ELTE Particle Physics Seminar

Budapest, 18 November 2015

Recent heavy ion results from the STAR experiment

1) Heavy flavor and Quarkonia
2) RHIC Beam energy scan

Róbert Vértesi

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Research Centre for Physics

Relativistic Heavy-Ion Collider

- The LHC era: bigger, better, higher energy, preciseness; so **why still RHIC?**

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- Heavy-Ion Physics: **not an energy frontier science**!
  - Higher energy <==> higher cross-sections
    but we are often readout-bound
  - "Full-featured" deconfined matter at $\sqrt{s_{NN}}$=200 GeV
- RHIC: extremely versatile
  - **Collides anything** from protons to Uranium, symmetric or asymmetric (even polarized protons for spin studies up to 510 GeV)
  - **From 7.7 (3) GeV to 200 GeV with the same apparatus**
- Continuous, ongoing machine and detector development
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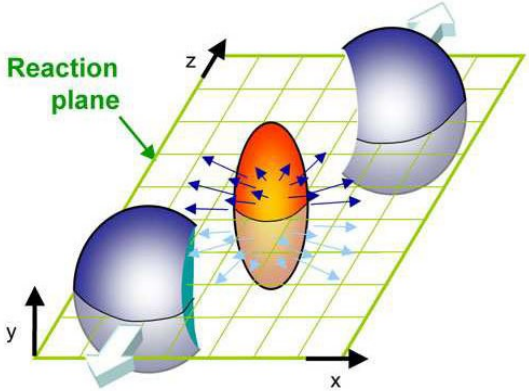
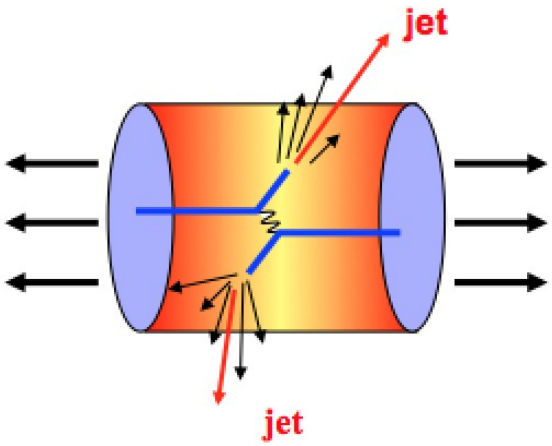
RHIC: the most colorful physics program in HE HI

Heavy Ion Physics at STAR

- **sQGP at top energy:**
  Thermal, dynamical properties
  - "**Soft**" (low-p_T)
    bulk behavior
    (collective dynamics)
  - "**Hard**" (high-p_T)
    "tomography"
    pQCD+medium





Heavy Ion Physics at STAR

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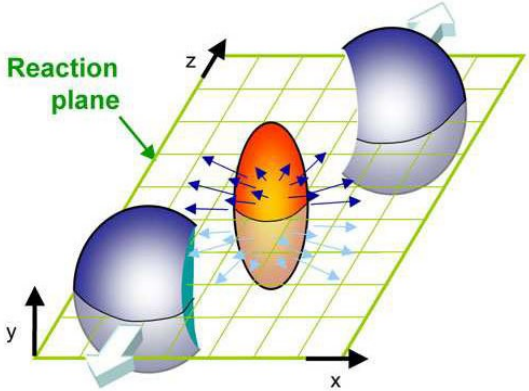
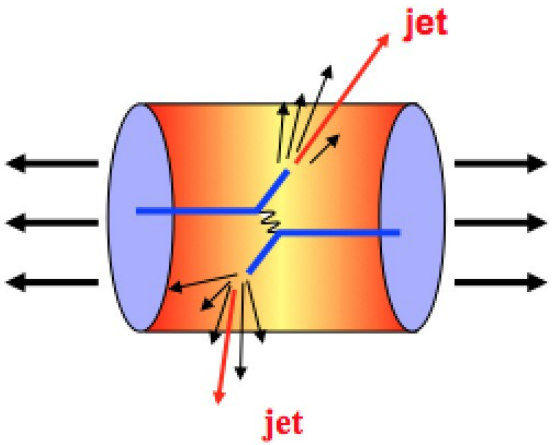
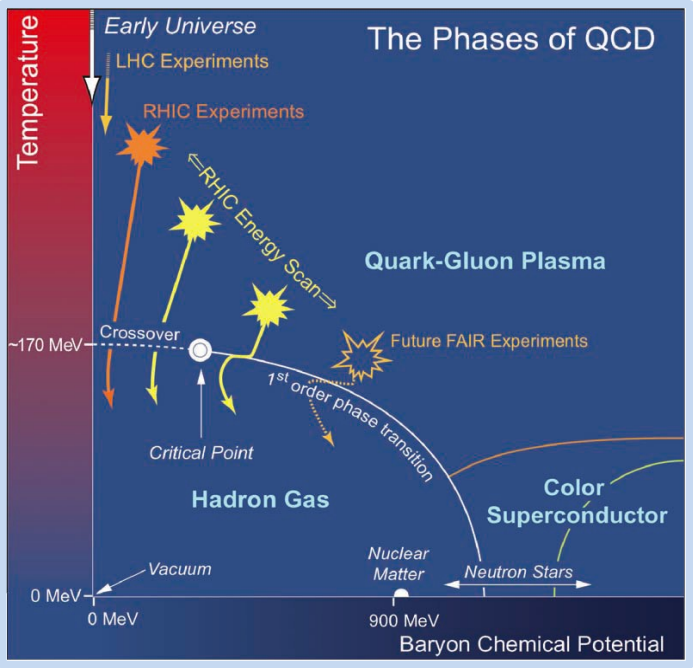
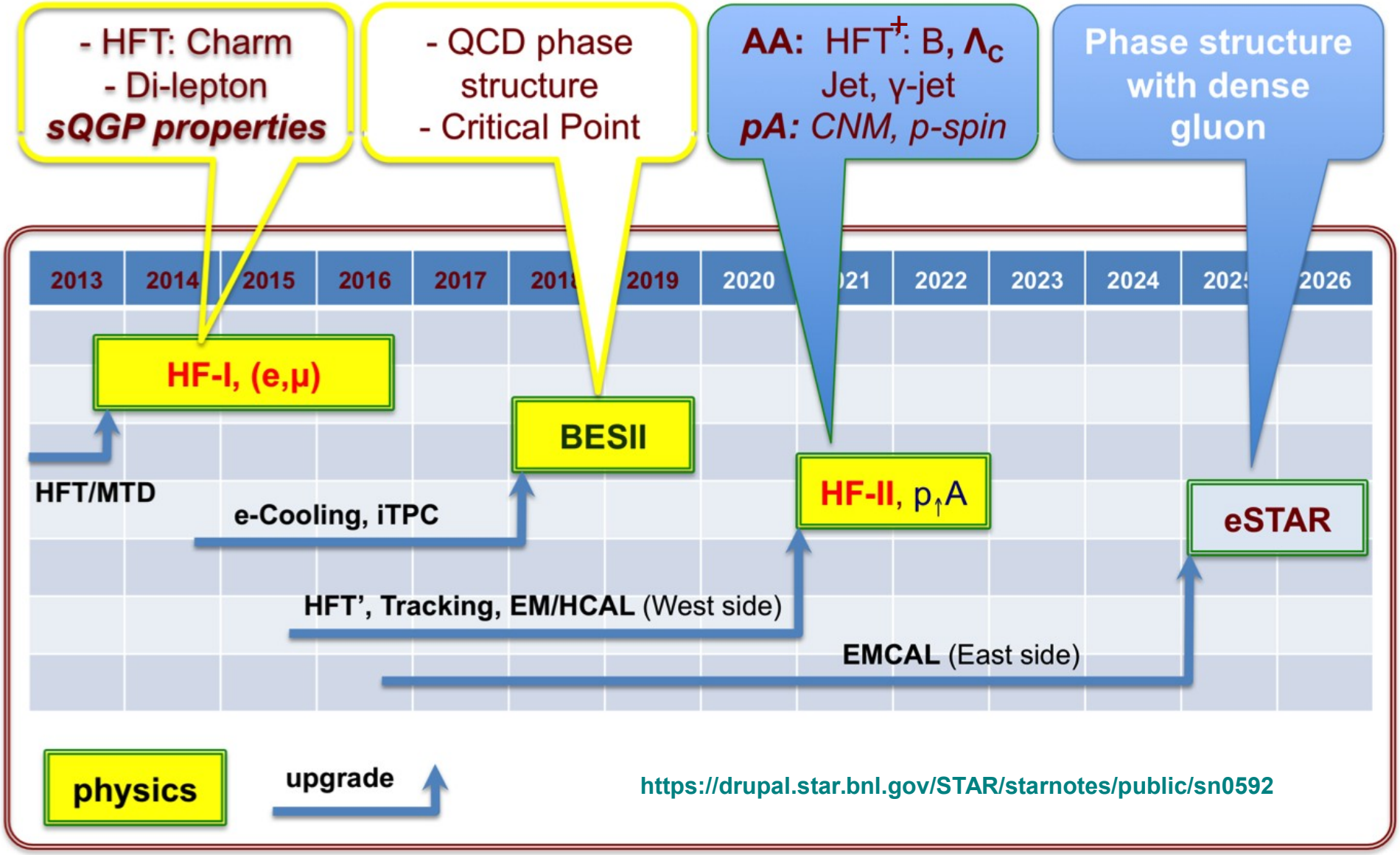




- **Beam Energy Scan:**
  explore the phase diagram
  - **Onset** of the sQGP
  - 1st order **phase transition**
  - Search for the **critical point**

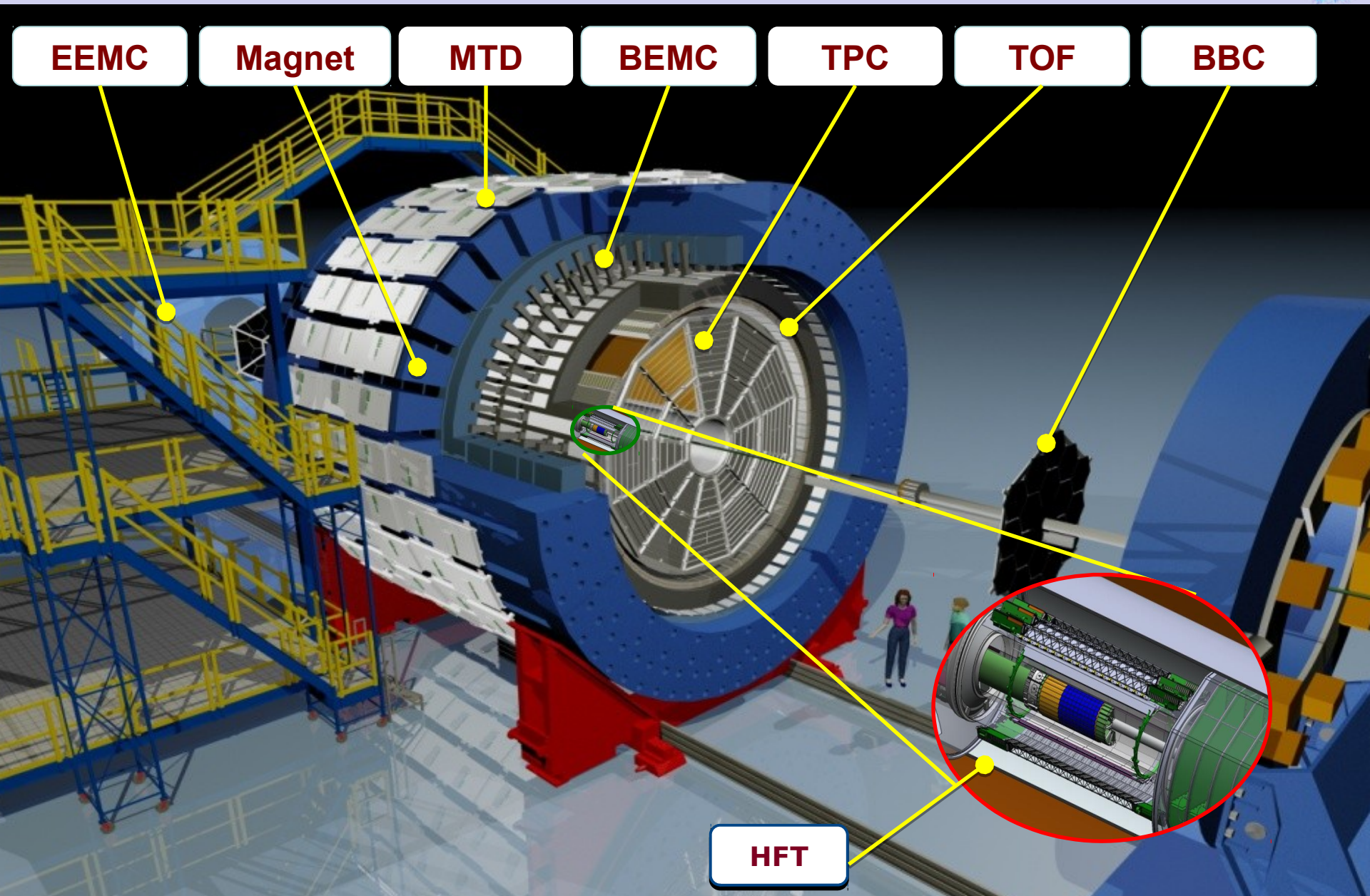


STAR Long-Term Plan

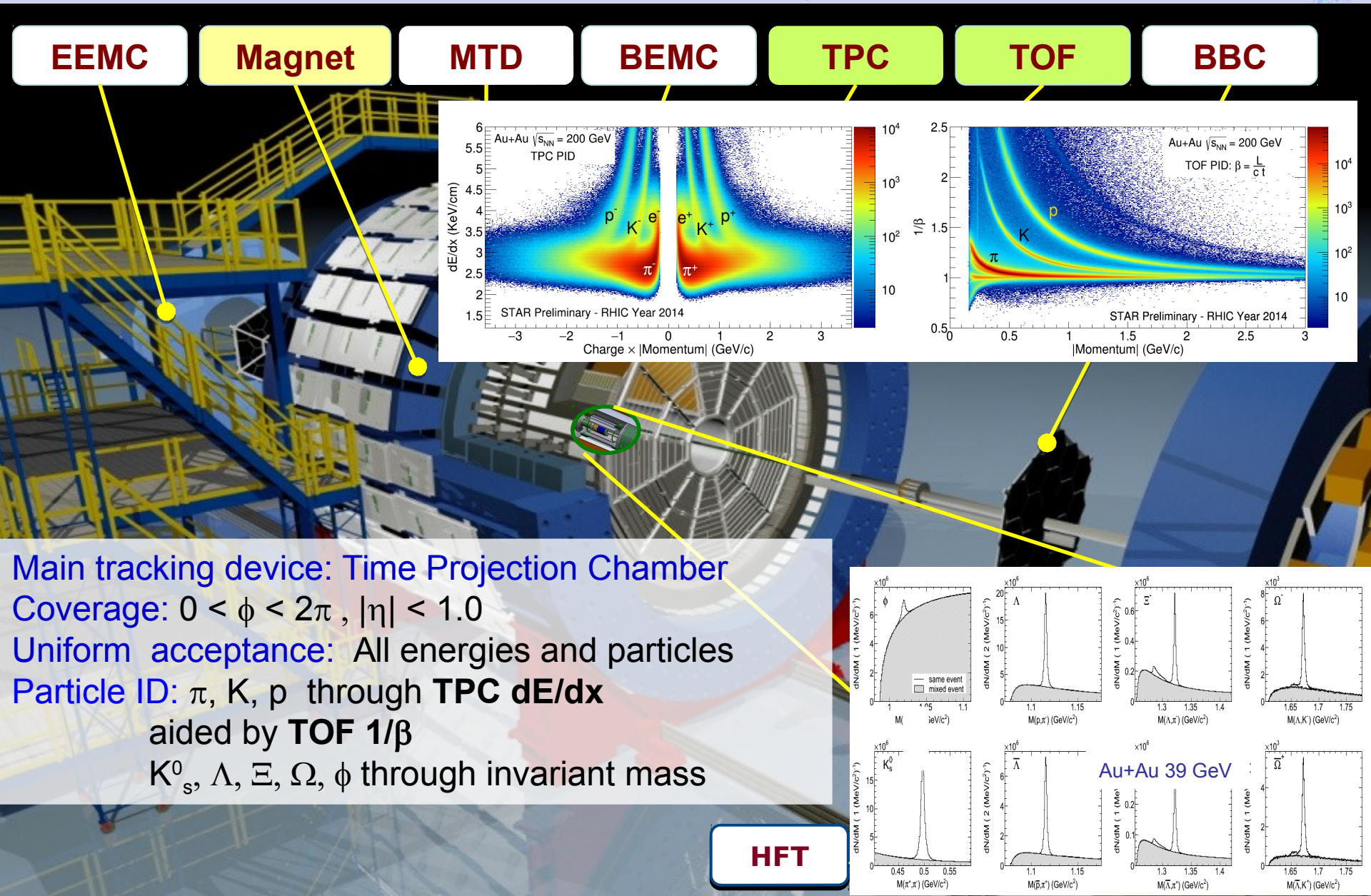


https://drupal.star.bnl.gov/STAR/starnotes/public/sn0592

STAR at RHIC



Tracking



Main tracking device: Time Projection Chamber

Coverage: $0 < \phi < 2\pi$, $|\eta| < 1.0$

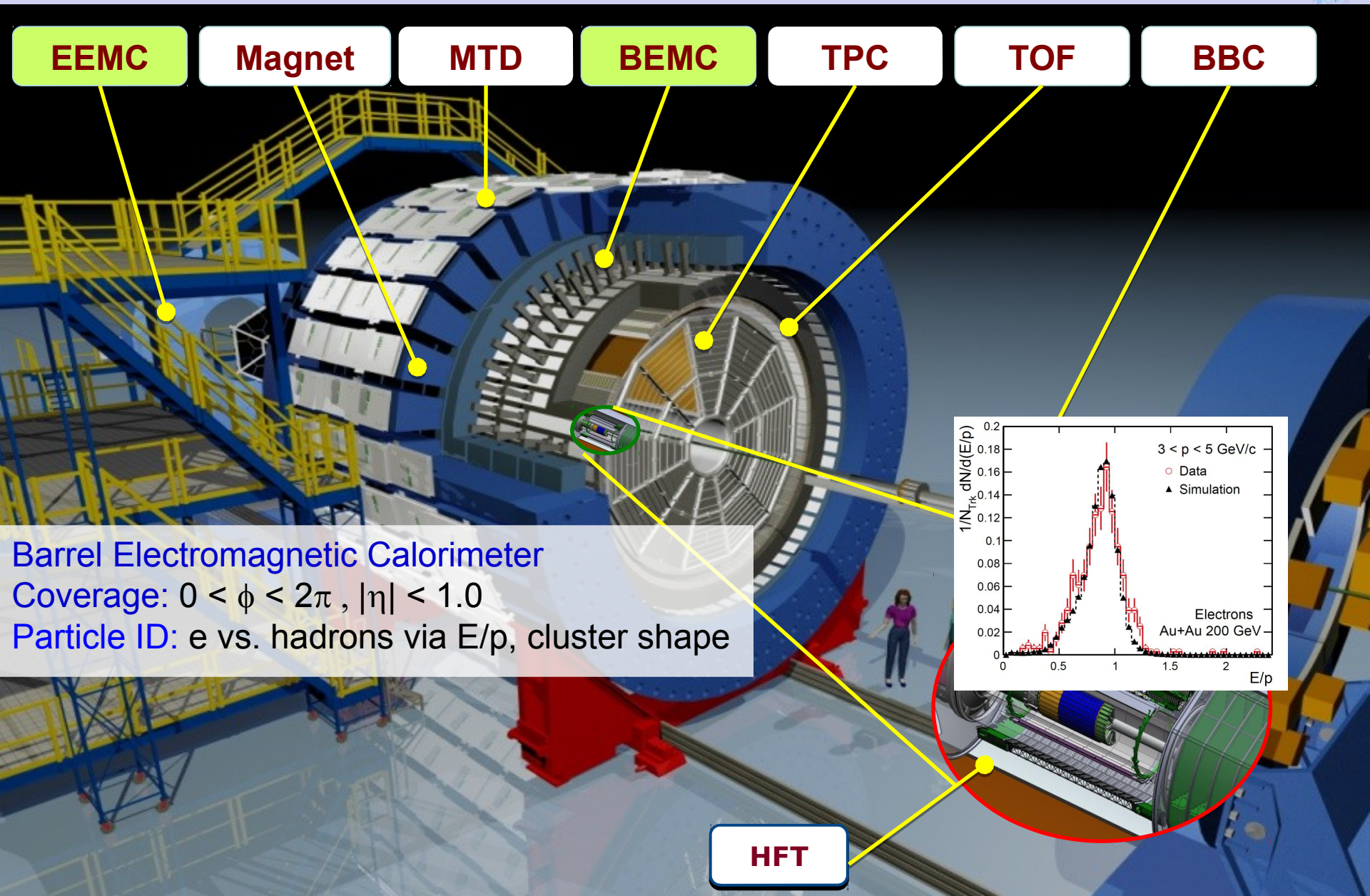
Uniform acceptance: All energies and particles

Particle ID: π, K, p through **TPC dE/dx**

aided by **TOF 1/β**

K^0_s, Λ, Ξ, Ω, ϕ through invariant mass

Calorimeter

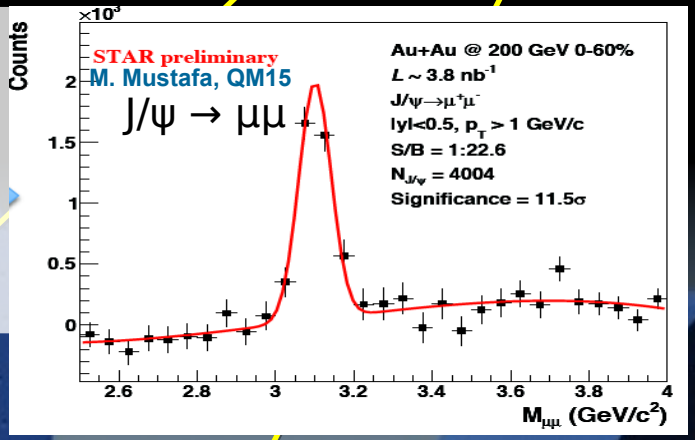


Barrel Electromagnetic Calorimeter
Coverage: $0 < \phi < 2\pi$, $|\eta| < 1.0$
Particle ID: e vs. hadrons via E/p, cluster shape

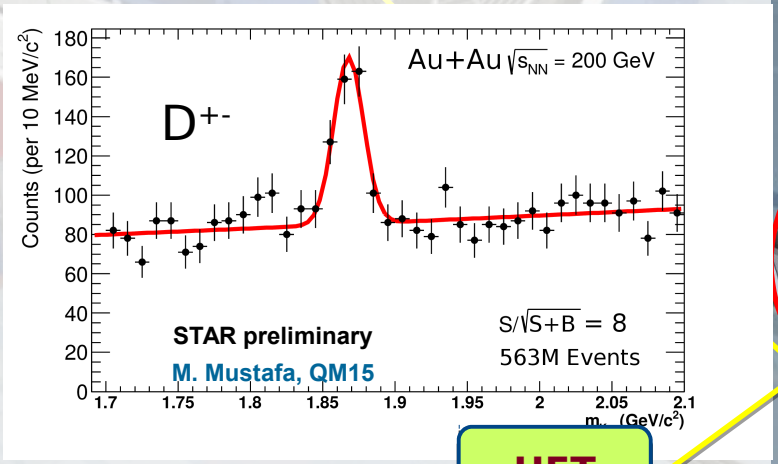
New 2014: heavy flavor and muons

EEMC | Magnet | MTD | BEMC | TPC | TOF | BBC

Muon Telescope Detector *(outermost)*
Coverage: 45% in azimuth , $|\eta| < 0.5$
Particle ID: muons
Goal: **Precise quarkonium measurements**
30% of 2014 Au+Au data processed



Heavy Flavor Tracker (innermost)
Secondary vertex reco
Goal: **Precise open HF measurements**
70% of 2014 Au+Au data processed



HFT

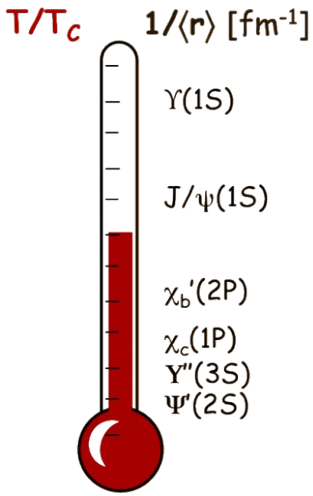
Quarkonia

- Debye screening of heavy quark potential
  → Quarkonia are expected to dissociate

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

Charmonia ($\bar{c}c$):
J/Ψ, Ψ', χ_c

Bottomonia ($\bar{b}b$):
$\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_B



- Sequential melting: Different states dissociate at different temperatures

  Á. Mócsy, P. Petreczky, Phys. Rev. D77, 014501 (2008)

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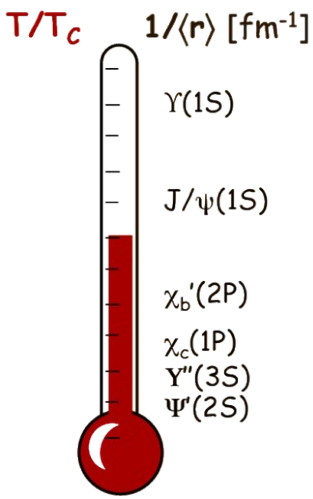

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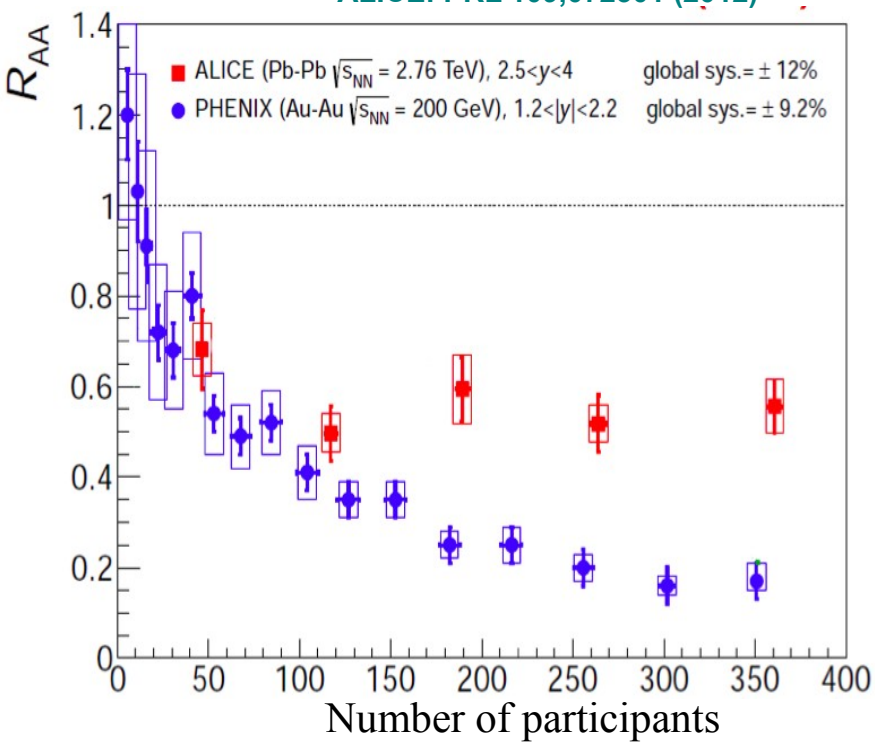
Quarkonia may serve as sQGP thermometer

“The J/ψ mystery”

PHENIX: PRC 84 (2011) 054912
ALICE: PRL 109,072301 (2012)



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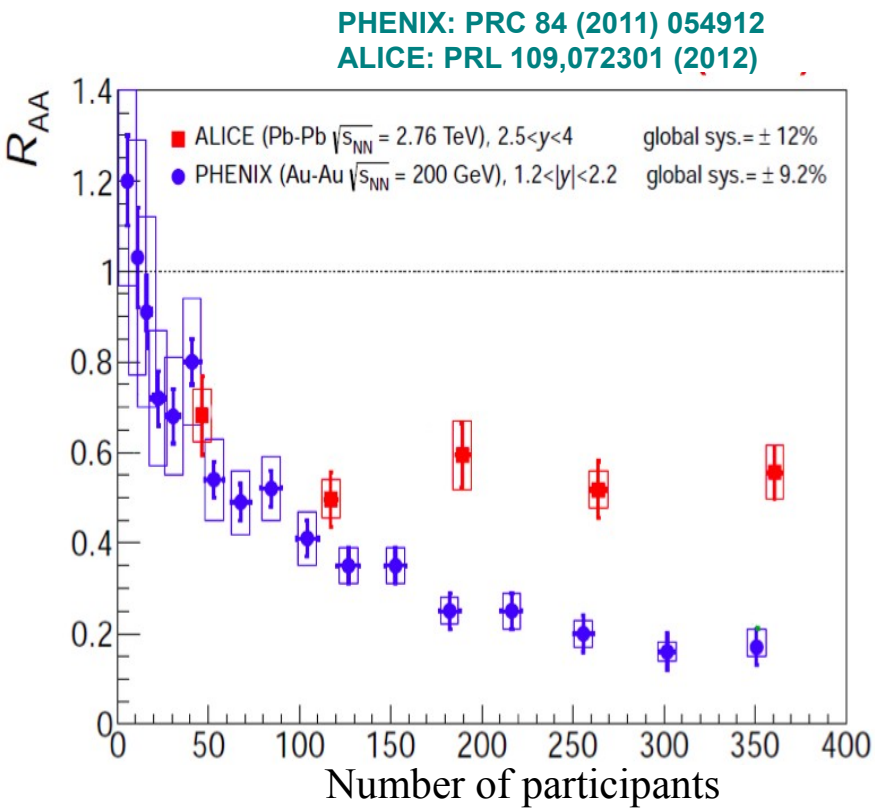
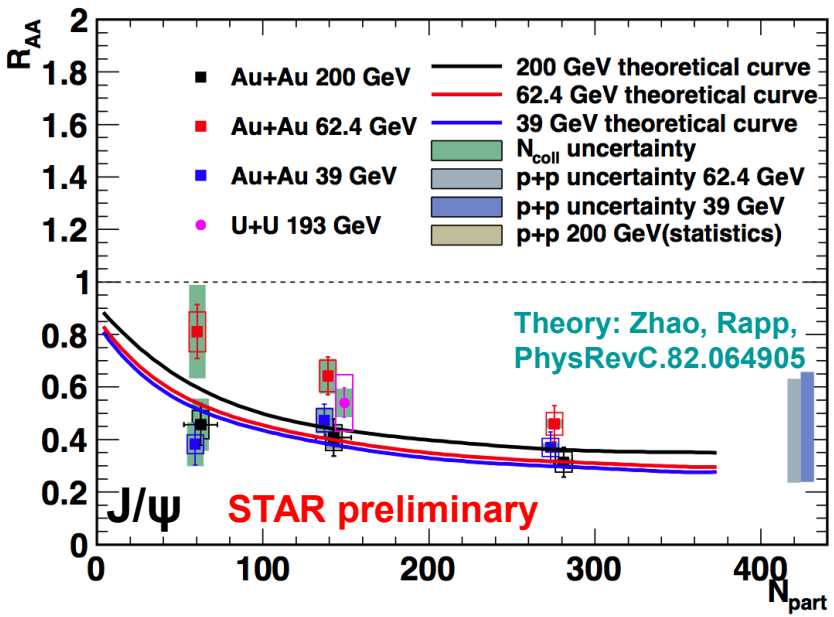


- Cold nuclear matter effects
  - Nuclear shadowing (PDF modification in the nucleus)
  - Initial state energy loss
  - Co-mover absorption
- Hot/dense medium effects
  - Coalescence of uncorrelated charm and bottom pairs
- Feed-down
  - χ_c, ψ’, B-meson decay to J/ψ
  - χ_b, ϒ(2S), ϒ(2S) to ϒ(1S) …

Contribution of different effects is not well understood

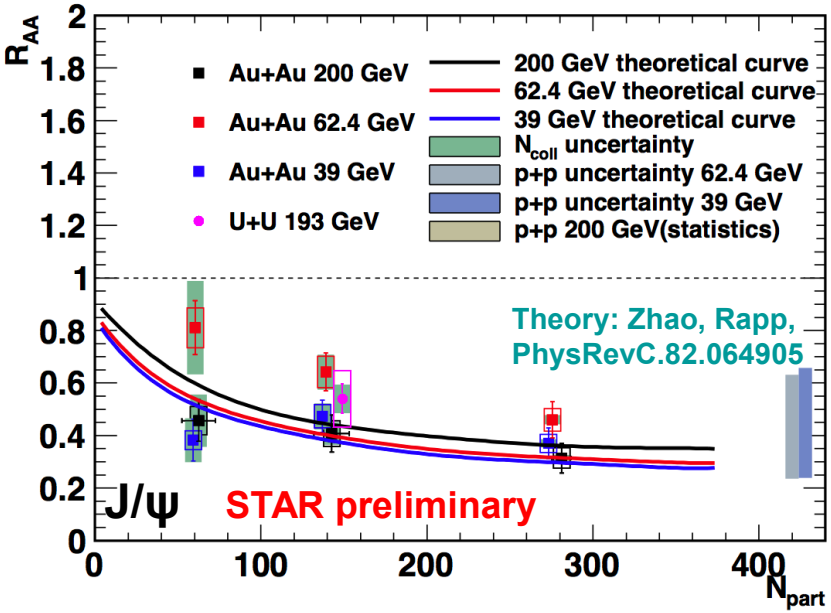
J/ψ suppression vs. beam energy

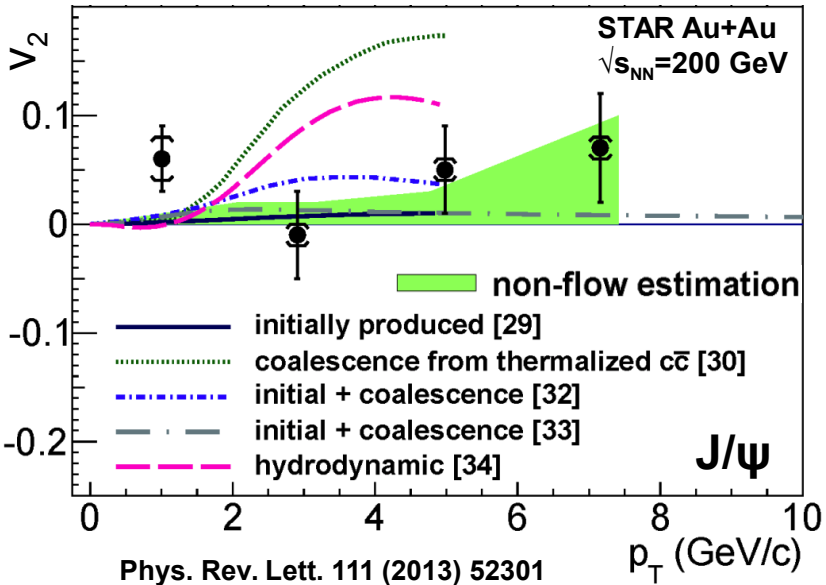


Suppression

- Similar to light hadrons
- Similar in central collisions from **39** thru **62.4** up to **200** GeV
  Note: 39 and 62.4 GeV CEM references have large uncertainties
- Similar in **U+U** and **Au+Au**
- Model with prompt production and regeneration consistent with data

J/ψ suppression and flow in Au+Au





Phys. Rev. Lett. 111 (2013) 52301

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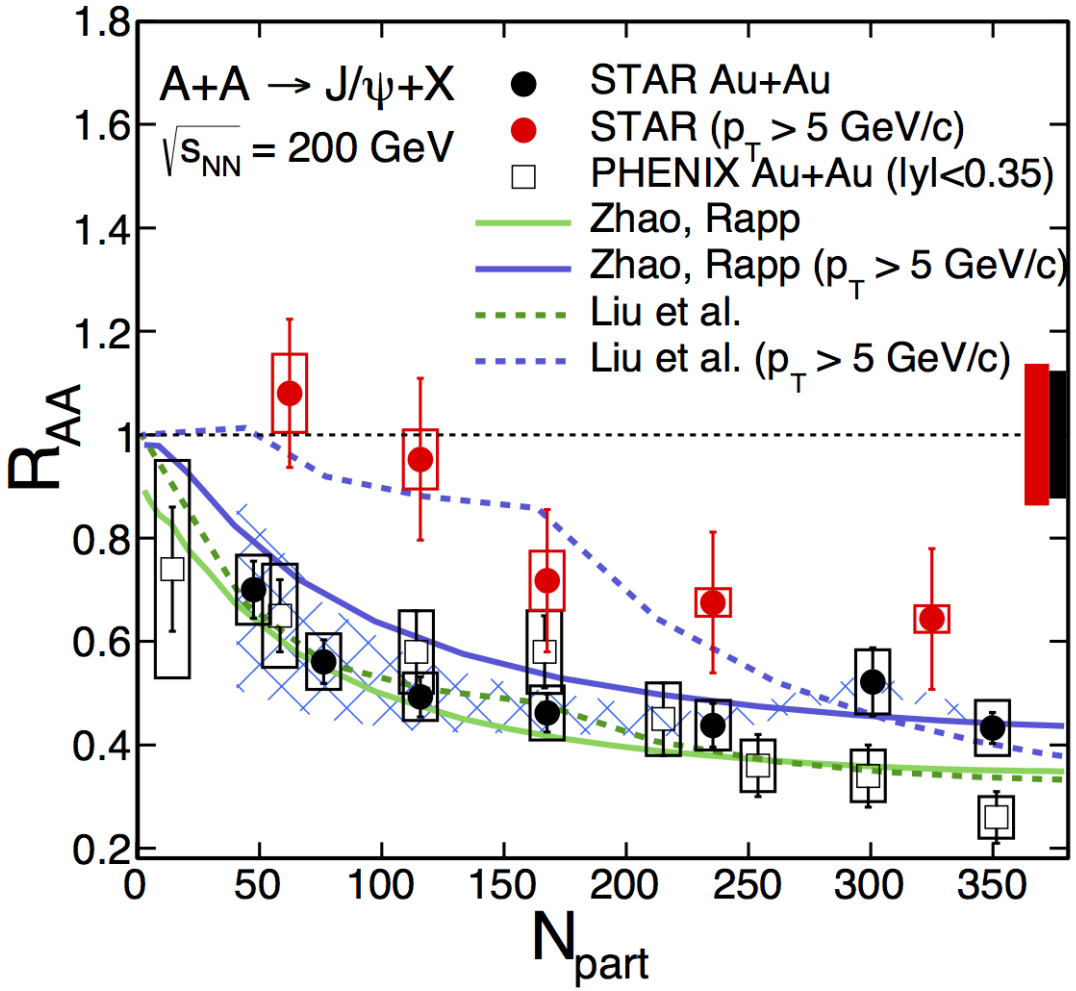
Anisotropy (v_2)

- **J/ψ v_2 consistent with non-flow** (p_T>2 GeV/c; unique among hadrons)
- Model with thermalized charm quark coalescence disfavored

[29] Yan, Zhuang,Xu, PRL97 (2006) 232301
[30] Greco, Ko, Rapp, PLB595 (2004) 202
[32] Zhao, Rapp, PLB 655 (2007) 126
[33] Liu,Xu,Zhuang, NPA834 (2010) 317c
[34] Heinz, Chen (2012)

High-p_T J/ψ in Au+Au



- CNM effects are small
- Less regeneration
- Suppression of high-p_T J/ψ in central collisions

STAR low-p_T : arXiv:1310.3563
STAR high-p_T : PLB722, 55 (2013)
Liu et al., PLB 678, 72 (2009)
Zhao and Rapp, PRC 82, 064905(2010), PLB 664, 253 (2008)
PHENIX Phys. Rev. Lett. 98, 232301 (2007)

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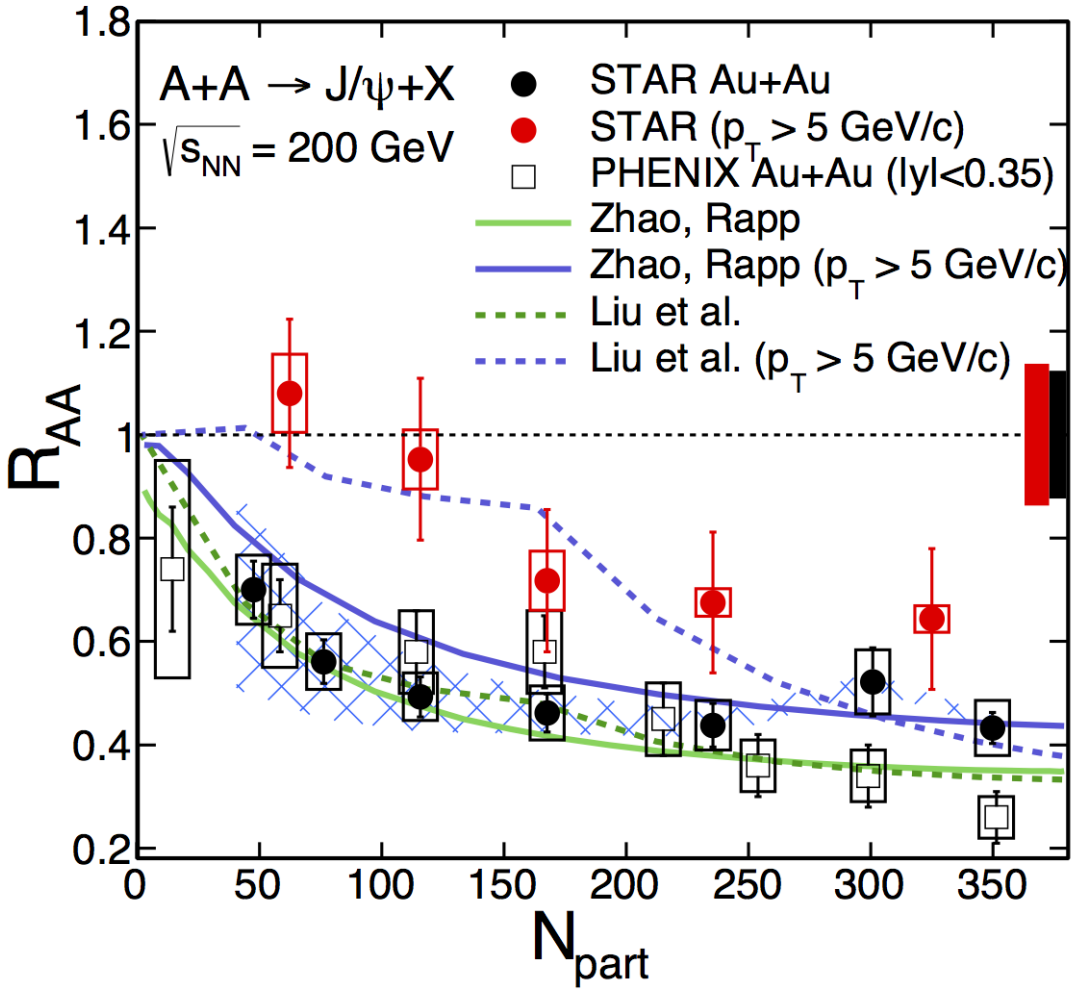

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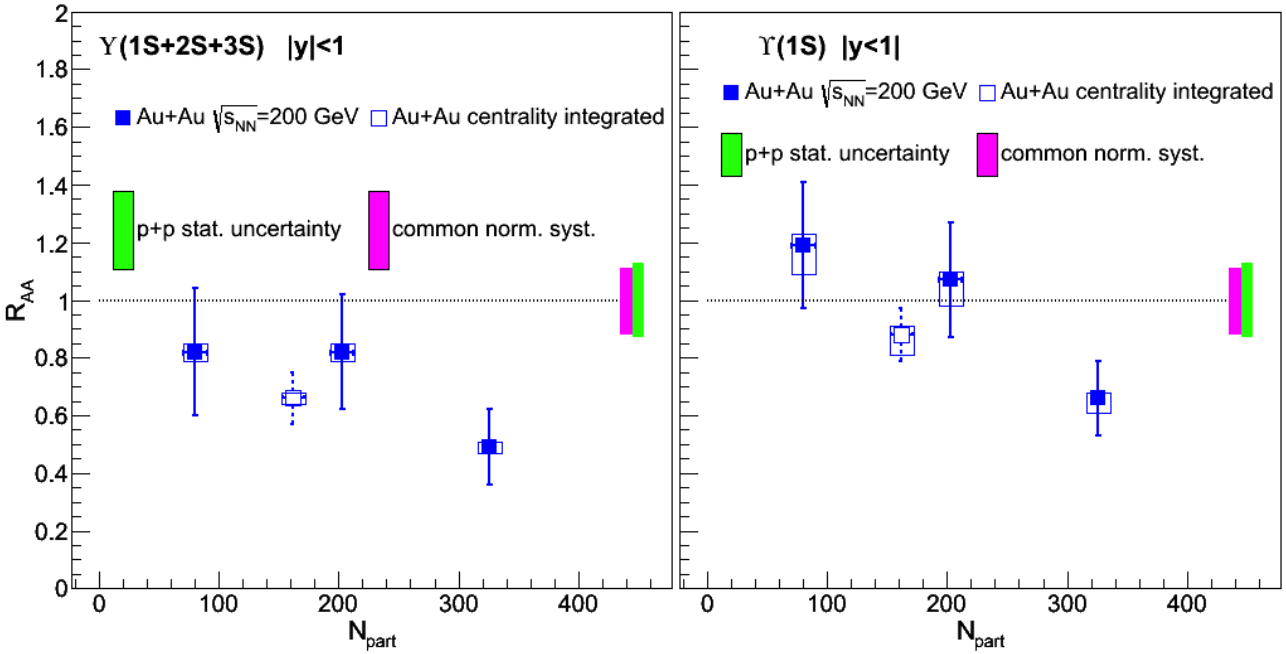
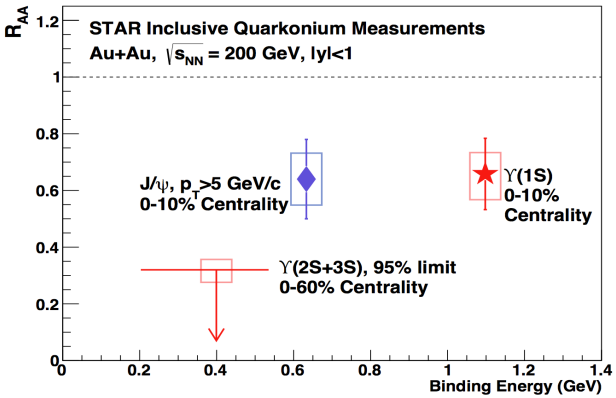
High-p_T J/ψ suppression is clearly an sQGP effect

R_{AA} of Υ states in Au+Au



STAR:
Phys.Lett. B735 (2014) 127



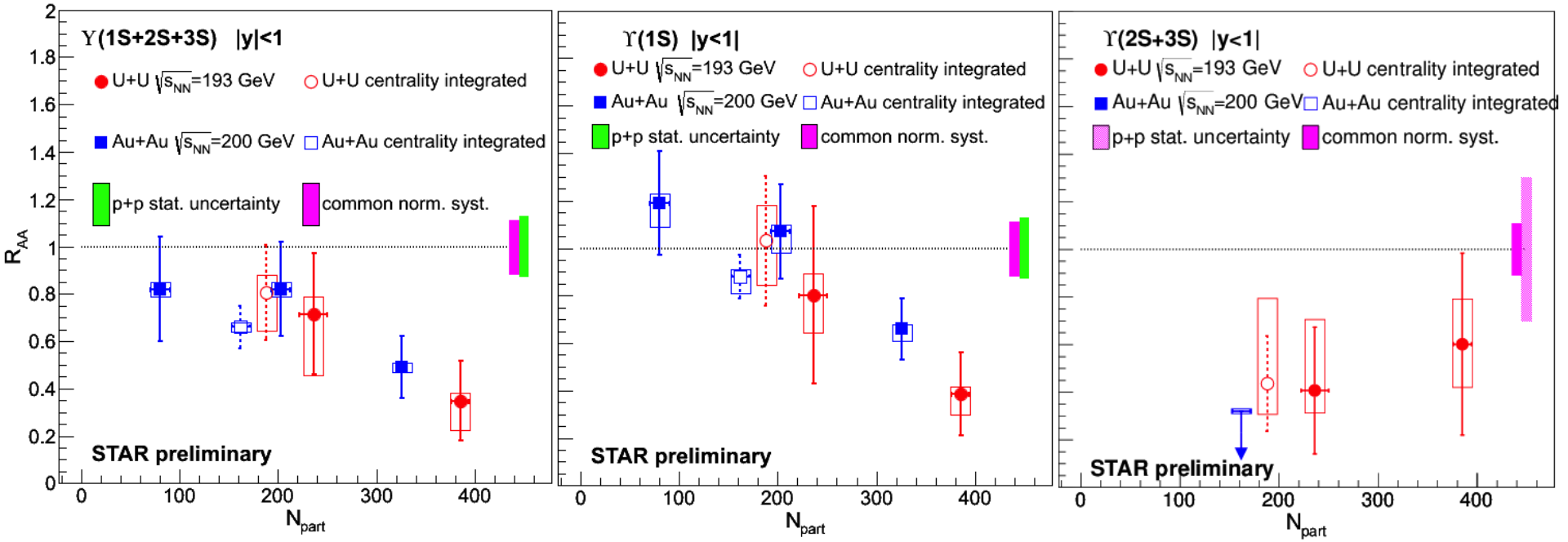
- Peripheral Υ consistent with no suppression
- Central Υ shows significant suppression

- Central $\Upsilon(1S)$: indication of a suppression

- Excited states $\Upsilon(2S)$ and $\Upsilon(3S)$ consistent with complete melting

Υ suppression pattern supports sequential melting

R_{AA} of Υ states: Au+Au vs. U+U



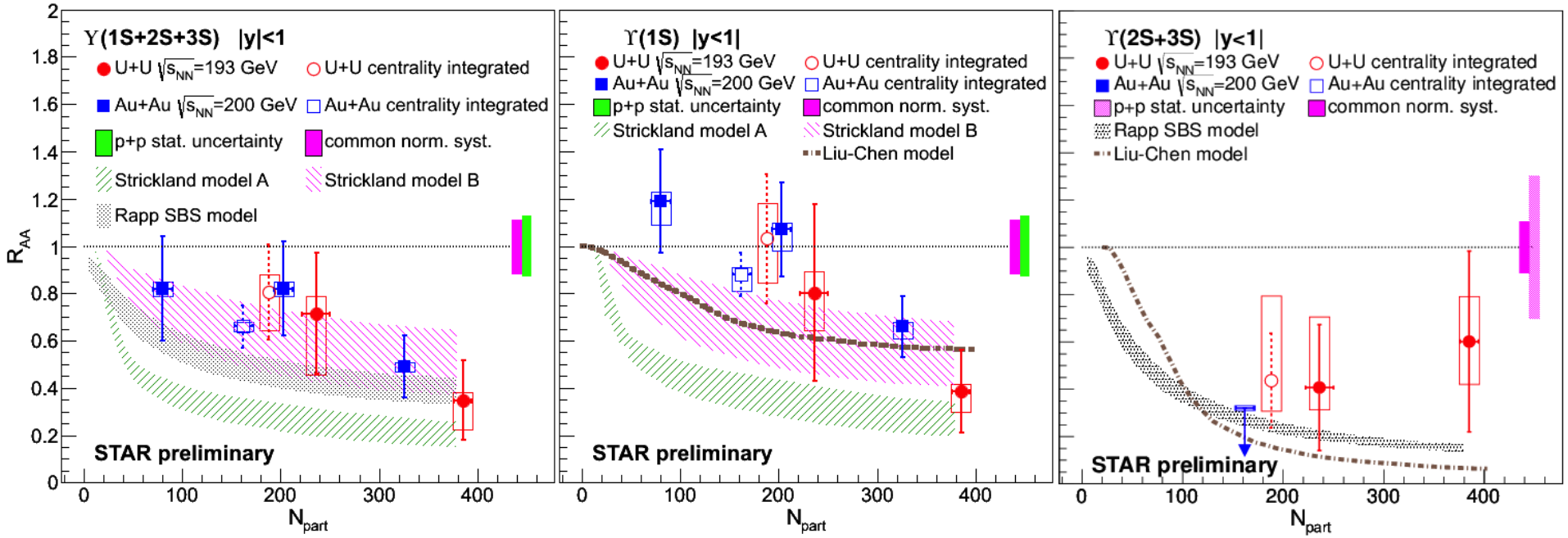
- Peripheral Υ consistent with no suppression
- Central Υ shows significant suppression

- Central Υ(1S): *significant suppression*

- Excited states Υ(2S) and Υ(3S) consistent with complete melting
- *Hint of their presence in U+U collisions*

New U+U data extends Au+Au trend – is U+U different?

R_{AA} of Υ states: data vs. models



Strickland, Bazov, Nucl.Phys.A 879, 25 (2012)

- No CNM effects, **428<T<443 MeV**
- Potential model 'B' based on **heavy quark internal energy**
- Potential model 'A' based on heavy quark free energy (disfavored)

Liu, Chen, Xu, Zhuang, Phys.Lett.B 697, 32 (2011)

- Potential model, no CNM effects
- T=340 MeV, only excited states dissociate

Emerick, Zhao, Rapp, Eur.Phys.J A48, 72 (2012)

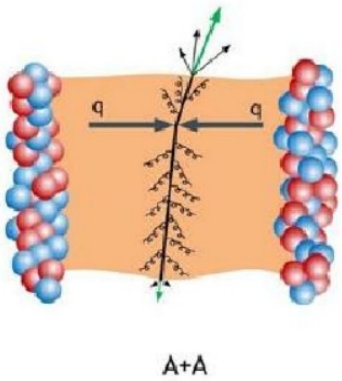
- **CNM effects** included
- Strong binding scenario

Suppression indicates Υ melting in a deconfined medium

However: CNM effects to be understood → **RHIC 2015 p+Au run**

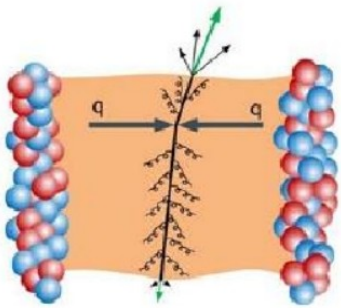
Open heavy flavor

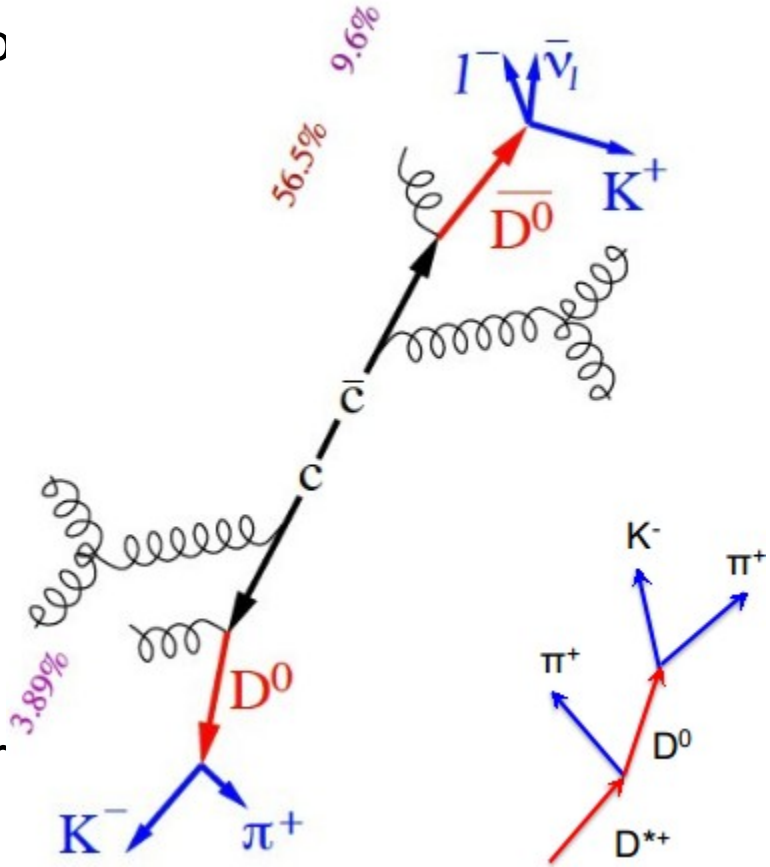
- Heavy quarks c, b
  - Produced in initial hard processes
  - Probe the strongly interacting Quark–Gluon Plasma
  - Modified spectrum: access parton energy loss
  - Flow: sensitive to dynamics, thermalization



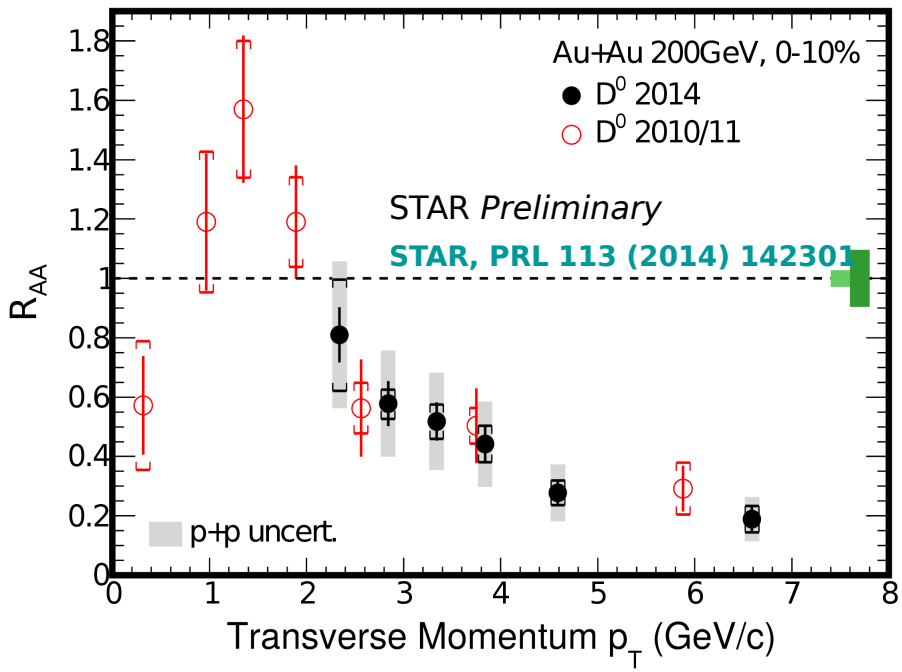
Open heavy flavor

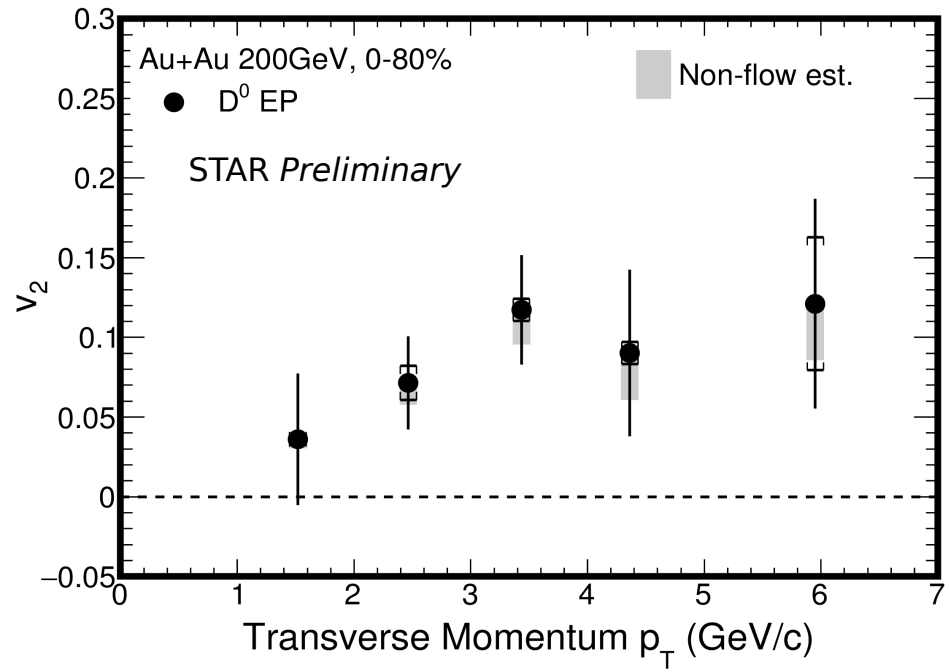
- Heavy quarks c, b
  - Produced in initial hard processes
  - Probe the strongly interacting Quark–Gluon Plasma
  - Modified spectrum: access parton energy loss
  - Flow: sensitive to dynamics, thermalizatic
- Semi-leptonic decays
  - Higher branching ratio, easy to trigger on
  - Indirect access to kinematics
  - mixture of c and b contributions
- **Hadronic reconstruction**
  - Direct access to kinematics
  - Large combinatorial bg., difficult to trigger
    ==> HFT: highly enhanced S/B





D^0 measurements: R_{AA} and v_2



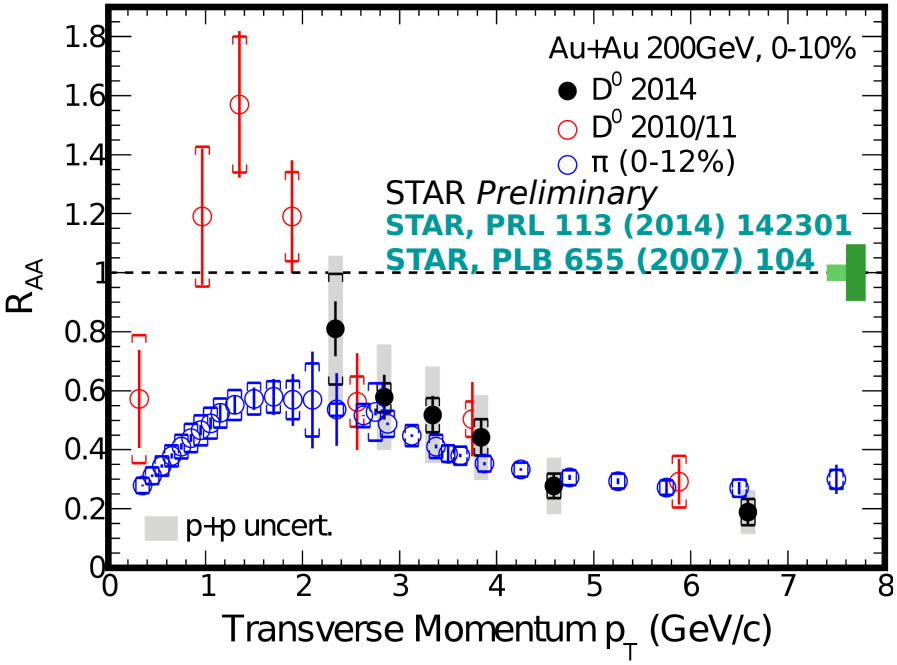


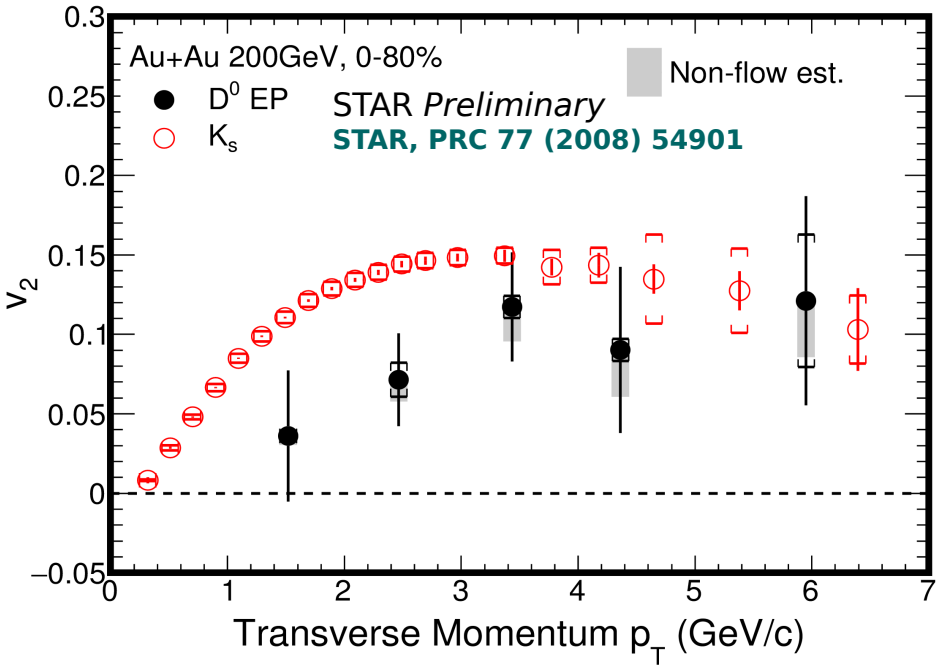
- **Significant suppression** in central Au+Au collisions at high p_T
- "Hump" at p_T<2 GeV/c is from the charm-medium coalescence
- *Note: overall charm is conserved*

- **Sizeable flow** (significant v2 above non-flow component at p_T>2 GeV/c

M. Mustafa, QM15

D^0 measurements: R_{AA} and v_2



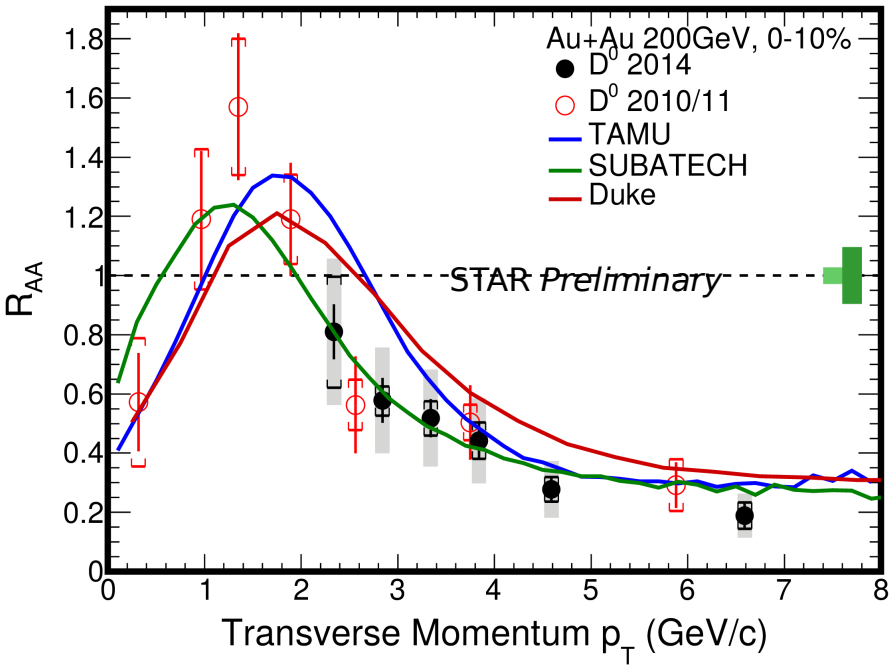


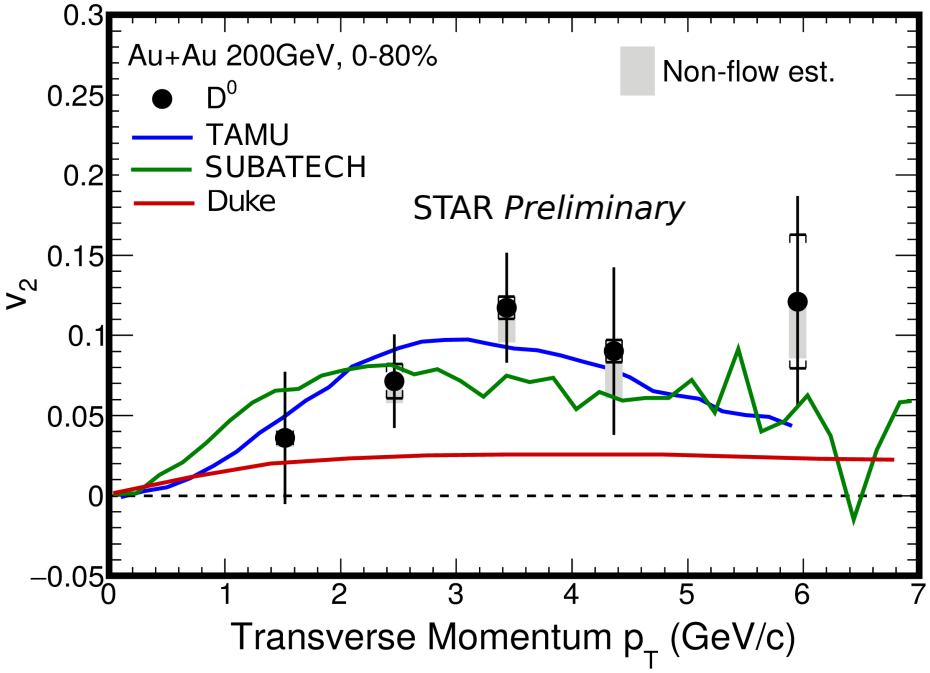
- **Significant suppression** in central Au+Au collisions at high p_T
- Agrees with light meson suppression

- **Sizeable flow** (significant v2 above non-flow component at p_T>2 GeV/c
- Less than that observed for light hadrons

M. Mustafa, QM15

D^0 measurements: theory comparison





- Data favors models with charm diffusion

  → **charm exhibits collectivity with the medium**

	HQ prod.	QGP-hydro	HQ e.loss	Coalesc	CNM
TAMU	LO pQCD	ideal	Coll.	yes	Cronin
SUBA TECH	FONLL	ideal	Coll.+rad.	yes	Cronin
Duke	LO pQCD	viscous	Coll.+rad.	yes	Shadow

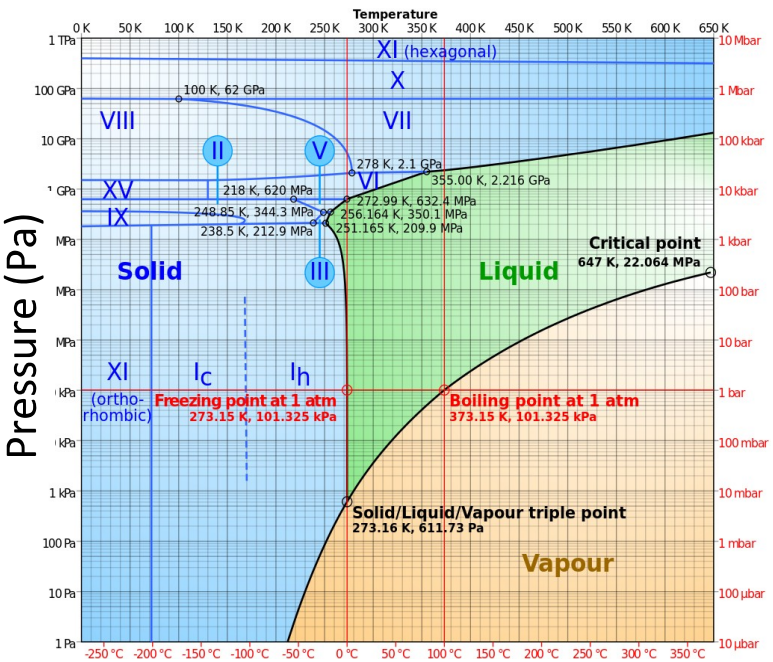
arXiv:1506.03981 (2015) & private comm.

- CNM effects may also be important

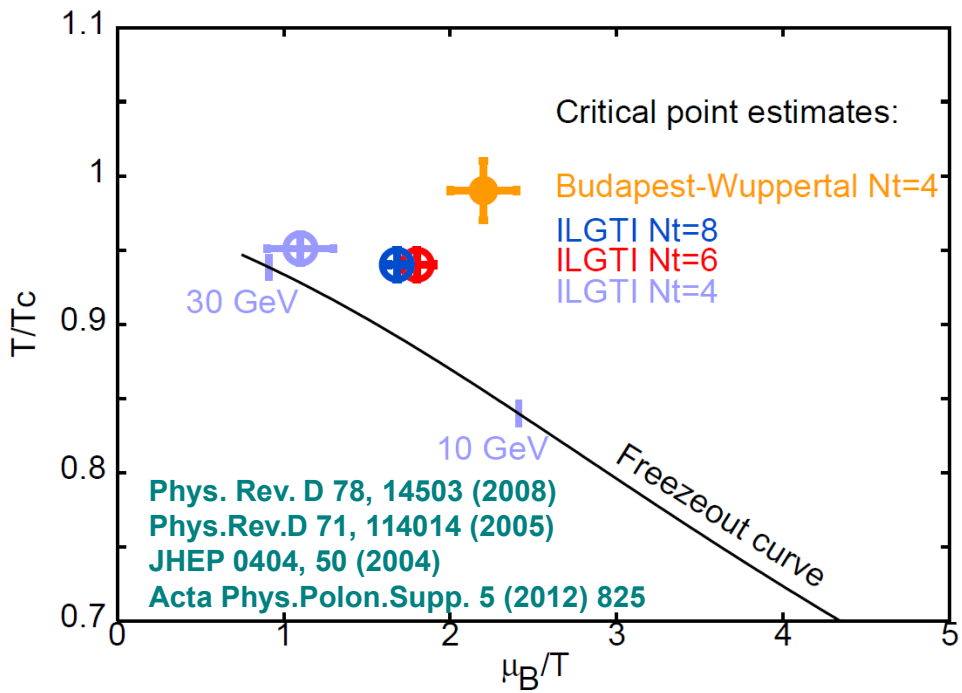
M. Mustafa, QM15

Beam Energy Scan

- 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

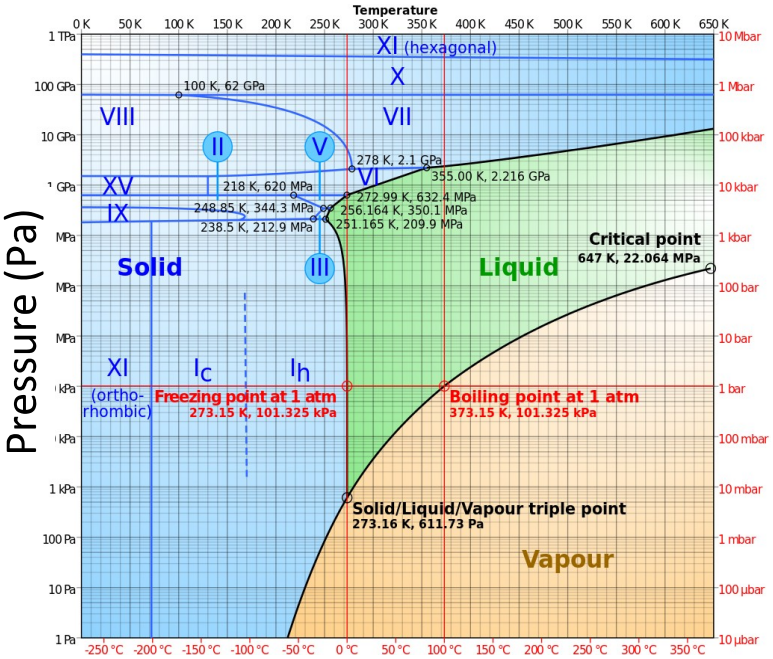


temperature



Beam Energy Scan

- 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



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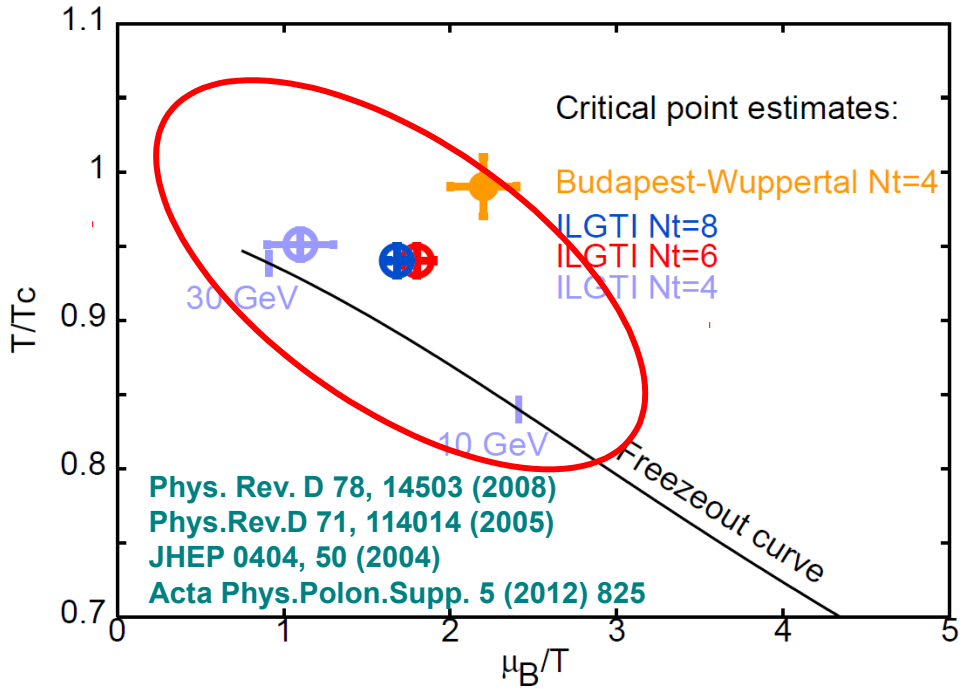
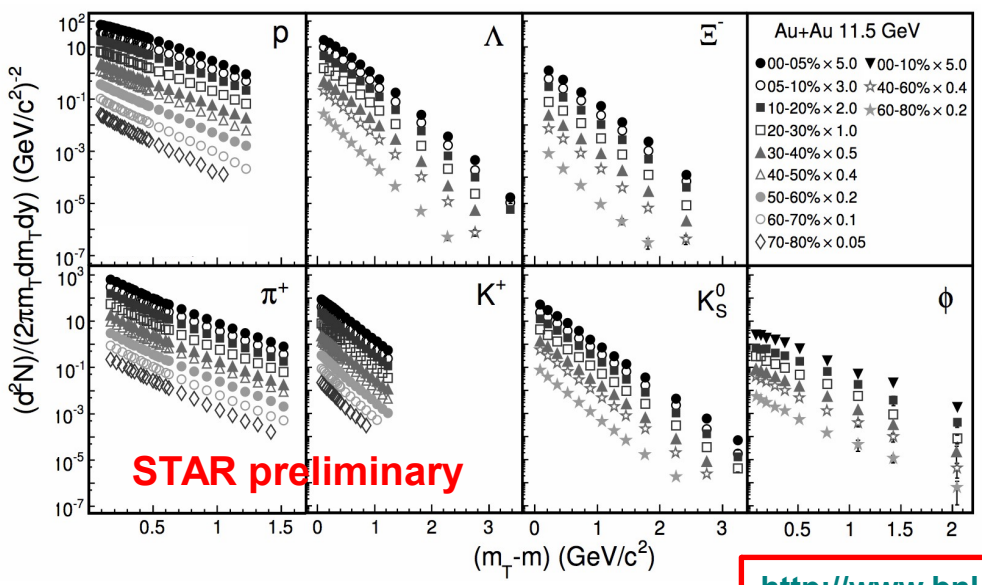
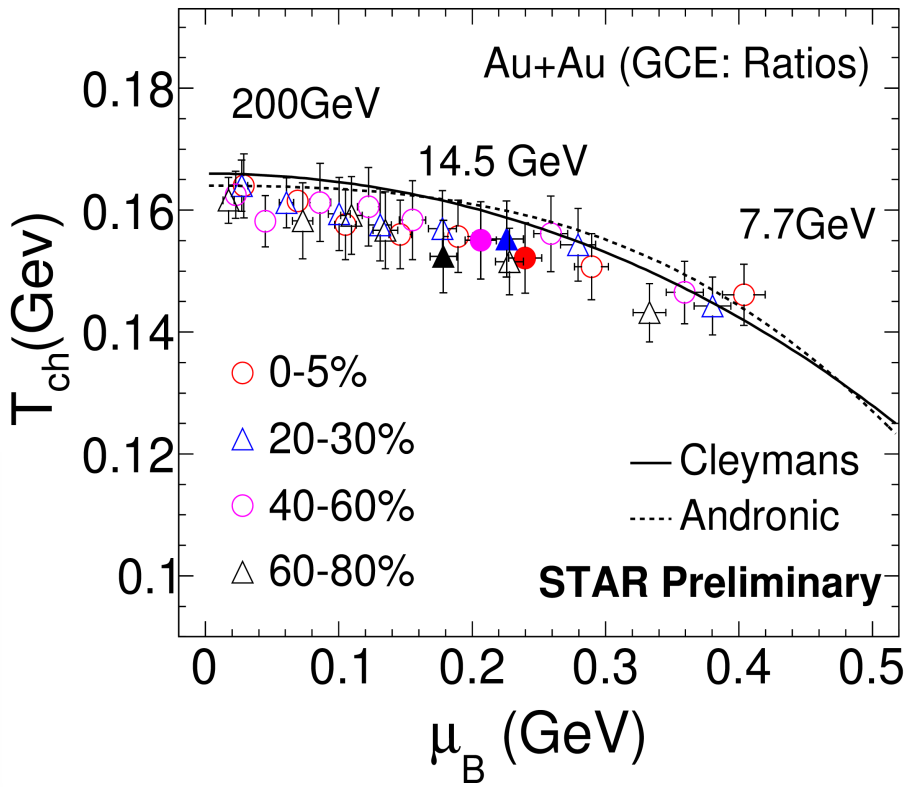


STAR BES-I

$\sqrt{s_{NN}}$ (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





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

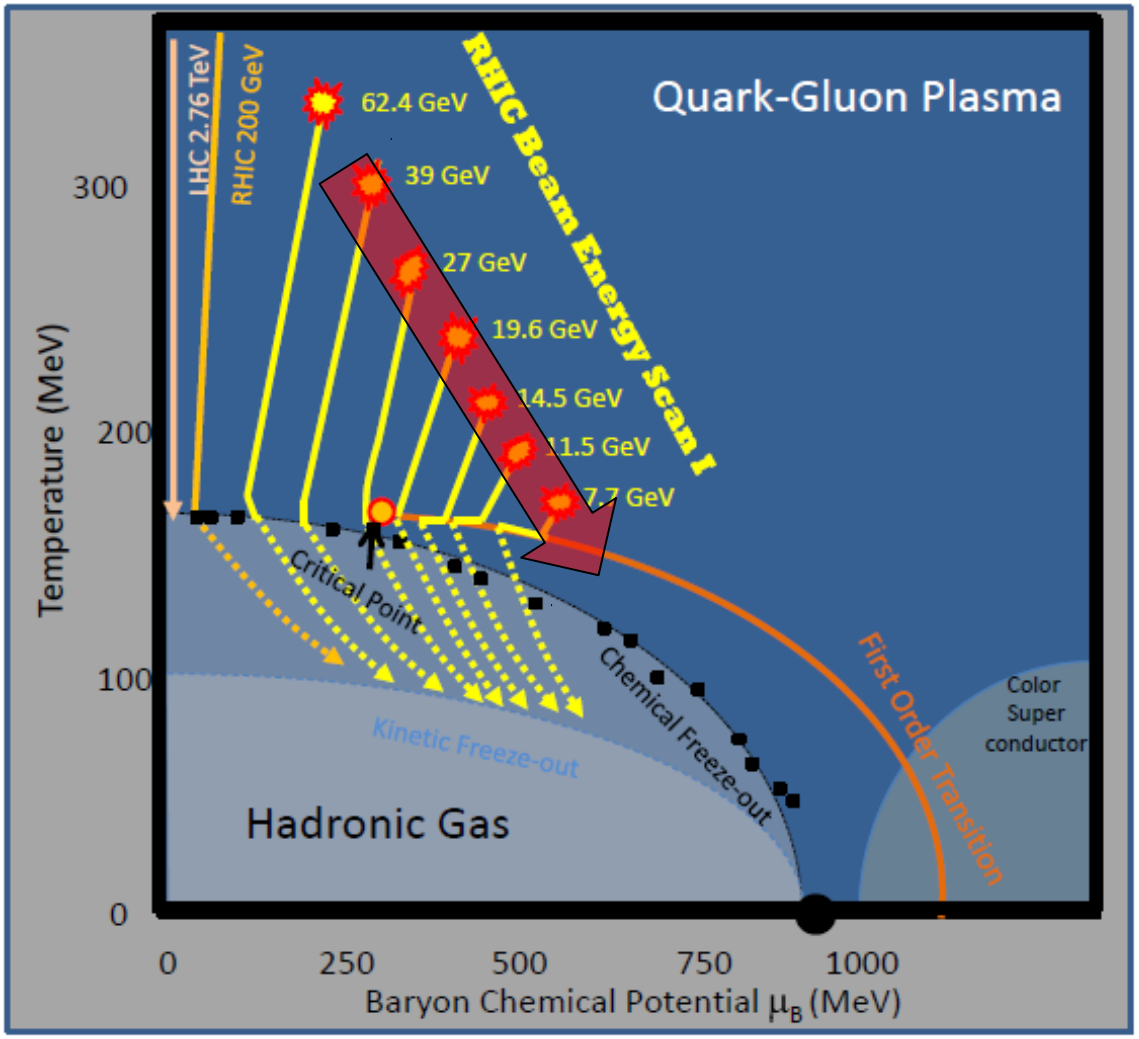
Exploring the QCD phase diagram

Find…

1) Turn-off of sQGP signatures

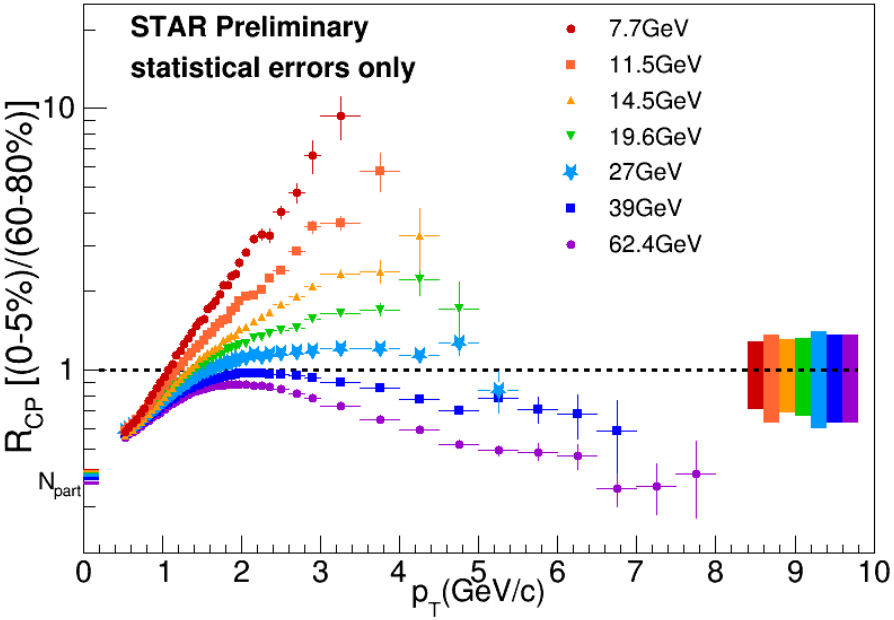
2) 1st order phase transition signs

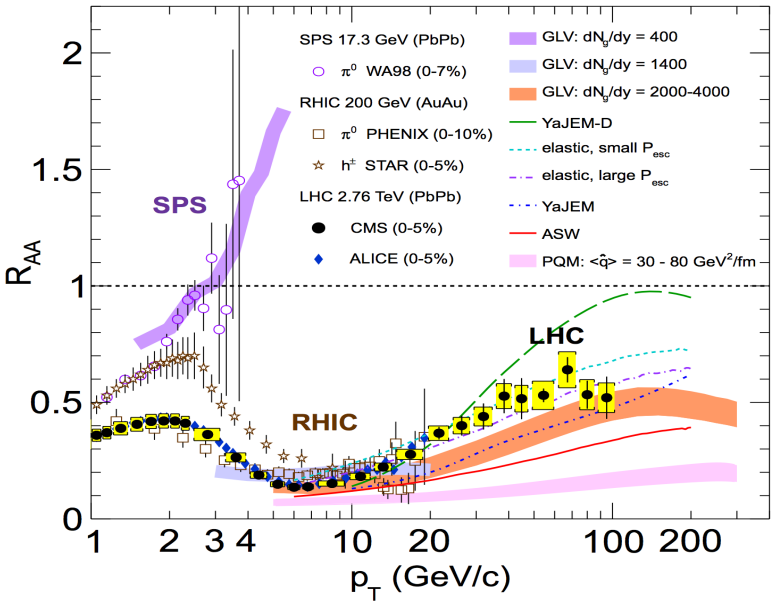
3) The QCD critical point



http://arxiv.org/abs/1007.2613

High-p_T hadron suppression

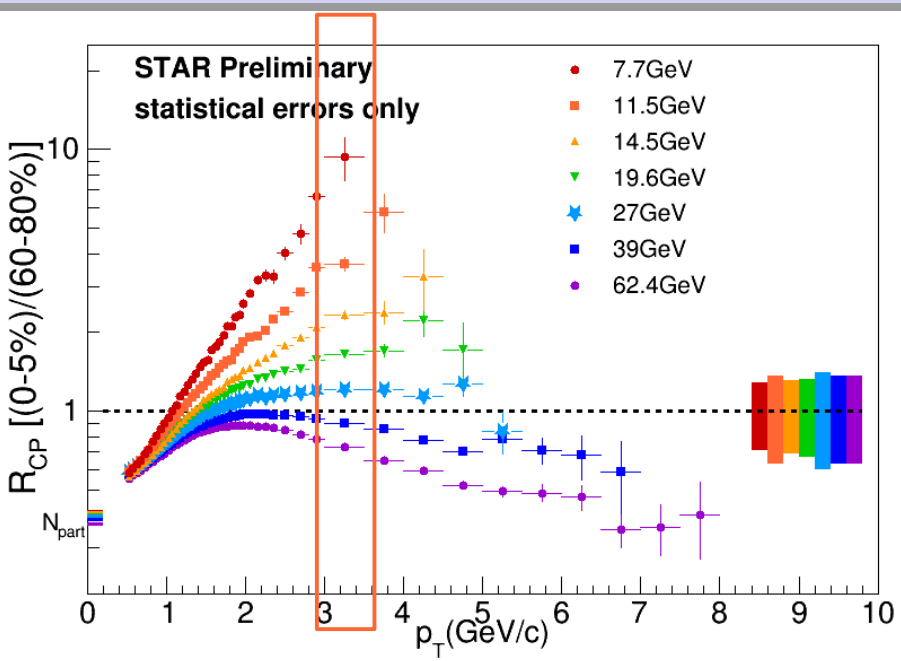


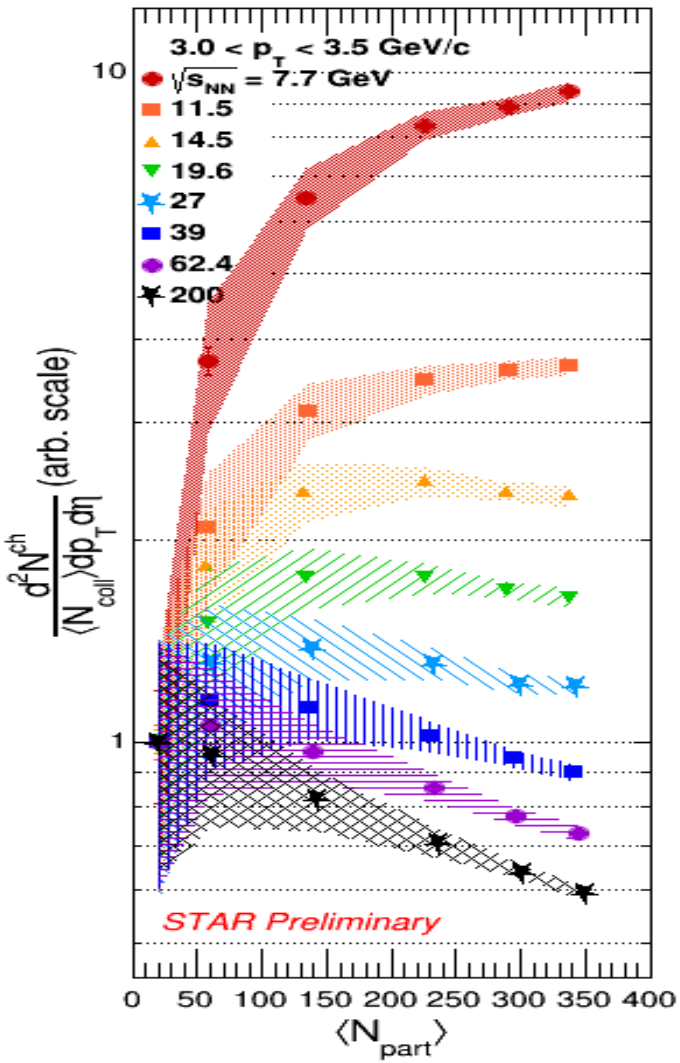


- **Suppression from 39 GeV up to 2.76 TeV (LHC)**
- Enhancement at lower energies

  Understanding: Cronin effect;
  more dominant at lower energies
- Smooth transition

High-p_T hadron suppression



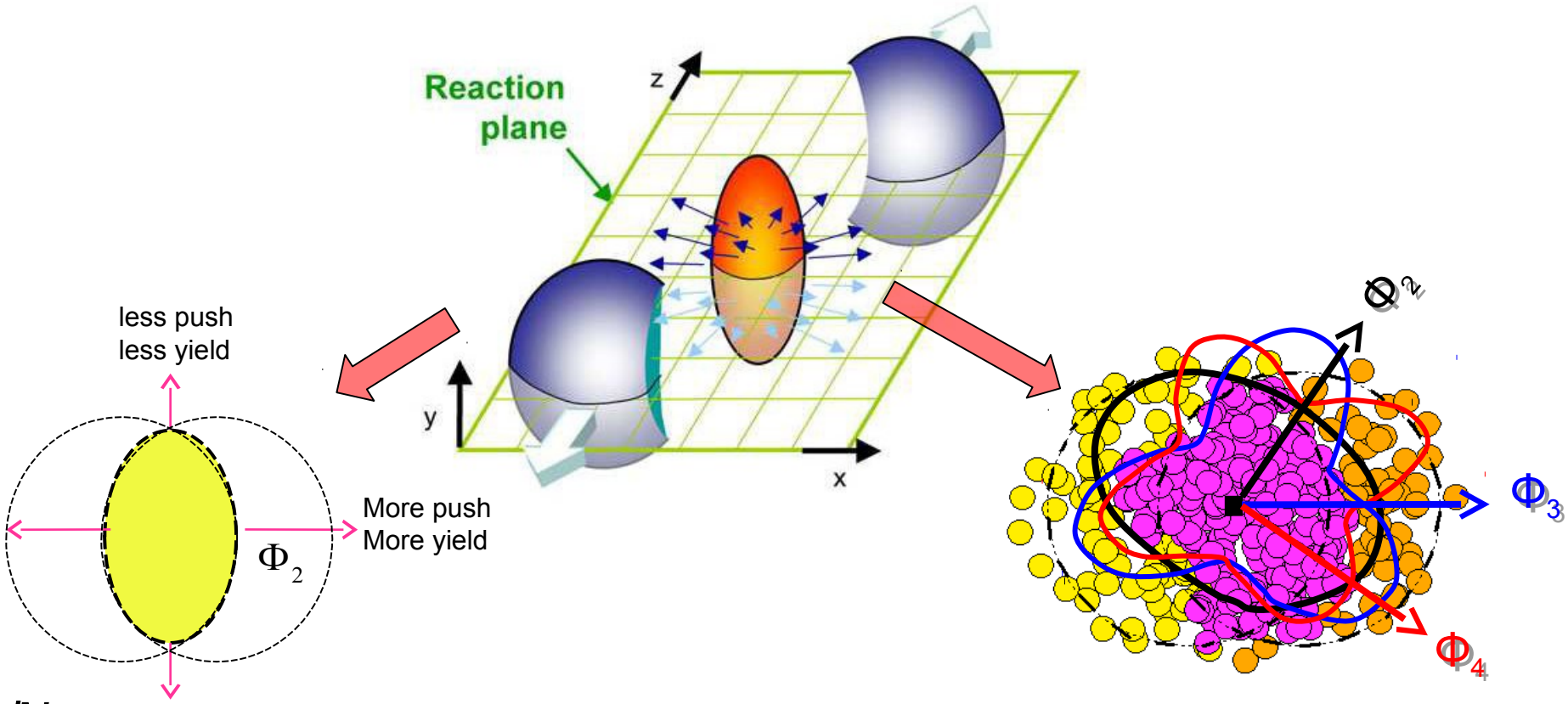


- Suppression from 39 GeV up to 2.76 TeV (LHC)
- Enhancement at lower energies

  Understanding: Cronin effect; more dominant at lower energies
- Smooth transition
- Enhancement balances suppression at ~$\sqrt{s_{NN}}$ = 14.5 GeV.

S. Horvat, QM15

Azimuthal anisotropy ("flow")



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi_2)$$

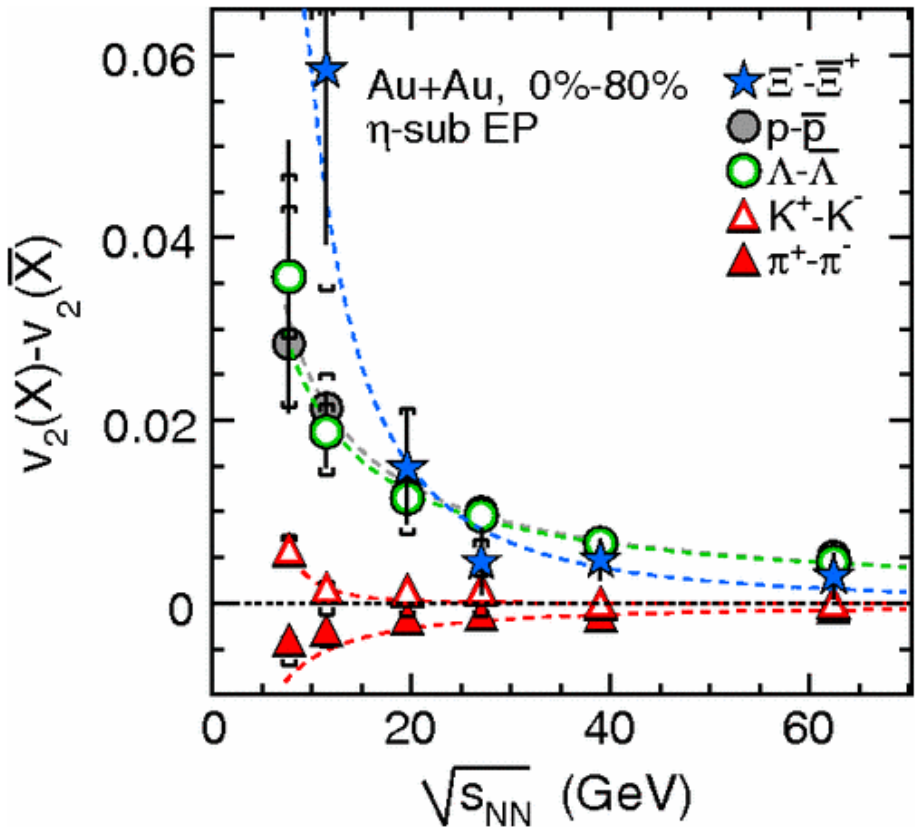
"elliptic flow" (v2)

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

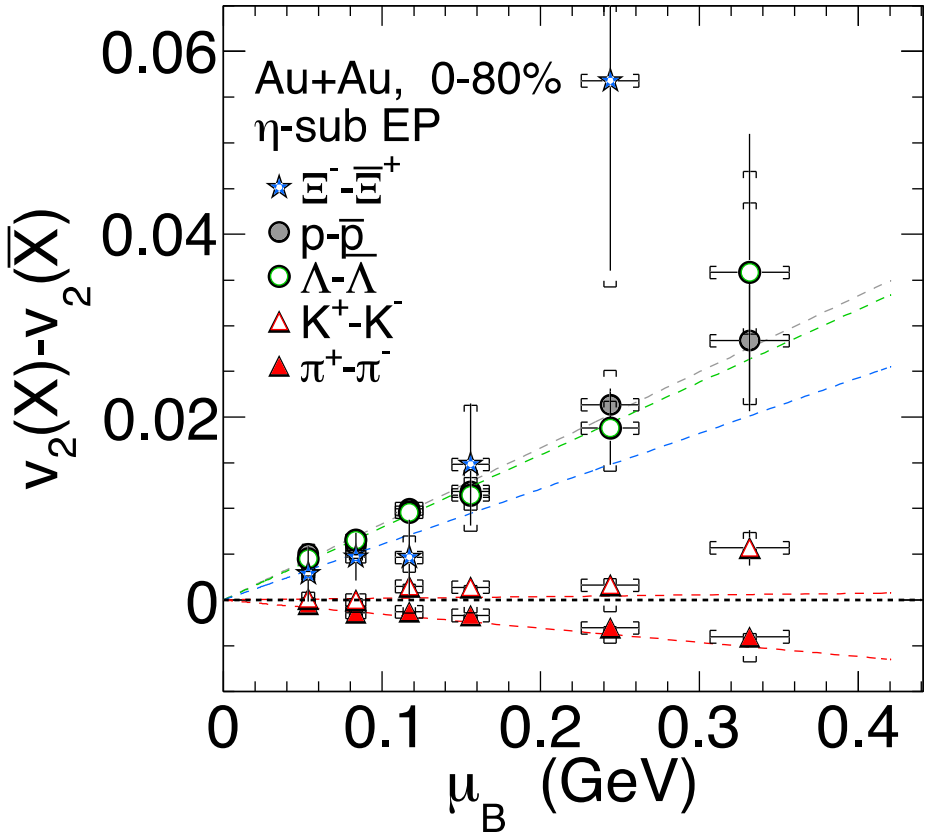
Directed flow (v1),
Triangular flow (v3) ...

"Elliptic flow" v_2 particle – antiparticle

Phys.Rev.Lett. 110 (2013) 142301

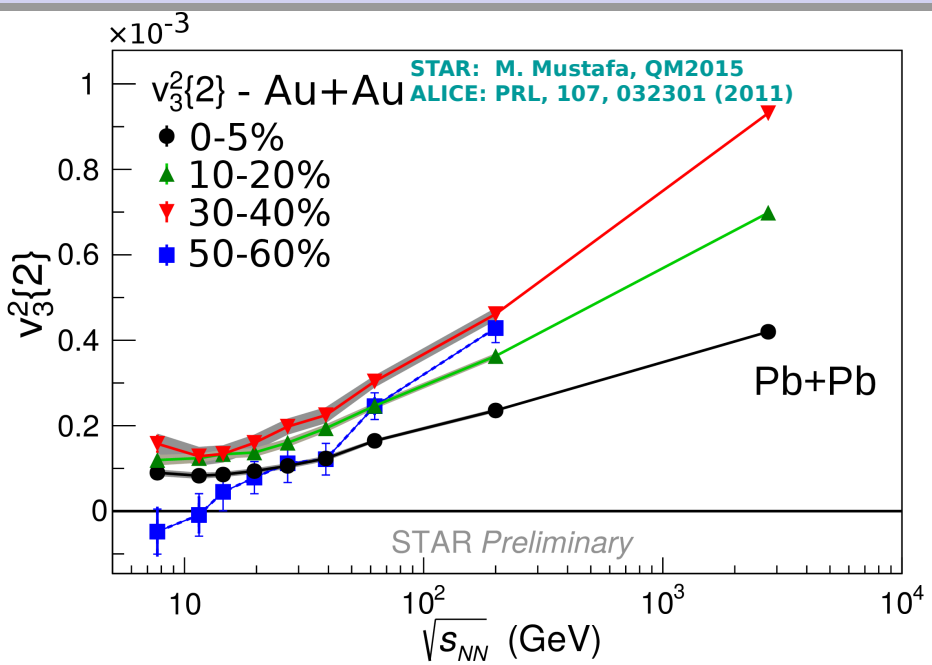


Phys. Rev. C 88 (2013) 14902



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

"Triangular flow" v_3

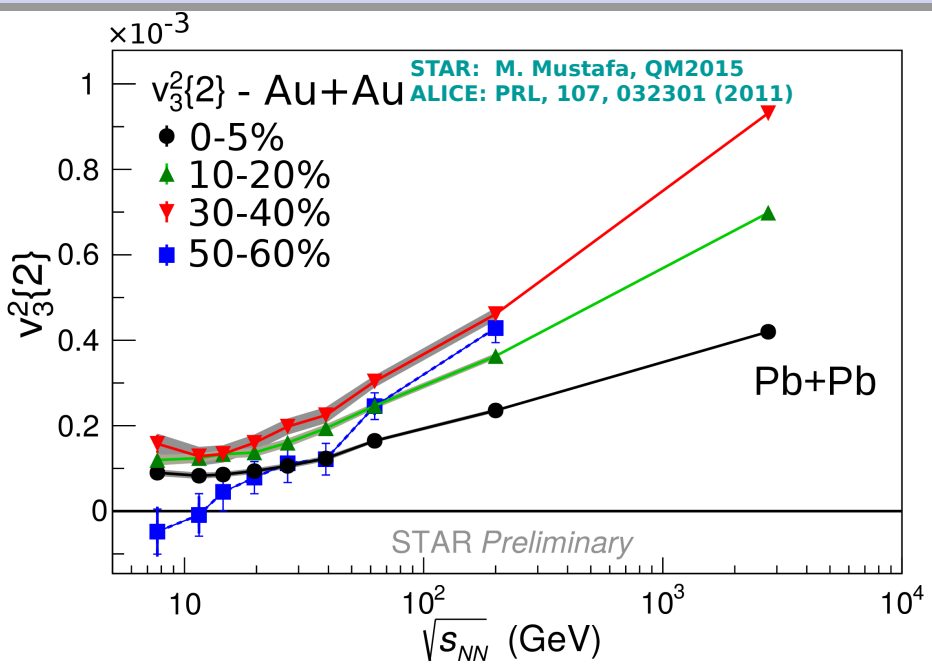


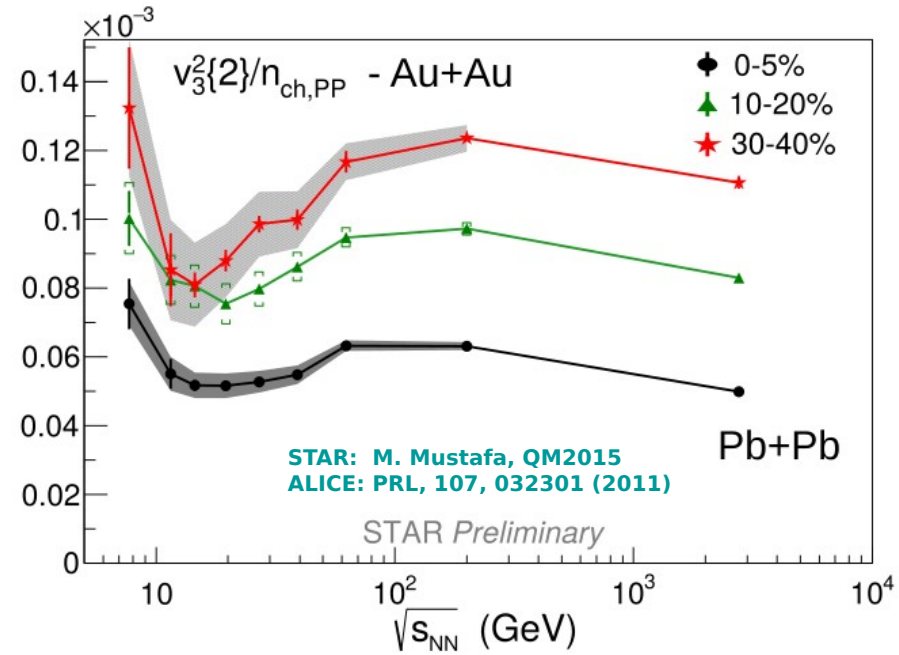
- **Triangular flow** is sensitive to the initial state fluctuations ==> **Related to the duration of low-viscosity phase**

  J. Aunvine, H. Petersen PRC 88, 064908

  - Sizable v_3 at lower energies in central to mid-central centralities
  - Peripheral collisions: v_3 consistent with zero for $\sqrt{s_{NN}} < 14.5$ GeV

"Triangular flow" v_3





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  - Sizable v_3 at lower energies in central to mid-central centralities
  - Peripheral collisions: v_3 consistent with zero for $\sqrt{s_{NN}} < 14.5$ GeV

- Scaling out energy density

  $n_{ch,PP} = dN_{ch}/d\eta/(N_{part}/2)$ is the multiplicity per participant pair ~ system energy density

  Flat trend $\sqrt{s_{NN}} = 7.7 - 20$ *GeV* **: softening of the EOS?**

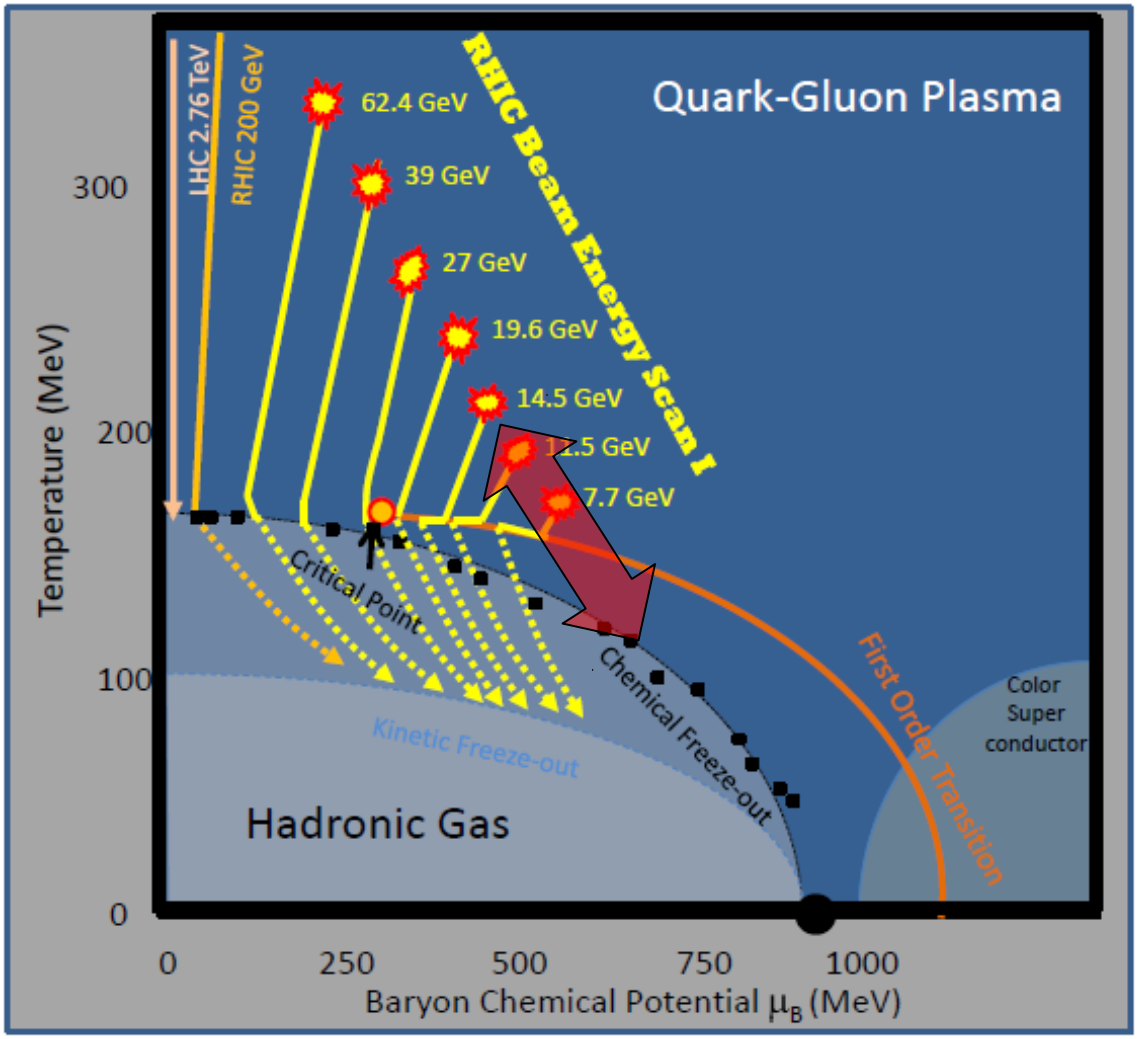
Exploring the QCD phase diagram

Find…

1) Turn-off of sQGP signatures

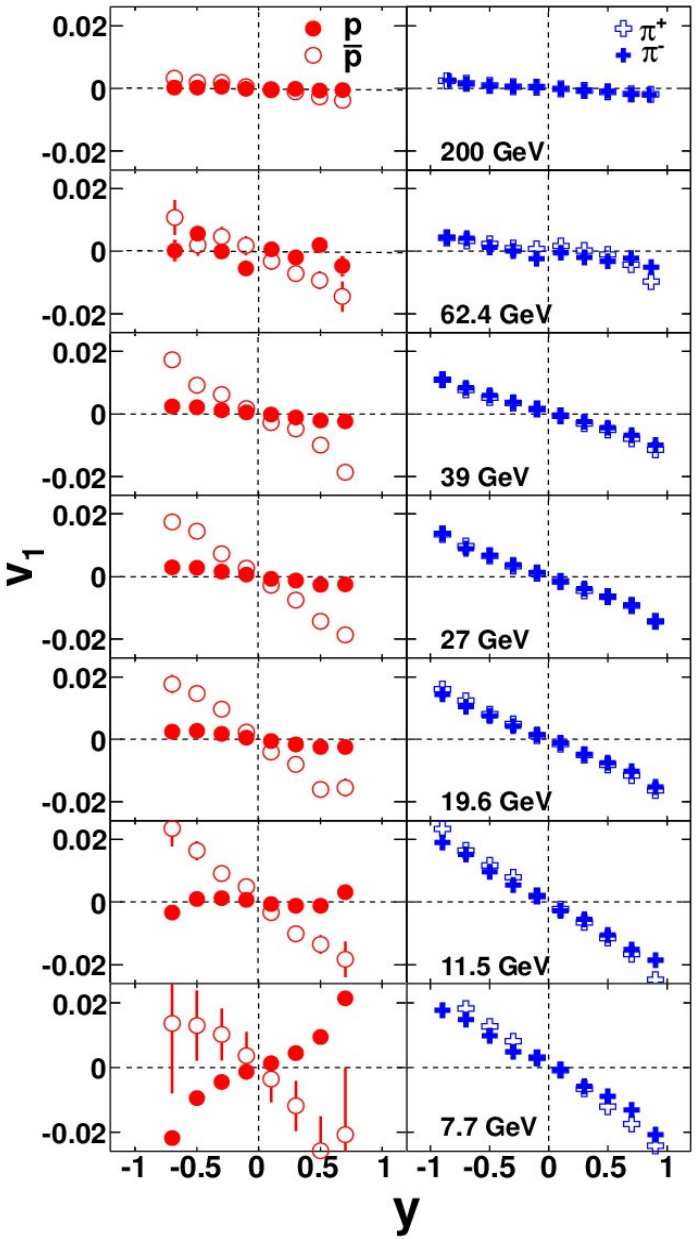
2) 1st order phase transition signs

3) The QCD critical point

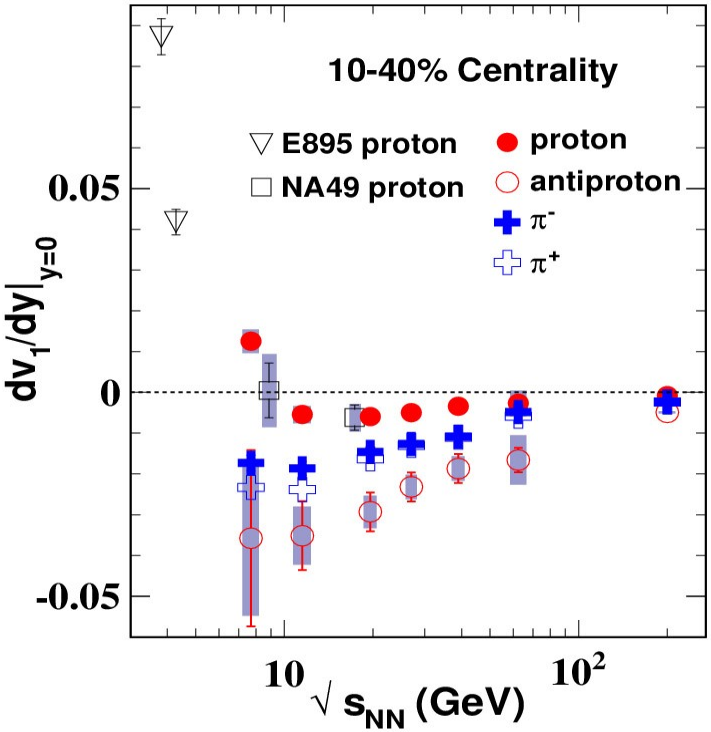


http://arxiv.org/abs/1007.2613

Directed flow (v_1)



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

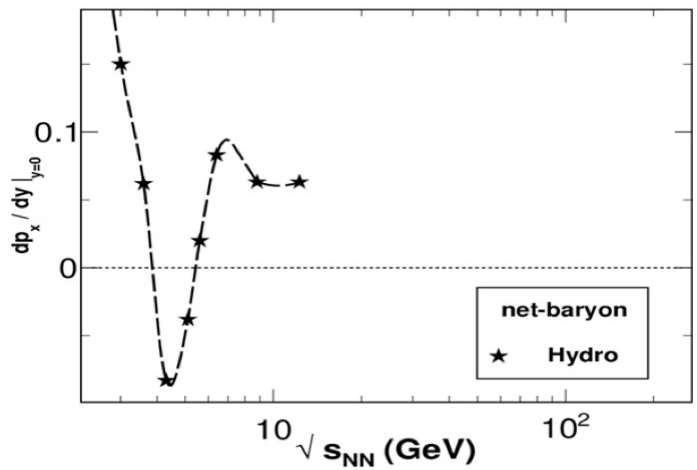


- Opposite charge pions follow the same trend
- Protons-antiprotons are different
  → baryon number transport is important
- Proton v_1 slope changes sign

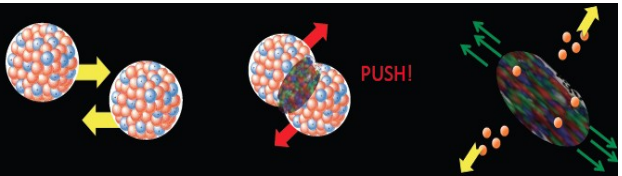
Net proton v_1 slope

- Net protons: double sign change
  - Simple hydro predicts structure
  - More sophisticated UrQMD fails

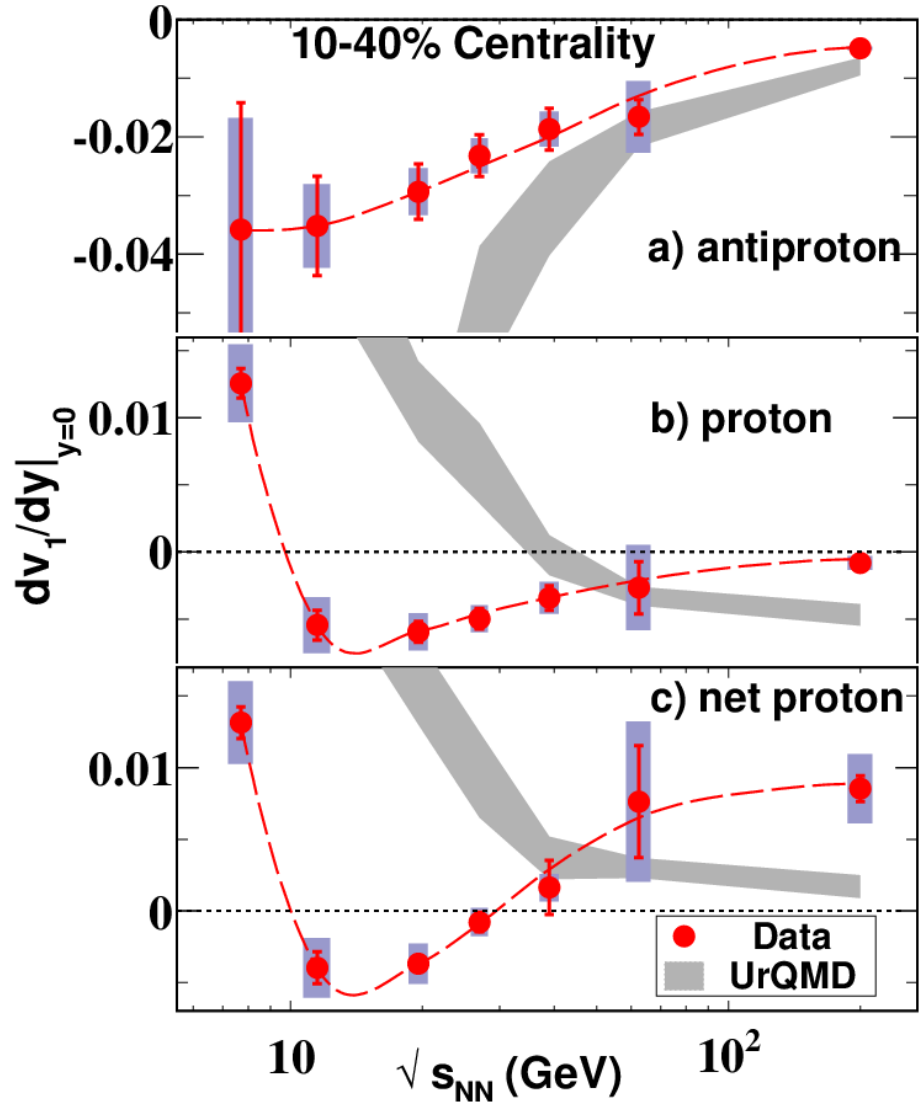
H. Stoecker, Nucl. Phys. A 750, 121 (2005).



- Softening of EOS?
  - Expected in mixed phase



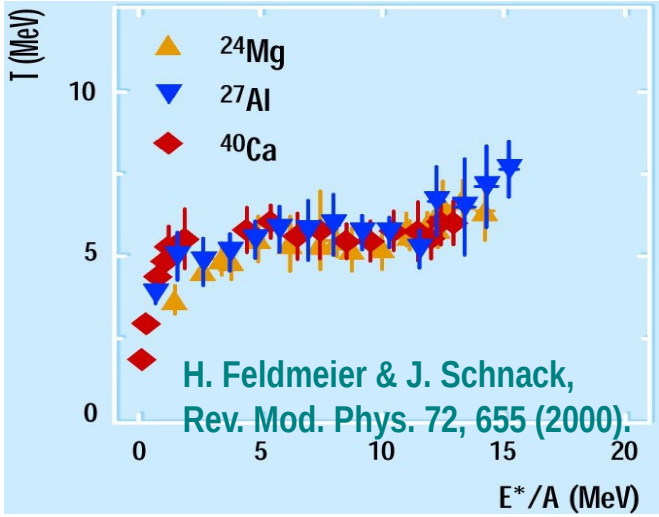
Phys. Rev. Lett. 112, 162301 (2014)



Caloric curve

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

nuclear liquid-vapor PT



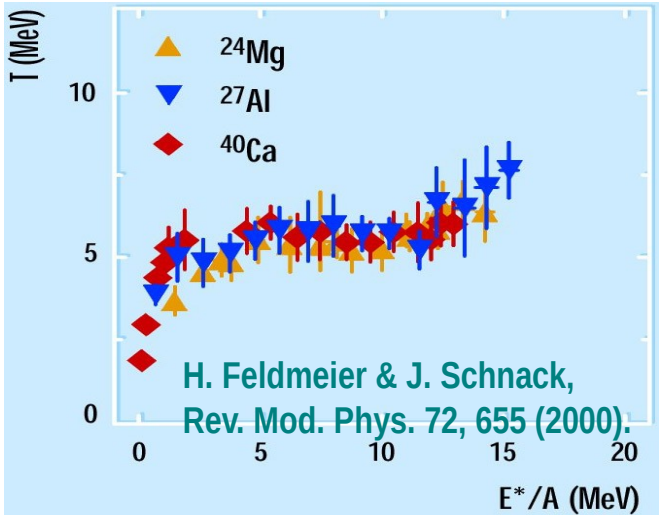
H. Feldmeier & J. Schnack, Rev. Mod. Phys. 72, 655 (2000).

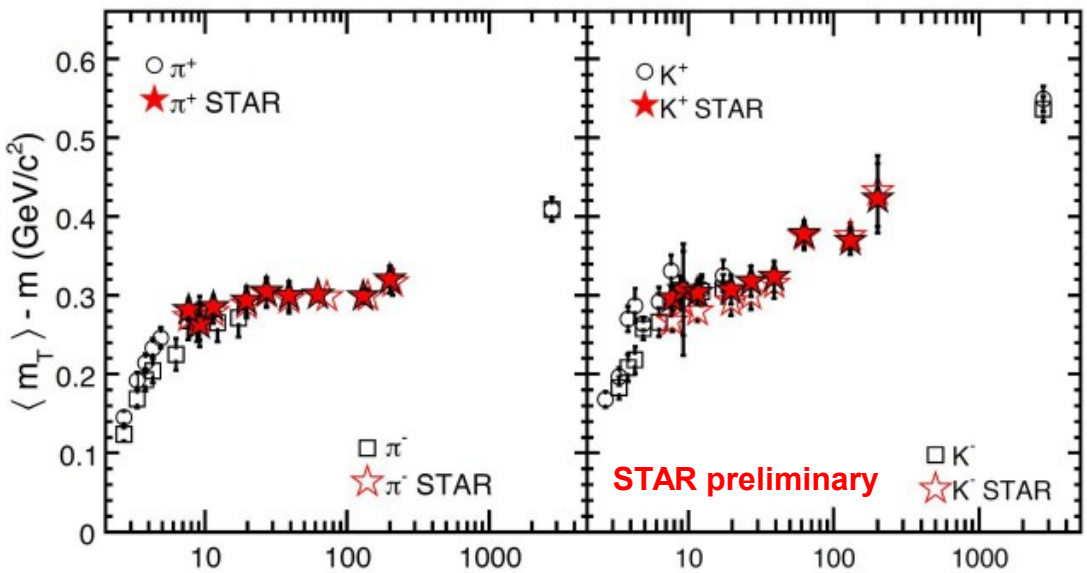
Caloric curve

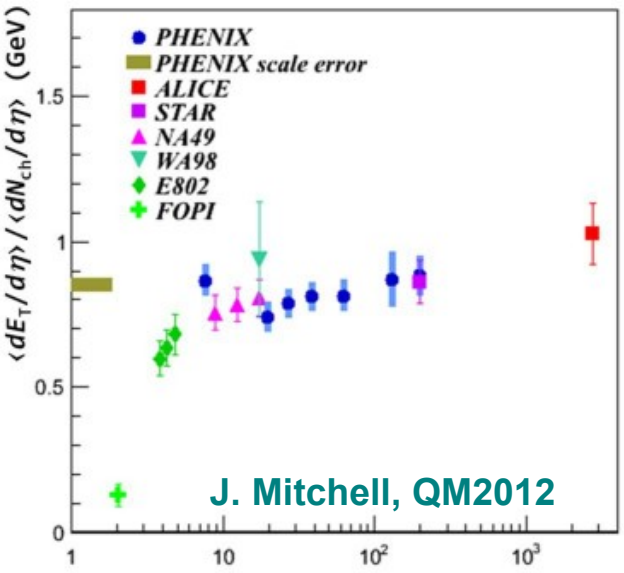
- 1st order phase transition
  → T(E) plateau

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

nuclear liquid-vapor PT

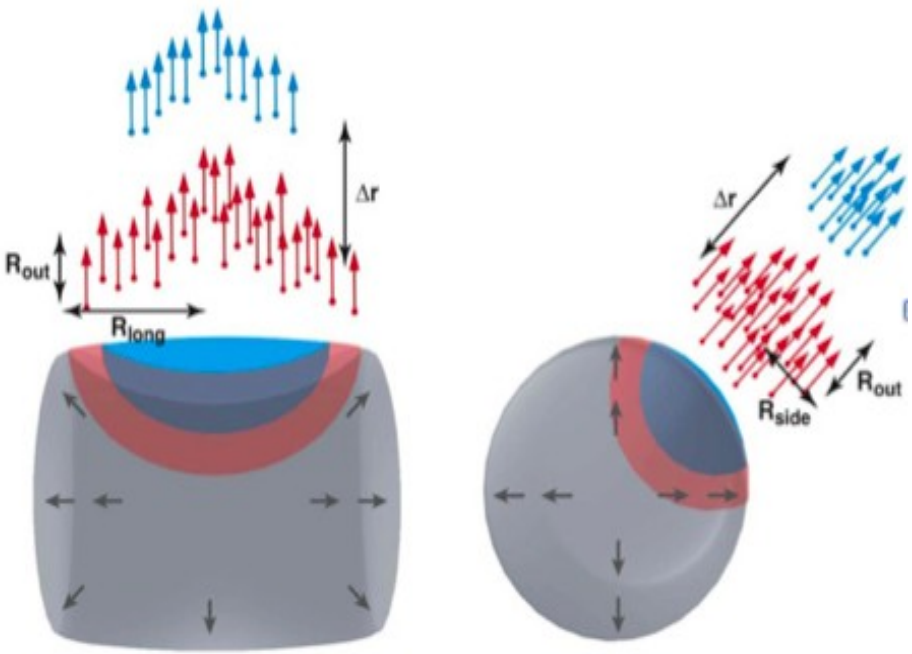






Center of Mass Collision Energy $\sqrt{s_{NN}}$ (GeV)

Femtoscopy: HBT radii



Egy egyszerű modellben:
Makhlin, Sinyukov, ZPC.39.69 (1988)

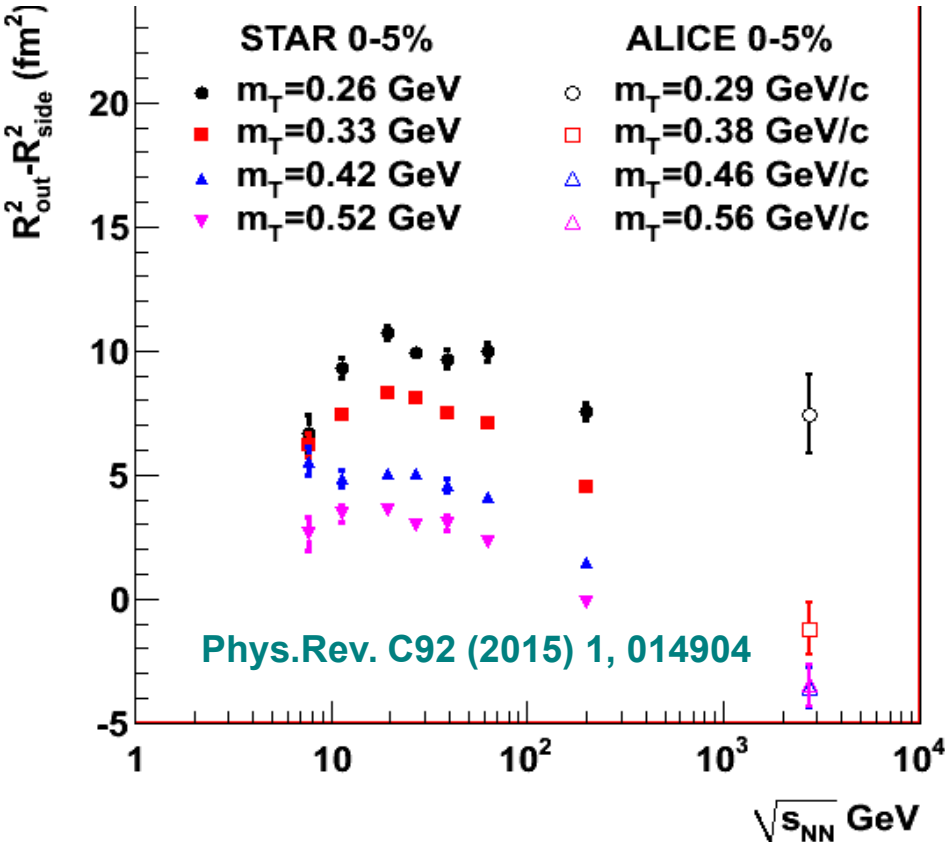
$$R_{side}^2 = \frac{R^2_{geo}}{1+\frac{m_T}{T}\beta_T^2}$$

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

$$R_{long}^2 \approx \frac{T}{m_T}\tau^2$$

- <u>Femtoscopy:</u>
  Study the particle emitting source via quantum-correlations

Femtoscopy and phase transition



In a simple model:
Makhlin, Sinyukov, ZPC.39.69 (1988)

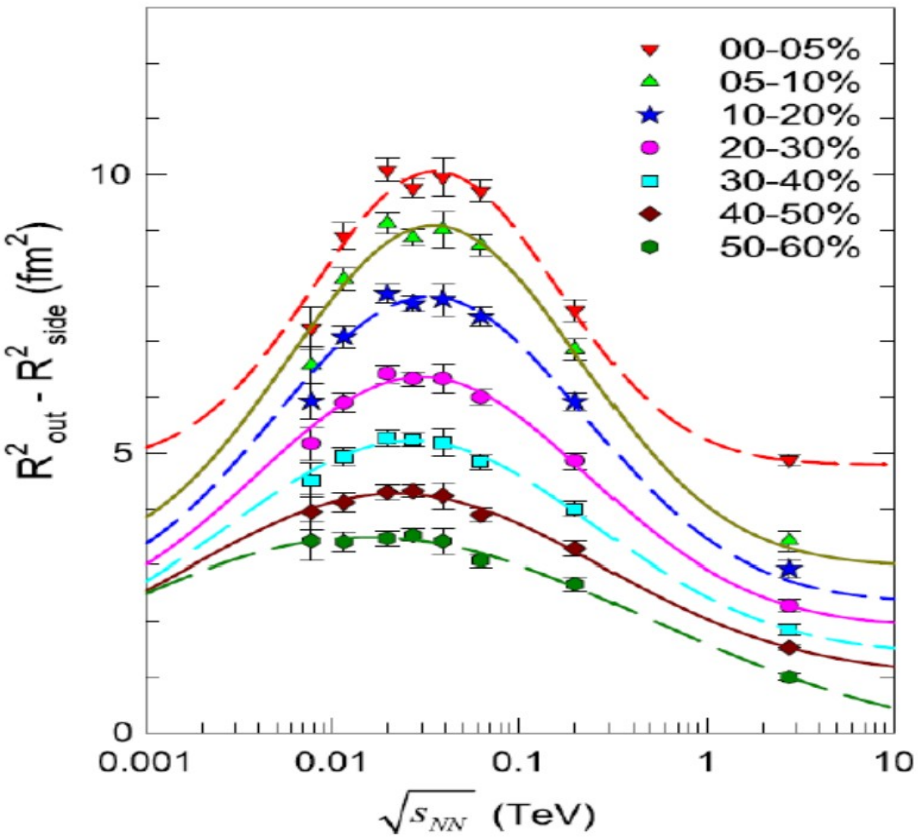
$$R^2_{side} = \frac{R^2_{geo}}{1+\frac{m_T}{T}\beta_T^2}$$

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

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

- If 1st order phase transition: longer emission duration expected
- Non-monotonity of R_{out}^2–R_{side}^2 may indicate change in dynamics

Femtoscopy and critical point?

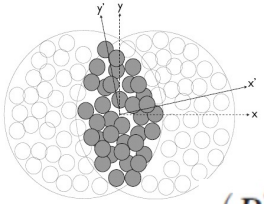


Data: STAR (& PHENIX, ALICE)

R.Lacey, PRL114,142301(2015)

Finite size scaling?

- Infinite size: susceptibilities diverge at CP
- Finite size: susceptibility peaks close to CP



$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

$$(R^2_{\text{out}} - R^2_{\text{side}})^{\max} \propto \bar{R}^{\gamma/\nu}$$

$$\sqrt{s_{NN}}(V) = \sqrt{s_{NN}}(\infty) - k \times \bar{R}^{-(1/\nu)}$$

height: $\chi_T^{\max}(V) \sim L^{\gamma/\nu}$

width: $\delta T(V) \sim L^{-1/\nu}$

position: $\tau_T(V) \sim T^{CEP}(V) - T^{CEP}(\times) \sim L^{-1/\nu}$

R. Lacey: $\bar{R} \sim L$
Fitting the scaling for CP:
$\mu_B \sim 95$ MeV, $T \sim 165$ MeV

M. Lisa, QM15

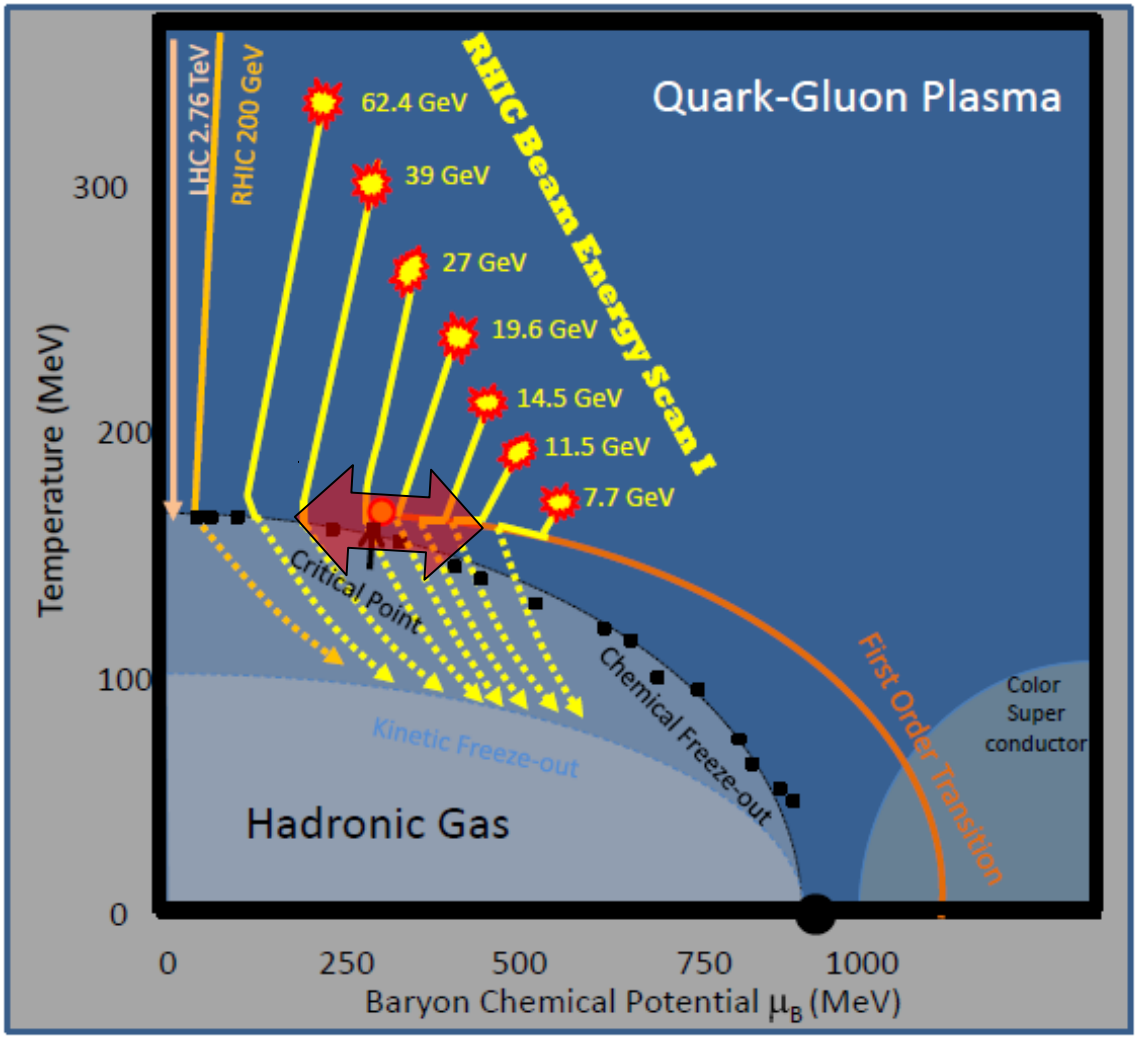
Exploring the QCD phase diagram

Find…

1) Turn-off of sQGP signatures

2) 1st order phase transition signs

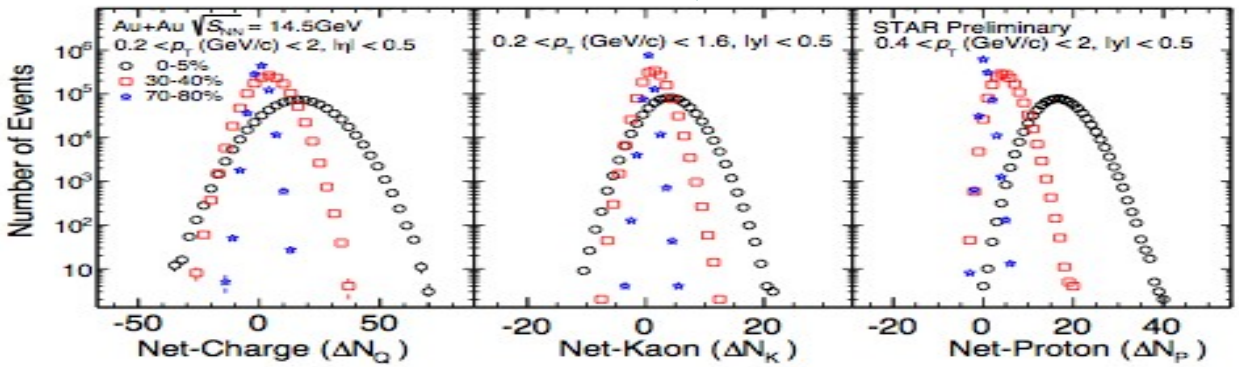
3) The QCD critical point



http://arxiv.org/abs/1007.2613

Net multiplicities

J. Thaeder, QM15



Uncorrected raw event-by-event net-particle multiplicity distribution: New data from $\sqrt{s_{NN}}$ = 14.5 GeV Au+Au collisions

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

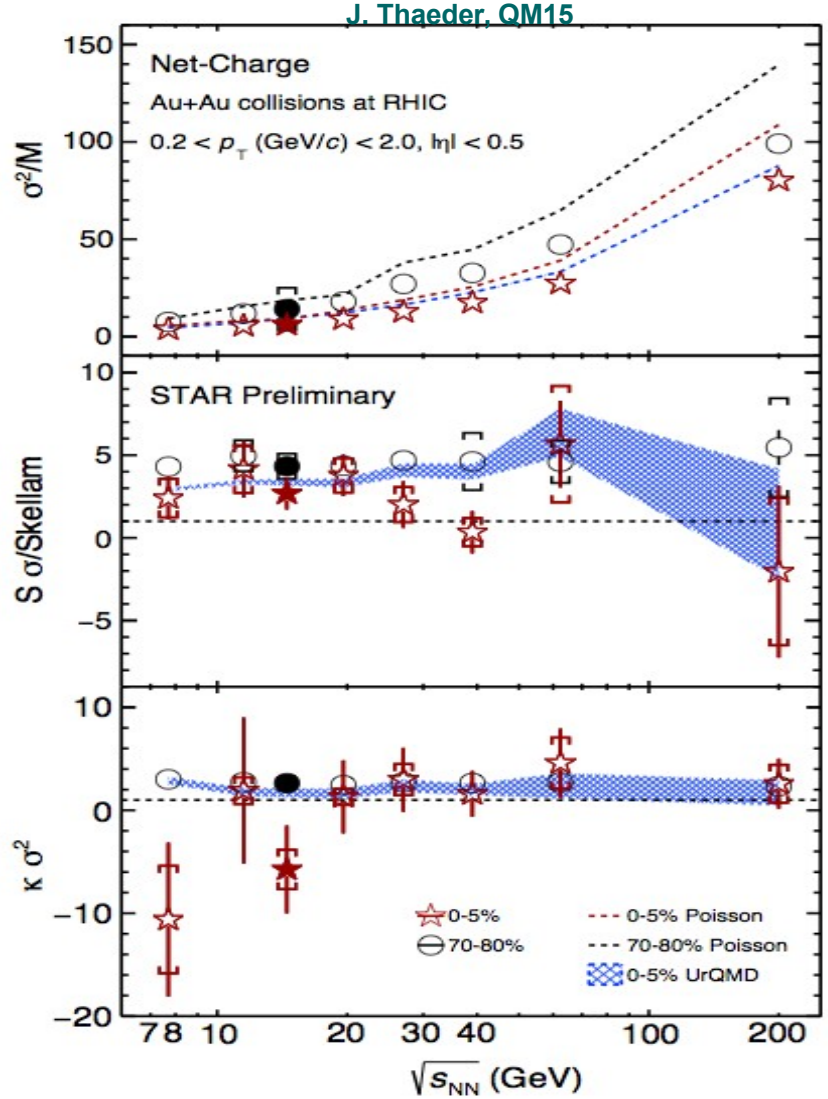
$$\chi_B^{(n)} = \left.\frac{\partial^n (P/T^4)}{\partial (\mu_B/T)^n}\right|_T \qquad \chi_B^4/\chi_B^2 = (\kappa\sigma^2)_B \qquad \chi_B^3/\chi_B^2 = (S\sigma)_B$$

- **Non-monotonic behavior** expected around critical point

Net charge multiplicity moments (Q)

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

J. Thaeder, QM15

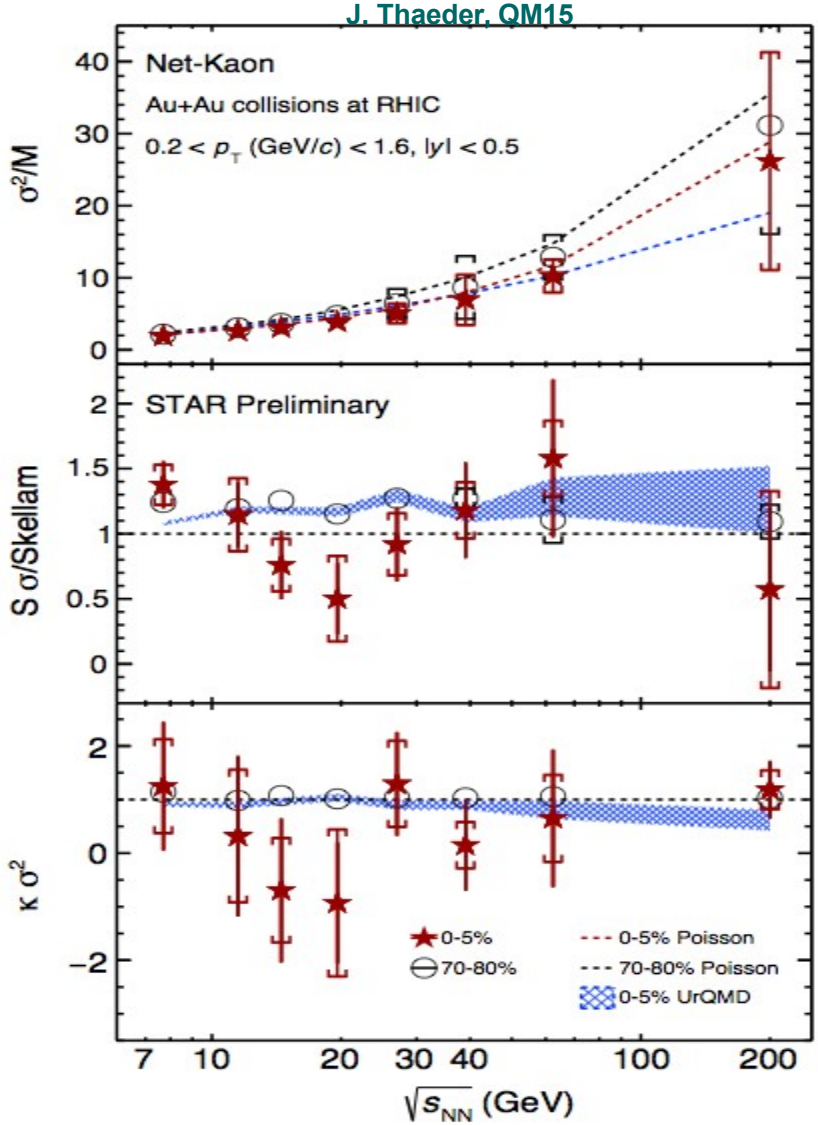


Open points: **Phys. Rev. Lett. 113 (2014) 92301**

Net kaon multiplicity moments (S)

- **No significant non-monotonous behavior seen**
  - σ^2/M increases with increasing collision energy
  - For most central collisions (0-5%), $\kappa\sigma^2$ and $S\sigma$/Skellam are consistent with Poisson expectation
- UrQMD (no Critical Point), shows no energy dependence

J. Thaeder, QM15

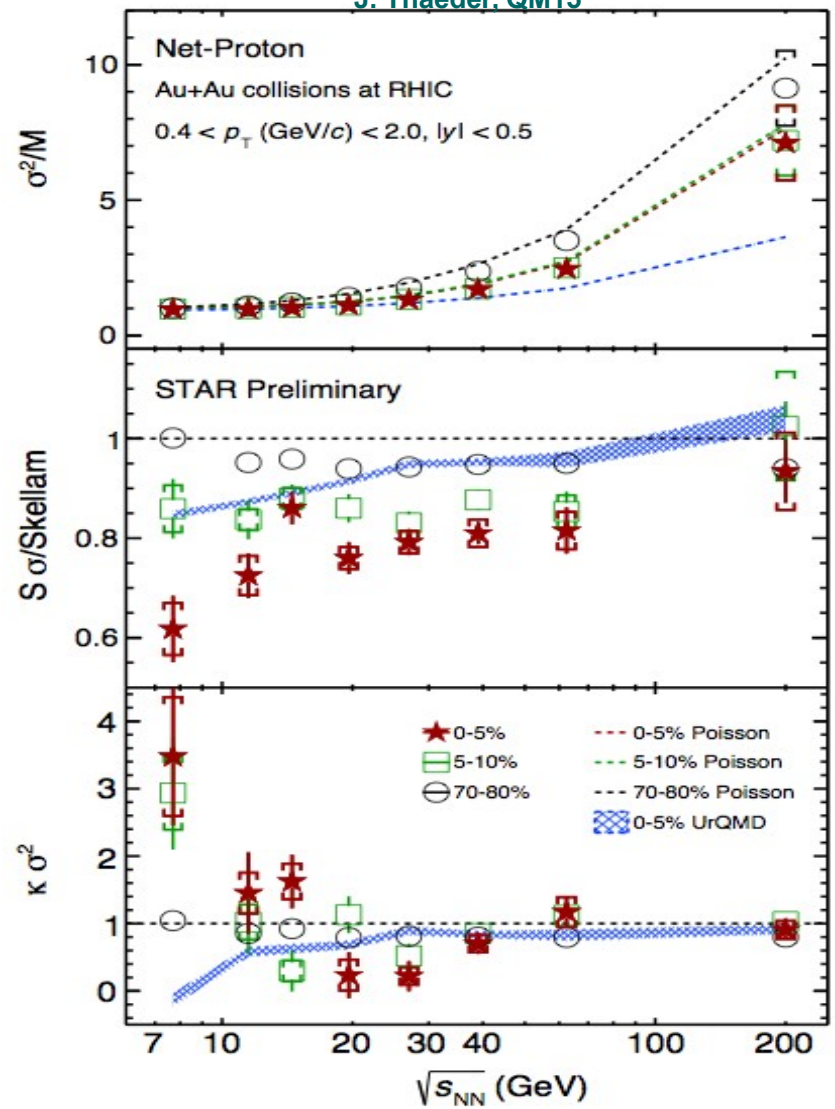


Open points: **Phys. Rev. Lett. 113 (2014) 92301**

Net proton multiplicity moments

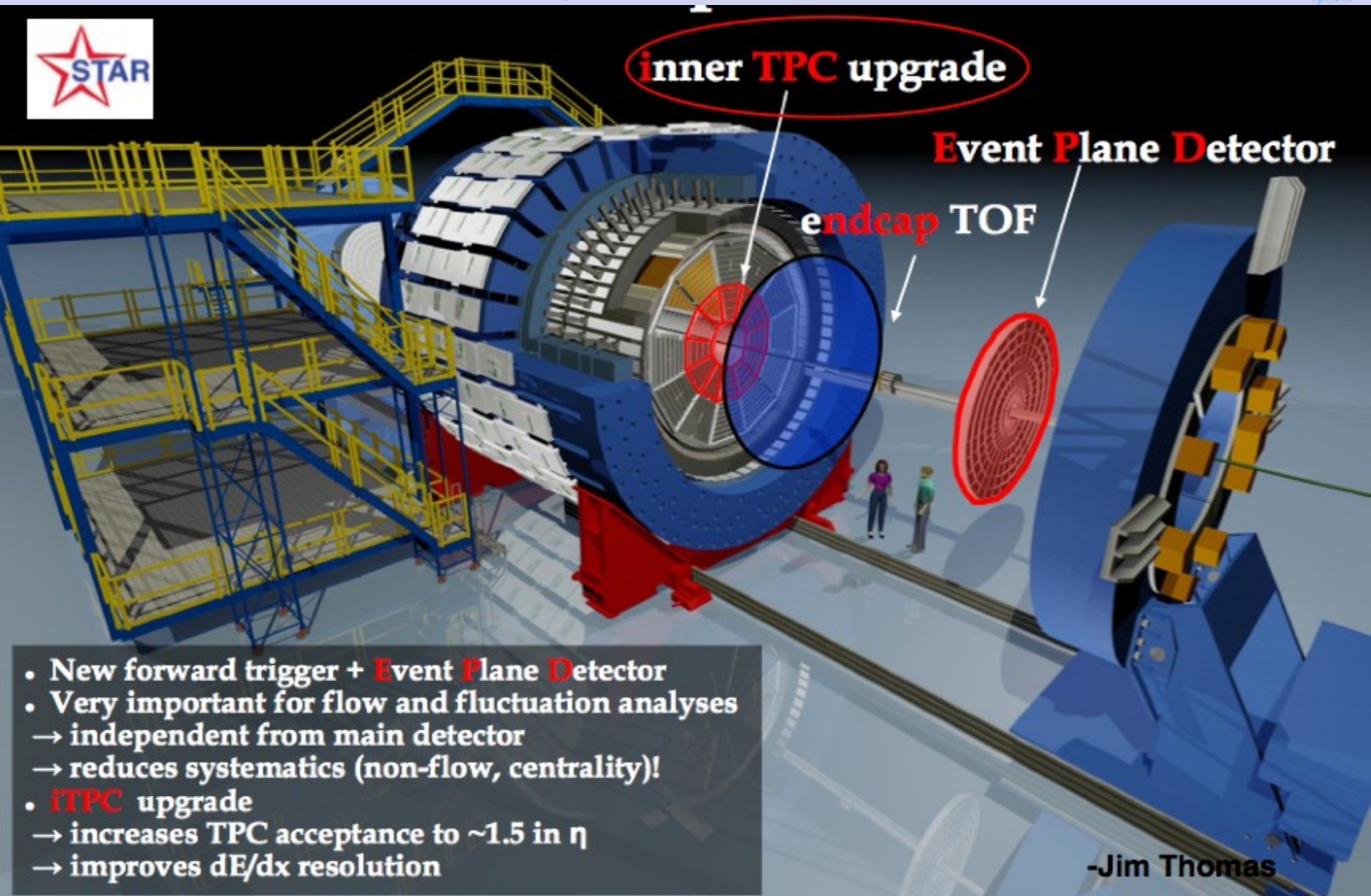
- **Non-monotonous behavior (B) in central data**
  - σ^2/M increases with energy, consistent with poissonian
  - $S\sigma$/Skellam increases with energy
  - **$\kappa\sigma^2$ different from unity, break in trend**
- No effect in peripheral data
- UrQMD (no Critical Point) suppression at lower energies is due to baryon number conservation

J. Thaeder, QM15

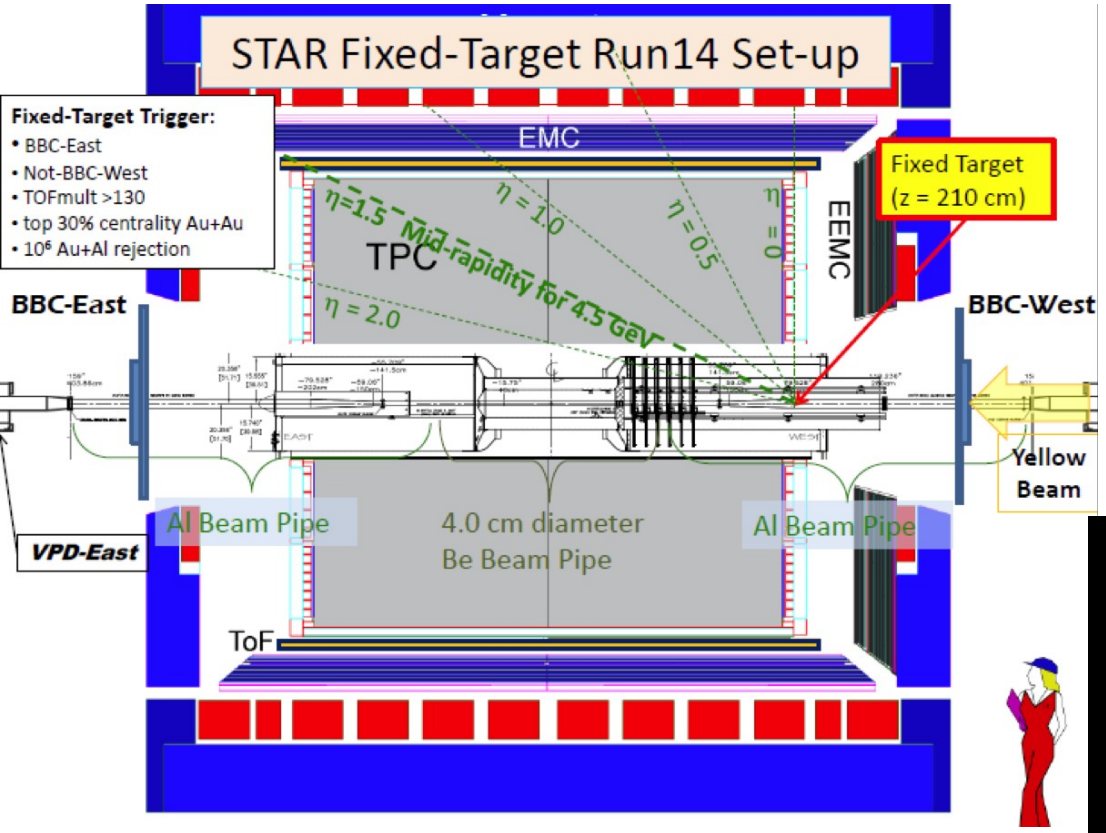


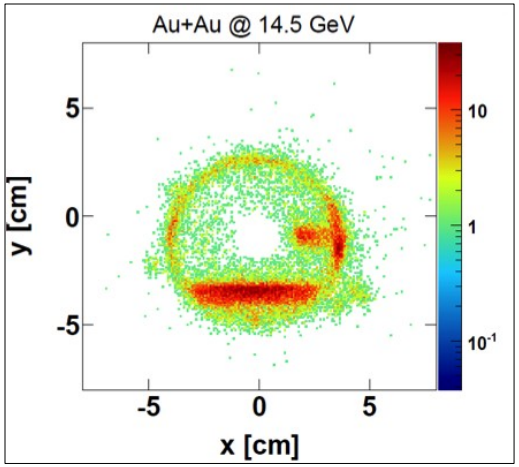
Open points: **Phys. Rev. Lett. 113 (2014) 92301**

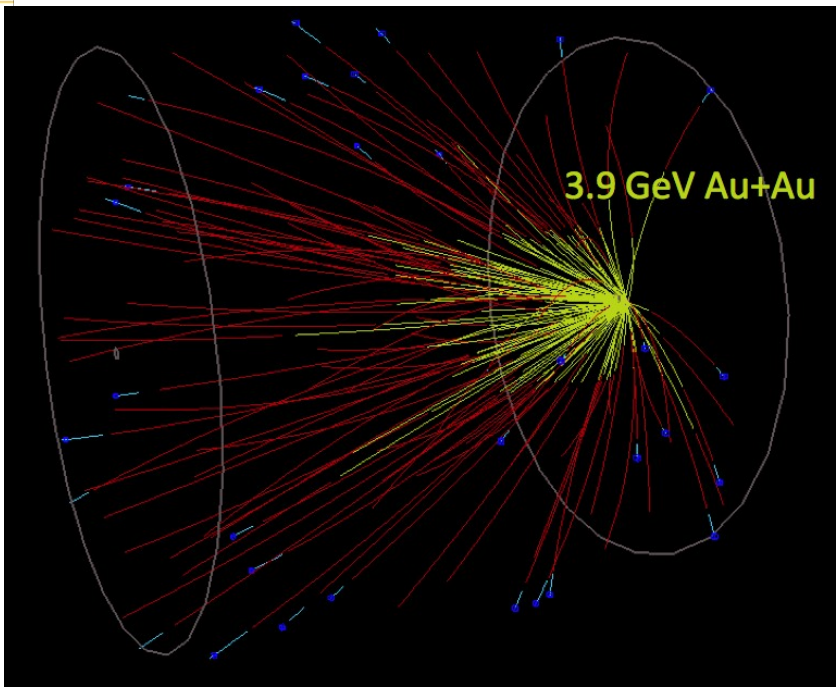
STAR upgrades for BES II



Fixed target program at STAR







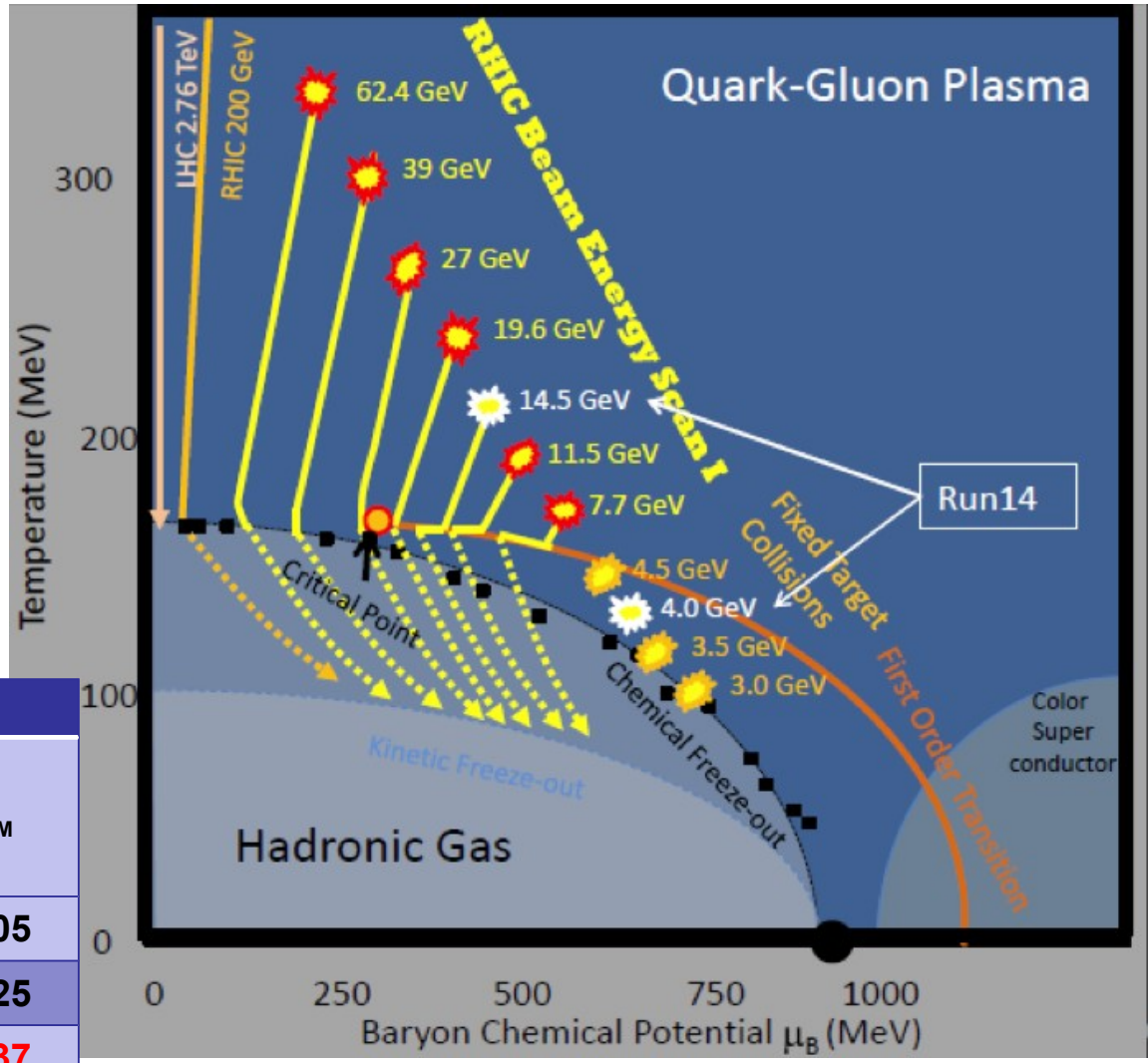
- Target inserted into beam pipe
- Only a small percentage
- Does not interfere with collider mode data taking

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**

Summary

1. Heavy Flavor

Quarkonia

- High-p_T J/ψ and ϒ suppression: proof for sQGP
- Upsilons in Au+Au and U+U: sequential melting

Open heavy flavor

- D^0 mesons suggest charm-medium coalescence

2. Beam Energy Scan

BES-I covers the right (wide) μ_B range

- sQGP-turnoff signatures: R_{CP}, Δv_2, chiral magnetic effect
- Phase transition: non-monotonic v_1, HBT radii, caloric curve
- Critical point: Net-proton moments are the most convincing

BES-II: decisive measurements, finer scan between 7-20 GeV

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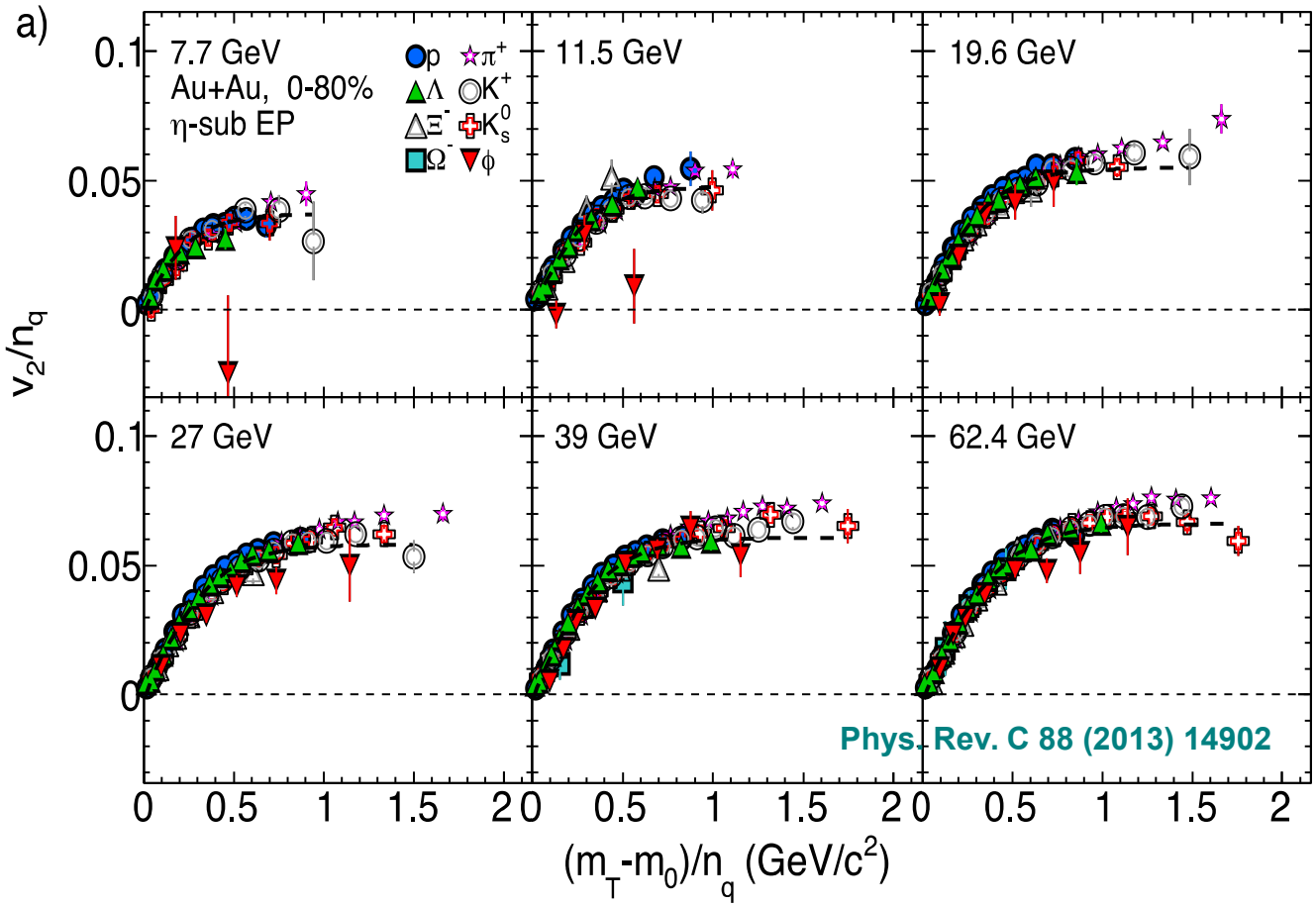
BES-II: decisive measurements, finer scan between 7-20 GeV

Toward understanding the QCD properties

Extra slides

Elliptic flow (v_2) – particles

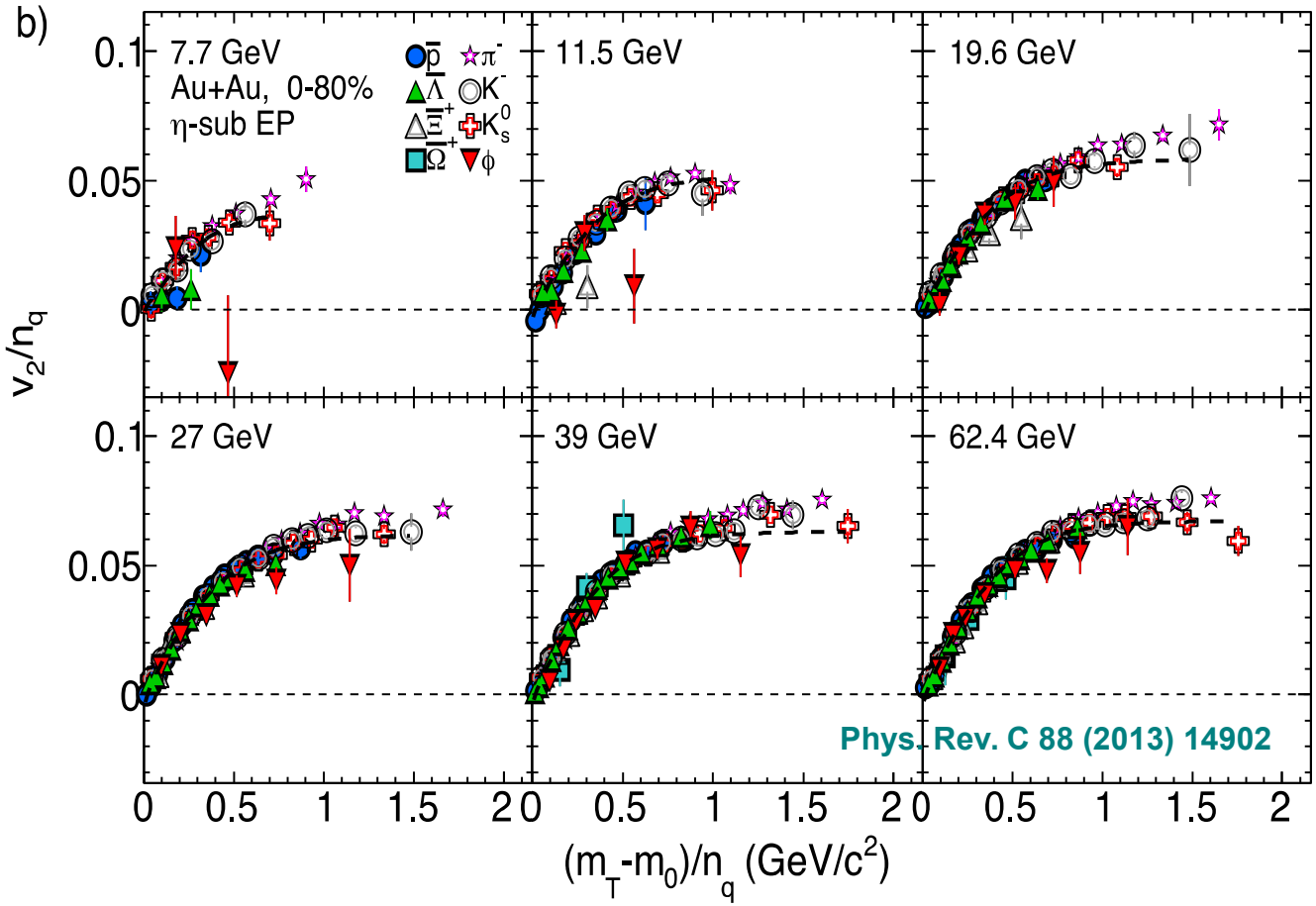


- Approximate NCQ scaling holds… DOF=quarks?

  Exception: ϕ at 7.7 and 11.5 GeV

  deviation ~2σ – more statistics needed

Elliptic flow (v_2) – antiparticles

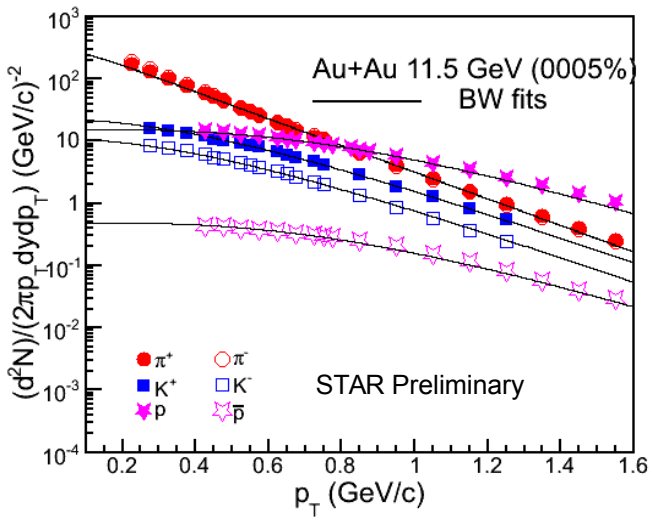


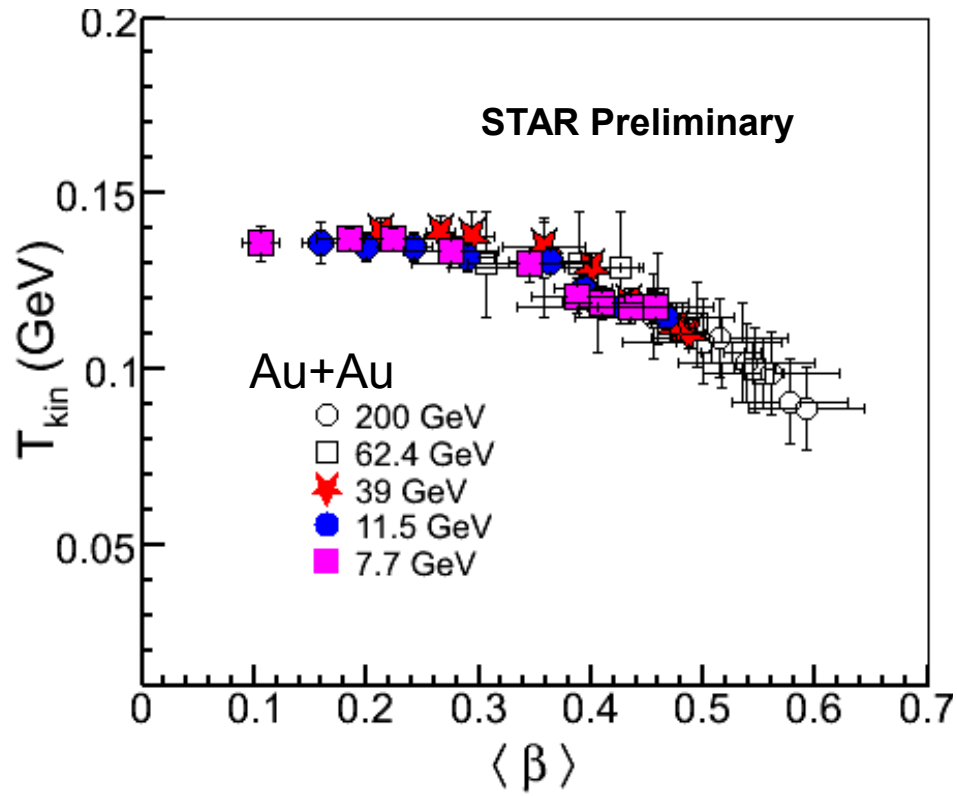
- Approximate NCQ scaling holds… DOF=quarks?
- …but particles and antiparticles are different

Kinetic freeze-out

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

Particles used: π,K,p

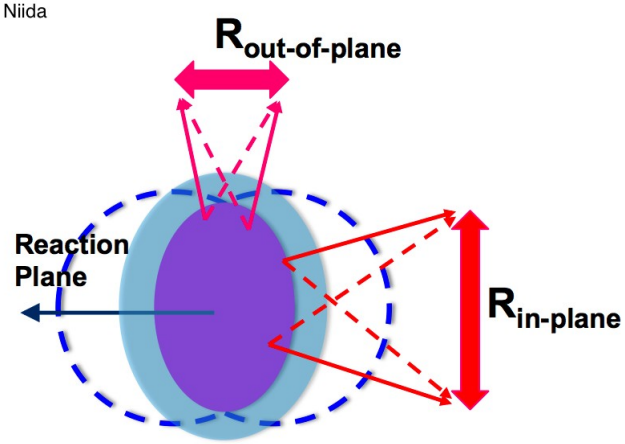




✧ Higher kinetic temperature corresponds to lower value of average flow velocity and vice-versa

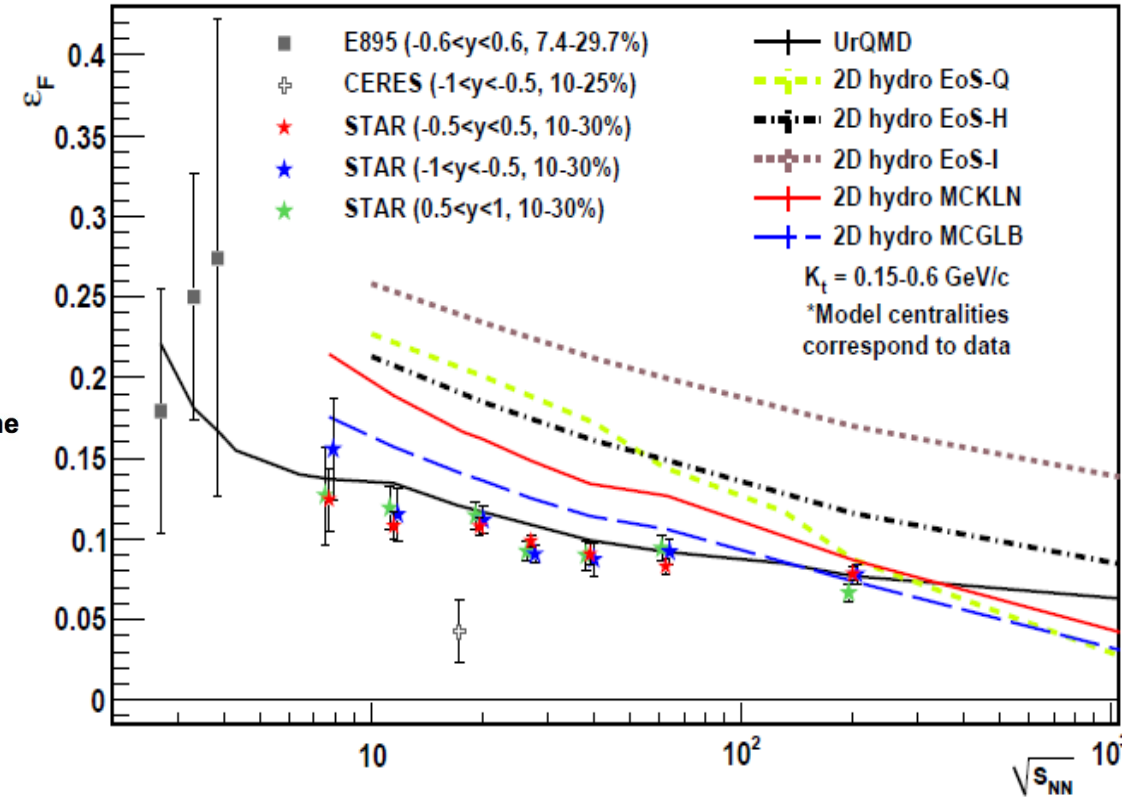
Azimuthally sensitive HBT

Illustration from: T. Niida



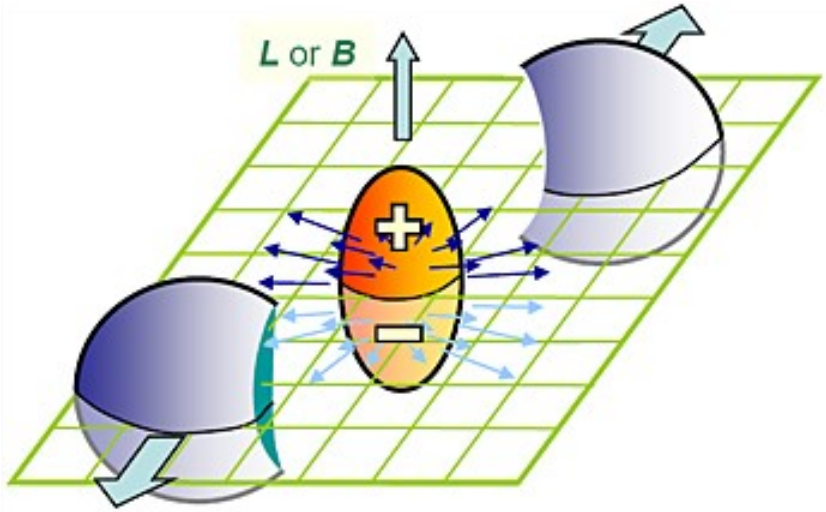
elliptical shape : $R_{in\text{-}plane} > R_{out\text{-}of\text{-}plane}$
spherical shape : $R_{in\text{-}plane} = R_{out\text{-}of\text{-}plane}$

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

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

- Measure: 3-point correlator, charge separation

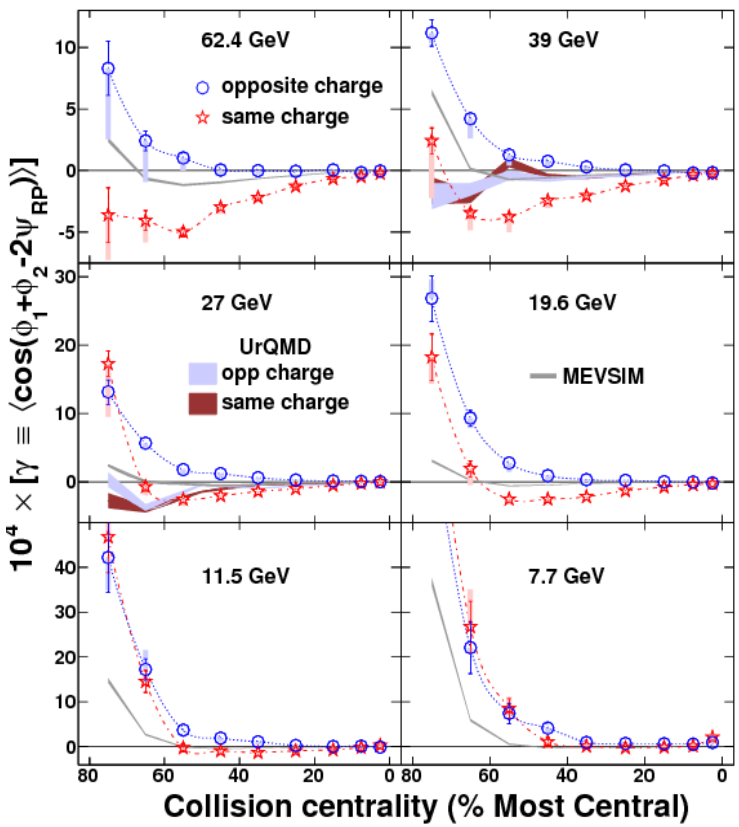
$$\gamma \equiv \langle \cos(\varphi_1 + \varphi_2 - 2\Psi_{RP}) \rangle$$

$$H^\kappa = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2).$$

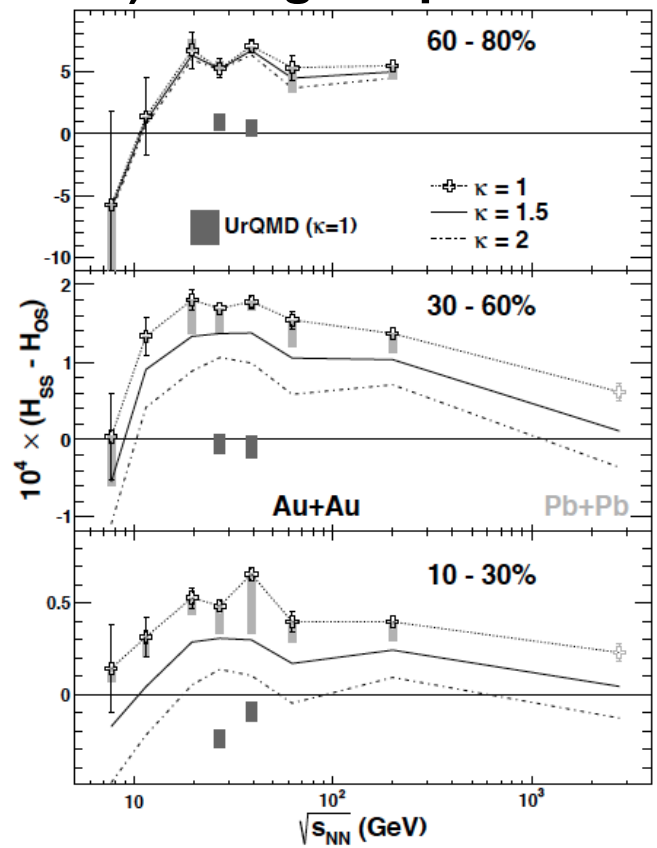
Chiral magnetic effect

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

1) Three-point correlator



2) Charge separation



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

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

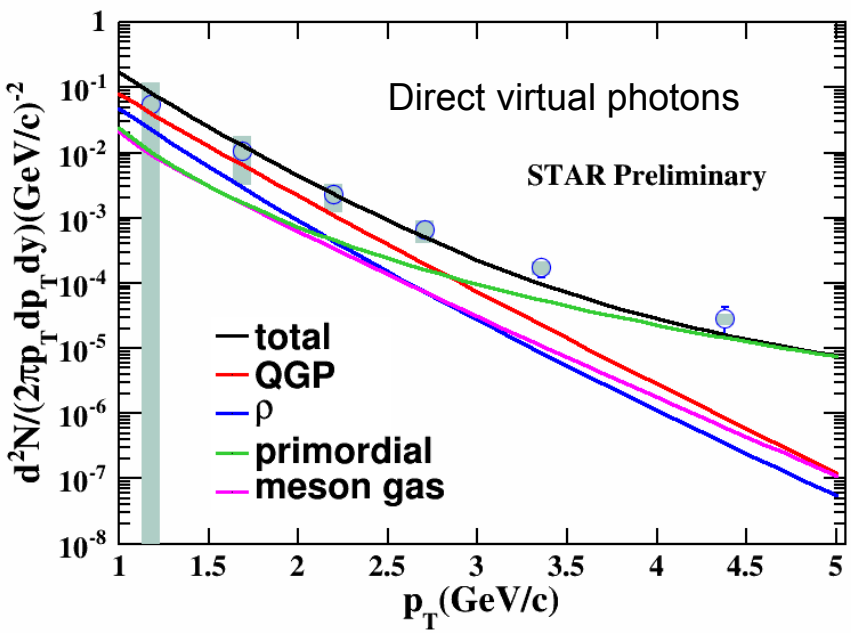
Quantify the Spectral Function

Temperature dependence of rho spectral function

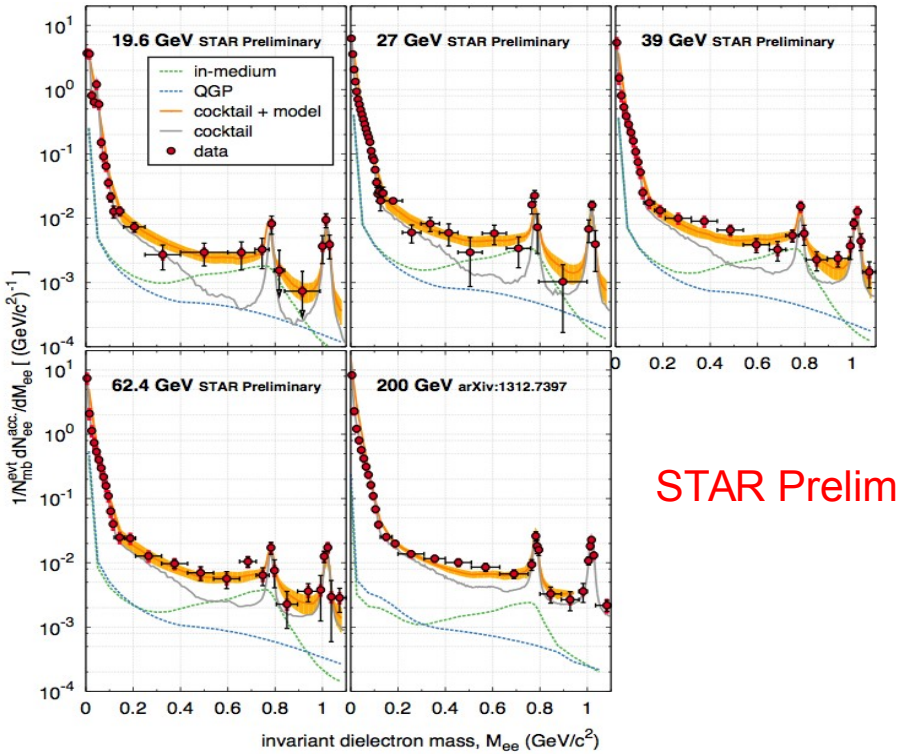
1. Beam energy range where final state is similar
2. Initial state and temperature evolution different
3. Density dependence by Azimuthal dependence (v_2)
4. Use centrality dependence as another knob
5. Direct photon results should match with extrapolation

Baryon dependence of rho spectral function

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



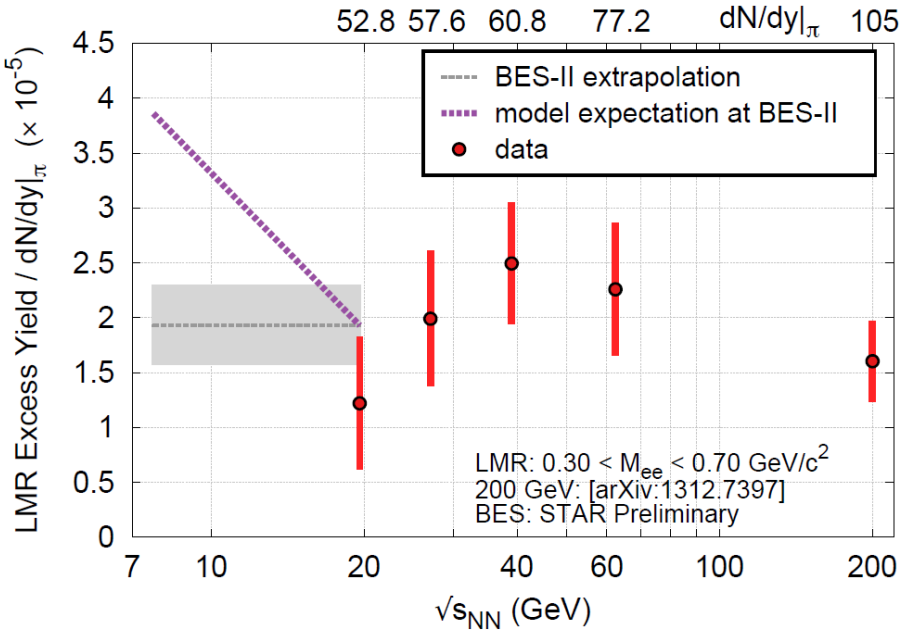
QM14: Chi Yang, Patrick Huck



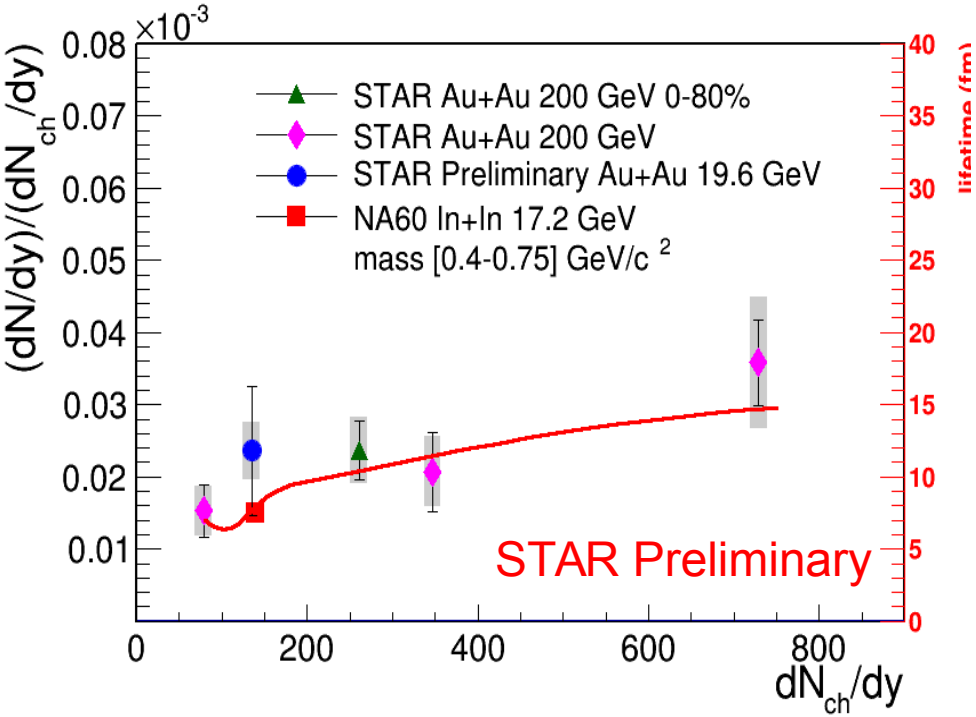
STAR Preliminary

Dilepton Measurements at BES II

Beam Energy

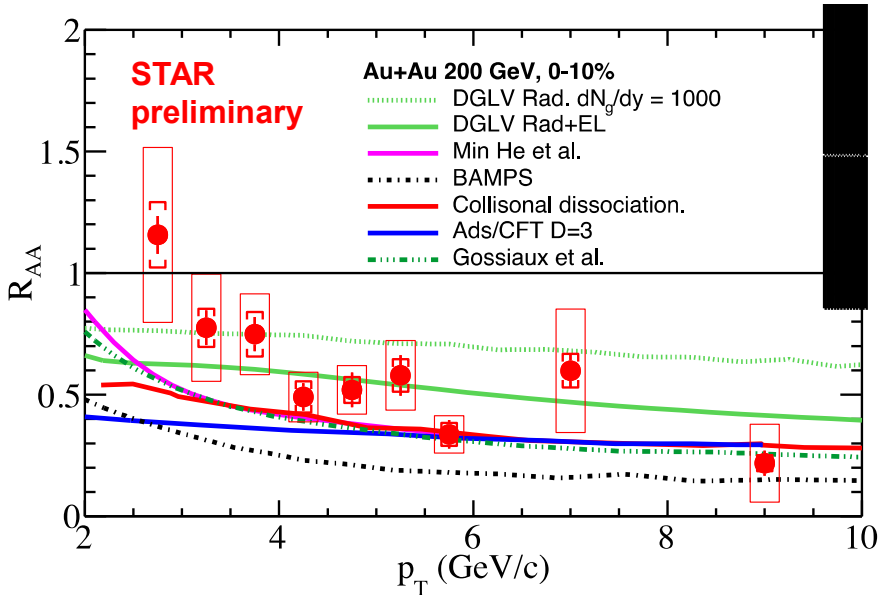


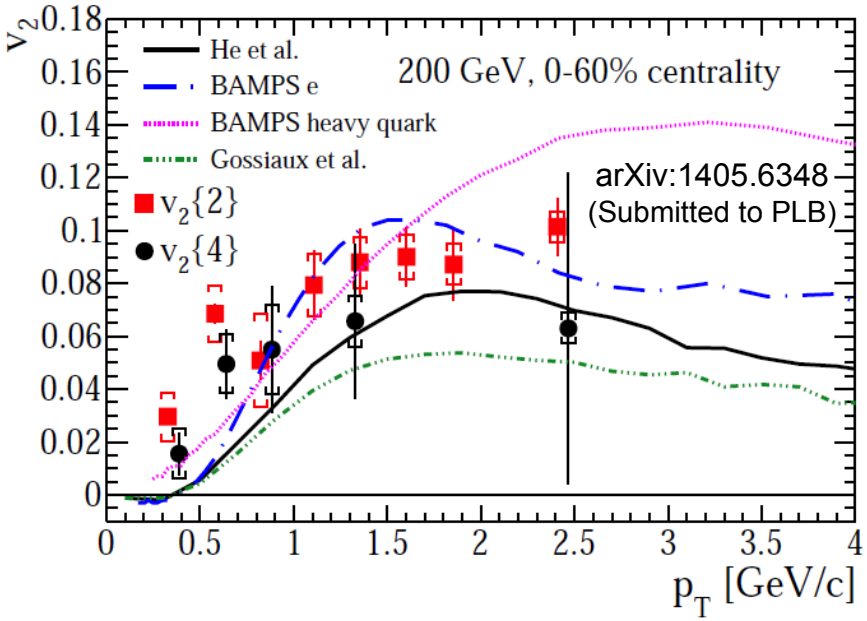
Centrality



BES II enables measurements at energy <20GeV

Non-photonic electrons: 200 GeV





Suppression

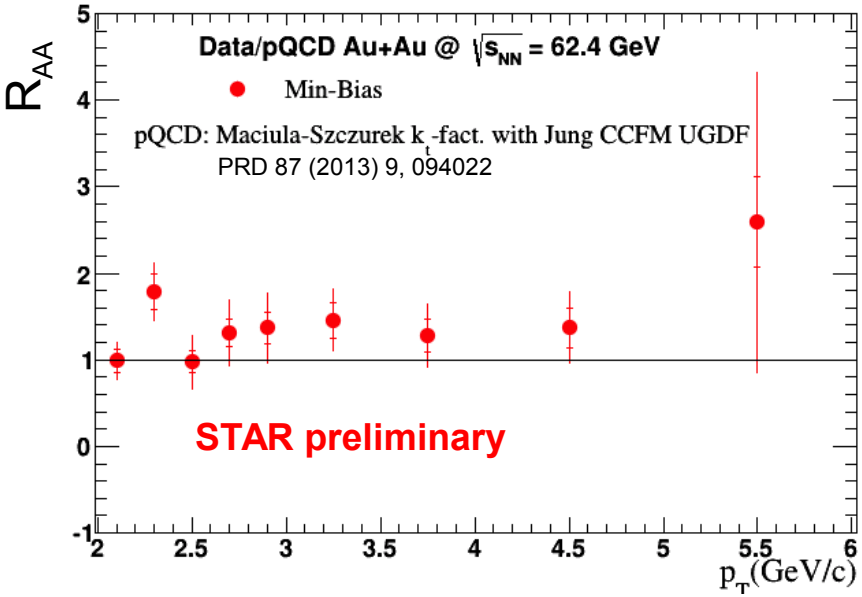
- Significant suppression of NPE in central collisions (p_T>4 GeV/c)
- Similar to that of light hadrons and D^0 mesons

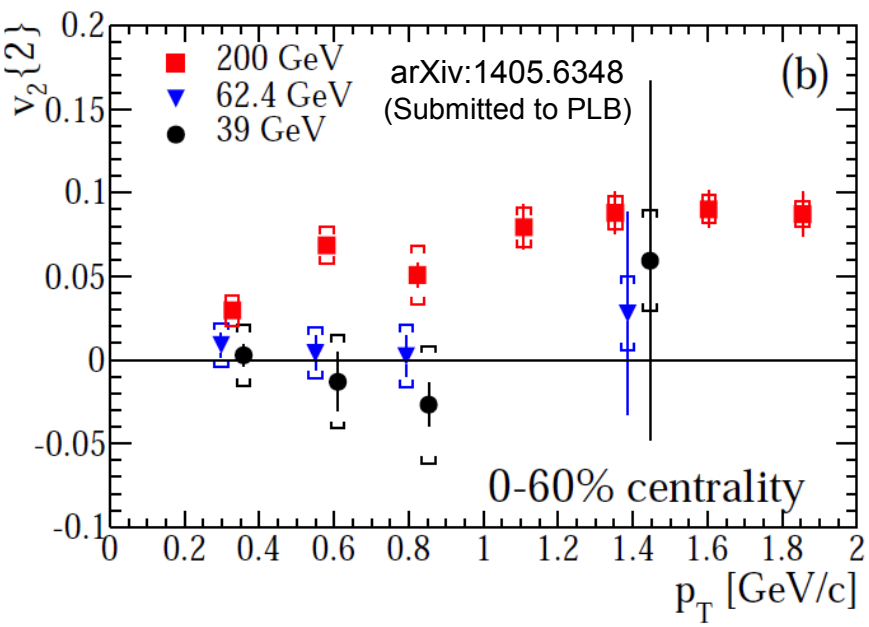
Anisotropy (v_2)

- 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

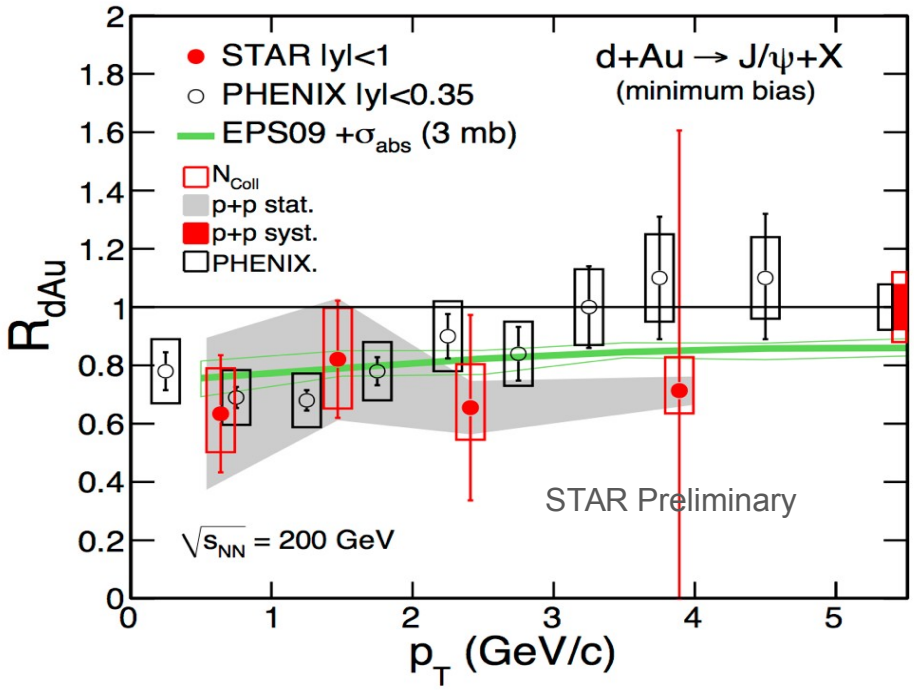
Anisotropy (v_2)

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

Motivation for high-p_T J/ψ

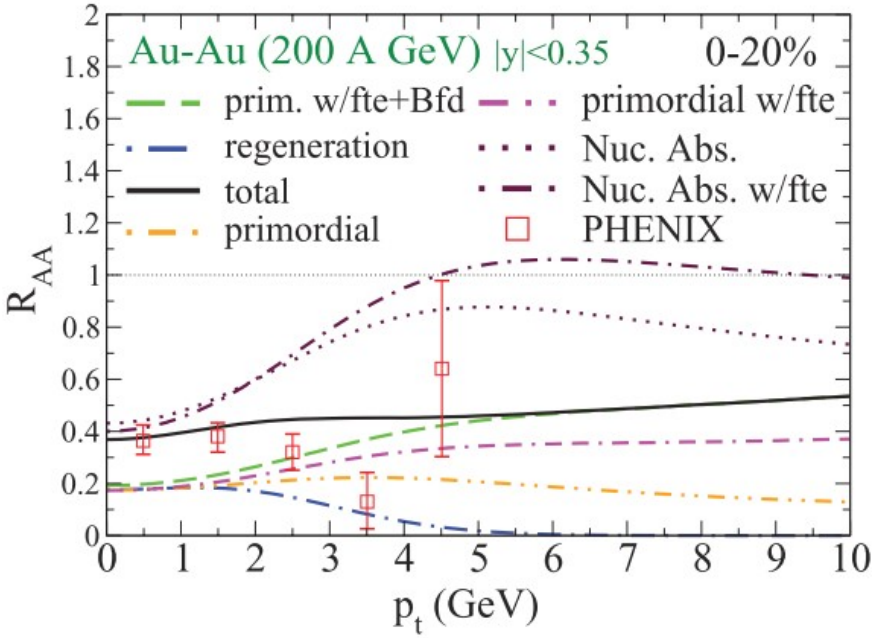
- d+Au → study of cold nuclear matter effects
- $R_{dAu} \approx 1$ for high p_T

→ CNM effects are small at high-p_T



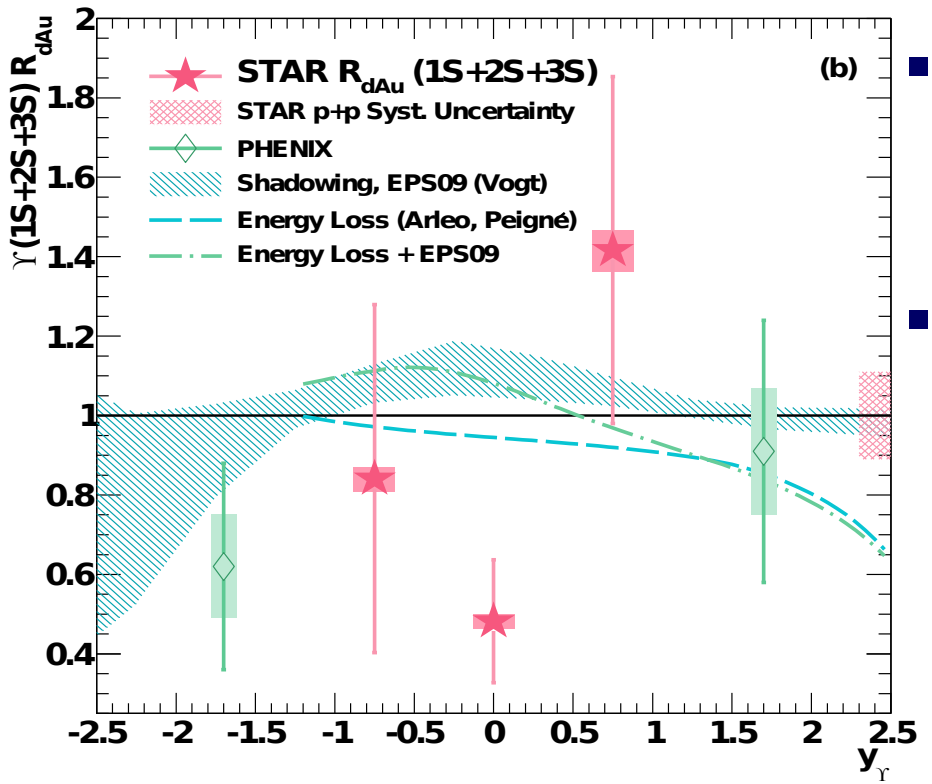
Model:
X. Zhao, R.Rapp, PRC82, 064905 (2010)

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



- Much less regeneration

Υ R_{dAu} – CNM effects



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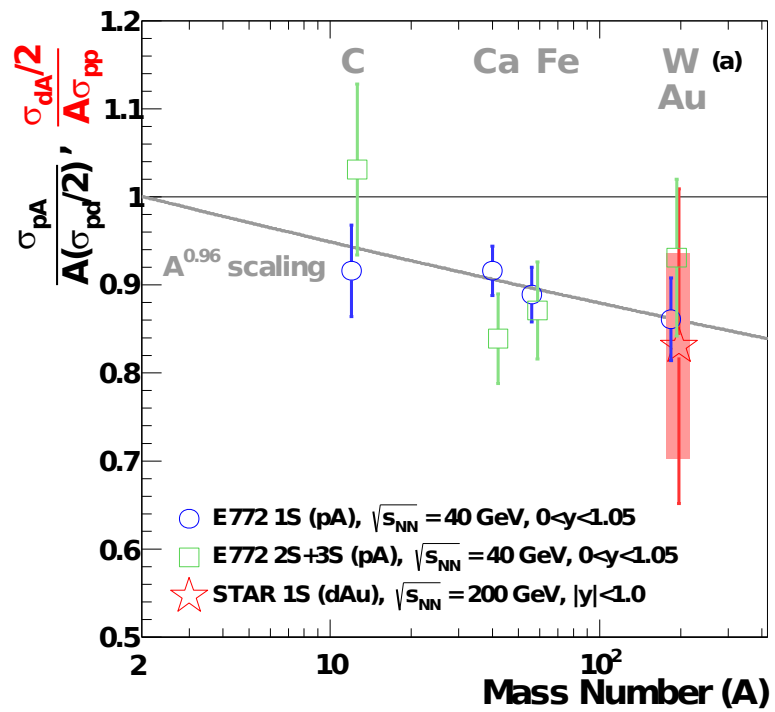
R_{dAu}=0.48 ± 0.14(stat) ± 0.07(syst) ± 0.02 (pp stat) ± 0.06 (pp syst)

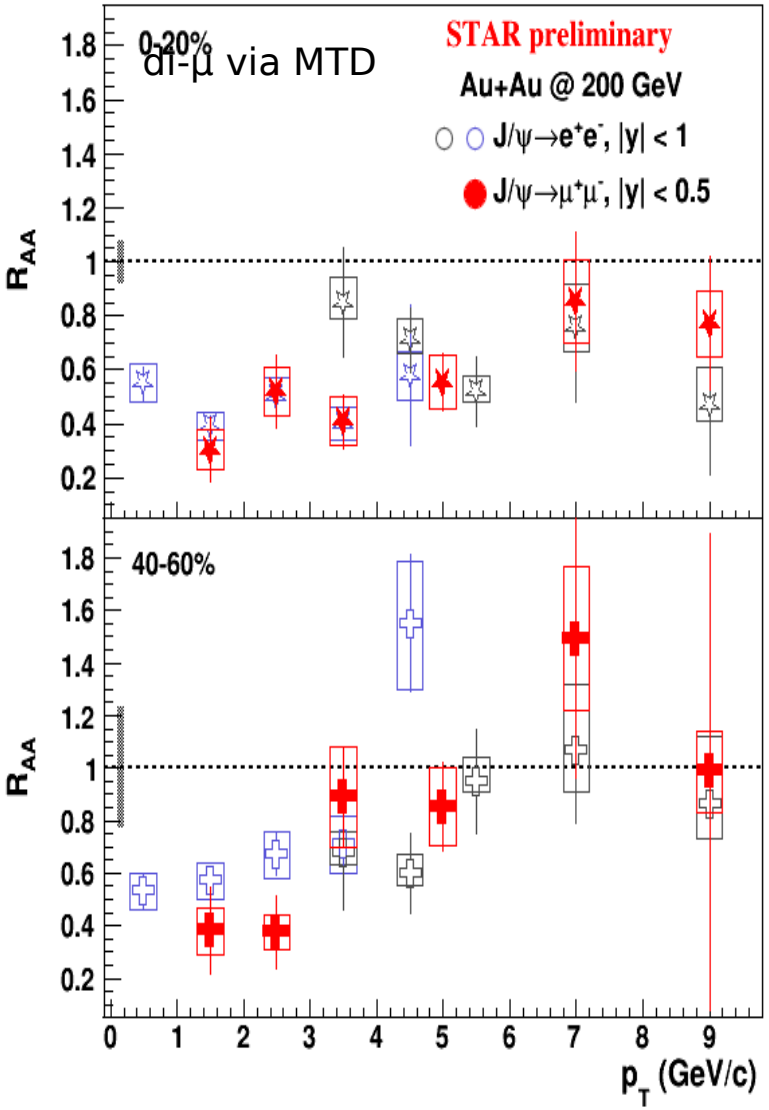
|y|<0.5

- Models include
  - Gluon nPDF (Anti)shadowing
  - Initial parton energy loss
- Indication of suppression at mid-rapidity beyond models

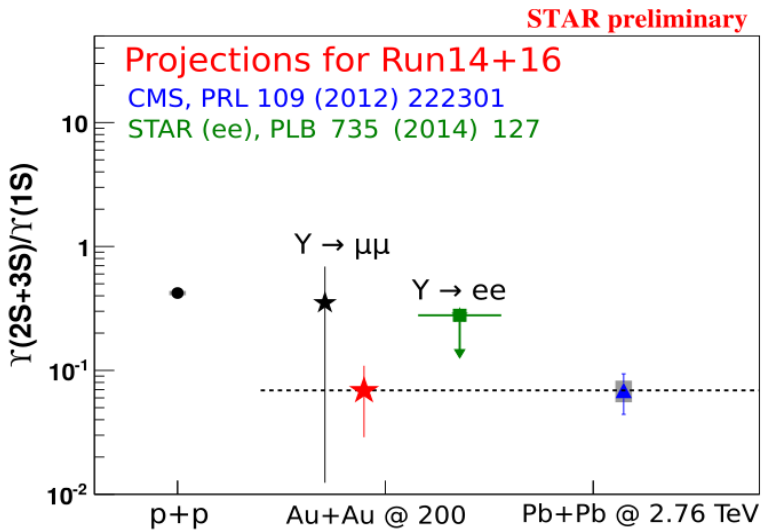


- STAR data consistent with E772

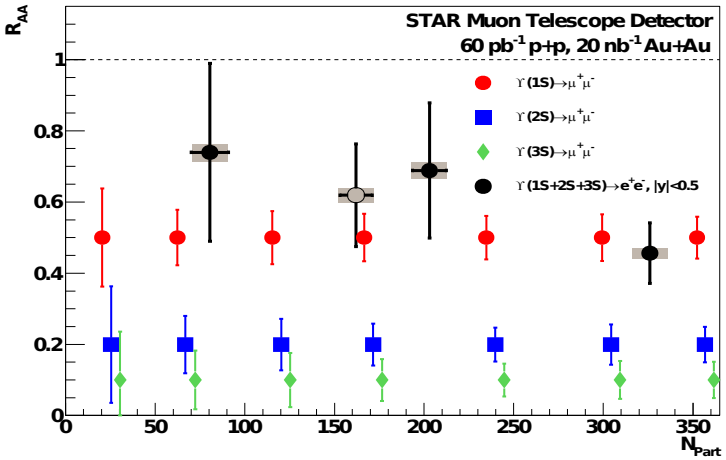
Quarkonia in Au+Au with MTD



Di-electron: PLB 722 (2013) 55, PRC 90, 024906 (2014)

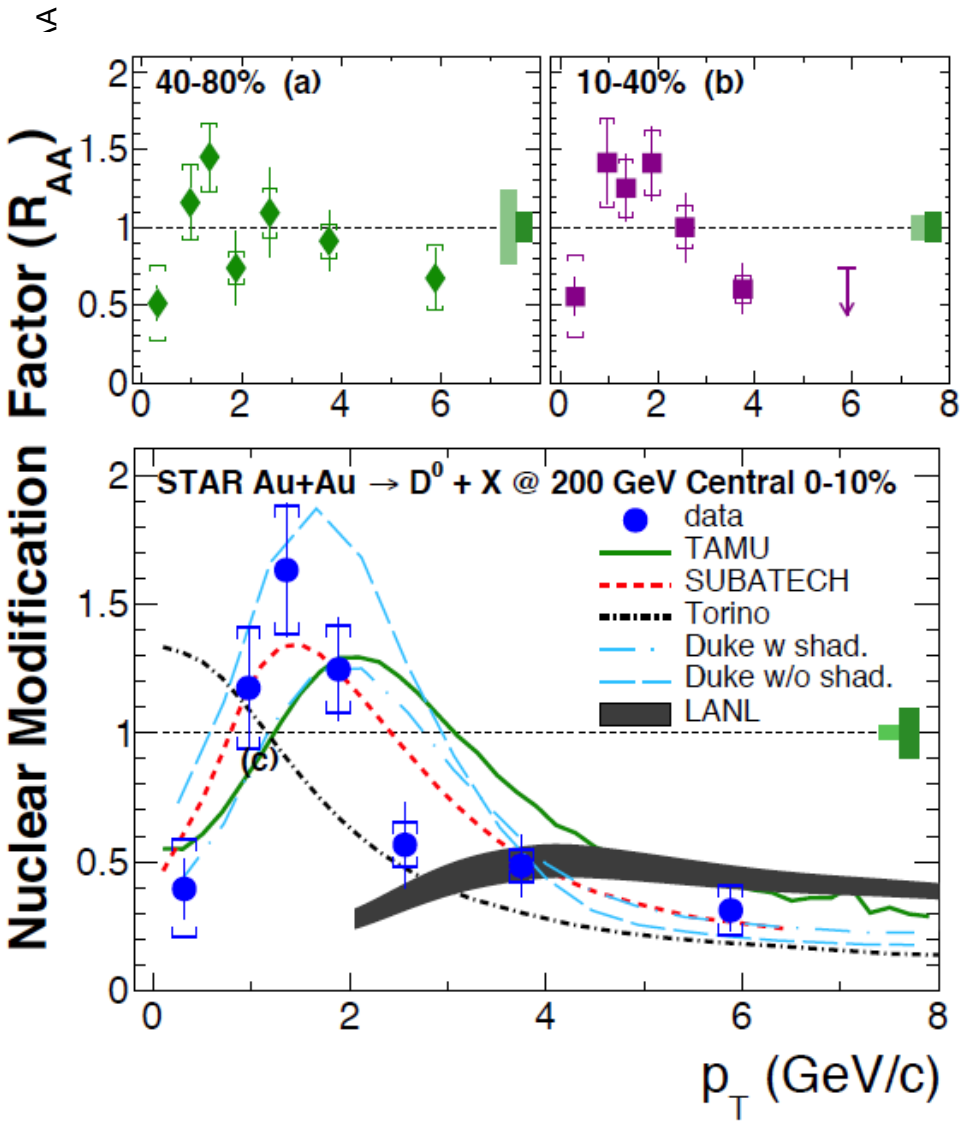


Υ projection, full MTD data



Mustafa QM15

D^0, model ingredients



	TAMU	SUBATECH	Torino	Duke	LANL
HQ prod.	LO	FNOLL	NLO	LO	LO
QGP-Hydro	ideal	ideal	viscous	viscous	ideal
HQ eLoss	coll.	coll. +rad.	coll. +rad.	coll. +rad.	diss. +rad.
Coalescence	Yes	Yes	No	Yes	No
Cronin effect	Yes	Yes	No	No	Yes
Shadowing	No	No	Yes	Yes/No	Yes

Zhenyu Ye, QM2014