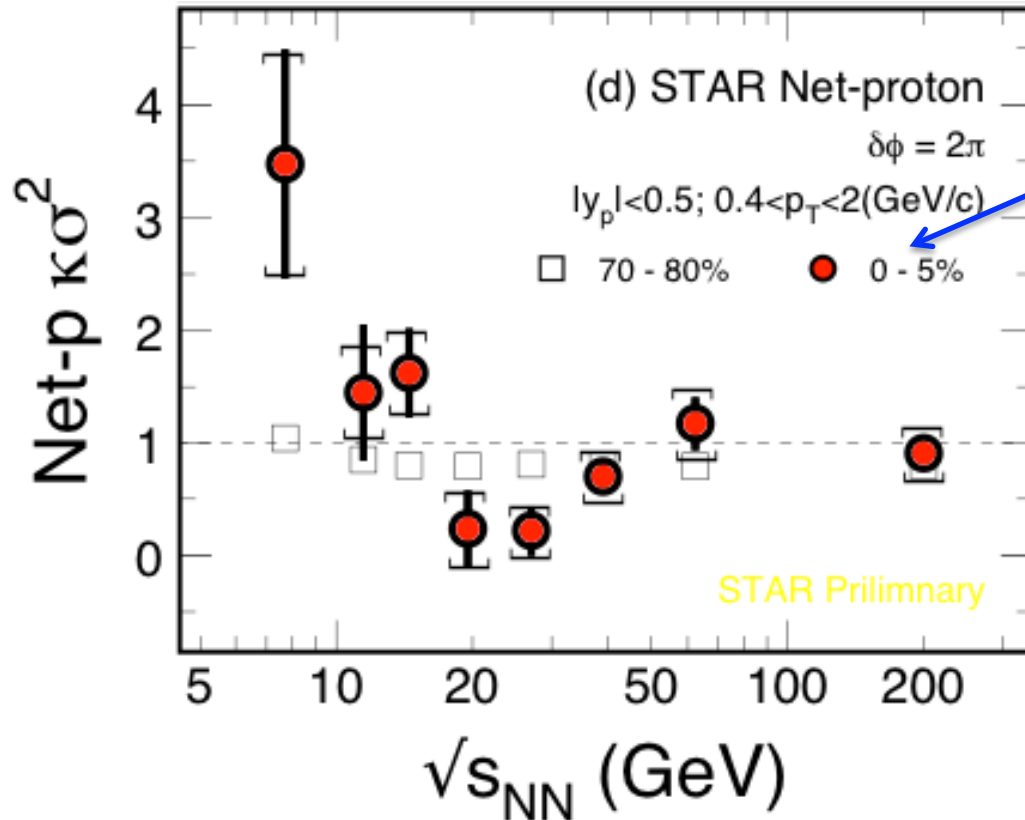
net-proton reflects the fluctuation
of net-baryon number

$$\Delta N_p = N_p - N_{\bar{p}}$$

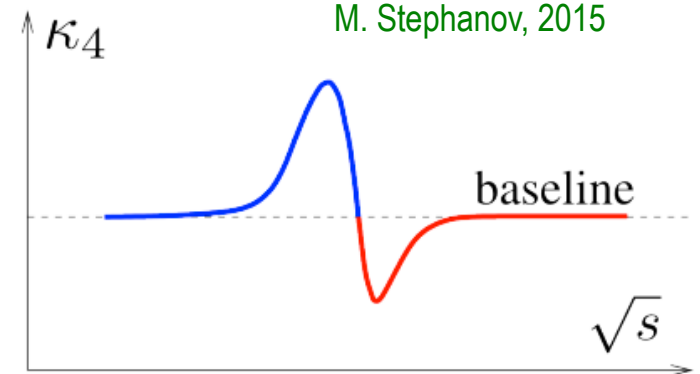
0-5% distribution are less
peaked and more symmetric
compared to 70-80%.

High moments of net-proton multiplicity

STAR, PRL 112 (2014) 032302, CPD2014, QM2015

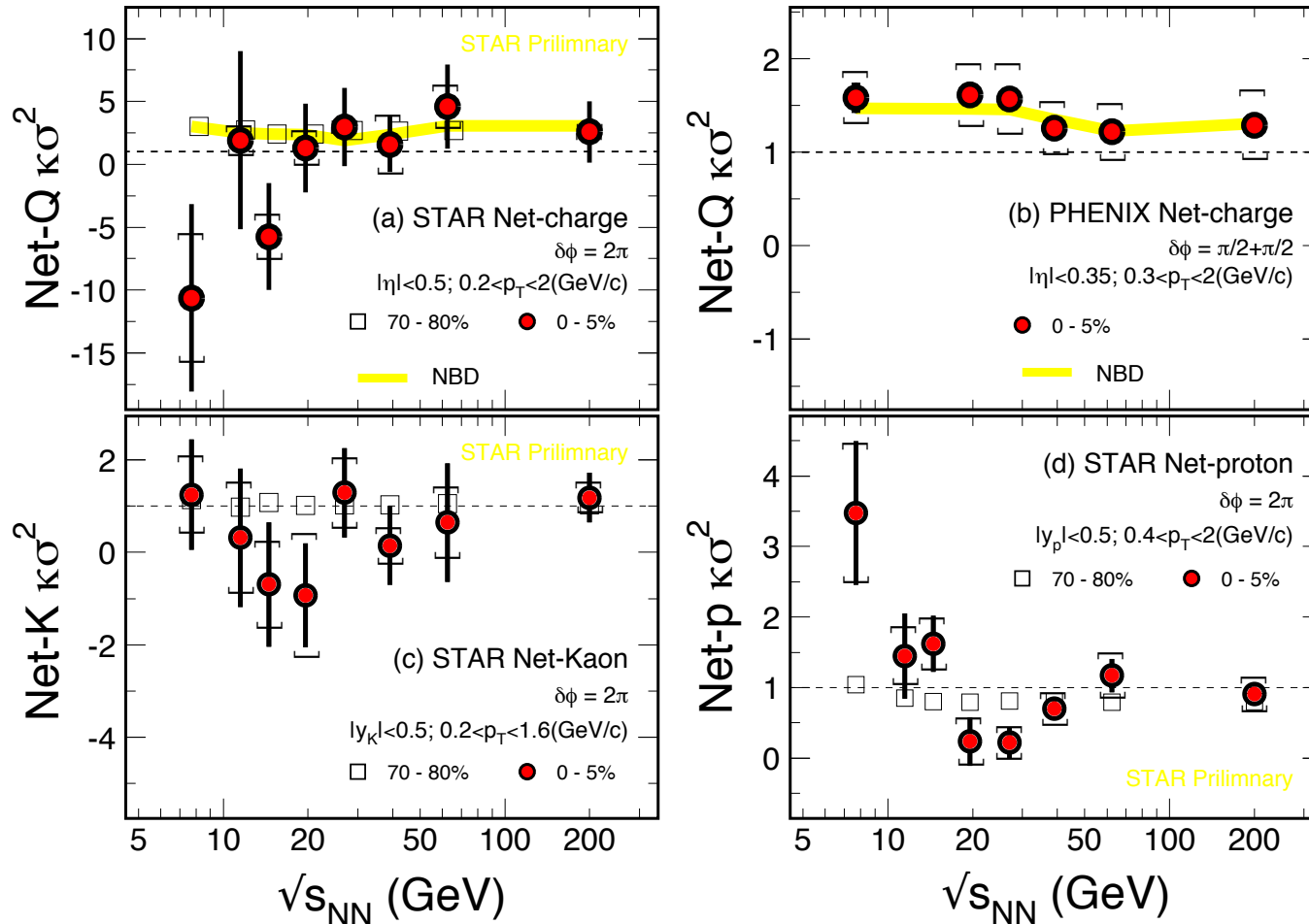


top central 5% Au+Au @ 200 GeV



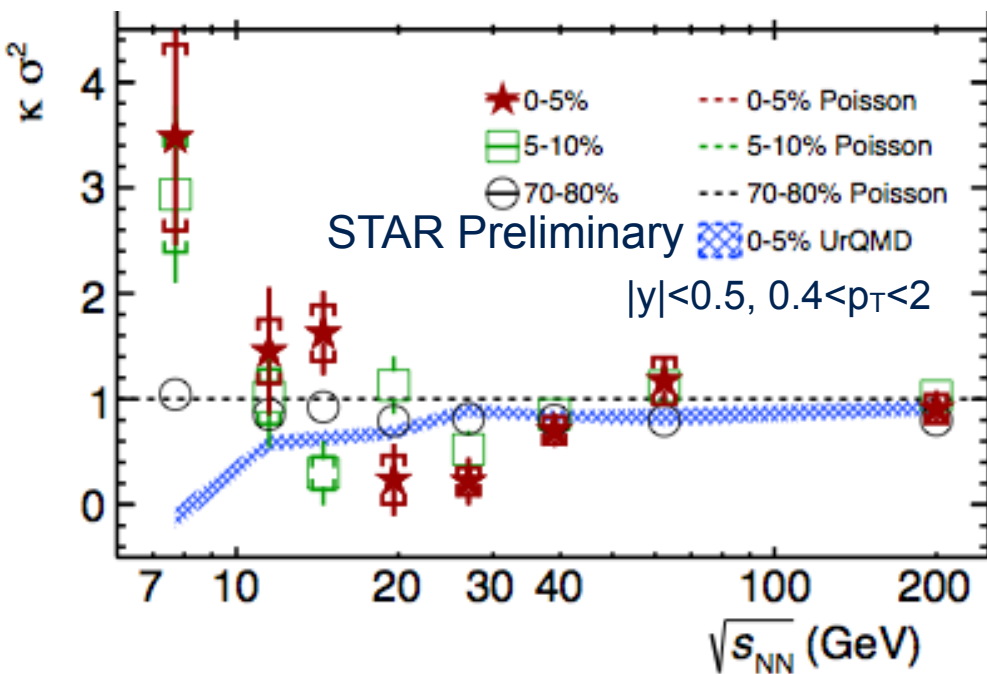
- A non-monotonic behavior observed for net-proton $\kappa\sigma^2$ vs. energy in central Au+Au collisions
 - connection to critical fluctuations? Peripheral collisions – smooth trend
- Future precision measurements at low energies with enlarged acceptance

Fluctuations at RHIC

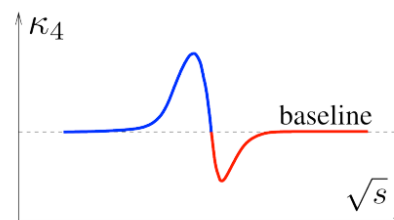


Net-Q and net-Kaon show flat energy dependence

Net-p shows **non-monotonic energy dependence** in the most central Au+Au collisions starting at $\sqrt{s_{NN}} < 27 \text{ GeV}$!



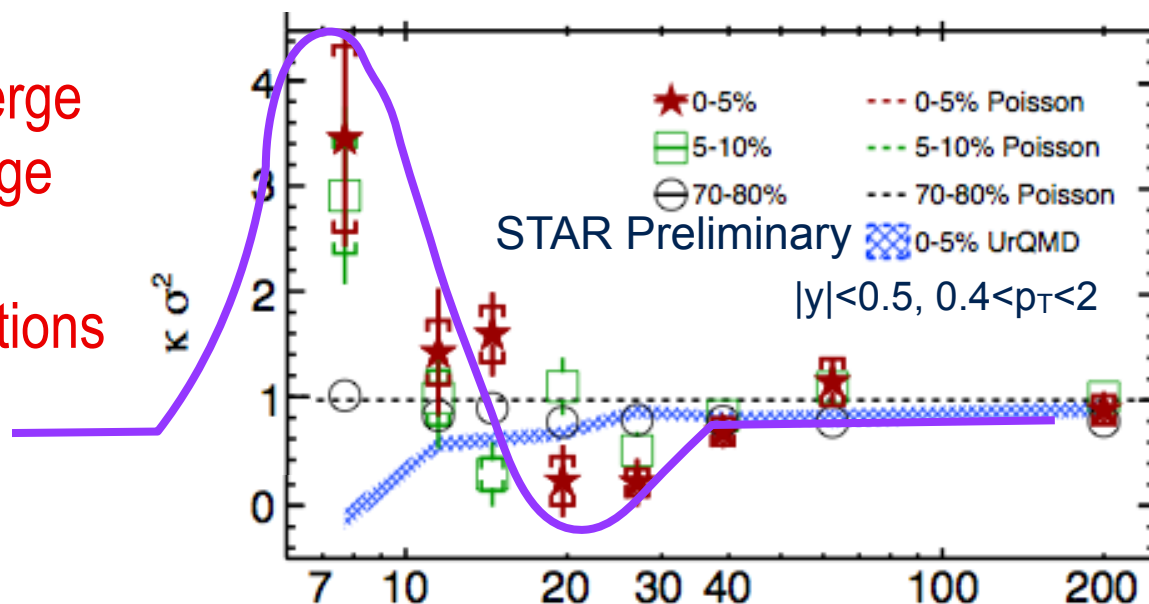
UrQMD (no Critical Point)
 Shows suppression at lower energies
 - due to baryon number conservation



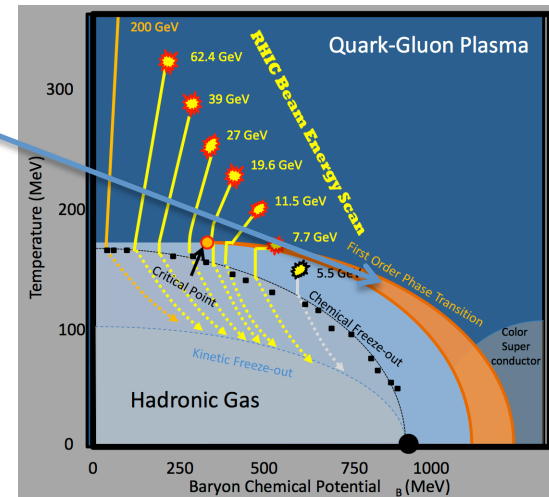
?

Correlation lengths diverge
 → Net-p $\kappa \sigma^2$ diverge

Hints of Critical Fluctuations



1st order phase transition

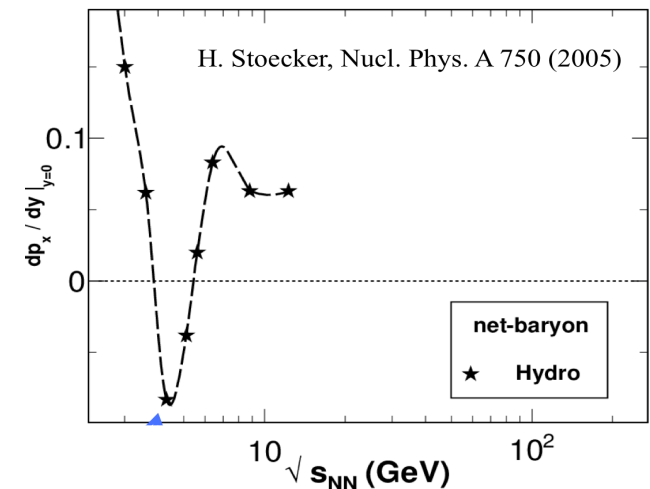
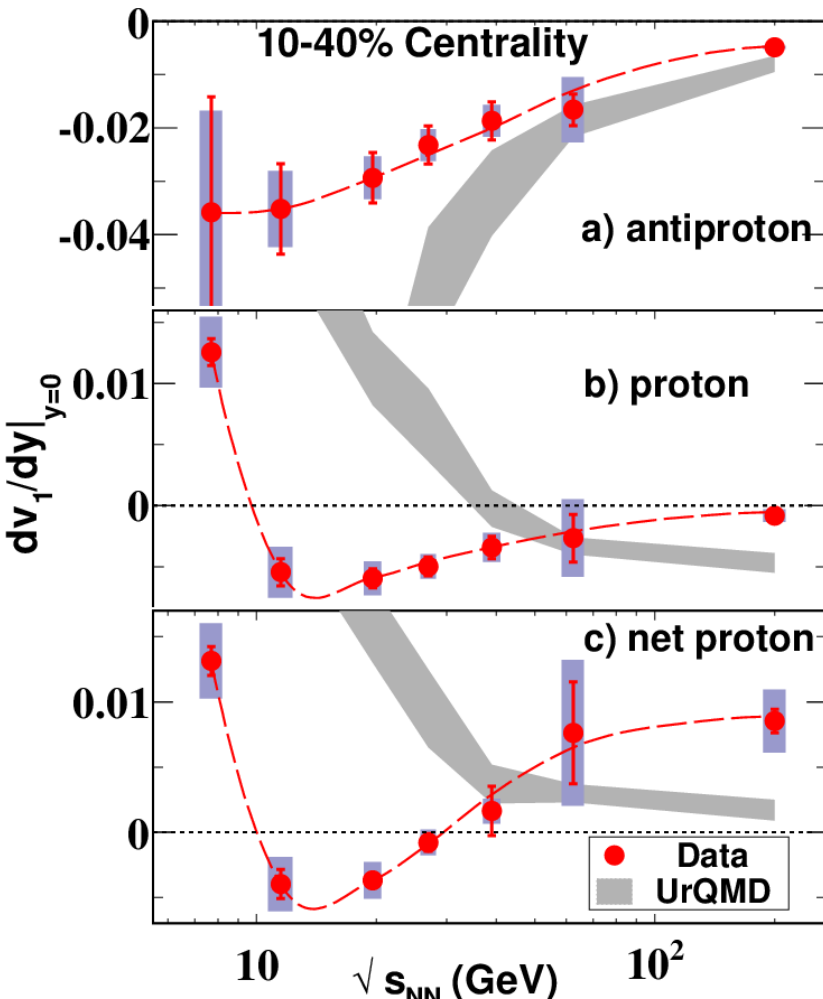


can we demonstrate the softening of EOS ?

Directed flow (v_1) of identified particles

v_1 probes early stage of collision, sensitive to compression, should be sensitive to 1st order phase transition; change of sign in the slope of dv_1/dy for protons has been proposed to be a probe to the softening of EOS and/or the first-order phase transition ...

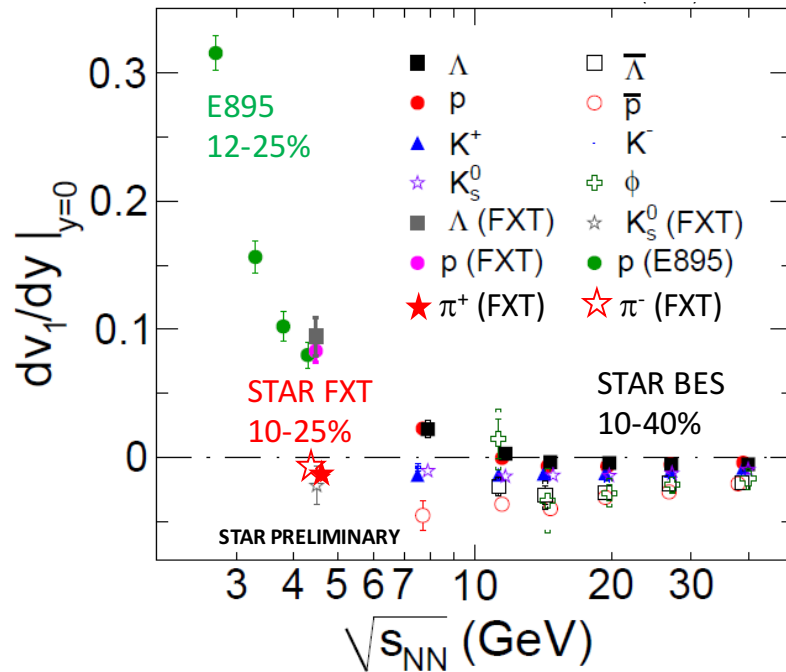
PRL 112, 162301 (2014)



- Net-proton v_1 slope at midrapidity changes sign twice between $\sqrt{s_{NN}} = 7.7 - 11.5$ GeV
- EOS softest point ? (1st order phase transition ?)

but: - dip at different position than model
- error bars for other particles and different centralities are large – more statistics needed and better RP resolution needed

57
Model calculations yet to reproduce the observation



low $\sqrt{s}$:

slope v_1 (baryons) – positive

slope v_1 (mesons) – negative

Beam energy baryon dv_1/dy trend - complex interplay of:

- v_1 baryons transported from beam

- v_1 from pair production

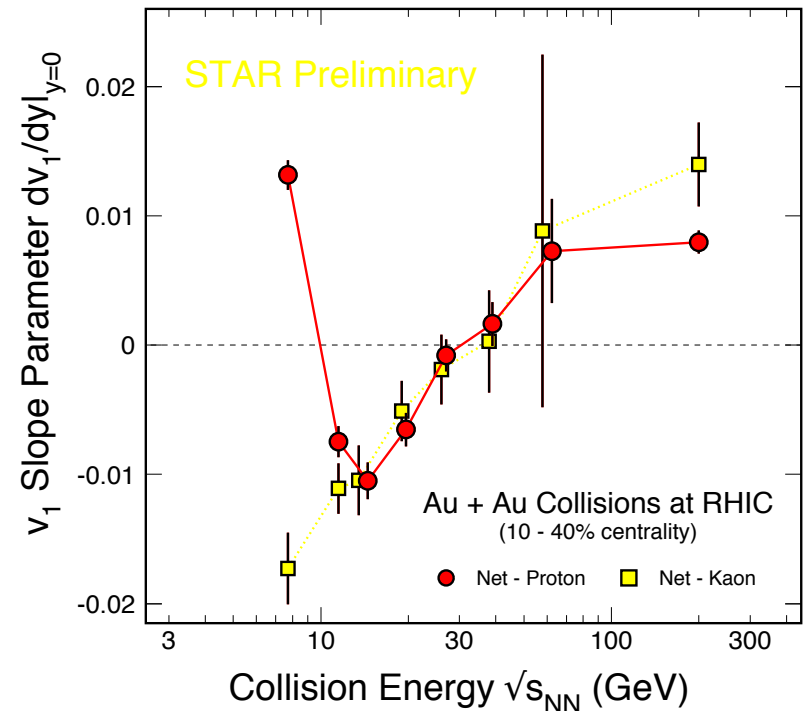
Net protons isolates directed flow of transported baryons

Double sign change in dv_1/dy

Not seen in net-kaons

Results not yet reproduced by theory

Softening of EoS ?



Summary, but not conclusion

What have we learned from BES Phase-I

STAR and RHIC excellent performance down to 7.7 GeV

BES at RHIC fully spans the most promising energy range of the QCD phase diagram

Several signatures demonstrate the dominance of parton regime at the BES high energies, these signatures either disappear, lose significance, or lose sufficient reach in the low energy region of the scan

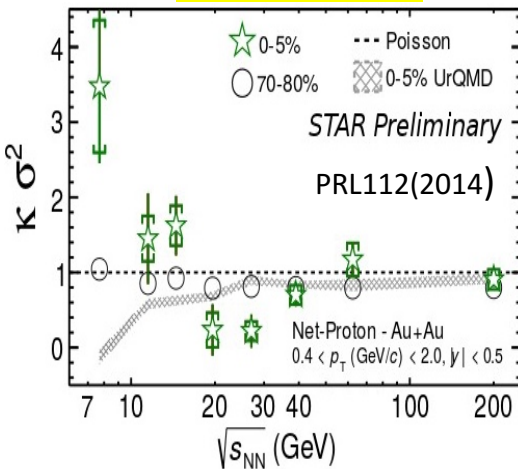
- *but hard probes become less accessible at lowest collision energies*
- *“turn-off” of hard signature does not imply the absence of deconfinement*

Indication of a softening of EOS around 11.5-19.6 GeV could be indicative of a 1st order phase transition

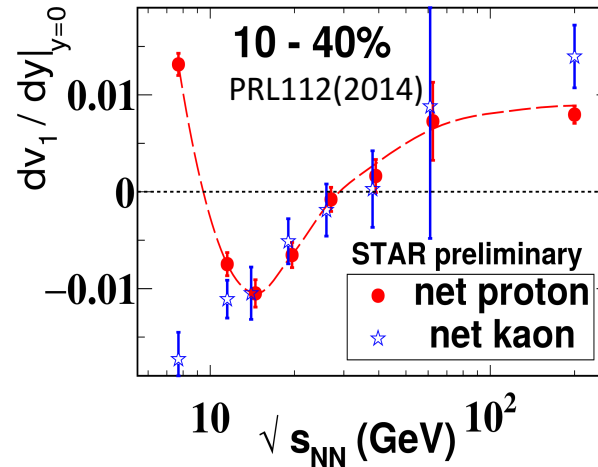
Suggestive signs of critical fluctuations (?) would present compelling evidence, but these are highly statistics hungry analyses (→ BES II: larger statistics and smaller steps in μ_B)

A lot is happening around $\sqrt{s_{NN}} \sim 20$

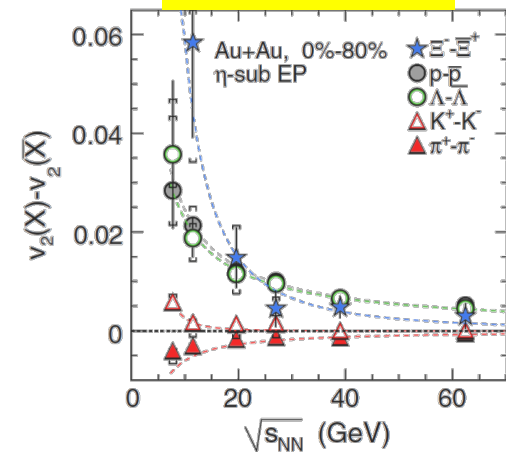
Critical Point



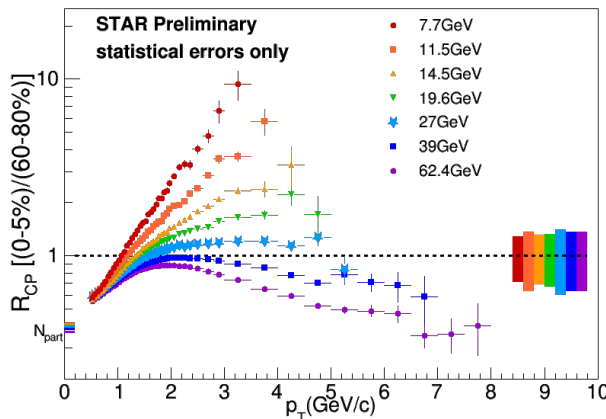
Phase Transition



Bulk Behavior



Energy Loss



- RHIC BES explored QCD phase structure in an interesting region
- Interesting behaviors seen on many fronts ...
- Hard to believe this is a conspiracy of different underlying causes
- ... but a compelling picture requires
 - better statistics, especially at lower energies
 - finer energy scan 7~20 GeV region
 - ideally, reach to lower energies



We are NOT
done yet !

BES Phase II

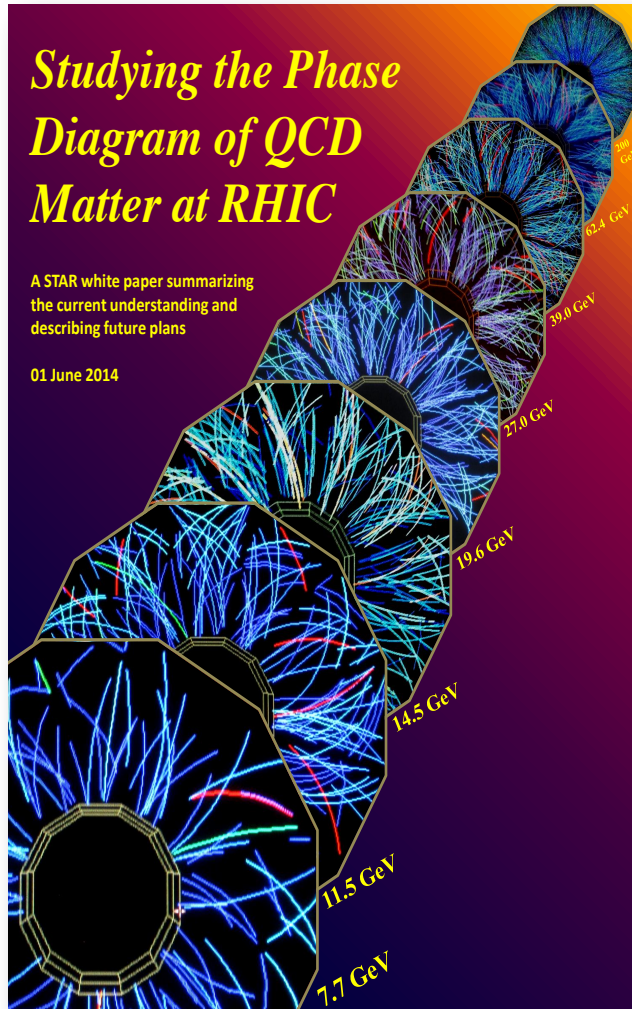
Improving on current data :

more statistics, maximize fraction particles measured
probe lower $\sqrt{s} - \mu_B$ extended due to fixed target mode
to be run in 2019 and 2020

detector + machine upgrades (higher luminosity)

turn trends and features into definite conclusions

STAR Beam Energy Scan – Phase II



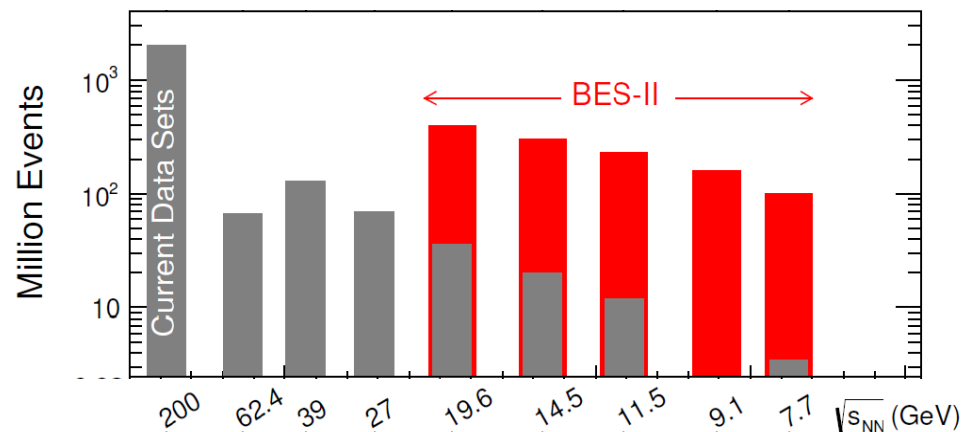
Dedicated second phase of the BES program, proposed in 2014

1. Determine T and μ_B for Au+Au collisions where the onset of deconfinement occurs
 - establish basic structure of the QCD phase diagram
 2. Seek evidence of the softening of the EOS to understand the nature of the phase boundary
 - first order phase transition?
 3. Look for signatures of critical behavior such as enhanced fluctuations
 - localize a critical point, should there be a phase boundary change from 1st order to cross-over
- Observe in-medium modifications of light vector mesons at high baryon densities
 - quantify the effect of chiral symmetry restoration

BES II Proposal

Long Range Plan 2015

Strong endorsement by NSAC:
"Trends and features in BES-I data provide compelling motivation for [...] experimental measurements with higher statistical precision from BES-II"

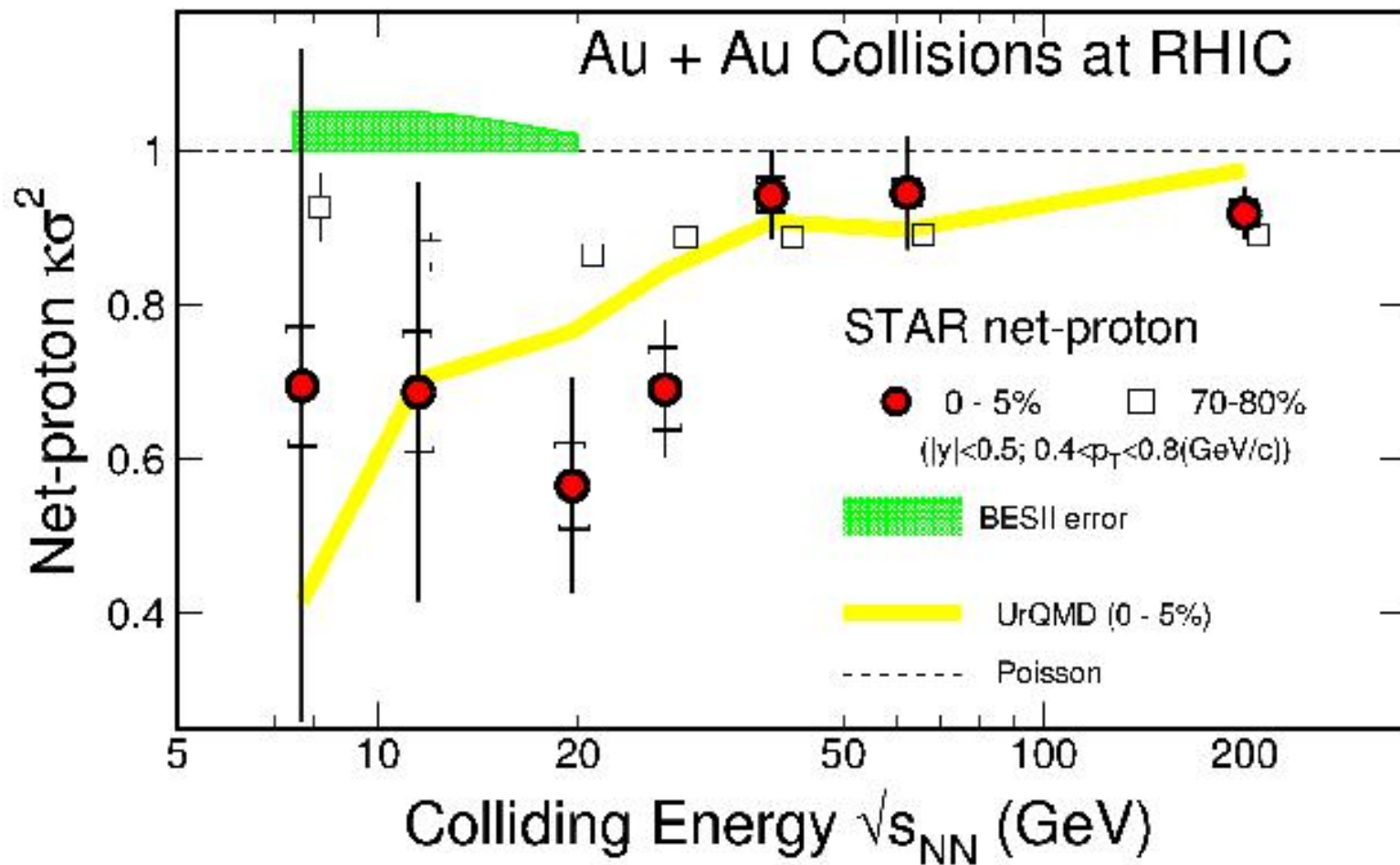


http://science.energy.gov/~media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

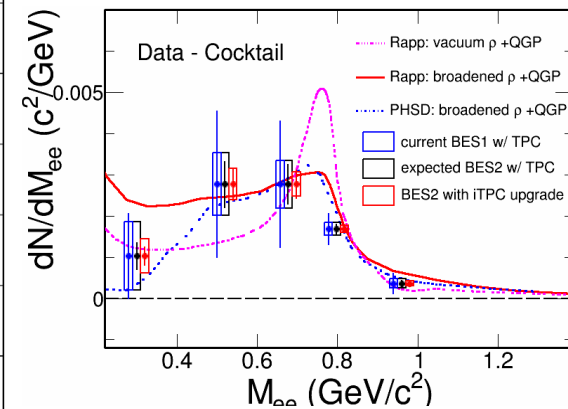
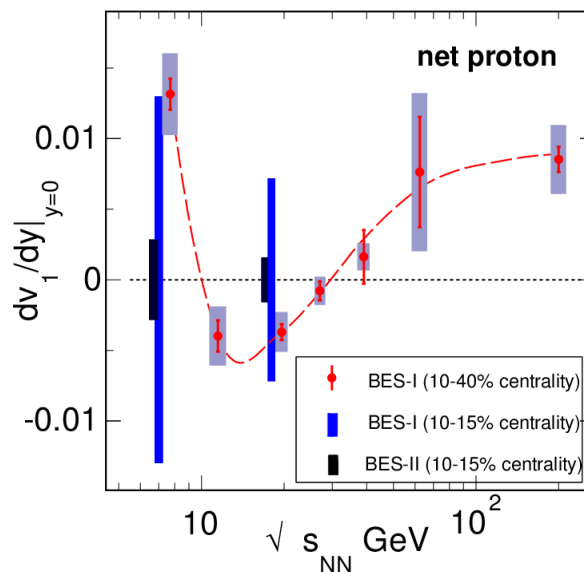
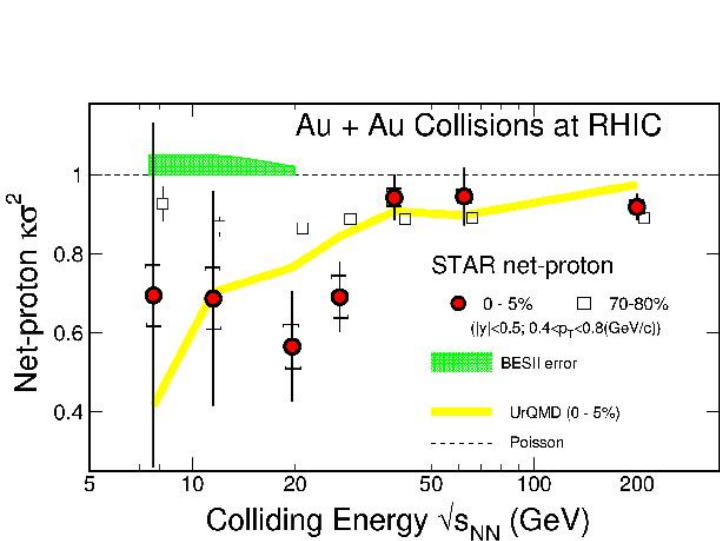
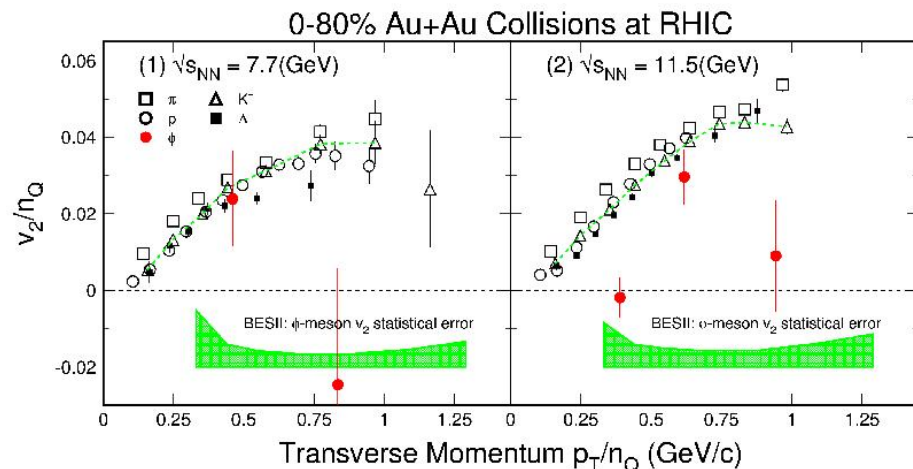
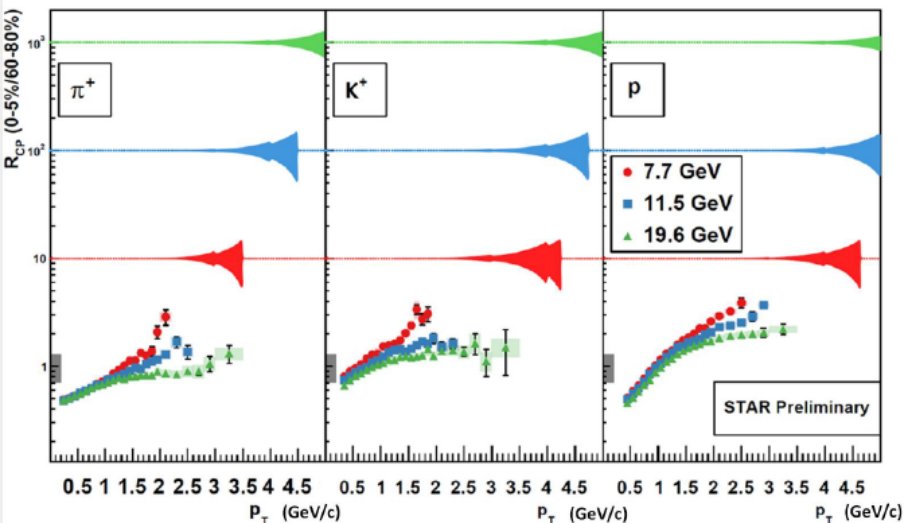
Table 2. Event statistics (in millions) needed for Beam Energy Scan Phase-II for various observables.

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

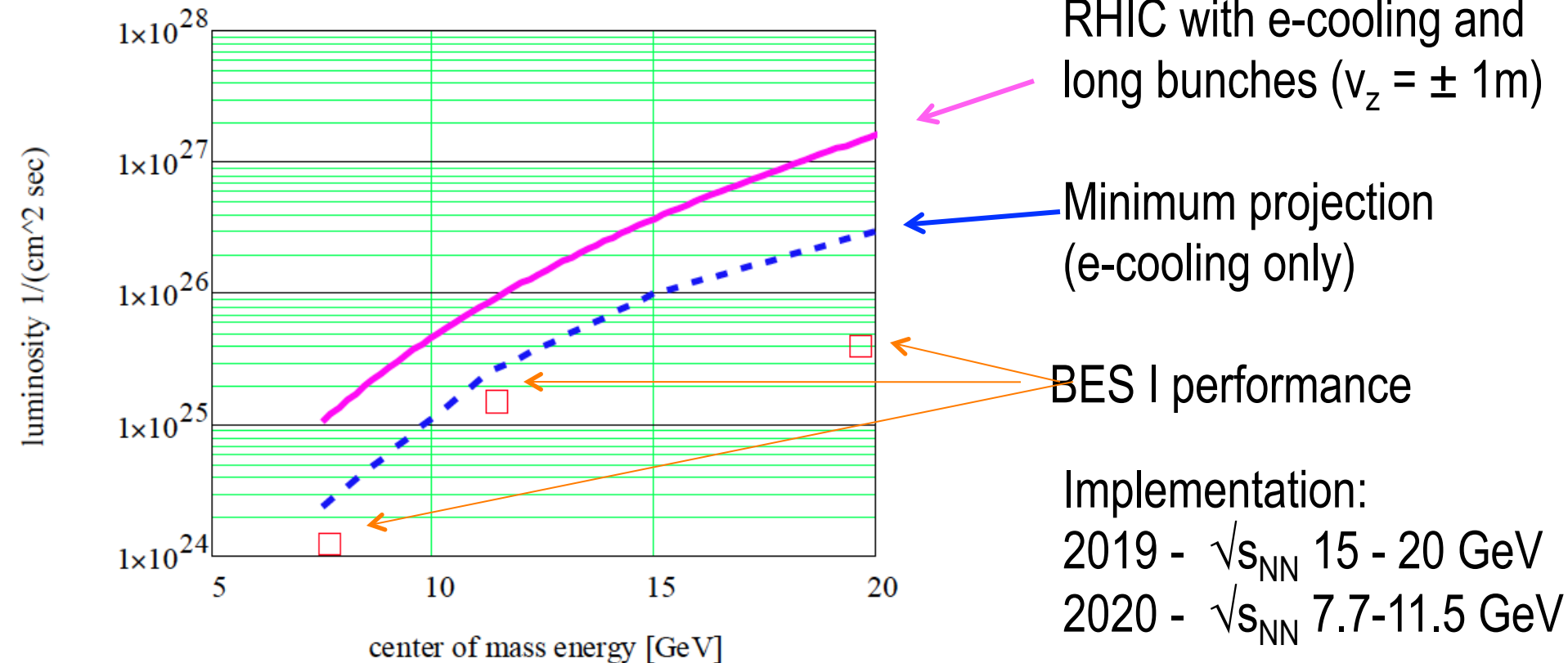
Statistical errors in moment analysis



BES II measurement errors will be **SMALL**

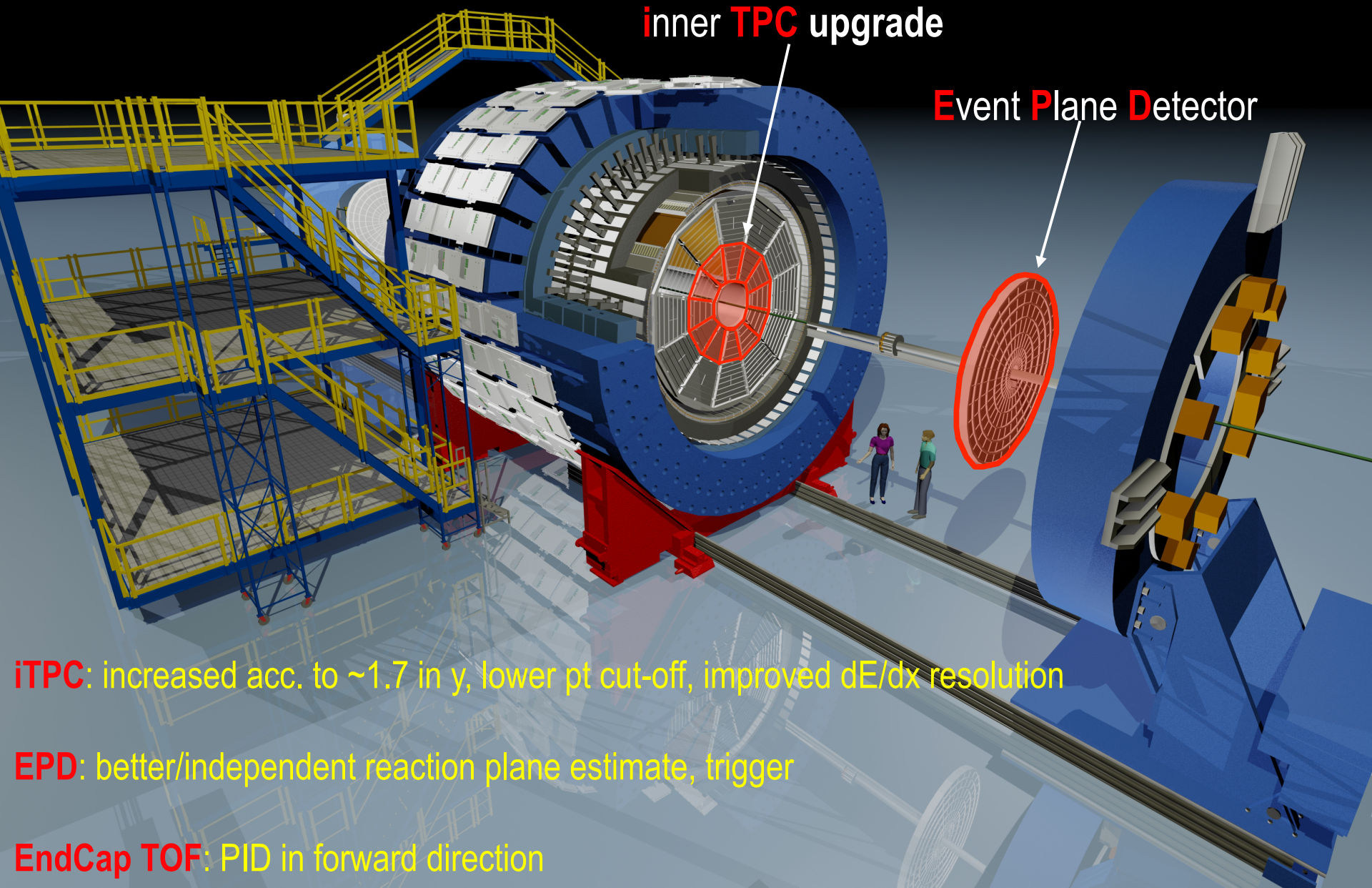


Luminosity improvements for BES II



Electron cooling + longer beam bunches for BES II provide factor 4-15 improvement in luminosity compared to BES I
Every energy available with electron cooling

STAR Detector Developments for BES II



inner **TPC** upgrade

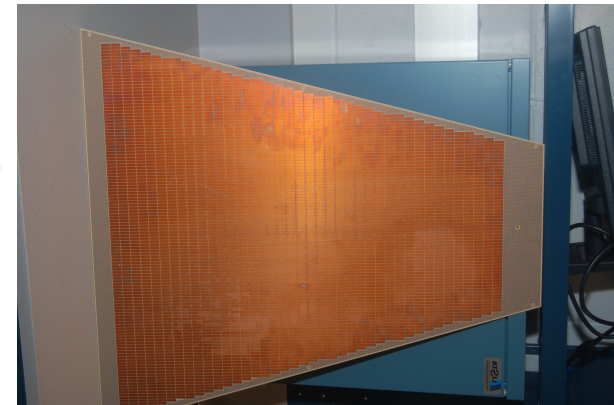
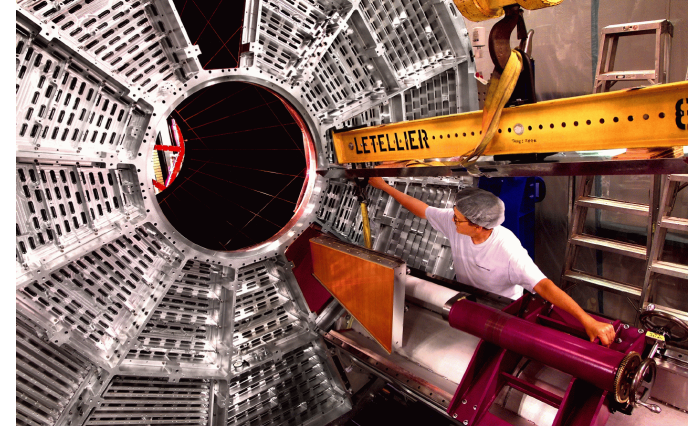
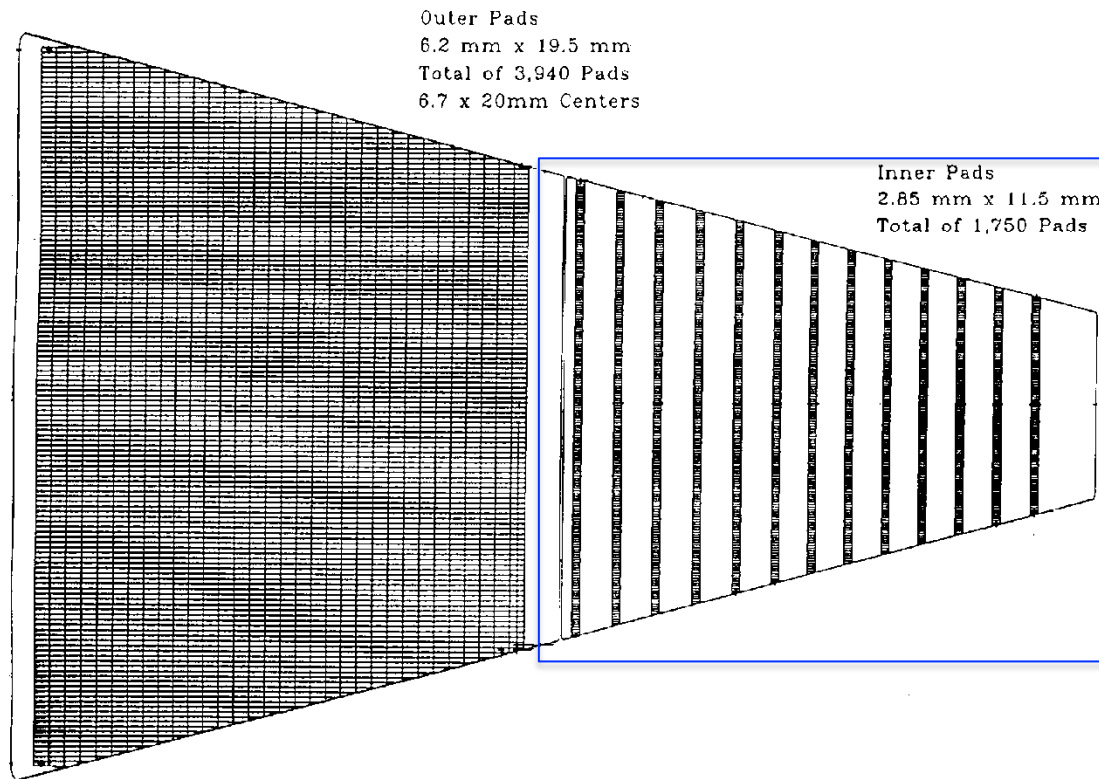
Event **P**lane **D**etector

iTPC: increased acc. to ~ 1.7 in y , lower p_t cut-off, improved dE/dx resolution

EPD: better/independent reaction plane estimate, trigger

EndCap TOF: PID in forward direction

iTPC Inner sectors upgrade



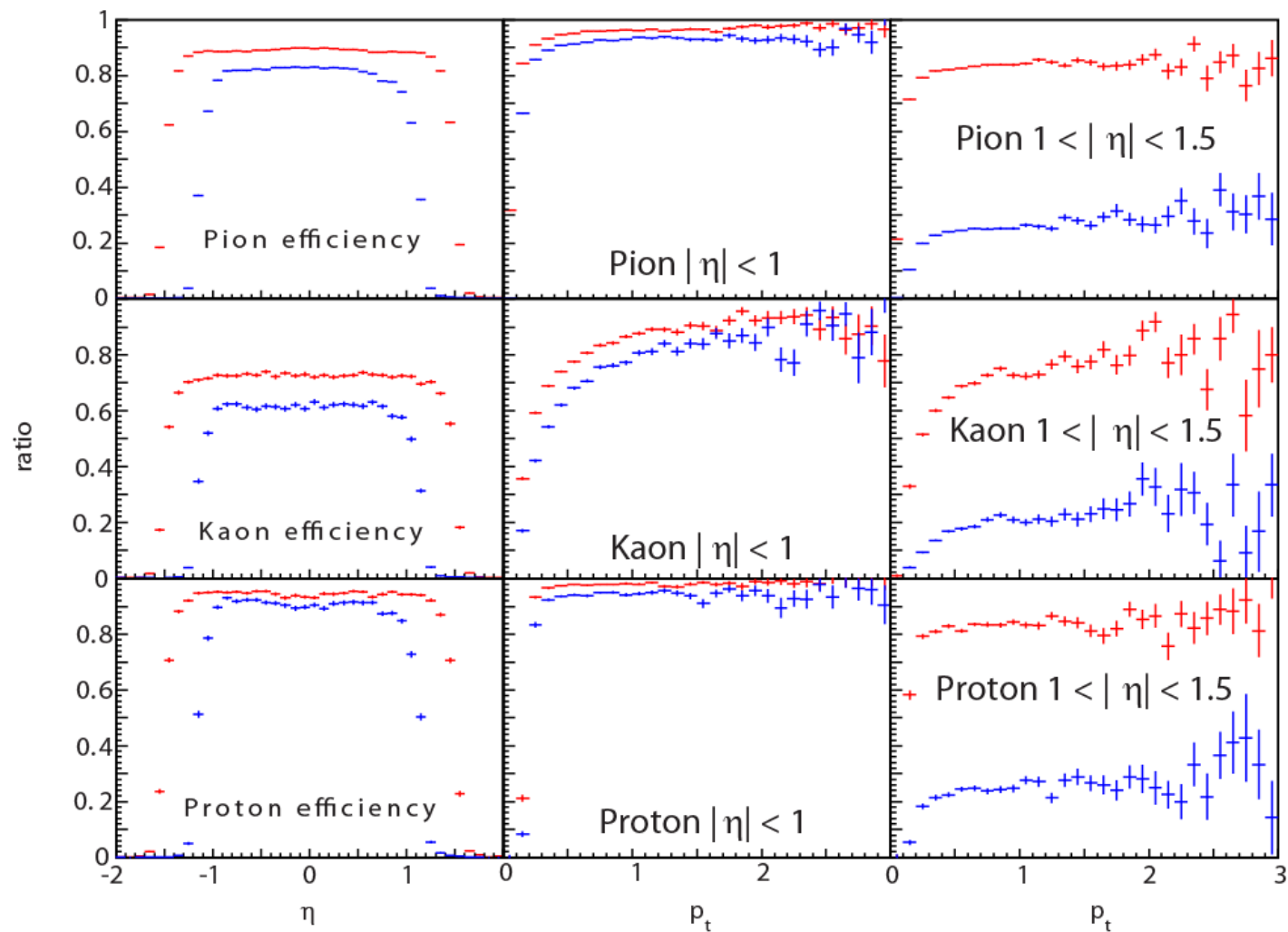
The outer pad plane is hermetic ... while the inner pad plane is not

- Increase the segmentation on the inner pad plane, new electronics for inner sectors
- Renew the inner sector wires which are showing signs of aging

Better momentum resolution, better dE/dx resolution, and improved acceptance at high η

Old: $-1 < \eta < 1$ New: $-1.5 < \eta < 1.5$

iTPC upgrade - improved acceptance at high η



extended the meaningful acceptance from 1.0 to 1.5 units for all particles

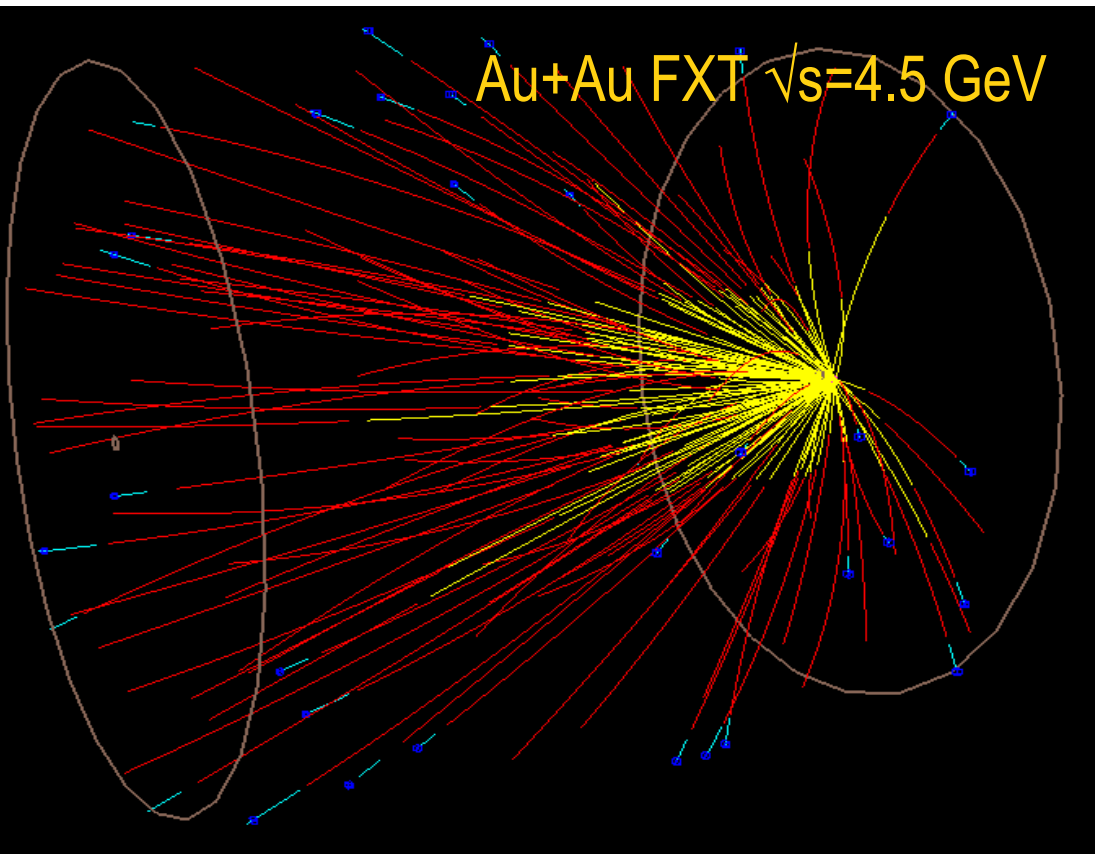
Fixed Target program in STAR

NA49 claims onset of deconfinement at $\sqrt{s} = 7.7$ GeV

Collider can not run below 7.7 GeV

Target in beam pipe at $z = 210$ cm

Dedicated short runs more efficient, successful test completed

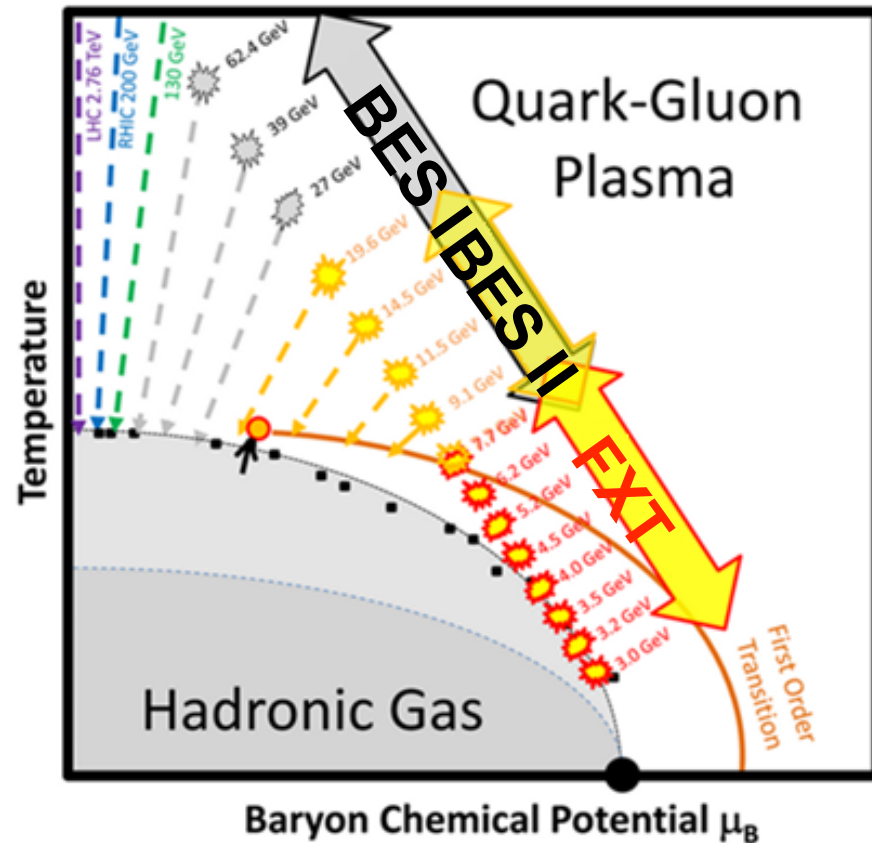


Precision investigation with
new techniques and the same
detector

Reach 7.7 in FXT mode

- compare with collider mode
- control systematic errors

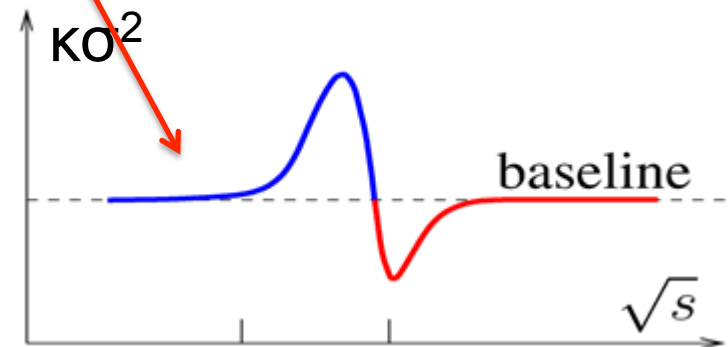
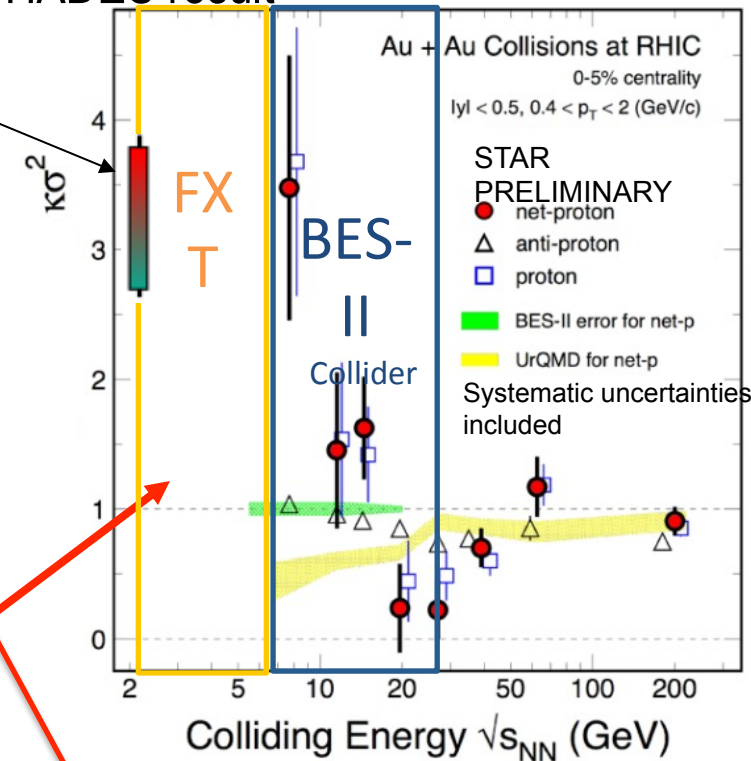
Why a Fixed-Target Program?



Preliminary HADES result

0-10%
(QM 2017)

Need data here!



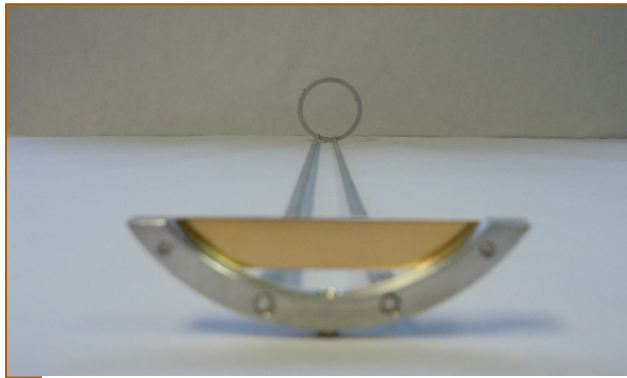
- FXT could provide control measurements for searches for critical point and onset of deconfinement
- Kurtosis measurement is one of the future program goals
- Test run focused on demonstrating STAR FXT capabilities

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

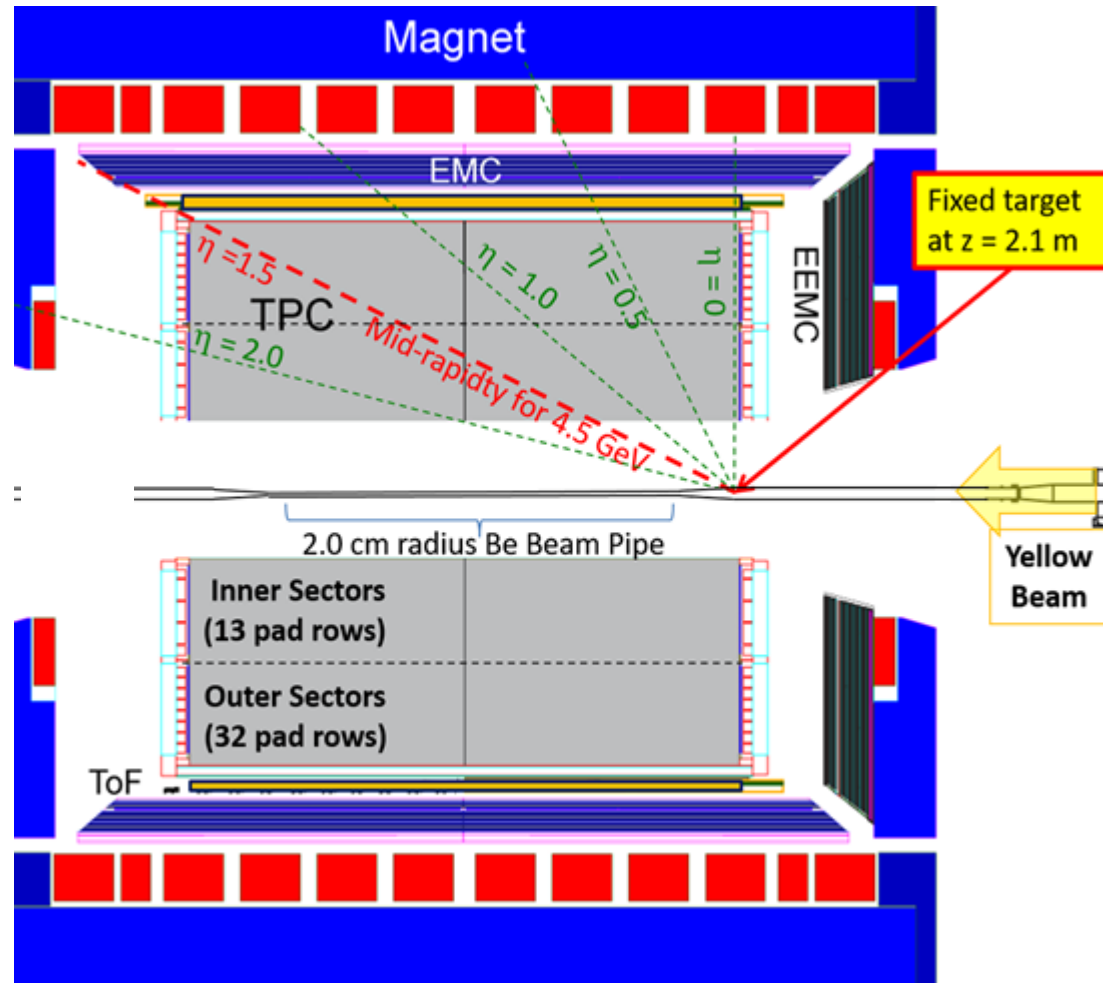
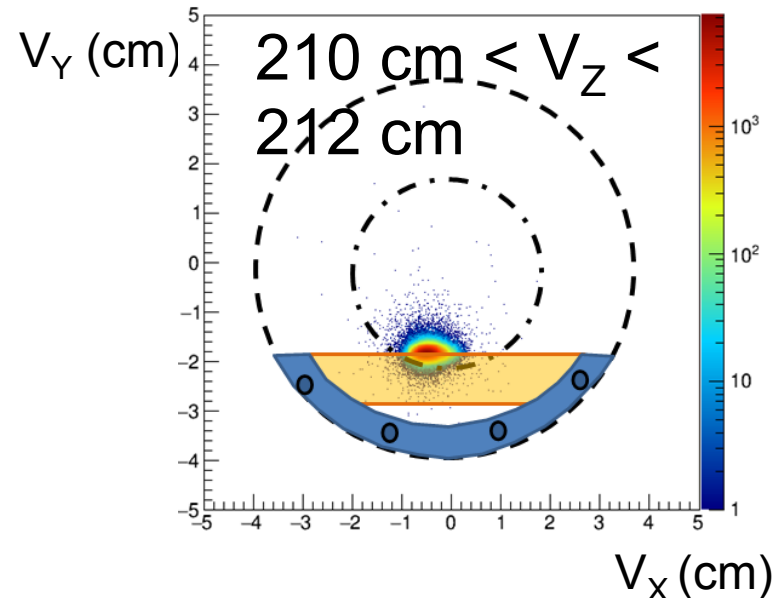
Extends energy range from $\sqrt{s} = 7.7$ down to 3 GeV
 Increase μ_B range from 420 MeV to 720 MeV

First dedicated FTX Au+Au run at sNN = 4.5 GeV in 2015

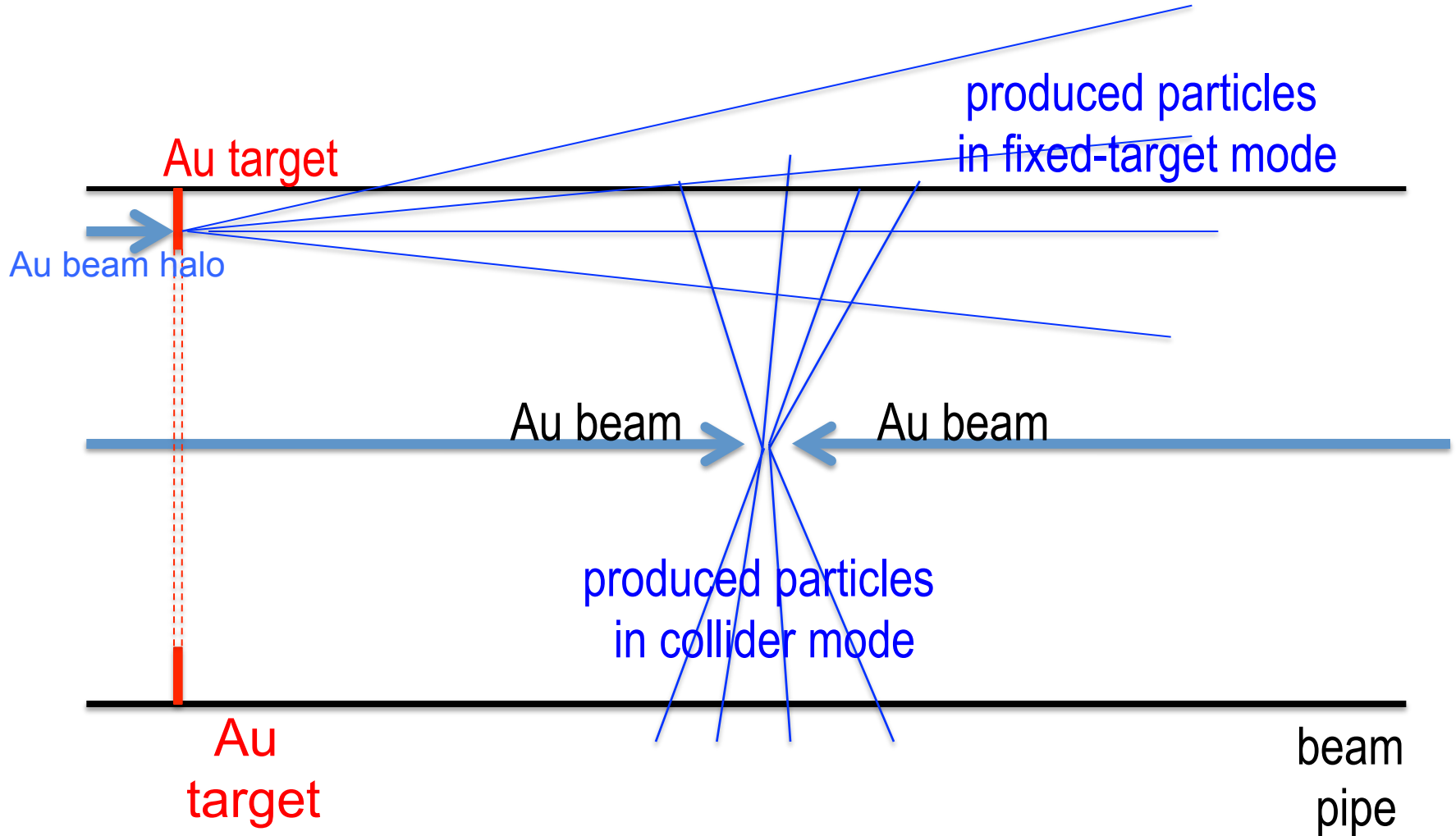
- 1.3 million events, top 30% central trigger
- Filled trigger bandwidth → DAQ limited
- 1 mm thick (4% interaction probability) gold foil target



V_y vs. V_x Distribution

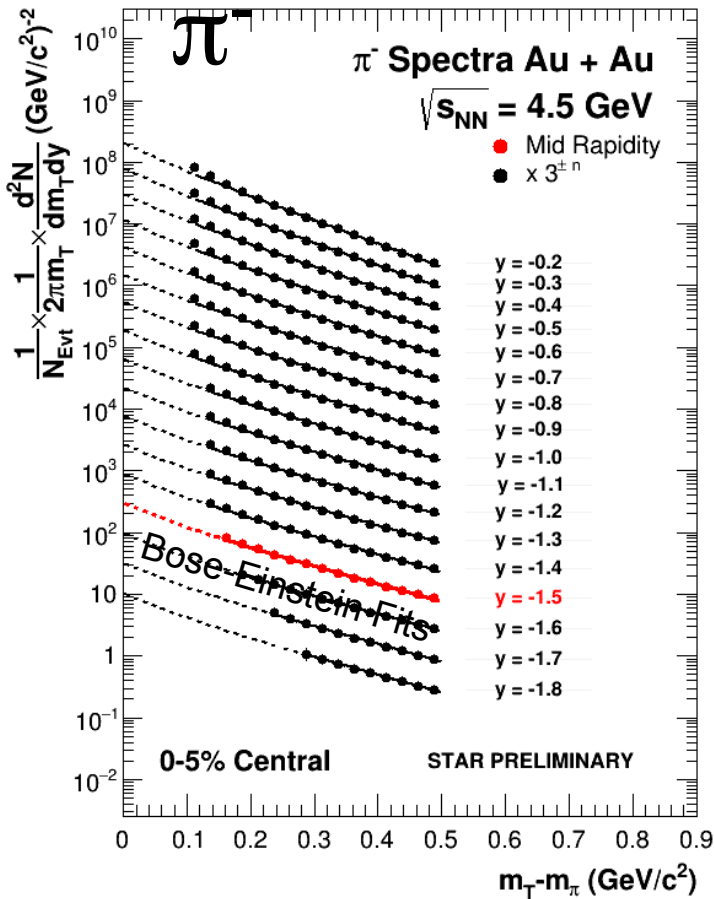


Fixed-target: schematics of concurrent running in STAR



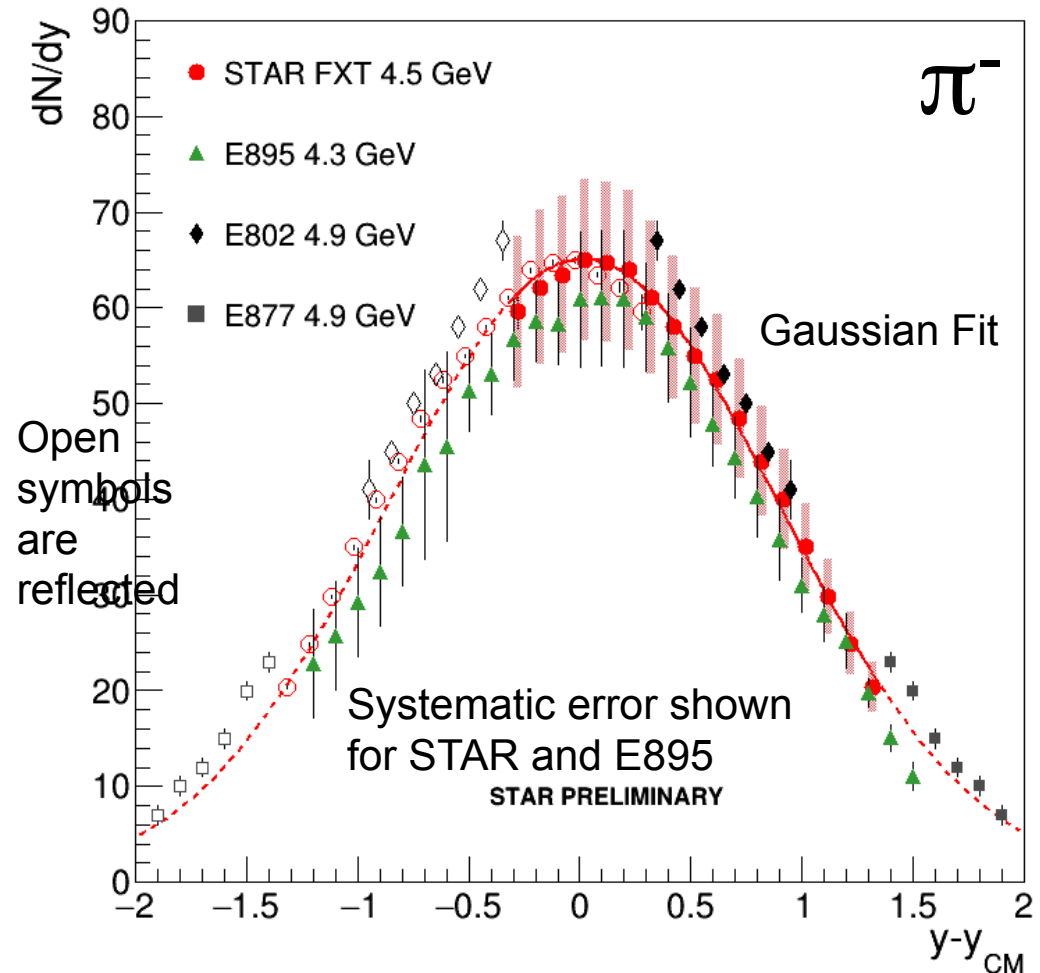
fixed-target events taken while waiting for collider mode collisions

TPC pion spectra and dN/dy



- Amplitudes and widths of the rapidity densities are consistent with AGS
- $m_T - m_0$ and y range will be extended with time-of-flight detector

π^- Rapidity Density

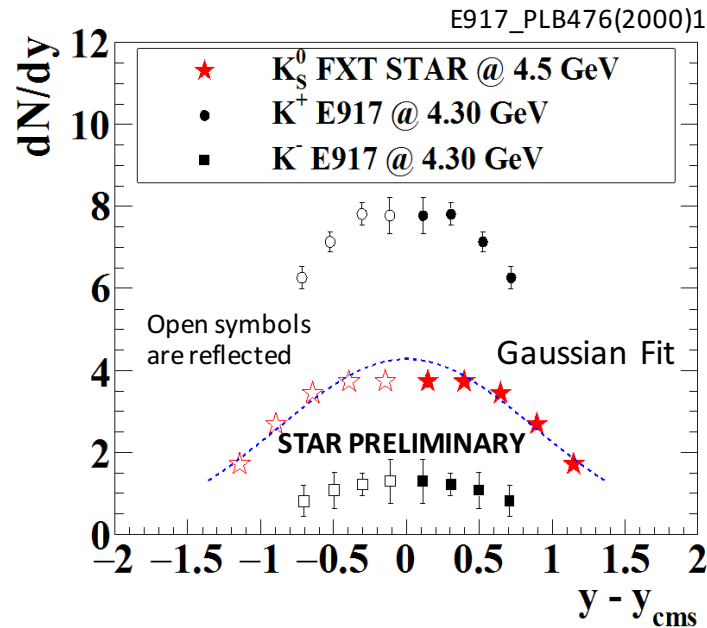
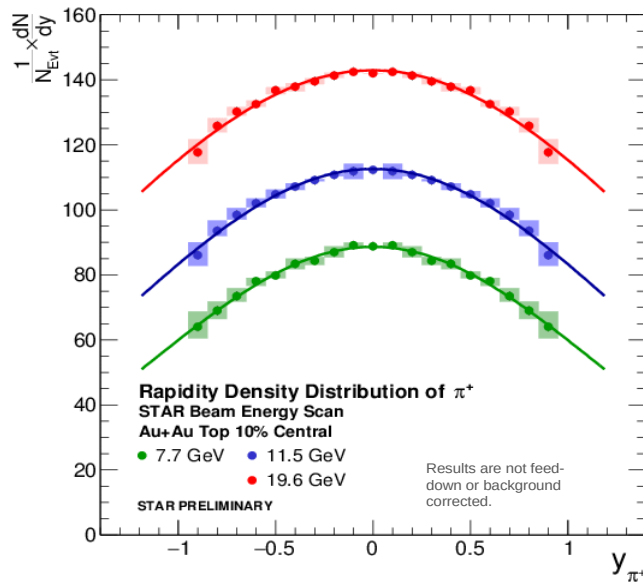


E802_PRC57(1998)R466

E877_PRC62(2000)024901

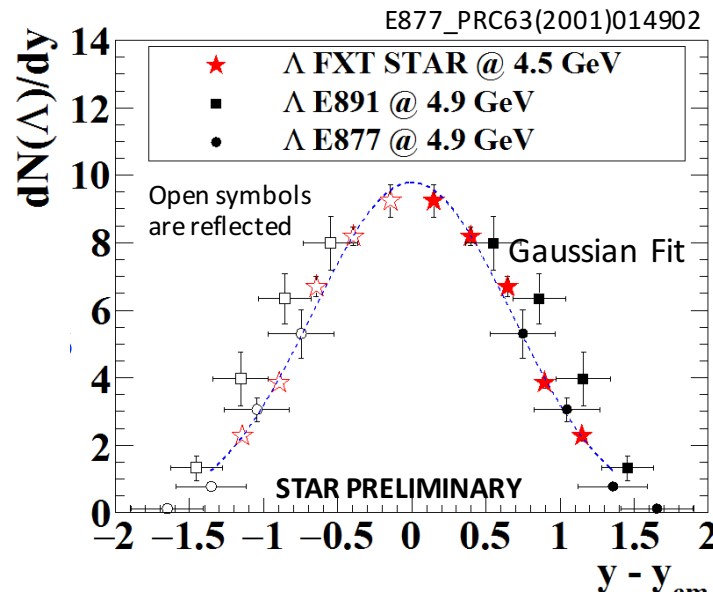
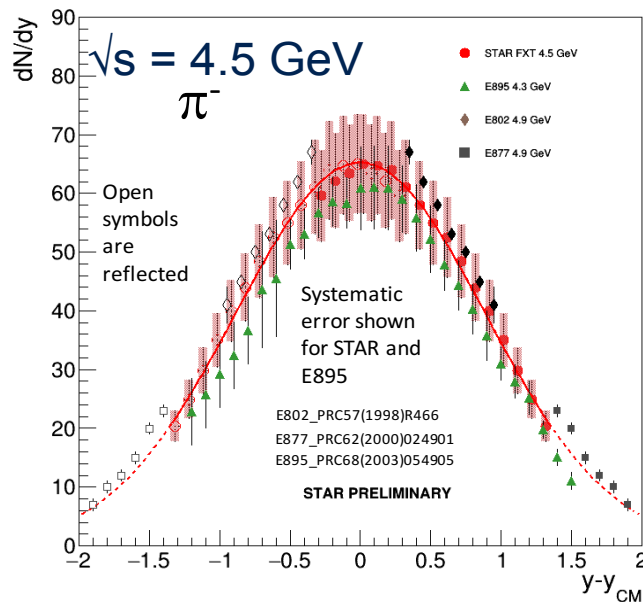
E895_PRC68(2003)054905

Establishing “basics”



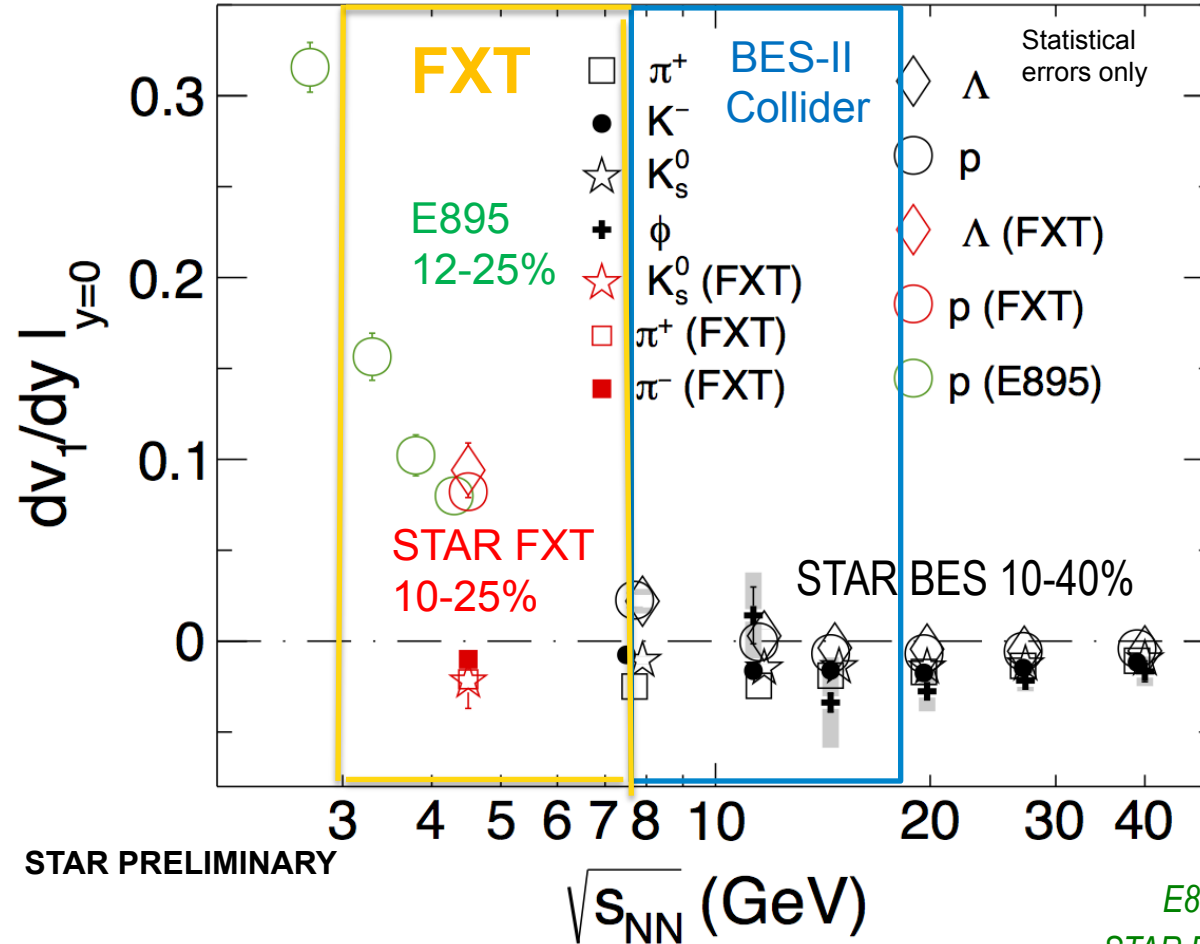
1.
agreement
between
experiments

2.
moving towards full
phase space
measurements (!)



FXT:
K.Meehan
QM 2017

Directed flow: comparison across experiments and energies



E895_PRL84(2000)5488
STAR PRL112 (2014) 162301

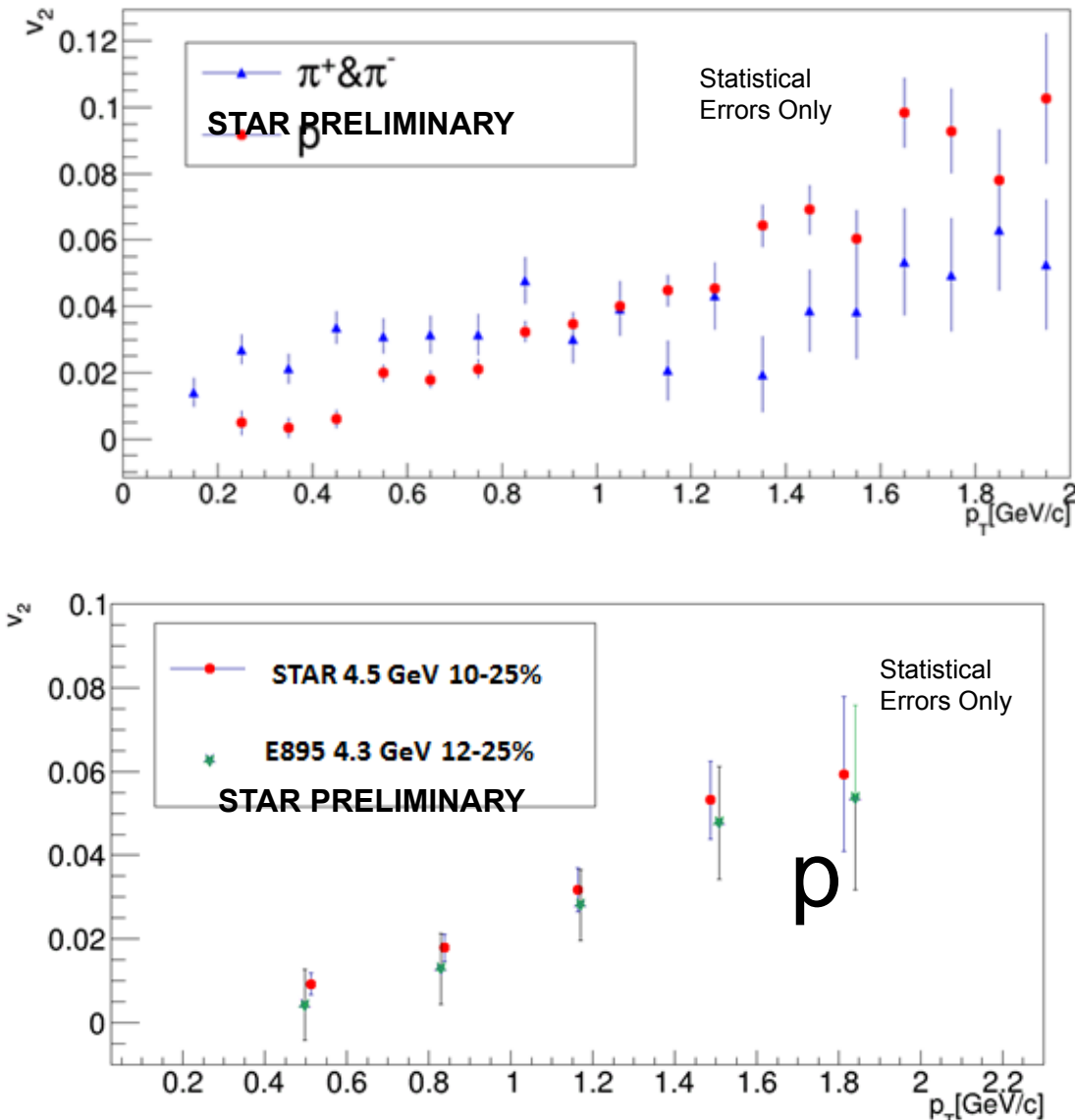
First π flow results for this energy range

Mesons continue the trend of negative flow seen at higher energies

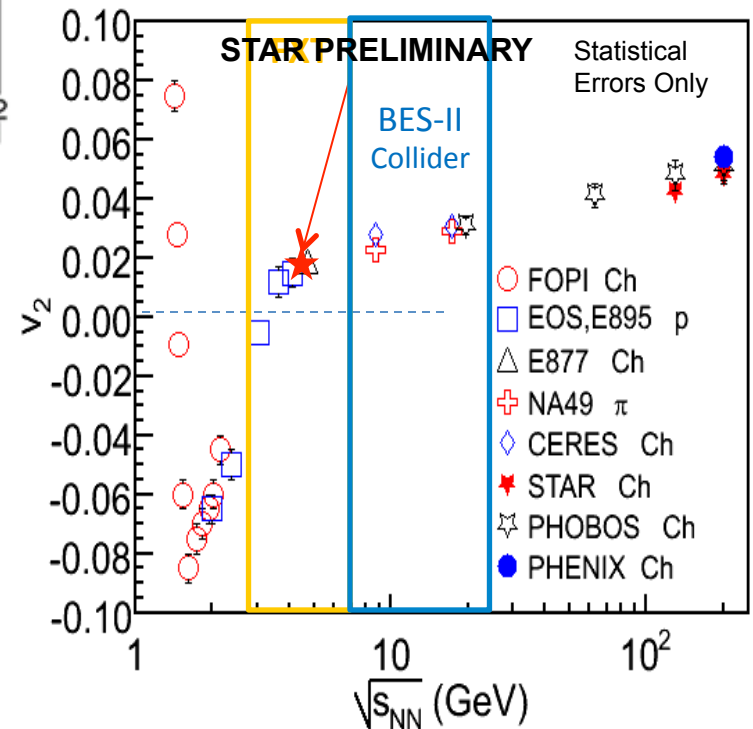
p and Λ are consistent with positive flow indicative of compression

Elliptic flow: v_2 of pions and protons

Lukasz Kozyra from PW !



- Mass ordering between pions and protons continues to be observed at this energy
- Good agreement with E895



STAR FXT tests show :

STAR operates successfully in FXT mode despite being optimized as a collider experiment

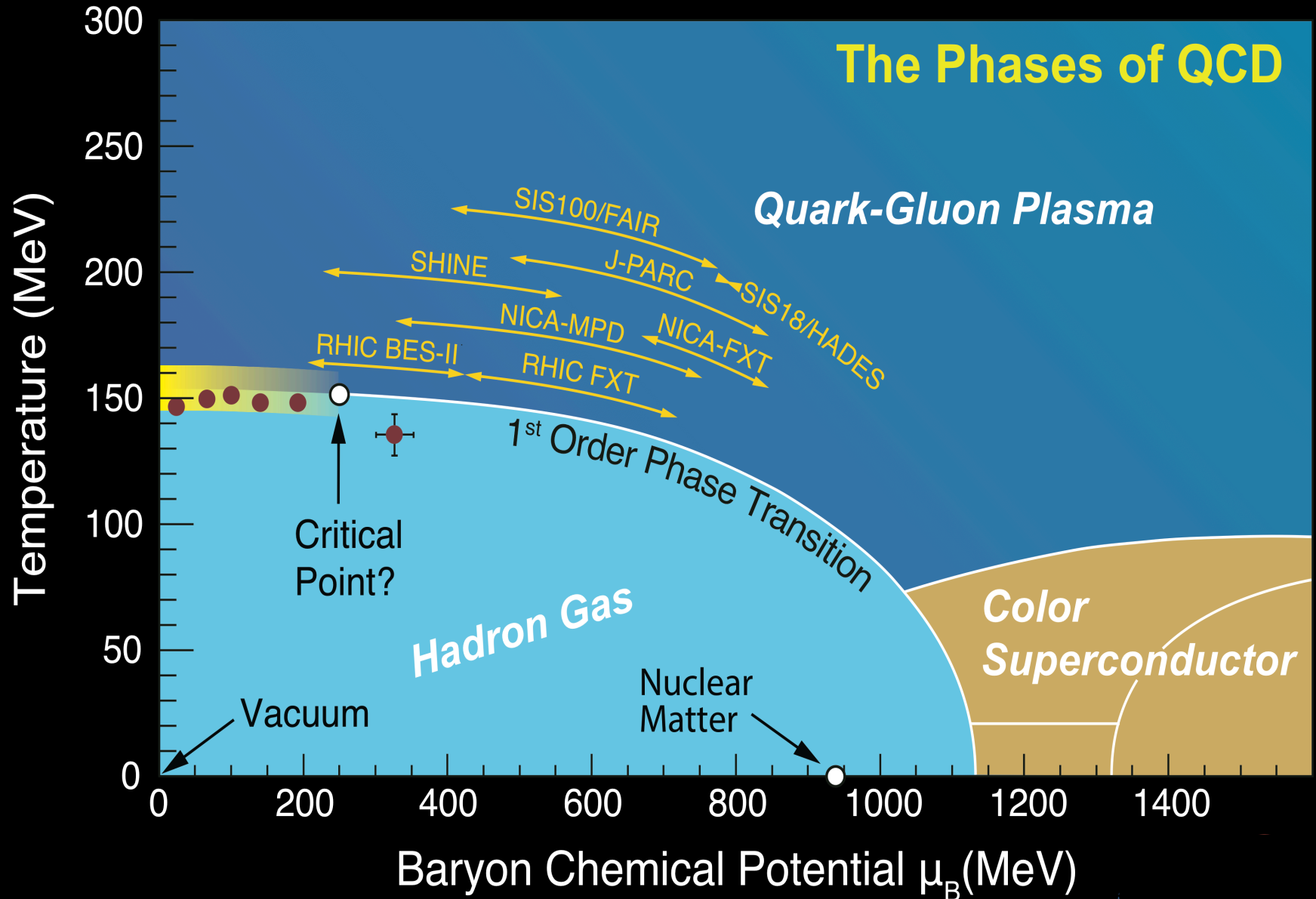
Spectra and yields comparable with AGS data

Direct and elliptic flow measured first time at this energy range (as well as HBT, fluctuations, strange particles etc – not in this talk)

FXT will extend BES II reach down to $\sqrt{s} = 3$ GeV ($\mu_B = 720$ MeV) to include high baryon density region of phase diagram

We are not alone

Karsch INT-BES 2017, Bazavov et al., arXiv:1701.04325



Planned low energy running

V.Kekelidze, T. Sakaguchi, P.Senger, QM 2017

μ_B (MeV)	560 - 230	850 - 670	790	720 - 210	750 - 330	780 - 400	850 - 490
$\sqrt{s_{NN}}$ (GeV)	4.9-17.3	2-3.5	2.4	3-19.6	2.7-11	2.7-8.2	2-6.2
Facility	SPS	NICA	SIS-18	RHIC	NICA	SIS-100	J-PARC HI
Experiment	NA61/SHINE	BM@N	HADES/miniCBM	STAR	MPD	CBM	
Start Year	2009	2017	2018	2019	2020	2025	2025 (earliest)
Physics	CP & Onset	Dense Baryon	Dense Baryon	CP and Onset	Onset & Dense Baryon	Onset & Dense Baryon	Onset & Dense Baryon

Expect wealth of new insights over next ~ 5 years

Summary

Data exists over wide range of $\sqrt{s}$ for heavy & light ions, p(d), and pp

High statistics exploration of QCD phase diagram and its key features is about to begin

Wealth of data in hand and more coming soon (RHIC, SPS, NICA, FAIR)

Significant upgrades to detection capabilities compare to existing data

Strong theoretical interest focused in BEST and HICforFAIR

Turn trends and features into definite conclusions

Thank you !