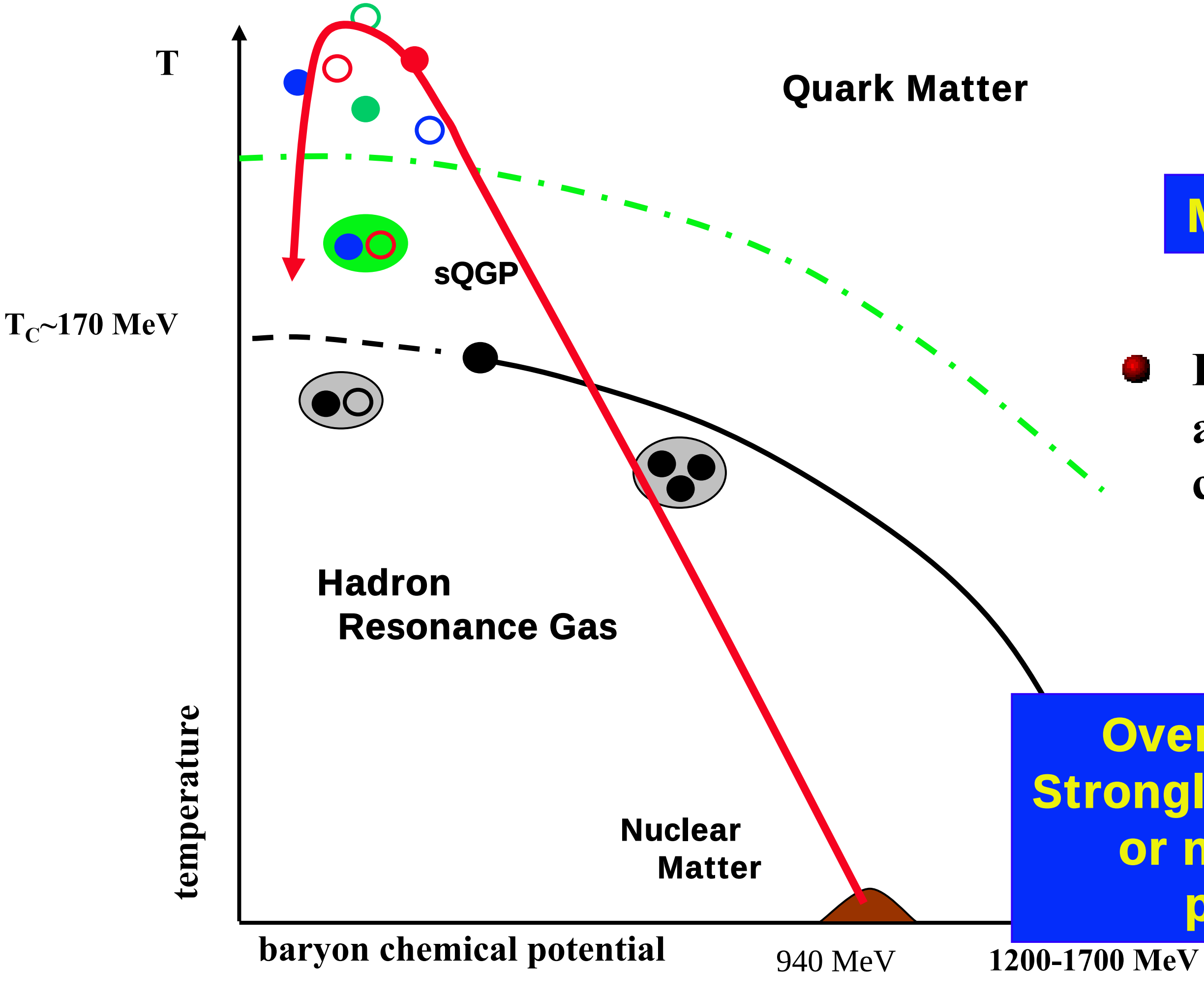
High T QCD at RHIC II

- Introduction
  - High T QCD and RHIC
  - Fundamental open questions
- Experimental quest for answers
  - Hard probes: jet tomography and heavy flavor
  - Expected progress with upgrades of RHIC
- Ongoing and planed improvements to RHIC
  - Time line, detector and accelerator upgrades (RHIC II)
- Summary

Study high T and ρ QCD in the Laboratory

Exploring the Phase Diagram of QCD



- **Quark Matter: Many new phases of matter**
  - **Asymptotically free quarks & gluons**
  - **Strongly coupled plasma**
  - **Superconductors, CFL ….**

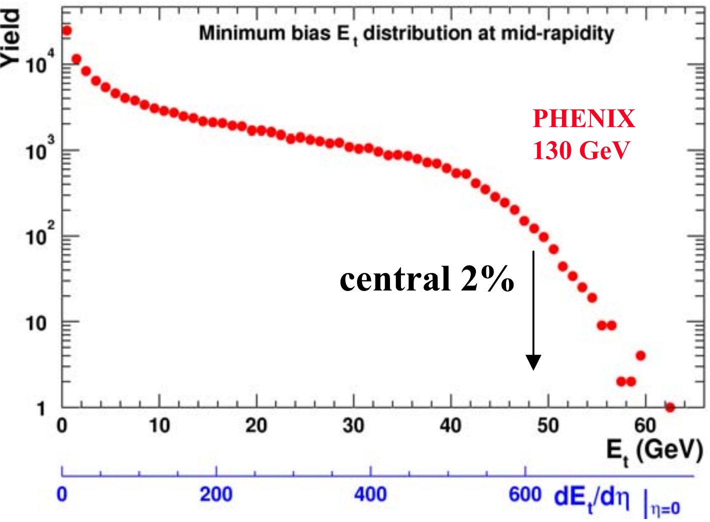
Mostly uncharted territory

- **Experimental access to "high" T and moderate ρ region: heavy ion collisions**
  - **Pioneered at AGS and SPS**
  - **Ongoing program at RHIC**

Overwhelming evidence: Strongly coupled quark matter or nearly perfect liquid produced at RHIC

Quark Matter Produced at RHIC

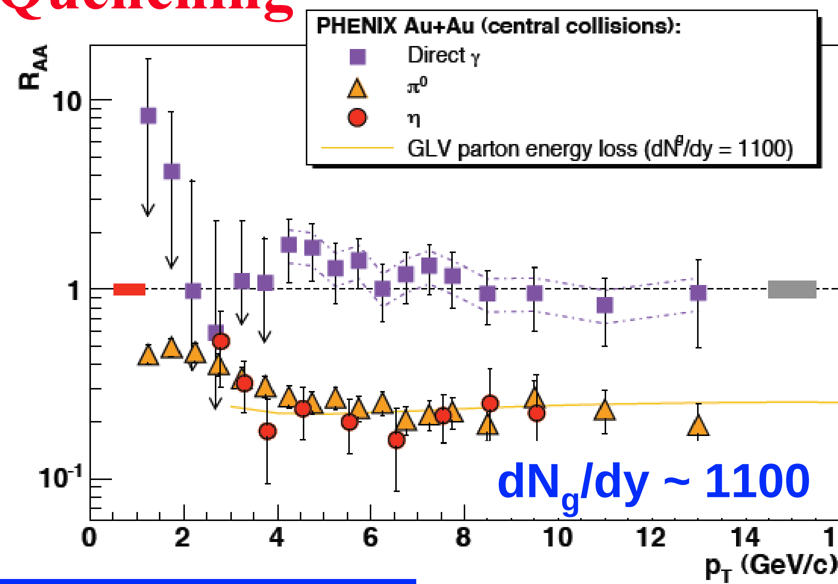
I. Transverse Energy



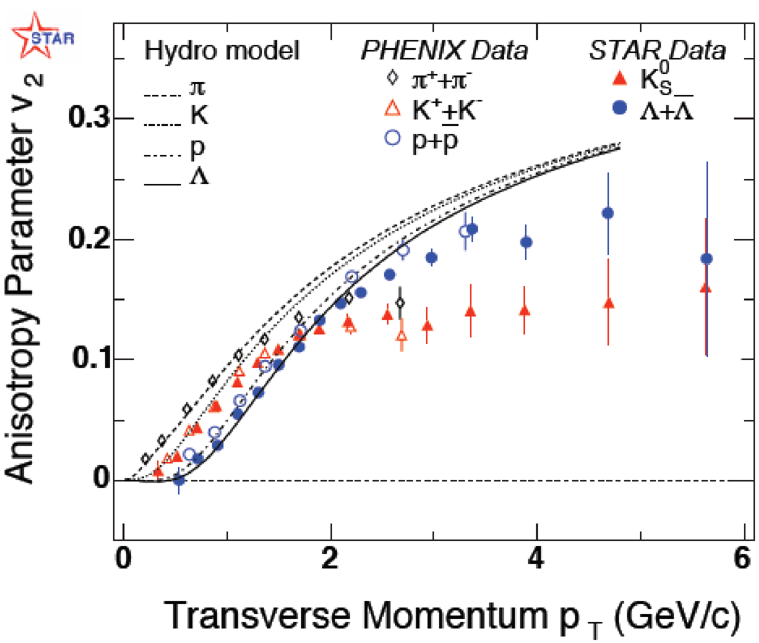
Bjorken estimate:

$\tau_0 \sim 0.3$ fm

III. Jet Quenching



$\varepsilon_{initial} \sim$ 10-20 GeV/fm^3



II. Flow → Hydrodynamics

Initial conditions: $\tau_{therm} \sim$ 0.6 -1.0 fm/c

$\varepsilon \sim$15-25 GeV/fm^3

Heavy ion collisions provide the laboratory to study high T QCD!

Fundamental Questions

that can now be addressed at RHIC

from "Future Science at the Relativistic Heavy Ion Collider"
BNL-77334-2006-IR, 12/30/2006

- **What are the properties of new state of matter?**
  - **Temperature, density, viscosity, speed of sound, diffusion coefficient, transport coefficients, color screening length**
  - **Is it a perfect liquid?**

    If it's a fluid: What is the nature a relativistic quantum fluid?

    If not: What is it and what are the relevant degrees of freedom?
  - **Is chiral symmetry restored?**
  - **What is the mechanism of rapid thermalization?**
  - **How does the deconfined matter transform into hadrons?**

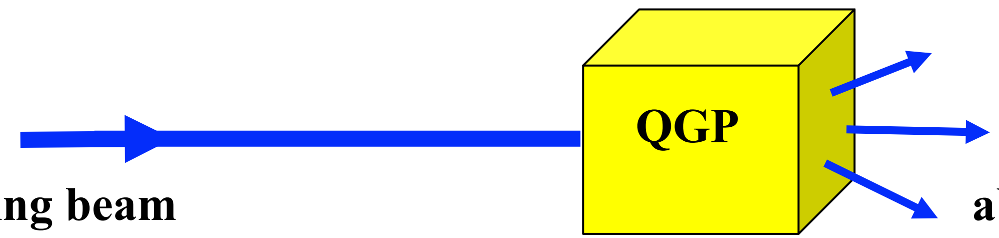
- **Is there a critical point in the QCD phase diagram and where is it located?**

Key are precision measurements with hard probes and collective behavior currently not accessible at RHIC

→ RHIC upgrades: improved detectors and increased luminosity

Key Experimental Probes of Quark Matter

Rutherford experiment	$\alpha \rightarrow$ atom	discovery of nucleus
SLAC electron scattering	$e \rightarrow$ proton	discovery of quarks



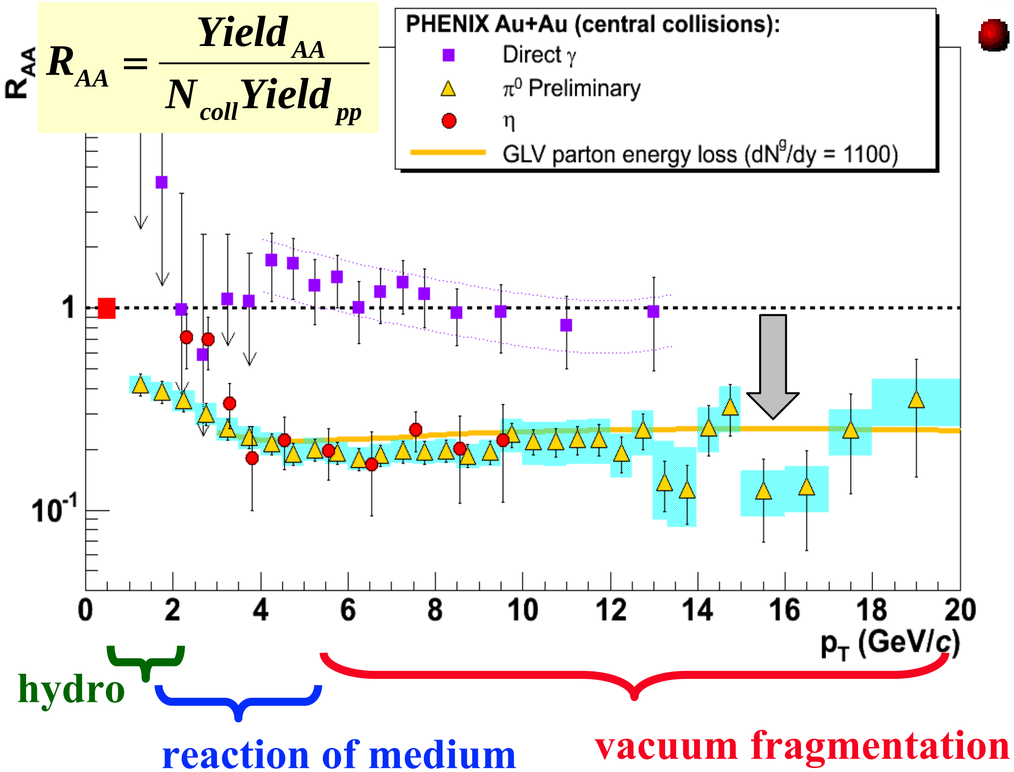
penetrating beam
(jets or heavy particles)

absorption or scattering pattern

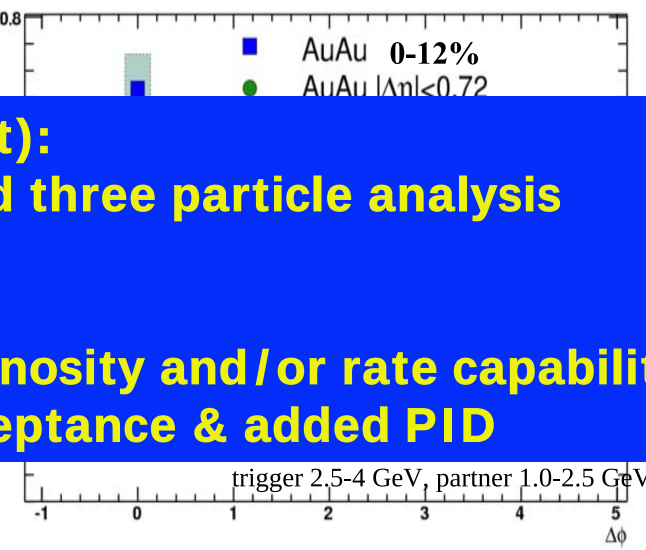
Nature provides penetrating beams or "hard probes" and the QGP in A-A collisions

- Penetrating beams created by parton scattering before QGP is formed
  - High transverse momentum particles $\rightarrow$ jets
  - Heavy particles $\rightarrow$ open and hidden charm or bottom
  - Calibrated probes calculable in pQCD
- Probe QGP created in A-A collisions as transient state after ~ 1 fm

Hard Probes: Light quark/gluon jets

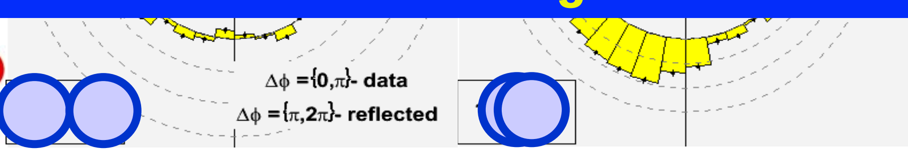


- **Status**
  - Calibrated probe
  - Strongly modified in opaque medium
    - Jet quenching
    - Reaction of medium to probe
    - (2 particle corr. → Mach cones, etc)
  - Open issues:
    - Which observables are sensitive to details of energy loss mechanism?
    - What is the energy loss mechanism?
    - What phenomena relate to reaction of media to probe?



Answers will come from jet tomography (γ-jet):
single, two and three particle analysis

Will be possible at RHIC II:
statistics (p_T reach) → increased luminosity and/or rate capability
kinematic coverage → increased acceptance & added PID



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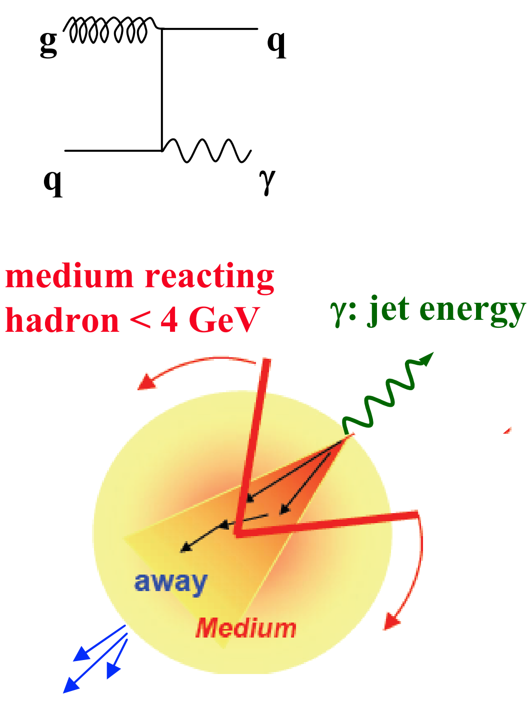
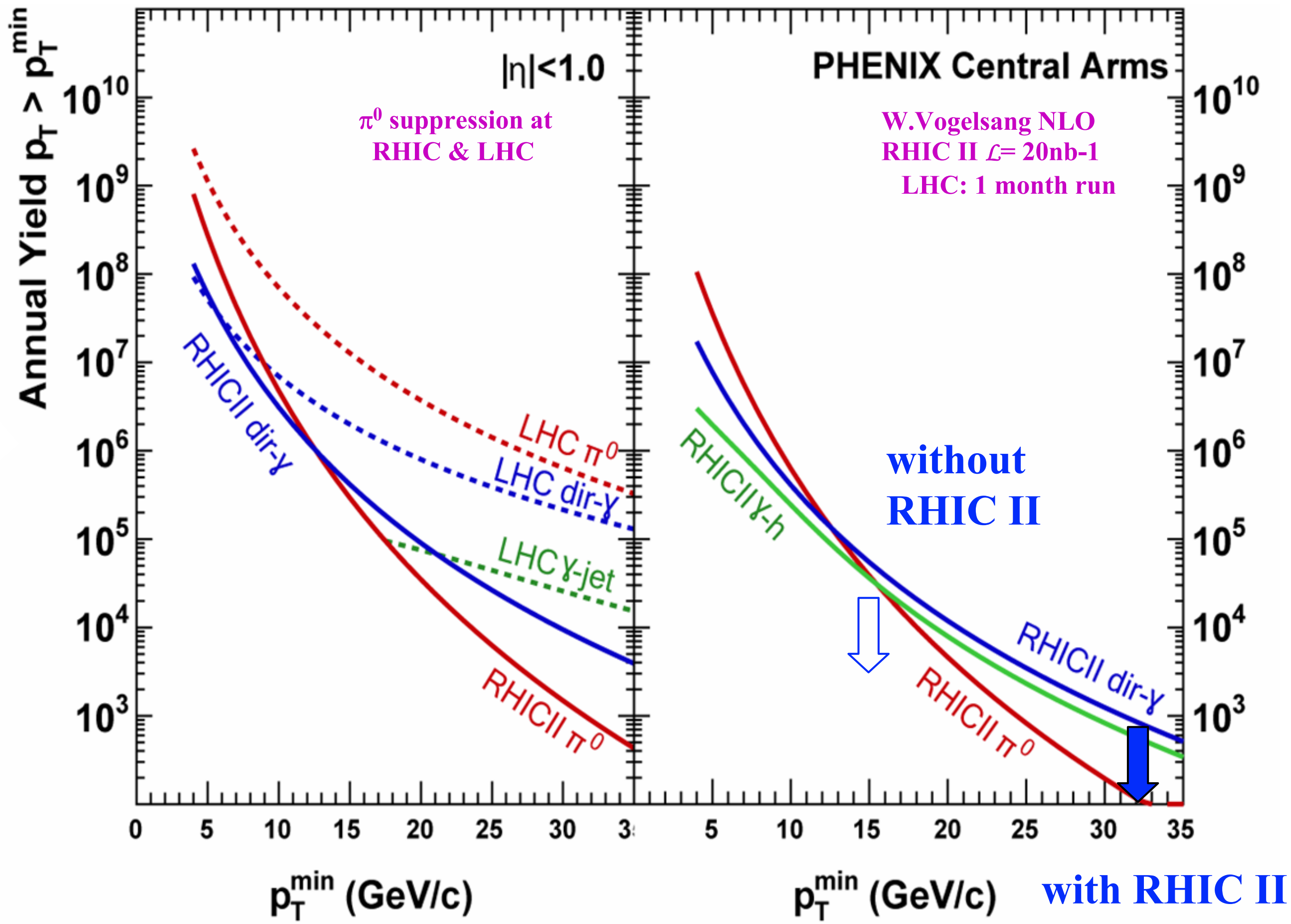
Jet Tomography at RHIC II





RHIC II will give jets up to 50 GeV

- → separation of medium reaction and energy loss
- → sufficient statistics for 3 particle correlations p_T > 5 GeV
- → 2-3 particle correlations with identified particles

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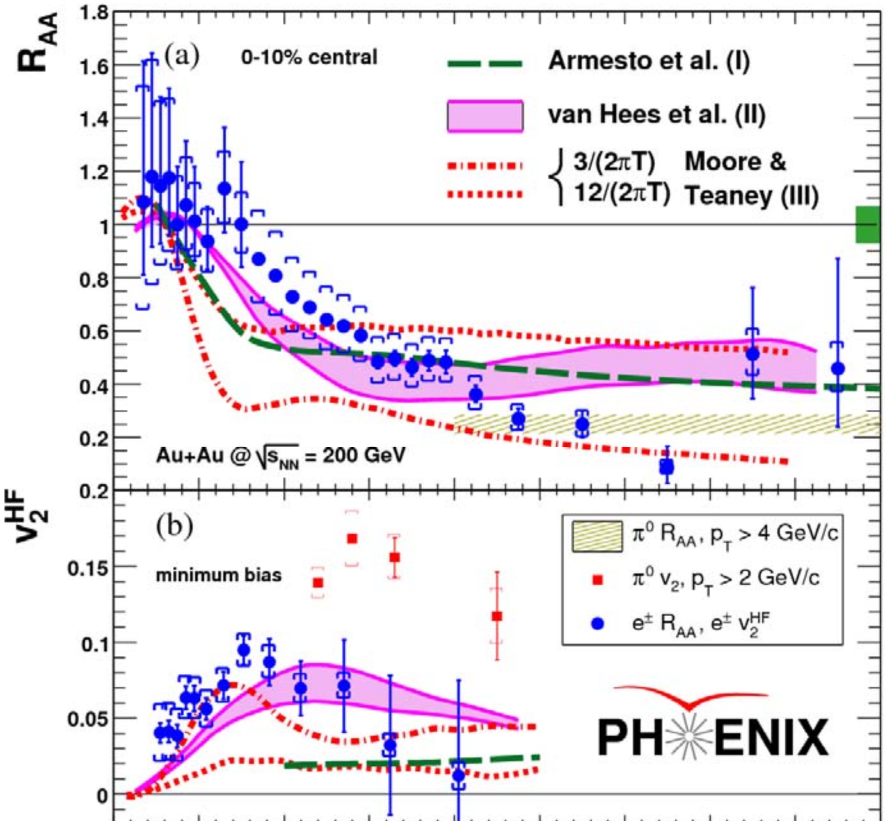
Hard Probes: Open Heavy Flavor

Electrons from c/b hadron decays



- **Status**
  - Calibrated probe?
    - pQCD under predicts cross section by factor 2-5
    - Factor 2 experimental differences in pp must be resolved
    - Charm follows binary scaling
  - Strong medium effects
    - Significant charm suppression and v2
    - Upper bound on viscosity ?
  - Open issues:
    - Limited agreement with energy loss calculations
    - What is the energy loss mechanism?
    - Are there medium effects on b-quarks?

Answers expected from direct charm / beauty measurements

Will be possible at RHIC II:

b-c separation → decay vertex with silicon vertex detectors

statistics ($B \rightarrow J/\psi$) → increased luminosity and / or rate capability

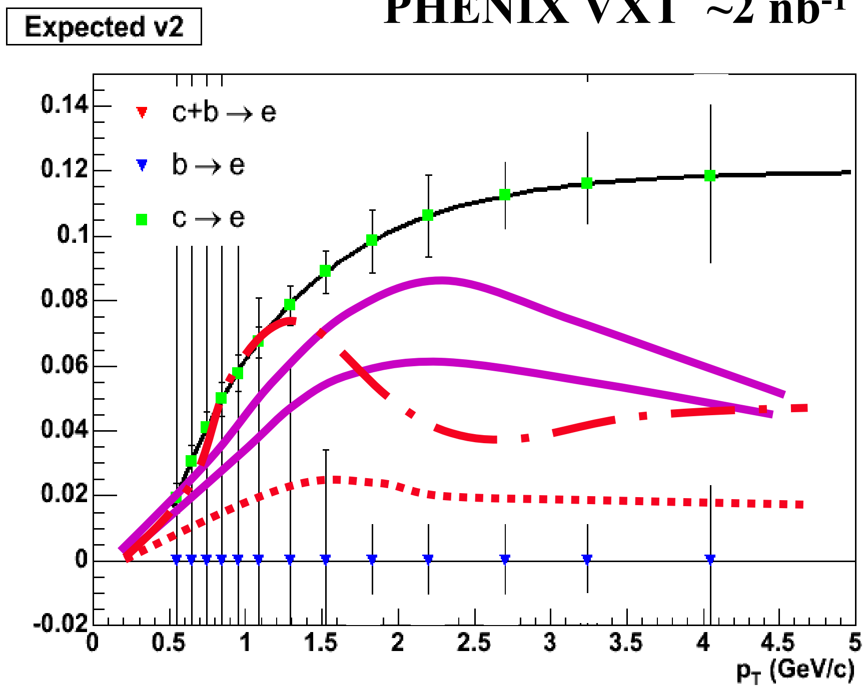
Direct Observation of Charm and Beauty

Detection options with vertex detectors:

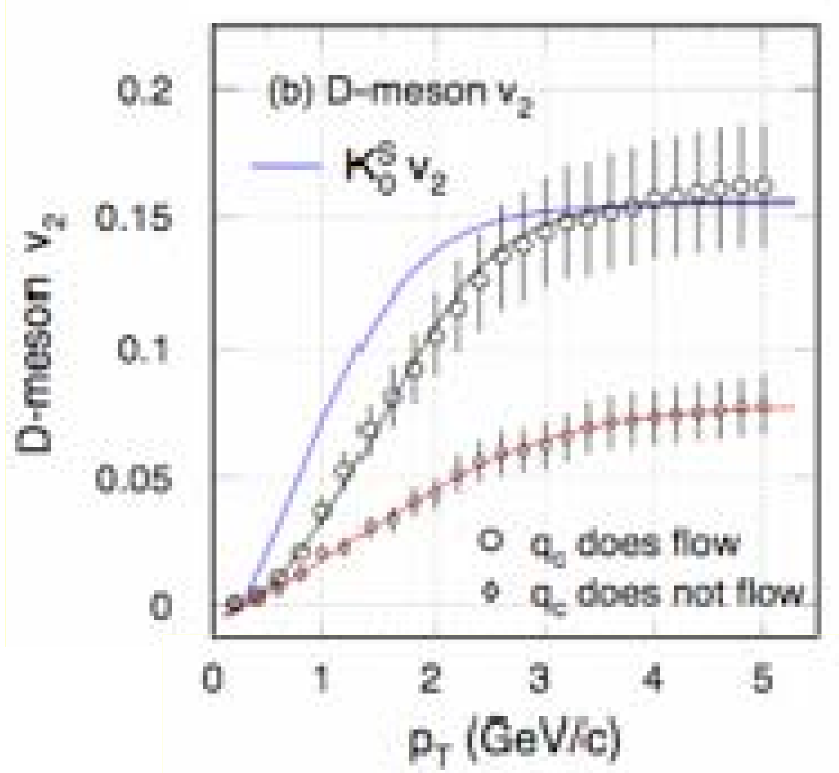
- Beauty and low p_T charm through displaced e and/or μ
- Beauty via displaced J/ψ
- High p_T charm through $D \rightarrow \pi K$

	m GeV	cτ μm
D^0	1865	125
$D^{\pm}$	1869	317

PHENIX VXT ~2 nb^{-1}

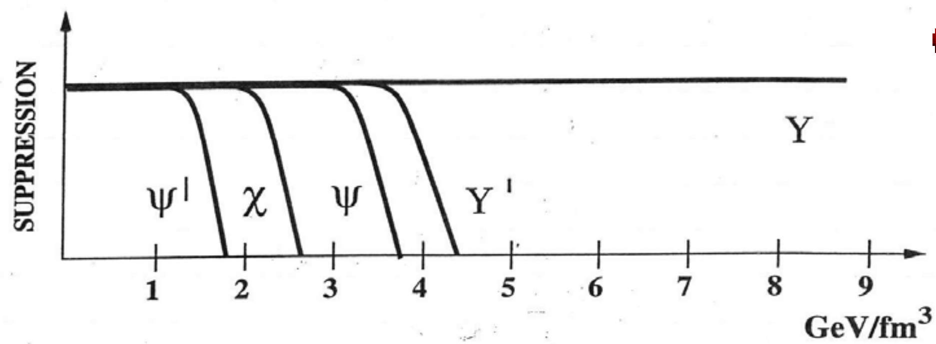


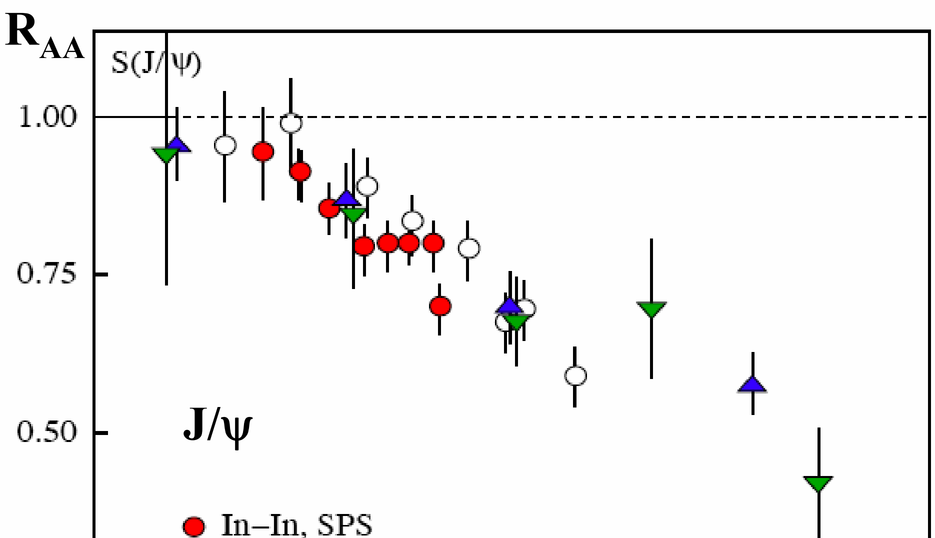
STAR HFT ~20 nb^{-1}



RHIC II increases statistics by factor >10

Hard Probes: Quarkonium





- **Status**
  - **J/ψ production is suppressed**
    - **Similar at RHIC and SPS**
    - **Consistent with consecutive melting of χ and ψ'**
    - **Consistent with melting J/ψ followed by regeneration**
  - **Open issues:**
    - **Recent Lattice QCD developments Quarkonium states do not melt at T_C**
    - **Is the J/ψ screened or not?**
    - **Can we really extract screening length from data?**

Answers require "quarkonium" spectroscopy including p_T and reaction plan dependence

Will be possible at RHIC II:

statistics (ψ', Υ) → increased luminosity and/or rate capability

Quarkonium and Open Heavy Flavor

	RHIC II 25 nb^{-1}		LHC on month		
Signal $\|\eta\|$ **or** η	**PHENIX** <0.35, 1.2-2.4	**STAR** <1	**ALICE** <0.9, 2.5-4	**CMS** <2.4	**ATLAS** <2.4
$J/\Psi \rightarrow \mu\mu$ or ee	440,000	220,000	800,000	180,000	8000-100,000
$\Psi' \rightarrow \mu\mu$ or ee	8000	4000	19,000	-	1400-1800
$\chi_c \rightarrow \mu\mu\gamma$ or eeγ	120,000 *	-	-	-	-
$\Upsilon \rightarrow \mu\mu$ or ee	1400	11,000**	11,000	37,000	15,000
$B \rightarrow J/\Psi \rightarrow \mu\mu$ (ee)	6500	2500	12,900	-	
$D \rightarrow K\pi$	8000****	30,000***	8,000	1	

LHC relative to RHIC
Luminosity ~ 10%
Running time ~ 25%
Cross section ~ 10-50x

~ similar yields!

* large background
** states maybe not resolved
*** min. bias trigger
**** pt > 3 GeV

Heavy flavor in heavy ion collisions at RHIC and RHIC II
A.D.Frawley, T.Ullrich and R.Vogt

Will be statistics limited at RHIC II (and LHC!)

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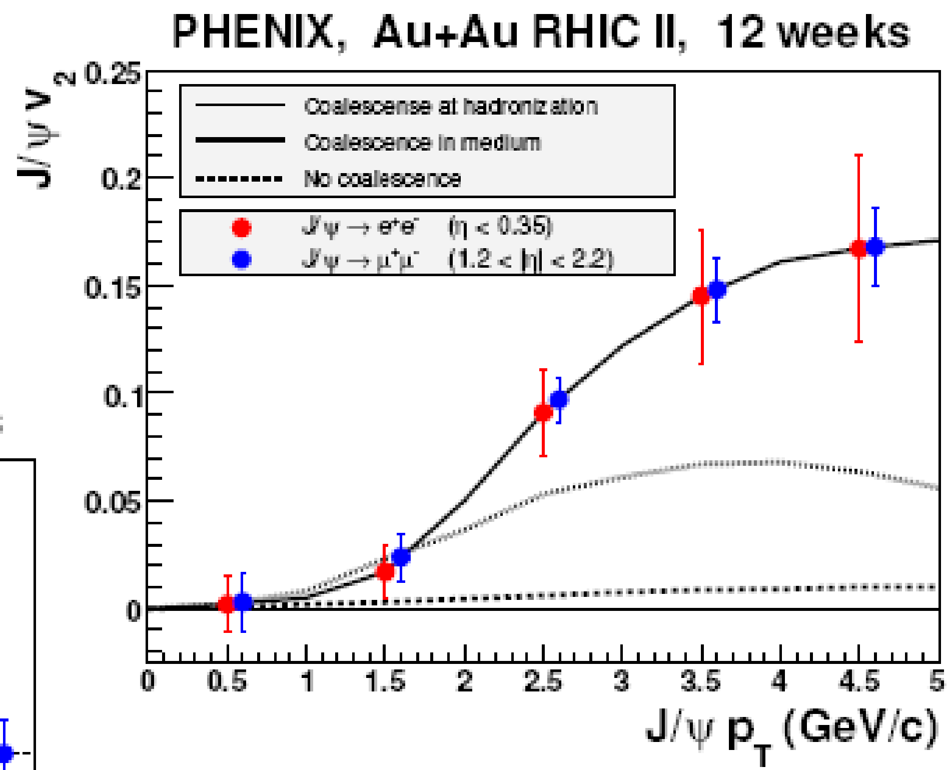
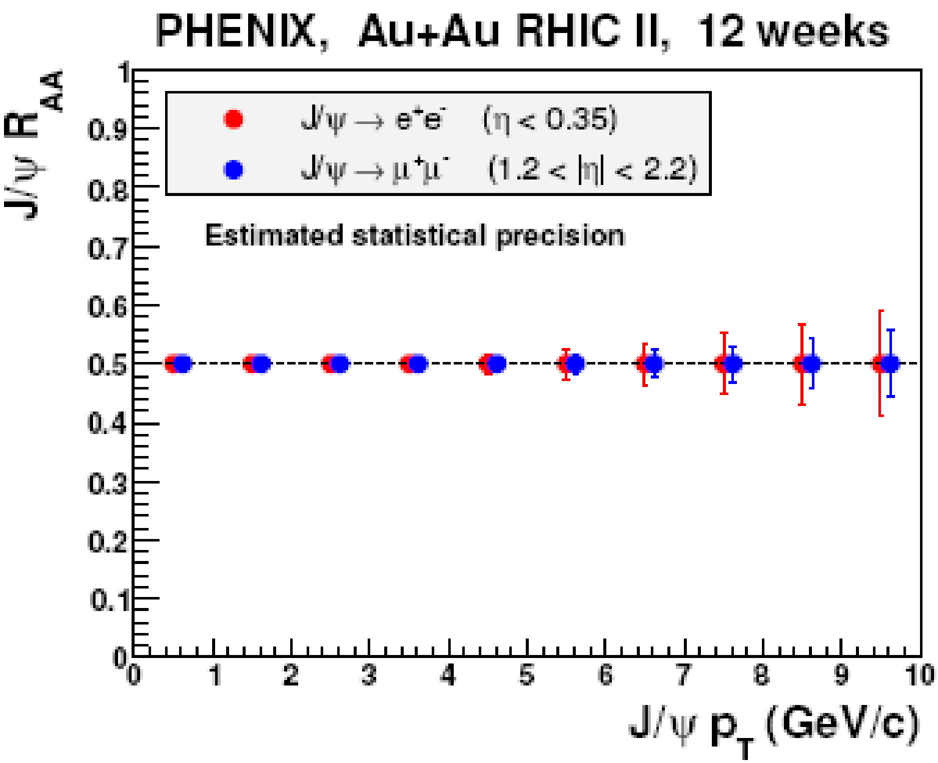
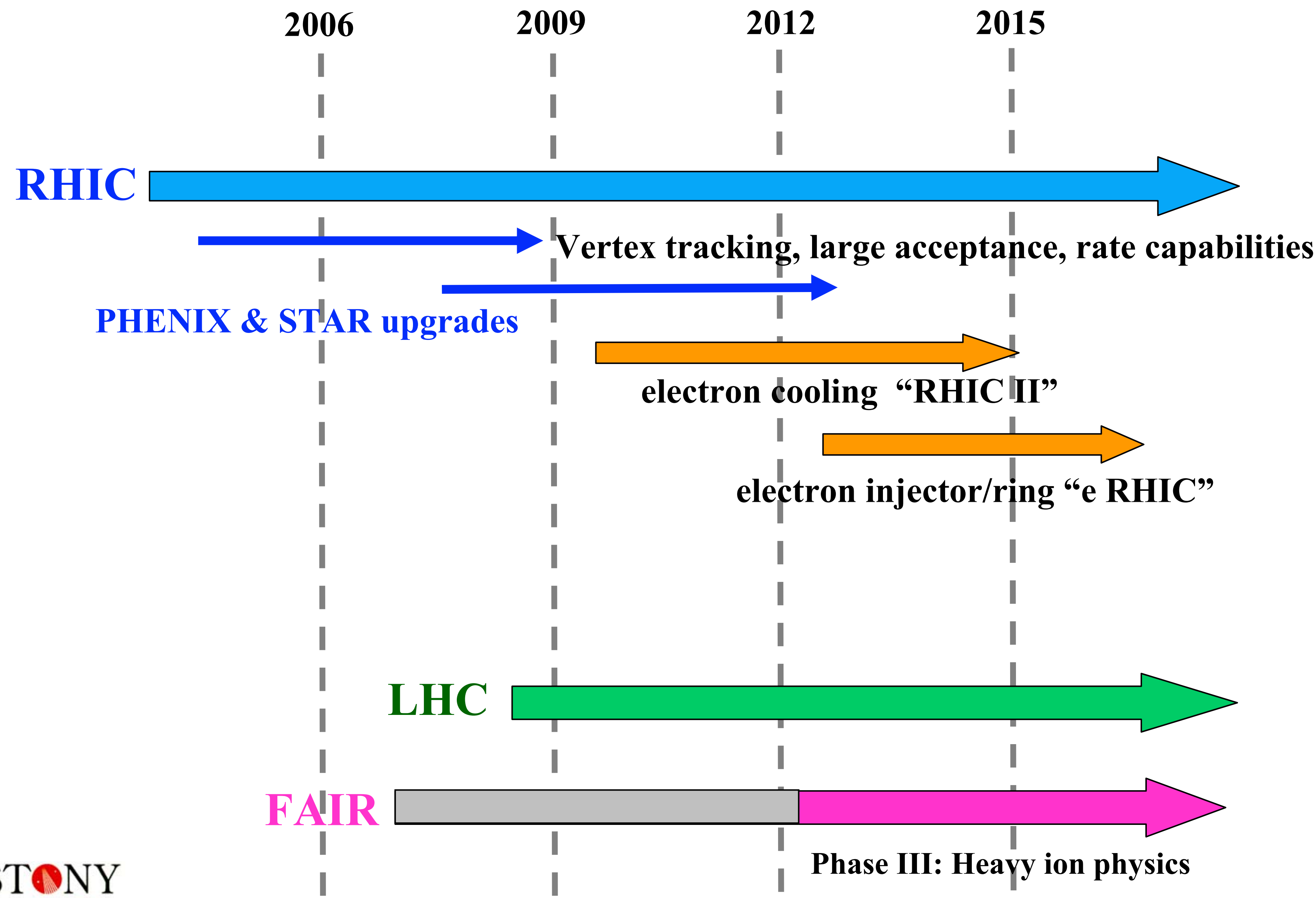
Examples of Quarkonium Spectroscopy at RHIC II

J/ψ measurements will reach high precision





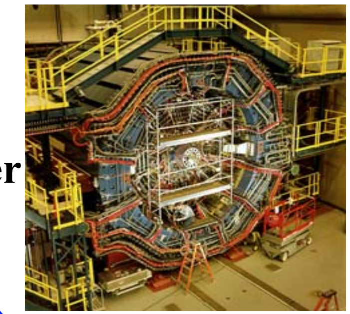
Long Term Timeline of Heavy Ion Facilities



RHIC Upgrades

On going effort with projects in different stages

Detector upgrades



forward meson spectrometer
DAQ & TPC electronics
full ToF barrel
heavy flavor tracker (HFT)
intermediate silicon tracker (IST)
forward GEM tracker (FGT)

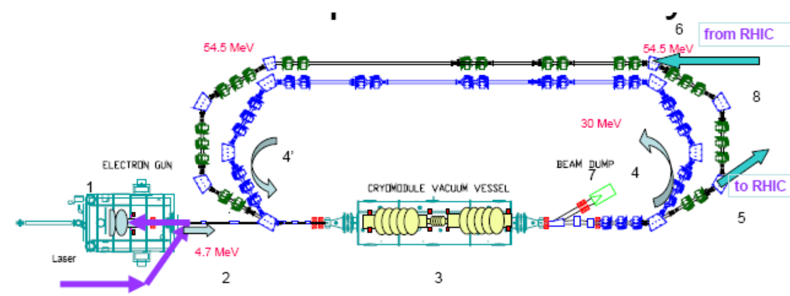
STAR

PHENIX

hadron blind detector
muon Trigger
silicon vertex barrel (VTX)
forward silicon (FVTX)
forward EM calorimeter (NCC)

Completed, on going,
expect funding in FY08, in preparation

Accelerator upgrades



EBIS ion source (started)

Electron cooling (x10 luminosity) by 2010

- at 200 GeV extra x10
- Au+Au ~40 KHz event rate

Electron cooling at <20 GeV

- Additional factor of 10
- Au+Au 20 GeV ~15 KHz event rate
- Au+Au 2 GeV ~150 Hz event rate

Which Measurements are Unique at RHIC?

- General comparison to LHC
  - LHC and RHIC (and FAIR) are complementary
  - They address different regimes (CGC vs sQGP vs hadronic matter)
  - RHIC is a dedicated machine with broad program, LHC may run 4-5 weeks/year
  - Experimental issues: "Signals" at RHIC overwhelmed by "backgrounds" at LHC

- Measurement specific (compared to LHC)
  - Jet tomography: measurements and capabilities complementary
    RHIC: large calorimeter and tracking coverage with PID in few GeV range
    Extended p_T range at LHC
  - Charm measurements: favorable at RHIC
    Abundant thermal production of charm at LHC, no longer a penetrating probe
    Charm is a "light quark" at LHC, signal from jet fragmentation and bottom decay
    Bottom may assume role of charm at LHC
  - Quarkonium spectroscopy: J/ψ, ψ' , χ_c easier to interpreter at RHIC
    Large background from bottom decays and thermal production at LHC
    Rates about equal; LHC 10-50 σ, 10% luminosity, 25% running timer

RHIC II Perspectives

- **RHIC II has potential to provide key measurements and many precision measurements unavailable at RHIC today!**

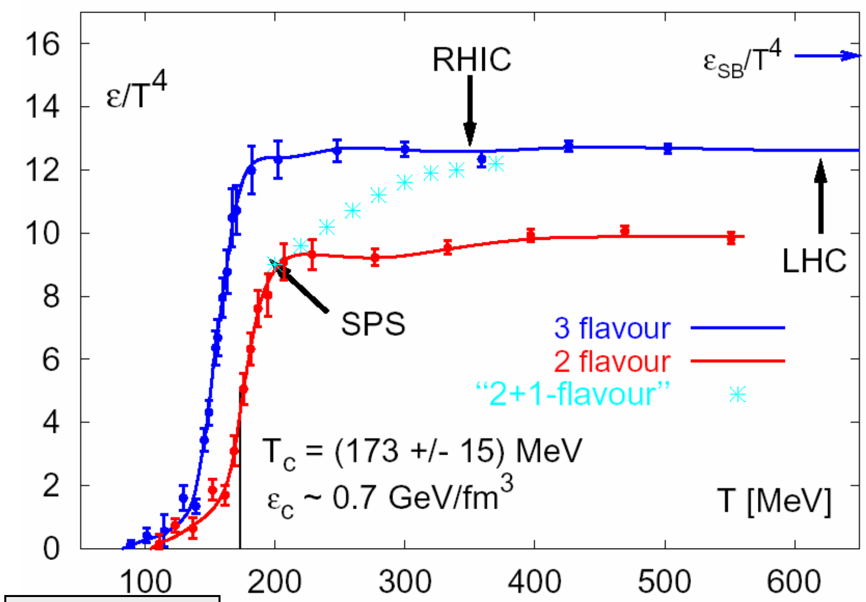
- **Progress from:**
  - **Improved detectors (STAR and PHENIX)**
    vertex tracking, large acceptance, rate capability
  - **Luminosity upgrade (RHIC II)**
    electron cooling for all energies
  - **Improved theoretical guidance**
    phenomenological tools (e.g. 3-D viscous hydro)
    lattice QCD (e.g. finite density)
    new approaches (e.g. gauge/gravity correspondence)

- **RHIC II will continue to spearhead research in high T QCD through the LHC area.**

Backup

Comparison of Heavy Ion Facilities

Initial conditions



FAIR ≤ T_C

RHIC ≤ 2 T_C

LHC 3-4 T_C

RHIC is unique and at "sweet spot"

Complementary programs with large overlap:

High T: LHC → adds new high energy probes

→ test prediction based on RHIC data

High ρ: FAIR → adds probes with ultra low cross section

- **FAIR: cold but dense baryon rich matter**
  - fixed target p to U
  - $\sqrt{s_{NN}}$ ~ 1-8 GeV U+U
  - Intensity ~ 2 10^9/s → ~10 MHz
  - ~ 20 weeks/year
- **RHIC: dense quark matter to hot quark matter**
  - Collider p+p, d+A and A+A
  - $\sqrt{s_{NN}}$ ~ 5 – 200 GeV U+U
  - Luminosity ~ 8 10^{27} /cm²s → ~50 kHz
  - ~ 15 weeks/year
- **LHC: hot quark matter**
  - Collider p+p and A+A
  - Energy ~ 5500 GeV Pb+Pb
  - Luminosity ~ 10^{27} /cm²s → ~5 kHz
  - ~ 4 week/year

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Low Energy Running at RHIC

- **Physics goals:**
  - **Search for critical point → bulk hadron production and fluctuations**

    Requires moderate luminosity

    can maybe be done in next years
  - **Chiral symmetry restoration → dilepton production**

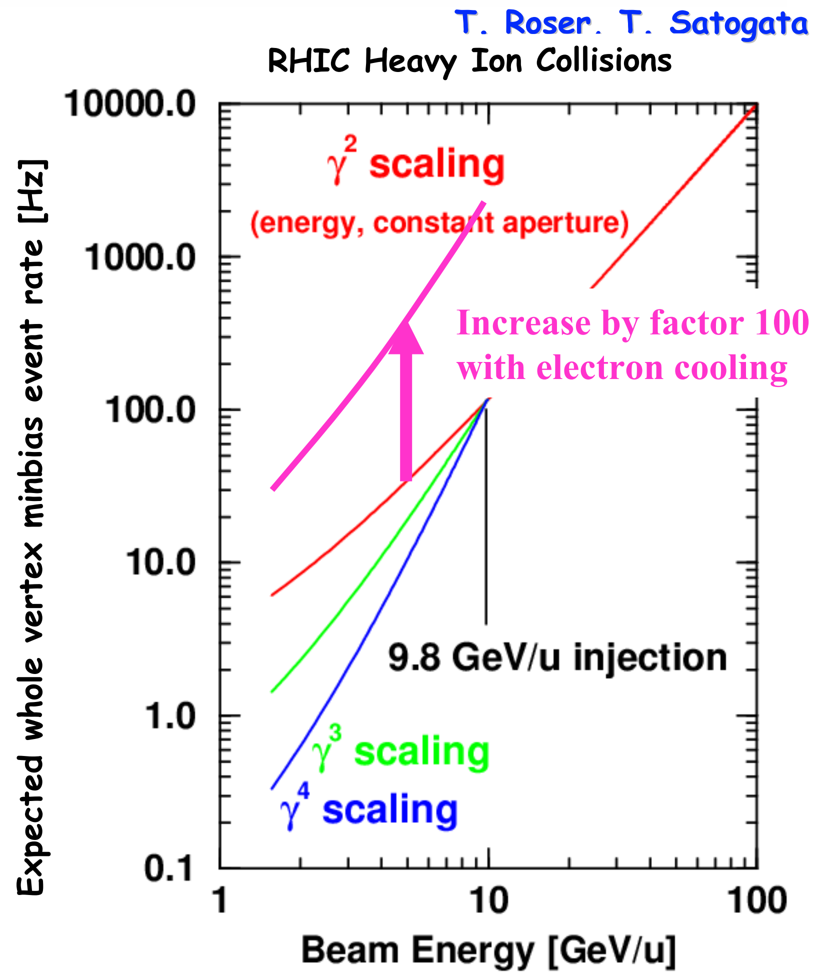
    Requires highest possible luminosity, i.e. electron cooling

- **Luminosity estimate with electron cooling**
  - **Assume 4 weeks of physics each, 25% recorded luminosity and sufficient triggers**

20 GeV	**→**	**10^9 events**
2 GeV	**→**	**10^7 events**

CERES best run ~ 4×10^7 events

NA60 In+In ~ 10^{10} sampled events



SPS

FAIR

RHIC

Very strong low energy program possible at RHIC

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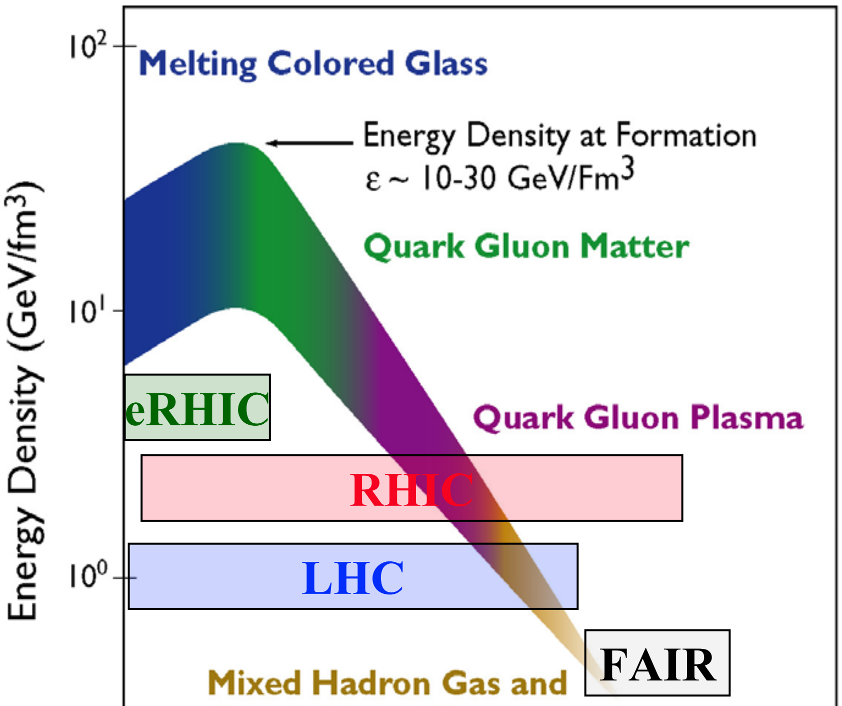
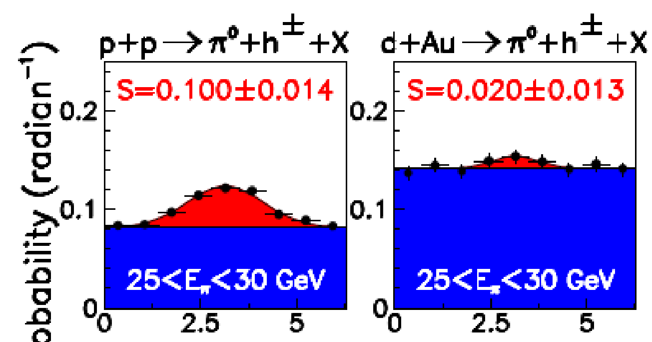
Fundamental Questions (IIII)

- **How are colliding nuclei converted into thermal quark-gluon plasma so rapidly?**
  - **Initial state and entropy generation.**
  - **What is the low x cold nuclear matter phase?**



- **Status:**
  - **Intriguing hints for CGC (color glass condensate) at RHIC**
    - **Bulk particle multiplicities**
    - **"mono jets" at forward rapidity**

STAR



Answers at RHIC from hard probes at forward rapidity, ultimately EIC needed

Progress at RHIC limited by:
detection capabilities → forward detector upgrades

Compelling Physics of RHIC II

Provide key measurements so far inaccessible at RHIC in three broad areas:

- **High T QCD (A+A, d+A, and p+p):**
  - **Electromagnetic radiation (e^+e^- pair continuum)**
  - **Heavy flavor (c- and b-production)**
  - **Jet tomography (jet-jet and γ-jet)**
  - **Quarkonium (J/ψ, ψ' , χ_c and $\Upsilon(1s)$,$\Upsilon(2s)$,$\Upsilon(3s)$)**

requires highest AA luminosity

- **Spin structure of the nucleon:**
  - **Quark spin structure $\Delta q/q$ (W-production)**
  - **Gluon spin structure $\Delta g/g$ (heavy flavor and γ-jet correlations)**

- **Low *x* phenomena**
  - **gluon saturation in nuclei**
    (particle production at forward rapidity)

"Low x" ⇔ "forward measurements"

All measurements require upgrades of detectors and/or RHIC luminosity

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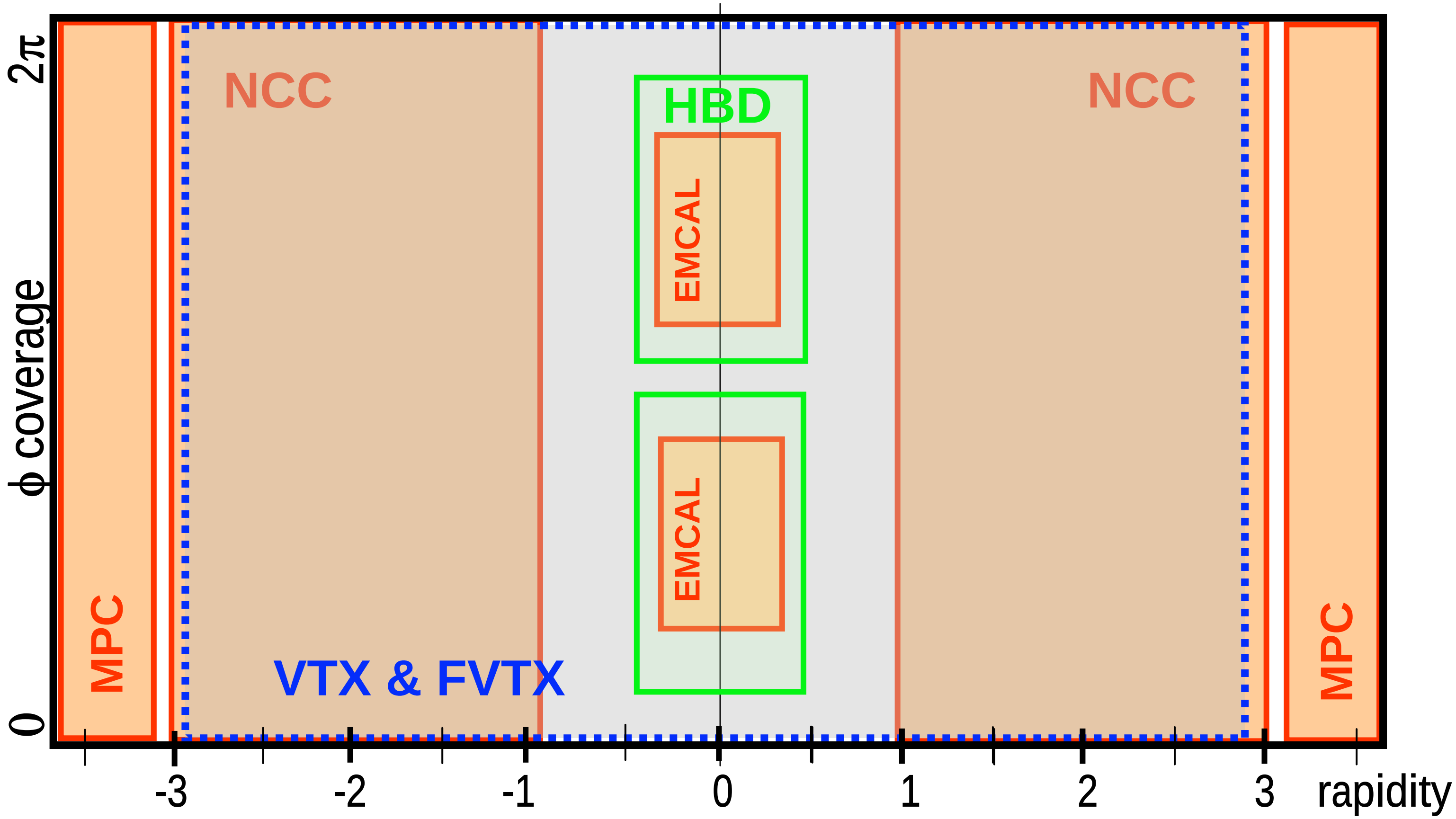
RHIC Upgrades Overview

Upgrades	High T QCD				Spin		Low x
	e+e-	heavy flavor	jet tomography	quarkonia	W	ΔG/G	
PHENIX							
hadron blind detector (HBD)	X						
Vertex tracker (VTX and FVTX)	X	X	O	O		O	O
μ trigger				O	X		
forward calorimeter (NCC)			O	X	O		X
STAR							
time of flight (TOF)		O	X	O			
Heavy flavor tracker (HFT)		X	O	O			
tracking upgrade		O	O		X	O	
Forward calorimeter (FMS)						O	X
DAQ		O	X	X	O	O	O
RHIC luminosity	O	O	X	X	O	O	O

X upgrade critical for success
O upgrade significantly enhancements program

Future PHENIX Acceptance for Hard Probes



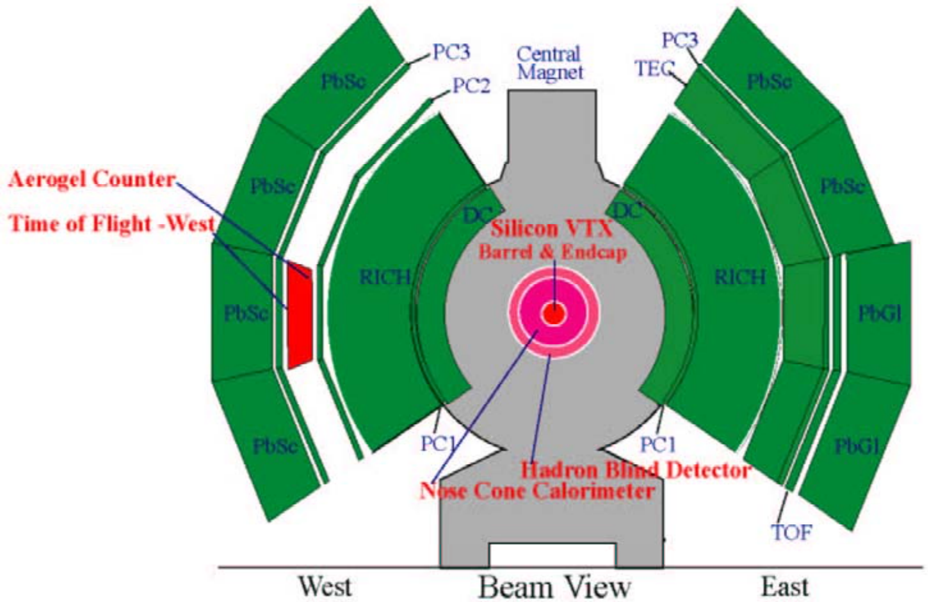
(i) π^0 and direct γ with combination of all electromagnetic calorimeters

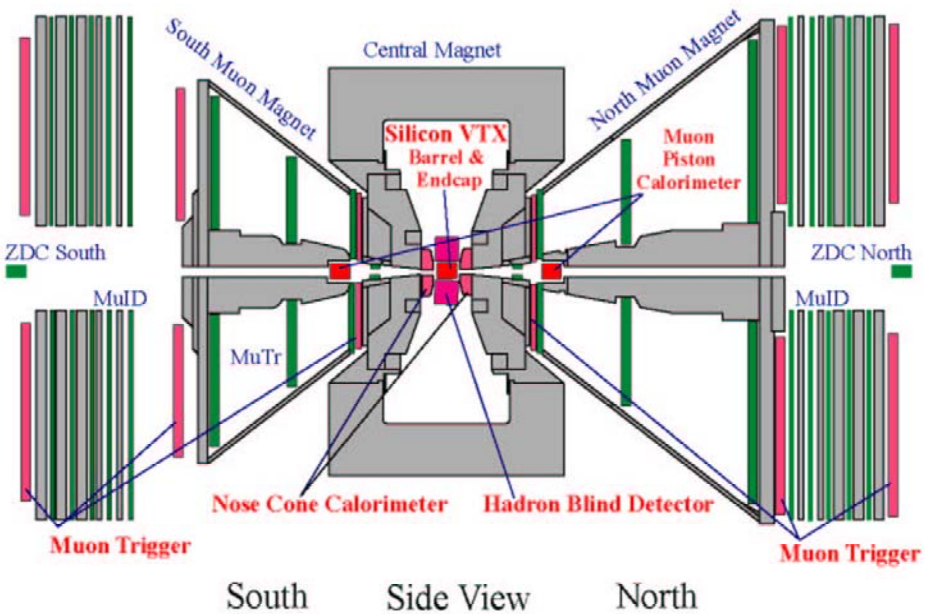
(ii) heavy flavor with precision vertex tracking with silicon detectors

combine (i)&(ii) for jet tomography with γ-jet

(iii) low mass dilepton measurments with HBD + PHENIX central arms

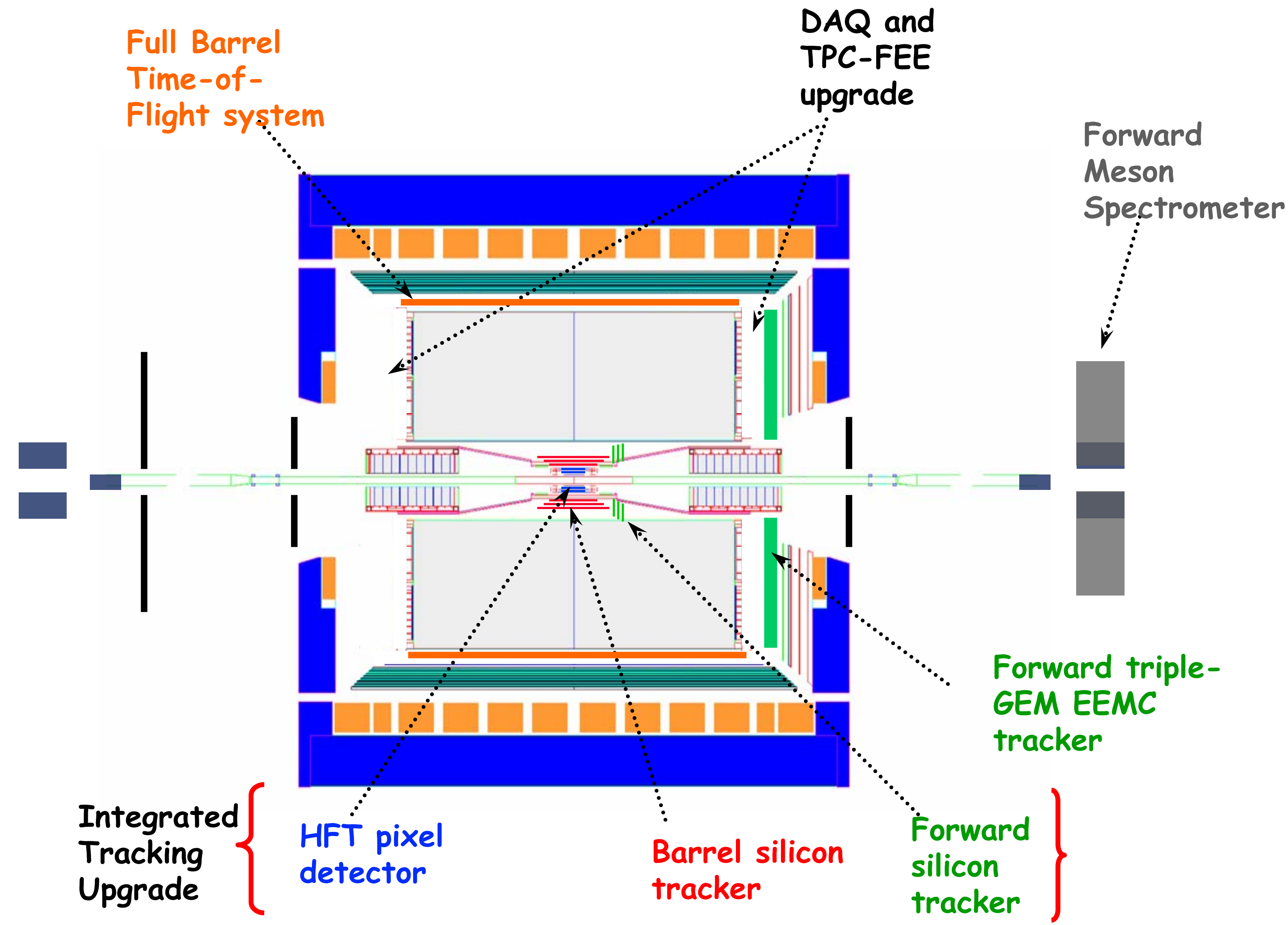
PHENIX Detector Upgrades at a Glance





- **Central arms:**
  - **Electron and Photon measurements**
    - Electromagnetic calorimeter
    - Precision momentum determination
    - Dalitz/conversion rejection (HBD)
    - Precision vertex tracking (VTX)
  - **Hadron identification**
    - PID (k,π,p) to 10 GeV (Aerogel/TOF)
- **Muon arms:**
  - **Muon**
    - Identification
    - Momentum determination
    - High rate trigger (μ trigger)
    - Precision vertex tracking (FVTX)
  - **Electron and photon measurements**
    - Muon arm acceptance (NCC)
    - Very forward (MPC)

STAR Upgrades



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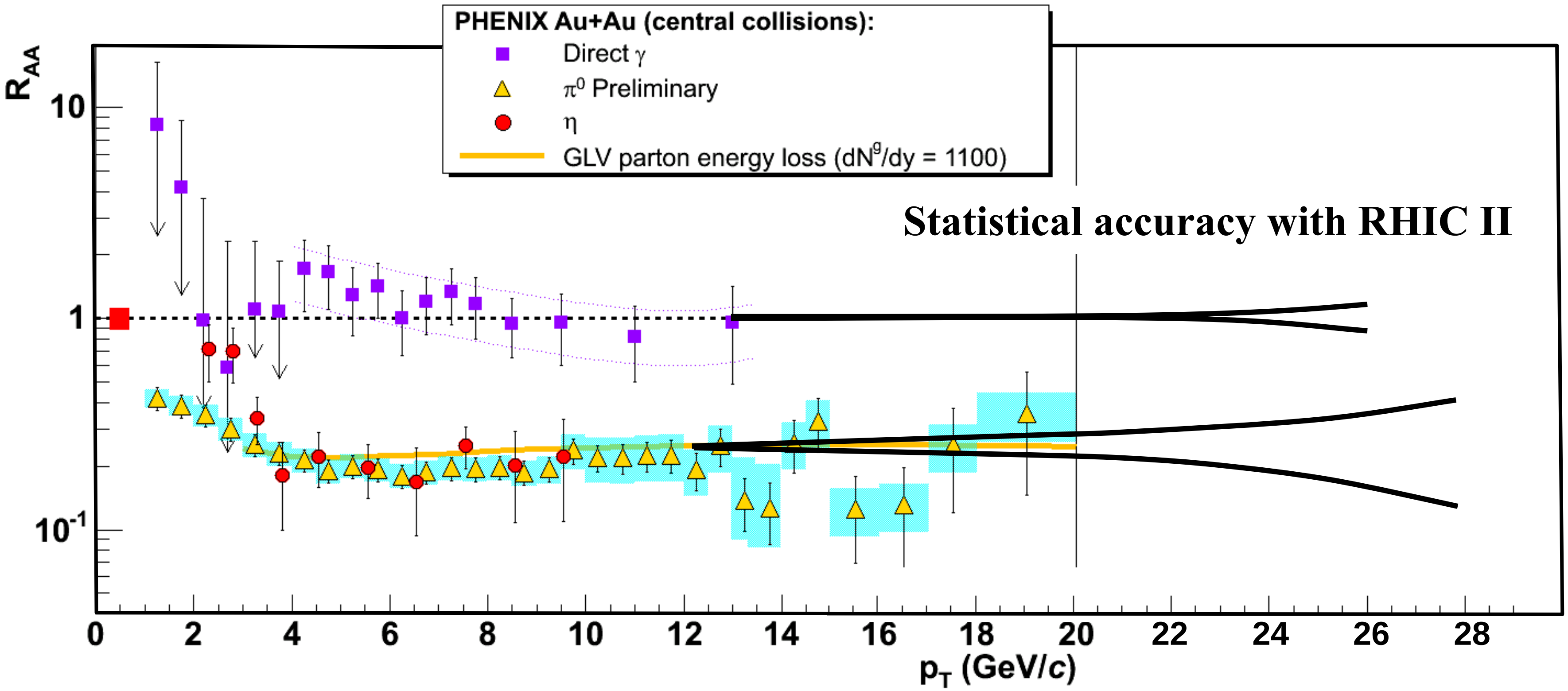
Jet Tomography with RHIC II



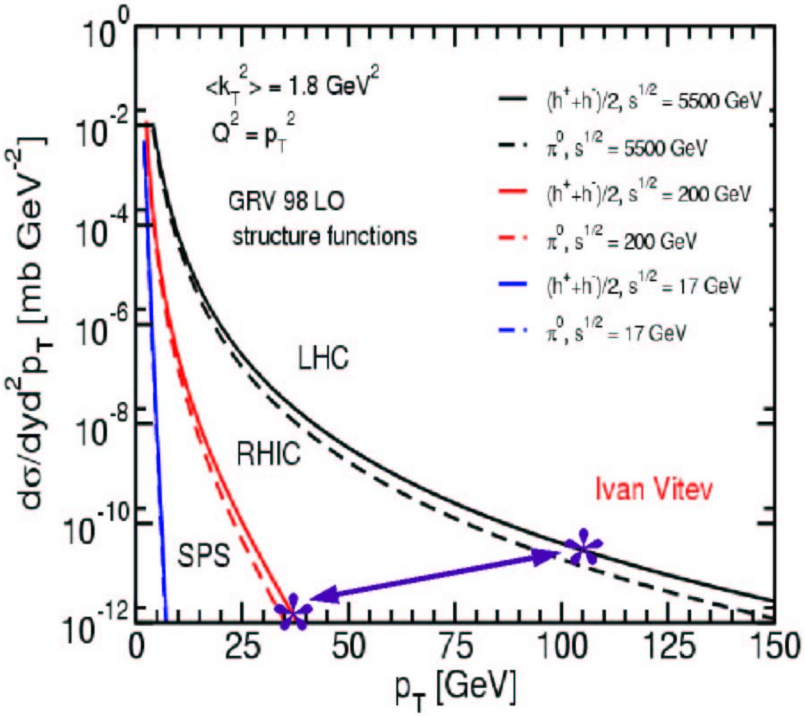
RHIC II will give jets up to 50 GeV

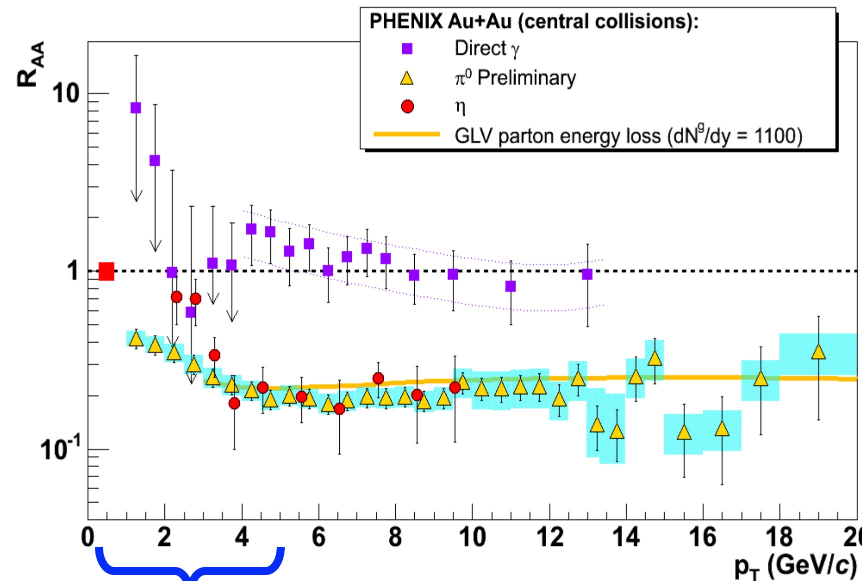
→ separation of medium reaction and energy loss

→ sufficient statistics for 3 particle correlations p_T > 5 GeV

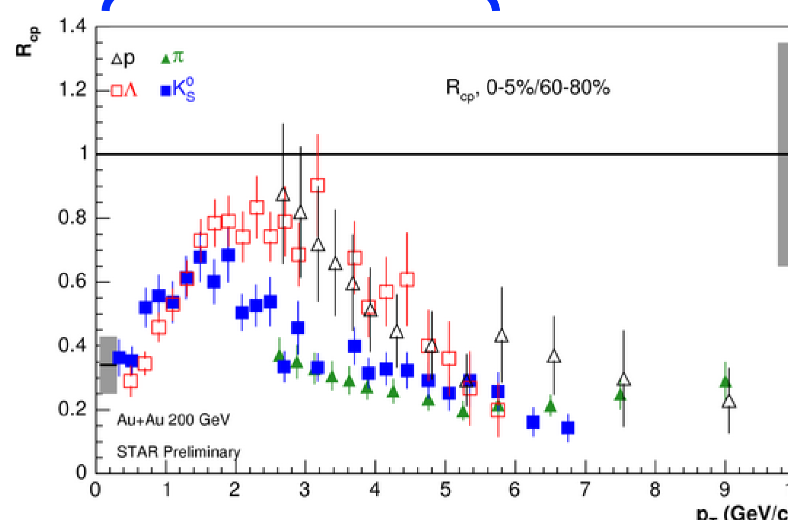
→ 2-3 particle correlations with identified particles

Comments on High p_T Capabilities





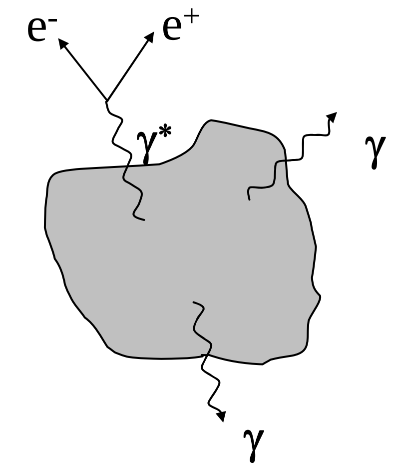
Region of interest for associated particles up to $p_T \sim 5$ GeV



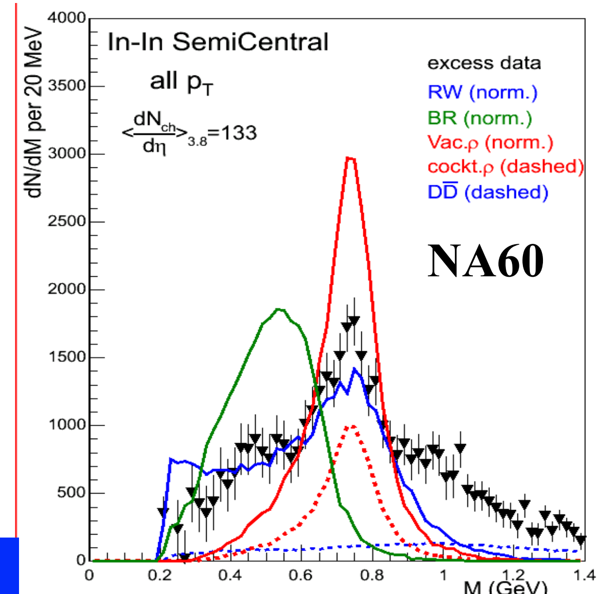
- **LHC**
  - Orders of magnitude larger cross sections
  - ~3 times larger p_T range
- **RHIC with current detectors (+ upgrades)**
  - Sufficient p_T reach
  - Sufficient PID for associated particles
  - What is needed is integrated luminosity!

Fundamental Questions (I & II)

- **Key probe: electromagnetic radiation:**
  - **No strong final state interaction**
  - **Carry information from time of emission to detectors**
    - **γ and dileptons sensitive to highest temperature of plasma**
    - **Dileptons sensitive to medium modifications of mesons**
    - **(only known potential handle on chiral symmetry restoration!)**



- **Status**
  - **First indication of thermal radiation at RHIC**
  - **Strong modification of meson properties**
    - **Precision data from SPS, emerging data from RHIC**
  - **Theoretical link to chiral symmetry restoration remains unclear**



Can we measure the initial temperature?
Is there a quantitative link from dileptons to chiral symmetry resoration?

Answers will come with more precision data → upgrades and low energy running

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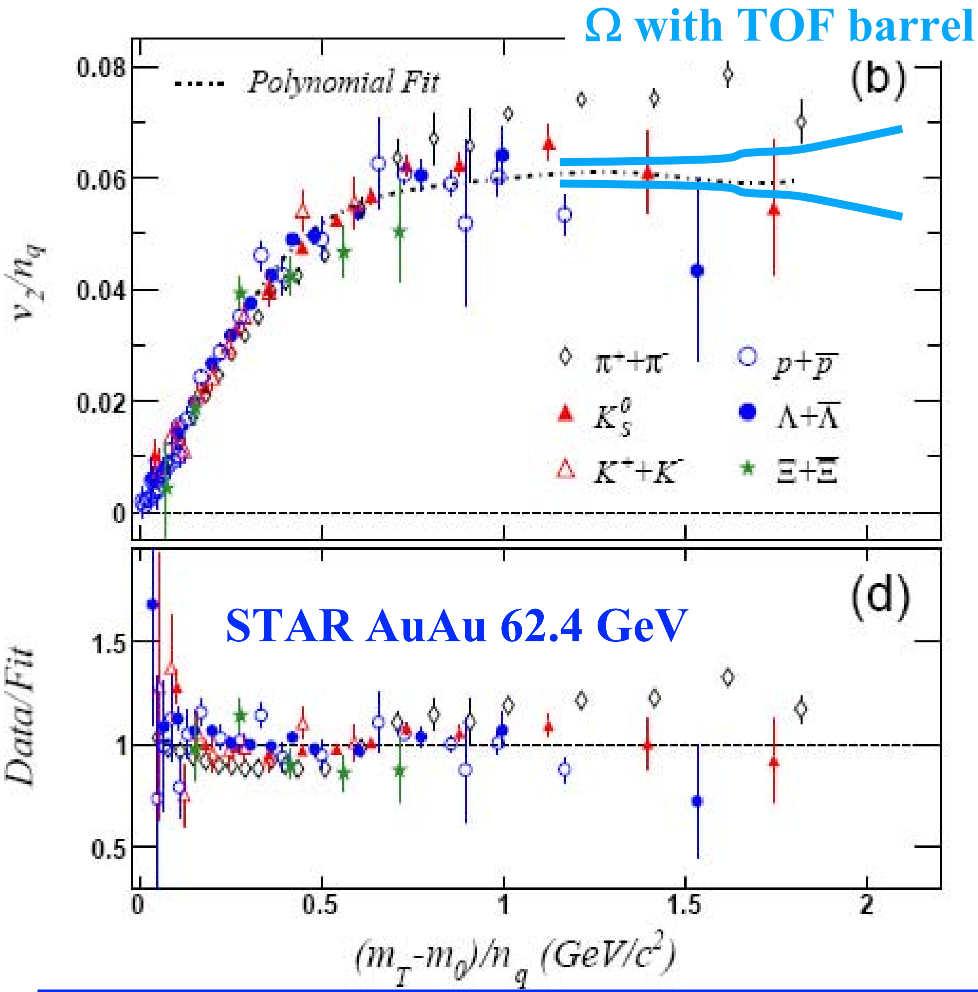
Fundamental Questions (III)



- **How does the deconfined matter transform into hadrons?**
- **Status:**
  - **Elliptic flow (v2)**
    - **v_2 of mesons and baryons scale with constituent quark number**
  - **Evidence for deconfined quarks**
    - **Hadronisation via recombination of constituent quarks in QGP**

Progress from √s and flavor dependence of collective flow

Limited by:

flavor detection capabilities s, c, b mesons and baryons

→ vertex detectors and extended particle ID

Beyond PHENIX and STAR upgrades?

- **Do we need (a) new heavy ion experiment(s) at RHIC?**
  - **Likely, if it makes sense to continue program beyond 2020**
    - **Aged mostly 20 year old detectors**
    - **Capabilities and room for upgrades exhausted**
    - **Delivered luminosity leaves room for improvement**
  - **Nature of new experiments unclear at this point!**
    - **Specialized experiments or 4π multipurpose detector ???**
- **Key to future planning:**
  - **First results from RHIC upgrades**
    - **Detailed jet tomography, jet-jet and γ-jet**
    - **Heavy flavor (c- and b-production)**
    - **Quarkonium measurments (J/ψ, ψ' , ϒ)**
    - **Electromagnetic radiation (e^+e^- pair continuum)**
    - **Status of low energy program**
  - **Tests of models that describe RHIC data at LHC**
    - **Validity of saturation picture**
    - **Does ideal hydrodynamics really work**
    - **Scaling of parton energy loss**
    - **Color screening and recombination**

New insights and short comings of RHIC detectors will guide planning on time scale 2010-12