RHIC Beam Energy Scan Program

Experimental Approach to the QCD Phase Diagram

Grazyna Odyniec / LBNL, Berkeley

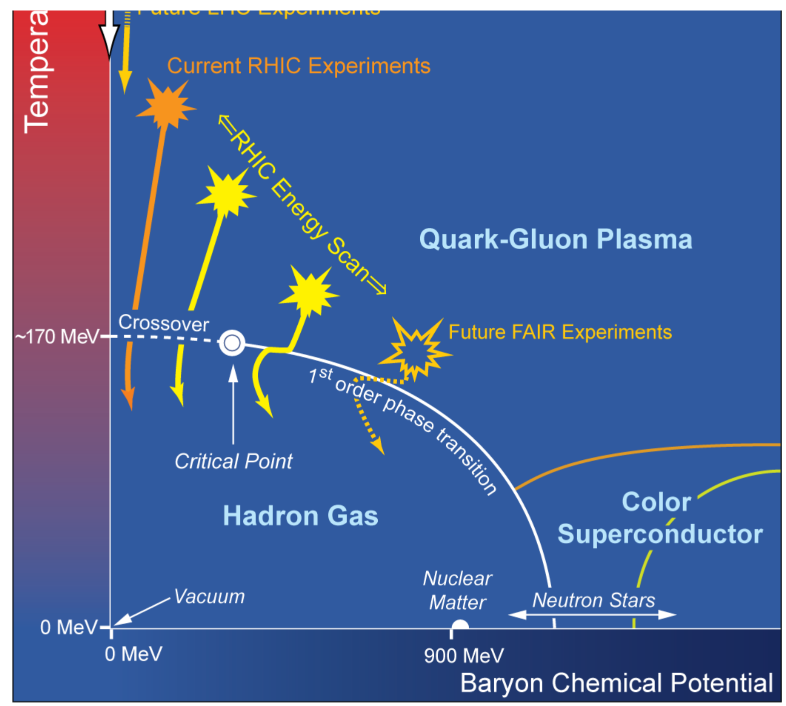
<u>Outline</u> :

QCD phase diagram

Heavy Ion Collisions – the only experimental tool

BES @ RHIC: Physics goals and observables:

- search for the CP and 1st order phase transition
- demonstrate the onset of deconfinement (QGP)



USA-NSAC 2007 Long-range Plan

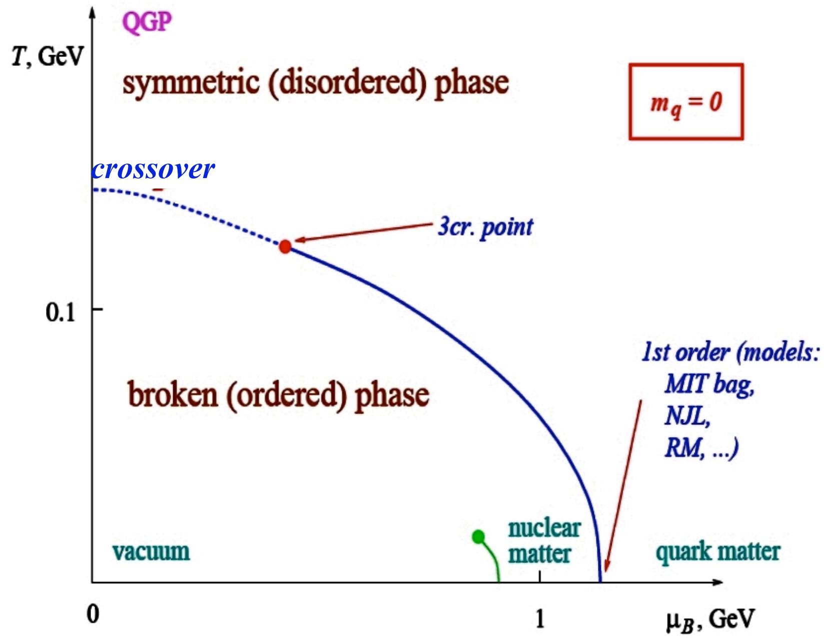
QCD phase diagram - Theory

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 μ_B~0
2. Various models find a strong 1st order transition at large μ_B

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



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

⟶ CP range: $160 < \mu_B < 500$ MeV

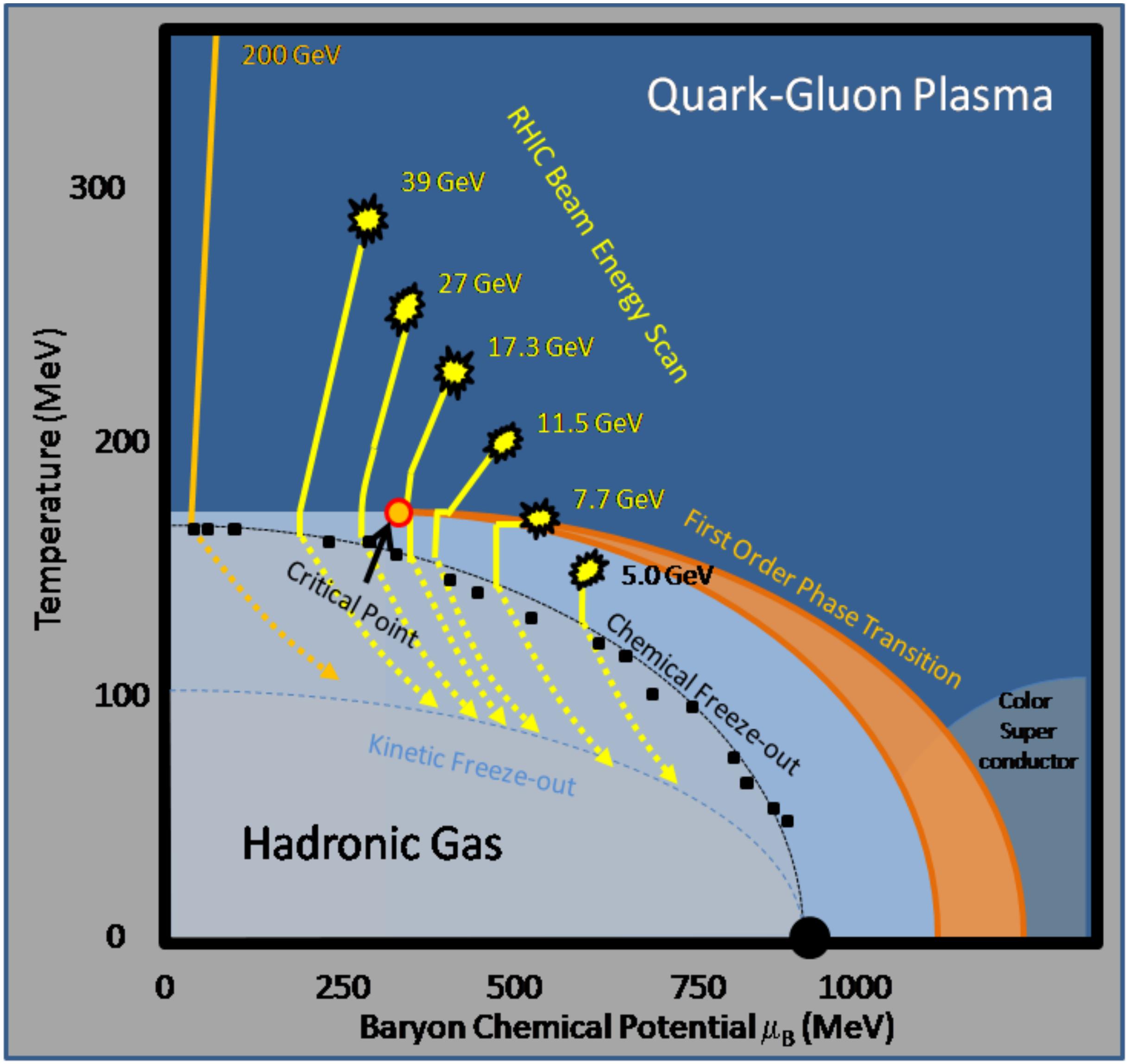
Given the significant theoretical difficulties, data may lead the study of QCD phase diagram

➡ Beam Energy Scan Program at RHIC will cover this range

Beam Energy Scan at RHIC: $\sqrt{s_{NN}}$ ~ 5-50 GeV

<u>experimental window to QCD phenomenology</u>

at finite temperature and baryon number density



at RHIC : indications of sQGP but remain <u>unknown</u>:

- boundary between hadronic and partonic phases
- critical point

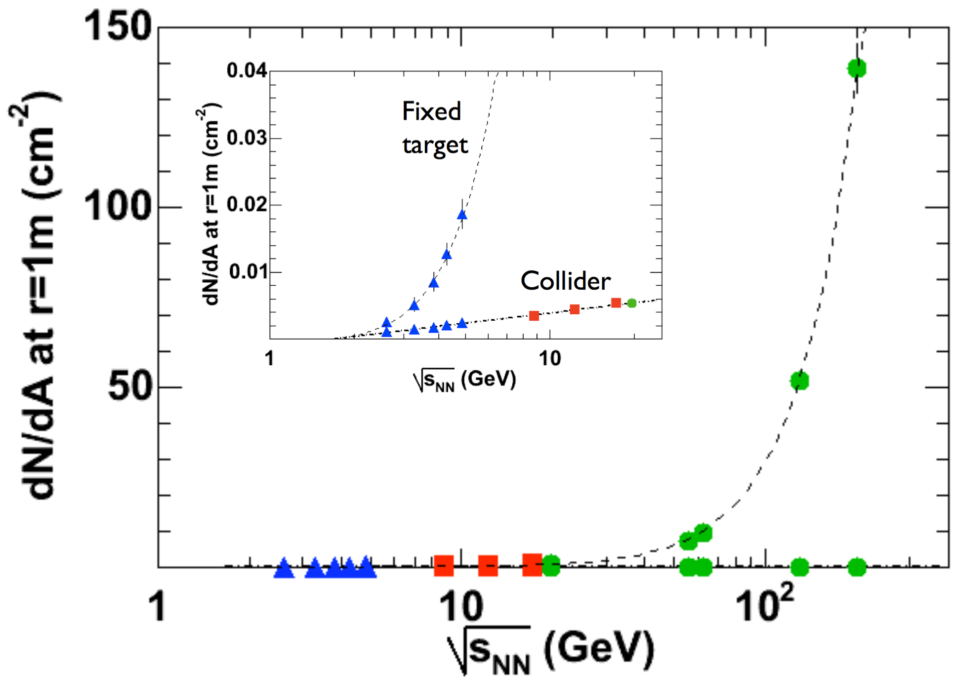
HOW to investigate it ?

BES @ RHIC

160 MeV<μ_B<500 MeV

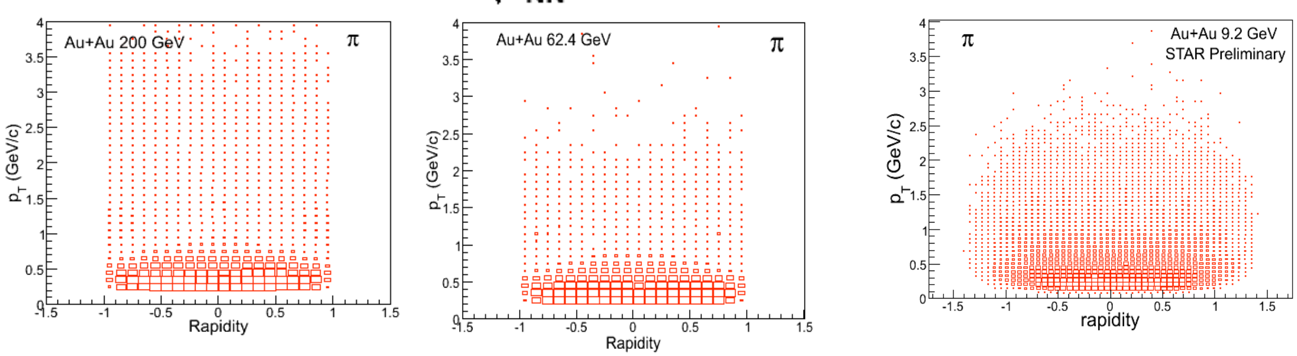
also: SPS, FAIR (fixed target)

Why RHIC is such an excellent choice ? - Collider



1.

occupancy for detectors in collider geometry is much less dependent on beam energy (➡ less technical difficulties in tracking)

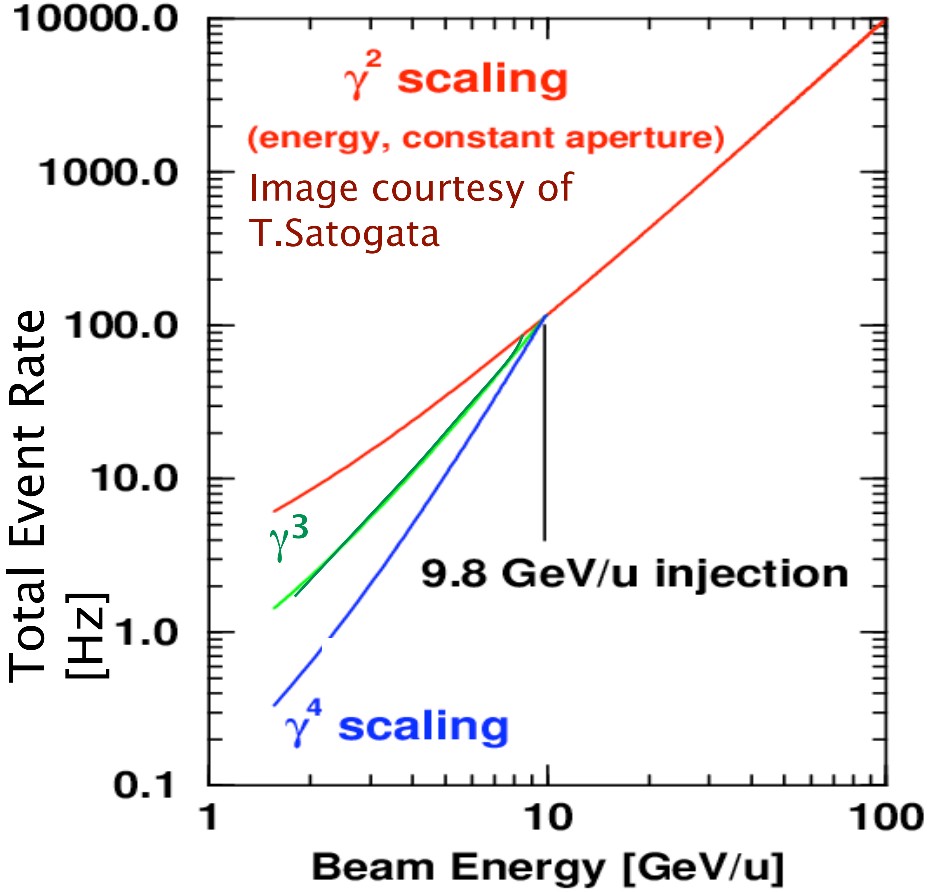


2.

acceptance for collider detectors is independent of beam

Excellent control of systematics !

Luminosity is the key issue



Determined collision rate for 2008 9.2 GeV Au+Au test to be ~1Hz.

Rate can be increased by:

- factor 2 by adding more bunches, only 56 used for tests (max 120).
- factor 3-6 by operating with higher charge in bunches.
- factor few by running in continuous injection mode
- electron cooling in RHIC (after 2012)

Expect to reach γ^3 rate even at lowest energies

BES: Experimental Program

http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493

Search for:

(1) indications of the existence of Critical Point & phase transition

- fluctuation measures
  - higher moments of net proton distribution (kurtosis) ★
- azimuthally-sensitive femtoscopy
- elliptic & directed flow
- …

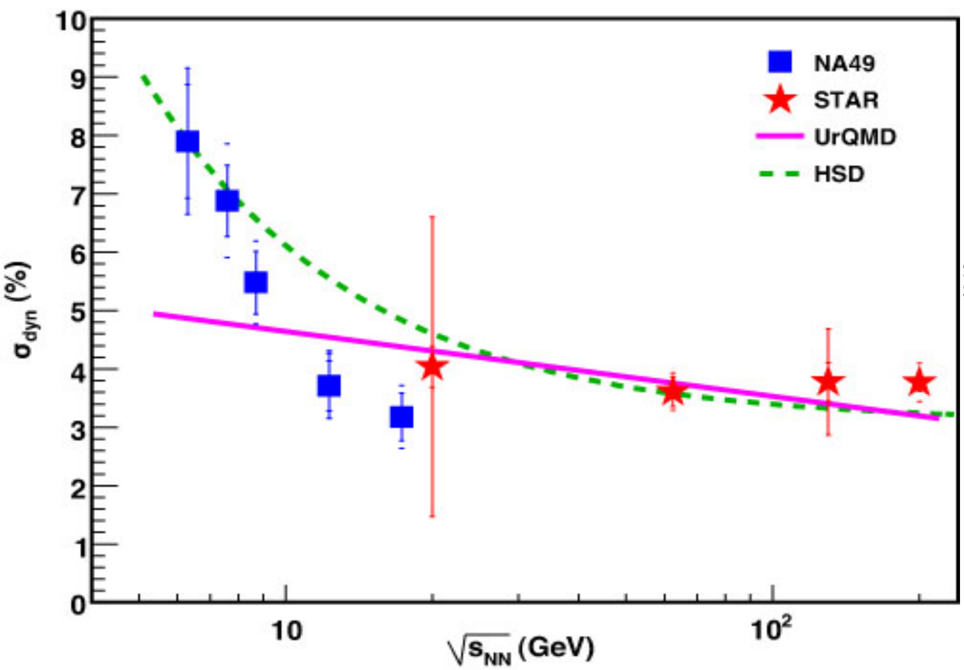
(2) disappearance of signals of partonic degrees of freedom seen at 200 GeV

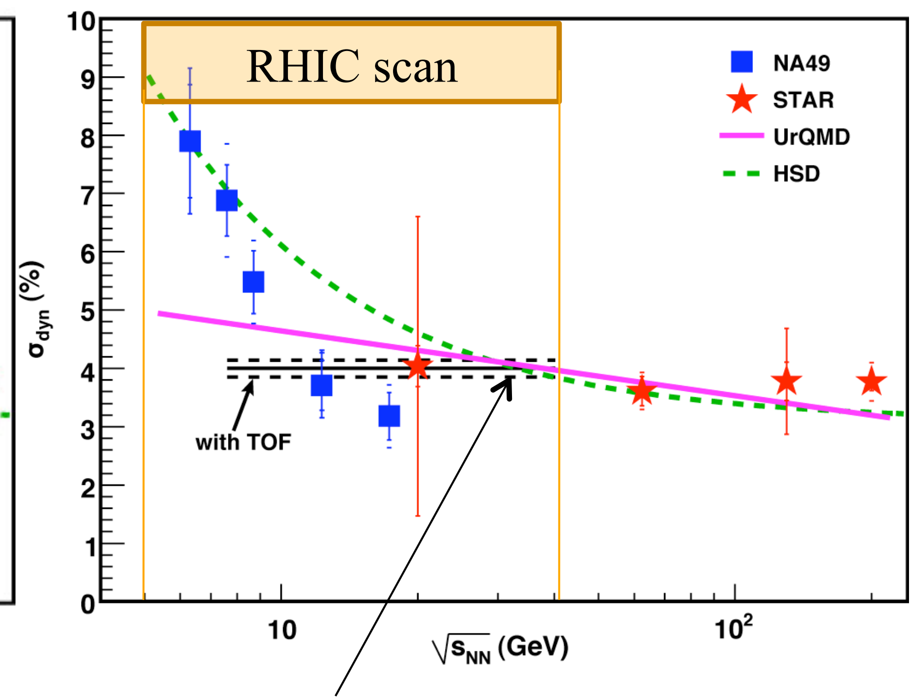
- disappearance of constituent-quark-number scaling of v_2 ★
- disappearance of hadron suppression in central collisions
- disappearance of ridge
- local parity violation
- …

Critical Point search – Fluctuations maximized at CP

example: e-by-e fluctuations in K/π ratio

PRL 103, 092301 (2009)



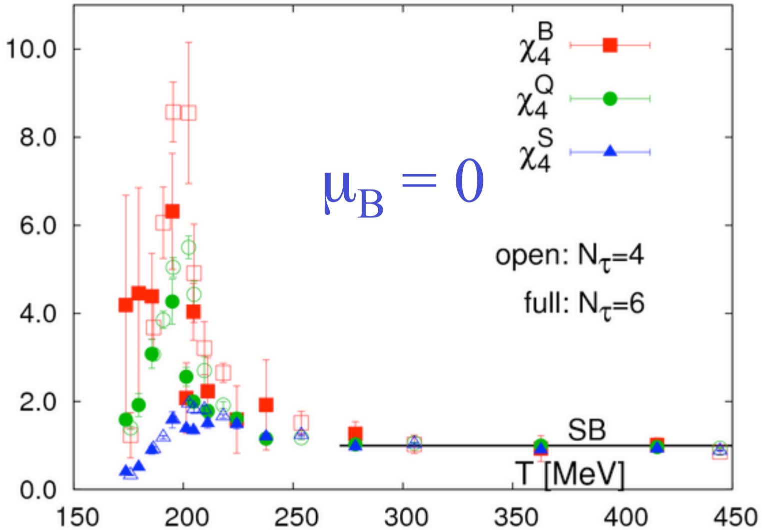


Expected error with 250 k central events

NA49 fluct. > STAR fluct. ?

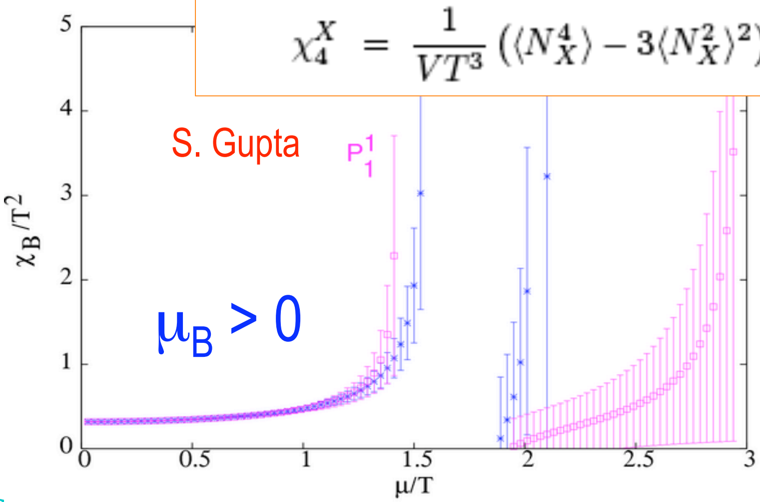
CP at lower energies ? (but diff. acceptance).

more sensitive : - Higher Moments



$$\chi_2^X = \frac{1}{VT^3}\langle N_X^2 \rangle$$

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



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

Lattice QCD: Spikes for both χ_B and χ_S

Berdnikov, Rajagopal, PRD61, 105017 (00)
Stephanov, Rajagopal, Shuryak, PRD 60, 114028 (99)
Hatta, Stephanov, PRL. 91, 102003 (03)

Observable:

Kurtosis of net-proton & net-C

- *connect to lattice calculations!*
- *sensitive to long range fluctuations*

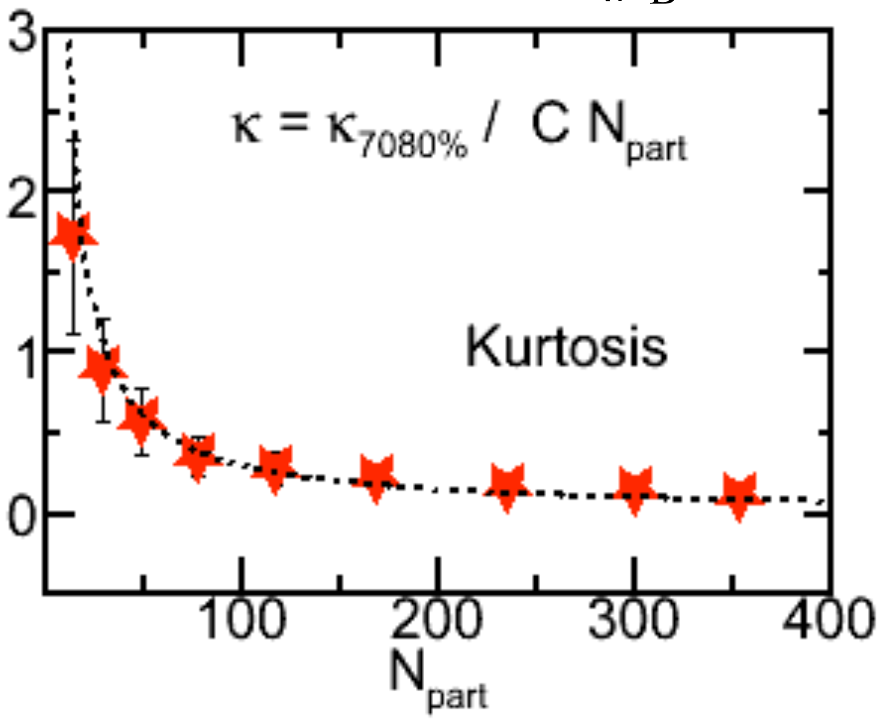
Caveats: dynamical effects in collisions

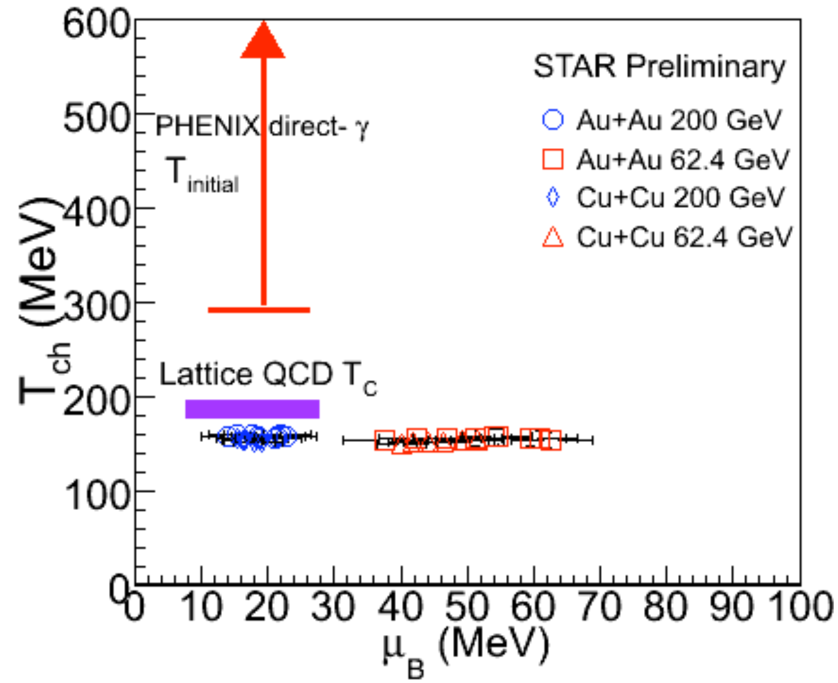
- *finite time and size*
- *critical slowing*

Centrality dependence of net-proton Kurtosis

STAR Preliminary:

200 GeV Au+Au ($\mu_B \leq 25$ MeV)





First Kurtosis measurement for net-protons in high-energy nuclear collisions

Monotonic behavior observed at relatively small μ_B region → baseline

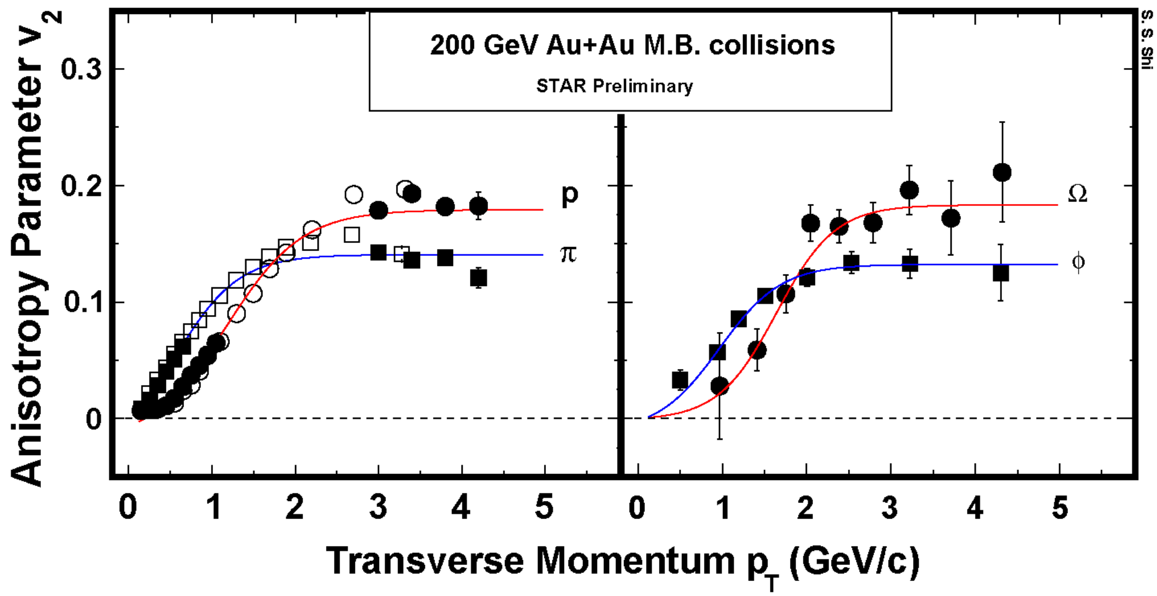
Disappearance of partonic degrees of freedom (I)

(Onset of sQGP)

disappearance of n_q scaling, disappearance of hadron suppression at high pt, … (a long list)

n_q scaling observed at RHIC:

STAR, QM 2009

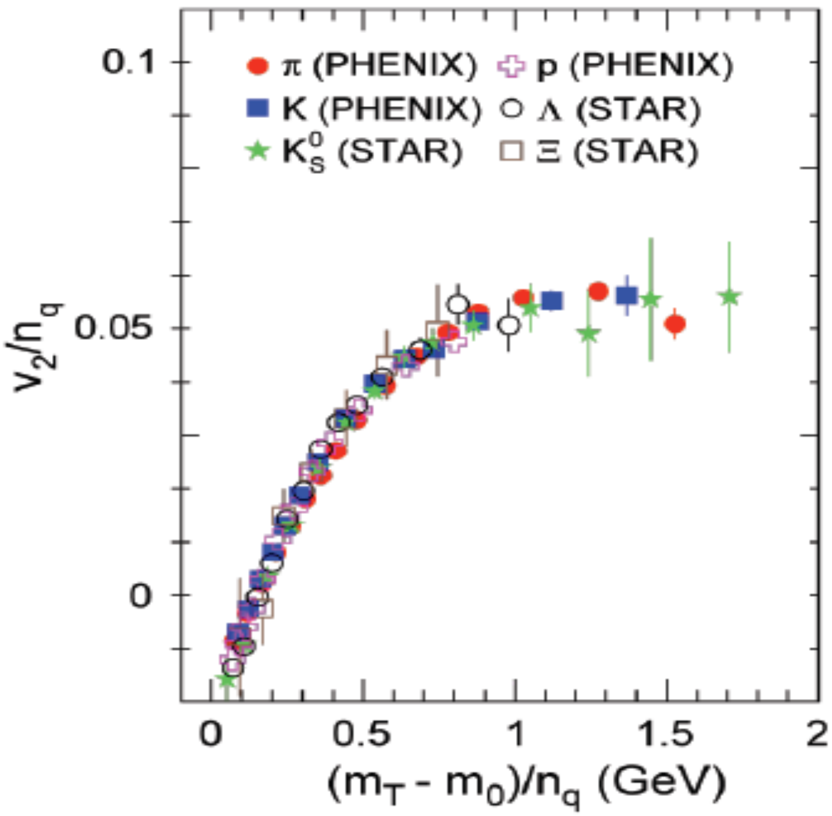


(1) Mass separation at low p_T

(2) Light and heavy quarks have similar magnitude of flow

(3) In intermediate p_T: separation between baryon and meson band

Disappearance of partonic degrees of freedom (II)



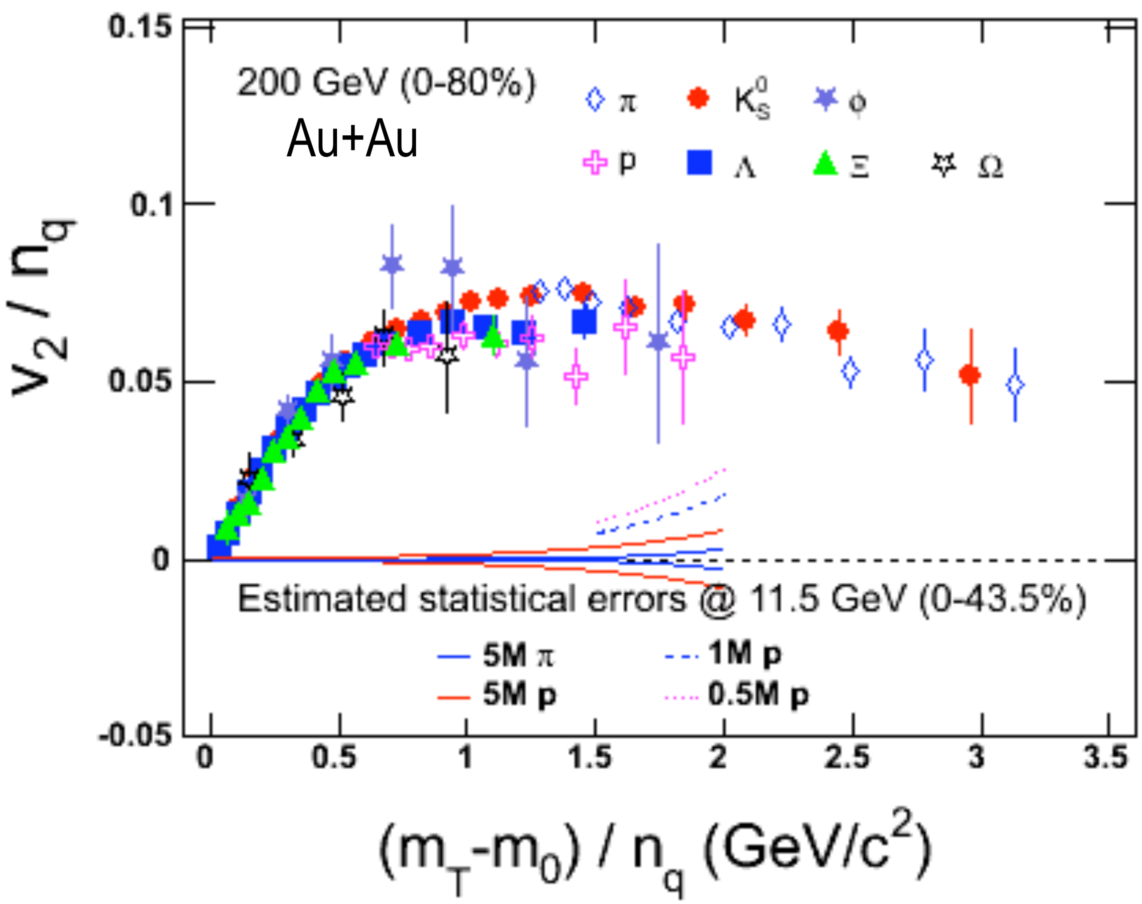
Scaling flow parameters by quark content n_q (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons

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

Will we be able to see it ?

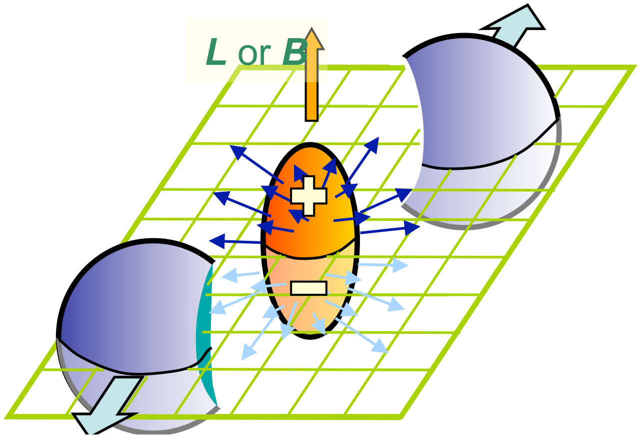
PRL 92, 052302(04), 95, 122301(05), nucl-ex/0405022, QM05

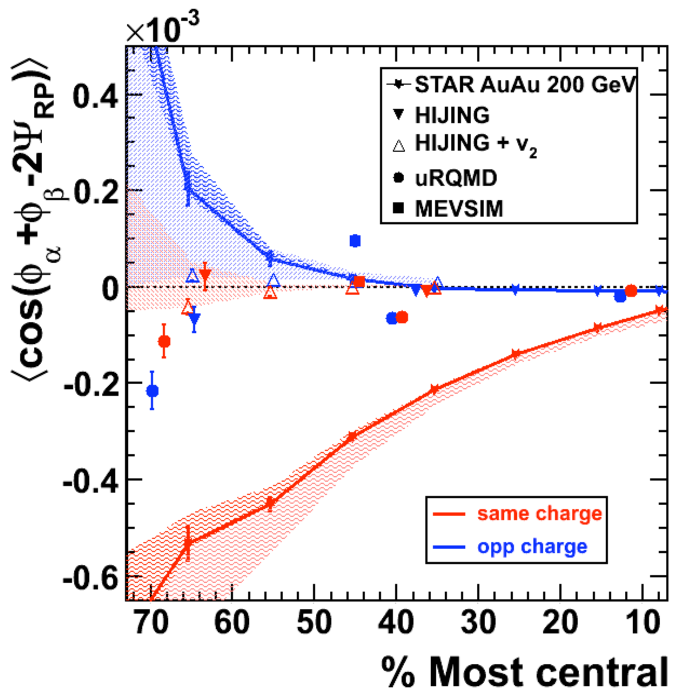


Yes, a few M is enough !

Local Parity Violations in Deconfined Medium

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





(1) Under strong magnetic field, when the system is in the state of deconfinement and chiral symmetry restoration is reached, local fluctuation may lead to parity violation.

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

(3) In RHIC Beam Energy Scan program:

- test the model prediction

- the energy when the charge separation disappear => phase boundary http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493

Collision Energies (GeV)	**5**	**7.7**	**11.5**	**17.3**	**27**	**39**
Observables	Millions of Events Needed					
v_2 (up to ~1.5 GeV/c)	**0.3**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**
v_1	0.5	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Azimuthally sensitive HBT	4	**4**	**3.5**	**3.5**	**3**	**3**
PID fluctuations (K/π)	1	**1**	**1**	**1**	**1**	**1**
net-proton kurtosis	5	**5**	**5**	**5**	**5**	**5**
differential corr & fluct vs. centrality	4	**5**	**5**	**5**	**5**	**5**
n_q scaling π/K/p/Λ $(m_T-m_0)/n$<2GeV	8.5	**6**	**5**	**5**	**4.5**	**4.5**
ϕ/Ω up to p_T/n_q=2 GeV/c		56	25	**18**	**13**	**12**
R_{CP} up to p_T ~4.5 GeV/c (at 17.3) 5.5 (at 27) & 6 GeV/c (at 39)				**15**	**33**	**24**
untriggered ridge correlations		27	13	**8**	**6**	**6**
parity violation		**5**	**5**	**5**	**5**	**5**

Requested Beam Energies and # of Days Running (from STAR BUR)

Beam Energy sqrt(s) (GeV)	μ_B (MeV)	Event Rate (Hz)	Days/1M Events	Events proposed	8-hr days proposed
5	550	0.8	45	200 k	9
7.7	410	3	11	5M	56
11.5	300	10	3.7	5M	19
17.3	230	33	1.1	15M	16
27	150	92	0.4	33M	12
39	110	190	0.2	24M	5

Sufficient rates for the initial physics program at all energies

“binary” experiment: YES/NO (no “maybe’s” & more statistics needed)

Recommendations of BNL Nuclear and Particle Physics Program Advisory Committee (PAC):

Run 10 (2010):

1. 10 weeks of Au+Au at 200 GeV
2. 12 weeks for a beam energy scan (BES) with Au+Au collisions:
    1. - 4 weeks 62 GeV
    2. - 8 weeks lower energies
        1. 0.5 week 39 and 27 GeV
        2. 1 week at 18 GeV (10 M)
        3. 2 weeks at 11 GeV (6 M)
        4. 4 weeks at 7.7 GeV (3.6 M)

Post-PAC realism (BNL "straw man" proposal): 7.7 GeV run -> run11
run 10: 39 GeV -1.5 w, 27 GeV – 3.5 w, 18 Gev- 2.5 w, 11.5 GeV -2.5 w, 7GeV – 1w.

STAR already has experience with low energy running

- STAR has already experiences with low energy running

19.6 GeV Au+Au (2001)

22.4 GeV Cu+Cu (2005)

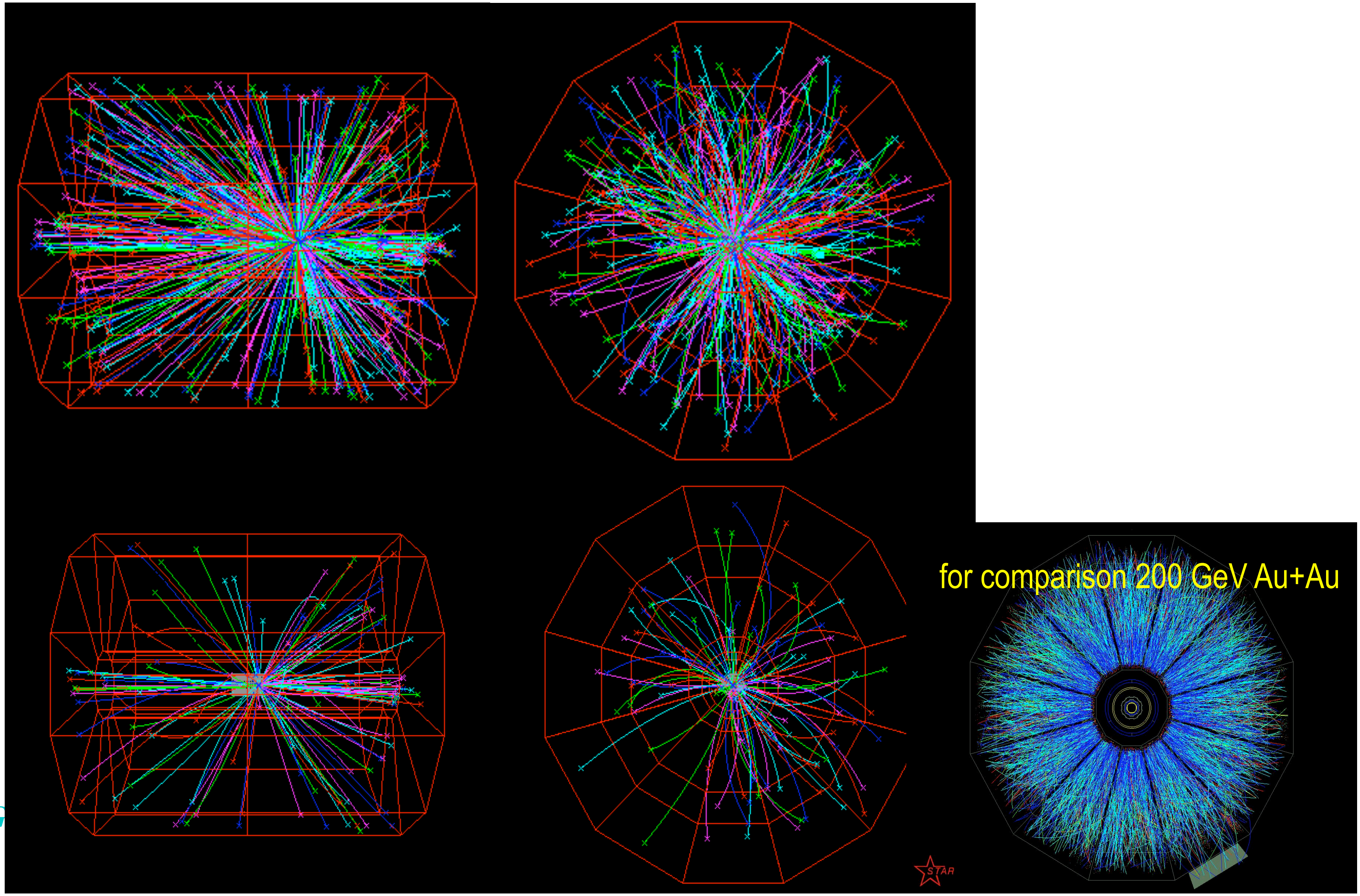
9.9 GeV Au+Au (2007)

9.2 GeV Au+Au (2008)

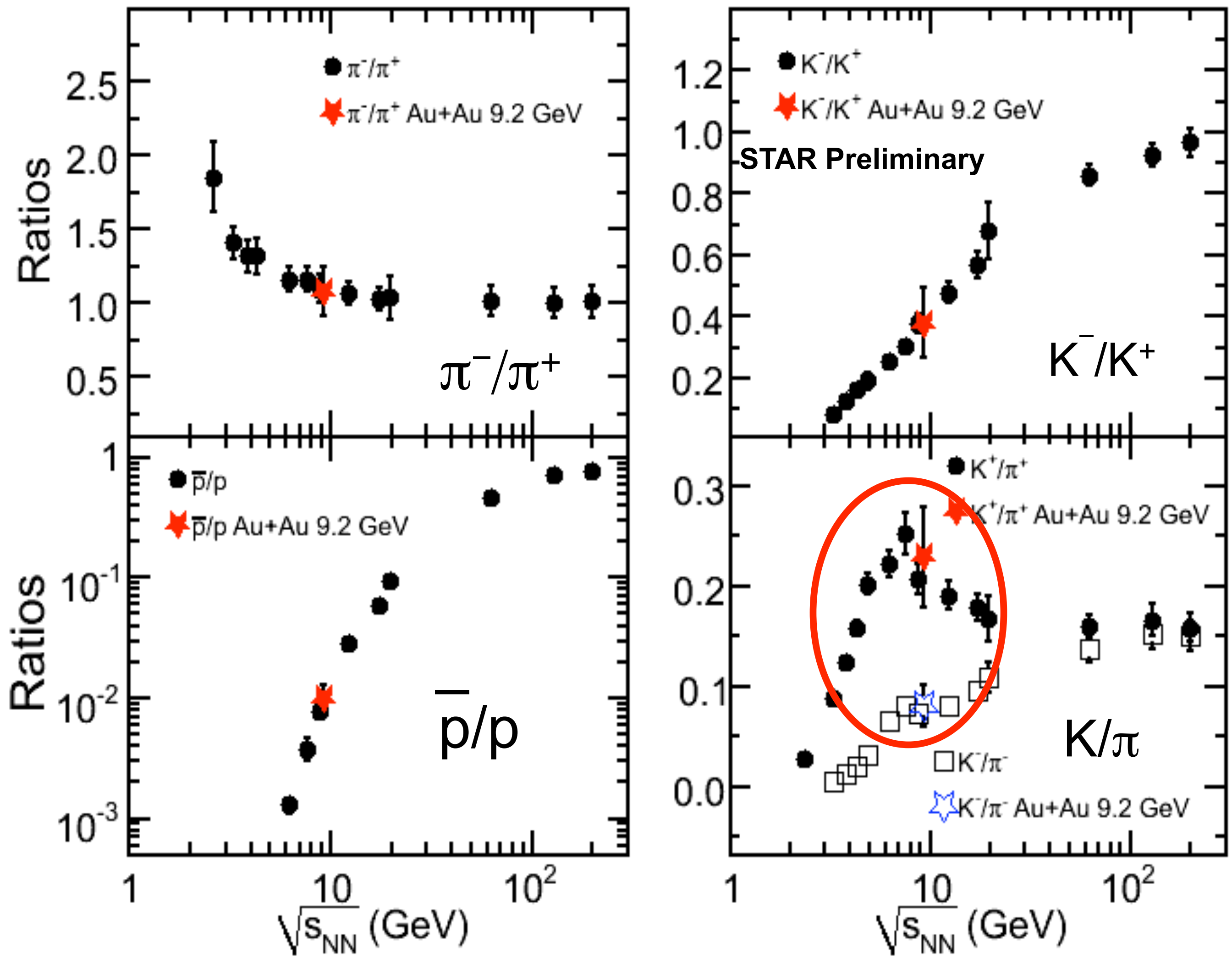
What have we done to get ready for a BES ?

STAR Upgrades : trigger, Time of Flight (TOF), DAQ1000

9.2 GeV Au+Au March 2008



STAR experiment demonstrated capabilities



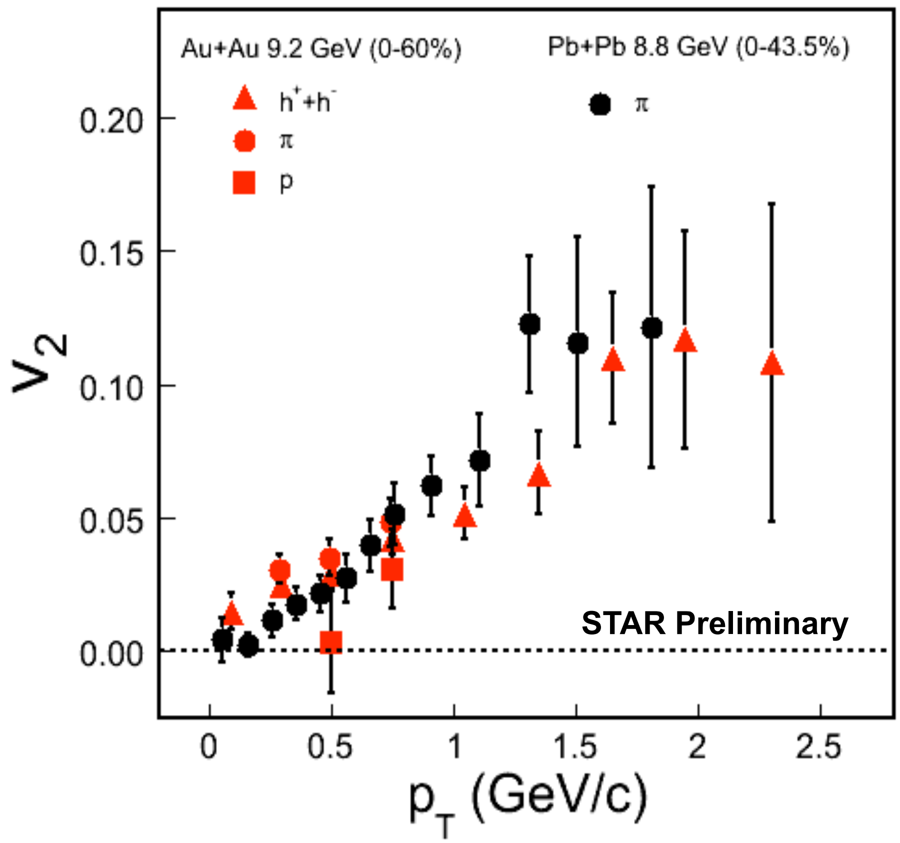
9.2 GeV results consistent with the published data

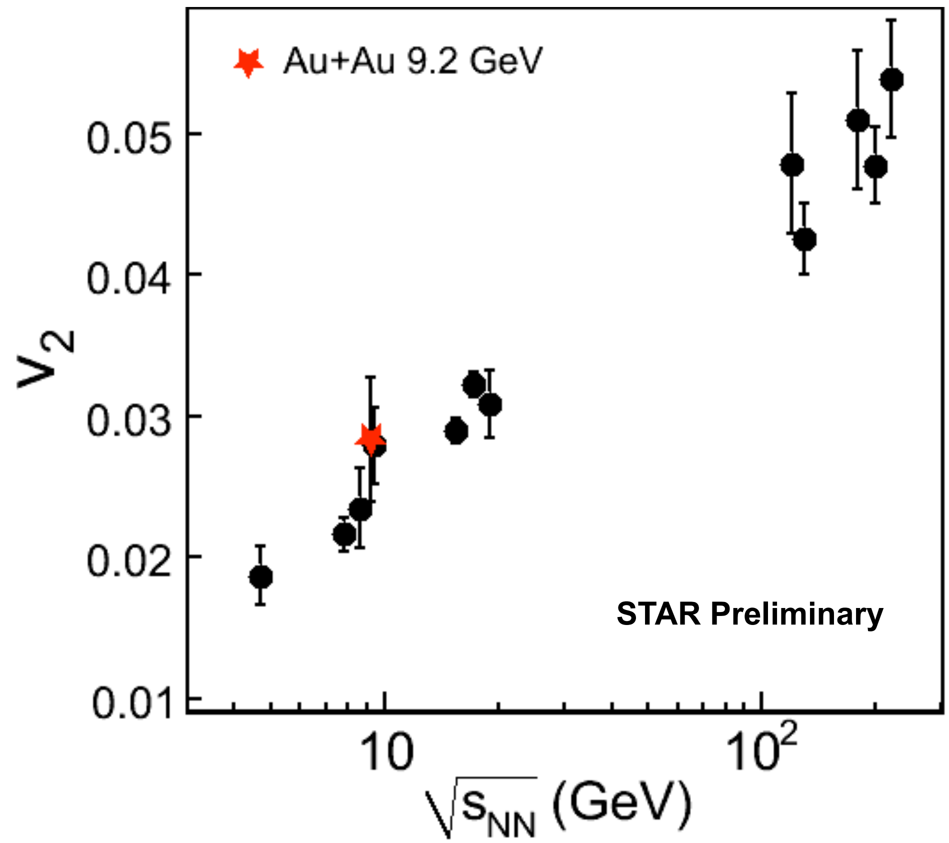
STAR : PRC 79 (2009) 034909, arXiv: 0903.4702

NA49 : PRC 66 (2002) 054902, PRC 77 (2008) 024903, PRC 73 (2006) 044910

E802(AGS) : PRC 58 (1998) 3523, PRC 60 (1999) 044904, PRC 62 (2000) 024901, PRC 68 (2003) 054903

Elliptic Flow



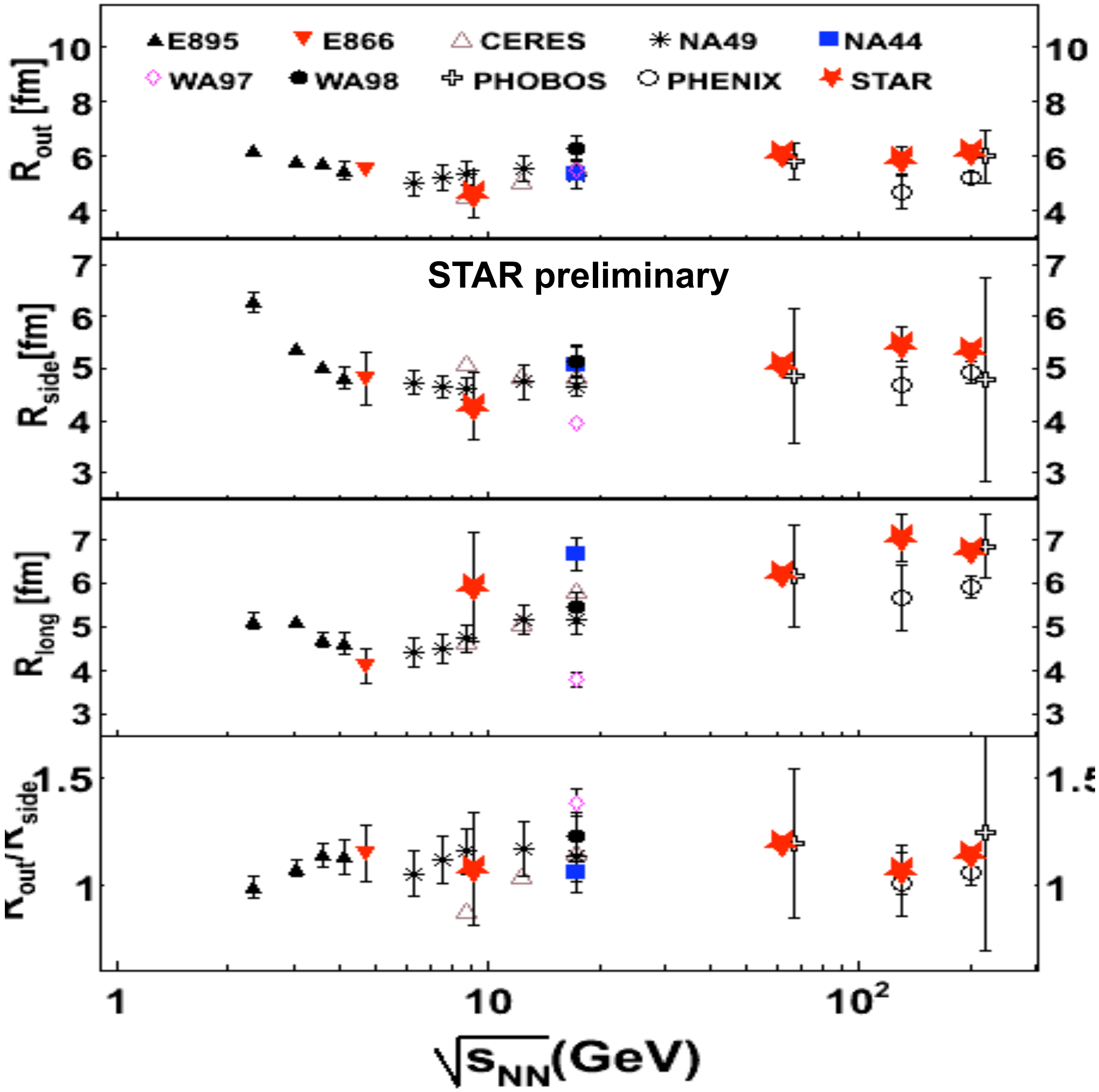


NA49 : PRC 68 (2003) 034903
AGS : PLB 474 (2000) 27
STAR : PRC 77 (2008) 054901 : PRC 75 (2007) 054906, PRC 72 (2005) 014904
PHOBOS : PRC 72 (2005) 051901 : PRL 98 (2007) 242302
PHENIX : PRL 98 (2007) 162301

STAR and NA49 results are consistent

STAR 9.2GeV v_2 fits with the observed trends

Pion Interferometry



π^-

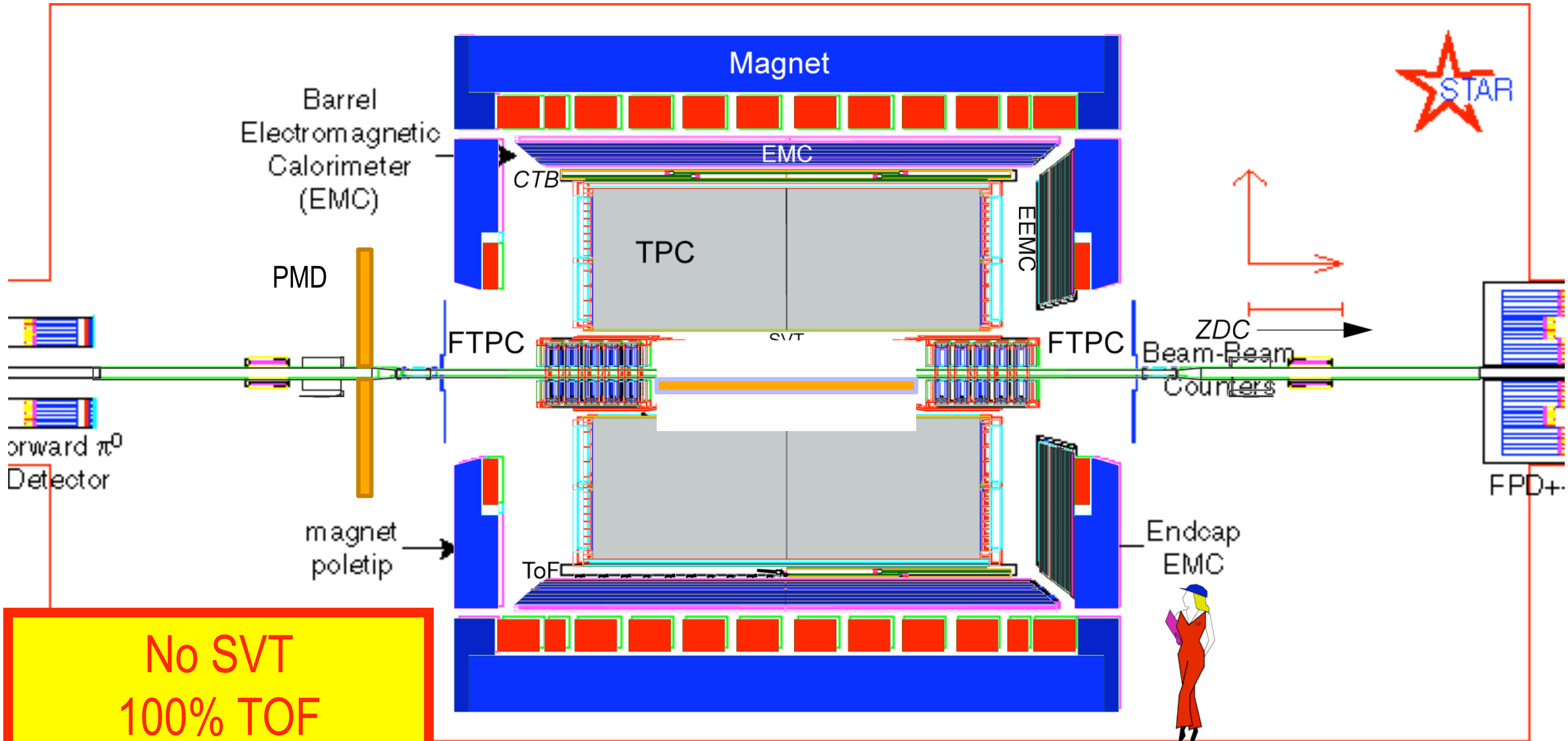
error bars for Au+Au 9.2 GeV are statistical
systematic errors < 10 % for all radii

STAR : PRC 71 (2005) 044906, PRL 87 (2001) 082301
PHENIX : PRL 88 (2002) 192302, PRL 93(2004) 152302
E802 : PRC 66 (2002) 054906
CERES : NPA 714 (2003) 124
E895 :PRL 84 (2000) 2798
PHOBOS : PRC 73 (2006) 031901
NA44 : PRC 58 (1998) 1656
E866 : NPA 661 (1999) 439
NA49 : PRC 77 (2008) 64908
WA97 : JPG 27 (2001) 2325

9.2 GeV Au+Au paper in preparation (PRC)

Results from the 9.2 GeV run demonstrate STAR readiness to take up the proposed Beam Energy Scan Program

STAR Experimental Configuration for Run 10 (2010)



No SVT
100% TOF
FTPCs
Large beam pipe

Summary – part I (BES@RHIC)

Main directions of Beam Energy Scan program at RHIC are established:

- Search for turn-off of sQGP signatures
- Search for the evidence of CP and/or 1st order phase transition
- + many other measurements

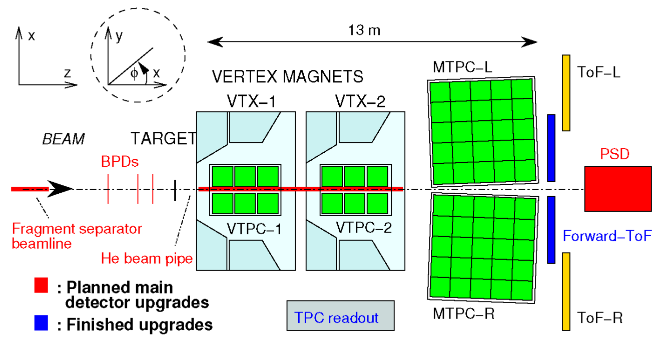
We propose to first scan available phase space with 6 equally spaced points between 5 and 39 GeV (we already have 62, 130, 200 data), and return to “interesting” regions for more detailed studies in the next year

STAR is ready:

- STAR BES program will be definite (yes/no)
- Demonstrated capabilities to complete program
- Perfect time: low interior mass, PID due to TOF, DAQ with DAQ1000

CERN Beam Energy Scan Program – NA61/ SHINE

Outline of setup.



Detector upgrades are necessary.

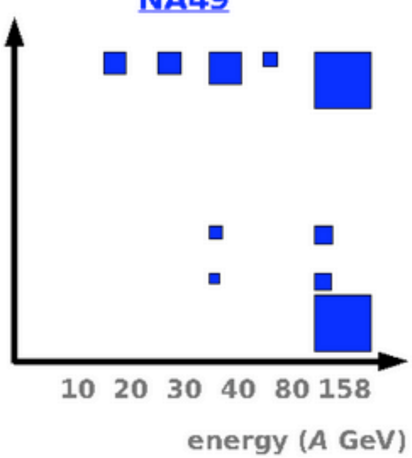
What is the difference vs. NA49 ?

New spectator calorimeter for centrality selection
Forward Time-Of-Flight
Beam pipe
TPC readout

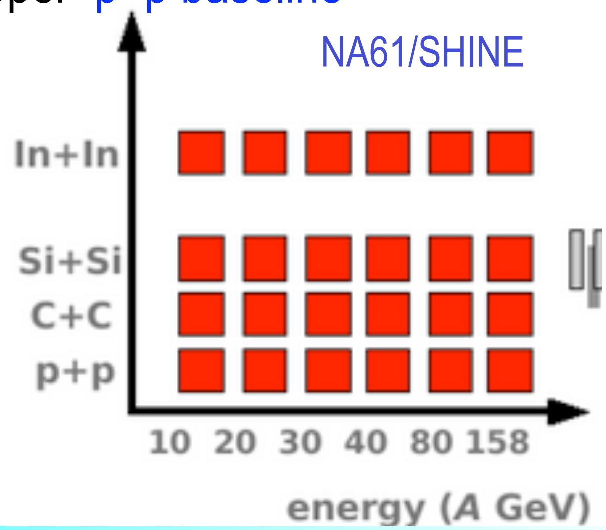
Physics program:

Studying QCD Critical Point and Onset of various observations with varying colliding ion size, collision centrality and having a proper p+p baseline

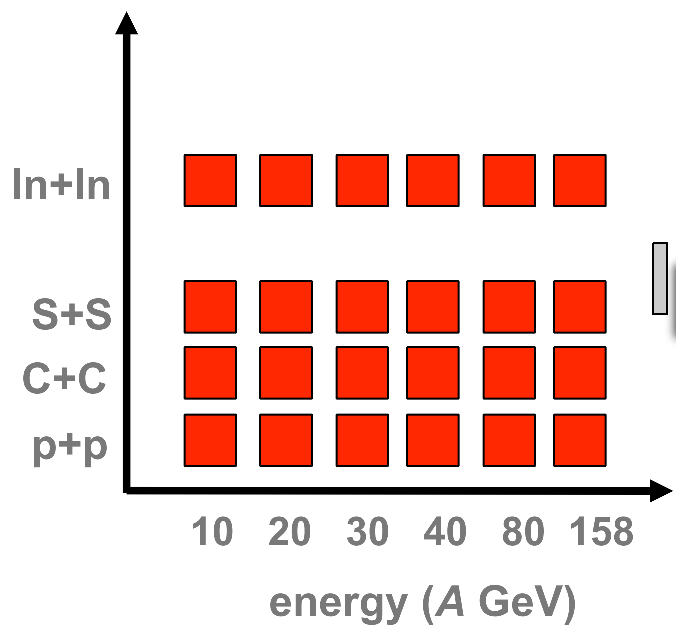
NA49

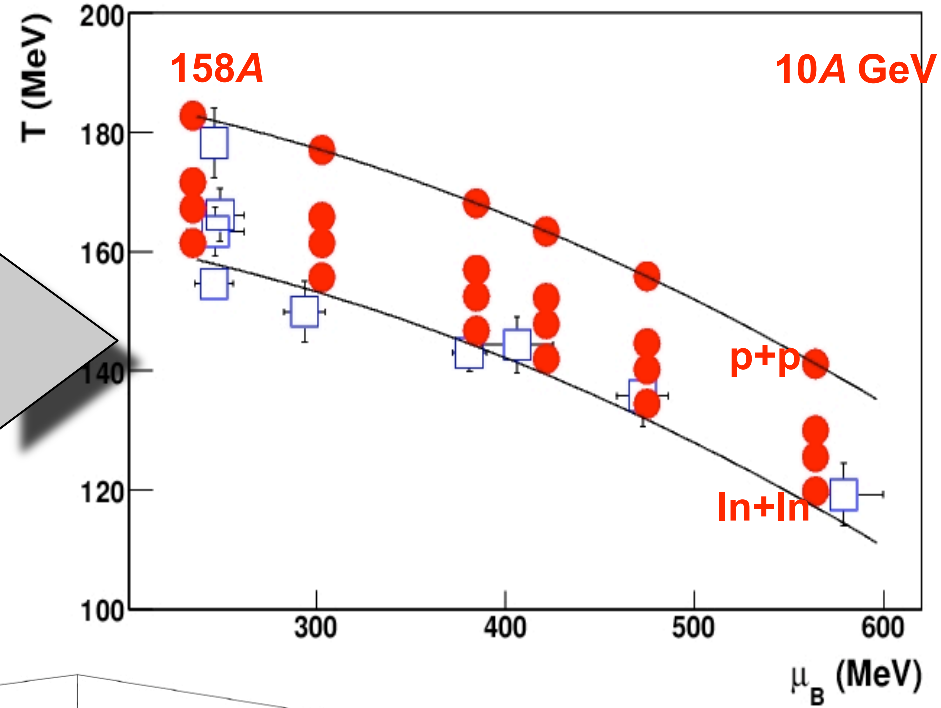


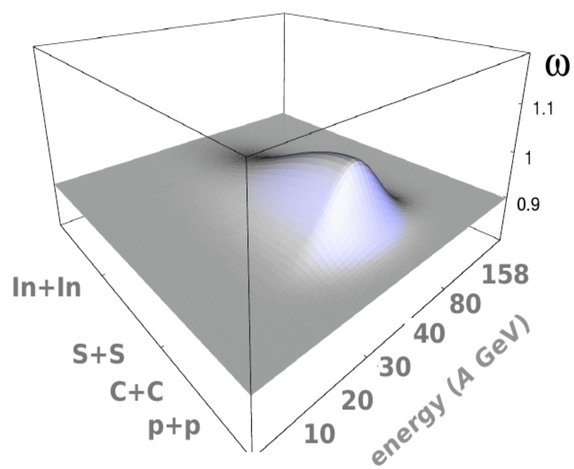
NA61/SHINE



NA61/Shine search for the critical point







Look for the hill of fluctuations

Summary - part II

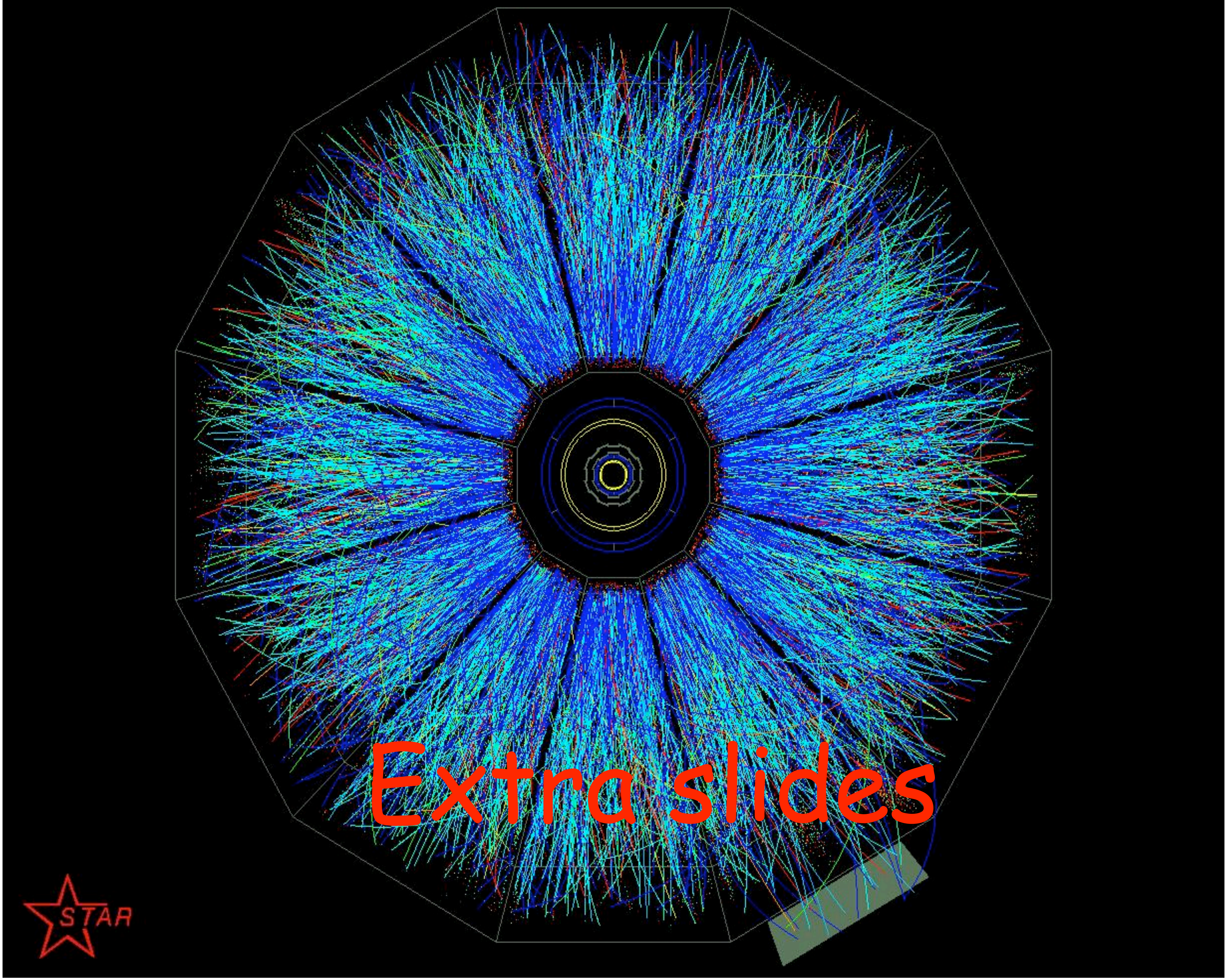
Train is leaving the station …

BES at RHIC (STAR,PHENIX, collider exp.) starting date December 2009 (run 10) to continue in 2011 (run 11)

BES at CERN (NA61/Shine, fixed targ.exp.) starting date with ion data 2011 (A~30) to continue in 2012 and 2013 (with lighter and heavier ions)

Other facilities: FAIR/Darmstadt, NICA/Dubna – much later (~ 2015)

Extra slides



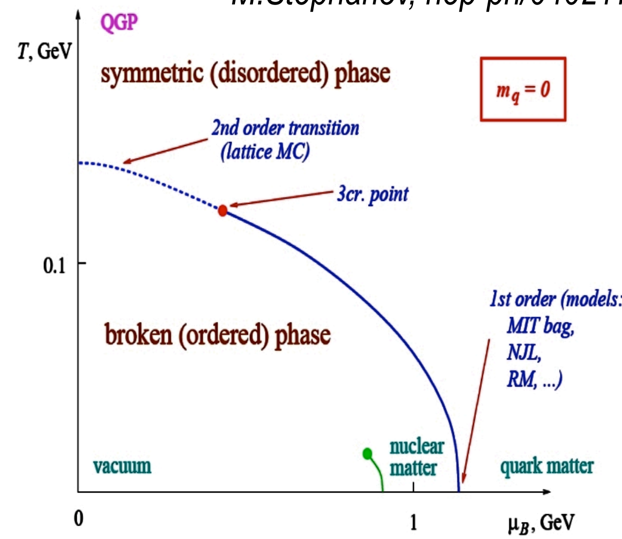
QCD phase diagram - Theory

Theory at the "edges" is believed to be well understood:

1. Lattice QCD finds a rapid, but smooth, crossover at large T and μ_B~0
2. Various models find a strong 1st order transition at large μ_B

So, there must be a critical point.

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

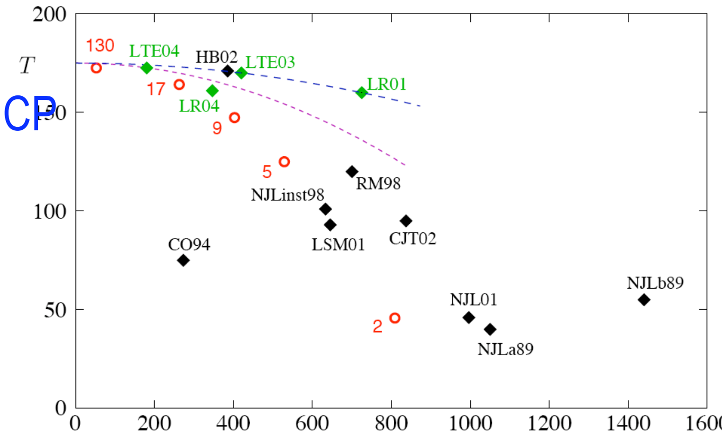


Location of CP still <u>not determine</u>:

μ_B = 0: Several methods on lattice (*no agreement so far):*

- Reweighting : Fodor + Katz -> CP – LR01, LR04
- Imaginary μ: D'Elia + Lombardo, de Forcrand+Philipsen -> no CP
- Taylor expansion of the pressure: Karsh, Gavai Gupta, -> CP – LTE03, LTE04

hep-lat/0701002v1



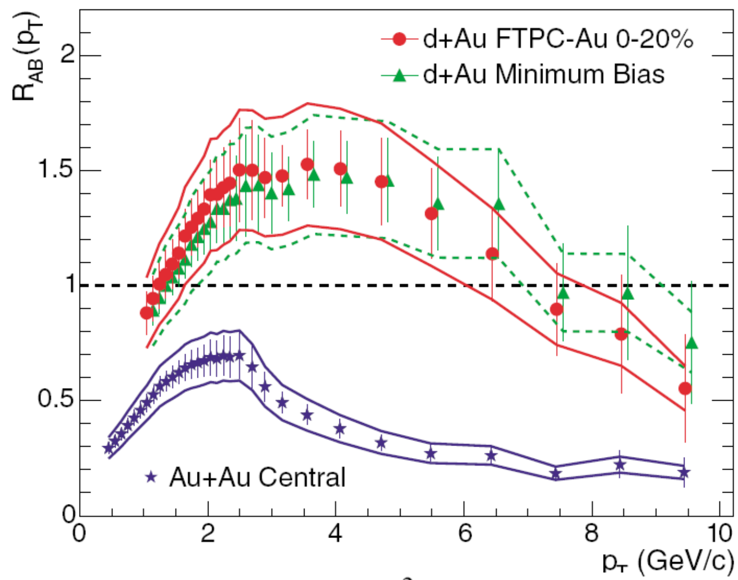
CP: 160<μ_B<500 MeV

Given the significant theoretical difficulties,

data may lead the study of QCD phase diagram

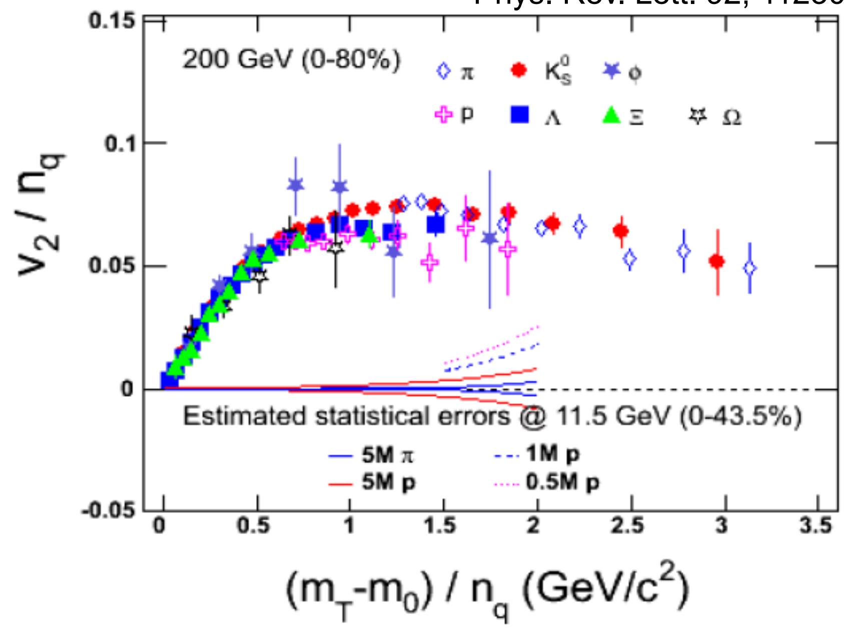
RHIC: indication of QGP presence

Phys. Rev. Lett. 91, 072304 (2003)



$$R_{AB}(p_T) = \frac{d^2N/dp_T d\eta}{T_{AB} d^2\sigma^{pp}/dp_T d\eta},$$

Phys. Rev. Lett. 92, 052302 (2004)
Phys. Rev. C 72, 014904 (2005)
Phys. Rev. Lett. 95, 122301(2005)
Phys. Rev. Lett. 92, 112301(2004)

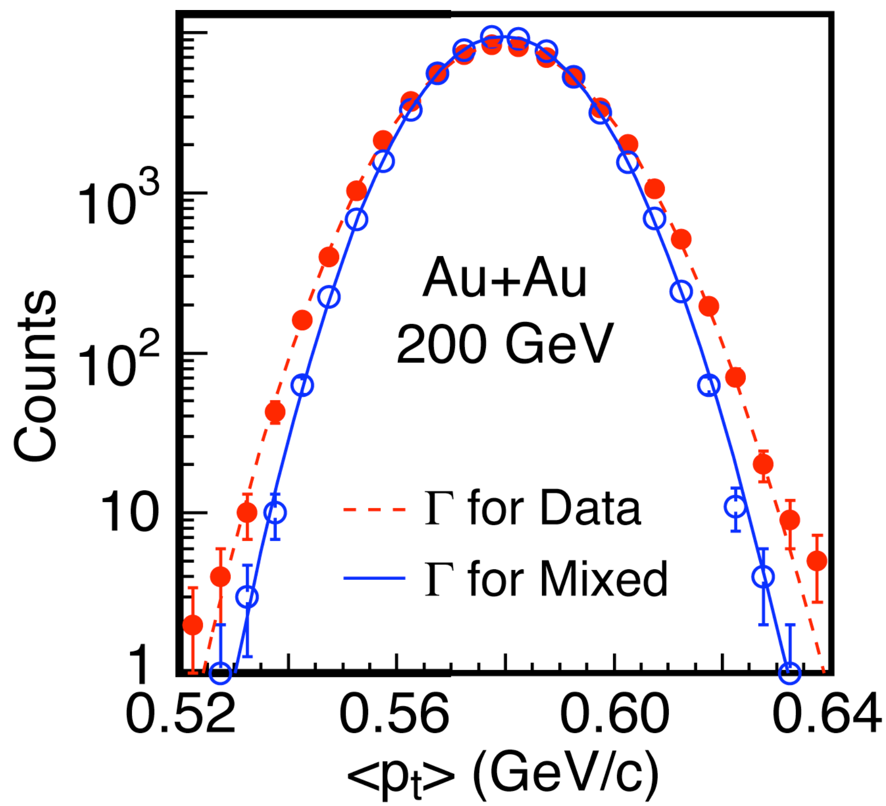


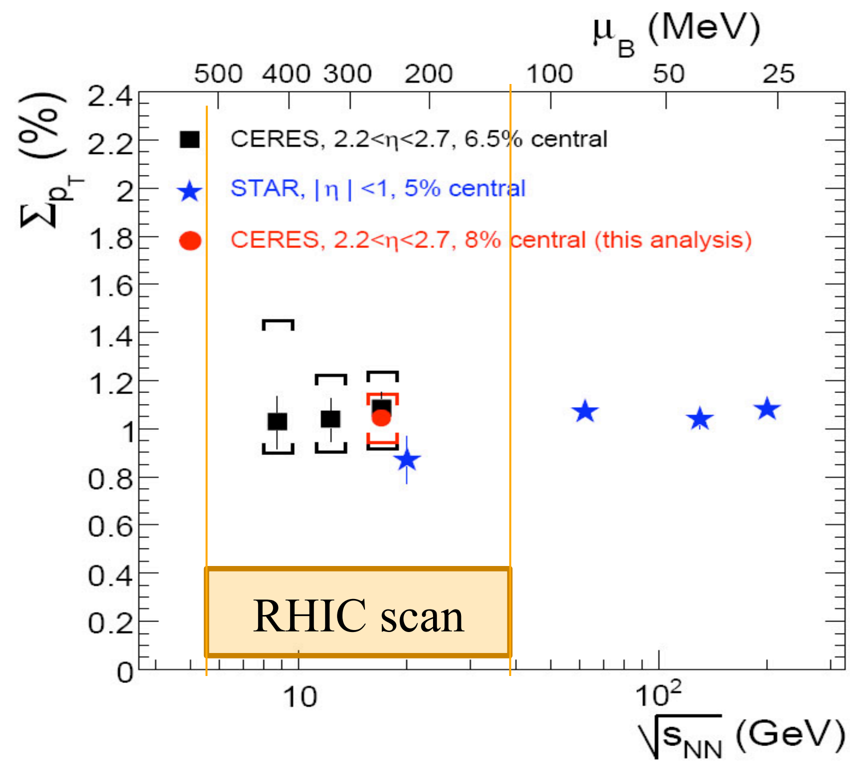
strong suppression of high p_T hadrons

number of constituent quark scaling in v_2 measurements

Where will this break down ?

<p_T> Fluctuations





Long range correlations will induce fluctuations in p_T when the system is in the vicinity of a critical point

See talk by G. Westfall CPOD 2009 Monday