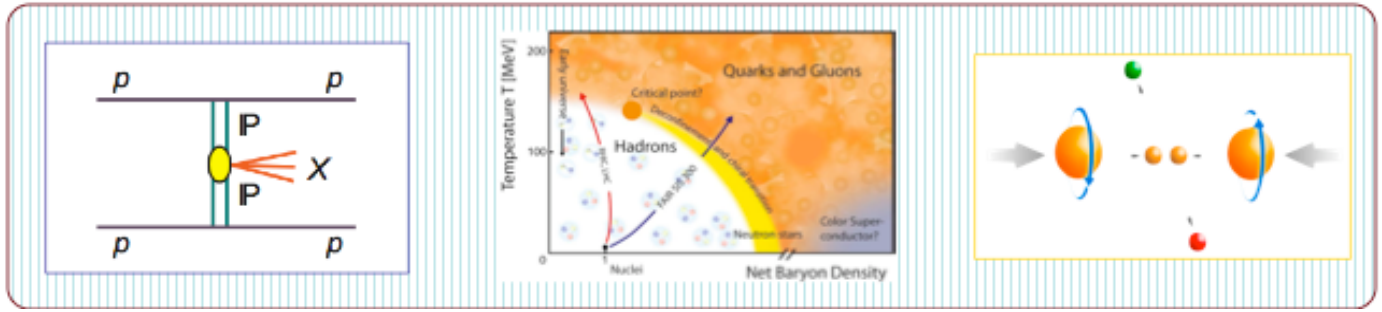
STAR Experiment at RHIC

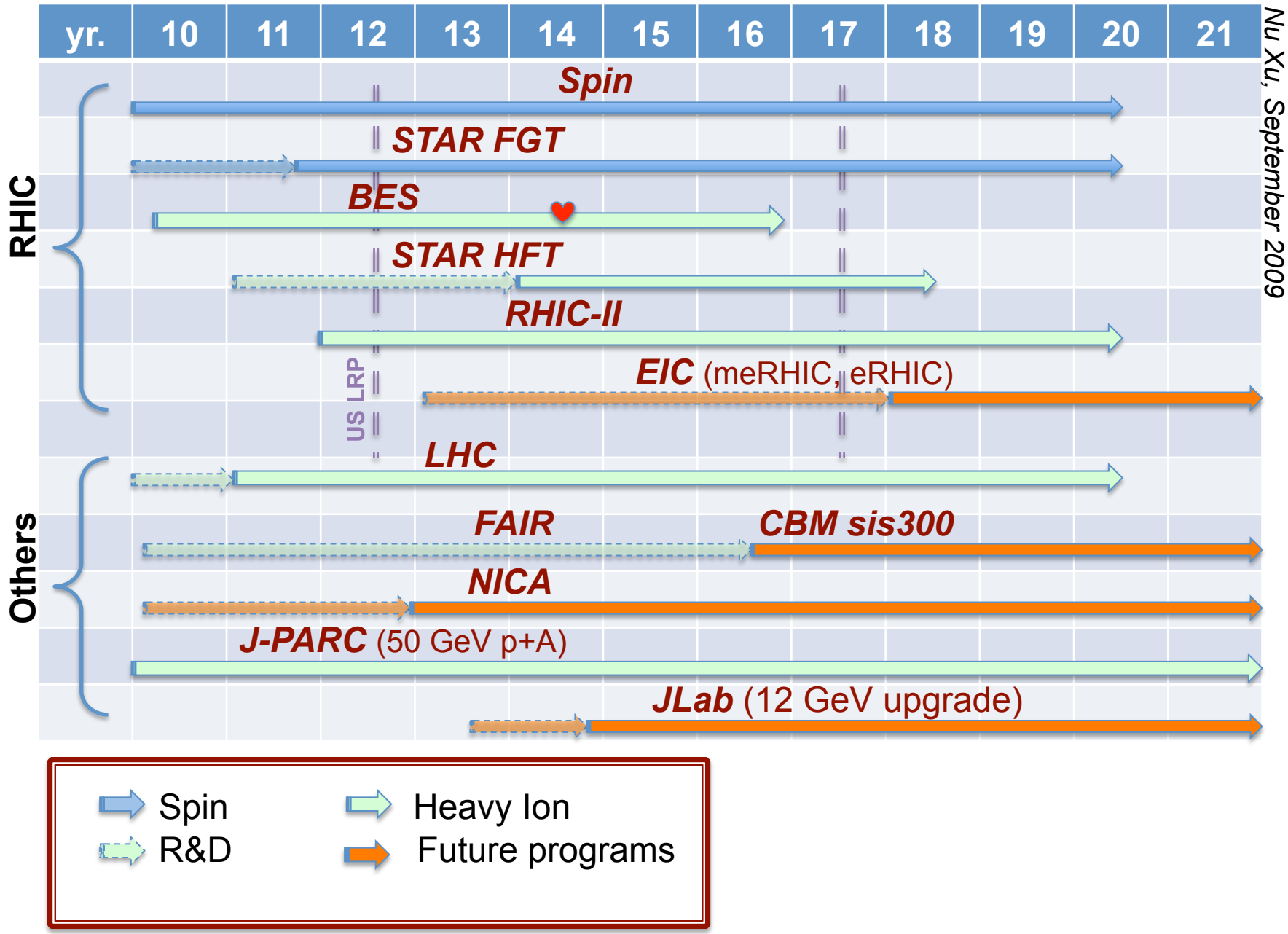
Nu Xu



Outline

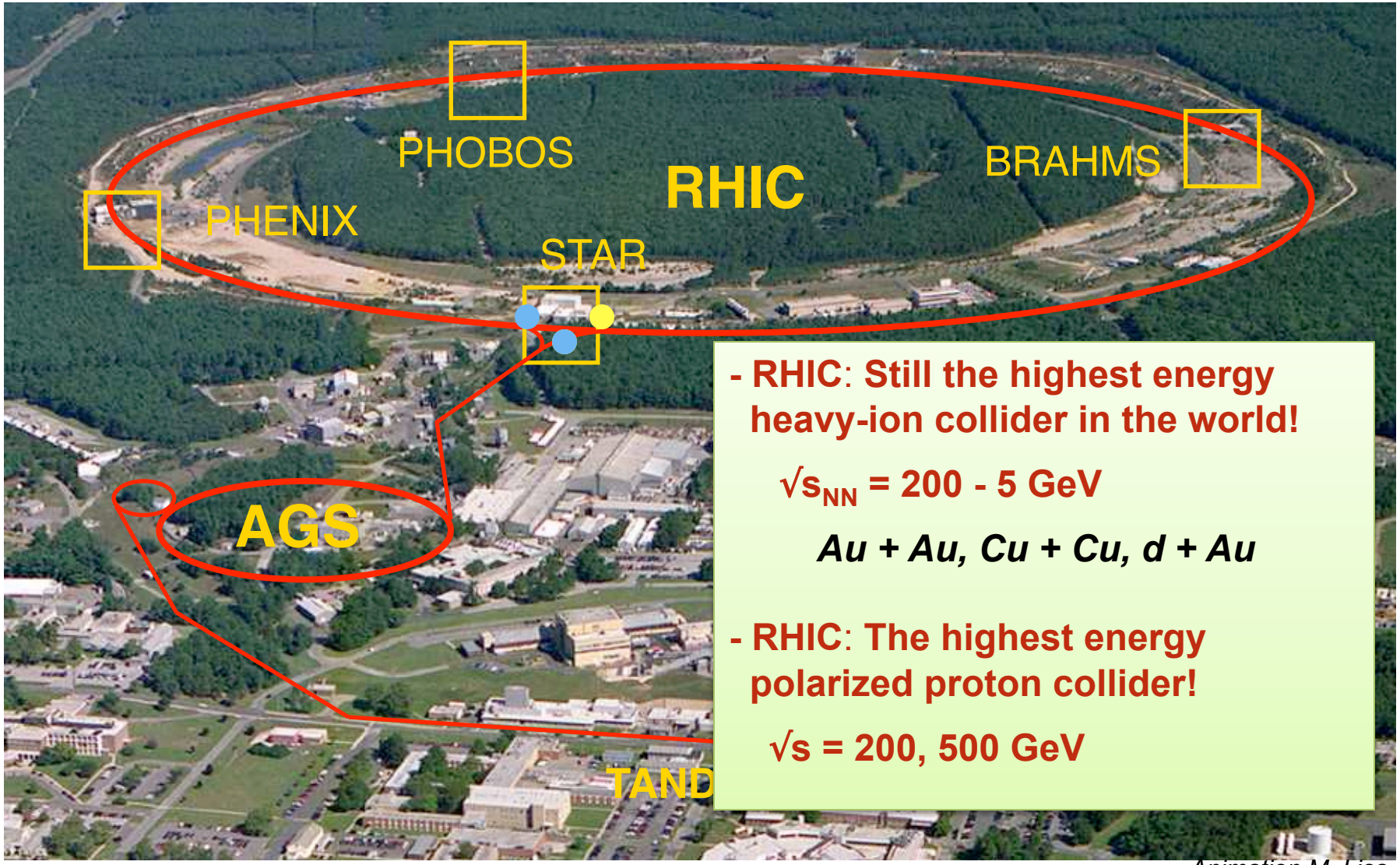
1) Introduction
2) STAR Physics Program
3) Upgrades
4) Summary

Timeline of QCD and Heavy Ion Facilities



Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY



- RHIC: Still the highest energy heavy-ion collider in the world!

  $\sqrt{s_{NN}}$ = 200 - 5 GeV

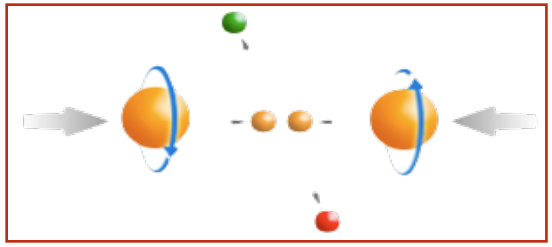
  Au + Au, Cu + Cu, d + Au

- RHIC: The highest energy polarized proton collider!

  $\sqrt{s}$ = 200, 500 GeV

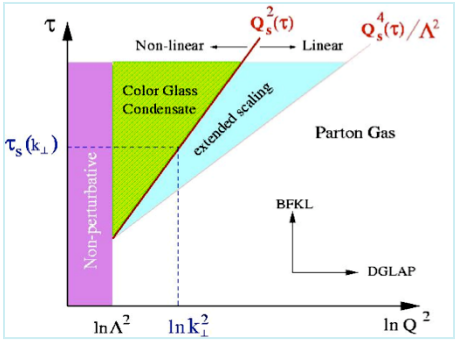
Animation M. Lisa

STAR Physics Focus



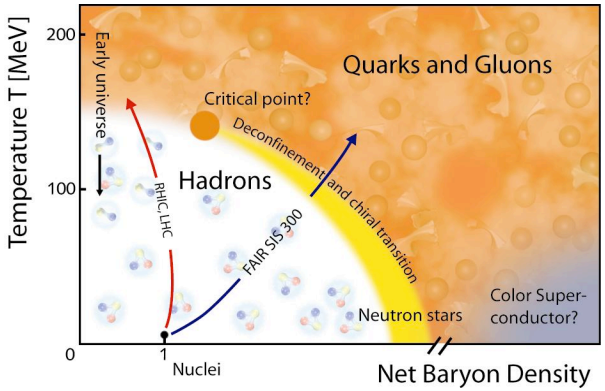
Polarized *p+p* program

- Study ***proton intrinsic properties***



Forward program

- Study low-x properties, search for ***CGC***
- Study elastic (inelastic) processes (pp2pp)
- Investigate ***gluonic exchanges***



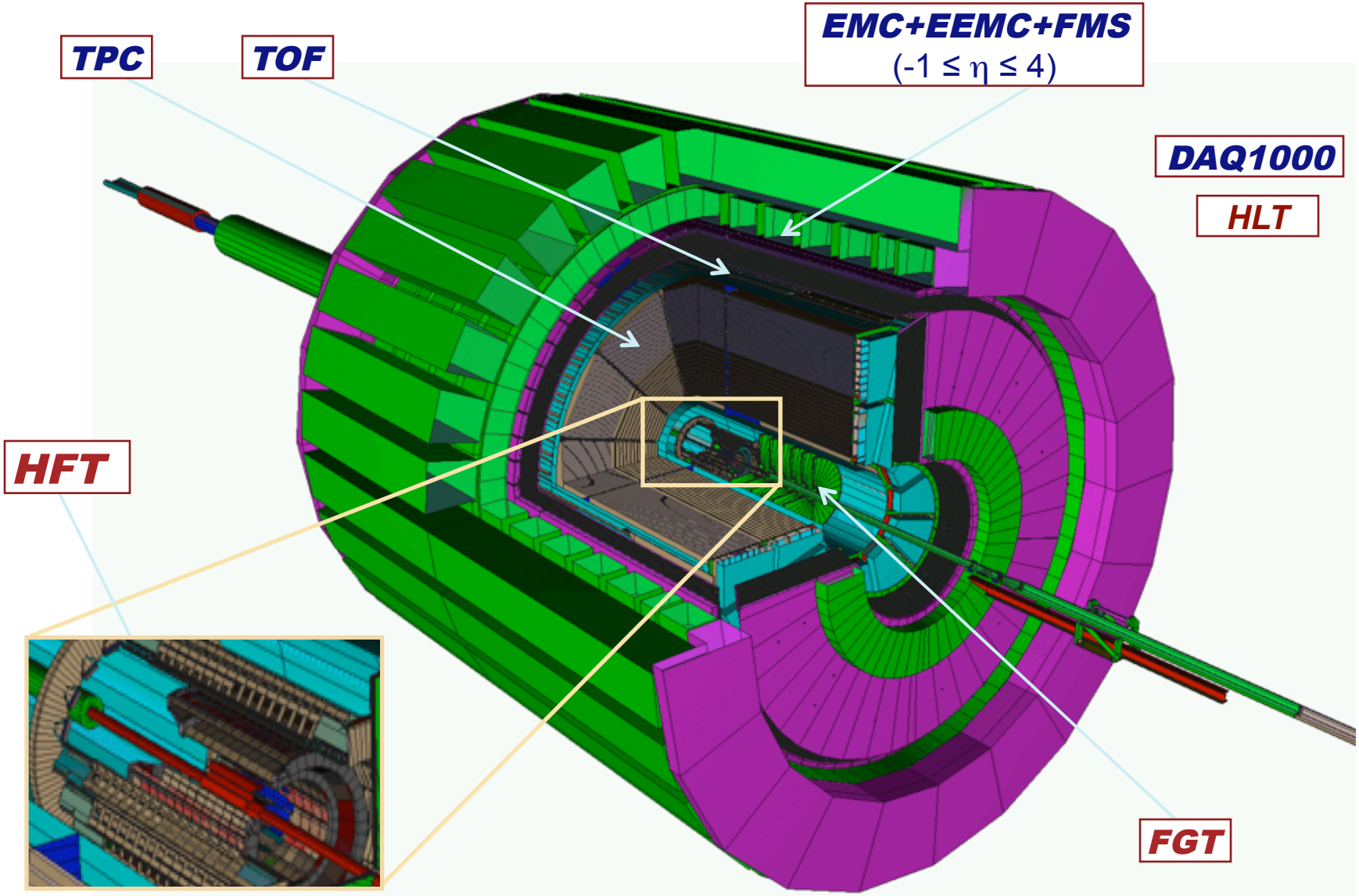
1) At 200 GeV top energy

- Study ***medium properties, EoS***
- pQCD in hot and dense medium

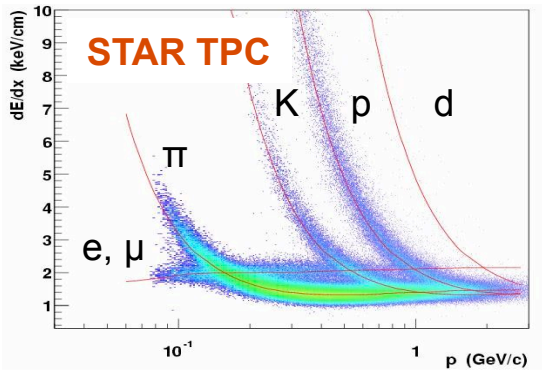
2) RHIC beam energy scan

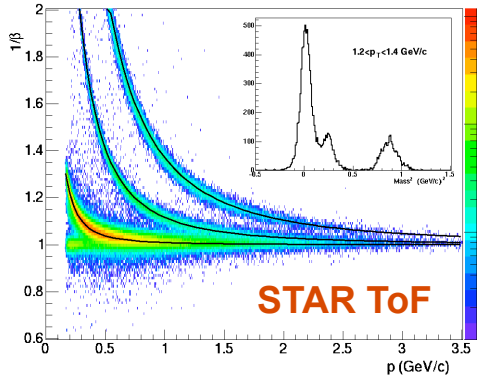
- Search for the ***QCD critical point***
- Chiral symmetry restoration

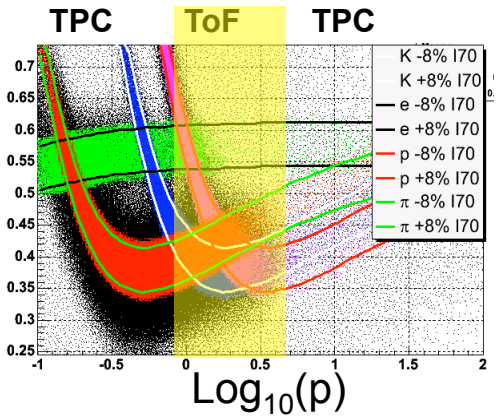
STAR Detectors: *Full 2π particle identification!*

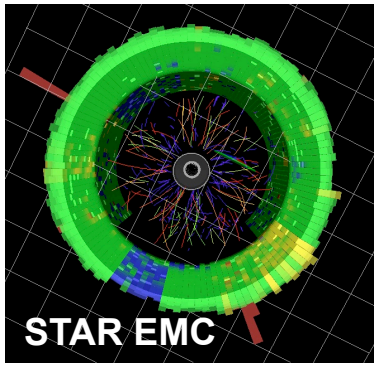


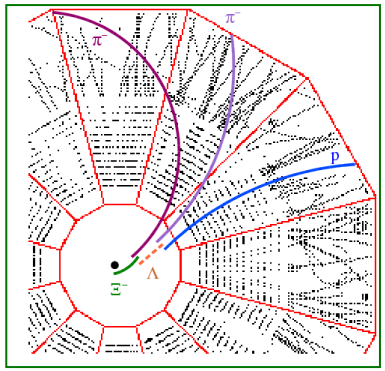
Particle Identification at STAR

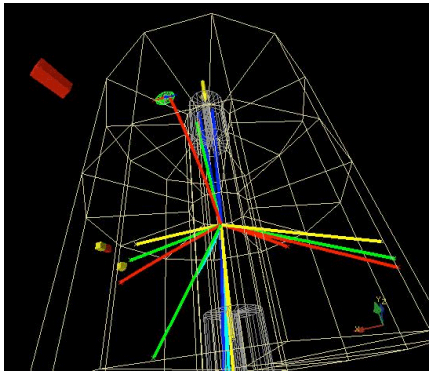


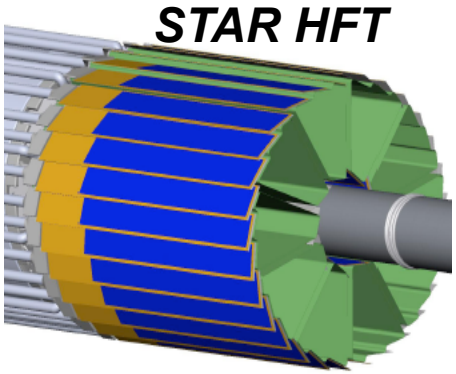






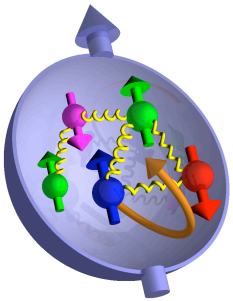




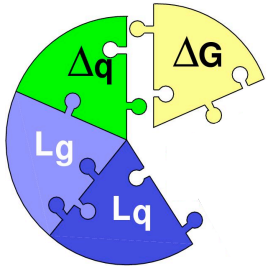


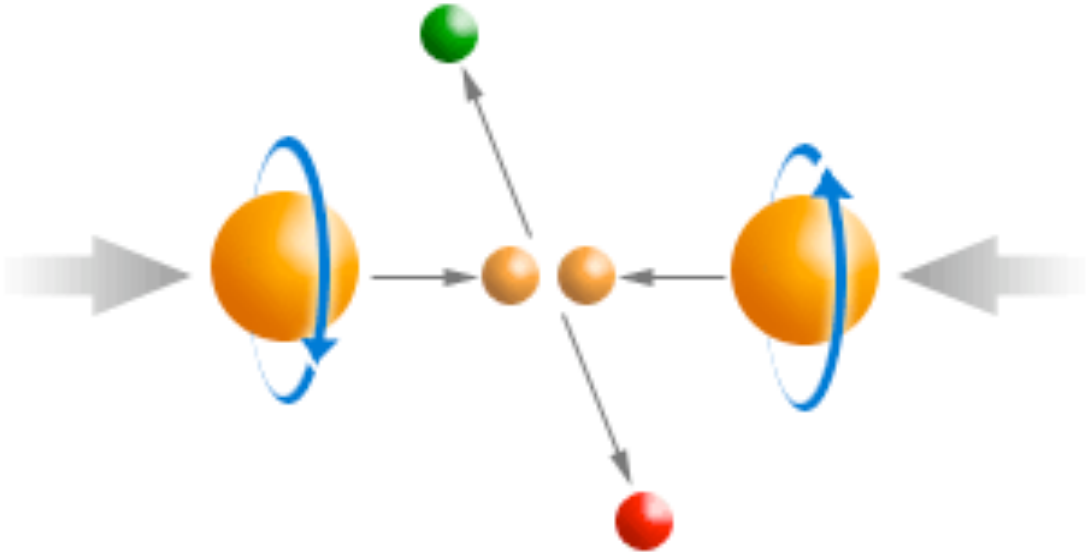
Neutral particles **Strange hyperons** **Jets** **Heavy Quark Hadrons**

Multiple-fold correlations among the identified particles!



Proton Spin Physics





Helicity Distributions - gluons

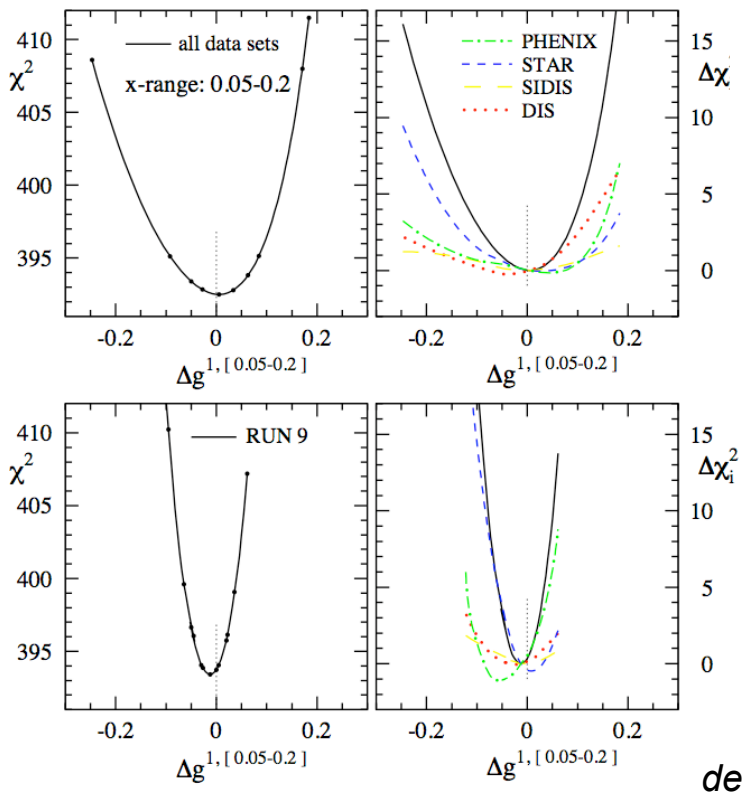
Run 9: STAR bottom line is to collect **FoM: 6.5 pb^{-1}** (Run9: 2.3 pb^{-1})

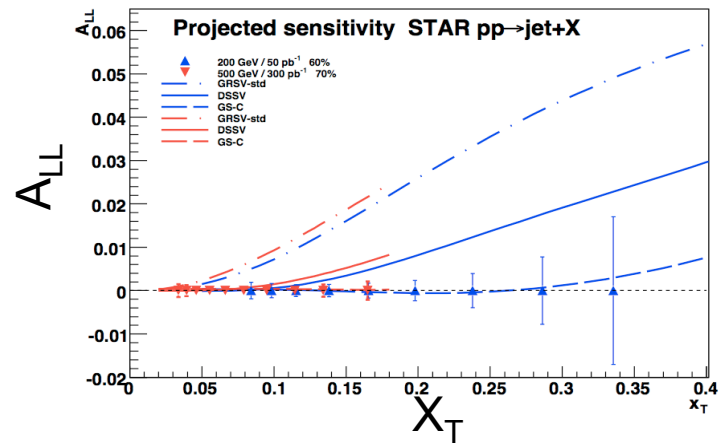
inclusive jet, di-jets, γ-jet… analysis

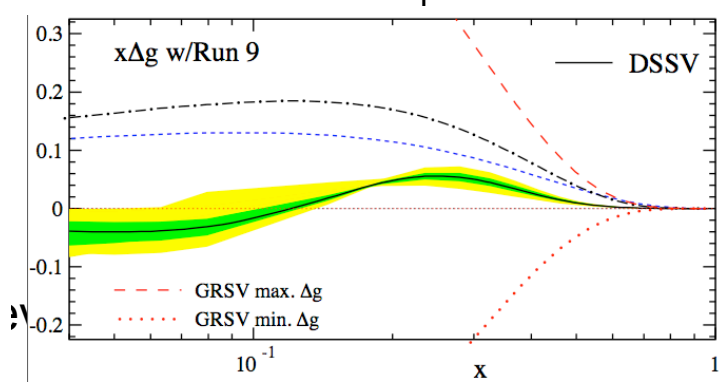
STAR: internal review of the *strategy* for spin physics in light of Run9.

Run 6

Run 9

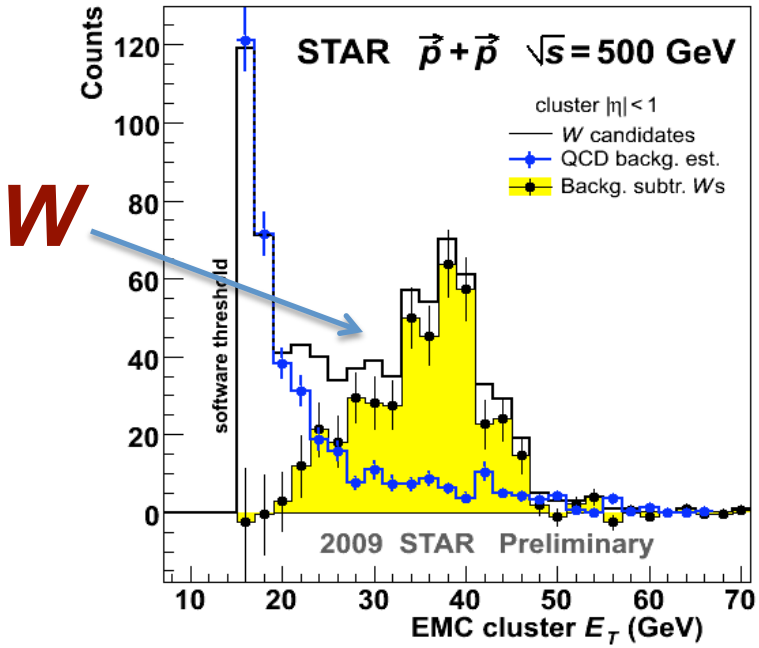


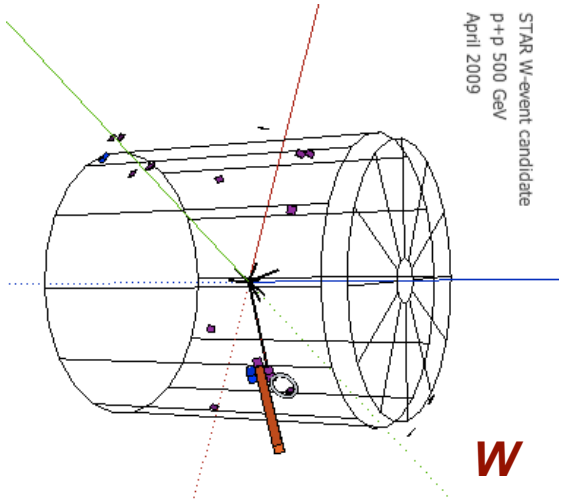


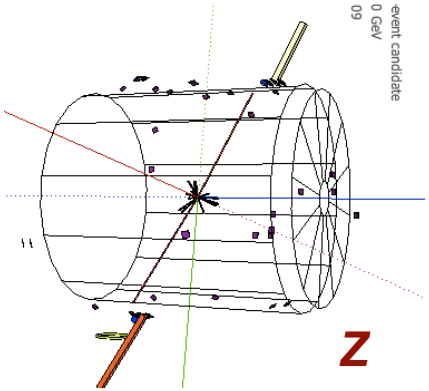


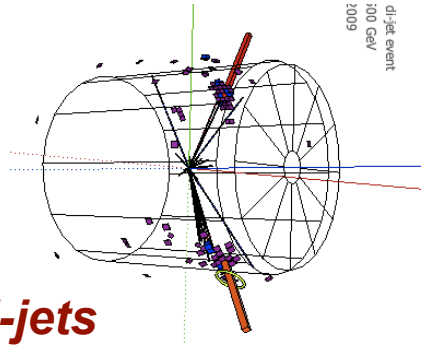
de Florian et al, arXiv: 0804.0422 //PRL 101:072001(08)

500 GeV p+p collisions



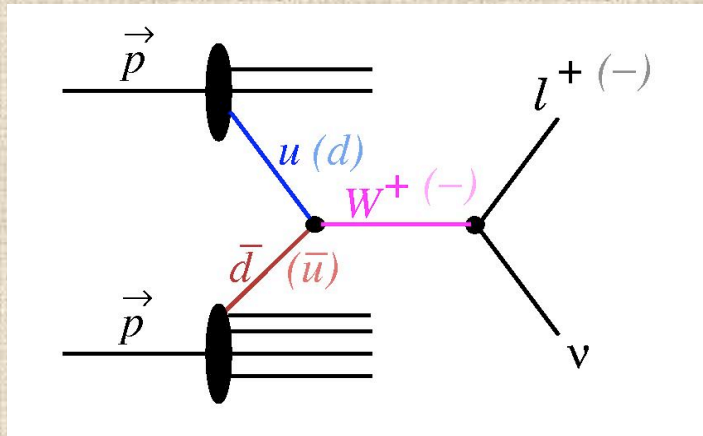






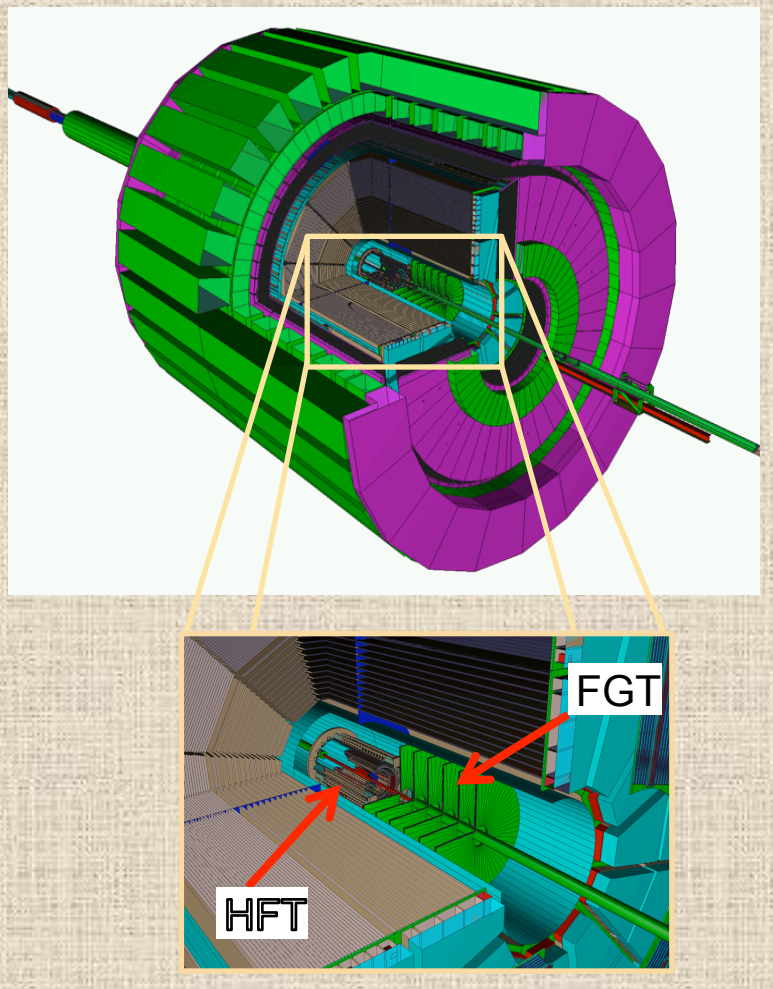
STAR: The *Sea-Quark* Program

500 GeV p+p collisions



$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu$$

$$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}$$



Forward GEM Tracker: FGT

1) Charge sign identification for high momentum electrons from W± decay (Energy determined with EEMC)

2) Triple-GEM technology, Summer 2011 for Run12

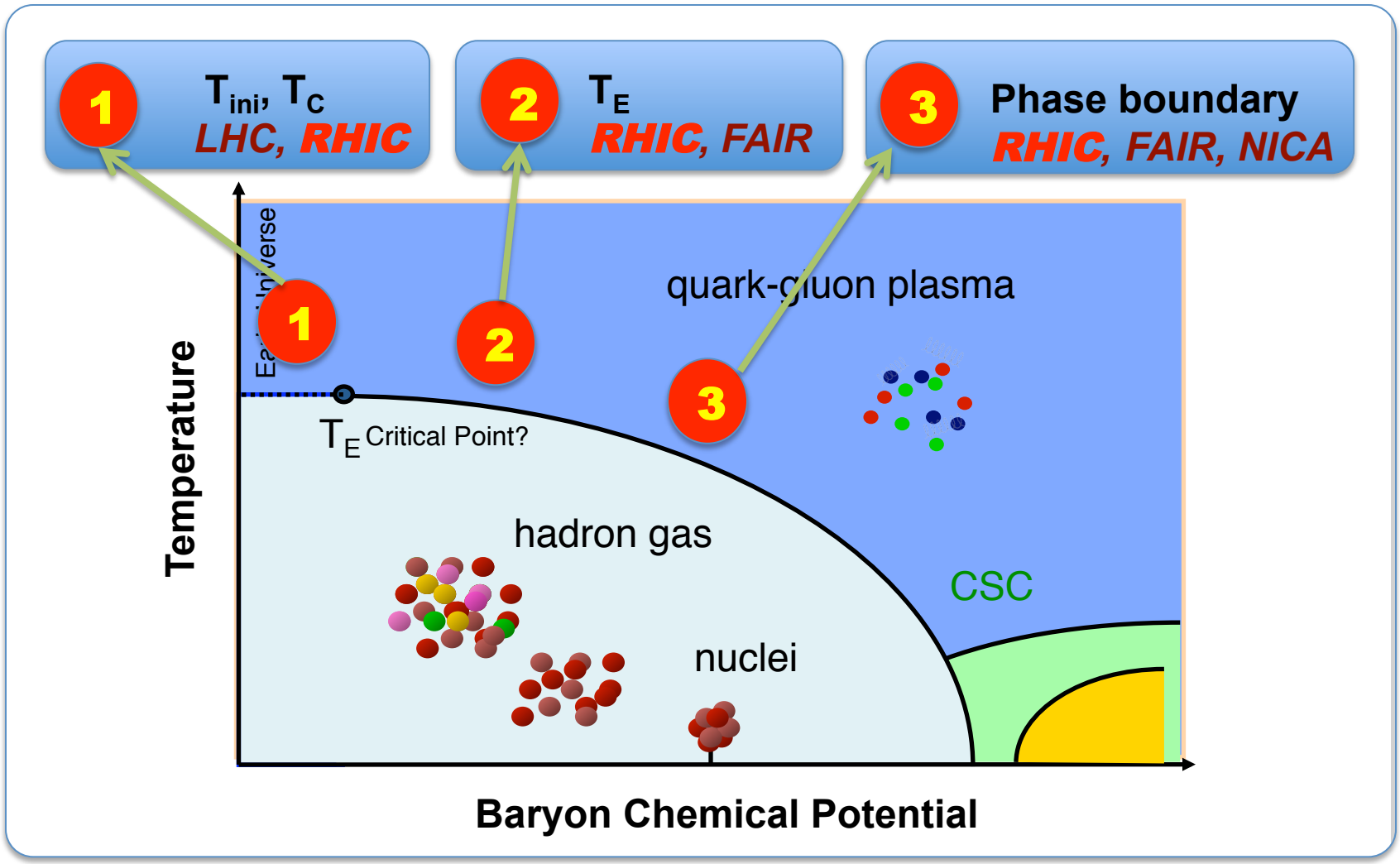
Summary: Spin Program

(1) Complete the Δg program

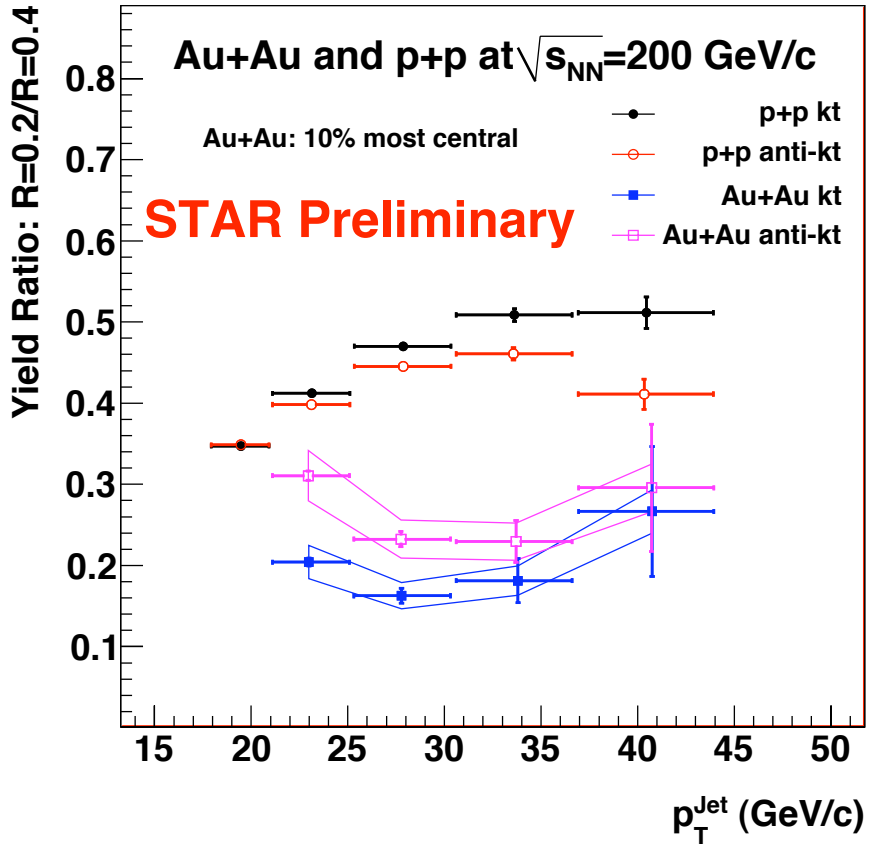
(2) Sea quark study will start in run12

(3) Transverse spin program

The QCD Phase Diagram and High-Energy Nuclear Collisions

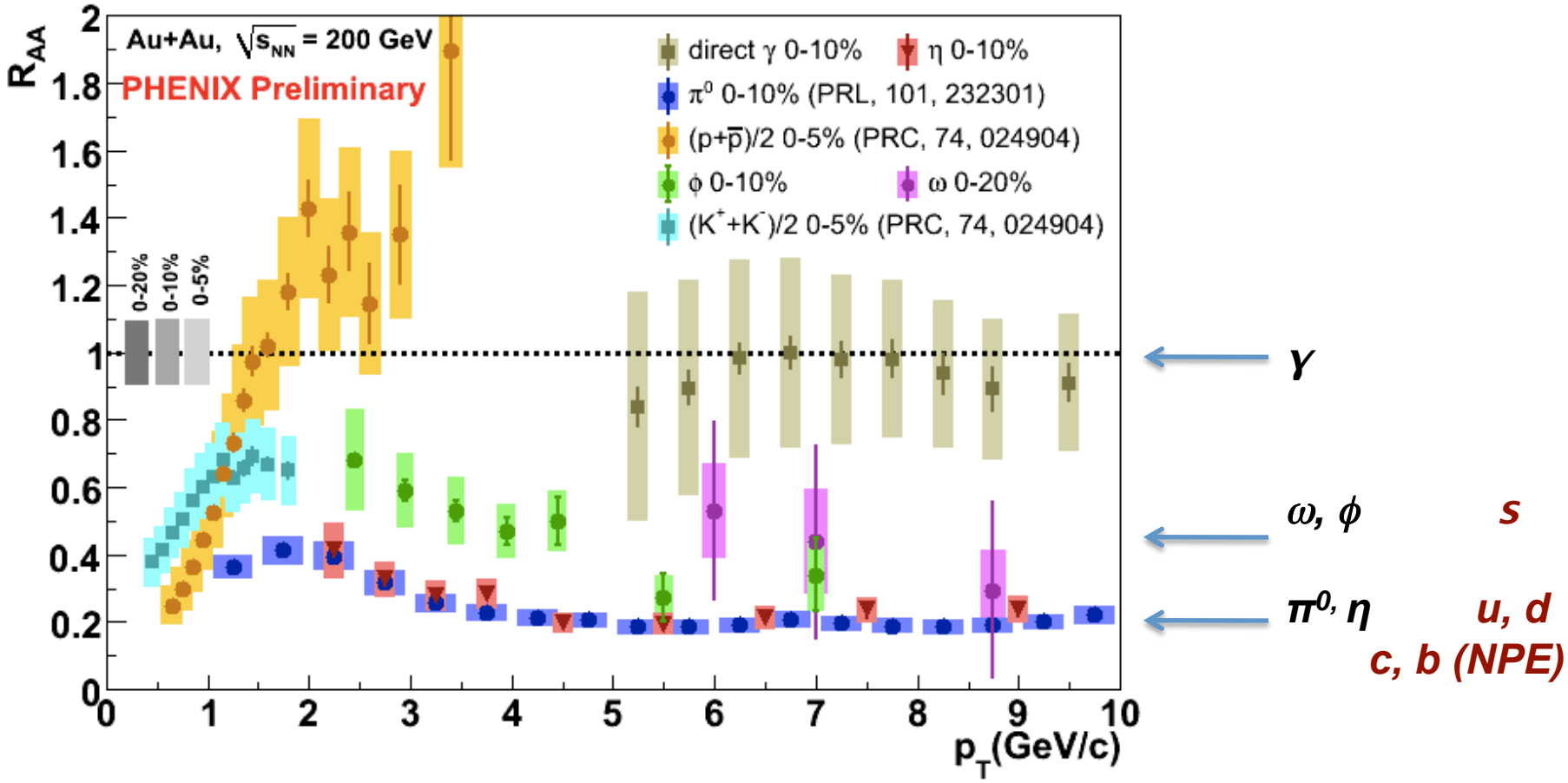


Full Jet Reconstruction At RHIC



- Clear cone size dependent
- Jets are broadened in Au+Au collisions

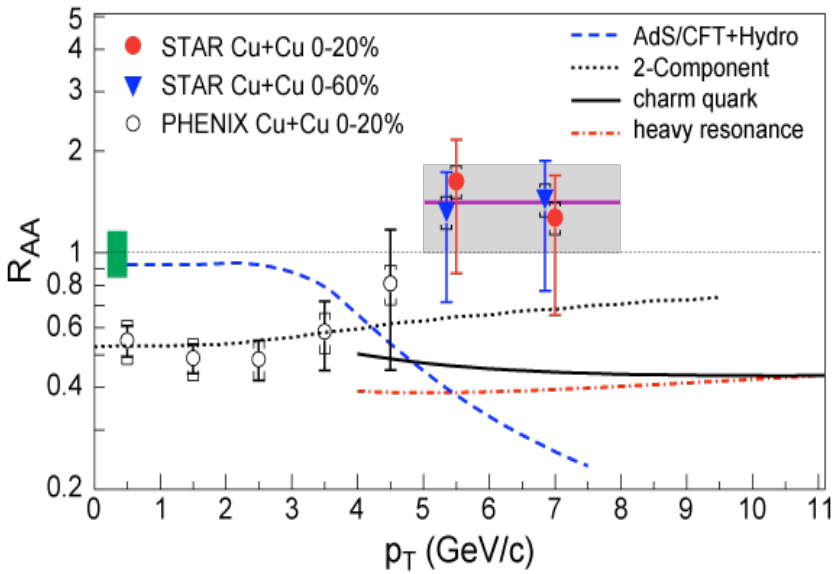
Nuclear Modification Factor R_{AA}



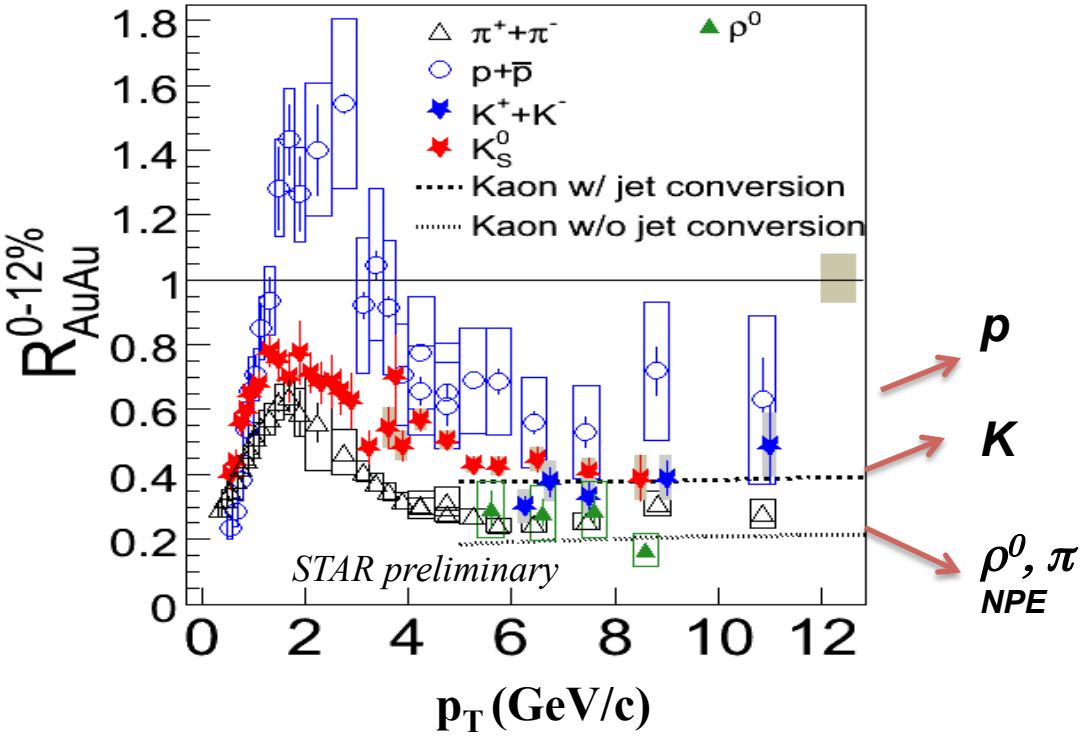
S. Esumi, M. Neglis et al.

Nuclear Modification Factor R_{AA}

STAR: PRC®, 0904.0439



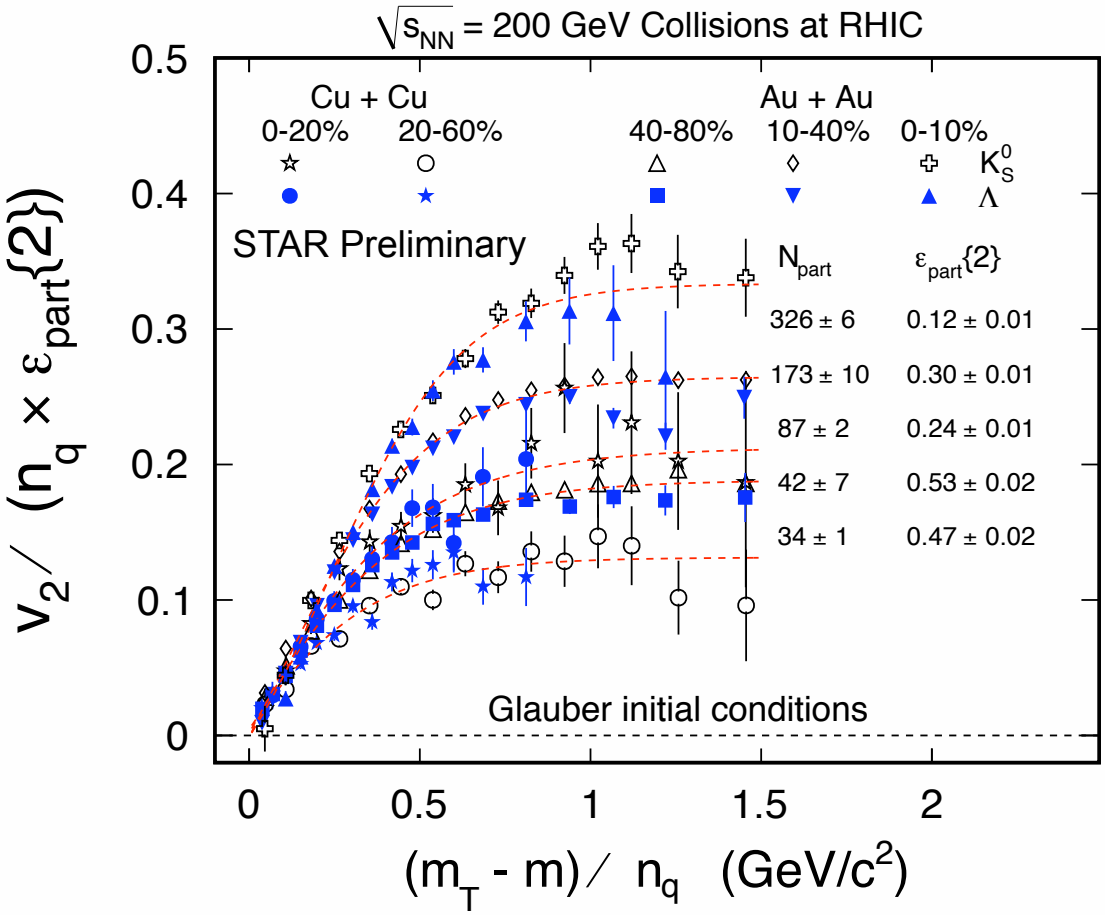
Y. Xu, SQM09



1) **Flavor ?:** $R_{AA}(\pi) \sim R_{AA}(\rho^0) < R_{AA}(\phi) < R_{AA}(J/\psi)$
2) **Mass ?** $R_{AA}(\pi) < R_{AA}(K) < R_{AA}(p)$

Challenges to pQCD calculations

System Size Driven Collectivity

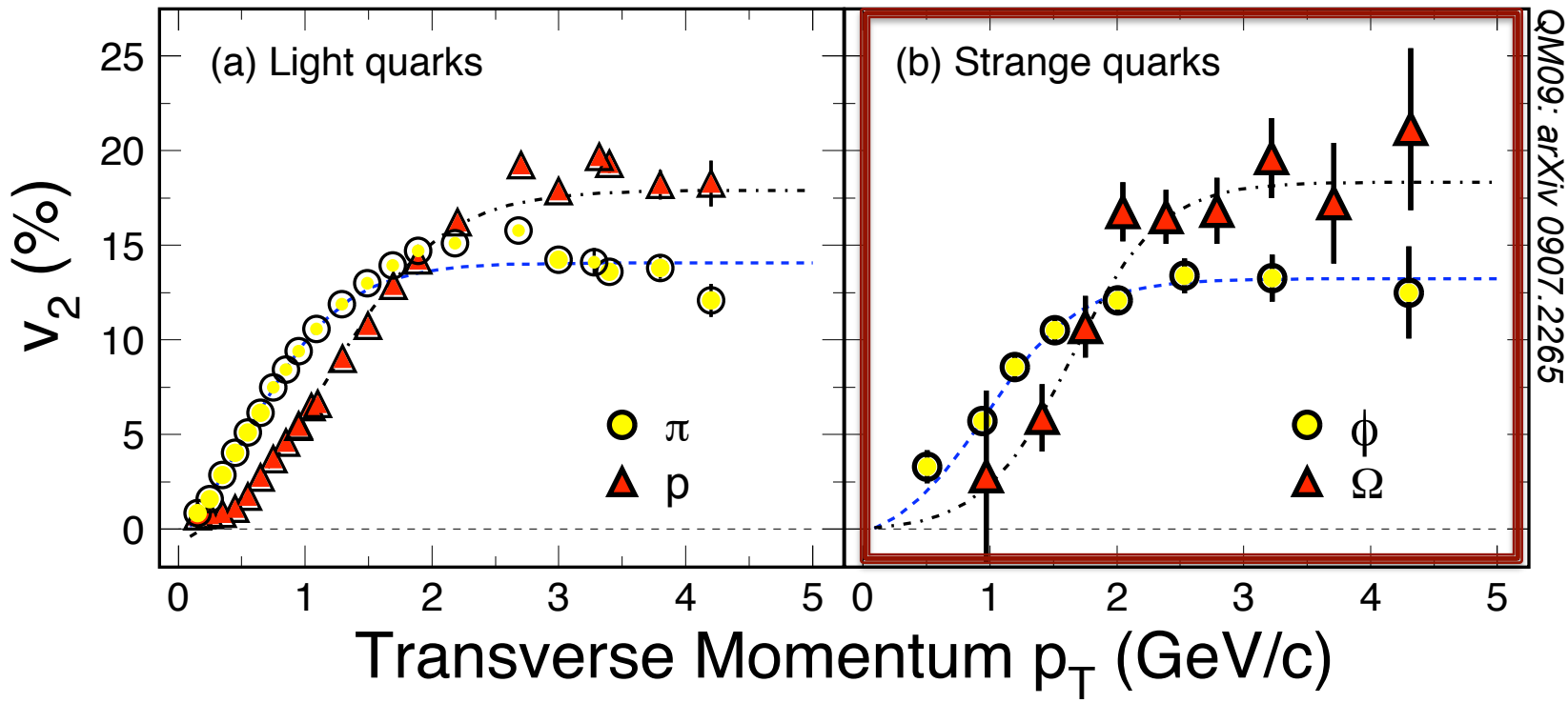


Collectivity: Driven by number of participants, *NOT* by eccentricity.

Caution: Local equilibrium and perfect fluid

Partonic Collectivity at RHIC

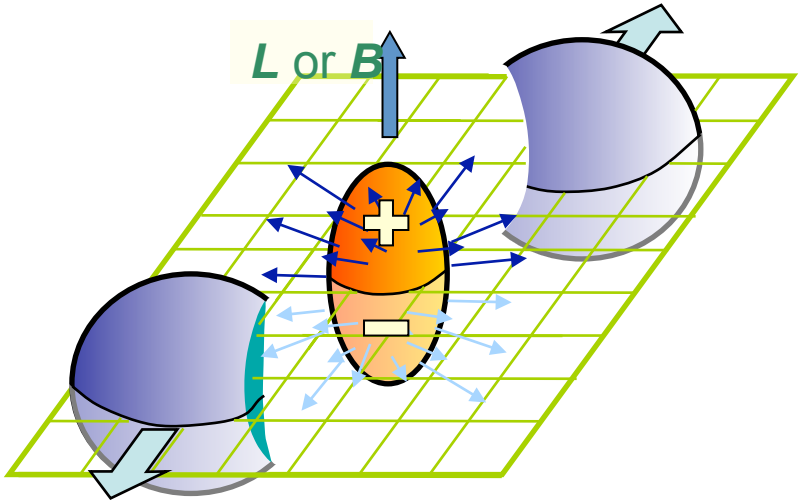
$\sqrt{s_{NN}}$ = 200 GeV ^{197}Au+^{197}Au Collisions at RHIC

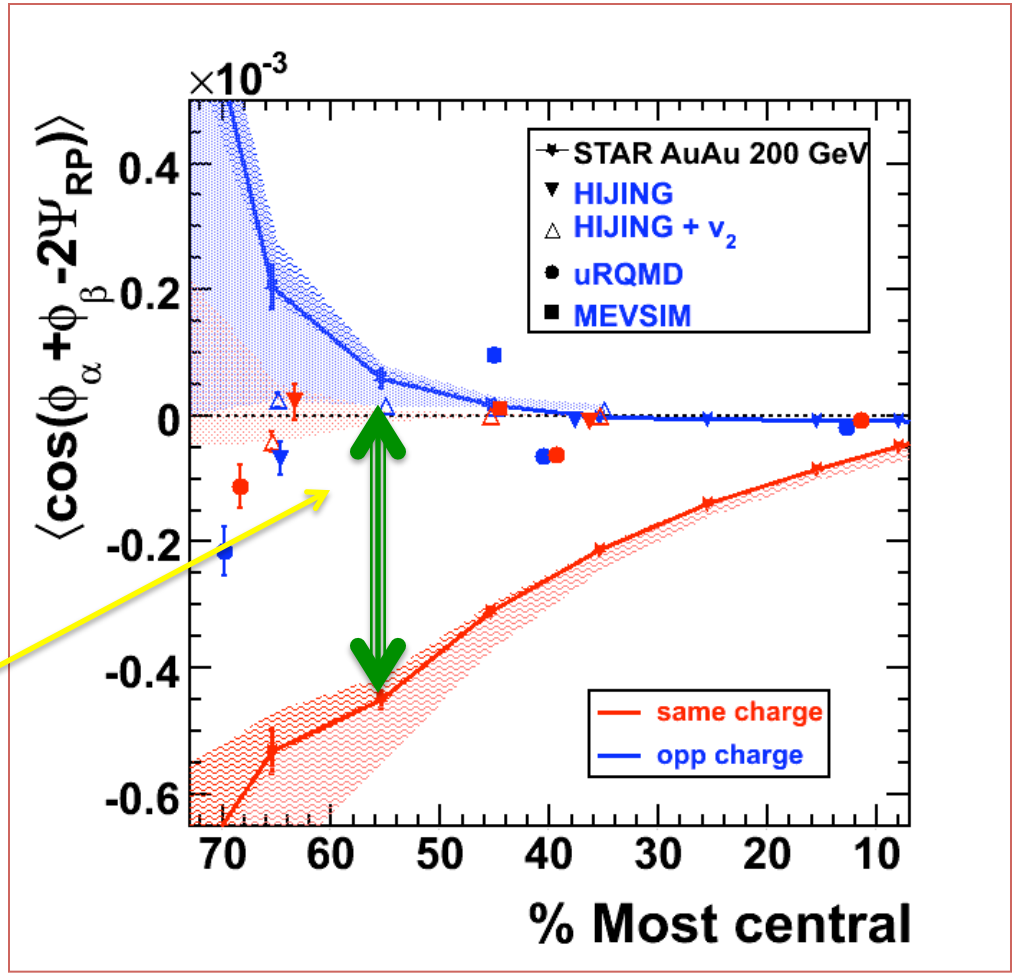


Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): number of quarks ordering
s-quark hadron: smaller interaction strength in hadronic medium
light- and s-quark hadrons: similar v_2 pattern

=> Collectivity developed at partonic stage!

Search for Local Parity Violation …



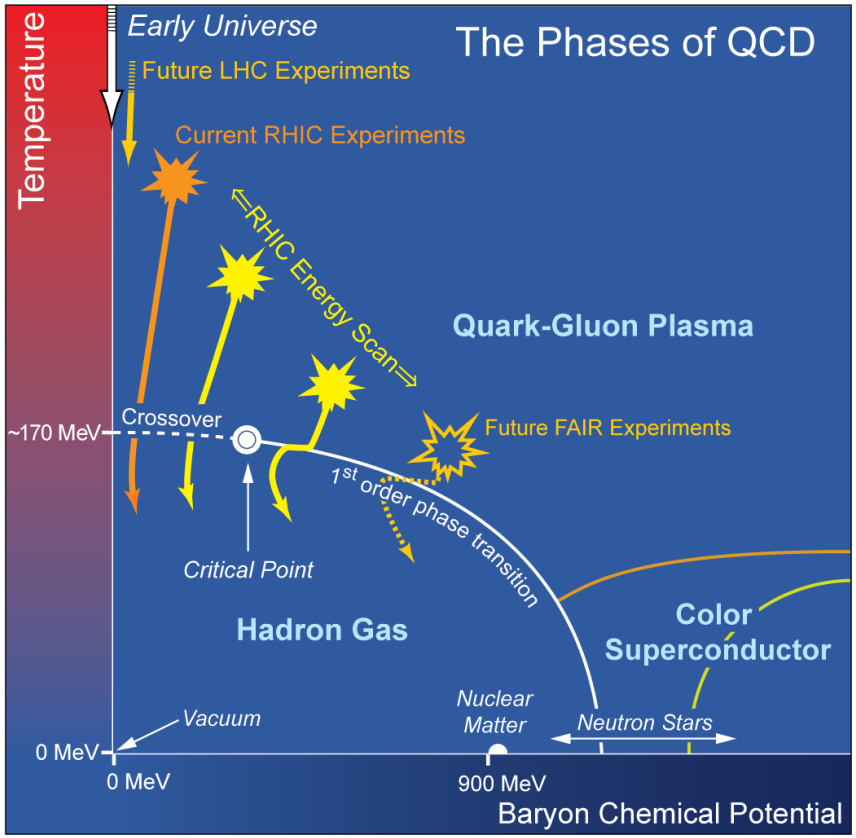


The separation between the same-charge and opposite-charge correlations.

- Strong EM fields
- De-confinement and Chiral symmetry restoration

- **STAR**; *arXiv: 0909.1739 (**PRL**); 0909.1717 (PRC)*
- PID LPV analysis with TOF
- RHIC BES: disappearance

The QCD Phase Diagram and the CP



RHIC (200) & LHC: Determine the temperature T_{ini}, T_C

BES: Explore the QCD phase diagram T_E **and the location of** ***phase boundary***

- LGT prediction on the transition temperature T_C is robust.

- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram* at finite baryon chemical potential.

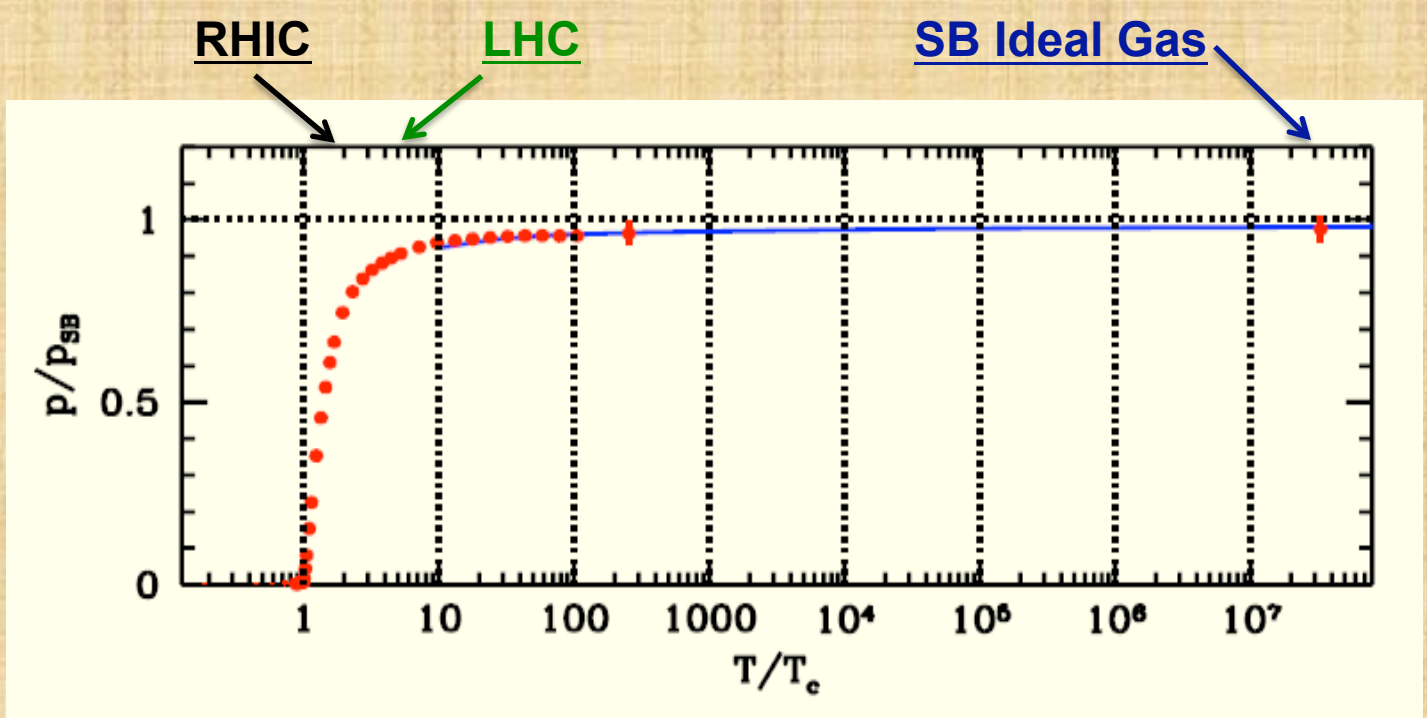
- Experimental evidence for either the critical point or 1st order transition is important for our knowledge of the QCD phase diagram*.

** Thermalization has been assumed*

*M. Stephanov, K. Rajagopal, and E. Shuryak, PRL **81**, 4816(98); K. Rajagopal, PR **D61**, 105017 (00)*

http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf

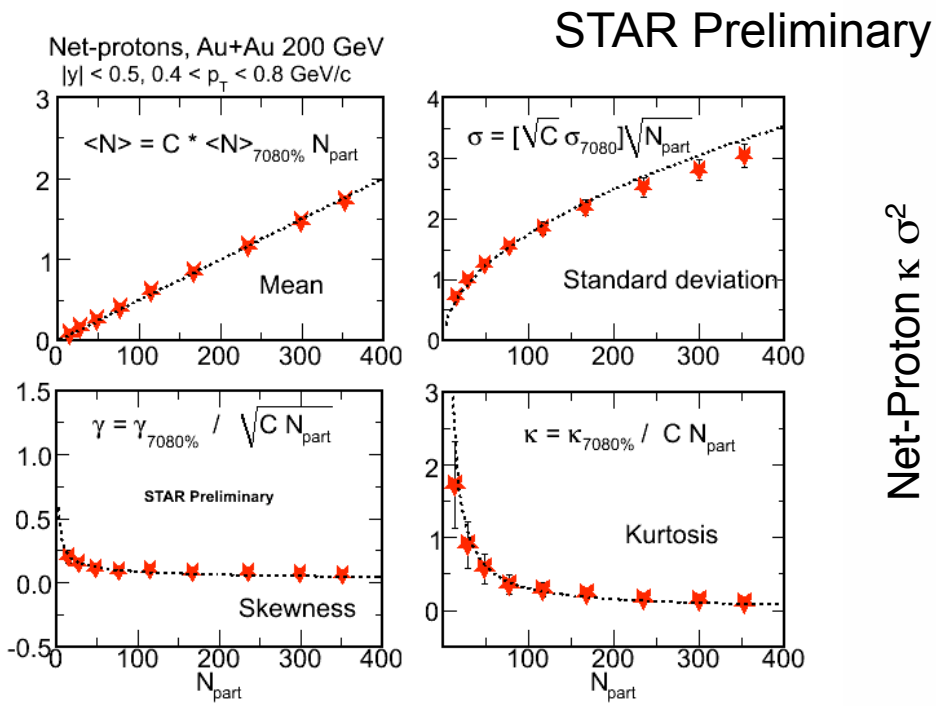
QCD Thermodynamics

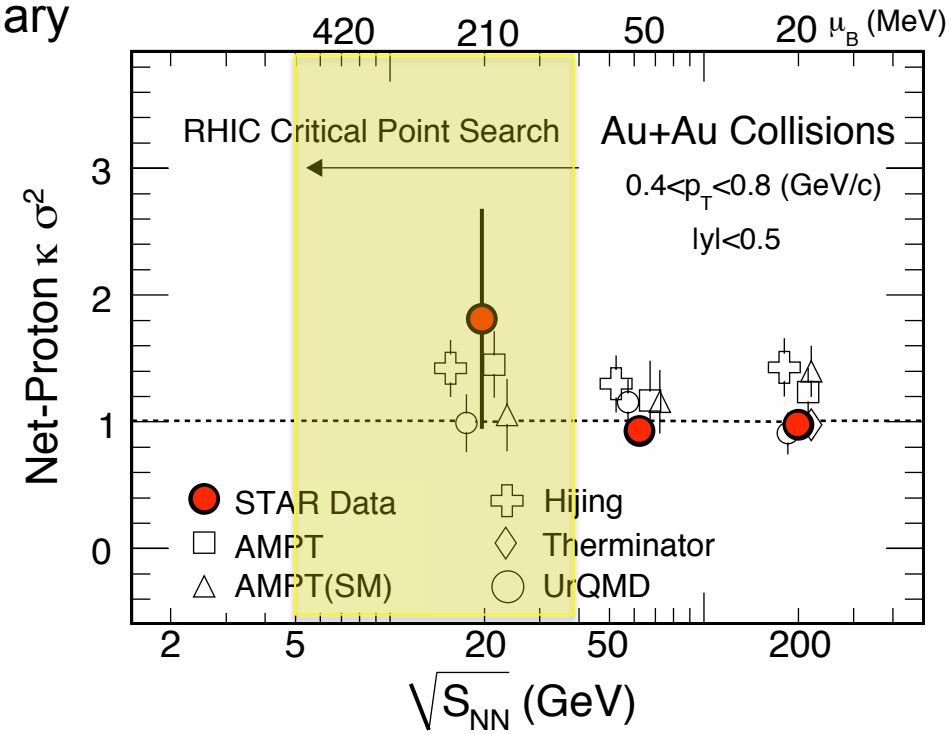


1) At $\mu_B = 0$: cross over transition, $150 < T_c < 200$ MeV
2) The SB ideal gas limit: $T/T_c \sim 10^7$
3) T_{ini} (LHC) ~ 2-3*T_{ini} (RHIC)
4) Thermodynamic evolutions are similar for RHIC and LHC

Zoltan Fodor, Lattice 2007

High Moment Analysis (BES)





1) High moments are more sensitive to critical point related fluctuation.

2) The 4th moment, Kurtosis, is directly related to the corresponding thermodynamic quantity: susceptibility for conserved quantum numbers such as Baryon number, charge, strangeness…

Run10 Physics Programs

RHIC cool down mid-Nov.

Cool down to 4.5°K: Dec. 1; Shift starts Dec. 7; Data taking: Jan. 2

Shift committee: *O. Barannikova*
Trigger board: *Z.B. Xu (chair)*
QA board: *C. Whitten (chair)*

Beam Energy (GeV)	25 cryo-week	30 cryo-week	Physics
200	10 3/16	10	Thermalization J/Ψ v_2, m_{ee}
62.4	4 4/15	4	
39	1.5 4/28	1.5	BES programs, T_E, *phase boundary*
27			
18			
11.5		2 6/19	
7.7	4 5/25	4	
5.5	0.5 5/28	0.5	

Weekly info: *http://www.c-ad.bnl.gov/esfd/RMEM_10/rhic_planning.htm*

Summary: Heavy Ion Program

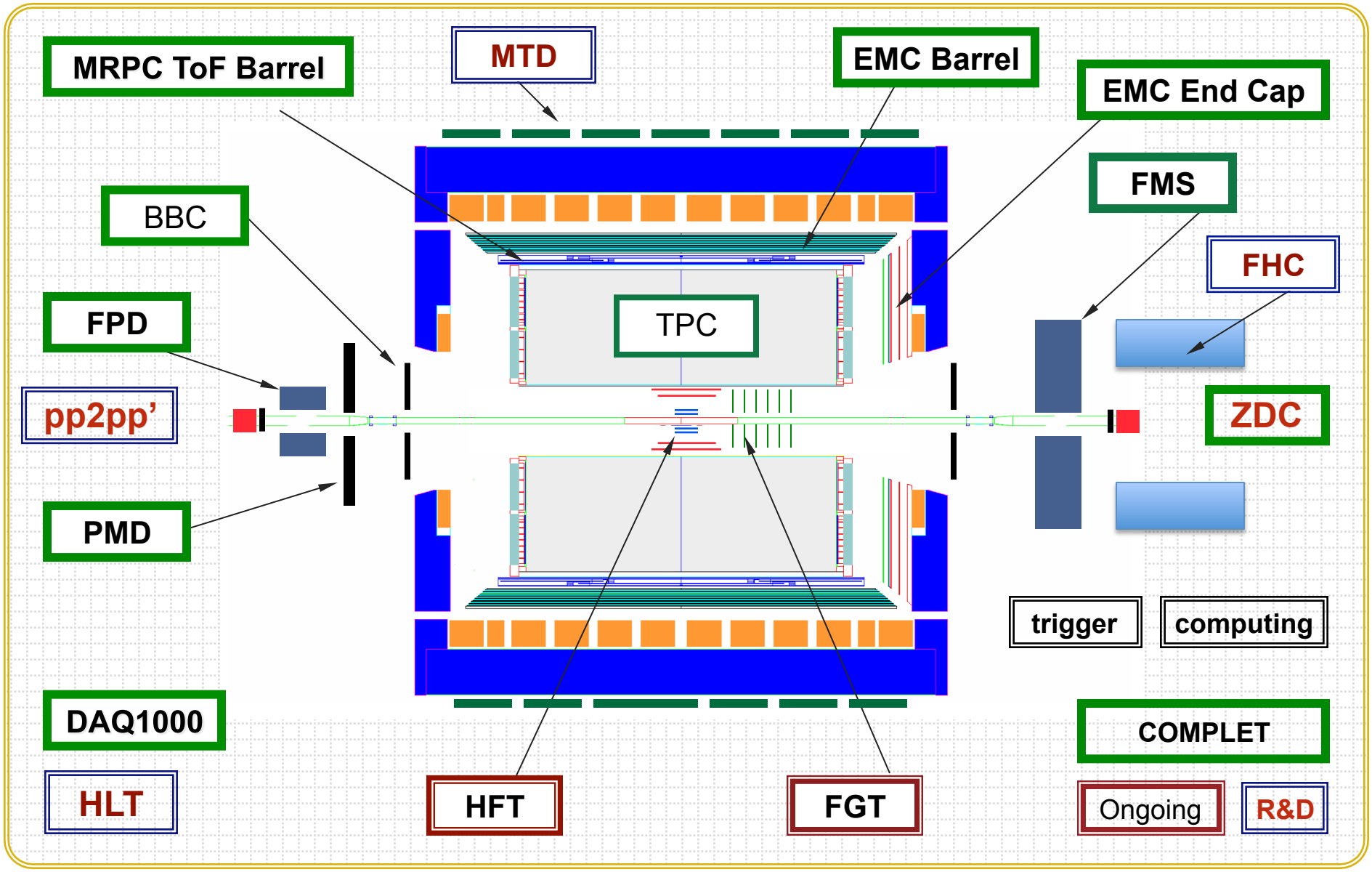
(1) Medium properties at 200 GeV

- collectivity done; light quark thermalization

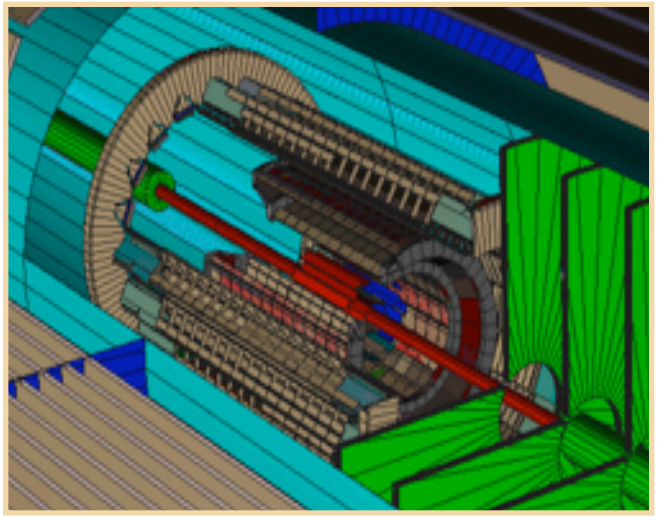
(2) Beam Energy Scan at RHIC – phase structure

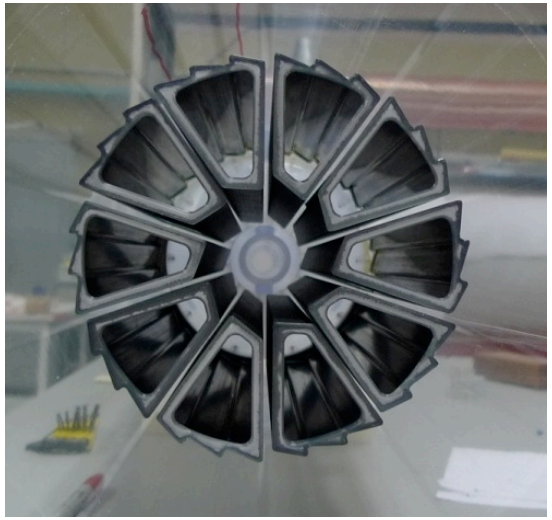
(3) *d*+*Au* collisions – effect of the cold nuclear matter

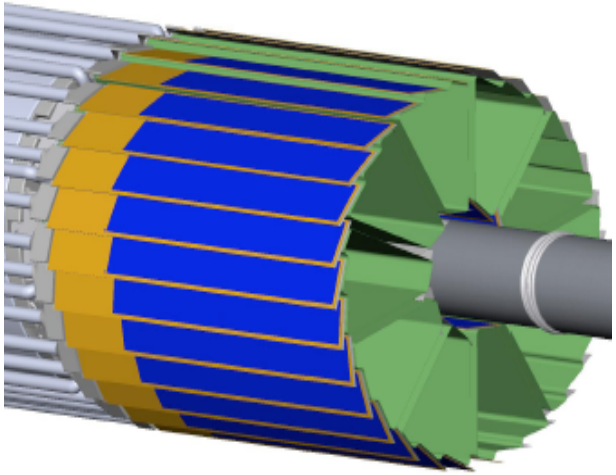
STAR Experiment



STAR Heavy Flavor Tracker





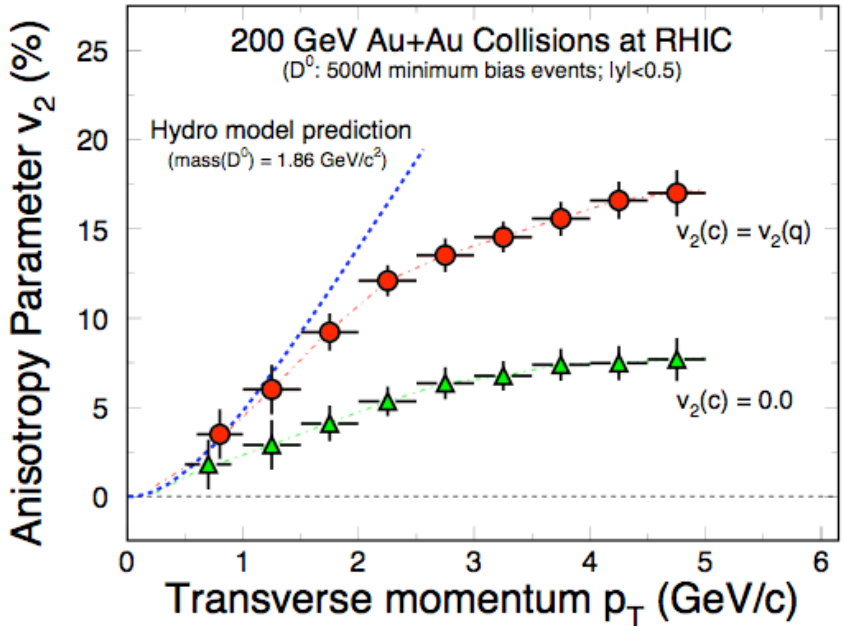


HFT: **2012-2014**

1) 2-layer thin CMOS pixels; 1-layer strips; SSD
2) First layer at 2.5 cm close to the beam pipe, 2pi coverage

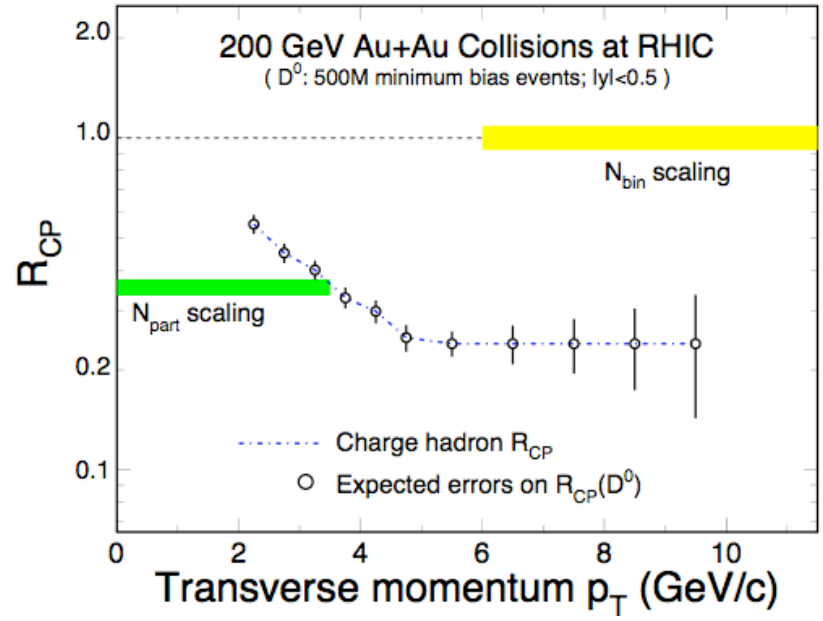
➔ Measure down to low p_T ~ 0.5 GeV/c for open charm hadrons

HFT: Charm Hadron v_2 and R_{AA}



- 200 GeV Au+Au m.b. collisions (500M events).
- Charm hadron collectivity ⇨ drag/diffusion constants ⇨

Medium properties!



- 200 GeV Au+Au m.b. collisions (|y|<0.5 500M events)
- Charm hadron R_{AA} ⇨

- Energy loss mechanism!
- QCD in dense medium!

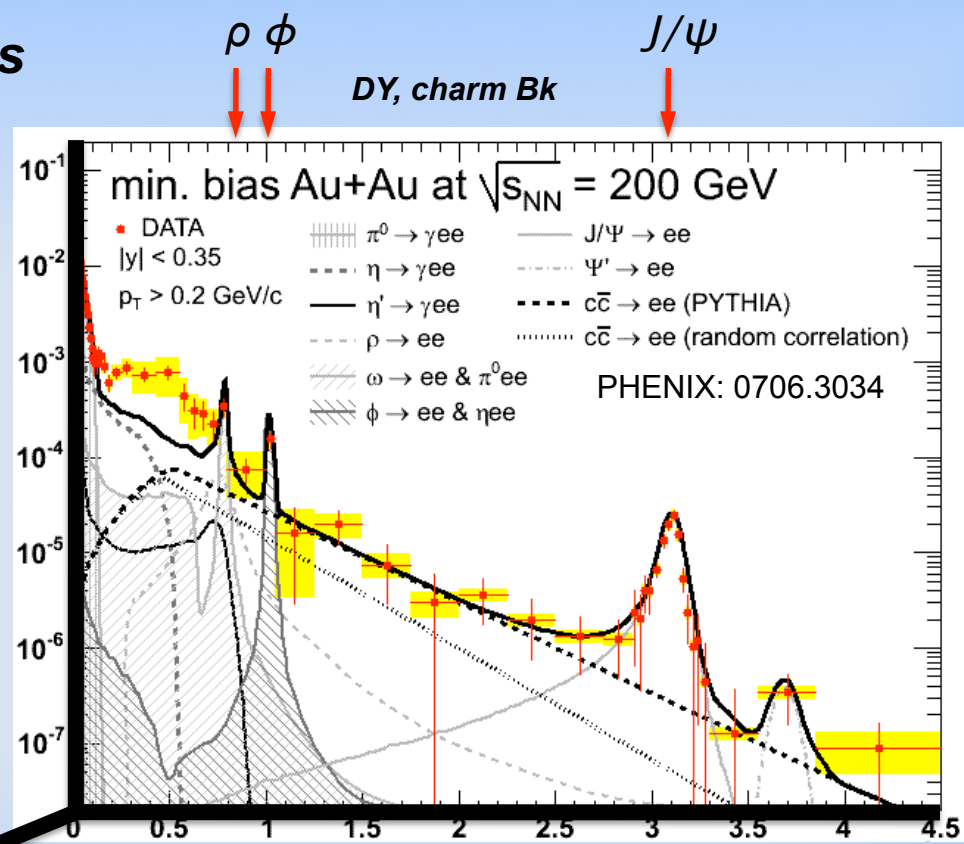
The di-electron Program at STAR

TOF + TPC + *HFT*

(1) ***σ, mass***

(2) v_2

(3) R_{AA}



p_T (GeV/c)

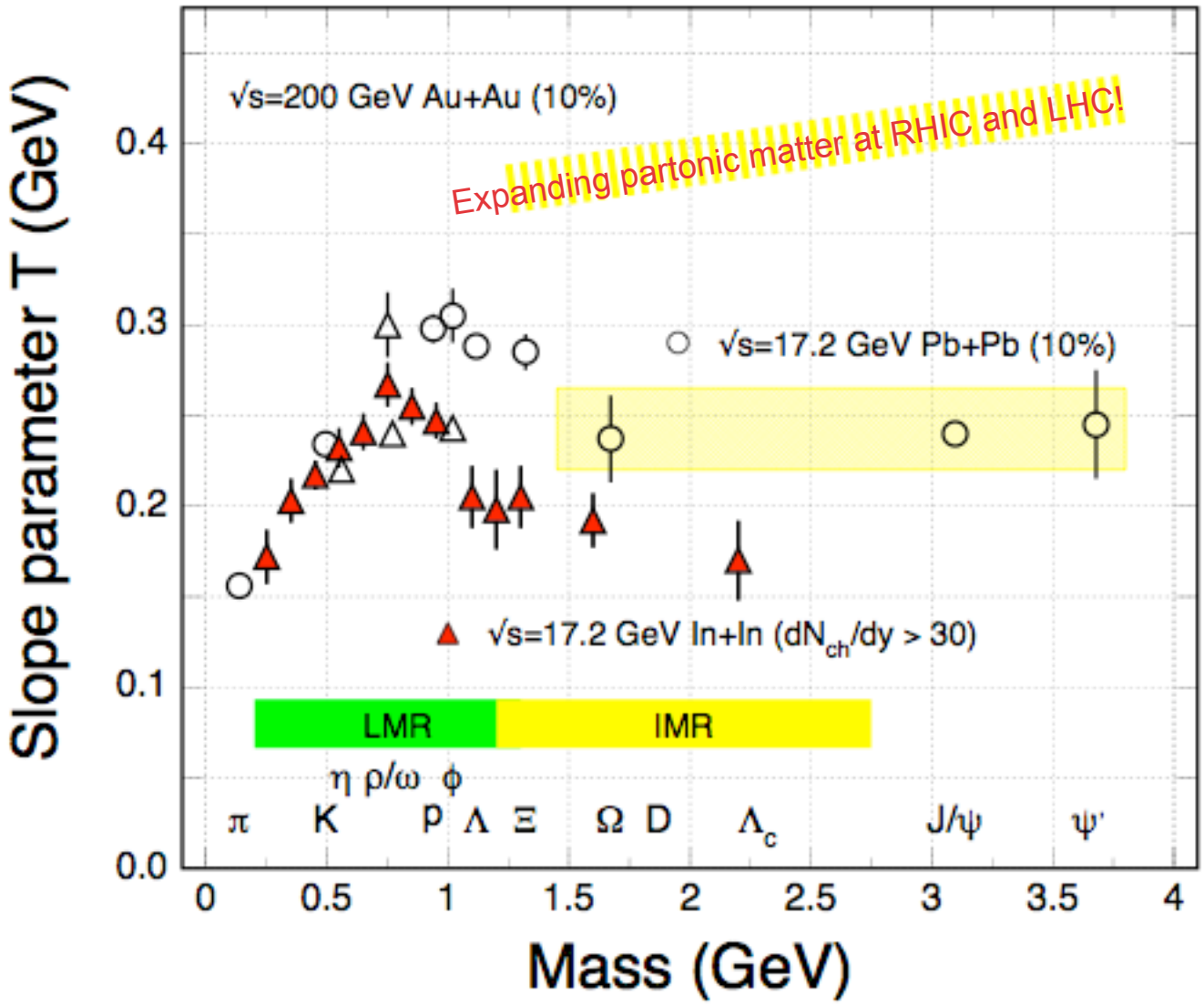
✓ **Direct radiation from the Hot/Dense Medium**

✓ **Chiral symmetry Restoration**

⇨ ***A robust di-lepton physics program extending STAR scientific reach***

HFT: removing irreducible correlated charm background!

Direct Radiation



Di-leptons allow us to measure the direct radiation from the matter with partonic degrees of freedom, no hadronization!

- Low mass region:
  $\rho, \omega, \phi \Rightarrow e^-e^+$
  $m_{inv} \Rightarrow e^-e^+$

  medium effect
  Chiral symmetry

- High mass region:
  $J/\psi \Rightarrow e^-e^+$
  $m_{inv} \Rightarrow e^-e^+$

  Direct radiation

Summary

STAR QCD physics program for next decade:

Spin Physics: (cold nucleon)

- 200 GeV: ***Δg*** inclusive and di-jets, γ-jet
- 500 GeV: ***sea quark*** helicity distributions
- 200/500 GeV: transverse spin phenomena

Low-x Physics: (cold nucleus)

- Study gluon-rich phenomena at RHIC
- Color glass condensate

Heavy Ion Physics: (hot nuclear matter)

- Thermalization at 200 GeV
- QCD phase boundary and critical point, starts in 2010
- In medium properties

DOE Milestone for HP

Year	#	DOE Milestone (HP)
2013	HP8	Measure flavor-identified q and anti-q contributions to the spin of the proton via the longitudinal-spin asymmetry of **W production**.
2013	HP12	Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if **gluons** have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton.
2015	HP13*	Test unique QCD predictions for relations between **single-transverse spin phenomena** in p-p scattering and those observed in deep-inelastic lepton scattering

http://www.er.doe.gov/np/nsac/docs/PerfMeasEvalFinal.pdf

DOE Milestone for DM

Year	#	DOE Milestone (DM)
2010	DM5	Measure the energy and system size dependence of **J/ψ production** over the range of ions and energies available at RHIC.
2010	DM6	Measure e+e- production in the mass range **$0.5 \leq m_{e+e-} \leq 1.0$ MeV/c^2** in $\sqrt{s_{NN}}$ = 200 GeV collisions.
2010	DM7	Complete realistic calculations of jet production in a high density medium for comparison with experiment.
2012	DM8	Determine **gluon densities at low *x*** in cold nuclei via p + Au or d + Au collisions.
2014	DM10*	Perform calculations including viscous hydrodynamics to quantify, or place an upper limit on, the viscosity of the nearly perfect fluid discovered at RHIC.
2014	DM11*	Measure jet and photon production and their correlations in A≅200 ion+ion collisions at energies from $\sqrt{s_{NN}}$ = 30 GeV up to 5.5 TeV.
2015	DM9*	Measure bulk properties, particle spectra, correlations and fluctuations in Au + Au collisions at $\sqrt{s_{NN}}$ from 5 to 40 GeV to search for evidence of a critical point in the QCD matter phase diagram.
2016	DM12*	Measure production rates, high-p_T spectra, and correlations in heavy-ion collisions at $\sqrt{s_{NN}}$=200 GeV for identified hadrons with heavy flavor valence quarks to constrain the mechanism for parton energy loss in the quark-gluon plasma.
2018	DM13*	Measure real and virtual thermal photon production in p+p, d+Au and Au+Au collisions at energies up to $\sqrt{s_{NN}}$ = 200 GeV.