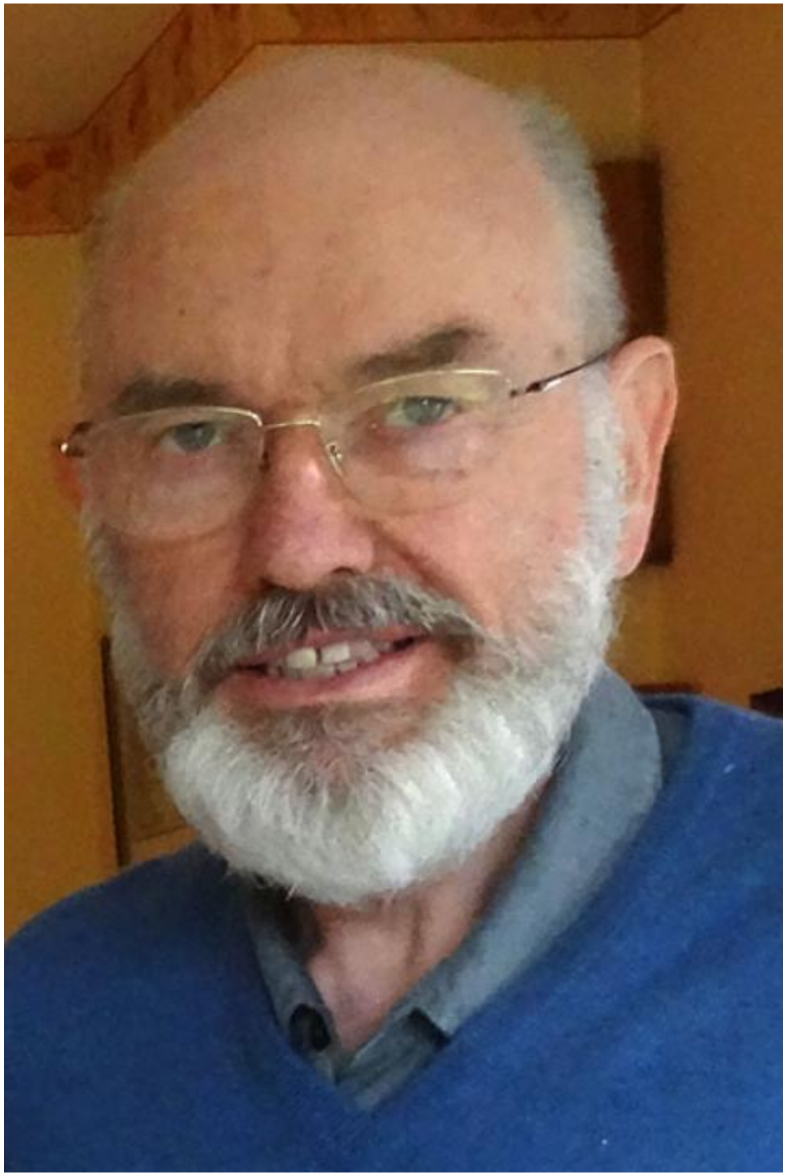


Connecting experiment to the QCD phase diagram

Grazyna Odyniec / LBNL

A special symposium on Advances in Nuclear Matter Dynamics

A tribute to the oustanding career of Declan Kean!

Outline:

- LBL Streamer Chamber experiments (Bevalac, LBL, early 80's)
~ 40 years ago

.... *fast forward* ....

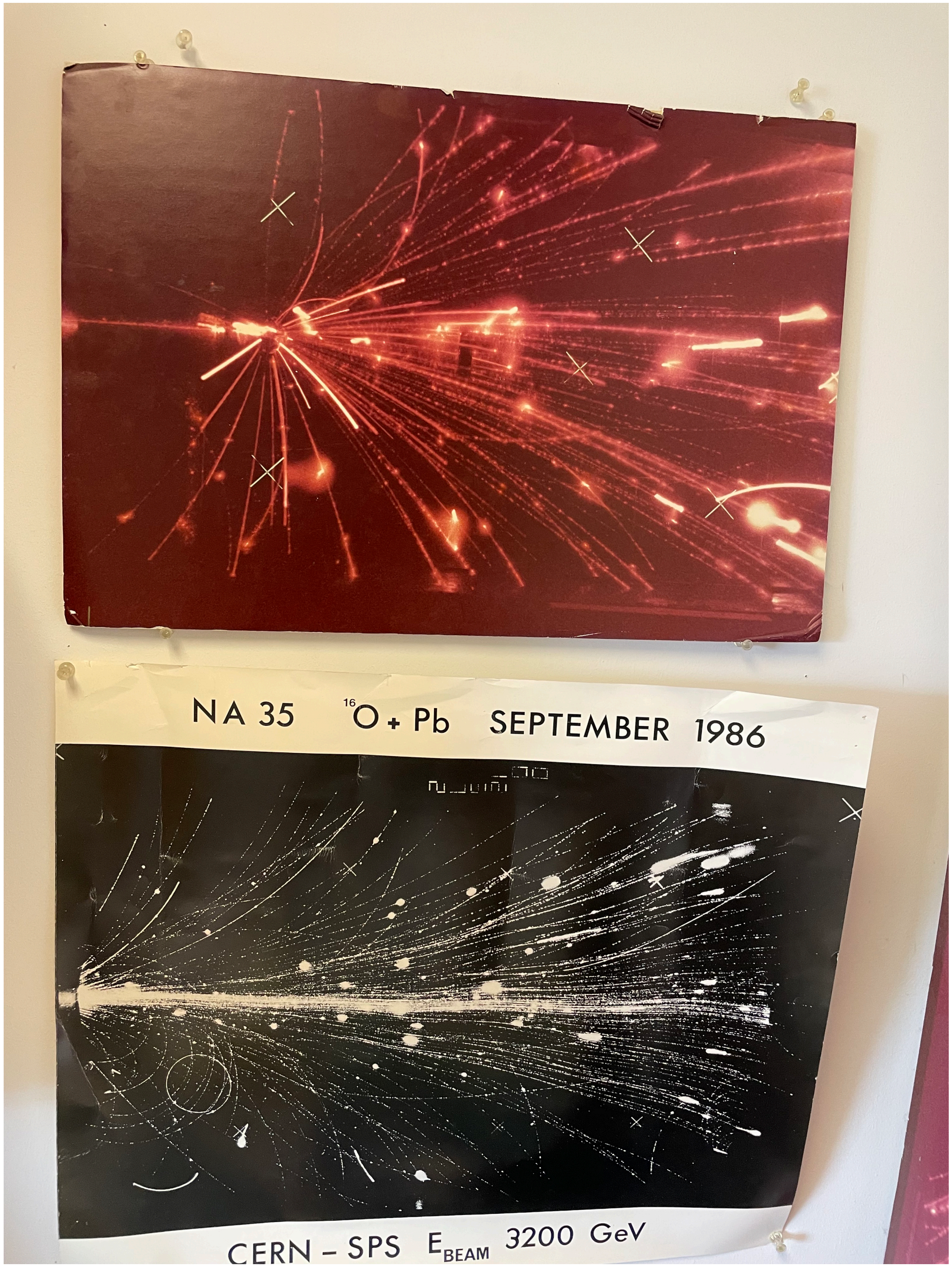
- Beam Energy Scan Focus Group in STAR (from 2008 – present)

➡ **Connecting experiment to the QCD Phase Diagram**

La+La,
800 MeV/n

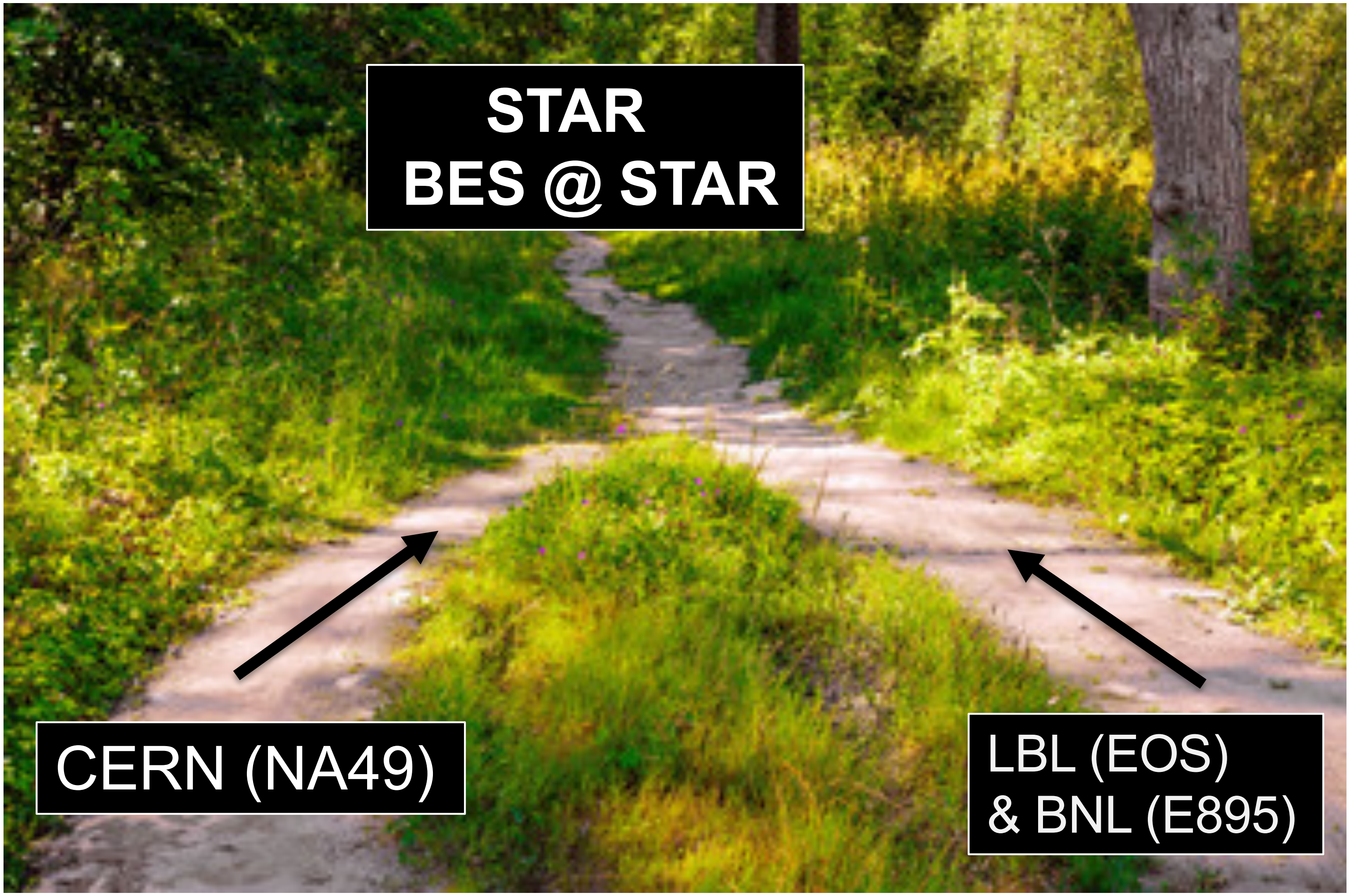
Streamer Chamber picture (Bevalac), small data sets (a few hundreds events)

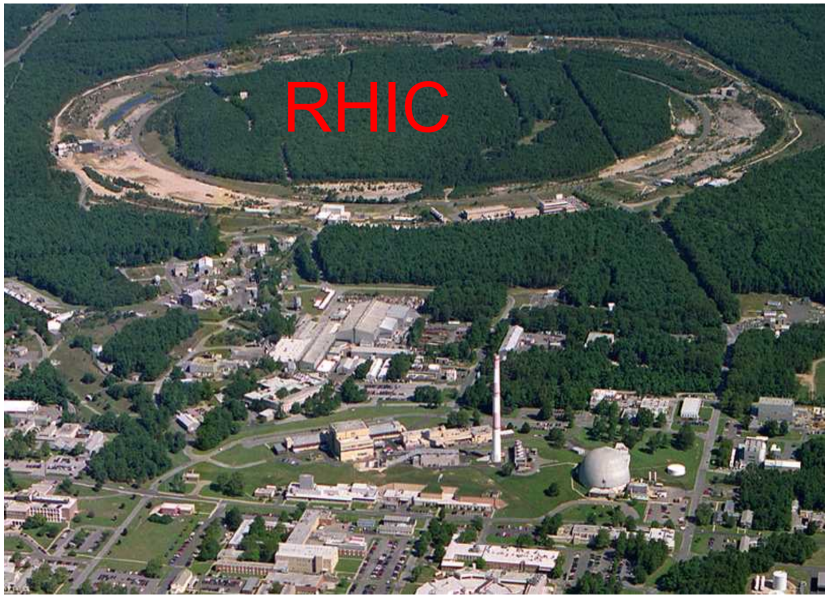
see Hans Georg Ritter presentation

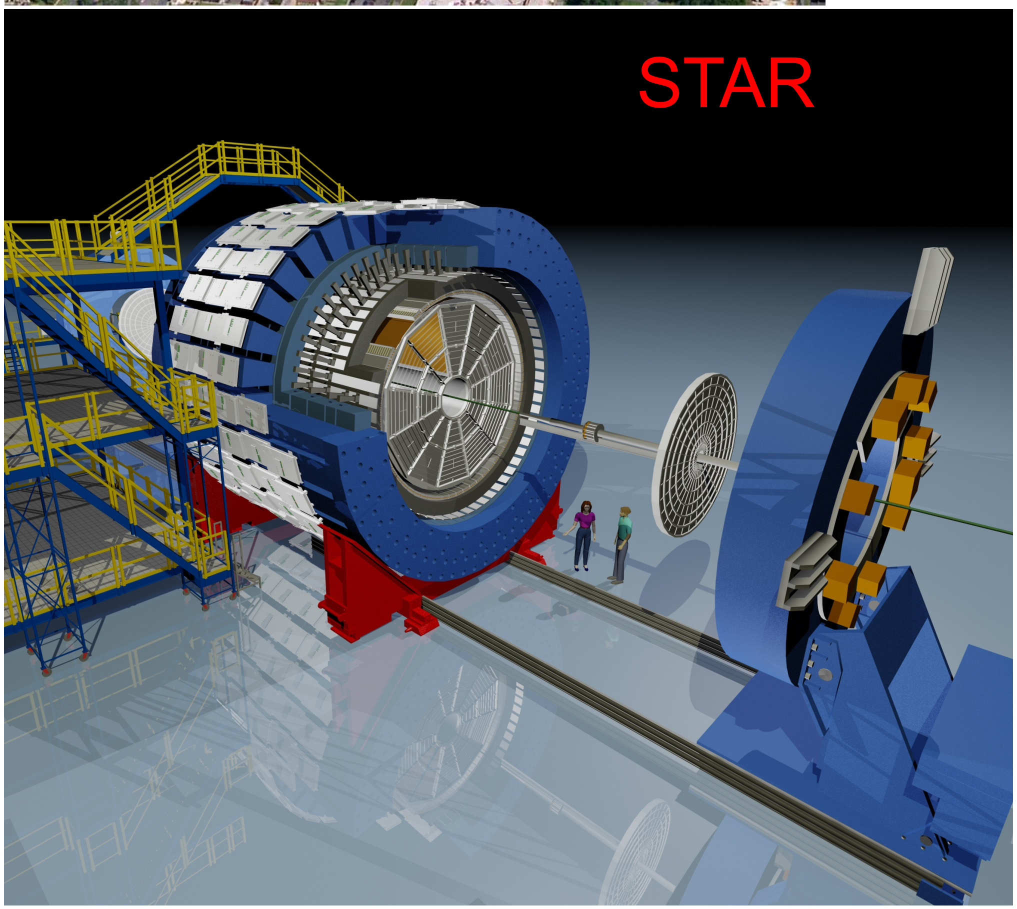


Bevalac

CERN SPS


STAR
BES @ STAR
CERN (NA49)
LBL (EOS)
& BNL (E895)





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

Top discoveries at RHIC:

Strong elliptic flow

- collective flow of created matter
- partonic collectivity
- deconfinement

Jet quenching

- energy loss of high p_t partons in hot and dense medium
- medium response

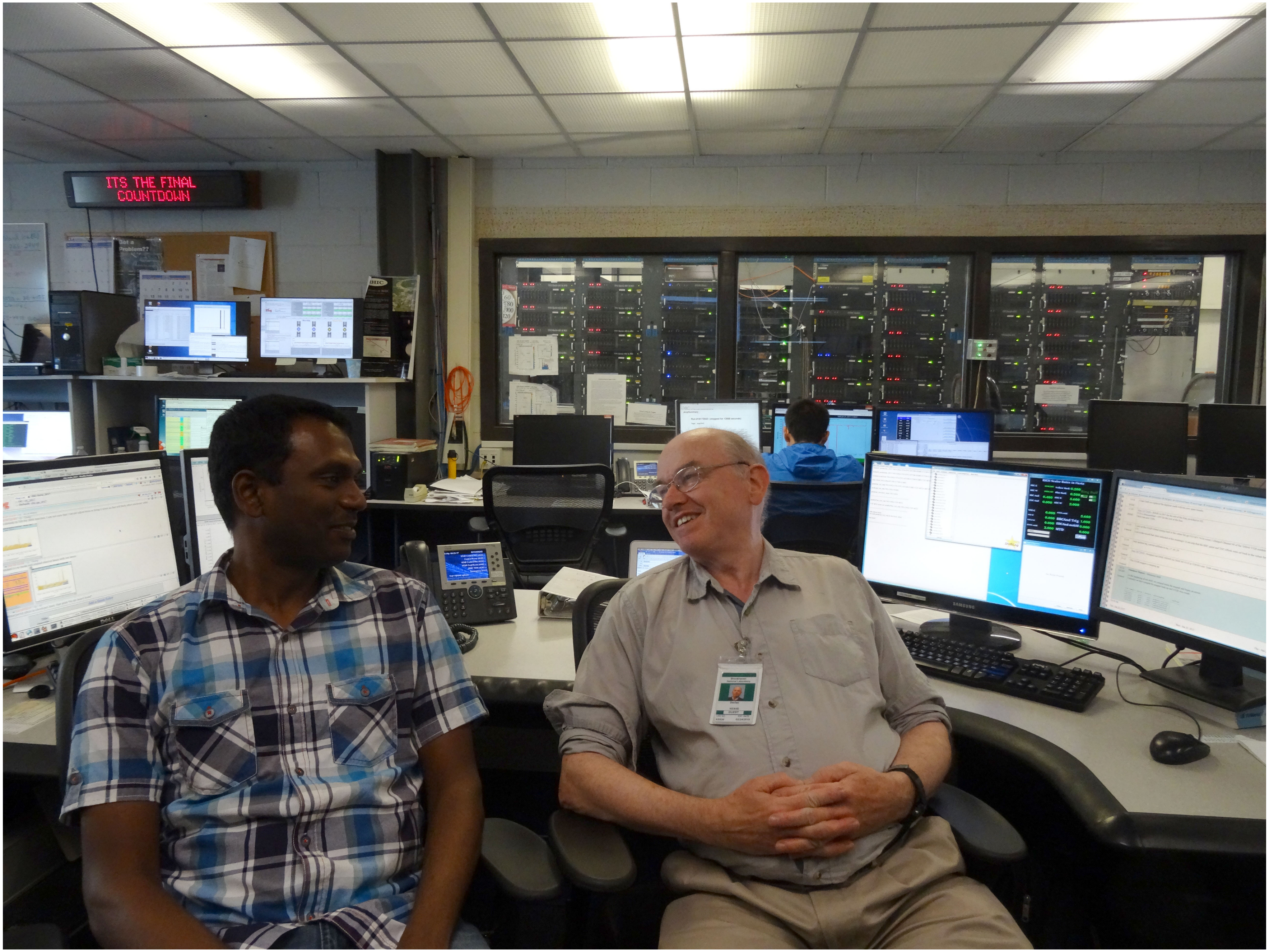
Production mechanism at medium p_t via recombination/coalescence (not via fragmentation)

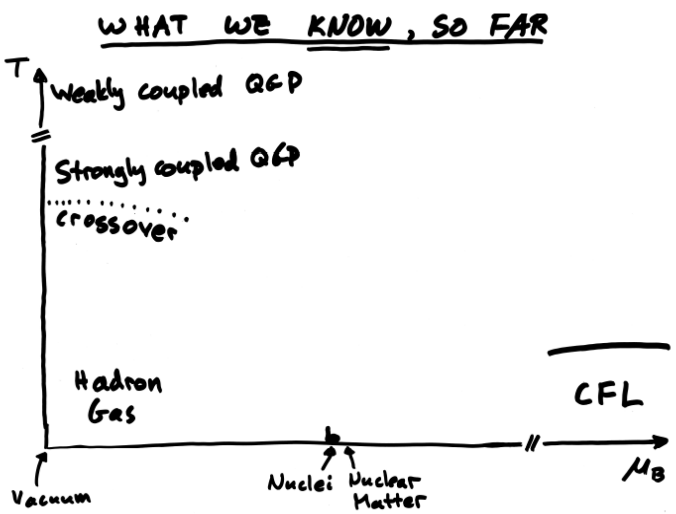
➡ strongly coupled QGP (sQGP) established

but remain unknown:

- properties of sQGP
- boundary between hadronic and partonic phases
- possible critical point

happy days in STAR control room





"The QCD diagram is fairly EMPTY …"

K.Rajagopal (INT Aug. 2008, opening talk)

Exploring the rest of QCD phase diagram (T, μ) by:
- heavy ion collisions
- lattice calculations

"Locate" the CP (:= second order point, where a line of 1st order transition ends) either
- via experimental detection of signatures
- via lattice calculations

stress on plural !

- need agreement of several signatures
- need agreement of different calculations

Road Map by K.Rajagopal (INT,Aug.2008):

HOW CAN EXPERIMENTS LOCATE THE CRITICAL POINT?

① Need evidence that at large $\sqrt{s}$, ie small μ, collisions equilibrate well above the crossover. V_2@RHIC.

② Decrease $\sqrt{s}$, moving freezeout point to larger and larger μ_B.

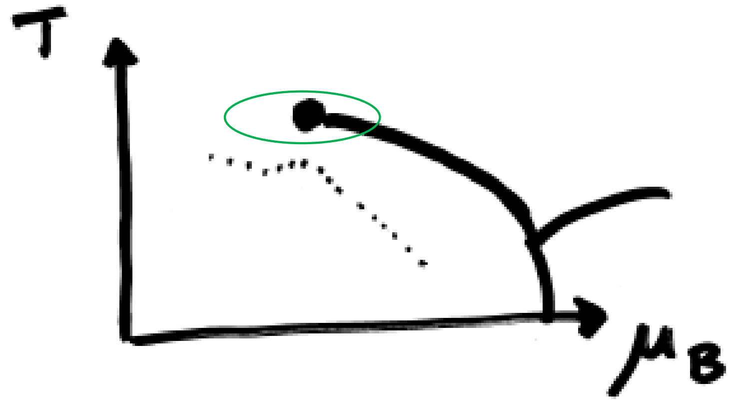
③ Look for signatures:

a) Of the critical point itself. Those relying on the long wavelength gaussian fluctuations occurring only near ●. Rise and then fall as μ_B increases.

b) Onset of signatures of non-equilibri "lumpy" final state expected after cooling through a first order transitio

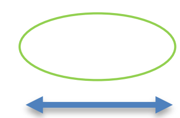
Mishustin; Dumitru Paech Stöcker; Randrup; Koch Majumder Randrup; ...

→ NON Gaussian fluctuations



but

no need to hit CP(!) – signature will be just large enough if you pass anywhere in



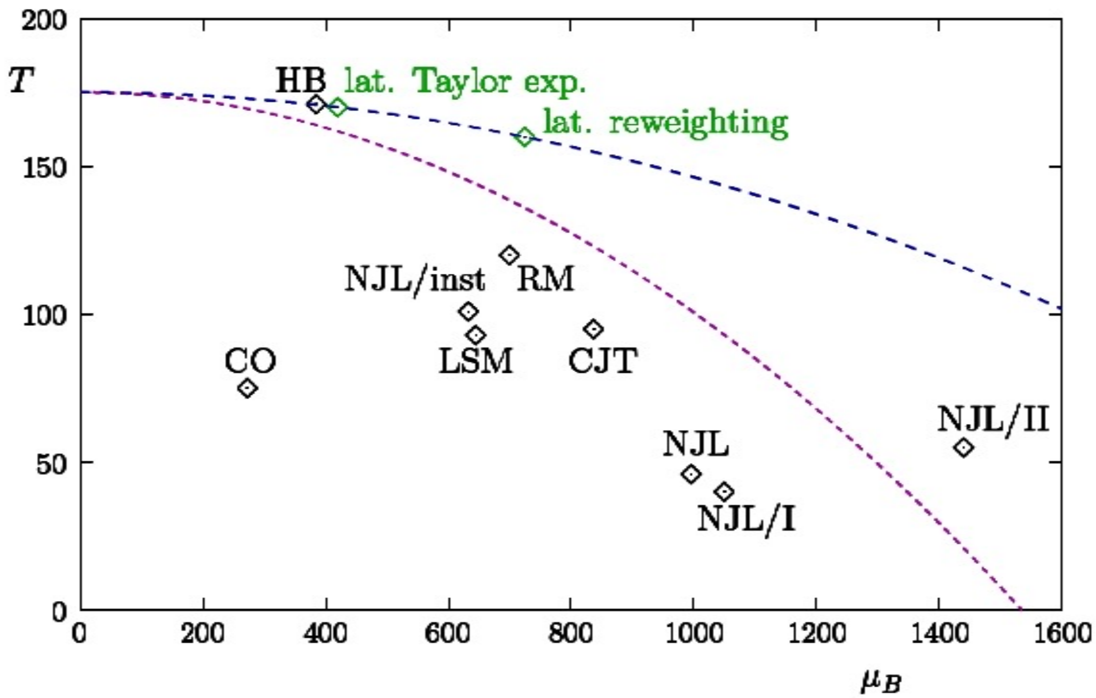
$\Delta\ \mu_B \sim 100$ MeV

focusing of trajectories that pass near the critical point = NO

need to take very small steps in m_B

we have had some predictions …

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

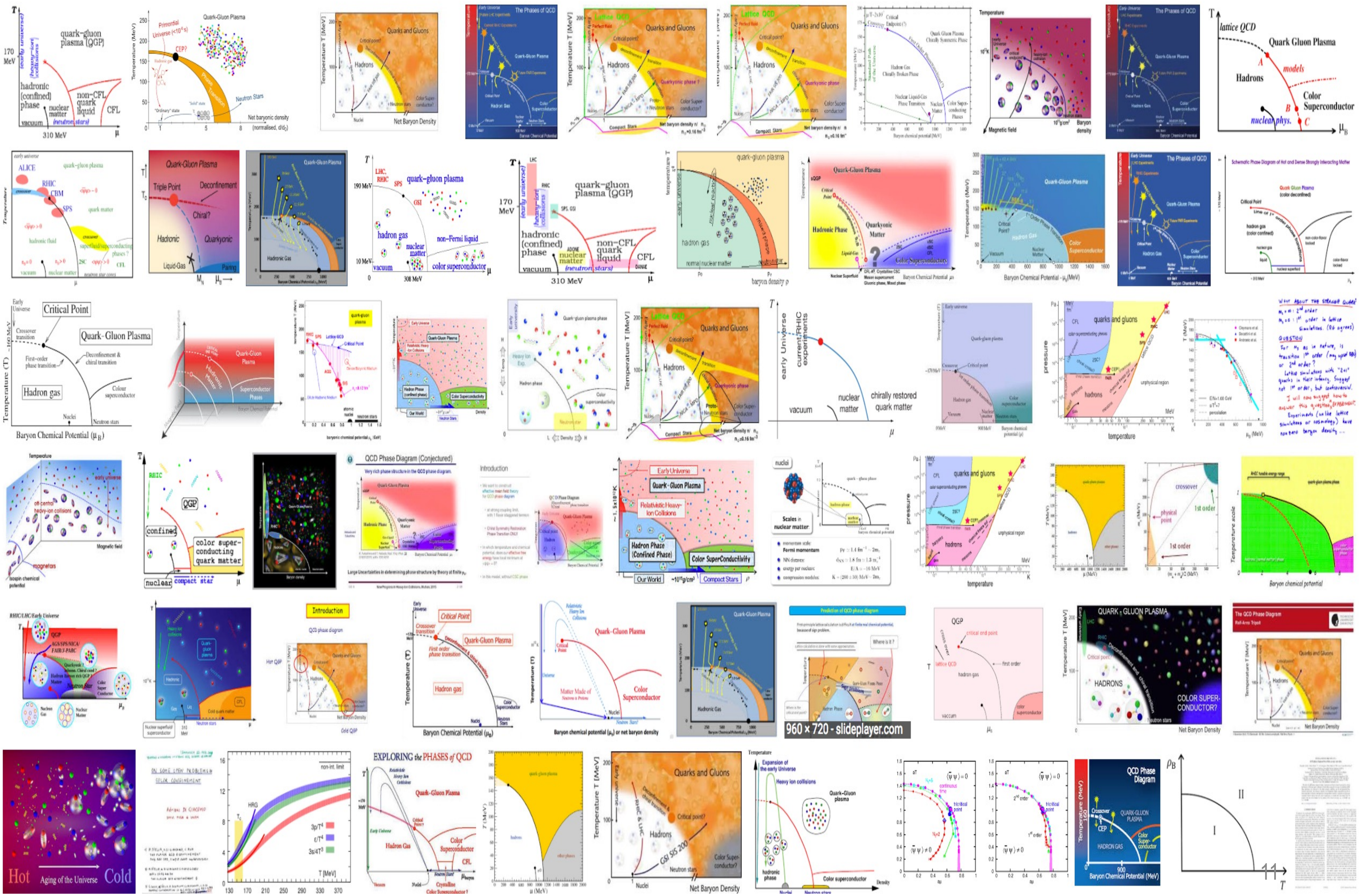


this figure is of great historical interest but it does <u>not represent</u> the span of theories that are currently pointing towards μ_B > 600 - 650 MeV

Given the very significant theoretical difficulties,

<u>data</u> may lead the study of QCD phase diagram …

B.Zajc, QM 2017



Challenge accepted !

From: starmail-l-bounces@lists.bnl.gov <mailto:starmail-l-bounces@lists.bnl.gov> [mailto:starmail-l-bounces@lists.bnl.gov <mailto:starmail-l-bounces@lists.bnl.gov>] On Behalf Of Tim Hallman
Sent: Monday, August 27, 2007 10:34 PM
To: 'starmail'
Cc: Hallman
Subject: [Starmail-l] Formation of a STAR Beam Energy Scan Focus Group

excerpts:

Dear STAR Collaborators,

As you know, a major component of the future STAR physics program-proposed and accepted by the BNL PAC – is a AuAu energy scan extending to low root_s. Among other things, this energy scan will provide a unique opportunity to search for a key landmark, a possible critical point, in the phase diagram of QCD.

....

Running at very low root_s poses major new challenges.

....

Some important first steps have been taken to examine some of these questions, but great deal of homework remains to fully prepare the Collaboration for the word-leading measurements STAR is capable of.

For this reason, I am announcing the formation of the “Beam Energy Scan Focus Group”.

The charge for the Beam Energy Scan Focus Group:

…………..

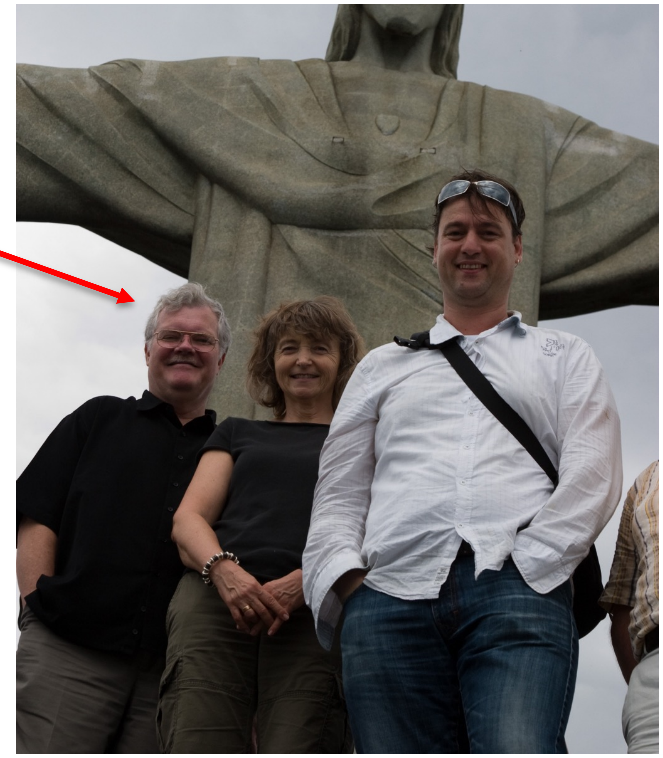
To consolidate interest within the STAR Collaboration to exploit the full physics potential of forthcoming bean energy scan, including the search for a critical point in the QCD phase diagram, as well as other novel physics possibilities.

The charge includes coordinating STAR's preparation for the scan, including realistic simulations to examine the detector's sensitivity to the most promising observables, and the design of new instrumentation, if any, that maybe required to maximize the potential for new physics.

……………

I have asked Declan Keane, Paul Sorensen, and Grazyna Odyniec to lead this group initially and to provide a staus report on where STAR stands/what is needed by the time of the next Analysis Meeting in BNL.

+ more concrete questions from Tim Hallman:



What is needed to develop an effective trigger ?

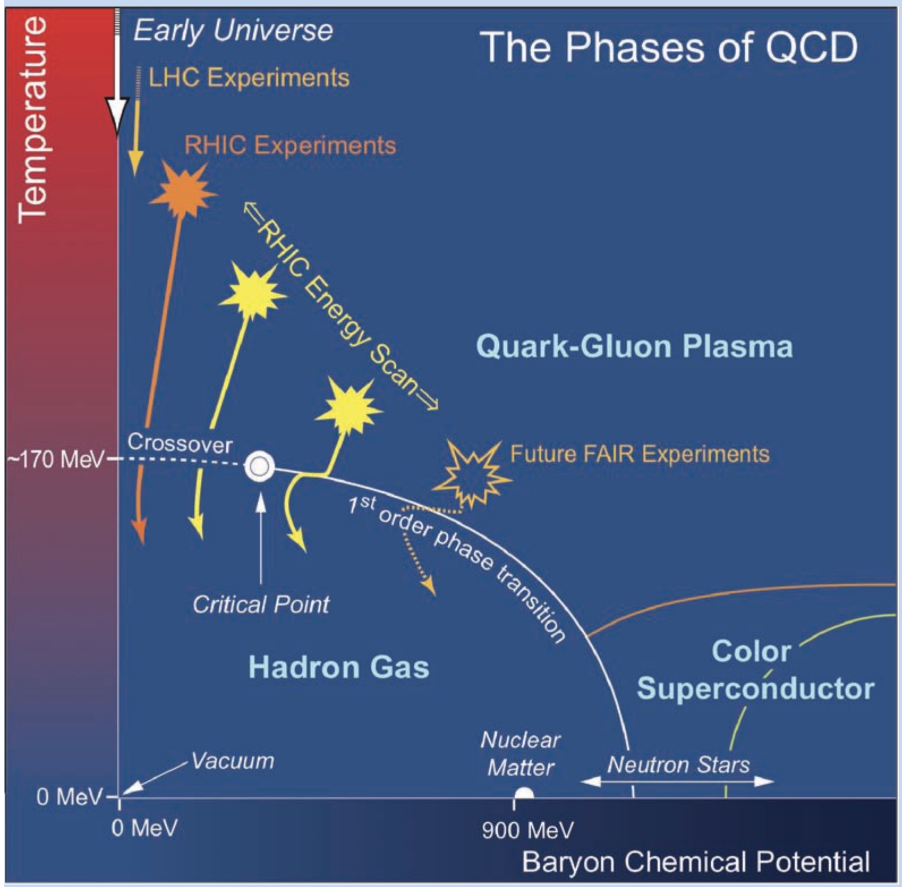
What are the most promising observables to study ?

What sensitivity to the underlying science do they provide for a given amount of beam-time ?

What kind of vertex distribution/backgrounds will we have to deal with ?

Is the new instrumentation required ? If so, what need to be built, and what is its design ?

What does it cost, and when can it be ready ?



in 2010

BES at RHIC – phase I

Search the QCD phase diagram for evidence of :

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

$\sqrt{s_{NN}}$	M_{events} in $-1<\eta<1$
7.7	4.3
11.5	11.7
14.5	24**
19.6	35.8
27	70.4
39	130.4
62.4	67.3

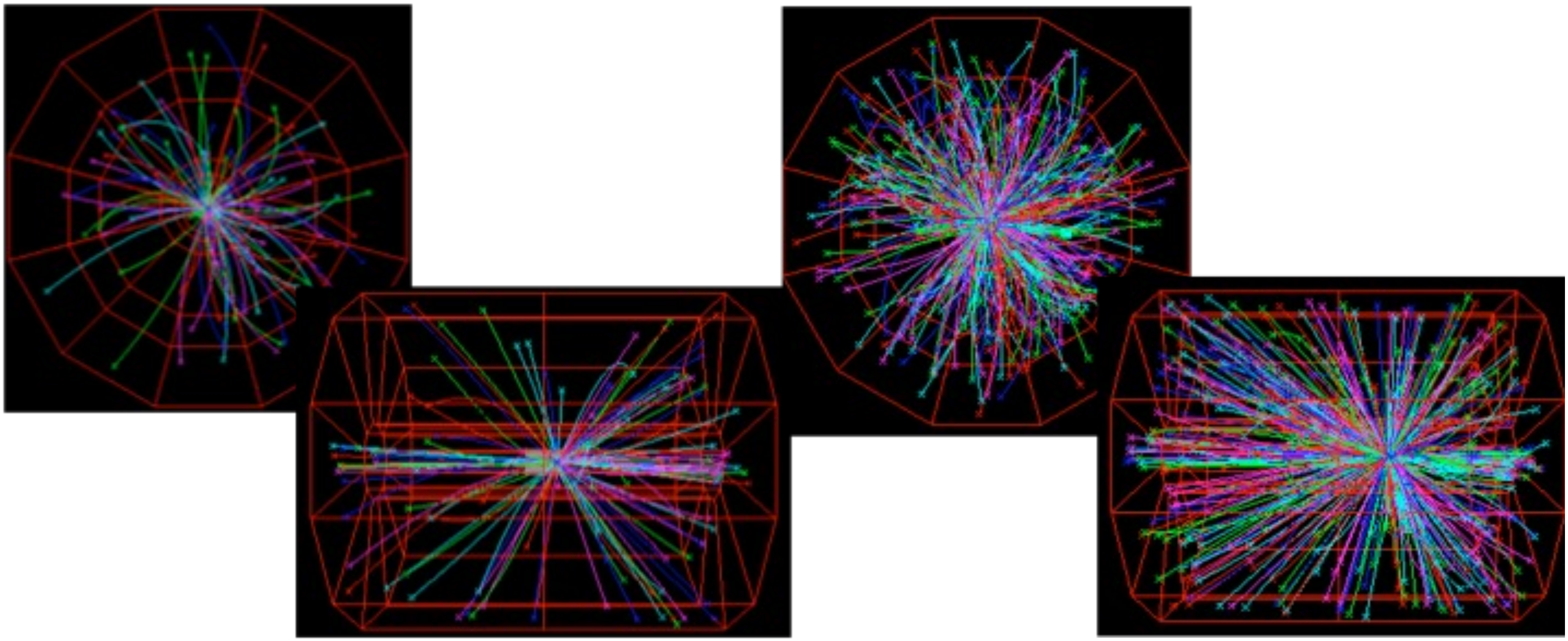
** taken in 2014

BES-I (2010, 2011 and 2014):
$\sqrt{s_{NN}}$ = 7.7, 11.5, **14.5**, 19.6, 27, 39GeV
+ 62.4, 130 and 200 GeV

STAR earlier experience with "Low Energy RHIC running":

2001: 19.6 GeV Au+Au
2004: 22.4 GeV Cu+Cu
2007: 9 GeV Au+Au
2008: 9 (5) GeV Au+Au

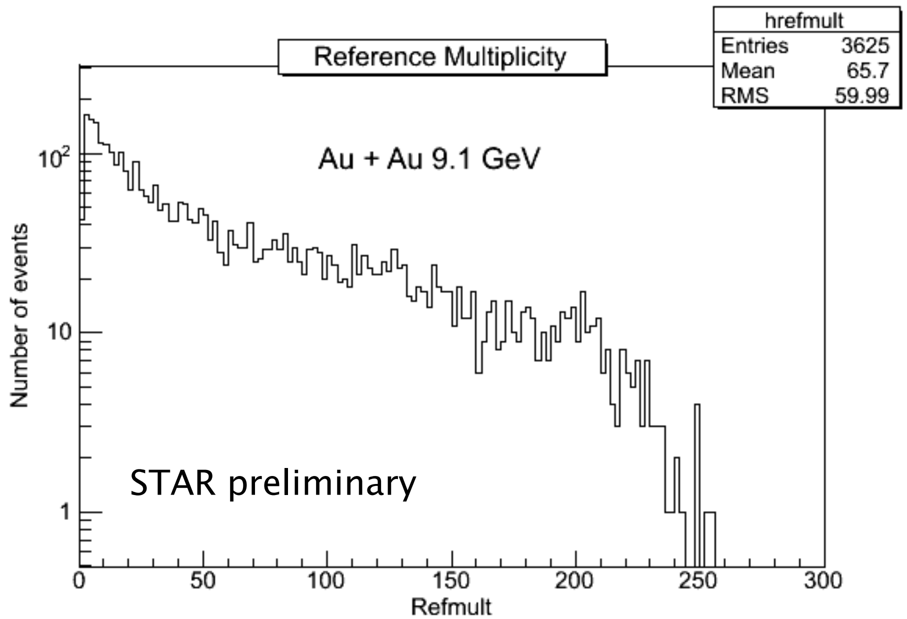
2008: Injecting and colliding Au+Au at $\sqrt{s_{NN}}$ = 9.2 GeV (4.6 GeV each beam)
a few hours -> 4K good events!



Short test allowed study of beam optics

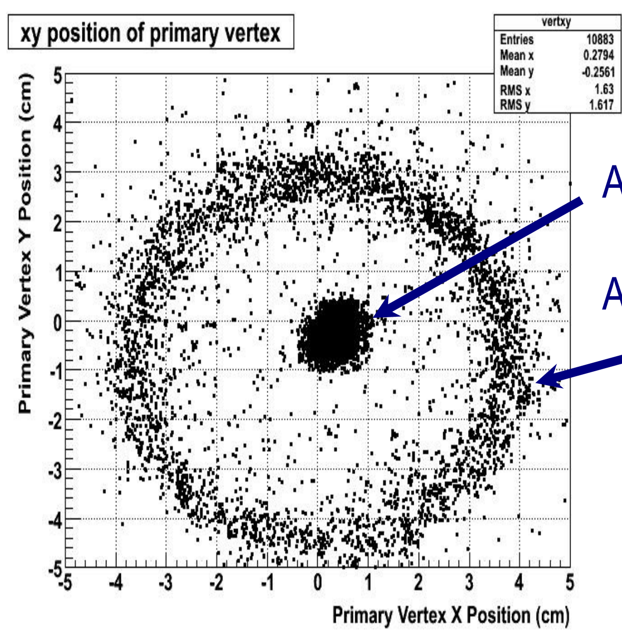
9.2 GeV data analysis:

→ Lokesh Kumar thesis work



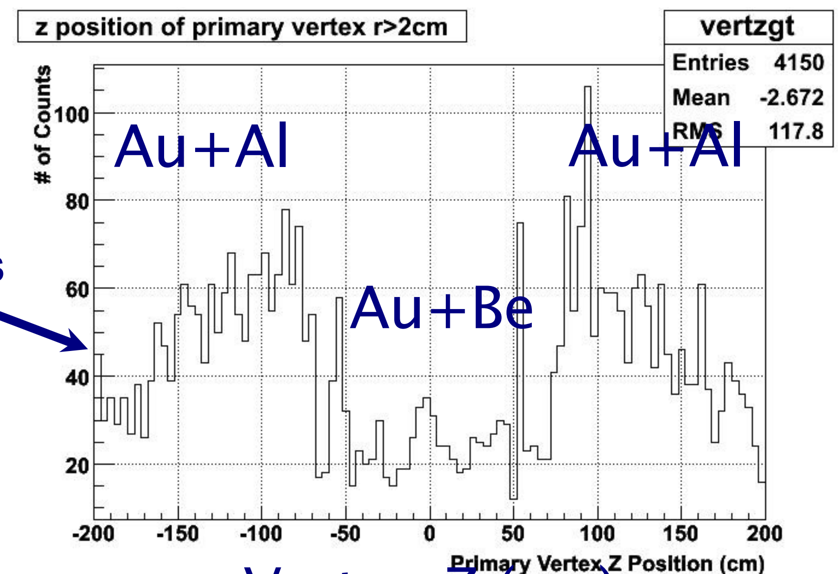
raw multiplicity

primary vertex location

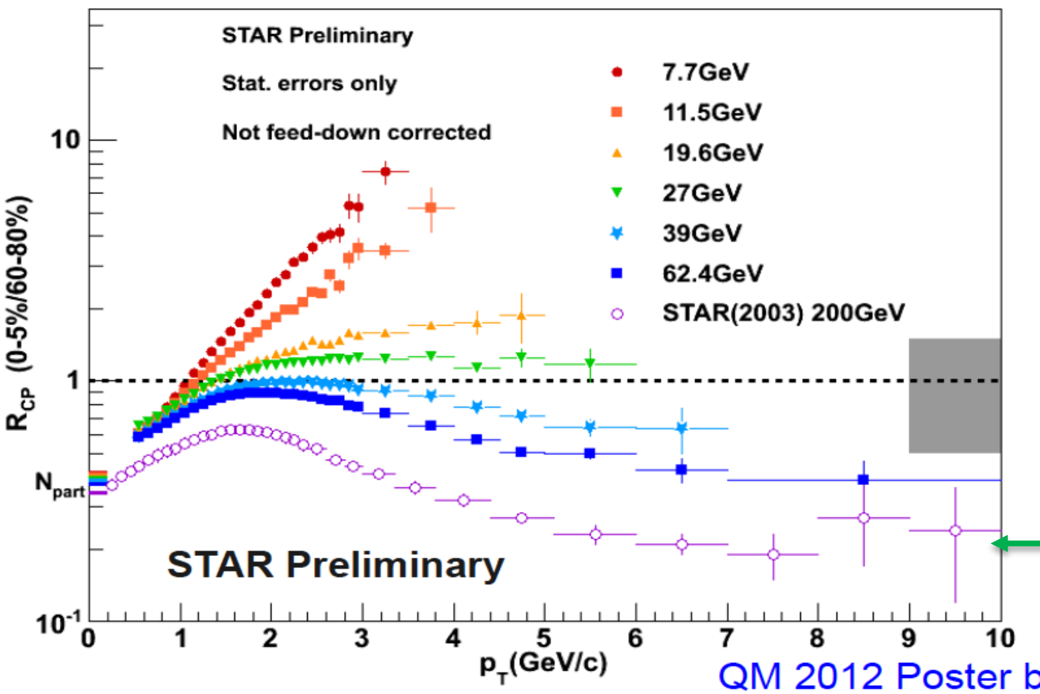


Au+Au collisions

Au+beampipe collisions



Disappearance of signals of partonic degrees of freedom seen at 200 GeV (easiest)



High p_t suppression seen at 39, 62.5 and 200 GeV - "turn-off" signature between 27 and 39 GeV?

… but insufficient reach to search for evidence of high p_t suppression below 19.5 GeV

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

CP: High moments of conserved quantities

-> see Nu Xu presentation

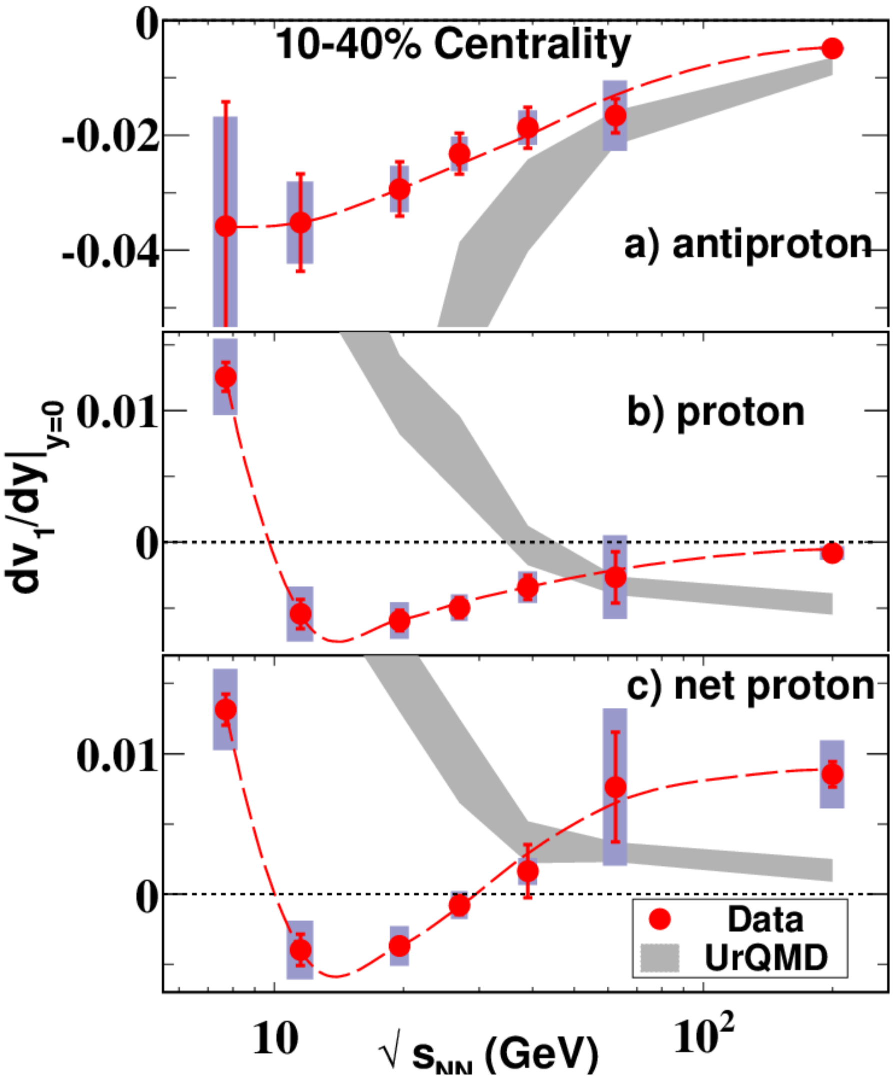
1st order phase transition: directed flow, v_1

-> Declan's favorite observable

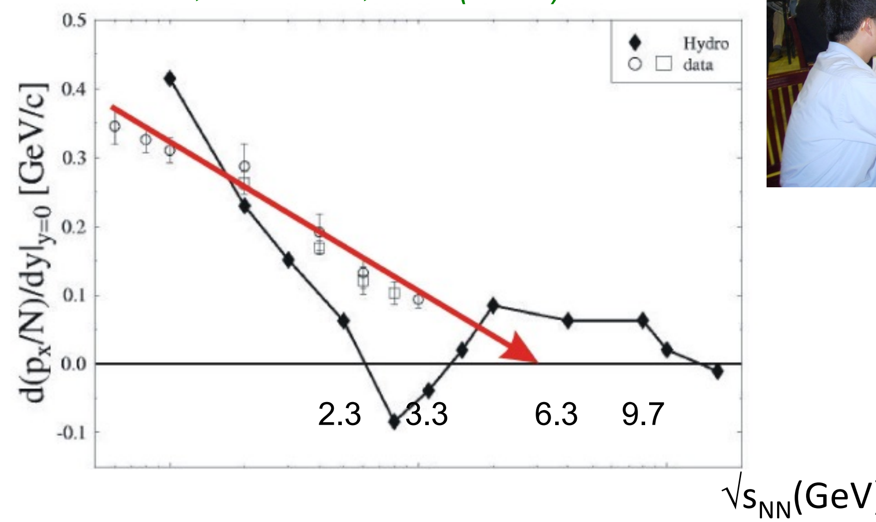
Directed flow (v_1) of identified particles

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)



H.Stocker, NP A750, 121 (2005)



- 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

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*

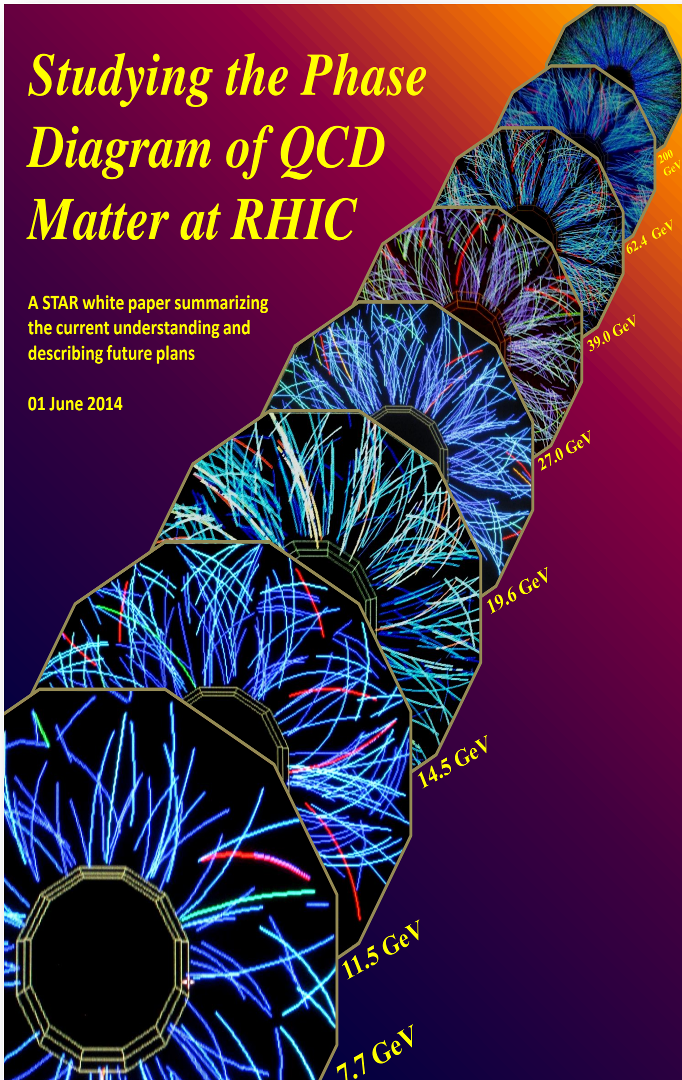
Indication of a softening of EOS around 11.5-19.6 GeV could be indicative of a 1st order phase transition

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

→

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

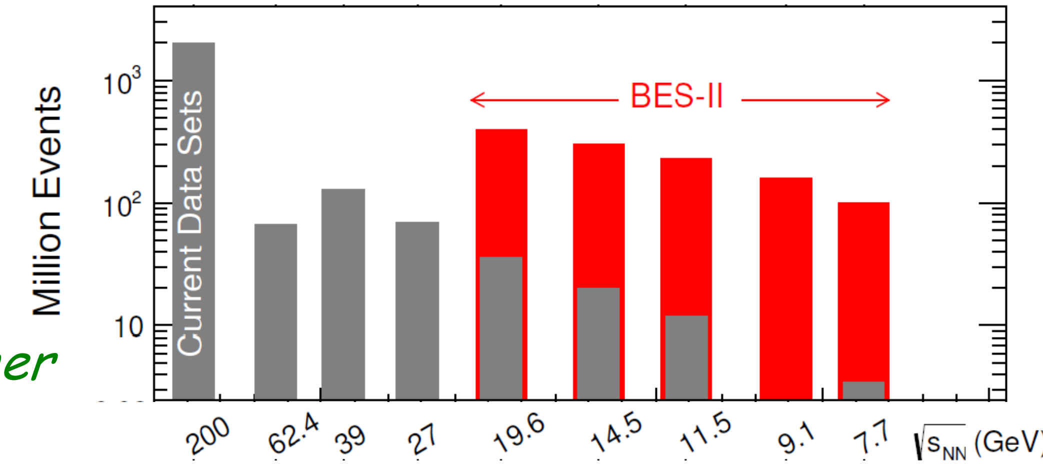
➢ Observe in-medium modifications of light vector mesons at high baryon densities
   - quantify the effect of chiral symmetry restoration

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"



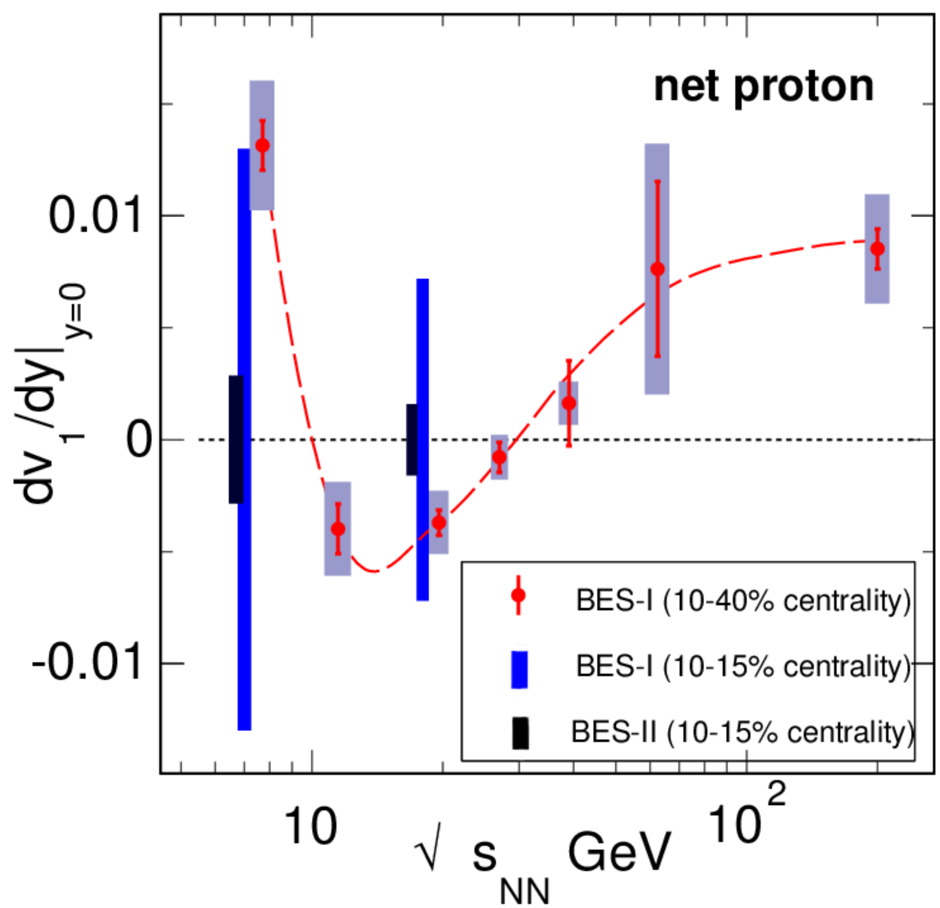
http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

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

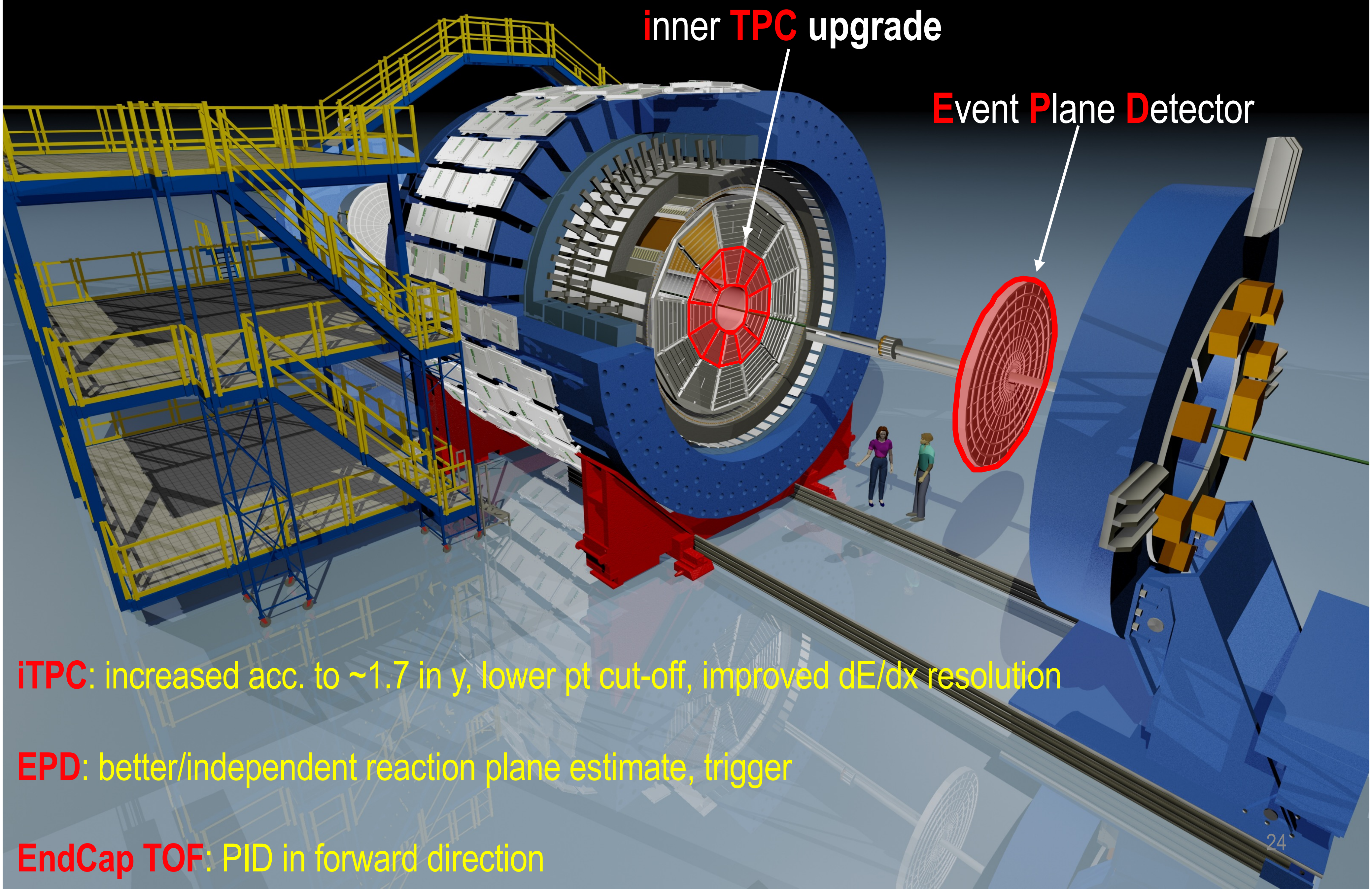
Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	–		160	125	92
Elliptic Flow (ϕ mesons)	100	150	200	200	400
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	50	75	100	100	200
Azimuthal Femtoscopy (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**

STAR Note 598

BES II measurement errors will be <u>**SMALL**</u>



STAR Detector Developments for BES II



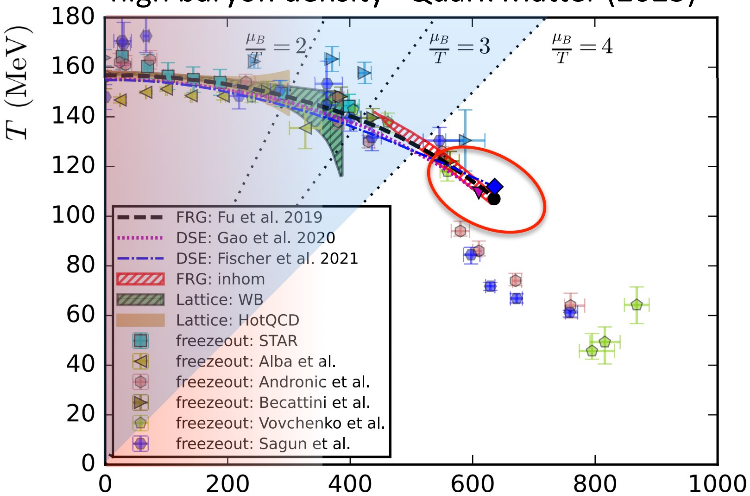
iTPC: increased acc. to ~1.7 in y, lower pt cut-off, improved dE/dx resolution

EPD: better/independent reaction plane estimate, trigger

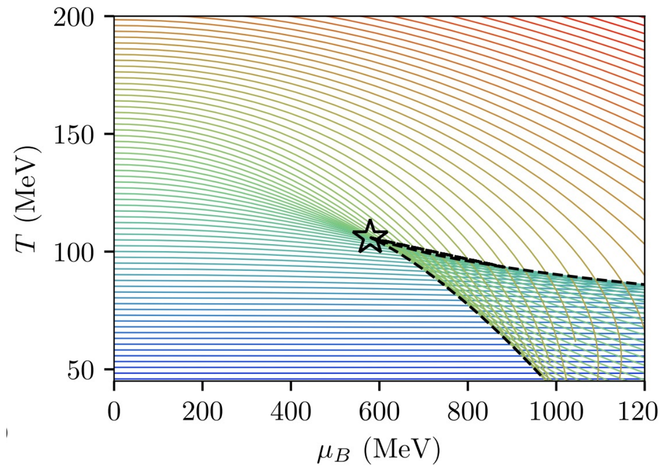
EndCap TOF: PID in forward direction

The latest expectations for Critical Point location (Quark Matter 2023, Houston):

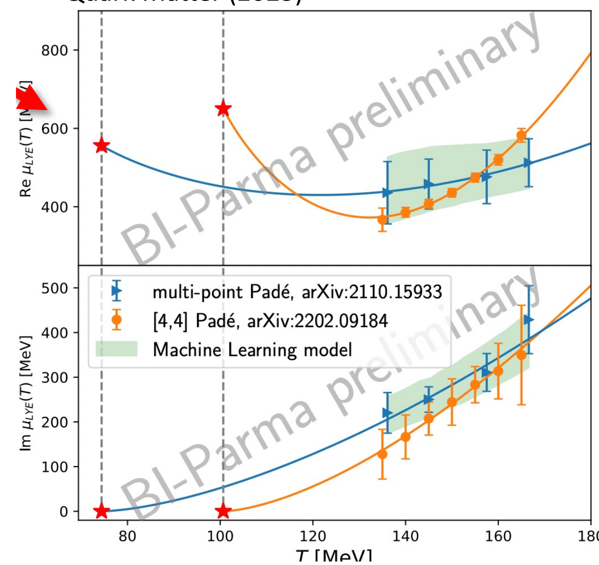
Wei-jie Fu, “Baryon number Fluctuations at high baryon density” Quark Matter (2023)



M. Hippert, et al. arXiv:2309.00579 (2023)



Jishnu Goswami, “Exploring the Critical Points in QCD with Multi-Point Padè and Machine Learning Techniques in (2+1)-flavor QCD” Quark Matter (2023)



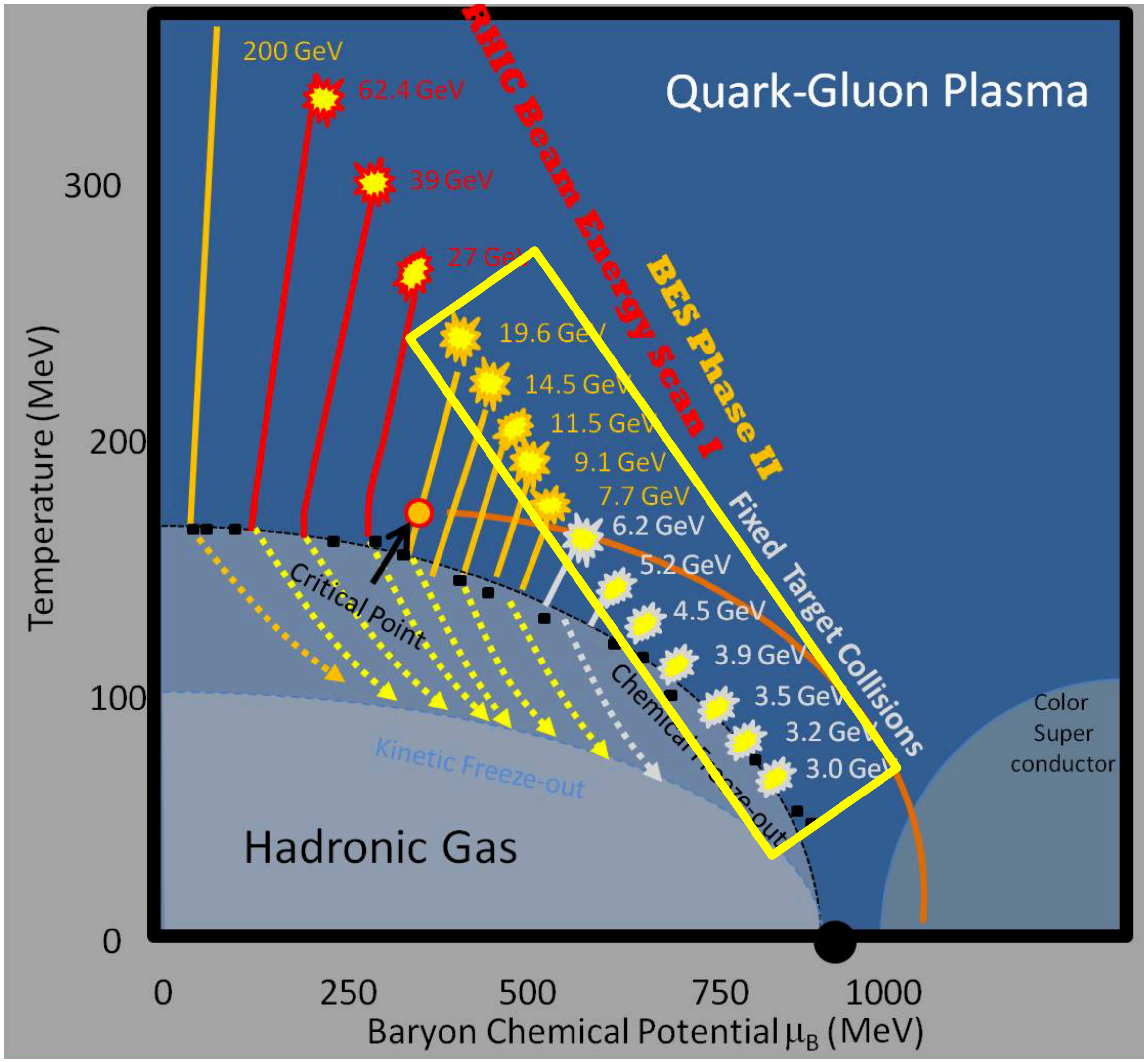
Wei-jie Fu: “Recent studies of QCD phase structure from both fRG and DSE have shown convergent estimate for the location of CP 600 < μ_B < 650 MeV”

Holographic Bayesian analysis:
- 560 < μ_B < 625 MeV

“Black-hole engineering”
(~ tweak holographic model to reproduce lattice QCD results)

Extrapolated estimate using machine-learning model from hotQCD :
μ_B ~ 600 +/- 80 MeV

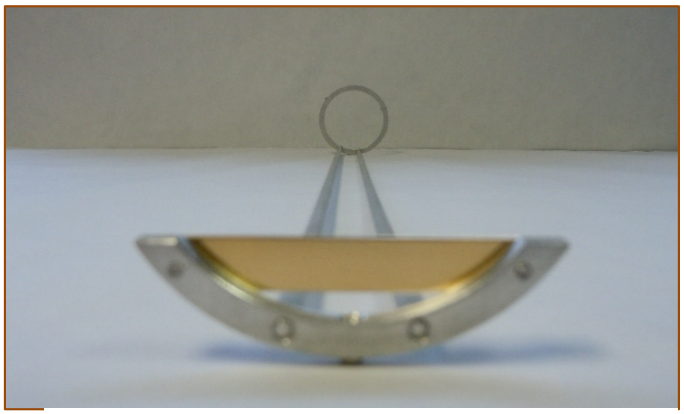
to get there: Fixed Target program to expand μ_B to lower values

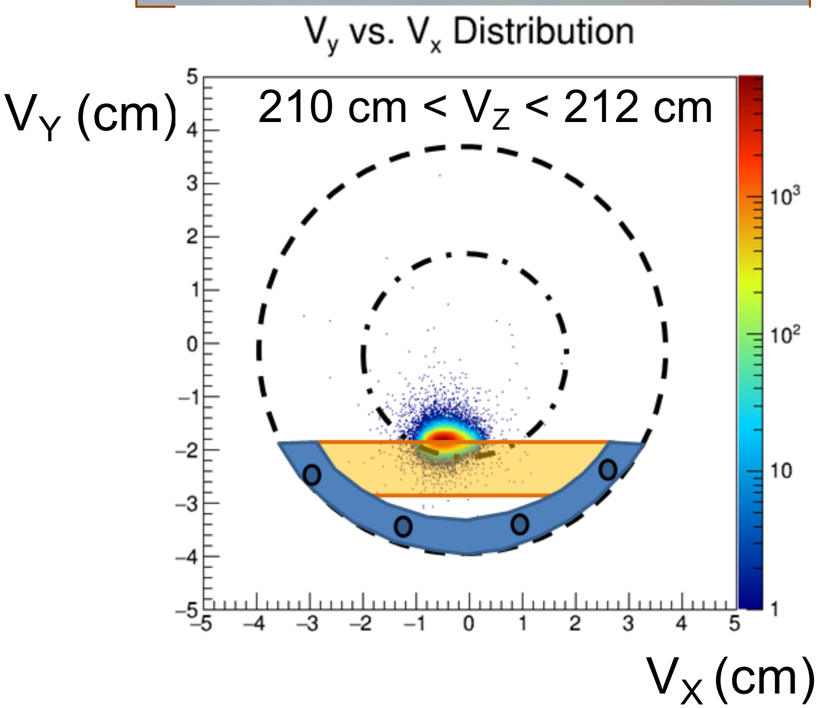


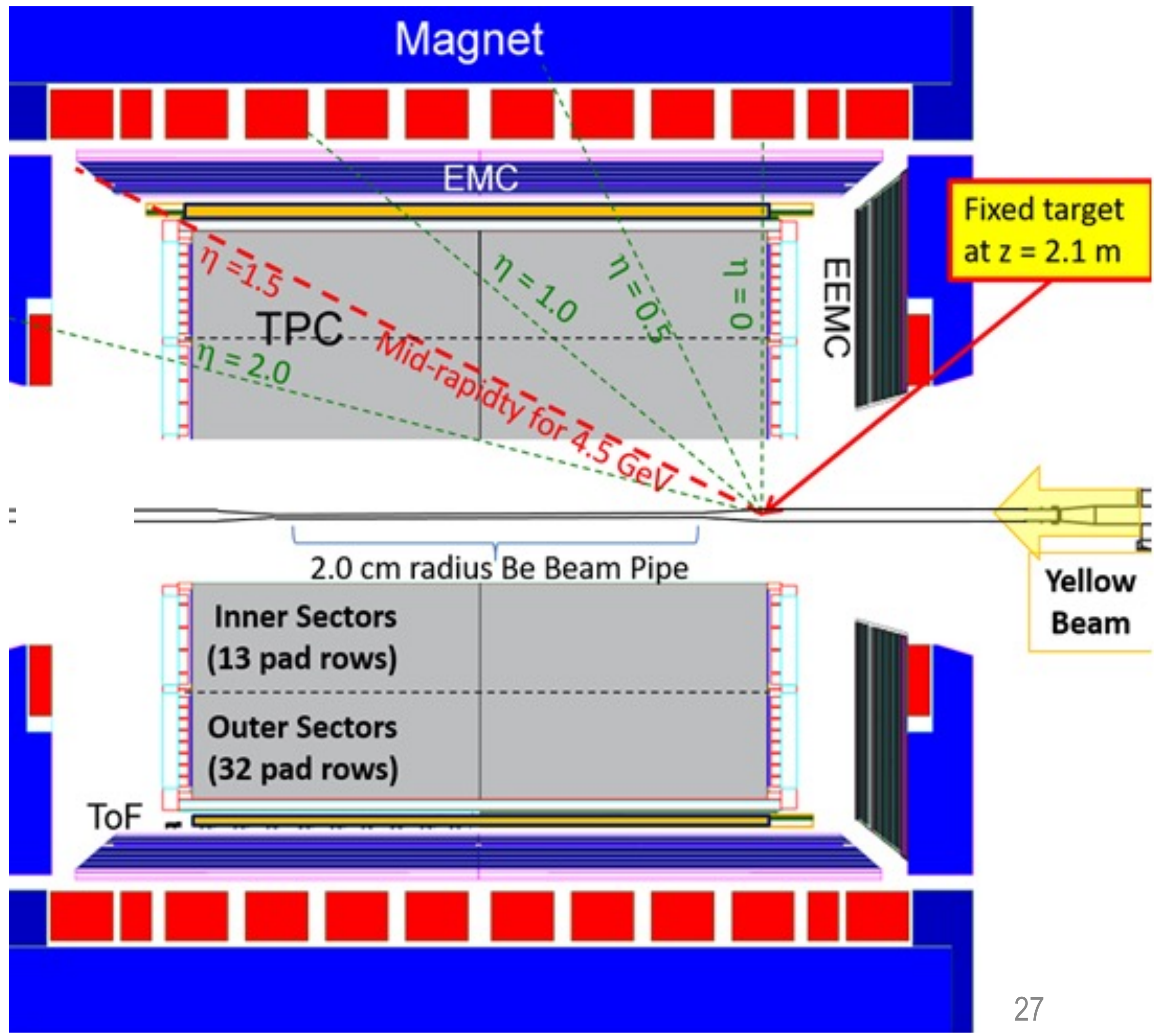
Collider can not run below 7.7 GeV ⟹ fixed target run with one beam only ⟹ Fixed Target Program in STAR with target in beam pipe at z = 210 cm (entry to TPC)

First dedicated FTX Au+Au run at $\sqrt{s_{NN}}$ = 4.5 GeV in 2015

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







Fixed Target program in STAR

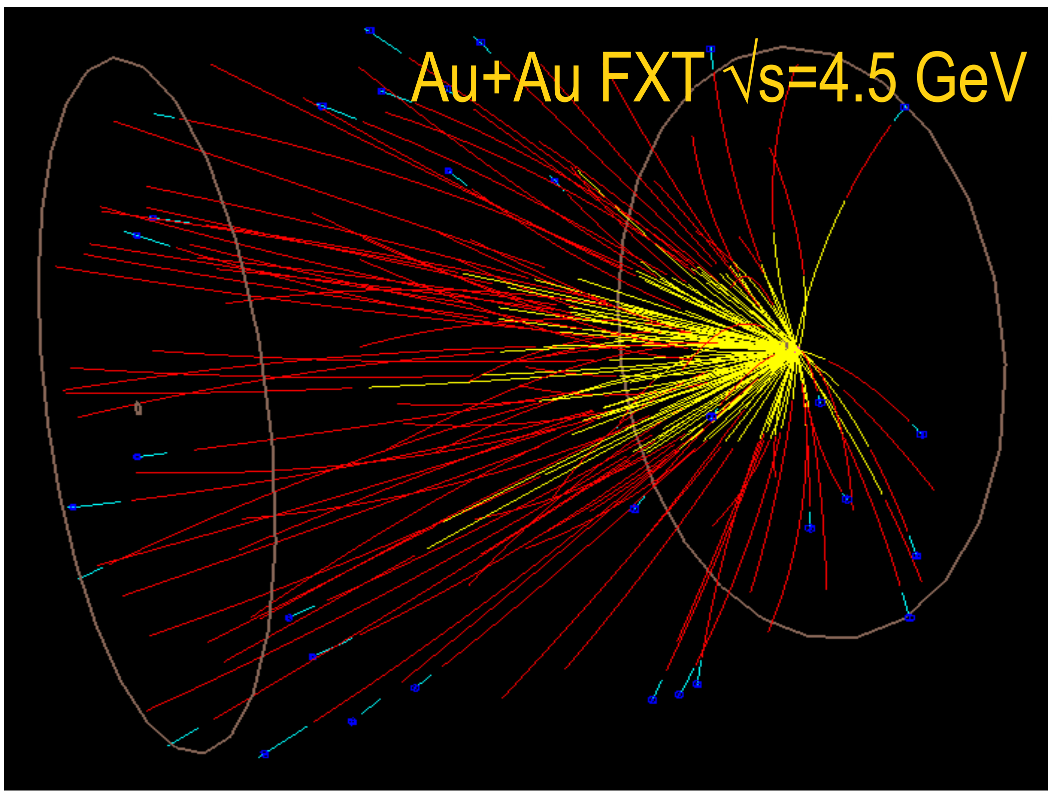
Extends energy range from $\sqrt{s}$ = 7.7 down to 3 GeV
Increase μ_B range from 420 MeV to 720 MeV

Test run with gold target in 2015

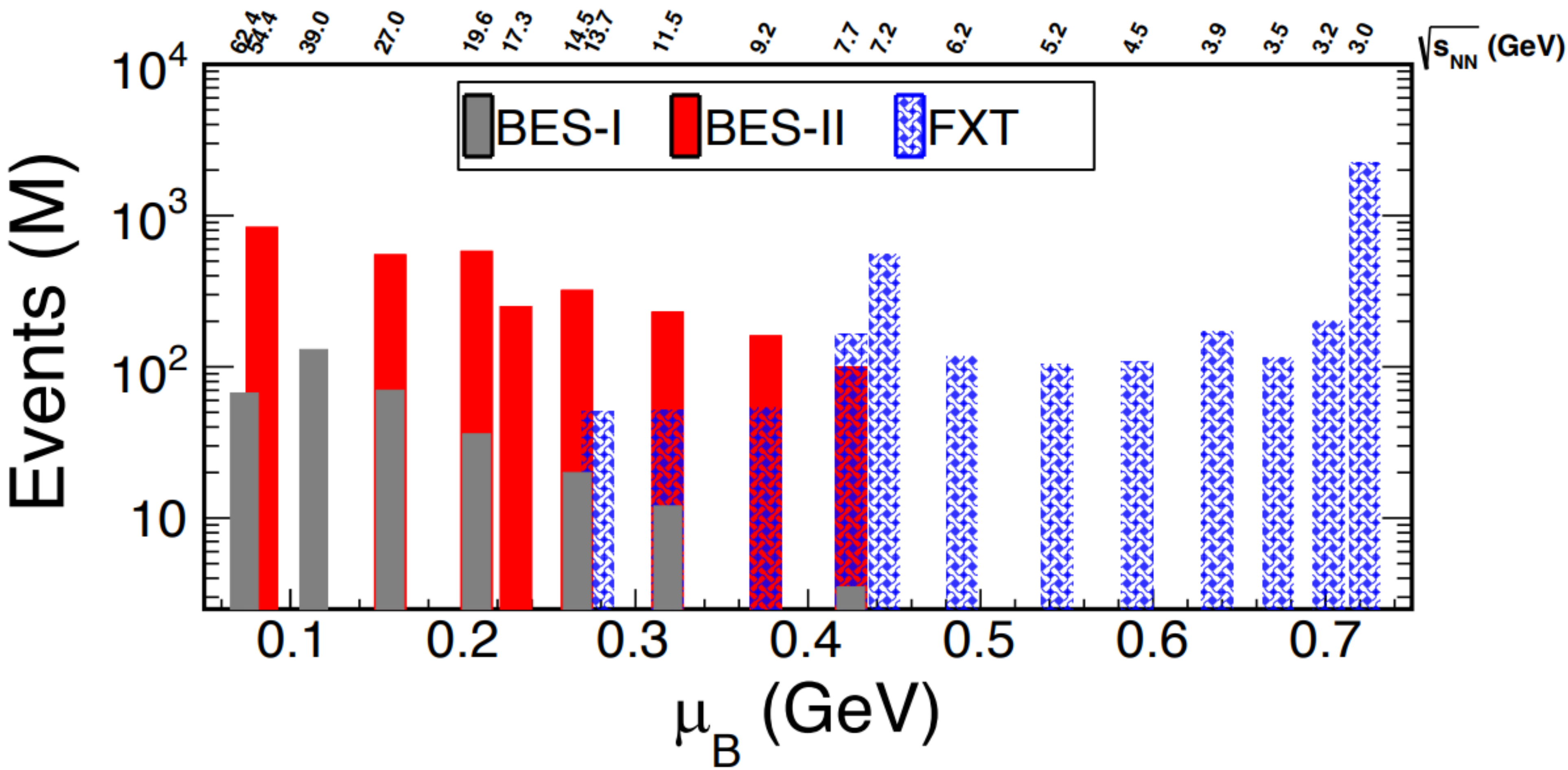
First physics runs at $\sqrt{s_{NN}}$ = 3 GeV and 7.2 GeV in 2018

Now have data at $\sqrt{s_{NN}}$ = 3.0, 3.2, 3.5, 3.9, 4.5, 5.5, 6.2, 7.2, and 7.7 GeV

Nominal $\sqrt{s}$ (GeV)	Chemical Potential μ_B (MeV)
3.2	697
3.5	666
3.9	632
4.5	589
5.2	541
6.2	487
7.2	443
7.7	420



Note: Reach 7.7 in FXT mode:
- compare with collider mode
- control systematic errors



https://www.agsrhichome.bnl.gov/RHIC/Runs/

	$\sqrt{s_{NN}}$ (GeV)	Beam E (GeV)	# of Good Events	BES-I
2017	54.4		1350 M	
2018	27		560 M	70 M
	7.2	26.5 (FXT)	155 M	
	3.0	3.85 (FXT)	258 M	
2019	19.6		582 M	36 M
	14.6		324 M	20 M
	7.7	31.2 (FXT)	50.6 M	
	3.9	7.3 (FXT)	52.7 M	
	3.2	4.59 (FXT)	201 M	
2020	11.5		235 M	12 M
	9.2		162 M	
	7.7	31.2 (FXT)	112 M	
	7.2	26.5 (FXT)	317 M	
	6.2	19.5 (FXT)	118 M	
	5.2	13.5 (FXT)	103 M	
	4.8	11.5 (FXT)	235 M	
	4.5	9.8 (FXT)	108 M	
	3.9	7.3 (FXT)	117 M	
	3.5	5.75 (FXT)	116 M	
2021	17.3		250 M	
	7.7		101 M	5 M
	13.5	100 (FXT)	50.7 M	
	11.5	70 (FXT)	51.7 M	
	9.1	44.5 (FXT)	53.9 M	
	3.0	3.85 (FXT)	2.0 B	

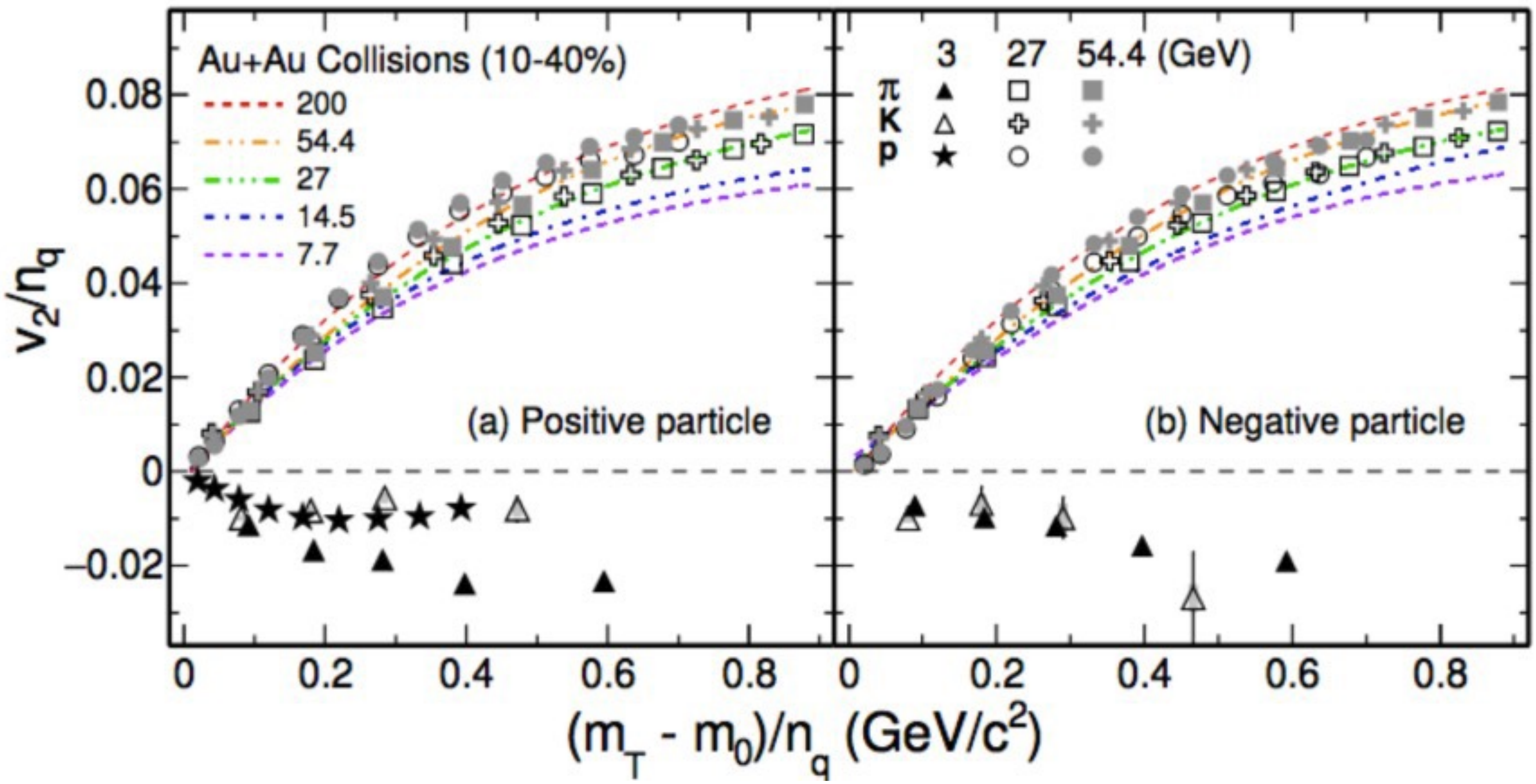
BES-II Datasets

x10-20 more statistics compare to BES-I

2020-2021 – COVID

Compilation by X.Dong

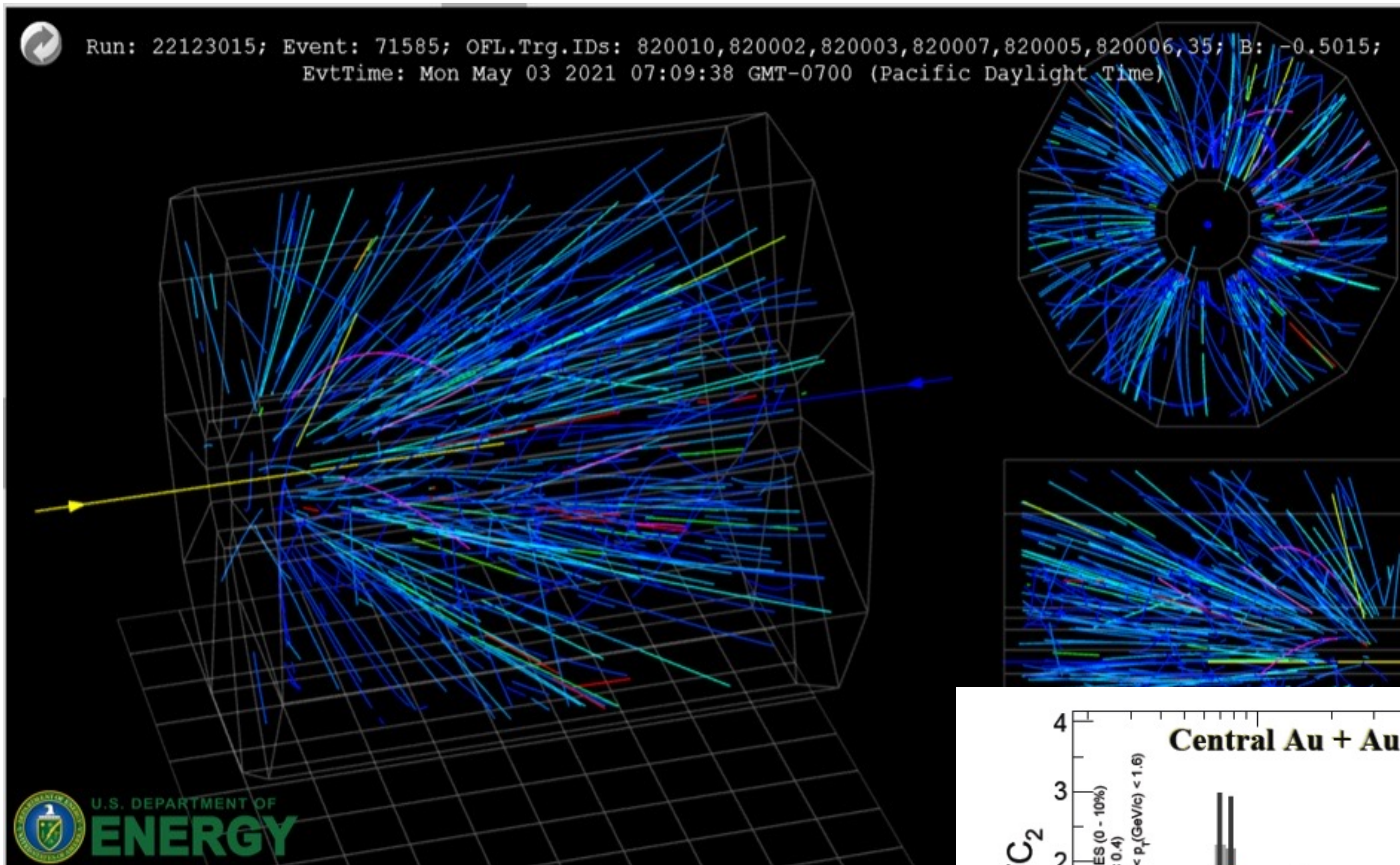
Particle Collectivity at Au+Au collisions at 3 GeV



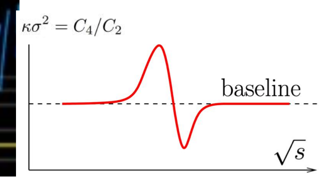
No NCQ scaling at 3 GeV Au+Au collisions

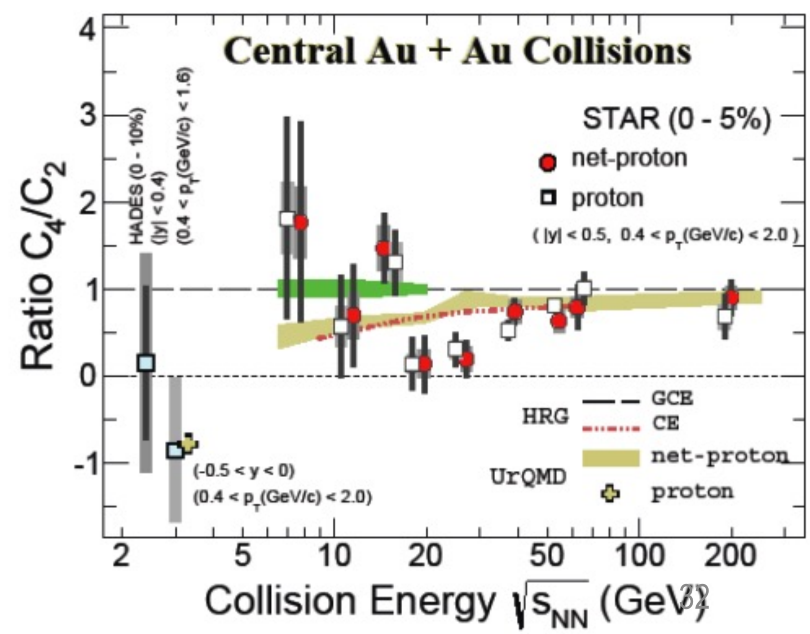
UrQMD with baryonic mean-field potential qualitatively consistent with data

➡ Equation-of-State dominated by baryonic interactions at 3 GeV Au+Au



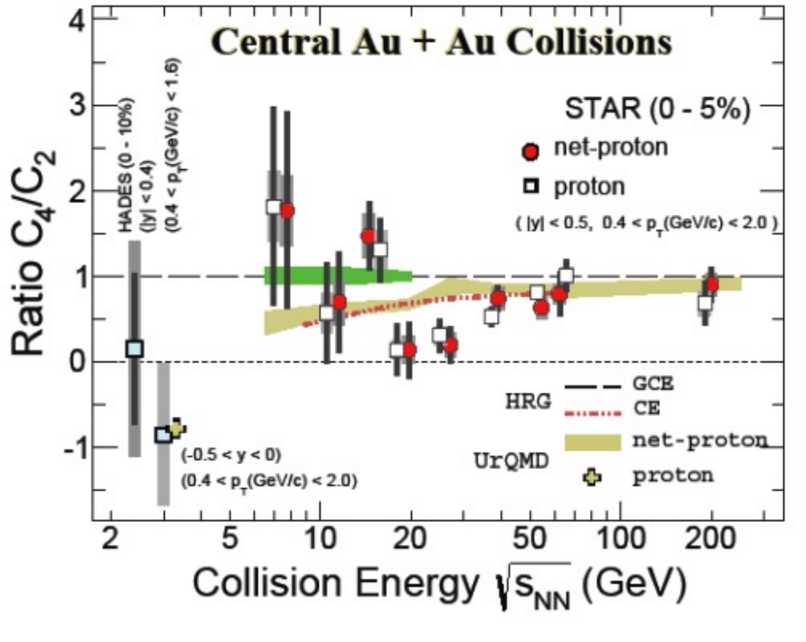
Au+Au,
3 GeV
FXT





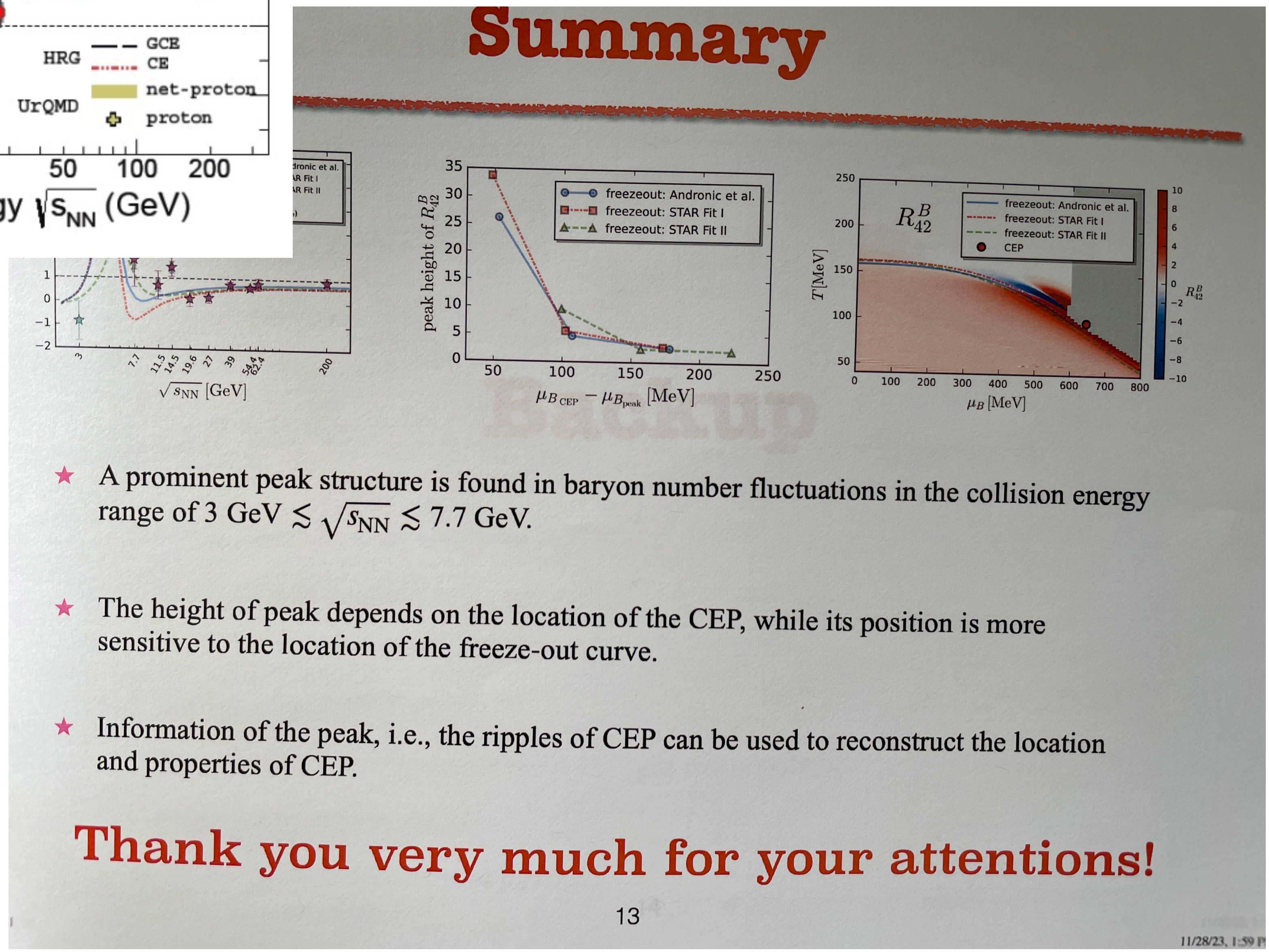
CP somewhere between 3 and ~20 GeV ?

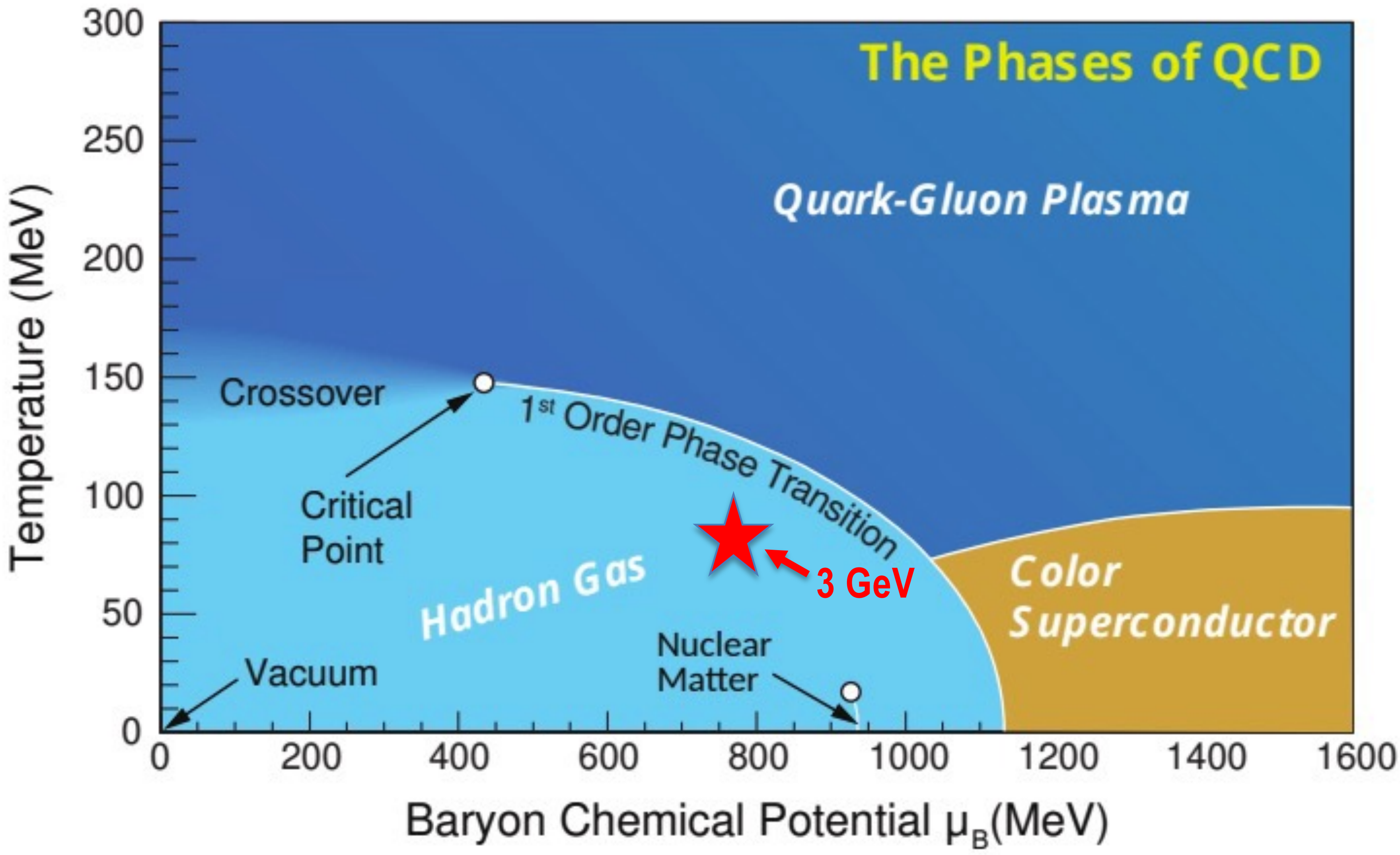
STAR, Phys. Rev. Lett. 128, 202303 (2022) ; arXiv : 2209.11940.
Phys. Rev. Lett. 126, 092301 (2021); Phys. Rev. C 104, 024902 (2021)



From theorists' point of view:

Slide from Wei-jie Fu presentation at QM 2023:





Au+Au @ 3 GeV – hadronic phase

BES presentations at QM 2023

Measurements of p-Λ and d-Λ correlation functions in Au+Au collisions from STAR BES – II -Yu Hu

Probing the nature of the QCD phase transition with higher-order net-proton number fluctuation and local parton density fluctuation measurements at STAR-RHIC - Dylan Neff

Elliptic and triangular flow of light (anti-)nuclei in Au+Au collisions at BES-II energies using STAR - Rishabh Sharma

Anisotropic flow of identifed particles in Au + Au Collisions at sqrt{s_{NN}} = 3.0 - 19.6 GeV - Zuowen Liu

Light- and Hyper-Nuclei Collectivity in Au+Au Collisions at RHIC - Chengdong Han

First Order Event Plane Correlated Directed and Triangular Flow in BES-II Au+Au Collisions at STAR - Xiaoyu Liu

Exploring electromagnetic field effects and constraining transport parameters of QGP using STAR BES II data - Aditya Prasad Dash

Beam energy and system size dependence of heavy flavor production at STAR - Yan Wang

Strangeness production in Au+Au collisions at sqrt{s_{NN}}=19.6, 14.5, 7.7, 200 GeV from STAR - Yi Fang

Particle production in Au+Au collisions at Beam Energy Scan (BES) II energies with STAR at RHIC - Matthew Harasty

Thermal dielectron measurement in Au+Au collisions at sqrt{s_{NN}} =7.7 14.6, 19.6 GeV with STAR - Yiding Han

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+ posters

Following the Phys. Rev. Lett. 112 publication, directed flow v_1 analysis continues:

Phys. Rev. Lett. 120 (2018) 62301
PI: Prashanth Shanmuganathan, Declan's student
Beam-Energy Dependence of Directed Flow of Λ, $\bar{\Lambda}$, $K^{\pm}$, K^0_s and φ in Au+Au Collisions

Phys. Rev. Lett. 123, 162301 (2019)
PI: Subhash Singha, Declan's postdoc
First observation of the directed flow of D^0 and $\bar{D}^0$ in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

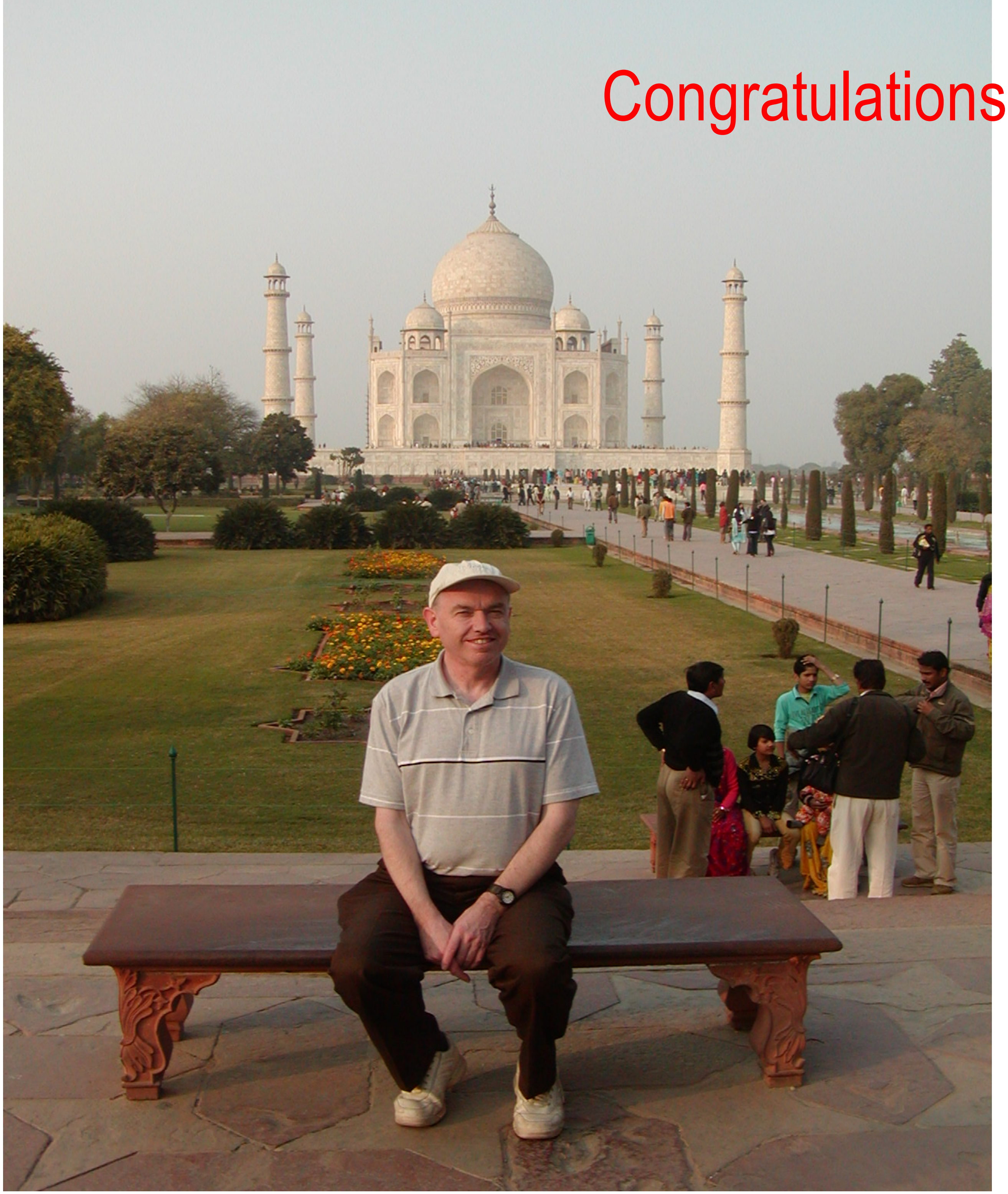
Submitted to Phys. Rev. Lett. on Apr. 10, 2023
arXiv: 2304.02831v1
PI: Ashik Ikbal Sheikh, Declan's postdoc
Electric charge and strangeness-dependent directed flow splitting of produced quarks in Au+Au collisions

Poster at QM 2023, Houston, September 2023
PI: Emmy Duckworth, Declan's student

Currently, BES-II proton v_1 analysis -> see Sooraj Skradhakrishnan' presentation

Following Declan's work in E895 and BES-I (2 papers):
1. Disappearance of partonic collectivity in GeV Au+Au collisions at RHIC, Phys.Lett.B827,137003(2022)
2. Observation of Directed Flow of Hypernuclei ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ in $\sqrt{s_{NN}}$ = 3 GeV Au+Au Collisions at RHIC
arXiv: 2211.16981, Phys. Rev. Lett. 130 (2023) 21, 212301

Congratulations, Declan !



Happy Birthday, Declan!

and thank you for
your great contributions to our field !
your passion and superbly high standards !
couching and training younger generation !
and for your friendship !

and the very best wishes for the future …

Thanks to all of you for your attention
and have a wonderful celebration for Declan !