14. Zimányi
WINTER SCHOOL ON HEAVY ION PHYSICS
Dec. 1. - Dec. 5., Budapest, Hungary

Recent STAR results from the RHIC Beam Energy Scan program

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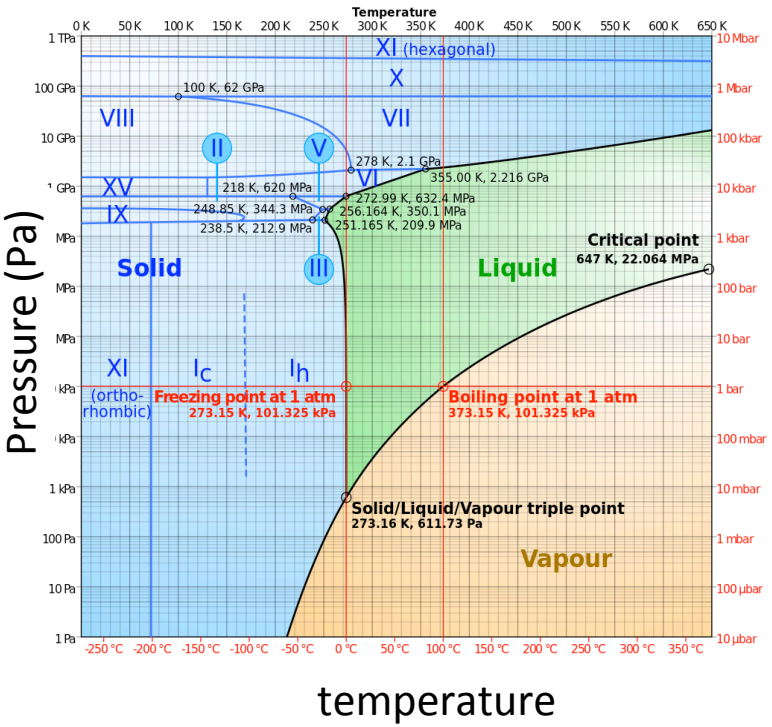
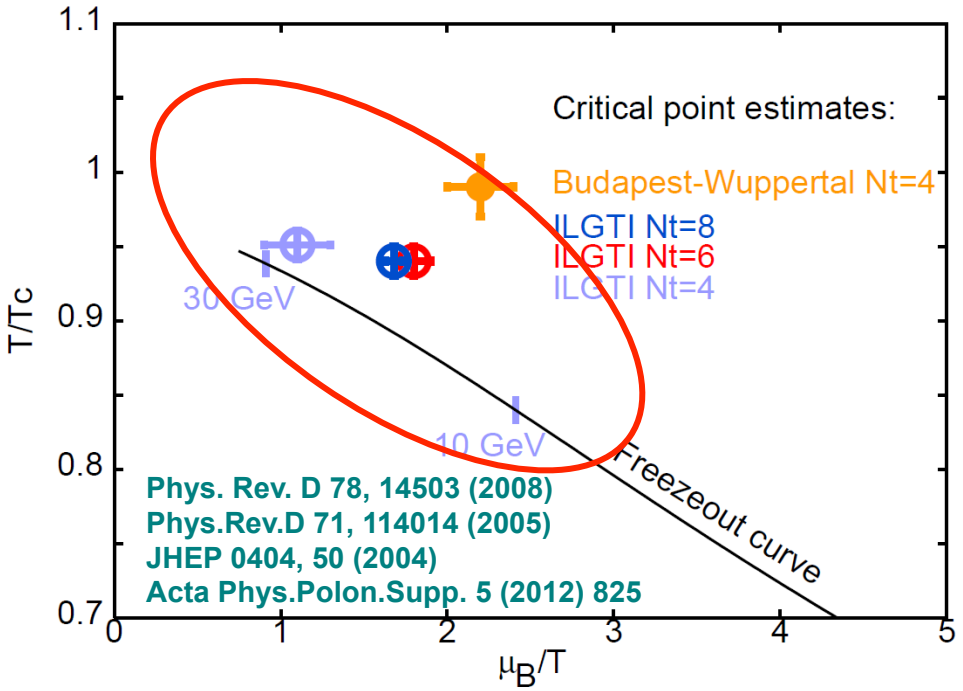
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Motivation

- Experimental exploration of the **QCD phase diagram**
- Theory: Critical point may be around $10<\sqrt{s_{NN}}<30$ GeV
- Vary T, μ_B by setting different **collision energy**, species
- **RHIC:** access to a wide range with the same apparatus





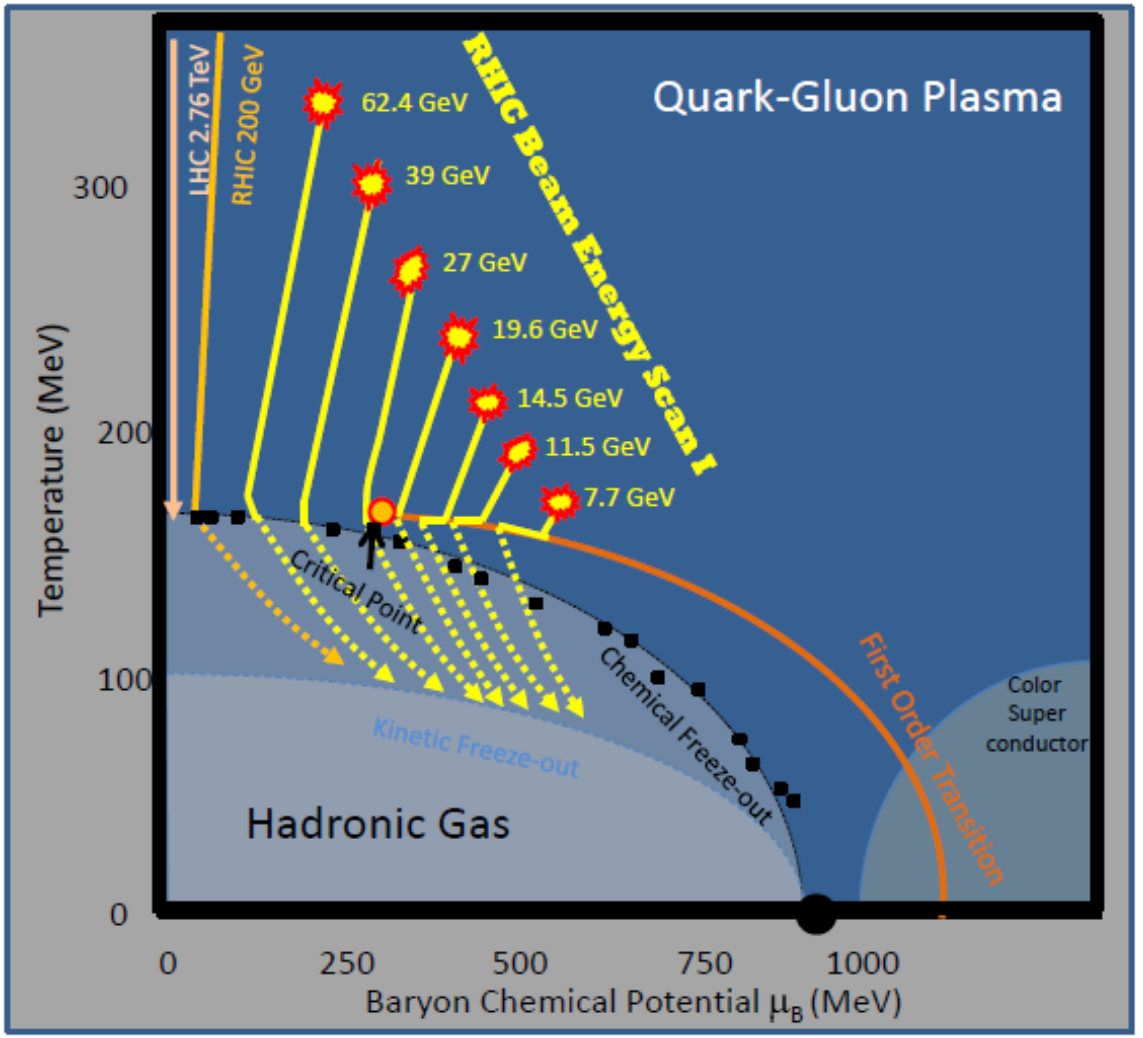
Exploring the QCD phase diagram

Find…

1) Turn-off of sQGP signatures

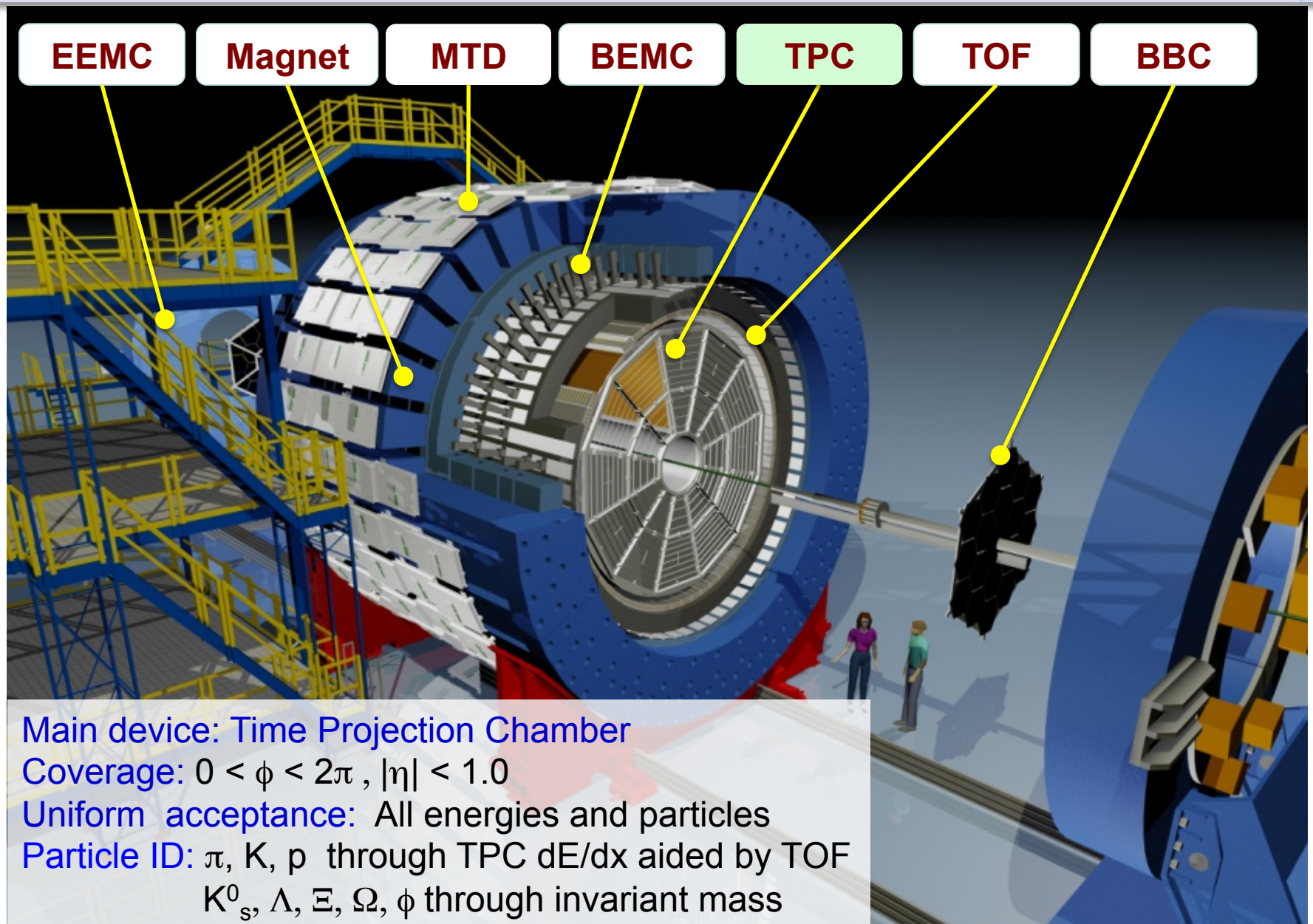
2) 1st order phase transition signs

3) The QCD critical point



http://arxiv.org/abs/1007.2613

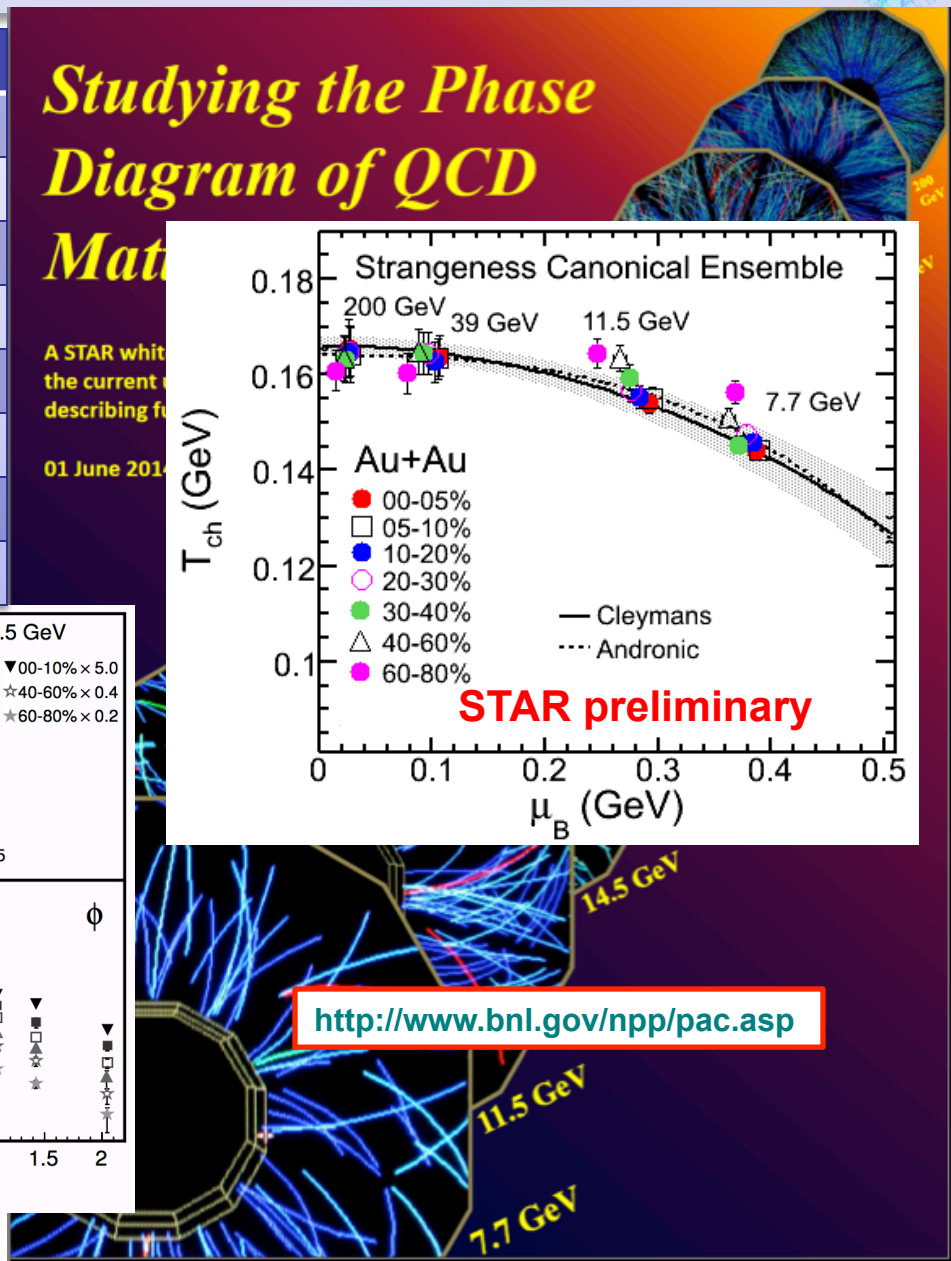
STAR at RHIC

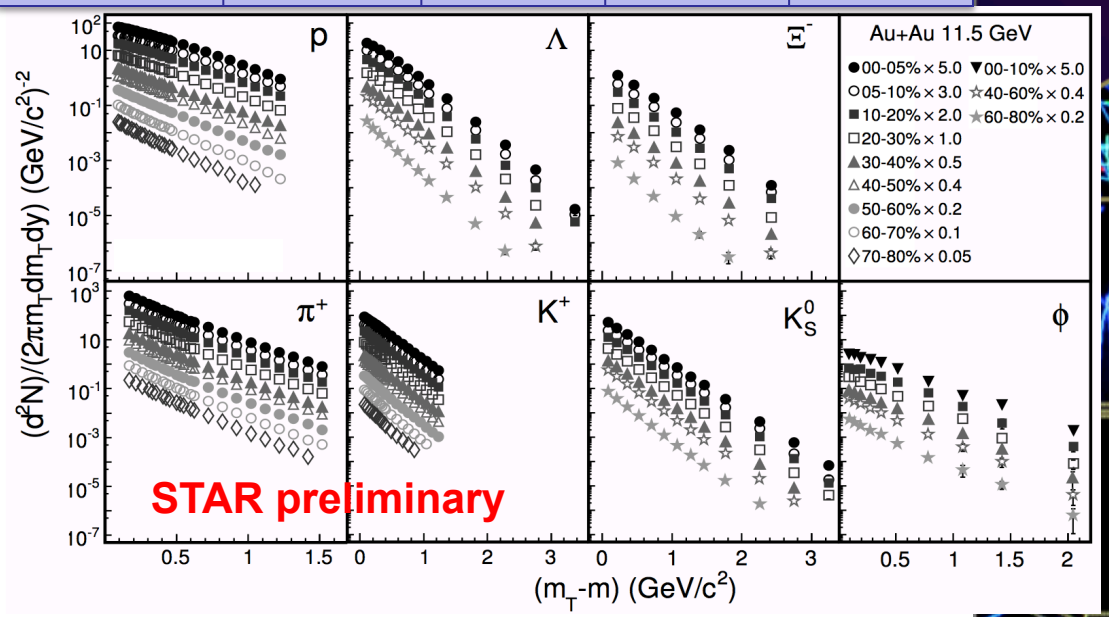


Main device: Time Projection Chamber
Coverage: $0 < \phi < 2\pi$, $|\eta| < 1.0$
Uniform acceptance: All energies and particles
Particle ID: π, K, p through TPC dE/dx aided by TOF
K^0_s, Λ, Ξ, Ω, ϕ through invariant mass

STAR BES-I

$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	#Events	#Weeks	Year
200	20	350 M	11	2010
62.4	70	67 M	1.5	2010
39.0	115	130 M	2	2010
27.0	155	70 M	1	2011
19.6	205	36 M	1.5	2011
14.5	260	20 M	3	2014
11.5	315	12 M	2	2010
7.7	420	4 M	4	2010





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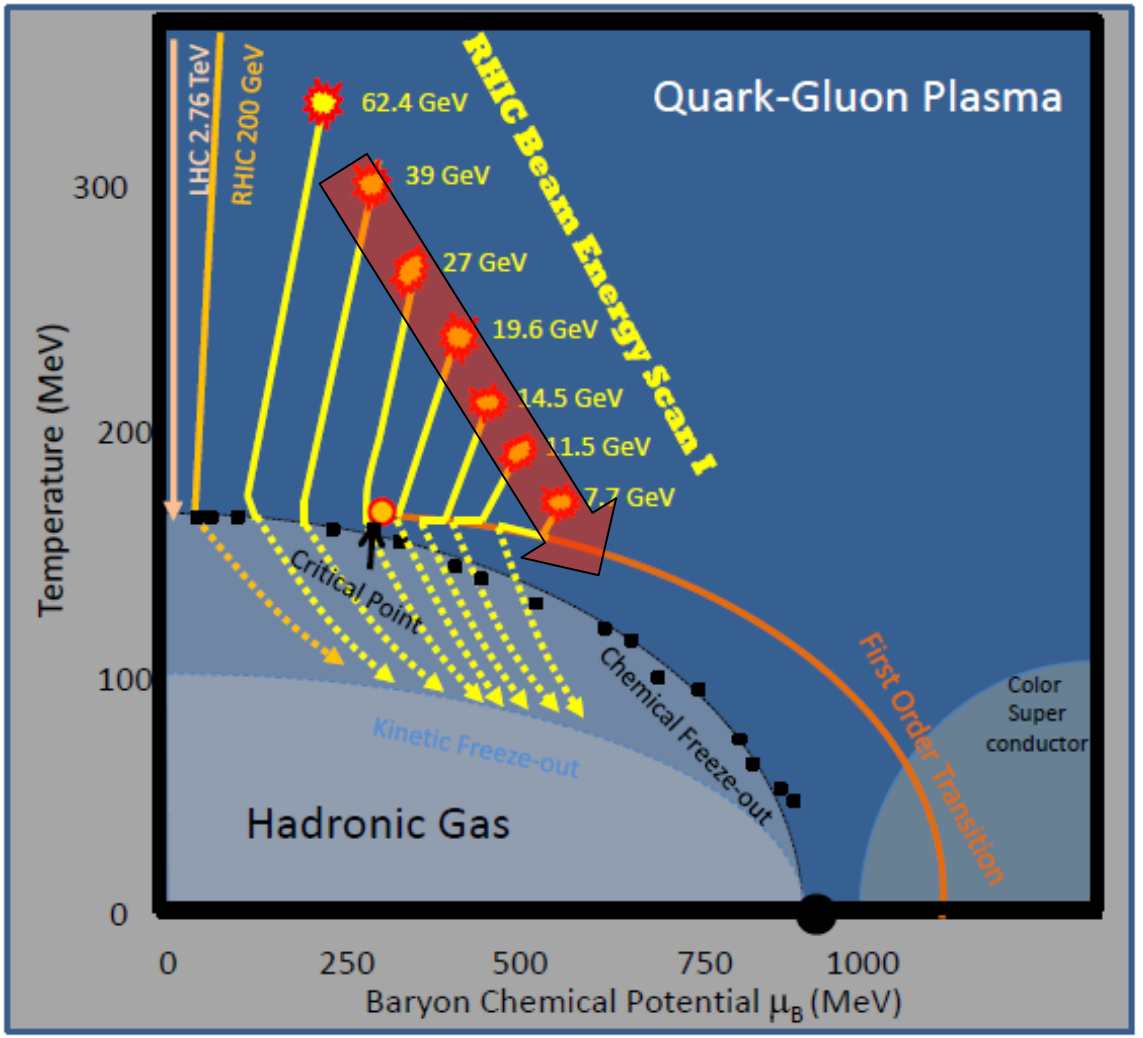

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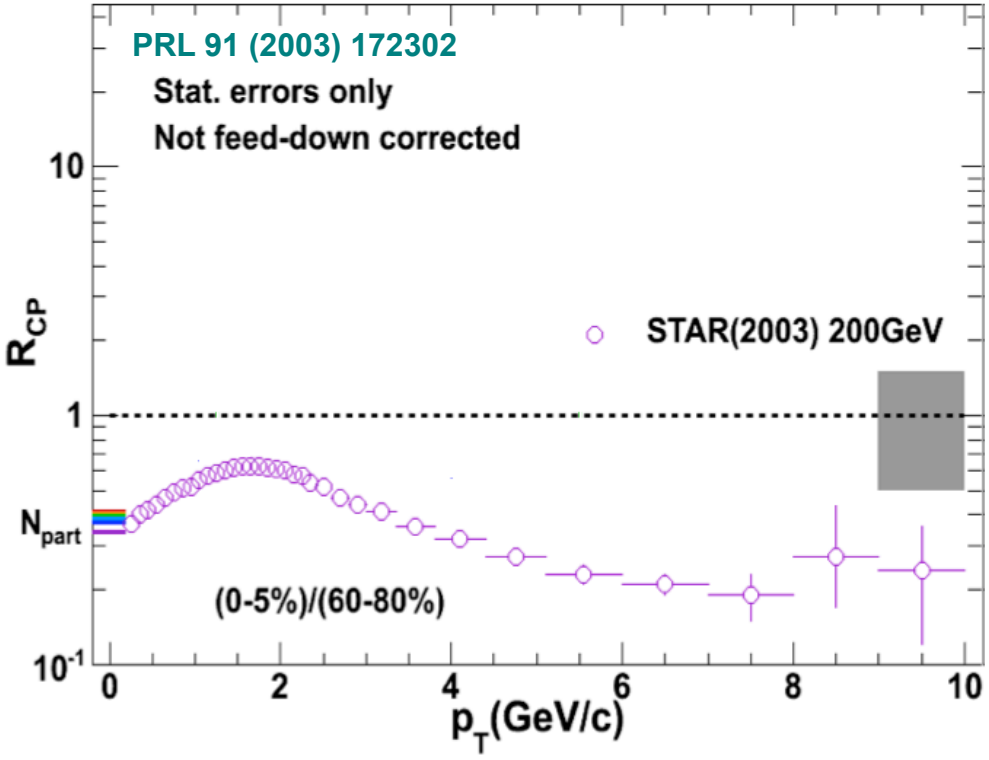
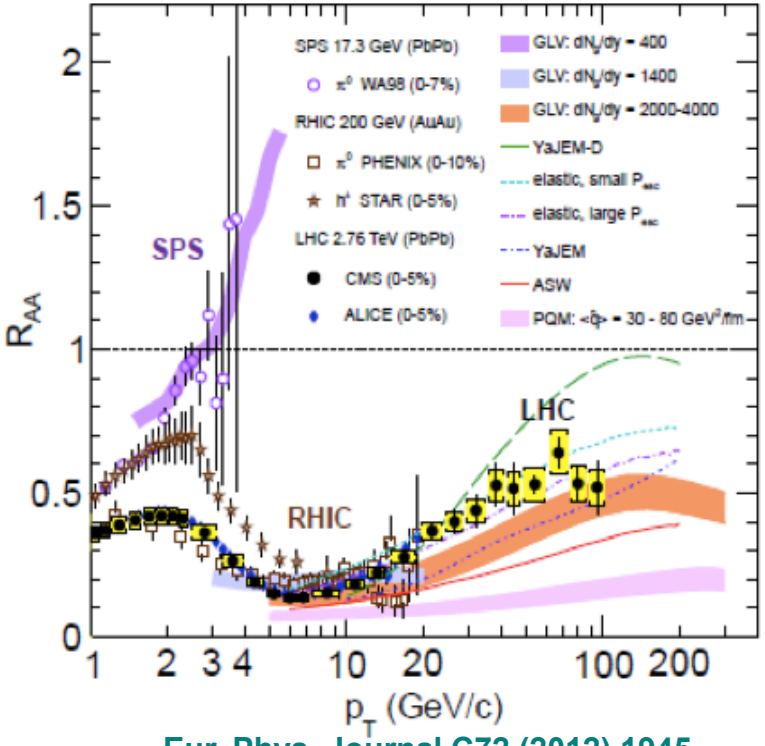
Suppression of high-p_T hadrons

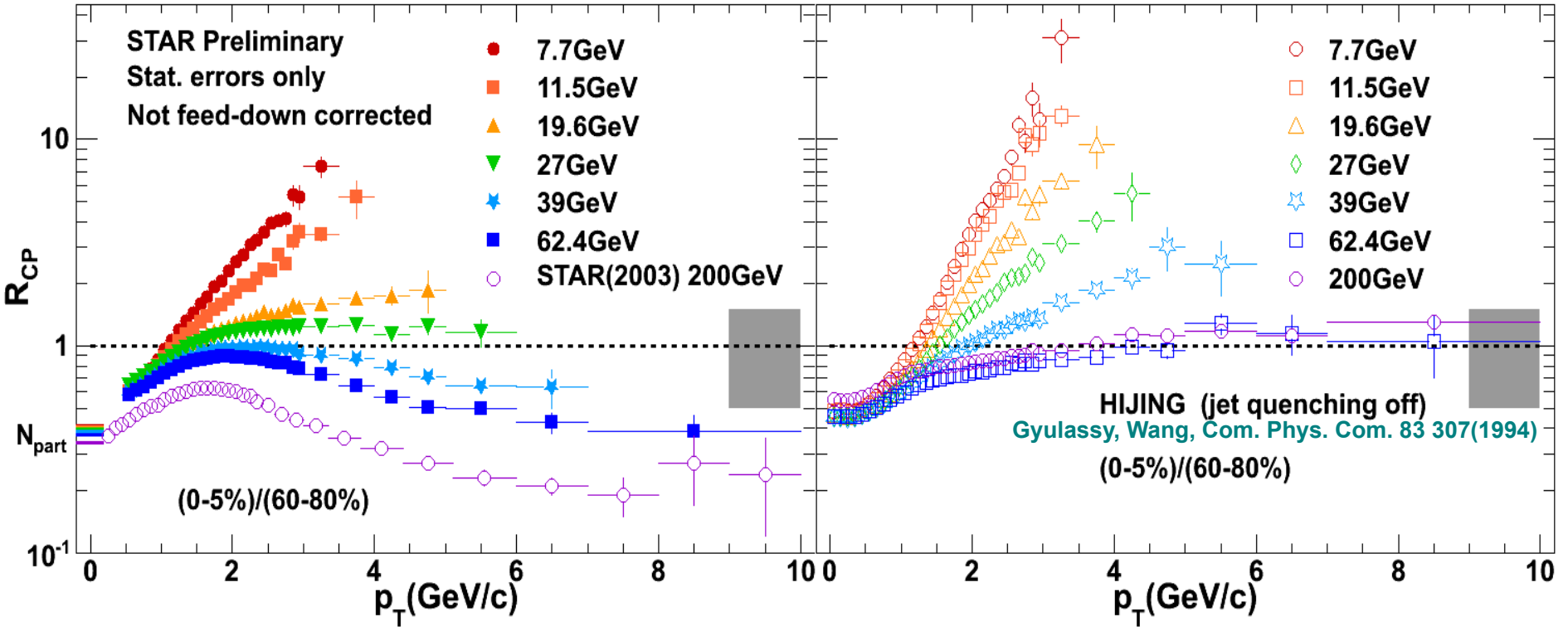




Eur. Phys. Journal C72 (2012) 1945

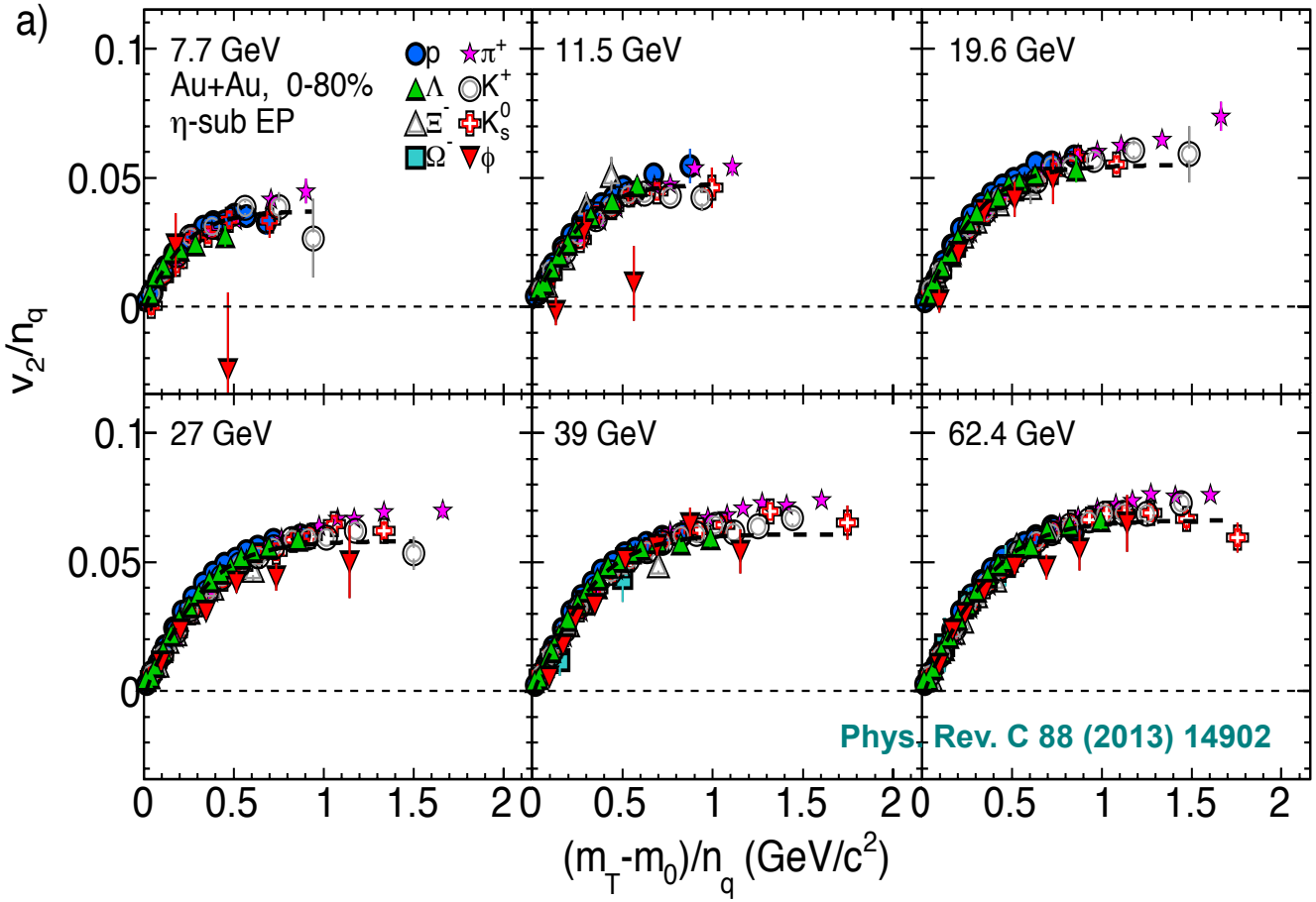
- Strong suppression in 200 GeV Au+Au collisions
- Present also in 2.76 TeV Pb+Pb collisions at LHC

Suppression of high-p_T hadrons



- Strong suppression in 200 GeV Au+Au collisions
- Present from 39 GeV to 2.76 TeV
- Enhancement at low energies
- Understanding: Cronin effect

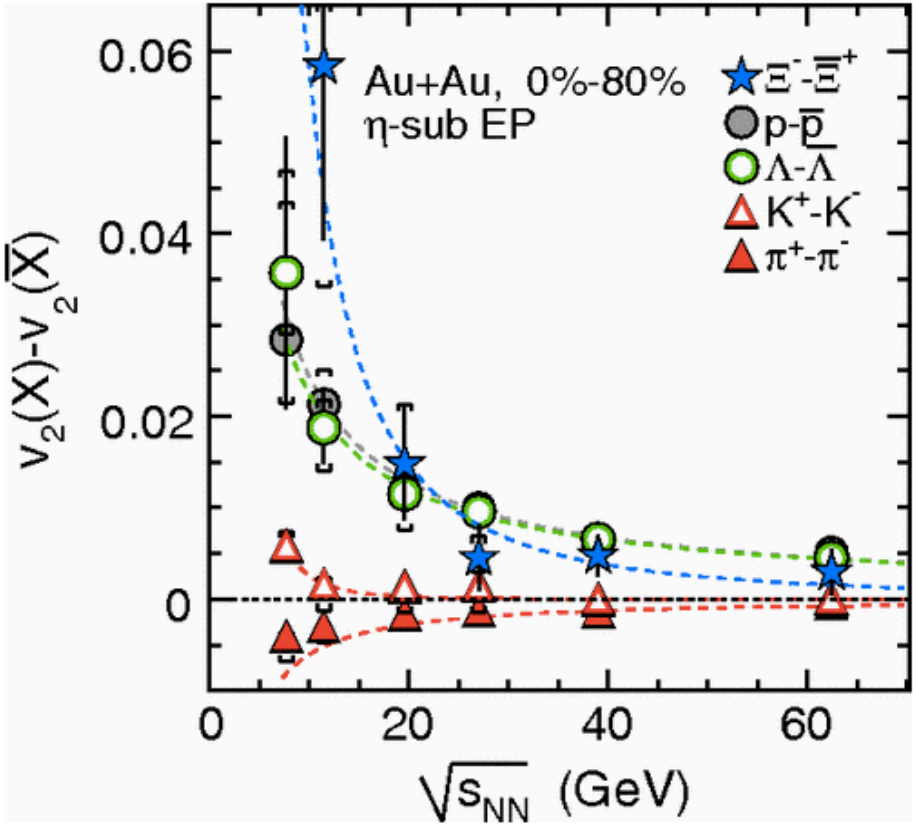
Elliptic flow (v_2) – particles



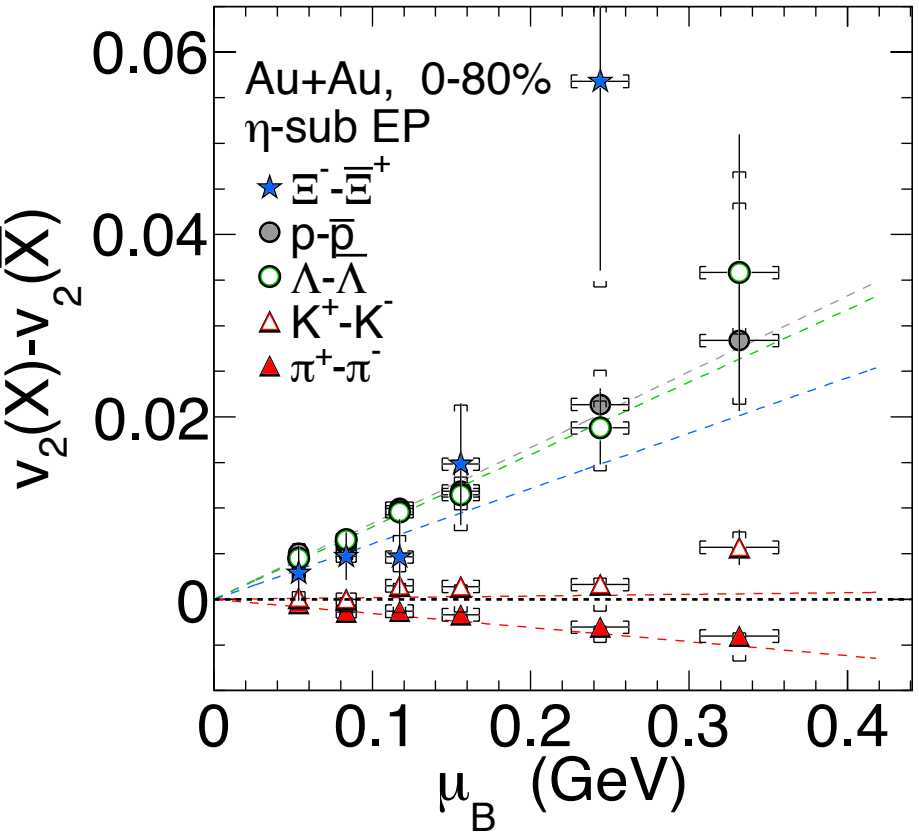
- Approximate NCQ scaling holds… DOF=quarks?
- Exception: ϕ at 7.7 and 11.5 GeV
  - deviation ~2σ – more statistics needed

v_2 particle – antiparticle

Phys.Rev.Lett. 110 (2013) 142301



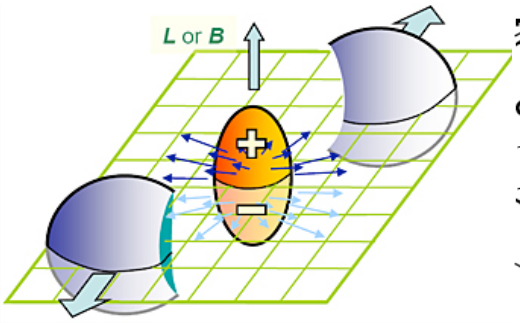
Phys. Rev. C 88 (2013) 14902



- Substantial particle-antiparticle split at lower $\sqrt{s_{NN}}$
- Linear dependence on the baryon chemical potential

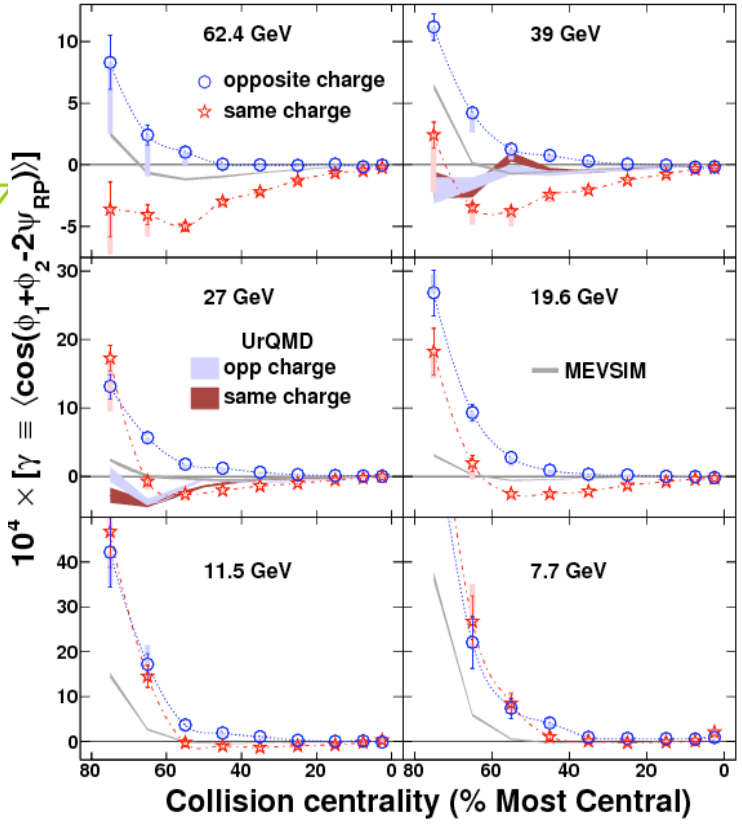
Chiral magnetic effect

- QCD allows for local parity violation in sQGP
- Possible signatures:

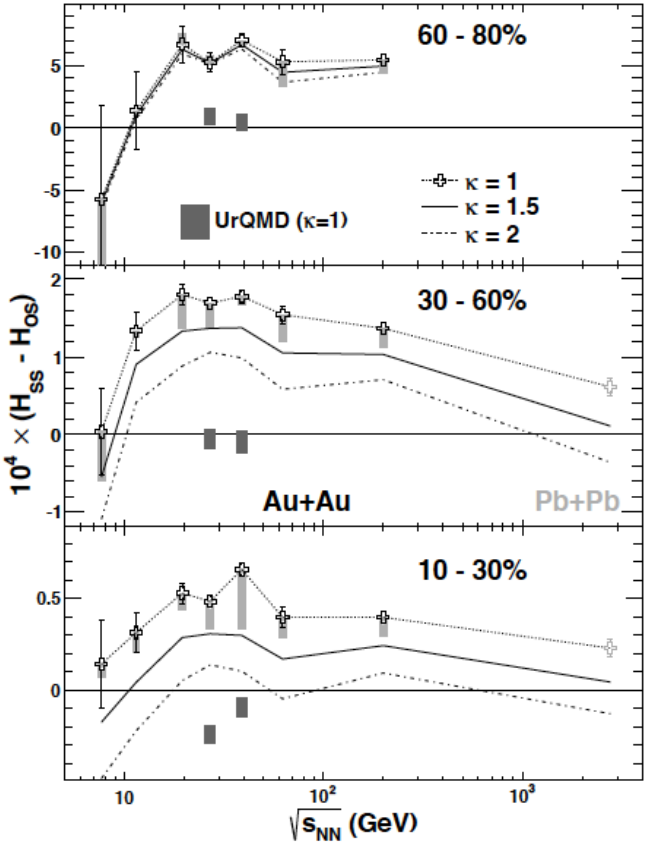


Phys.Rev.Lett. 113, 052302 (2014)

1) Three-point correlator



2) Charge separation



- Drop of charge separation below 11.5 GeV consistent with expectations in a dominant hadronic phase

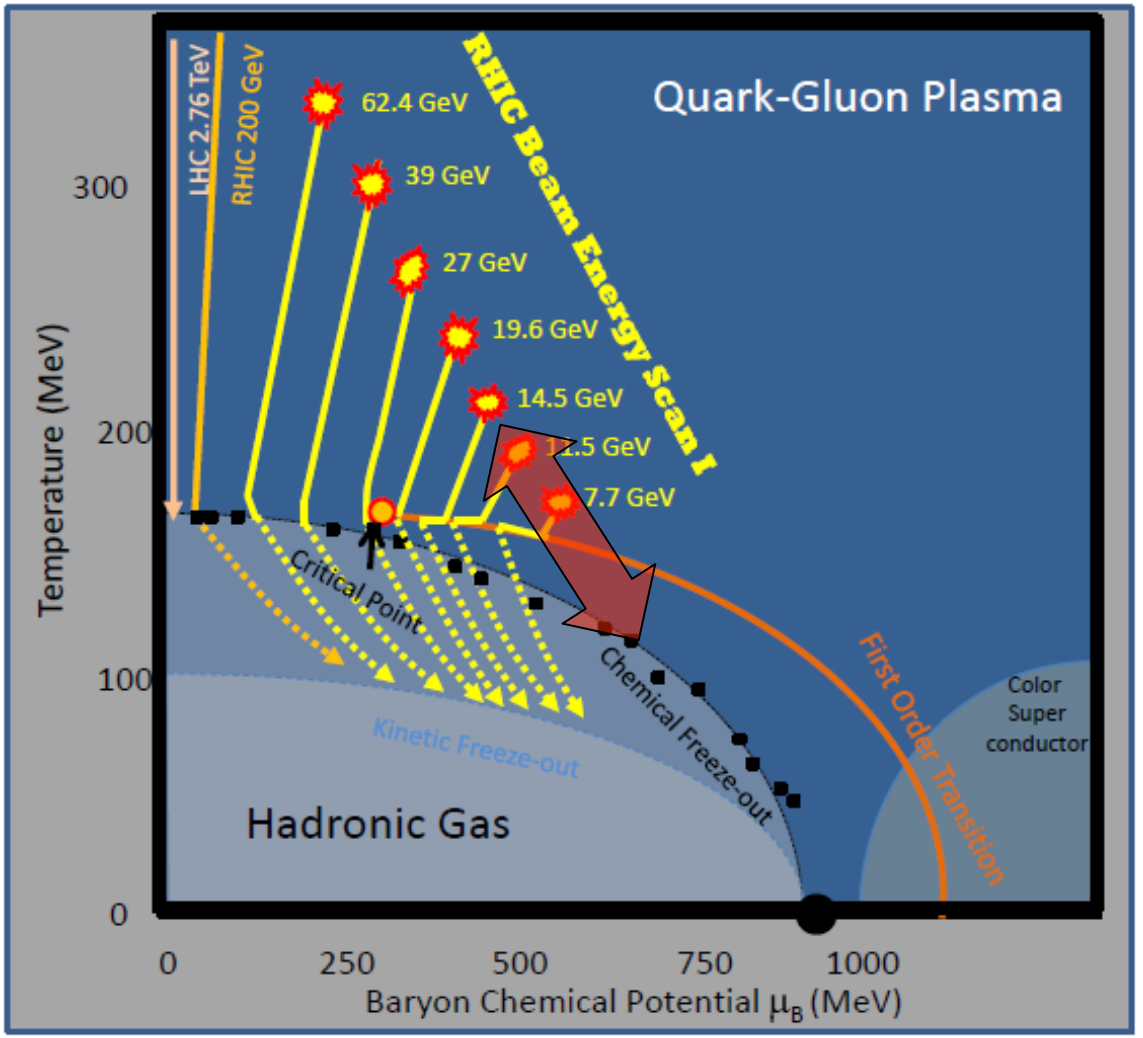
Exploring the QCD phase diagram

Find…

1) Turn-off of sQGP signatures

2) 1st order phase transition signs

3) The QCD critical point



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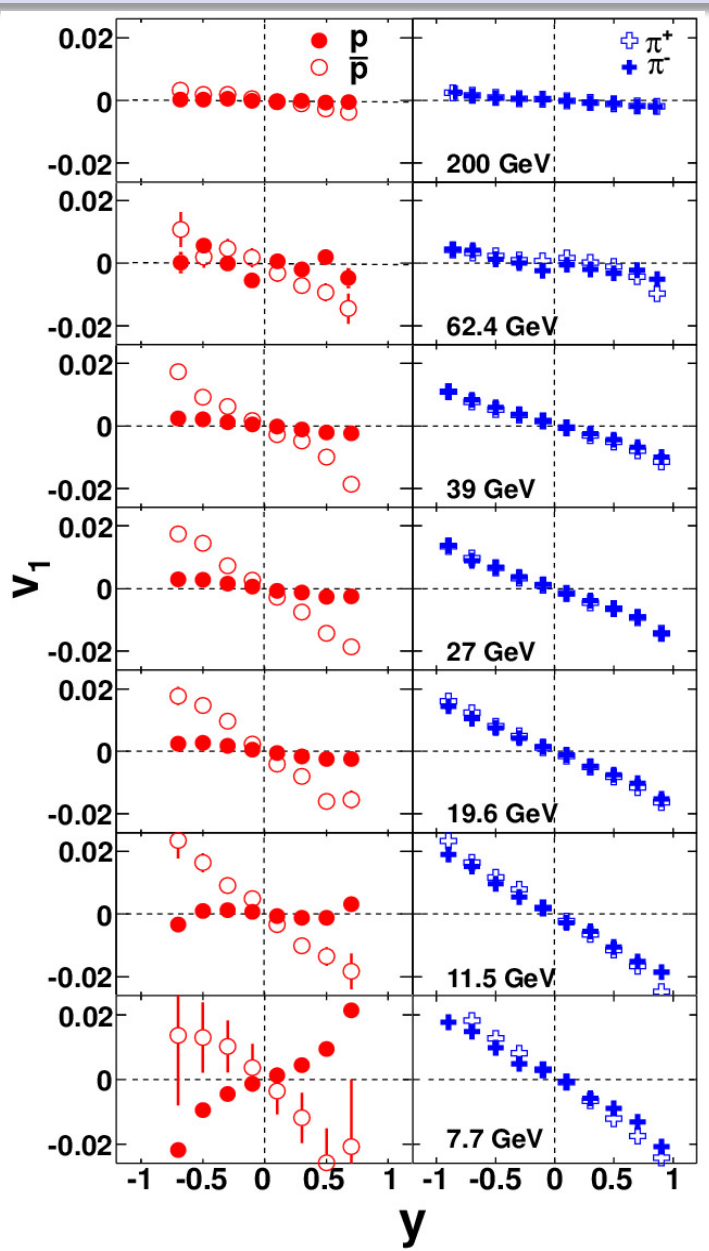
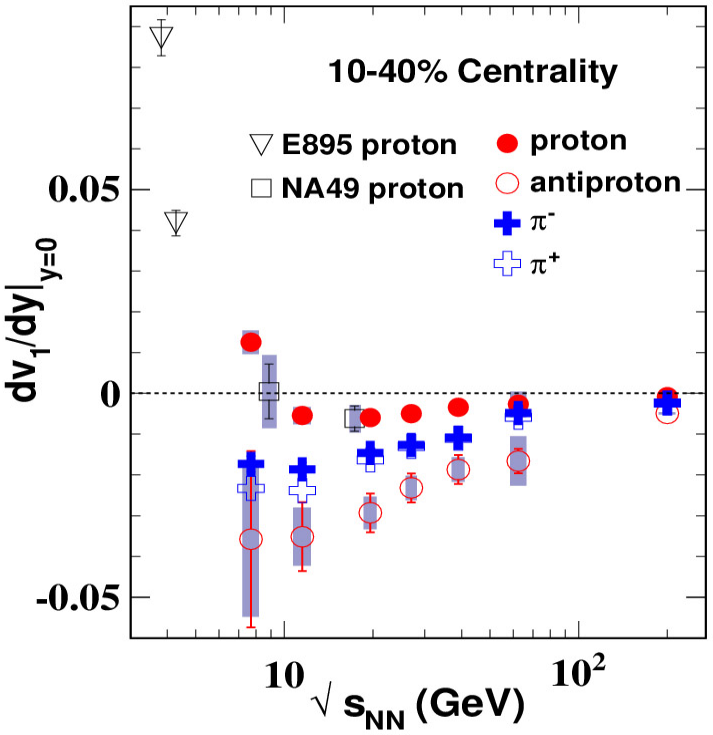
Directed flow (v_1)



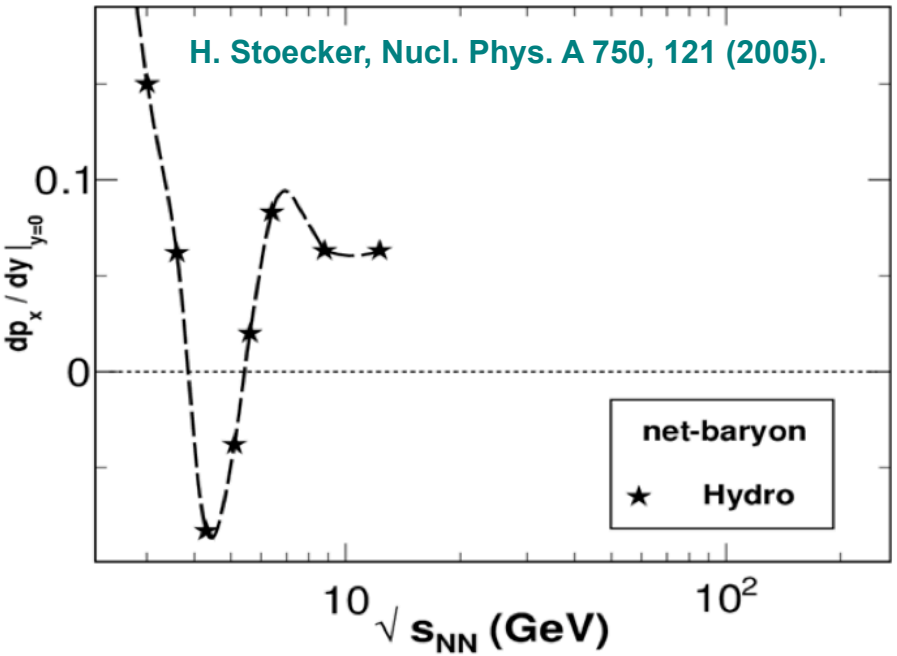
Phys. Rev. Lett. 112, 162301 (2014)



- Opposite charge pions follow the same trend
- Protons-antiprotons are different
  → baryon number transport is important
- Proton v_1 slope changes sign

Net proton v_1 slope

- Net protons: double sign change
  - Simple hydro predicts structure
  - More sophisticated UrQMD fails
- Softening of EOS?
  - Expected in mixed phase



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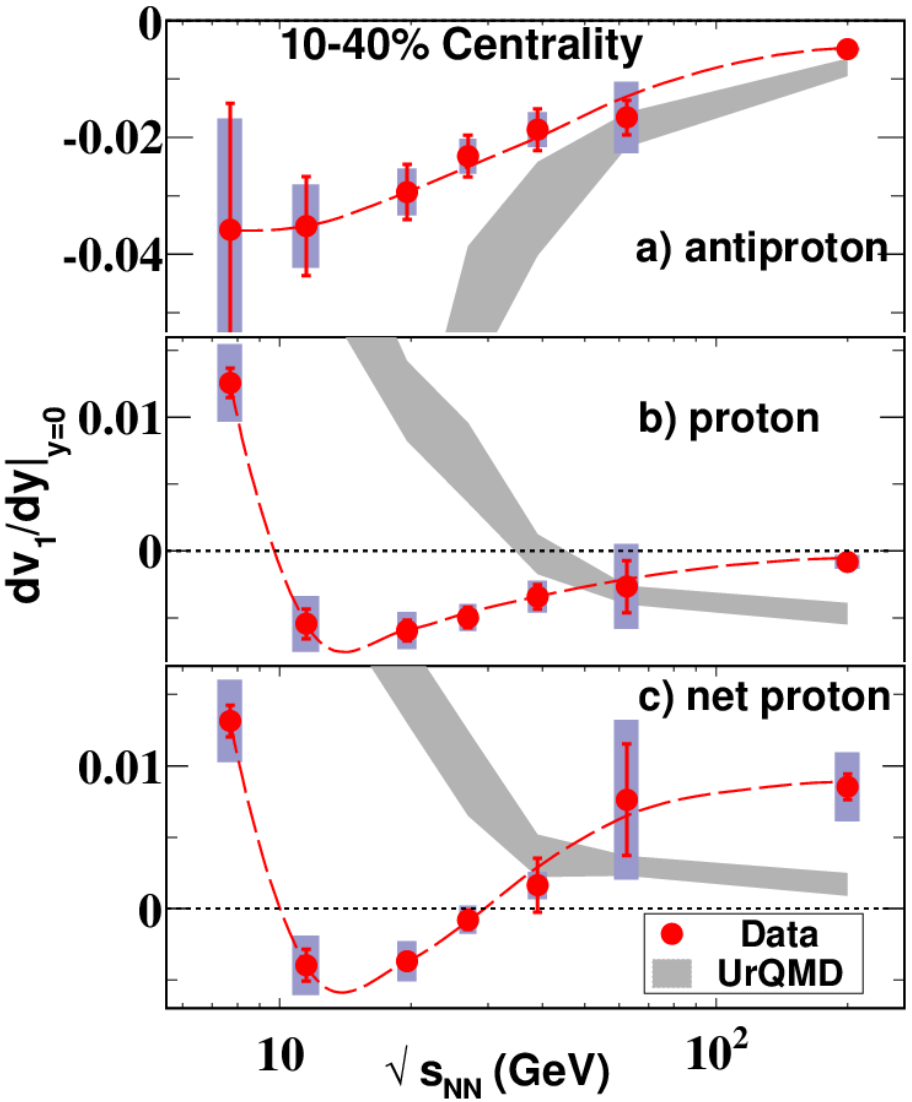
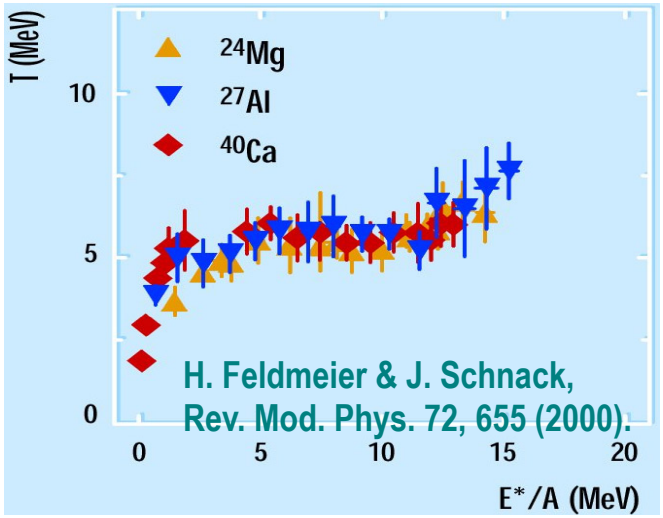


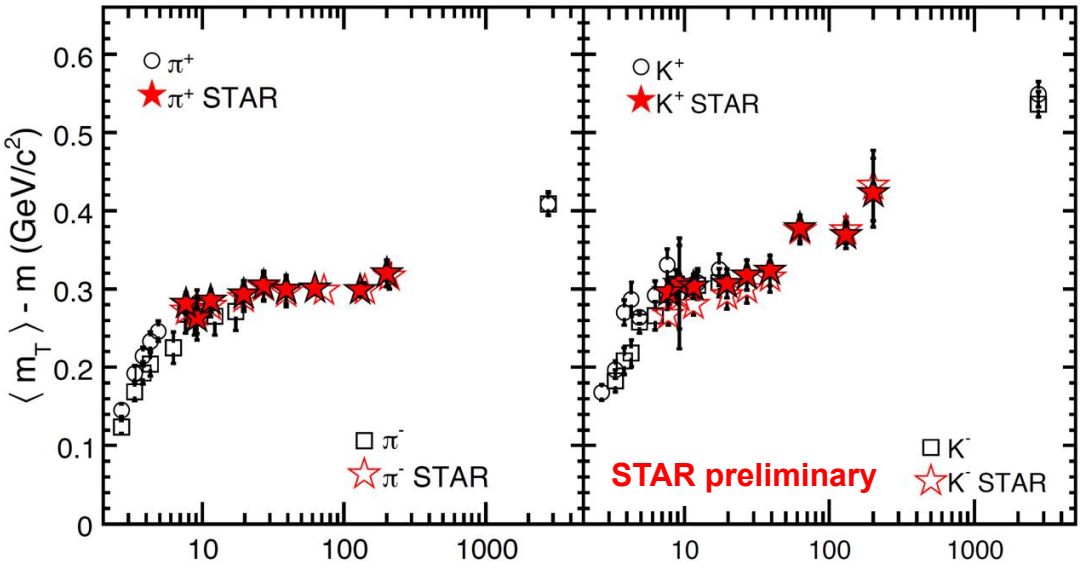
Caloric curve

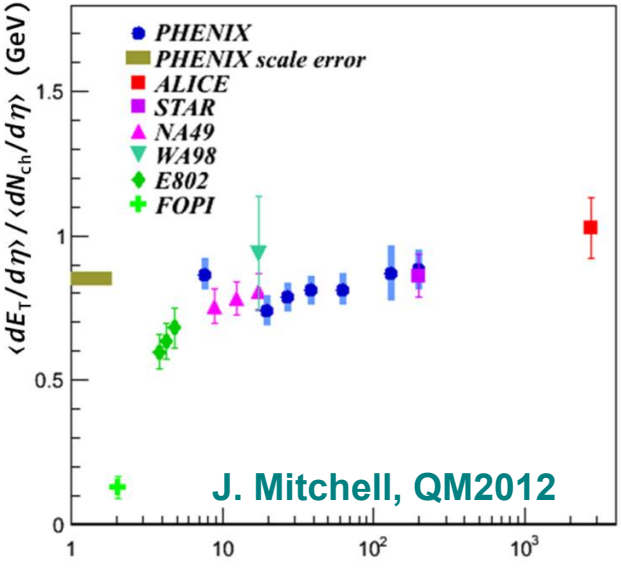
- 1st order phase transition
  → T(E) plateau

- Similar feature in RHIC data!
  - $\langle m_T \rangle$ is related to temperature
  - E_T is related to energy density

nuclear liquid-vapor PT



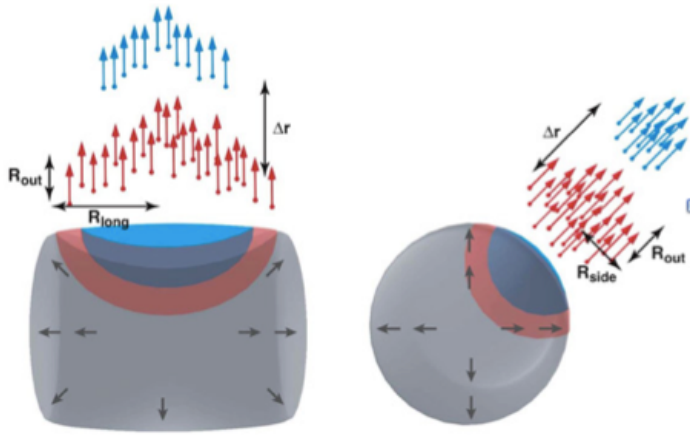




Center of Mass Collision Energy $\sqrt{s_{NN}}$ (GeV)

HBT radii (pions)

→ Martin Girard: Kaon BES HBT

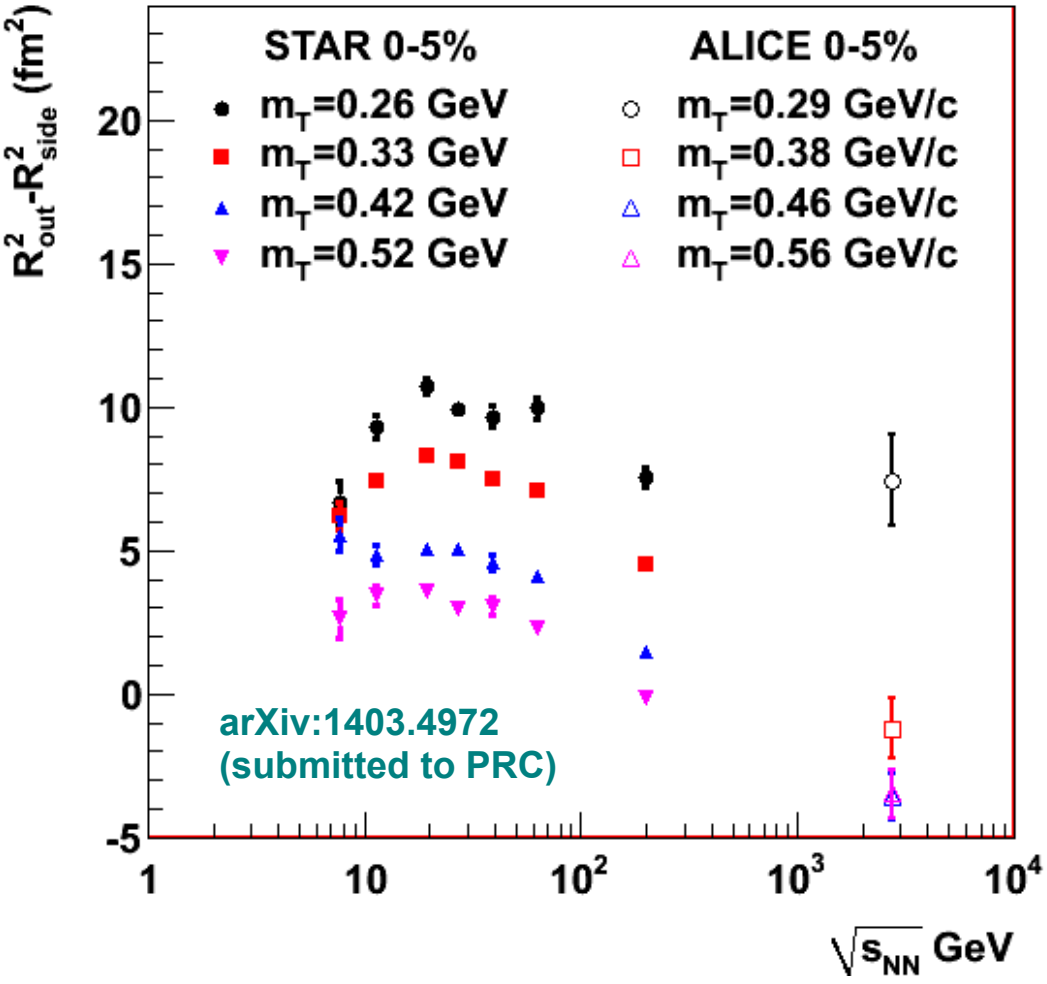


$$R^2_{side} = \frac{R^2_{geo}}{1+\frac{m_T}{T}\beta_T^2}$$

Makhlin, Sinyukov, ZPC.39.69 (1988)

$$R^2_{out} = \frac{R^2_{geo}}{1+\frac{m_T}{T}\beta_T^2} + \beta_T^2(\Delta\tau)^2$$

$$R^2_{long} \approx \tau^2 \frac{T}{m_T}\frac{K_2}{K_1}$$



- 1st order phase transition – longer emission duration expected
- Non-monotonicity R_{out}^2–R_{side}^2 may indicate changes in dynamics

Exploring the QCD phase diagram

Find…

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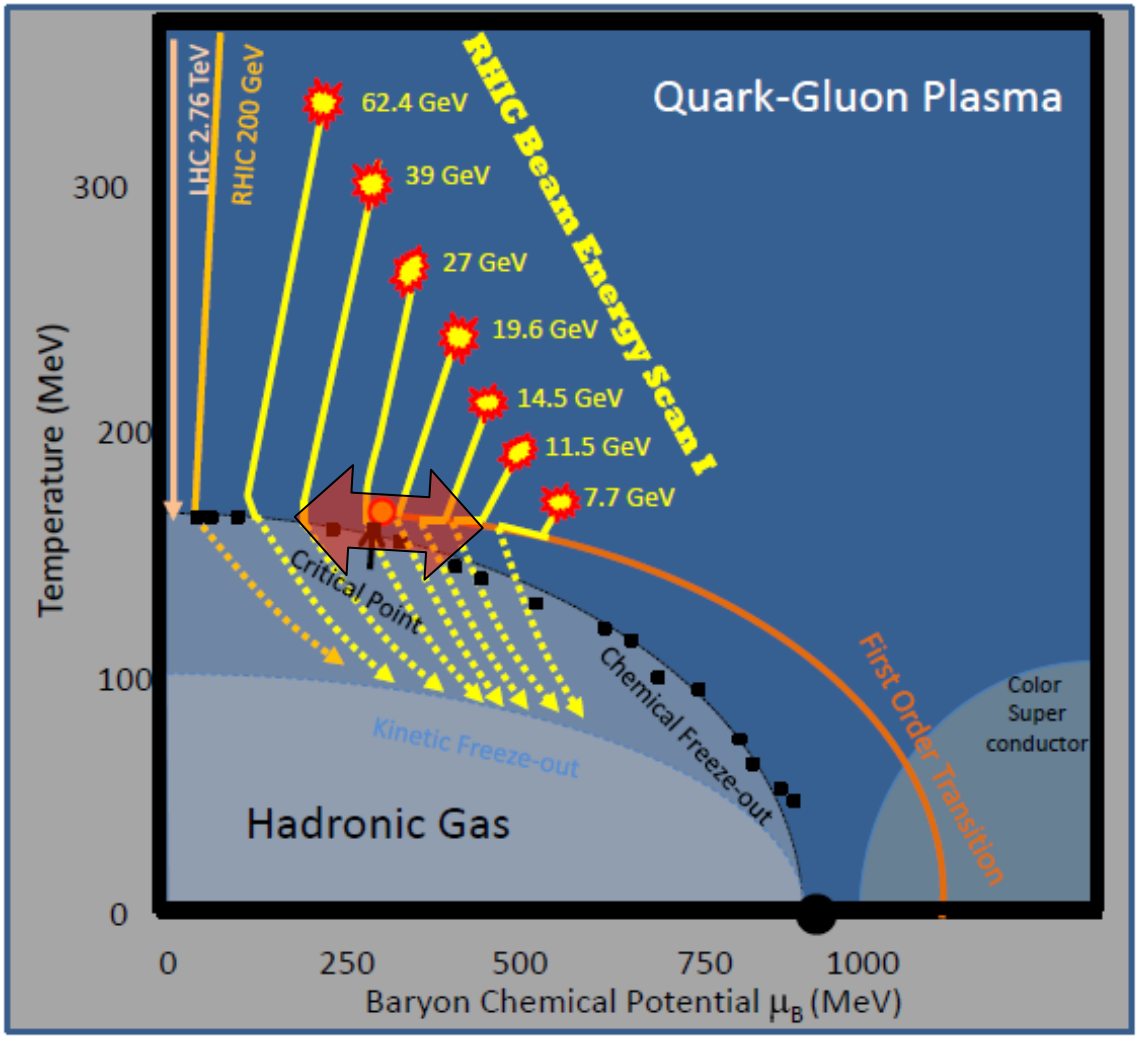


http://arxiv.org/abs/1007.2613

Net proton multiplicity moments

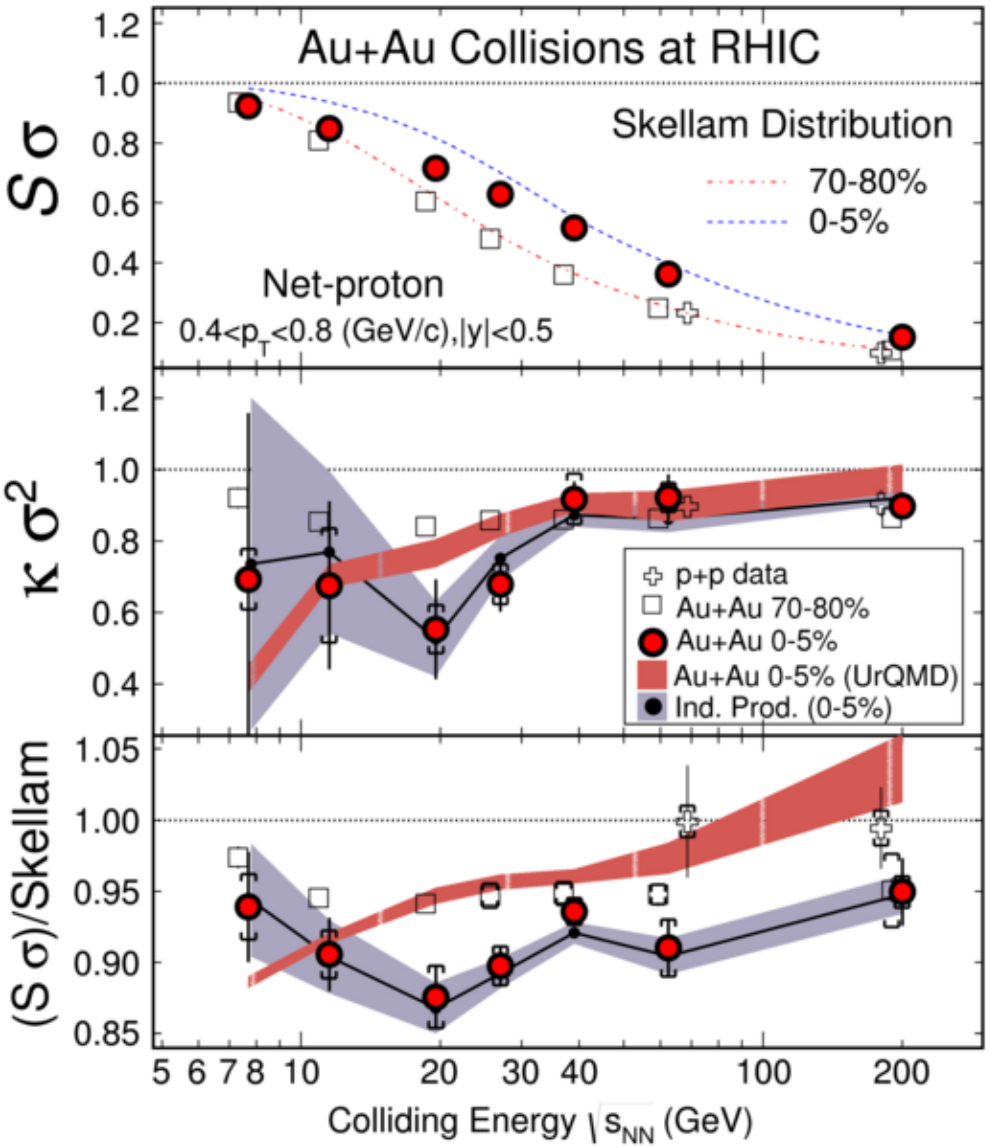
- Susceptibilities of conserved quantities (Q, B, S)
- Related to multiplicity distribution moments
- Volume effect → ratios

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

$$\chi_B^4 / \chi_B^2 = (\kappa\sigma^2)_B$$

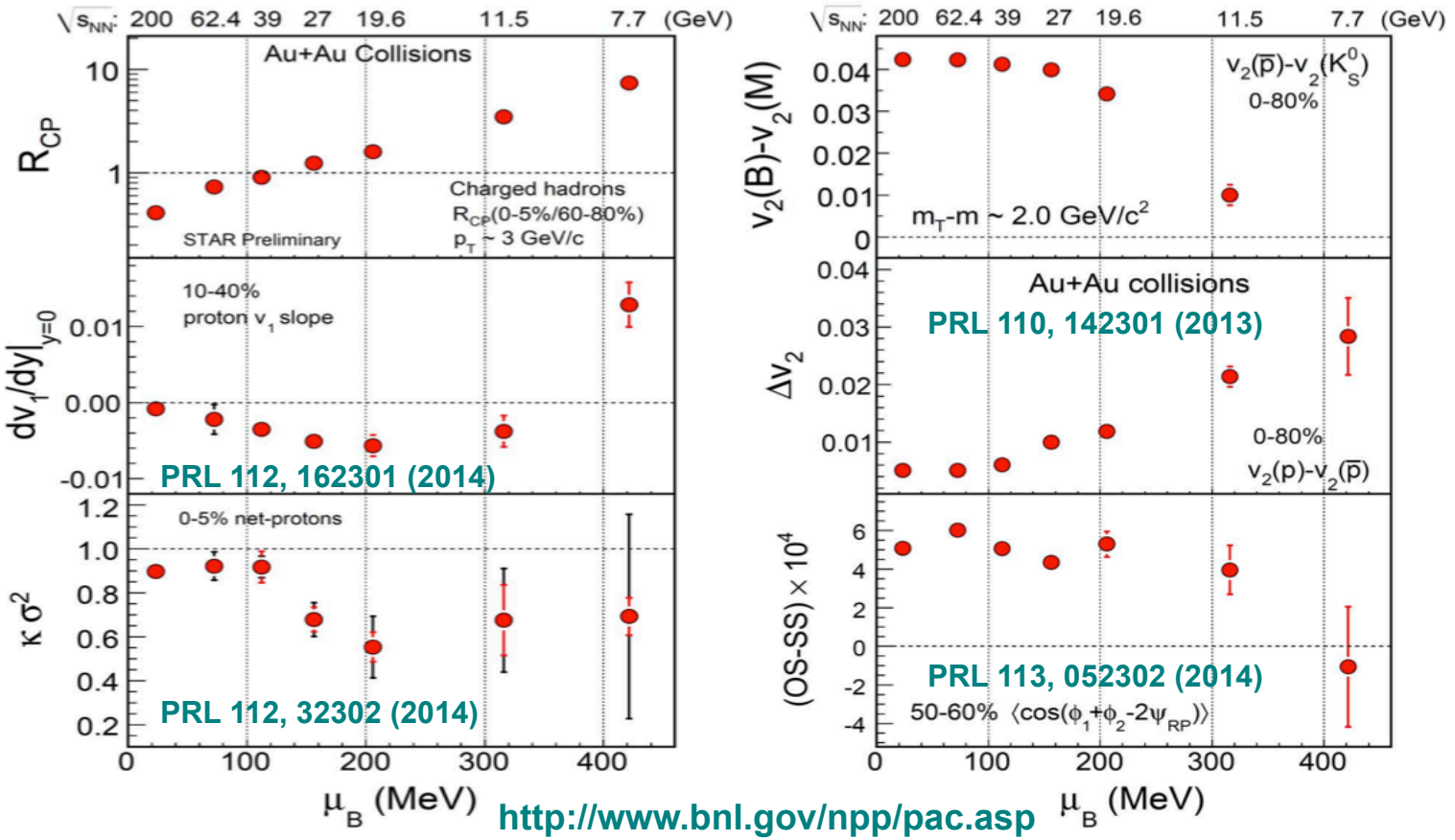
$$\chi_B^3 / \chi_B^2 = (S\sigma)_B$$

- Non-monotonic behavior?
- **Net proton mult.:** maybe, but we need more statistics!



Phys. Rev. Lett. 112 (2014) 32302

BES I – highlights

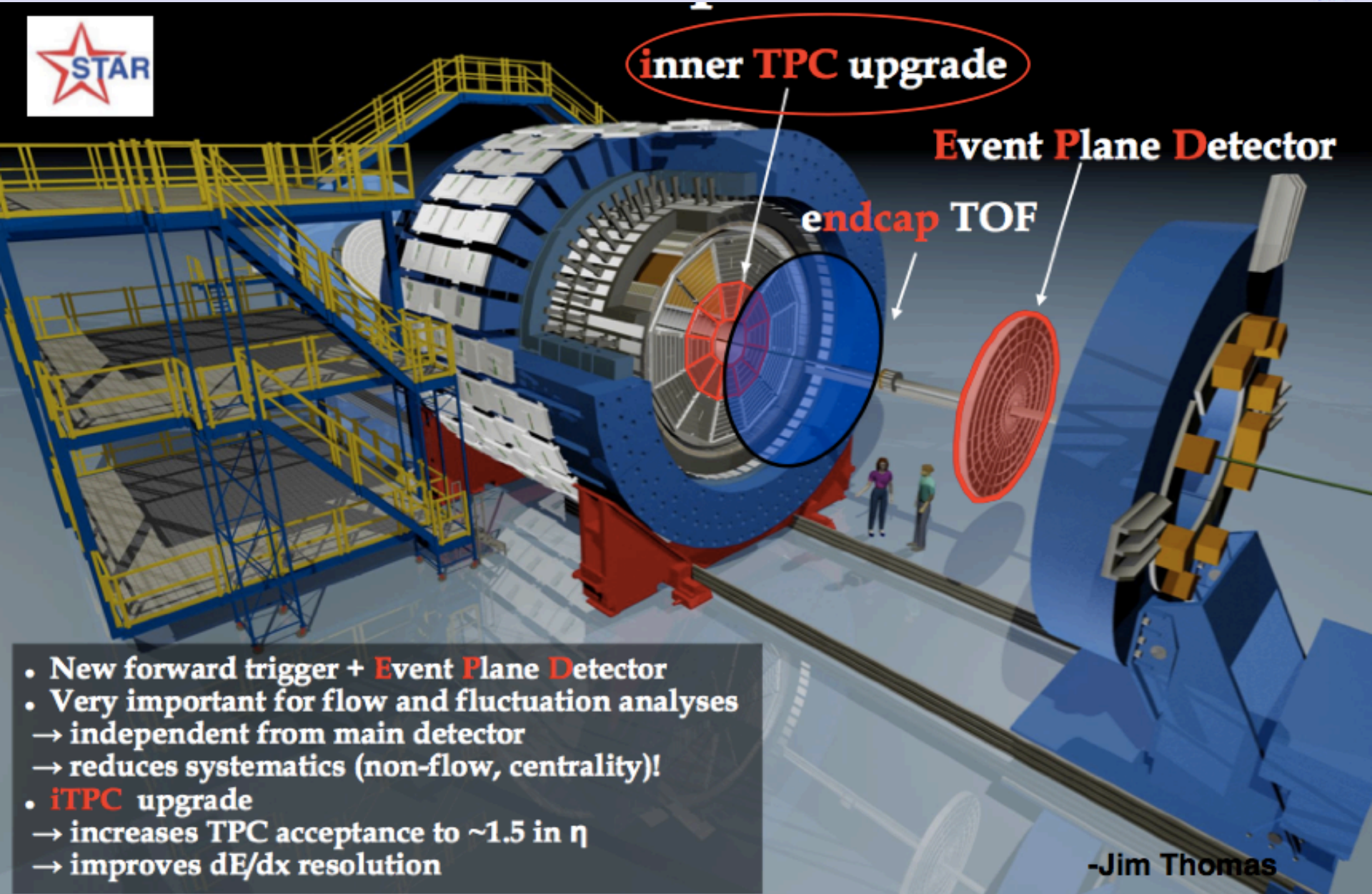


- A wide range of potential sQGP/PT/CP signatures measured
- Some key observables identified, interesting region localized
- Many of these require better statistics / detector performance

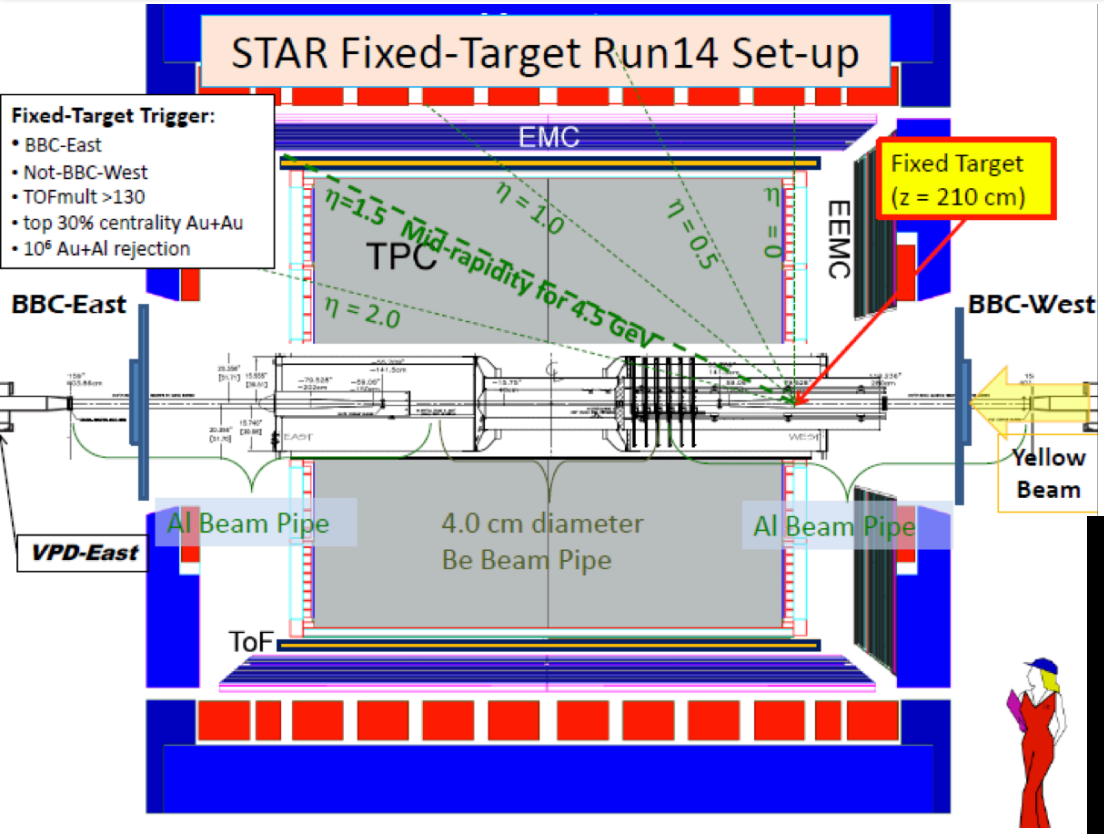
BES II plan

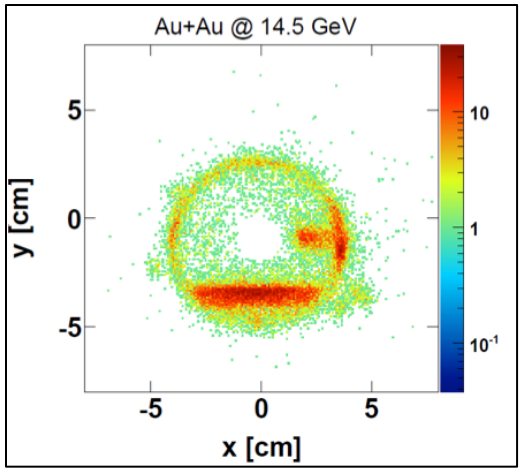
Collision Energies (GeV):	**7.7**	**9.1**	**11.5**	**14.5**	**19.6**
Chemical Potential (MeV):	**420**	**370**	**315**	**260**	**205**
Observables	Millions of Events Needed				
QGP	R_{CP} up to p_T 4.5 GeV	NA	NA	160	92	22
QGP	Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400
QGP	Local Parity Violation (CME)	50	50	50	50	50
1st P.T.	Directed Flow studies (v_1)	50	75	100	100	200
1st P.T.	asHBT (proton-proton)	35	40	50	65	80
C.P.	net-proton kurtosis ($\kappa\sigma^2$)	80	100	120	200	400
EM Probes	Dileptons	100	160	230	300	400
Proposed Number of Events:	**100**	**160**	**230**	**300**	**400**

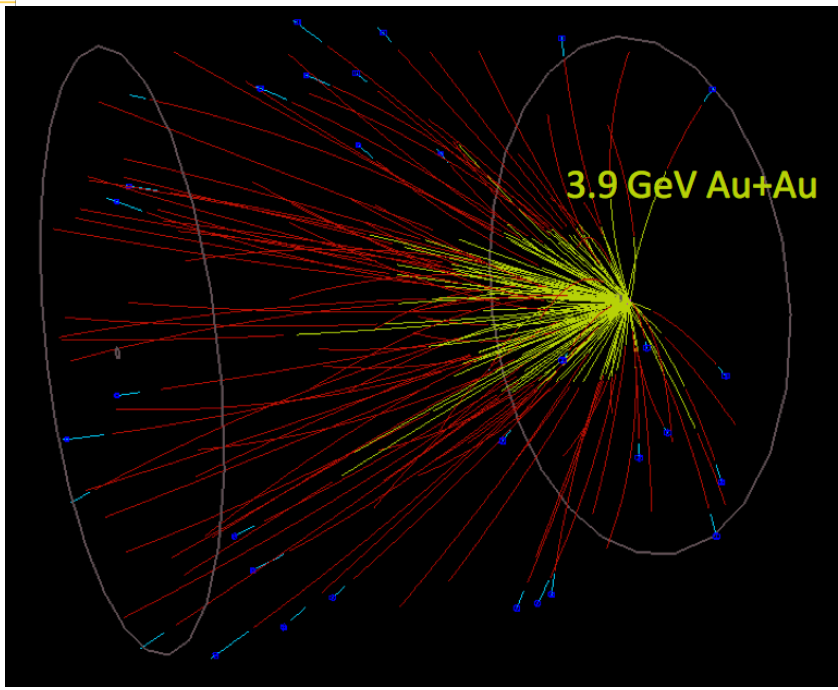
STAR upgrades for BES II



Fixed target program at STAR







- Target inserted into beam pipe
- Only a small percentage
- Does not interfere with collider mode data taking

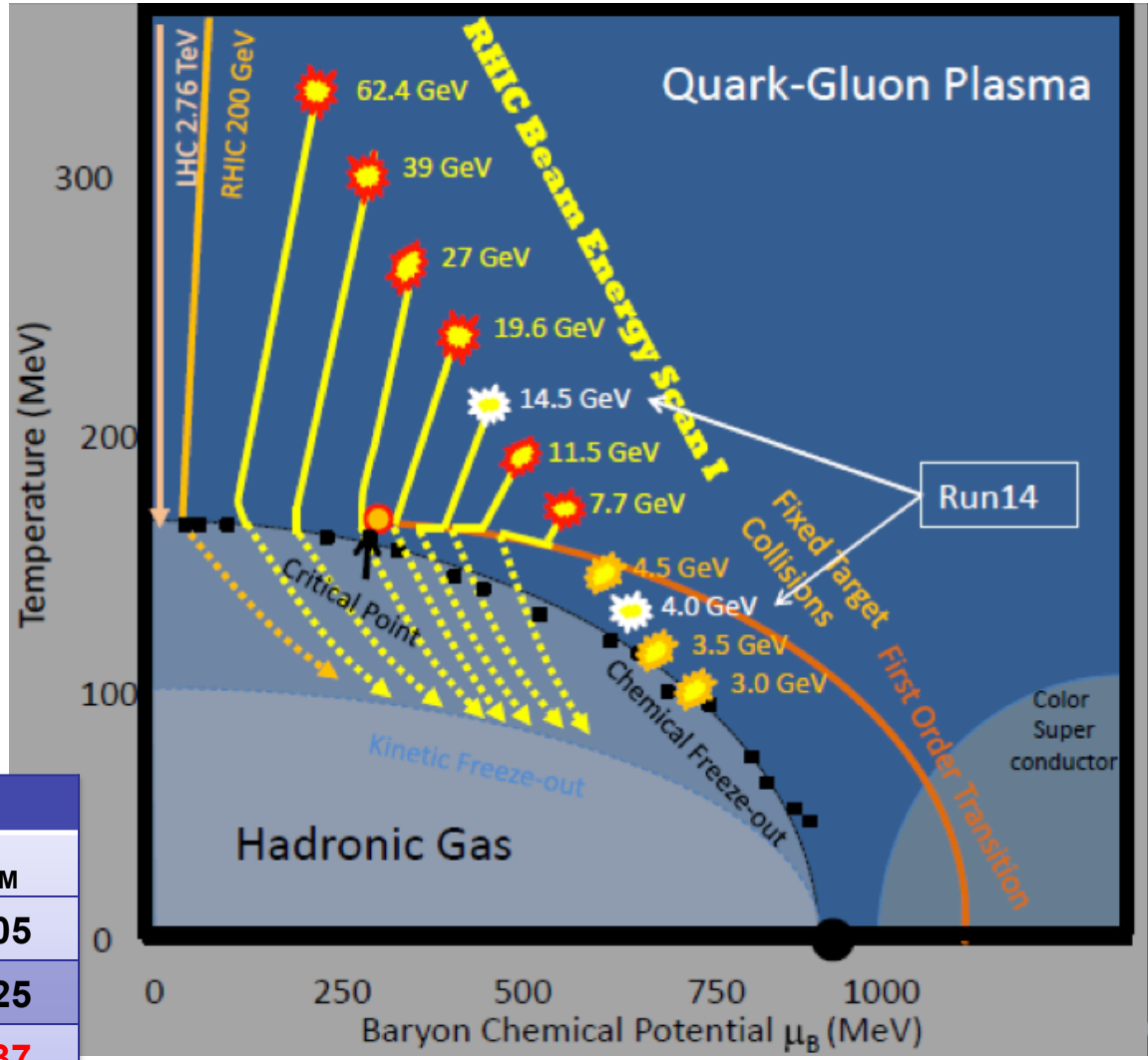
Fixed target program at STAR

- Extend range towards higher μ_B
- Started in 2014

Collider mode 14.5 GeV

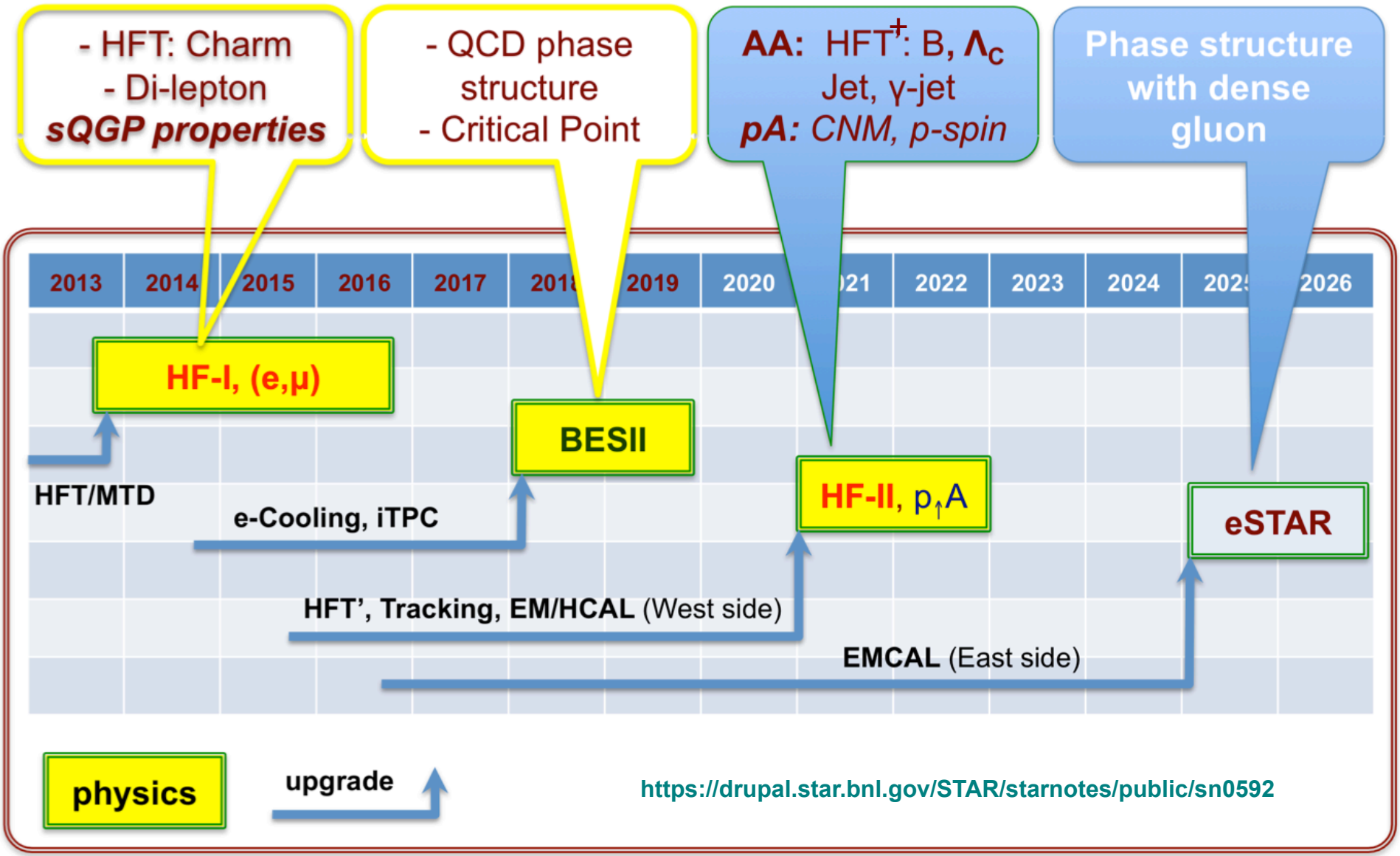
⇕

Fixed target 3.9 GeV



Collider mode $\sqrt{s_{NN}}$ (GeV)	Fixed target		
	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	y_{CM}
7.7	**3.0**	720	**1.05**
11.5	**3.5**	670	**1.25**
14.5	**3.9**	633	**1.37**
19.6	**4.5**	585	**1.52**

STAR Long-Term Plan



https://drupal.star.bnl.gov/STAR/starnotes/public/sn0592

Summary

BES-I covers the right (wide) μ_B range

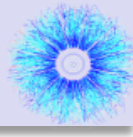
- Interesting behavior seen:
  - sQGP-turnoff: R_{CP}, Δv_2, chiral magnetic effect
  - Phase transition: non-monotonic v_1, HBT radii, caloric curve
  - Critical point: Net-proton moments
  - …and much more!

BES-II more statistics in a finer scan between 7-20 GeV

- Decisive measurements of likely signatures
- New measurements

Toward understanding the QCD phase diagram

Thank You!



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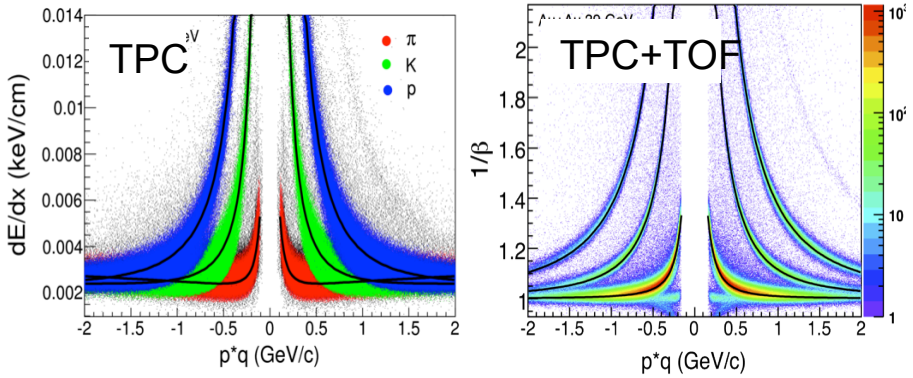
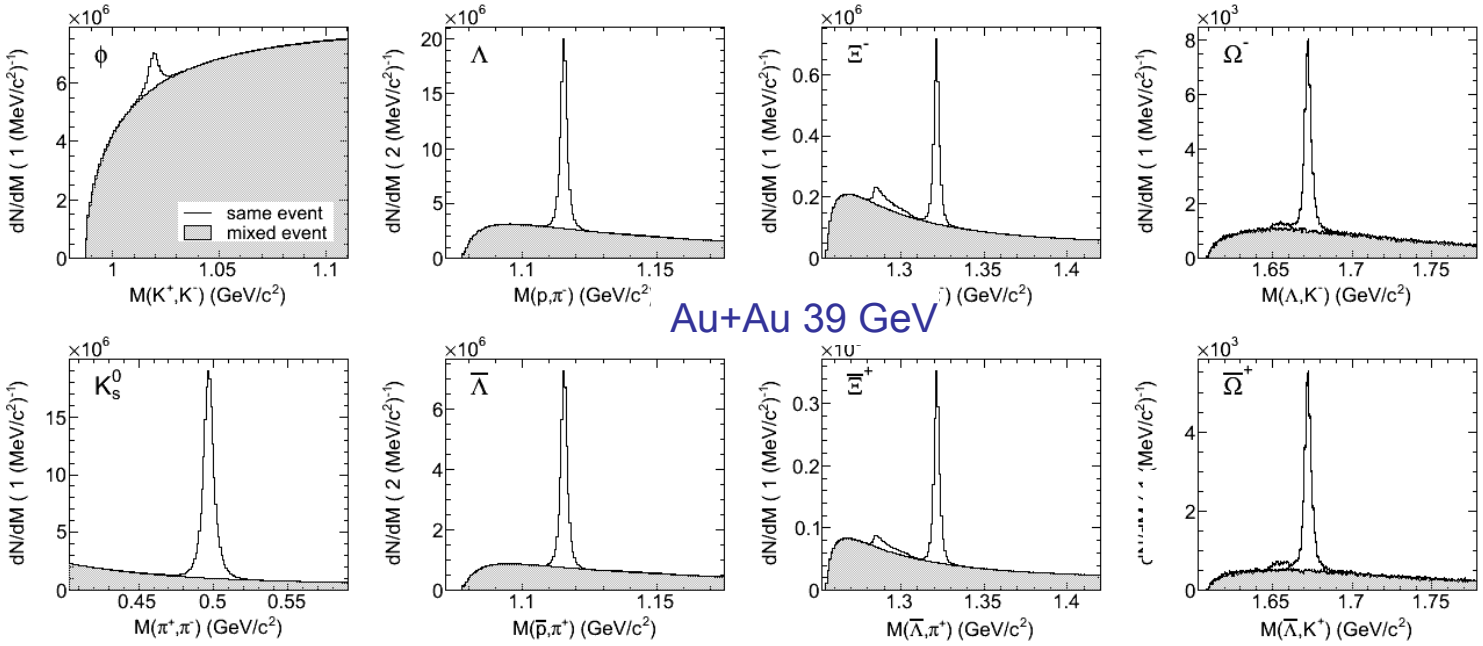
STAR Collaboration

Particle Identification

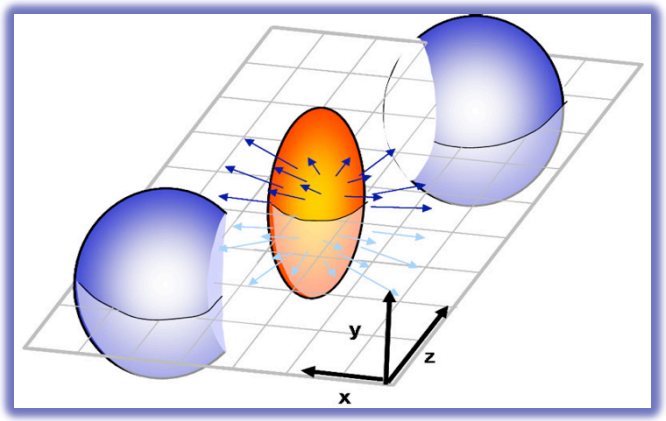


PID (TPC+TOF):
π/K: p_T~1.6 GeV/c
p: p_T~3.0 GeV/c
Strange hadrons:
decay topology & invariant mass



Au+Au 39 GeV

Azimuthal Anisothropy



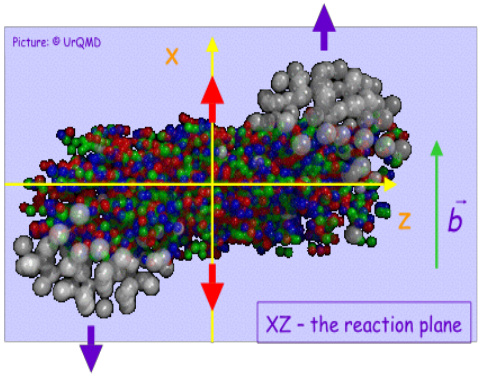
$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

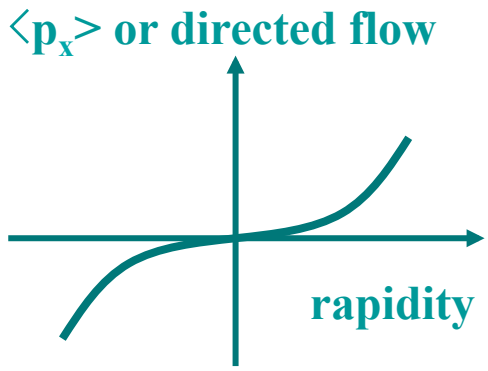
Directed flow is quantified by the first harmonic: $v_1 = \langle \cos(\phi - \Psi_r) \rangle$

$$\phi = \tan^{-1}\left(\frac{p_x}{p_y}\right)$$

- Directed flow is due to the sideward motion of the particles within the reaction plane.
- Generated already during the nuclear passage time ($2R/\gamma \approx .1$ fm/c@200GeV)

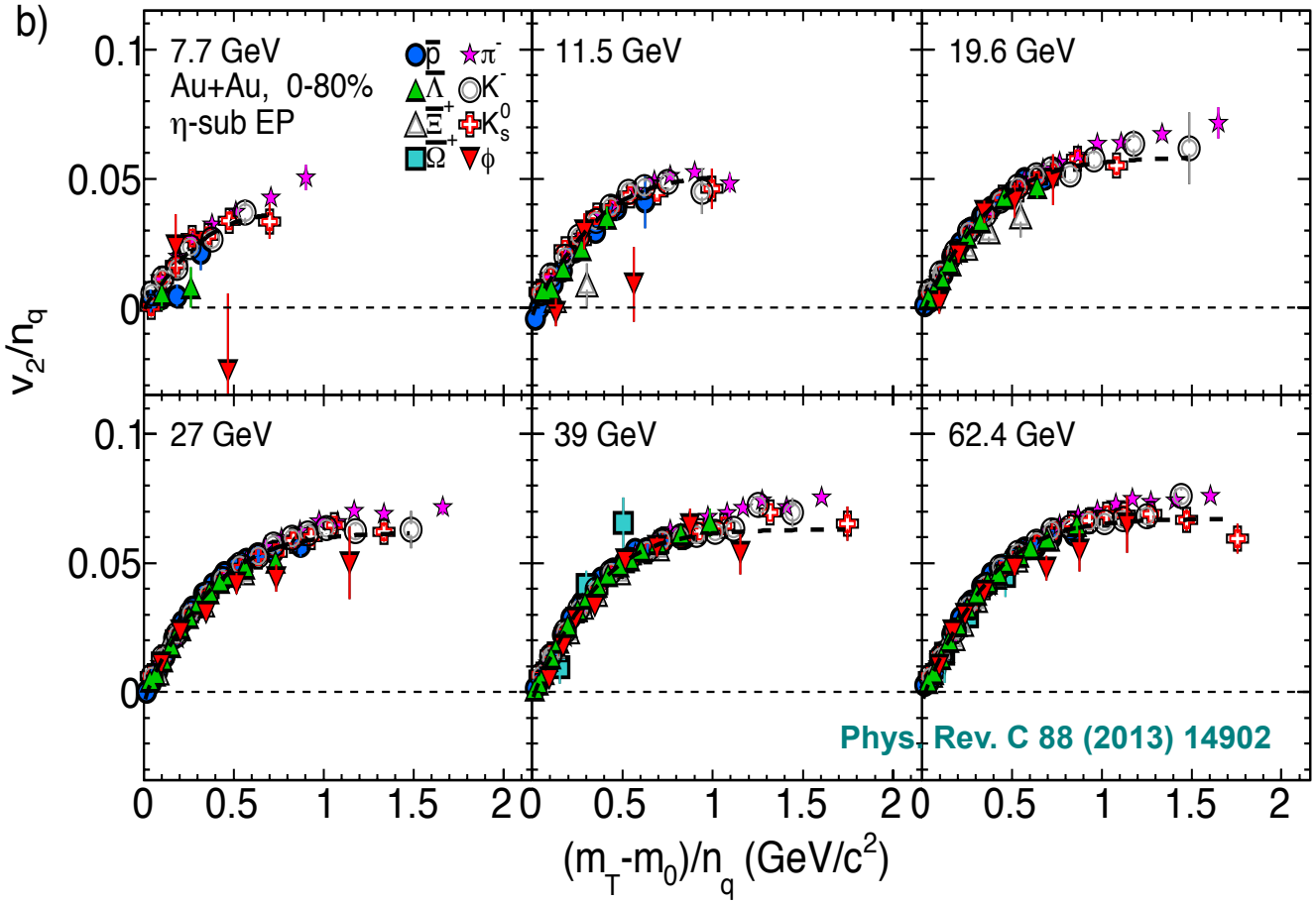
⇒ It probes the onset of bulk collective dynamics during thermalization





$v_1(y)$ is sensitive to baryon transport, space - momentum correlations and QGP formation

Elliptic flow (v_2) – antiparticles

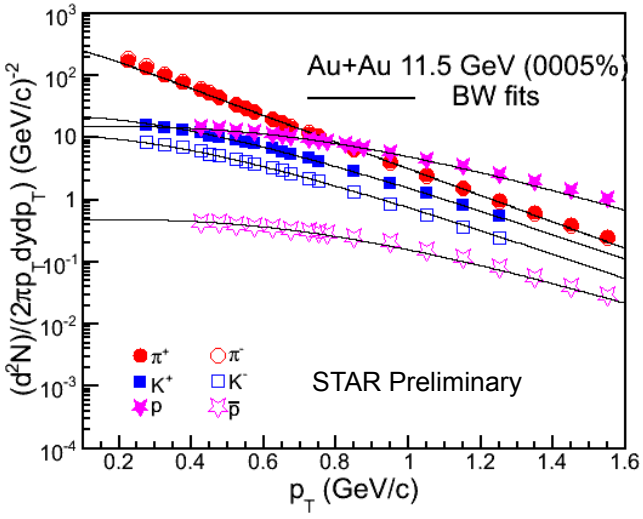


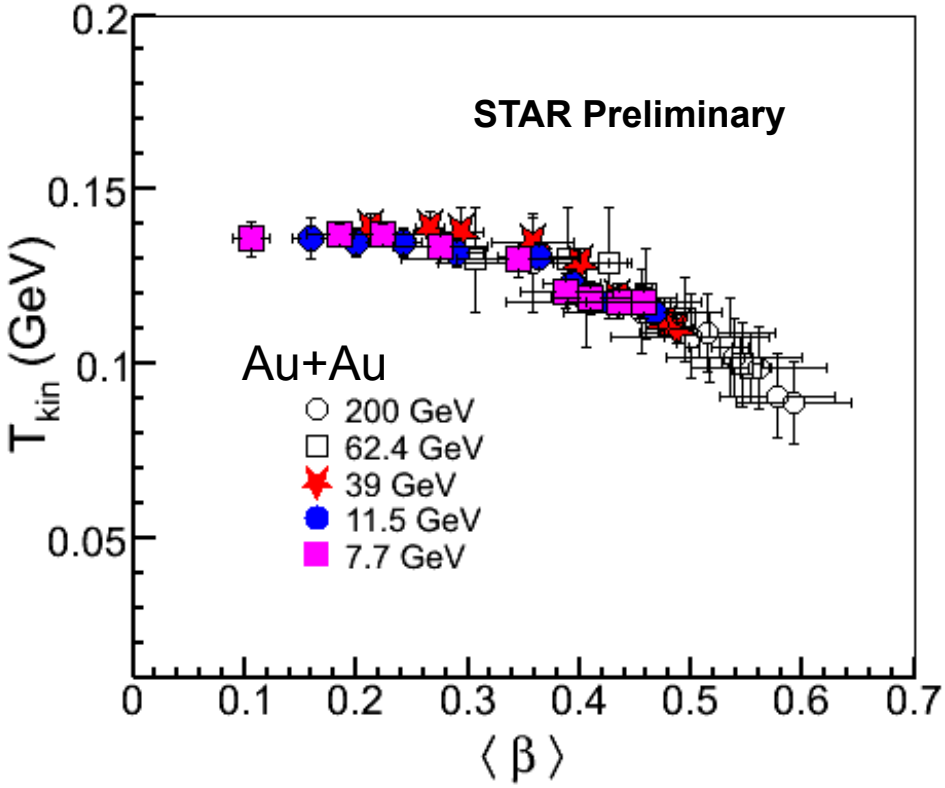
- Approximate NCQ scaling holds… DOF=quarks?
- …but particles and antiparticles are different

Kinetic freeze-out

Blast Wave: T_{kin} and $\langle\beta\rangle$

Particles used: π,K,p

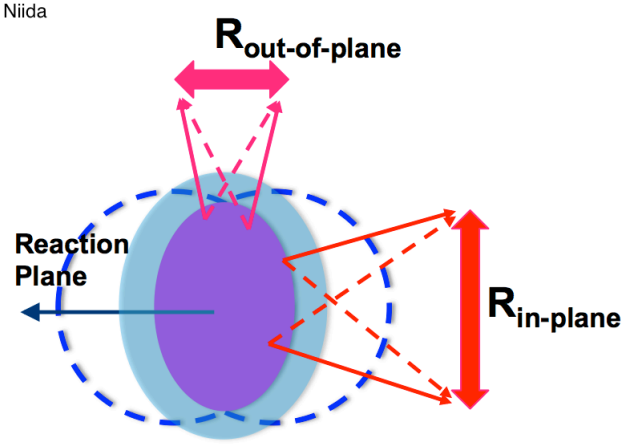




✧ Higher kinetic temperature corresponds to lower value of average flow velocity and vice-versa

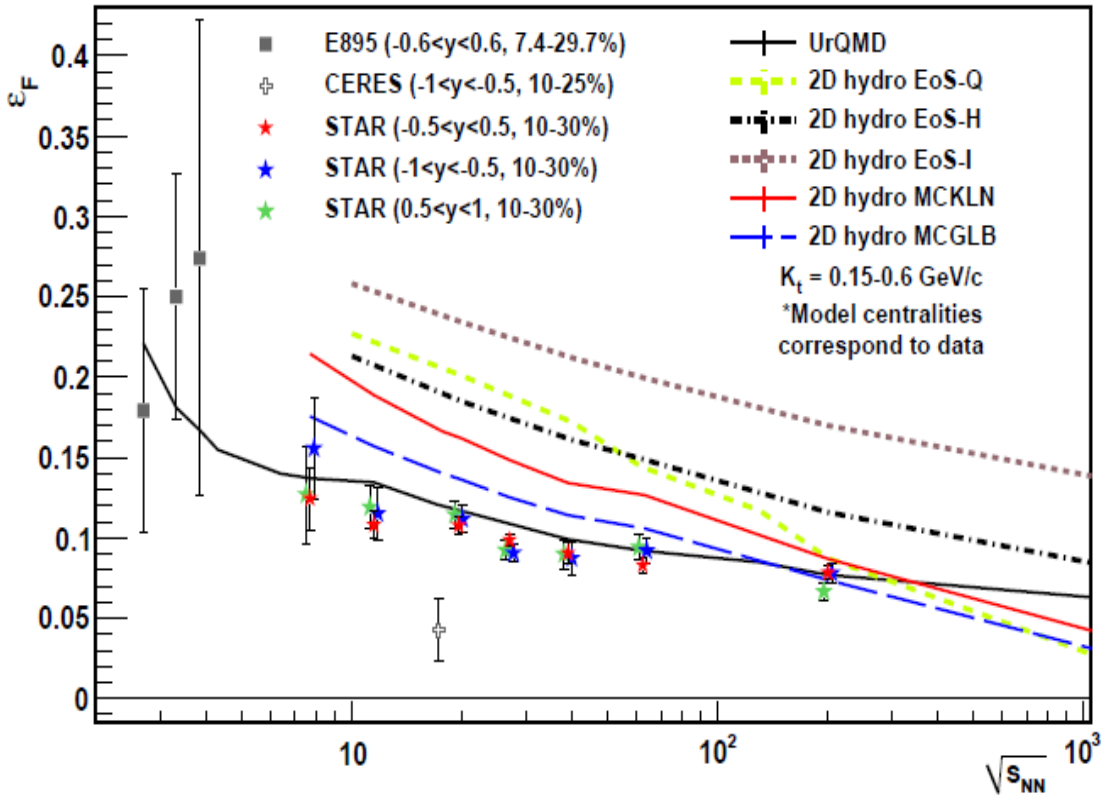
Azimuthally sensitive HBT

Illustration from: T. Niida



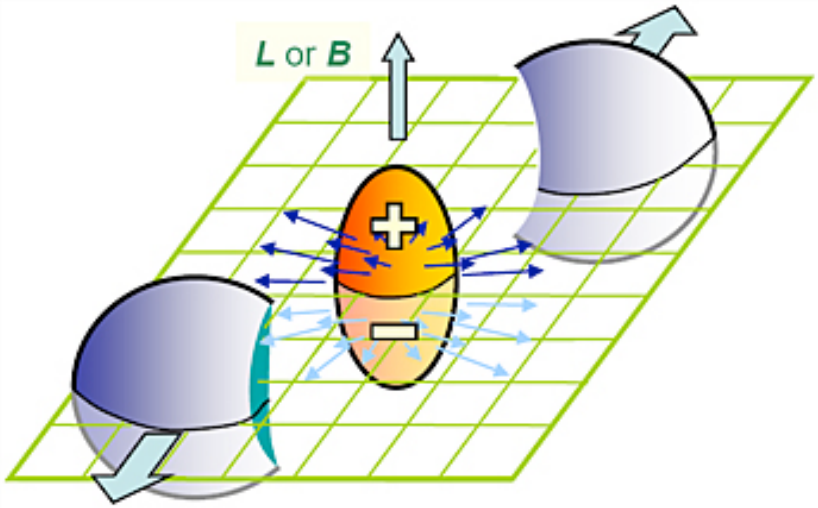
elliptical shape : $R_{in\text{-}plane} > R_{out\text{-}of\text{-}plane}$
spherical shape : $R_{in\text{-}plane} = R_{out\text{-}of\text{-}plane}$

arXiv:1403.4972 (submitted to PRC)



- Spatial eccentricity at the kinetic freeze-out, ε_F
- Sensitive to EOS
- Smooth, monotonous behavior observed over the BES range

Chiral magnetic effect



- Chiral-magnetic effect:
  Local parity violation in sQGP

$$\frac{dN_\alpha}{d\phi} \propto 1 + 2v_1 \cos(\Delta\phi) + 2a_\alpha \sin(\Delta\phi) + 2v_2 \cos(2\Delta\phi) + \ldots$$

- Measure: 3-point correlator, charge separation

$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{\mathrm{RP}}) \rangle \qquad H^\kappa = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2).$$

Net charge multiplicity moments

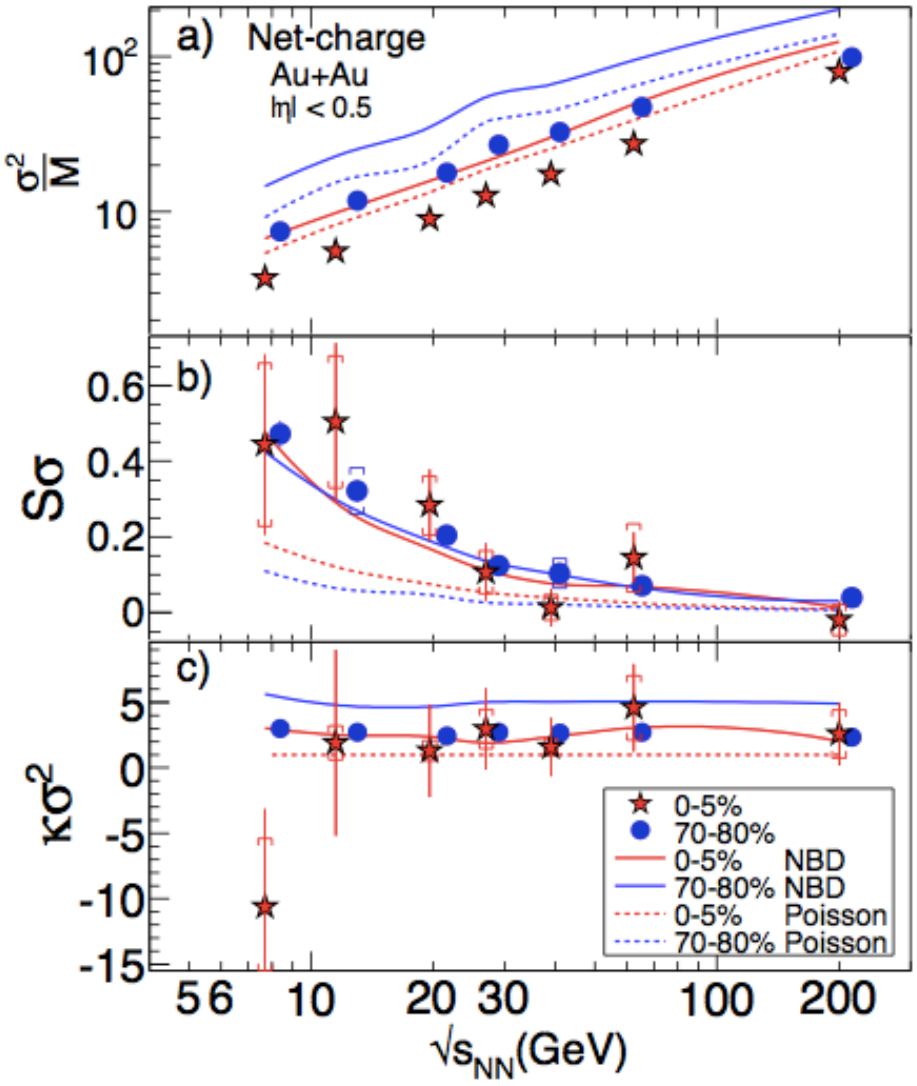
- Susceptibilities of conserved quantities (Q, B, S)
- Related to multiplicity distribution moments
- Volume effect → ratios

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

$$\chi_B^4 / \chi_B^2 = (\kappa\sigma^2)_B$$

$$\chi_B^3 / \chi_B^2 = (S\sigma)_B$$

- Non-monotonic behavior?
- **Net charge mult.:** no non-monotonic behavior seen



Phys. Rev. Lett. 113 (2014) 92301

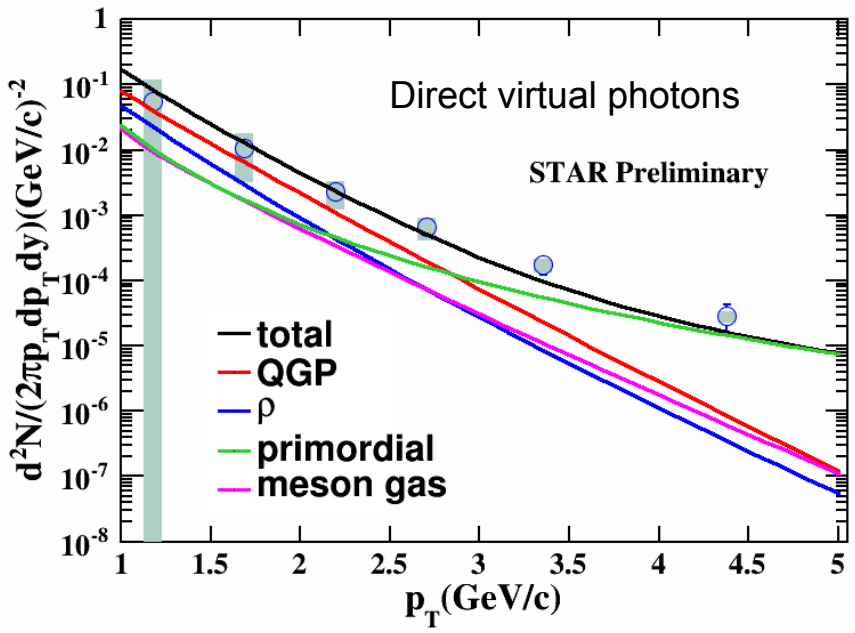
Quantify the Spectral Function

Temperature dependence of rho spectral function

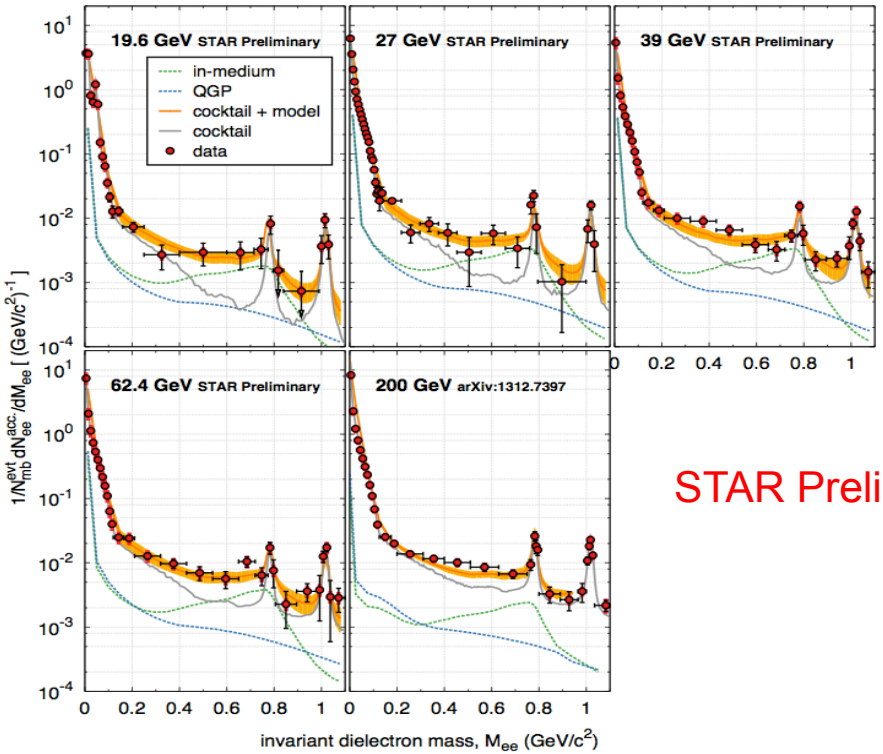
1. Beam energy range where final state is similar
2. Initial state and temperature evolution different
3. Density dependence by Azimuthal dependence (v_2)
4. Use centrality dependence as another knob
5. Direct photon results should match with extrapolation

Baryon dependence of rho spectral function

1. LMR excess expected to be consistent with total baryon density increase

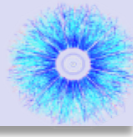


QM14: Chi Yang, Patrick Huck

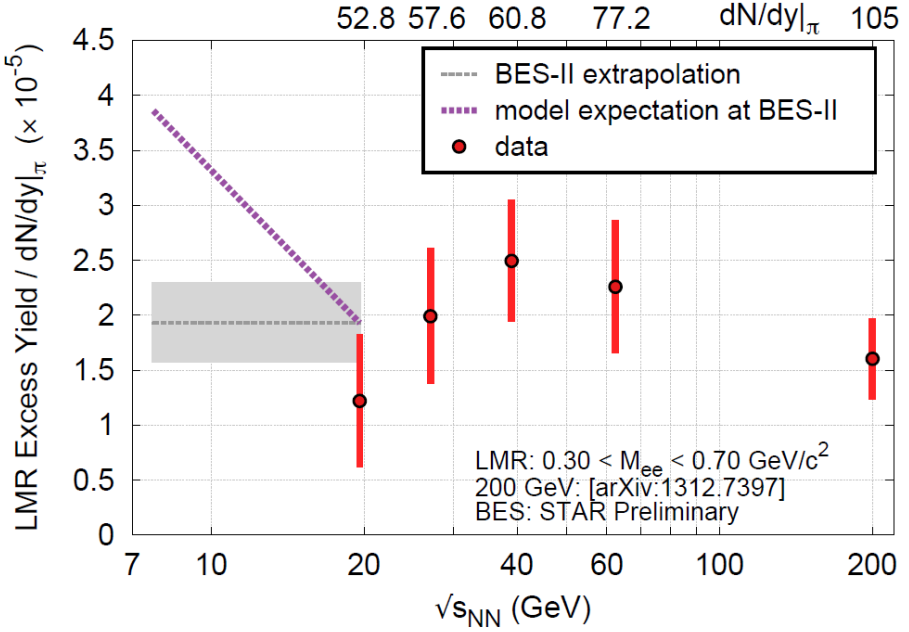


STAR Preliminary

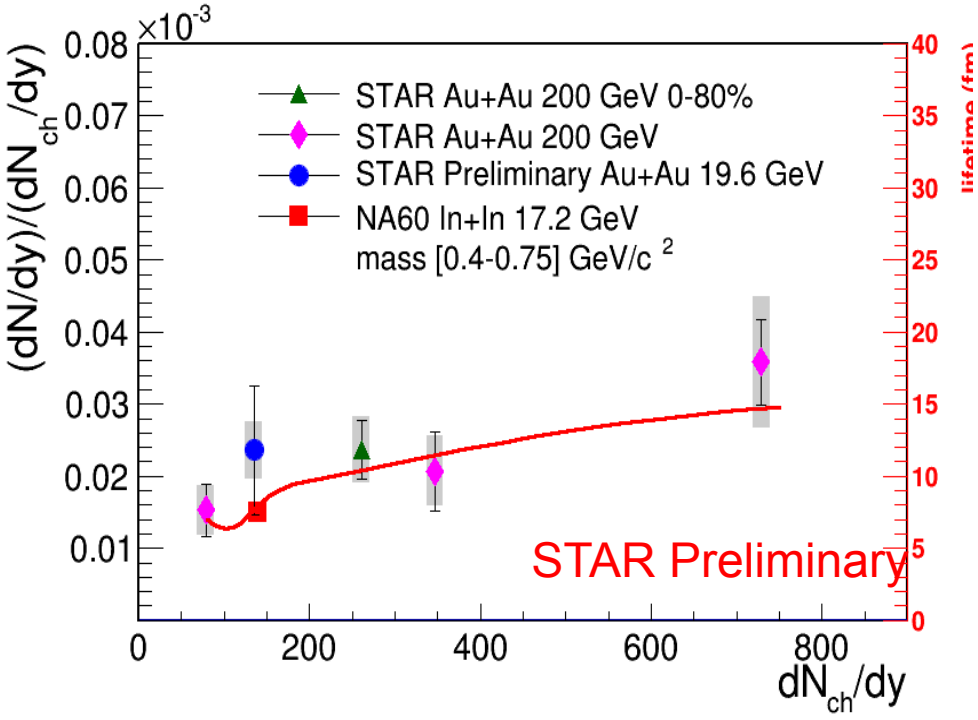
Dilepton Measurements at BES II



Beam Energy



Centrality



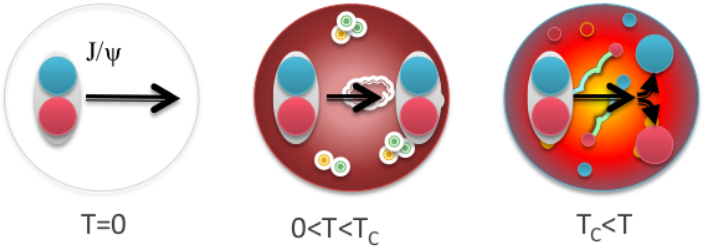
BES II enables measurements at energy <20GeV

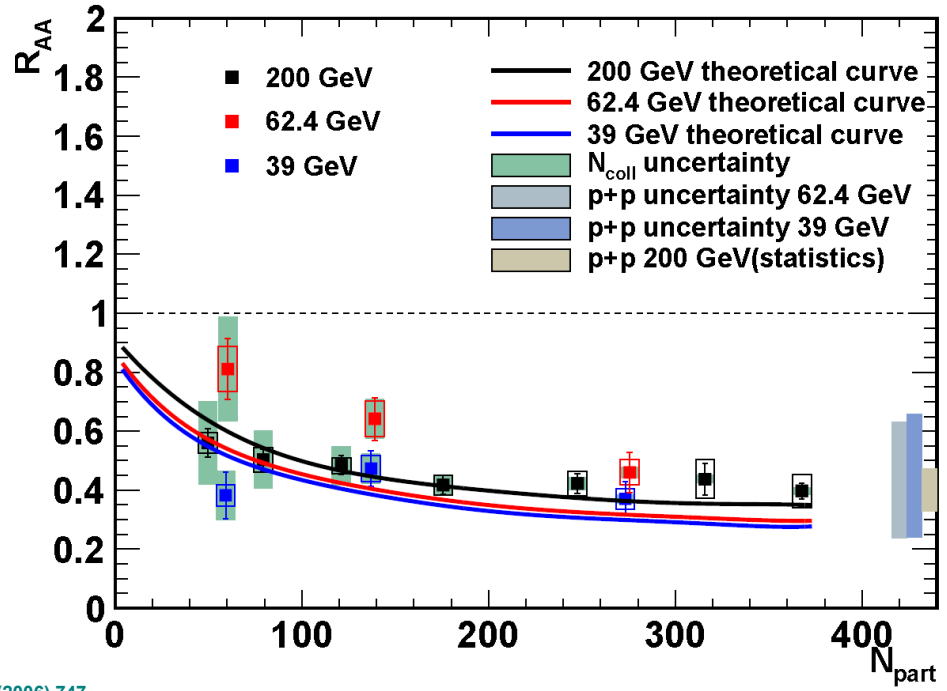
J/ψ R_{AA} vs. beam energy

Expectation

- Debye screening
  → dissociation of quarkonia
- **J/ψ melting** to be a smoking gun signature of **QGP**

T. Matsui, H. Satz, Phys.Lett. B178, 416 (1986)

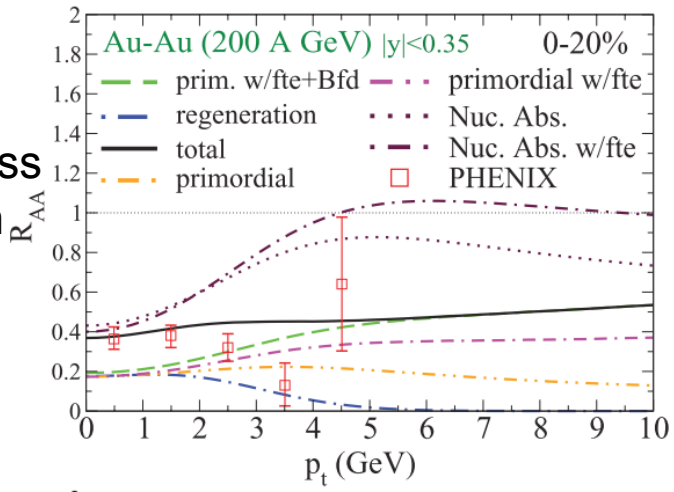




A complicated story

- Nuclear shadowing
- Initial state energy loss
- Co-mover absorption
- Coalescence of uncorrelated charm and bottom pairs.

PHENIX, Nucl.Phys. A 774 (2006) 747



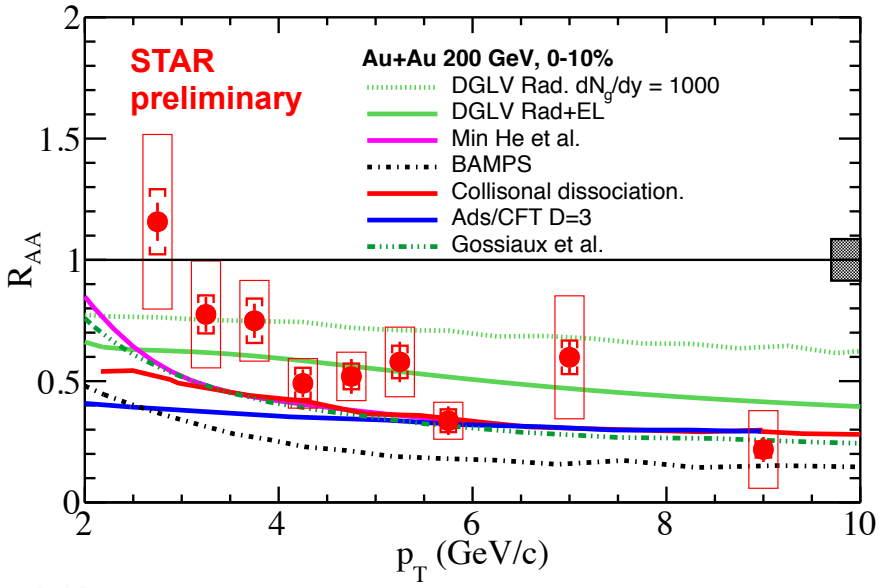
STAR Data (Au+Au)

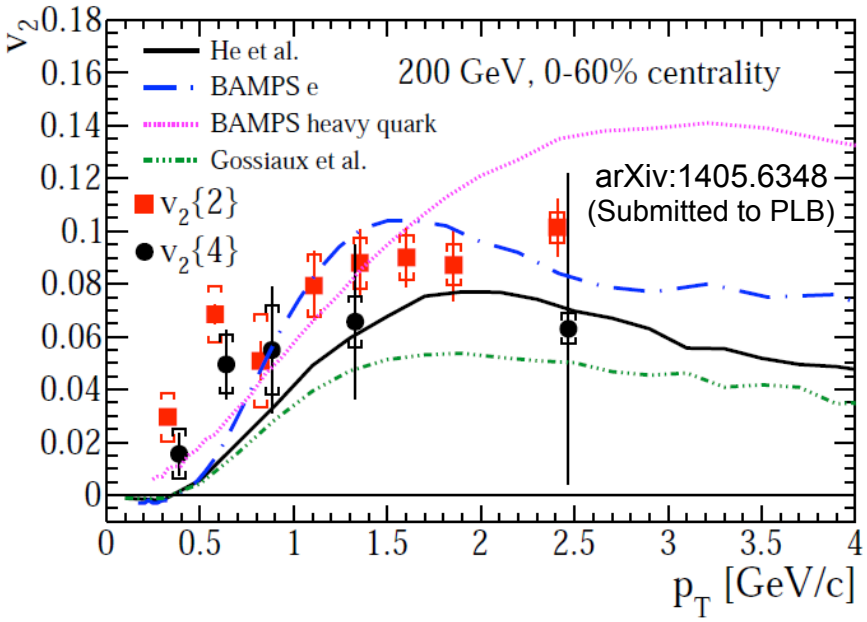
- Similar suppression in Au+Au at **200**, **62.4** and **39** GeV

Note: 62.4 and 39 GeV p+p reference is based on CEM calculations, large uncertainty
Nelson, Vogt et al., PRC87, 014908 (2013)

- Does coalescence compensate for melting?
  Zhao, Rapp, PRC82, 064905 (2010)

Non-photonic electrons: 200 GeV





Suppression

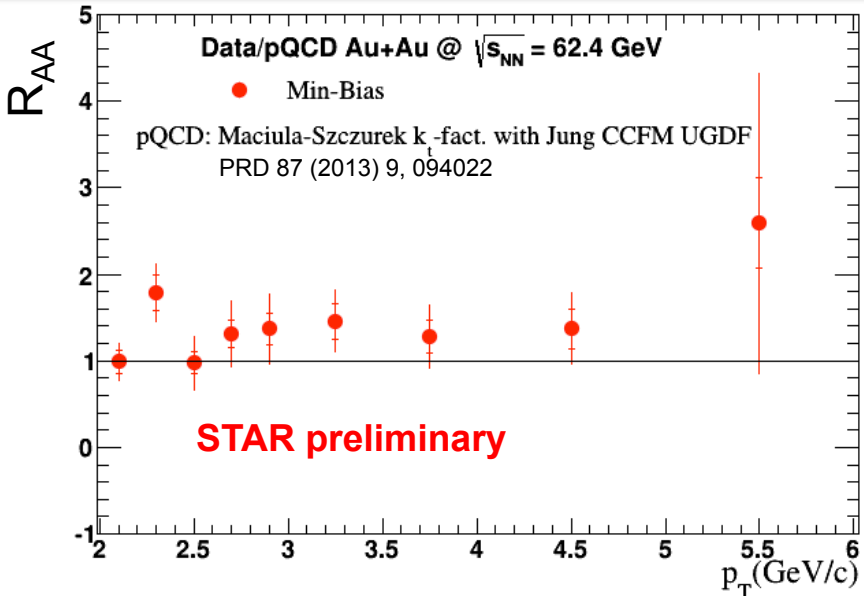
- Significant suppression of NPE in central collisions (p_T>4 GeV/c)
- Similar to that of light hadrons and D^0 mesons

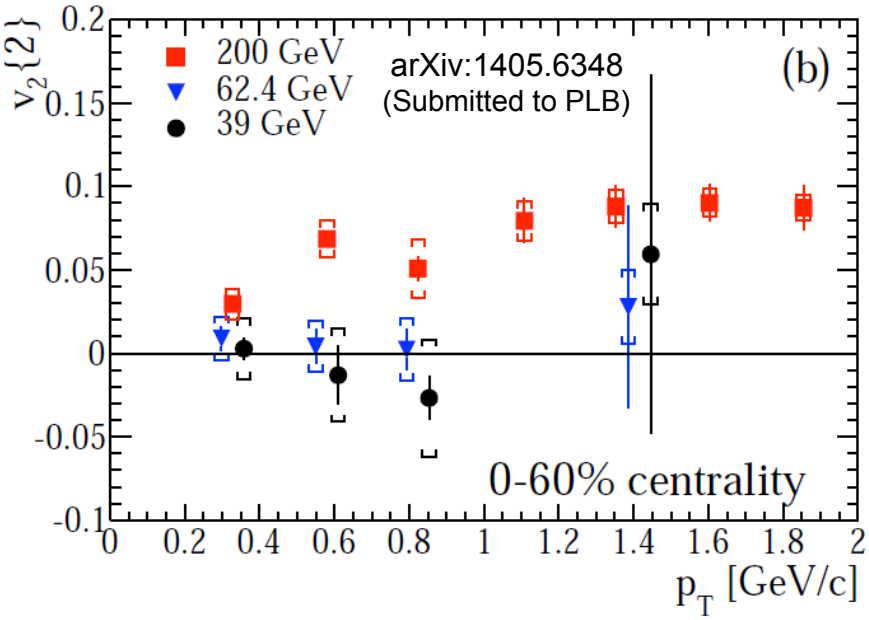
Anisotropy (v_2)

- Substantial elliptic flow of NPE is seen in 200 GeV Au+Au collisions

Note: it's challenging for models to describe suppression and flow at the same time

Non-photonic electrons: 39, 62.4 GeV





Suppression

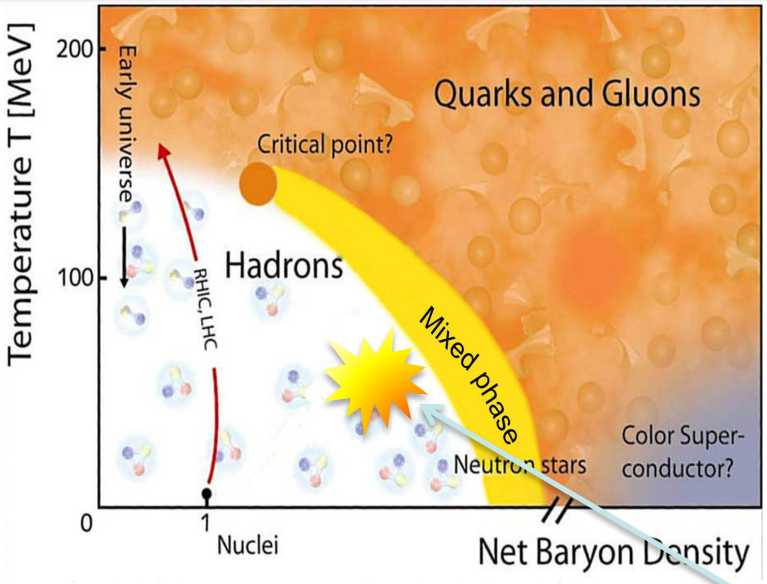
- **No sign of suppression** of NPE in 62.4 GeV Au+Au collisions

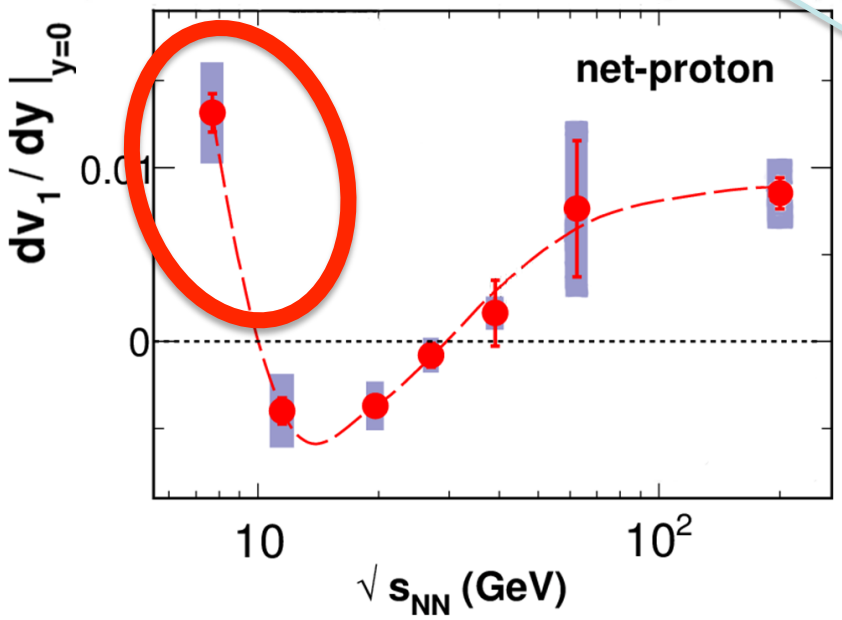
  Note: pQCD-scaled p+p reference

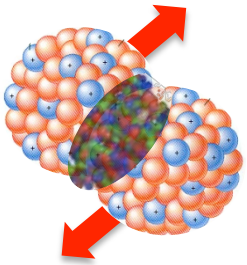
Anisotropy (v_2)

- NPE in 39 and 62.4 GeV Au+Au collisions **consistent with no flow** (p_T<1 GeV/c)

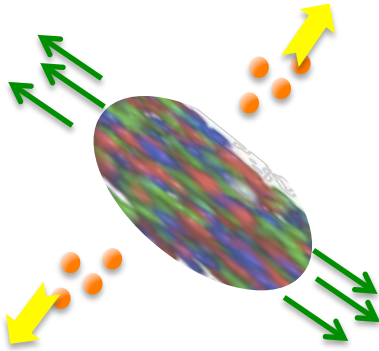
v_1 cartoon by Mike Lisa



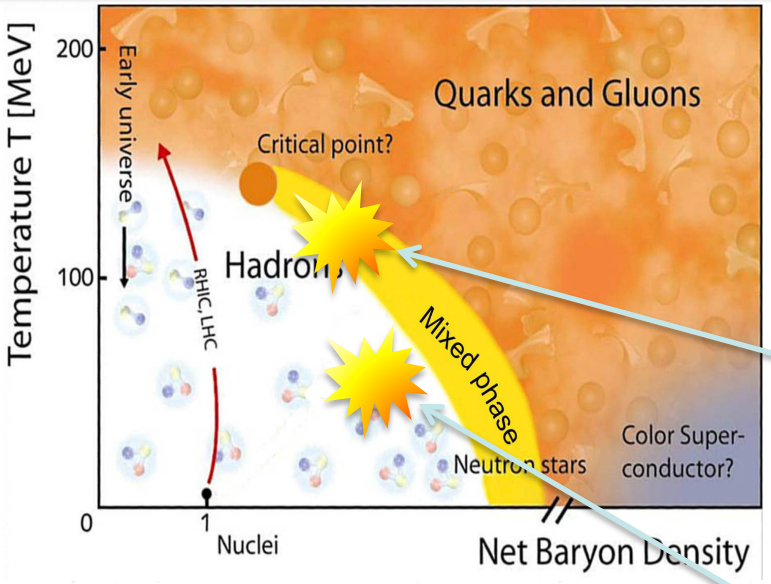


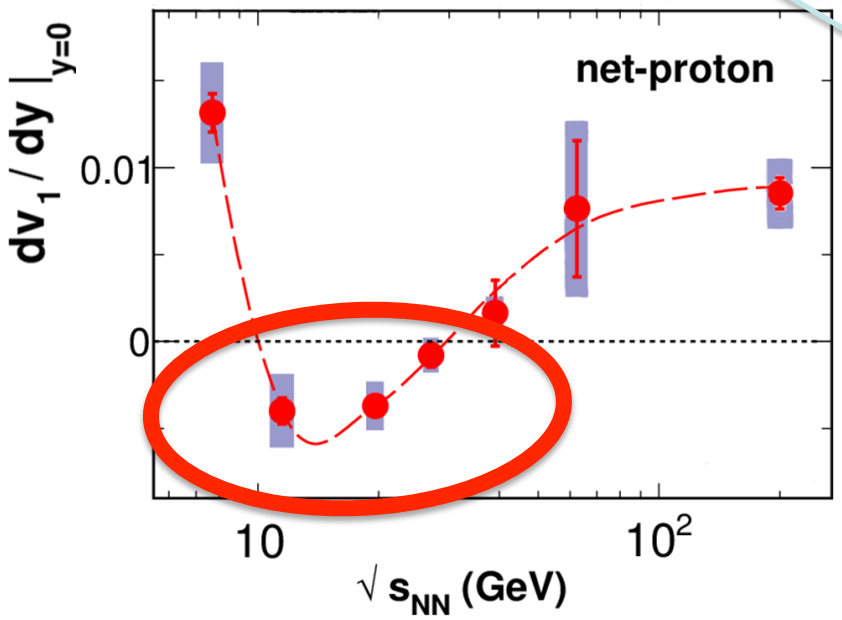


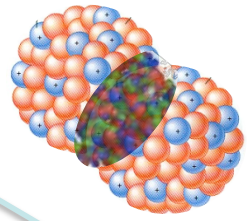
PUSH!



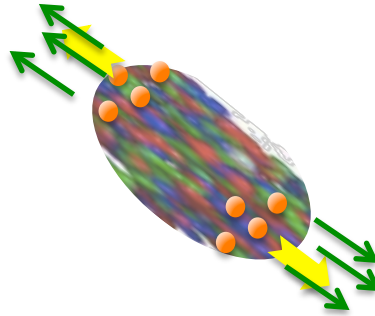
v_1 cartoon by Mike Lisa

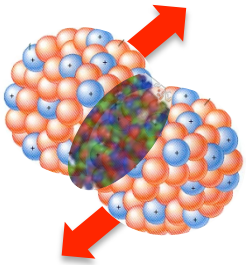






SOFT...





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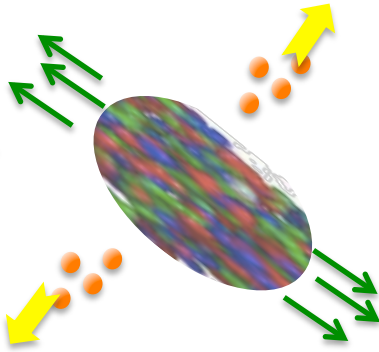
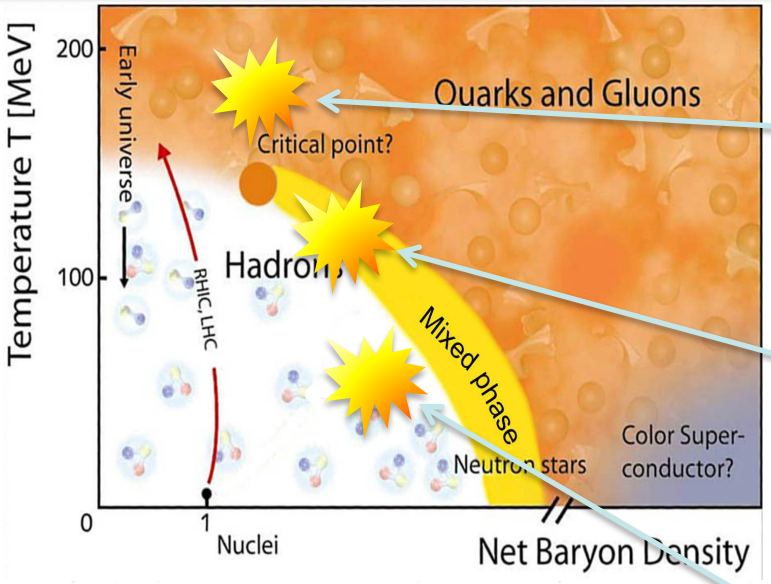
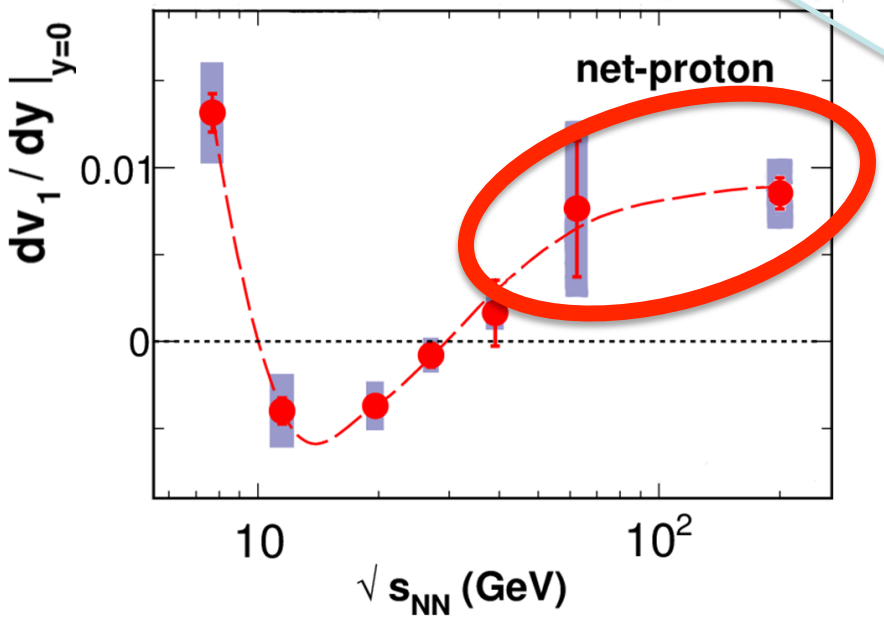
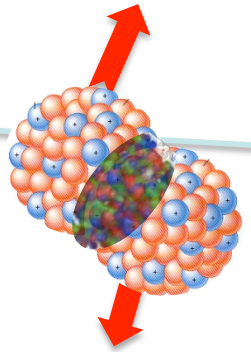


v_1 cartoon by Mike Lisa







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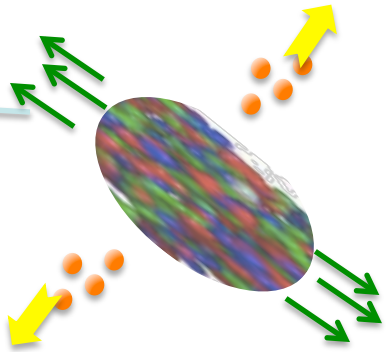

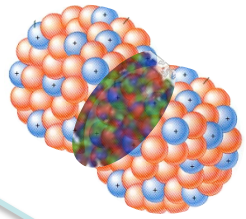

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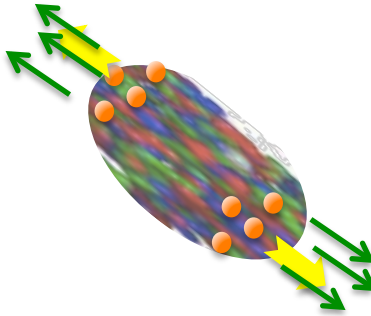

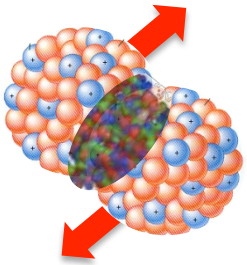

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