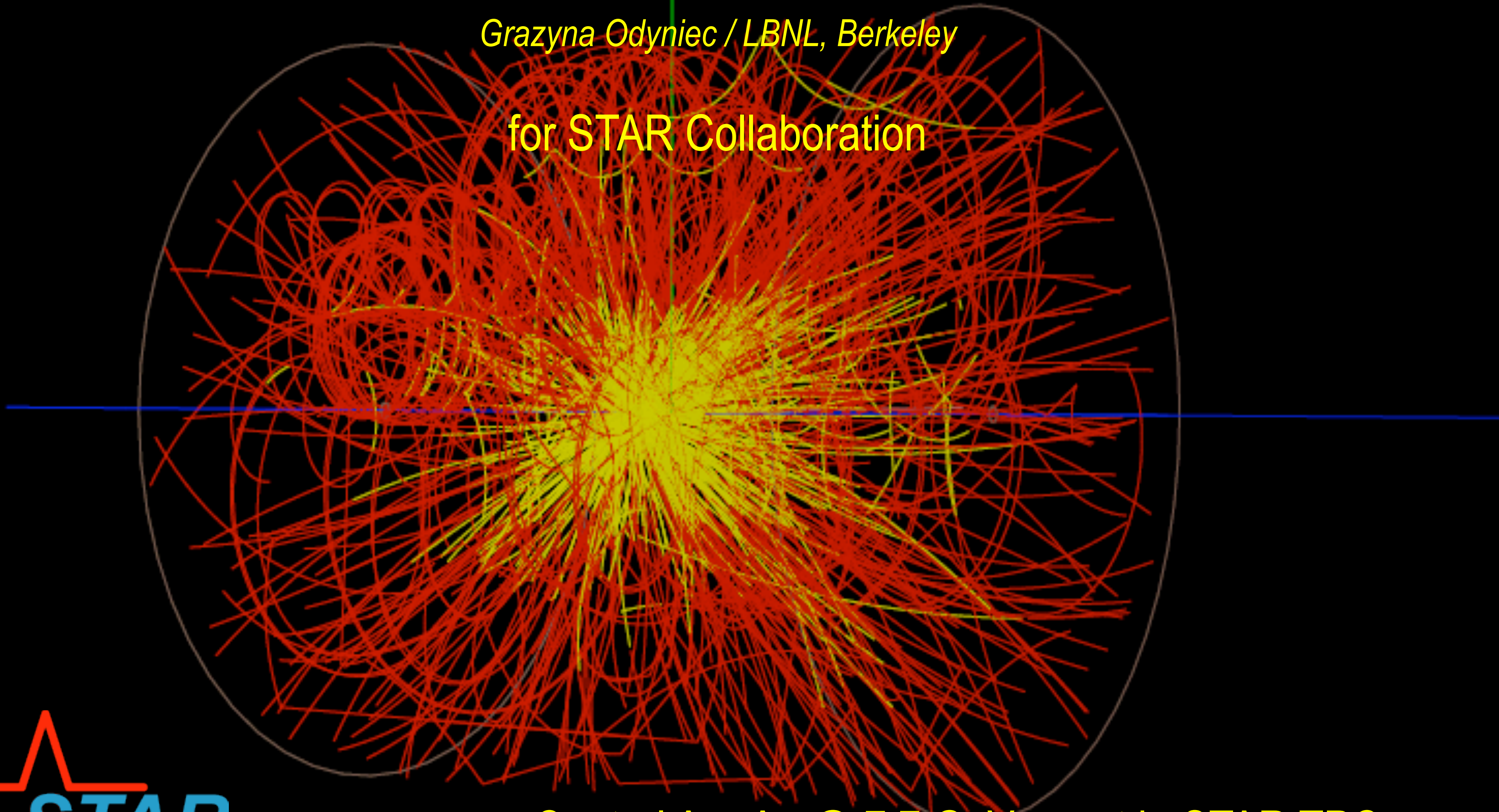
Beam Energy Scan Program in STAR

Experimental Approach to the QCD Phase Diagram

Grazyna Odyniec / LBNL, Berkeley

for STAR Collaboration



Central Au+Au @ 7.7 GeV event in STAR TPC

Outline :

Main goal of BES: study QCD phase diagram

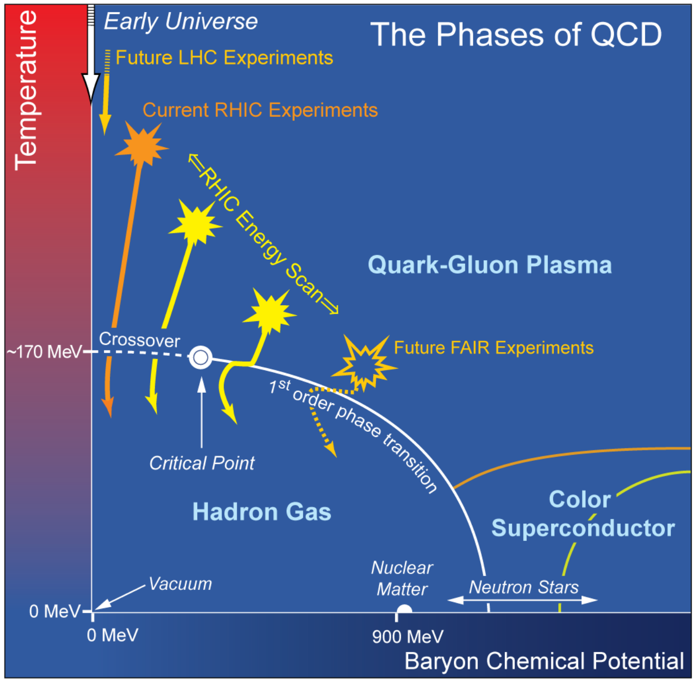
Heavy Ion Collisions – the only experimental tool

BES @ RHIC: Physics goals and observables:

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

Run 10 (2010) – STAR experience

Run 11 (2011)



USA-NSAC 2007 Long-range Plan

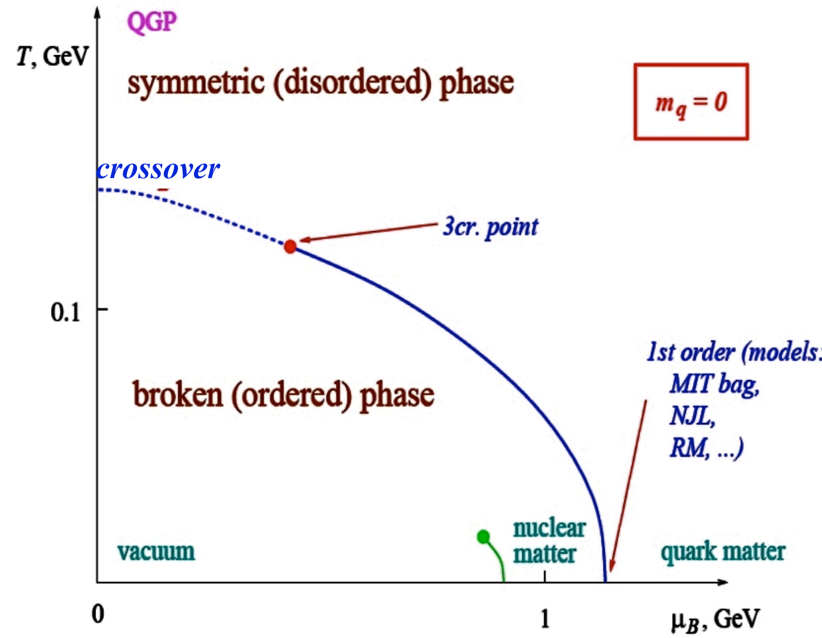
QCD phase diagram - Theory

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 predict a1-st order transition at large μ_B

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



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

⟶ CP range: $160<\mu_B<500$ MeV

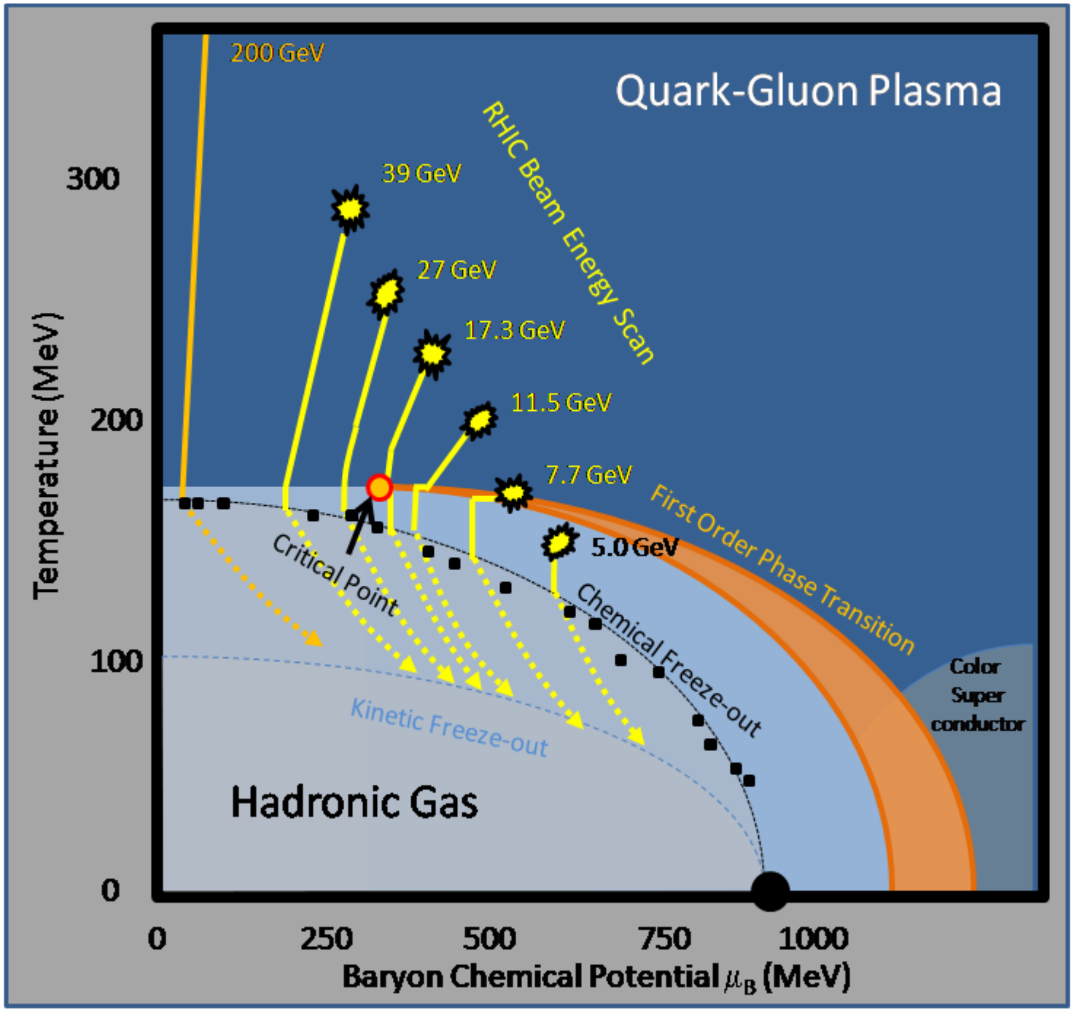
Given the significant theoretical difficulties, data may lead the study of QCD phase diagram

➡ Beam Energy Scan Program at RHIC will cover this range

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

experimental window to QCD phenomenology

at finite temperature and baryon number density



at RHIC : indications of sQGP but remain unknown:

- boundary between hadronic and partonic phases
- critical point

HOW to investigate it ?

BES @ RHIC

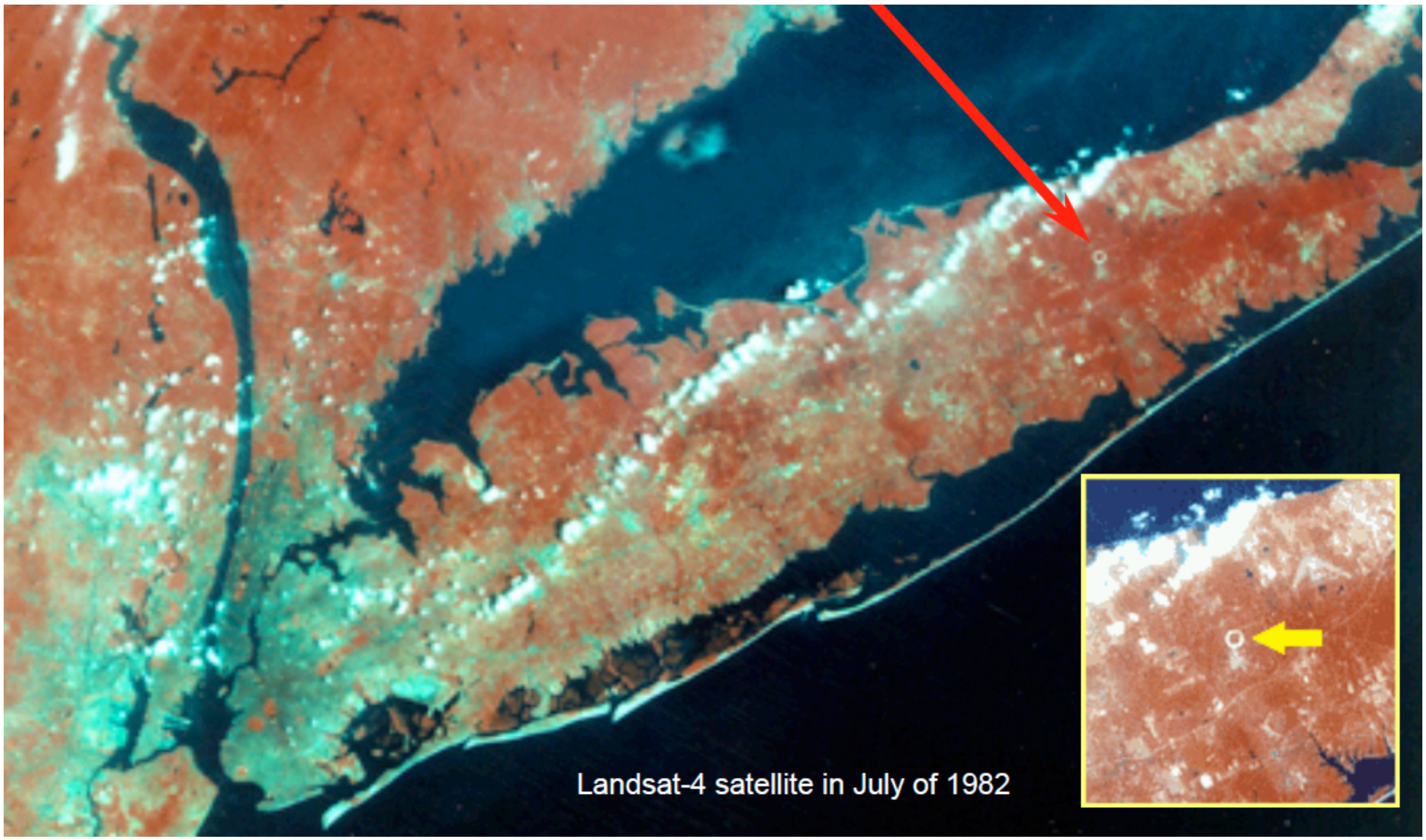
160 MeV<μ_B<500 MeV

also: NA61 at SPS, FAIR at GSI (fixed target), MPD at NICA

RHIC and BNL from space

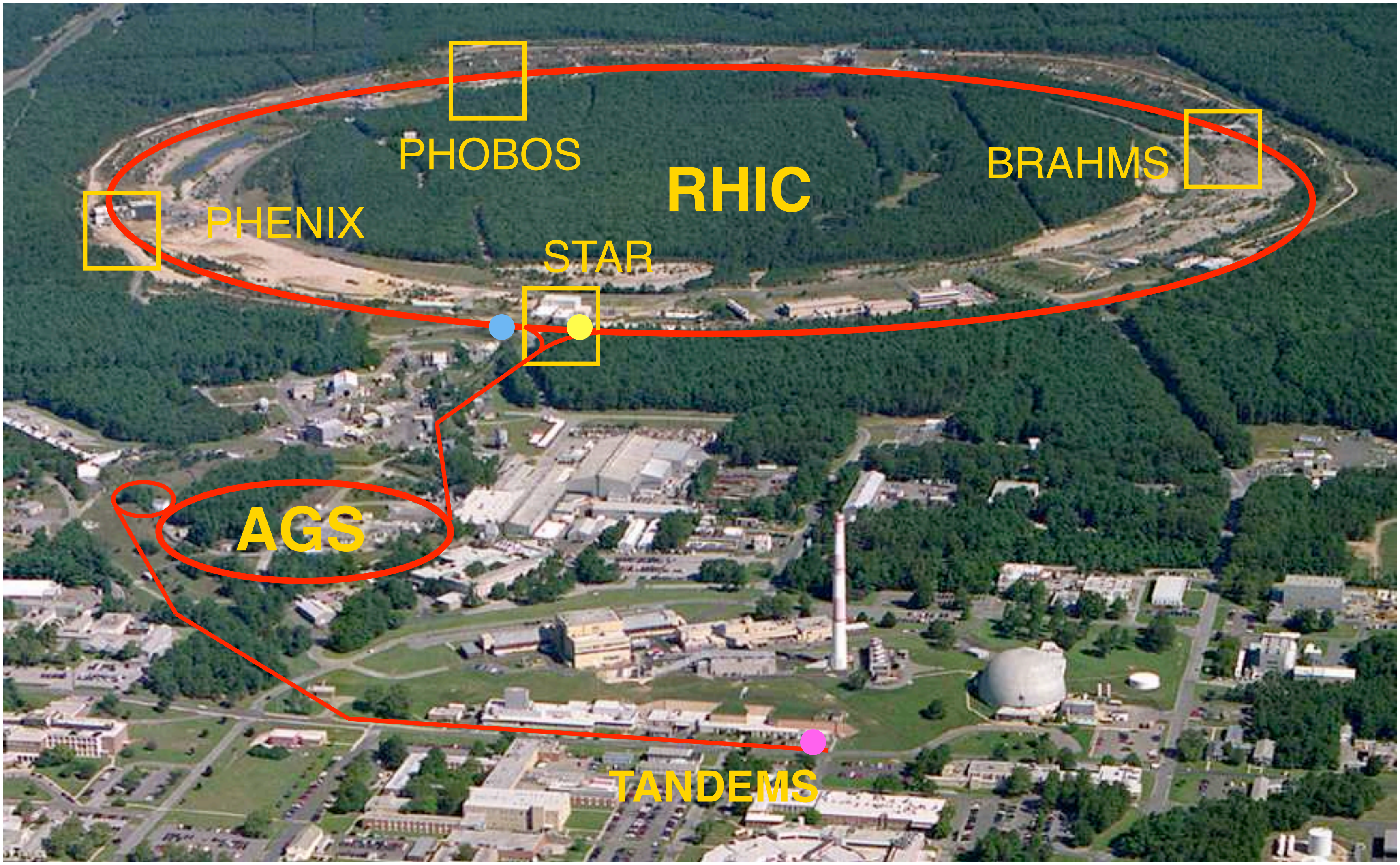
RHIC = Relativistic Heavy Ion Collider

Located at BNL= Brookhaven National Laboratory

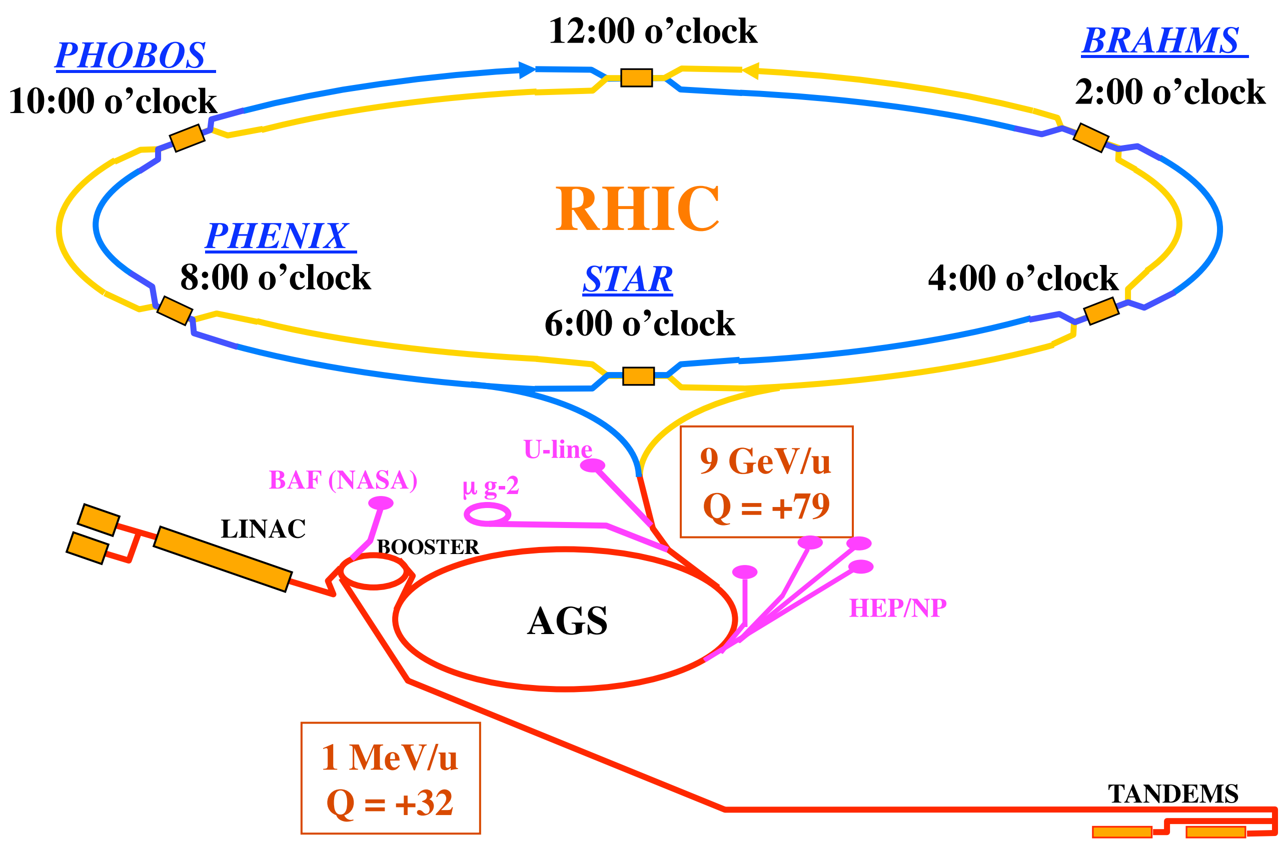


Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY



Relativistic Heavy Ion Collider (RHIC)



- 2 concentric rings of 1740 superconducting magnets
- 3.8 km circumference
- counter-rotating beams of ions from *p* to Au
- max center-of-mass energy: AuAu 200 GeV, pp 500 GeV

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
- …

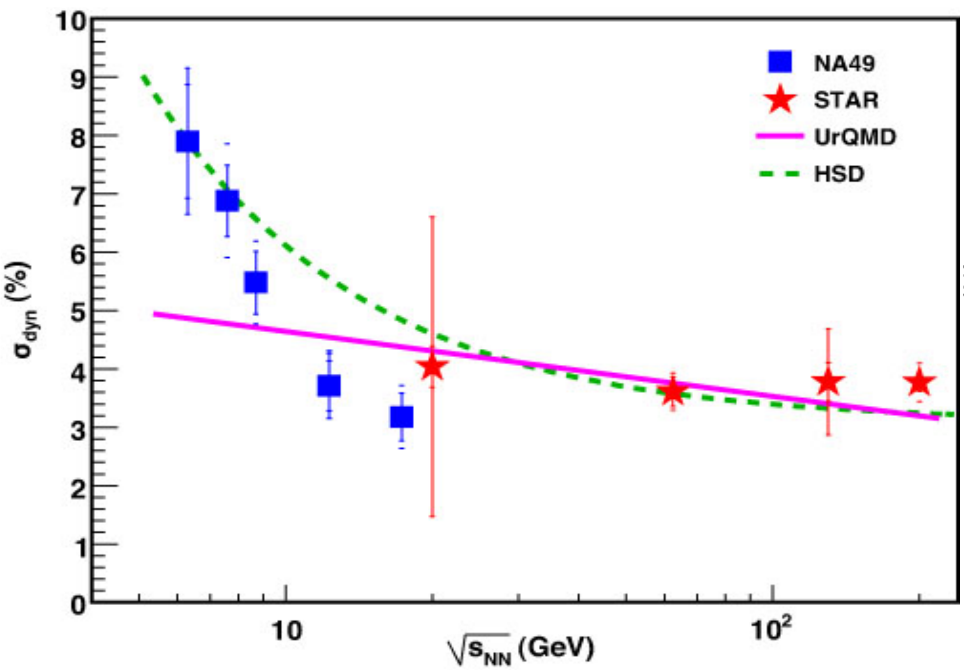
(2) disappearance of signals of partonic degrees of freedom seen at 200 GeV

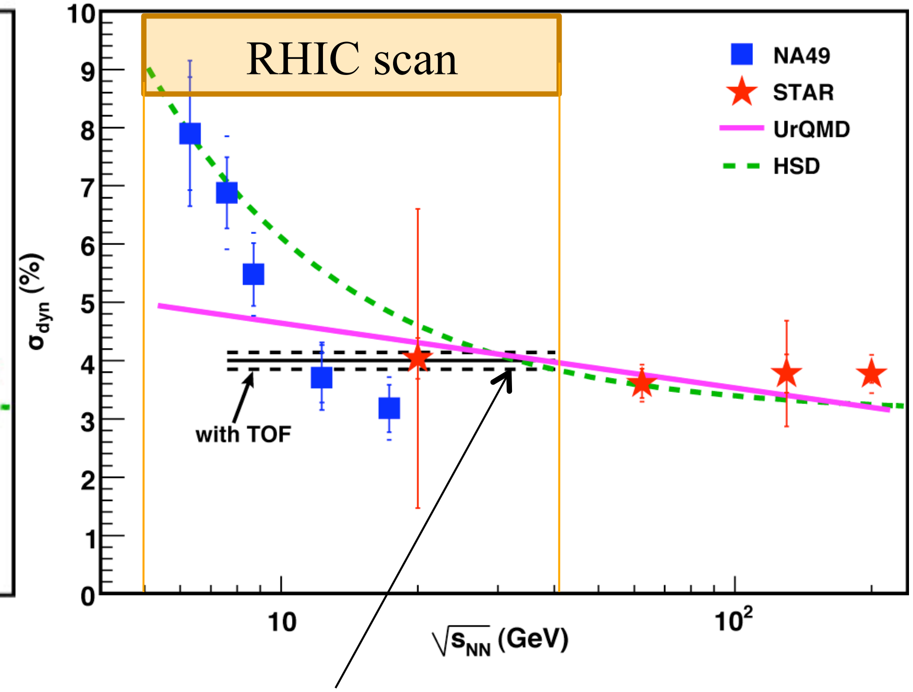
- disappearance of constituent-quark-number scaling of v_2 ★
- disappearance of hadron suppression in central collisions
- disappearance of ridge
- local parity violation
- …

Critical Point search – Fluctuations maximized at CP

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

PRL 103, 092301 (2009)





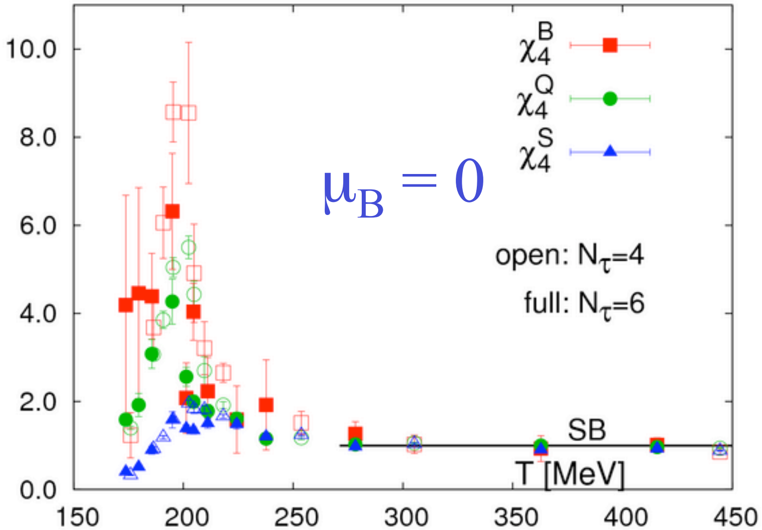
Expected error with 250 k central events

NA49 fluct. > STAR fluct. ?

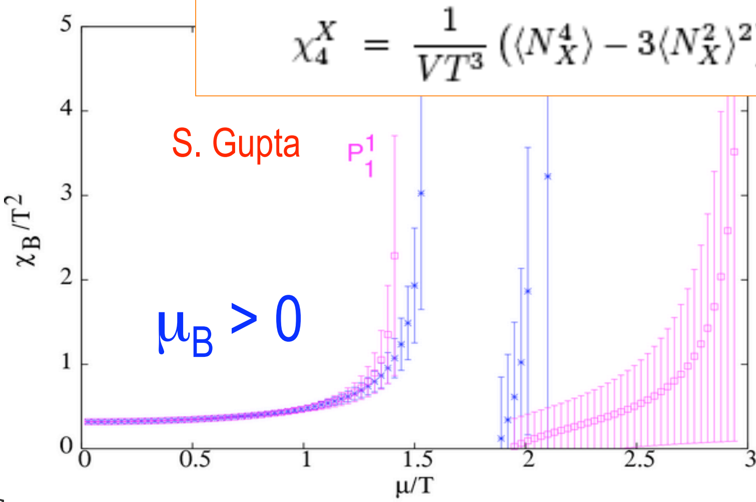
CP at lower energies ? (but diff. acceptance).

see Terry Tarnowsky talk

more sensitive : - Higher Moments



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



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

<u>Lattice QCD</u>: 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)
Gavai and Gupta, Phys. Rev. D 78,114503 (2008);
Gupta, arXiv:0909.4630 [nucl-ex].

<u>Observable:</u>

Kurtosis of net-proton & net-C

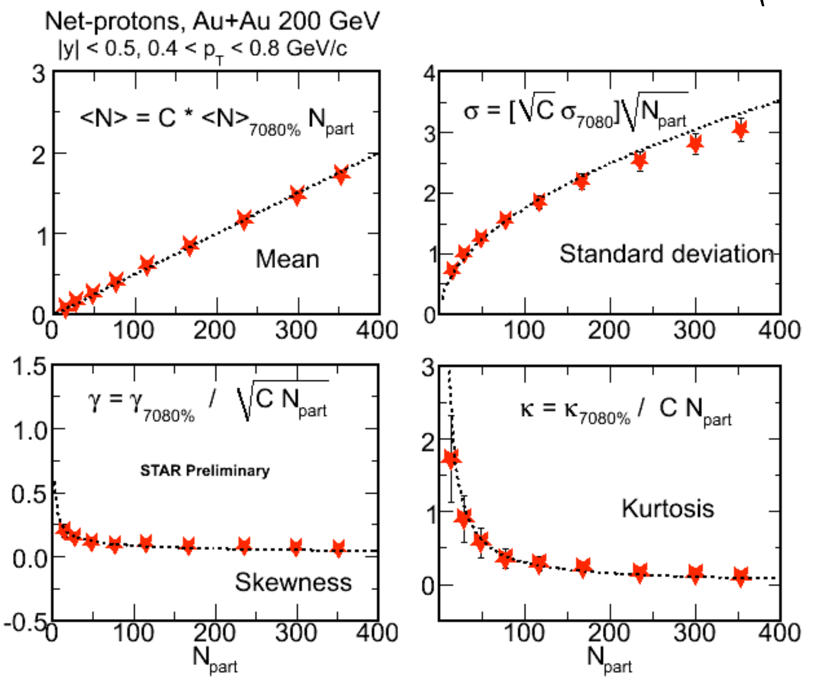
- *connect to lattice calculations!*
- *sensitive to long range fluctuations*

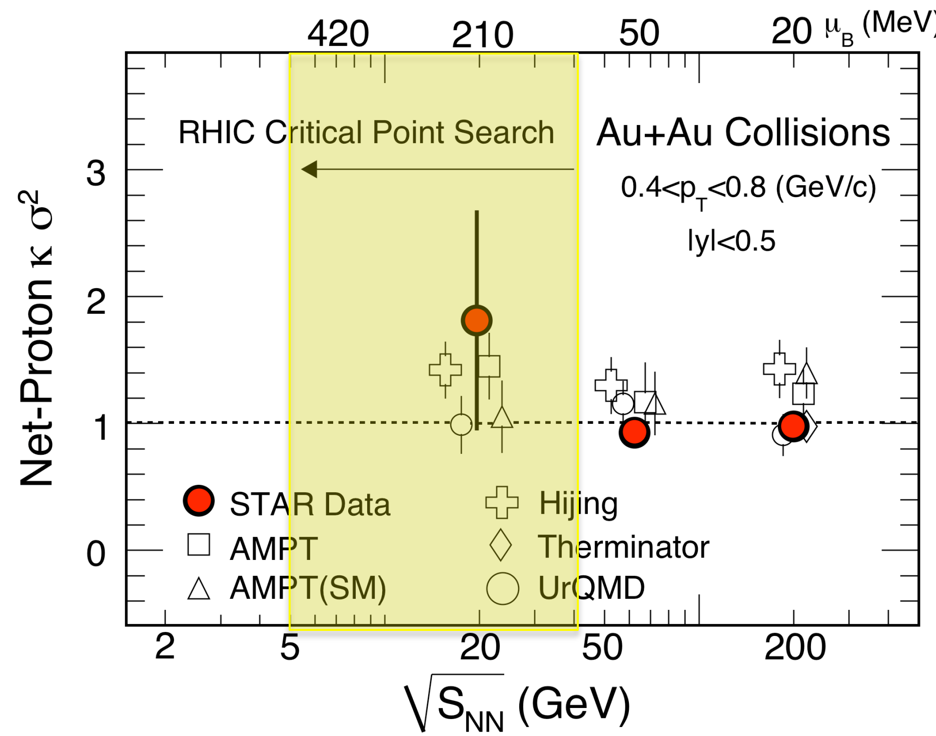
<u>Caveats</u>: dynamical effects in collisions

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

Higher Moment Analysis (BES)

STAR: PRL 105 (2010) 022302, aXiv:1004.4959





High moments are more sensitive to critical point related fluctuation.

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

Monotonic behavior observed at relatively small μ_B region ⟶ baseline

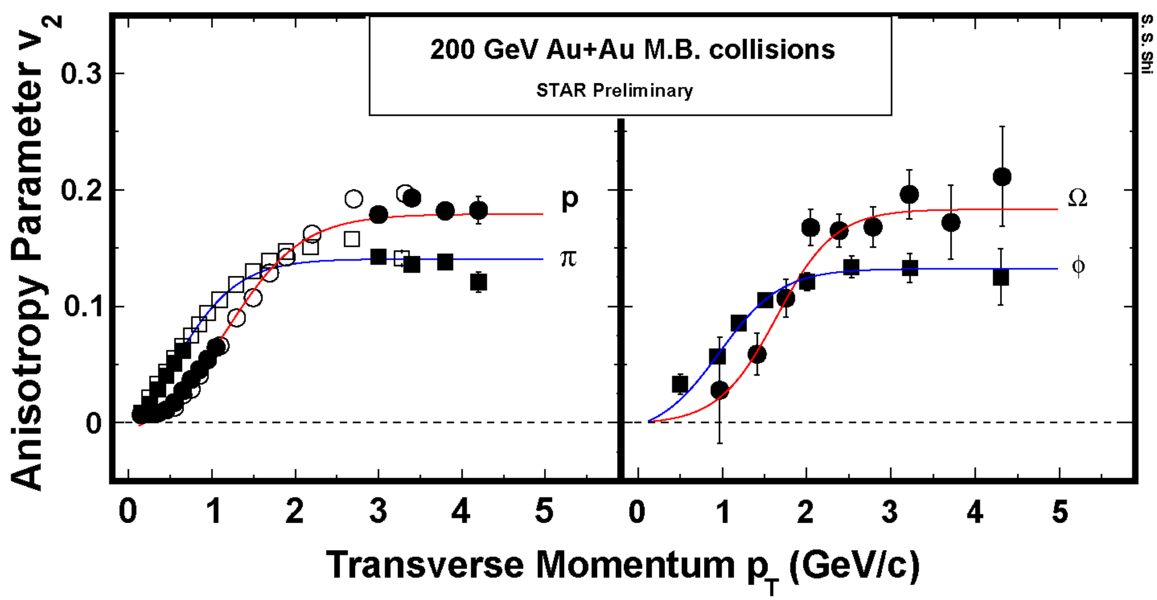
See Hans Georg Ritter talk

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, arXiv: 0907.2265

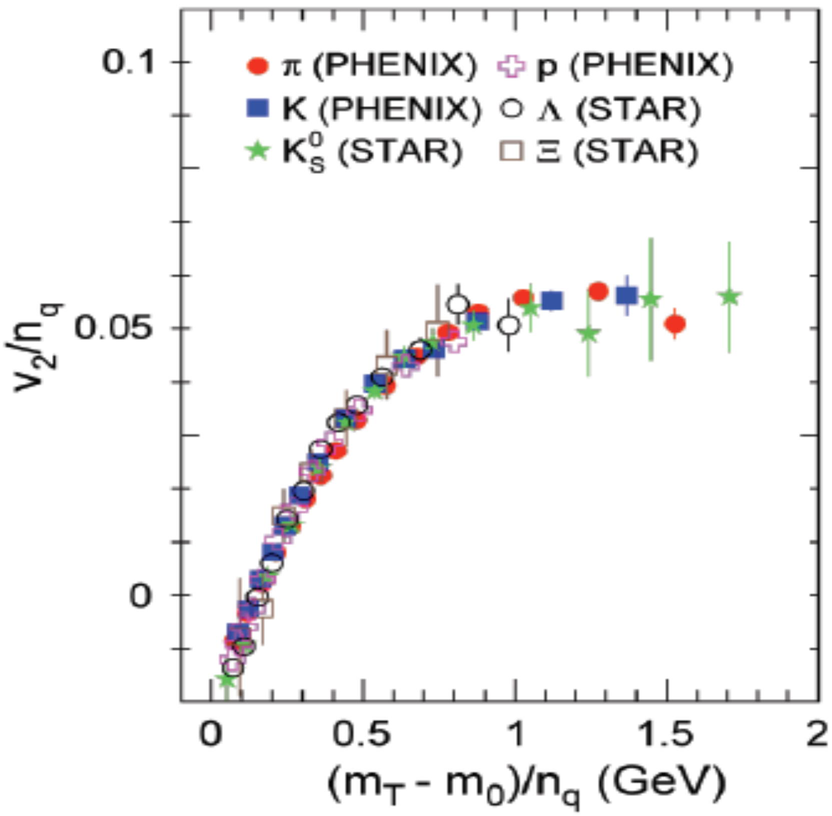


(1) Mass separation at low p_T

(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)



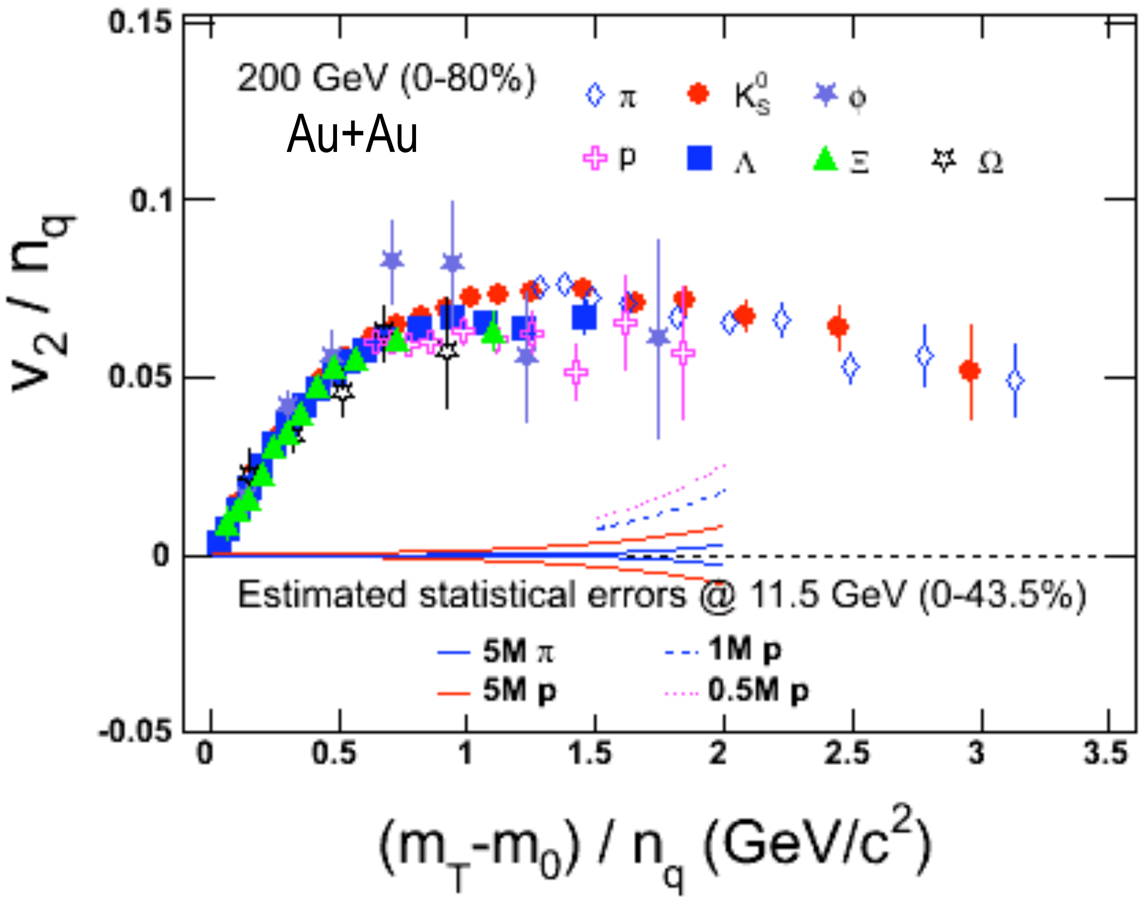
Scaling flow parameters by quark content n_q (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons

flow developed in pre-hadronic stage
DECONFINEMENT at RHIC

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

Will we be able to see it ?

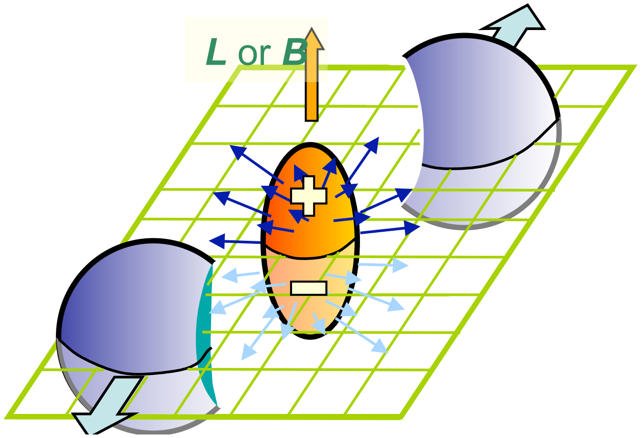
PRL 92, 052302(04), 95, 122301(05), nucl-ex/0405022, QM05



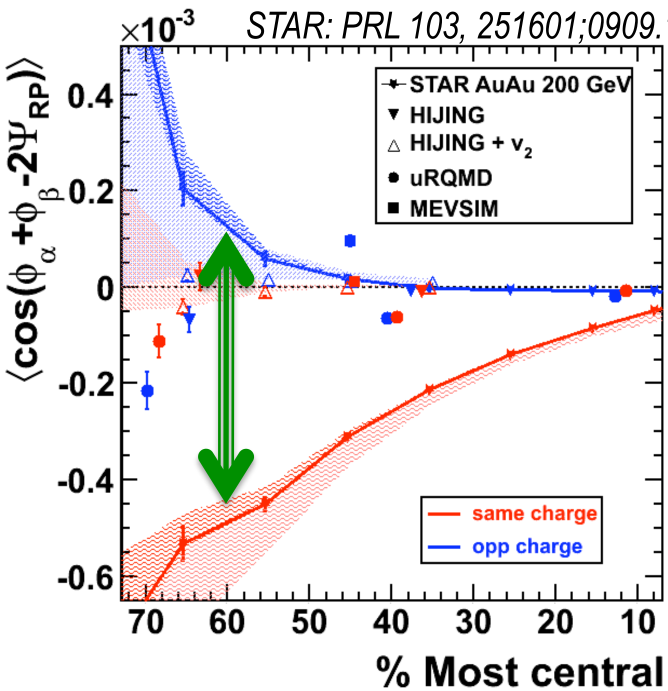
Yes, a few million events is enough !

Local Parity Violations in Deconfined Medium

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



STAR: PRL 103, 251601;0909.1717(PRC)



(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.

Parity even observable: $\left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{RP}\right)\right\rangle$

Voloshin, PR C62, 044901(00),

(3) In RHIC Beam Energy Scan program - test the model prediction

- the energy when the charge separation disappear => phase boundary

see Sergei Voloshin talk

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**

http://www.bnl.gov/npp/pac.asp

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

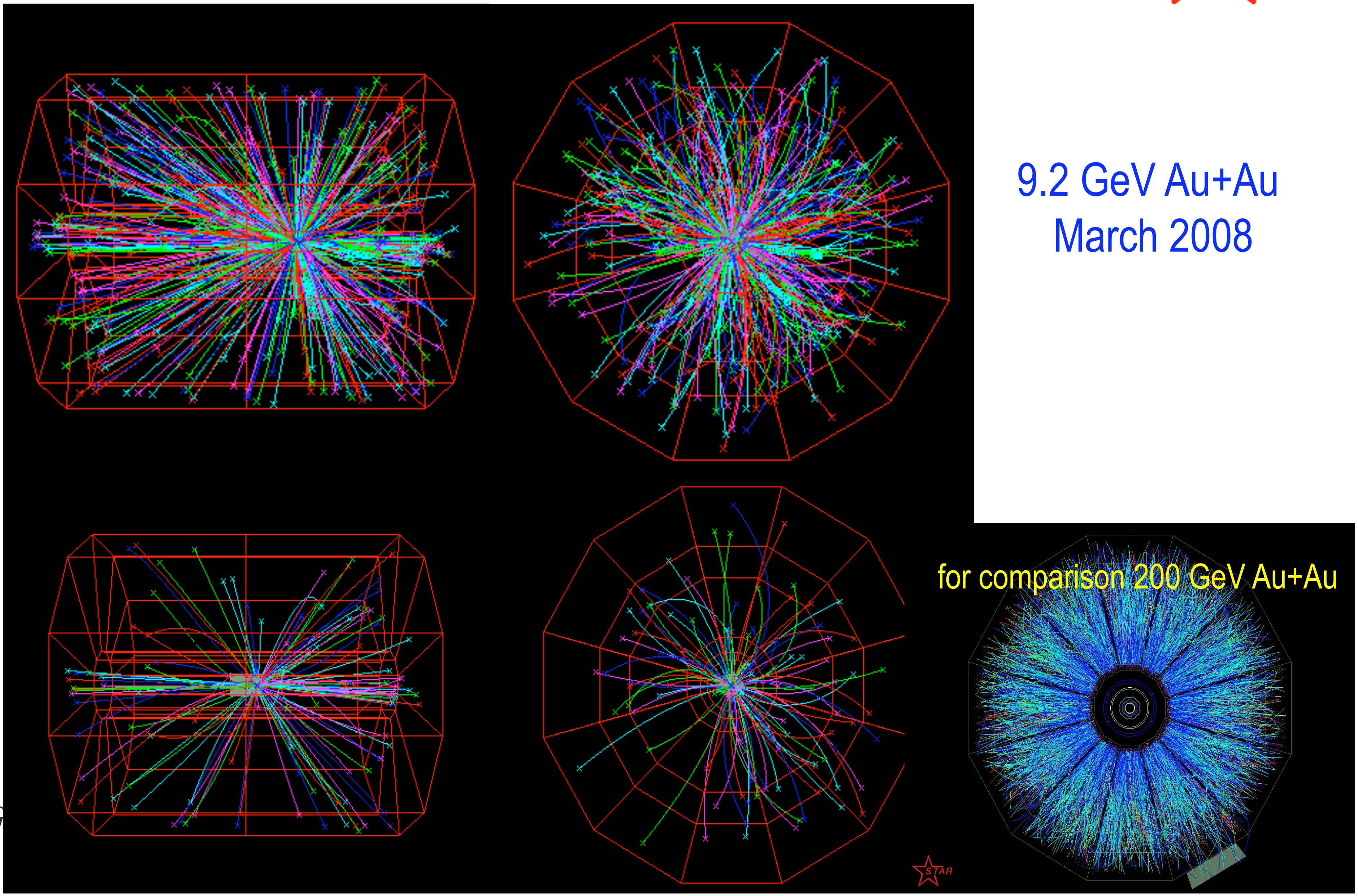
Run 10 (2010):

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)

Sufficient rates for the initial physics program at all energies

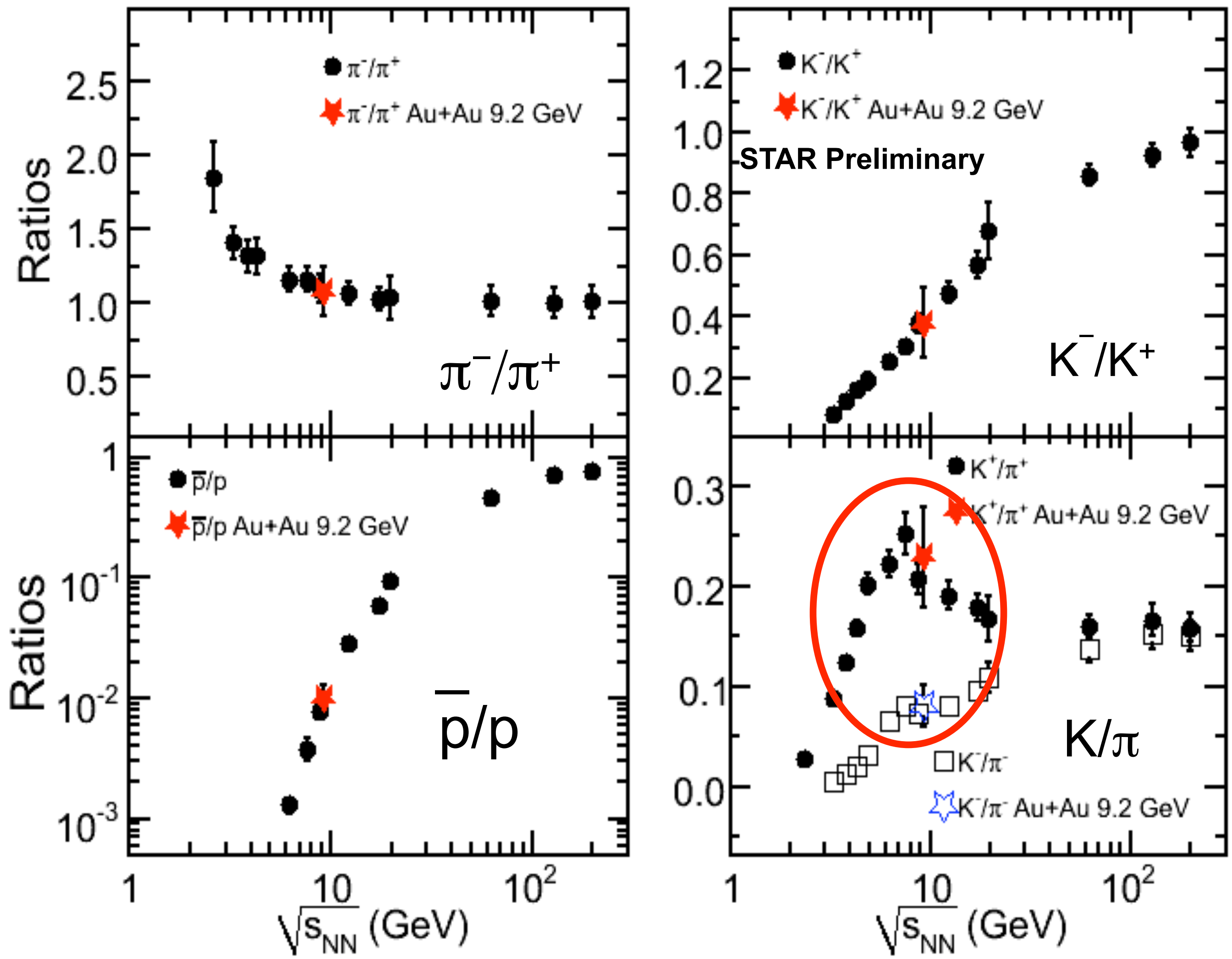
"binary" experiment: YES/NO (no "maybe's" & more statistics needed)

STAR experience with low energy running



9.2 GeV Au+Au
March 2008

STAR experiment demonstrated capabilities



only a few 10^3 events taken during machine test

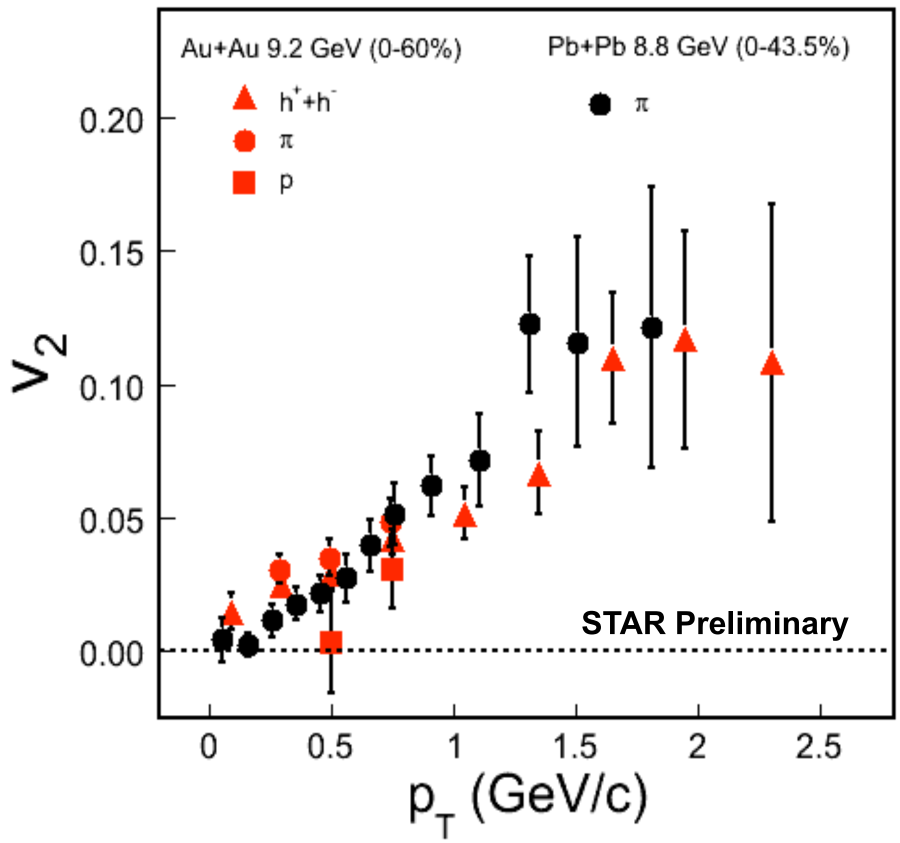
9.2 GeV results consistent with the published data

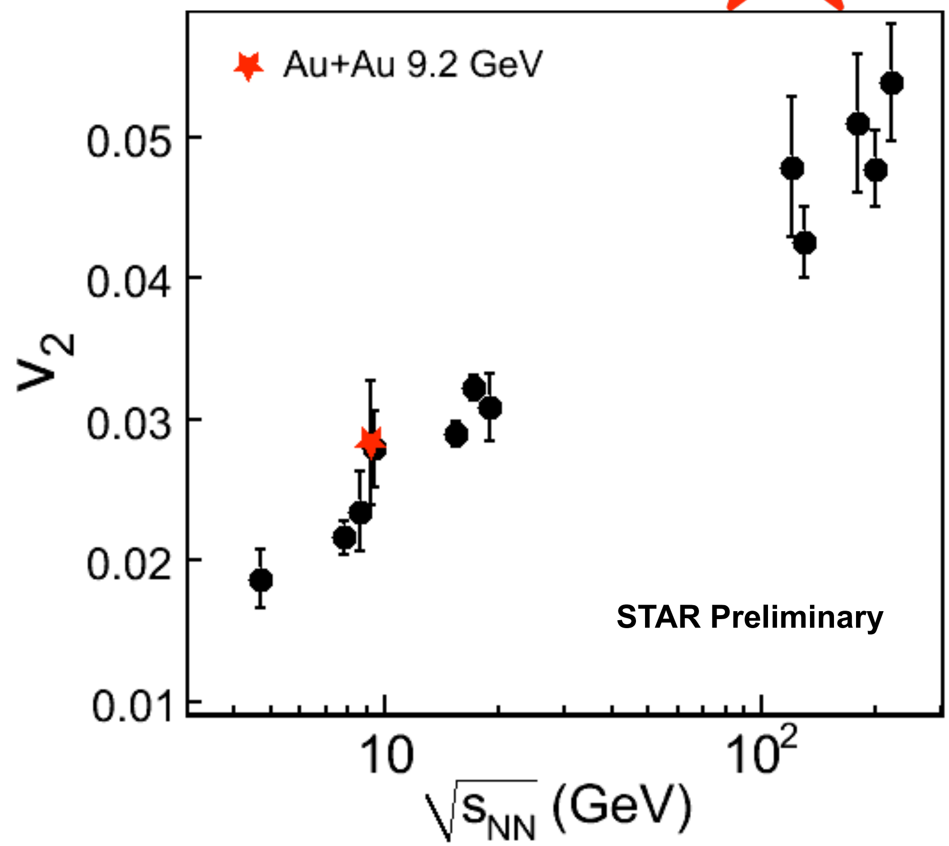
STAR : PRC 79 (2009) 034909, arXiv: 0903.4702

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



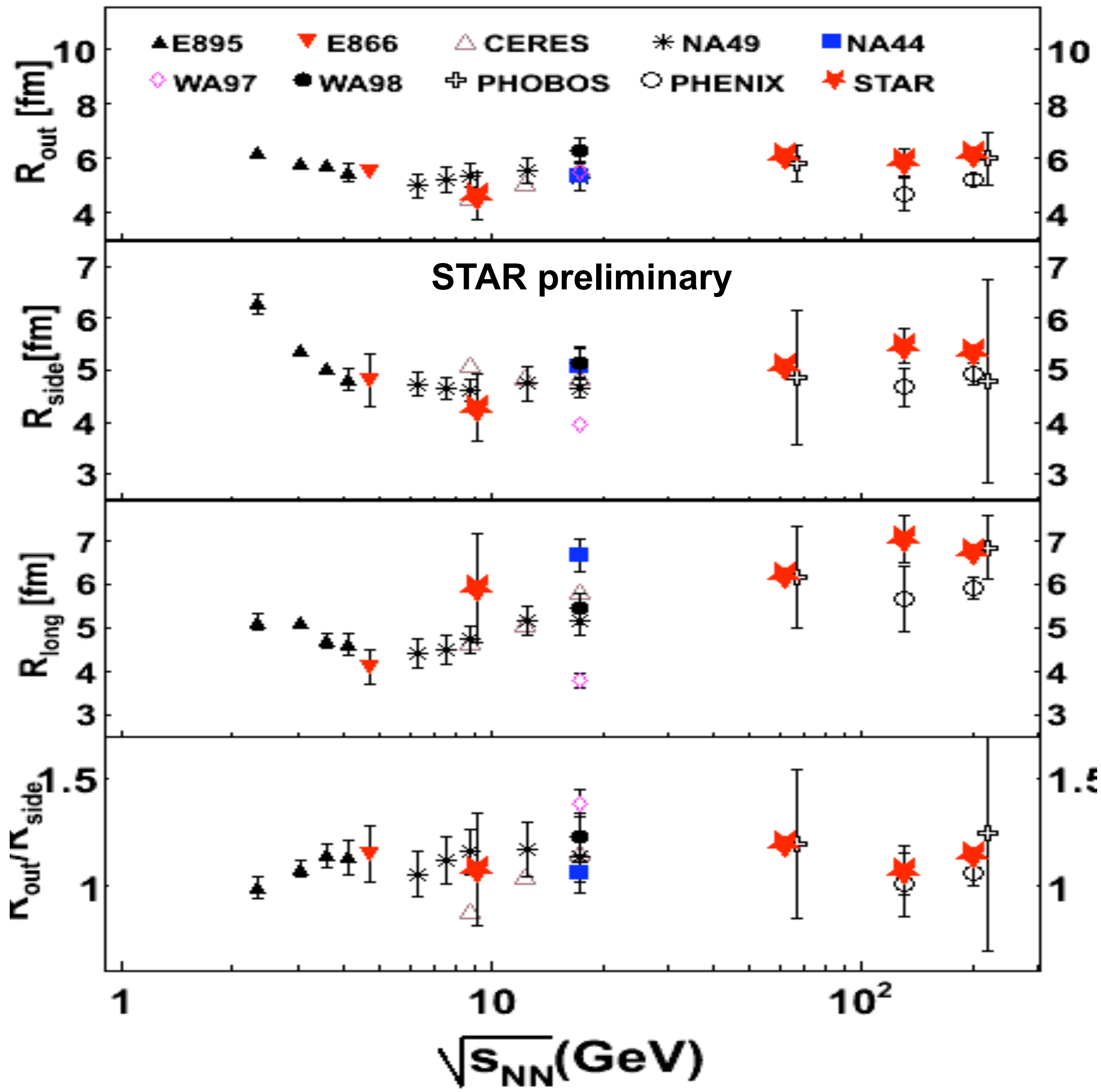


NA49 : PRC 68 (2003) 034903
AGS : PLB 474 (2000) 27
STAR : PRC 77 (2008) 054901 : PRC 75 (2007) 054906, PRC 72 (2005) 014904
PHOBOS : PRC 72 (2005) 051901 : PRL 98 (2007) 242302
PHENIX : PRL 98 (2007) 162301

STAR and NA49 results are consistent

STAR 9.2GeV v_2 fits with the observed trends

Pion Interferometry



π^-

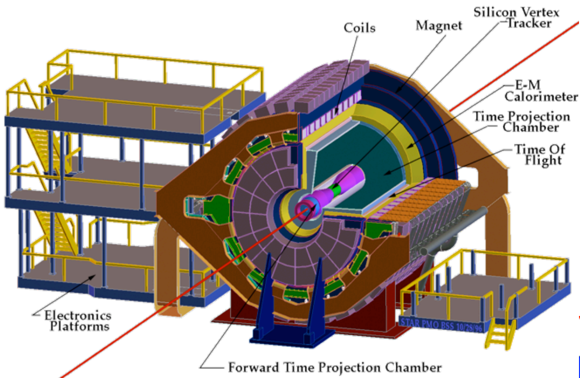
error bars for Au+Au 9.2 GeV are statistical
systematic errors < 10 % for all radii

STAR : PRC 71 (2005) 044906, PRL 87 (2001) 082301
PHENIX : PRL 88 (2002) 192302, PRL 93(2004) 152302

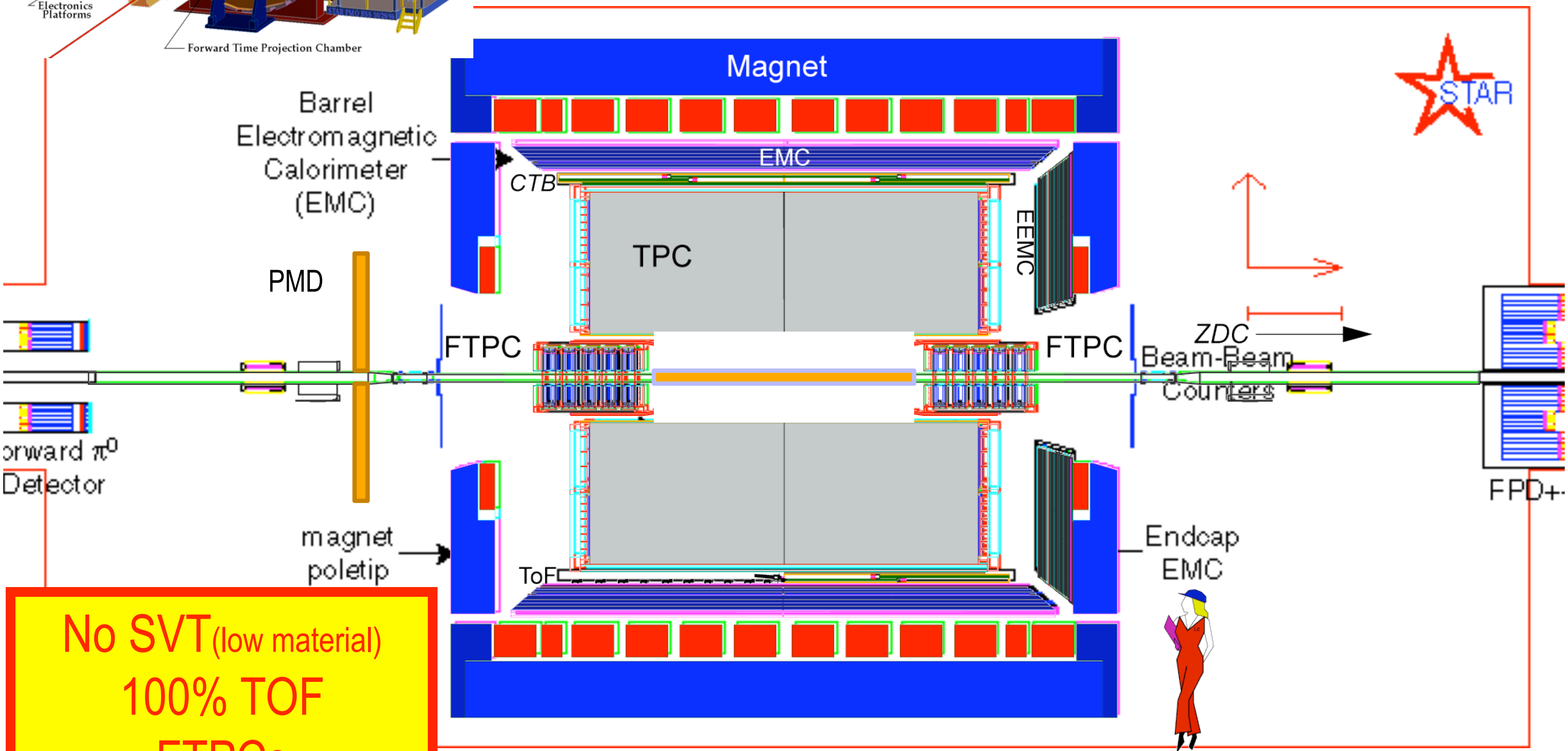
E802 : PRC 66 (2002) 054906
CERES : NPA 714 (2003) 124
E895 :PRL 84 (2000) 2798
PHOBOS : PRC 73 (2006) 031901
NA44 : PRC 58 (1998) 1656
E866 : NPA 661 (1999) 439
NA49 : PRC 77 (2008) 64908
WA97 : JPG 27 (2001) 2325

Phys. Rev. C 81, 024911(2010)

STAR was well prepared for the Beam Energy Scan Program in Run 10 !



STAR Experimental Configuration for Run 10 (2010)



No SVT (low material)

100% TOF

FTPCs

Large beam pipe

Run 10 – Part I of BES@RHIC

Hardware and operation improvements

Main directions of Beam Energy Scan program at RHIC established:

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

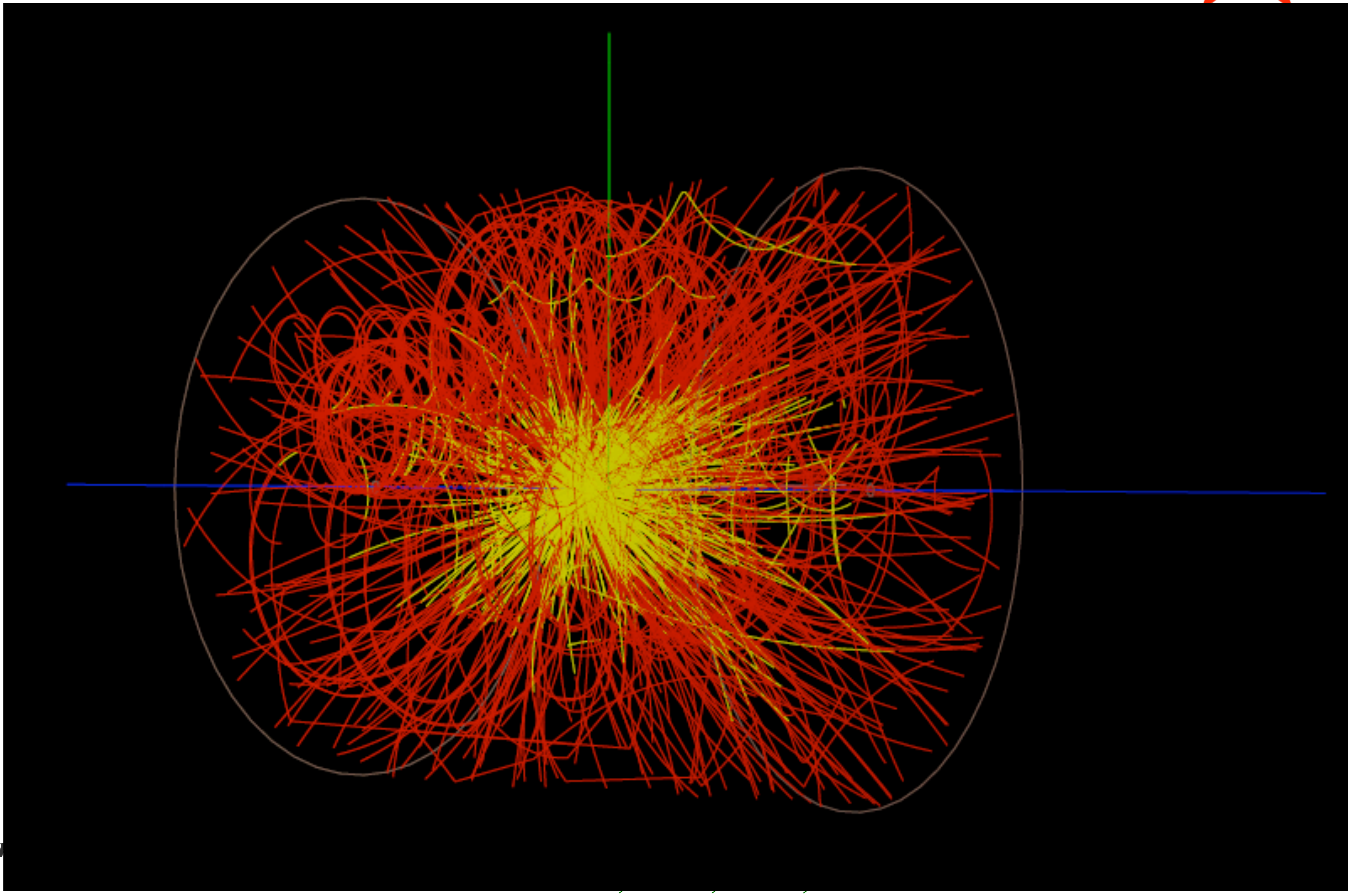
Strategy: scan available phase space with (6) equally spaced points between 5 and 39 GeV (we already have 62, 130, 200 data), and return to "interesting" regions for more detailed studies in the next year

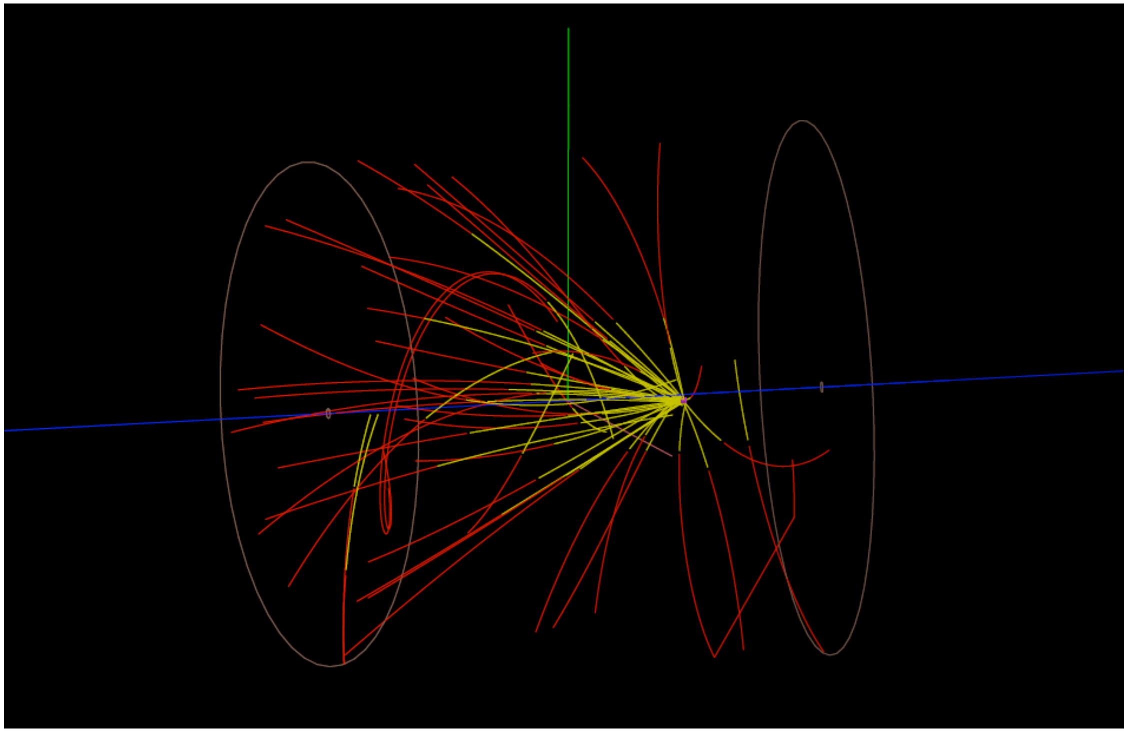
Train left the station on April 8th
with 39 GeV Au+Au collisions …

Run 10 :
39, 7.7 and 11.5 GeV Au+Au

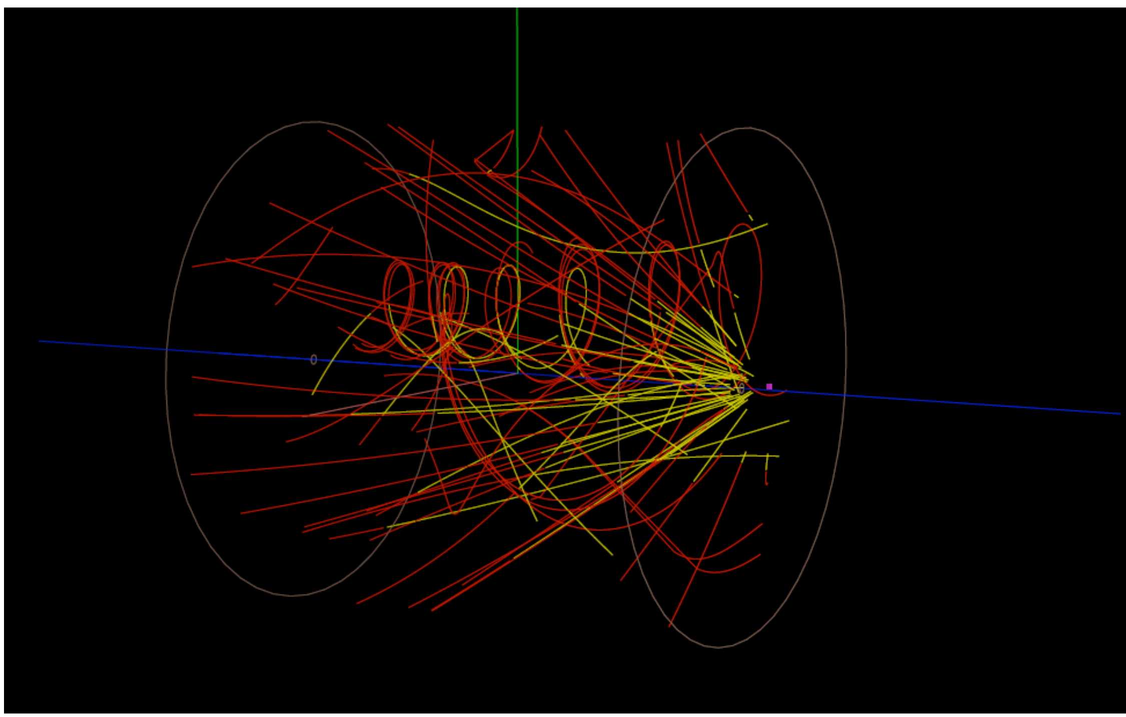
to be continued (Run 11) next year

Central Au+Au @ 7.7 GeV Event



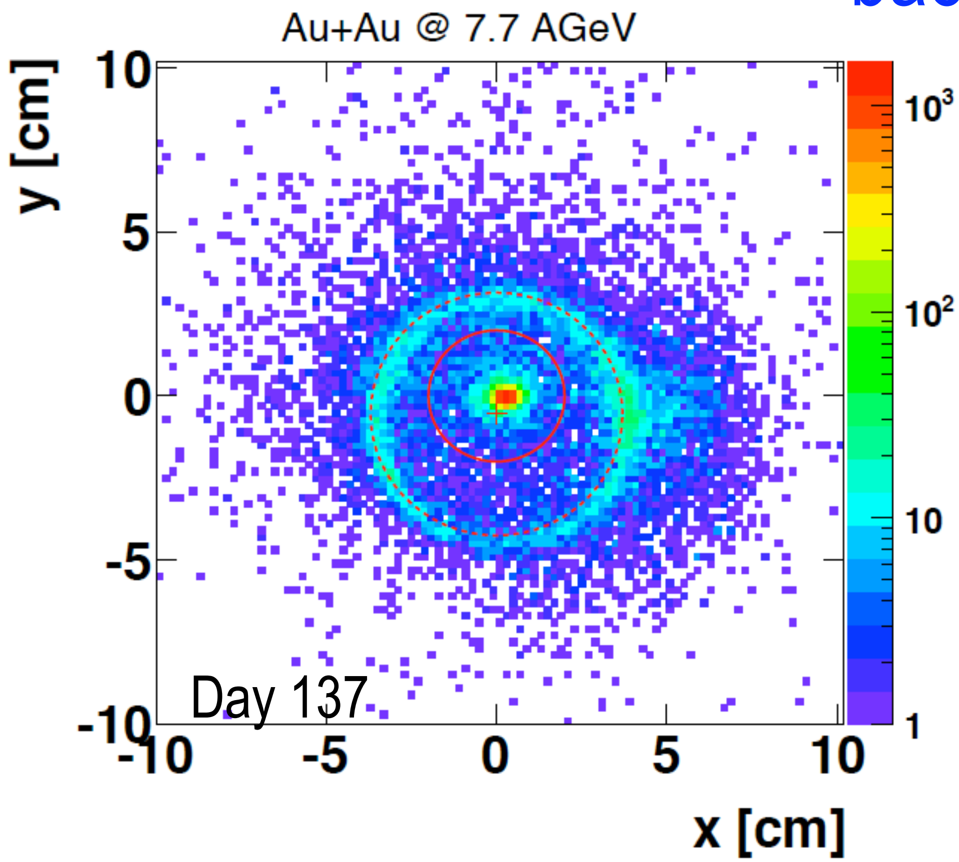


Typical Au+Beam-pipe @ 3.85 GeV event



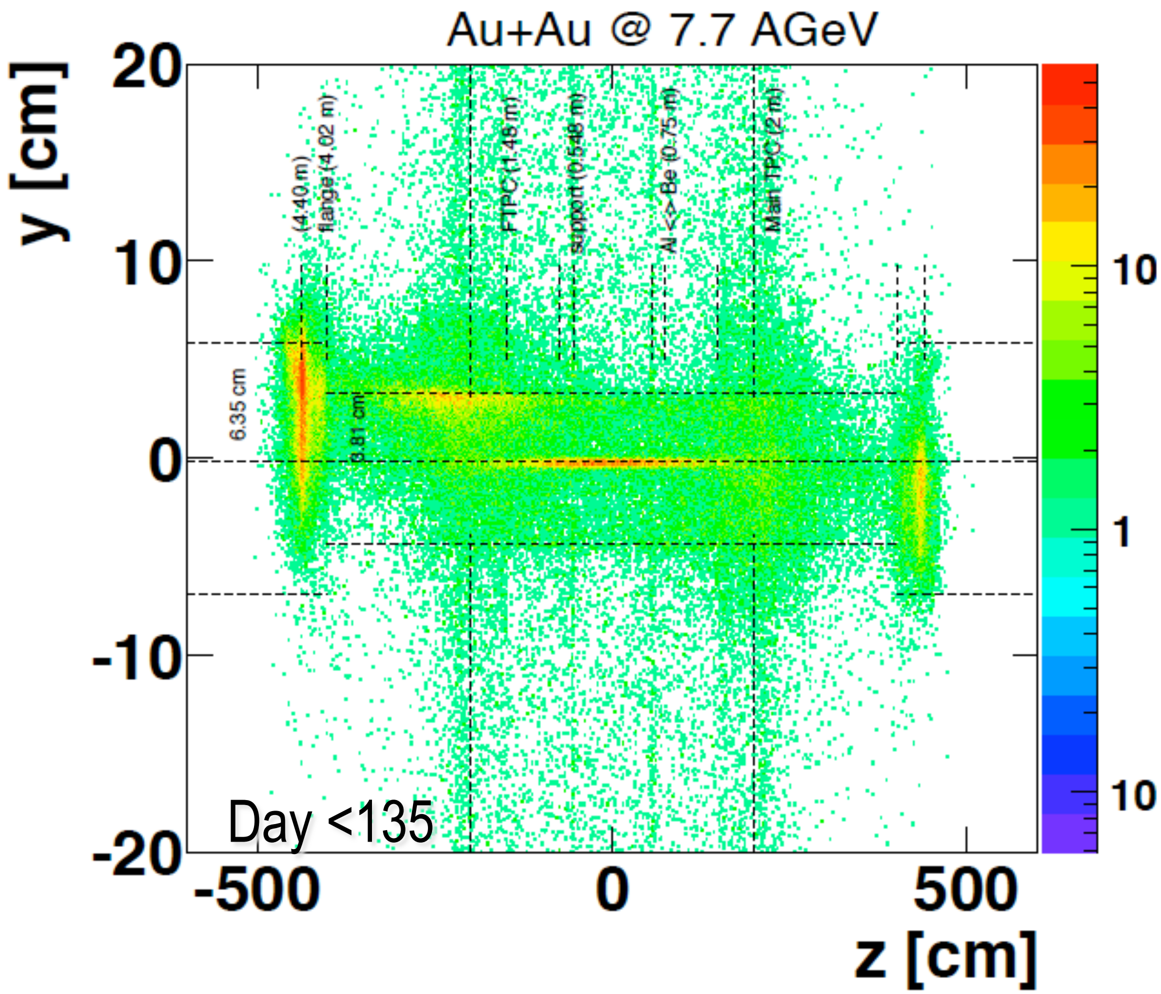
Event outside active TPC volume

Au+Au @ 7.7 AGeV - vertex reconstruction
- background !



- Au+beam-pipe events from the beam halo

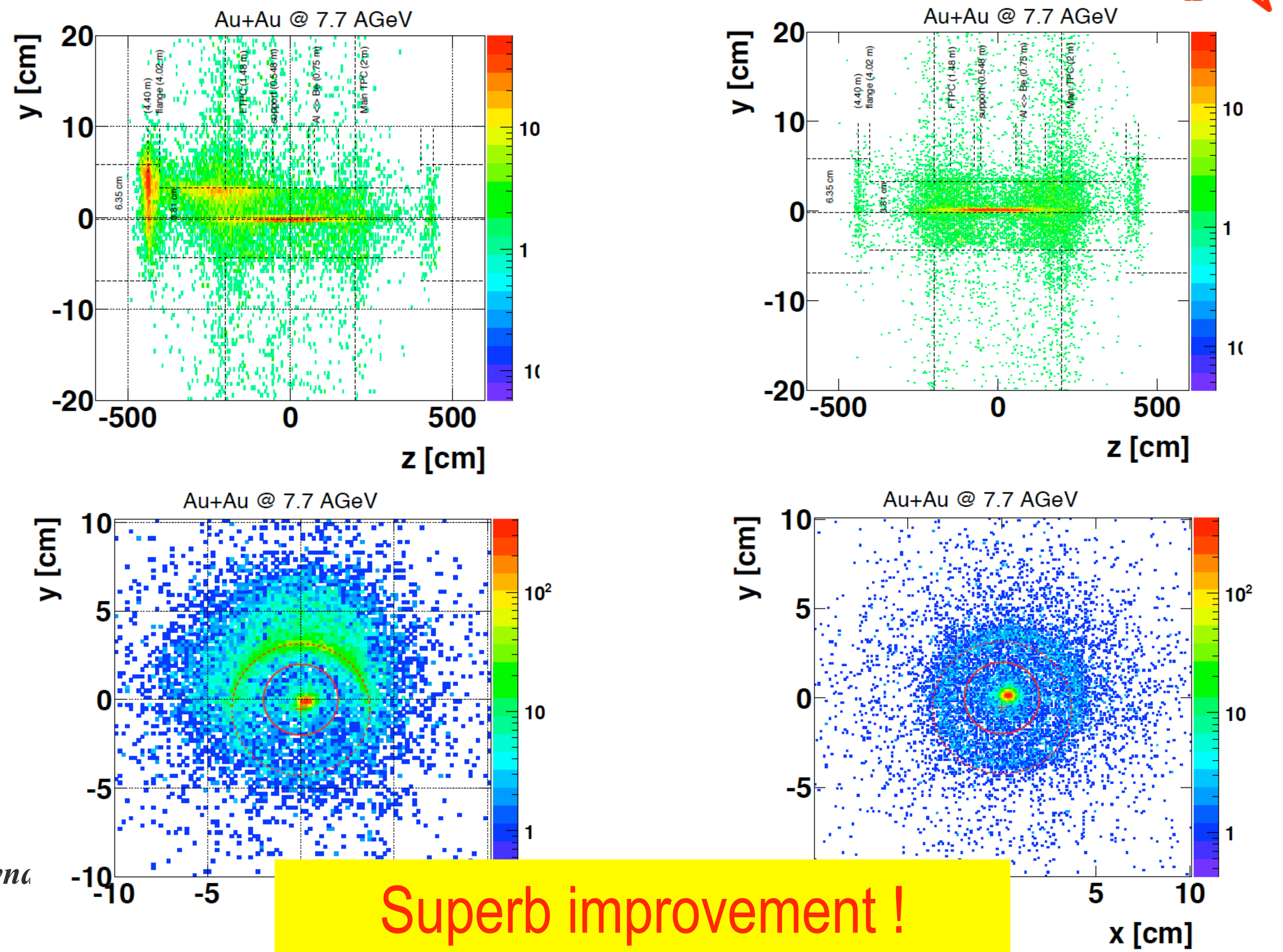
Au+Au @ 7.7 AGeV – sources of background



Two flanges at ± 4.4 m outside the TPC produced most of the background at the first days

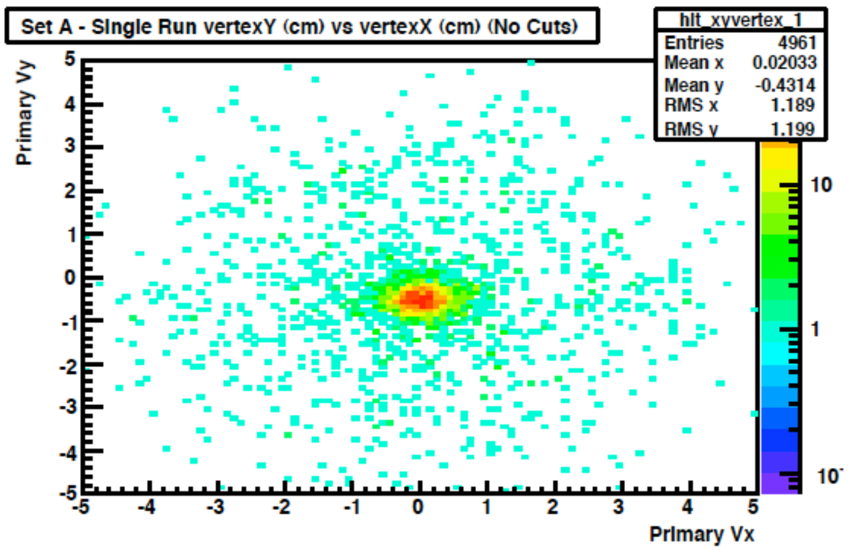
vertex distributions though the run …

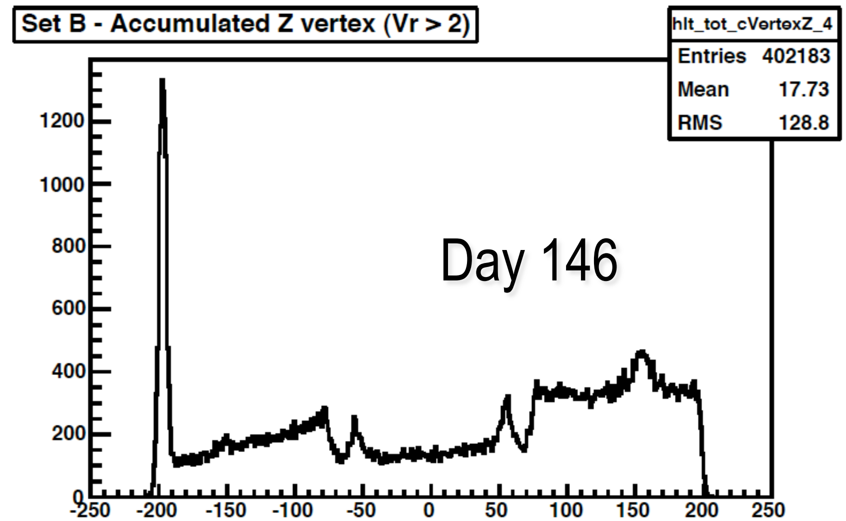
middle: Day 130 | end: Day 147



Superb improvement !

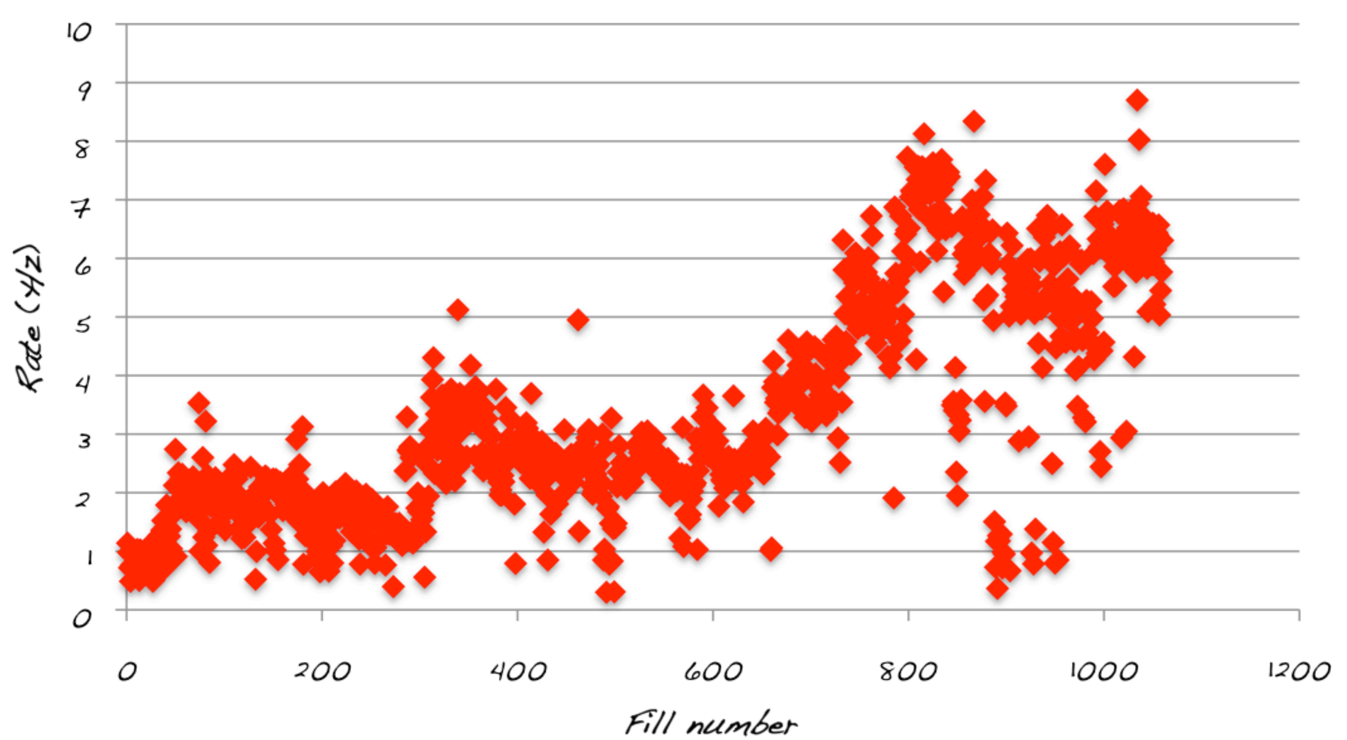
High Level Trigger (HLT): Vertex





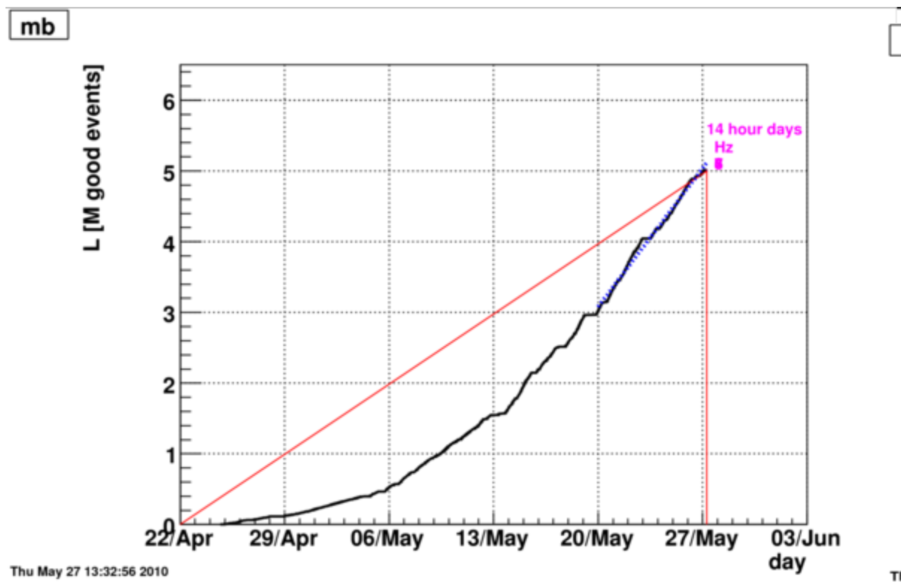
HLT is able to reconstruct online the primary vertices
HLT good event rate is very close to offline QA rate
Priceless redundancy !

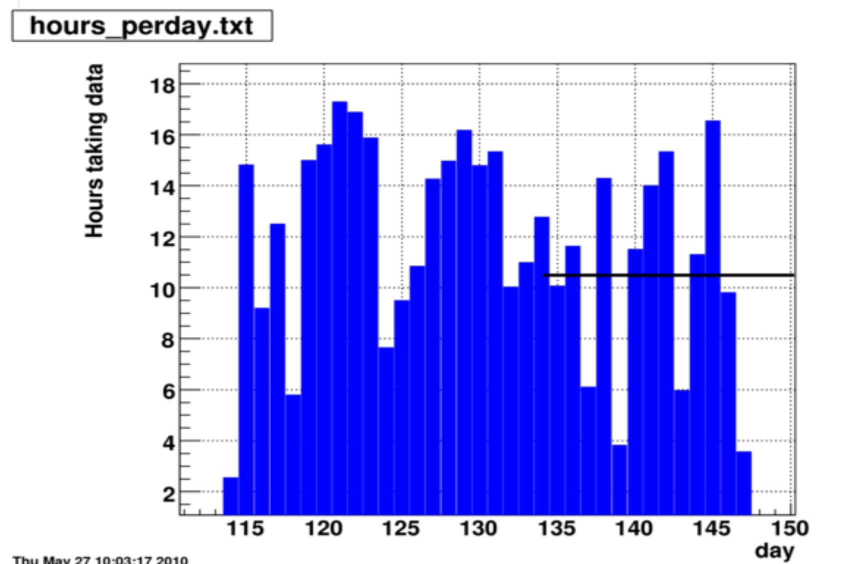
Online HLT good event rate

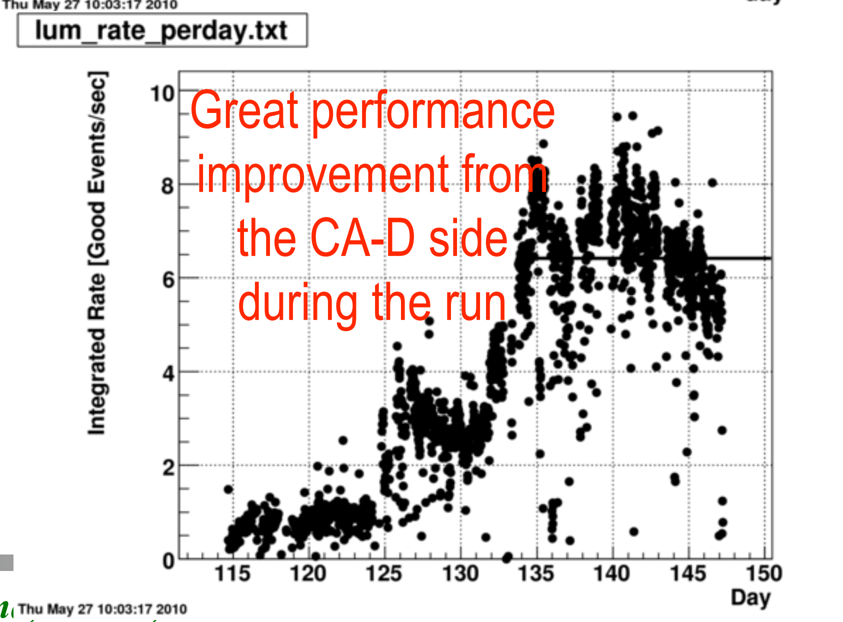


~ 9 Hz !

STAR data summary AuAu @ 7.7 GeV







Collected 5.014 M events

- met the goal !

Operated in 10 minutes stores environment

Average uptime ~ 11 hours

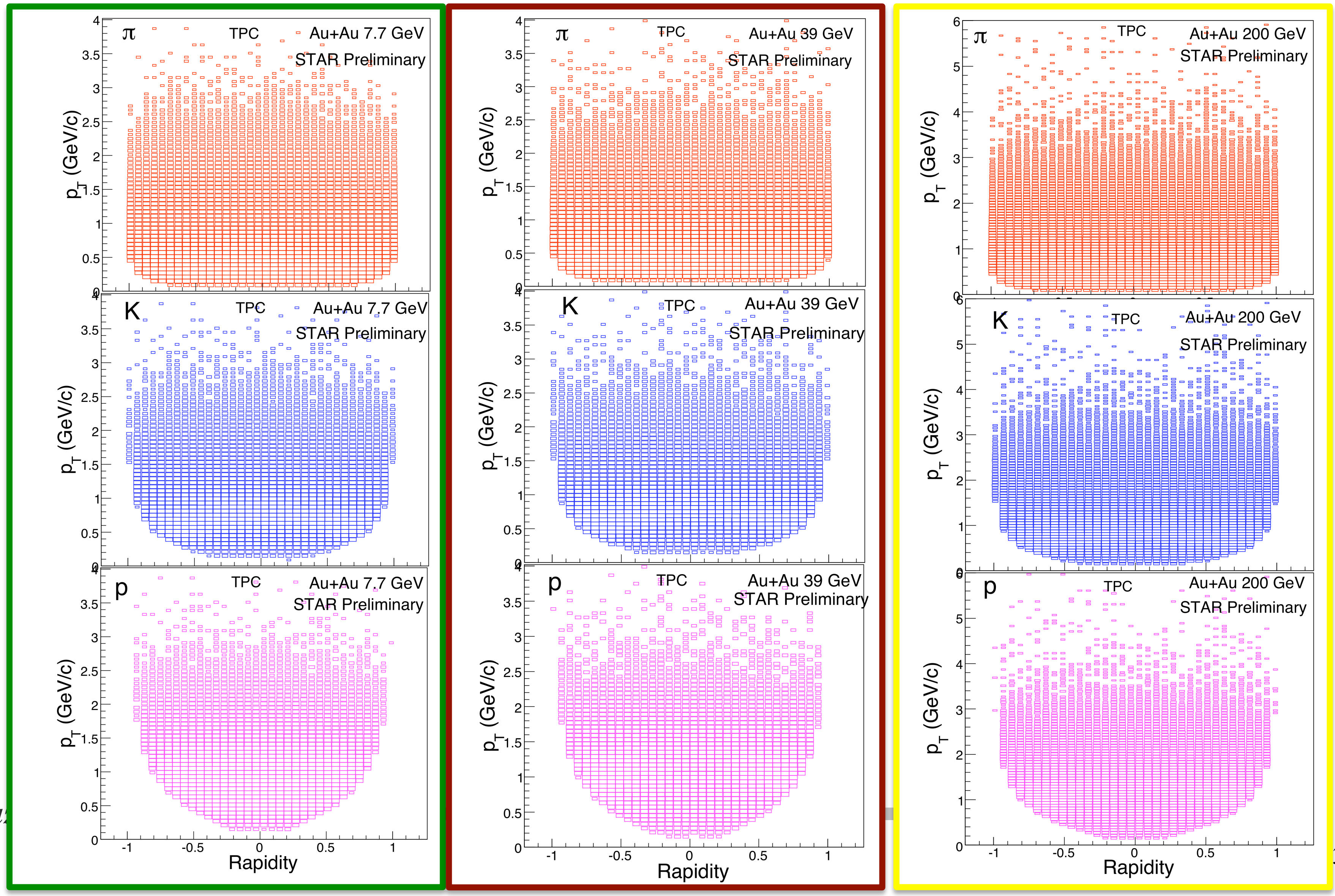
Collecting up to 350 k events per day

Statistics from Run 10

Beam Energy ($\sqrt{s_{NN}}$, GeV)	Minbias (Million)	Central (Million)	High-Tower Sampled Luminosity	FTPC+PMD (Million)
200	355	265	2.6 (nb^{-1})	5
62.4	140	33	175 (μb^{-1})	3.5
39	250		62 (μb^{-1})	23
7.7	5	N/A	N/A	N/A
11.5	≥ 7.5	N/A	N/A	N/A
5	Commissioning	N/A	N/A	N/A

Identified Particle Acceptance at STAR

Au+Au at 7.7 GeV | Au+Au at 39 GeV | Au+Au at 200 GeV



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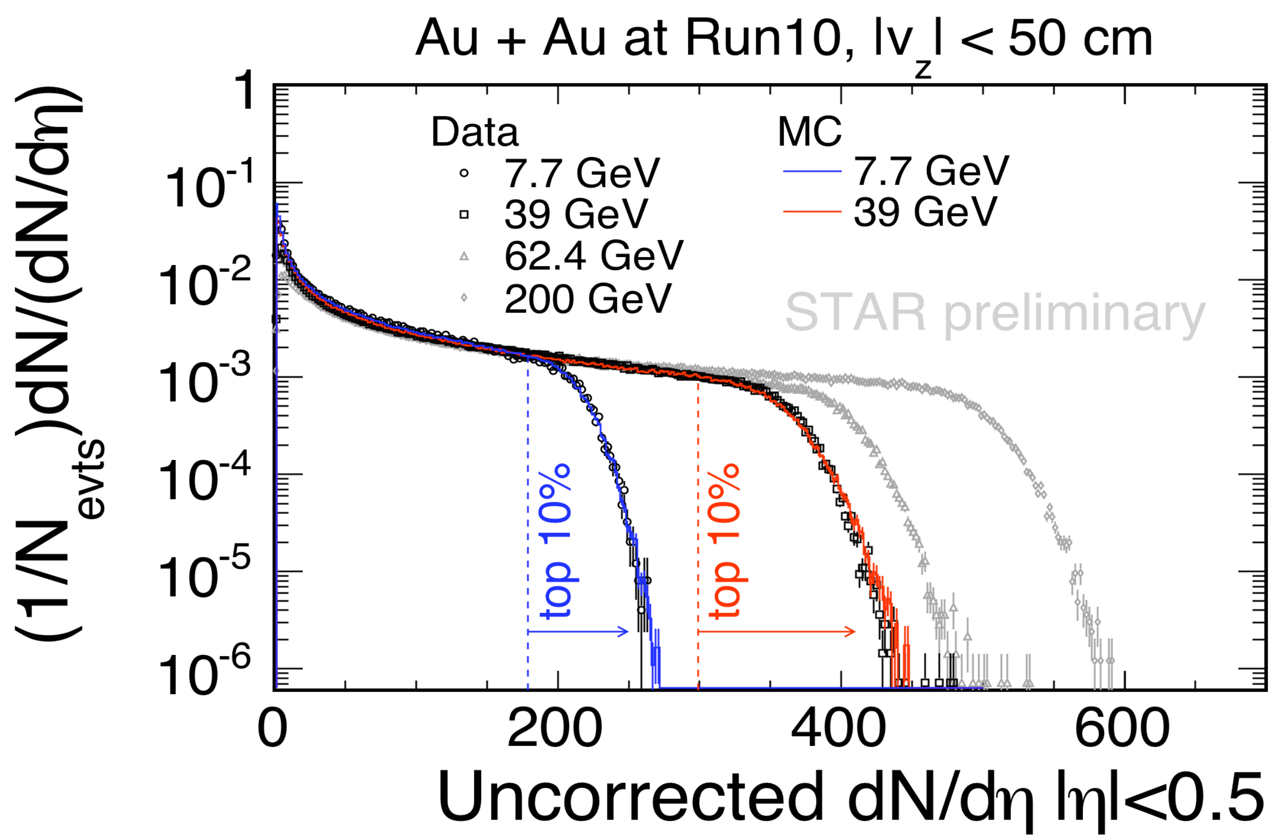
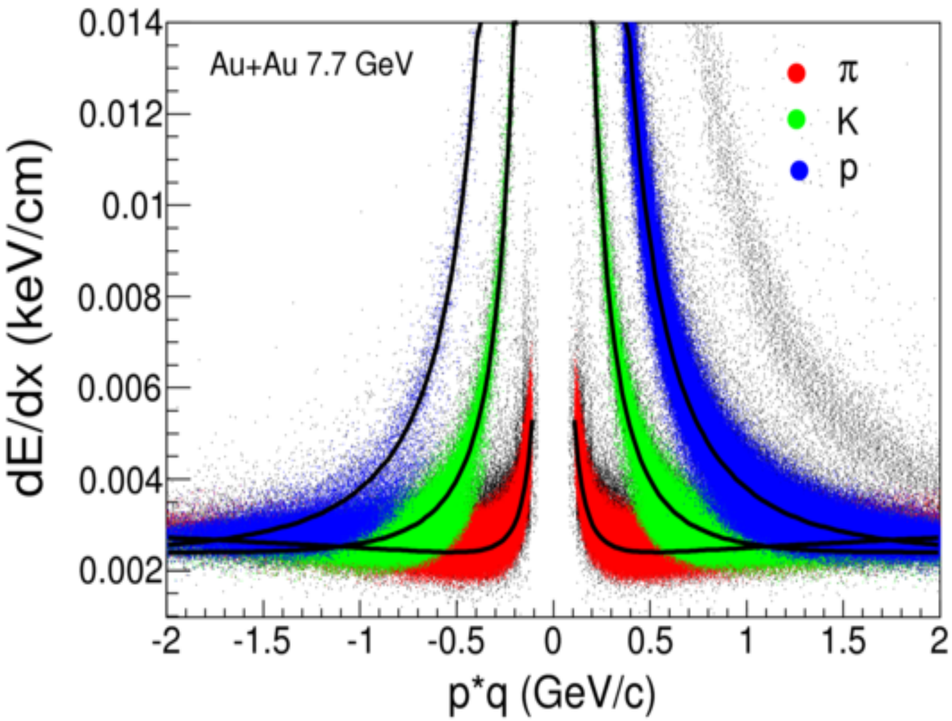
Multiplicity at 7.7, 39, and … GeV

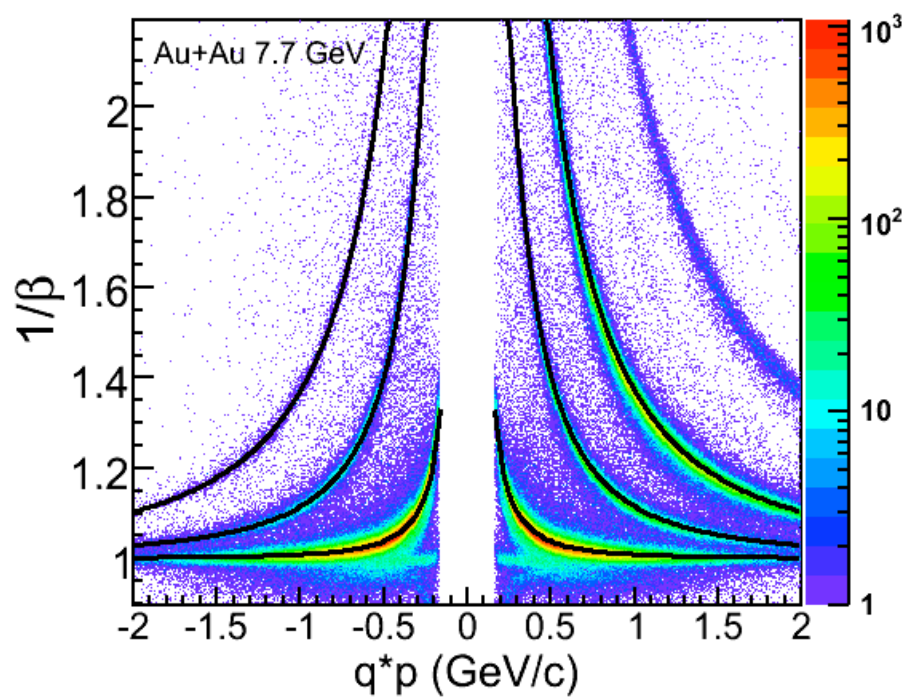


STAR Performance in Run 10
Particle Identification at 7.7 GeV

TPC PID

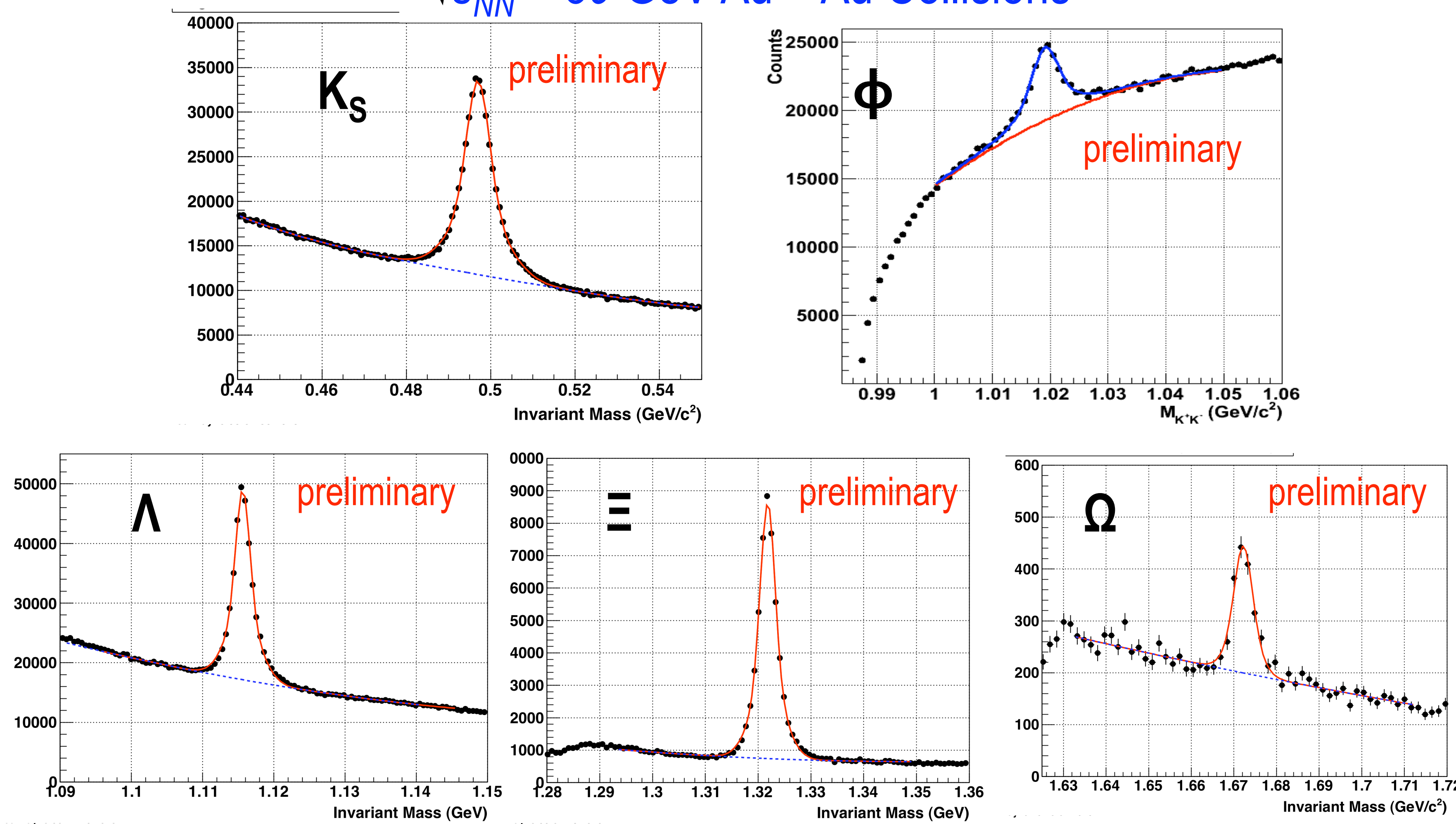


TPC+TOF PID

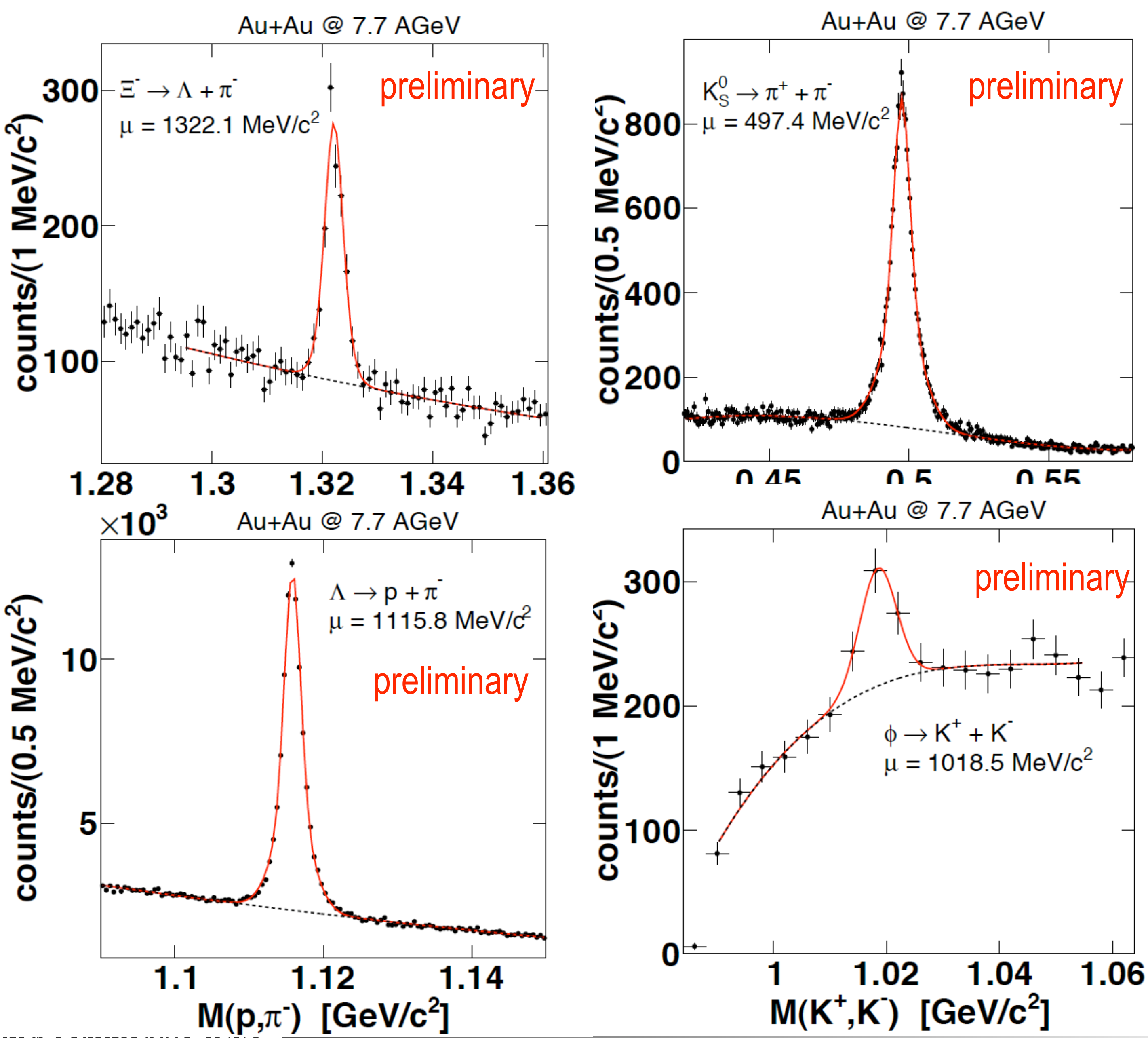


Particle Identification – part II

$\sqrt{s_{NN}}$ = 39 GeV Au + Au Collisions



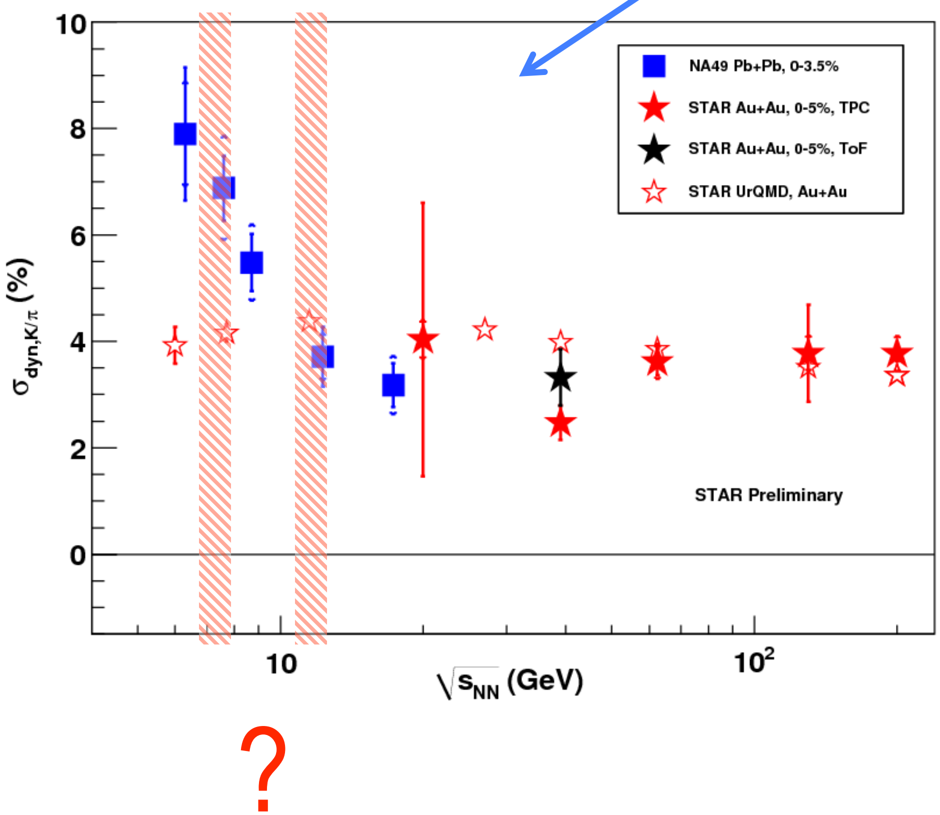
Invariant Mass (GeV)

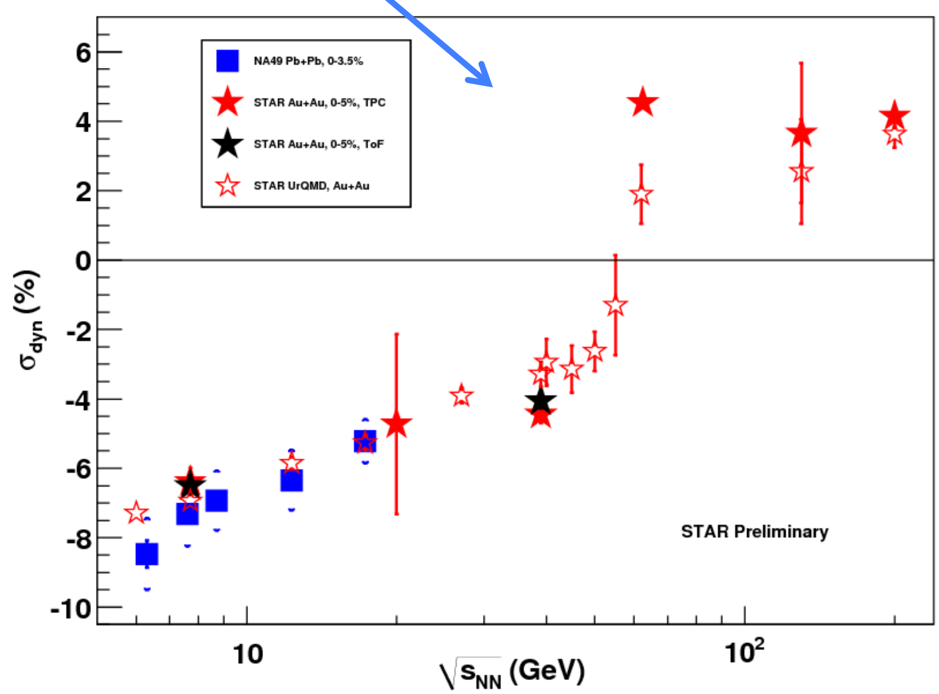

Au+Au @ 7.7 AGeV
$\Xi^- \to \Lambda + \pi^-$
μ = 1322.1 MeV/c^2
preliminary
counts/(1 MeV/c^2)
Au+Au @ 7.7 AGeV
$K^0_S \to \pi^+ + \pi^-$
μ = 497.4 MeV/c^2
preliminary
counts/(0.5 MeV/c^2)
Au+Au @ 7.7 AGeV
$\Lambda \to p + \pi^-$
μ = 1115.8 MeV/c^2
preliminary
counts/(0.5 MeV/c^2)
M(p,π^-) [GeV/c^2]
Au+Au @ 7.7 AGeV
preliminary
$\phi \to K^+ + K^-$
μ = 1018.5 MeV/c^2
counts/(1 MeV/c^2)
M(K$^+$,K$^-$) [GeV/c^2]

PID@ 7.7 GeV

From Terry Tarnovsky presentation:

Excitation Function for $\sigma_{dyn,K/\pi}$ and $\sigma_{dyn,p/\pi}$ Au+Au STAR data





Summary

- RHIC Beam Energy Scan - Fantastic success !

  Au + Au at 39, 7.7 and 11.5 GeV runs:
  - Met all goals and far exceeded for some data points
    - 7.7 GeV (34 days) and 11.5 GeV (8+3 days) : N_{events} > 5 M
    - 39 GeV (15 days): N_{events} ~ 170 M events
  - Dramatic improvement of the collider performance at 7.7 GeV
- Preliminary results based on fast offline Run 10 data look very promising
- Final calibration results soon
- **Last call for predictions on critical point !!!**

- PAC two month ago (June 2010) … the discussion of Run 11 begins !

STAR Beam Request Runs 11 and 12

Run	Beam Energy	Time	System	Goal	New Detector
11	$\sqrt{s_{NN}}$ = 18, 27 GeV	2 weeks	Au + Au	100, 150M minbias	HLT
	$\sqrt{s_{NN}}$ = 200 GeV	4 weeks	U + U	200M minbias 200M central	
	$\sqrt{s}$ = 500 GeV	5 weeks 6 weeks	$p_{\uparrow} p_{\uparrow}$ $p_{\rightarrow} p_{\rightarrow}$	trans. $P^2 {}^* L = 4\ pb^{-1}$ long. $P^2 {}^* L = 20\ pb^{-1}$	
		1 week	$p_{\uparrow} p_{\uparrow}$	pp2pp at high β^*	
12	$\sqrt{s}$ = 500 GeV	10 weeks	$p_{\rightarrow} p_{\rightarrow}$	long. $P^2 {}^* L = 50\ pb^{-1}$ $P^4 {}^* L = 15\ pb^{-1}$	FGT
	or		or	or	
	$\sqrt{s}$ = 200 GeV		$p_{\uparrow} p_{\uparrow}$ $p_{\rightarrow} p_{\rightarrow}$	trans. $P^2 {}^* L = 8.5\ pb^{-1}$ long. $P^4 {}^* L = 4.3\ pb^{-1}$	
	$\sqrt{s_{NN}}$ = 200 GeV	10 weeks	U + U or Au+Au	$3.5\ nb^{-1}$ U+U or $5\ nb^{-1}$ Au+Au	MTD

Request a CA-D test to determine the lowest possible collision energy at RHIC

Thank you !