Recent Results from PHENIX

Xiaochun He
Georgia State University
for the PHENIX Collaboration

Pioneering High Energy Nuclear Ion eXperiment

Recent Results from PHENIX

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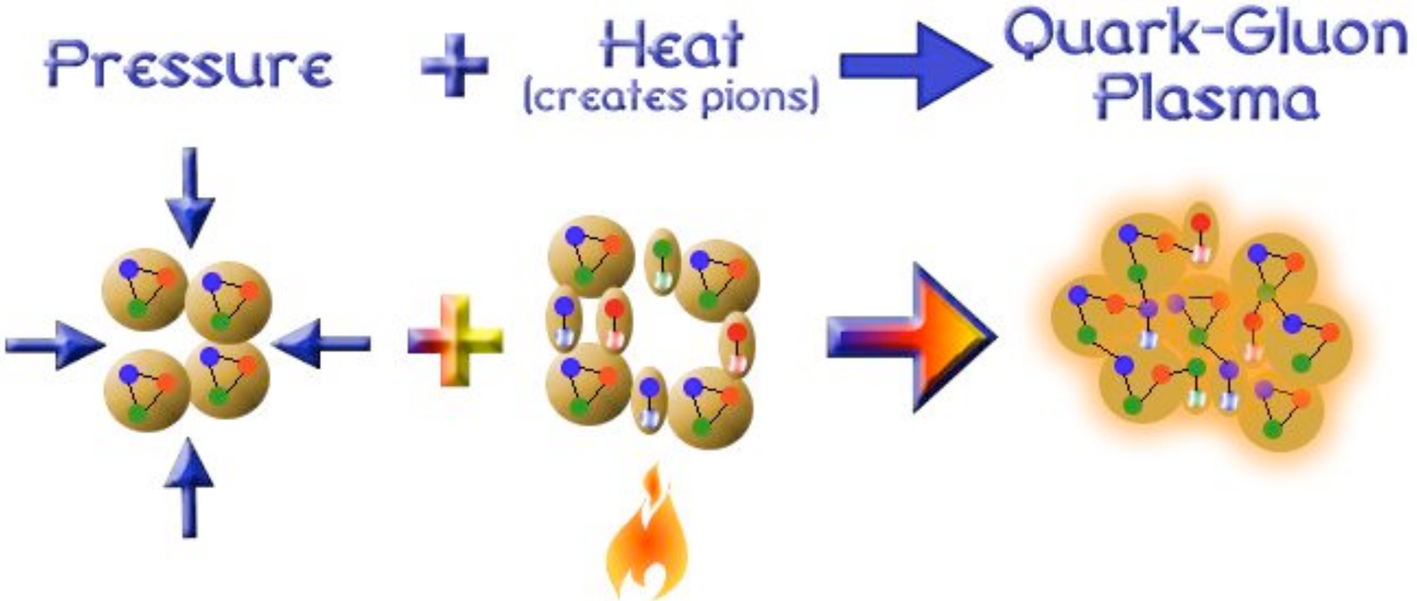
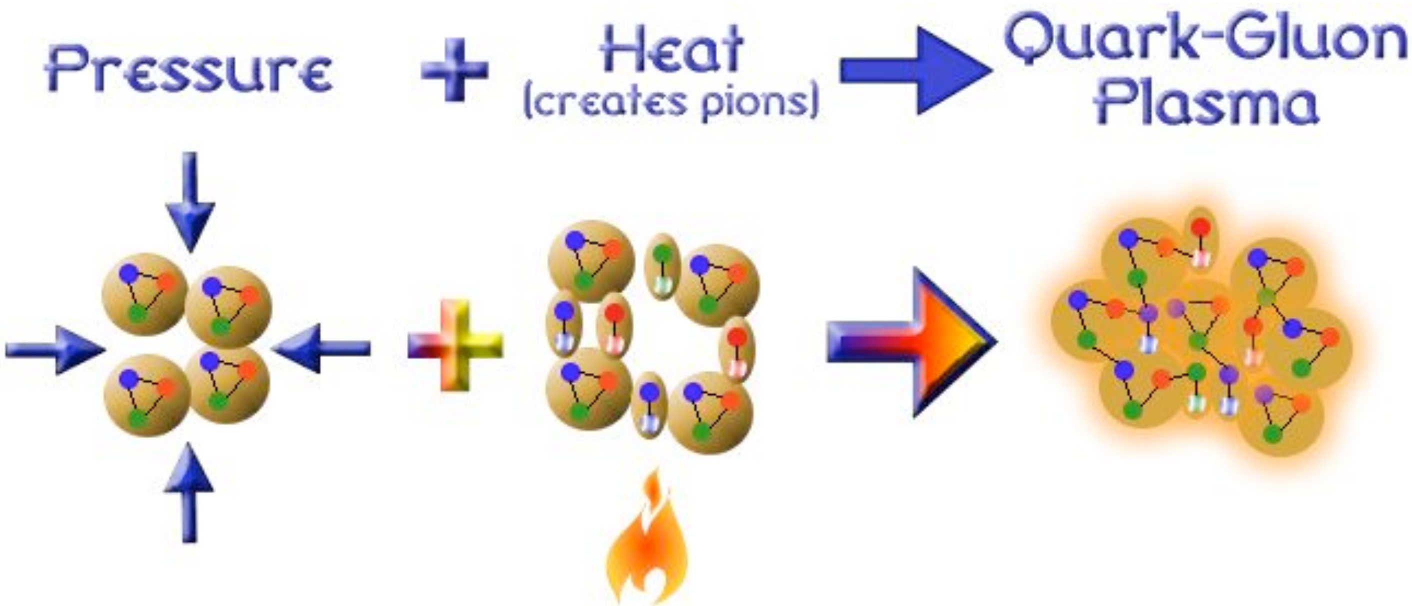
- Physics motivations
- Highlights from PHENIX (selected!)
- Recent exciting results
  - ✓ Temperature measurement
  - ✓ Heavy quarkonia suppression
- Summary & future plans

Pioneering High Energy Nuclear Ion eXperiment

Physics Motivations

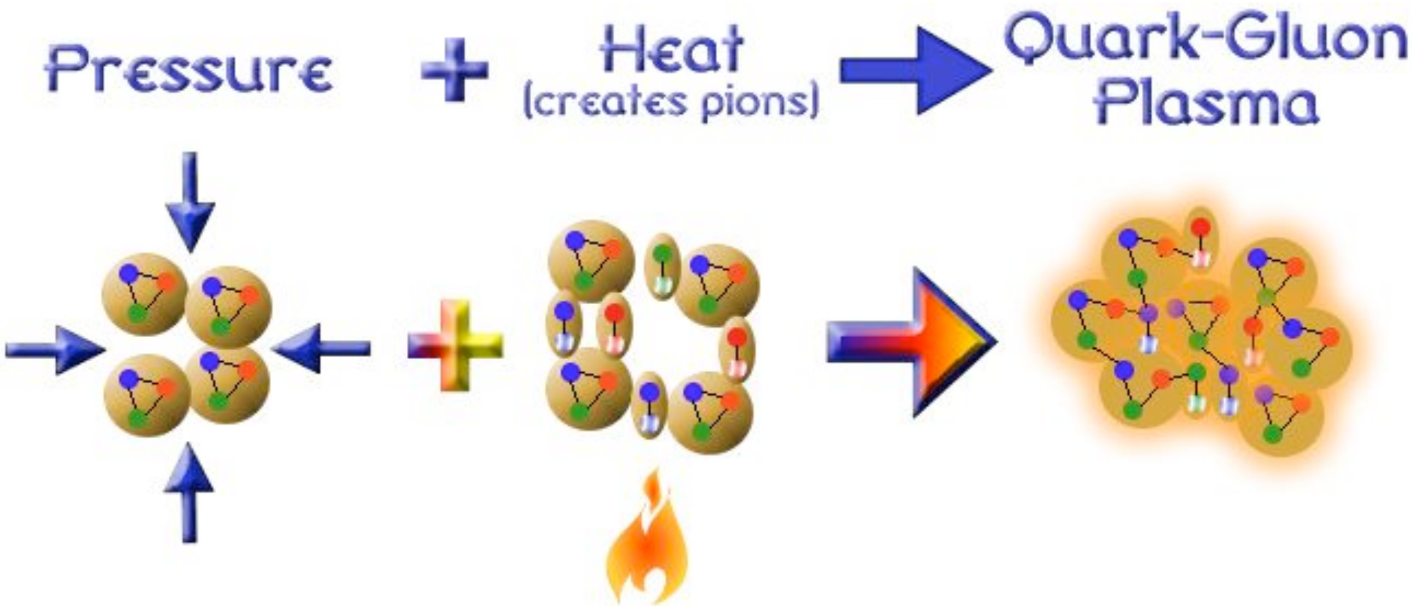


Physics Motivations



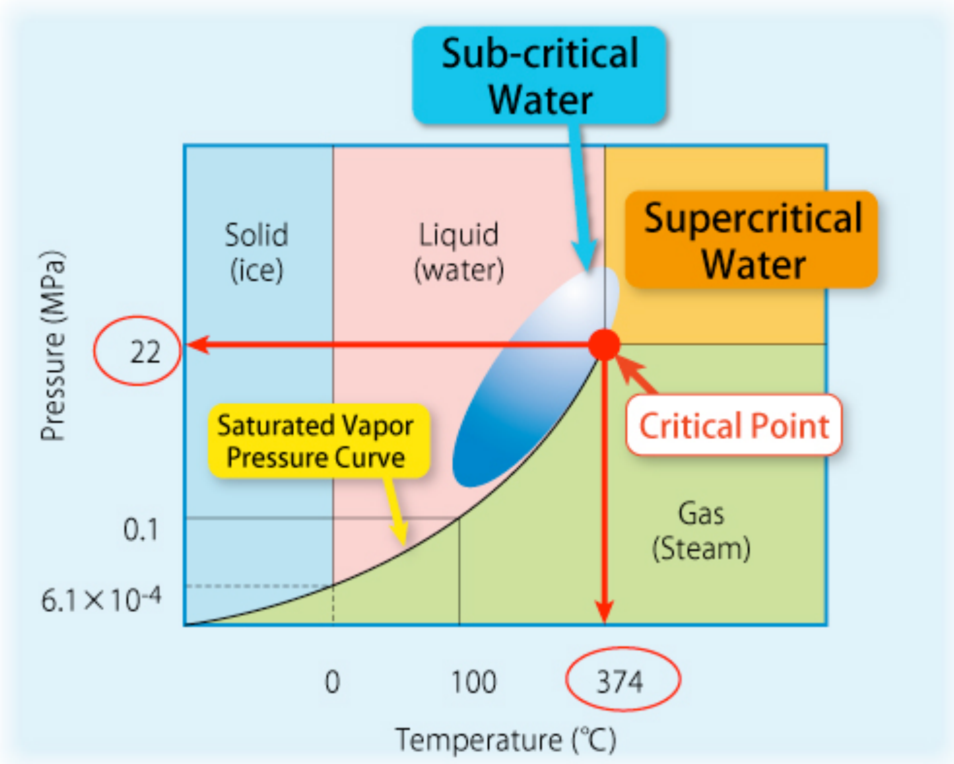
- **It is probably the only venue to study the properties of extreme high temperature and density QCD matter experimentally in a controlled environment, i.e., to explore the QCD matter phase space.**

Physics Motivations



- It is probably the only venue to study the properties of extreme high temperature and density QCD matter experimentally in a controlled environment, i.e., to explore the QCD matter phase space.
- It also provides a laboratory-based test of the standard model of cosmology – "big bang".

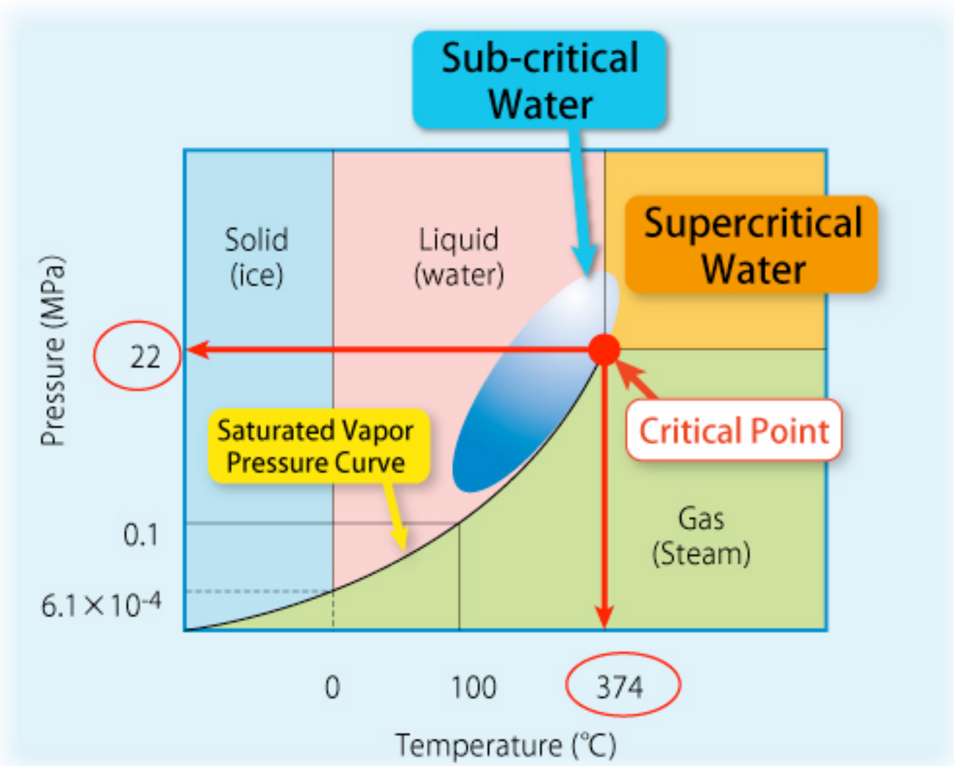
Phase Diagram (H_2O) – We Have Done This!



Phase Diagram (H_2O) – We Have Done This!

A fundamental understanding requires the knowledge of

i)The location of the Critical End Point (CEP)
ii)The location of phase coexistence lines
iii)The properties of each phase

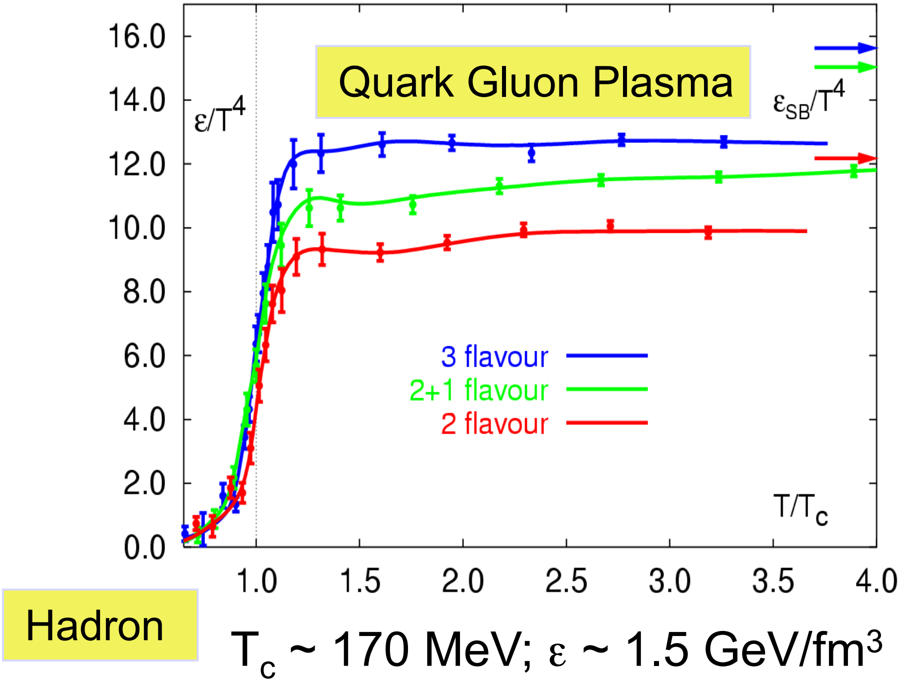


This knowledge is fundamental for studying the phase space properties of any substance !

Explore QCD Phase Space

- The colliding nuclei at RHIC energies would melt from protons and neutrons into a collection of quarks and gluons

$$\varepsilon_{SB}(T) = \frac{\pi^2}{30}(N_{bosons} + 7/8\, N_{fermions})T^4$$



T_c ~ 170 MeV; ε ~ 1.5 GeV/fm^3

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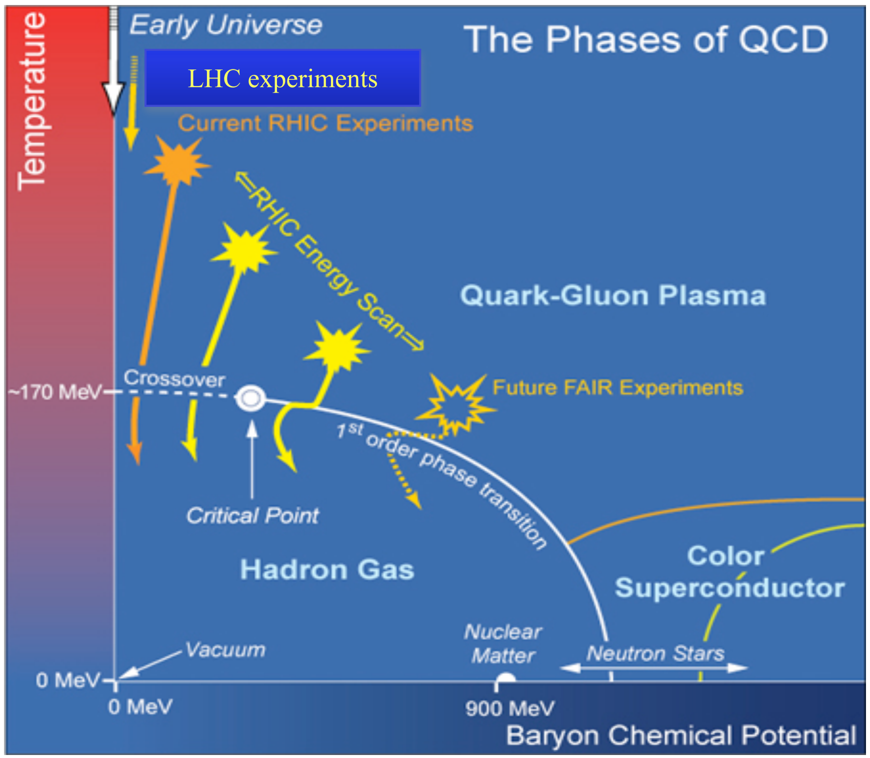

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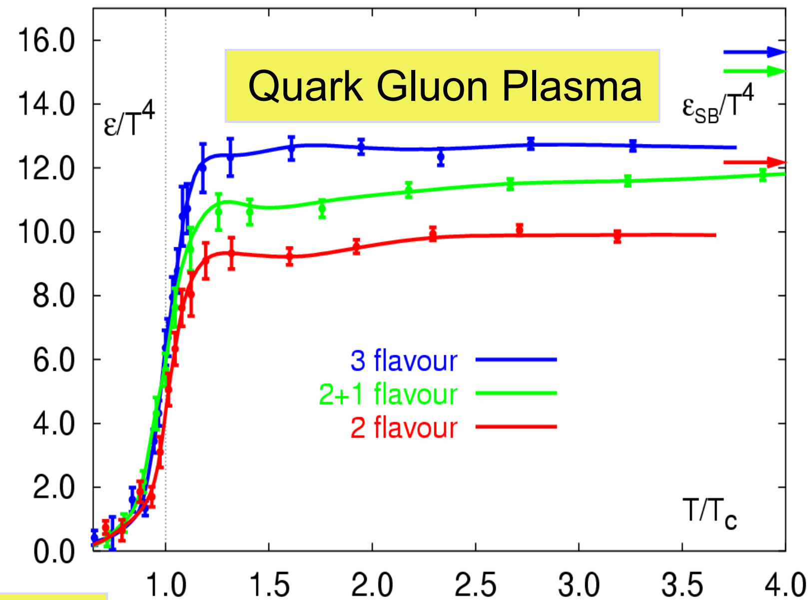
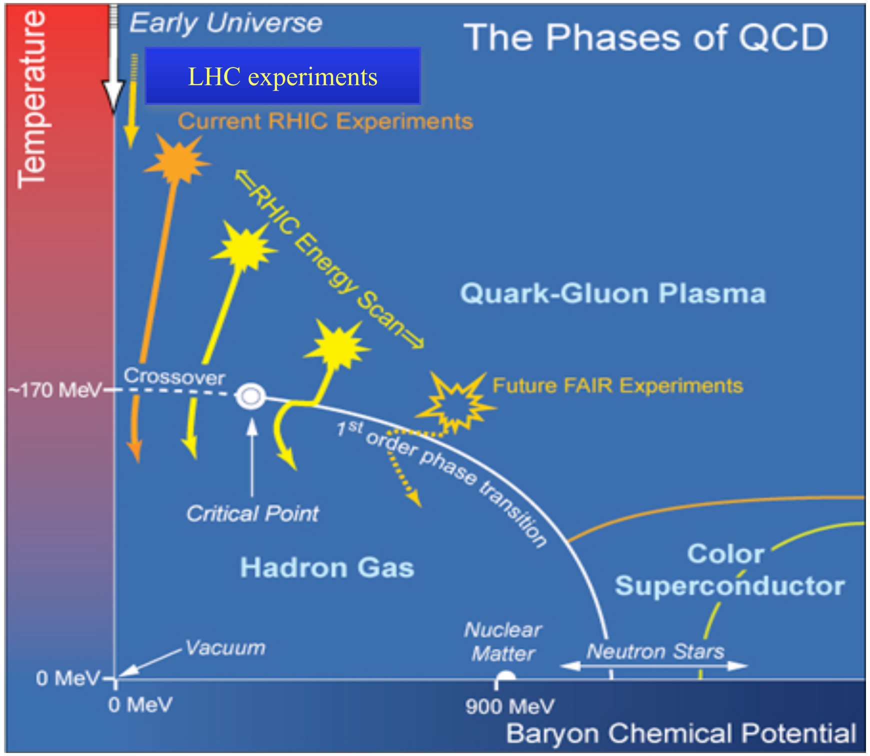


Hadron

T_c ~ 170 MeV; ε ~ 1.5 GeV/fm^3

Explore QCD Phase Space

- **The colliding nuclei at RHIC energies would melt from protons and neutrons into a collection of quarks and gluons**



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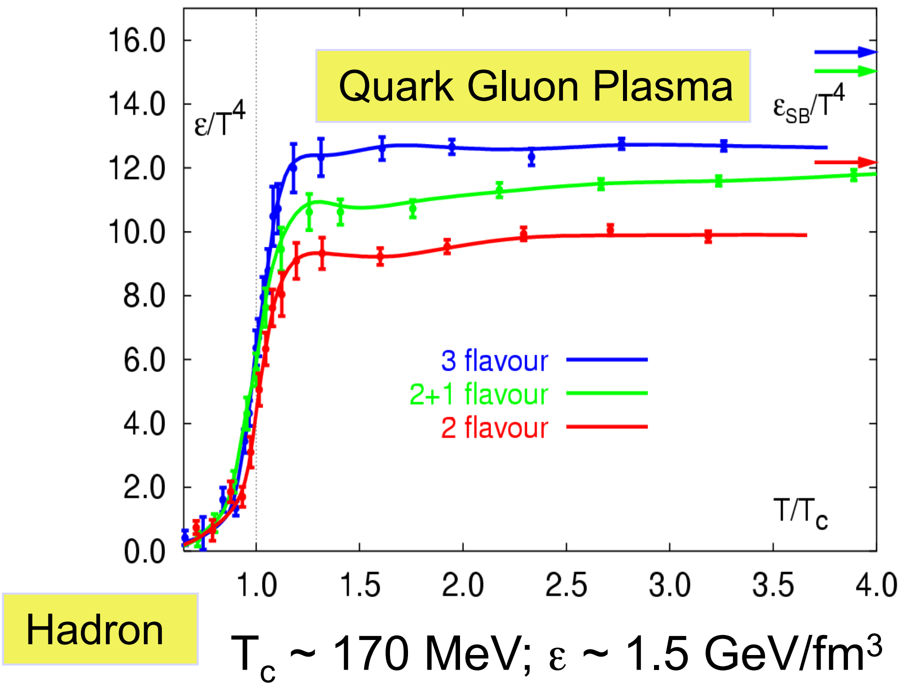


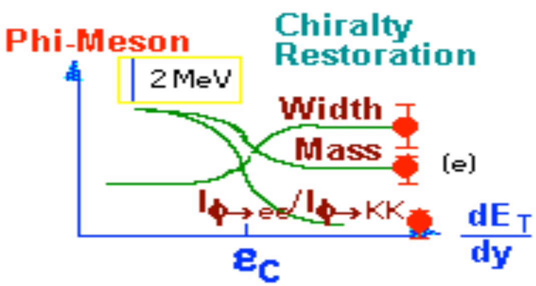
T_c ~ 170 MeV; ε ~ 1.5 GeV/fm^3

Measure the initial temperature of matter formed at RHIC

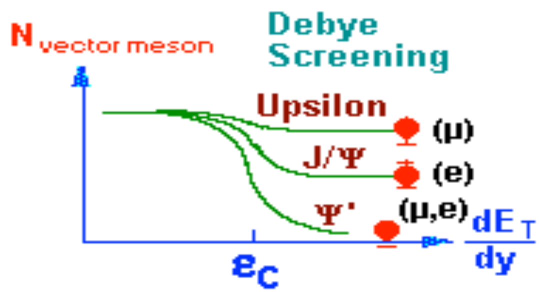
Is T_{init} higher than $T_c \sim 170$ MeV?

What We Set Out to Measure? (>25 yrs)

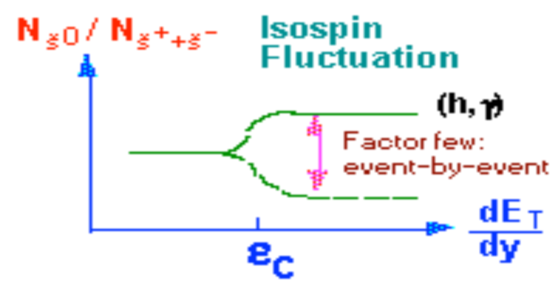
Theorists predicted a number of signals that might abruptly manifest themselves as soon as we crossed the critical temp. & density for the phase transition



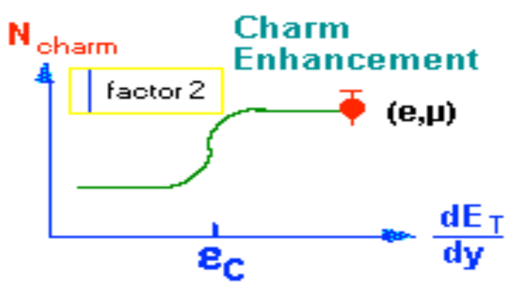
Change in mass, width of ϕ meson



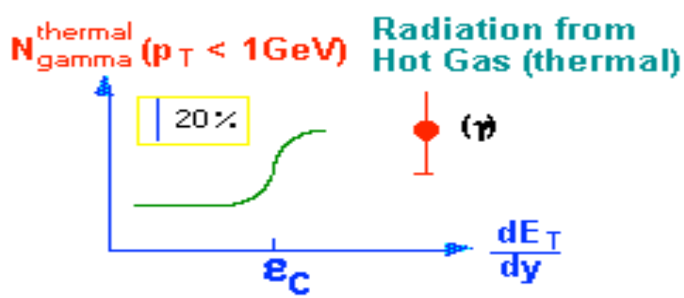
Disappearance of J/ψ



Change in pion charged/neutral



More particles containing the heavy charm quark

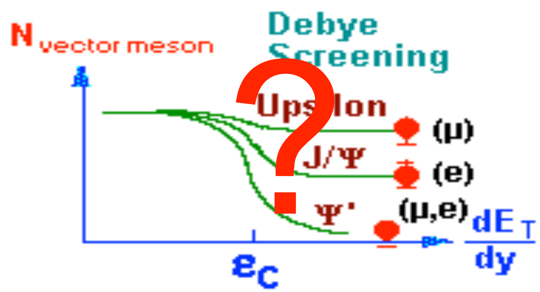


Increase in # of photons @ low momentum

How Did We Do on the Predictions?

Theorists predicted a number of signals that might abruptly manifest themselves as soon as we crossed the critical temp. & density for the phase transition

Change in mass, width of ϕ meson



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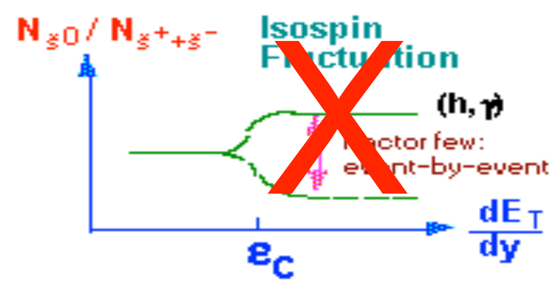

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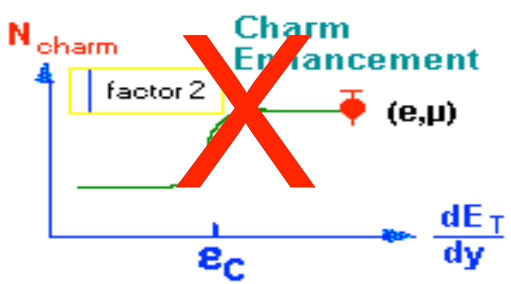

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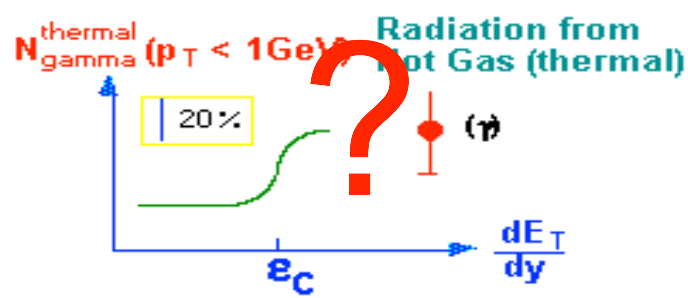
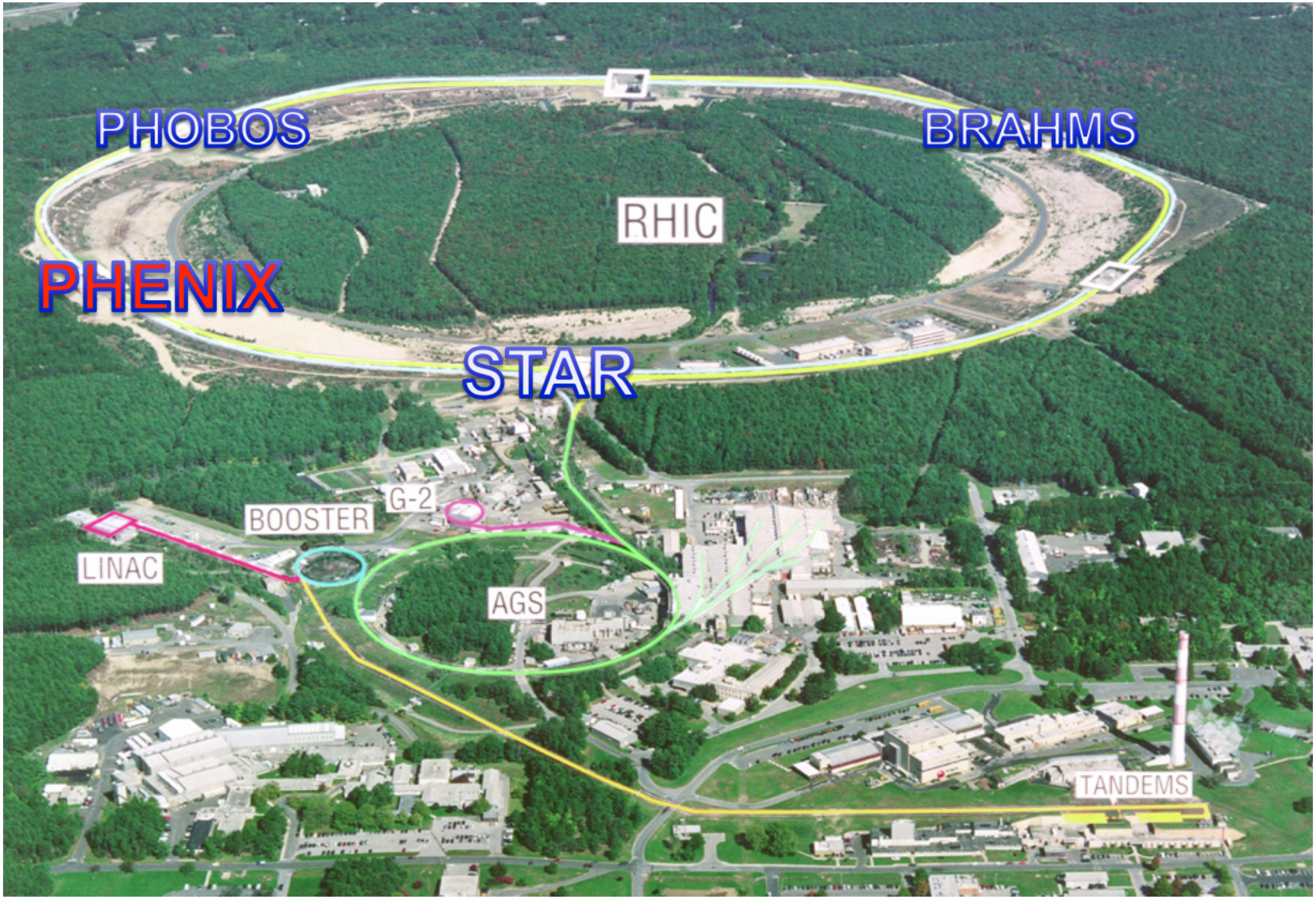


Increase in # of photons @ low momentum

RHIC Birdview



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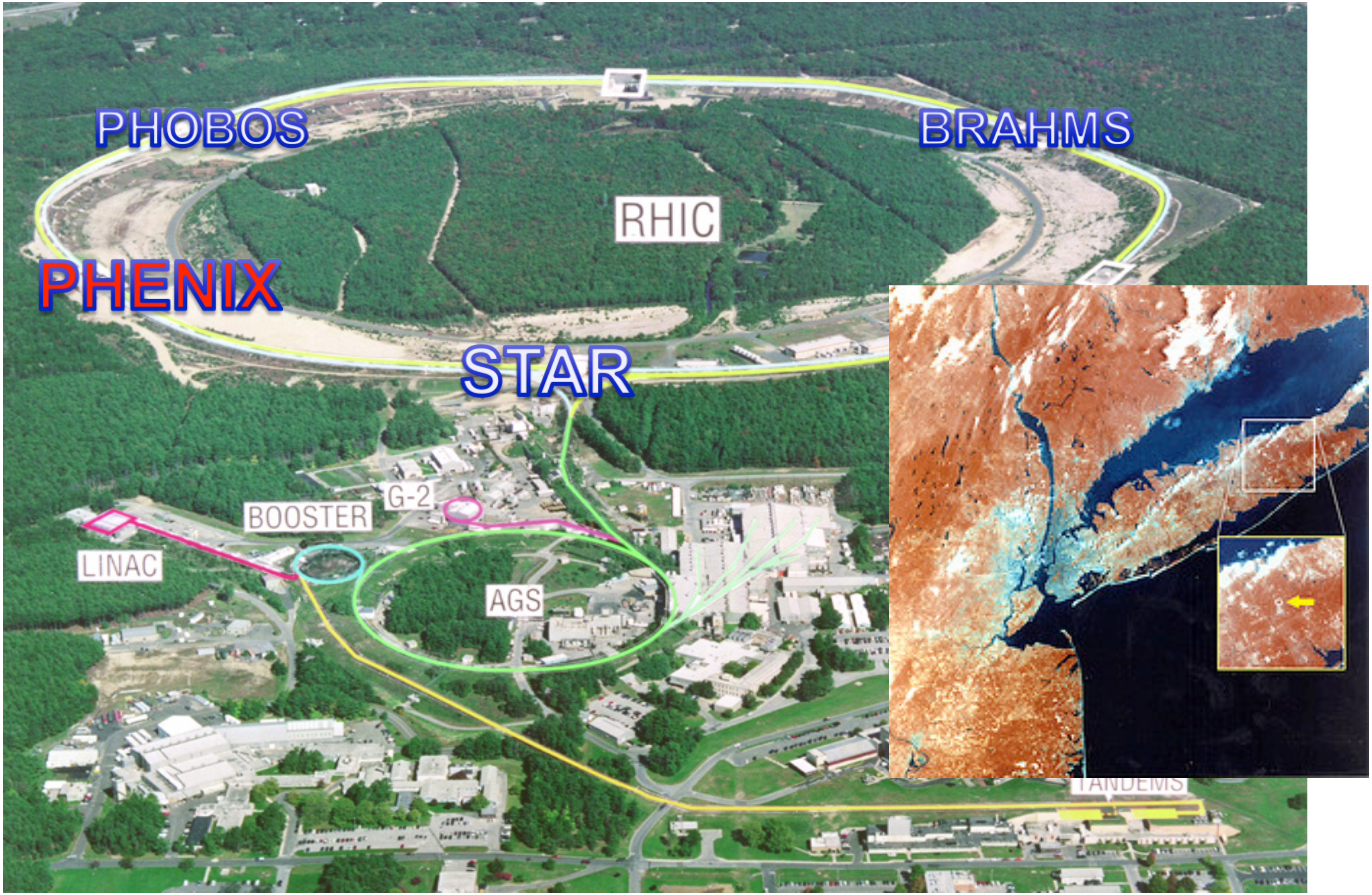
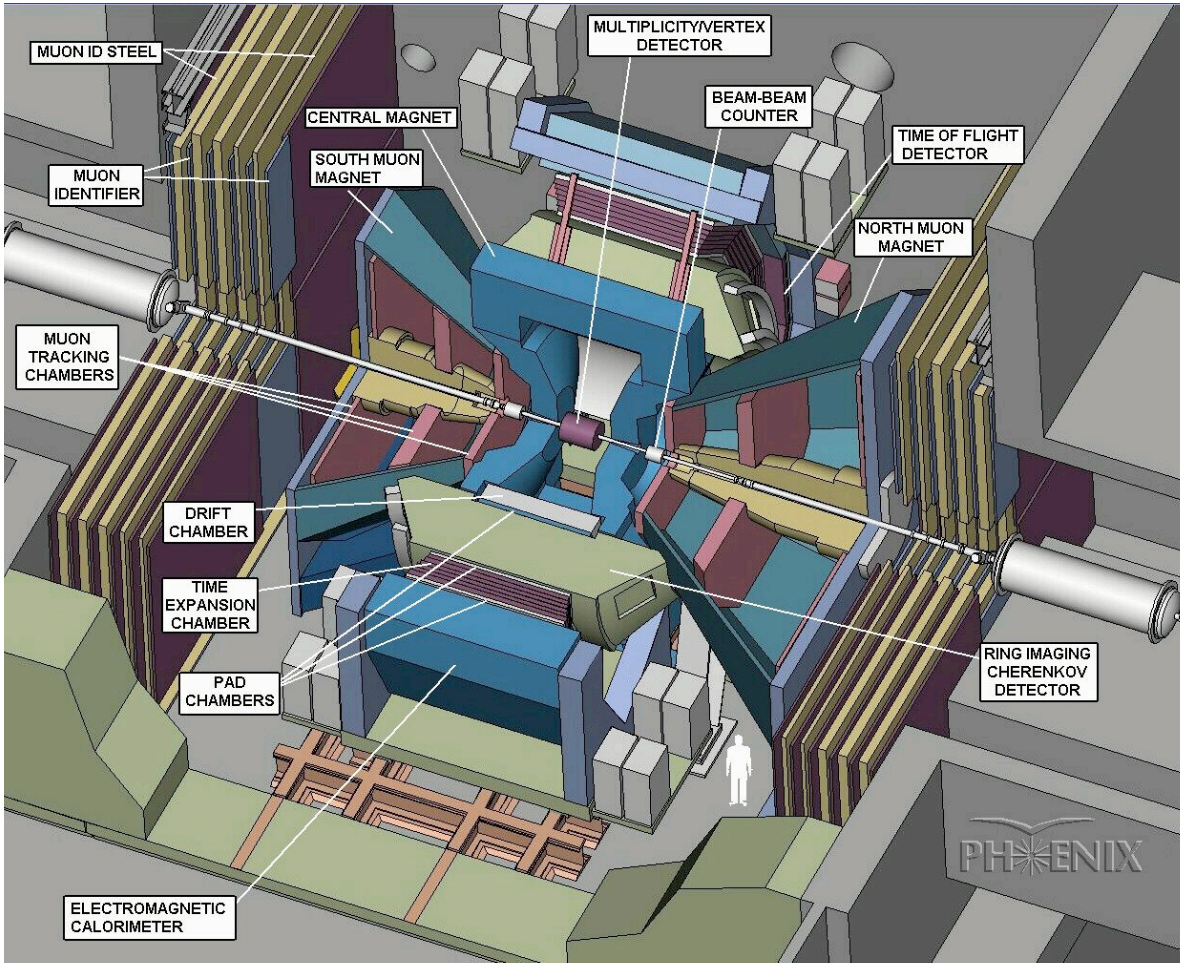


PHENIX Experiment

designed to measure rare probes:

Au-Au & p-p spin

+ high rate capability & granularity
+ good mass resolution and particle ID
- limited acceptance



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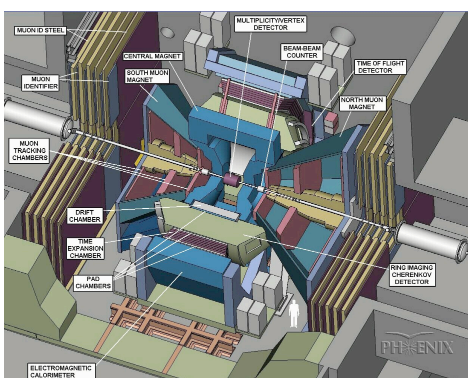
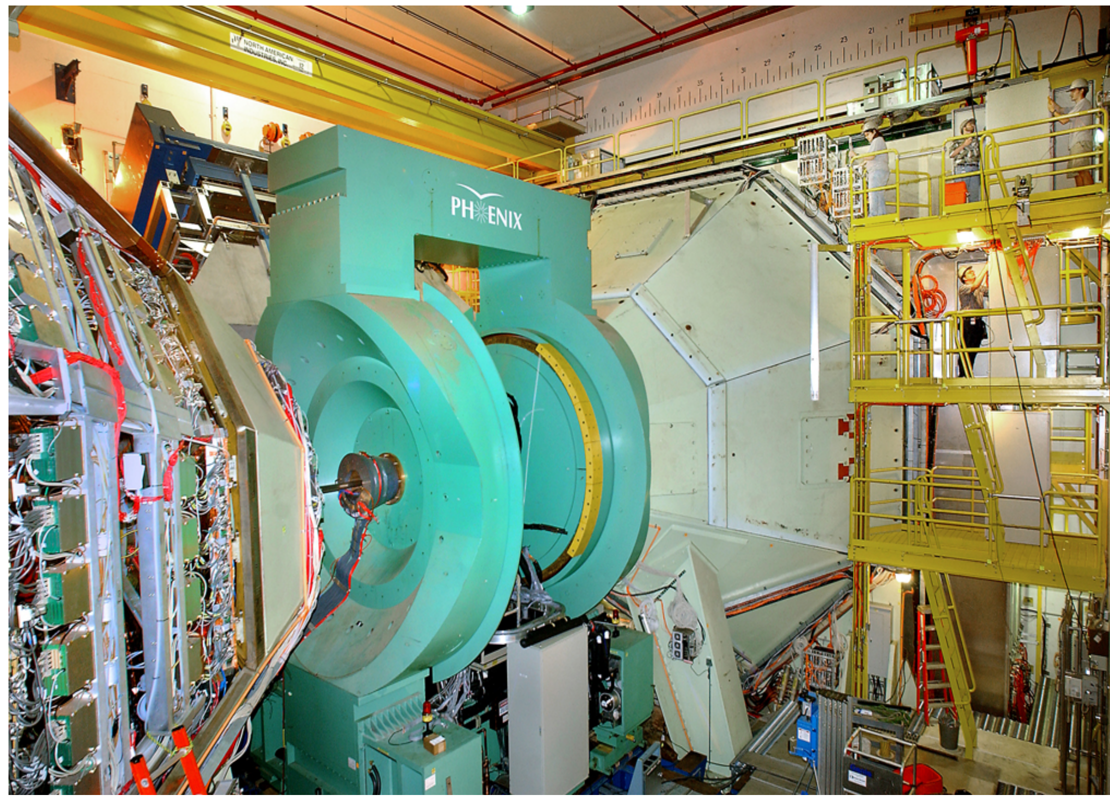
- 2 central arms





PHENIX Experiment

designed to measure rare probes:

+ high rate capability & granularity
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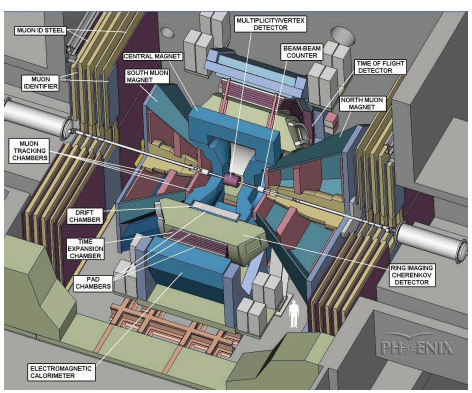
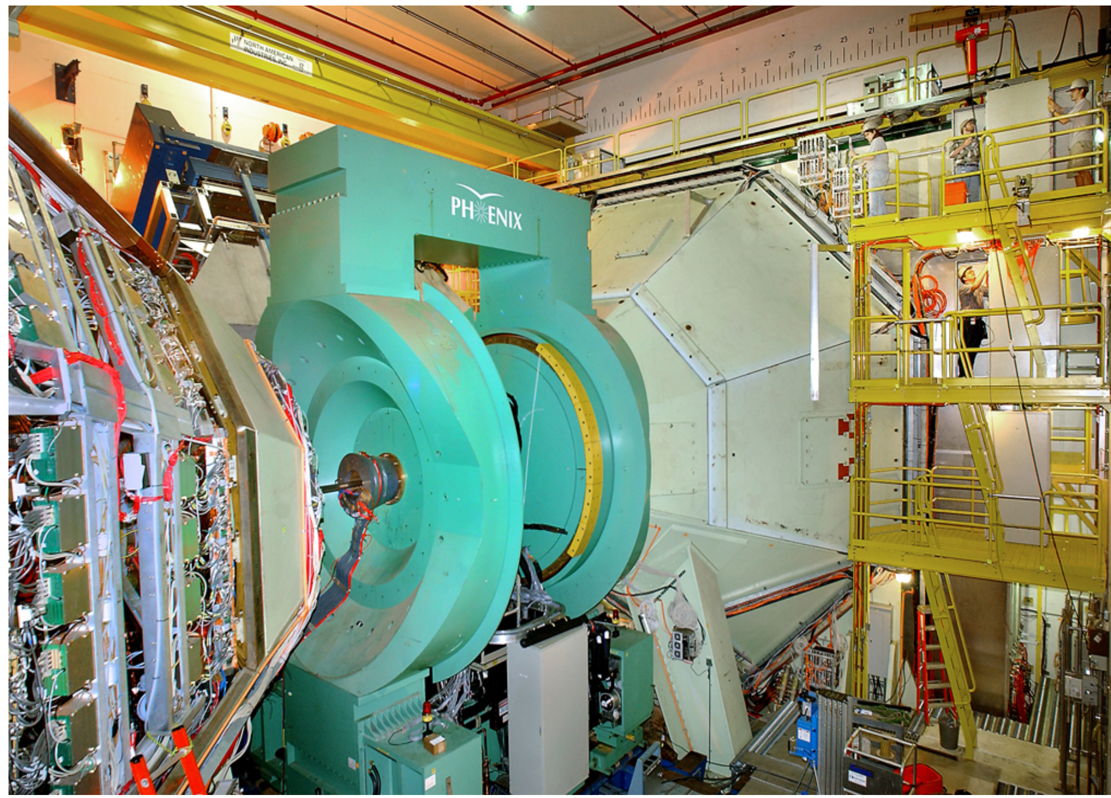
Au-Au & p-p spin

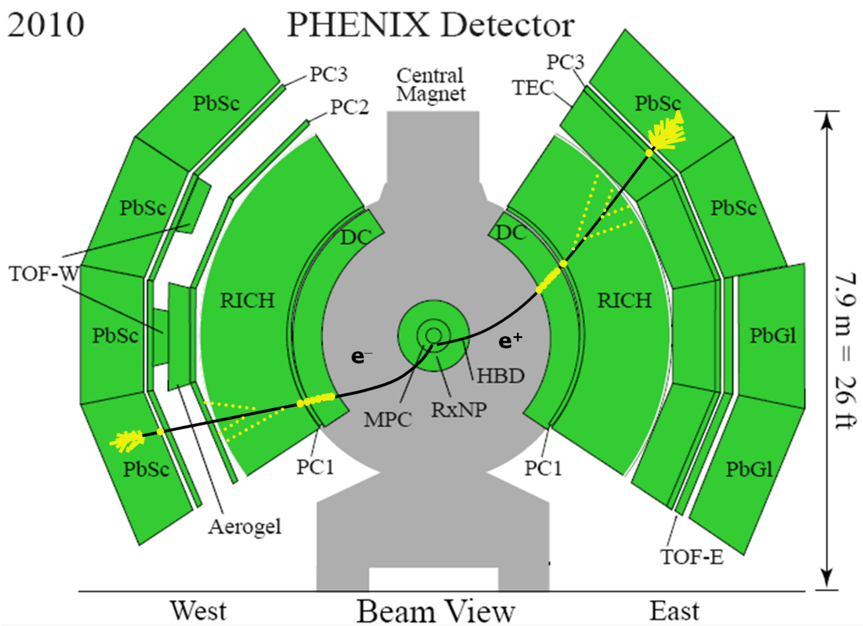
- 2 central arms

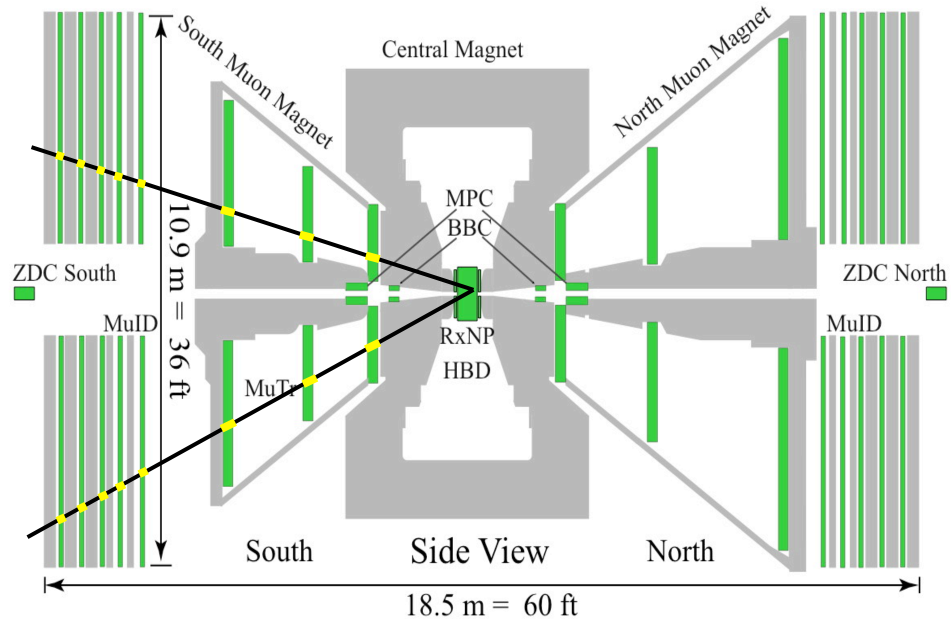
  electrons, photons, hadrons
  - charmonium J/ψ, ψ' -> e^+e^-
  - vector meson r, w, ϕ -> e^+e^-
  - high p_T π^o, π^+, π^-
  - direct photons
  - open charm
  - hadron physics
- 2 muon arms





The PHENIX Detector Acceptance





$$|\eta| < 0.35,\ \ \Delta\phi = 2 \times \frac{\pi}{2}$$

$$1.2 < |\eta| < 2.4,\ \ \Delta\phi = 2\pi$$

Central Arm:

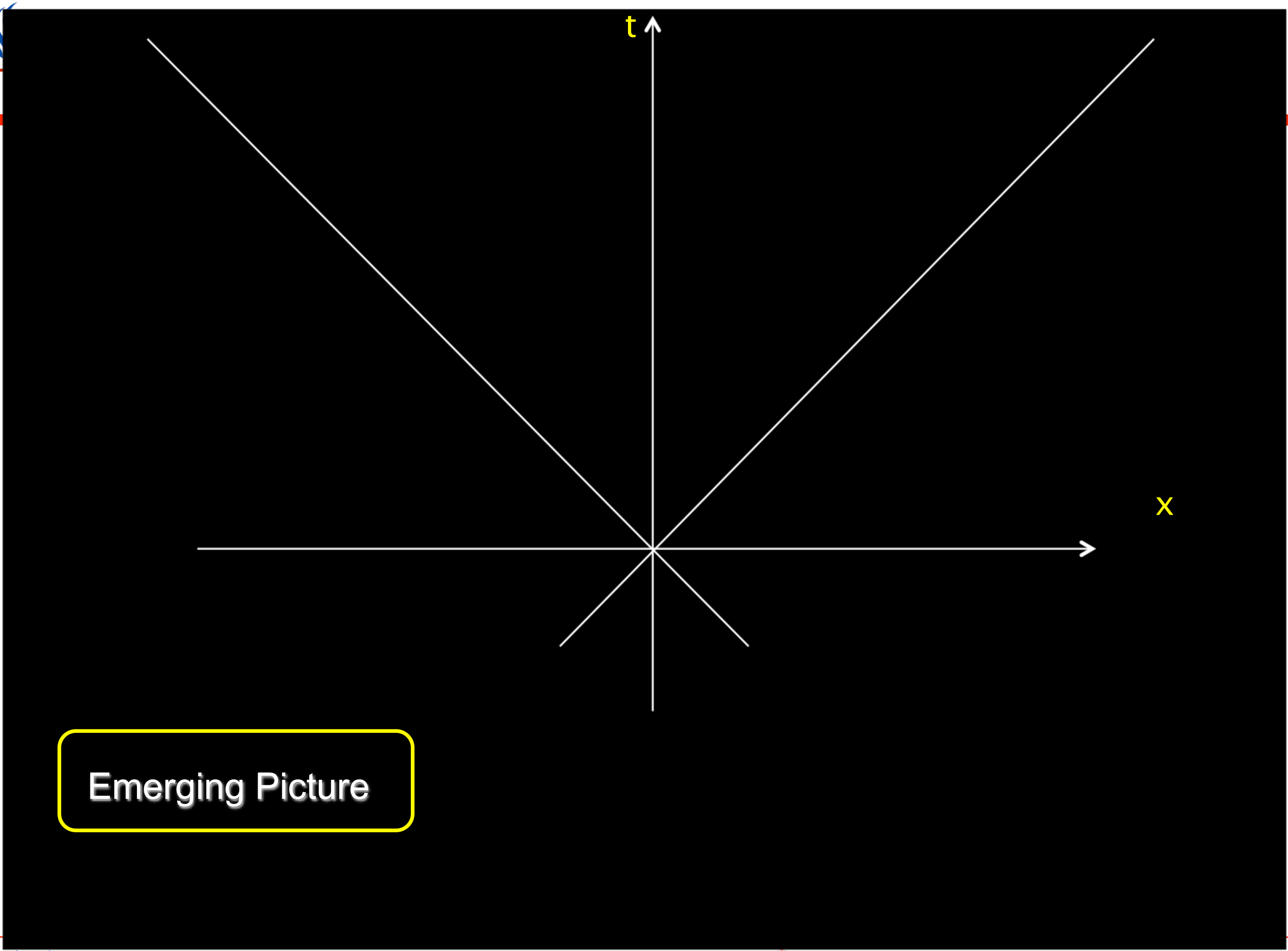
Muon Arm:

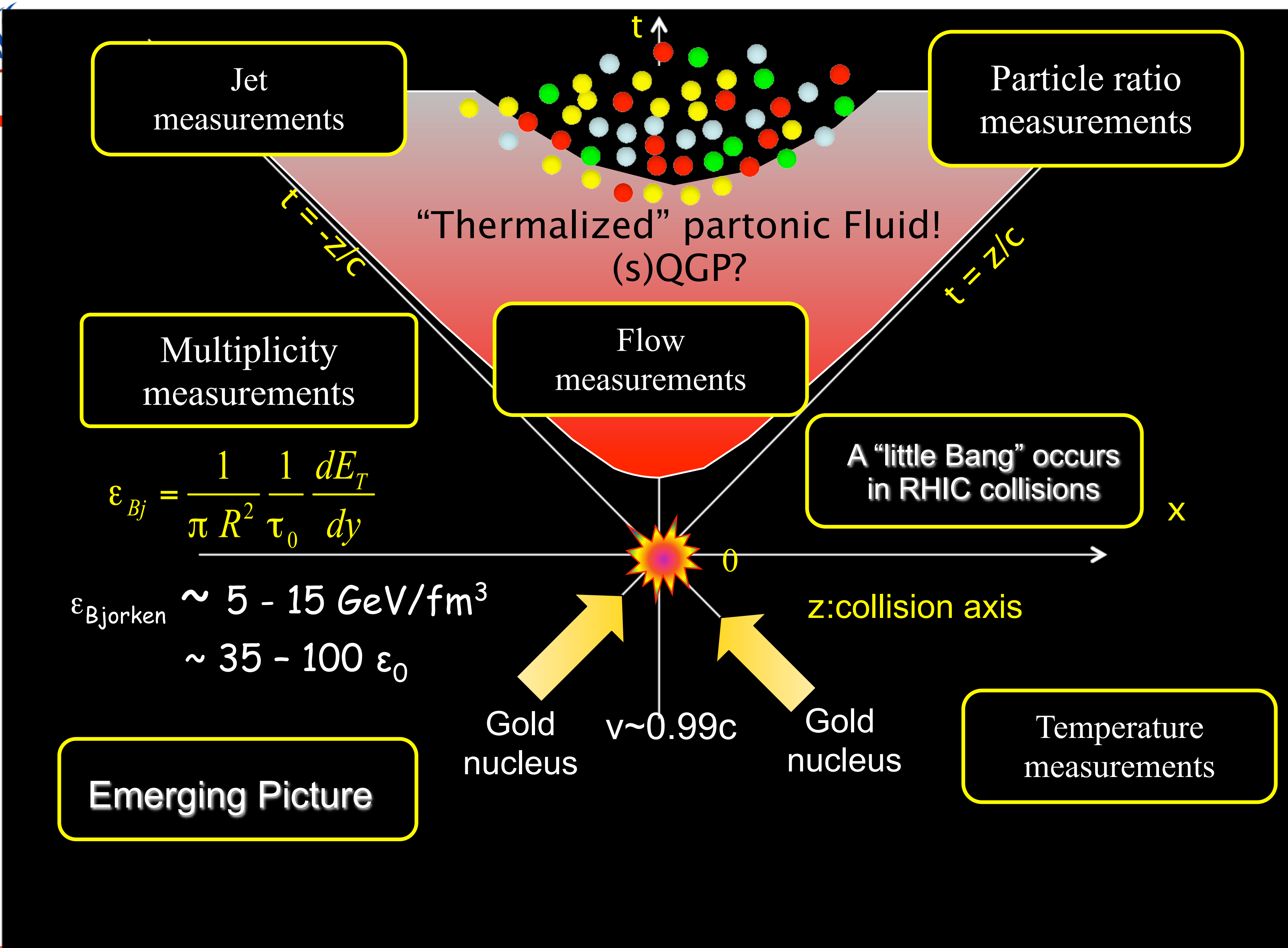
Run Summary

RHIC operating modes and total integrated luminosity delivered to 5 experiments

Run	species	total particle energy [GeV/nucleon]	calendar time in physics	total delivered luminosity	average store polarization
Run-1 CY2000 FY2000	Au^{79+}-Au^{79+}	27.9	3 shifts	$< 0.001\ \mu b^{-1}$	—
	Au^{79+}-Au^{79+}	65.2	5.3 weeks	$20\ \mu b^{-1}$	—
Run-2 CY2001/02 FY2001/02	Au^{79+}-Au^{79+}	100.0	15.9 weeks	$258\ \mu b^{-1}$	—
	Au^{79+}-Au^{79+}	9.8	2 shifts	$0.4\ \mu b^{-1}$	—
	polarized p-p	100.0	8.3 weeks total, no continous physics operation	$1.4\ pb^{-1}$	14%
Run-3 CY2002/03 FY2003	d-Au^{79+}	100.0	10.2 weeks	$73\ nb^{-1}$	—
	polarized p-p	100.0	9.0 weeks total, no continous physics operation	$5.5\ pb^{-1}$	34%
Run-4 CY2003/04 FY2004	Au^{79+}-Au^{79+}	100.0	12.0 weeks	$3.53\ nb^{-1}$	—
	Au^{79+}-Au^{79+}	31.2	9 days	$67\ \mu b^{-1}$	—
	polarized p-p	100.0	6.1 weeks total, no continous physics operation	$7.1\ pb^{-1}$	46%
Run-5 CY2004/05 FY2005	Cu^{29+}-Cu^{29+}	100.0	7.8 weeks	$42.1\ nb^{-1}$	—
	Cu^{29+}-Cu^{29+}	31.2	12 days	$1.5\ nb^{-1}$	—
	Cu^{29+}-Cu^{29+}	11.2	5 shifts	$0.02\ nb^{-1}$	—
	polarized p-p	100.0	9.4 weeks	$29.5\ pb^{-1}$	47%
	polarized p-p	204.9	2 stores	$0.1\ pb^{-1}$	30%
Run-6 CY2006 FY2006	polarized p-p	100.0	13.1 weeks	$88.6\ pb^{-1}$	55%
	polarized p-p	31.2	12 days	$1.05\ pb^{-1}$	50%
Run-7 CY2006/07 FY2006	Au^{79+}-Au^{79+}	100.0	12.8 weeks	$7.25\ nb^{-1}$	—
	Au^{79+}-Au^{79+}	4.6	3 shifts total, no continous physics operation	test only	—
Run-8 CY2007/08 FY2008	d-Au^{79+}	100.0	9.0 weeks	$437\ nb^{-1}$	—
	polarized p-p	100.0	3.4 weeks	$38.4\ pb^{-1}$	44%
	Au^{79+}-Au^{79+}	4.6	3 shifts	—	—
Run-9 CY2008/09 FY2009	pol. p-p	250.0	4.1 weeks	$110.4\ pb^{-1}$	34%
	polarized p-p	100.0	9.9 weeks	$114.0\ pb^{-1}$	56%
	polarized pp2pp	100.0	3.5 days	$0.6\ nb^{-1}$	63%
Run-10 CY2009/10 FY2010	Au^{79+}-Au^{79+}	100.0	10.9 weeks	$10.0\ nb^{-1}$	—
	Au^{79+}-Au^{79+}	31.2	2.9 weeks	$0.56\ nb^{-1}$	—
	Au^{79+}-Au^{79+}	19.5			
	Au^{79+}-Au^{79+}	3.85			
	Au^{79+}-Au^{79+}	5.75			

Run-11: Au+Au, p+p, Run-12 starts in January next year.

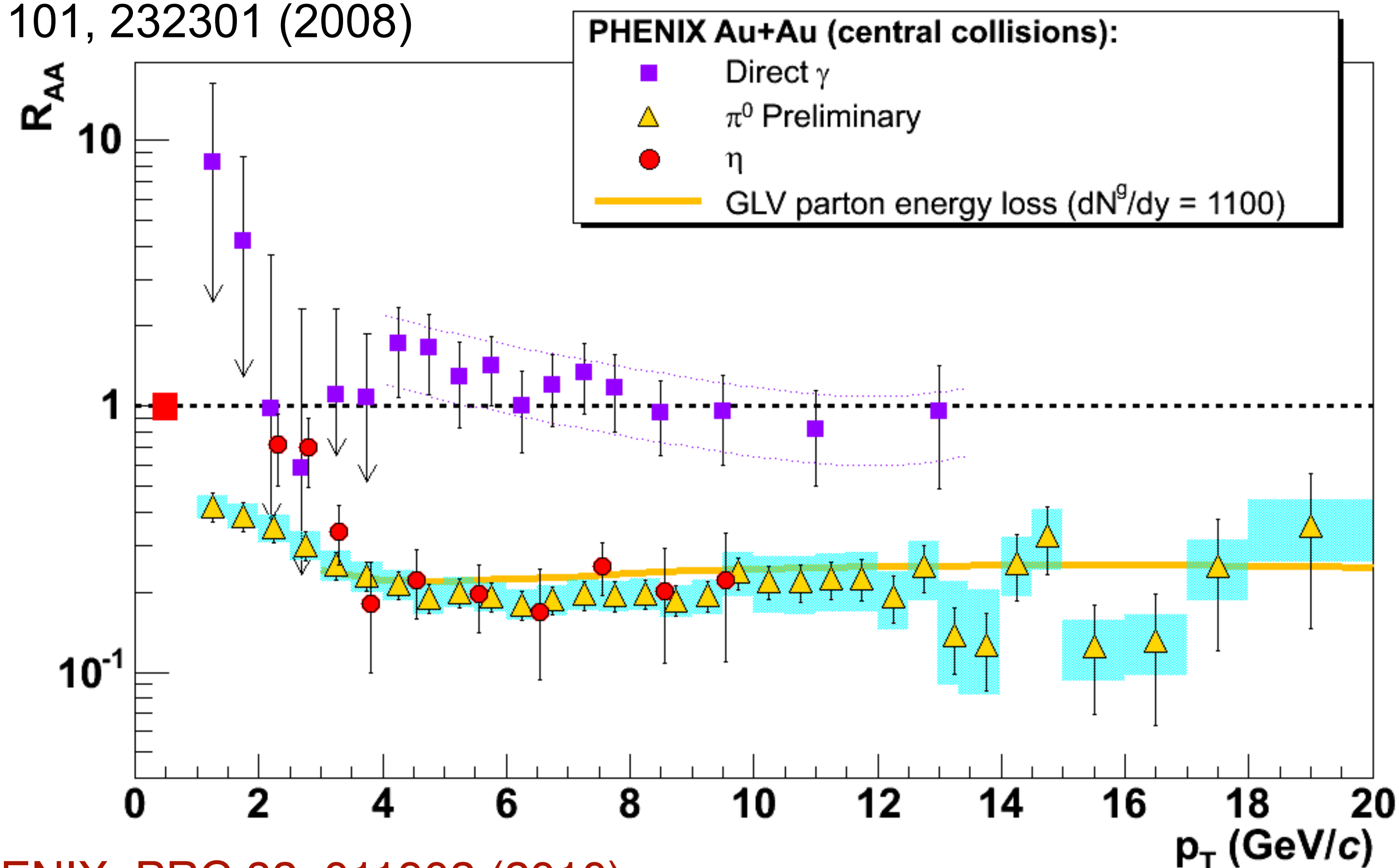

t
x
Emerging Picture



Jet measurements
Particle ratio measurements
t
"Thermalized" partonic Fluid!
(s)QGP?
t = -z/c
t = z/c
Multiplicity measurements
Flow measurements
A "little Bang" occurs in RHIC collisions
x
$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$
0
$\varepsilon_{Bjorken}$ ~ 5 - 15 GeV/fm^3
~ 35 – 100 ε_0
z:collision axis
Gold nucleus
v~0.99c
Gold nucleus
Temperature measurements
Emerging Picture

The matter is so opaque that even a 20 GeV π^0 is stopped.

PRL 101, 232301 (2008)



PHENIX: PRC 82, 011902 (2010)

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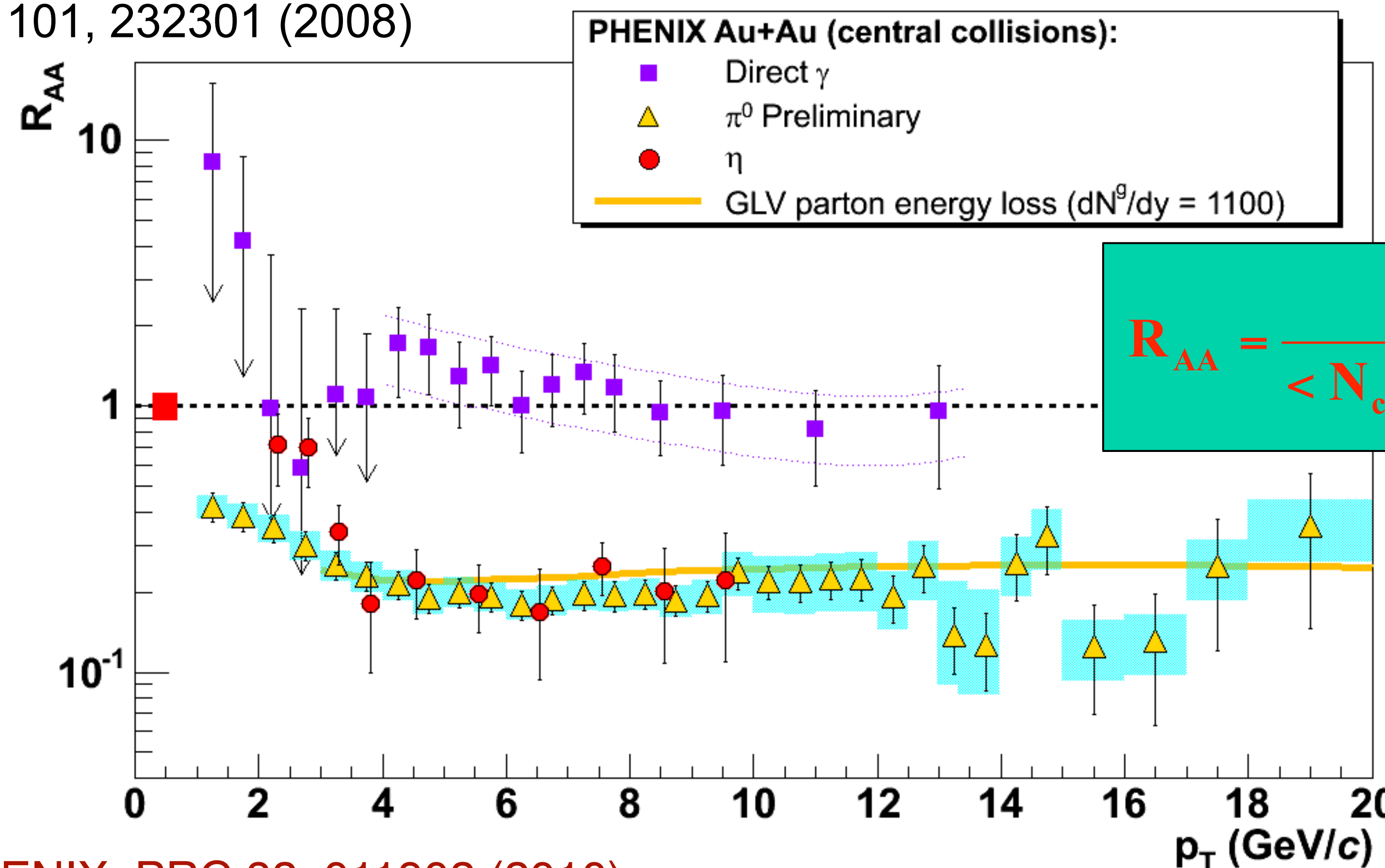

$$R_{AA} = \frac{dN_{AA}}{<N_{coll}> \times dN_{pp}}$$

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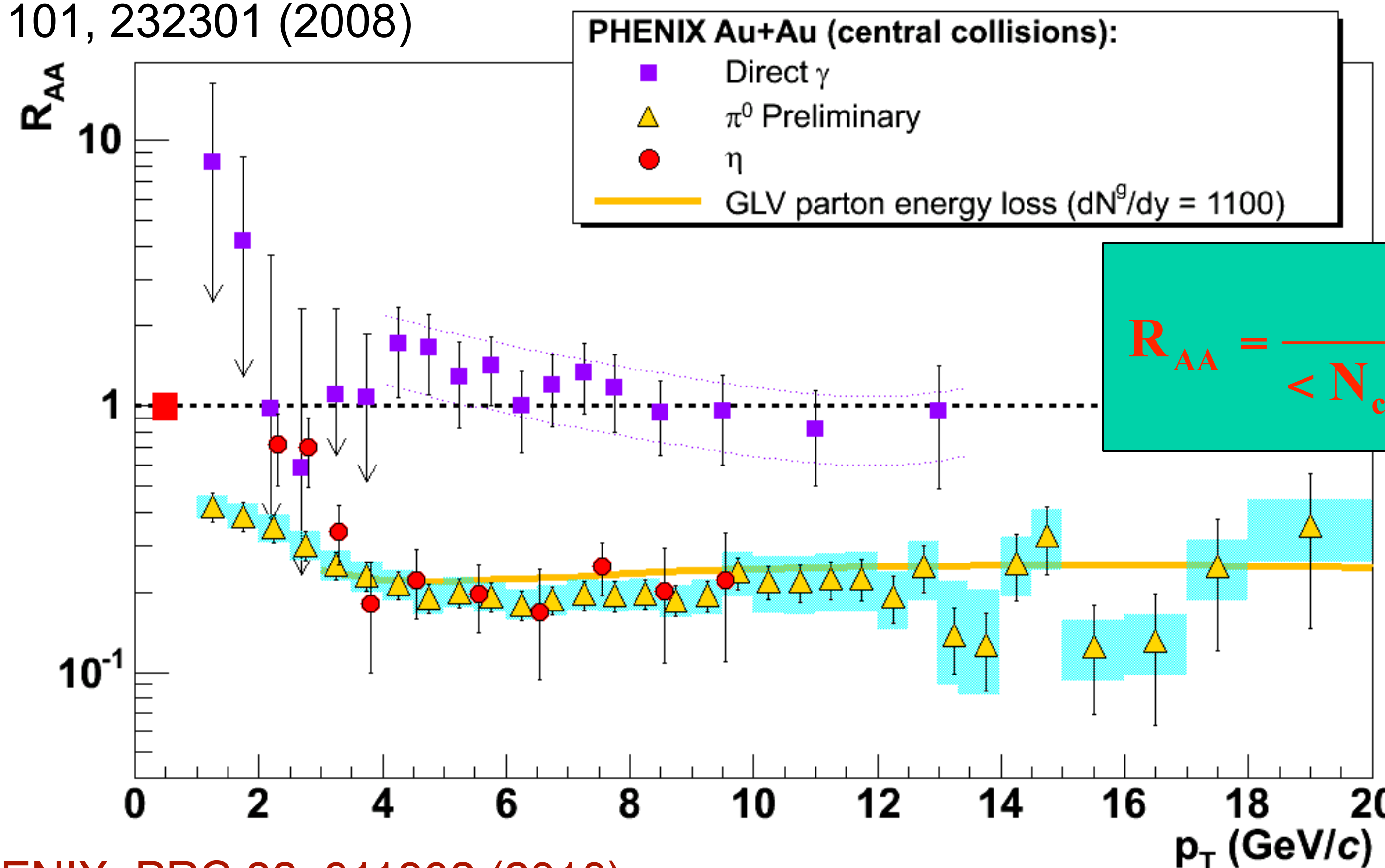


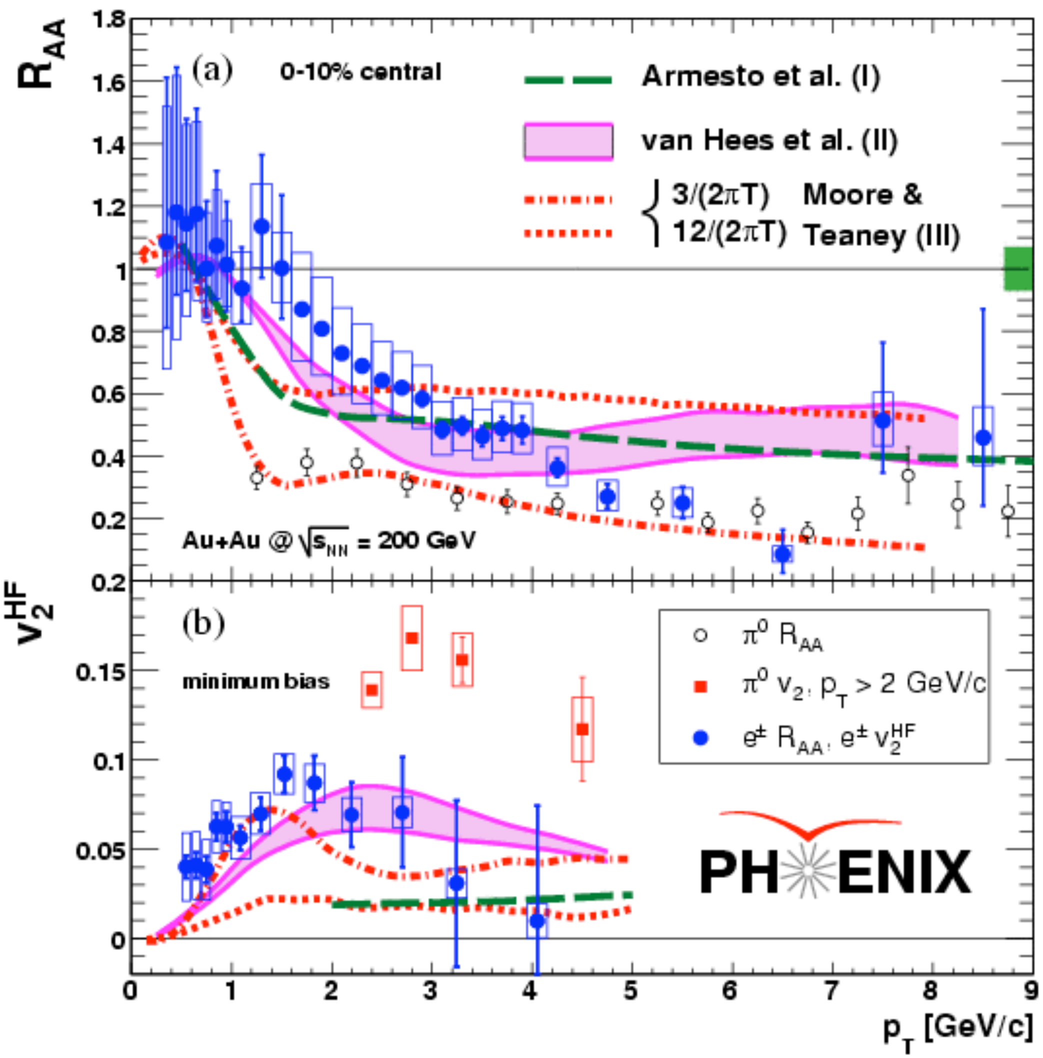
$$R_{AA} = \frac{dN_{AA}}{\langle N_{coll} \rangle \times dN_{pp}}$$

PHENIX: PRC 82, 011902 (2010)

- Suppression is very strong (R_{AA}=0.2!) and flat up to 20 GeV/c

The matter is so dense that even heavy quarks are stopped

PHENIX: PRL 98, 172301 (2007)



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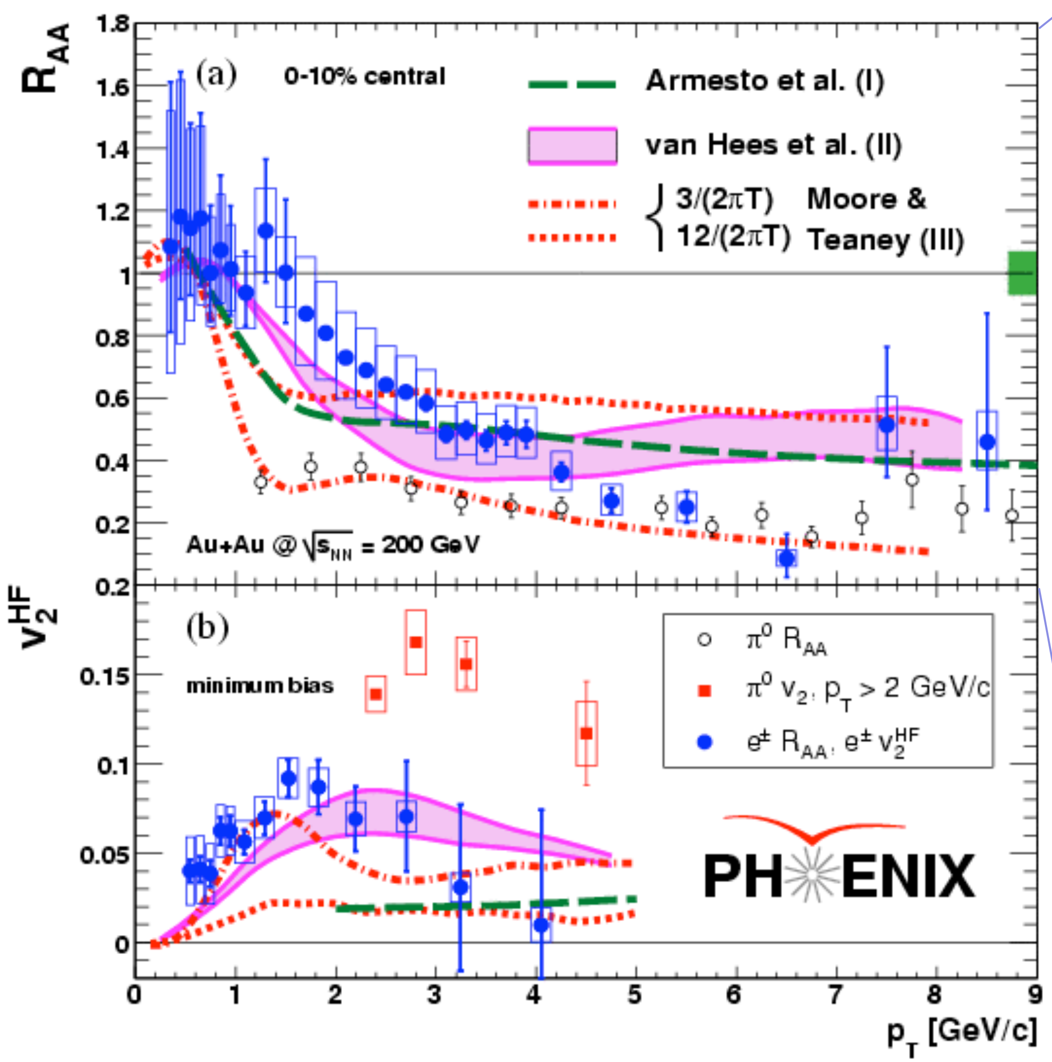
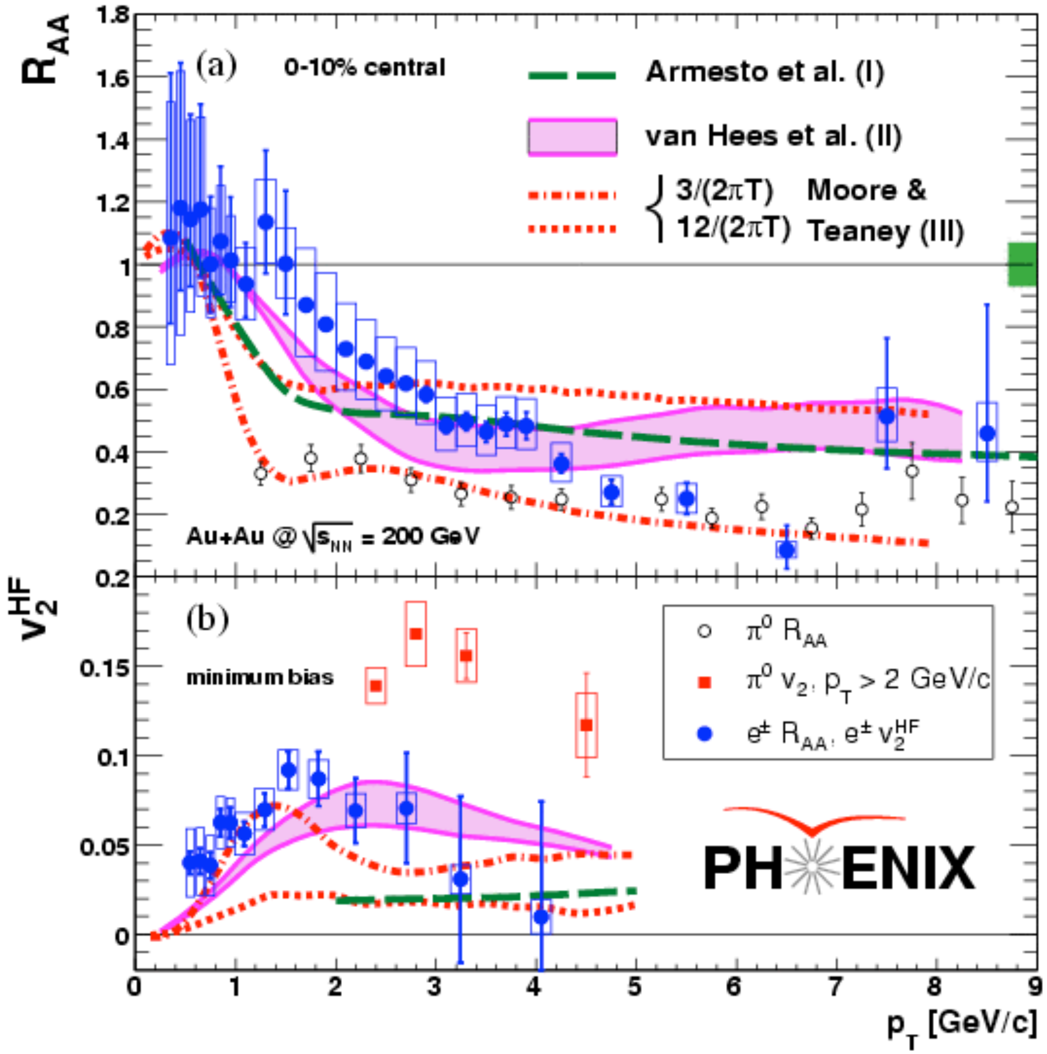
PHENIX: PRL 98, 172301 (2007)



- Even heavy quark (charm) suffers substantial energy loss in the matter
- The data provide a strong constraint on the energy loss models.
- The data suggest large c-quark-medium cross section; evidence for strongly coupled QGP.

The matter is so strongly coupled that even heavy quarks flow

PHENIX: PRL 98, 172301 (2007)



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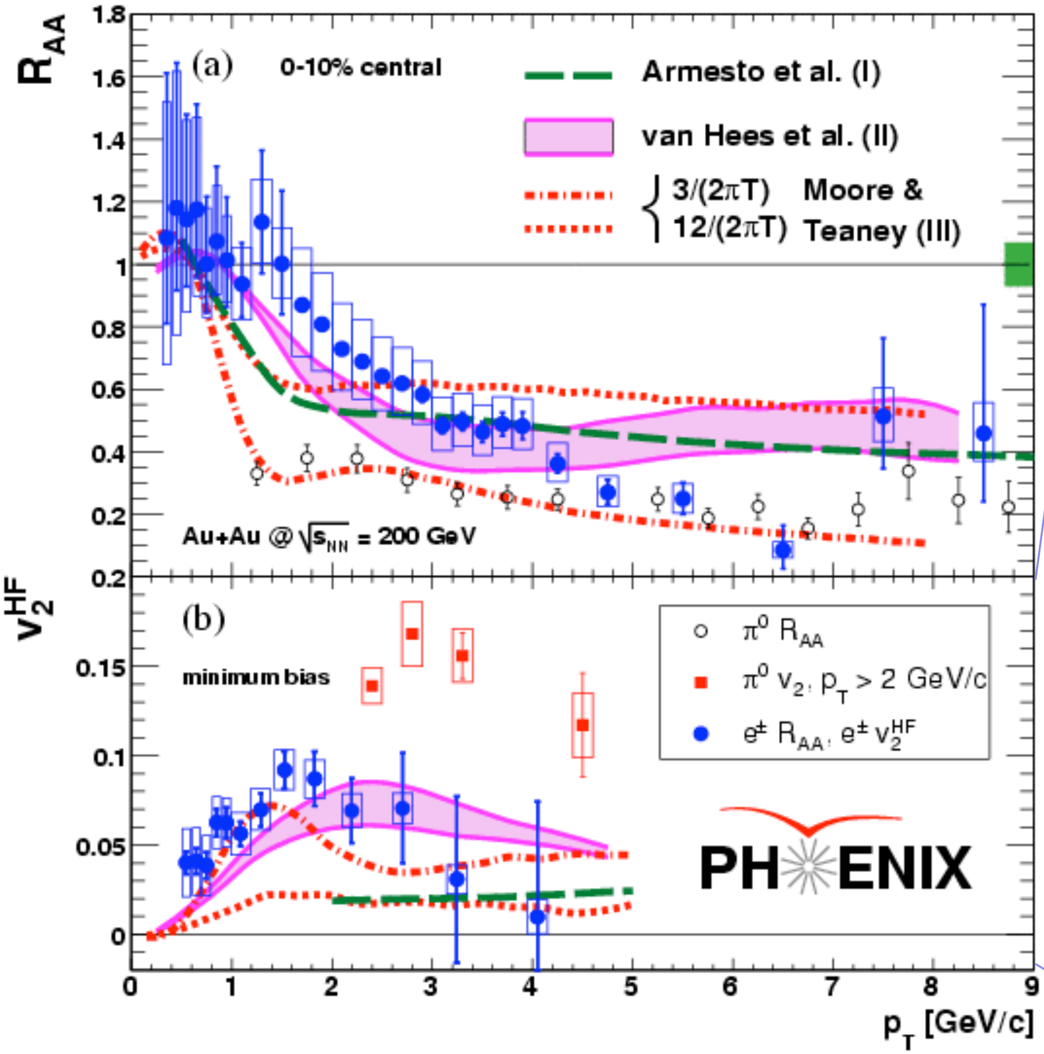
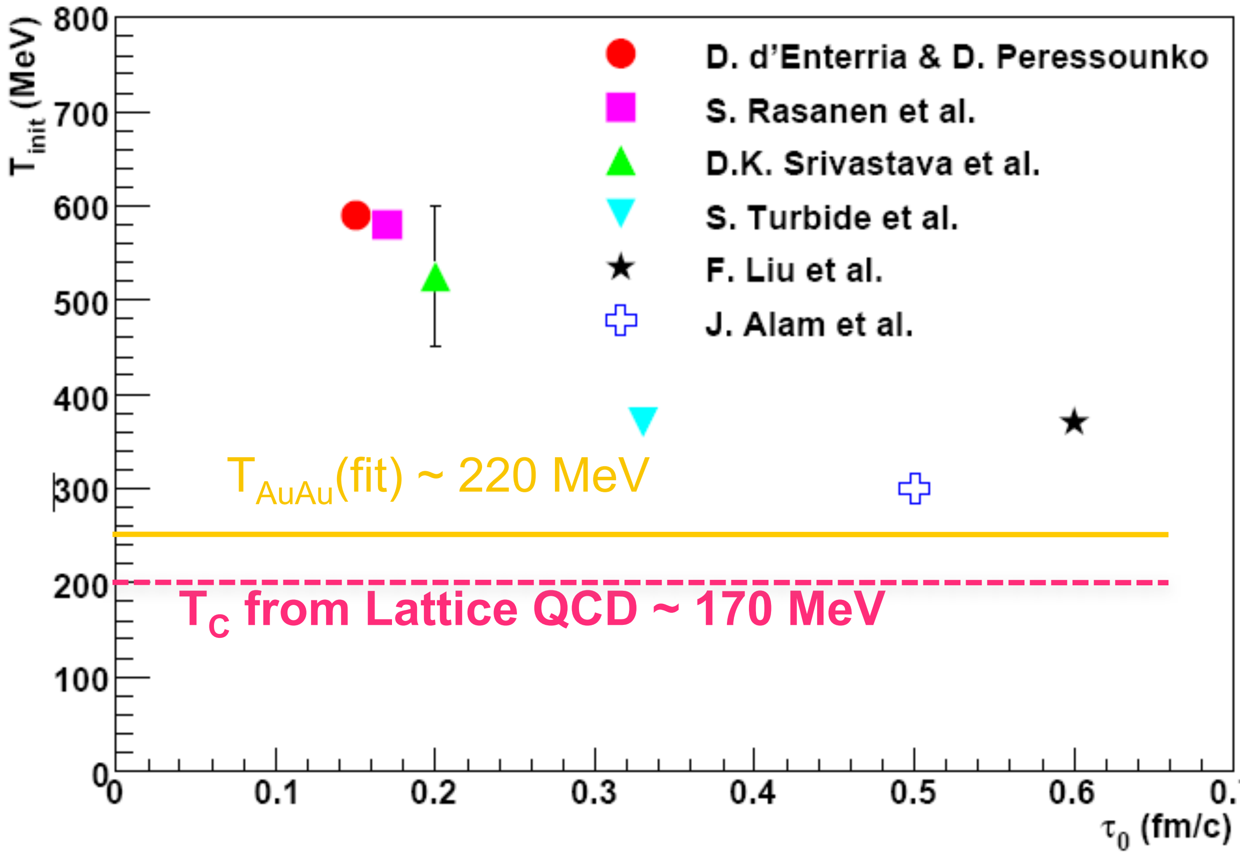
PHENIX: PRL 98, 172301 (2007)



- Charm flows, but not as strong as light mesons.
- Drop of the flow strength at high p_T. Is this due to b-quark contribution?
- The data favors the model that charm quark itself flows at low p_T.

The matter is so hot that it emits thermal photon copiously
Initial temperature

PHENIX, PRC 81, 034911 (2010)



From data: $T_{ini} > T_{AuAu} \sim 220$ **MeV**

From models: $T_{ini} = 300$ **to 600 MeV for** $t_0 = 0.15$ **to 0.6 fm/c**

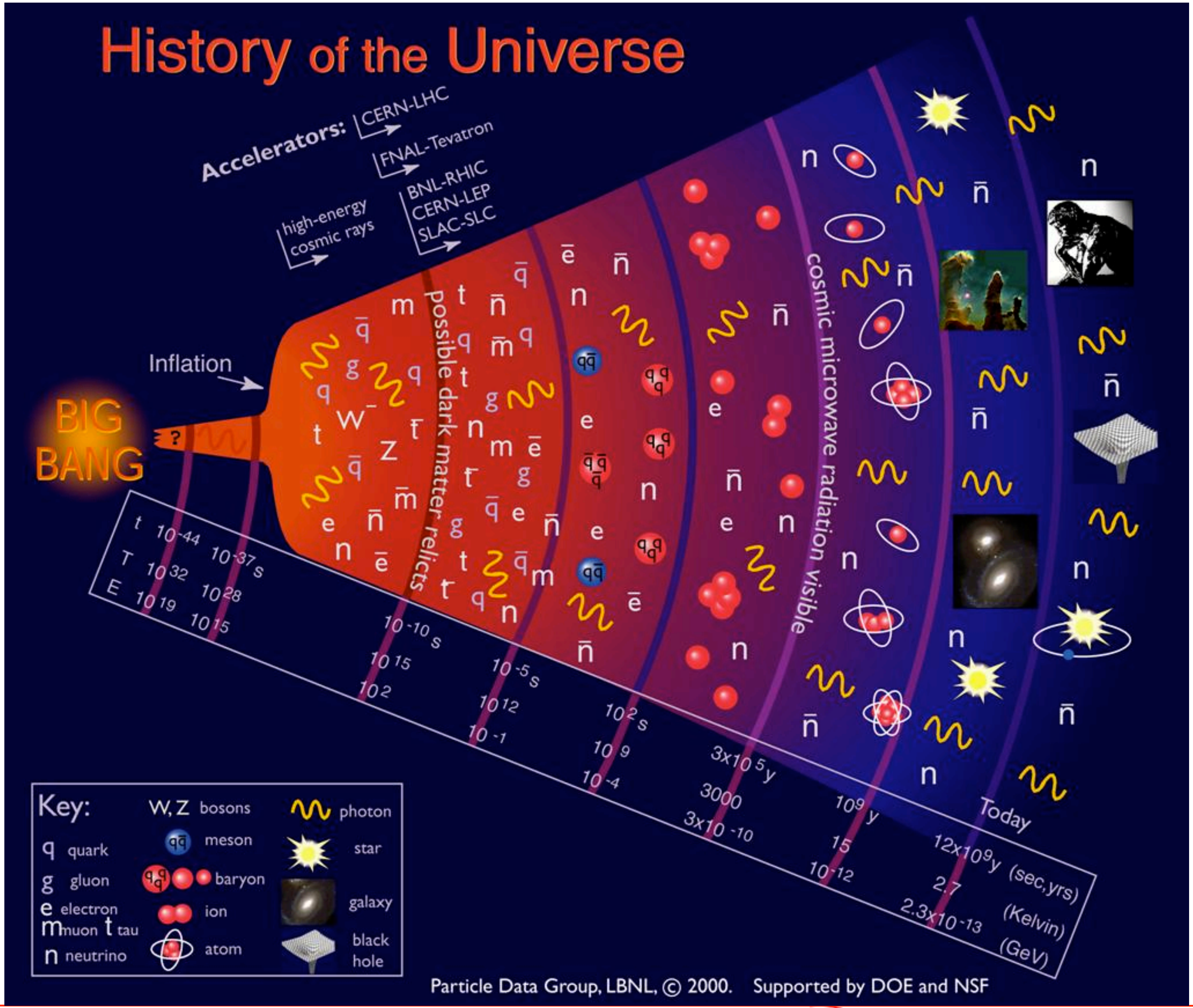
Lattice QCD predicts a phase transition to quark gluon plasma at $T_c \sim 170$ **MeV**

Phys. Rev. Lett. 104, 132301 (2010)

"Enhanced production of direct photons in Au+Au collisions at sqrt (s_NN)=200 GeV and implications for the initial temperature"

TEMPERATURE MEASUREMENT

Temperature is an Important Physical Variable in the Standard Model of Cosmology



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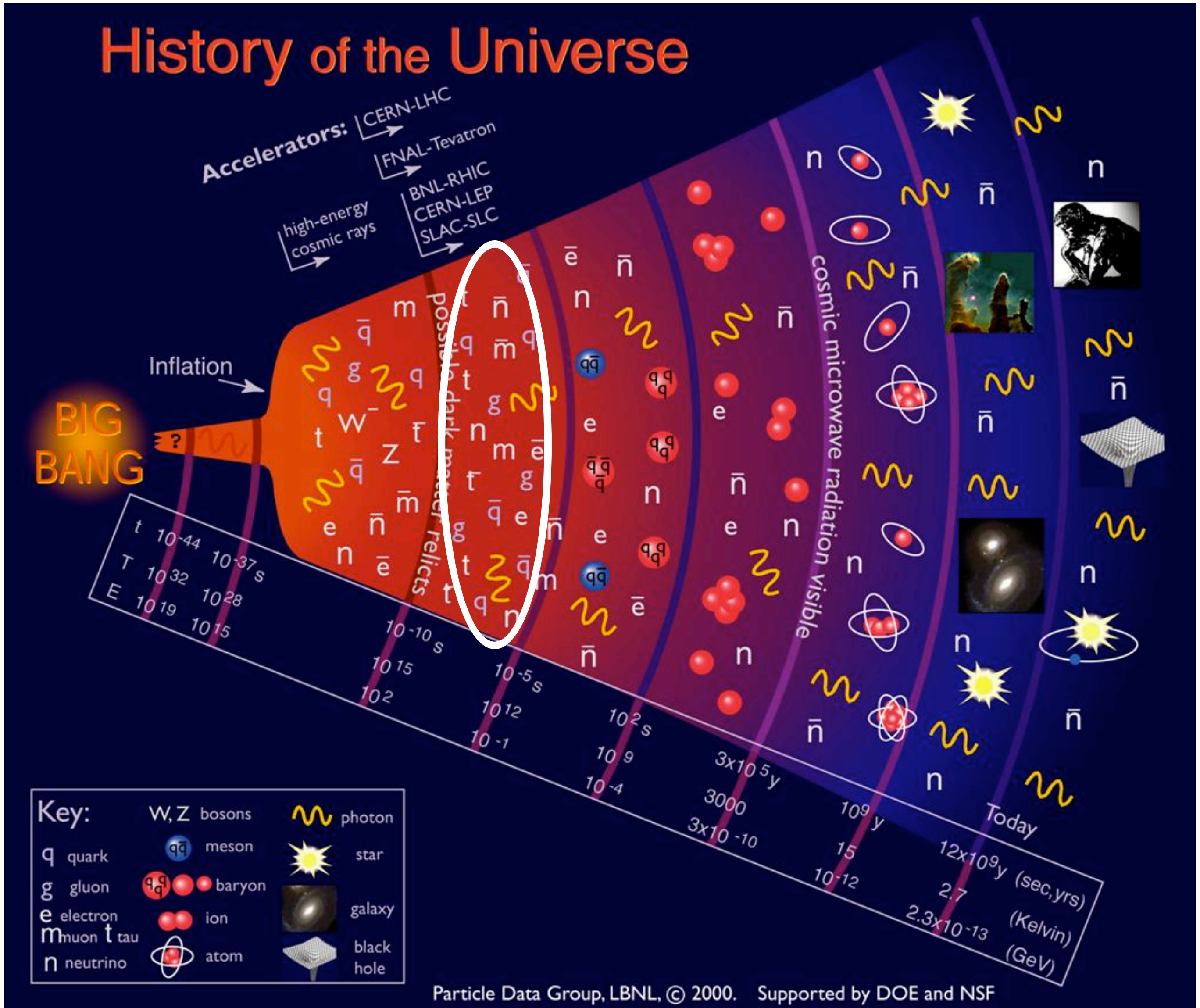

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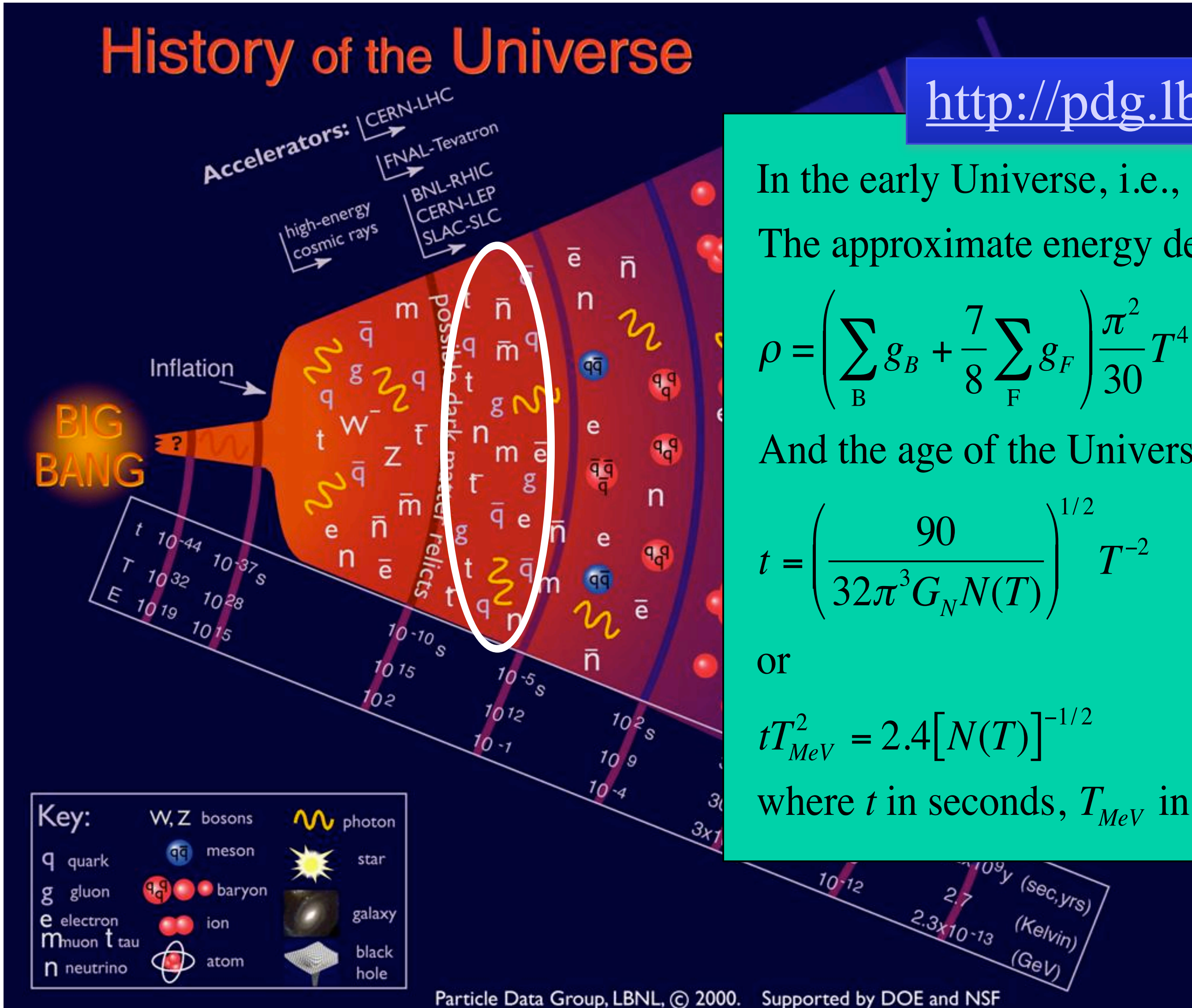


http://pdg.lbl.gov

In the early Universe, i.e., at very high T :

The approximate energy density is given as

$$\rho = \left(\sum_{B} g_B + \frac{7}{8} \sum_{F} g_F \right) \frac{\pi^2}{30} T^4 \equiv \frac{\pi^2}{30} N(T) T^4$$

And the age of the Universe

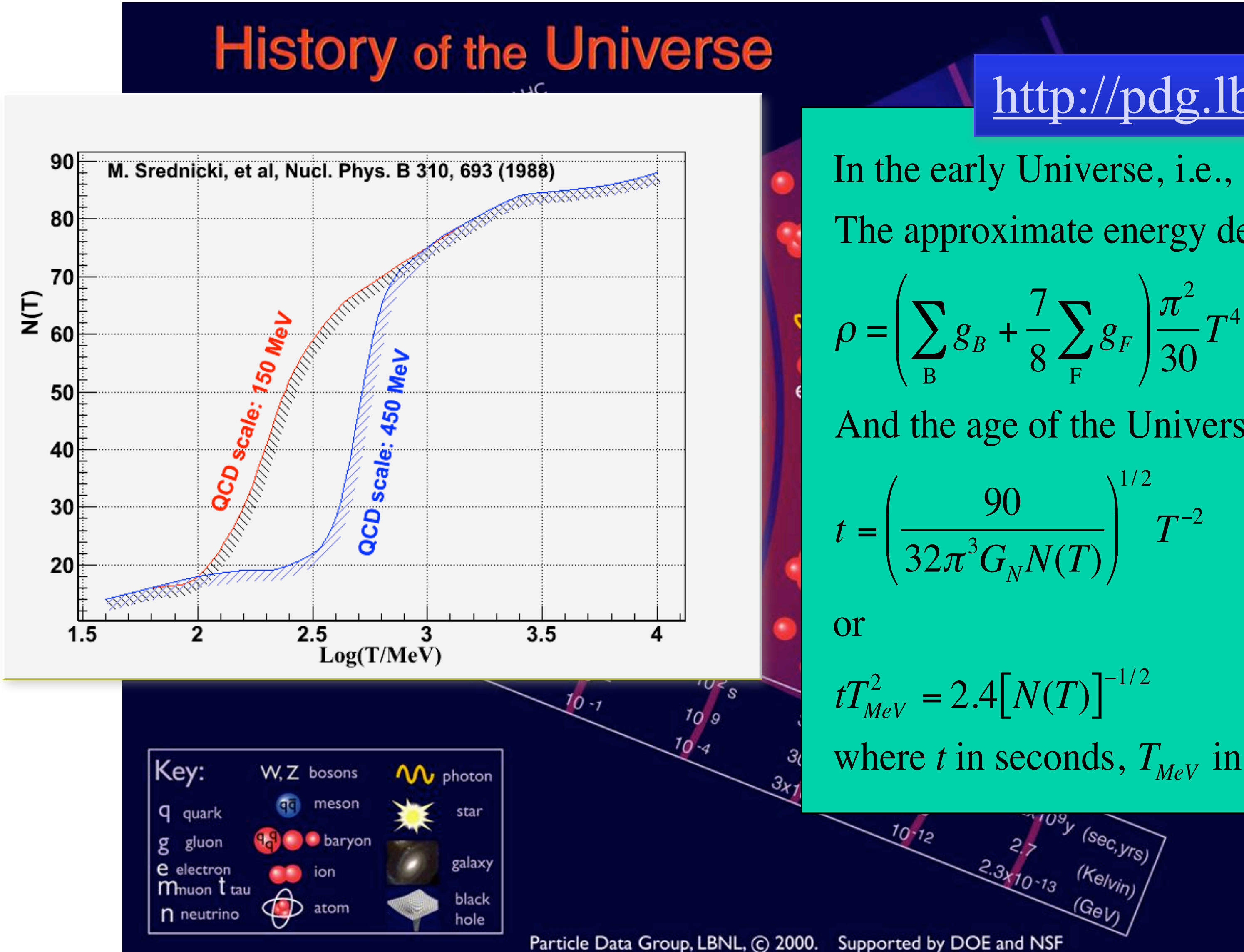
$$t = \left(\frac{90}{32\pi^3 G_N N(T)} \right)^{1/2} T^{-2}$$

or

$$t T_{MeV}^2 = 2.4 \left[N(T) \right]^{-1/2}$$

where t in seconds, T_{MeV} in MeV.

Temperature is an Important Physical Variable in the Standard Model of Cosmology



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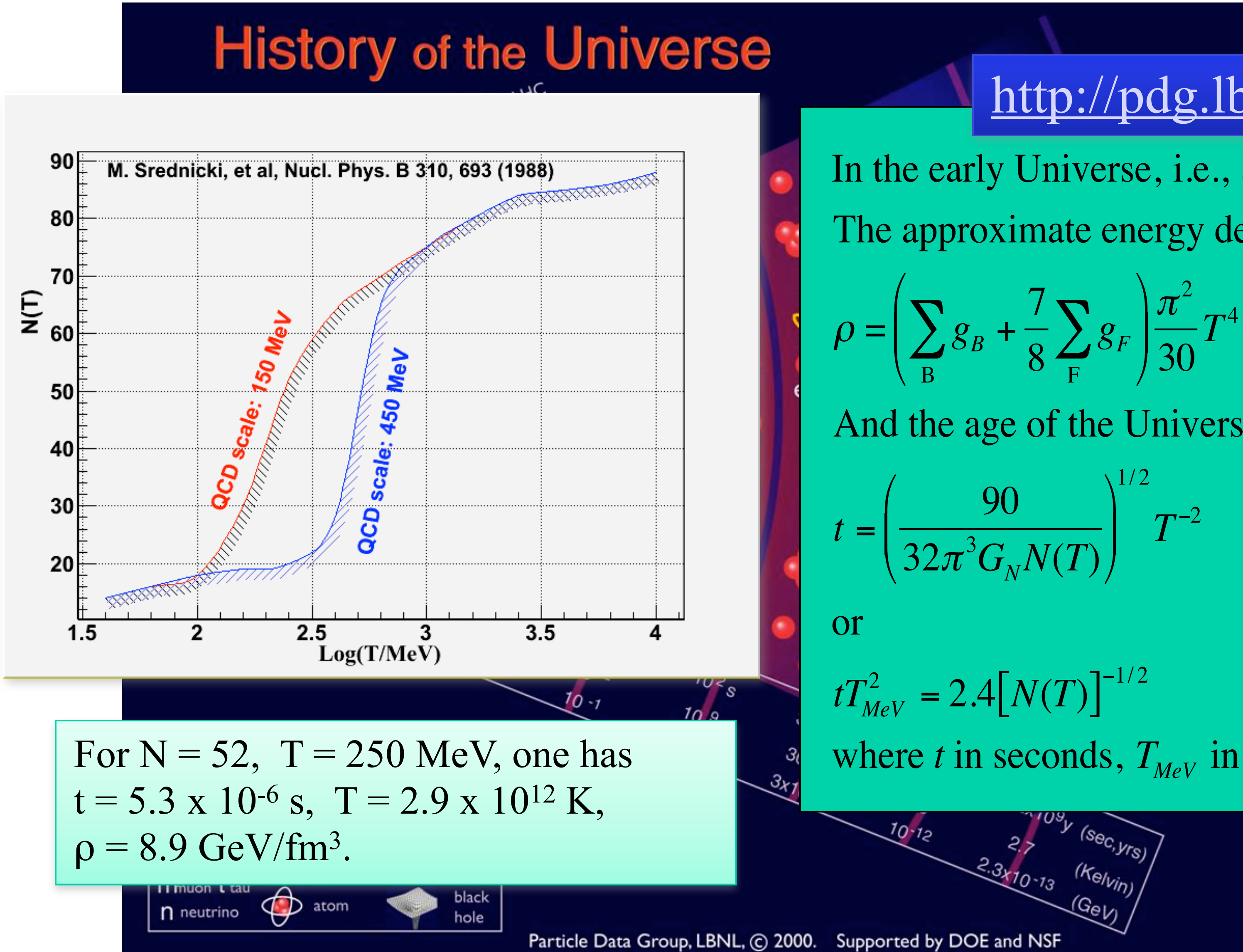

For N = 52, T = 250 MeV, one has
t = 5.3 x 10^{-6} s, T = 2.9 x 10^{12} K,
ρ = 8.9 GeV/fm³.

http://pdg.lbl.gov

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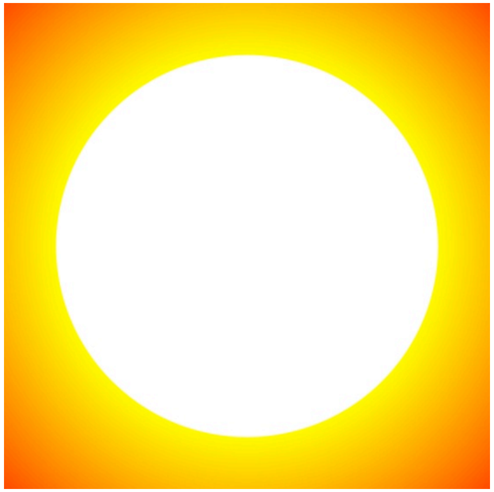
or

$$t T_{MeV}^2 = 2.4 \left[N(T) \right]^{-1/2}$$

where t in seconds, T_{MeV} in MeV.

Remote Temperature Sensing

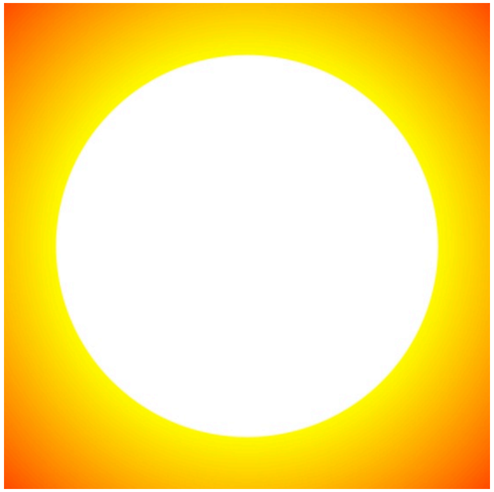
Red Hot



White Hot

Remote Temperature Sensing

Red Hot



White Hot

- **Hot objects produce thermal spectrum of EM radiation.**

Remote Temperature Sensing

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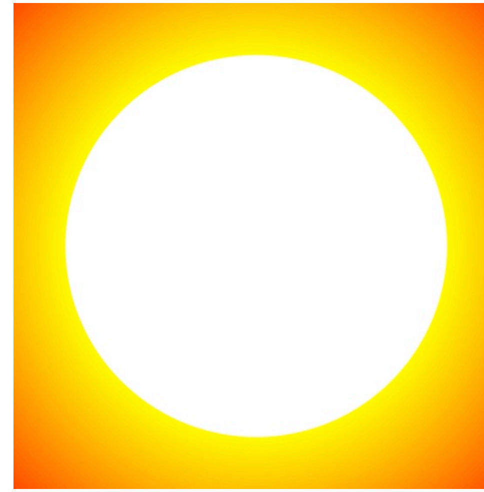
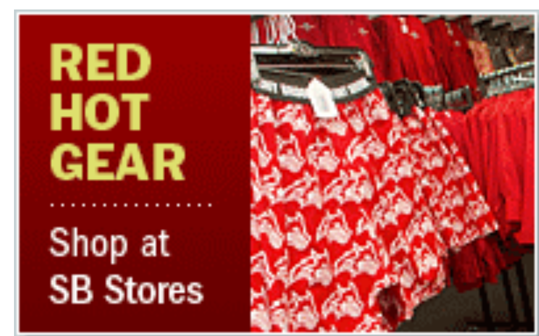


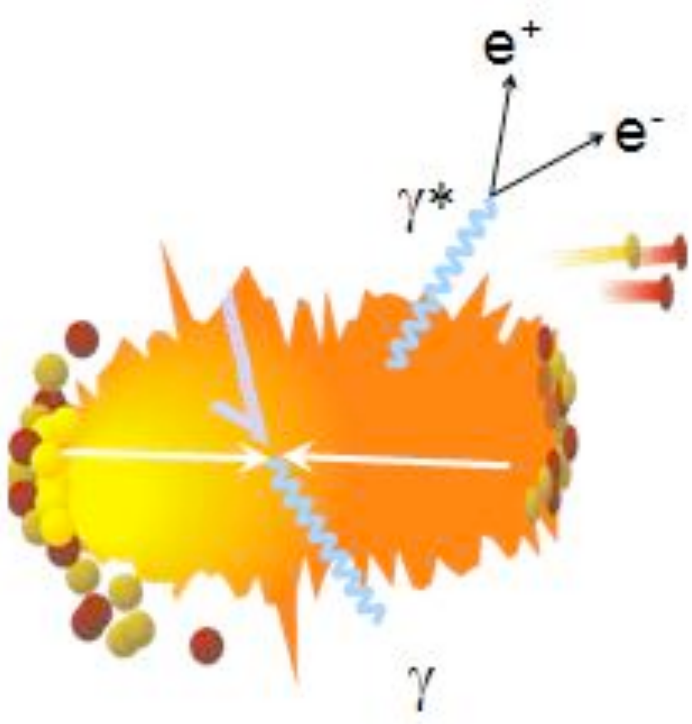
White Hot

- **Hot objects produce thermal spectrum of EM radiation.**
- **Red clothes are NOT red hot, reflected light is not thermal.**



Not Red Hot!

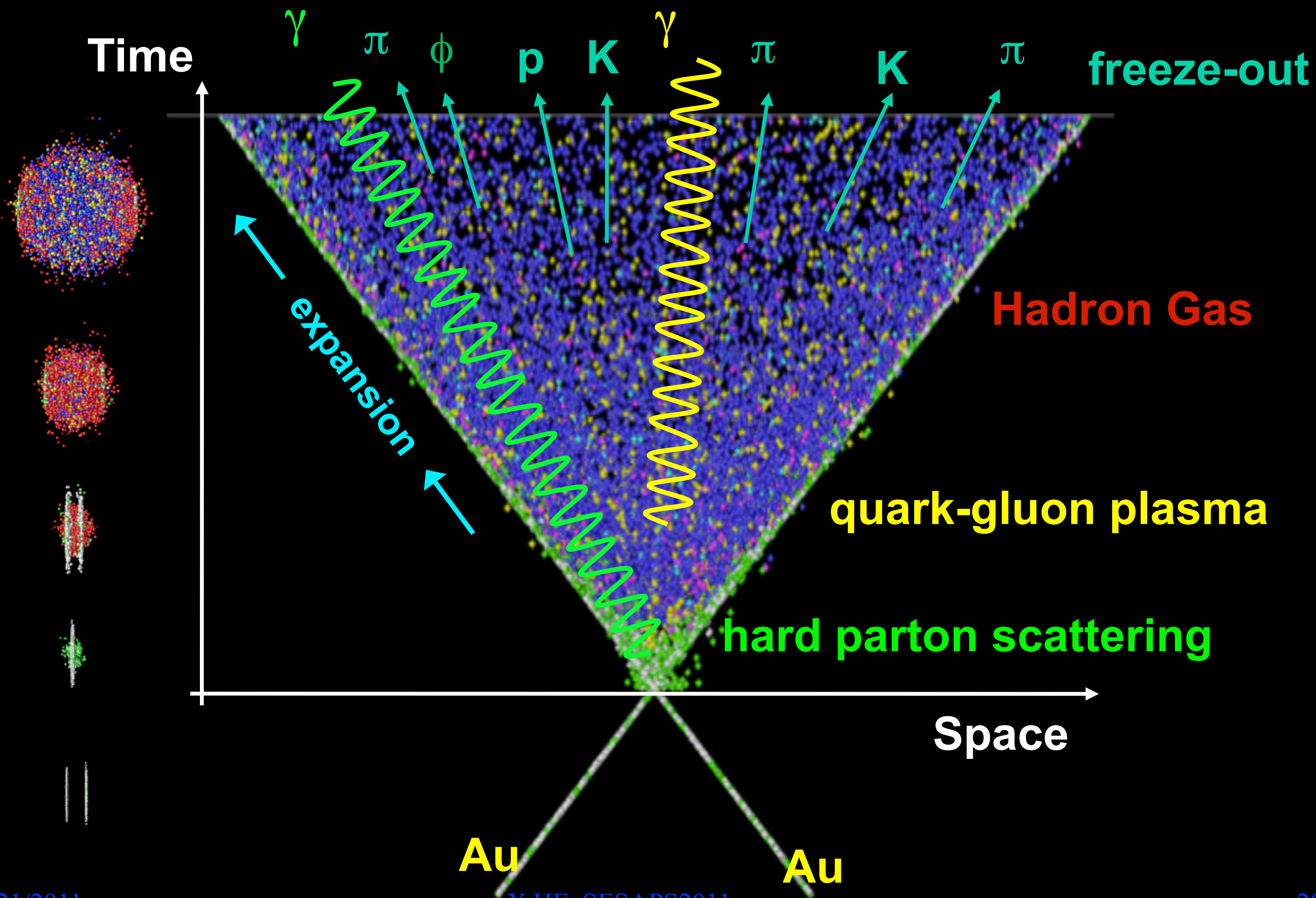
Thermal photon from hot matter



Hot matter emits thermal radiation

Temperature can be measured from the emission spectrum

Photon Probe of Nuclear Collisions



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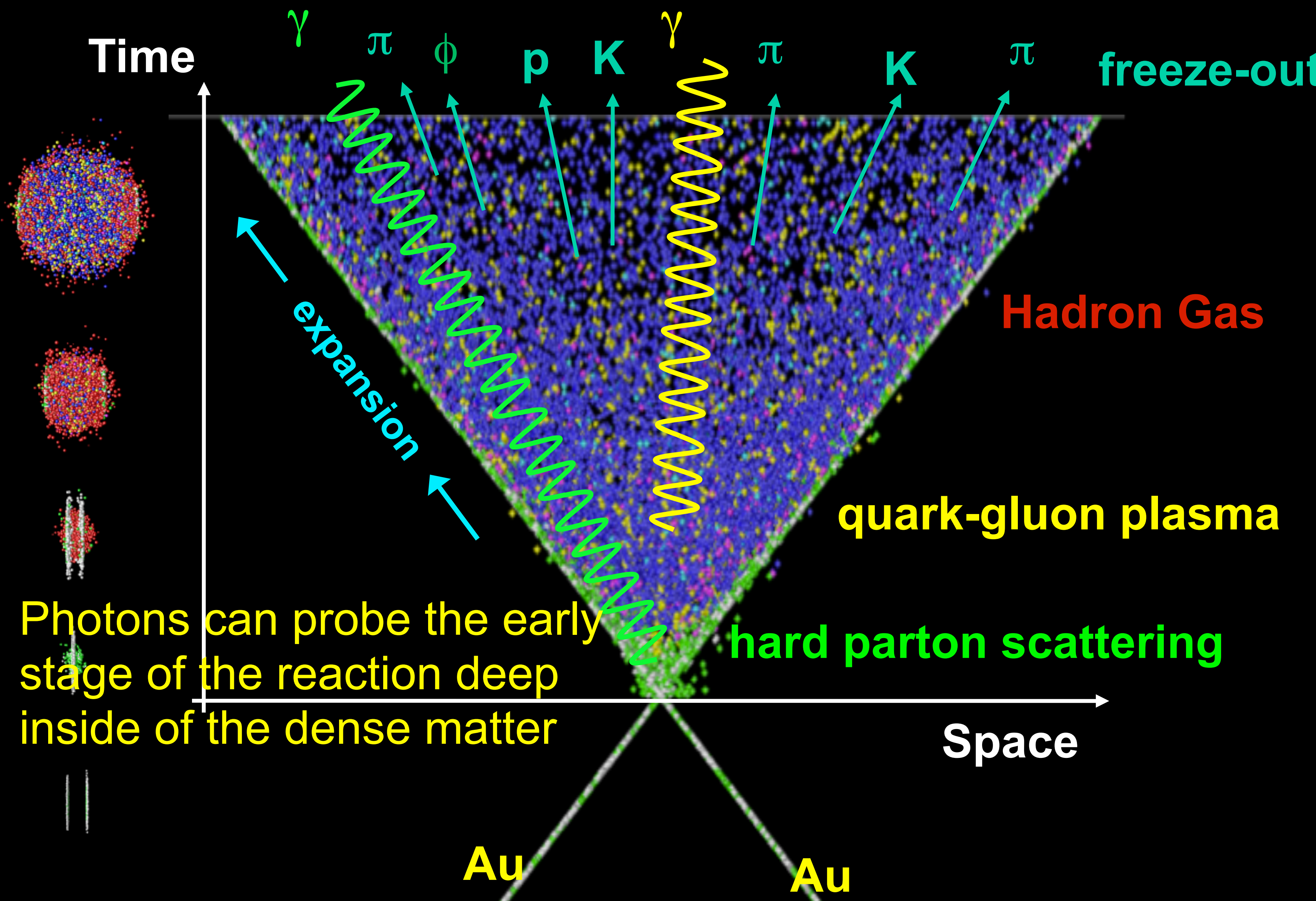
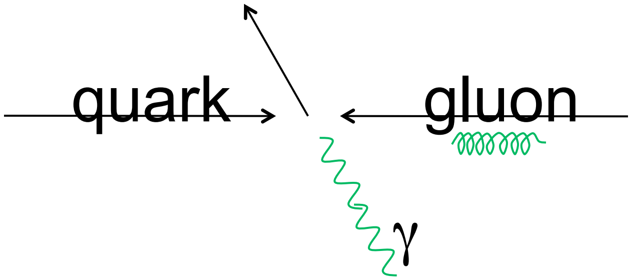


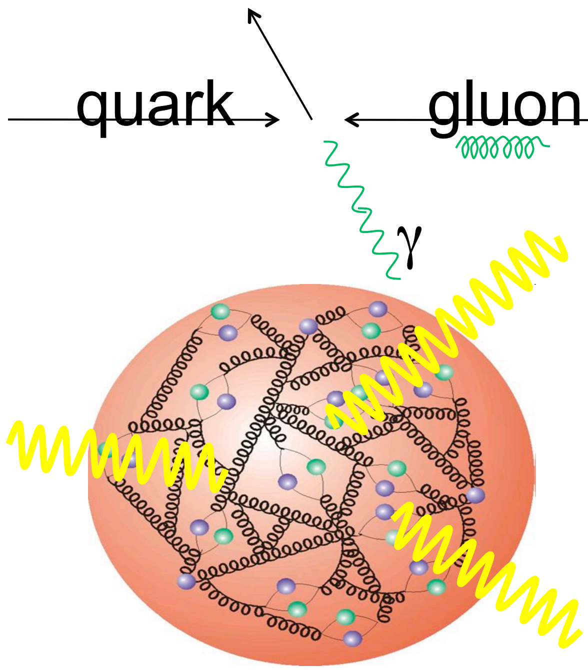
Photons can probe the early stage of the reaction deep inside of the dense matter

Many sources of photons



pQCD direct photons from initial *hard scattering* of quarks and gluons

Many sources of photons



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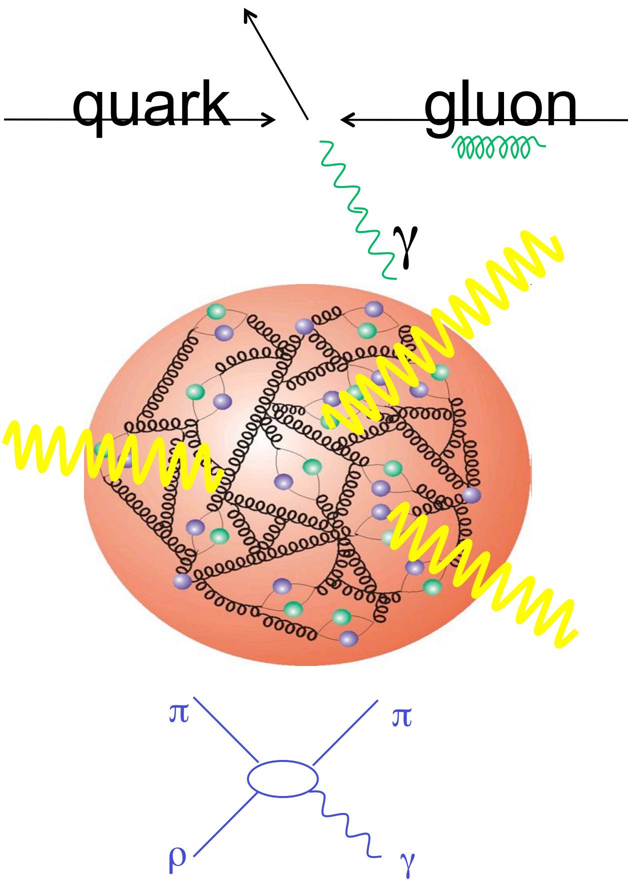

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Thermal photons from *hadron gas* after hadronization

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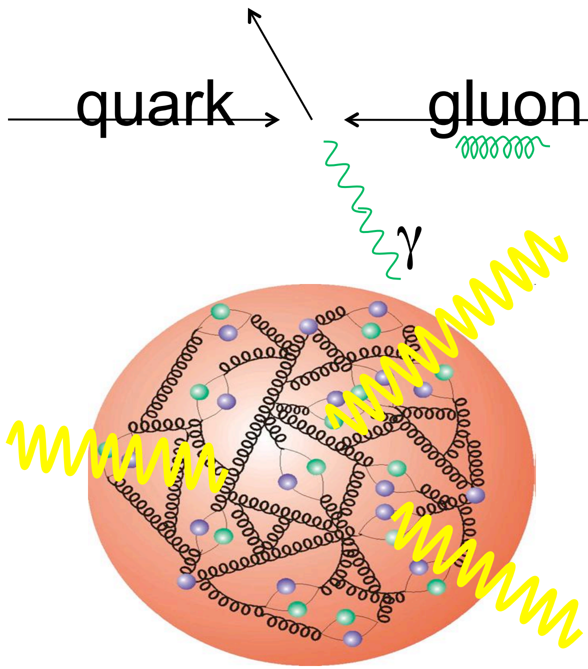

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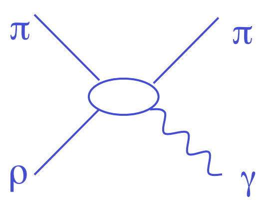
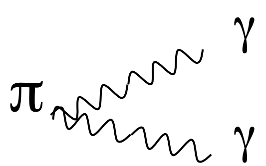


Thermal photons from *hadron gas* after hadronization



Decay Photons from hadrons (π^0, η, etc)

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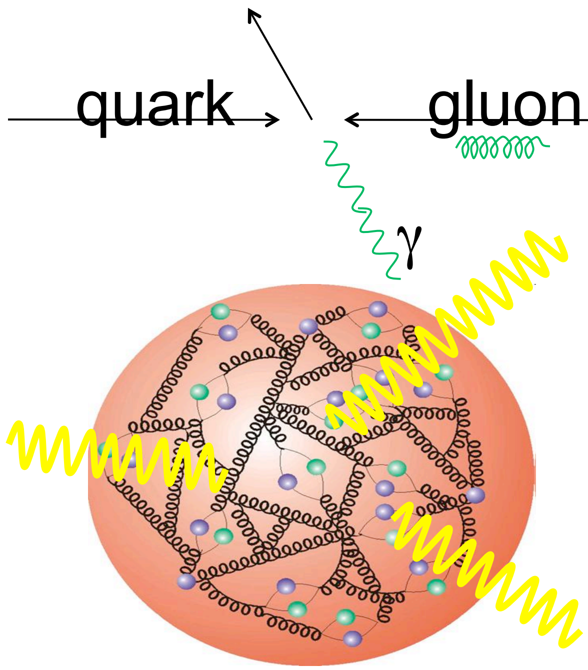

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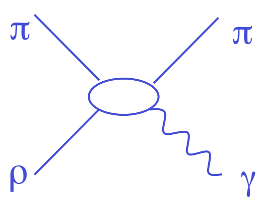
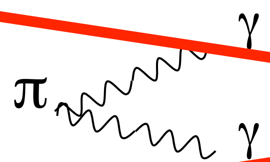


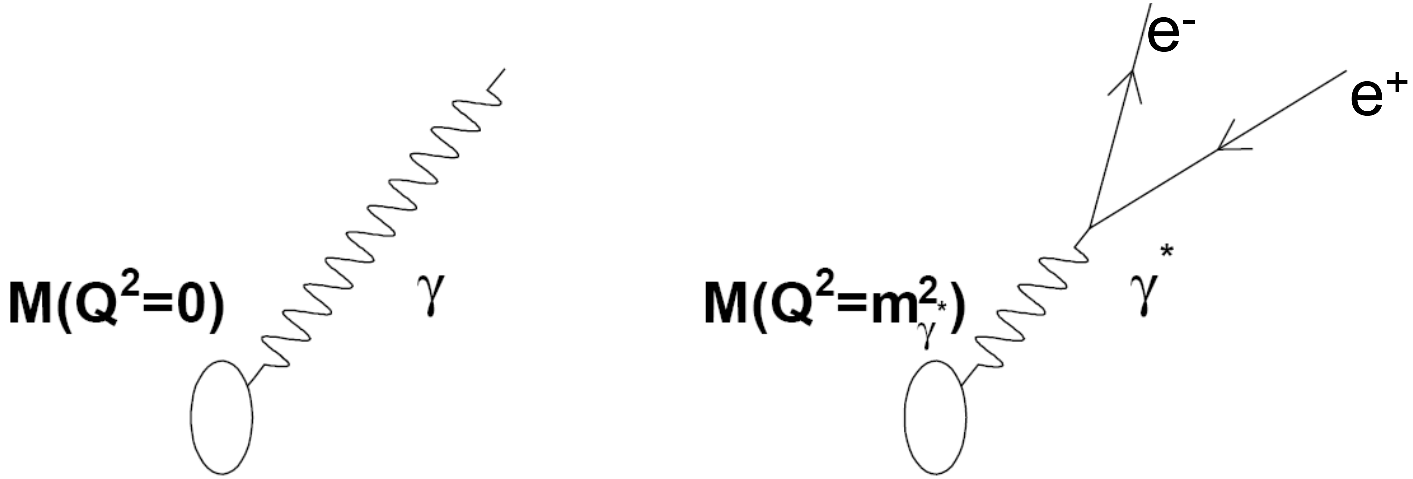
Thermal photons from *hadron gas* after hadronization

background



Decay Photons from hadrons (π^0, η, etc)

Virtual Photons Come to Rescue



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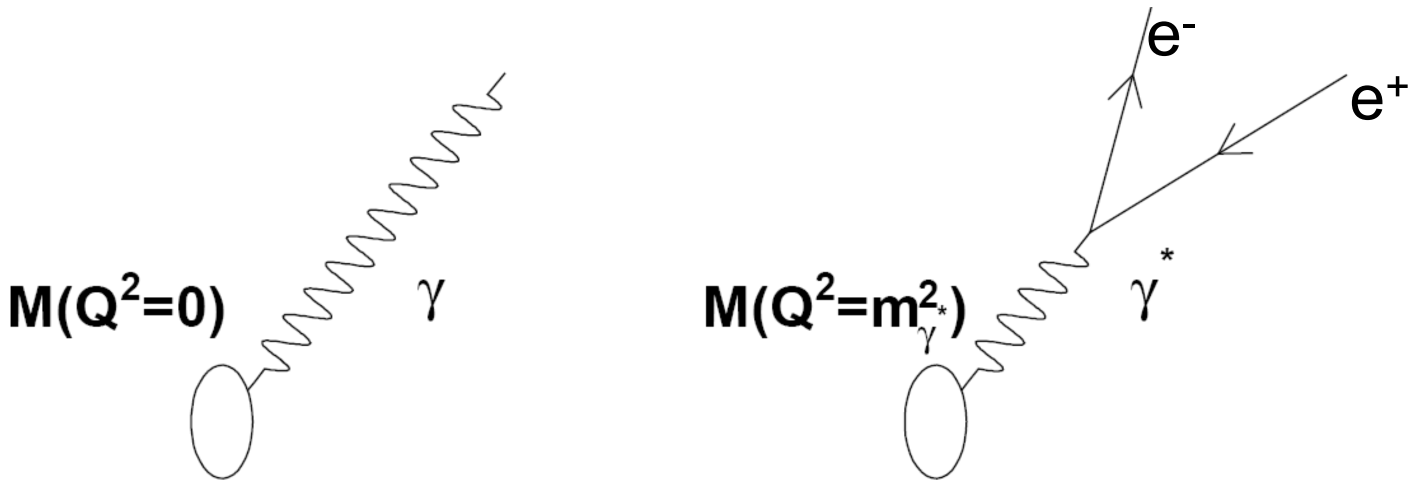
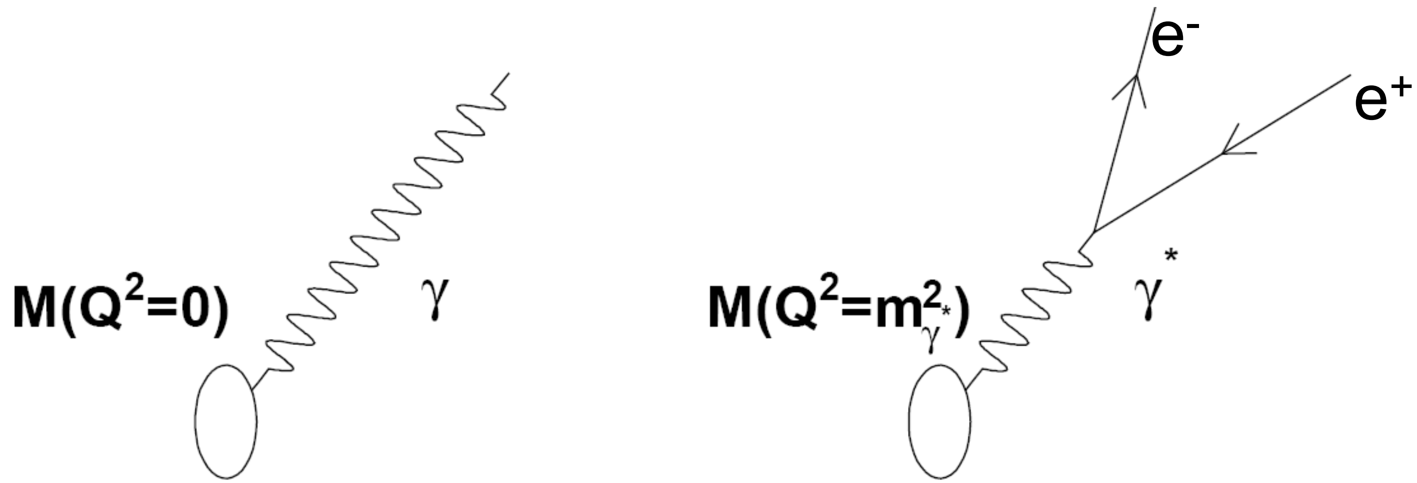


- Source of real photon should also be able to emit virtual photon

Virtual Photons Come to Rescue



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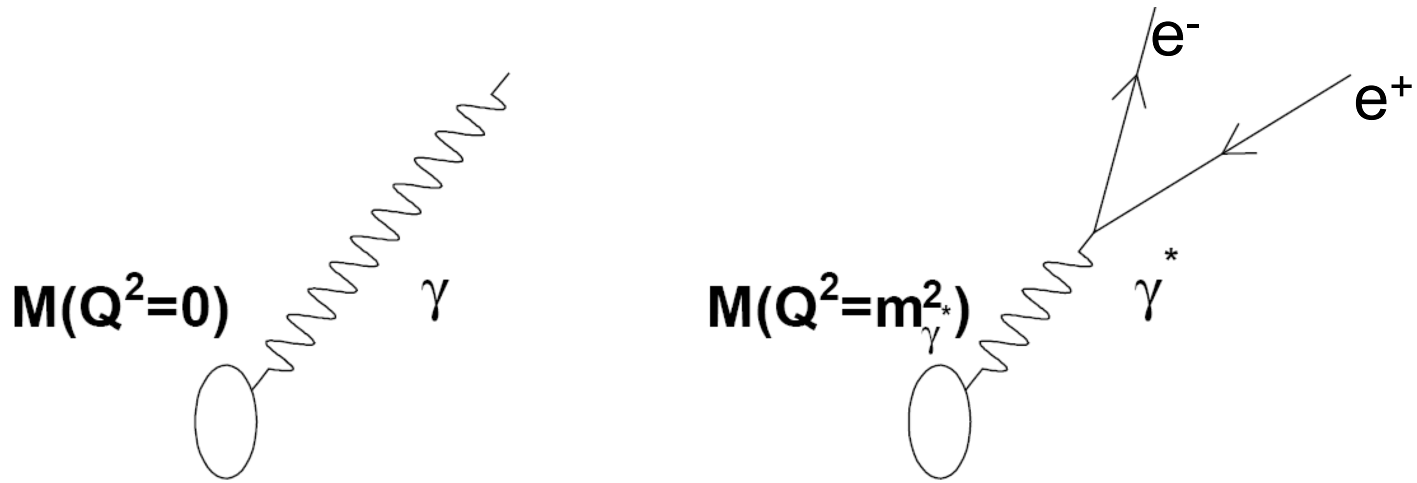

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→ Real photon yield can be measured from virtual photon yield, which is observed as low mass e^+e^- pairs

- Advantage: hadron decay background can be substantially reduced. For $m>m_\pi$, π^0 decay photons (~80% of background) are removed

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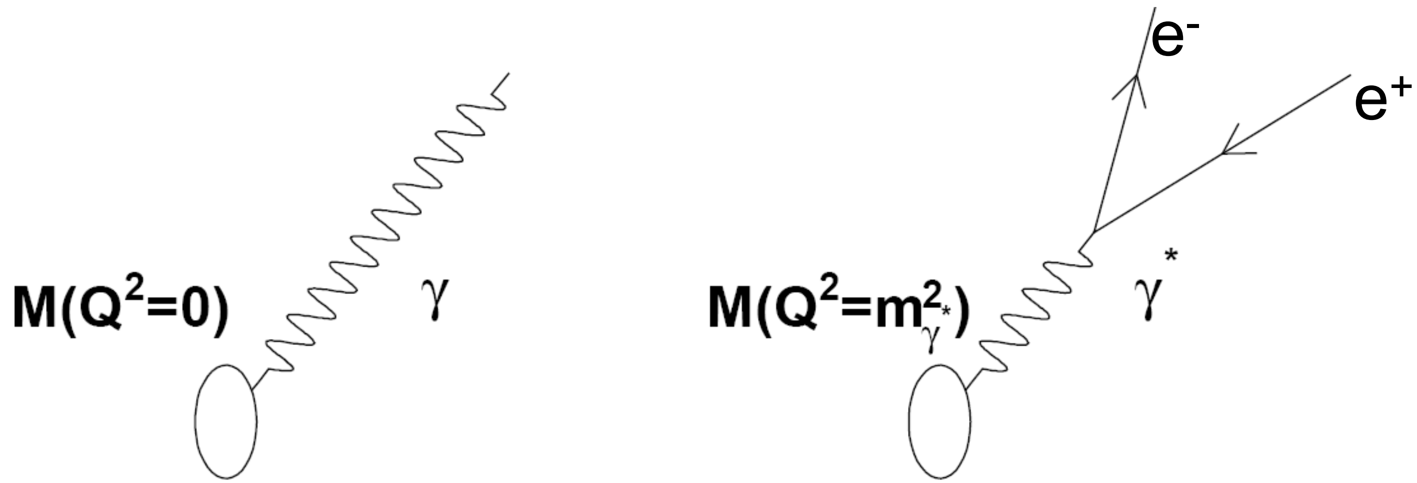

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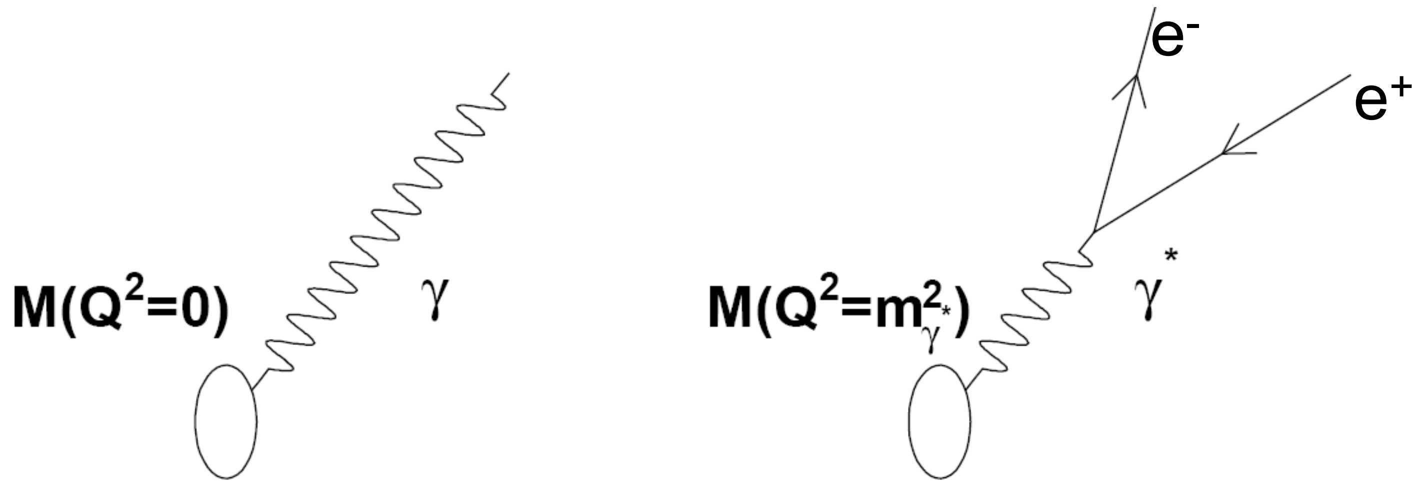

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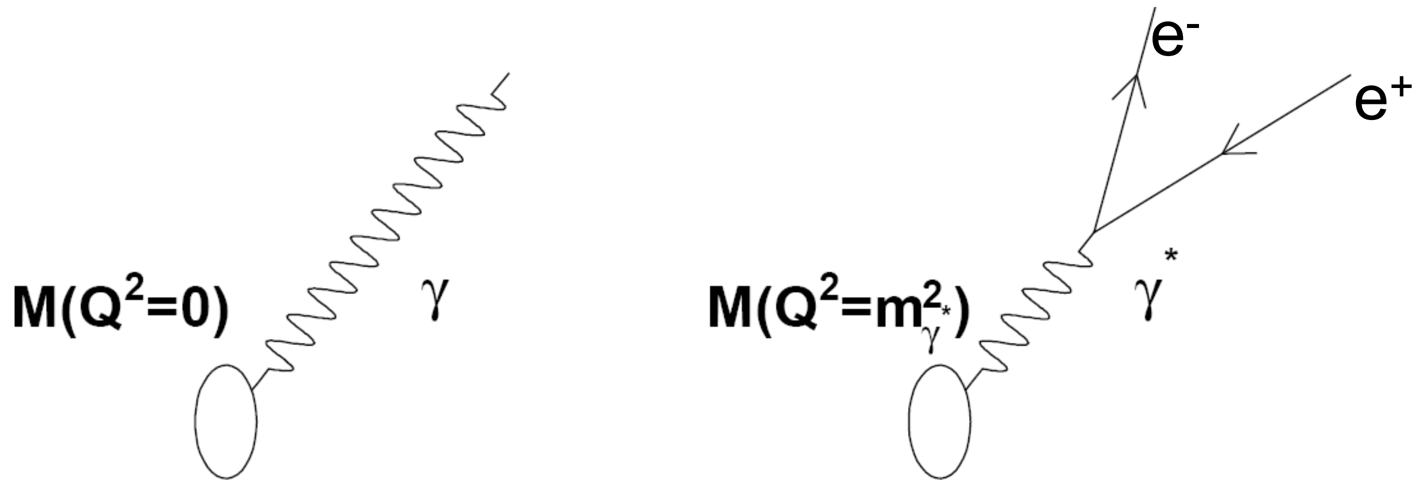

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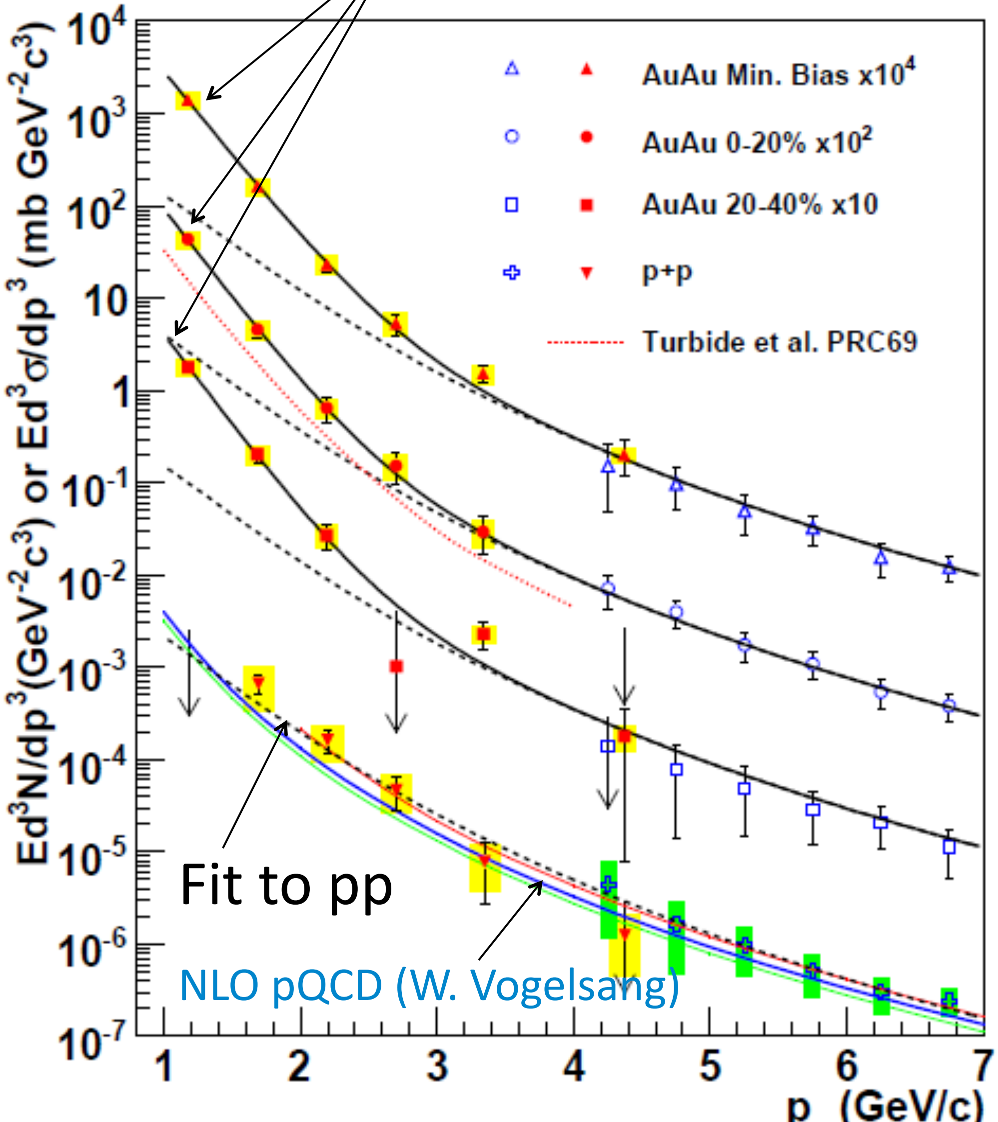
- Other advantages: photon ID, energy resolution, etc
- Cost: the yield is reduced by a large factor (~ $\alpha/3\pi \sim 1/1000$)

Direct Photon Spectra

A. Adare et al., PRL 104, 132301 (2010)



- Direct photon measurements
  - real (p_T>4GeV)
  - virtual (1<p_T<5GeV)
- pQCD consistent with p+p down to p_T=1GeV/c
- Au+Au data are above N_{coll} scaled p+p for p_T < 2.5 GeV/c
- Au+Au = scaled p+p + exp: $T_{AuAu} = 221 \pm 19^{stat} \pm 19^{syst}$ MeV
- Theoretical prediction of thermal photon by Turbide et al. agrees with the data within about a factor of two.

A 25-year old story (hypothesis)

" … If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then color screening prevents c-cbar binding in the deconfined interior of the interaction region … It is concluded that J/Ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation."

Quarkonia melt in a hot QGP - Matsui & Satz 1986, Karsch et al. 1988

HEAVY QUARKONIA

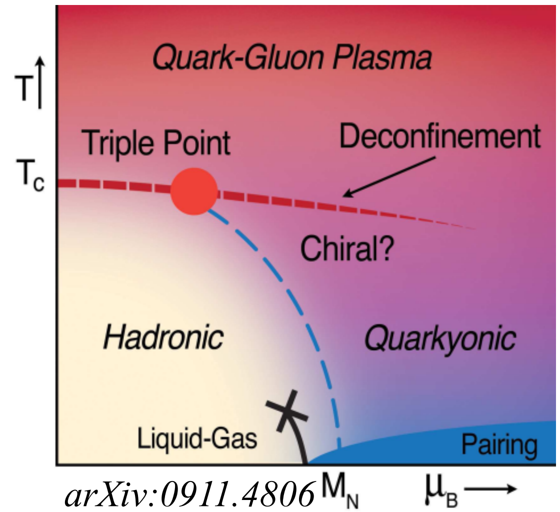
Melting - Quarkonia in A+A

state	J/ψ	χ_c	Ψ′	Υ_{1S}	Υ_{2S}	Υ_{3S}
mass [GeV]	3.10	3.53	3.6	9.46	10.02	10.36
radius [fm]	0.25	0.36	0.4	0.14	0.28	0.39

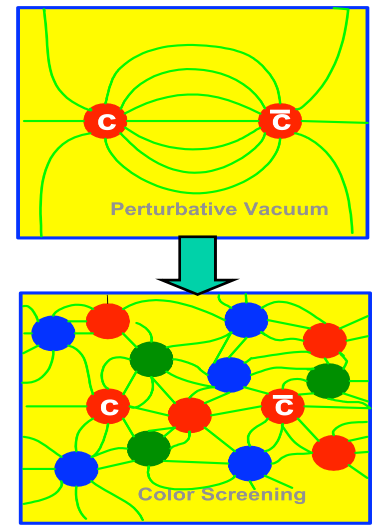
hep-ph/0609197v1 H. Satz

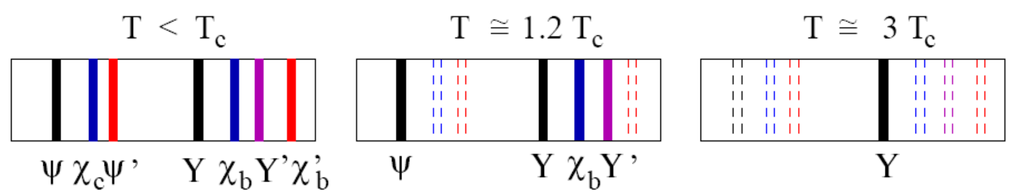
- Each quarkonium has different binding radius.

- Binding of a q-qbar pair is subject to color screening in QGP.
- Temperature of QGP can be probed by measurement heavy quarkonia.



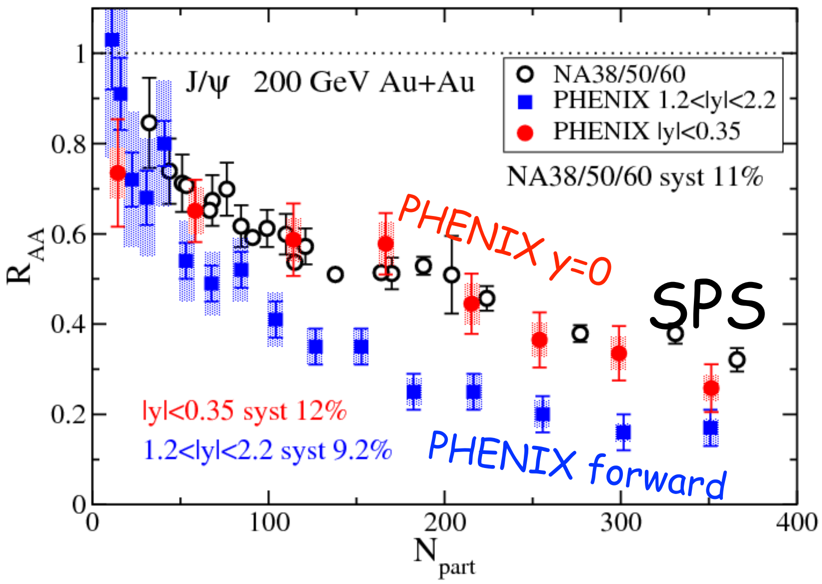
arXiv:0911.4806





Quarkonia Suppression Similarity in √s

PHENIX arXiv:1103.6269



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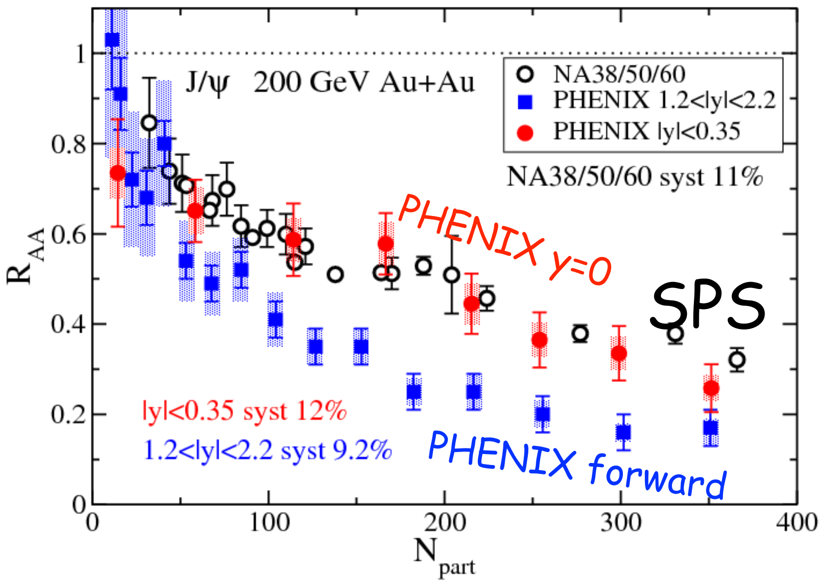

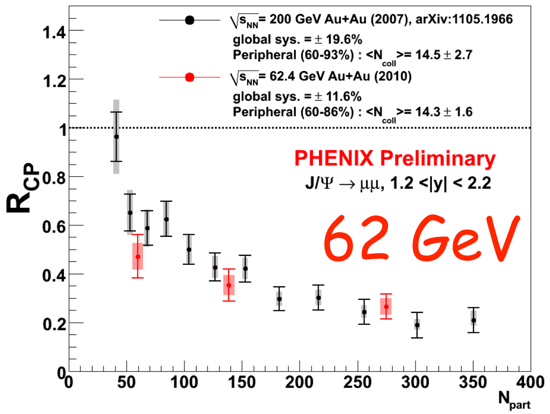

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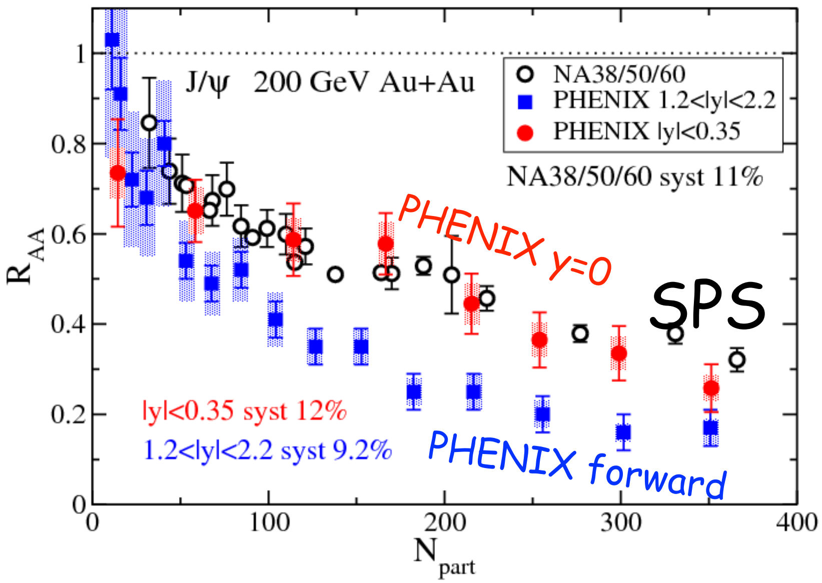

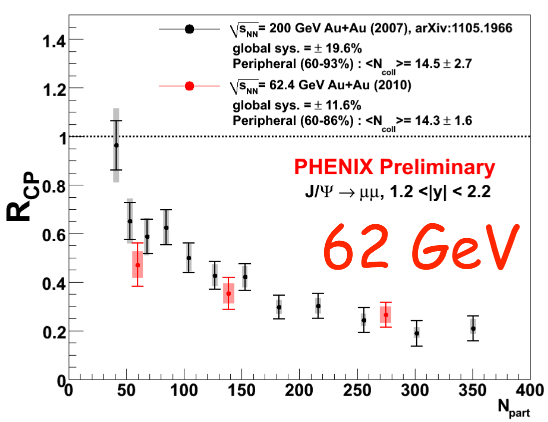

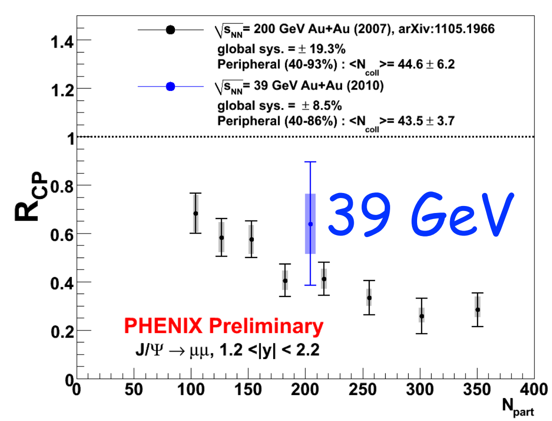

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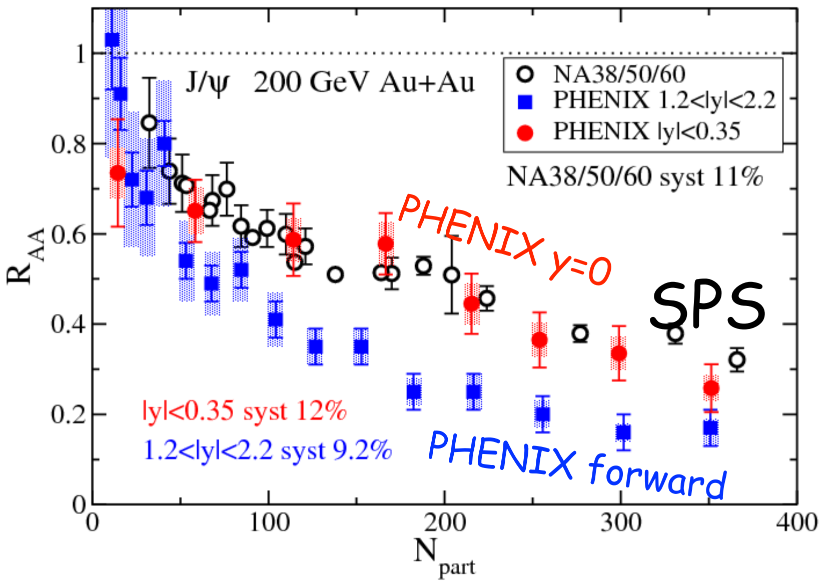

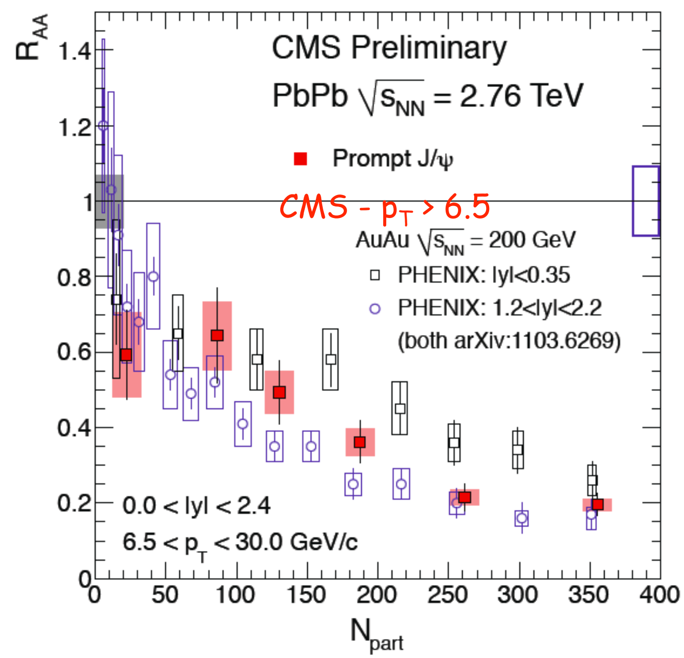

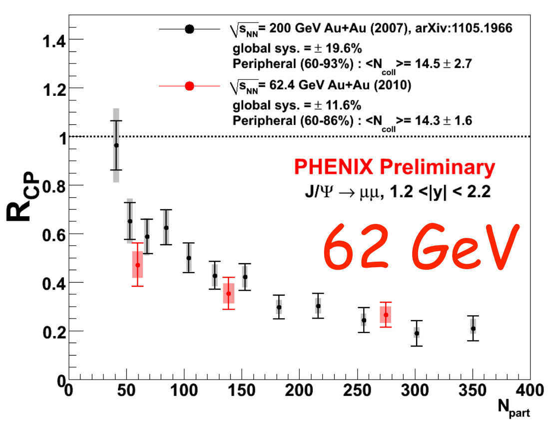

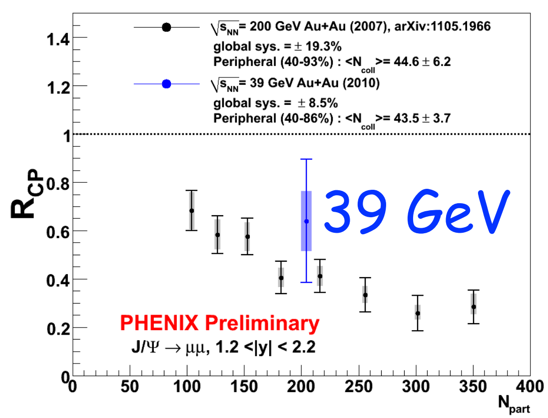

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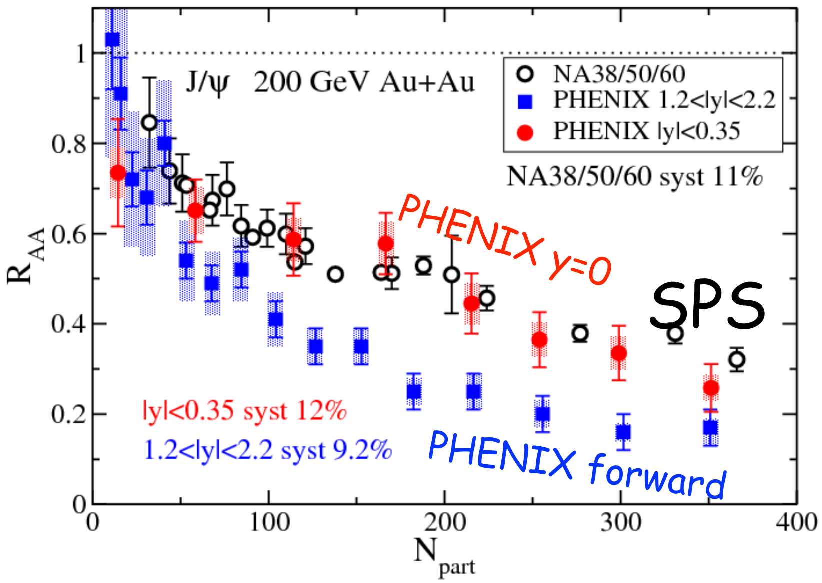
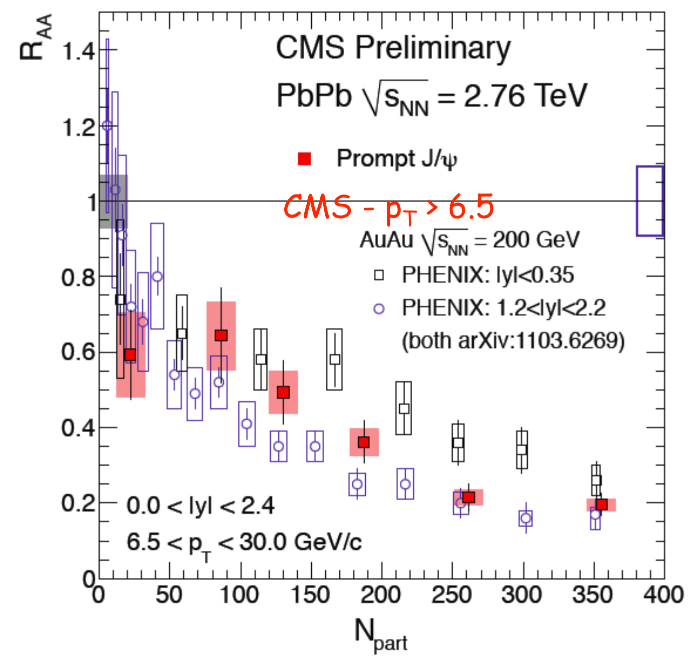
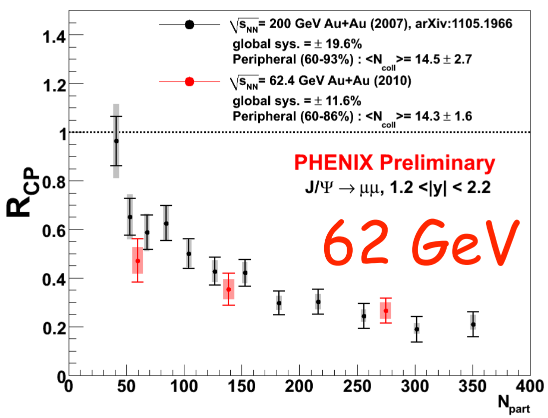
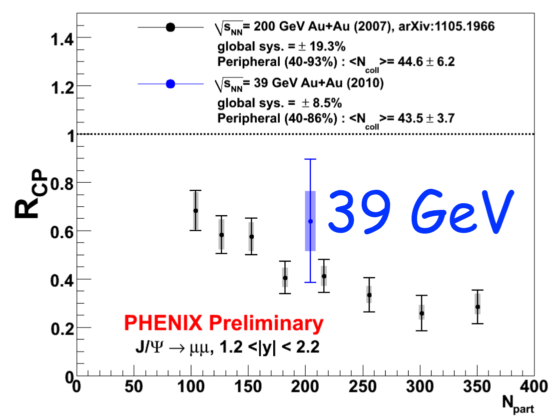


Overall suppression of J/ψ is very similar between RHIC, SPS, & LHC







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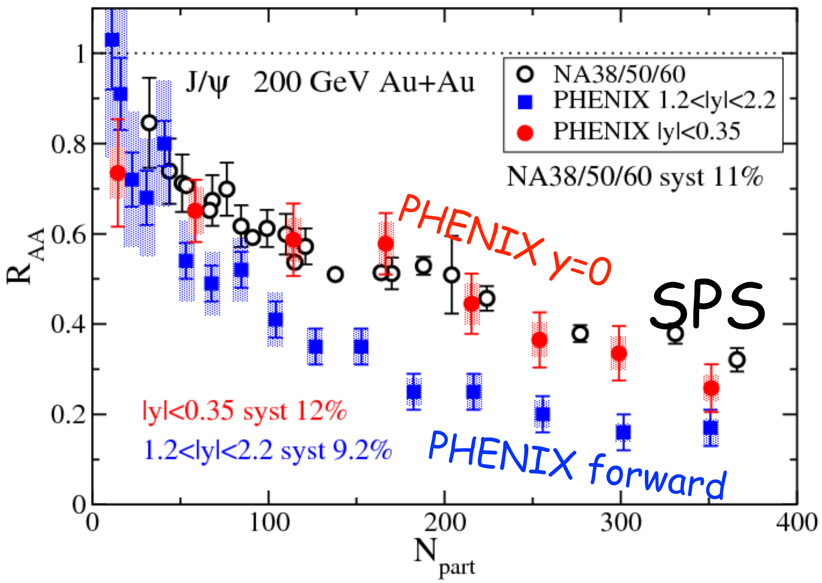

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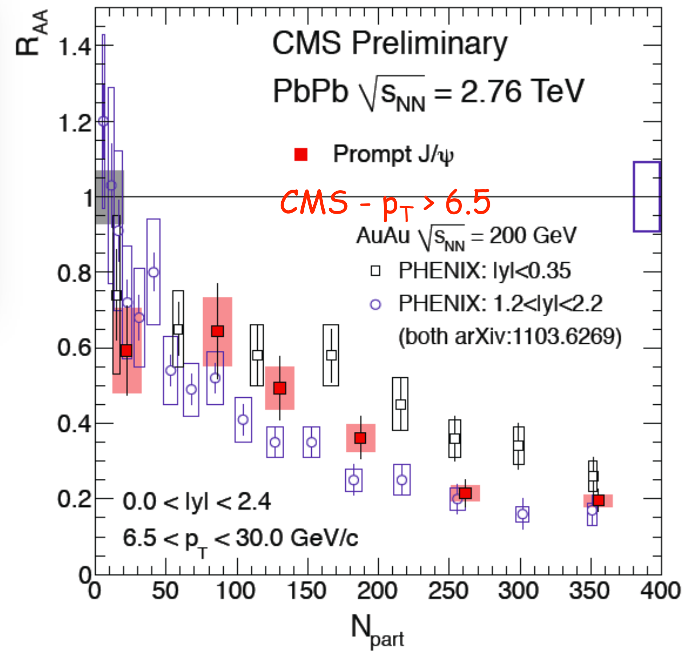

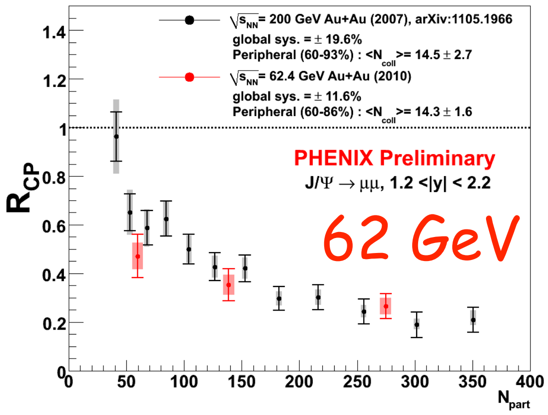

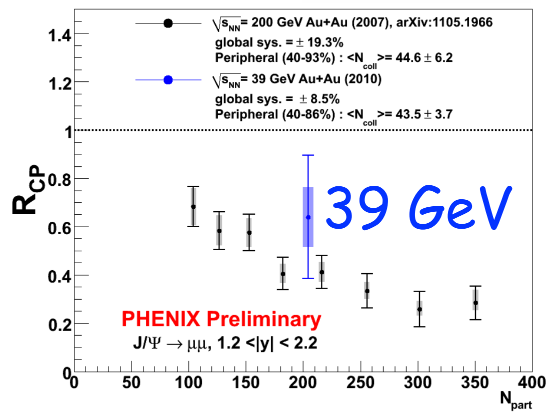

Quarkonia Suppression Levels Differ in Details

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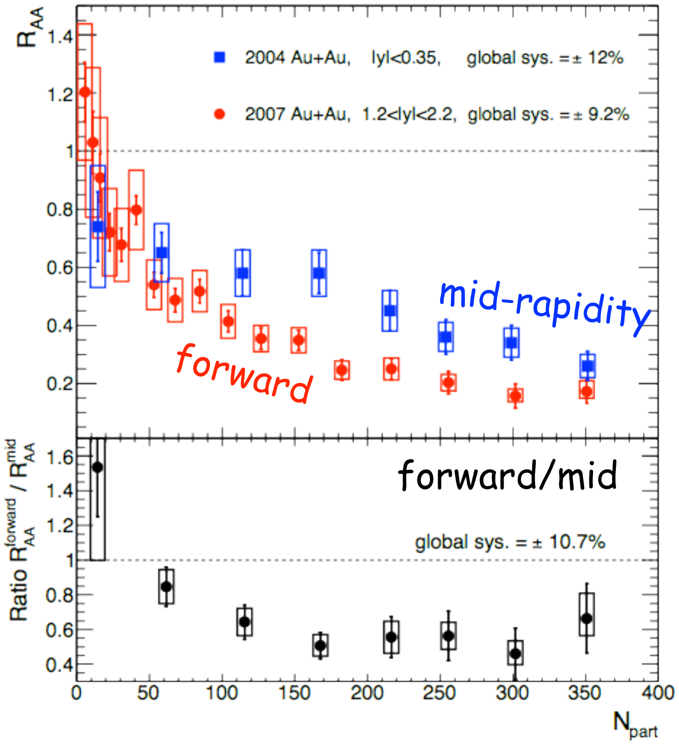

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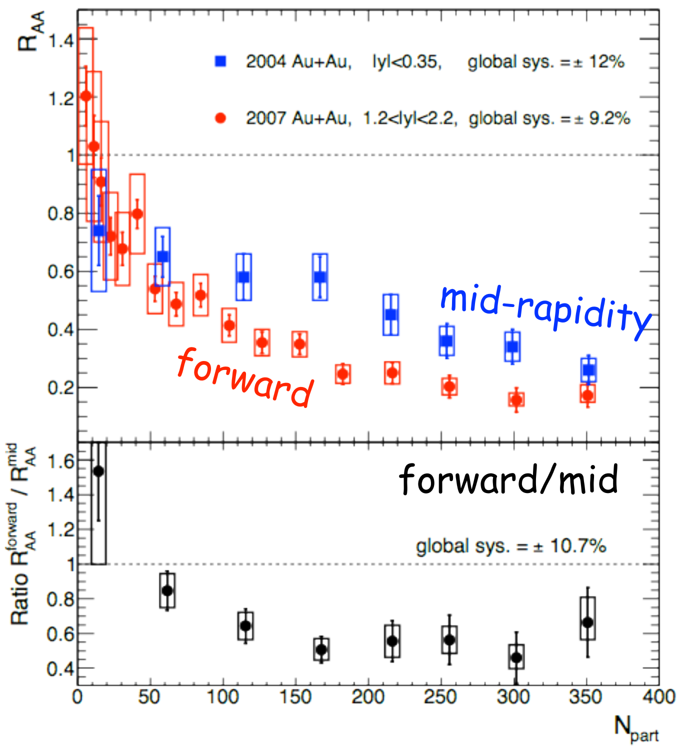

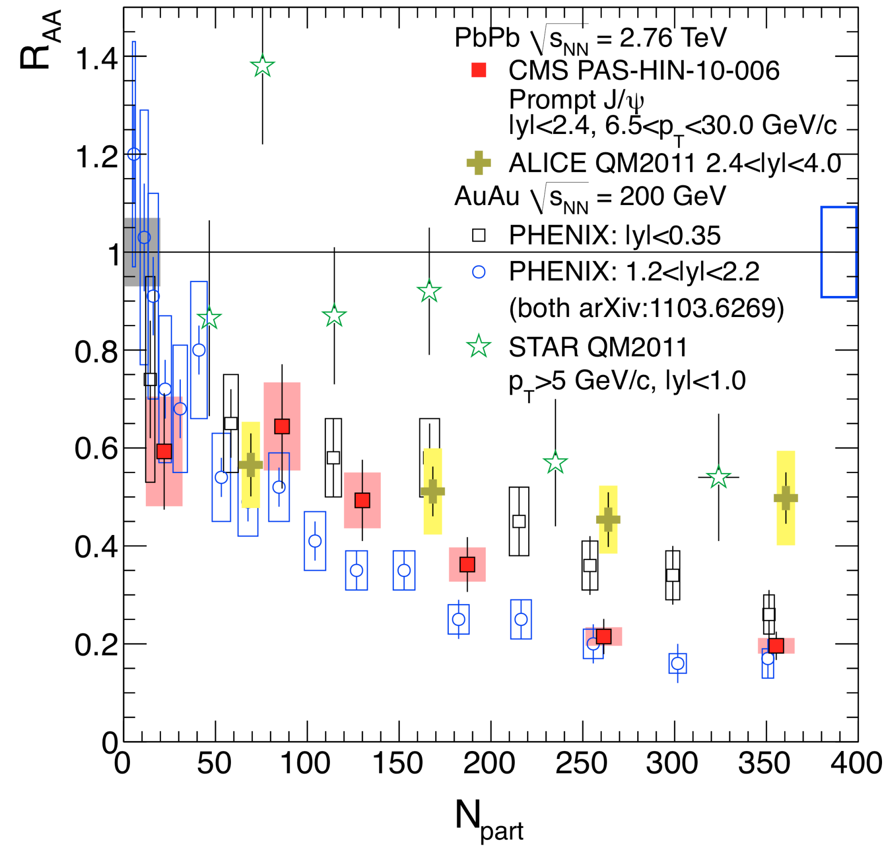

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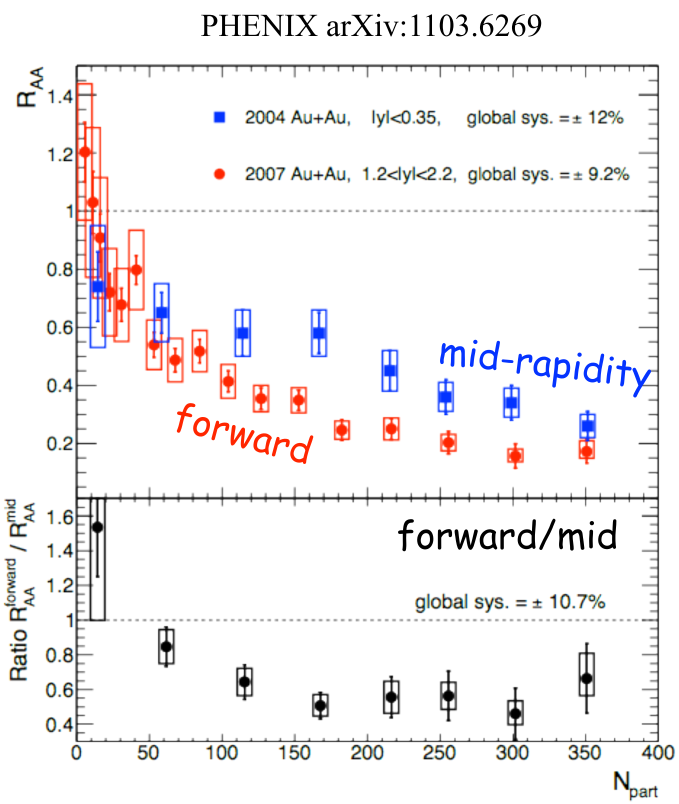

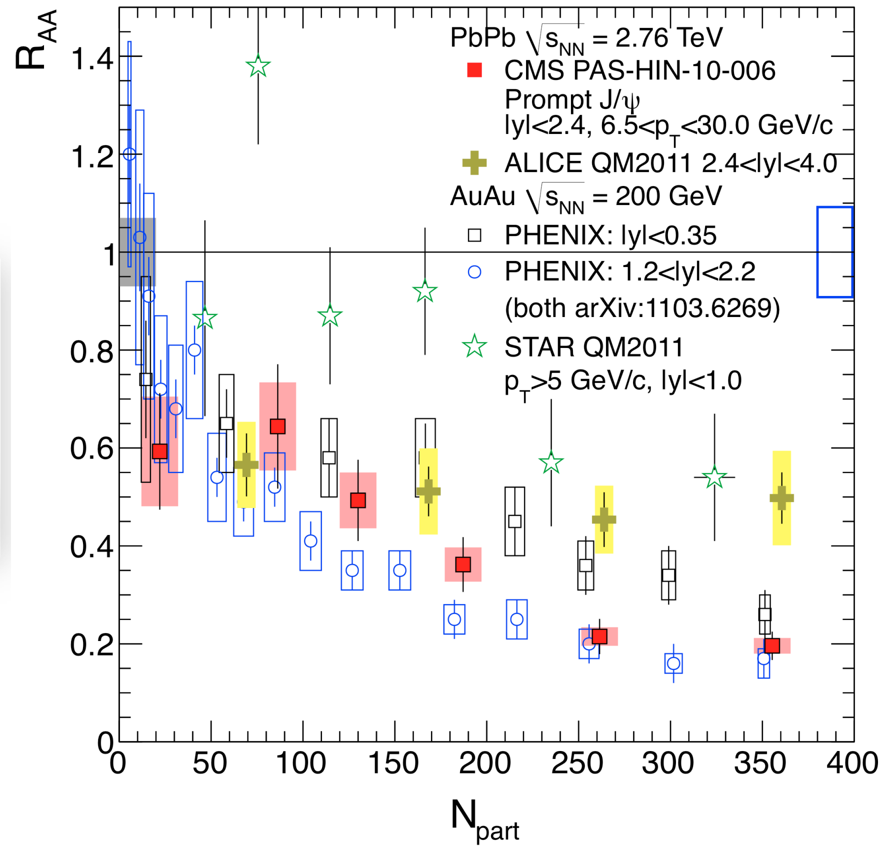

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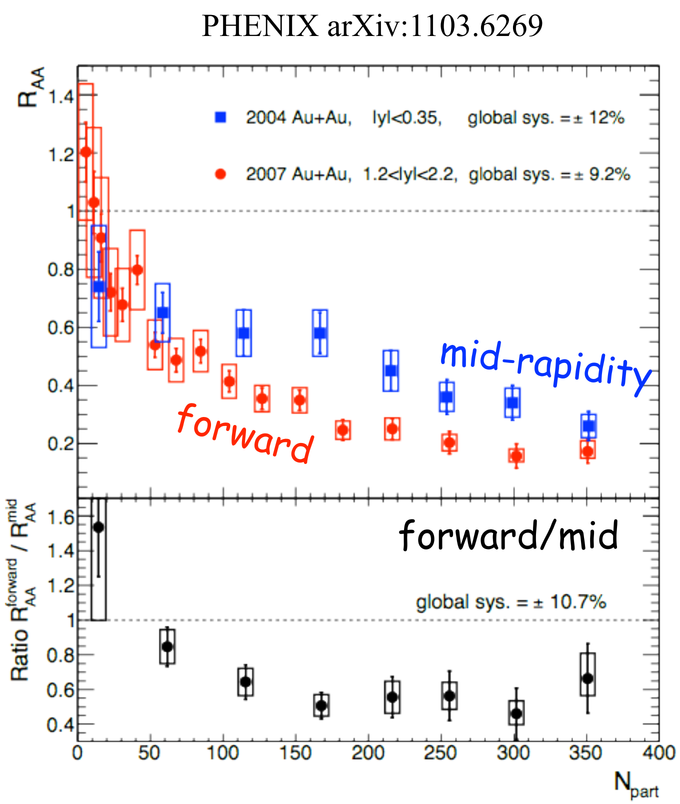
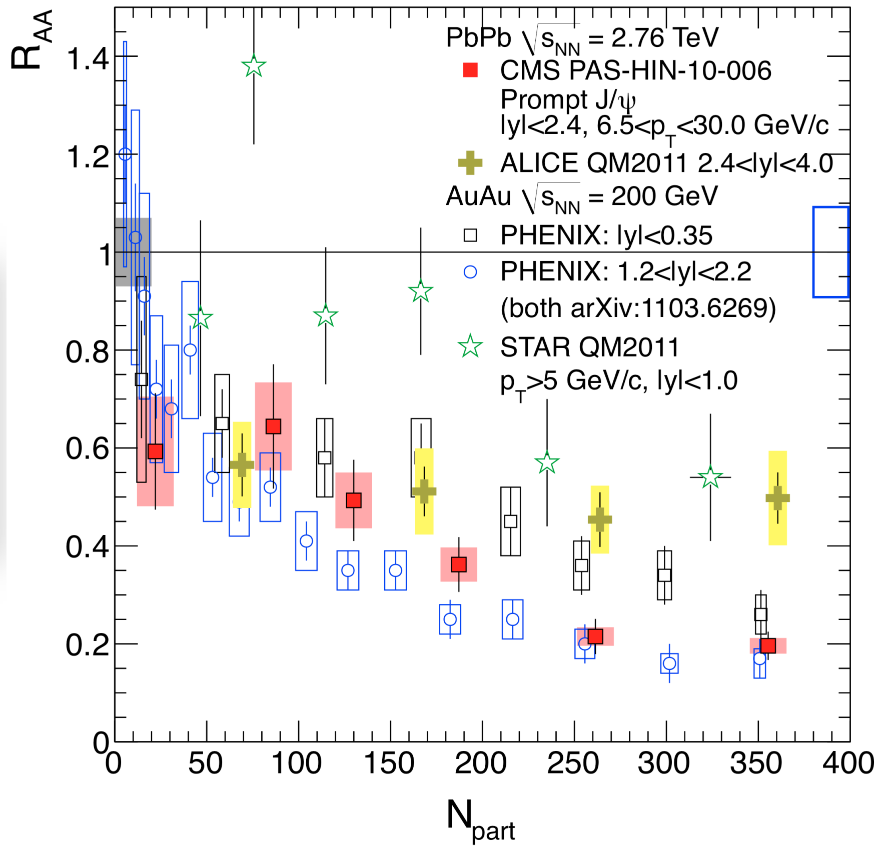
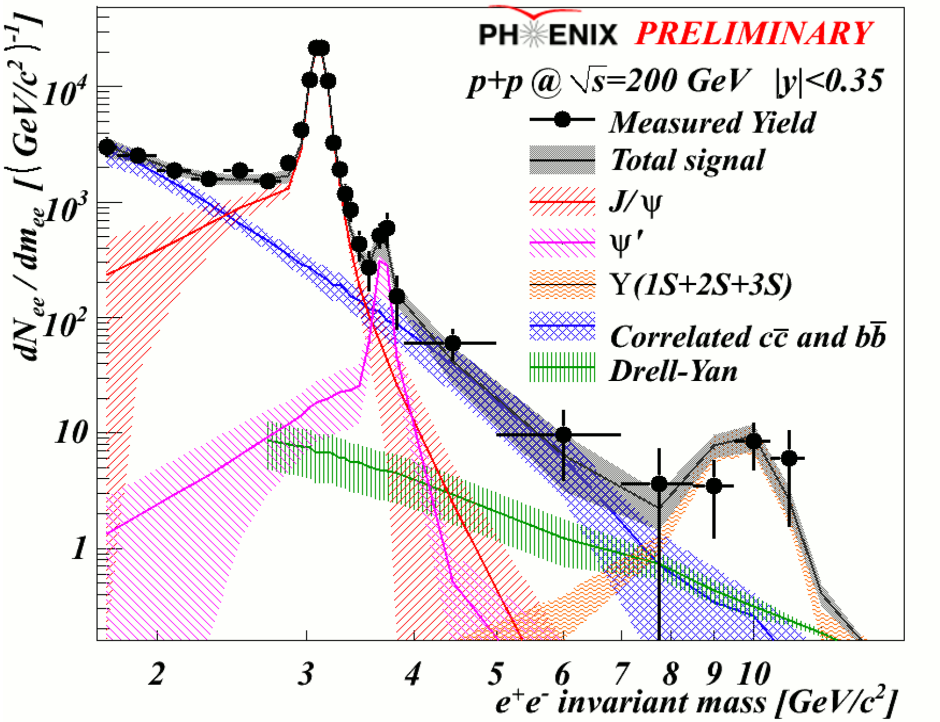




Forward-rapidity is suppressed more than Mid-rapidity

Better Knowledge about the Baseline

$\psi' \rightarrow e^+e^-$



$$F_{\Psi'}^{J/\Psi} = \frac{B_{J/\Psi}^{\Psi'}\sigma_{\Psi'}}{\sigma_{J/\Psi}} = (9.6 \pm 2.4)\%$$

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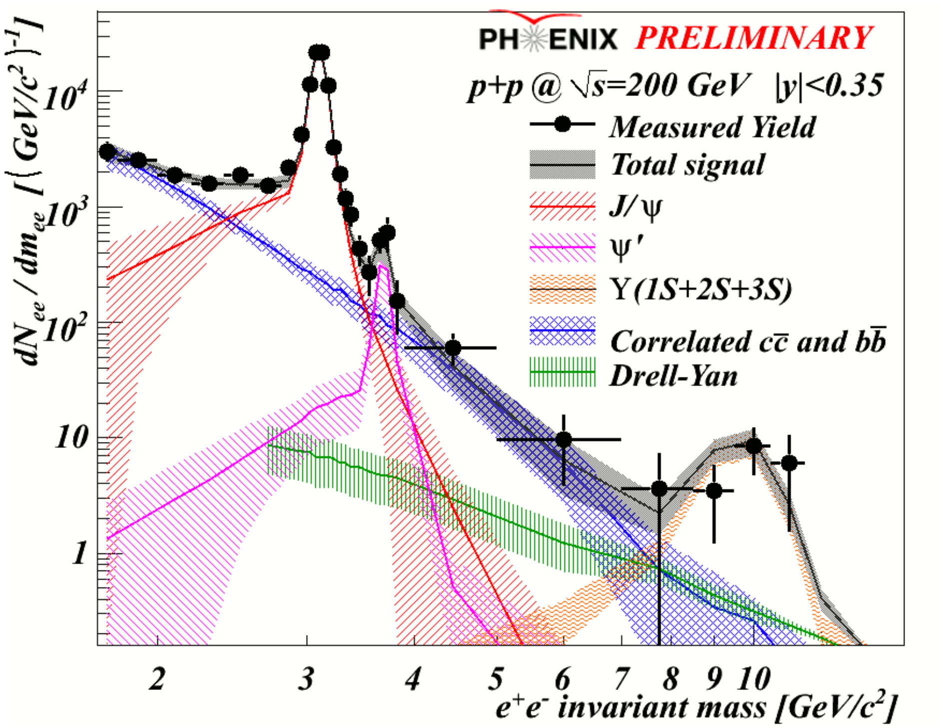

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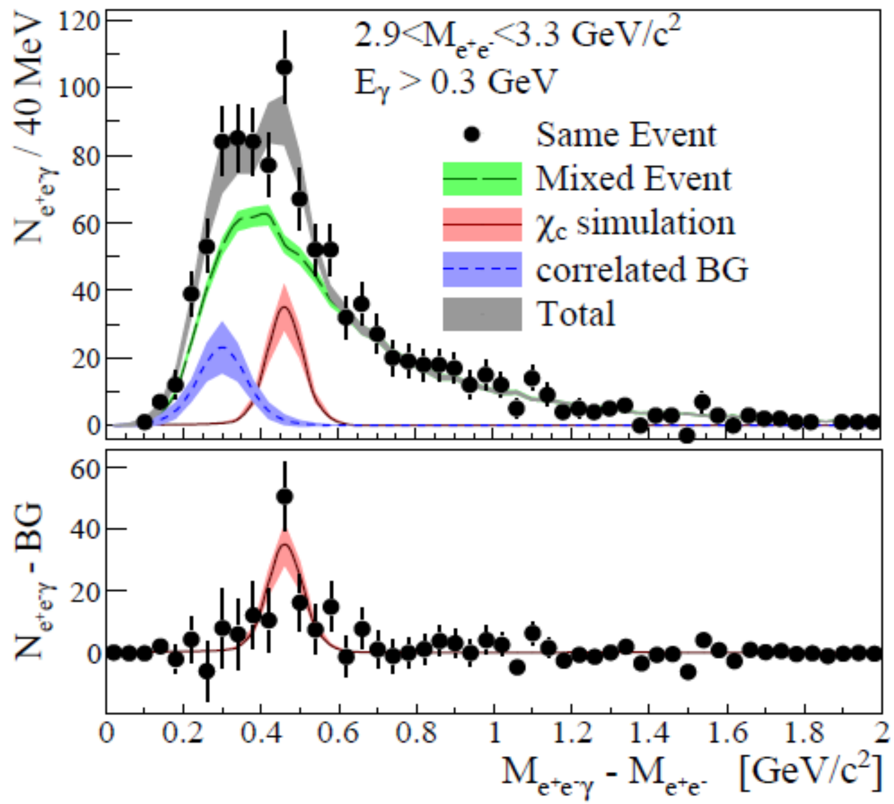
Consistent with world average!!!

$\chi_c \rightarrow J/\psi + \gamma$



$$F_{\chi_c}^{J/\Psi} = \frac{N_{\chi_c}}{N_{J/\Psi}} \frac{1}{<\varepsilon_{\chi_c}/\varepsilon_{J/\Psi}>} = (32 \pm 9)\%$$

Quarkonia Suppression with Feed-down

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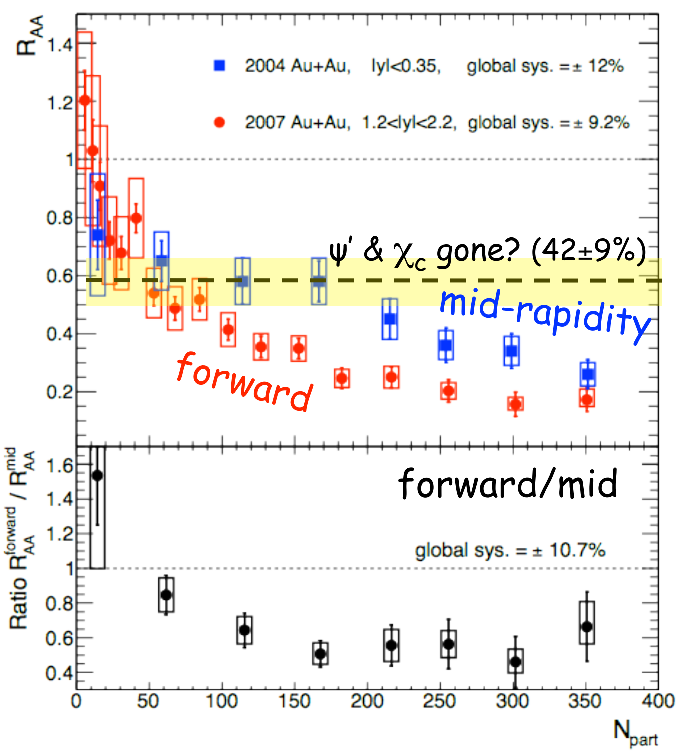

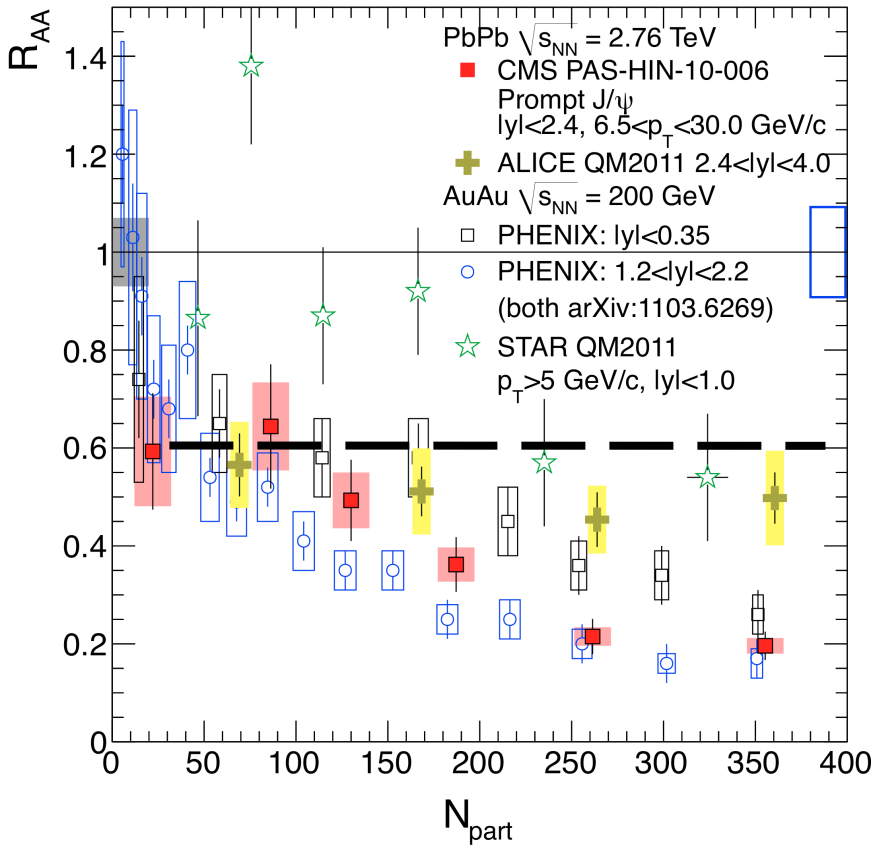

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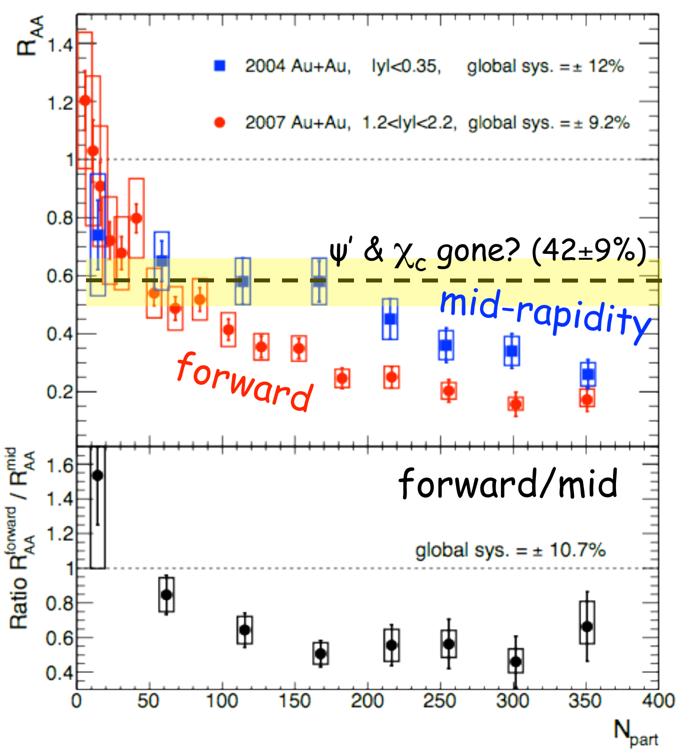
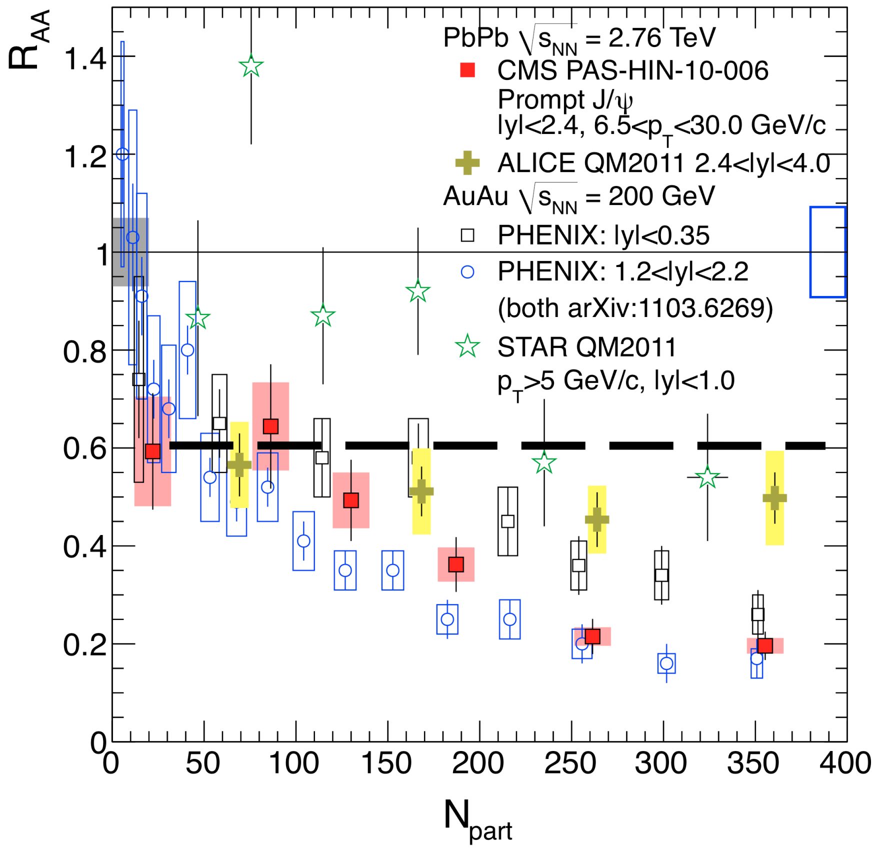
PHENIX arXiv:1103.6269





If Ψ' and χ_c are melted already, they account for ~40% maximum.
The suppression is much stronger in more central collisions!

PHENIX Is Rigorously Disentangling CNM Effects !!!

CNM effects appear to provide a large fraction of the observed suppression; so difficult to conclude much w/o a thorough understanding of CNM and its extrapolation to A+A from d+A

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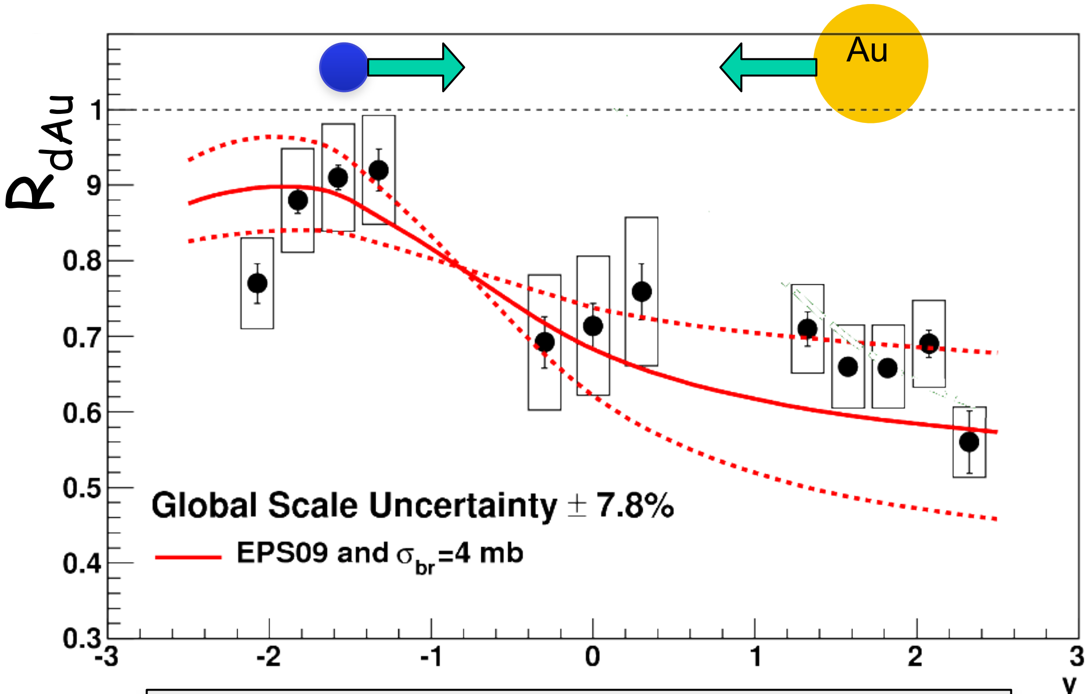

PHENIX arXiv:1010.1246, accepted in PRL

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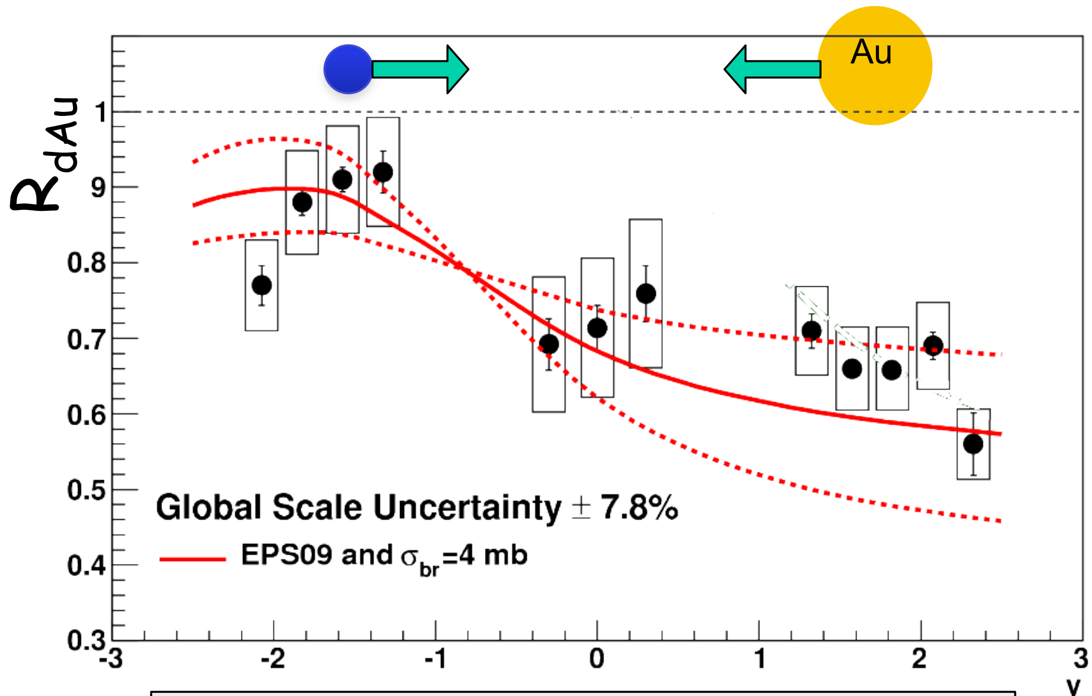

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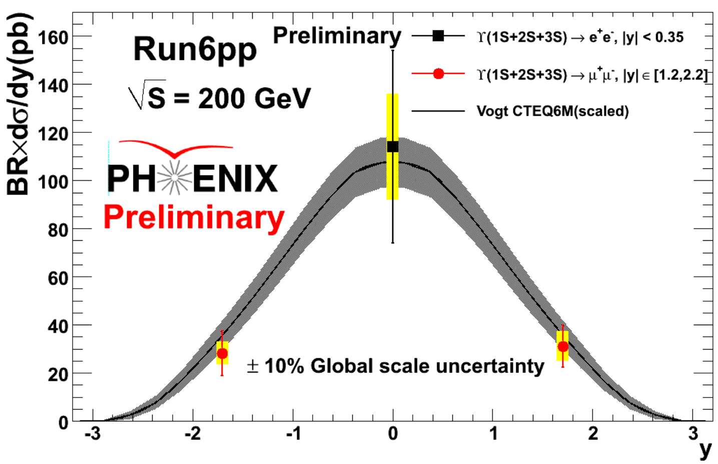
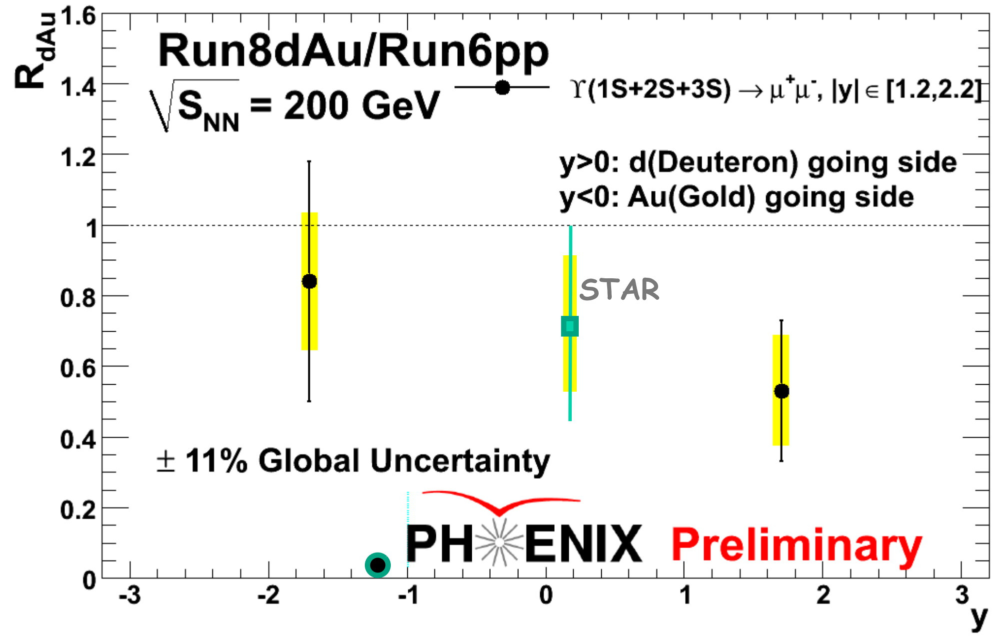
- **It looks like that we have to understand CNM in a fundamental way in order to obtain reliable/quantitative extrapolations to A+A.**

Heavier Quarkonia - Upsilons

Upsilons suppressed in CNM at RHIC





- Upsilon suppression in Au+Au at RHIC – watch out for CNM suppression.
- PHENIX has not completed the Upsilon suppression analysis for Au+Au yet. Hopefully it will come out soon.

The heavy flavor program for the next five years will be dominated by the new capabilities brought by the VTX and FVTX silicon detectors.

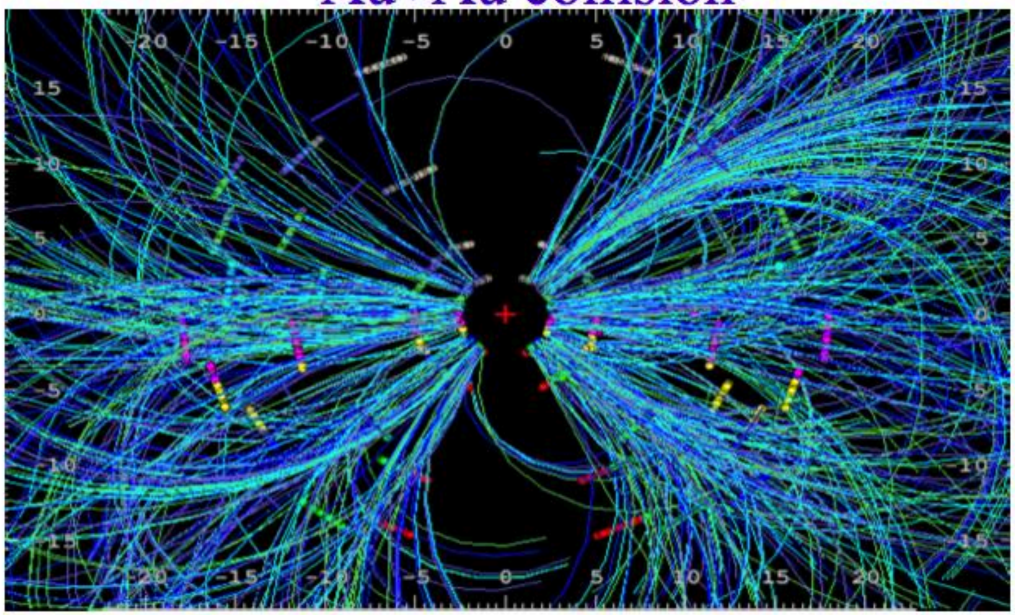
Beyond five years, the opportunity exists with sPHENIX to build a data set that will allow us to quantitatively use heavy flavors to characterize the thermodynamics of QGP.

FUTURE WORK

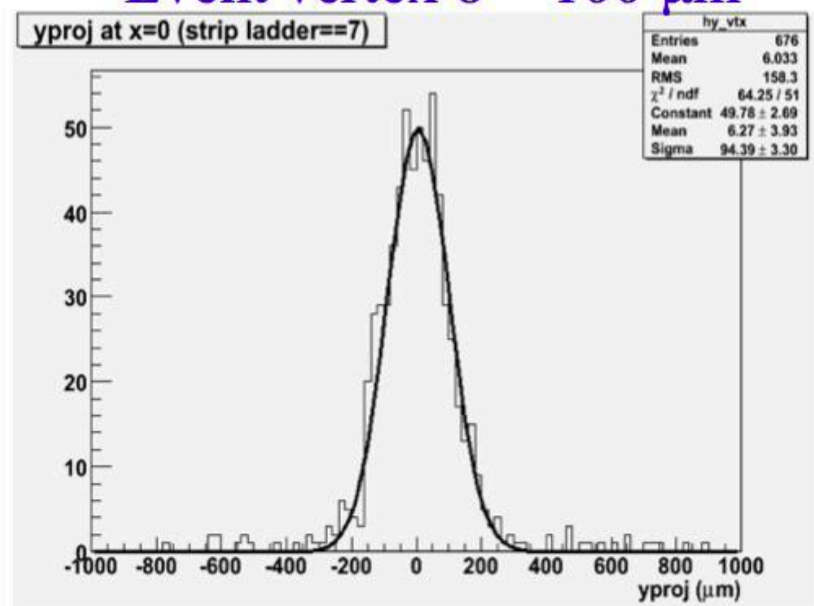
PHENIX VTX Detector

VTX – 2 pixel, 2 stripixel layers – added in Run 11, operating in Au+Au coverage |η| < 1 Added capabilities to central arms:
- **Separating D and B decays**
- **Improving mass resolution for quarkonia**

Au+Au collision

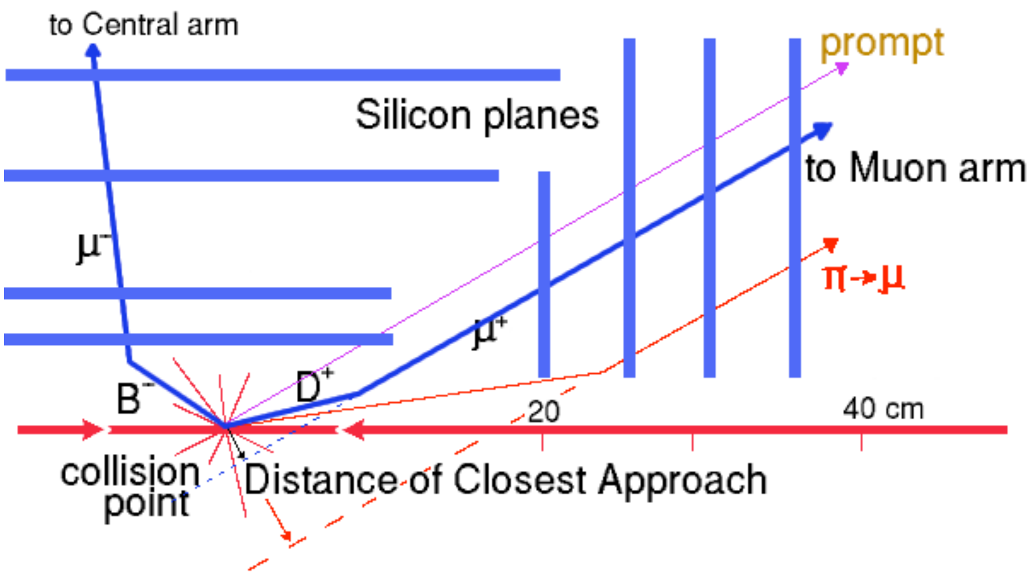


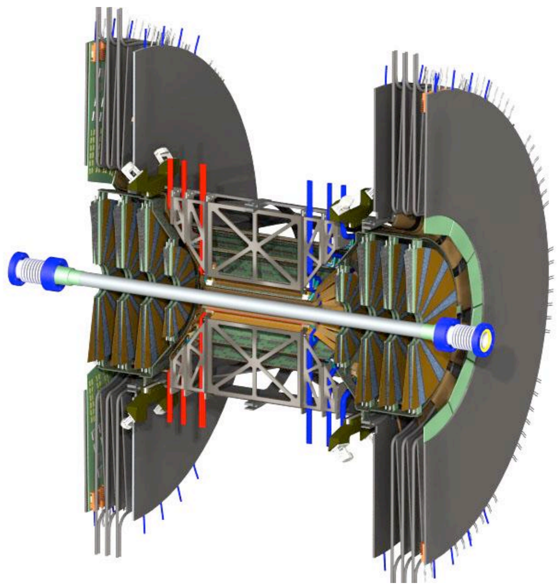
Event vertex σ ~ 100 μm



Data analysis is ongoing! Expecting much improved results!

FVTX – To Be Installed in Run-12



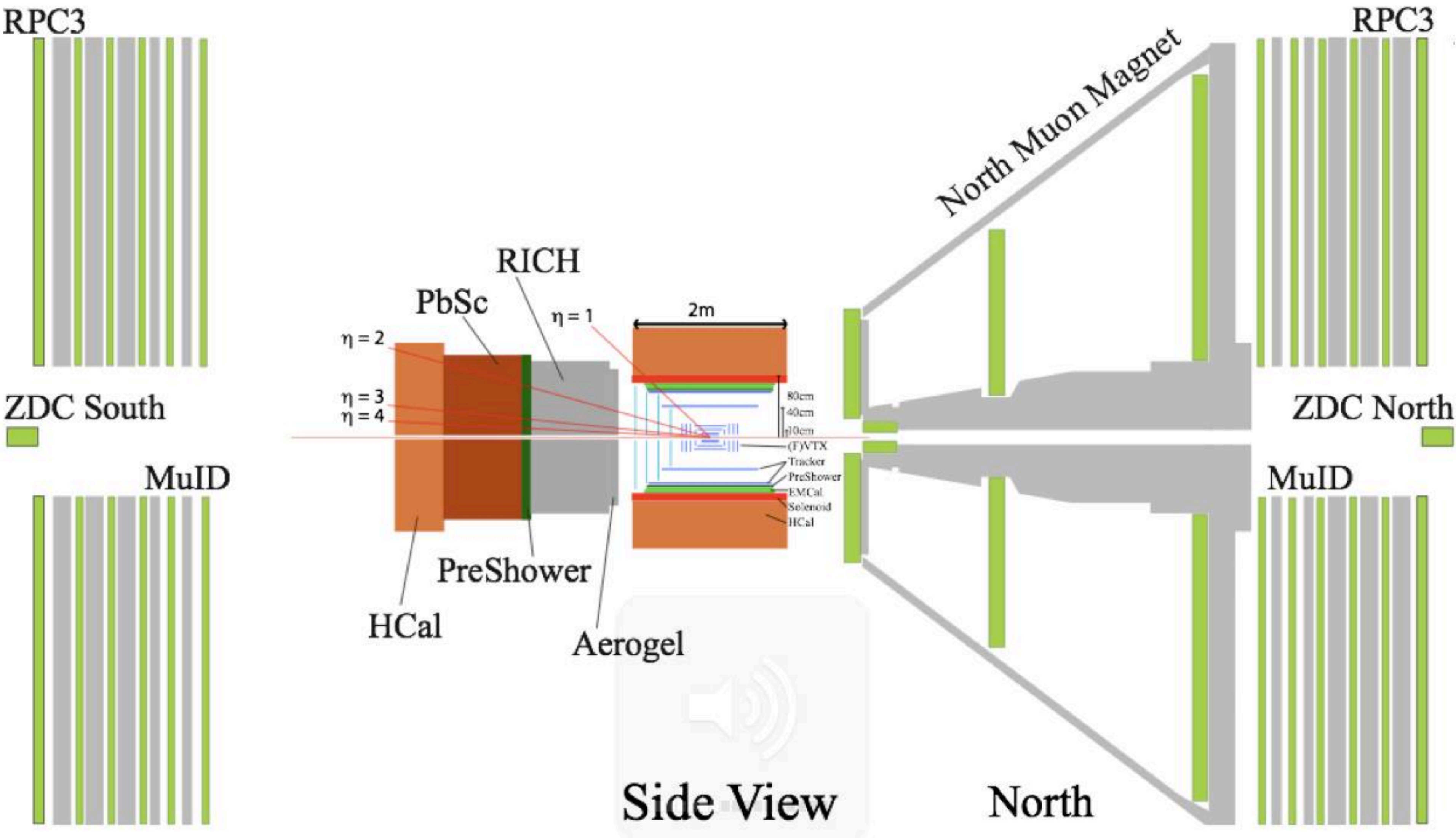


- **Mean π,K -> m, e decay distance is large**
- **D, B mesons travel some distance before semileptonic decay to muons or electrons**
- **Prompt m, e have 0 DCA**
- **By measuring the DCA to the primary vertex, we can separate D, B decays from prompt leptons and from long-lived decays from π, K**

Projected Luminosities & Strawman PHENIX Run Plan

Run	Species	√s	Wks	±30 cm	±10 cm	Pol	Comments
11	p+p	500	10	27 pb^{-1}		50%(L)	W program + ΔG
	Au+Au	19.6	1.5	13.7M MB evts			energy scan
	Au+Au	200	8		700 μb^{-1}		heavy flavor (VTX)
12	p+p	200	5	13.1 pb^{-1}	4.7 pb^{-1}	60%(T)	HI ref. + transv. spin
	p+p	500	8	100 pb^{-1}	35 pb^{-1}	50%(L)	W program + ΔG
	Au+Au	200	7		800 μb^{-1}		Heavy flavor (FVTX/VTX)
	U+U	200	1.5		0.3 nb^{-1}		explore geometry
	Au+Au	27	1	5.2 μb^{-1}			energy scan
13	p+p	500	10	200 pb^{-1}	74 pb^{-1}	60%(L)	W program
	p+p	200	5	20 pb^{-1}	4.7 pb^{-1}	60%(T)	HI ref. + transv. spin
	Cu+Au	200	5		2.4 nb^{-1}		geometry
	U+U	200	5		0.57 nb^{-1}		geometry
14	p+p	200	10	34 pb^{-1}	12 pb^{-1}	65%(T)	HI ref. + transv. spin
	p+p	62	3	0.6 pb^{-1}	0.2 pb^{-1}	60%(T/L)	HI ref. + transv. spin
	d+Au	200	8	260 nb^{-1}	150 nb^{-1}		CNM
	d+Au	62	2	6.5 nb^{-1}	3.8 nb^{-1}		CNM
15	Au+Au	200	10		2.8 nb^{-1}		high bandwidth
	Au+Au	62	4		0.13 nb^{-1}		HF vs √s
	$p+{}^{3}He$	132	5			(T)	test run

sPHENIX – Current Thinking



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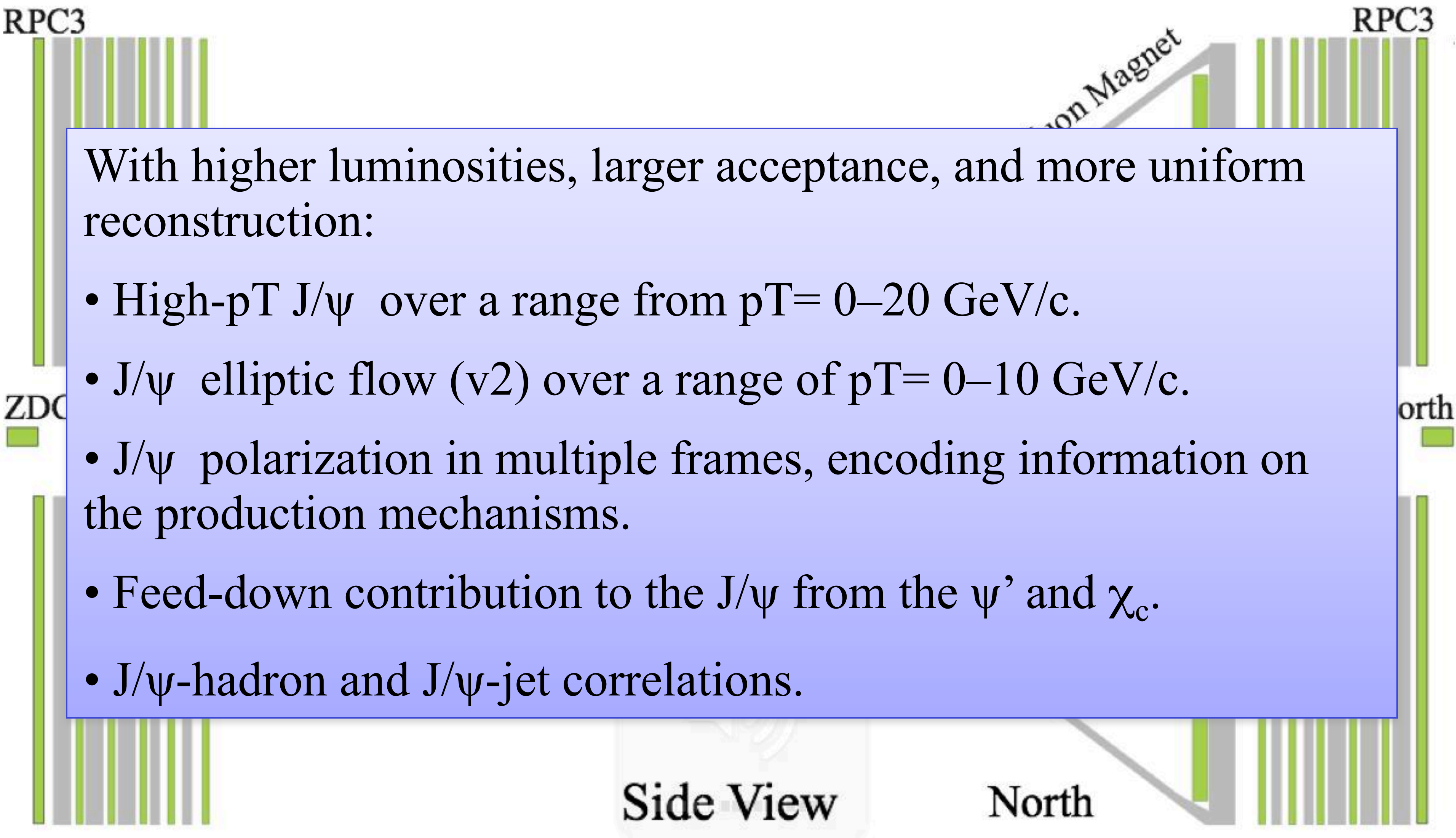


With higher luminosities, larger acceptance, and more uniform reconstruction:

- High-pT J/ψ over a range from pT= 0–20 GeV/c.
- J/ψ elliptic flow (v2) over a range of pT= 0–10 GeV/c.
- J/ψ polarization in multiple frames, encoding information on the production mechanisms.
- Feed-down contribution to the J/ψ from the ψ' and χ_c.
- J/ψ-hadron and J/ψ-jet correlations.

Summary

- The matter created in Au+Au collisions at per nucleon-nucleon cms energy of 200 GeV is **dense**. Quarks (both the light and the heavy) and gluons experience large energy loss while traversing this medium.
- The system is rapidly **thermalized** from the measurement of elliptic flow of light and charmed hadrons. The quark number scaling of the flow (v_2) indicates the partonic nature of the thermalized medium.
- Such a hot and dense medium emits **thermal radiation**. The observation of thermal photons allows the determination of the initial temperature of the matter!
- Quantitative study of heavy quarkonia suppression continues.

The dust isn't likely to settle soon!

Stay tuned.

THANKS

BACKUPS

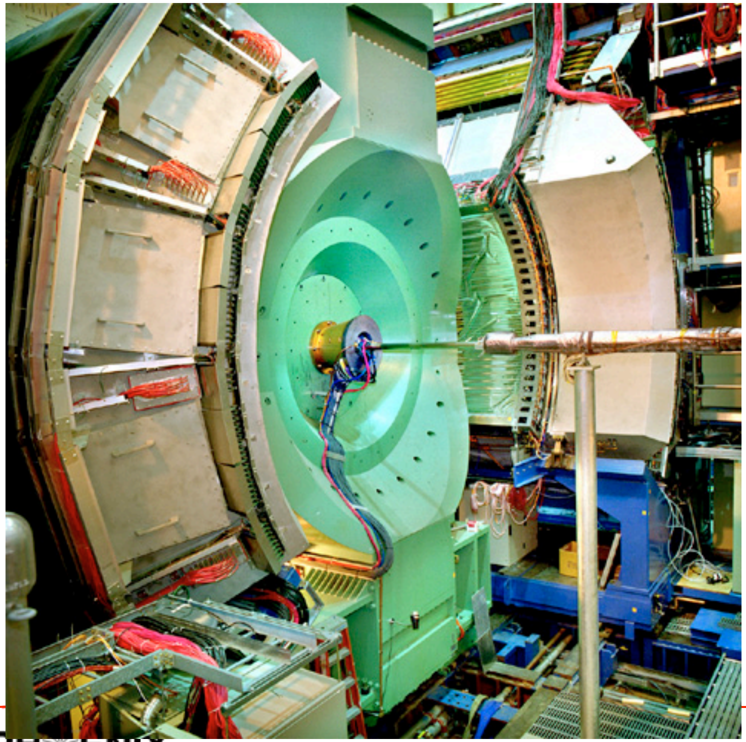
The PHENIX Experiment

Tale of the Tape:

- Begun Operation June 2000
- 550 Scientists, 14 Countries, 69 Inst.
- 18 Detector subsystems
- 4 Spectrometer arms
  - Large electromagnets
- Total weigh = 3500 Tons
- >300,000 readout channels now
- >3,000,000 channels w/Upgrades
- >125 Varieties of custom printed circuit boards
- We can take 16 Terabytes of data/day
  - Fills One 100 GB computer hard disk every 3 ½ minutes
- Operate 7-8 months/year (24/7)
  - Maintain/repair 4-5 months/yr
- Major components built everywhere
  - US, Russia, Japan, Brazil, Israel, France, Sweden, Germany, Korea
- It takes ~110 people/wk to operate PHENIX while taking data

PHENIX is designed to probe fundamental features of the strong nuclear force, Quantum Chromo Dynamics (QCD)

- PHENIX took approx. 10 years and $120M to design, build & commission
- We are finishing our 9th year of operation



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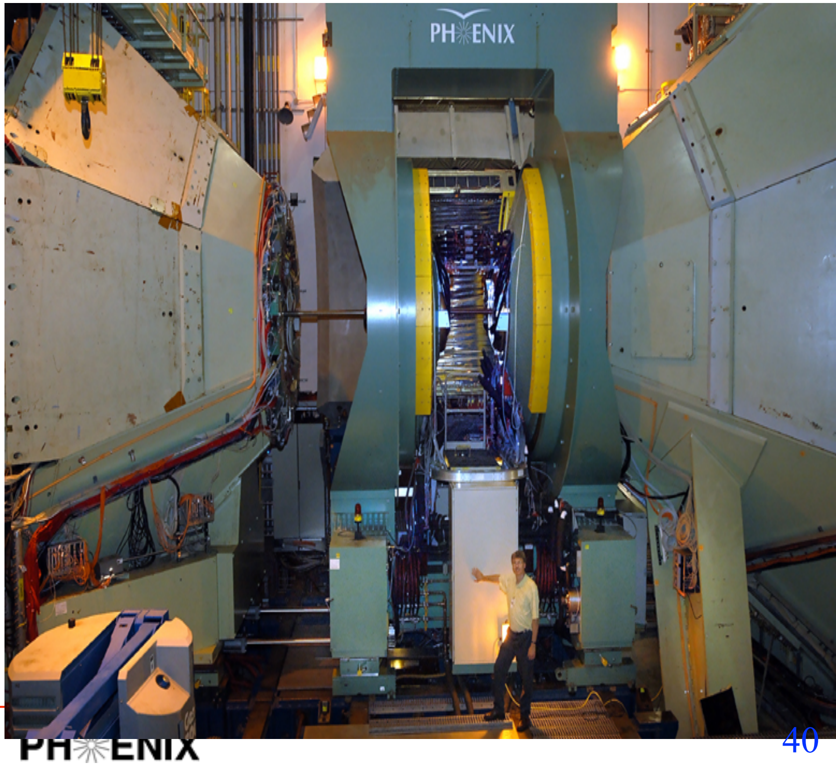

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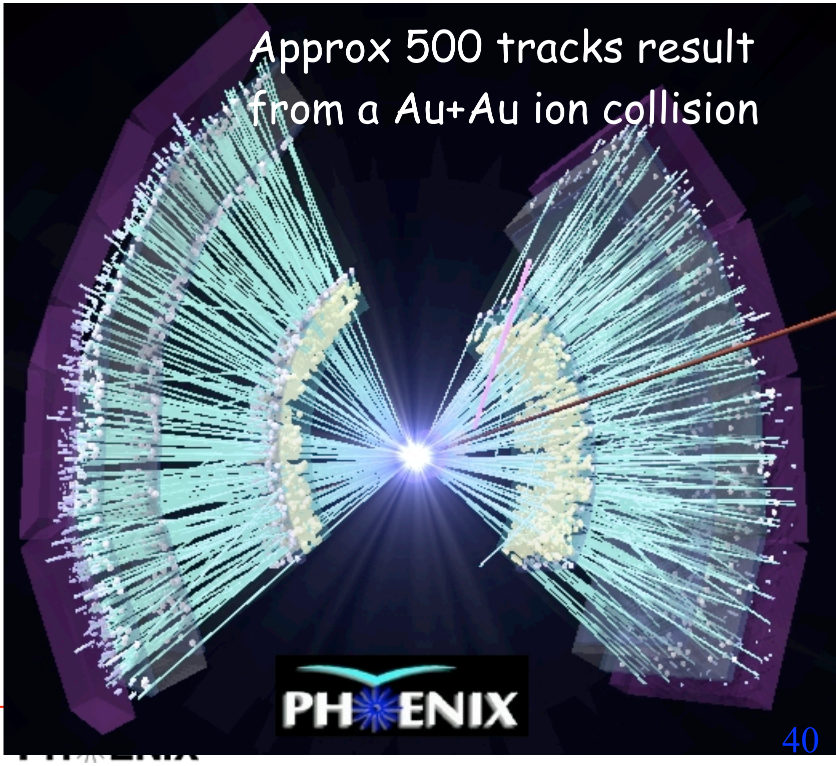
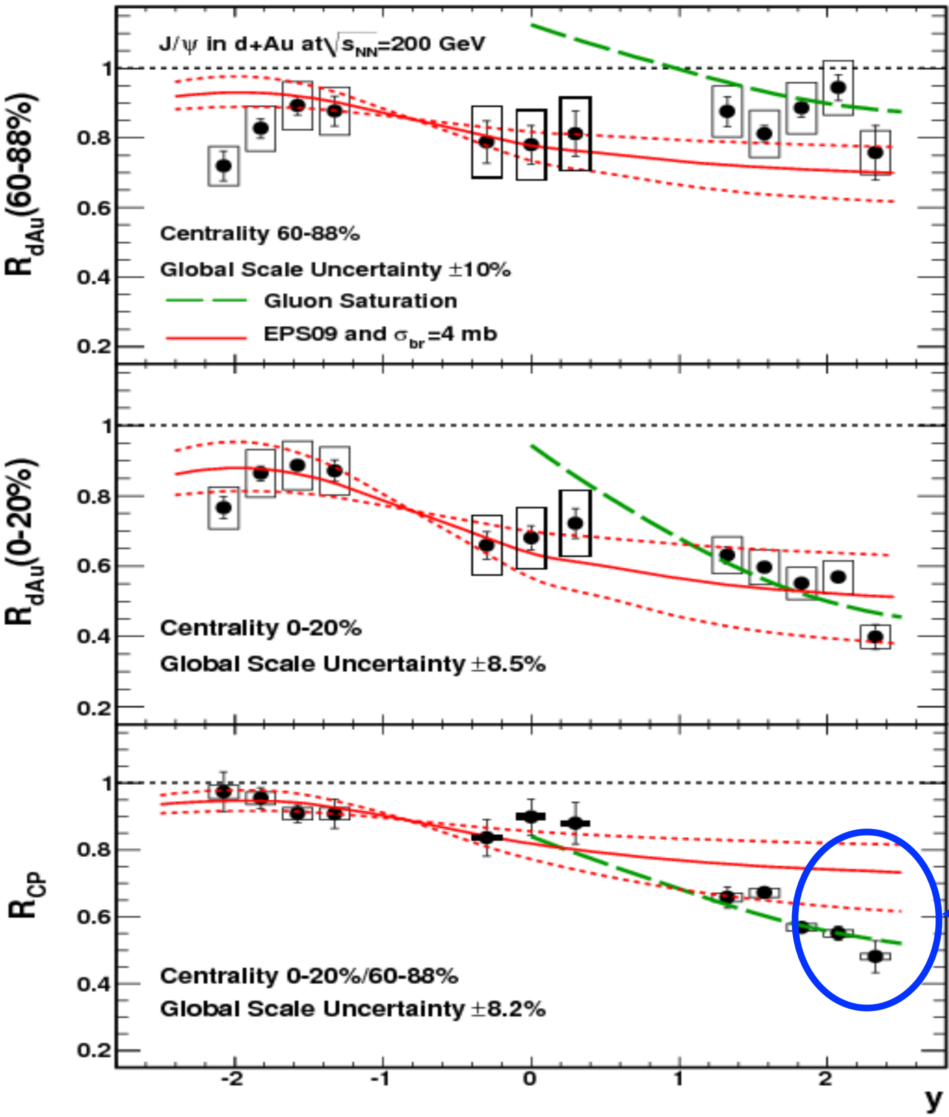


What are the CNM effects that are so strong in Quarkonia production?

J/ψ in d+Au – learning about CNM thickness dependence (I)

PHENIX arXiv:1010.1246, accepted in PRL



Reasonable agreement with EPS09 nPDF + σ_{br}=4 mb for central collisions but not peripheral

CGC calculations can't reproduce mid-rapidity (*Nucl. Phys. A 770(2006) 40*)

EPS09 with linear thickness dependence fails to describe centrality dependence of forward rapidity region.

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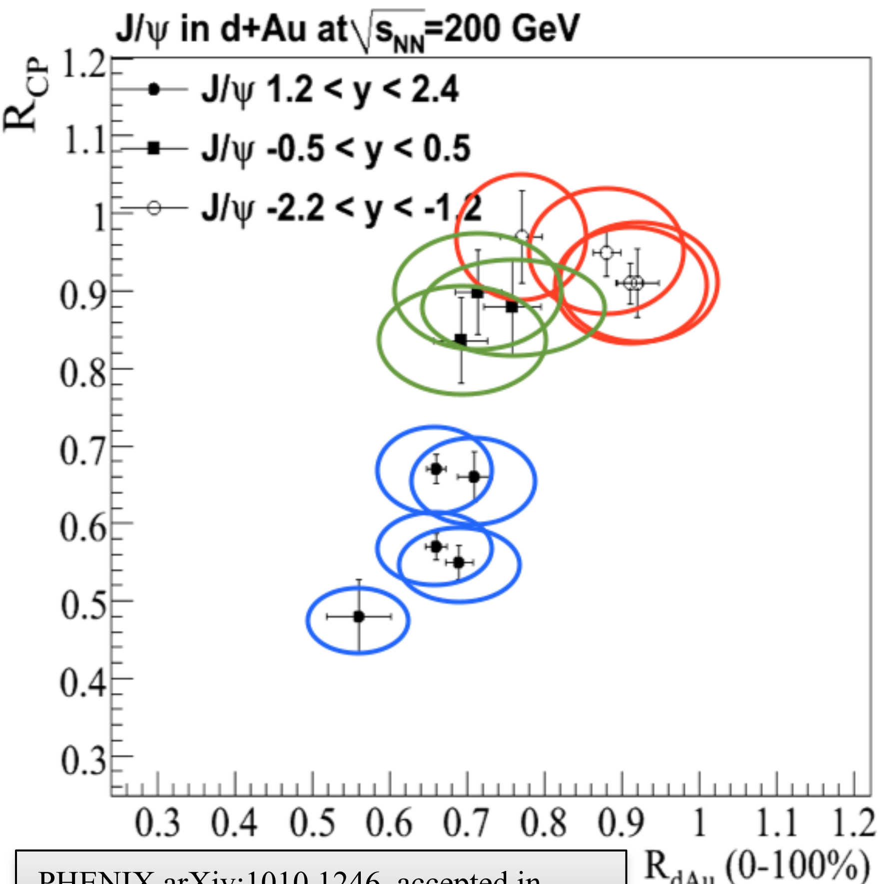
J/ψ in d+Au – learning about CNM thickness dependence (II)



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Vary the strength of suppression (a) & see what relationship between R_{dAu} and R_{CP} is given strictly by Glauber geometry for different dependences on density-weighted thickness

$$\Lambda(r_T) = \frac{1}{\rho_0}\int dz\,\rho(z, r_T)$$

Woods-Saxon

- Break-up has exponential dependence
- EPS09 & initial-state dE/dx have unknown dependences

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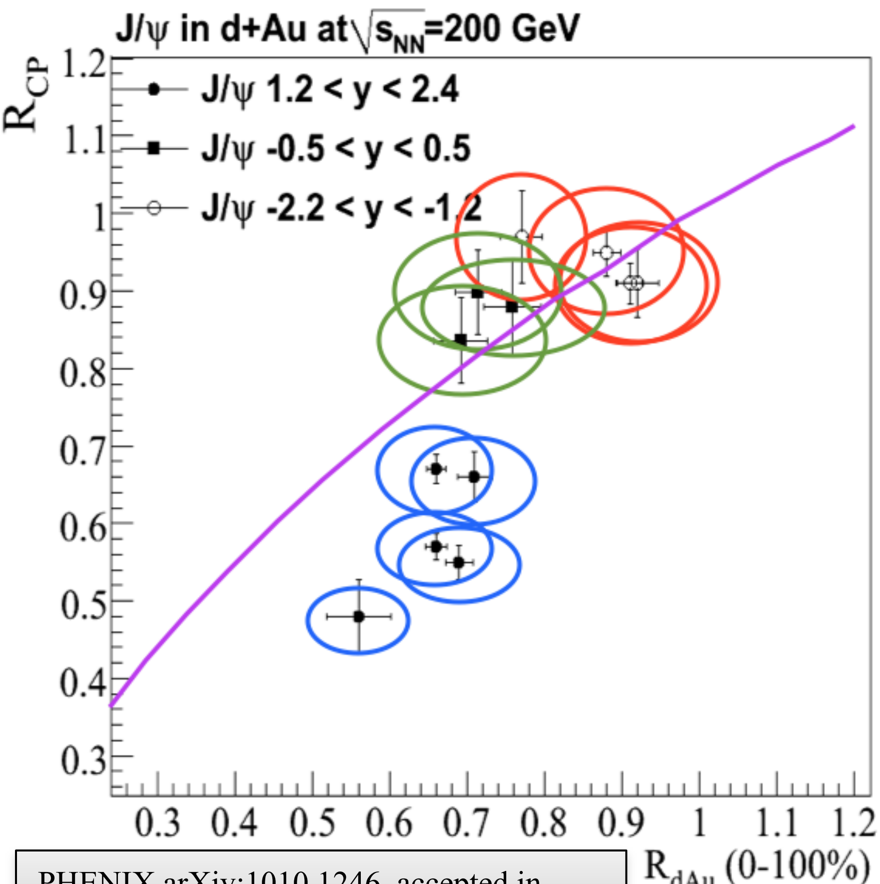

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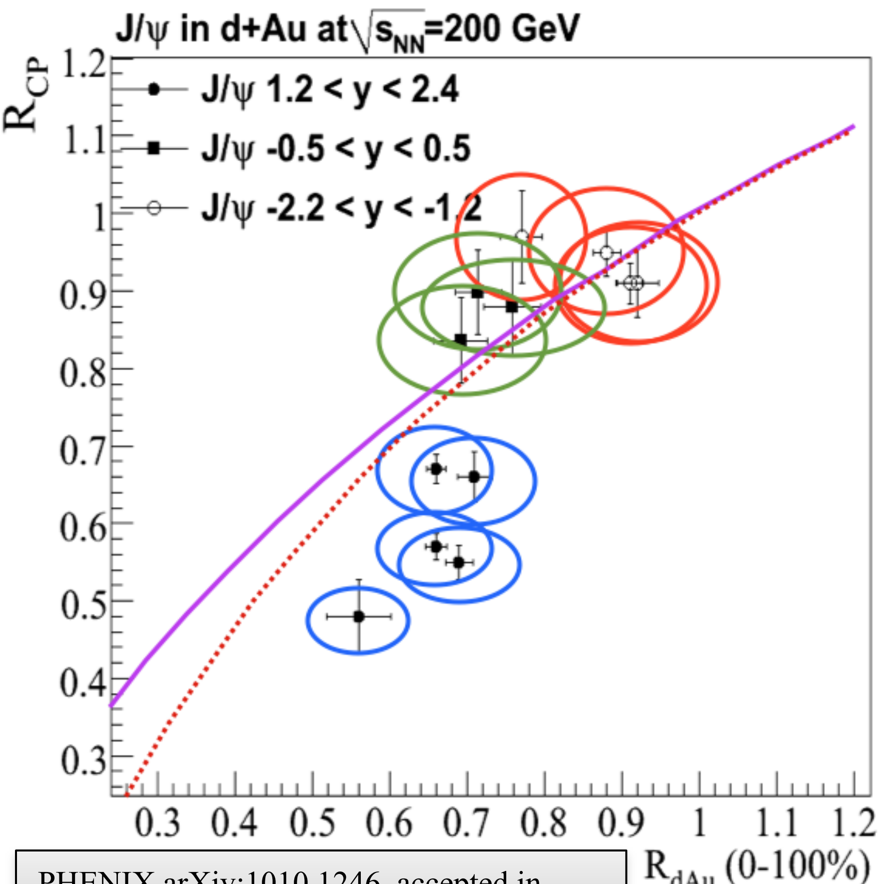

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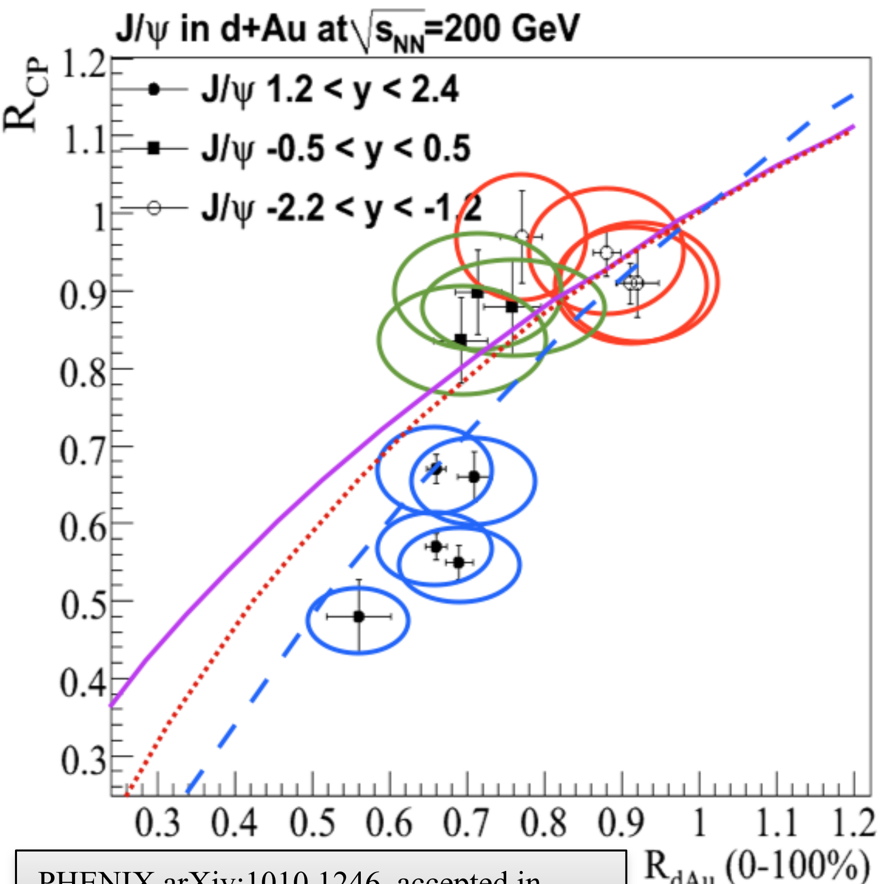

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Linear: $M(r_T) = 1 - a\Lambda(r_T)$

Quadratic: $M(r_T) = 1 - a\Lambda(r_T)^2$

- Break-up has exponential dependence
- EPS09 & initial-state dE/dx have unknown dependences

The forward rapidity points suggests a quadratic or higher geometrical dependence

Recreate the Matter State of the Early Universe

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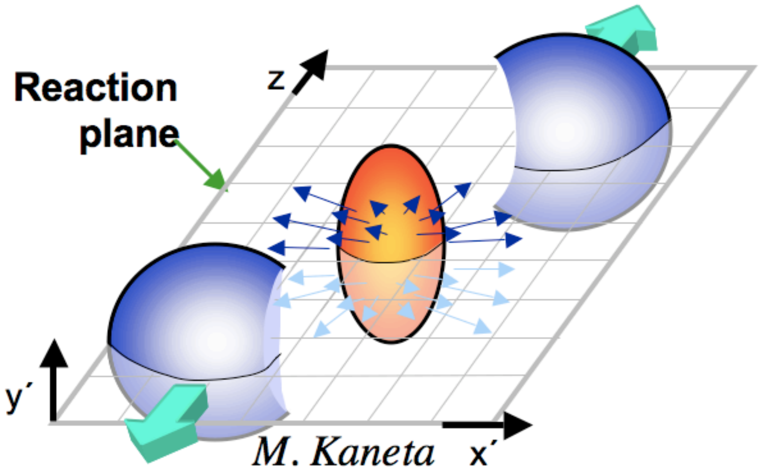
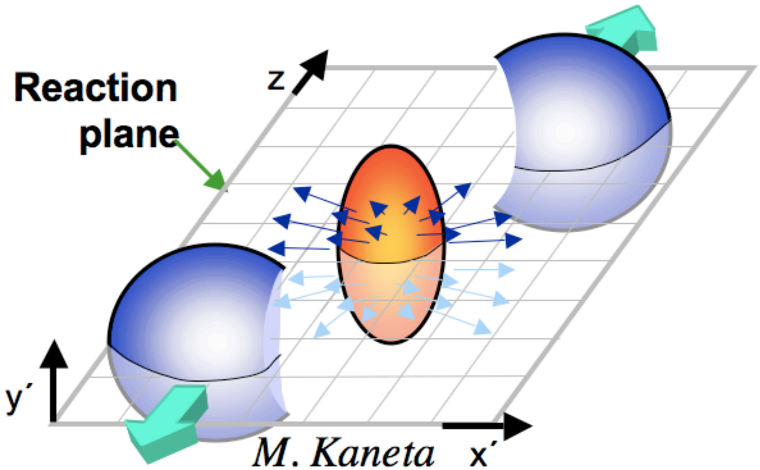
Reaction Plane and Elliptic Flow



Spatial anisotropy

Reaction Plane and Elliptic Flow



Spatial anisotropy

Fourier expansion of the distribution of produced particle angle wrt reaction plane (Δϕ):

$$\frac{dN}{d\Delta\varphi} = N_0\left[1 + 2v_1 \cos 2\Delta\varphi + 2v_2 \cos 2\Delta\varphi + \cdots\right]$$

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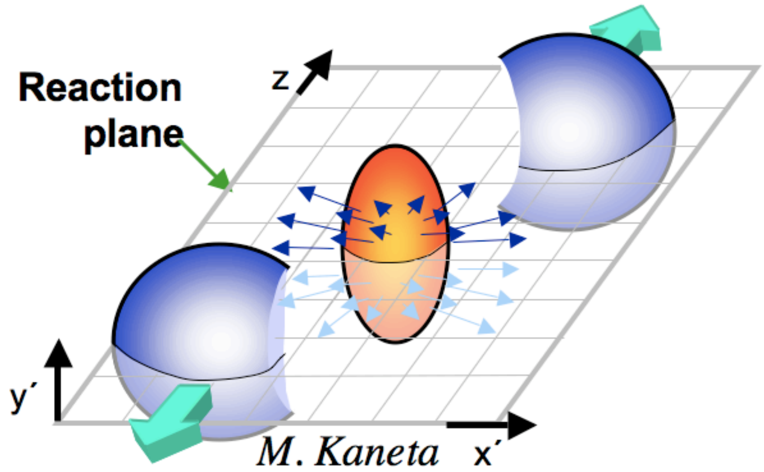

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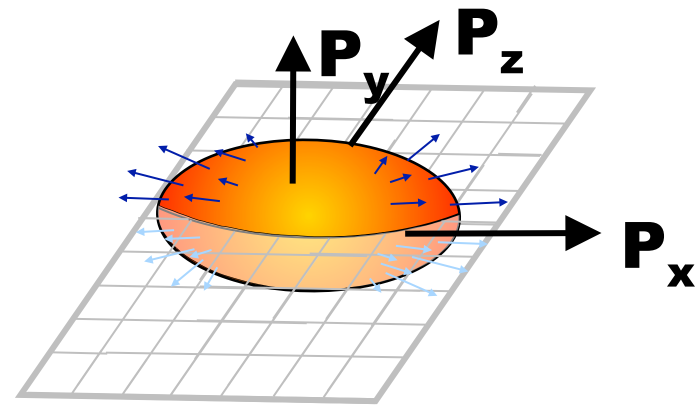

Momentum anisotropy

Fourier expansion of the distribution of produced particle angle wrt reaction plane (Δϕ):

$$\frac{dN}{d\Delta\varphi} = N_0\left[1 + 2v_1\cos 2\Delta\varphi + 2v_2\cos 2\Delta\varphi + \cdots\right]$$

- Momentum anisotropy reflects the characteristics of the hot, dense medium
  - Small mean free path, thermalization, pressure gradients
- v_2 long considered a powerful probe for QGP studies