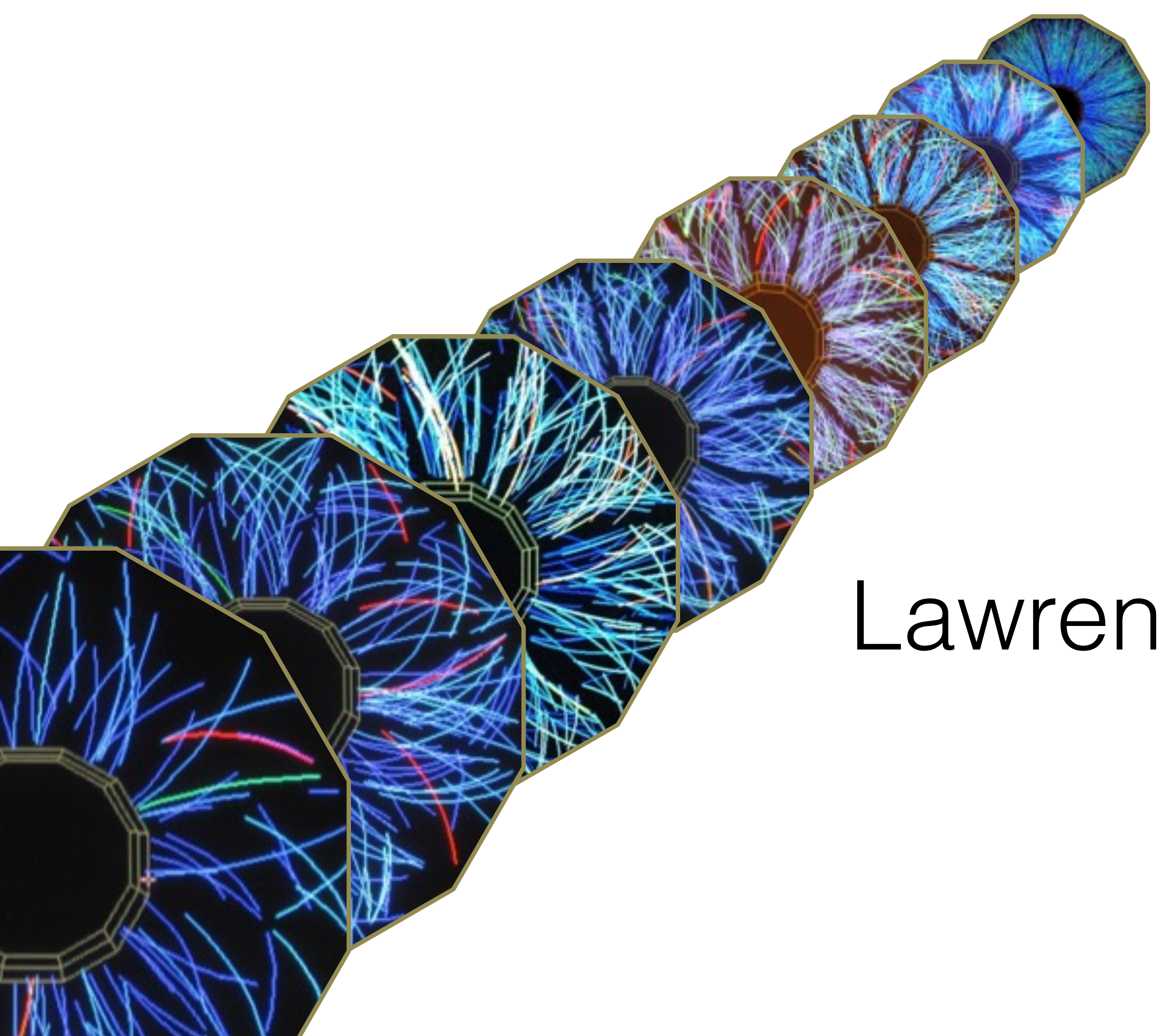
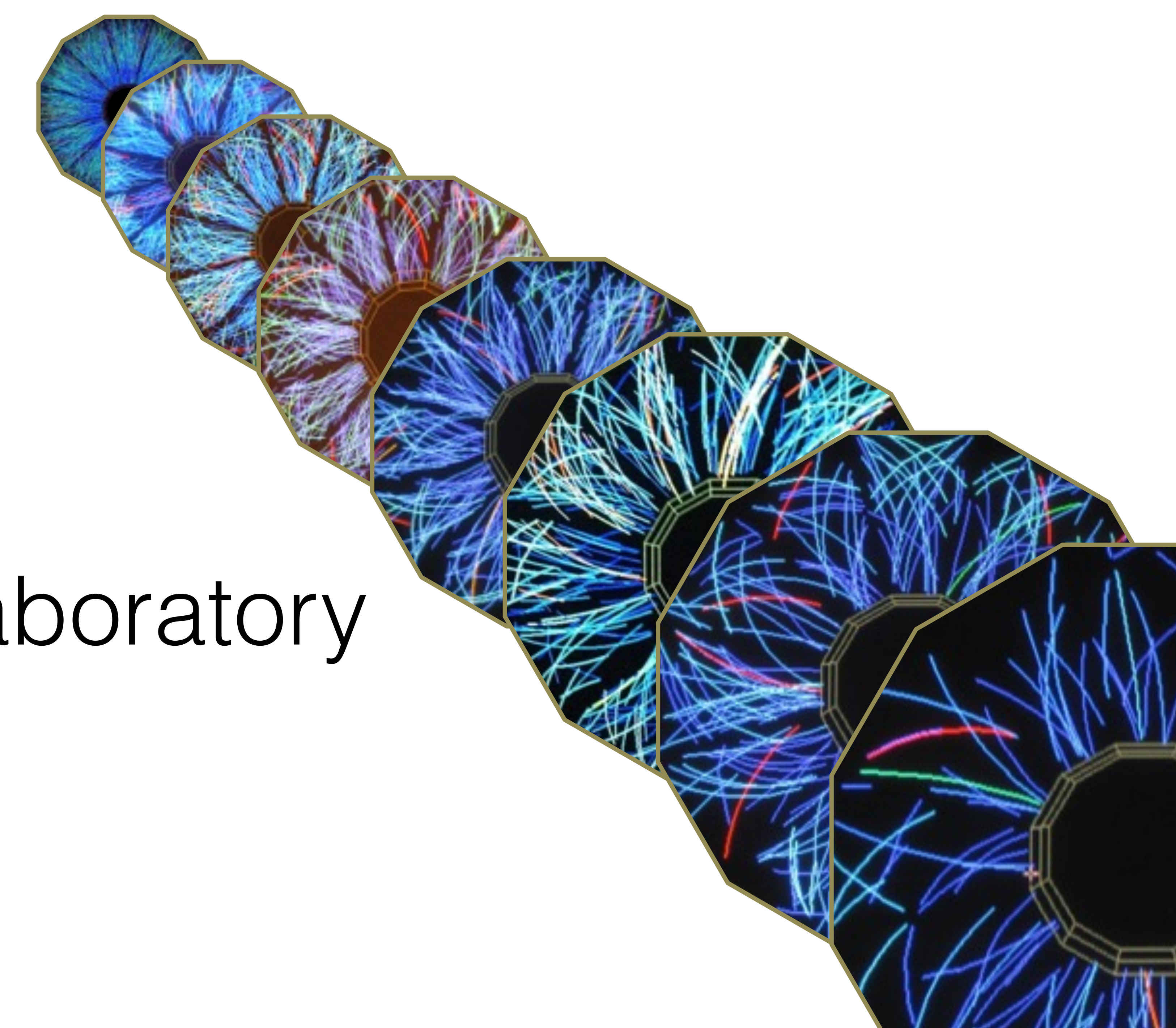
Overview of the Beam Energy Scan Program at RHIC



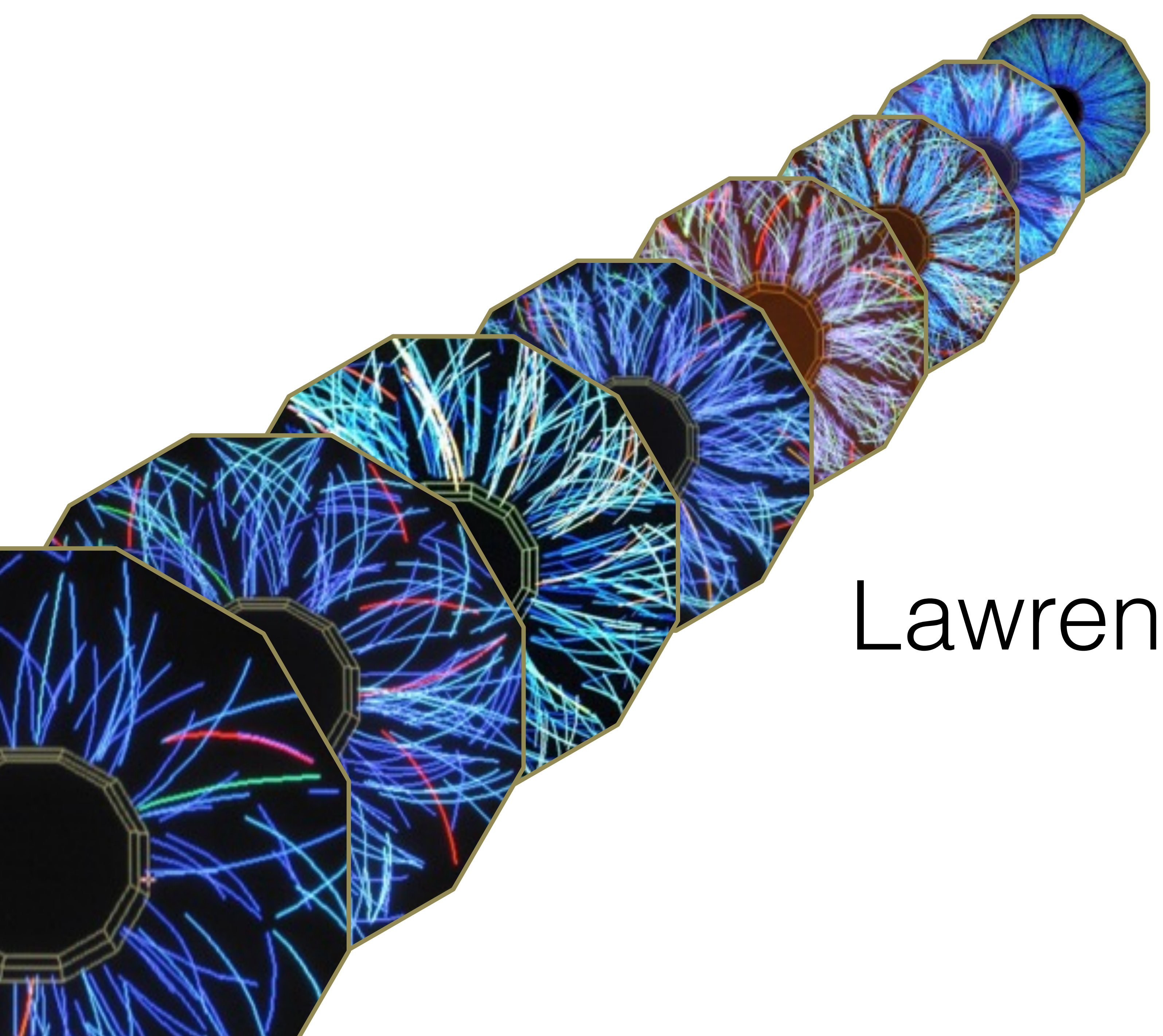


Jochen Thäder

Lawrence Berkeley National Laboratory

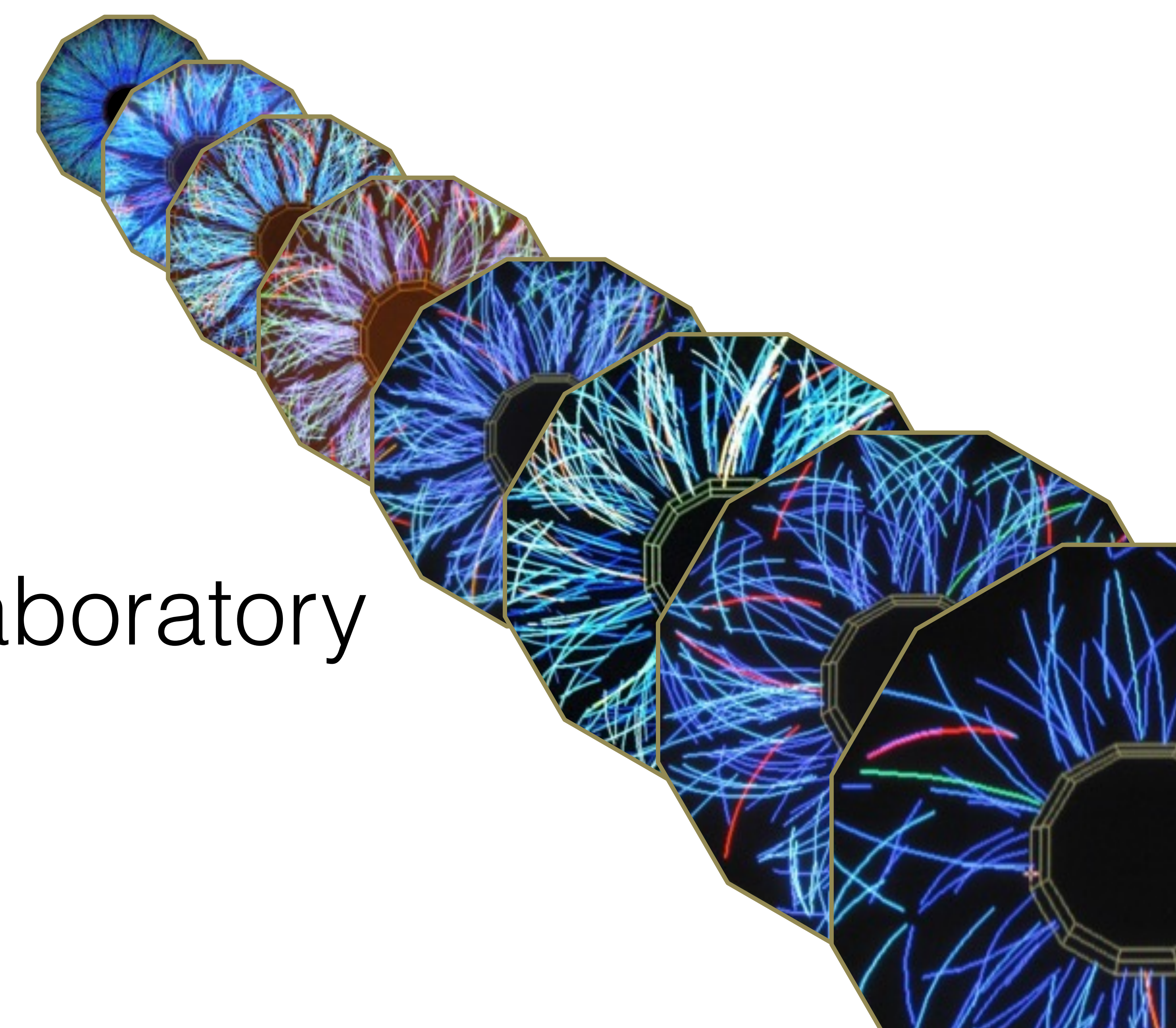
Fairness 2016

… Exploring the QCD Phase Diagram



Jochen Thäder

Lawrence Berkeley National Laboratory



Fairness 2016

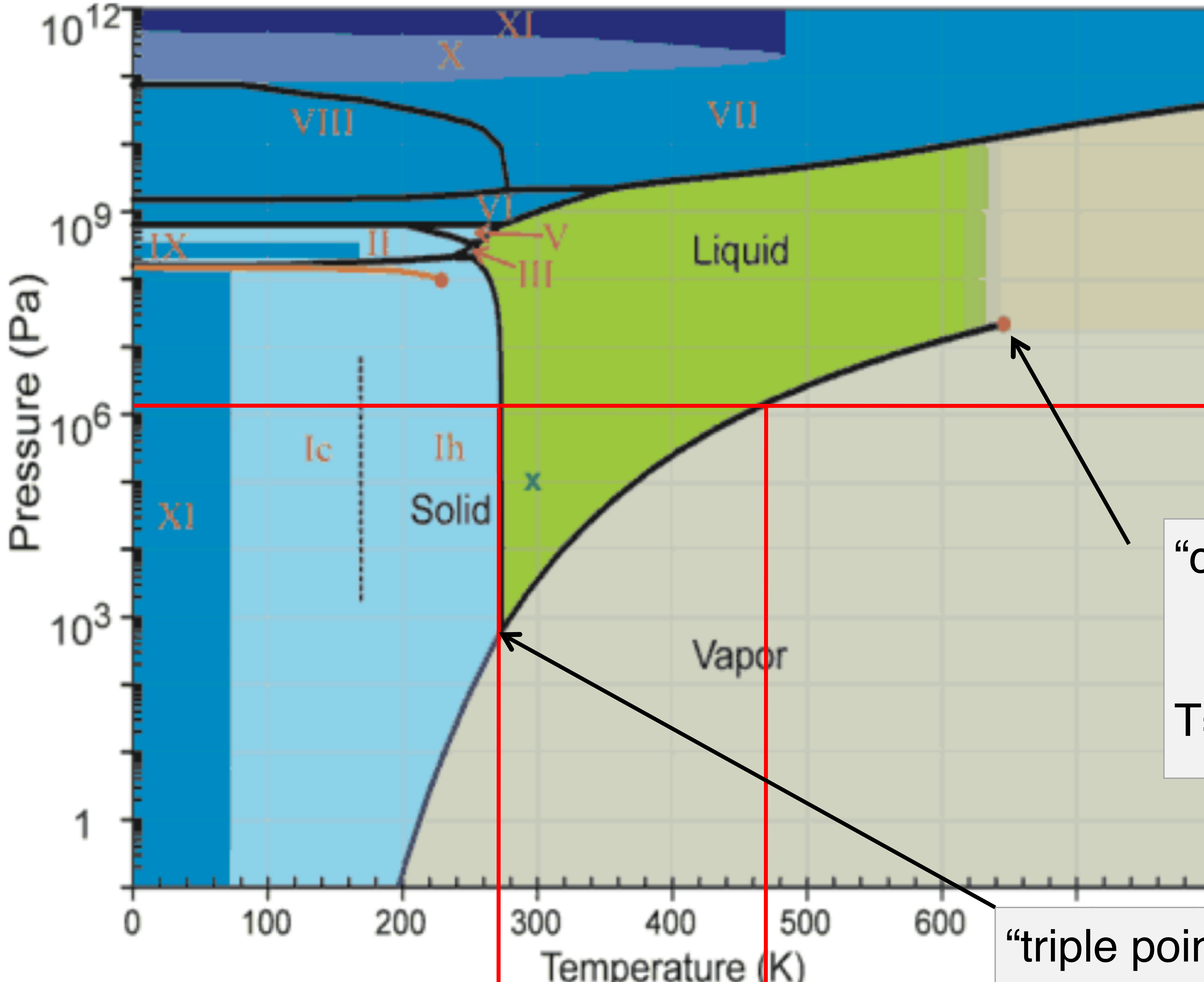
Outline

- Motivate the Beam Energy Scan (BES)
- The RHIC Facility
- Selected BES I results
- Outlook to BES II

"A slightly STAR biased view"

Motivation

The modern phase diagram of water



Solid
many crystalline & amorphous phases
Liquid
Vapor

1 "atmosphere"
101,325 Pa

"critical point"
liquid and gas phases merge & are indistinguishable
T= 647 K & 22.064 MPa

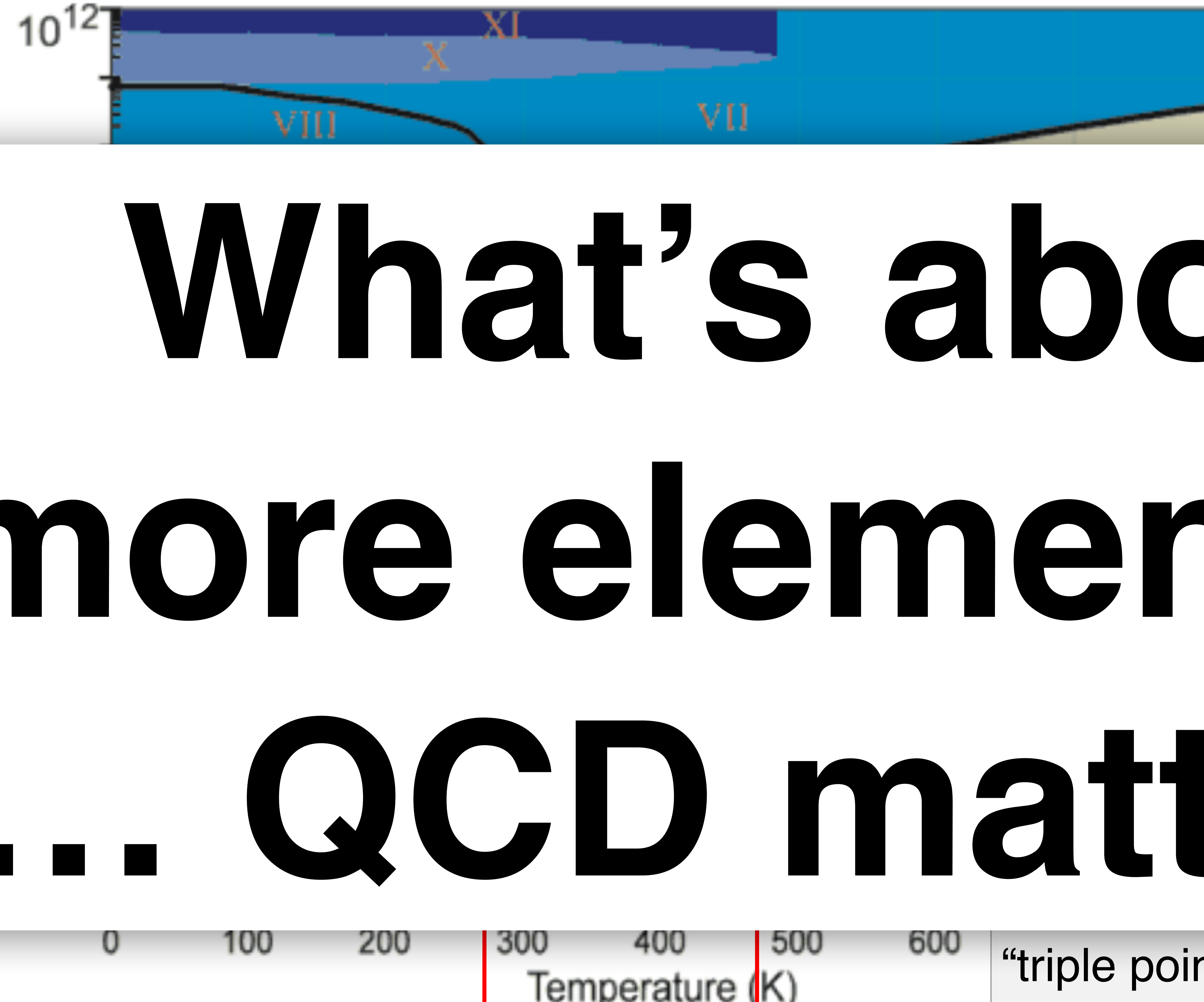
"triple point"
all three phases coexist
T=273.16 K (0.01 °C) by convention
P=611.73 Pa

"**Order Parameter**" has distinct values in the different phases. For water, it's the density.

273 K
0 deg C
2.4×10^{-8} MeV

373 K
100 deg C
3.2×10^{-8} MeV

The modern phase diagram of water



Solid

many crystalline & amorphous phases

What's about more elementary ... QCD matter ?

merge

"**Order Parameter**" has distinct values in the different phases. For water, it's the density.

273 K	373 K
0 deg C	100 deg C
2.4×10^{-8} MeV	3.2×10^{-8} MeV

"triple point"
all three phases coexist
T=273.16 K (0.01 °C) by convention
P=611.73 Pa

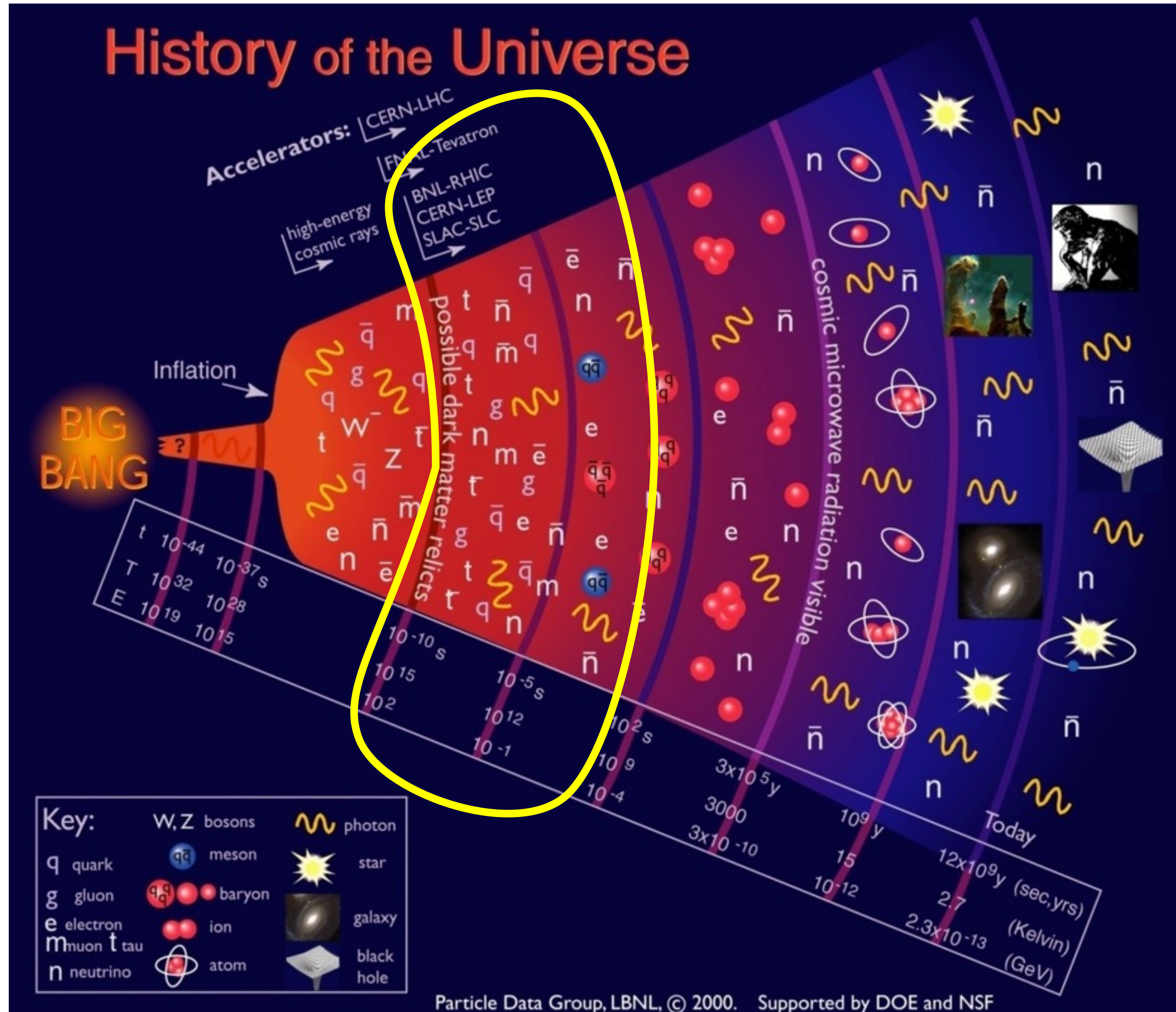
The universe (as far as we know)

A few μsec after the Big Bang

Went to different phases as well in its evolution.

High energy densities in the early stages of the universe.

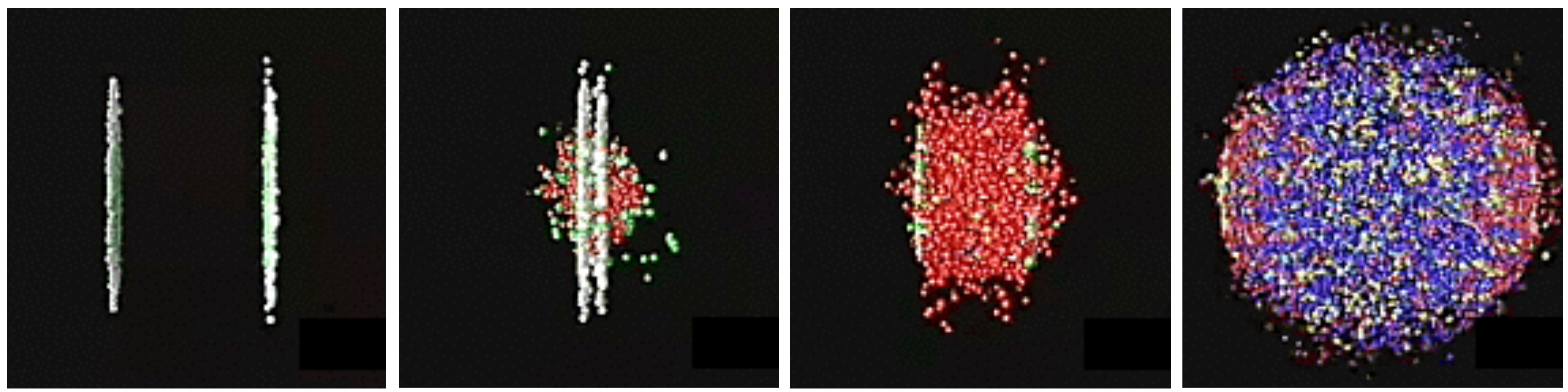
Partonic matter - Quark-Gluon Plasma



Relativistic Heavy-Ion Collisions

How do we produce such high energy densities in the lab and perhaps discover the QGP?

- Collisions of large nuclei at very high relative speed!
- Do such collisions of large atomic nuclei at very high energies allow us to reach densities high enough to create a Quark-Gluon Plasma?

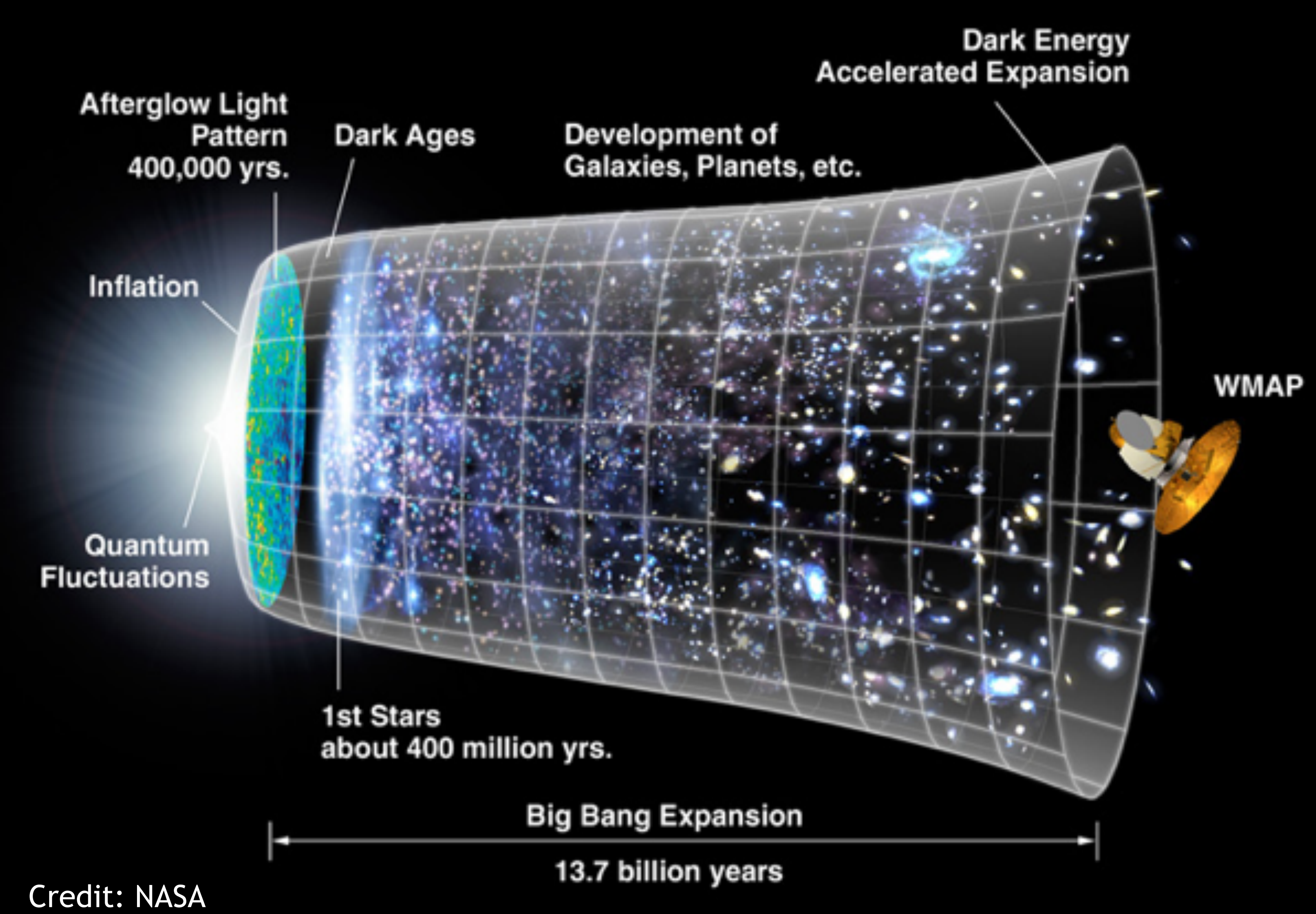


Is this picture correct? Can we detect it?

Relativistic Heavy-Ion Collisions

Slow vs Rapid Expansion

The Universe: Slow Expansion

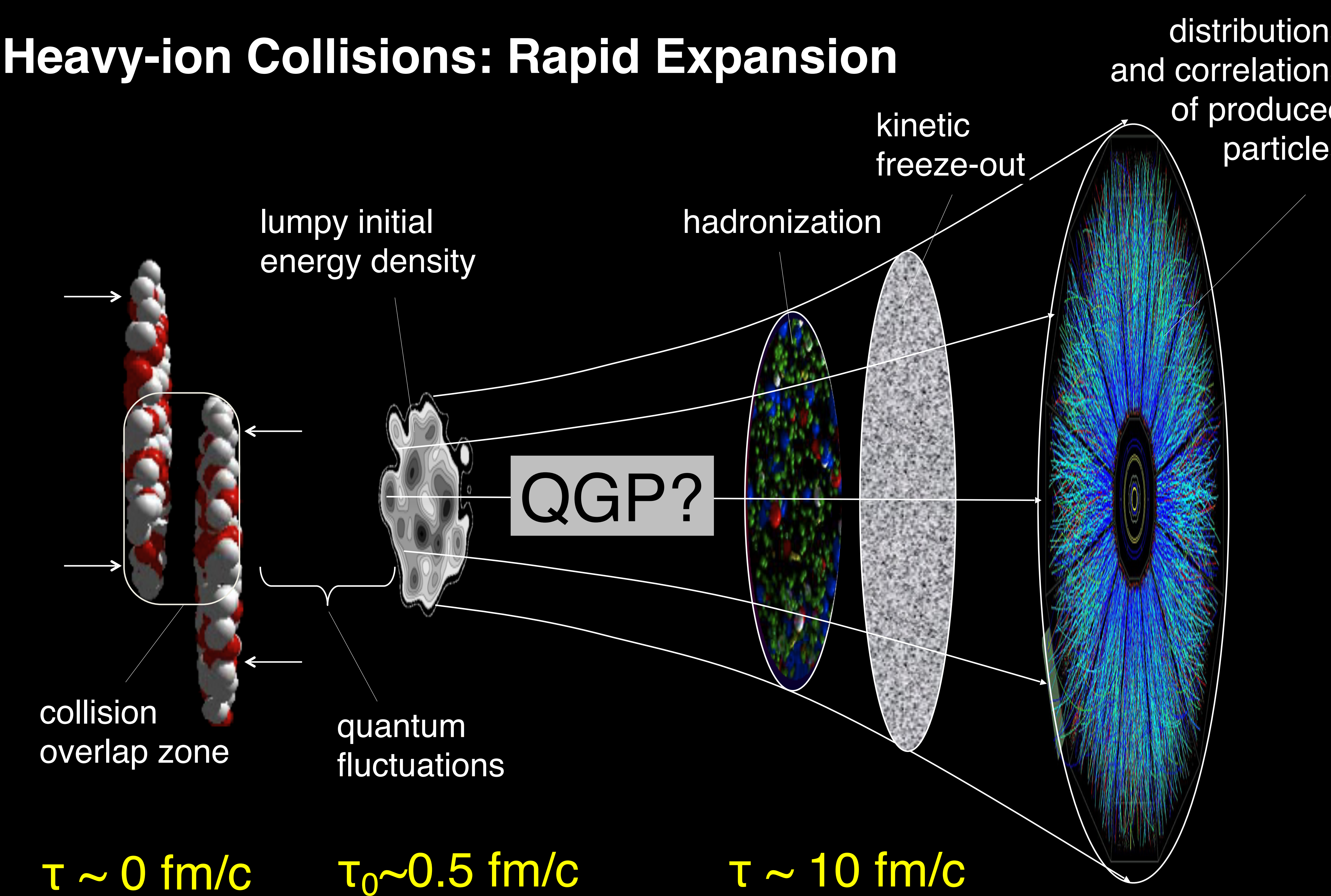


collision evolution

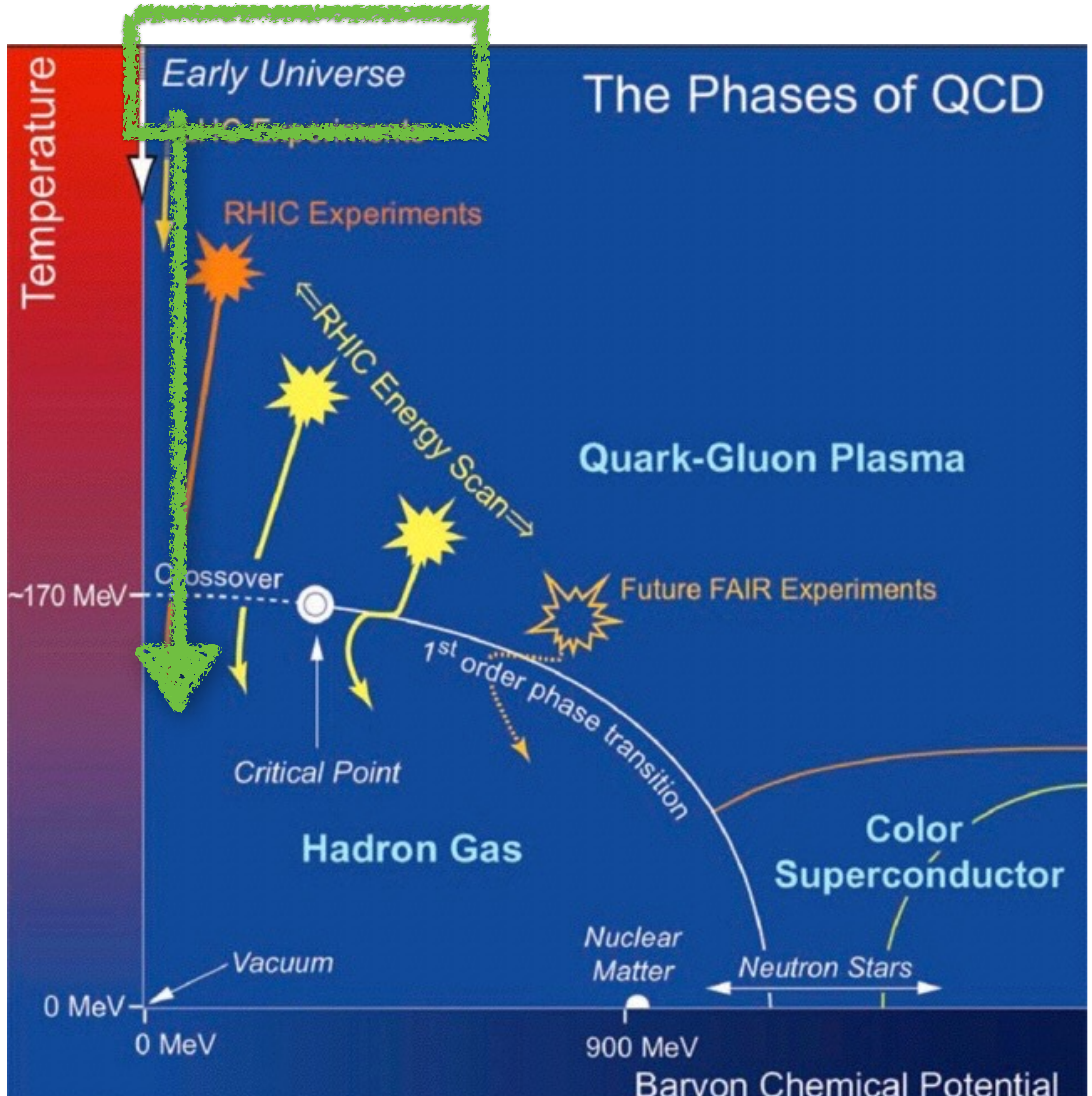
expansion and cooling

particle detectors

Heavy-ion Collisions: Rapid Expansion



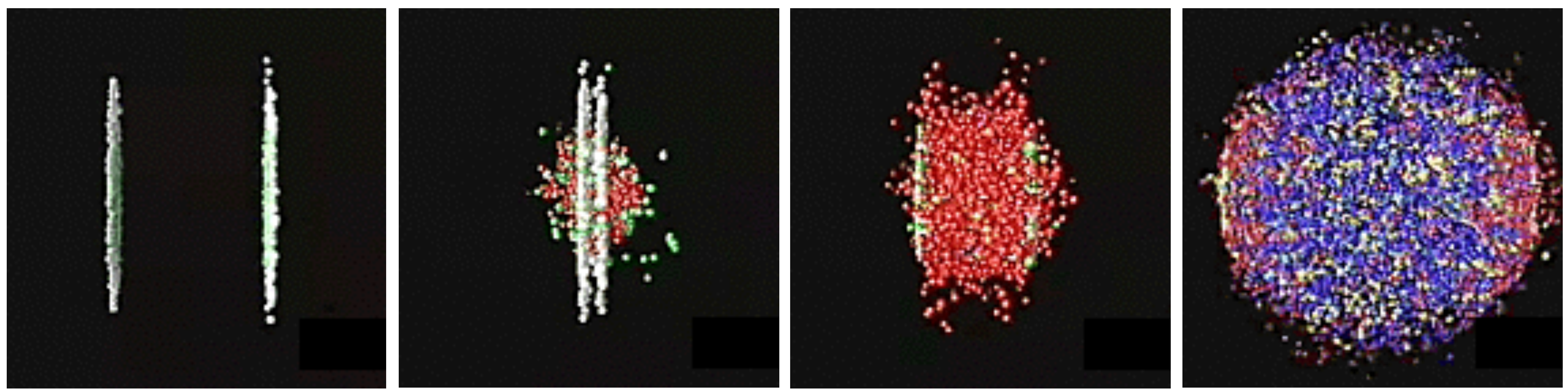
“A” QCD Phase Diagram



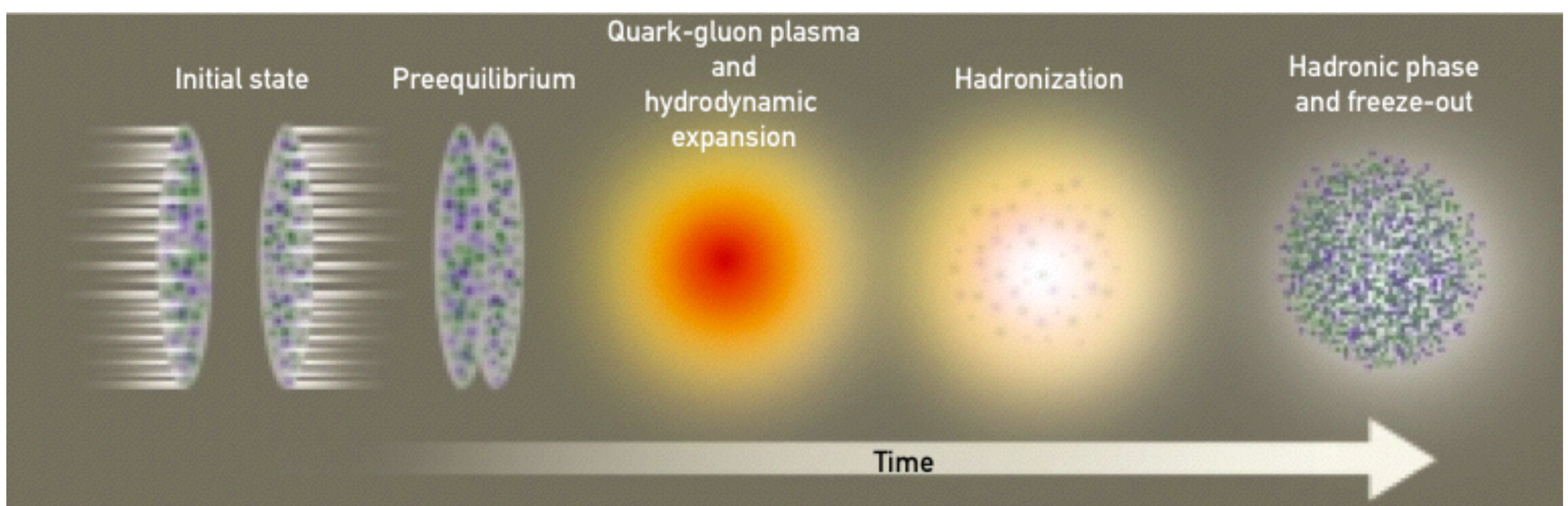
Relativistic Heavy-Ion Collisions

How do we produce such high energy densities in the lab and perhaps discover the QGP?

- Collisions of large nuclei at very high relative speed!
- Do such collisions of large atomic nuclei at very high energies allow us to reach densities high enough to create a Quark-Gluon Plasma?



Is this picture correct? Can we detect it?



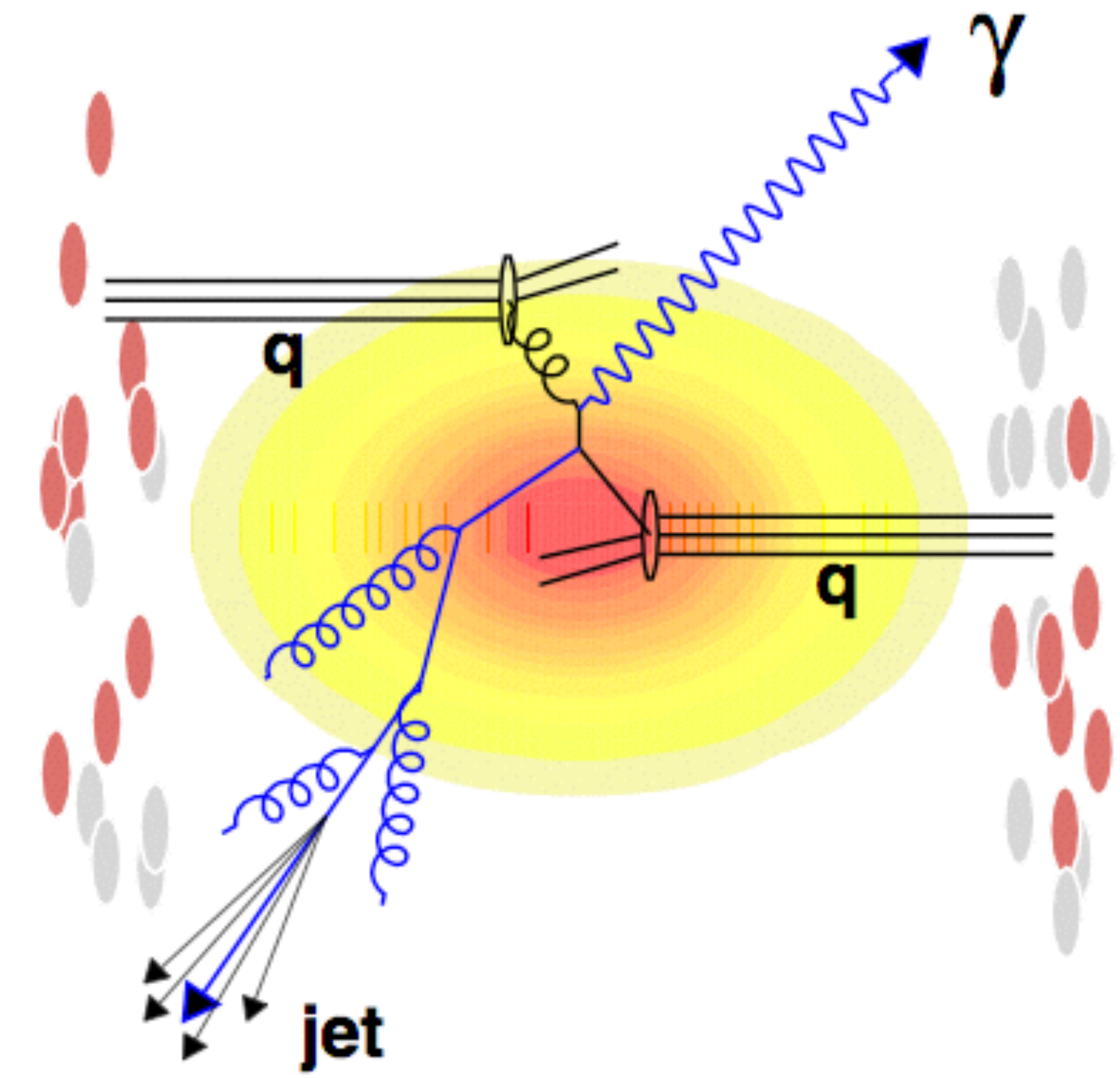
Relativistic Heavy-Ion Collisions

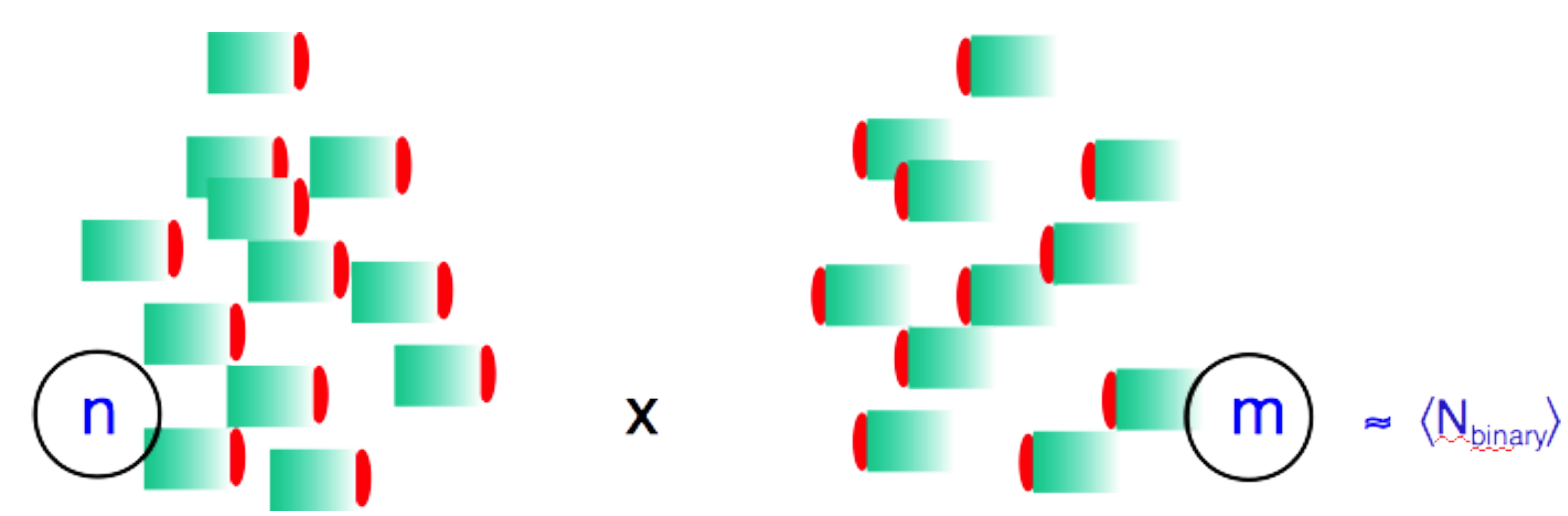
The Quark-Gluon Plasma

- Yes, we can detect it!
- Energy-loss / jet quenching at LHC and top RHIC energies
- Expressed as suppression in the nuclear modification factor R_{AA}

$$R_{AA} = \frac{\text{Particle yield in AA collisions}}{\text{Particle yield in pp collisions x Number of binary collisions}}$$

- $R_{AA} < 1$ for high p_T indicates energy loss in medium





Relativistic Heavy-Ion Collisions

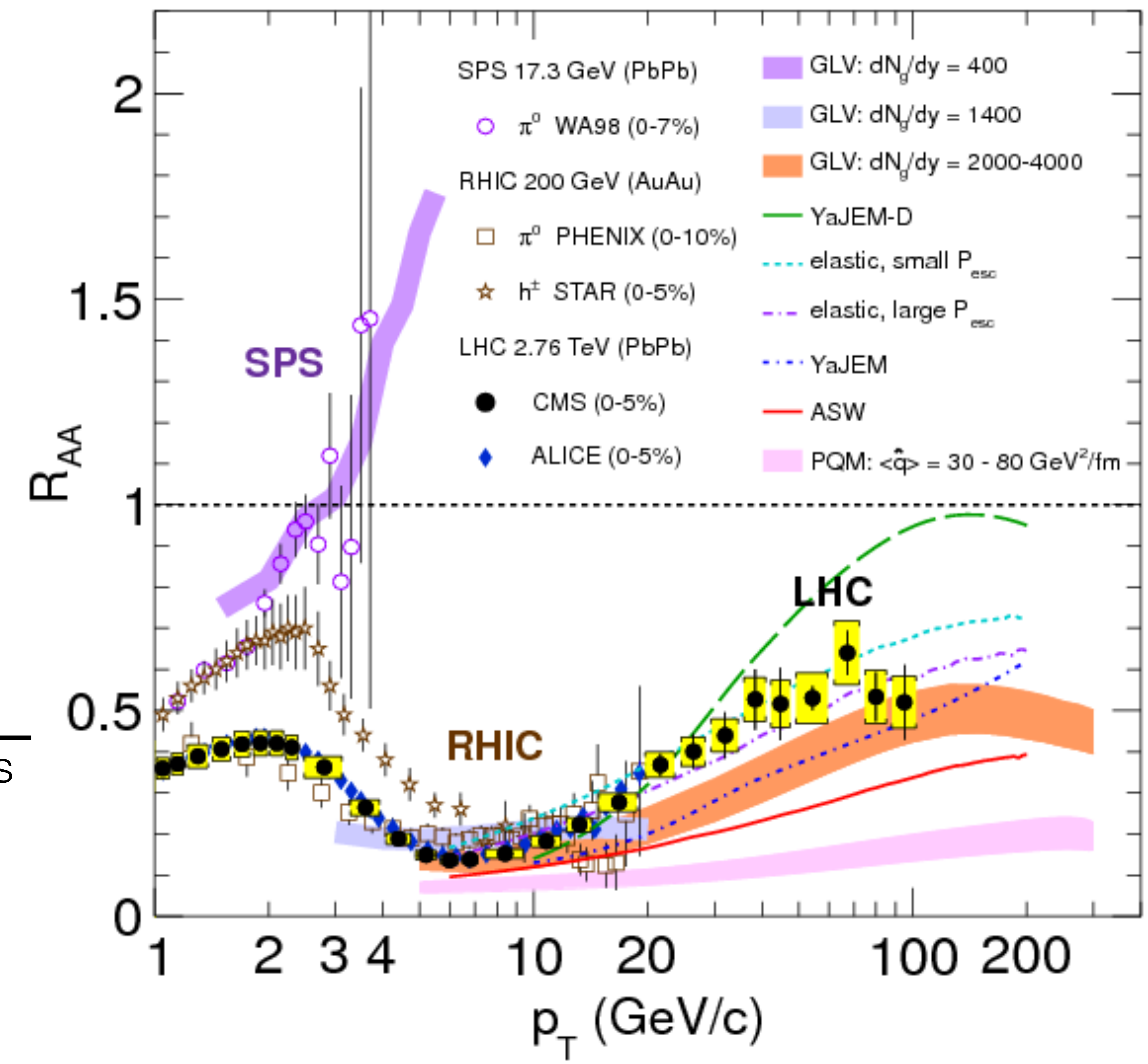
The Quark-Gluon Plasma

Eur.Phys.J. C72 (2012) 1945

- Yes, we can detect it!
- Energy-loss / jet quenching at LHC and top RHIC energies
- Expressed as suppression in the nuclear modification factor R_{AA}

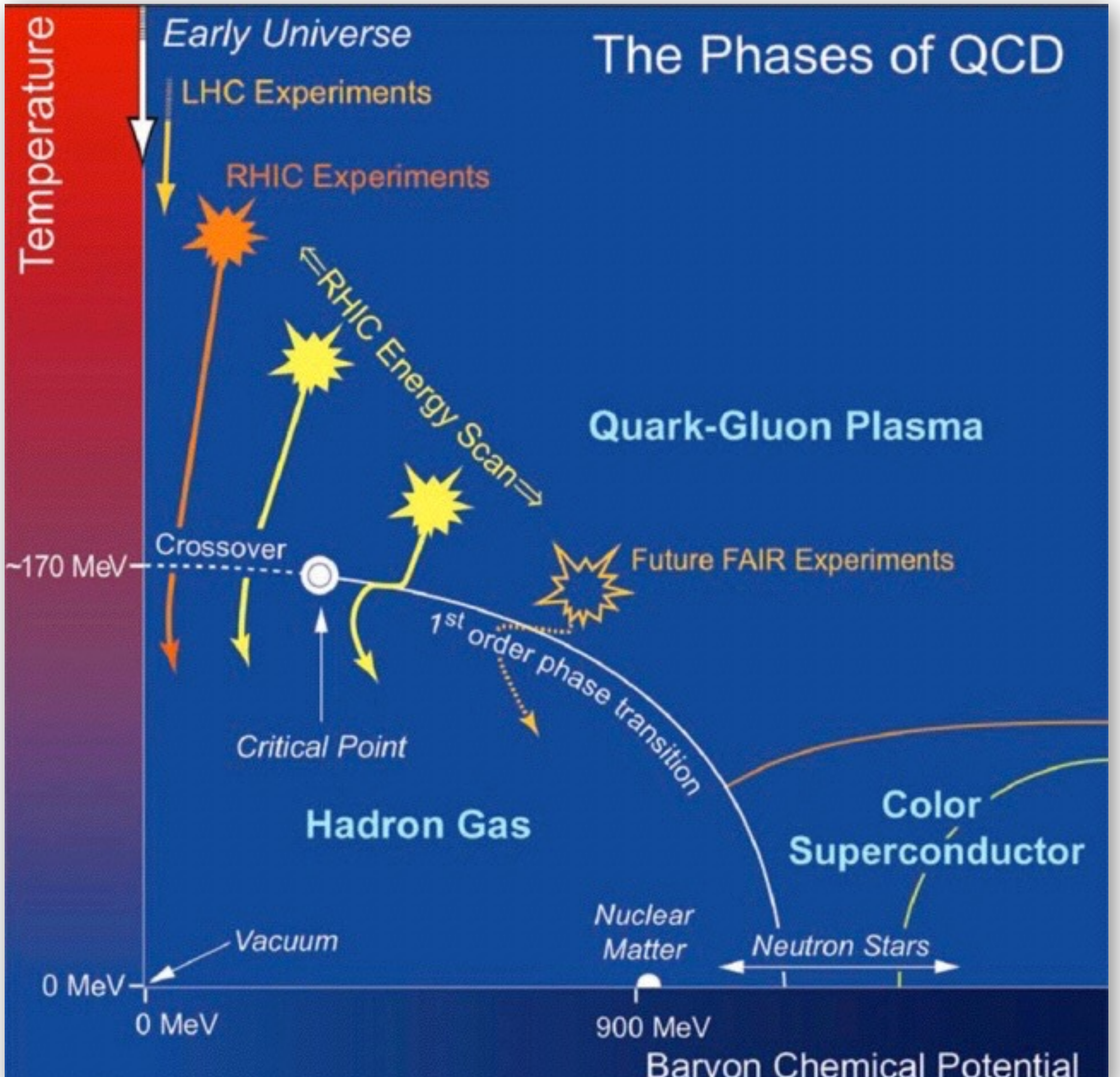
$$R_{AA} = \frac{\text{Particle yield in AA collisions}}{\text{Particle yield in pp collisions x Number of binary collisions}}$$

- $R_{AA} < 1$ for high p_T indicates energy loss in medium



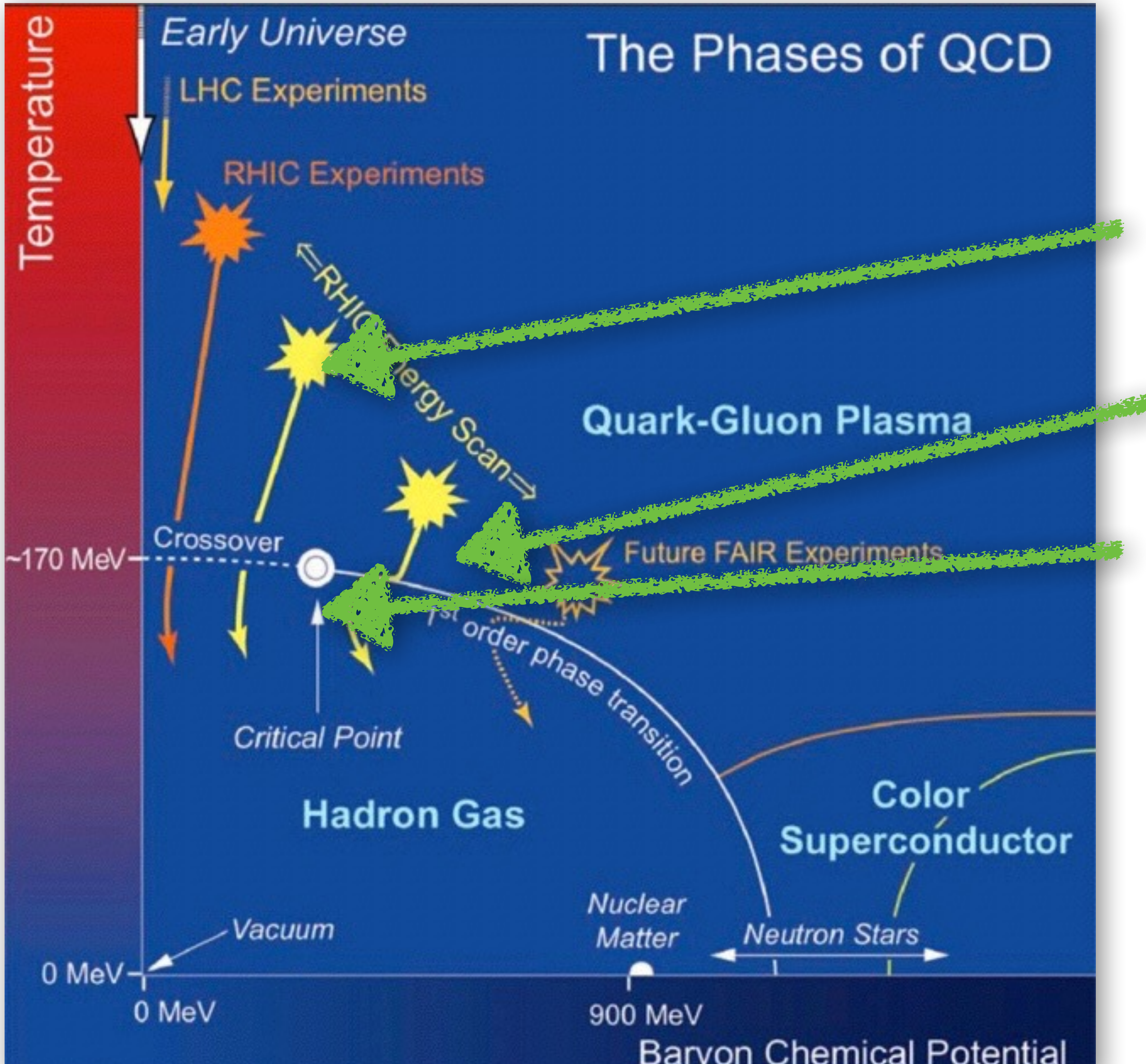
Explore the QCD Phase Diagram

What do we know?



- High Energy Heavy-ion Collisions ➔ partonic matter
- Highest energies ➔ transition is a cross over
- At increased μ_B, there might be a first-order phase transition
- And if so, there should be a critical point

Explore the QCD Phase Diagram
What do we look for?

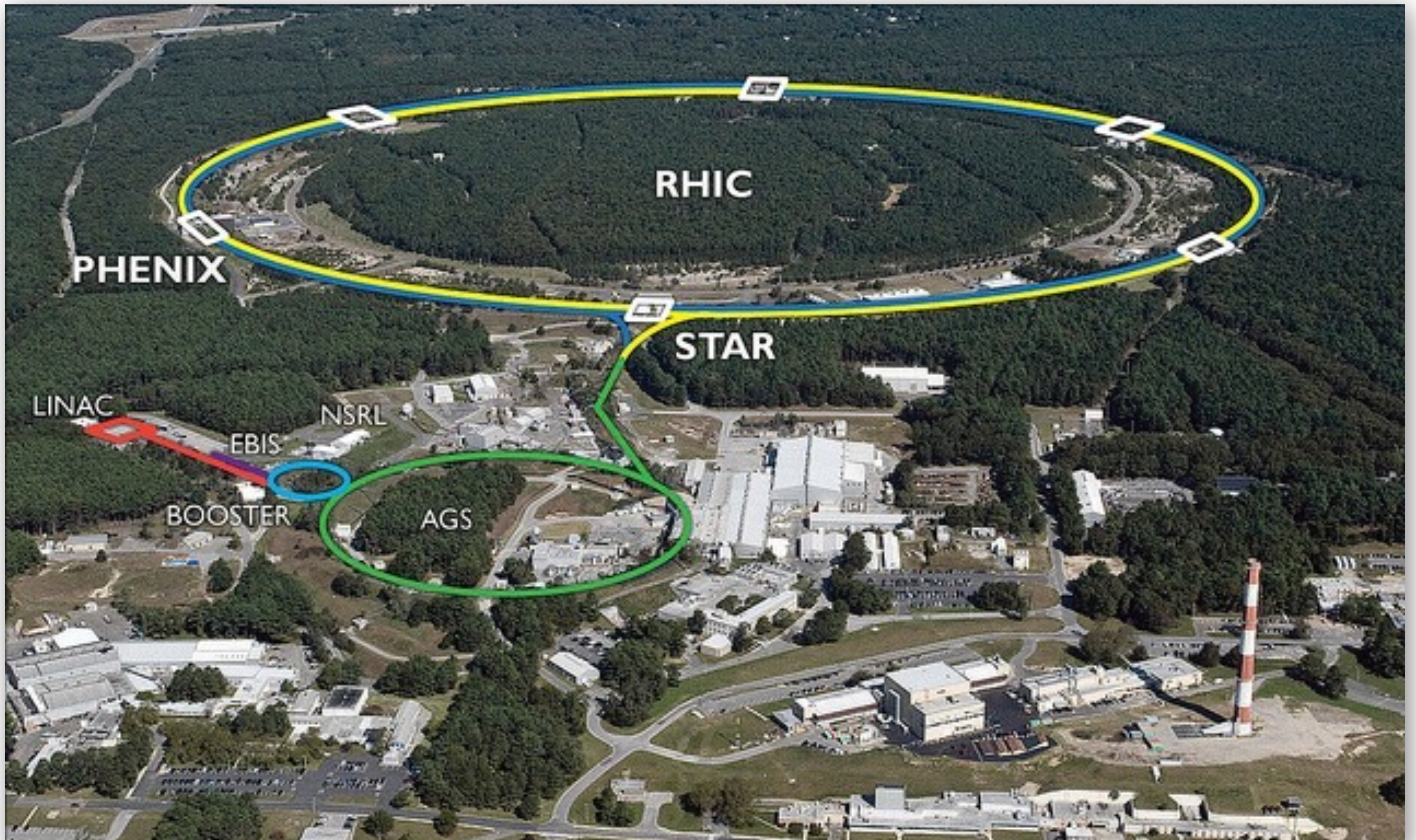


- Search for
  - Turn-off of QGP signatures
  - First order phase transition
  - Critical point

We need a tool to do so!

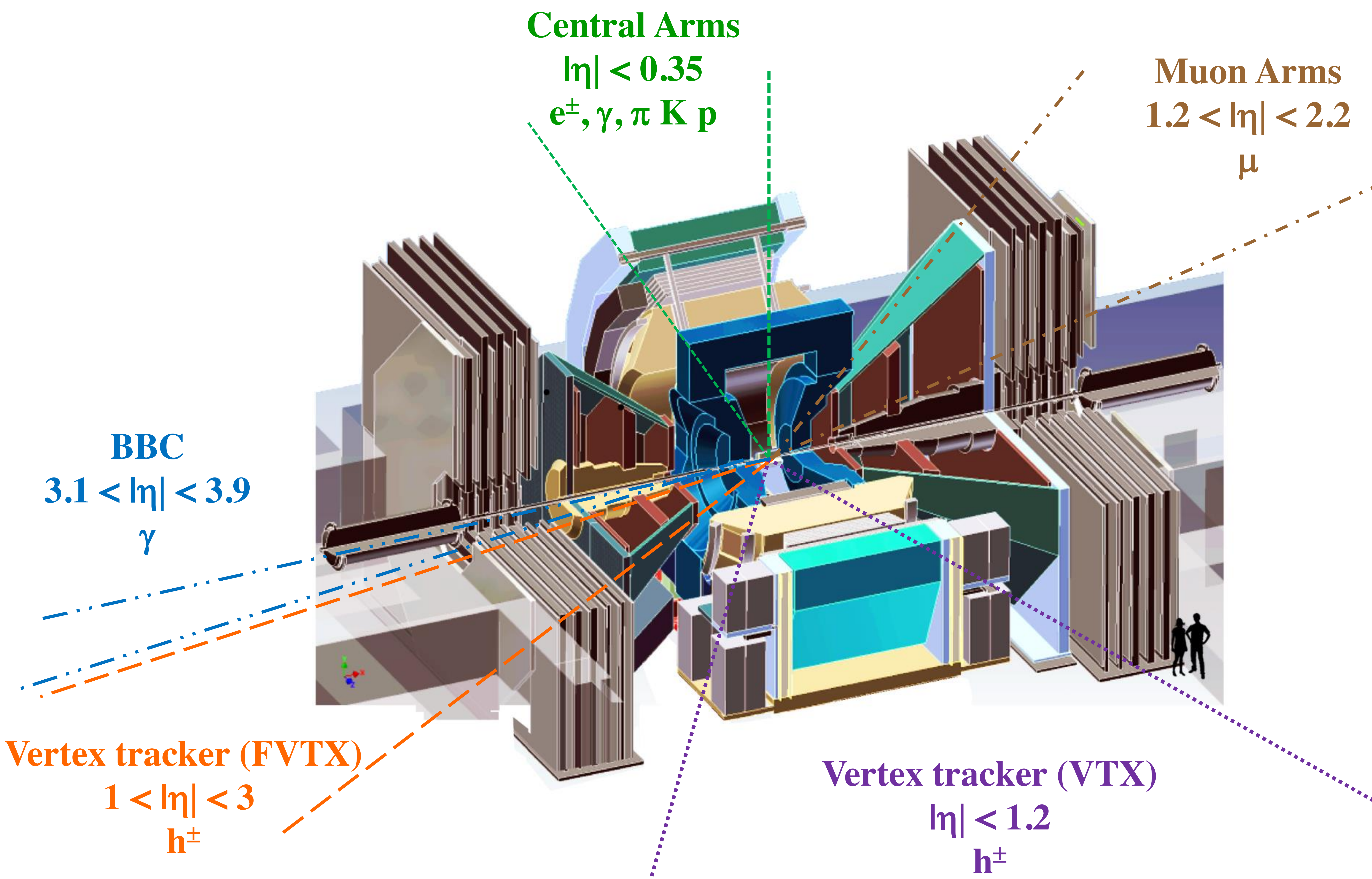
The Tools

The Relativistic Heavy Ion Collider (RHIC) at BNL



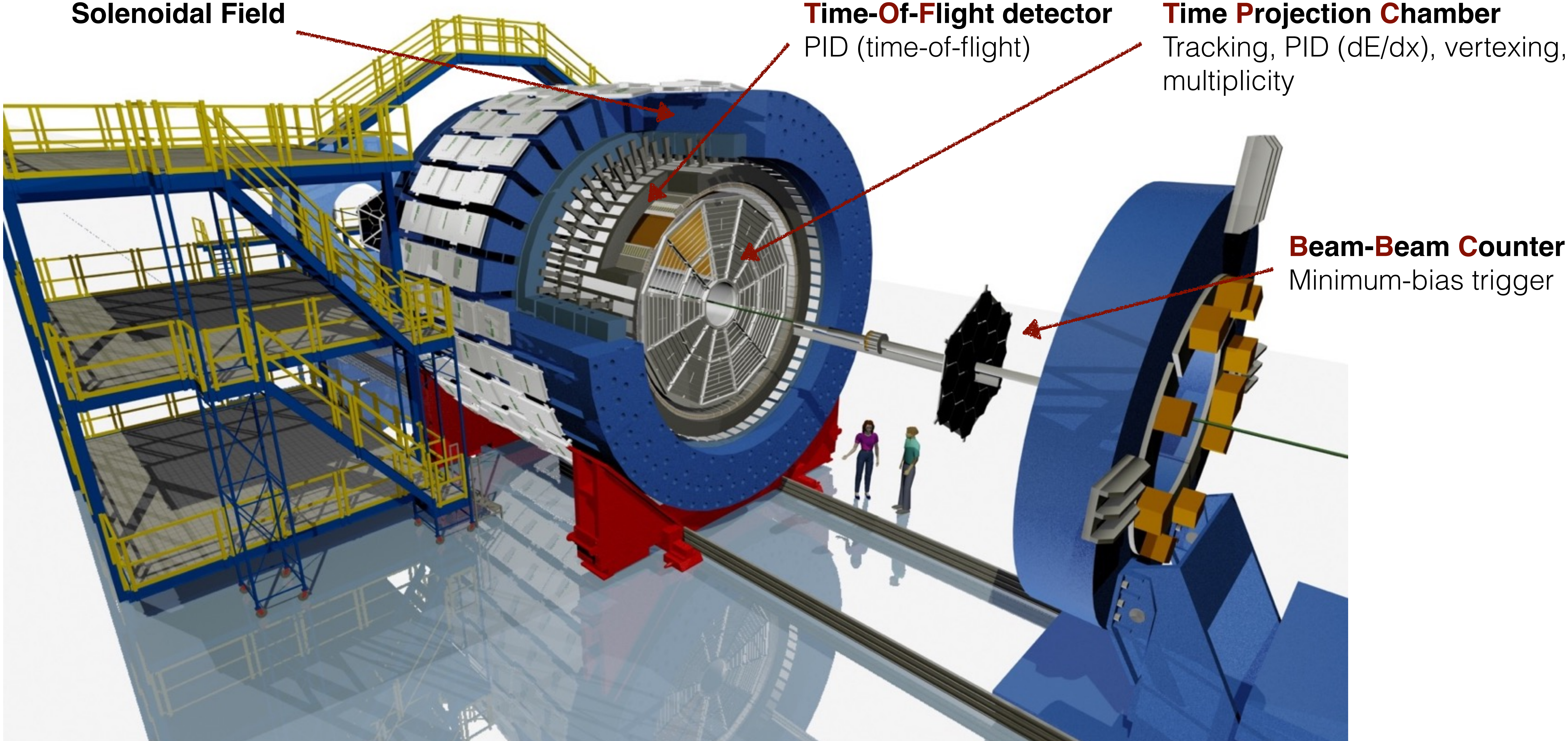
- Up to UU collisions
- Injection energy for AuAu : $\sqrt{s_{NN}}$ = 19.6 GeV
- Top energy for AuAu : $\sqrt{s_{NN}}$ = 200 GeV
- Two complementary detectors
  - STAR
  - PHENIX

The PHENIX detector



The STAR detector

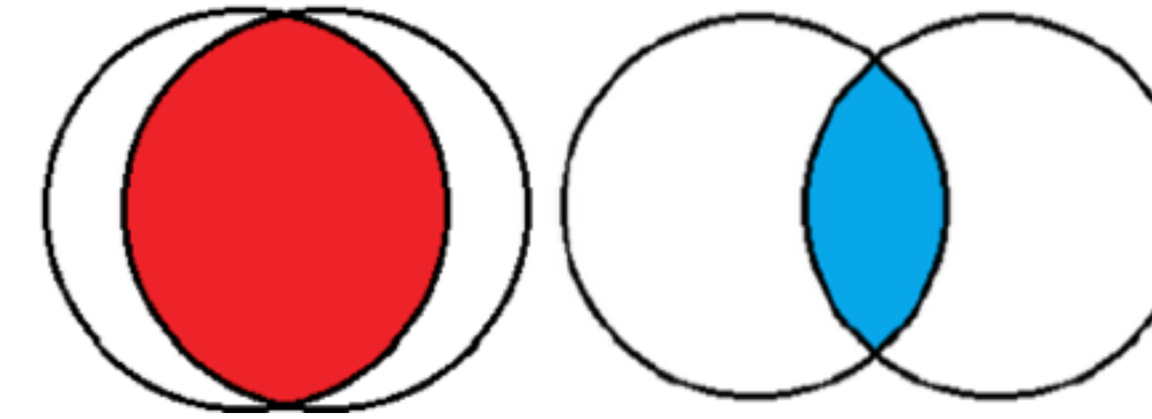
Full azimuthal coverage, |η| < 1 → excellent PID, large uniform acceptance



Peripheral vs. Central Collisions

Collision Centrality - How head on was the collision?

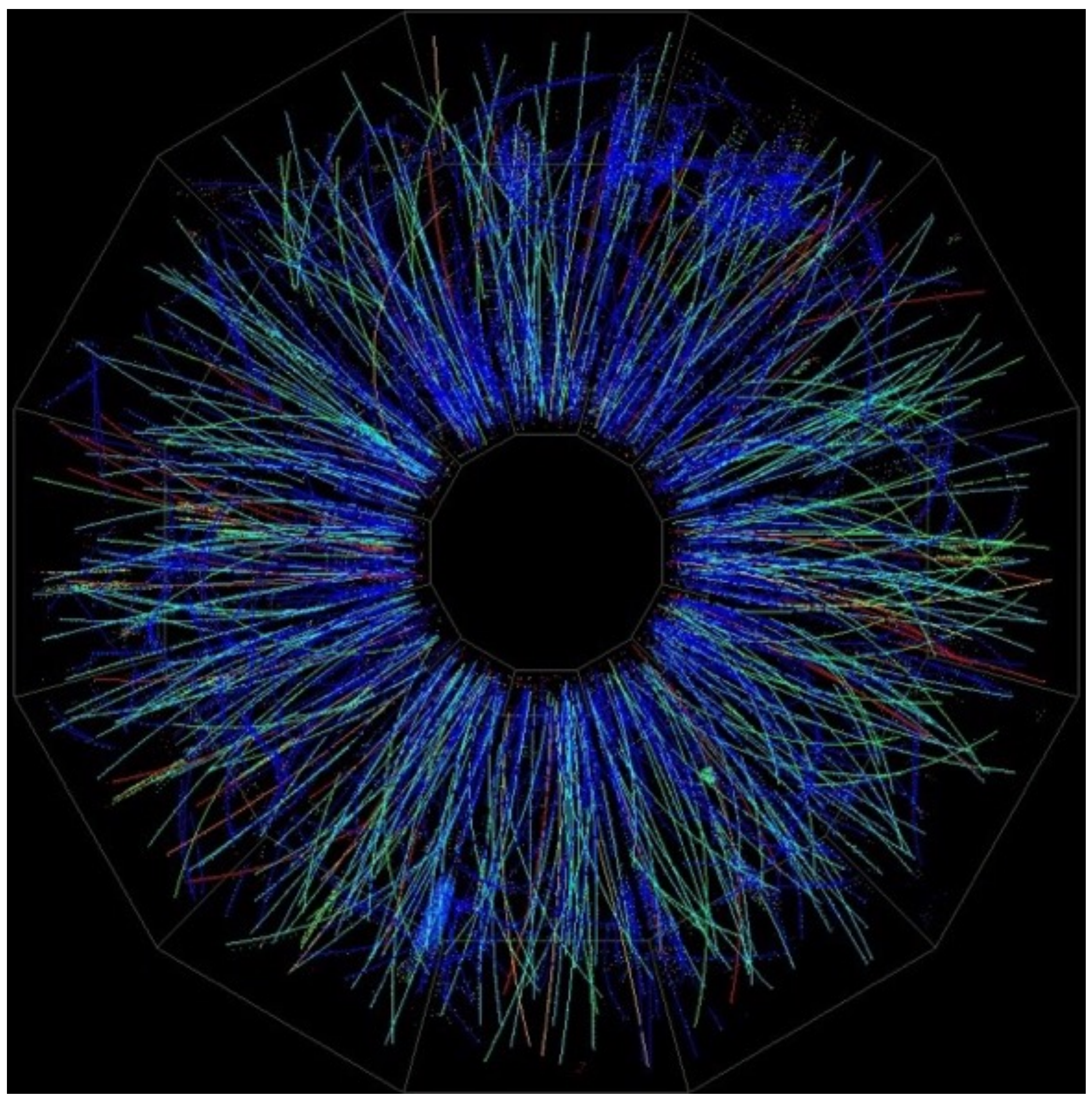
Looking along the beam axis:



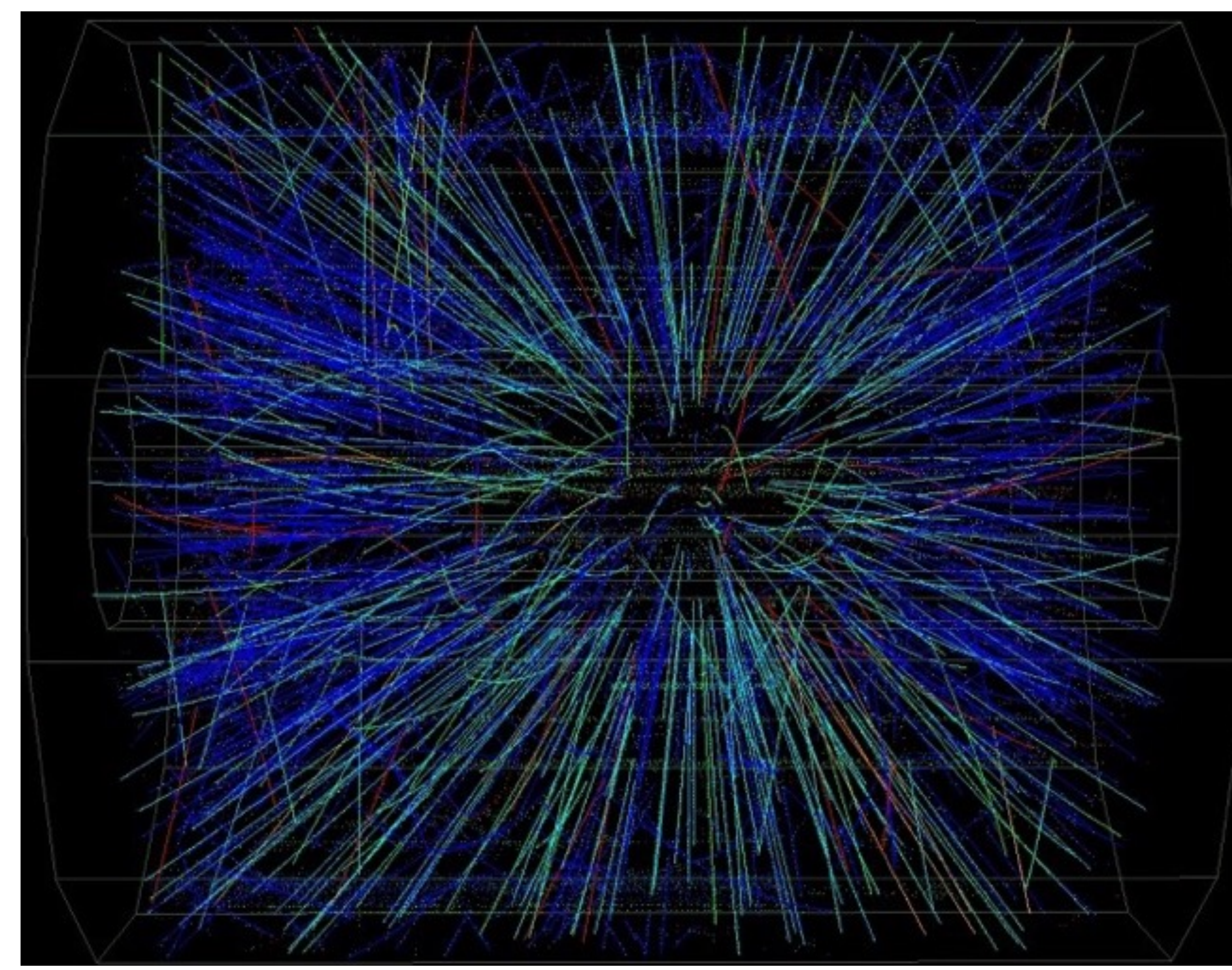
Impact parameter, b, is inferred from track multiplicities and a so-called Glauber calculation...

It is a very small distance! **$0 \leq b \leq 2R_{Au} \sim 14\times10^{-15}$ m**

STAR Online Event Display



front view: x-y plane



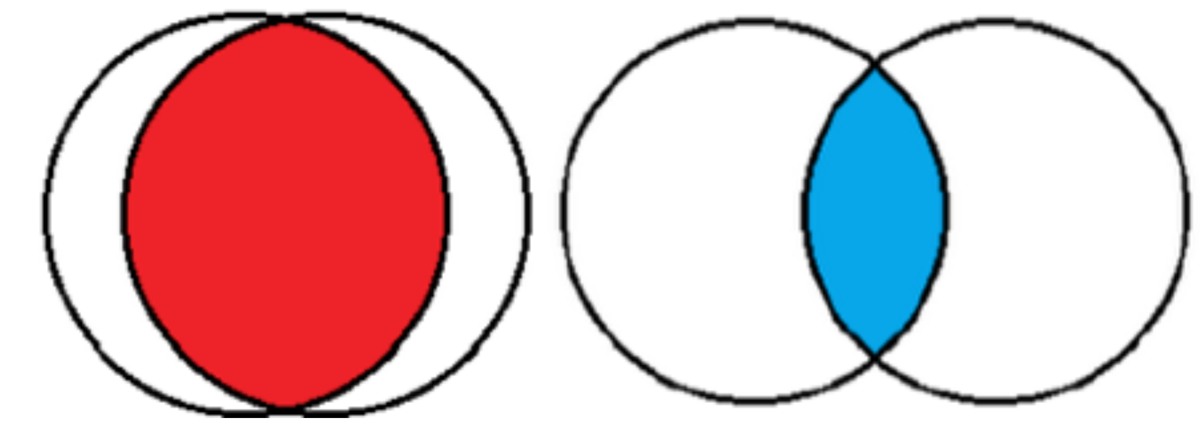
side view: x-z plane

Peripheral Event

Peripheral vs. Central Collisions

Collision Centrality - How head on was the collision?

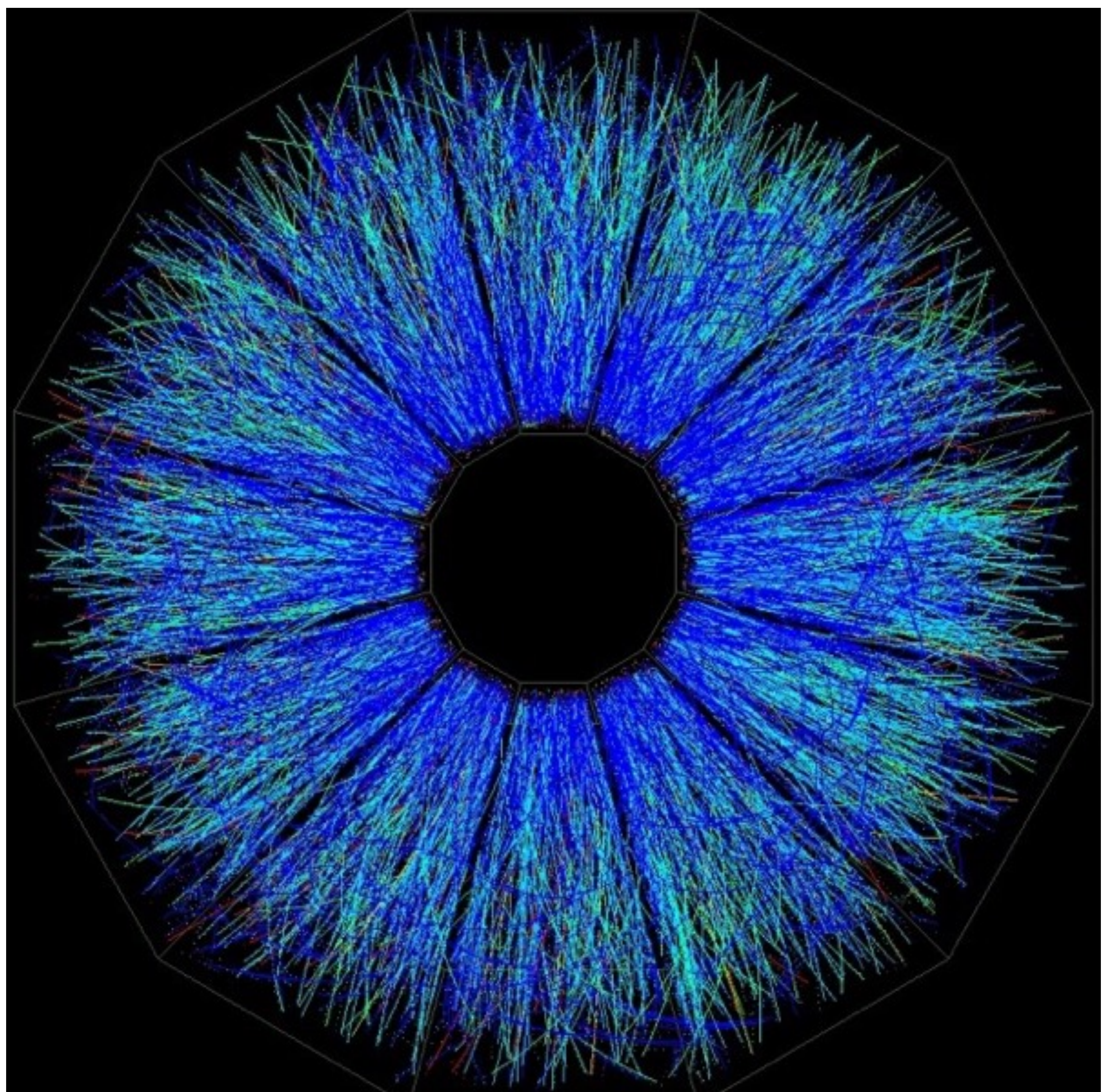
Looking along the beam axis:



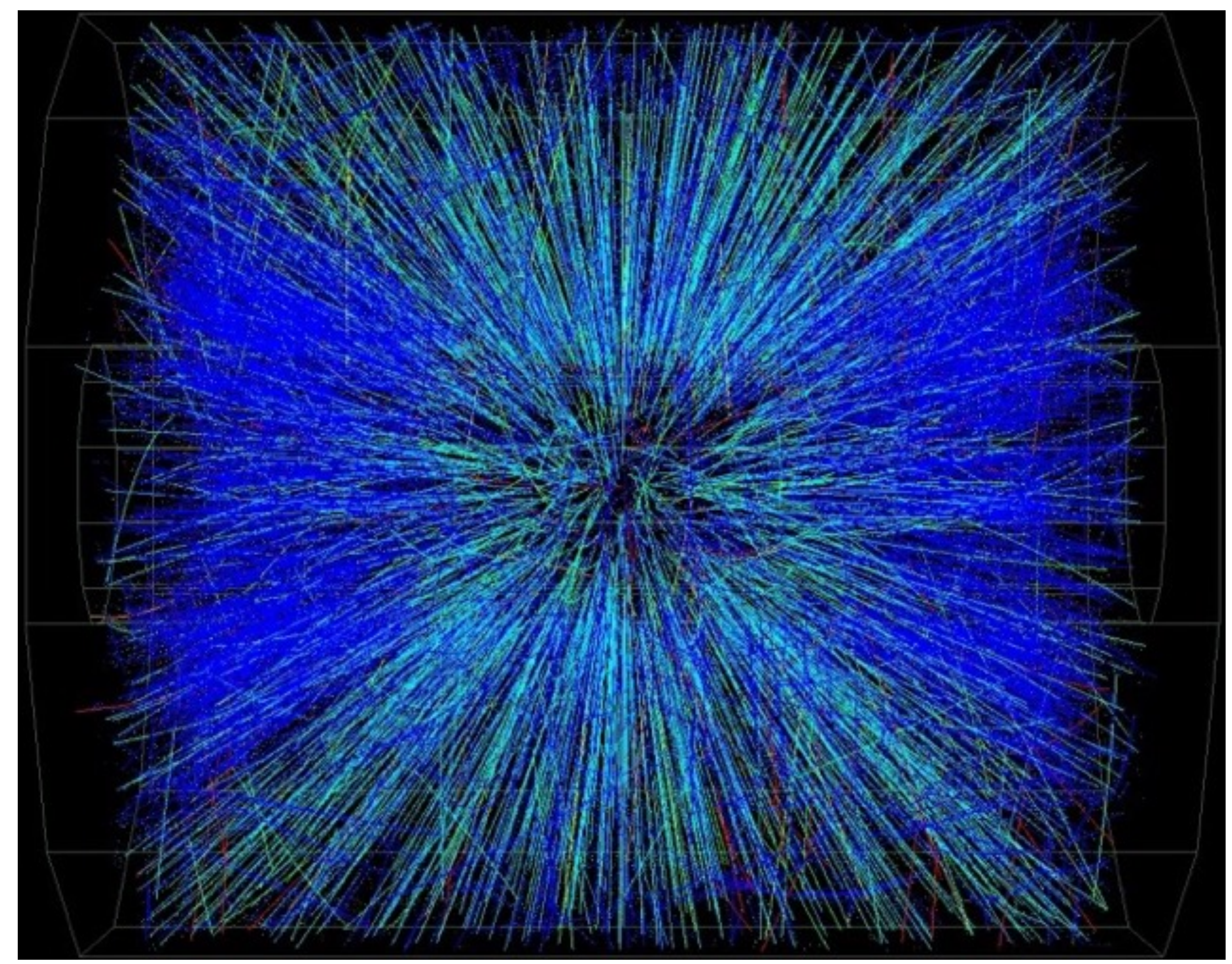
Impact parameter, b, is inferred from track multiplicities and a so-called Glauber calculation...

It is a very small distance! **$0 \leq b \leq 2R_{Au} \sim 14 \times 10^{-15}$ m**

STAR Online Event Display



front view: x-y plane



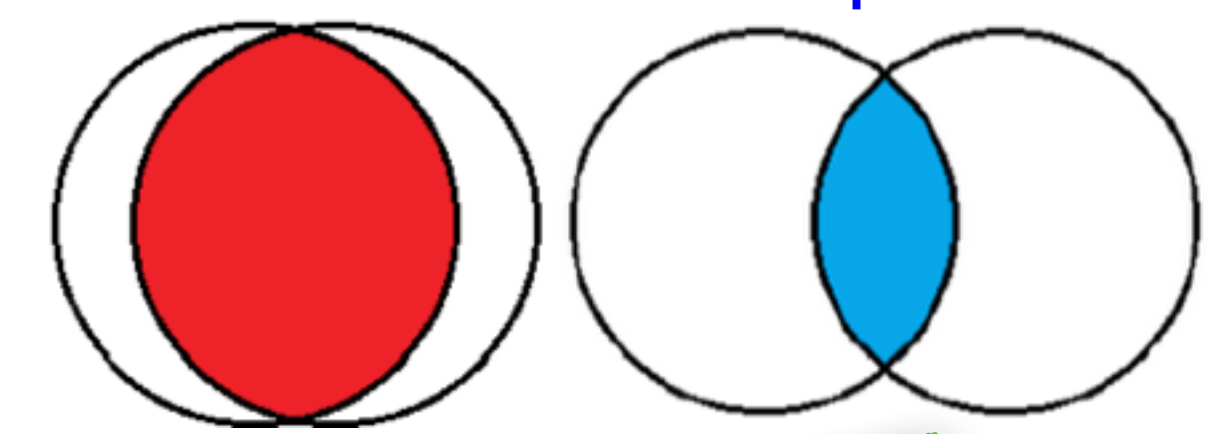
side view: x-z plane

Central Event

Peripheral vs. Central Collisions

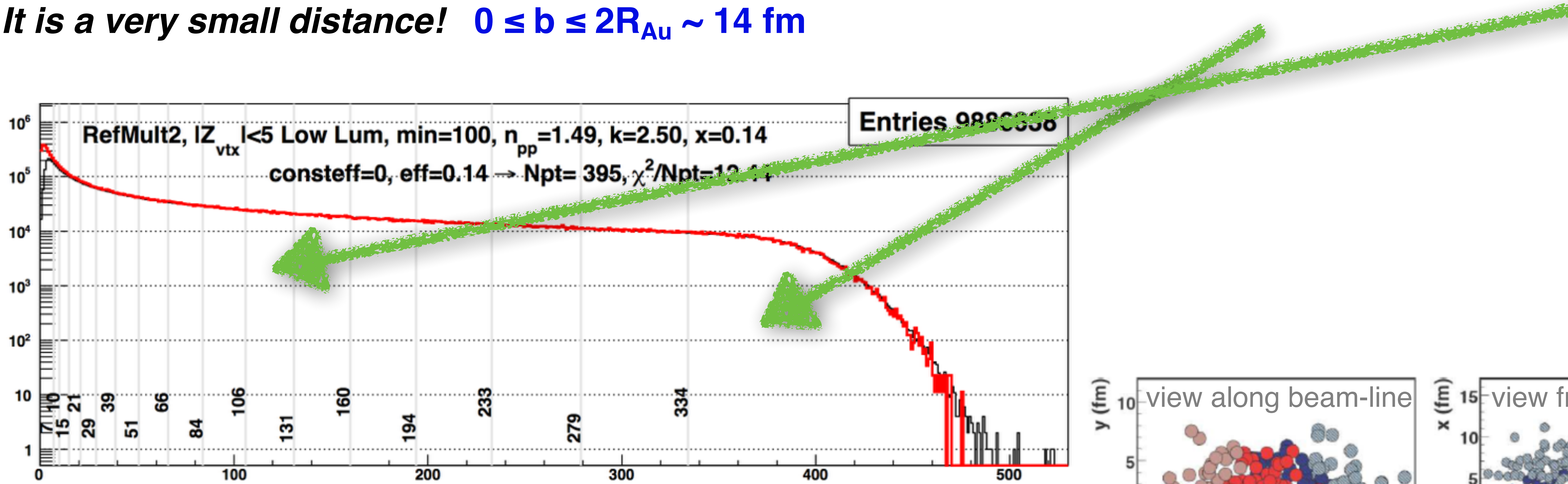
Collision Centrality - How head on was the collision?

Looking along the beam axis:

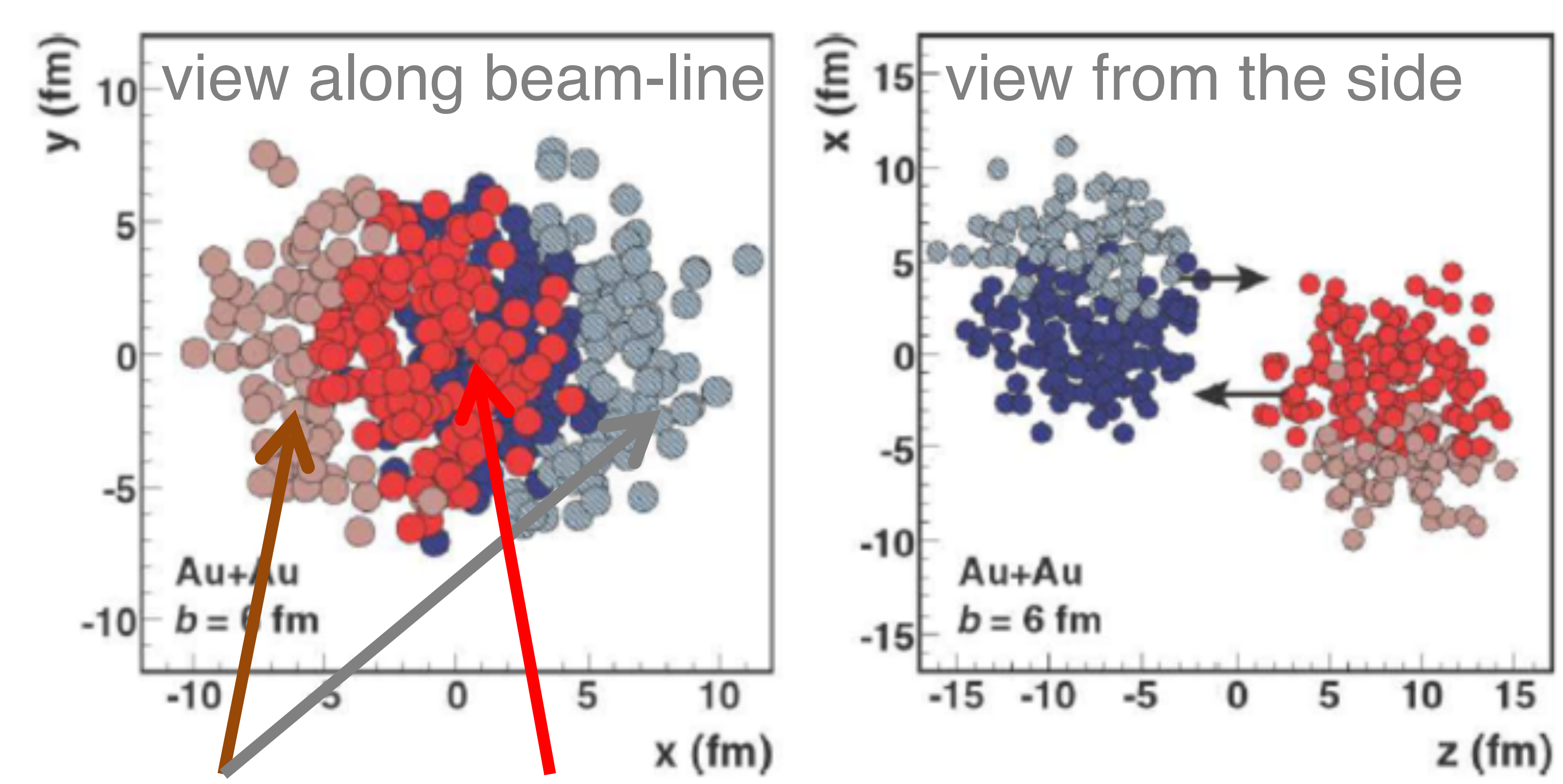


Impact parameter, b, is inferred from track multiplicities and a so-called Glauber calculation...

It is a very small distance! **$0 \leq b \leq 2R_{Au} \sim 14$ fm**



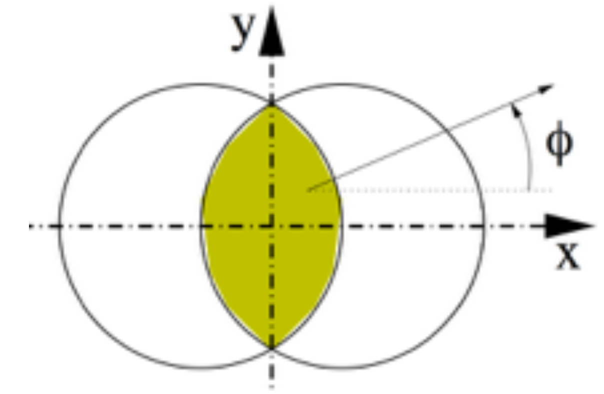
Track Multiplicities

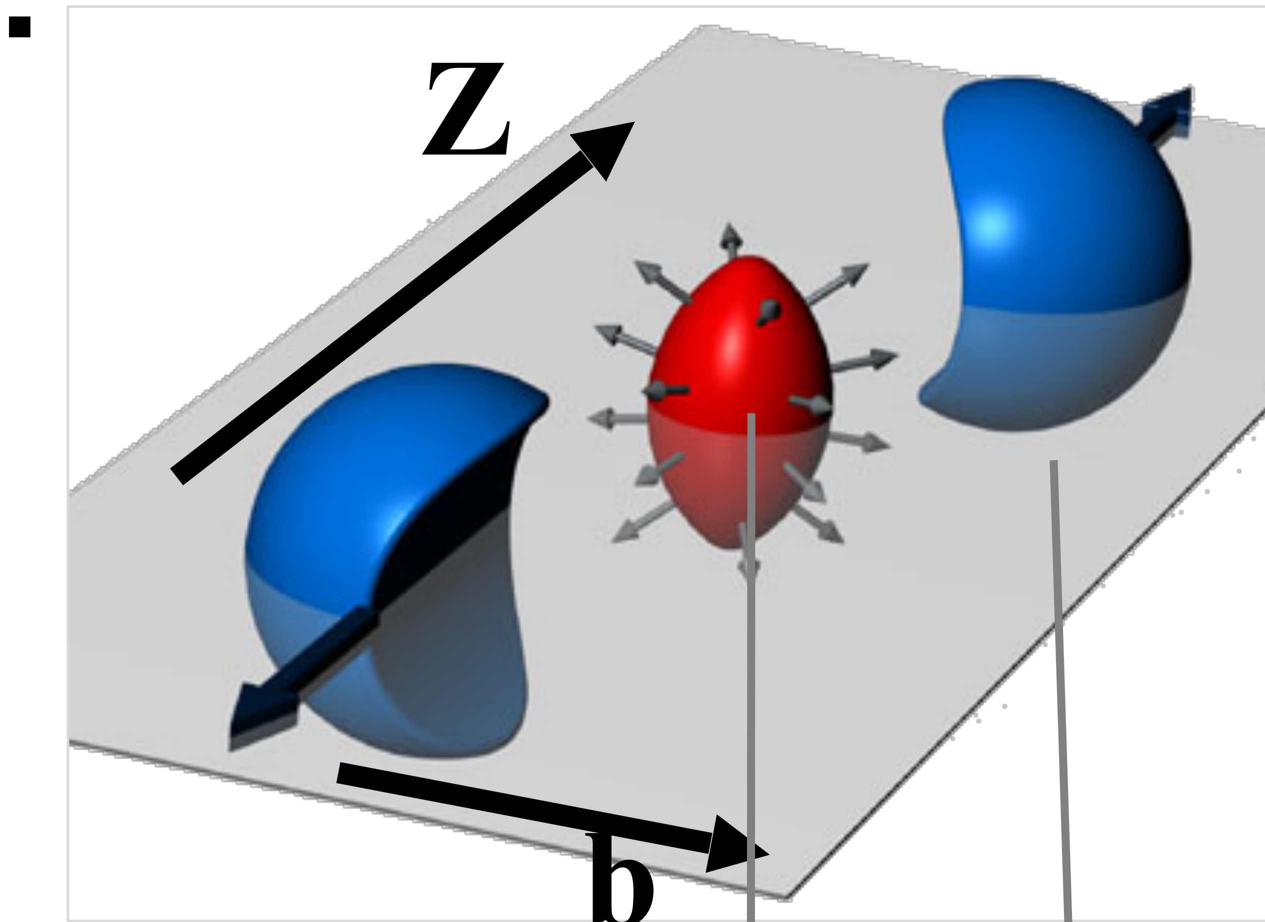


Determine percentage intervals of hadronic cross section

The event plane and some kinematic variables…

Event Plane: the plane defined by the beam direction *z* and the impact parameter *b*
Inferred from *e.g.* very forward tracks

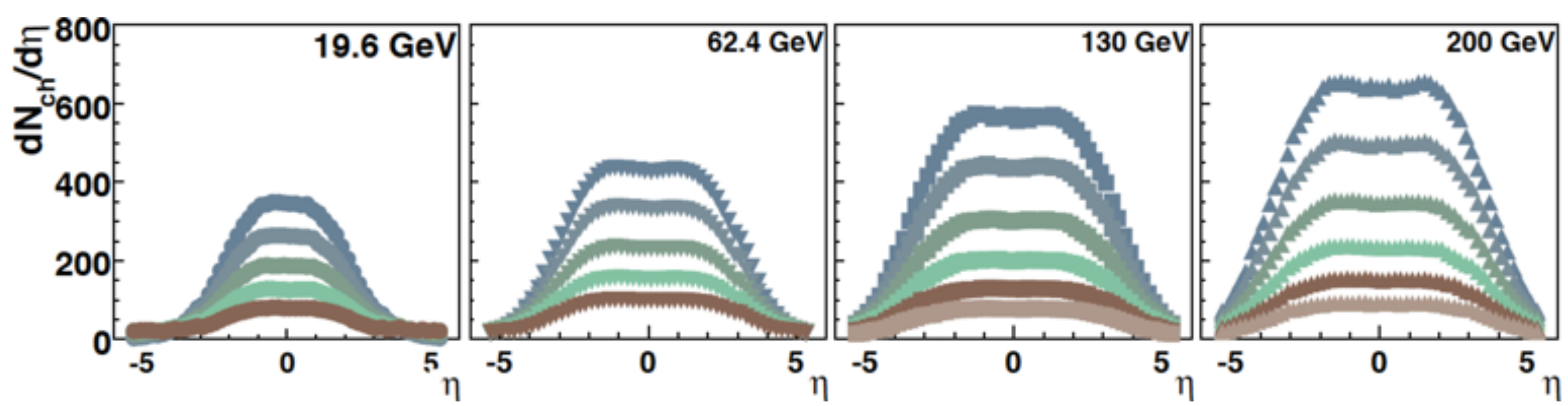


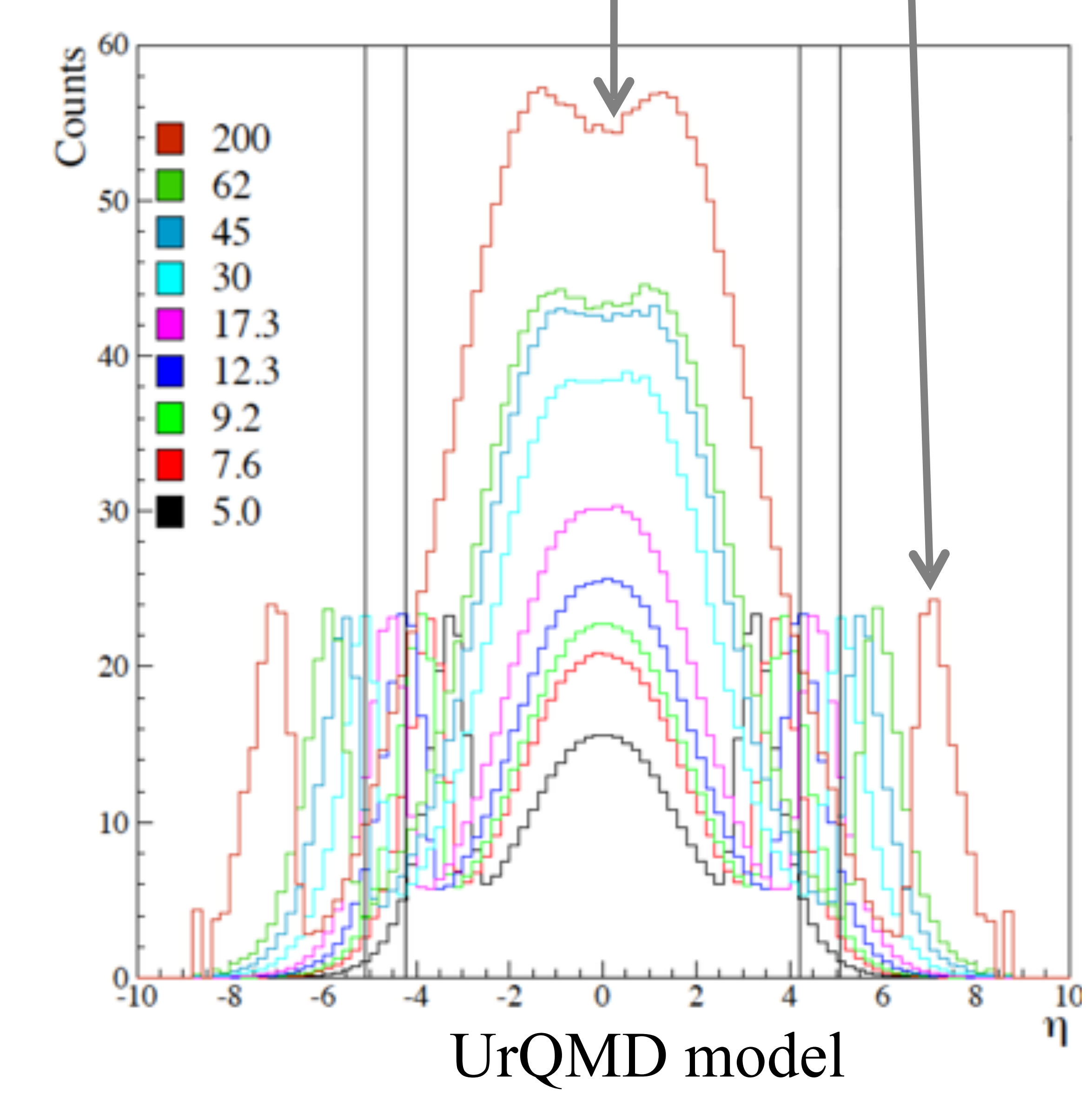


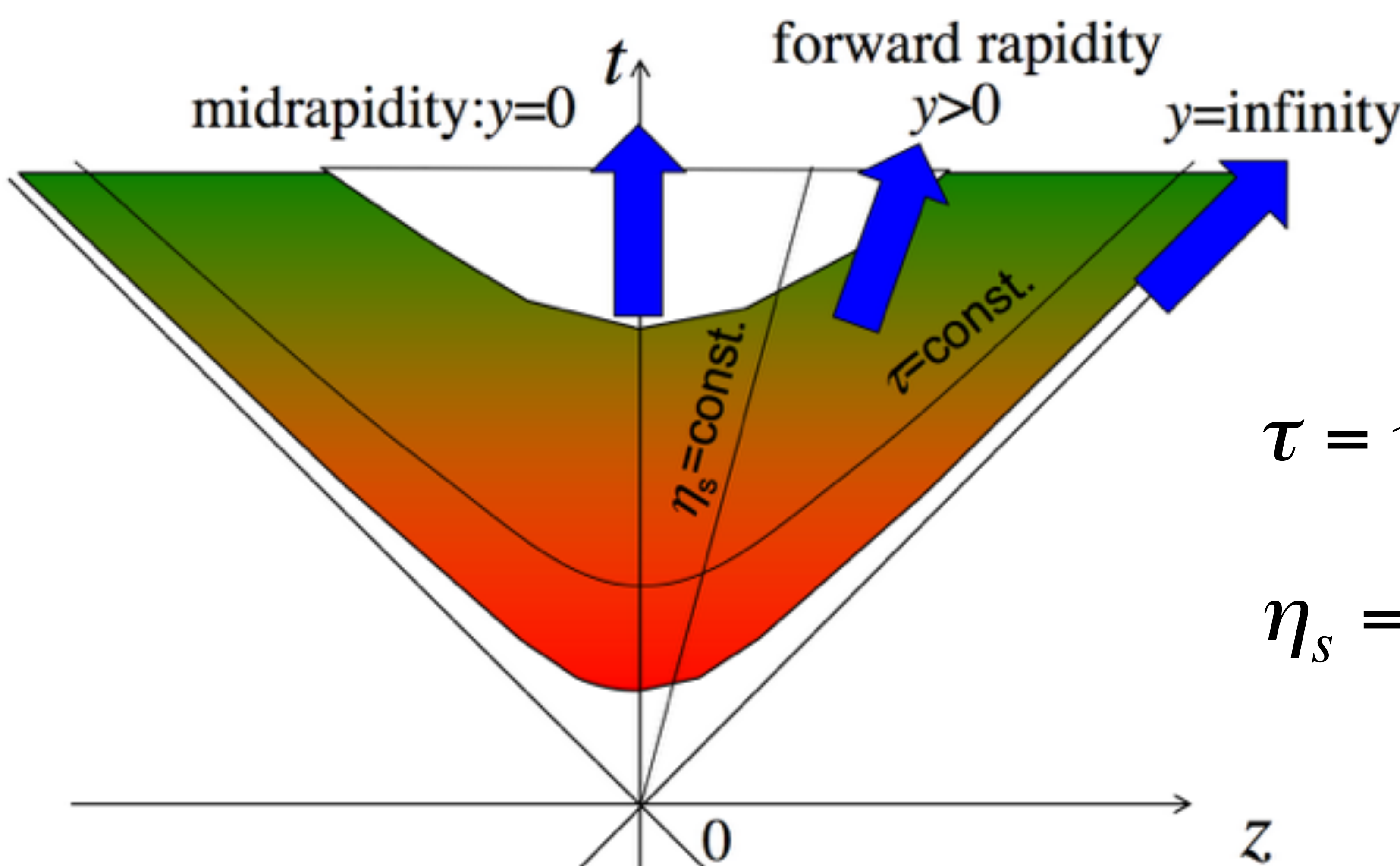
(Pseudo)-rapidity: a measure of the particles' angle w.r.t. the beamline

$$\eta = \lim_{\beta \to 1} y = -\ln\tan(\theta/2)$$

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$







$$\tau = \sqrt{t^2 - z^2}$$

$$\eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$$

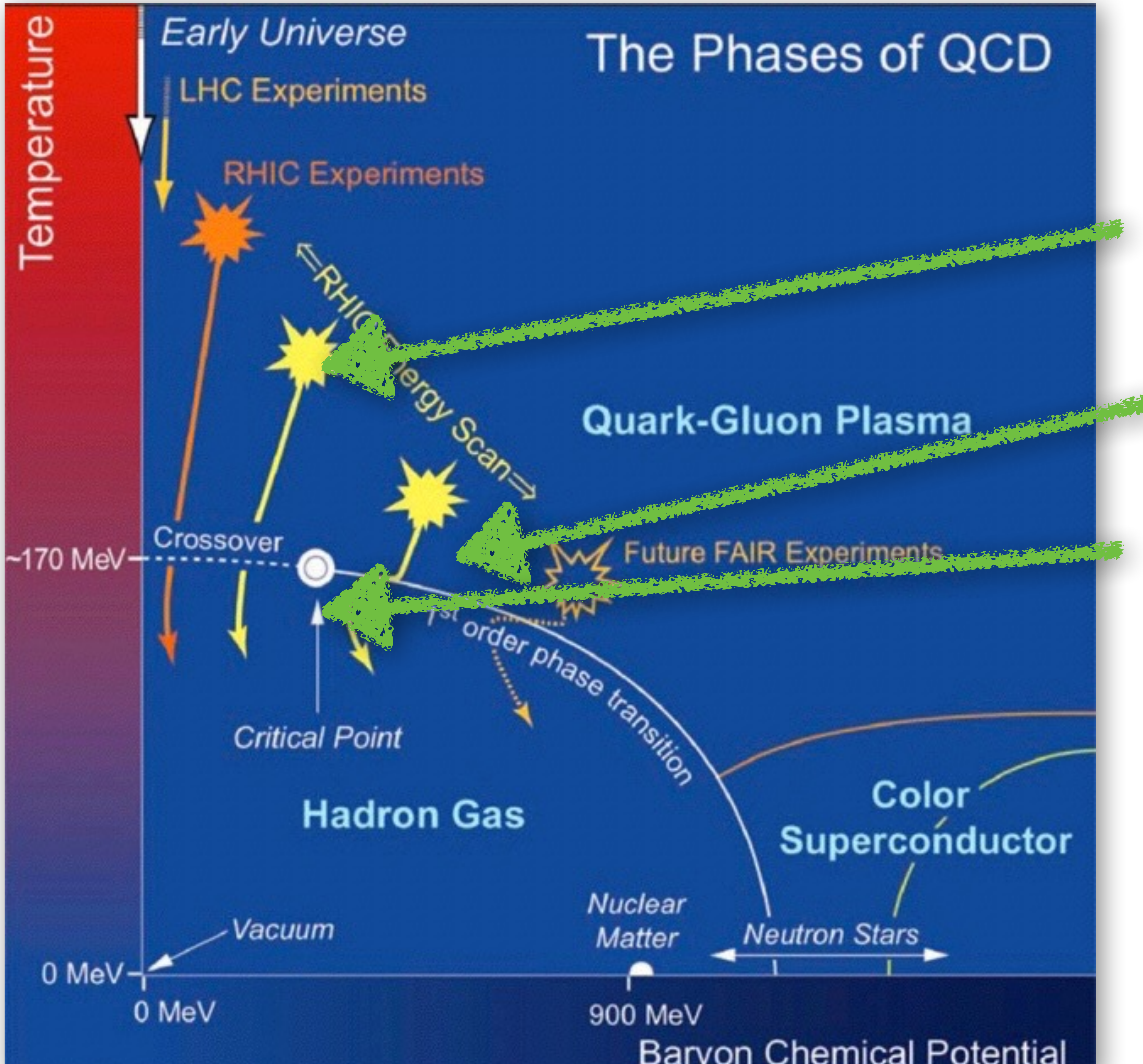
"boost invariance" J.D. Bjorken, Phys. Rev. D **27**, 140 (1983)
Dynamics depends on τ not η_s.

Beam Energy Scan I

2010 - 2011, and 2014

Explore the QCD Phase Diagram

What do we look for?

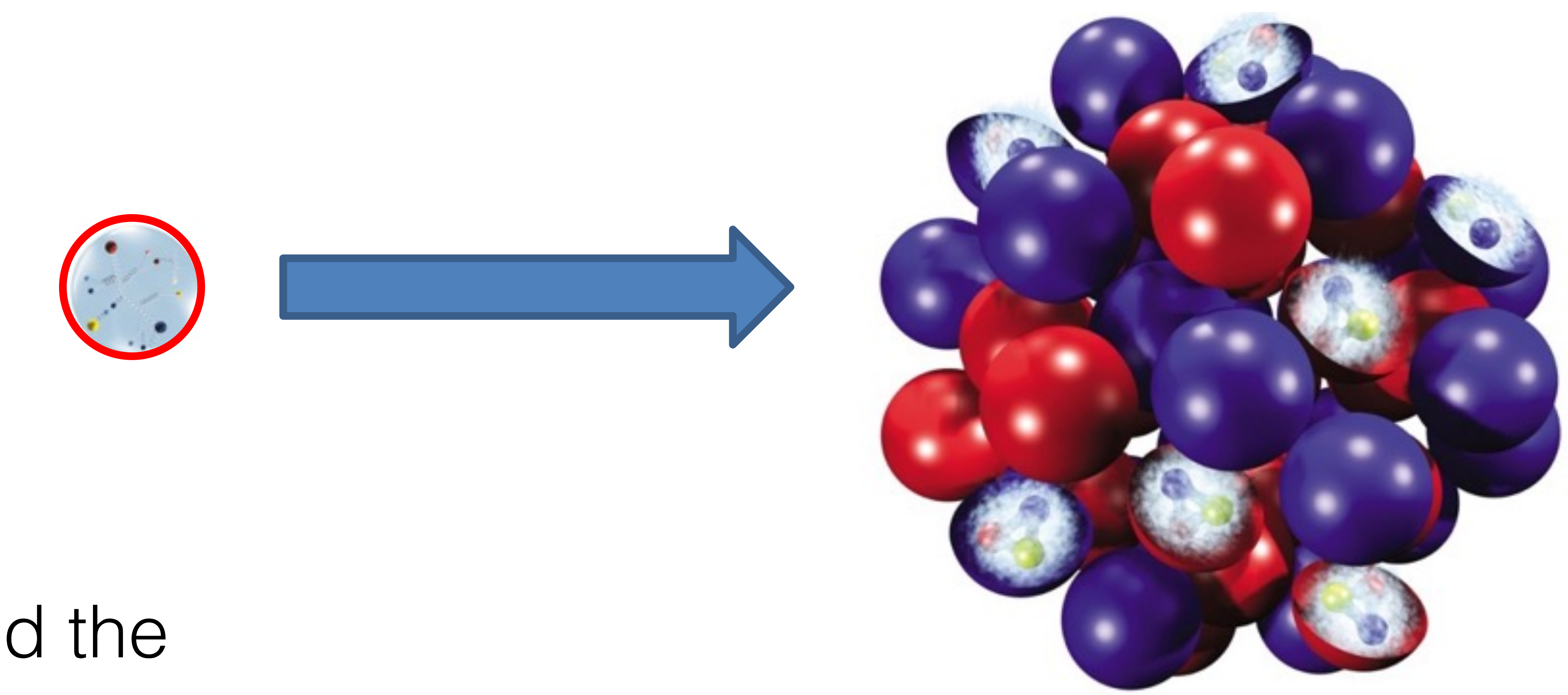


- Search for
  - Turn-off of QGP signatures
  - First order phase transition
  - Critical point

The Beam Energy Scan (BES) I

How the Collision Energy changes μ_B

- deBroglie wavelength of constituent partons is effected by the collision energy.
- Determines whether a parton images:
  - The whole nucleus
  - Individual nucleons
  - Individual partons
- At lower energy, nucleons are opaque, and the valence quarks are stopped in the fireball.
  Excess quarks ➔ higher μ_B
- At higher energy, nucleons are transparent, and the valence quarks are pass through and exit the fireball.
  Equal quarks and anti-quarks ➔ lower μ_B



The Beam Energy Scan (BES) I

How collision Energy changes μ_B

- deBroglie wavelength of constituent partons is effected by the beam energy.
- Determines whether a parton images:
  - The whole nucleus
  - Individual nucleons
  - Individual partons
- At lower energy, nucleons are opaque, and the valence quarks are stopped in the fireball.
  Excess quarks ➔ higher μ_B
- At higher energy, nucleons are transparent, and the valence quarks are pass through and exit the fireball.
  Equal quarks and anti-quarks ➔ lower μ_B

	Energy (GeV)	Baryon Chemical Potential* μ_B	Pred. Temp.* (MeV)
LHC	2760.0	2	166.0
RHIC	200.0	24	165.9
RHIC	130.0	36	165.8
RHIC	62.4	73	165.3
RHIC	39.0	112	164.2
RHIC	27.0	156	162.6
RHIC	19.6	206	160.0
SPS	17.3	229	158.6
RHIC	14.5	262	156.2
SPS	12.4	299	153.1
RHIC	11.5	316	151.6
SPS	8.8	383	144.4
RHIC	7.7	422	139.6
SPS	7.7	422	139.6
SPS	6.4	476	131.7
RHIC	4.9	562	118
AGS	4.7	573	114.6
RHIC	4.5	589	111
AGS	4.3	602	108.8
RHIC	3.9	633	101
AGS	3.8	638	100.6
RHIC	3.5	666	93
AGS	3.3	686	88.9
RHIC	3.0	721	76
AGS	2.7	752	70.4
SIS	2.3	799	55.8

* PRC73 (2006) 34905

The Beam Energy Scan (BES) I

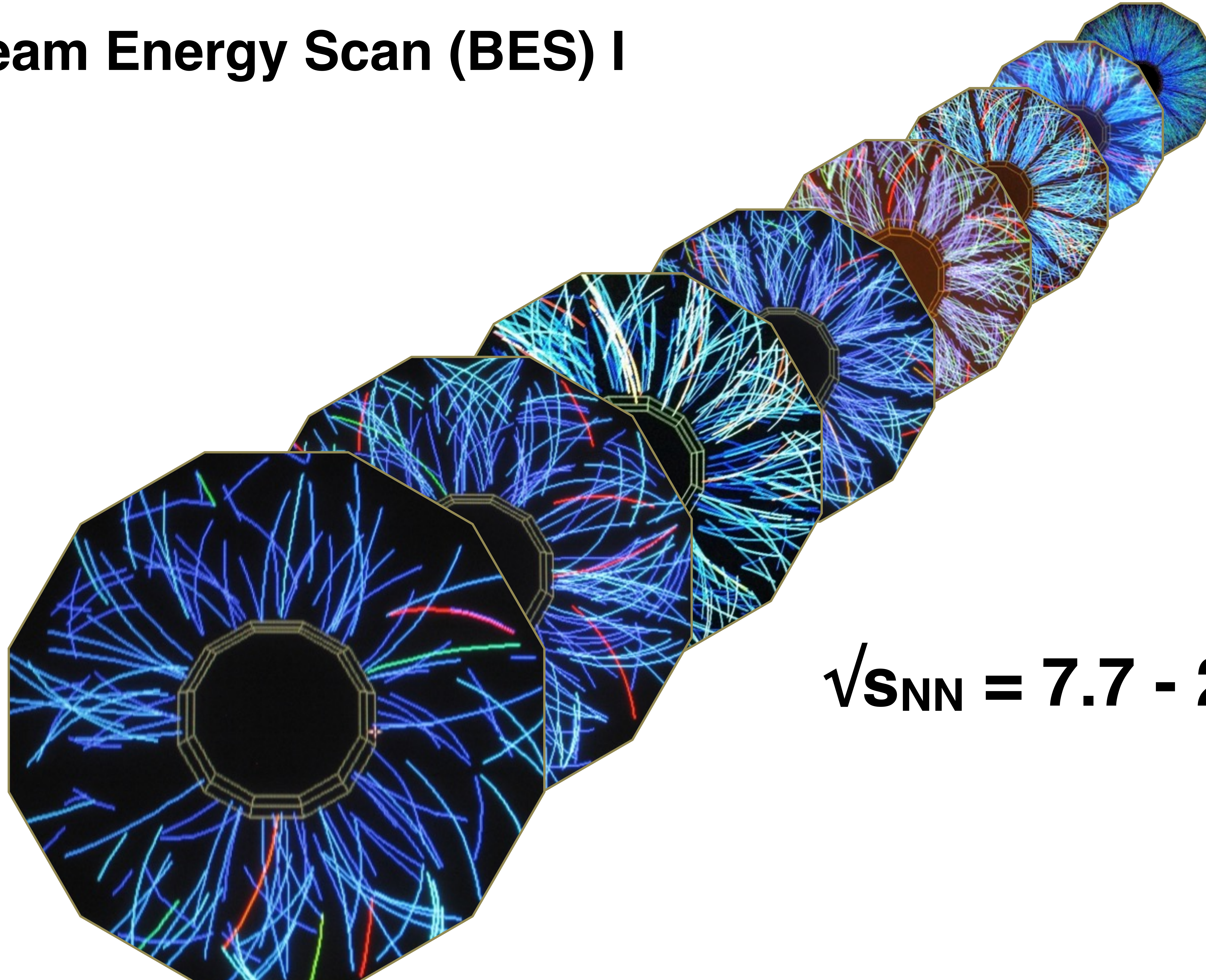
How collision Energy changes μ_B

- deBroglie wavelength of constituent partons is effected by the beam energy.
- Determines whether a parton images:
  - The whole nucleus
  - Individual nucleons
  - Individual partons
- At lower energy, nucleons are opaque, and the valence quarks are stopped in the fireball.
  Excess quarks ➔ higher μ_B
- At higher energy, nucleons are transparent, and the valence quarks are pass through and exit the fireball.
  Equal quarks and anti-quarks ➔ lower μ_B

	Energy (GeV)	Baryon Chemical Potential* μ_B	Pred. Temp.* (MeV)
LHC	2760.0	2	166.0
RHIC	200.0	24	165.9
RHIC	130.0	36	165.8
RHIC	62.4	73	165.3
RHIC	39.0	112	164.2
RHIC	27.0	156	162.6
RHIC	19.6	206	160.0
SPS	17.3	229	158.6
RHIC	14.5	262	156.2
SPS	12.4	299	153.1
RHIC	11.5	316	151.6
SPS	8.8	383	144.4
RHIC	7.7	422	139.6
SPS	7.7	422	139.6
SPS	6.4	476	131.7
RHIC	4.9	562	118
AGS	4.7	573	114.6
RHIC	4.5	589	111
AGS	4.3	602	108.8
RHIC	3.9	633	101
AGS	3.8	638	100.6
RHIC	3.5	666	93
AGS	3.3	686	88.9
RHIC	3.0	721	76
AGS	2.7	752	70.4
SIS	2.3	799	55.8

* PRC73 (2006) 34905

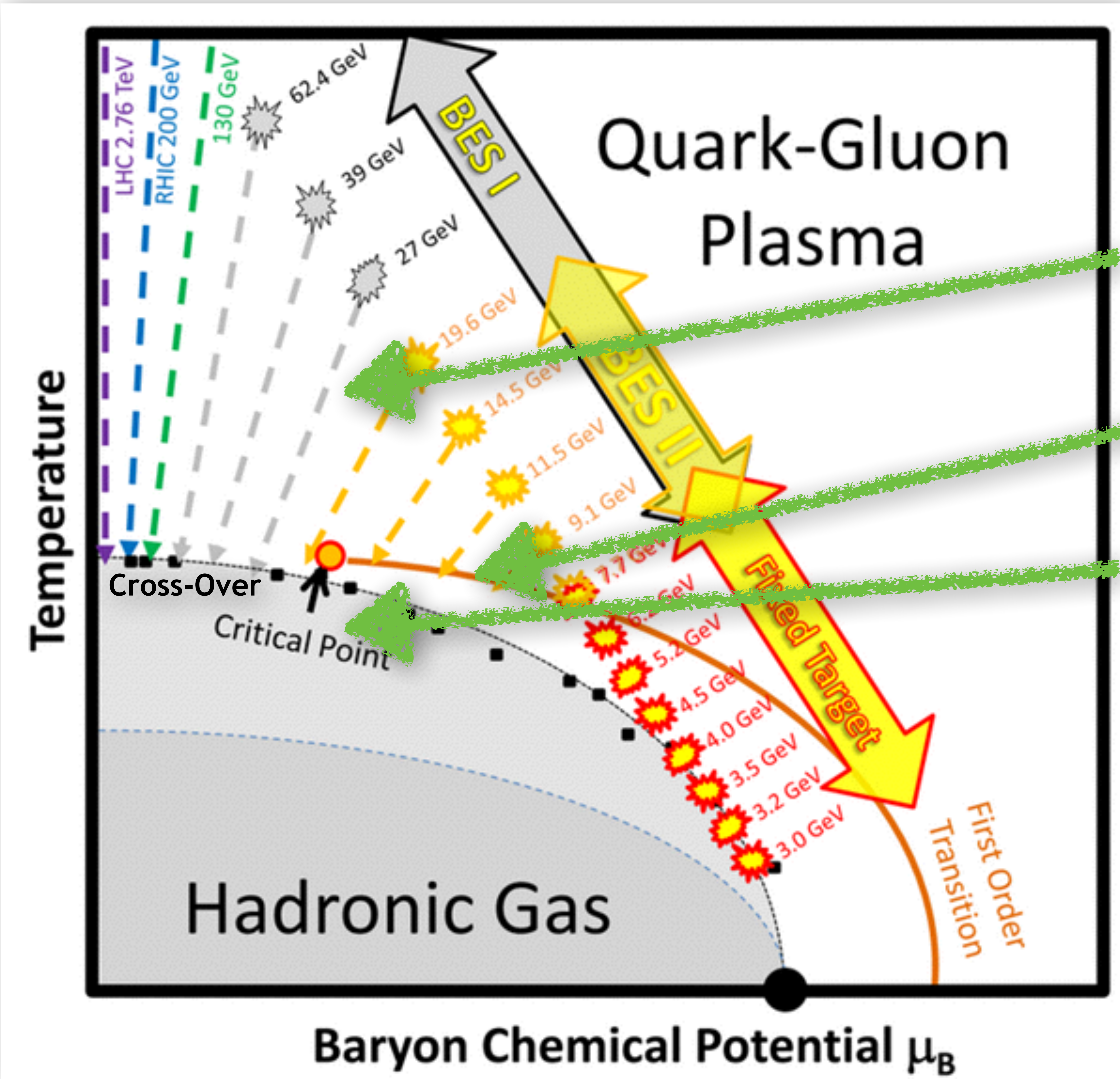
The Beam Energy Scan (BES) I



$\sqrt{s_{NN}}$ = 7.7 - 200 GeV

The Beam Energy Scan (BES) I

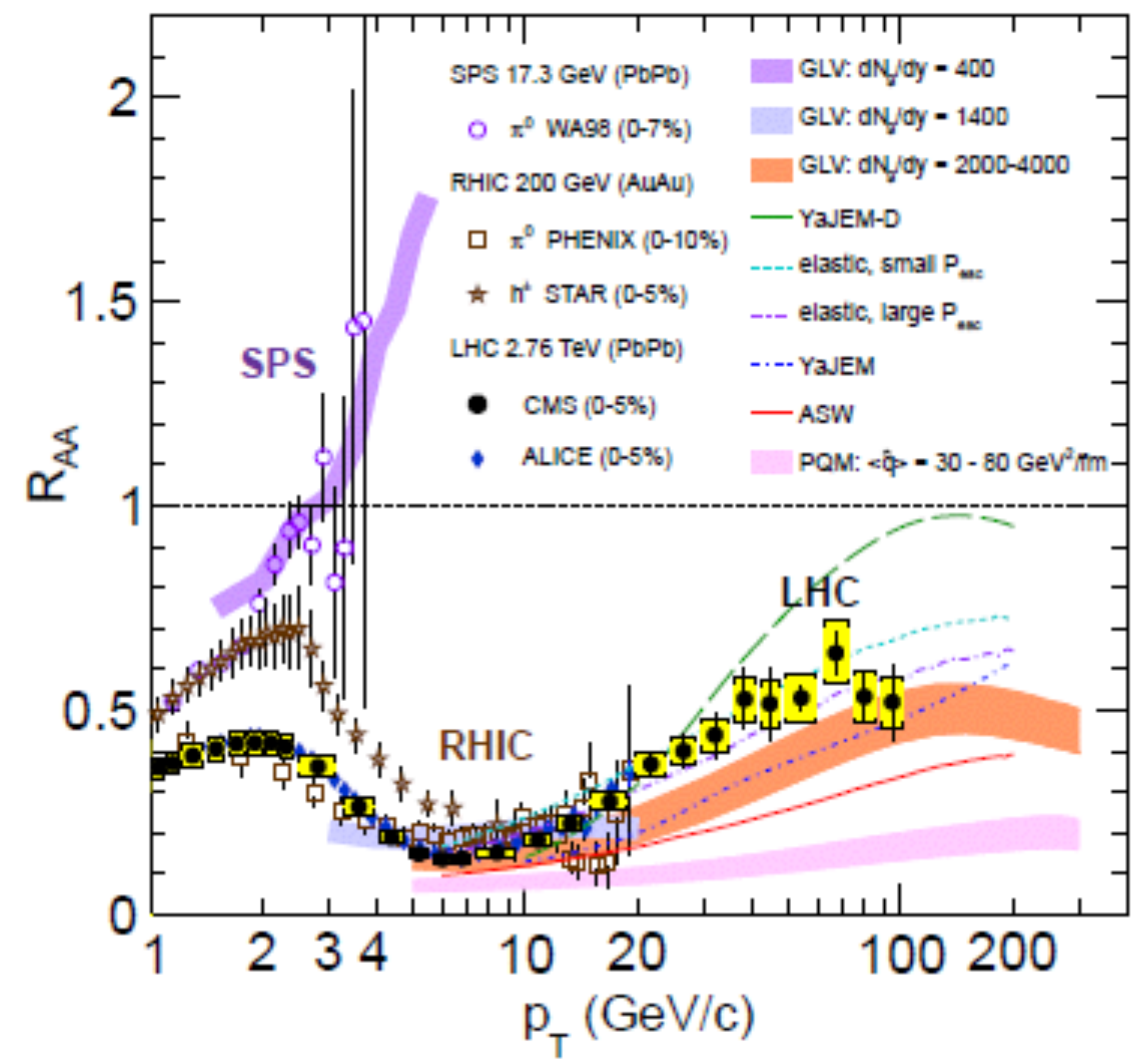
Overview

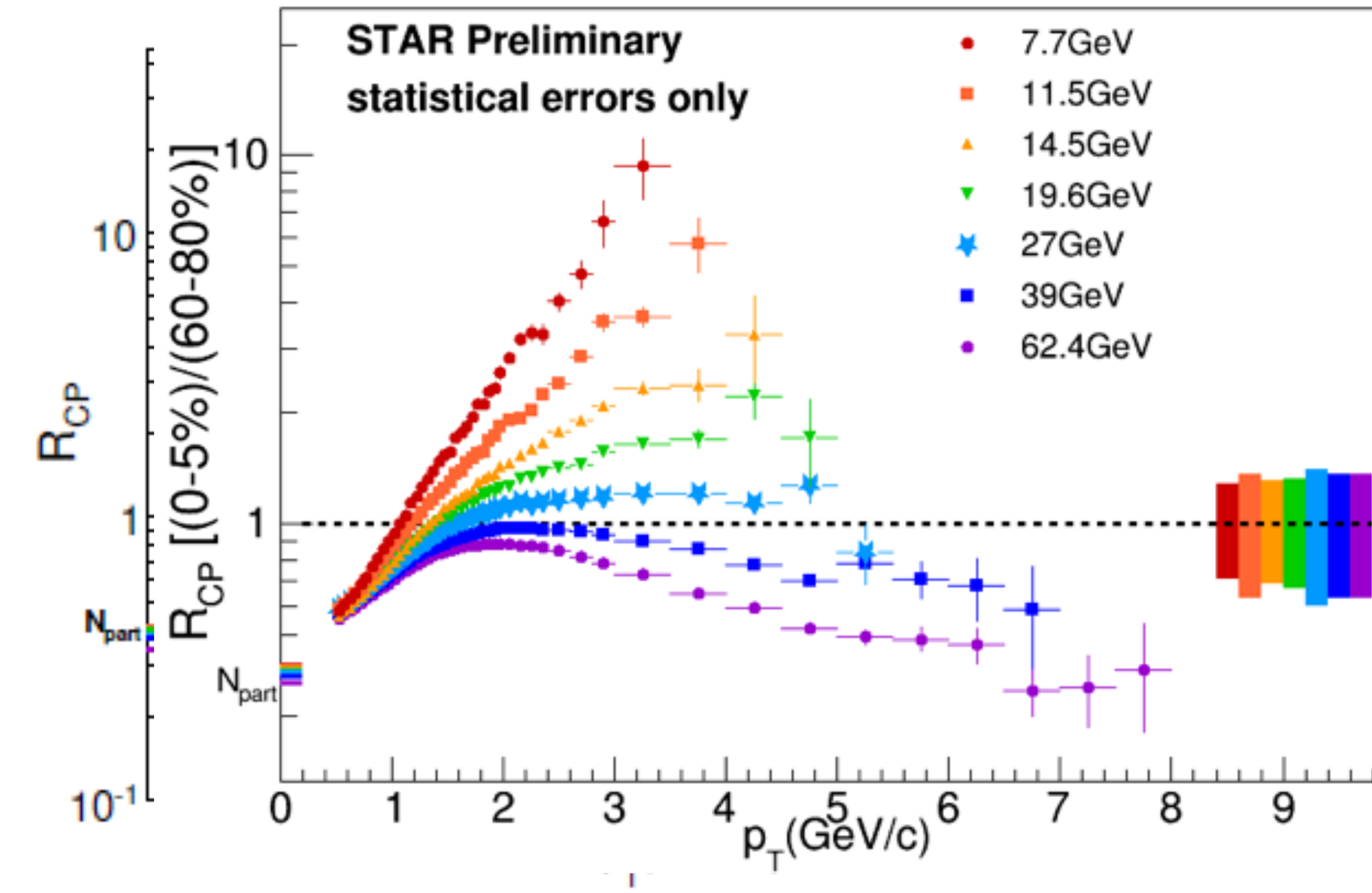


- Search for
  - Turn-off of QGP signatures
  - First order phase transition
  - Critical point

Disappearance of QGP Signatures - R_{CP}

- R_{CP} for hadrons and for identified particles can provide a measure of partonic energy loss in the medium.
- Not sufficient reach to search for evidence of high p_T suppression below 19.6 GeV
- Stopped Baryons complicate inclusive R_{CP} measurements
- pQCD calculations show high p_T suppression
- Hybrid calculations describe the low p_T behavior





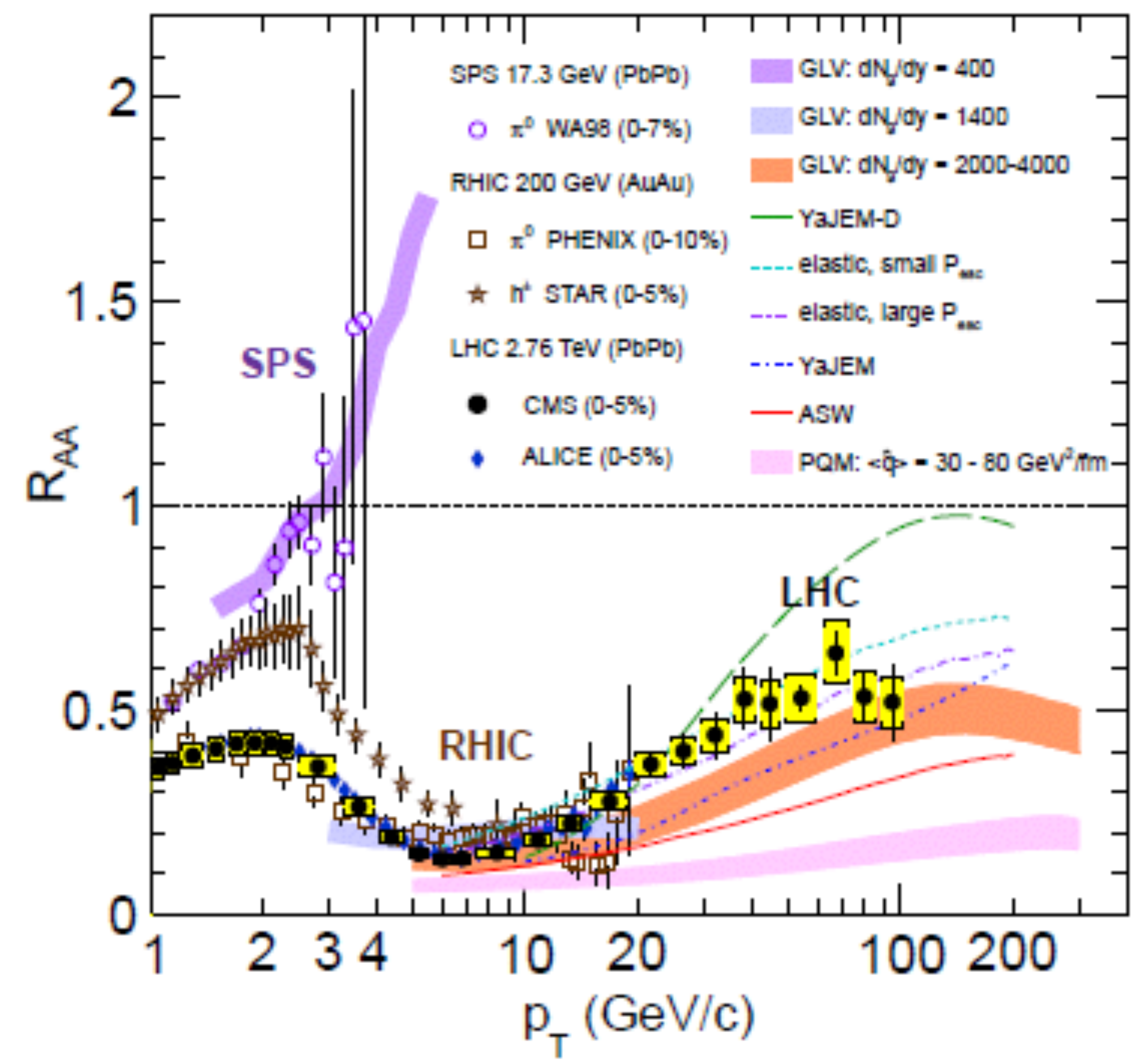
$$R_{AA} = \frac{\text{Particle yield in AA collisions}}{\text{Particle yield in pp collisions x Number of binary collisions}}$$

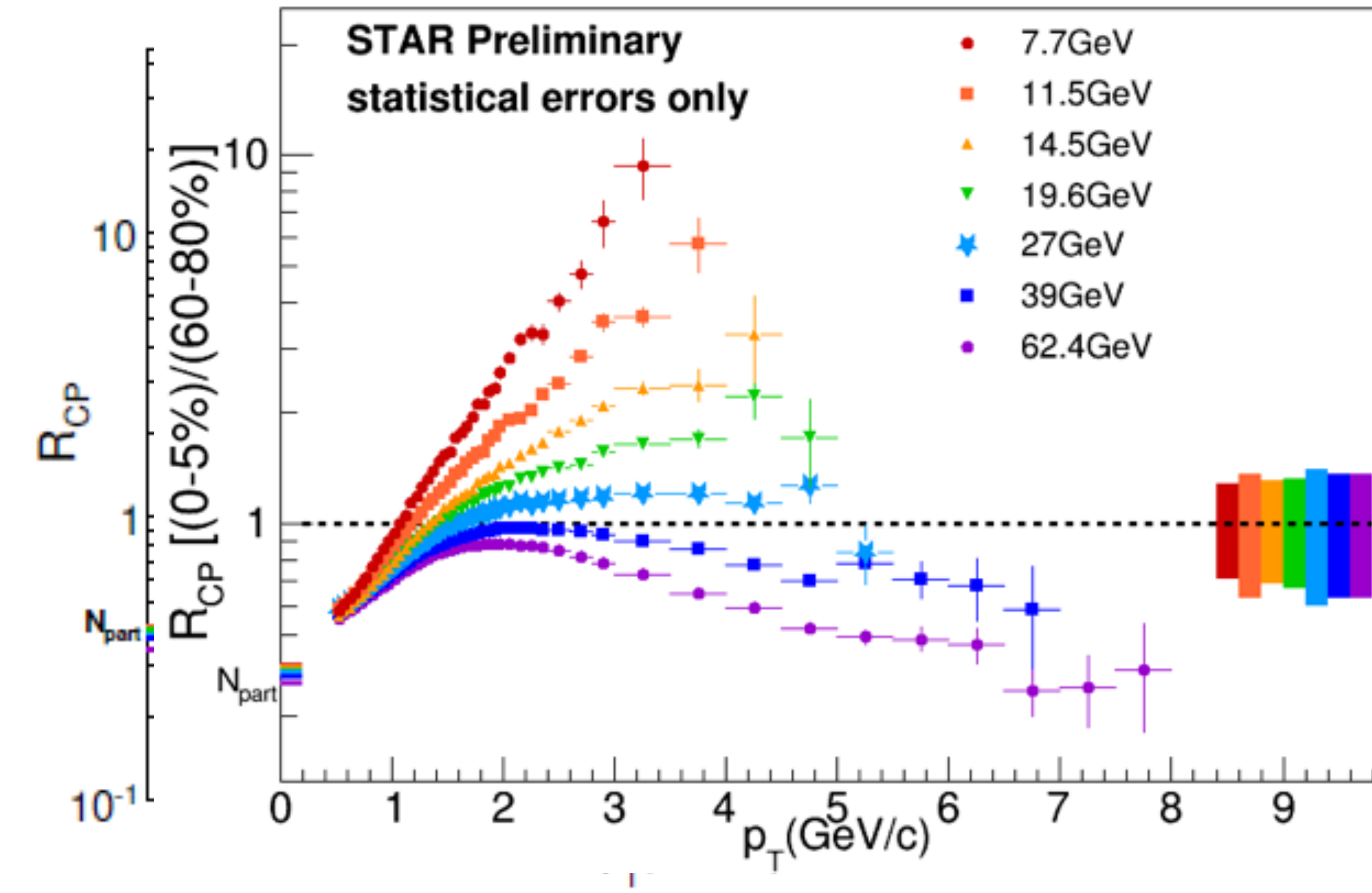
$$R_{CP} = \frac{\text{Particle yield in Central AA collisions}}{\text{Particle yield in Peripheral AA collisions}}$$

Not dependent on pp reference measurement!
Systematic errors cancel in ratio

Disappearance of QGP Signatures - R_{CP}

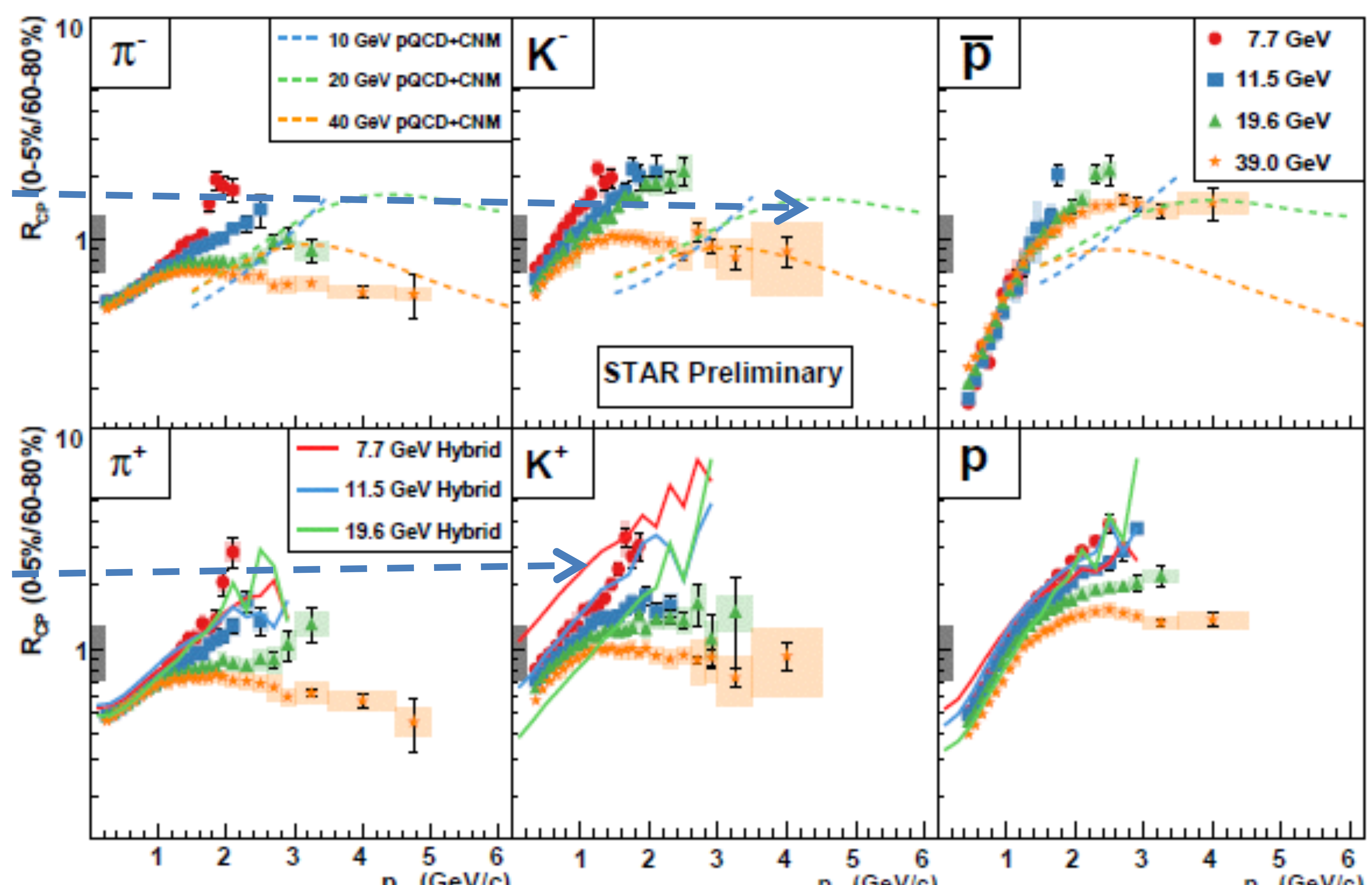
- R_{CP} for hadrons and for identified particles can provide a measure of partonic energy loss in the medium.
- Not sufficient reach to search for evidence of high p_T suppression below 19.6 GeV
- Stopped Baryons complicate inclusive R_{CP} measurements
- pQCD calculations show high p_T suppression
- Hybrid calculations describe the low p_T behavior





pQCD calculations

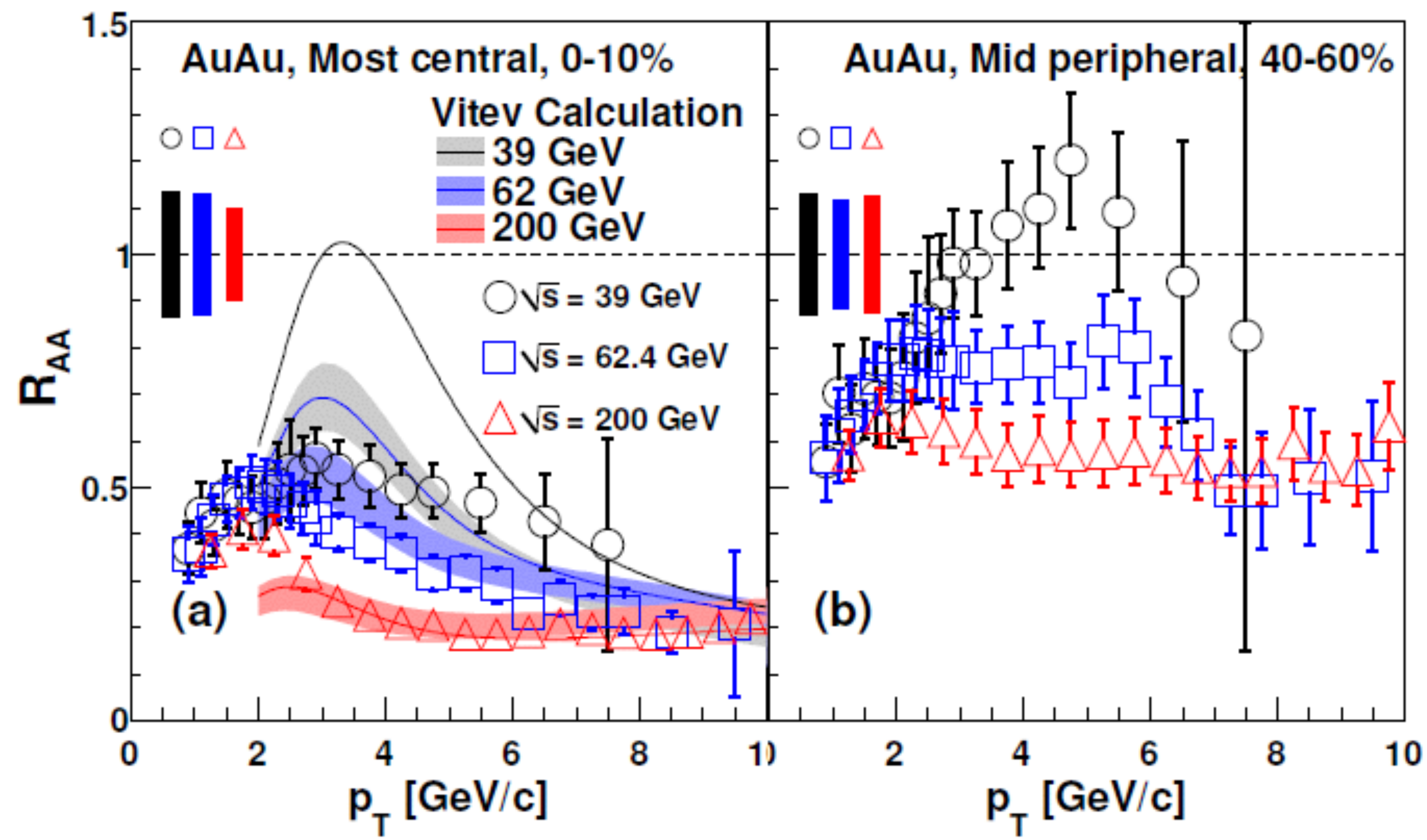
Hybrid calculations



Disappearance of QGP Signatures - R_{AA}

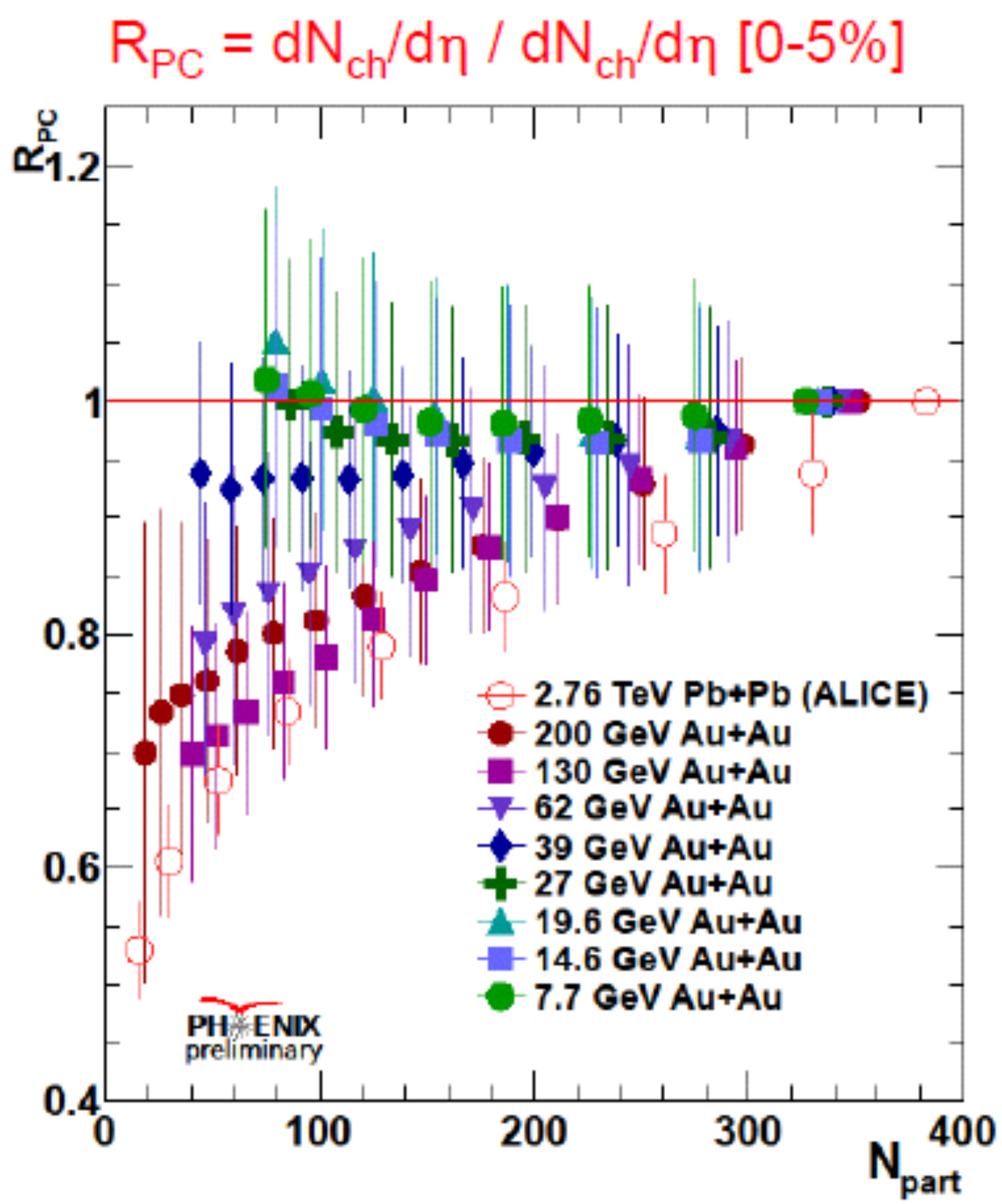
- π0 Nuclear modication factor in Au+Au collisions for the most central 0-10% and
- mid-peripheral 40-60% bin.
- Also shown for central collisions are two pQCD calculations with Cronin-effect (solid lines) and with the Cronin-effect reduced (bands) for all three energies.

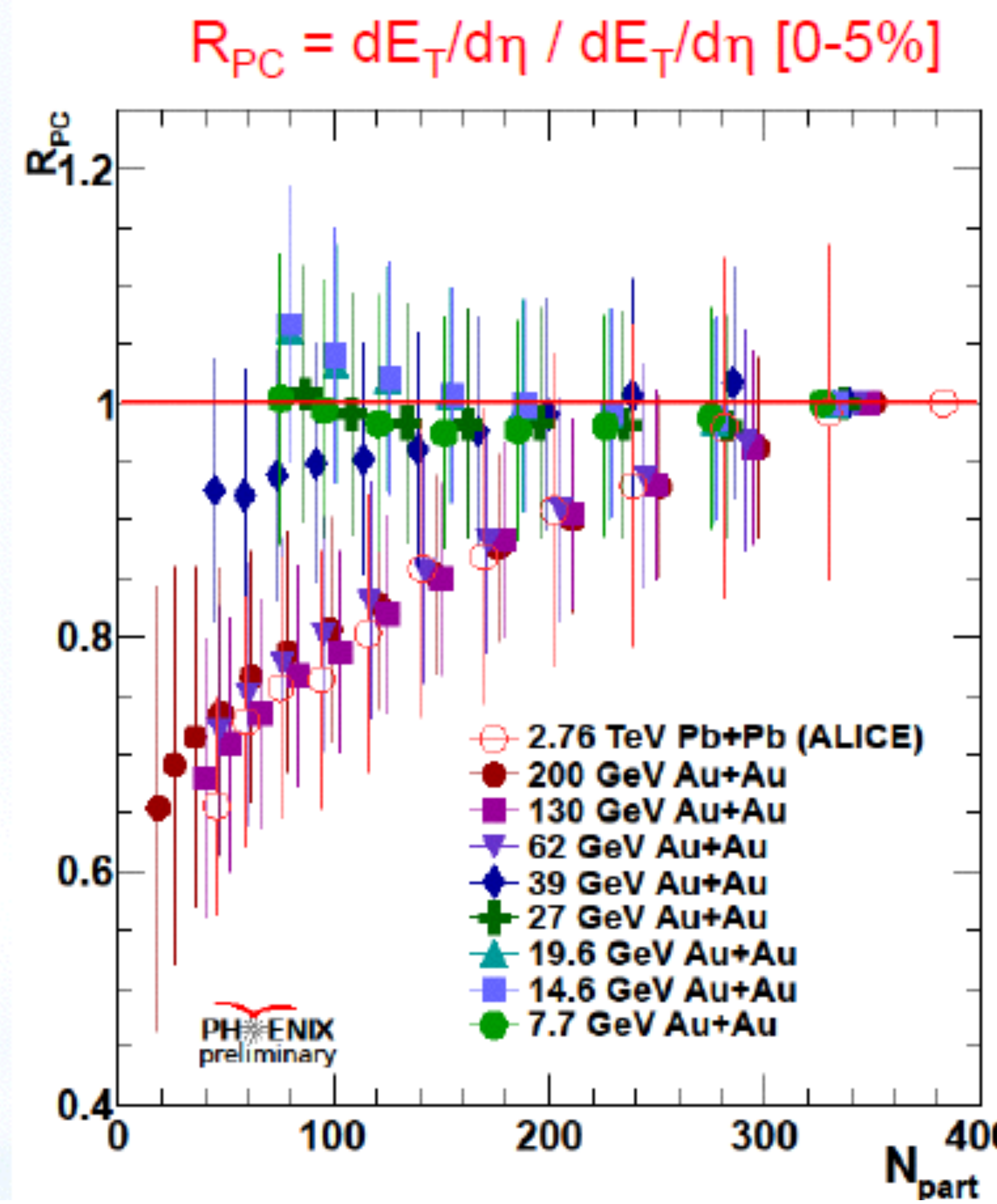
PRL 109 (2012) 152301



Disappearance of QGP Signatures - R_{AA}

10.1103/PhysRevC.89.044905

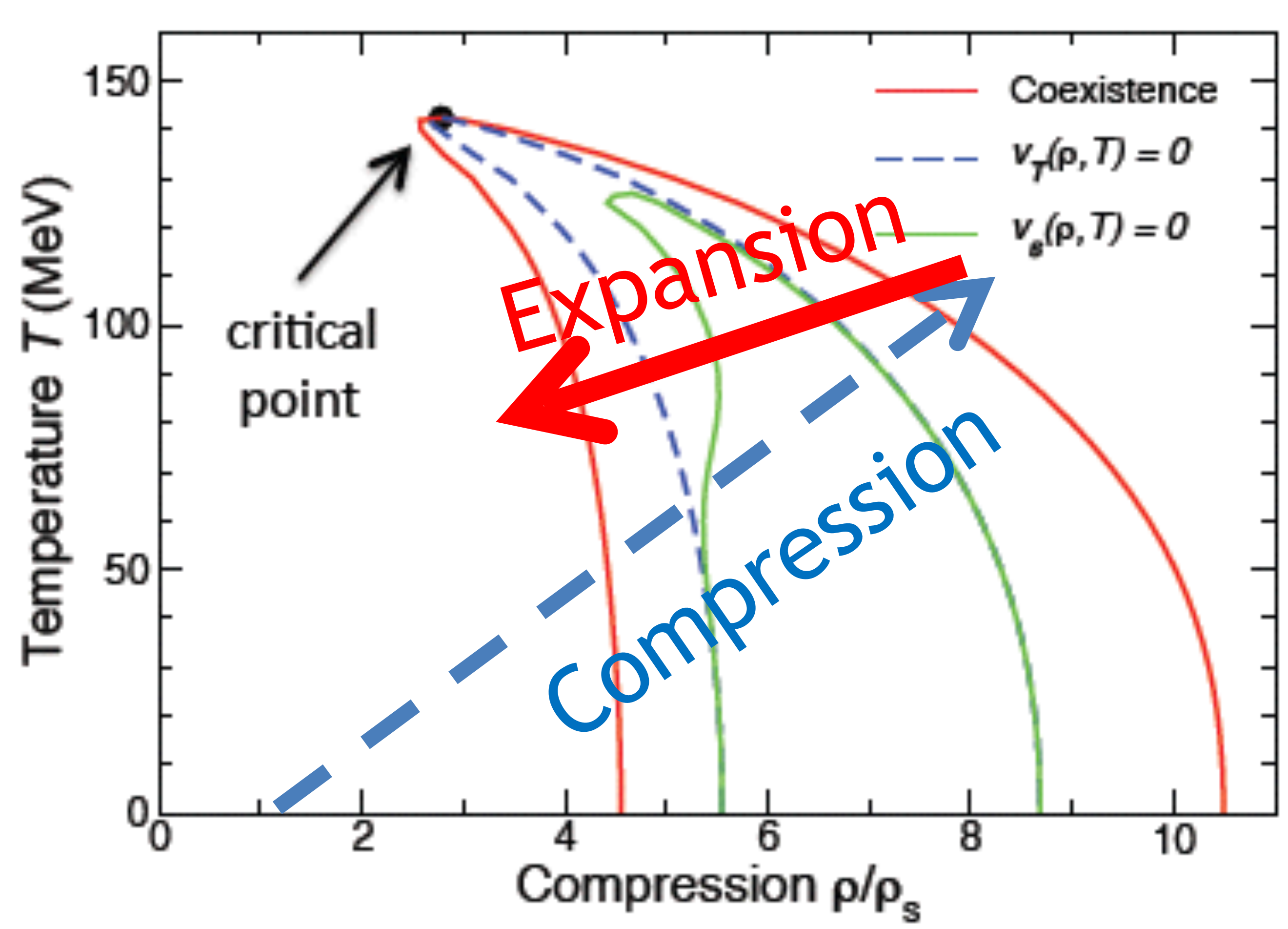




Search for 1st Order Phase Transition – Direct Flow v_1

- First order phase transition is characterized by unstable coexistence region. This spinodal region will have the softest Equation of State

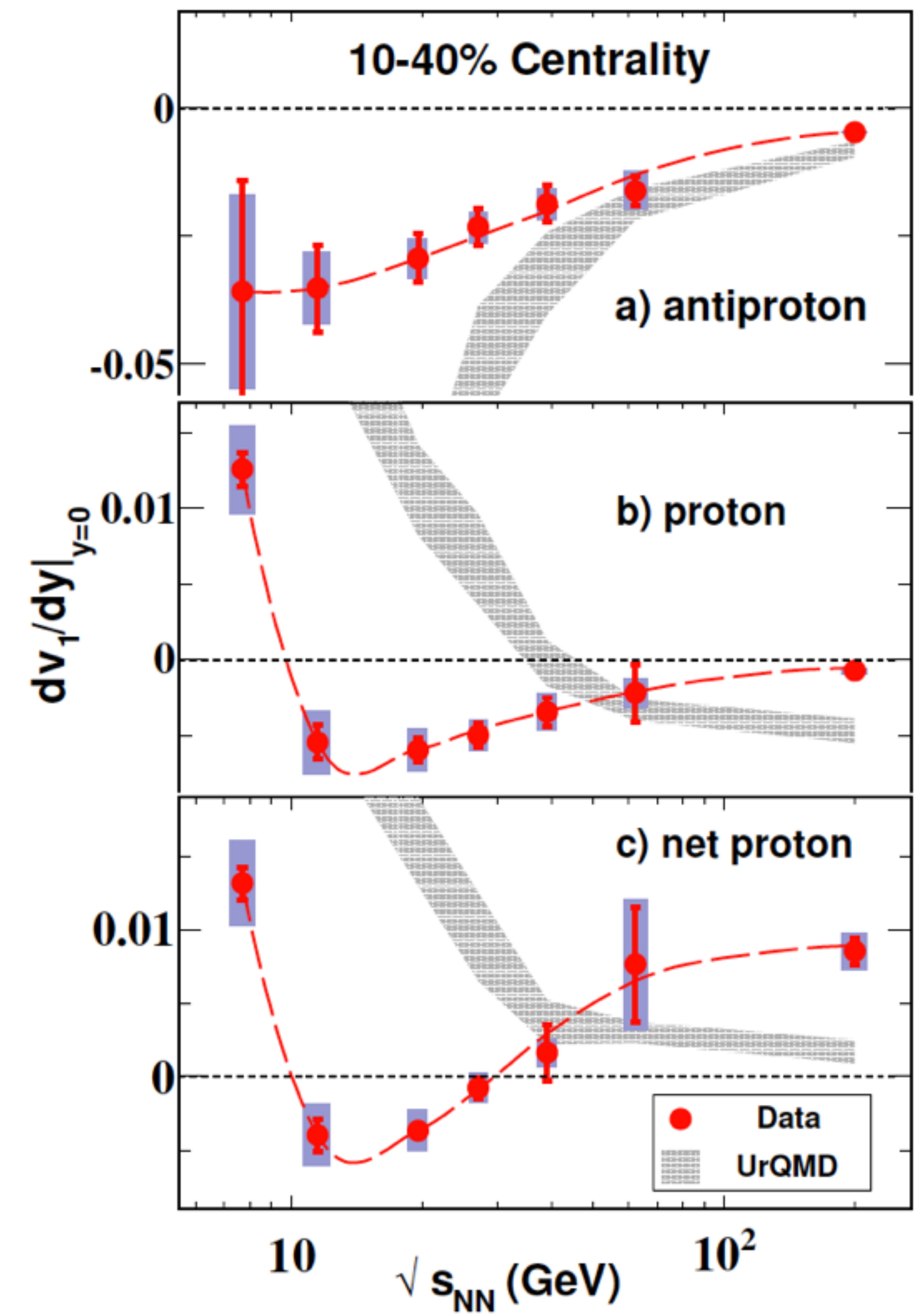
- v_1 is a manifestation of early pressure in the system



$v_T = 0$: isothermal spinodal

$v_s = 0$: isentropic spinodal

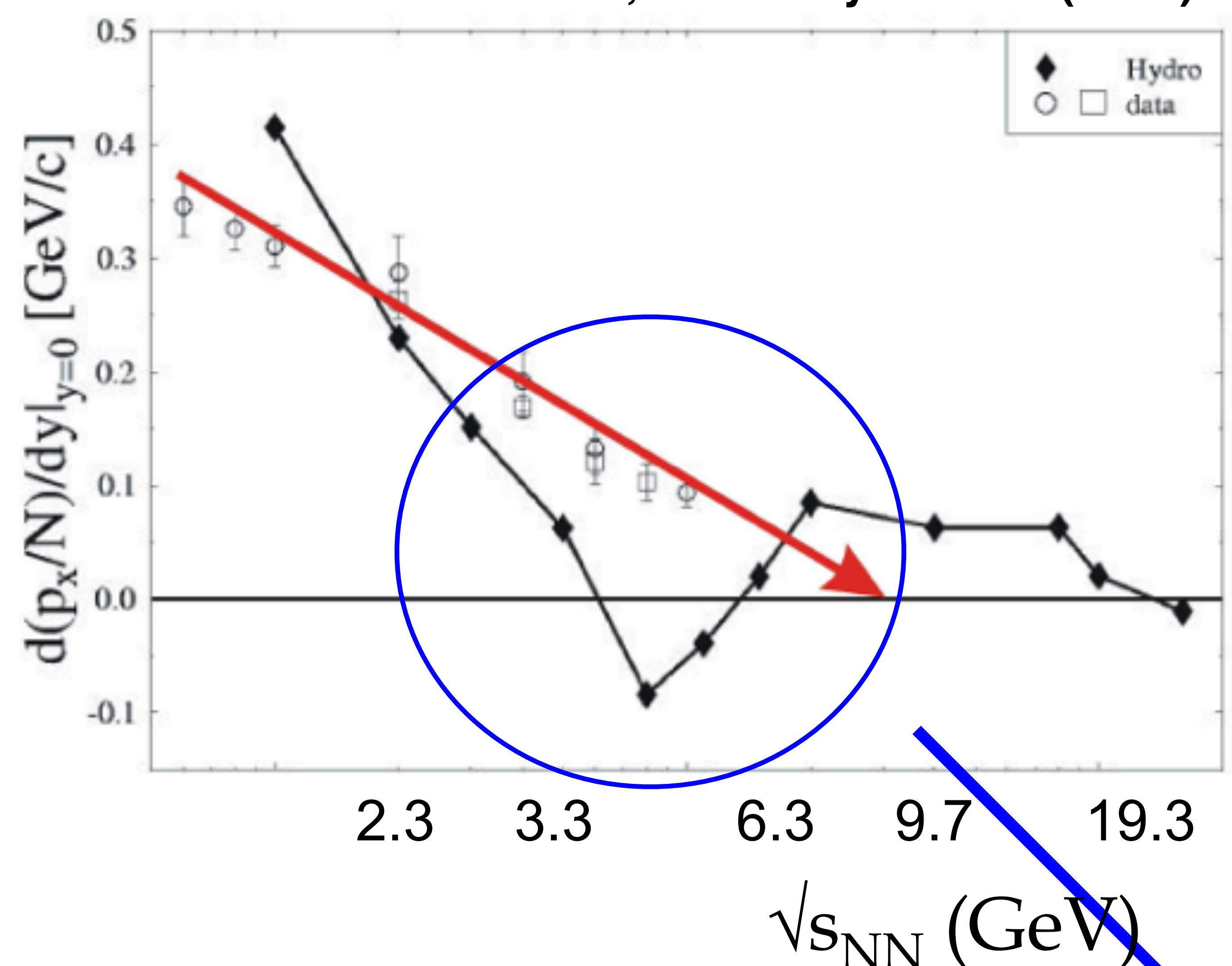
PRL, 112 (2014) 162301



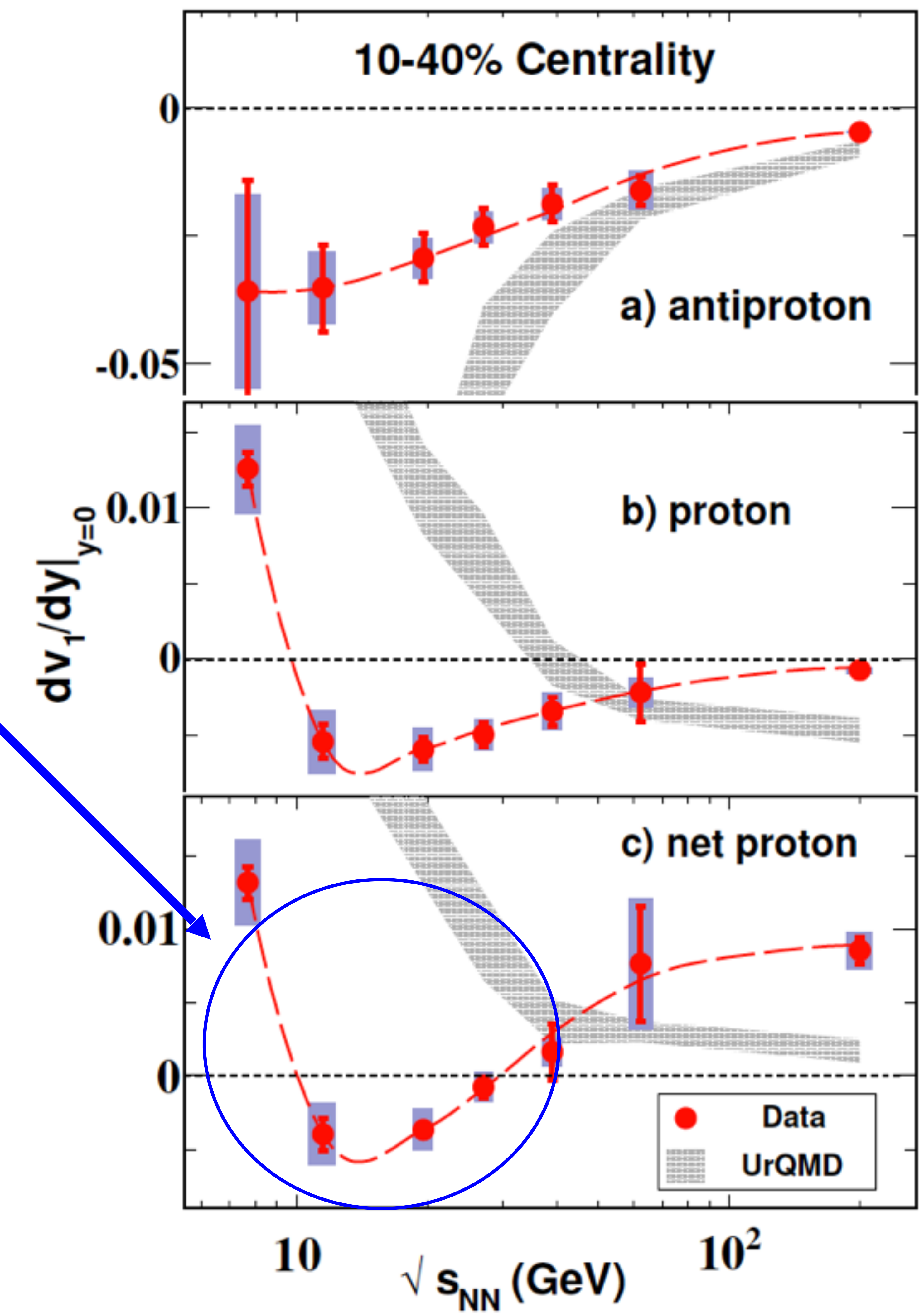
Search for 1st Order Phase Transition – Direct Flow v_1

- Dip in net-proton dv_1/dy reproduces theory prediction
- → Softest point of EoS?

H. Stoecker, Nucl. Phys. A 750 (2005)



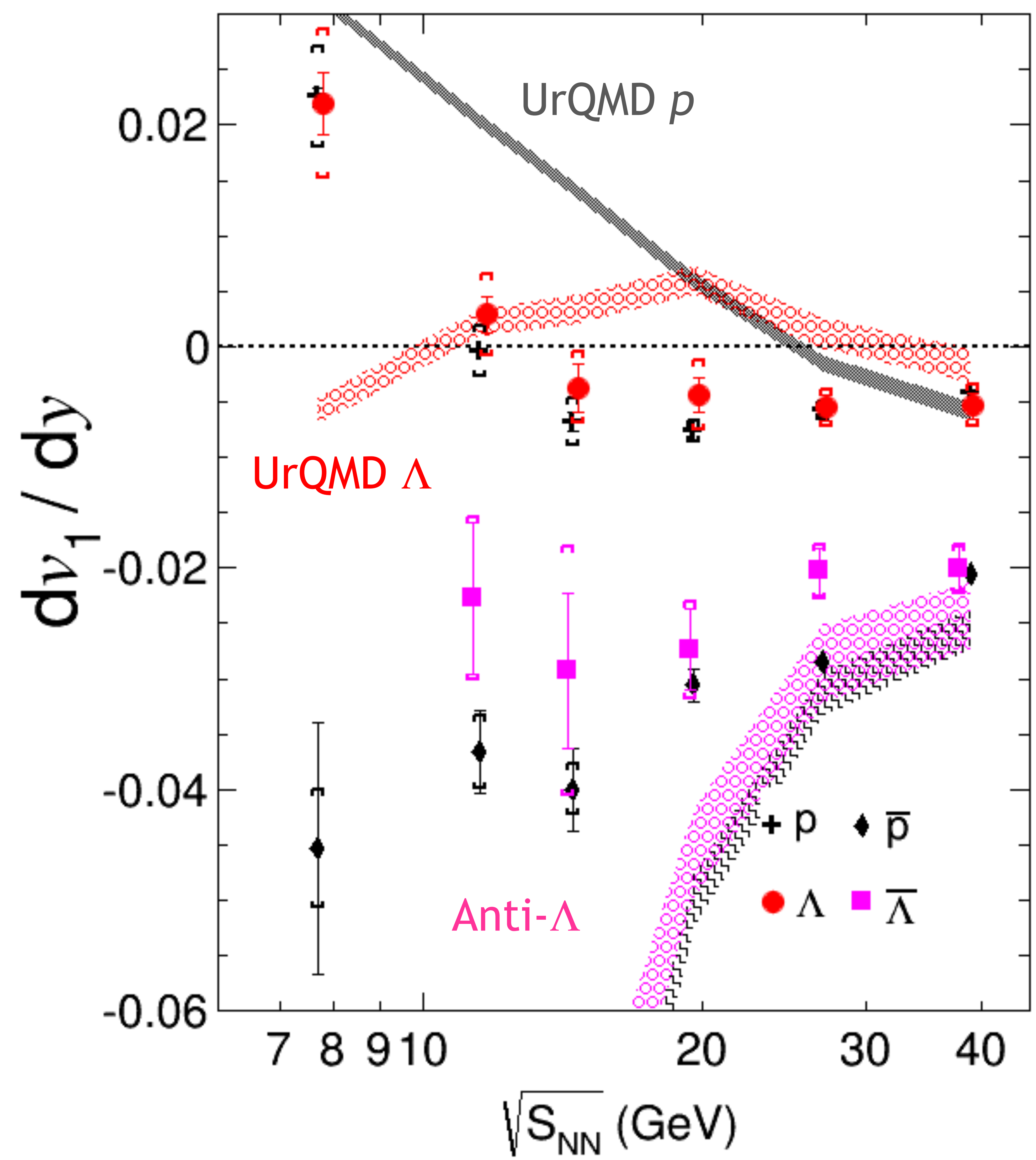
PRL, 112 (2014) 162301



- Rising and falling trends of protons and anti-protons qualitatively reproduced by UrQMD
- Dip at different position than model
- Centrality dependence important
- How does it look like for other particles?

Search for 1st Order Phase Transition – Direct Flow v_1

- Dip in net-proton dv_1/dy reproduces theory prediction
- → Softest point of EoS?
- Rising and falling trends of protons and anti-protons qualitatively reproduced by UrQMD
- Dip at different position than model
- Centrality dependence important
- How does it look like for other particles?



Search for the QCD Critical Point

So how could we find such a Critical Point if it exists?

- Assume that it's going to have the same basic features of other CPs
  - **divergence of the susceptibilities**, χ… e.g. magnetism transitions 0801.4256v2
  - **divergence of the correlation lengths**, ξ… e.g. critical opalescence
- Near a critical point, the sizes of the gas and liquid regions begin to fluctuate over increasingly large length scales.
- When the density fluctuations are of sizes comparable to the wavelength of light, the light is scattered and the substance appears cloudy...

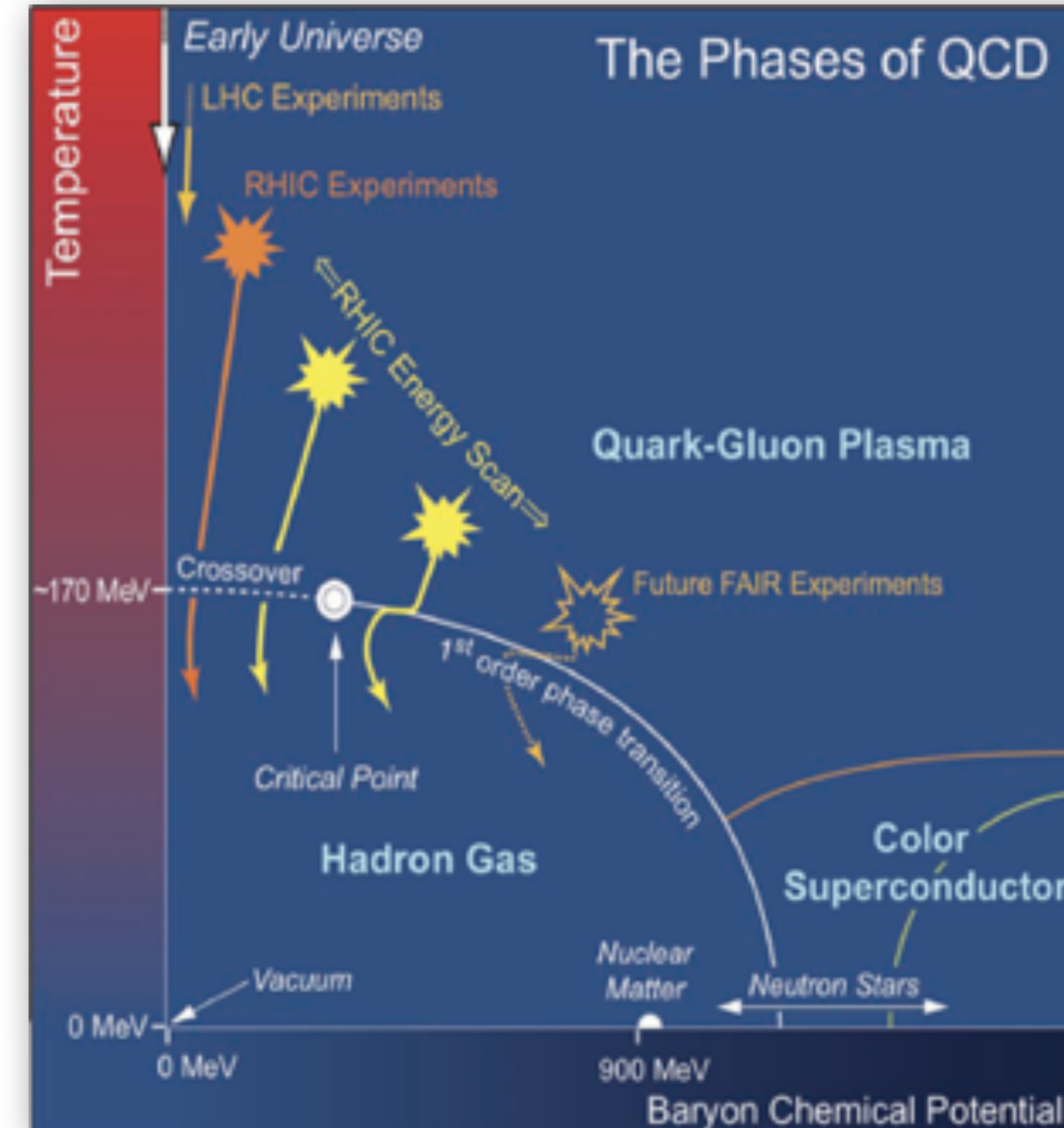
CO_2 near the liquid-gas transition

$T > T_C$ $T \sim T_C$ $T < T_C$

T. Andrews. Phil. Trans. Royal Soc., 159:575, 1869
M. Smoluchowski, *Annalen der Physik, 25 (1908) 205 - 226*
A. Einstein, *Annalen der Physik, 33 (1910) 1275-1298*

Search for the QCD Critical Point
Experimentally

- Critical Point: Endpoint of the first order phase transition
- Event-by-event fluctuations of conserved quantities to study of the phase transition
  - Charge **Q** / baryon number **B** / strangeness **S**



- Experimental observables:
  - Cumulants of event-by-event net-particle ($\Delta N = N_{pos} - N_{neg}$) multiplicity distributions: **Net-charge** / **net-proton** (proxy for net-baryon) / **net-kaon** (proxy for net-strangeness)
  - Volume independent cumulant ratios

Search for the QCD Critical Point

Experimentally

No. of net-particles in a single event...

Average No. of net-particles in all "similar" events...

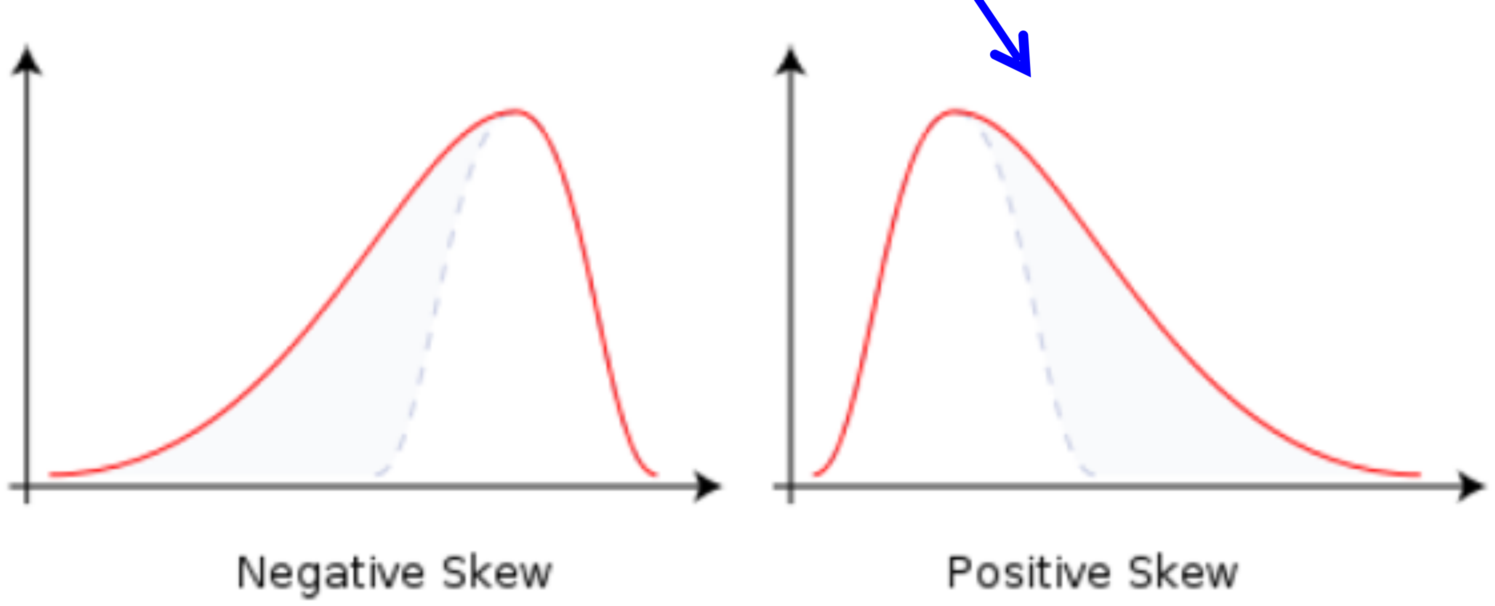
$$\delta x \equiv x - \langle x \rangle$$

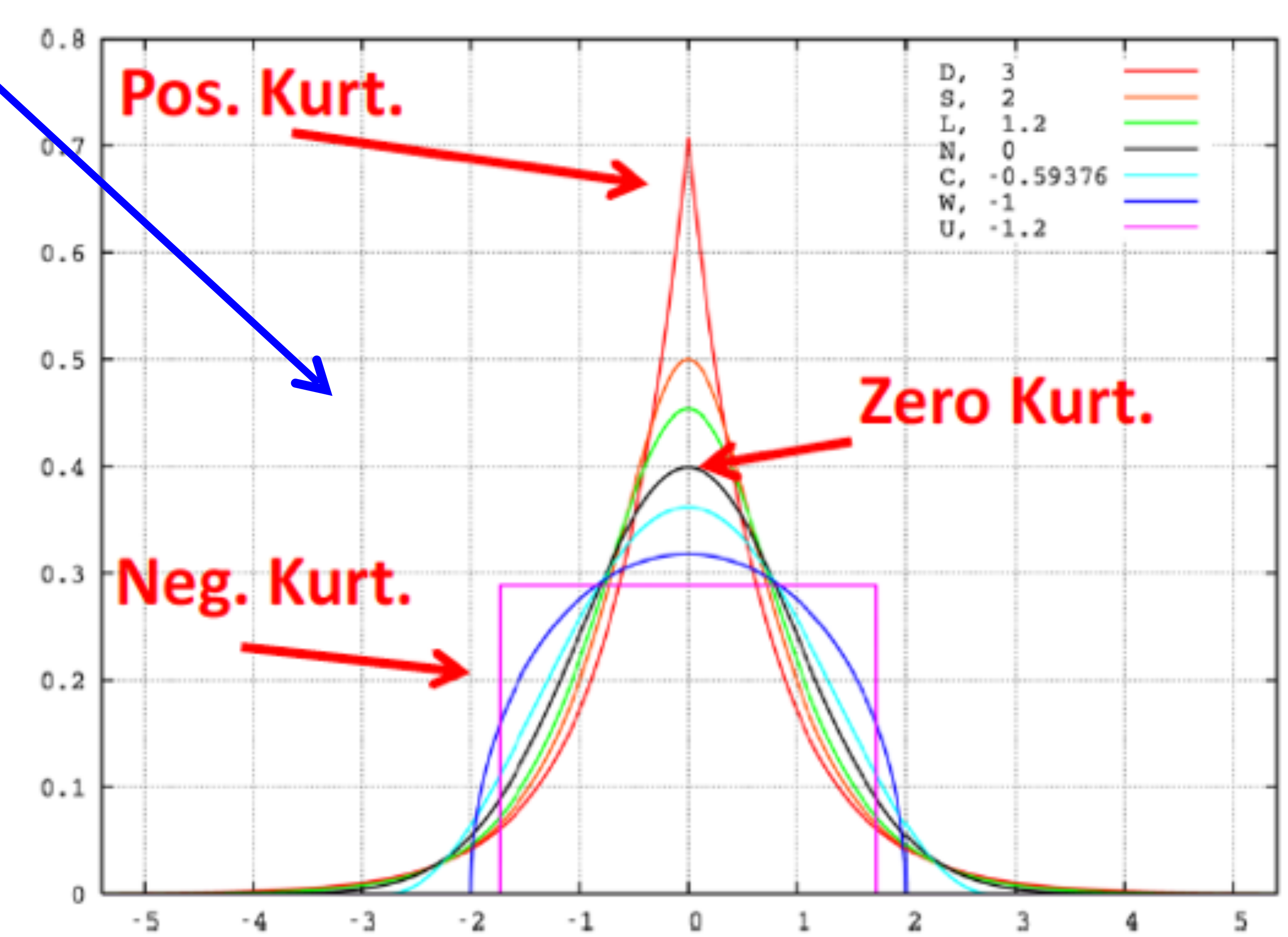
$$\kappa_{2x} \equiv \langle\langle x^2 \rangle\rangle \equiv \langle (\delta x)^2 \rangle$$

$$\kappa_{3x} \equiv \langle\langle x^3 \rangle\rangle \equiv \langle (\delta x)^3 \rangle$$

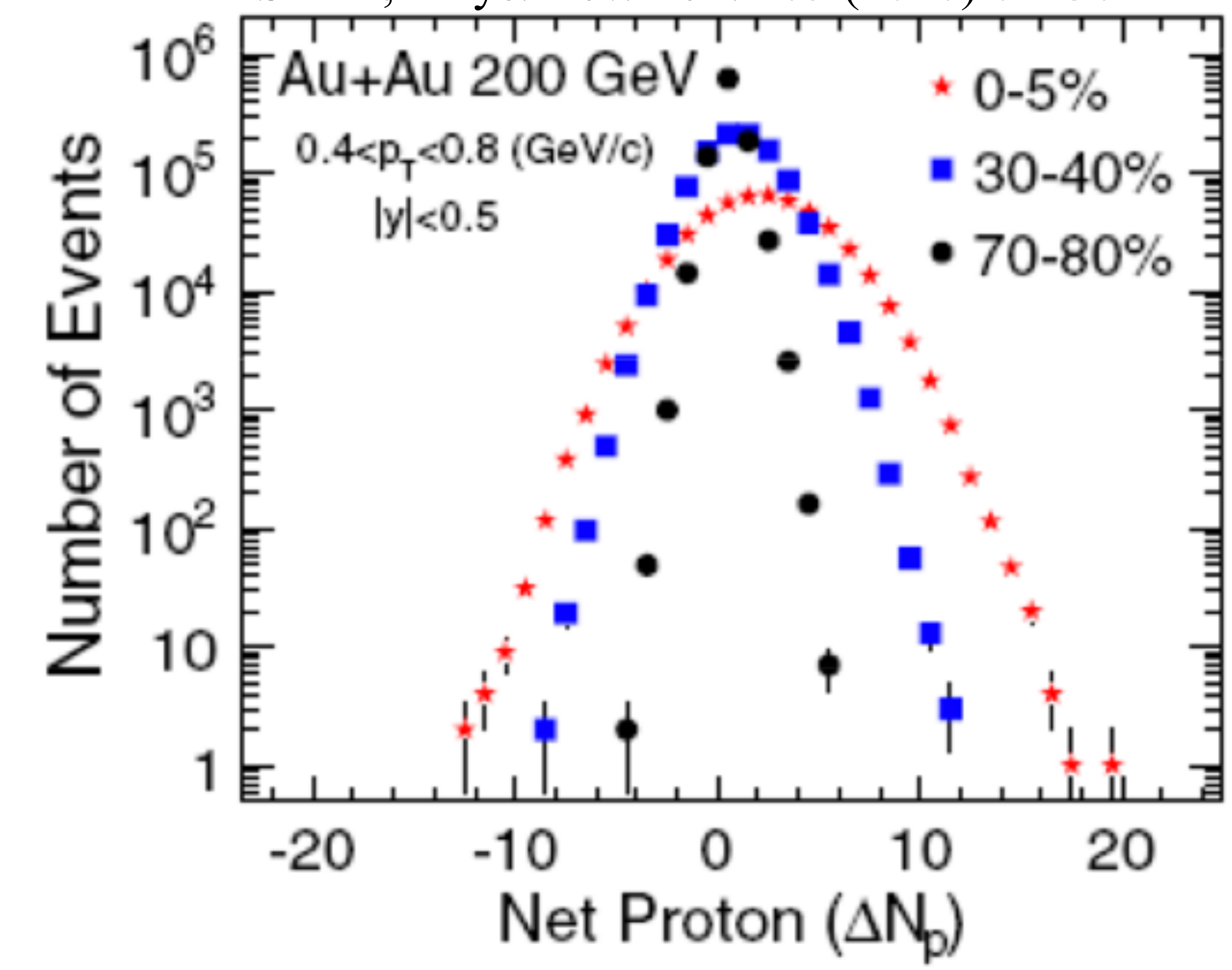
$$\kappa_{4x} \equiv \langle\langle x^4 \rangle\rangle \equiv \langle (\delta x)^4 \rangle - 3 \langle (\delta x)^2 \rangle^2$$

$$\text{skewness} = \frac{\kappa_3}{\kappa_2^{3/2}}, \ \text{kurtosis} = \frac{\kappa_4}{\kappa_2^2}$$





STAR, Phys. Rev. Lett. 105 (2010) 022302



Sensitive to the correlation length(ξ) :

$$\langle (\delta N)^2 \rangle \sim \xi^2$$

$$\langle (\delta N)^3 \rangle \sim \xi^{4.5}$$

$$\langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2 \sim \xi^7$$

M. A. Stephanov, PRL102, 032301 (2009);
M. Akasawa, et al., PRL103,262301 (2009).

Connection to Theoretical Calculations

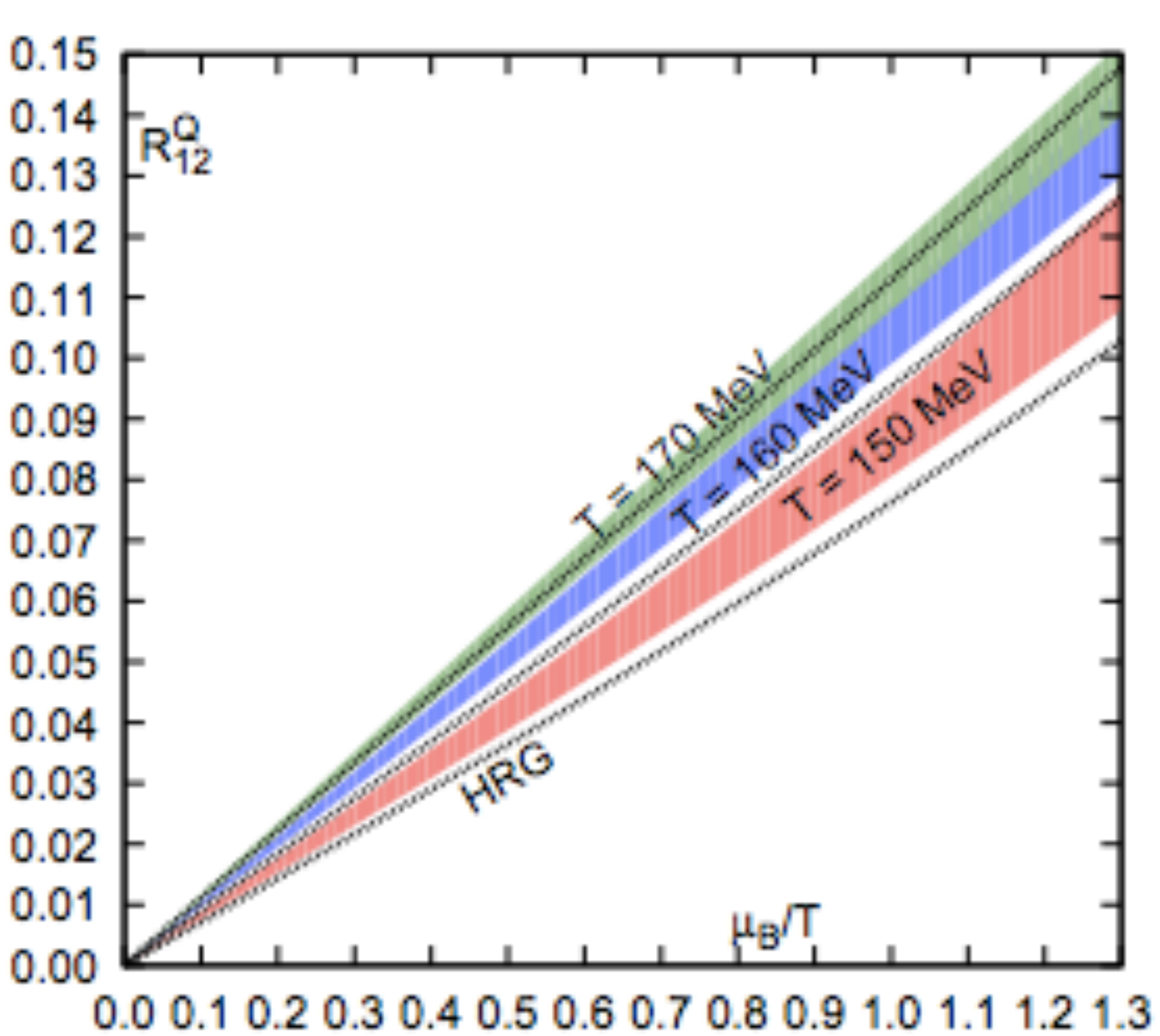
A. Bazavov et al. PRL109,192302,(2012).
F. Karsch et al, PLB 695,136(2011).

- Susceptibility ratios of conserved quantities are assumed to be related to the moments of experimentally measurable multiplicity distributions

$$\chi_n^B = \left.\frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}\right|_T$$

- Comparing first principal Lattice calculations with measured moments of conserved quantities, e.g. net-charge → extract the chemical freeze out parameters T and μ_B

Lattice QCD



HotQCD, PRL109, 192302 (2012)
WB Group, PRL111, 062005 (2013)

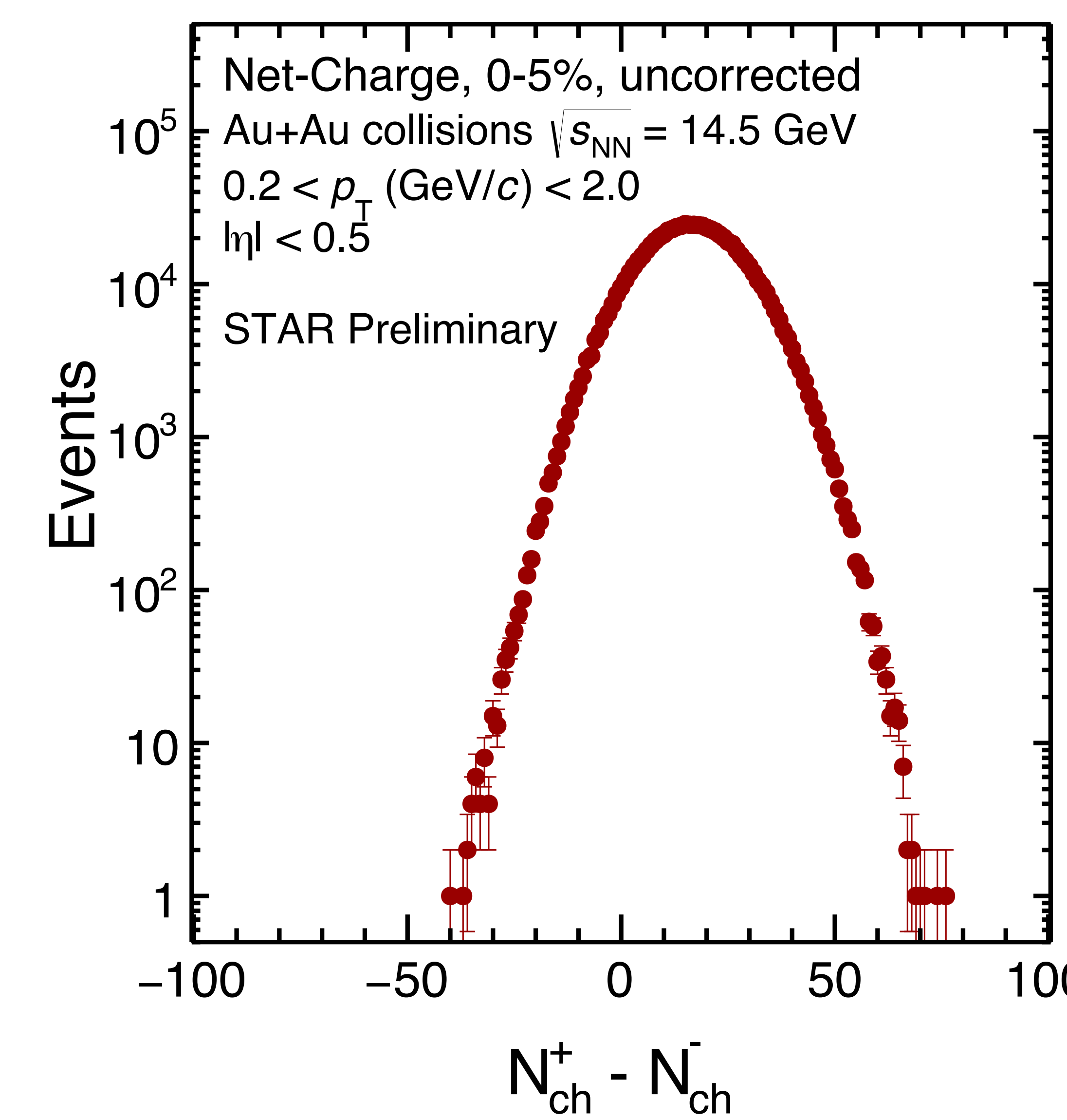
$$\frac{\chi_2^i}{\chi_1^i} = (\sigma^2/M)^i = \frac{c_2^i}{c_1^i}$$

$$\frac{\chi_3^i}{\chi_2^i} = (S\sigma)^i = \frac{c_3^i}{c_2^i}$$

$$\frac{\chi_4^i}{\chi_2^i} = (\kappa\sigma^2)^i = \frac{c_4^i}{c_2^i}$$

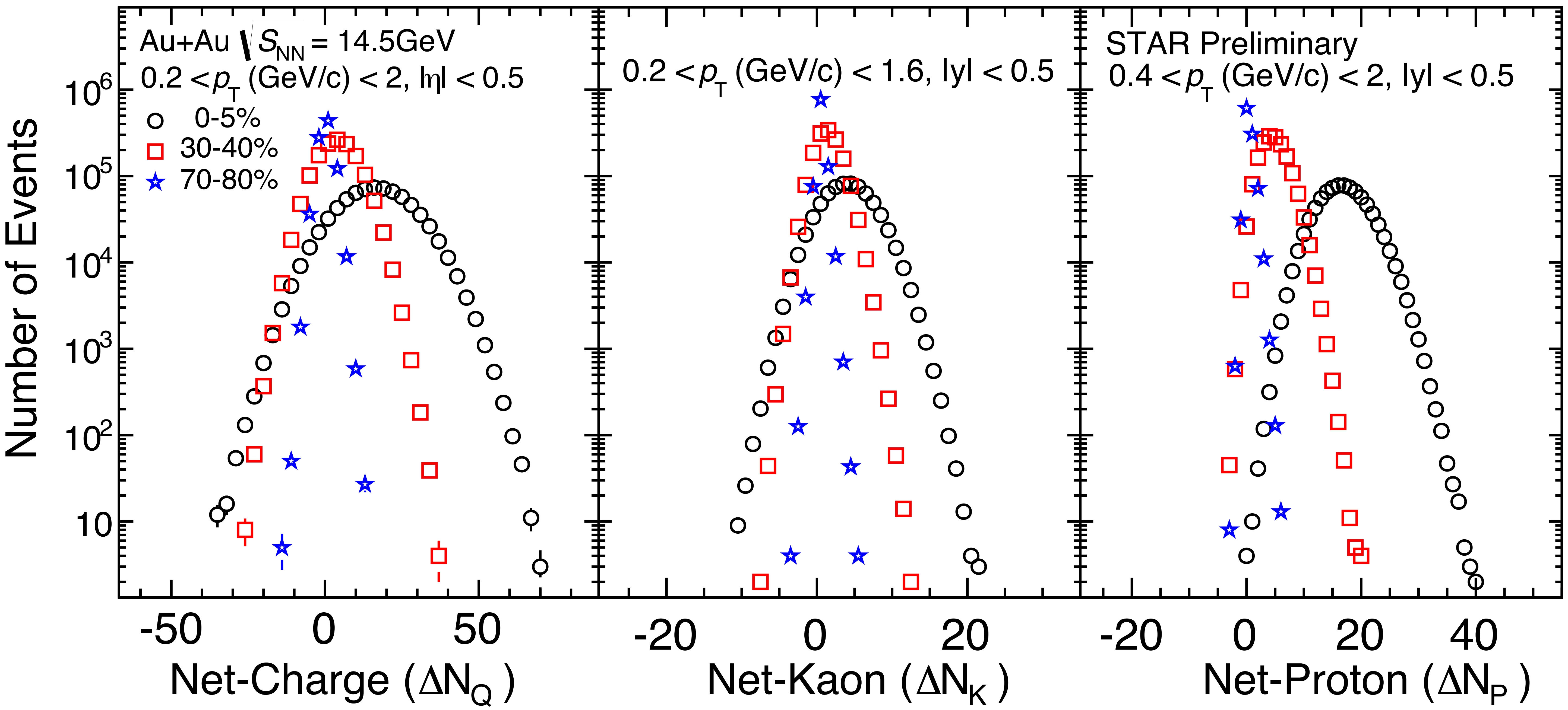
$$i = B, Q, S$$

Experiment



Event-By-Event Net-Particle Multiplicity Distribution

Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV



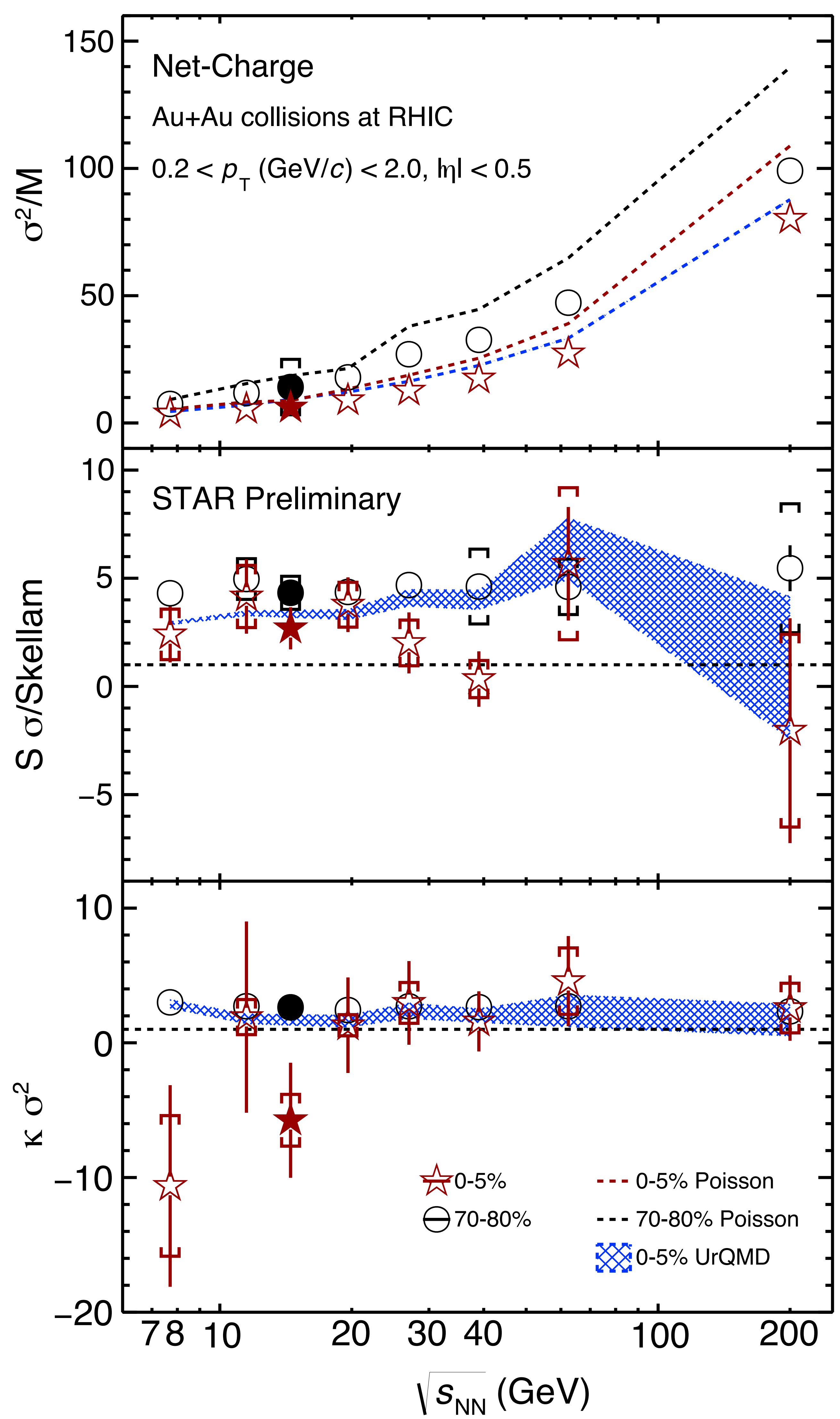
Apply correction on raw net-particle distributions

- **Finite Tracking / PID efficiency**
  → Factorial Moments
- **Volume fluctuations**
- **Remove auto-correlation effects**

- Uncorrected raw event-by-event net-particle multiplicity distribution for Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV

Corrected Cumulant Ratio of Net-Charge

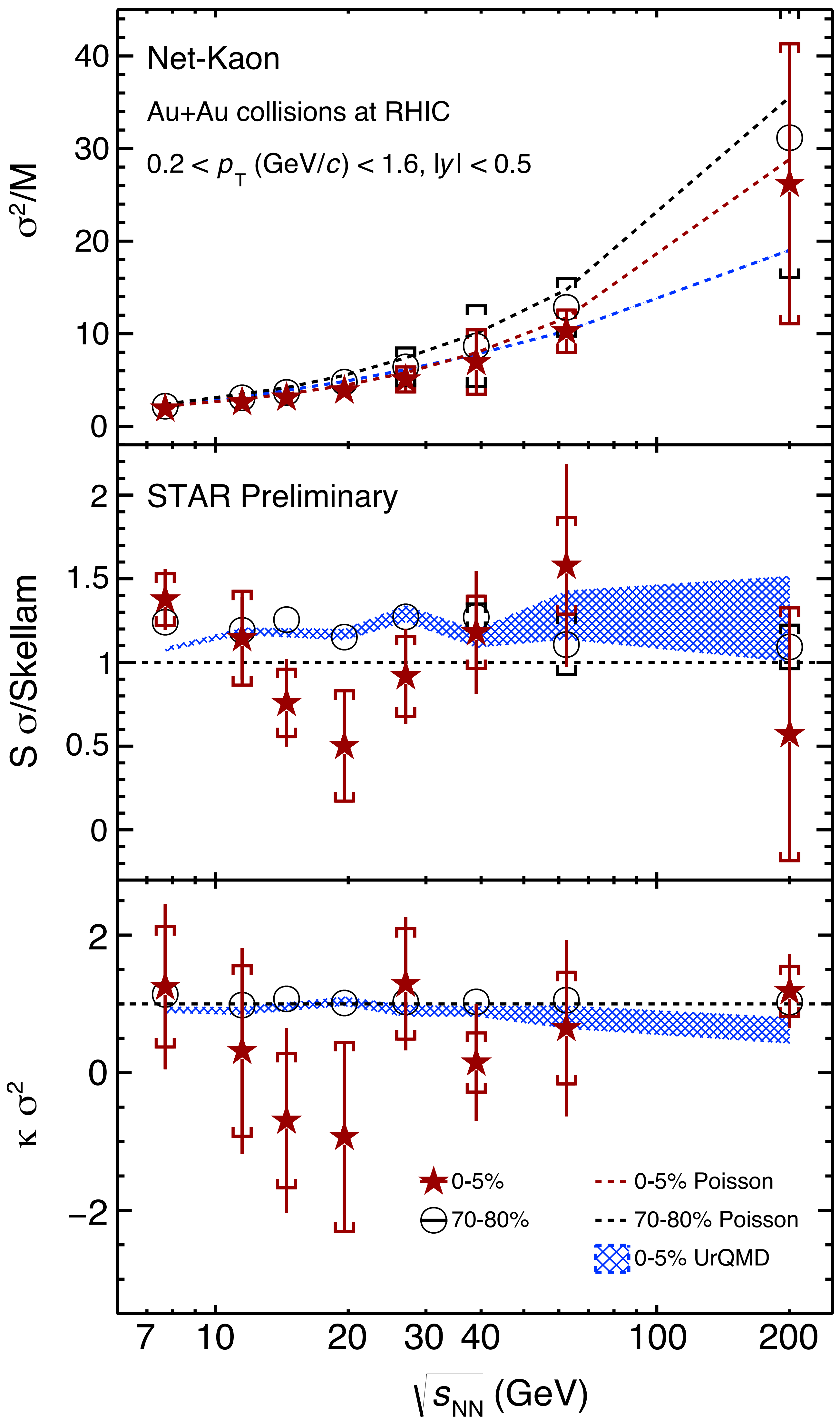
Collision Energy Dependence



- σ^2/M increases with increasing collision energy
- For most central collisions (0-5%), $\kappa\sigma^2$ and $S\sigma$/Skellam are consistent with unity
- UrQMD (no Critical Point), shows no energy dependence

Corrected Cumulant Ratio of Net-Kaon

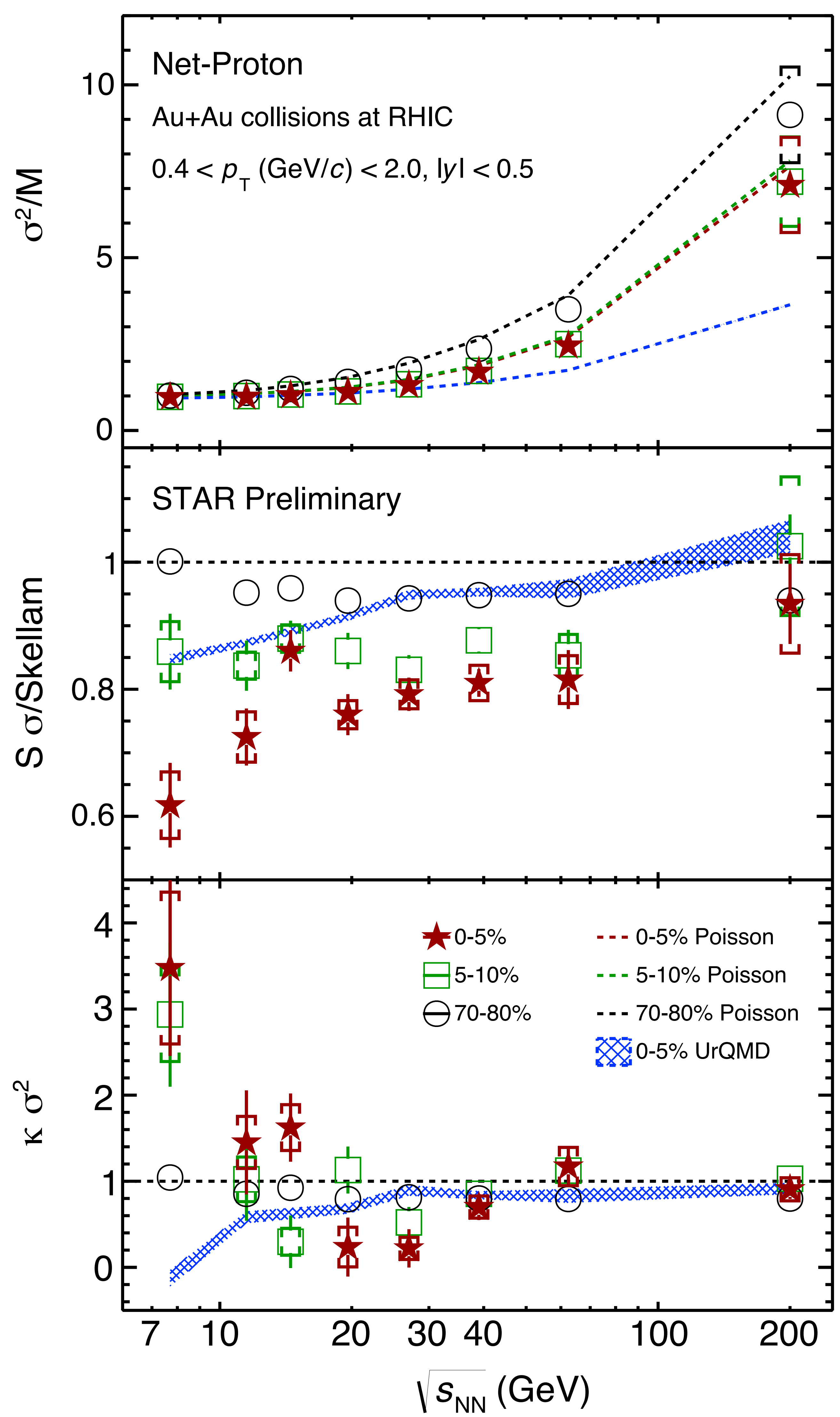
Collision Energy Dependence



- σ^2/M increases with energy
- σ^2/M and Sσ/Skellam are consistent with the Poisson expectation for most central collisions
- For most central collisions (0-5%), κσ^2 is consistent with unity (= Poisson expectation)
  - More statistics needed
- UrQMD (no Critical Point), shows no energy dependence

Corrected Cumulant Ratio of Net-Proton

Collision Energy Dependence

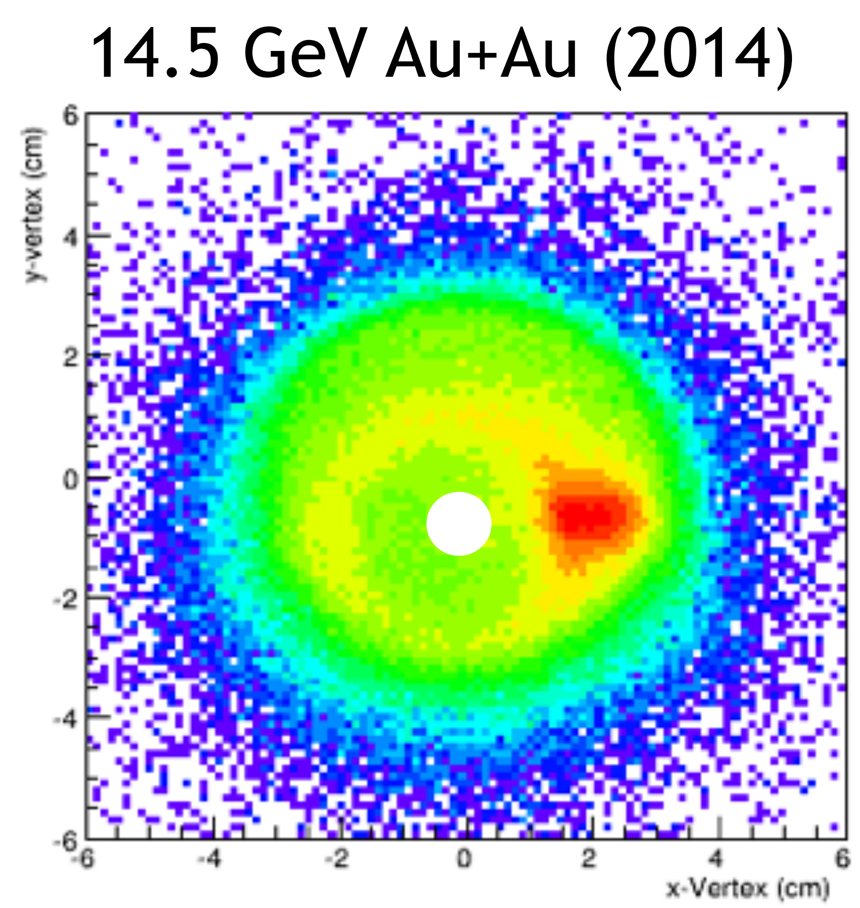


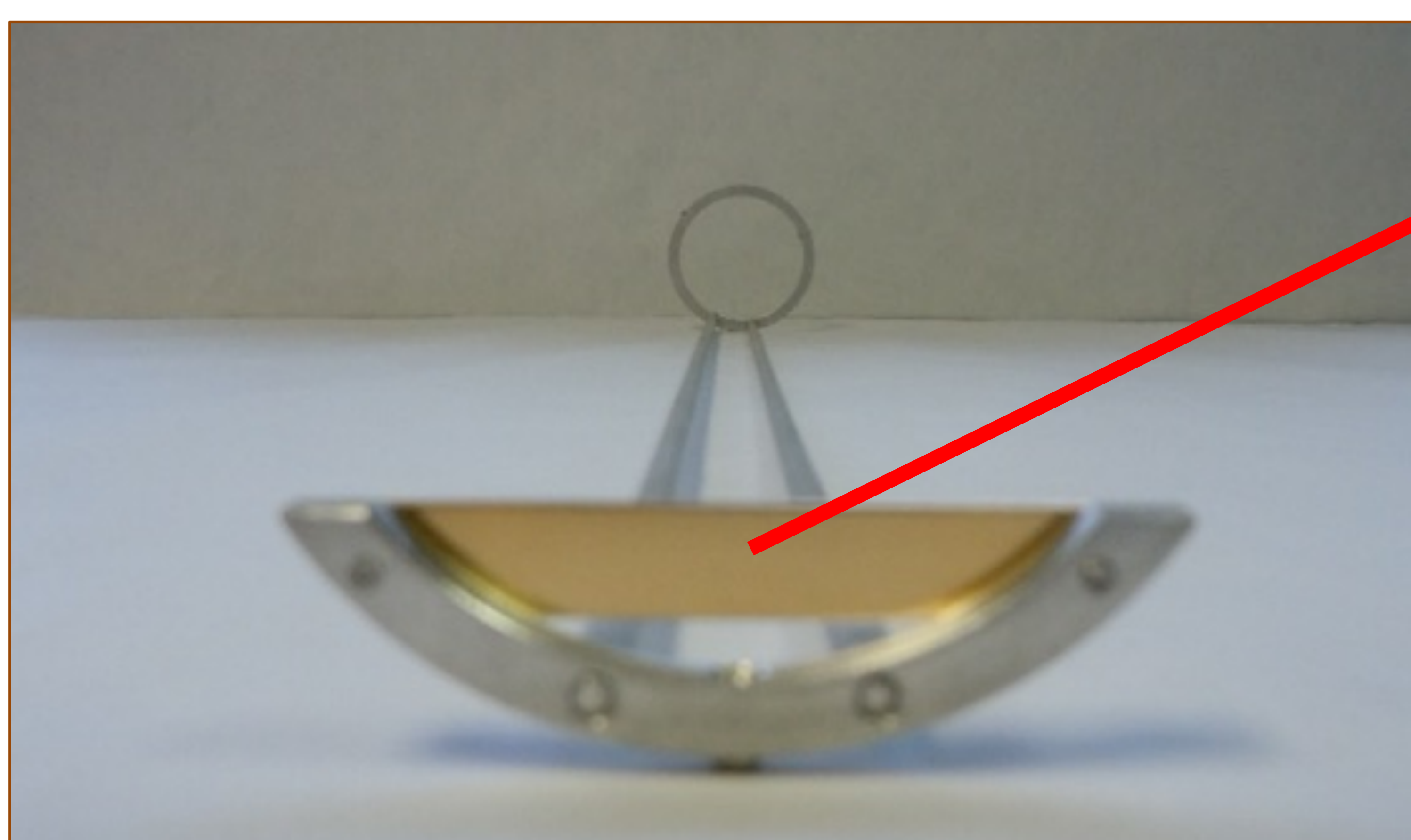
- σ^2/M increases with increasing energy, consistent with Poisson expectation
- Sσ/Skellam increases with increasing energy
- **Non-monotonic behavior** of net-proton $\kappa\sigma^2$ seen in top 5% central collisions
  - 5-10% central collisions in between
  - → however: smooth trend in centrality
  - Peripheral collisions show smooth trend
  - Detailed extensive studies have been carried out and are still in progress
- UrQMD (no Critical Point), shows suppression at lower energies - due to baryon number conservation

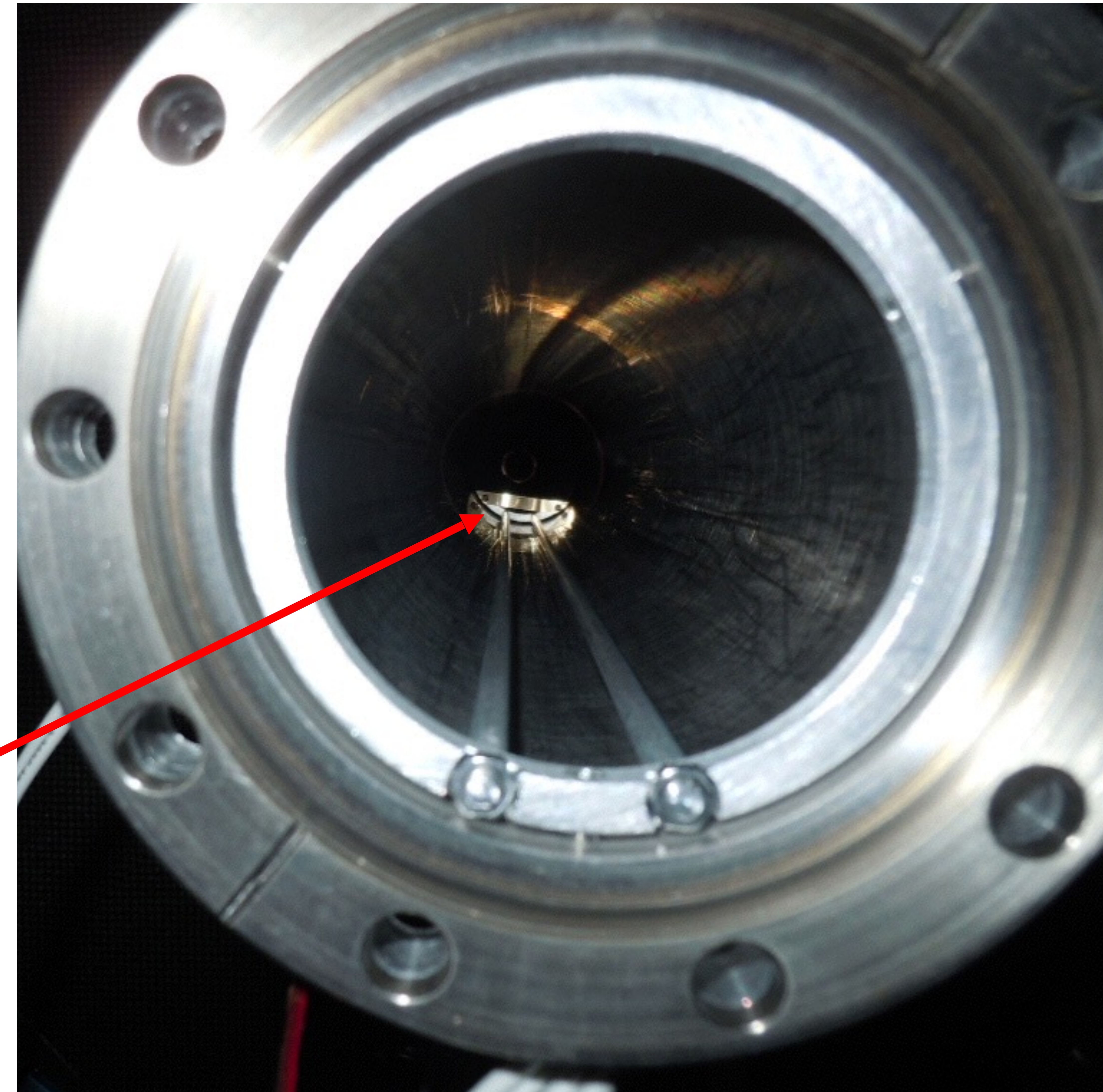
STAR Fixed Target Program

Target Design 2014 and 2015

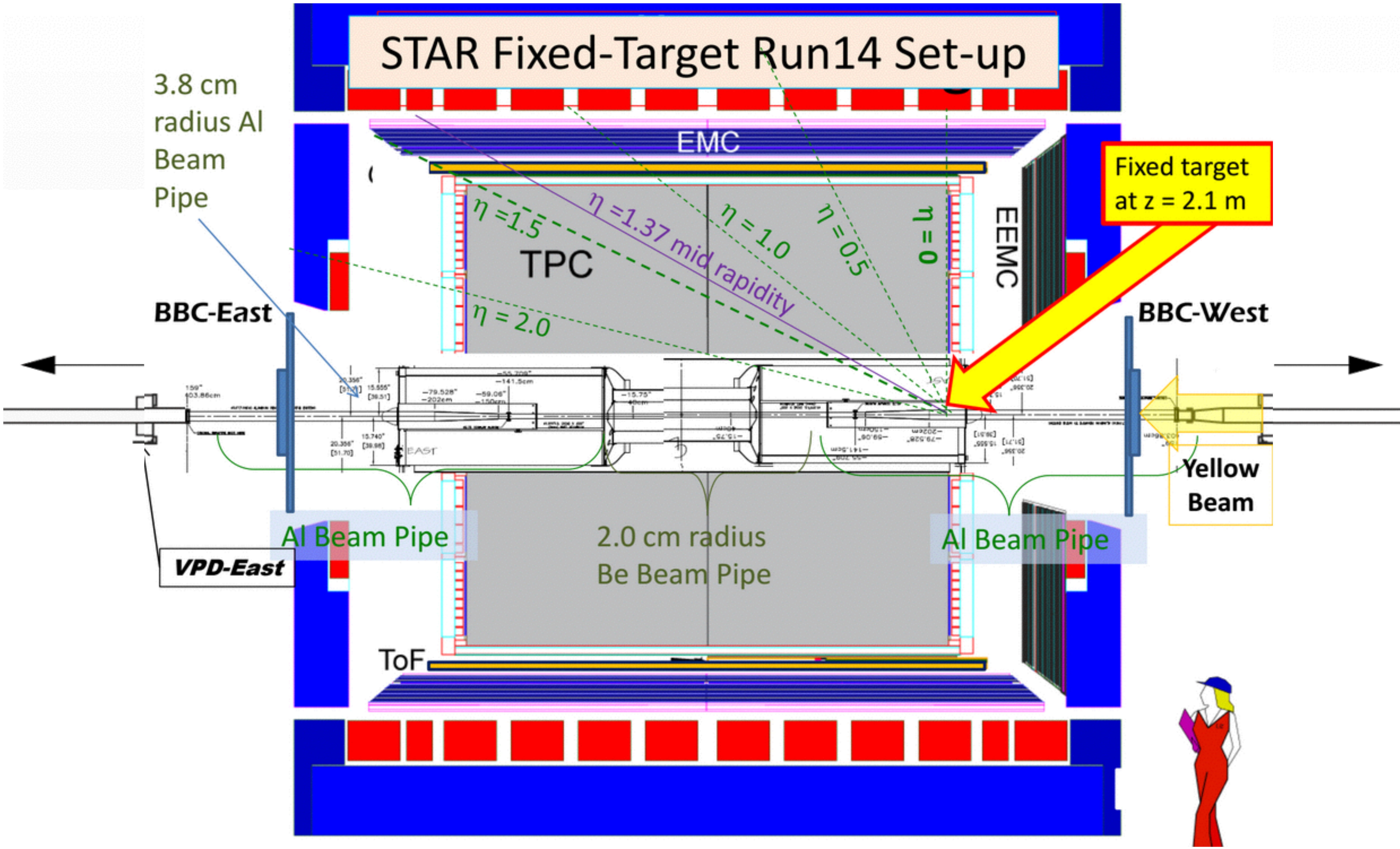
Target design:
- Gold foil
- 1 mm Thick
- ~1 cm High
- ~4 cm Wide
- 210 cm from IR



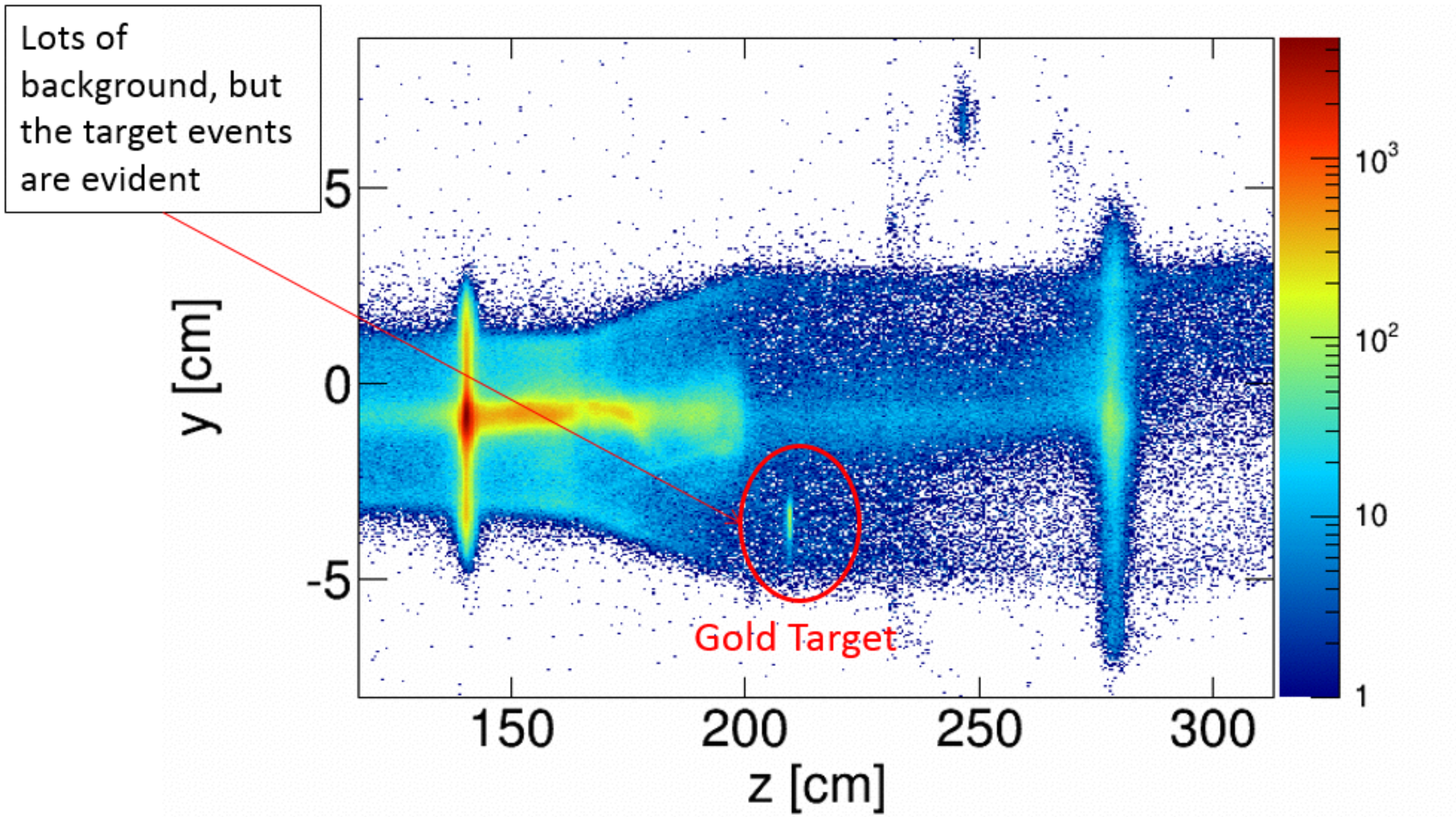




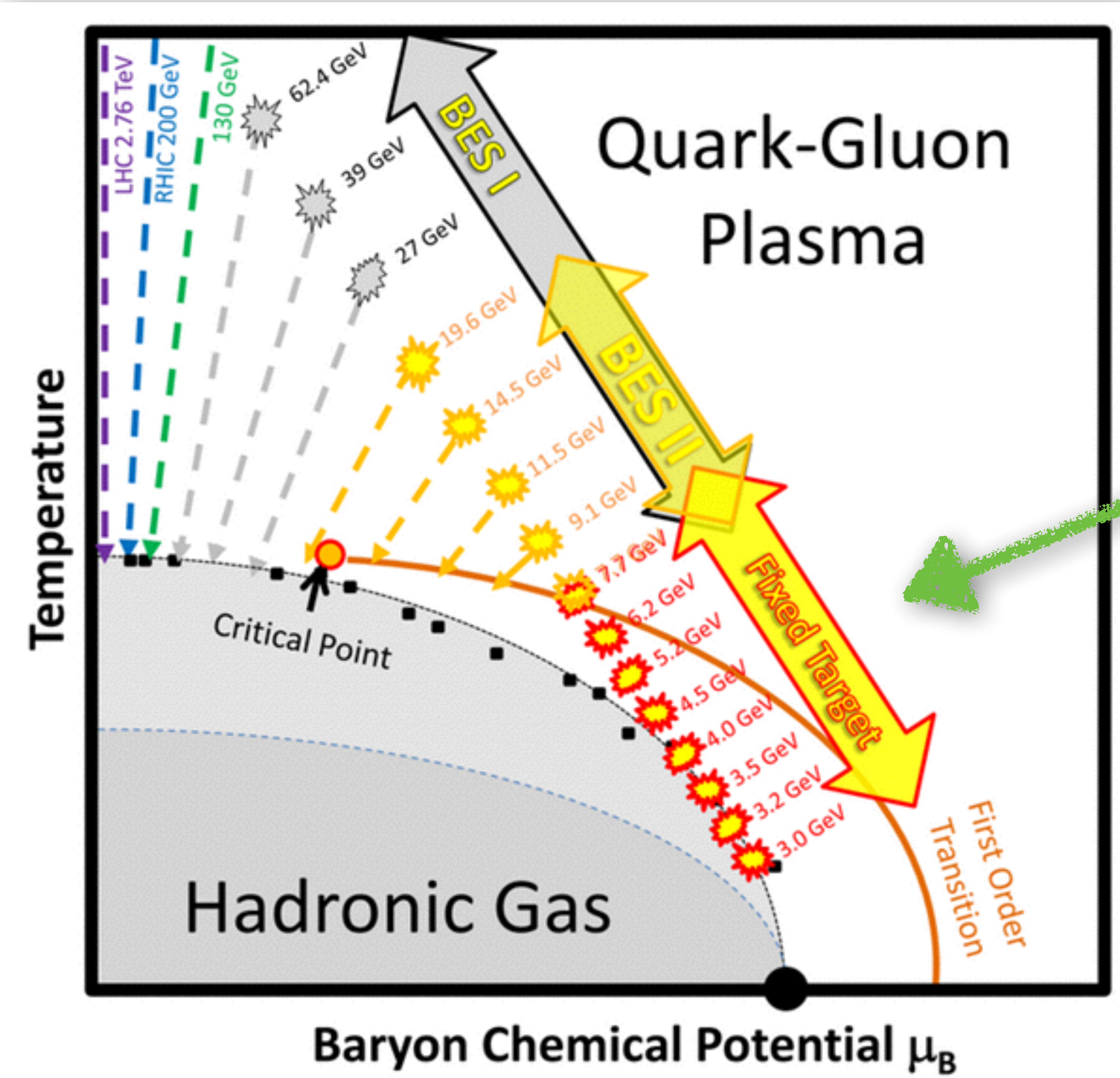
Run 14 and 15 Setup



Run 14 and 15 Setup
Identifying Target Events



STAR Fixed Target Program



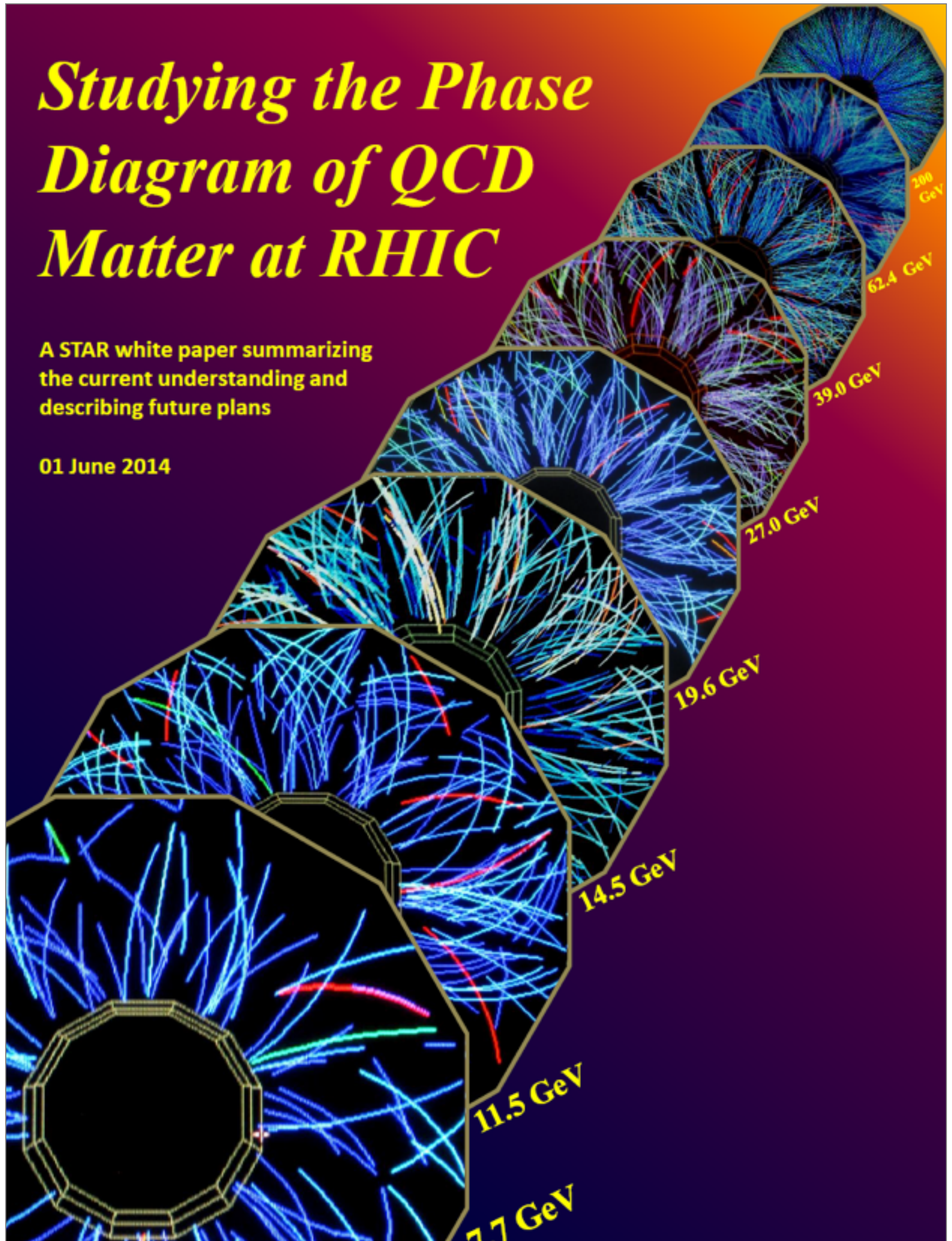
	Energy (GeV)	Baryon Chemical Potential* μ_B	Pred. Temp.* (MeV)
LHC	2760.0	2	166.0
RHIC	200.0	24	165.9
RHIC	130.0	36	165.8
RHIC	62.4	73	165.3
RHIC	39.0	112	164.2
RHIC	27.0	156	162.6
RHIC	19.6	206	160.0
SPS	17.3	229	158.6
RHIC	14.5	262	156.2
SPS	12.4	299	153.1
RHIC	11.5	316	151.6
SPS	8.8	383	144.4
RHIC	7.7	422	139.6
SPS	7.7	422	139.6
SPS	6.4	476	131.7
RHIC	4.9	562	118
AGS	4.7	573	114.6
RHIC	4.5	589	111
AGS	4.3	602	108.8
RHIC	3.9	633	101
AGS	3.8	638	100.6
RHIC	3.5	666	93
AGS	3.3	686	88.9
RHIC	3.0	721	76
AGS	2.7	752	70.4
SIS	2.3	799	55.8

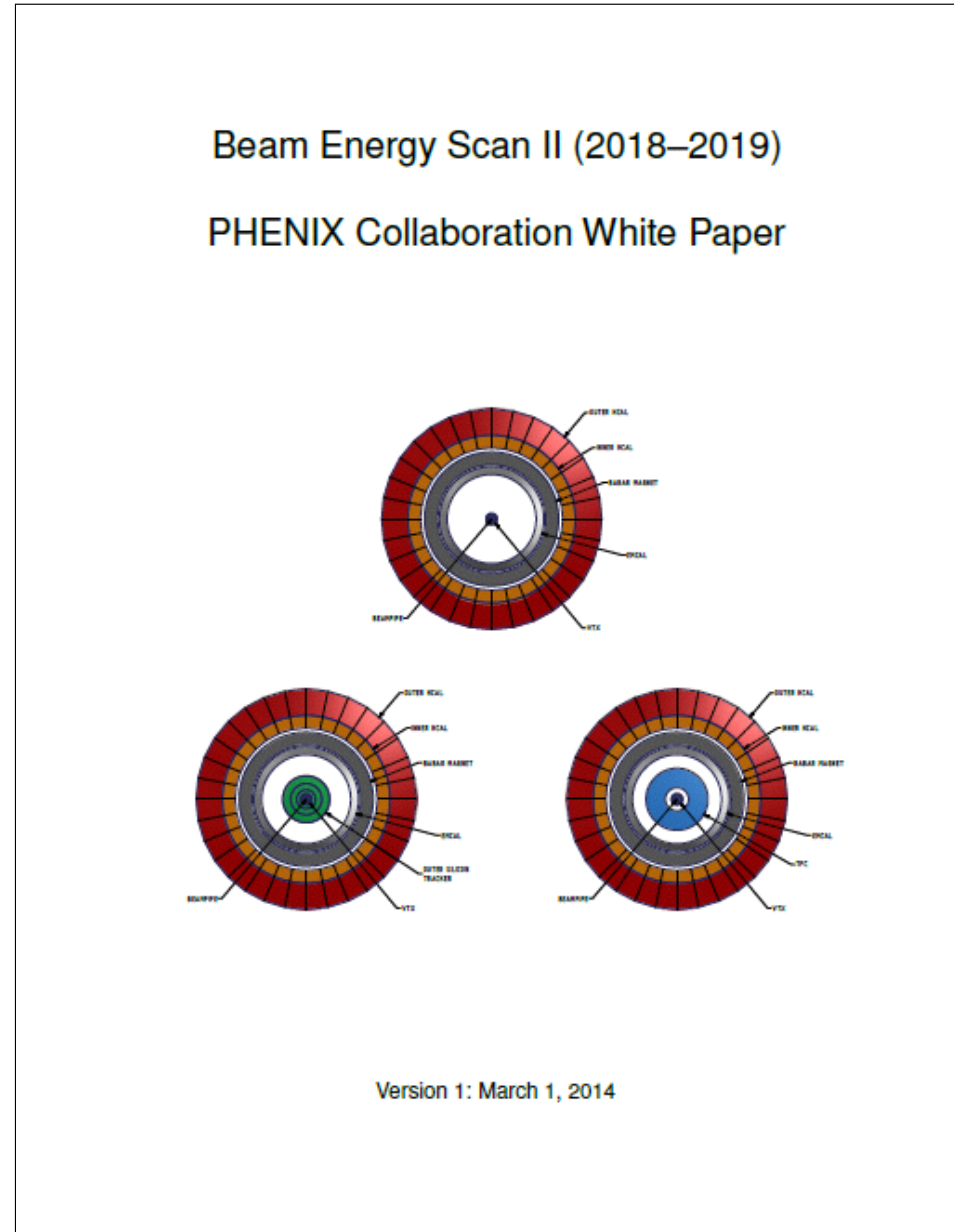
* PRC73 (2006) 34905

Beam Energy Scan II

2019 - 2020

STAR and PHENIX BES II White Papers

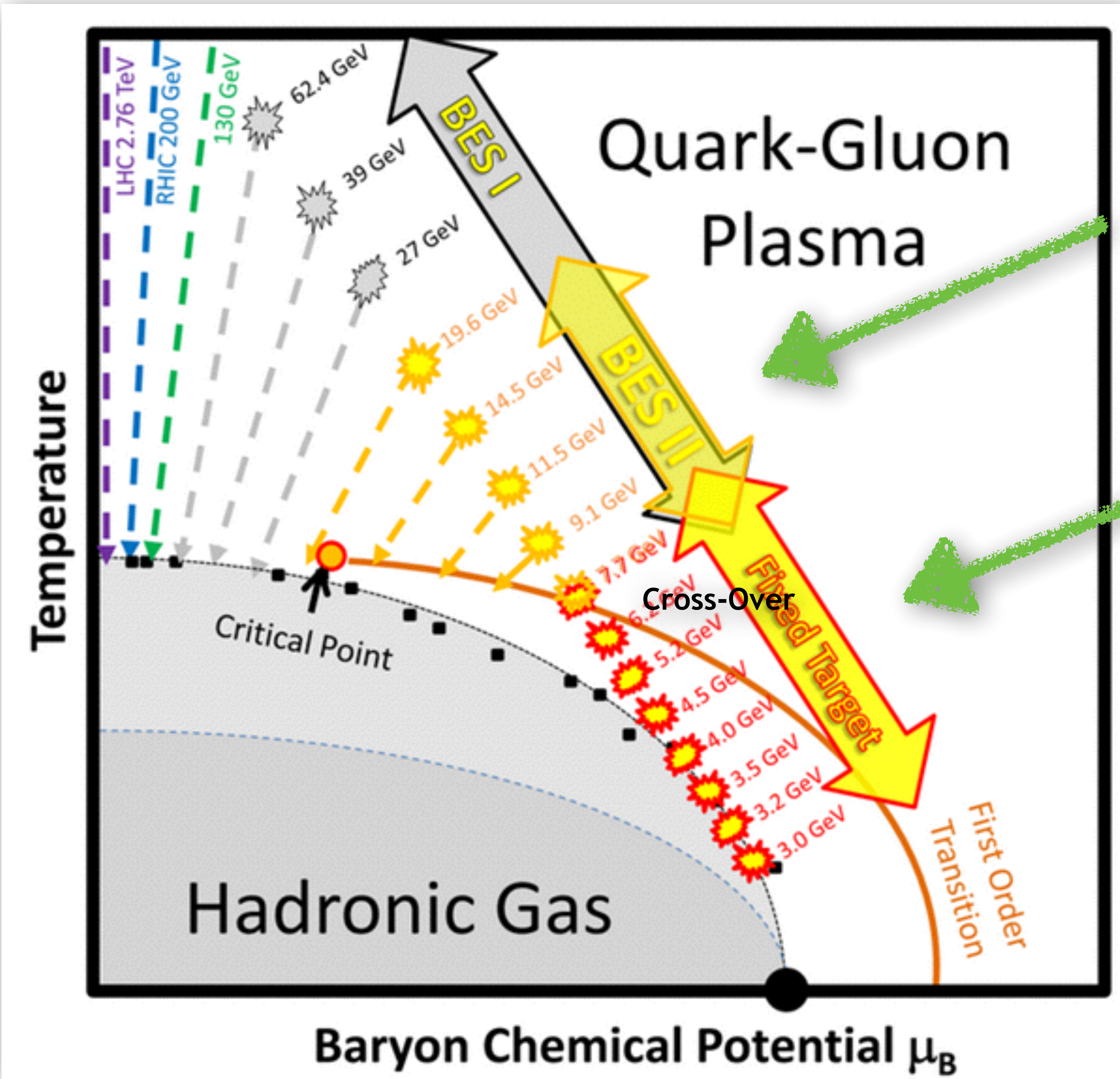


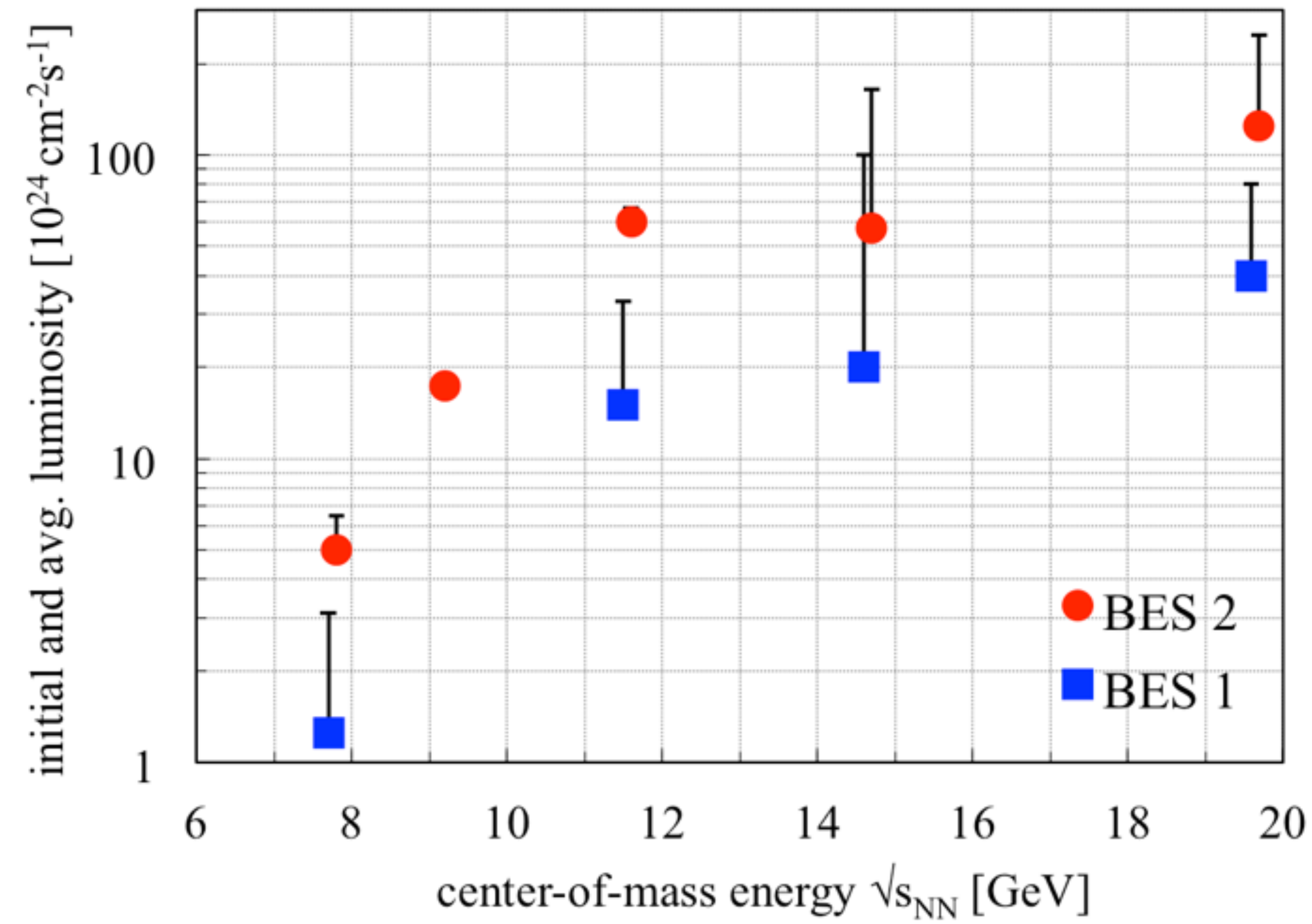

Beam Energy Scan II (2018–2019)

PHENIX Collaboration White Paper

Version 1: March 1, 2014

The Beam Energy Scan (BES) II





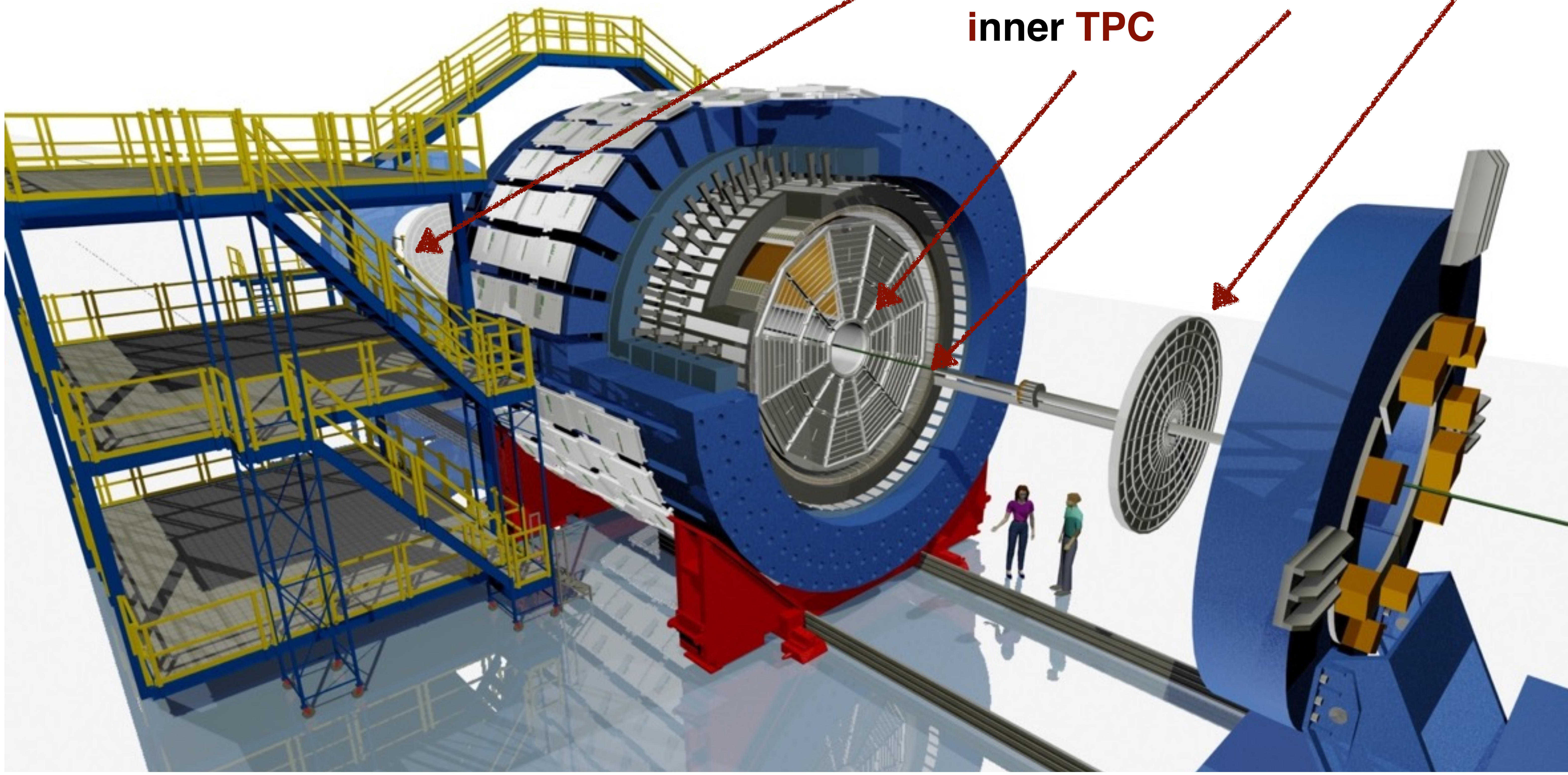
RHIC Upgrade:
Use Low Energy Electron Cooling

BES II Proposal

Planned for two 24 cryo-week runs in 2019 and 2020

$\sqrt{S_{NN}}$ (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV)	420	370	315	250	205
BES I (MEvts)	4.3	---	11.7	24	36
Rate(MEvts/day)	0.25		1.7	2.4	4.5
BES I L ($1\times10^{25}/cm^2sec$)	0.13		1.5	2.1	4.0
BES II (MEvts)	100	160	230	300	400
eCooling (Factor)	4	4	4	3	3
Beam Time (weeks)	**12**	**9.5**	**5.0**	**5.5**	**4.5**

Plans for STAR Upgrade
(2019-2020)

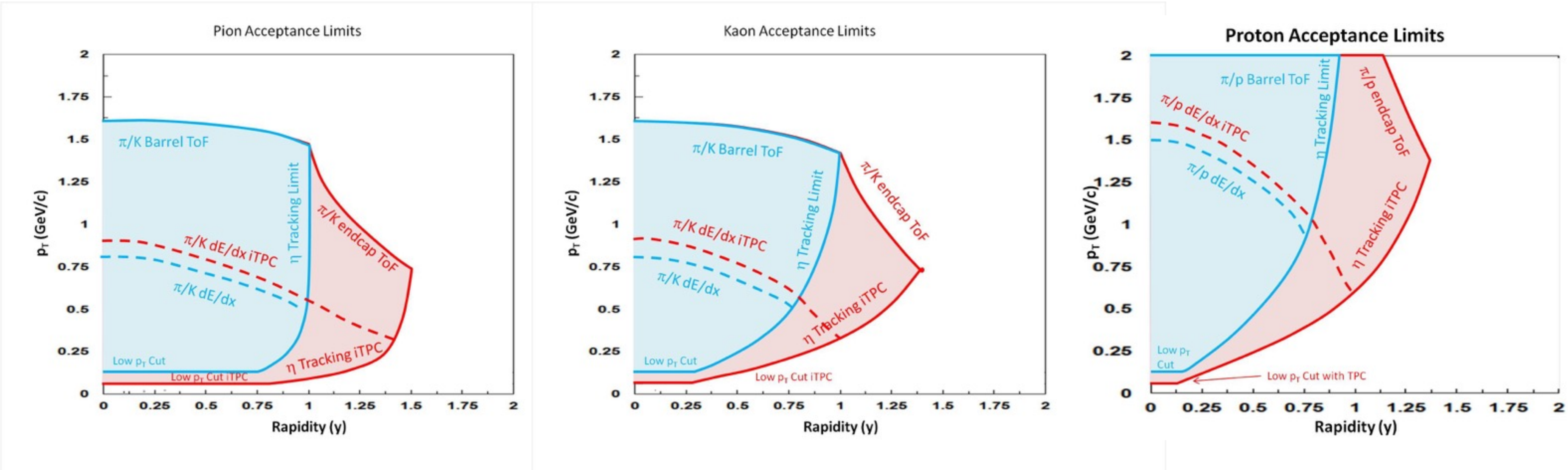


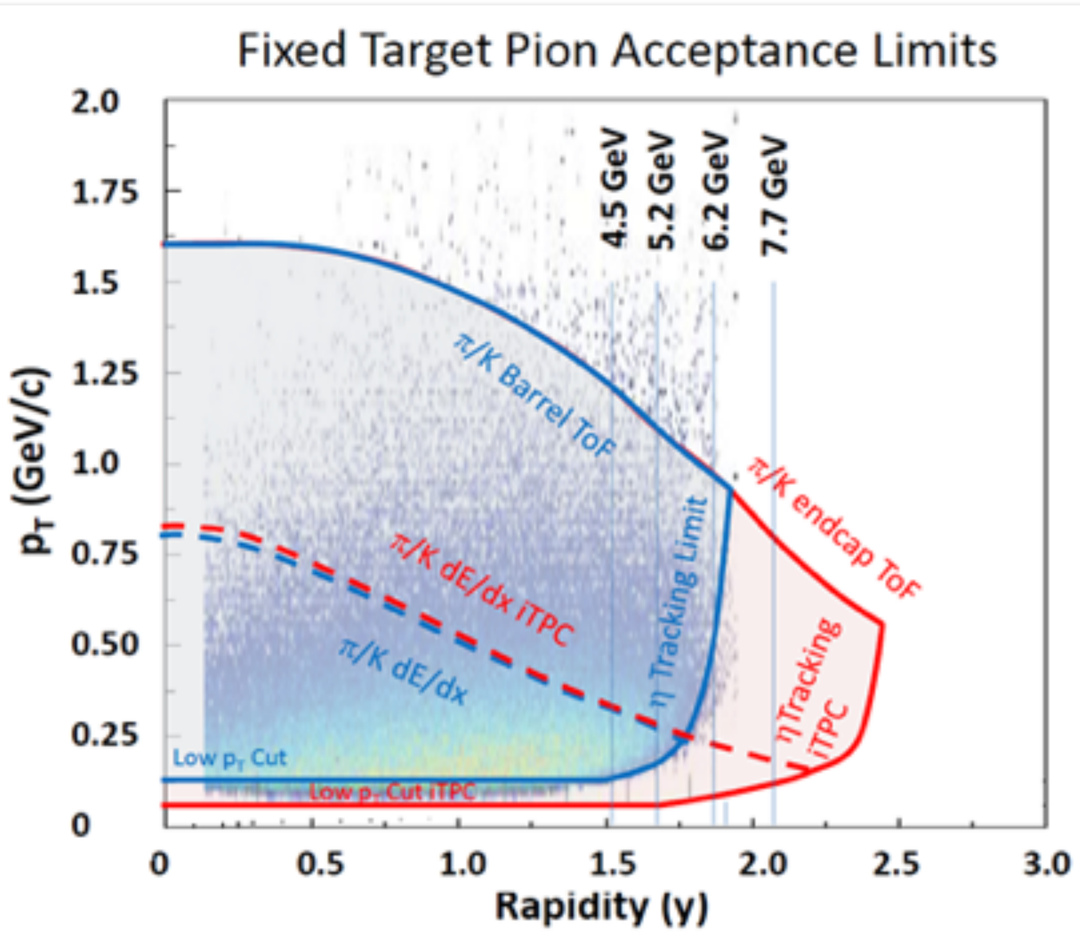
iTPC Upgrade
Replace aging wires
Full pad coverage
→ better dE/dx
$-1.5 < \eta < 1.5$
$p_T > 60$ MeV/c

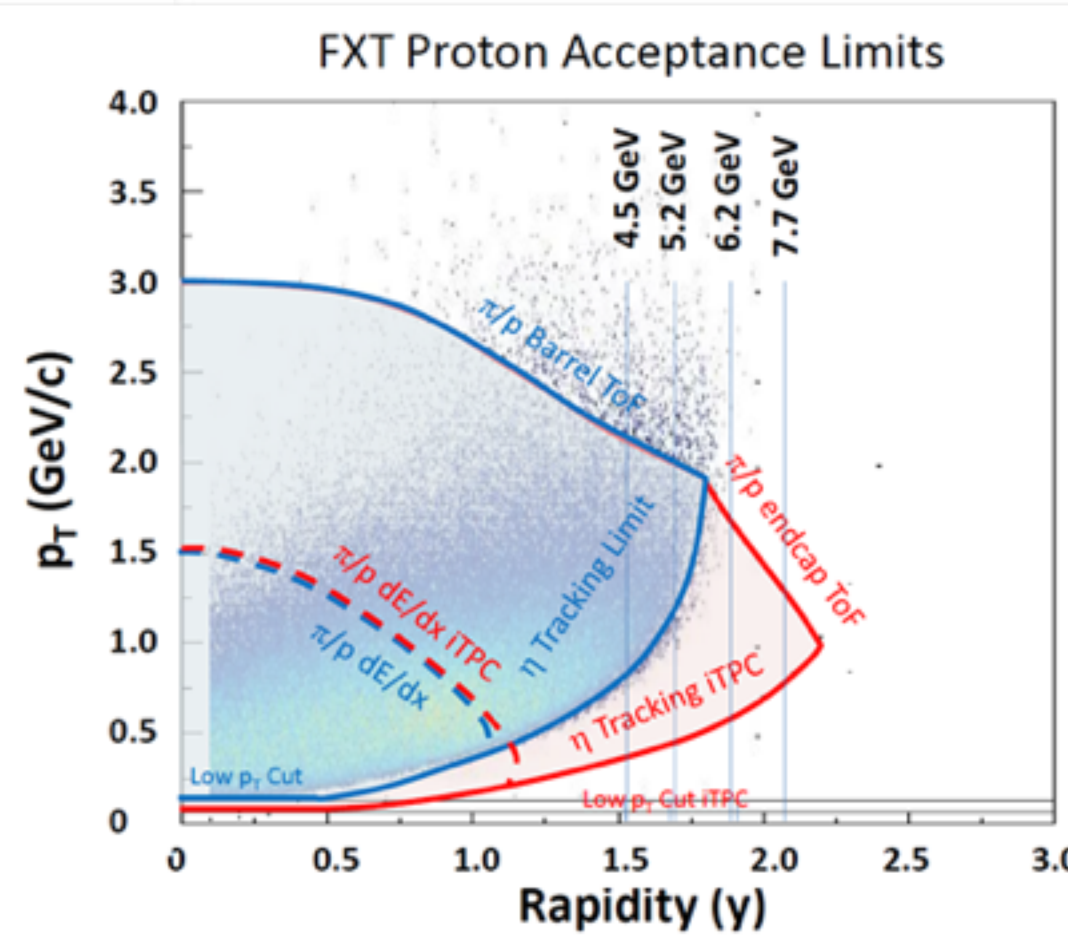
EPD Upgrade
Replaces aging BBC
Event centrality
→ Suppress auto-correlation
Better trigger & b/g reduction
$-4.5 < \eta < -1.8$, $1.8 < \eta < 4.5$

eTOF
Larger rapidity coverage
Extends PID in forward direction
$1.05 < \eta < 1.5$

STAR acceptance improvements

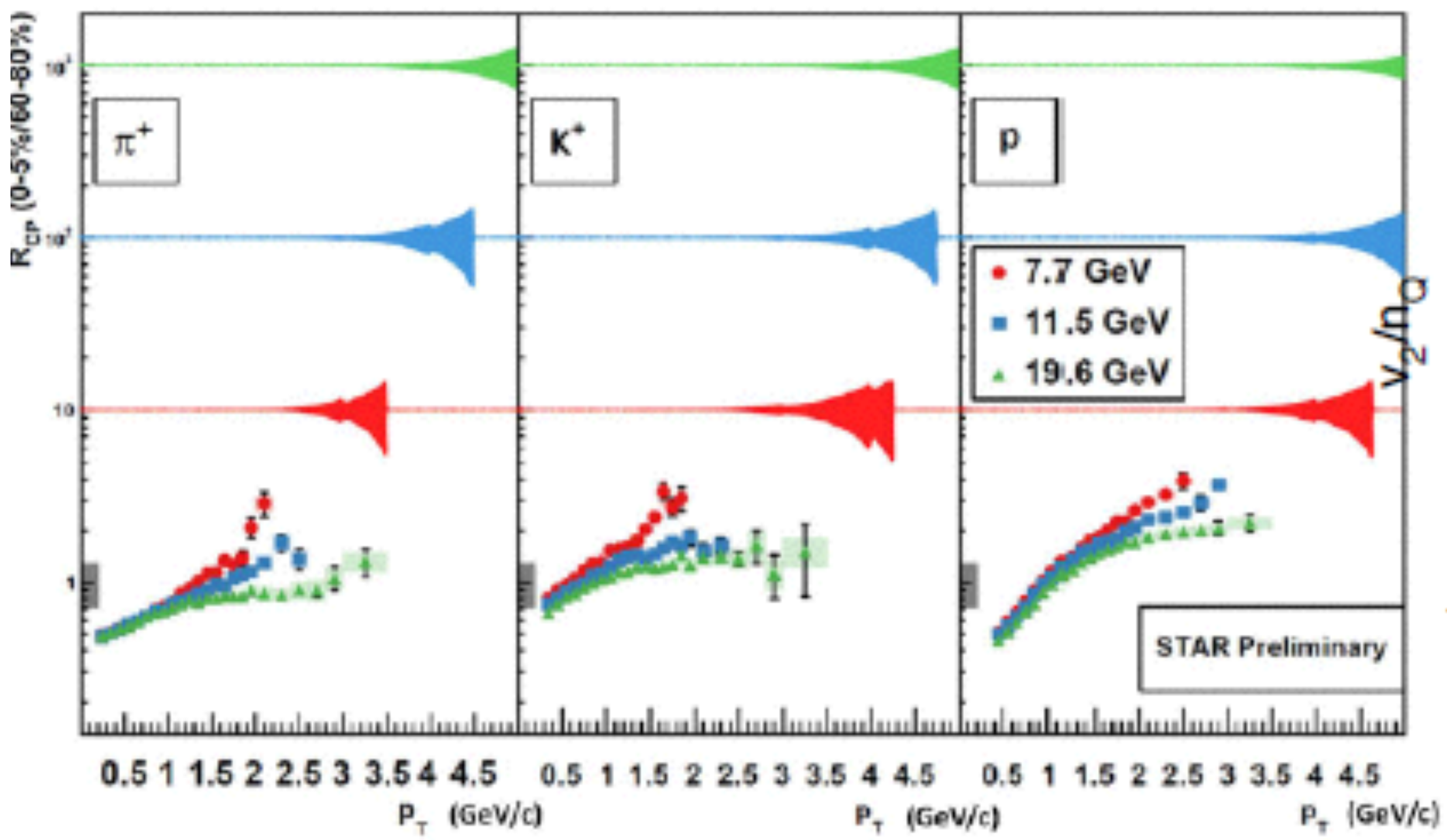


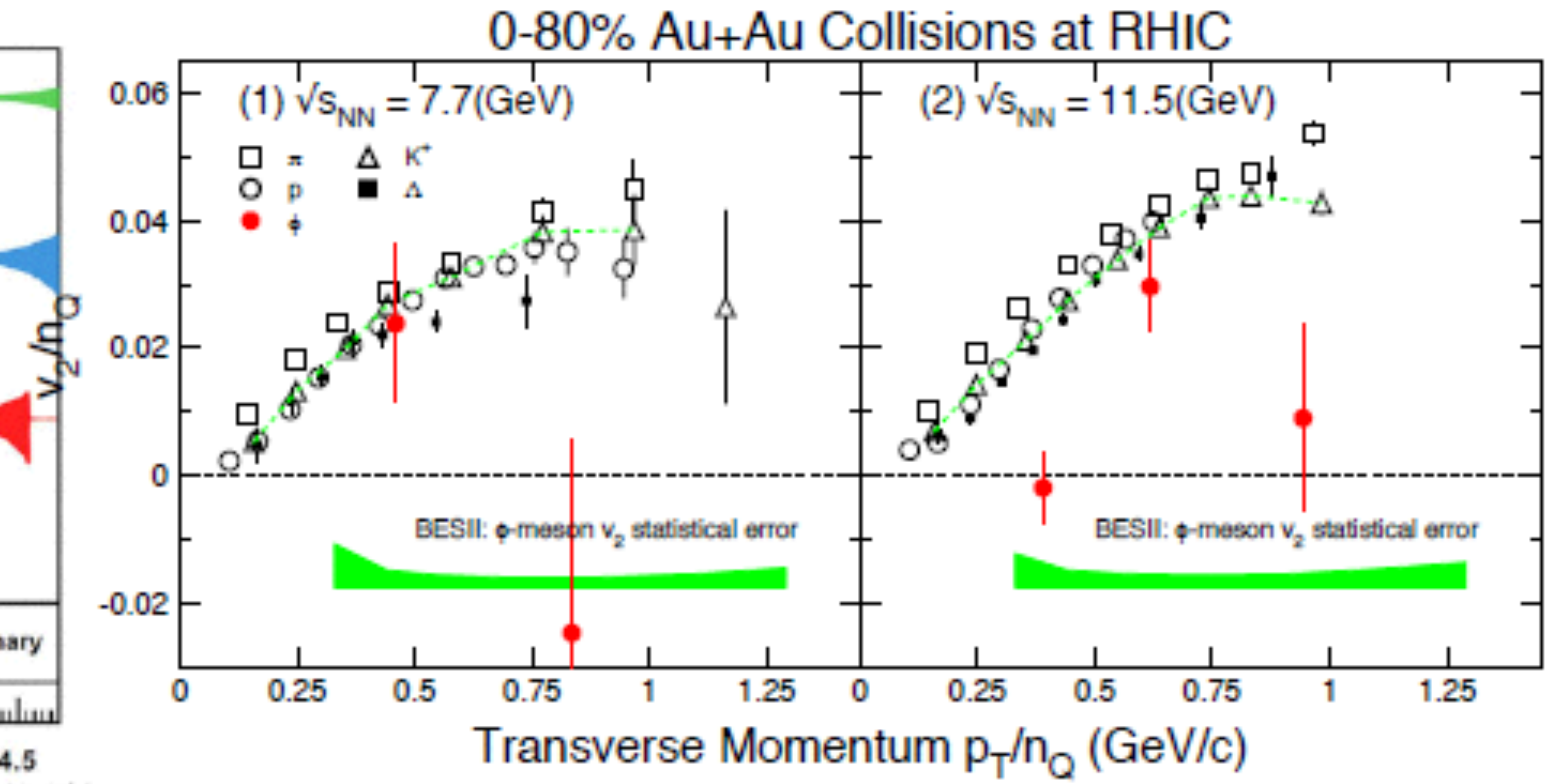


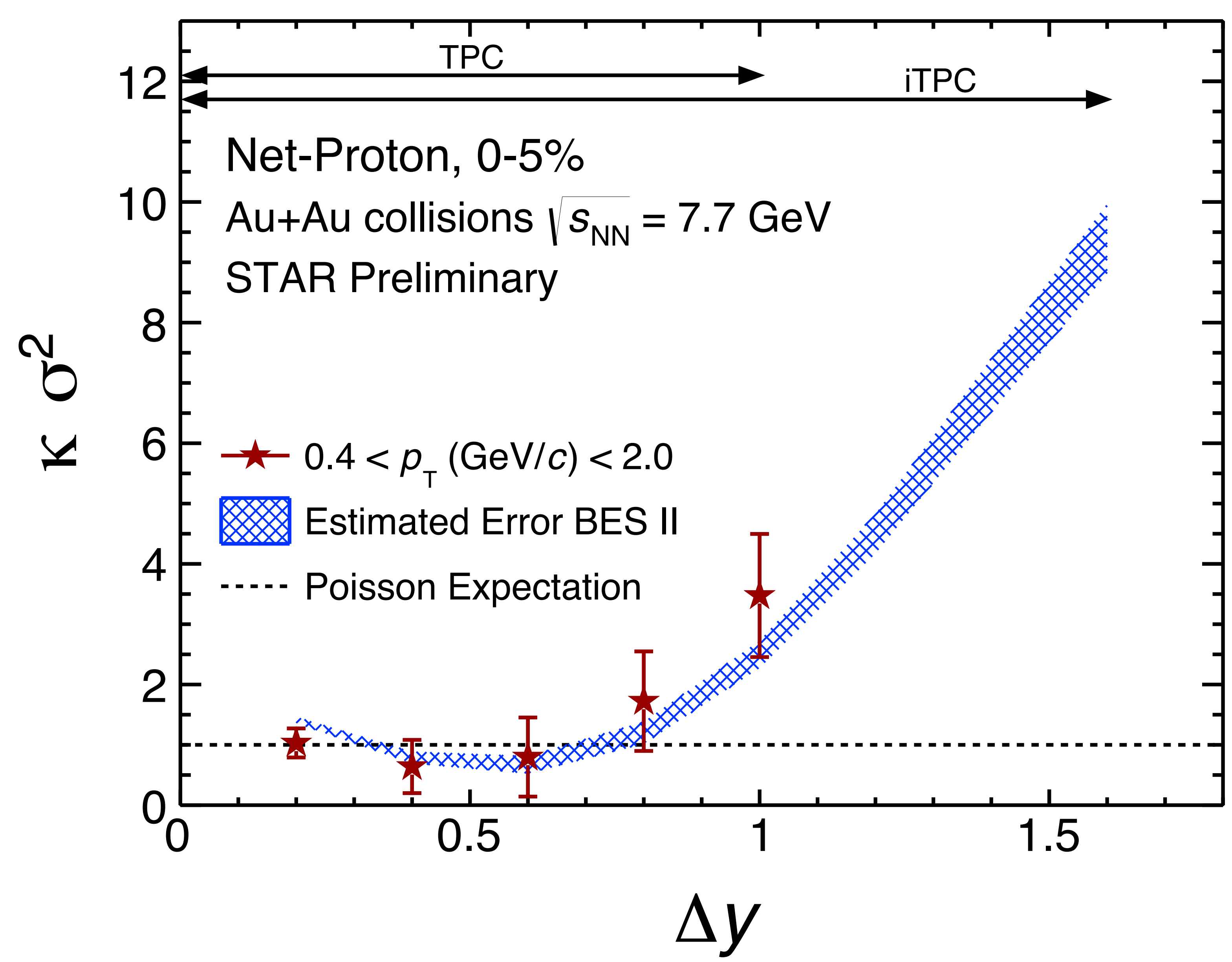


Fixed Target Program
may reach up to 7.7 GeV

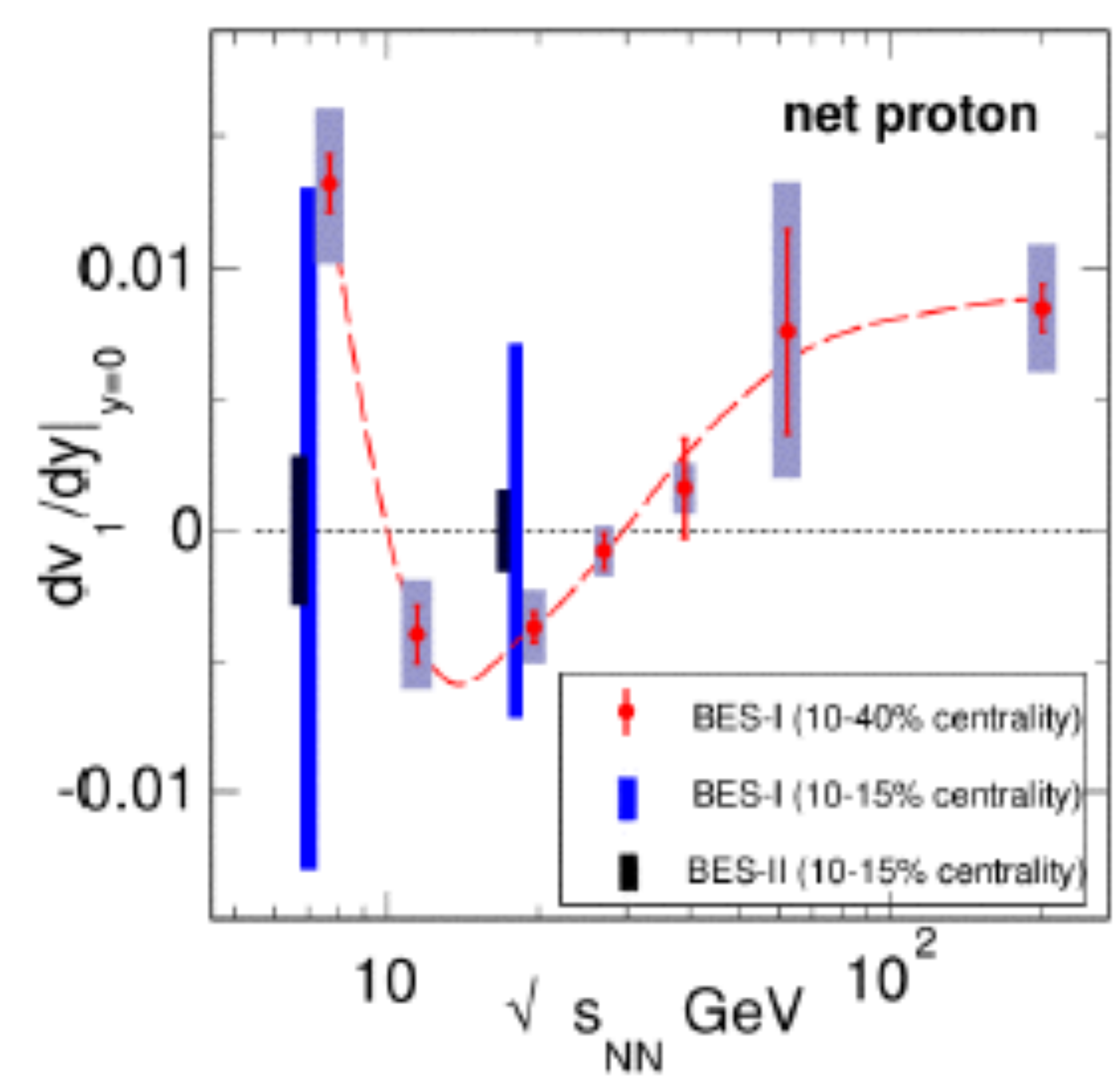
STAR statistics improvements







Larger rapidity acceptance crucial for further critical point search with net-protons



Outlook / Conclusion

- BES I told us the **regions of interest**
- **Fixed-target** program will **extend** reach of BES program
- Collider upgrades improve luminosity
- Detector upgrades extend physics reach
- The focused and improved studies of **BES II** will allow us to define the energy of the onset of deconfinement and allow us to characterize the **phases and transitions of QCD matter**


Thank you !!