Scanning for changes PHENIX results from the low energy RHIC runs

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introduction

RHIC : The Relativistic Heavy Ion Collider

Super conducting collider
3.8 km circumference
First beams in June 2000.

polarized p + p
Transversal, Longitudinal
62.4, 200, 500 GeV/c

d + Au
200 GeV/c

Au + Au
7.7, 9.2, 11, 19.6, 27, 39, 62.4, 130, 200 GeV/c

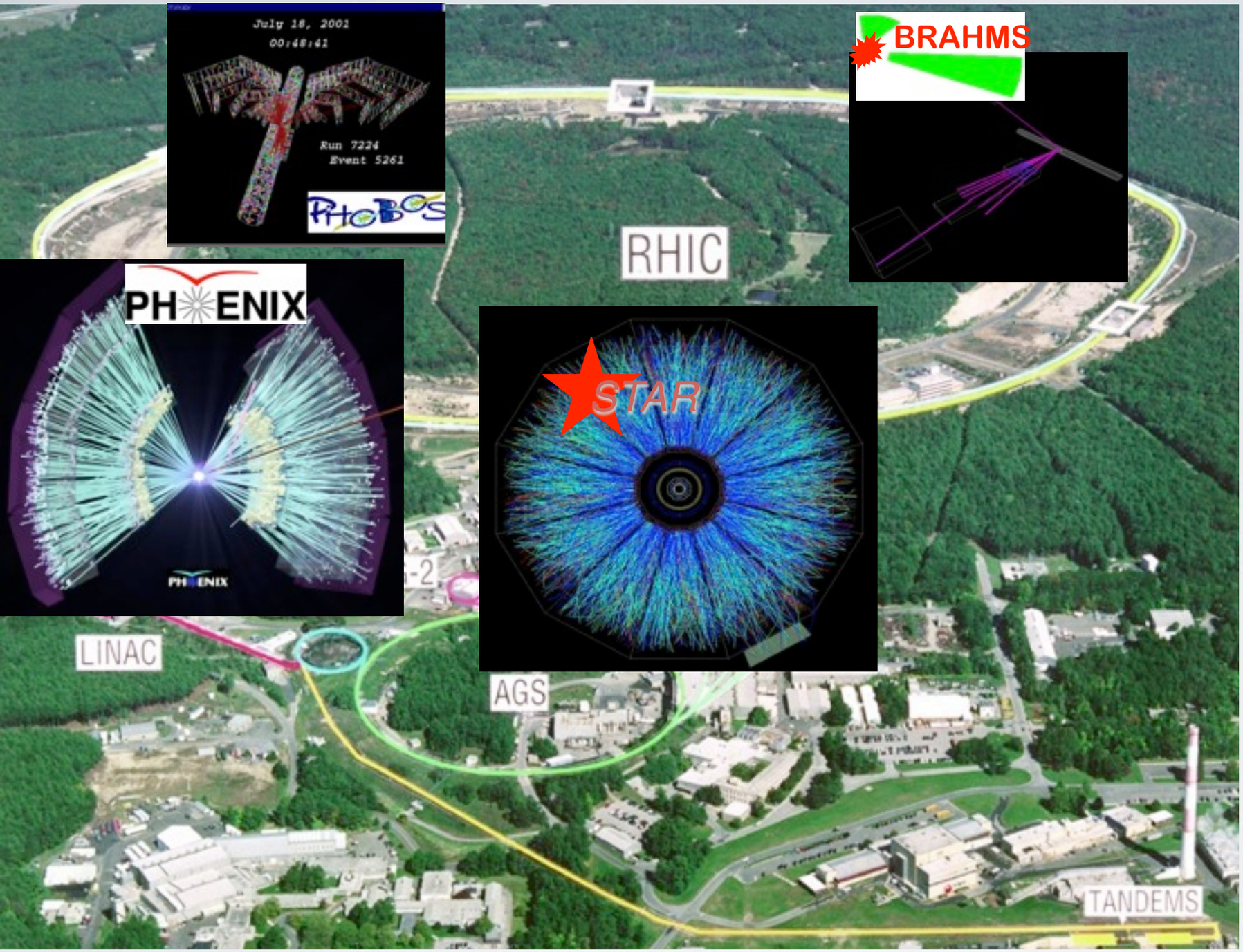
Cu + Cu
22.4, 62.4, 200 GeV/c

Cu + Au
200 GeV/c

U + U
193 GeV/c

Search for and study of the Quark-Gluon Plasma
Explore the partonic spin structure of the proton
Study of partonic structure of nucleon and nuclei

RHIC : The Relativistic Heavy Ion Collider



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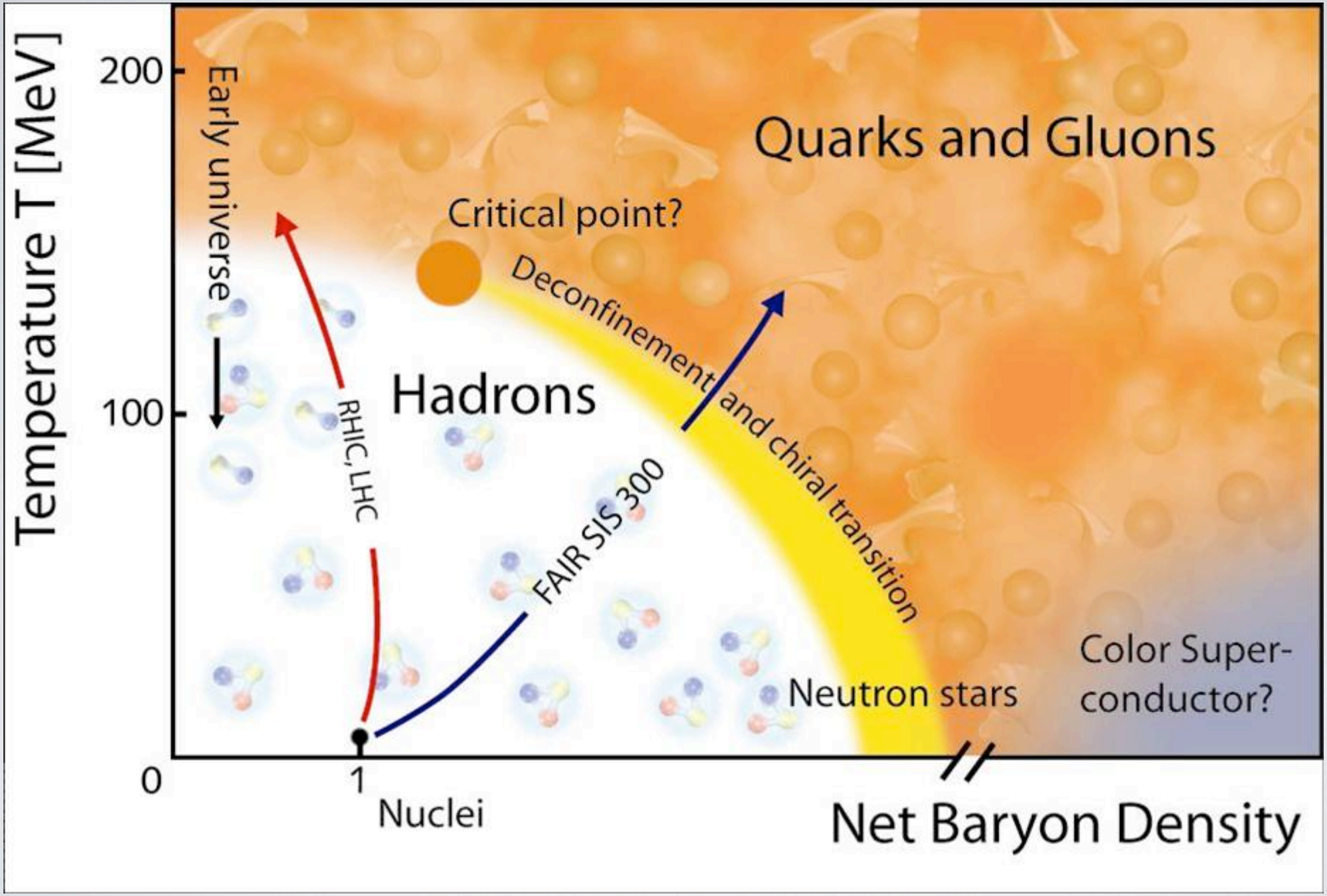
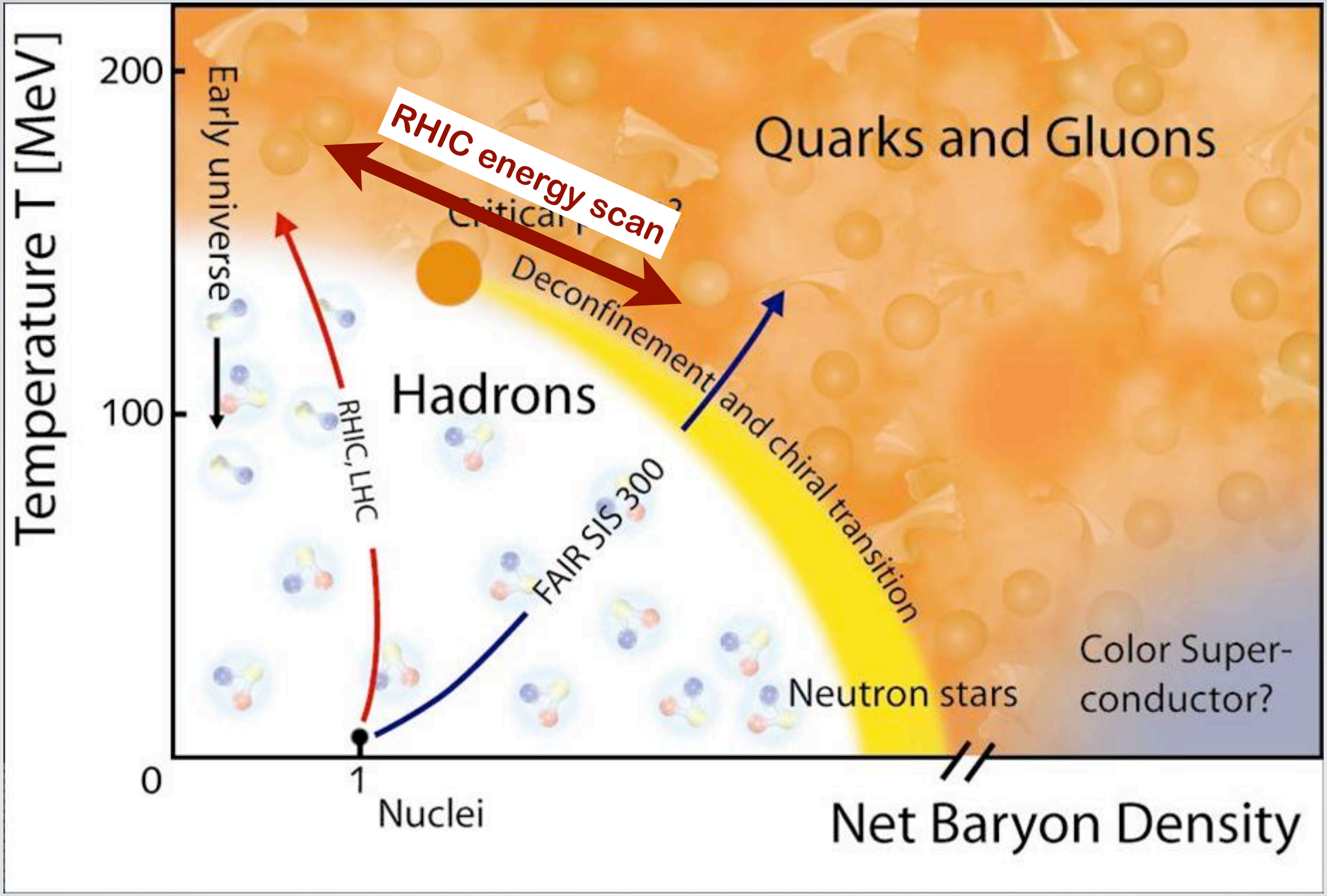
phase diagram of nuclear matter



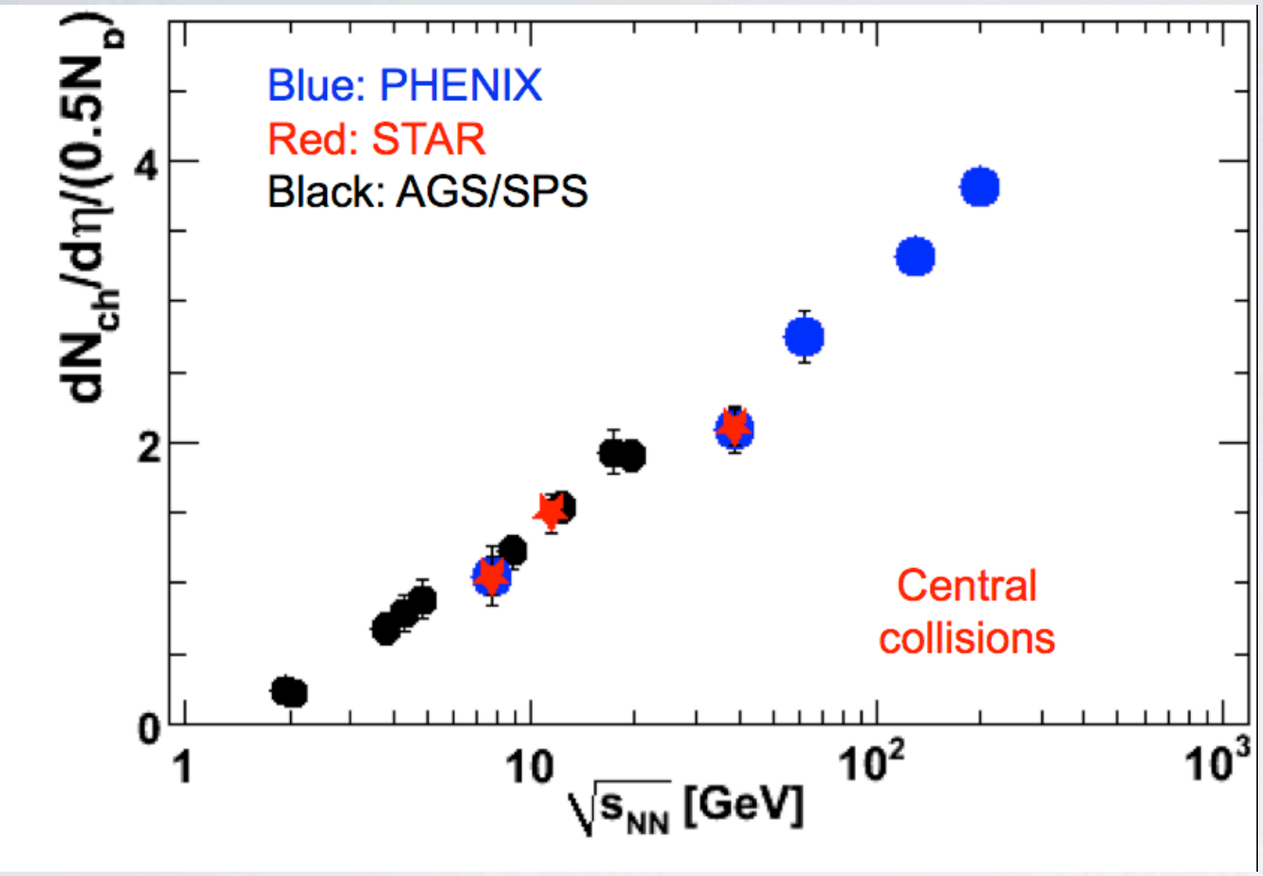
μ_B

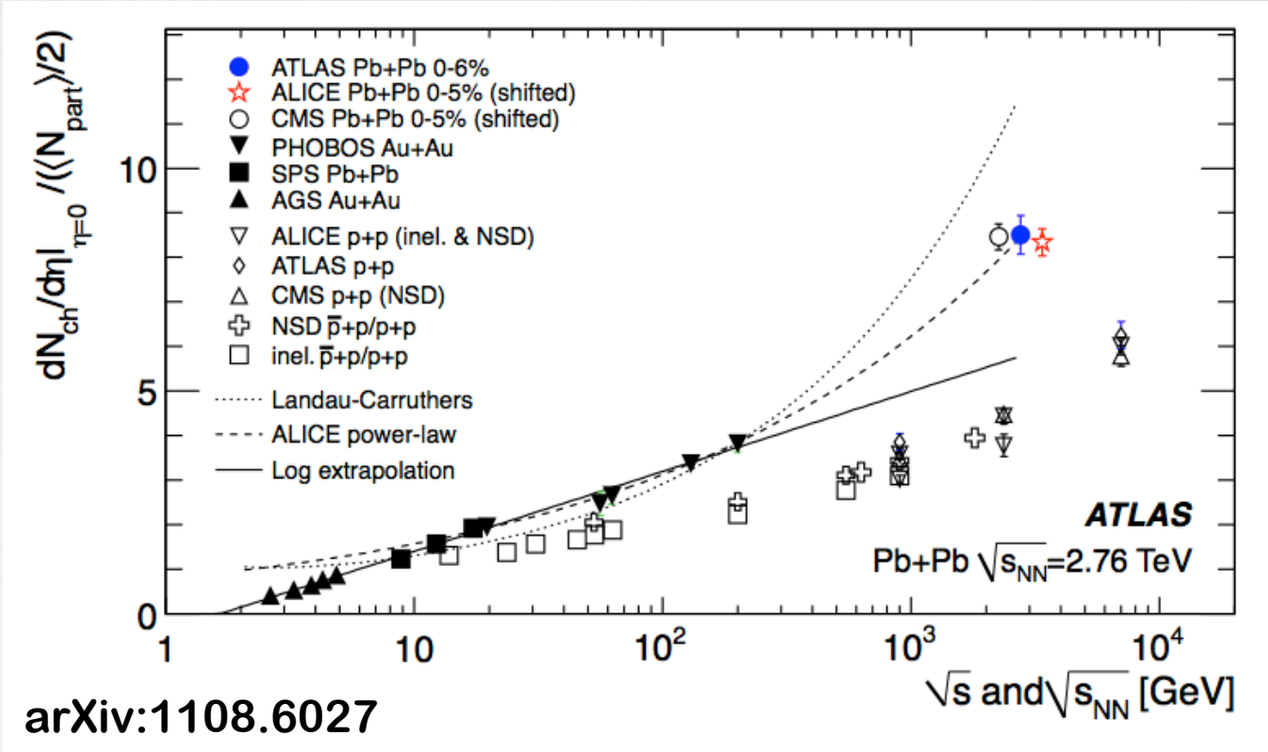
phase diagram of nuclear matter



global observables

$dN_{ch}/d\eta$ (1)

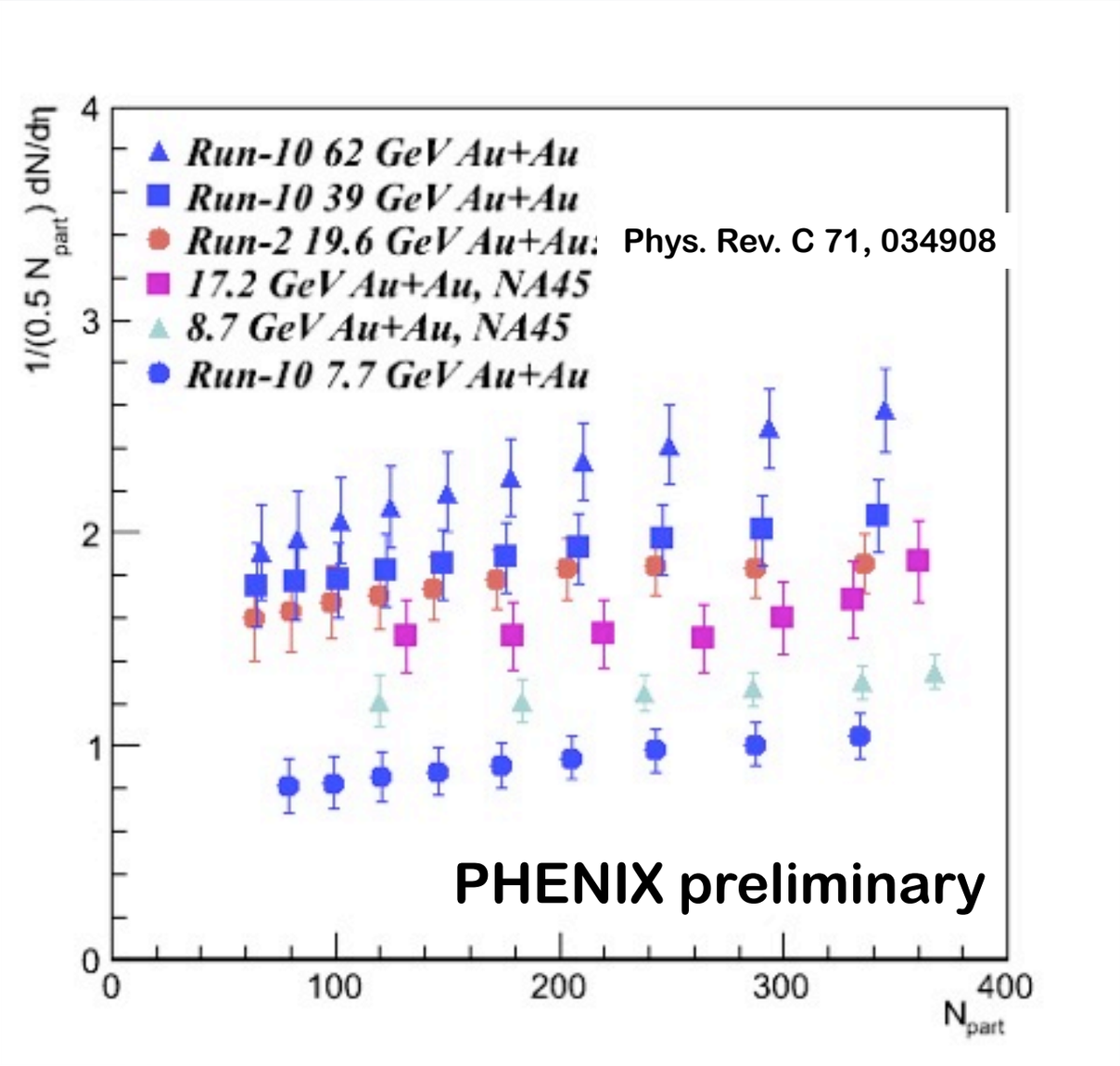


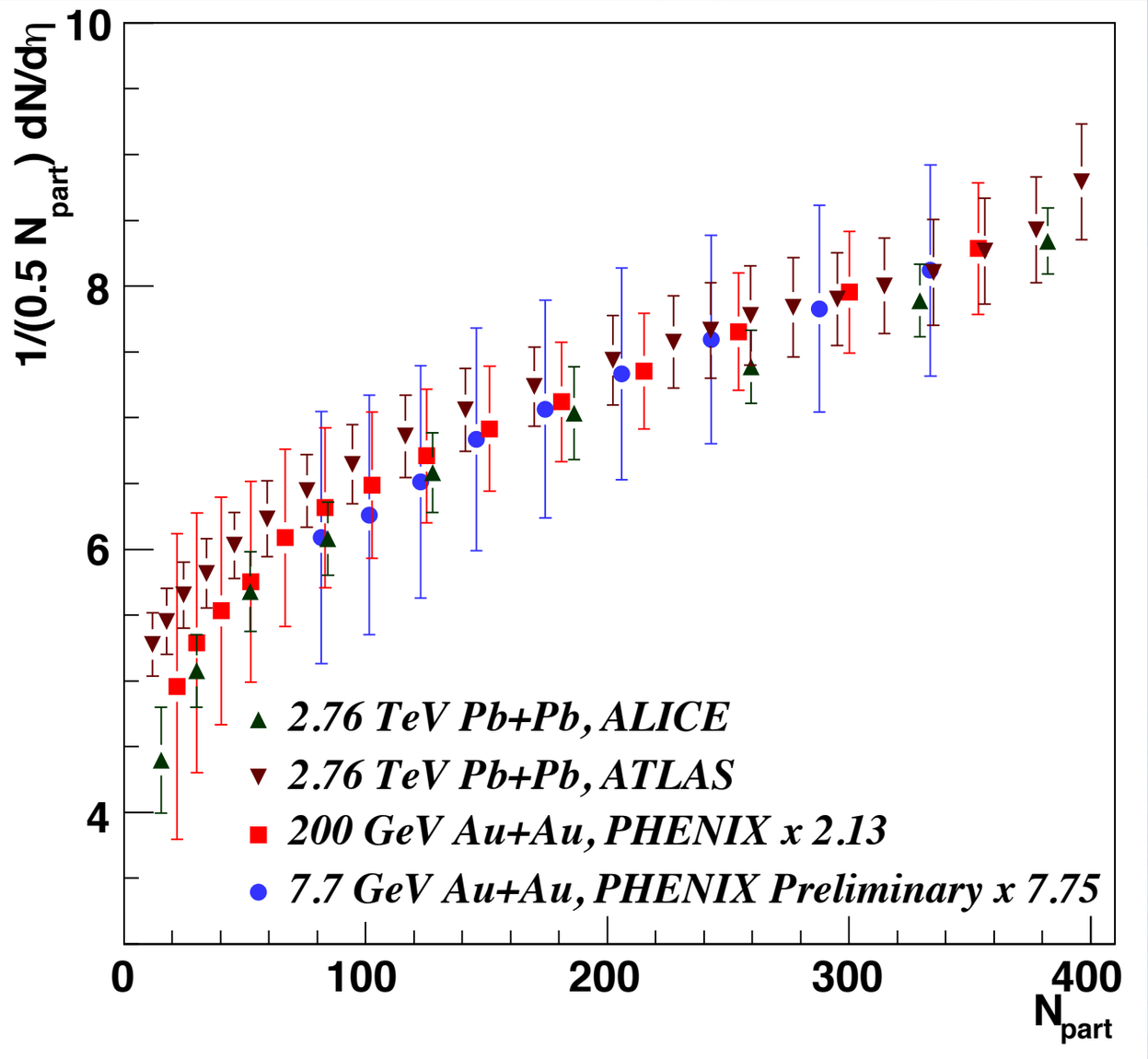


arXiv:1108.6027

- For RHIC energies the multiplicity per participant increases linearly with $\log(\sqrt{s_{NN}})$
- deviates for LHC energies

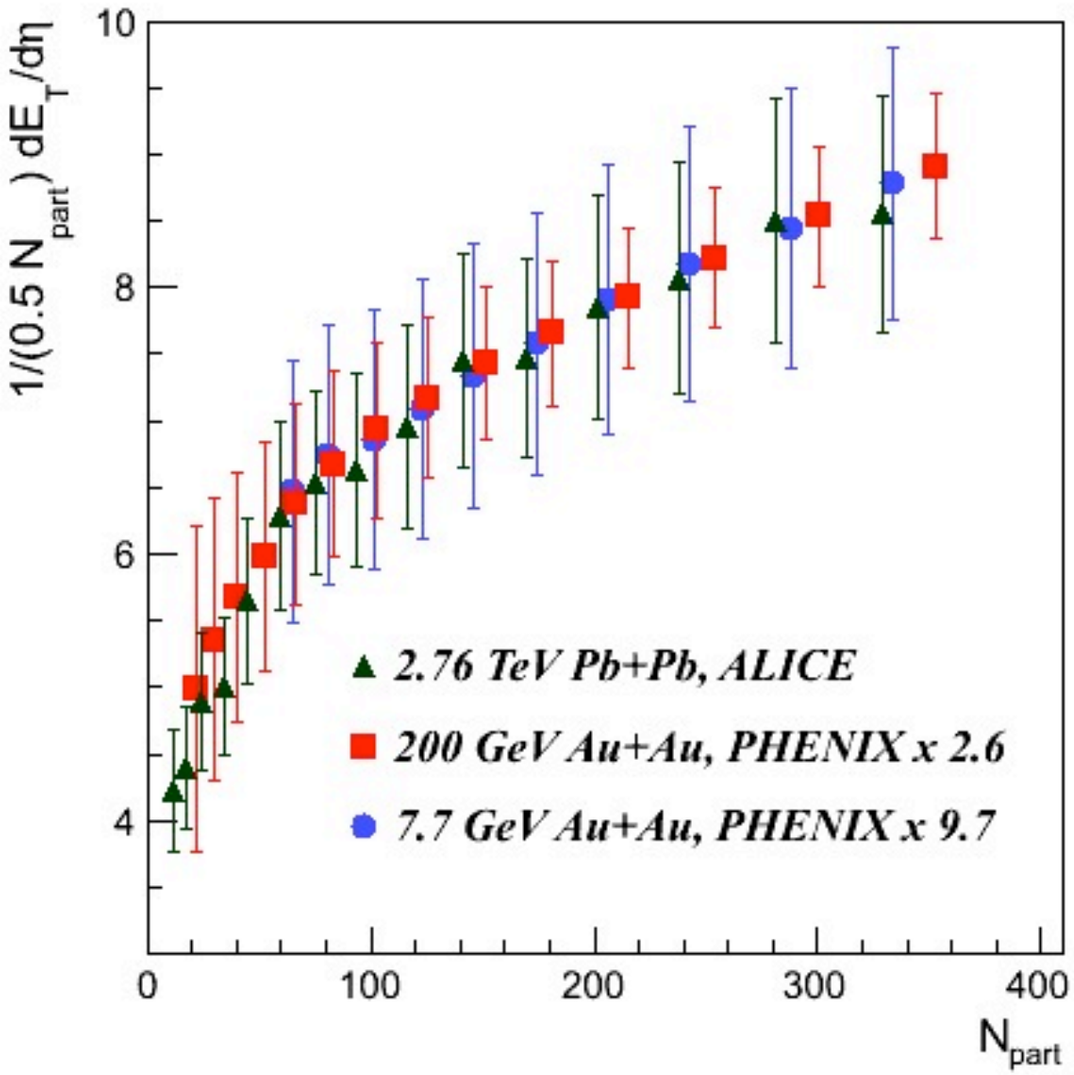
$dN_{ch}/d\eta$ (2)

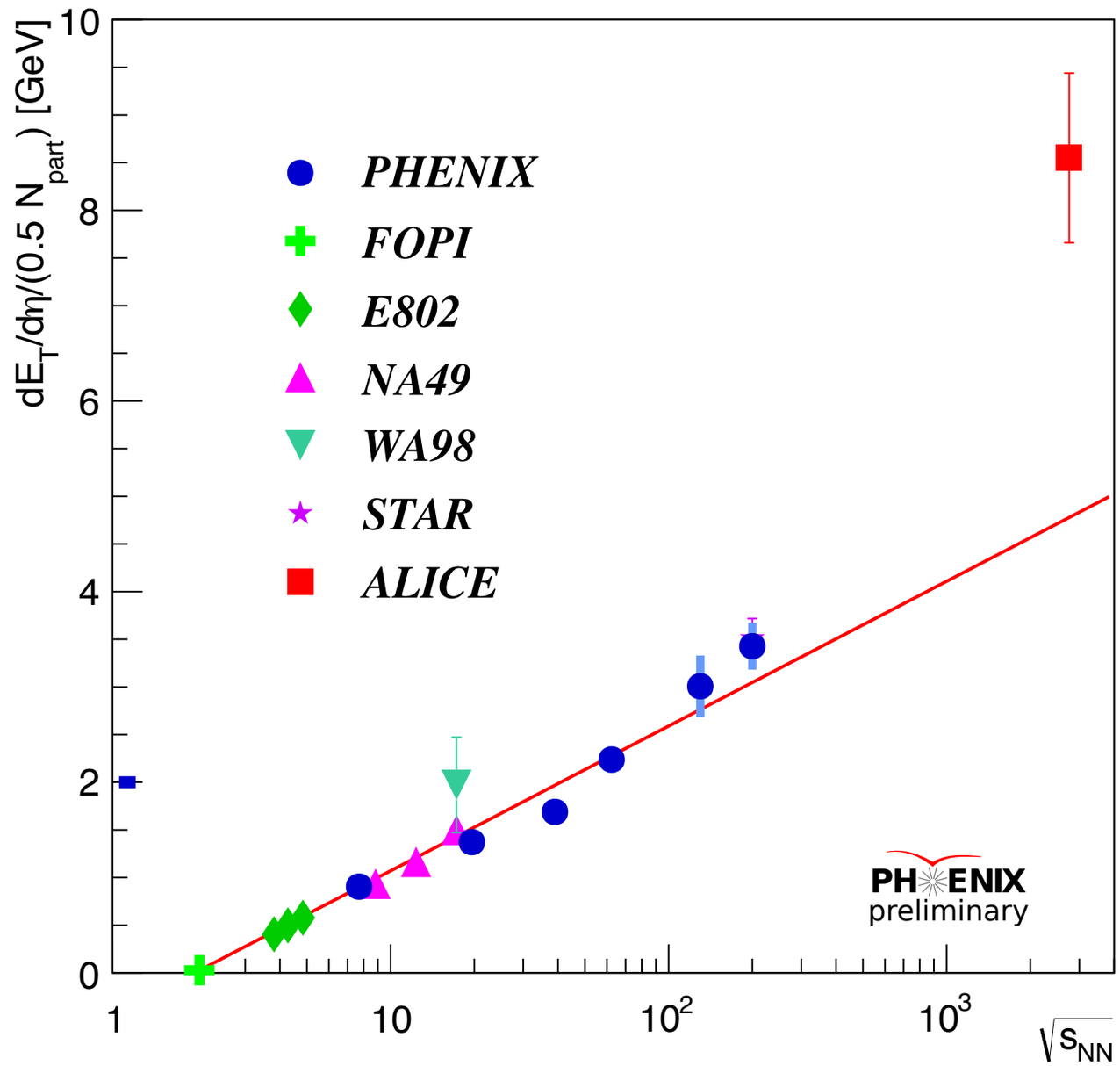




There is no significant change in the centrality-dependence of charged particle production between 7.7 GeV/c Au+Au and 2.76 TeV/c Pb+Pb collisions.

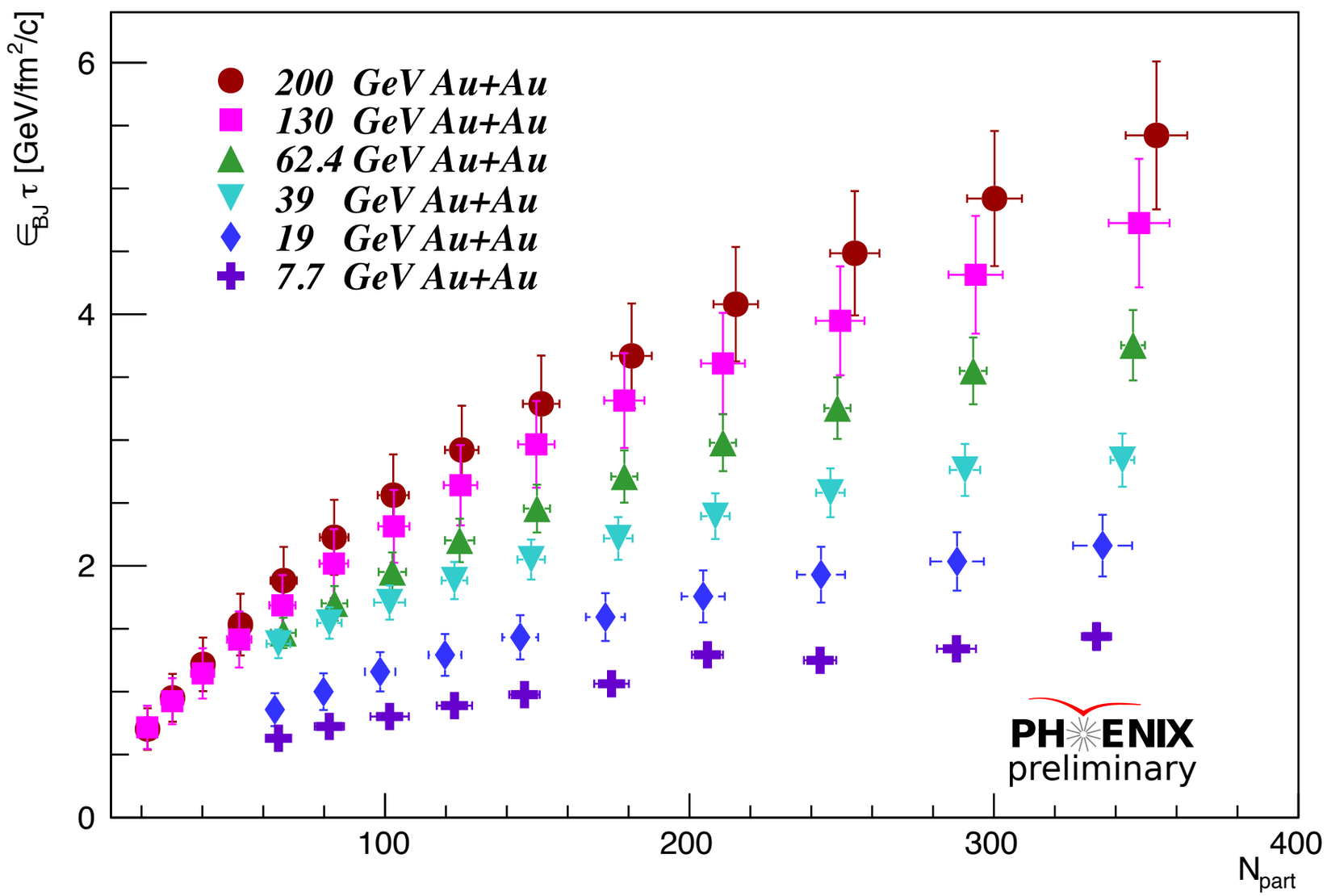
$dE_T/d\eta$





- **There is no significant change in the centrality-dependence of the transverse energy production between 7.7 GeV/c Au+Au and 2.76 TeV/c Pb+Pb collisions.**
- **$dE_T/d\eta$ per participants shows strong increase towards LHC energies.**

energy density



$$\epsilon_{Bj} = \frac{1}{A_\perp \tau} \frac{dE_T}{dy}$$

$A_\perp$ = transverse overlap area of the nuclei, determined from the Glauber model.

τ = formation time

$dE_T/d\eta$ is multiplied by 1.25 to obtain dE_T/dy at SPS energies.

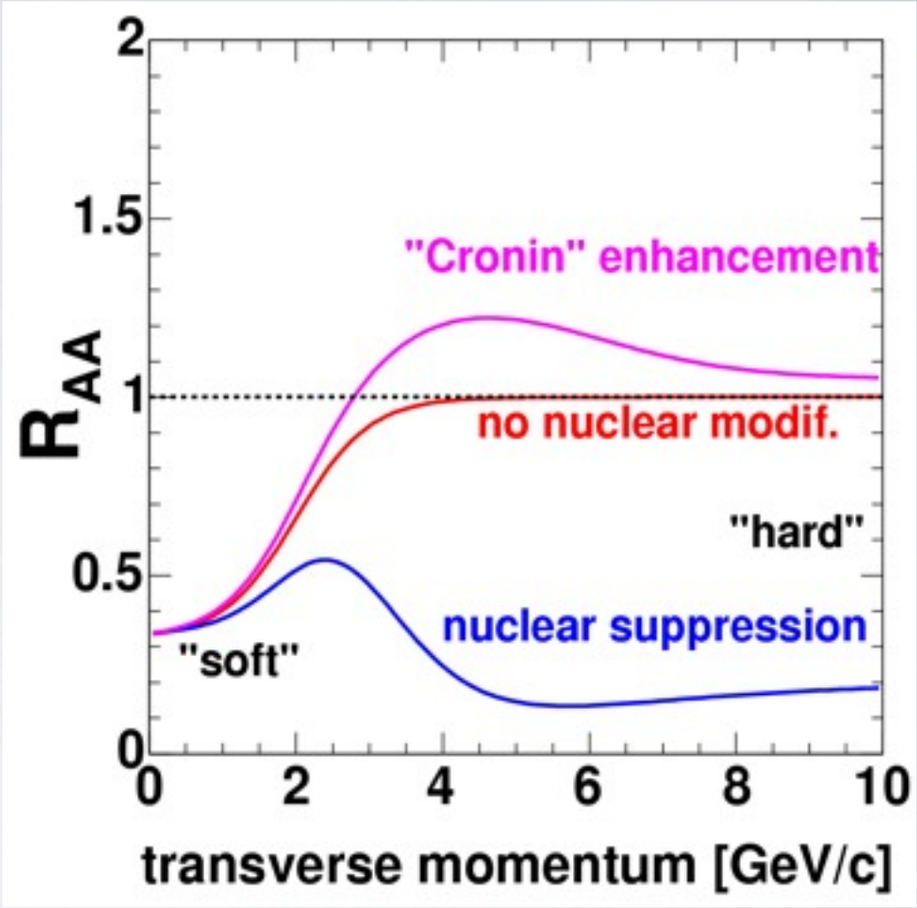
the Bjorken energy density in central collisions increases by a factor of 3.8 from 7.7 to 200 GeV/c.

It increases by a factor of 11.1 when going from 7.7 GeV/c to 2.76 TeV/c.

nuclear modification factor

nuclear modification factor - R_{AA}

$$R_{AA}(p_T) = \frac{\frac{1}{N_{AA}^{evt}} \frac{d^2 N_{AA}}{dp_T dy}}{<T_{AA}> \frac{d^2 \sigma_{pp}}{dp_T dy}}$$



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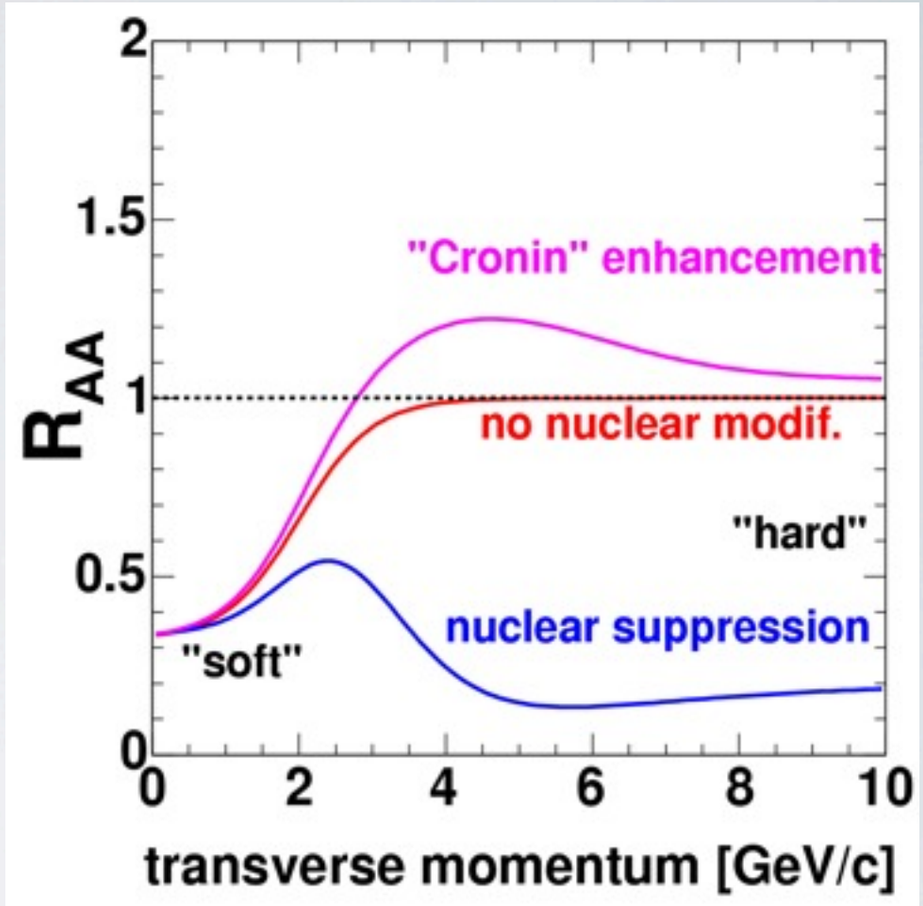
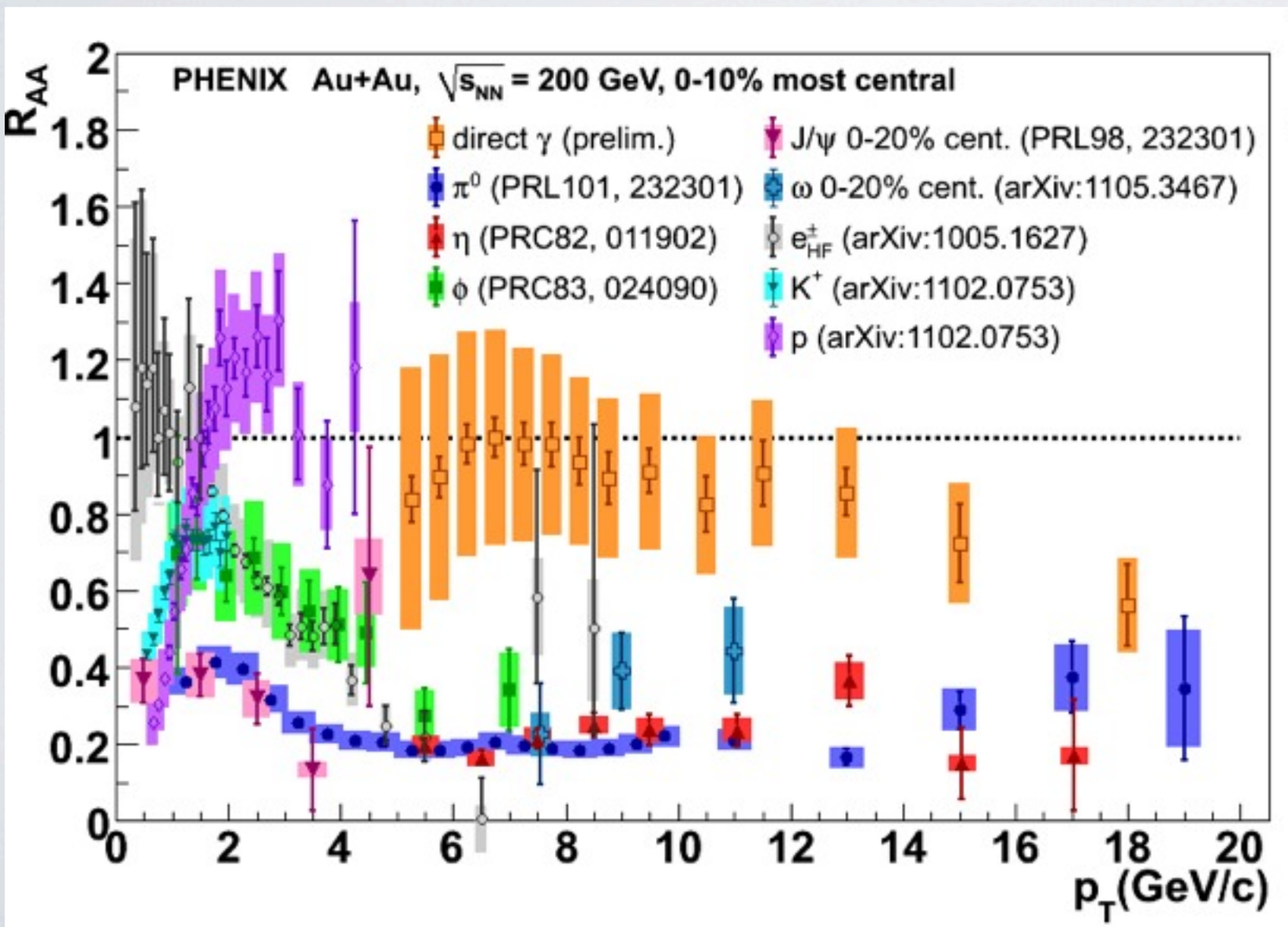


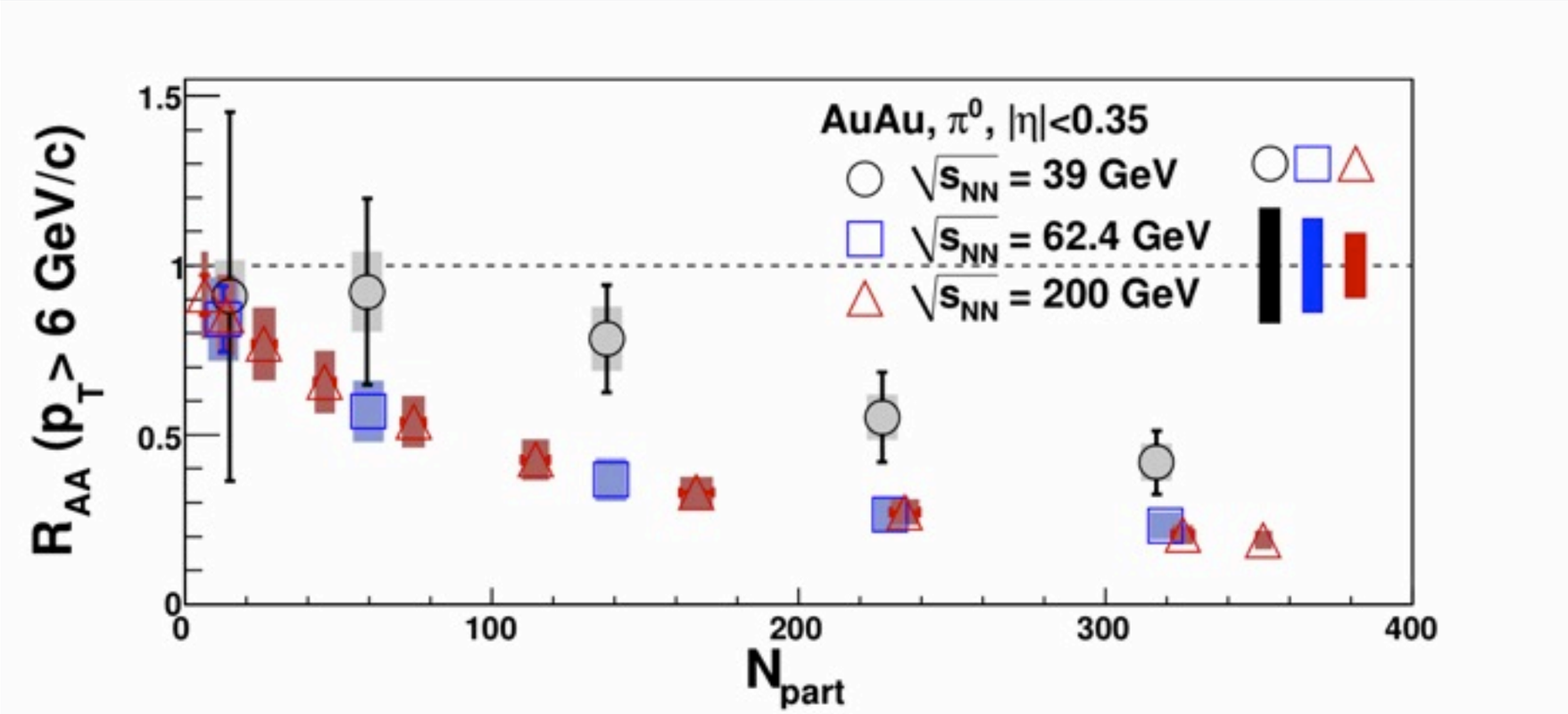


large dataset with various identified particles

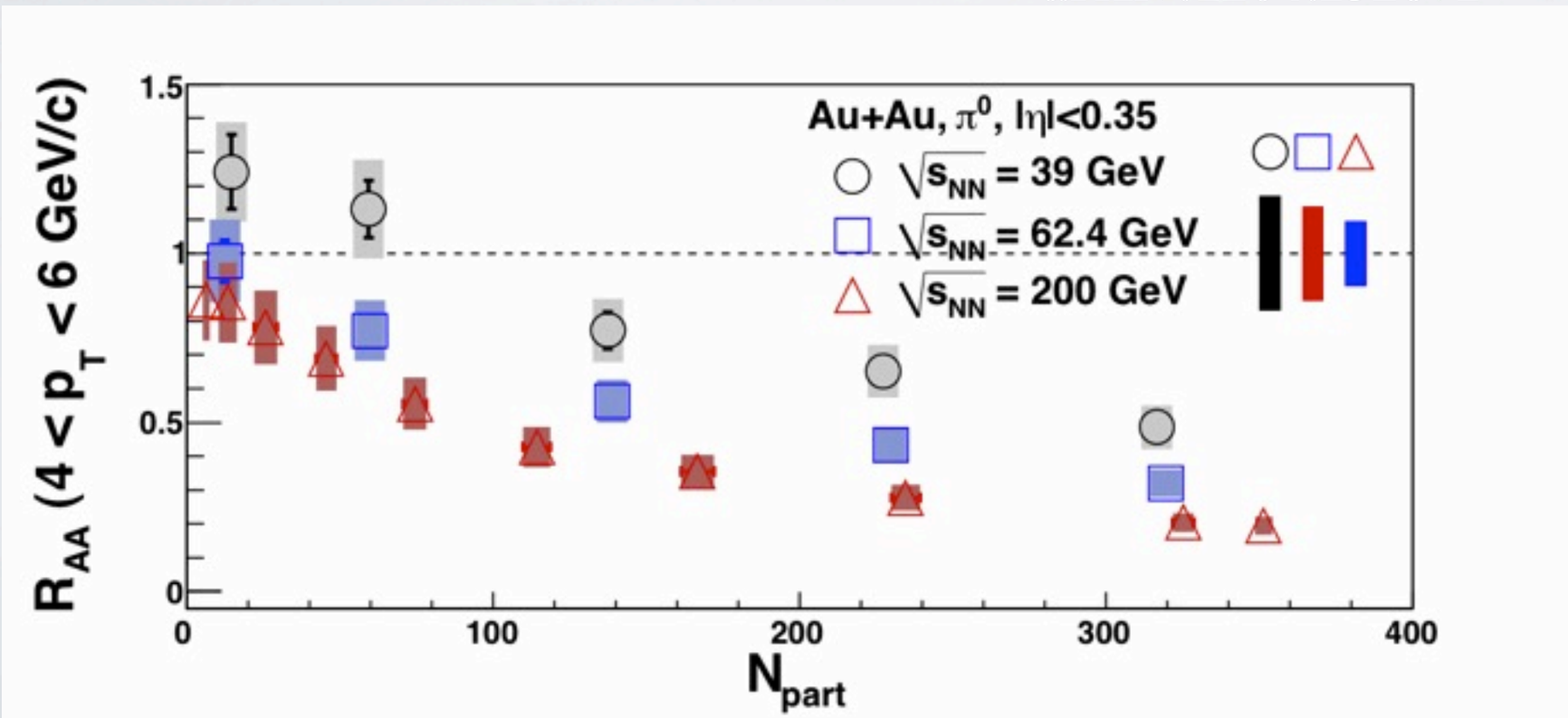
suppression even for heavy quarks, not for direct photons

challenge to theories and models

p_T averaged R_{AA} - AuAu @ $\sqrt{s_{NN}}$ = 39, 62.4, 200 GeV/c



arXiv:1204.1526v1



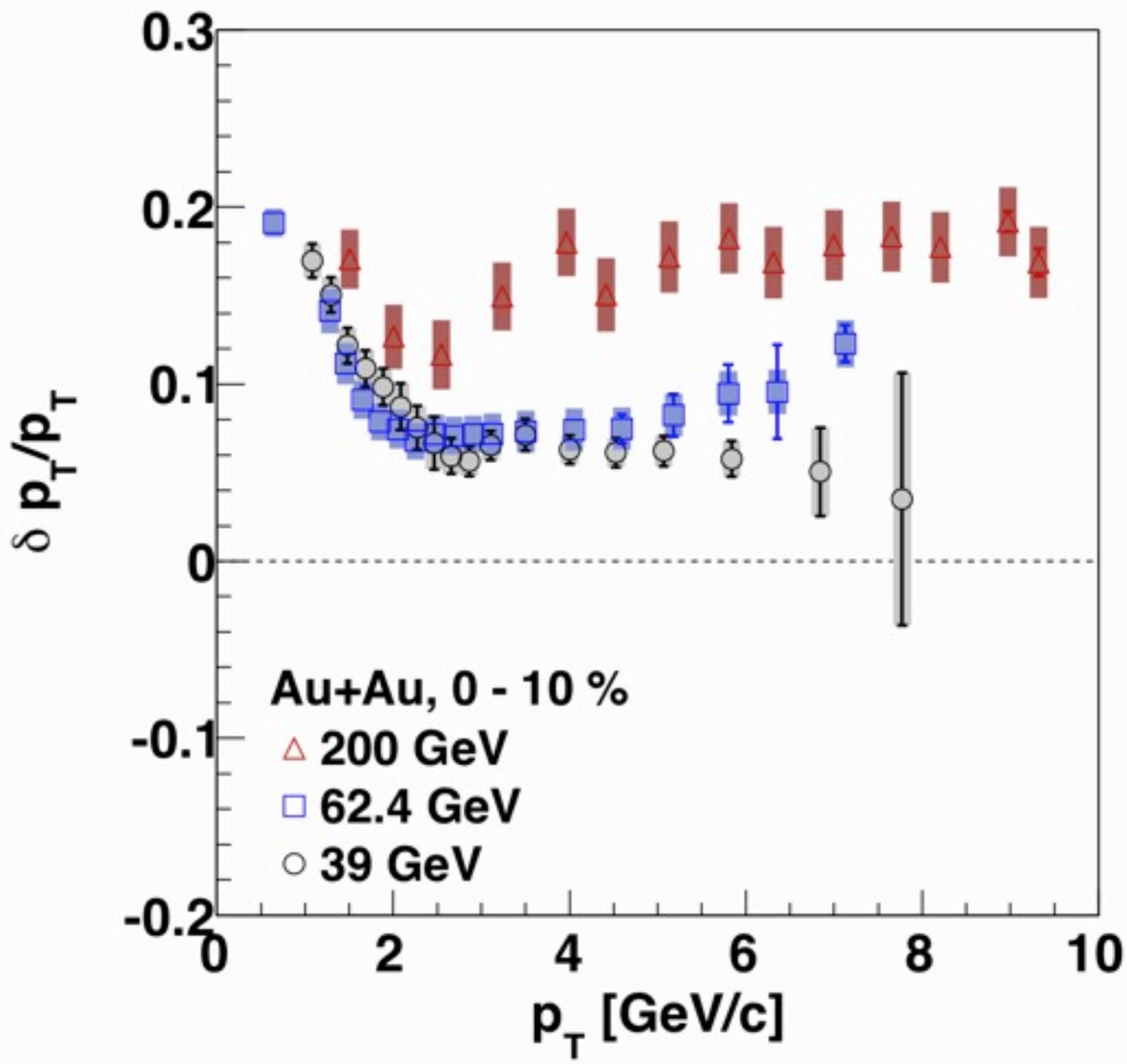
4 < p_T < 6 and p_T > 6

- 62.4-200 GeV are strongly suppressed
- 39.0 GeV data shows suppression for higher centrality only (N_{part}>100), soft processes still dominant
- For p_T > 6 GeV/c the 62.4 and 200 GeV data points are comparable

fractional energy loss - AuAu @ $\sqrt{s_{NN}}$ = 39, 62.4, 200 GeV/c

$$\frac{\left(1/N_{evt}^{AA}\right)d^2N^{AA}(p_T)/dp_T dy}{\langle T_{AA}\rangle} = \frac{d^2\sigma^{pp}\left[p_T' = p_T + S(p_T)\right]}{dp_T' dy}\cdot\left[1 + dS(p_T)/dp_T\right]$$

$= 0$



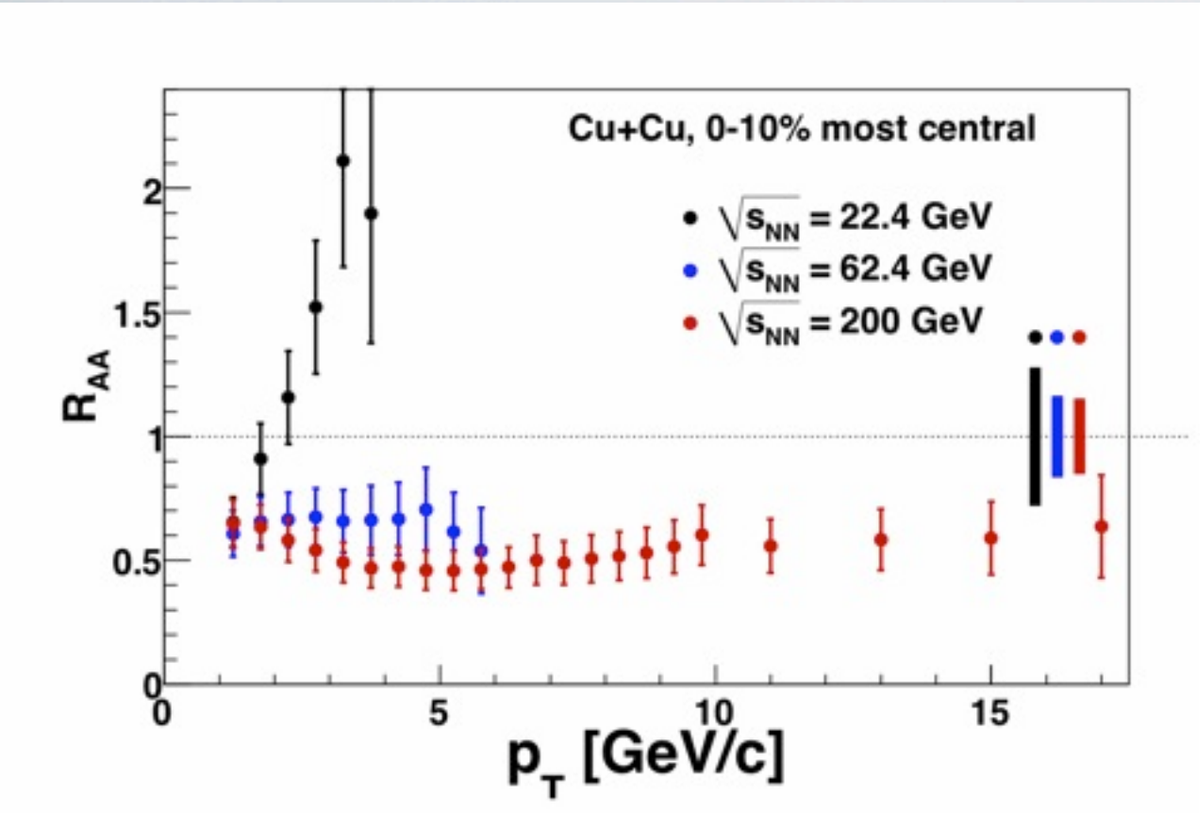
Fractional energy loss: $S(p_T) = \delta p_T / p_T$

The definition of the energy loss is the "horizontal" shift of the p+p spectrum towards the T_{AA} scaled Au+Au spectra:

- **200 GeV exhibits the largest energy loss**
- **62 GeV and 39 GeV data points are in agreement for p_T < 5 GeV/c**

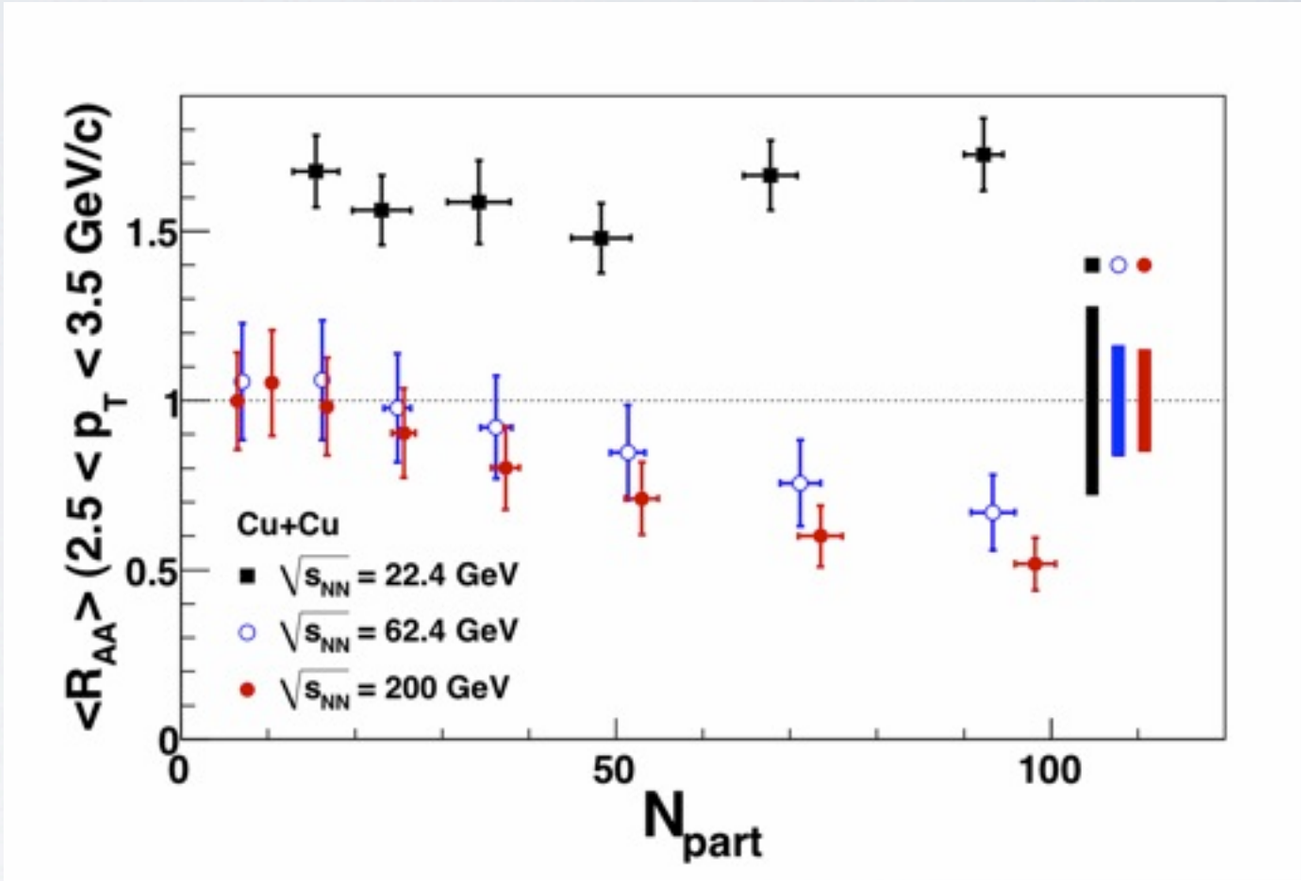
arXiv:1204.1526v1

π^0 R_{AA} - Cu Cu @ $\sqrt{s_{NN}}$ = 22.4, 62.4, 200 GeV/c



Phys. Rev. Lett.101, 162301 (2008)

$2.5 < p_T < 3.5$ GeV/c

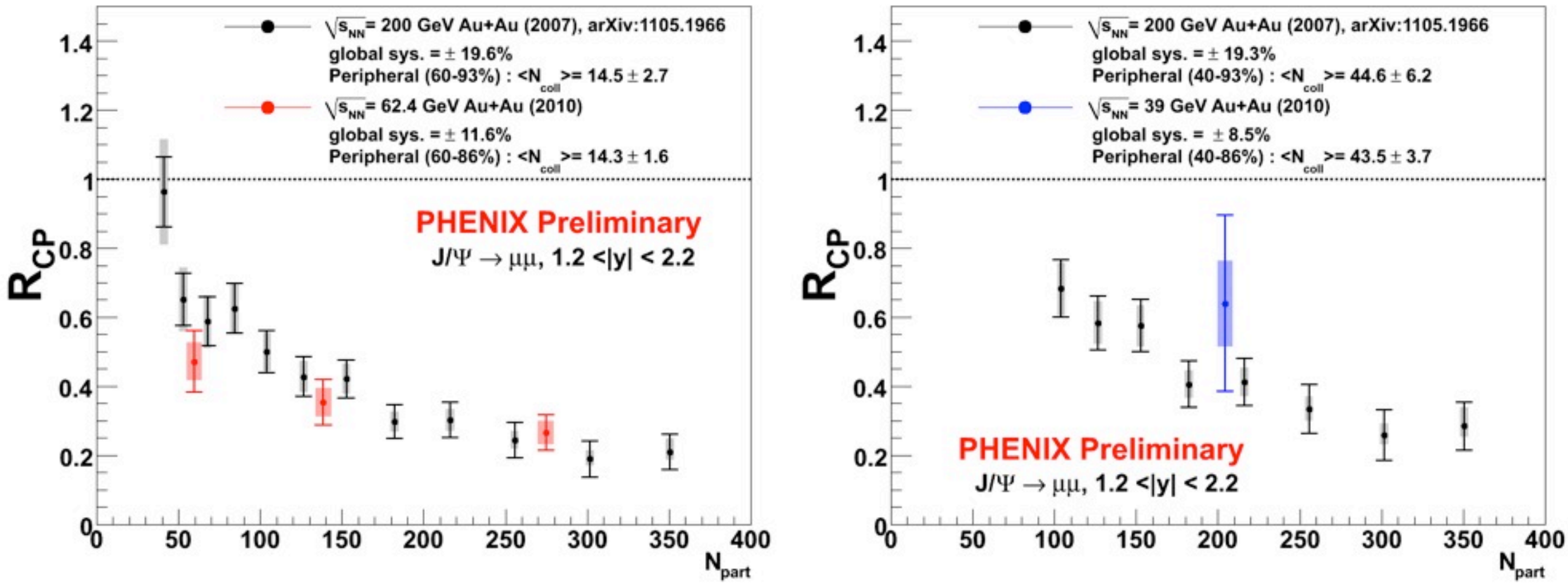


- no suppression, rather Cronin enhanced @ $\sqrt{s_{NN}}$ = 22.4 GeV
- centrality dependence of $\langle R_{AA} \rangle$ @ $\sqrt{s_{NN}}$ = 200 and 62.4 GeV
- no centrality dependence of $\langle R_{AA} \rangle$ @ $\sqrt{s_{NN}}$ = 22.4 GeV

for low p_T range

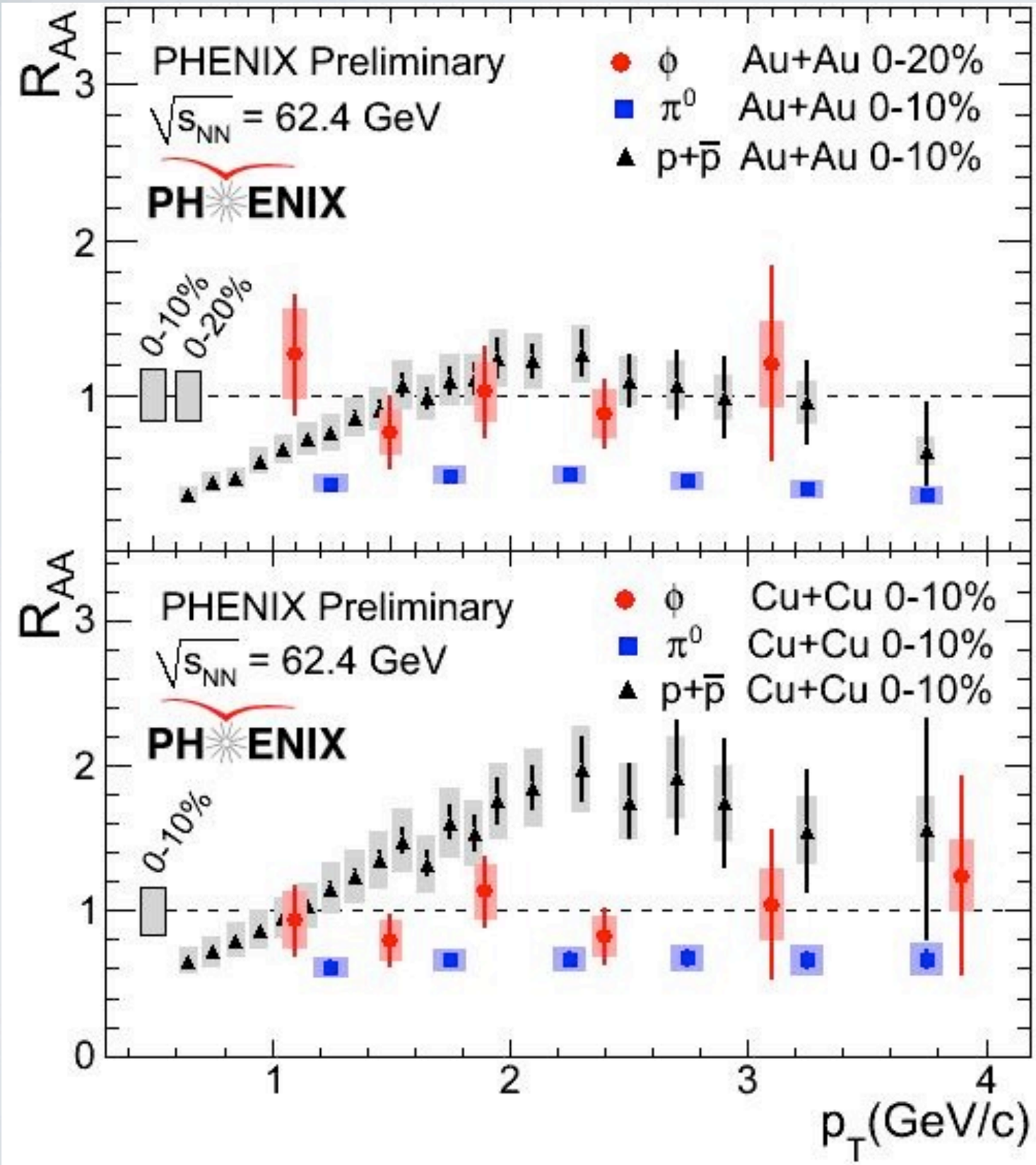
J/Ψ R_{cp} (central / peripheral) @ $\sqrt{s_{NN}}$ = 39, 62.4, 200 GeV/c

J. Phys. G: Nucl. Part. Phys. 38 124108



- PHENIX does not yet have a p+p reference at 39 and 62.4 GeV/c (working on it).
- lacking a reference, R_{CP} can still give us insight about the suppression level.
- the suppression is at a similar level at all energies.

Φ - R_{AA} - Au Au and Cu Cu @ $\sqrt{s_{NN}}$ = 62.4 GeV



Φ is not suppressed at $\sqrt{s_{NN}}$ = 62.4 GeV/c Au Au or Cu Cu

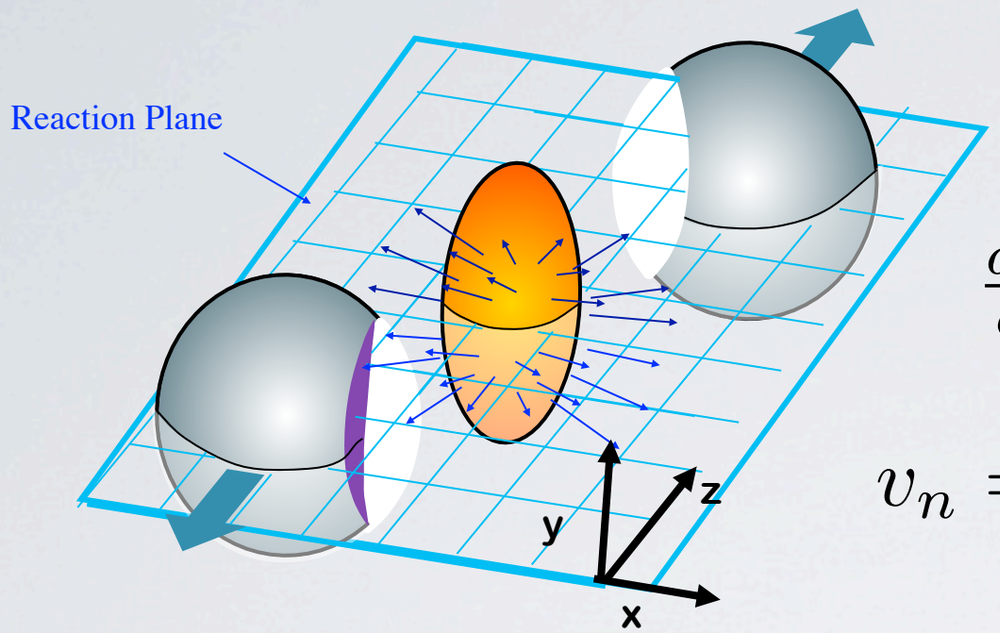
protons show a large Cronin enhancement in Cu Cu

overall level of suppression is reduced even for π^0

~0.2 for central 200GeV/c Au Au

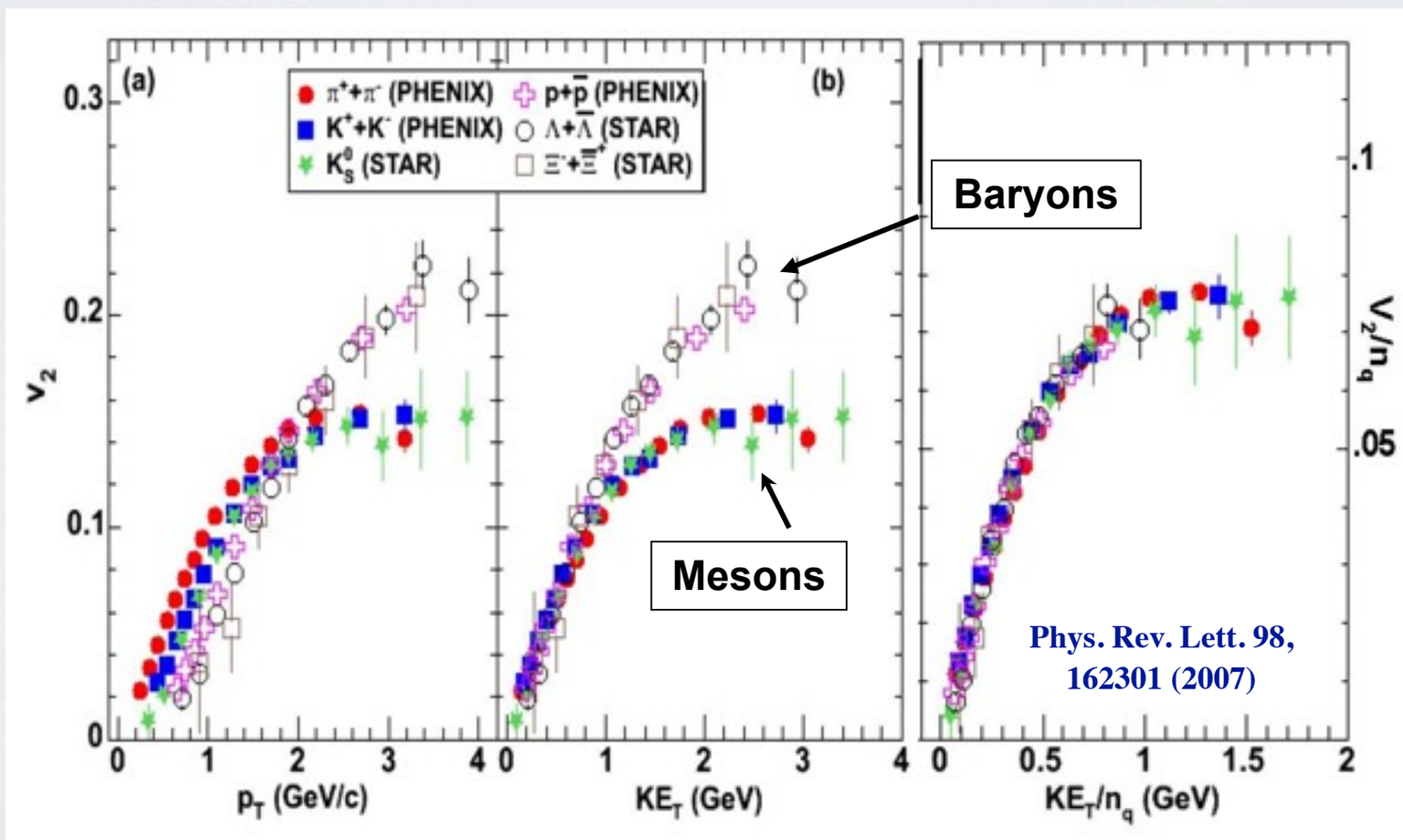
flow

flow

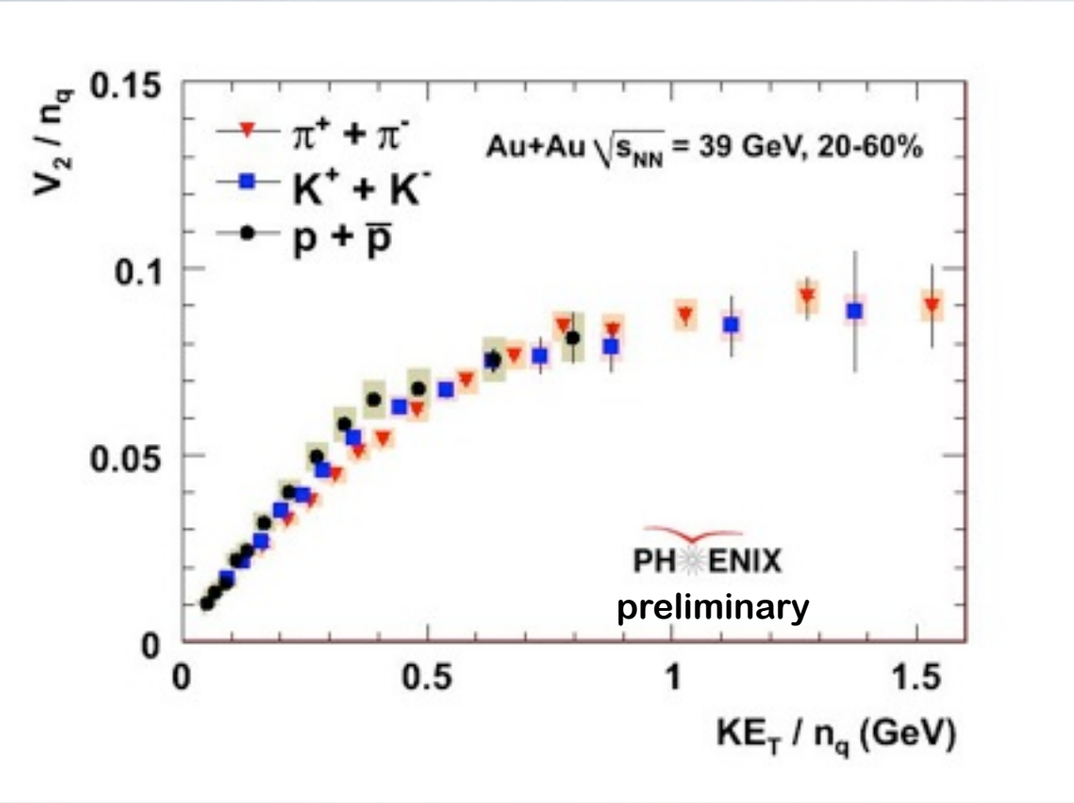


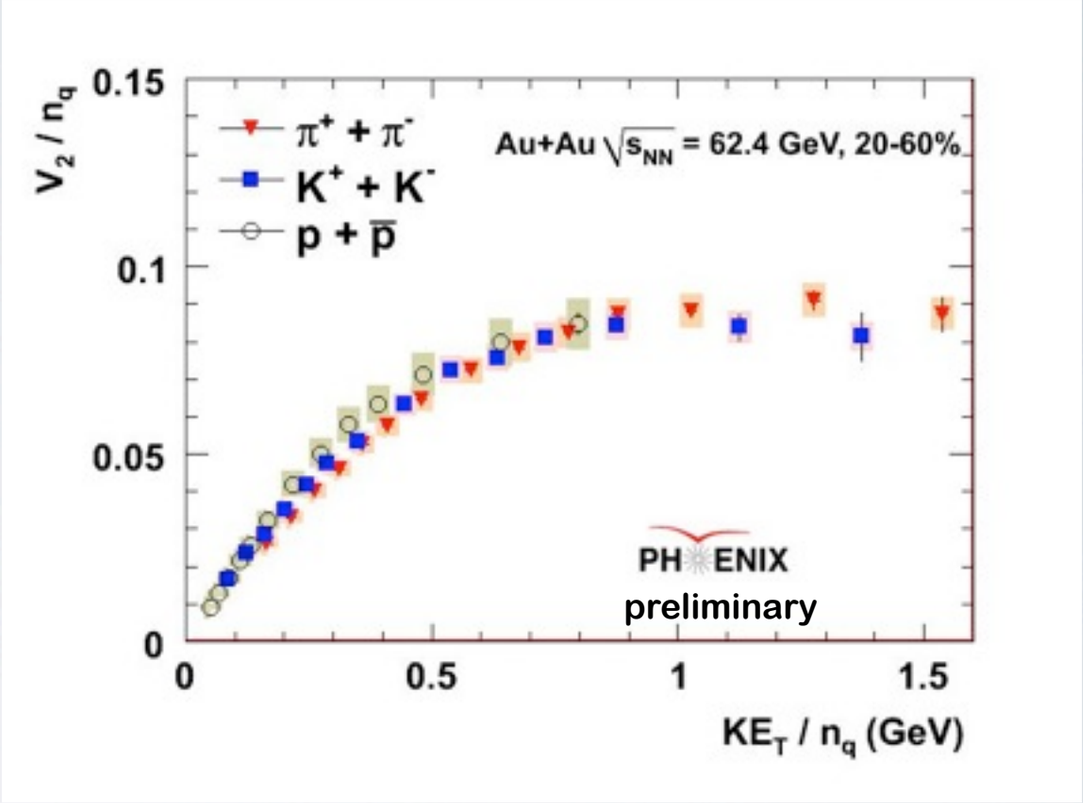
$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{m} 2v_n \cos(n(\phi - \Psi_n))$$

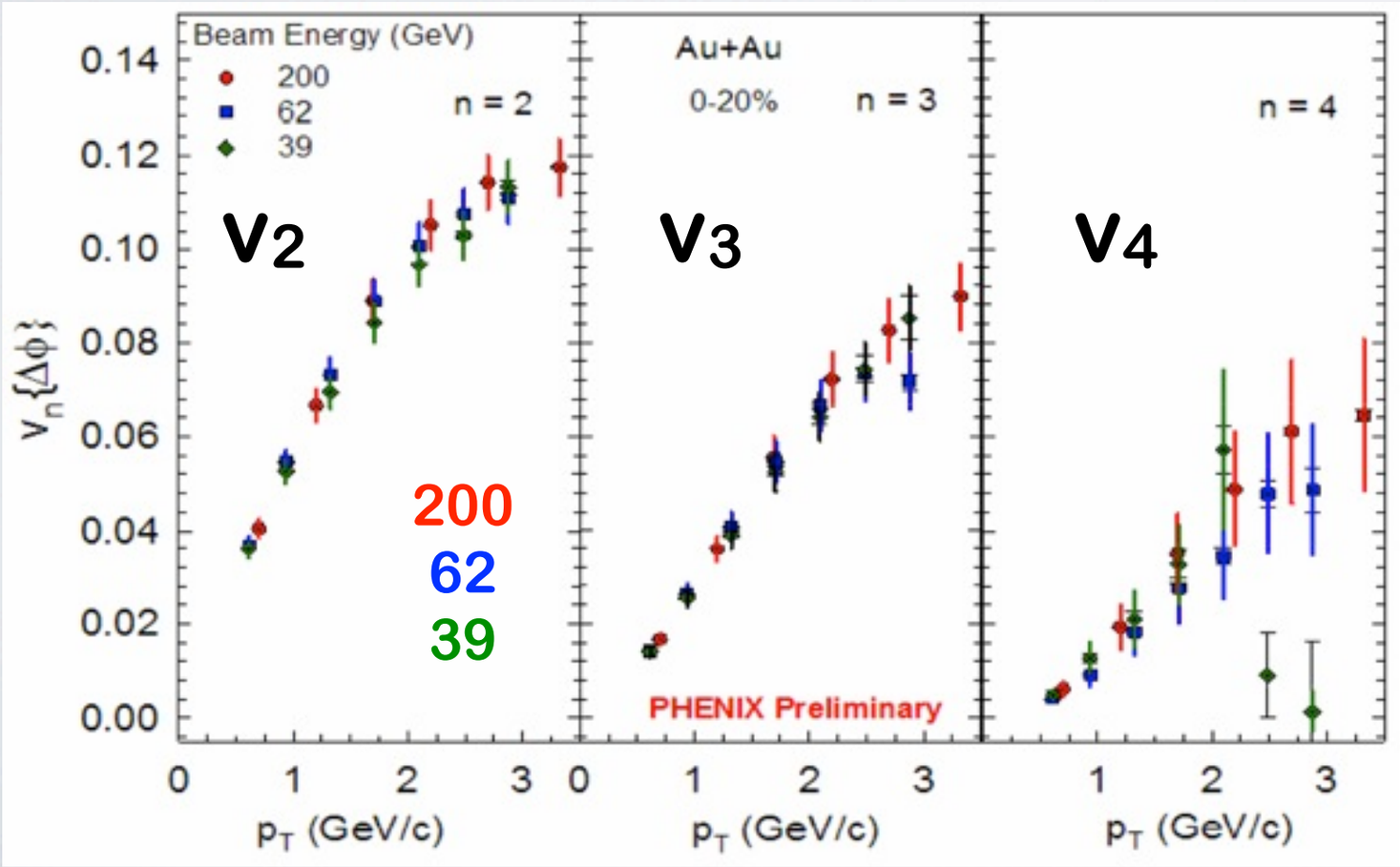
$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle, n = 1, 2, 3, \ldots, m$$



flow - from AuAu @ $\sqrt{s_{NN}}$ = 39, 62.4 and 200 GeV/c

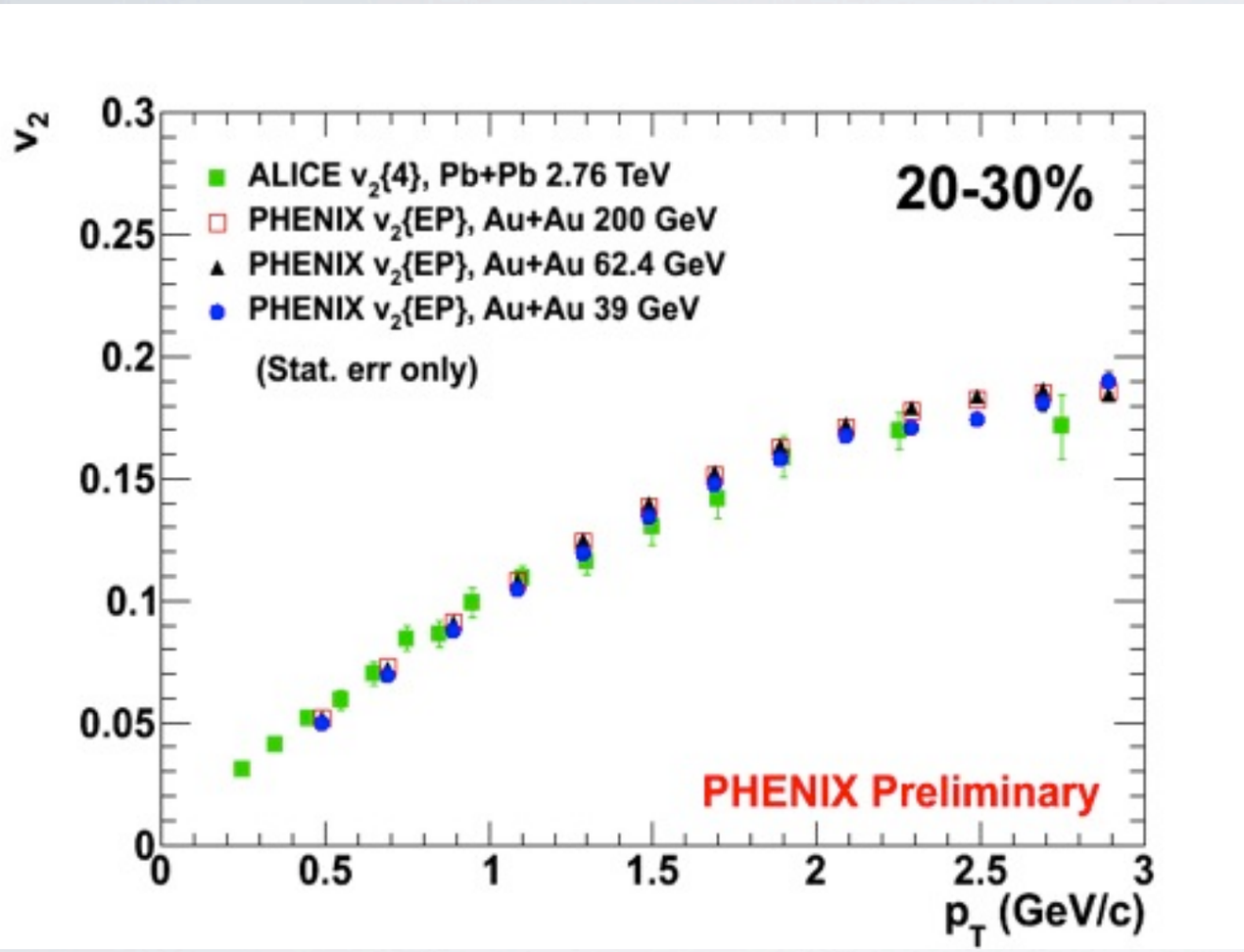


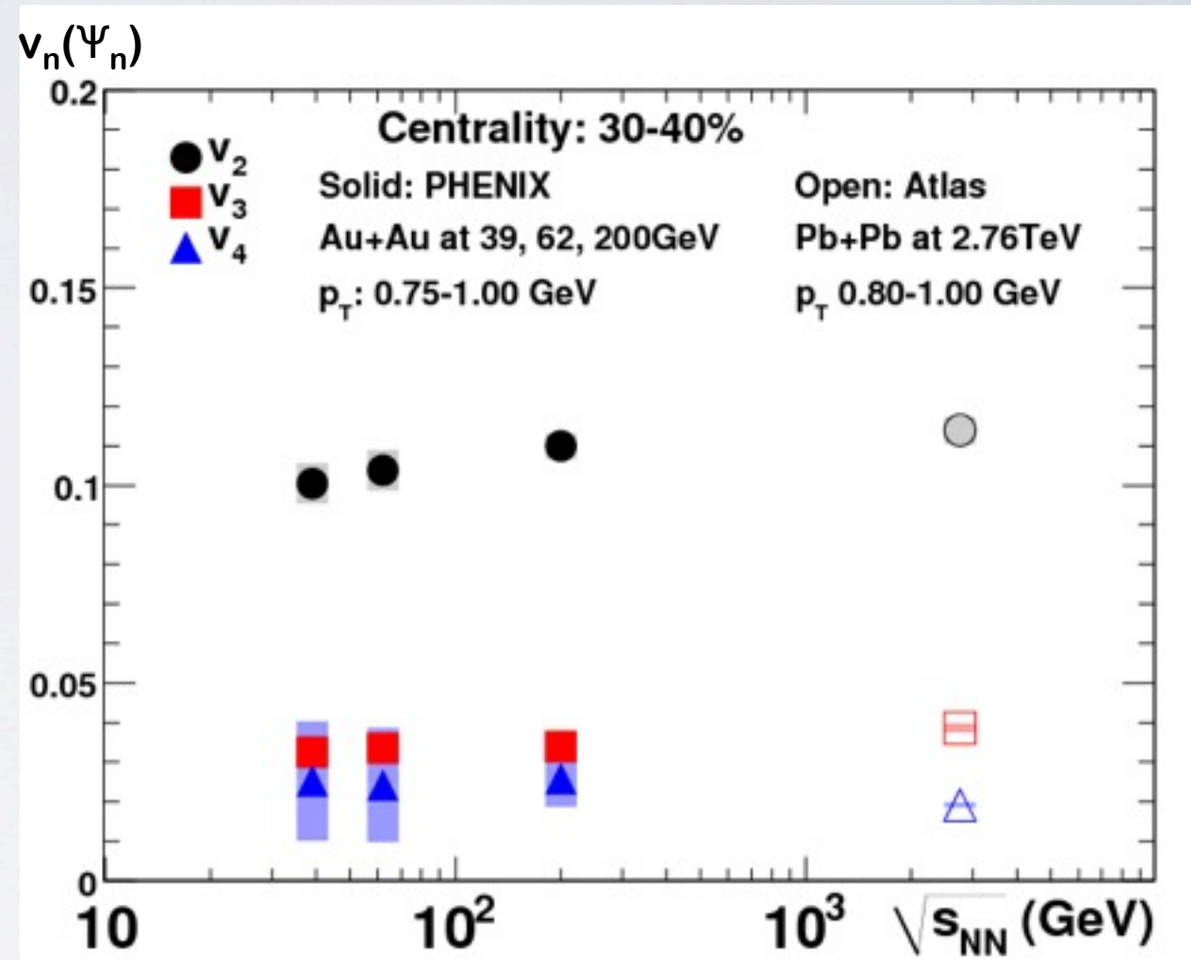




- n_q scaling holds for identified particles down to 39 GeV/c
- v_2,v_3,v_4 almost identical for 39 - 200 GeV/c

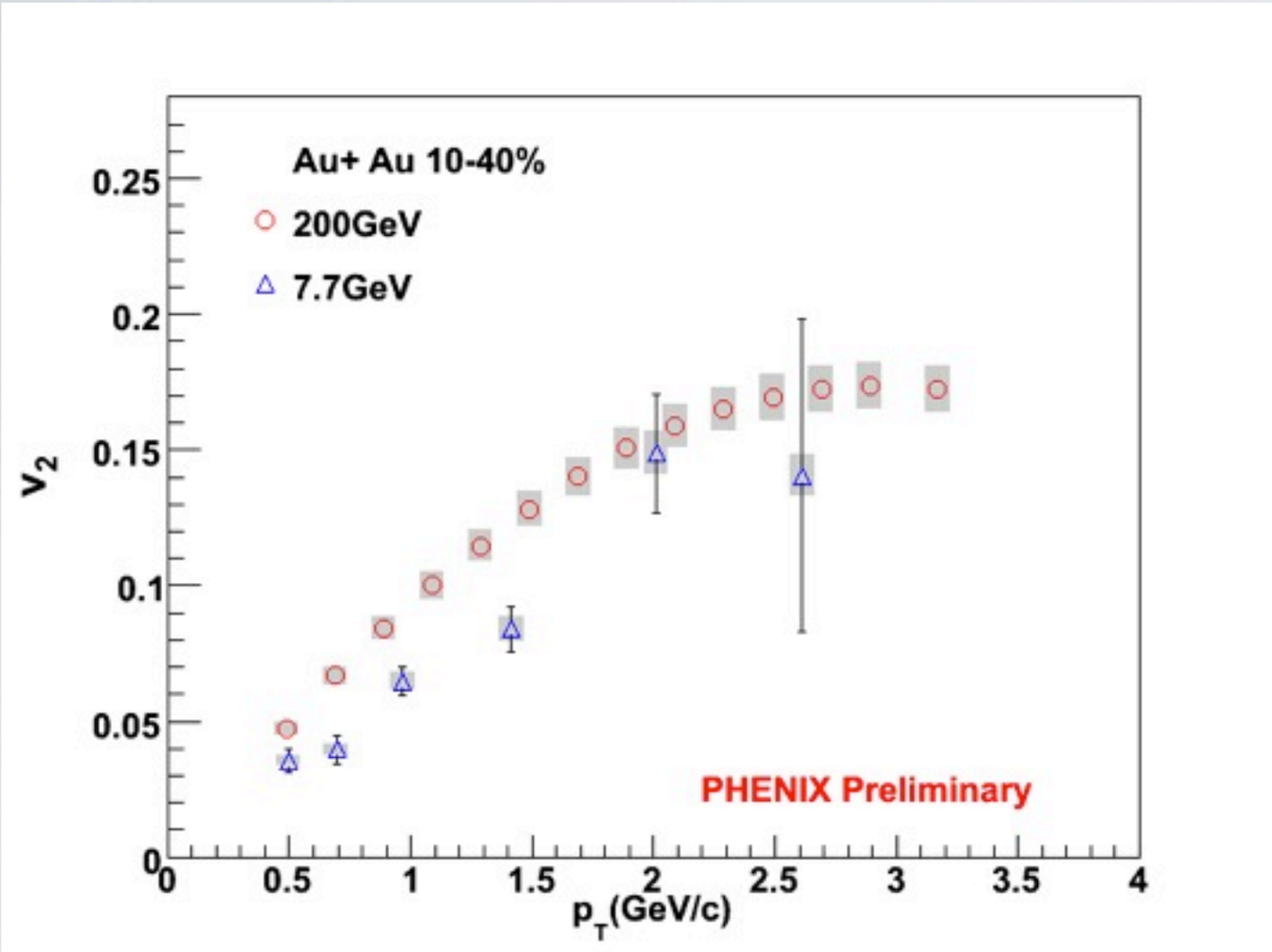
flow - @ higher $\sqrt{s_{NN}}$



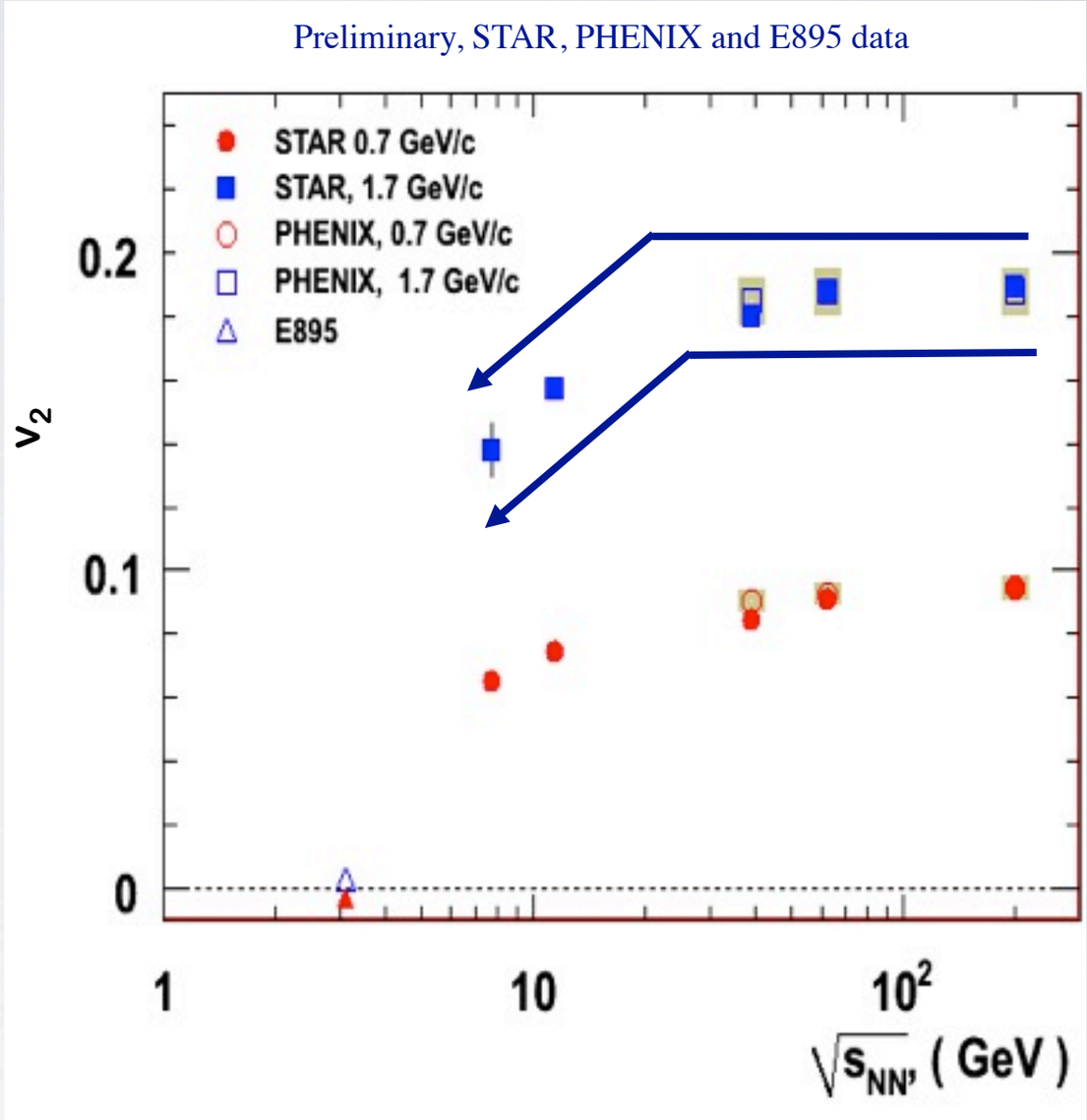


RHIC (0.039 TeV/c) to LHC (2.76 TeV/c) show only a moderate increase in v_2

flow - @ lower $\sqrt{s_{NN}}$



v_2 at 7.7 GeV is lower than 39, 62 and 200 GeV collisions.



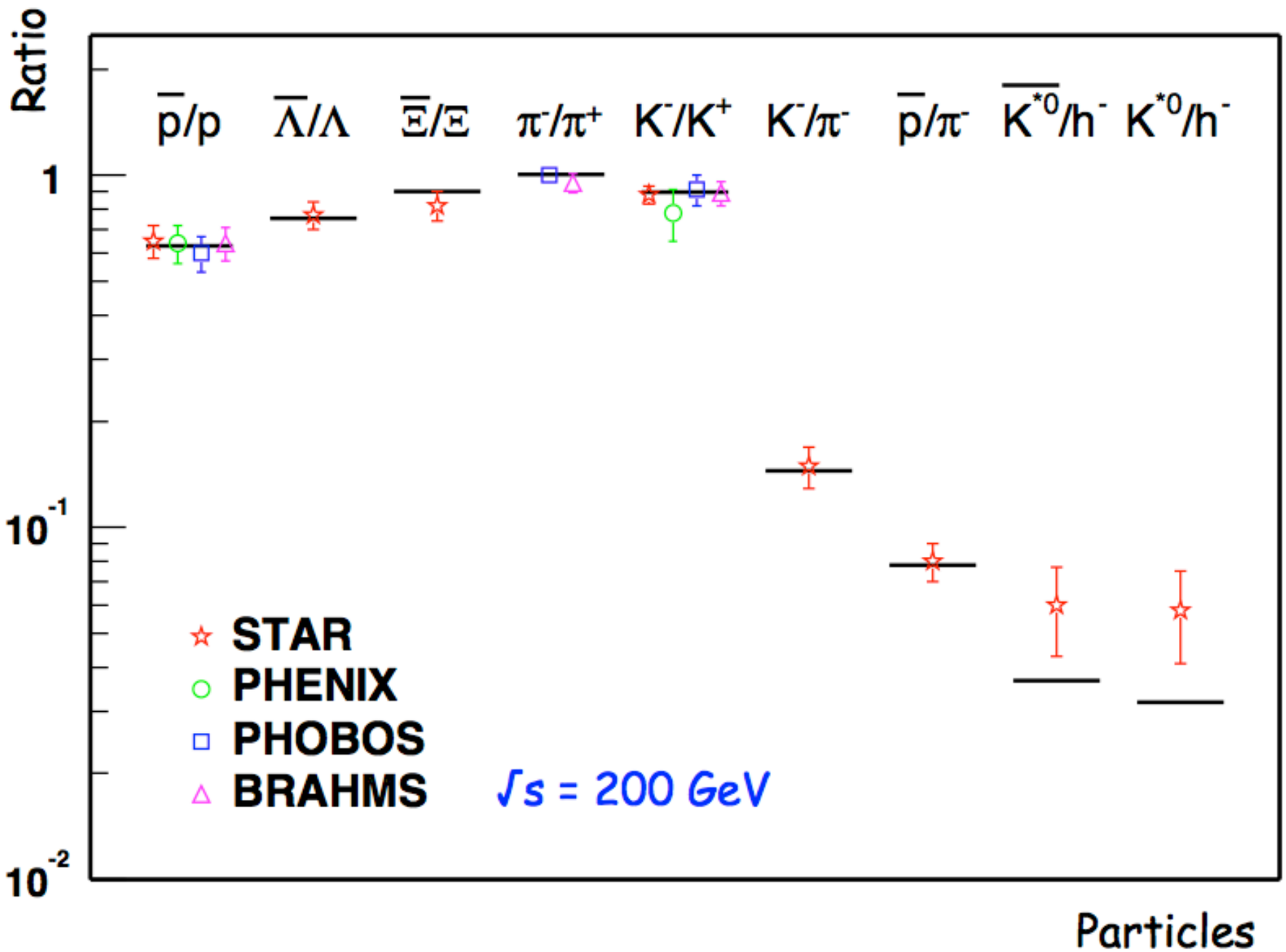
- v_2 flattens at 39 GeV/c and above, but starts decreasing somewhere below 39 GeV/c
- Change from partonic to hadronic flow between 39 GeV/c → 7.7 GeV/c ?
- data taken at 19.6 and 27 GeV/c last year to fill the gap

Summary

- RHIC energy scan should close the gap between SPS and higher RHIC energies to search for a possible critical point in matter phase diagram
- collider experiments are preferred as acceptance doesn't change, but low rate challenges detailed measurements
- collisions are geometry dominated, very similar centrality dependence in global observables like multiplicity, energy density and flow above 7.7 GeV/c all the way out to LHC
- R_{AA} shows supression from 39 - 200 GeV/c, but indications of a change for light ions at 22 GeV/c and heavy quarks already at 62 GeV/c
- v_2,v_3,v_4 very similar from 39 - 200 GeV/c, n_q scaling holds down to 39 GeV/c
- v_2 flat above 39 GeV/c all the way to LHC, with a moderate increase, but drops below 39 GeV/c, new data will fill that gap
- much more data on e.g. fluctuations, which would be a separate talk
- no smoking gun on critical point yet

backup slides

determining T and μ_B



Use thermal model to describe ratios of particles vs anti-part.

Agrees with T_c from theory

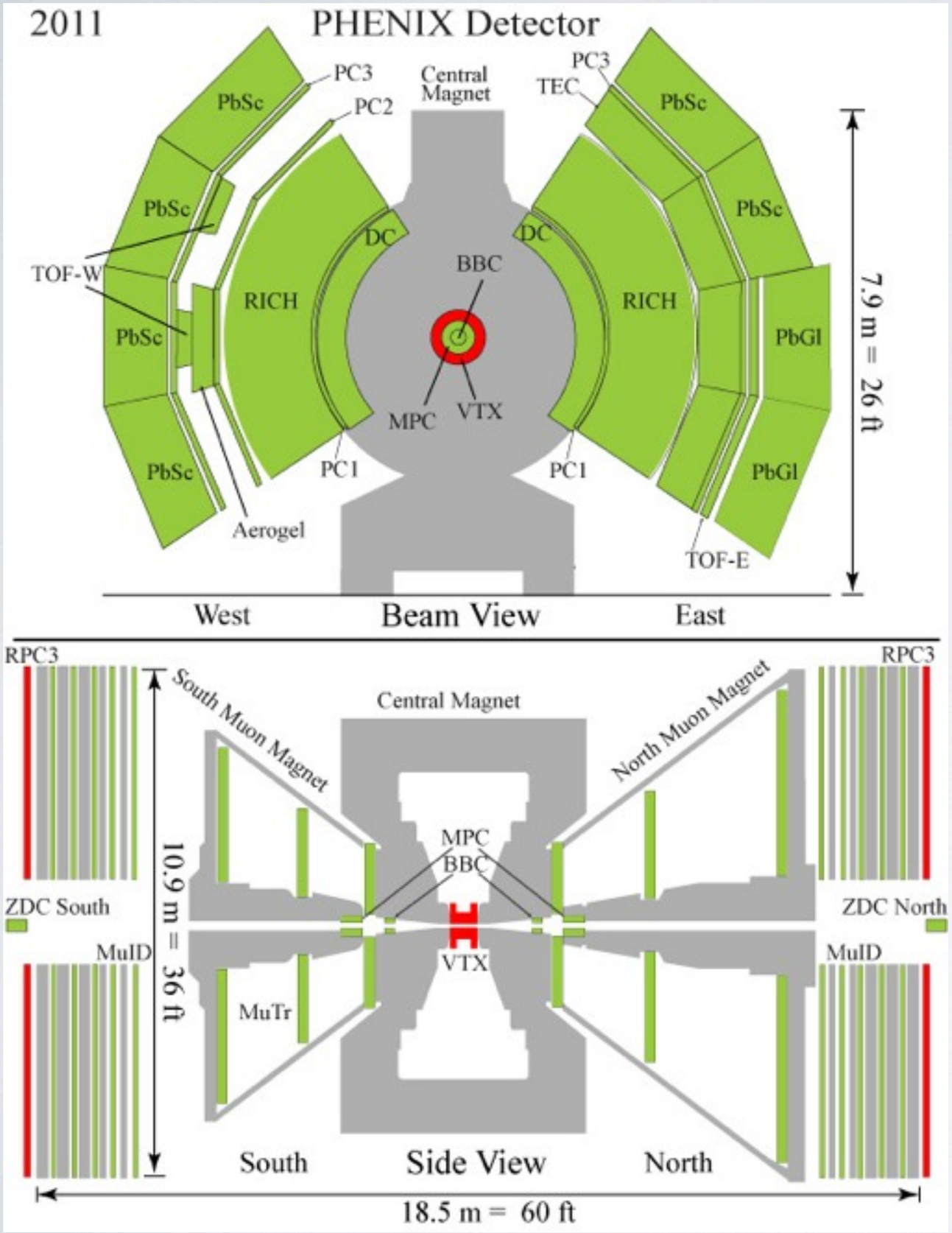
Fit:

$T = 174$ MeV

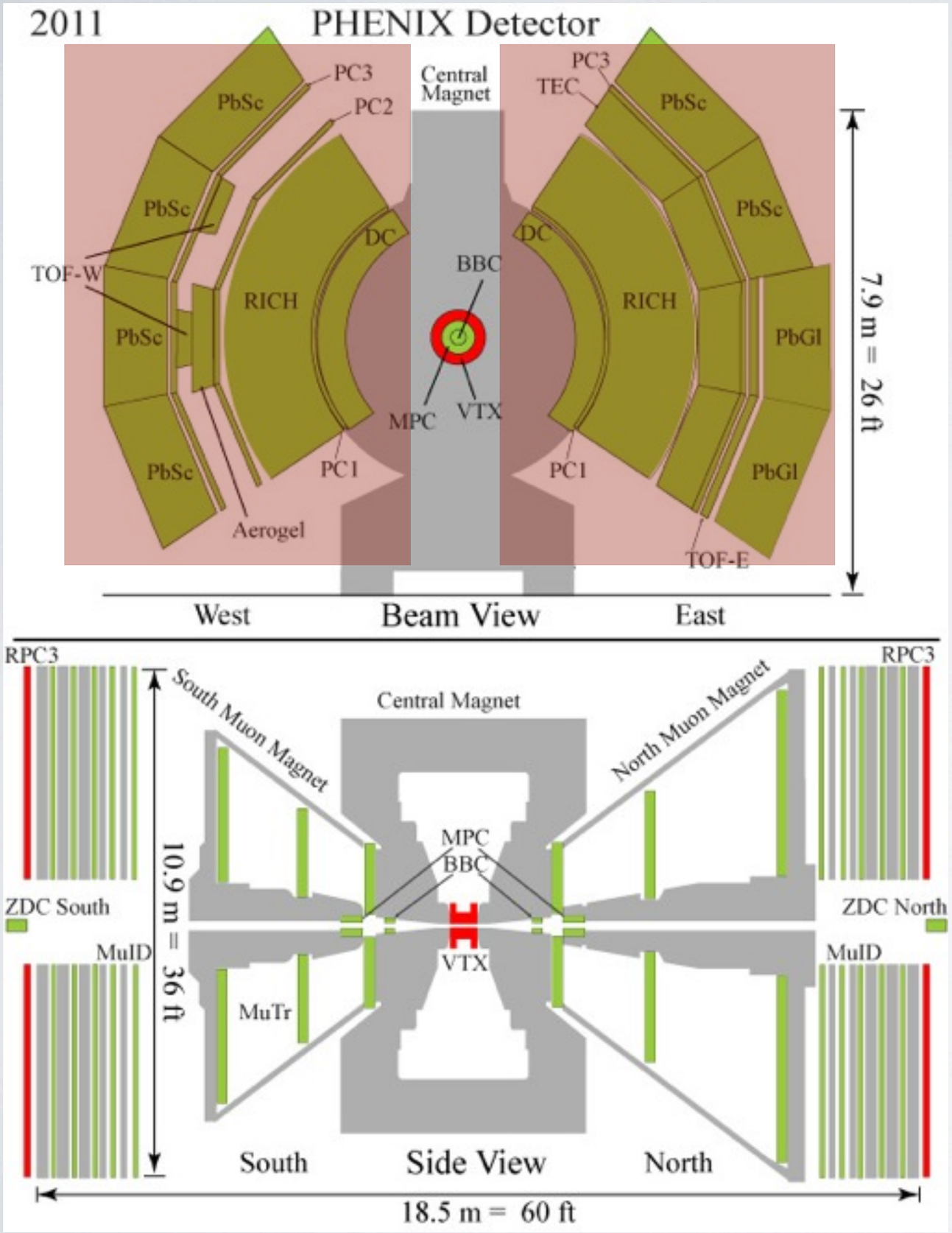
$\mu_B = 46$ MeV

RHIC @ BNL

PHENIX Detector at RHIC



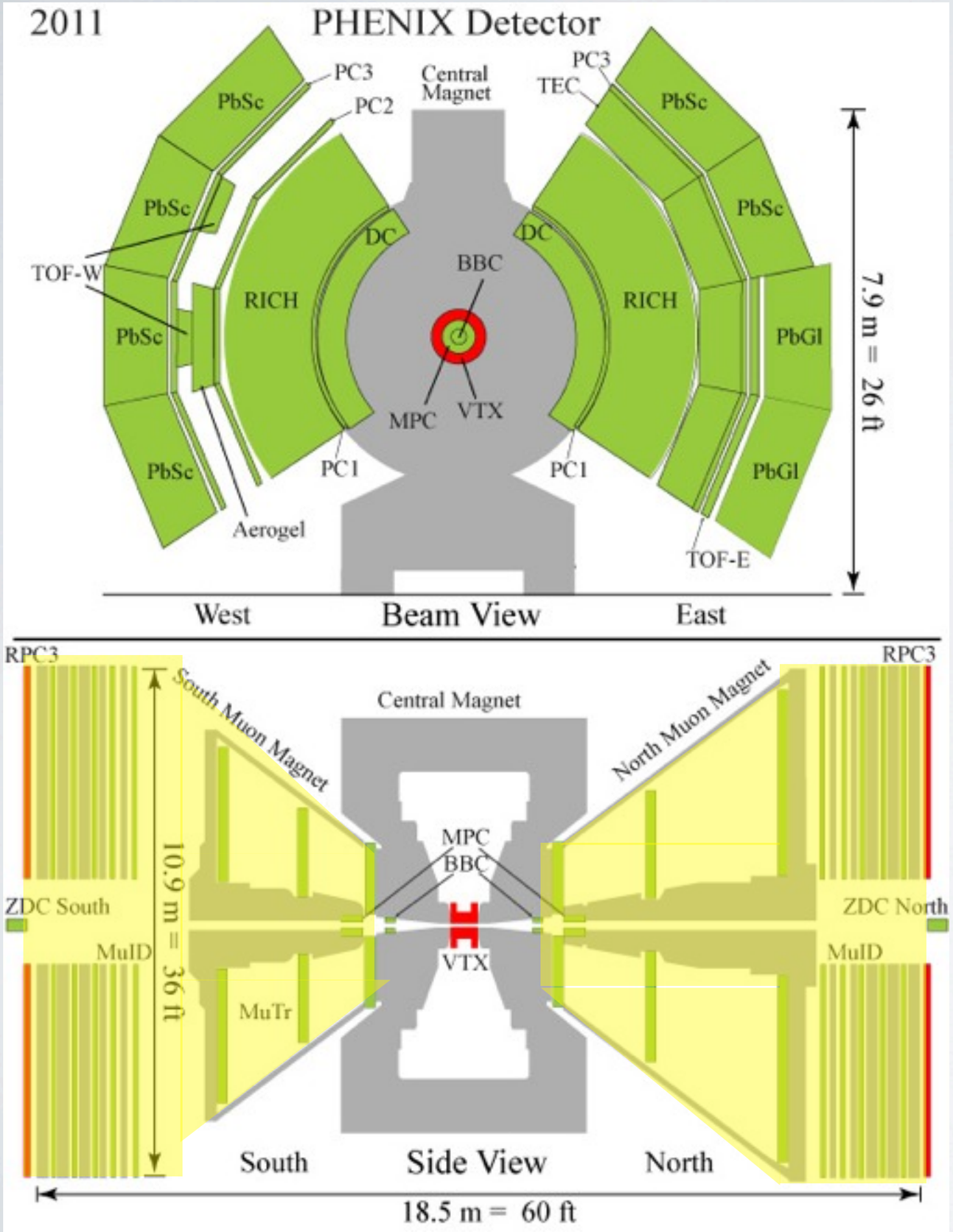
PHENIX Detector at RHIC



Central Arms $|\eta| < 0.35$

- Identified charged hadrons
- $e^{\pm}$, π^0, η
- Direct Photon
- J/Ψ, Ψ', X_c
- Heavy Flavor

PHENIX Detector at RHIC



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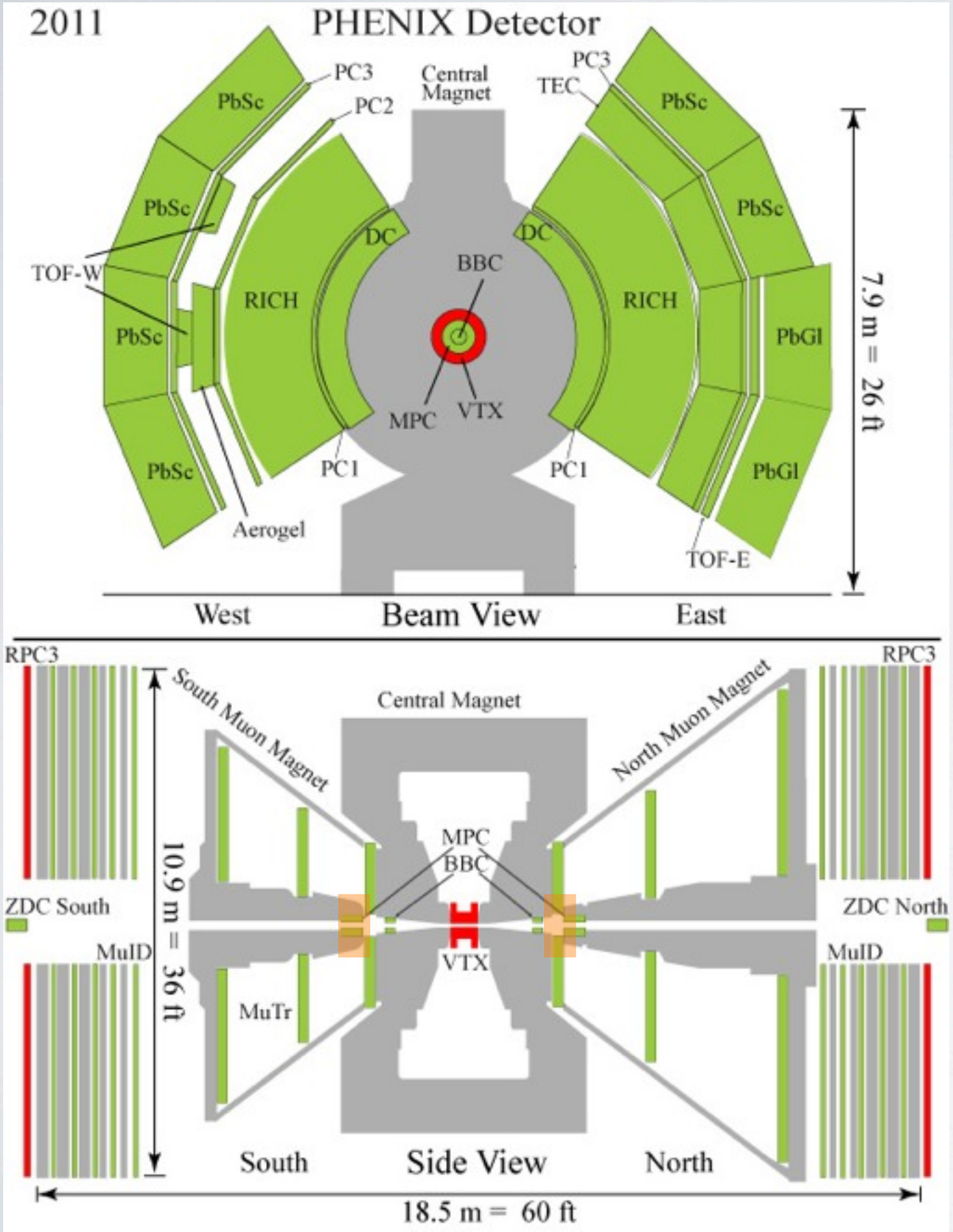
- Heavy Flavor

Muon Arms $1.2 < |\eta| < 2.4$

- J/Ψ, Υ
- Unidentified charged hadrons
- Heavy Flavor

PHENIX Detector at RHIC



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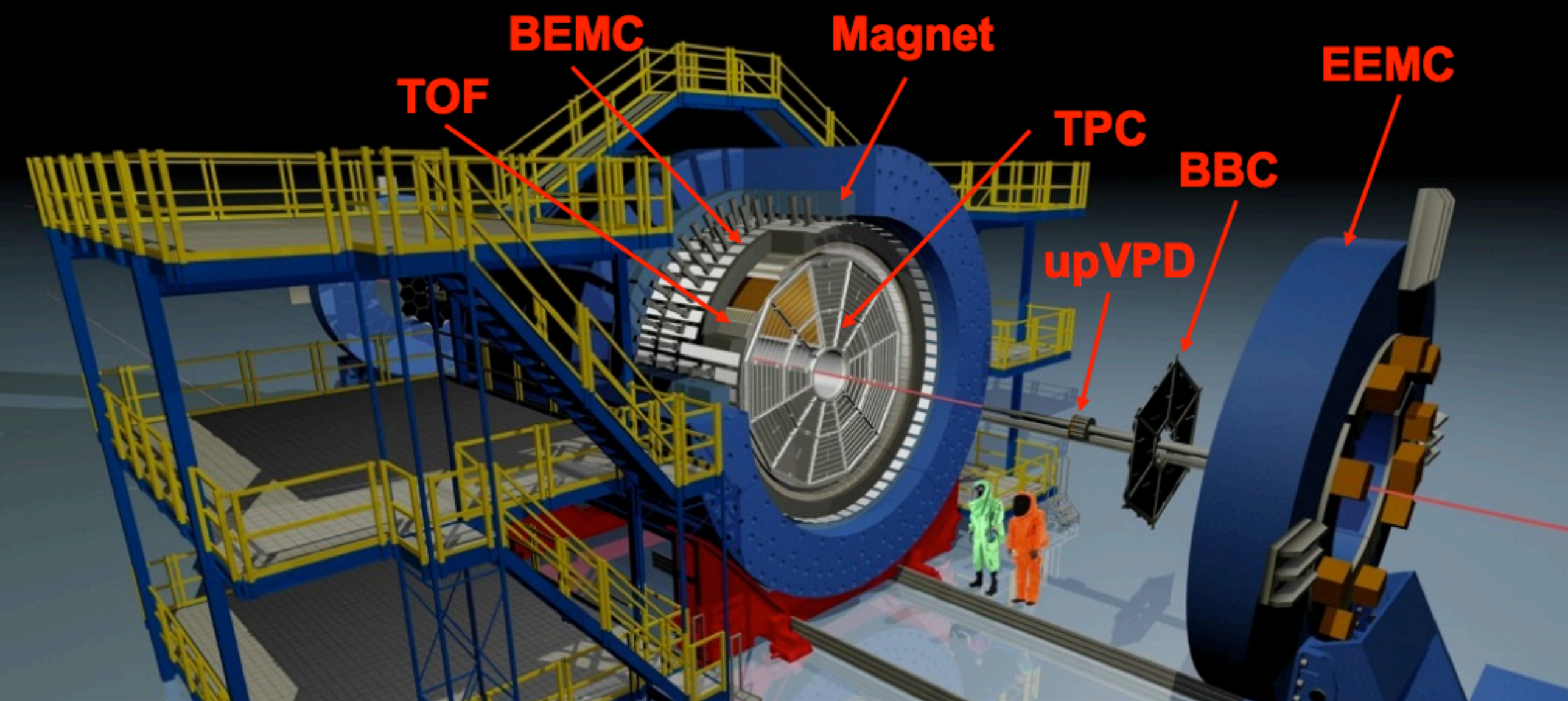
Muon Arms $1.2 < |\eta| < 2.4$

- J/Ψ, Υ
- Unidentified charged hadrons
- Heavy Flavor

MPC $3.1 < |\eta| < 3.9$

- π^0, η

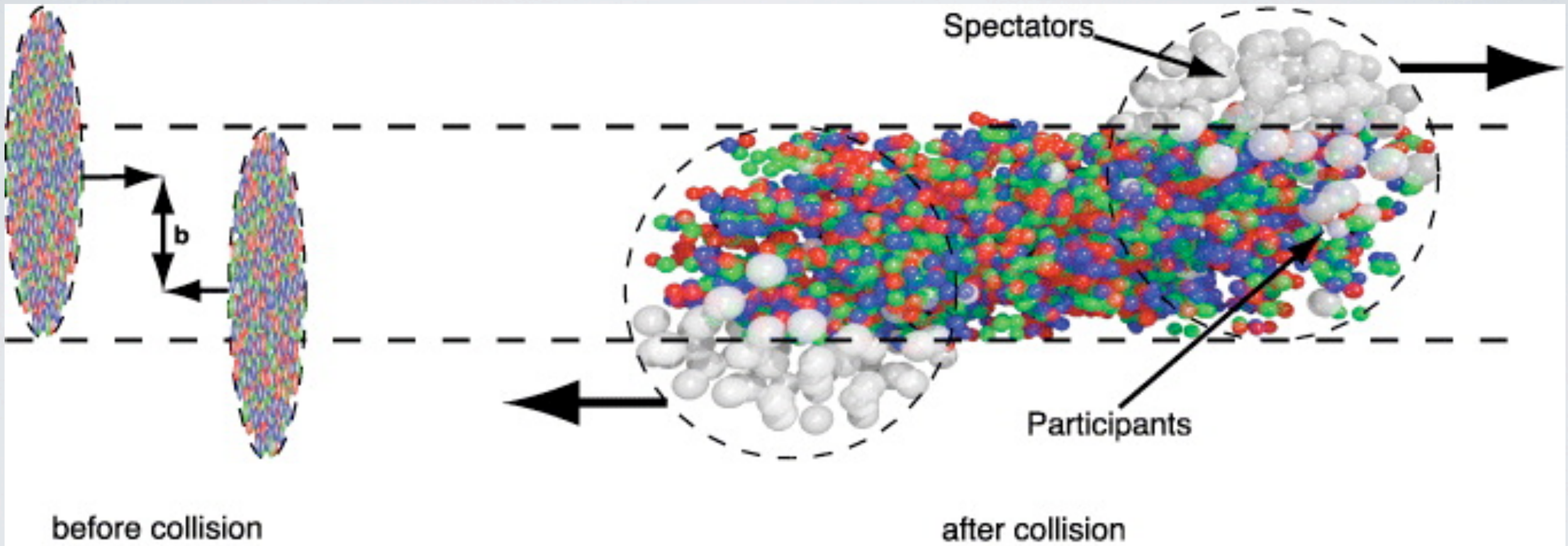
STAR experiment



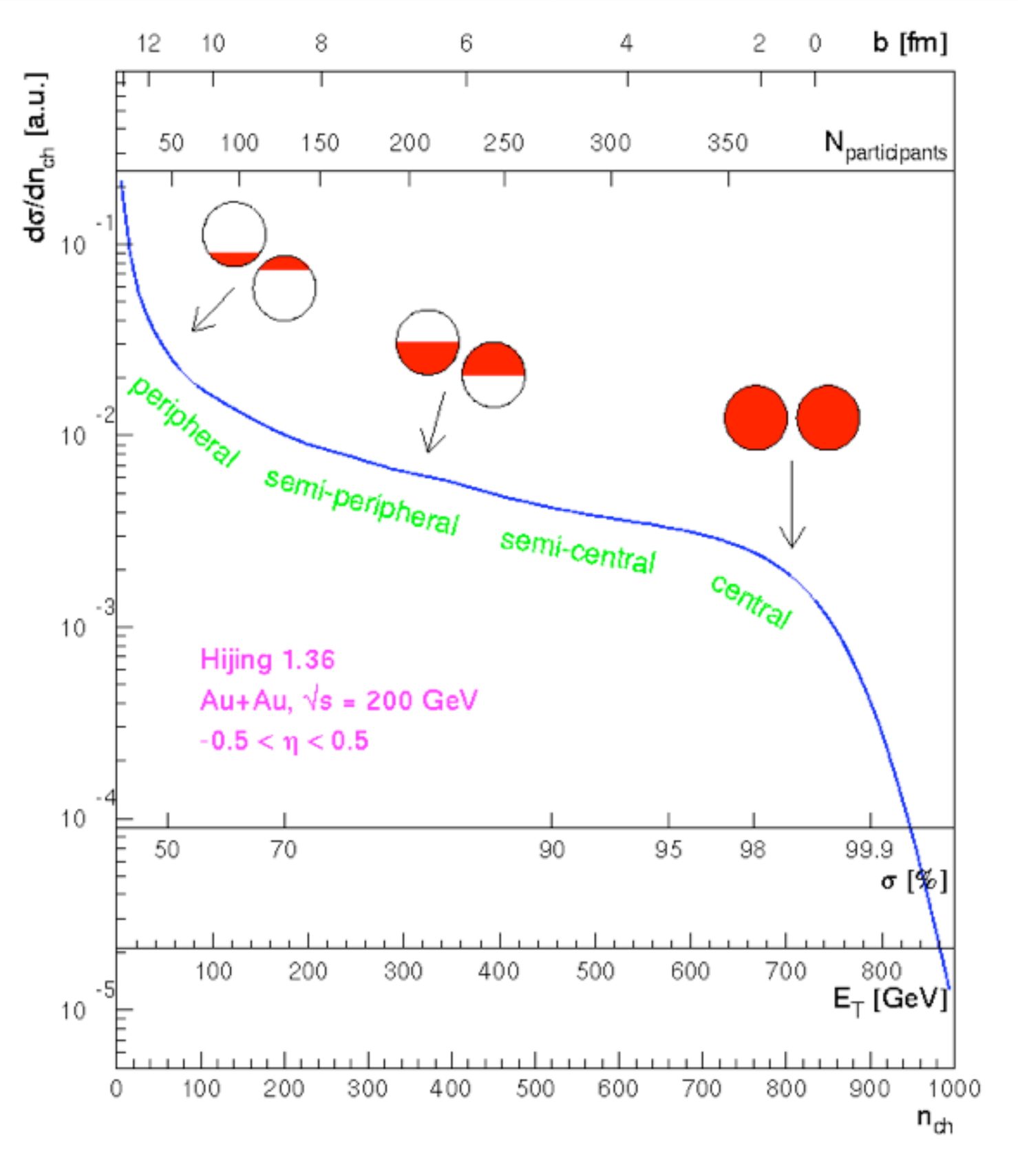
- **DAQ1000** since 2009
- Barrel Time-Of-Flight (**TOF**) (72% at 2009, 100% at 2010)
- High Level online tracking Trigger (**HLT**)
- Less material inside **TPC**

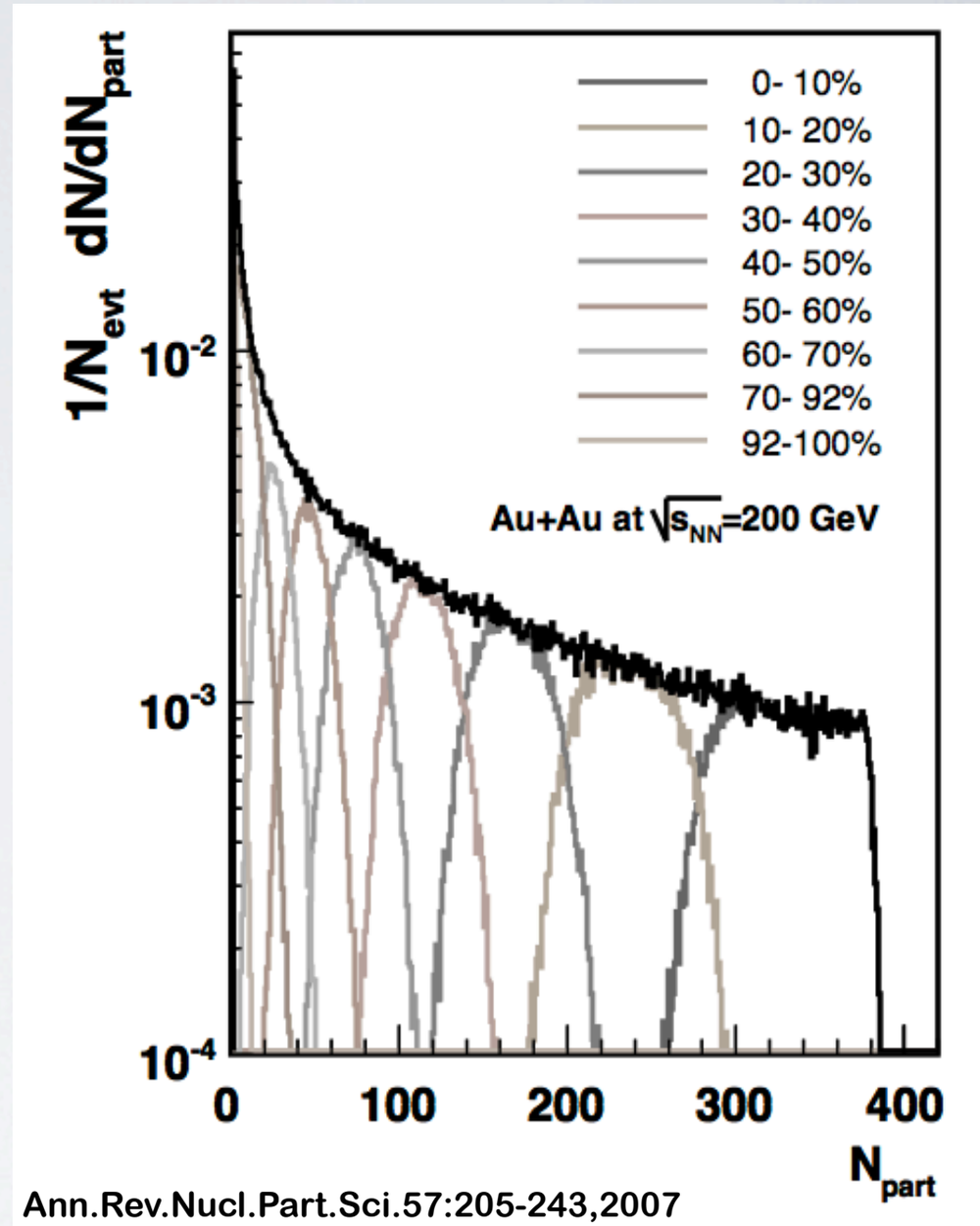
characterizing HI collisions

Heavy Ion collisions, impact parameter, centrality



Heavy Ion collisions, impact parameter, centrality





Ann.Rev.Nucl.Part.Sci.57:205-243,2007

Centrality classes determined by PHENIX BBC and ZDC signals

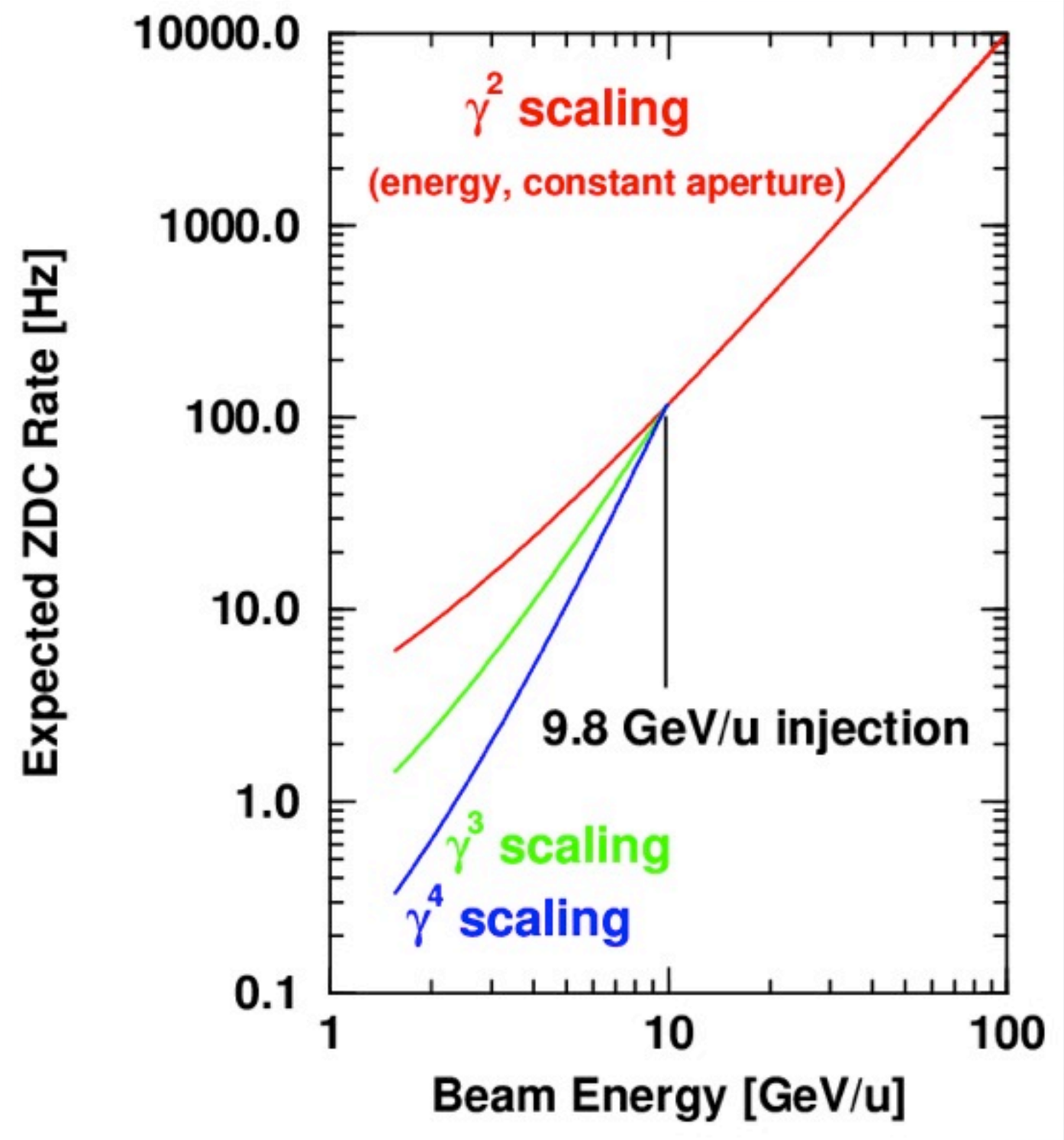
beam energy scan @ RHIC

collision rates

nominal RHIC injection energy for Au is 19.6 GeV/c

challenging environment for a smaller acceptance, high rate experiment like PHENIX

some energies do not allow simultaneous collisions at STAR and PHENIX

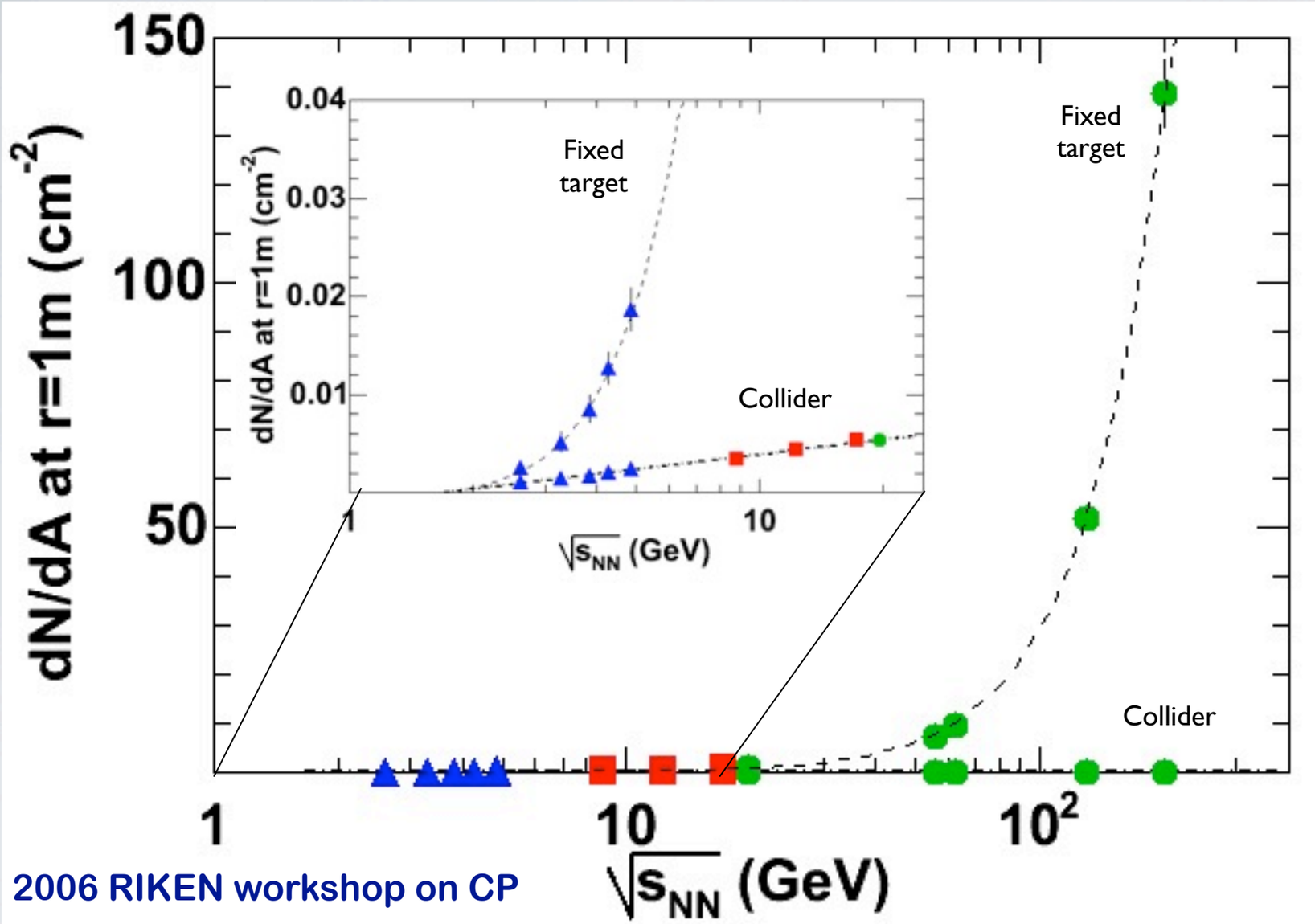


2006 RIKEN workshop on CP

http://www.bnl.gov/riken/qcdrhic/

https://www.bnl.gov/riken/qcdrhic/linked_files/talks/2006-03-10-LowEnergyWorkshop-Satogata.ppt

collider over fixed-target



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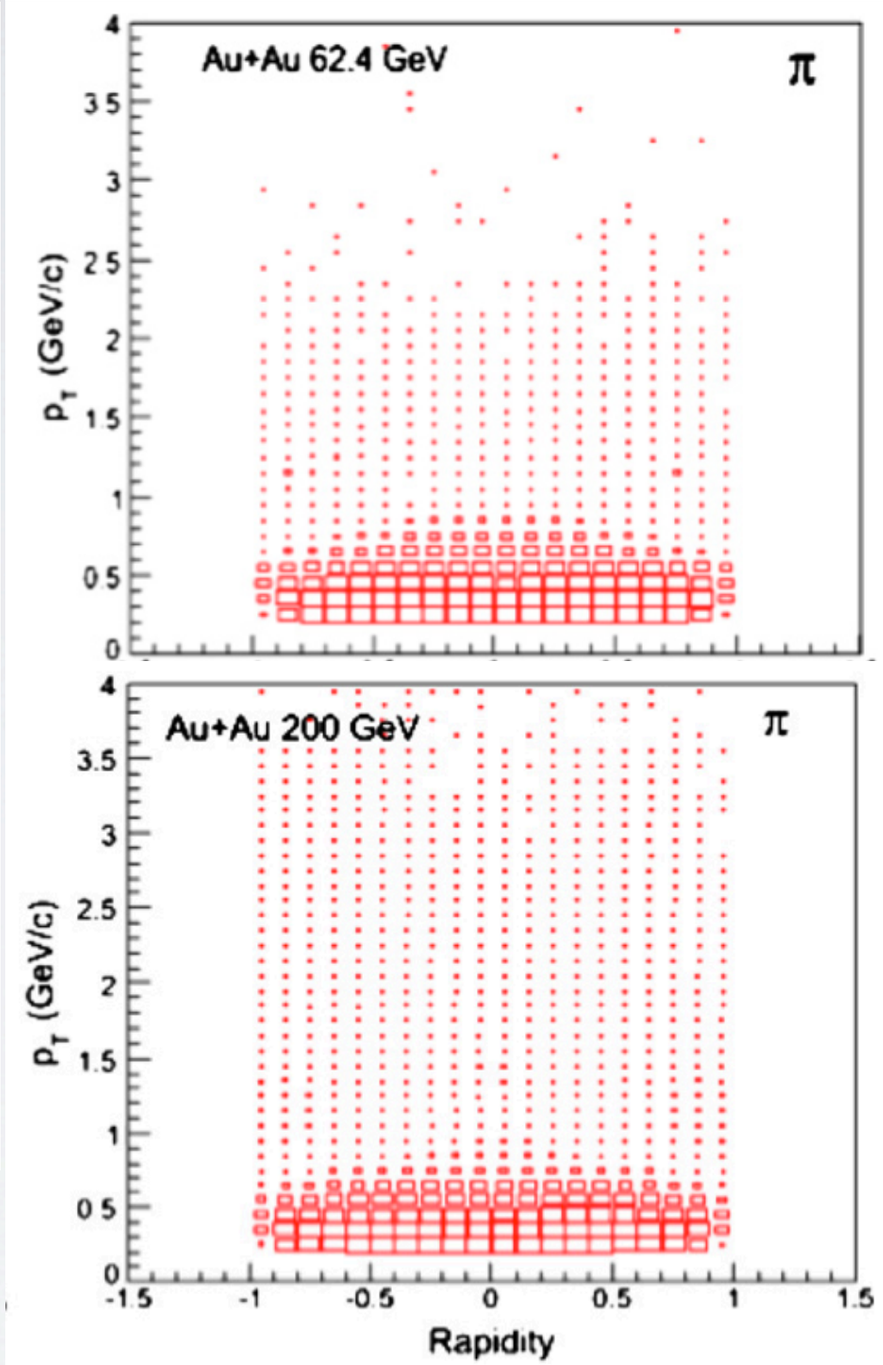
http://www.bnl.gov/riken/qcdrhic/

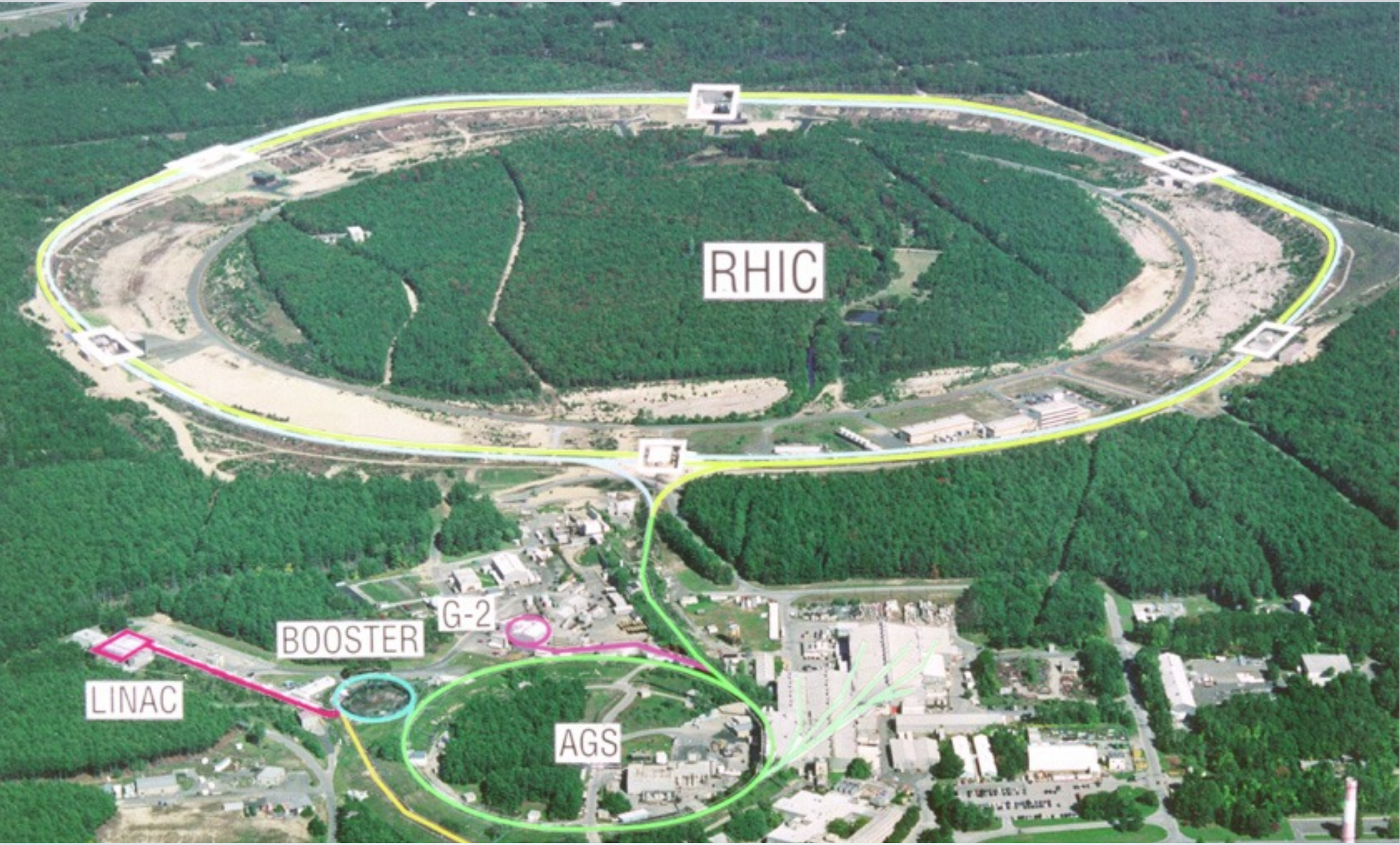
http://www.bnl.gov/riken/qcdrhic/linked_files/talks/Roland_low_E.ppt



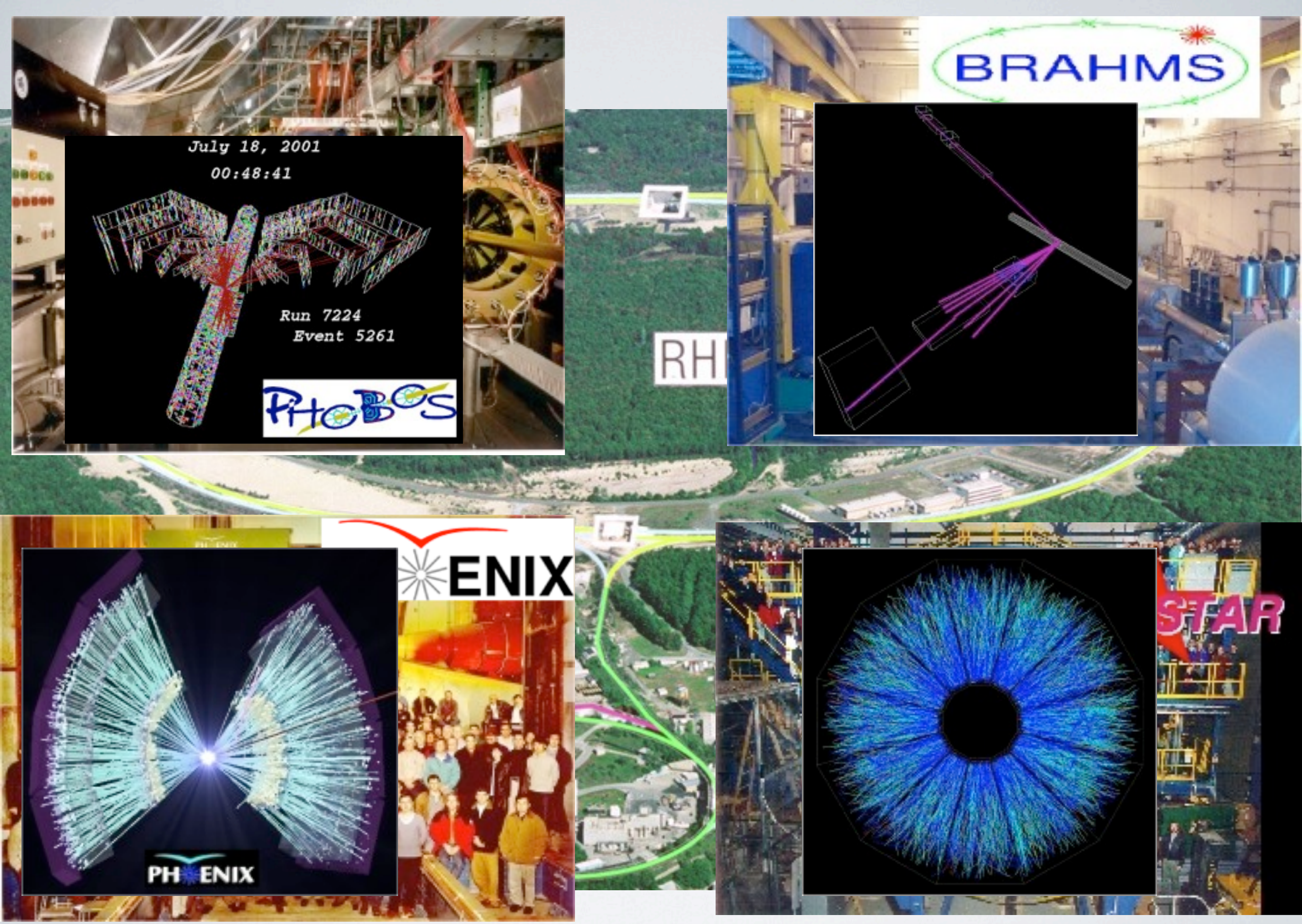
J. Phys. G: Nucl. Part. Phys. **37** (2010) 094028

lower track density

acceptance doesn't change


RHIC
G-2
BOOSTER
LINAC
AGS

PHOBOS
BRAHMS
PHENIX
STAR


July 18, 2001
00:48:41
Run 7224
Event 5261
PHOBOS
BRAHMS
ENIX
PHENIX
STAR

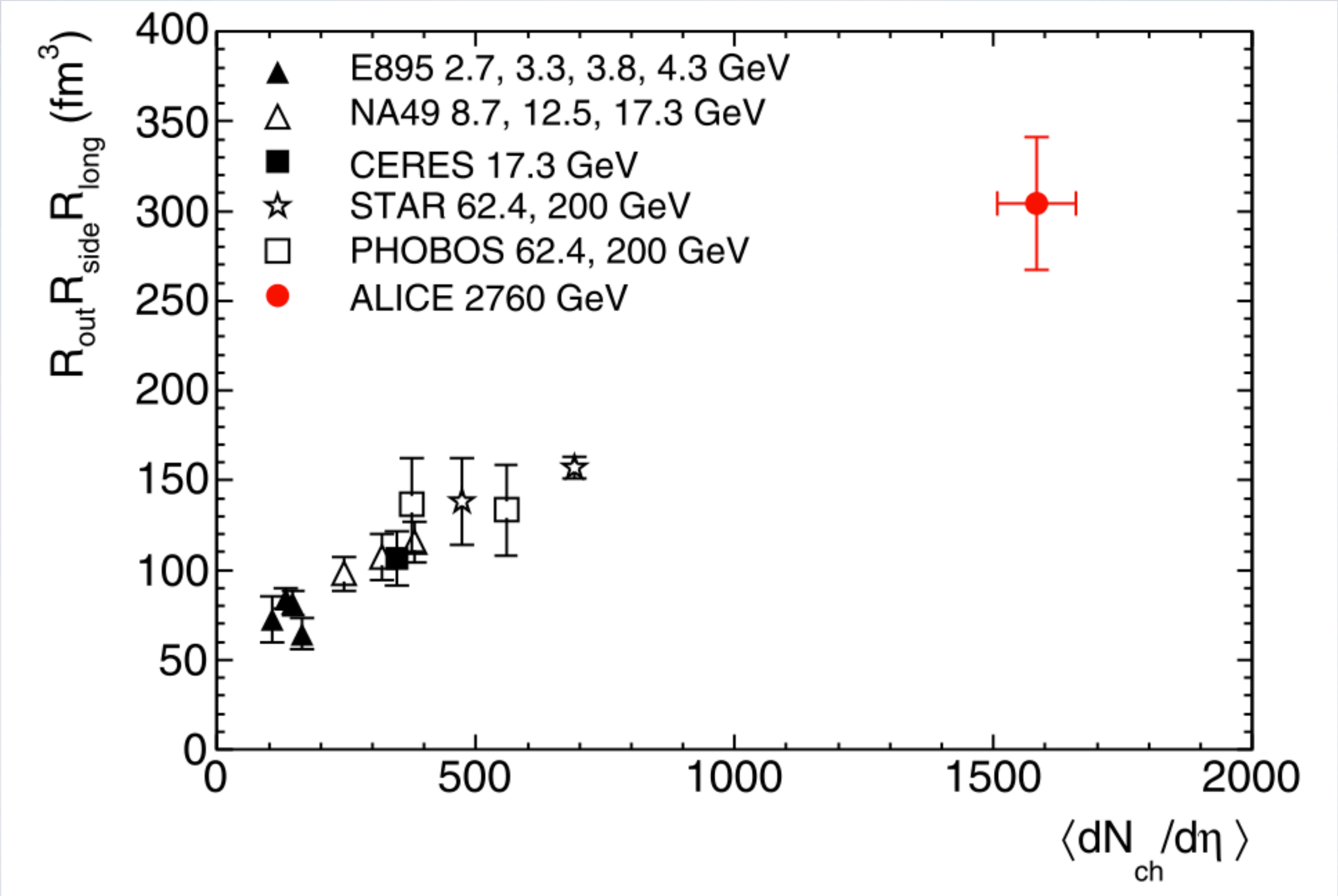
datasets

species	√sNN (GeV/c)	recent years
Au Au	200	2010, 2011 (most recent)
	130	2001
	62.4	2010
	39	2010
	27	2011
	19.6	2002 (1 day), 2011
	11	2010 (STAR only)
	9.2	2009 (short test)
	7.7	2010
Cu Cu	200	2005
	62.4	2005
	22	2005
Cu Au	200	2012
d Au	200	2008
U U	193	2012
p p	500	2009, 2011, 2012
	200	2009, 2012 (most recent)
	62.4	2006

RHIC Run Summary

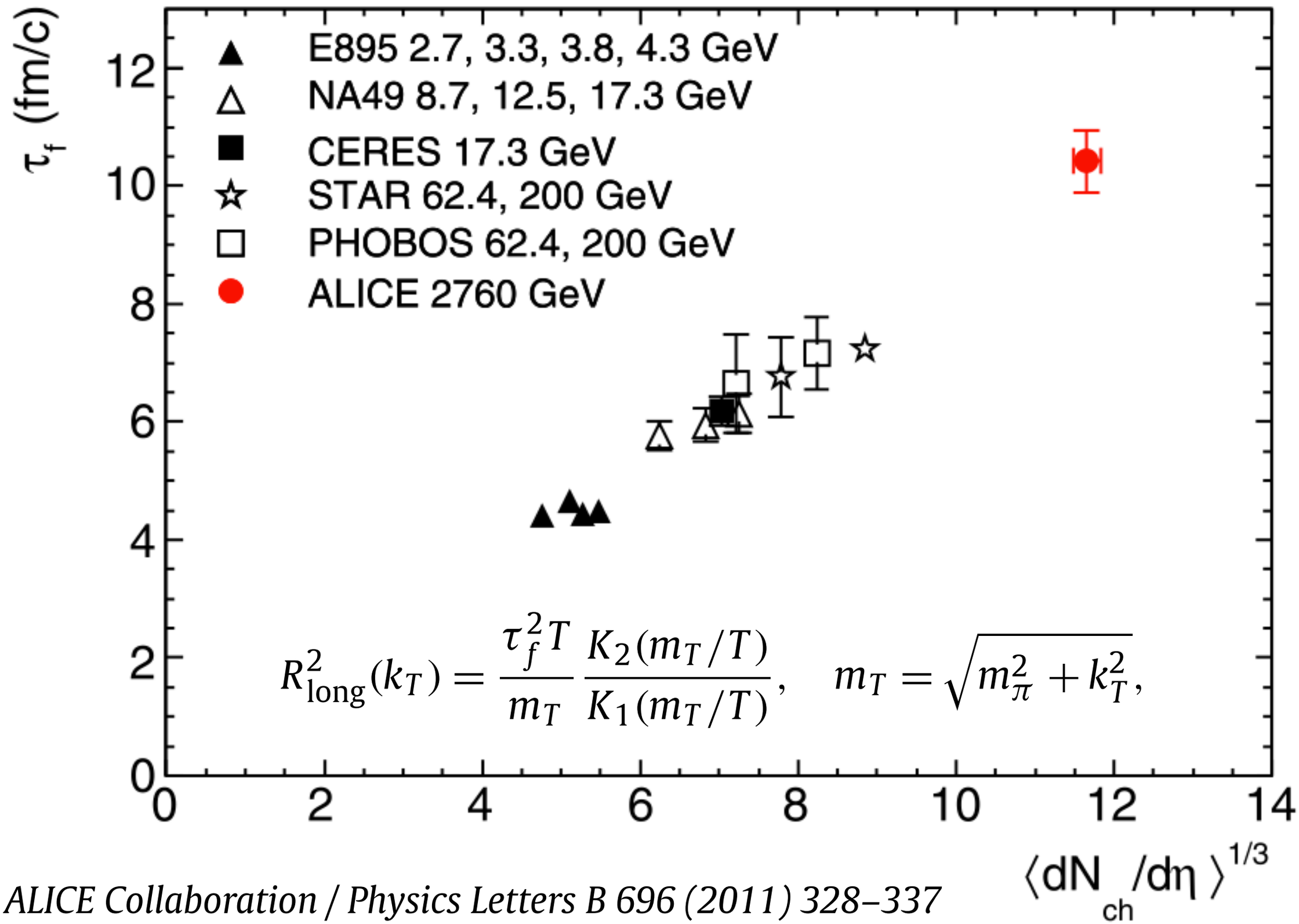
Run	species	total particle energy [GeV/nucleon]	calendar time in physics	total delivered luminosity	average store polarization, (H-jet)*
Run-1 CY2000, FY2000 33.6 cryo-weeks	$^{197}Au^{79+}$—$^{197}Au^{79+}$	27.9	3 shifts	$< 0.001\,\mu b^{-1}$	—
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	65.2	5.3 weeks	$20\,\mu b^{-1}$	—
Run-2 CY2001/02, FY2001/02 40.7 cryo-weeks	$^{197}Au^{79+}$—$^{197}Au^{79+}$	100.0	15.9 weeks	$258\,\mu b^{-1}$	—
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	9.8	2 shifts	$0.4\,\mu b^{-1}$	—
	polarized p—p	100.0	8.3 weeks total, no continuous physics operation	$1.4\,pb^{-1}$	14%
Run-3 CY2002/03, FY2003 30.4 cryo-weeks	d—$^{197}Au^{79+}$	100.7—100.0	10.2 weeks	$73\,nb^{-1}$	—
	polarized p—p	100.0	9.0 weeks total, no continuous physics operation	$5.5\,pb^{-1}$	34%
Run-4 CY2003/04, FY2004 26.7 cryo-weeks	$^{197}Au^{79+}$—$^{197}Au^{79+}$	100.0	12.0 weeks	$3.53\,nb^{-1}$	—
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	31.2	9 days	$67\,\mu b^{-1}$	—
	polarized p—p	100.0	6.1 weeks total, no continuous physics operation	$7.1\,pb^{-1}$	46%
Run-5 CY2004/05, FY2005 31.4 cryo-weeks	$^{63}Cu^{29+}$—$^{63}Cu^{29+}$	100.0	7.8 weeks	$42.1\,nb^{-1}$	—
	$^{63}Cu^{29+}$—$^{63}Cu^{29+}$	31.2	12 days	$1.5\,nb^{-1}$	—
	$^{63}Cu^{29+}$—$^{63}Cu^{29+}$	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 21.2 cryo-weeks	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 18.4 cryo-weeks	$^{197}Au^{79+}$—$^{197}Au^{79+}$	100.0	12.8 weeks	$7.25\,nb^{-1}$	—
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	4.6	3 shifts total, no continuous physics operation	small	—
Run-8 CY2007/08, FY2008 19.2 cryo-weeks	d—$^{197}Au^{79+}$	100.7—100.0	9.0 weeks	$437\,nb^{-1}$	—
	polarized p—p	100.0	3.4 weeks	$38.4\,pb^{-1}$	44%
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	4.6	3 shifts	small	—
Run-9 CY2008/09, FY2009 22.3 cryo-weeks	polarized p—p	250.0	4.1 weeks	$110\,pb^{-1}$	34%
	polarized p—p	100.0	9.9 weeks	$114\,pb^{-1}$	56%
	polarized pp2pp	100.0	3.5 days	$0.6\,nb^{-1}$	63%
Run-10 CY2009/10, FY2010 27.6 cryo-weeks	$^{197}Au^{79+}$—$^{197}Au^{79+}$	100.0	10.9 weeks	$10.3\,nb^{-1}$	—
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	31.2	2.9 weeks	$544\,\mu b^{-1}$	—
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	19.5	1.8 weeks	$206\,\mu b^{-1}$	—
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	3.85	4.6 weeks	$4.23\,\mu b^{-1}$	—
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	5.75	1.1 weeks	$7.8\,\mu b^{-1}$	—
Run-11 CY2010/11, FY2011 25.4 cryo-weeks	polarized p—p	250.0	9.7 weeks	$166\,pb^{-1}$	48%
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	9.8	1.4 weeks	$33.2\,\mu b^{-1}$	—
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	100.0	6.4 weeks	$9.79\,nb^{-1}$	—
	$^{197}Au^{79+}$—$^{197}Au^{79+}$	13.5	8 days	$63.1\,\mu b^{-1}$	—
Run-12 CY2011/12, FY2012 (20 cryo-weeks planned)	polarized p—p	100.0	4.4 weeks	$74.0\,pb^{-1}$	58.5%
	polarized p—p	255.0	— in progress —		
	$^{238}U^{92+}$—$^{238}U^{92+}$	96.4	— in preparation —		
	$^{63}Cu^{29+}$—$^{197}Au^{79+}$	99.9—100.0	— in preparation —		

Volume and lifetime - HBT



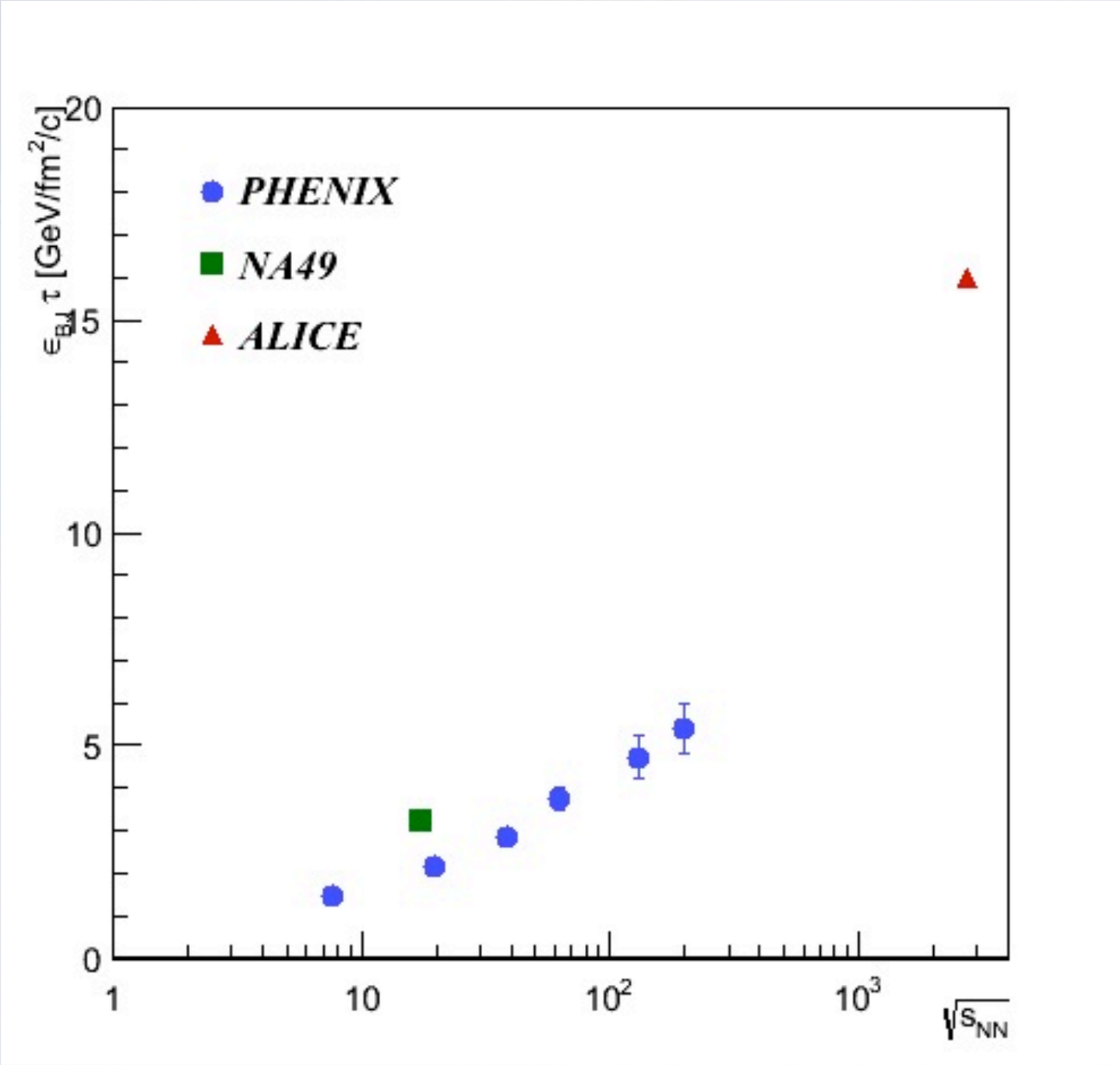
ALICE Collaboration / Physics Letters B 696 (2011) 328–337

Volume and lifetime - HBT



ALICE Collaboration / Physics Letters B 696 (2011) 328–337

energy density (2)

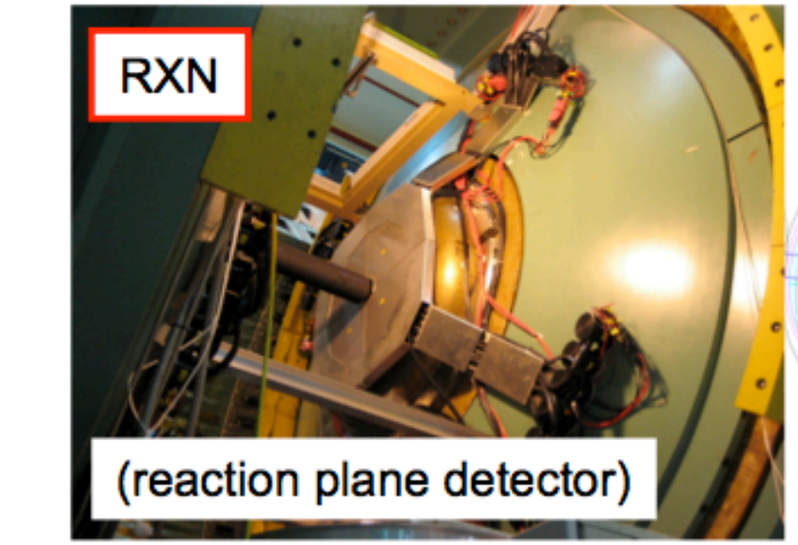


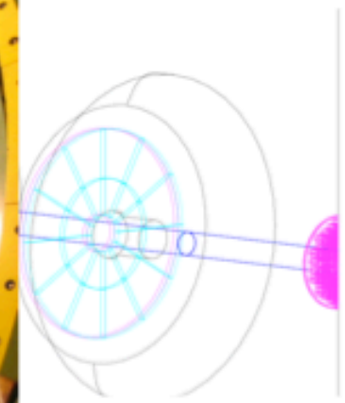
The Bjorken energy density in central collisions increases by a factor of 3.8 increase from 7.7 to 200 GeV/c.

It increases by a factor of 11.1 when going from 7.7 GeV/c to 2.76 TeV/c.

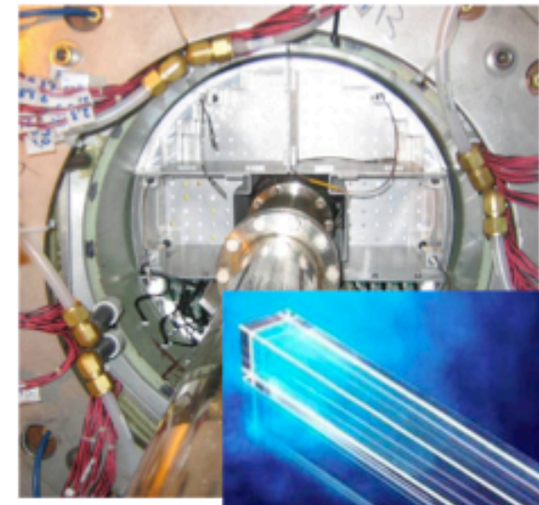
reflects the increase in $dE_T/d\eta$

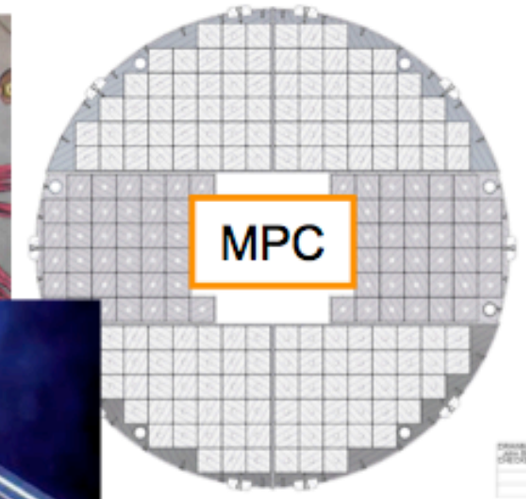
PHENIX reaction plane determination

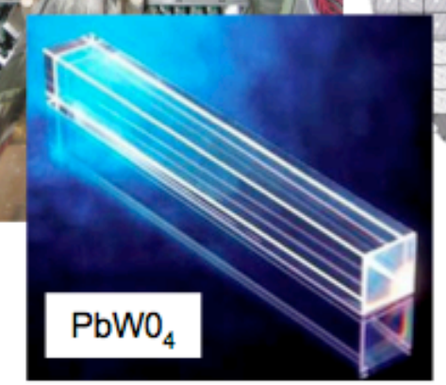




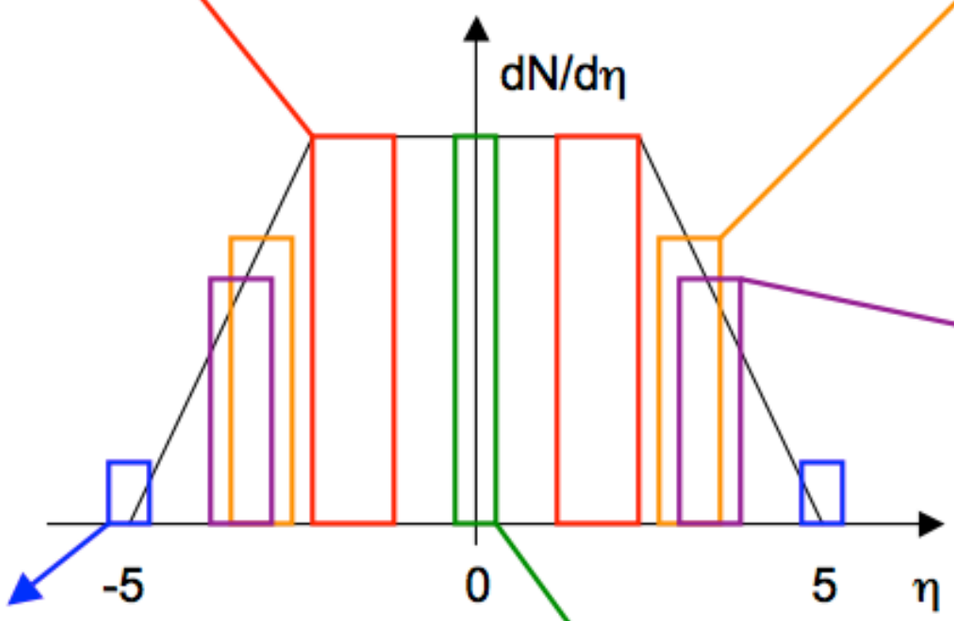
2cm Pb converter in front

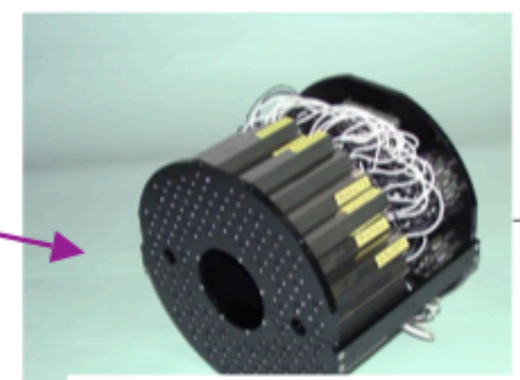




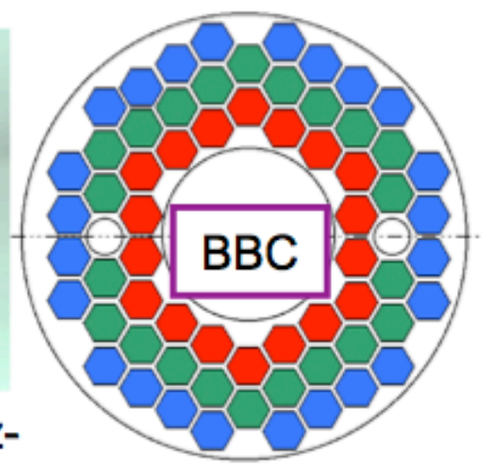


(muon piston EM-calorimeter)



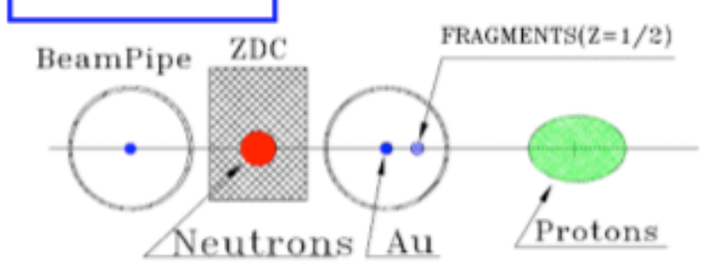


(beam-beam quartz-Cherenkov detector)

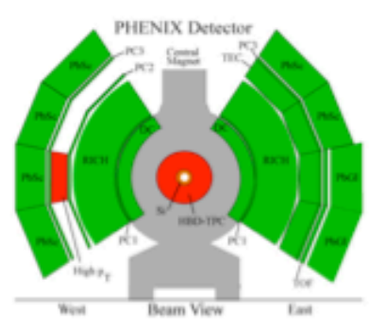


ZDC/SMD

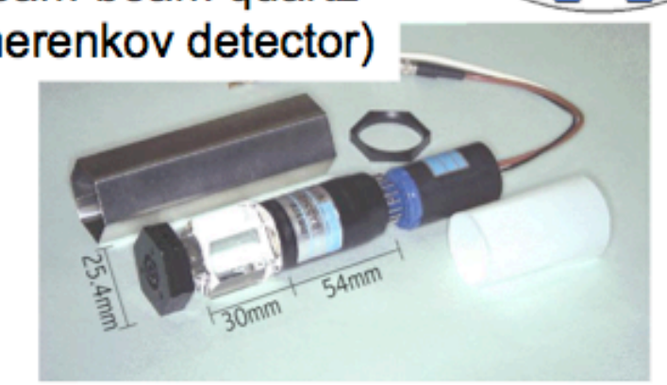
(zero degree n calorimeter /shower max detector)



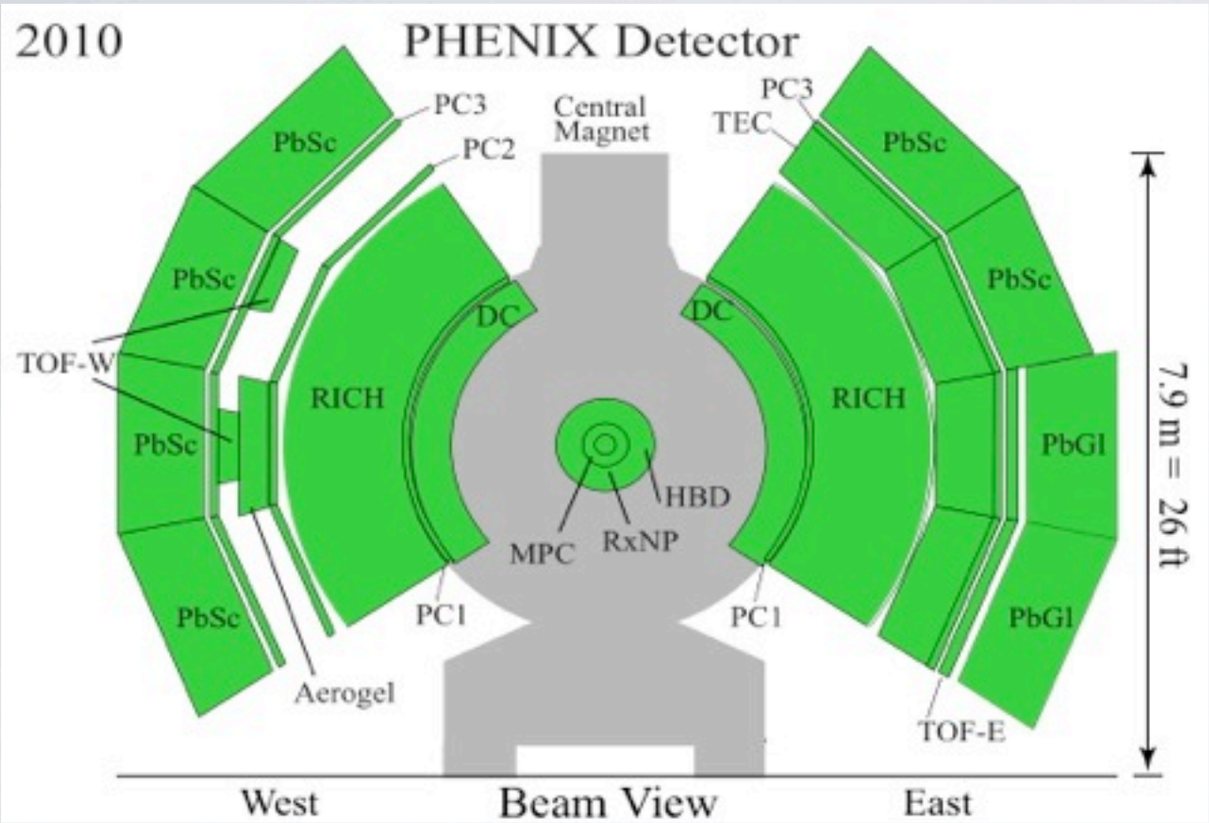
CNT



(PHENIX central tracking arm)



PHENIX Detectors for Event Plane

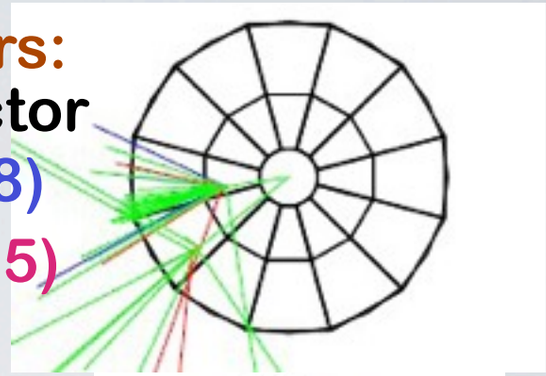


Event plane detectors:

Reaction plane detector

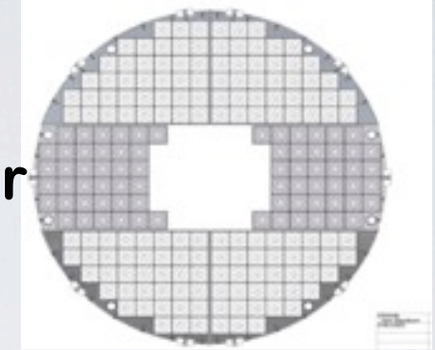
RXN_{IN} ($1.5<|\eta|<2.8$)

RXN_{OUT} ($1.0<|\eta|<1.5$)



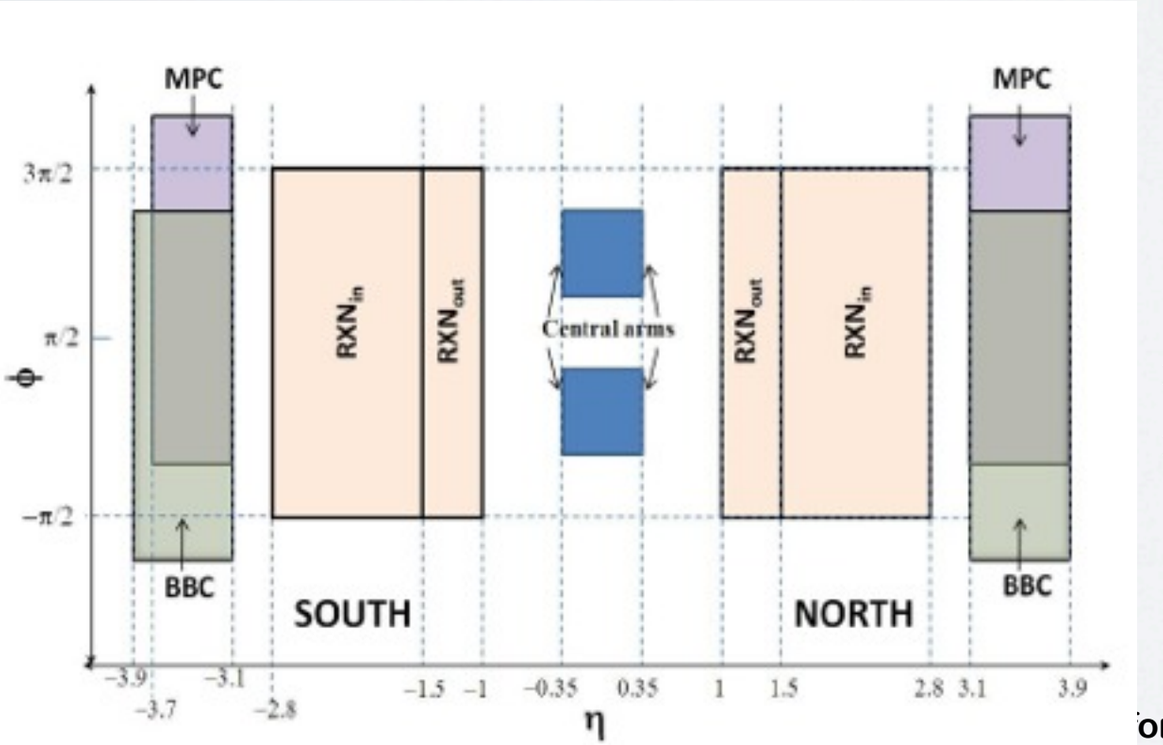
Muon piston Calorimeter

MPC ($3.1<|\eta|<3.9$)



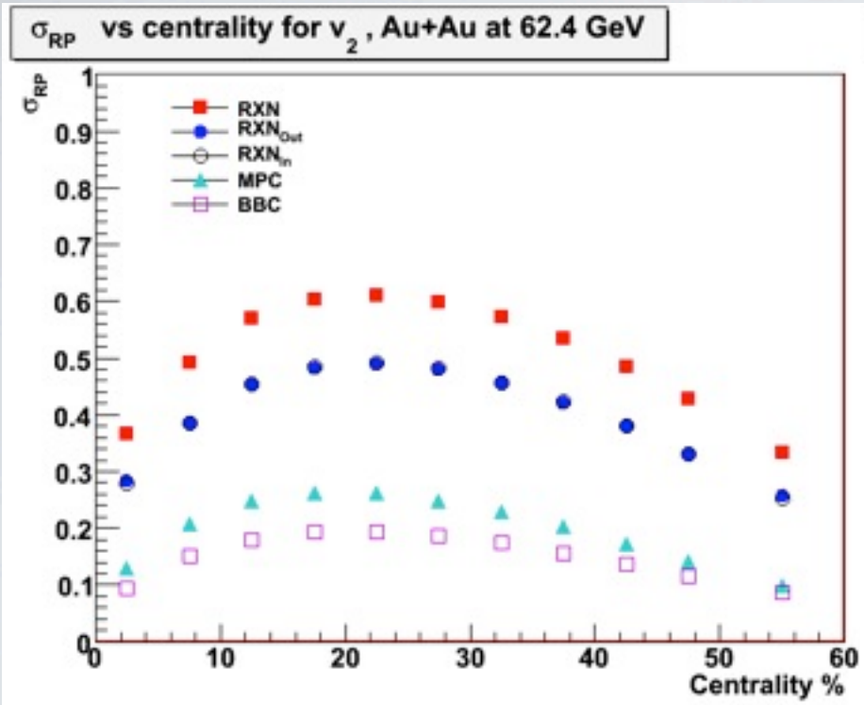
Beam-beam counter

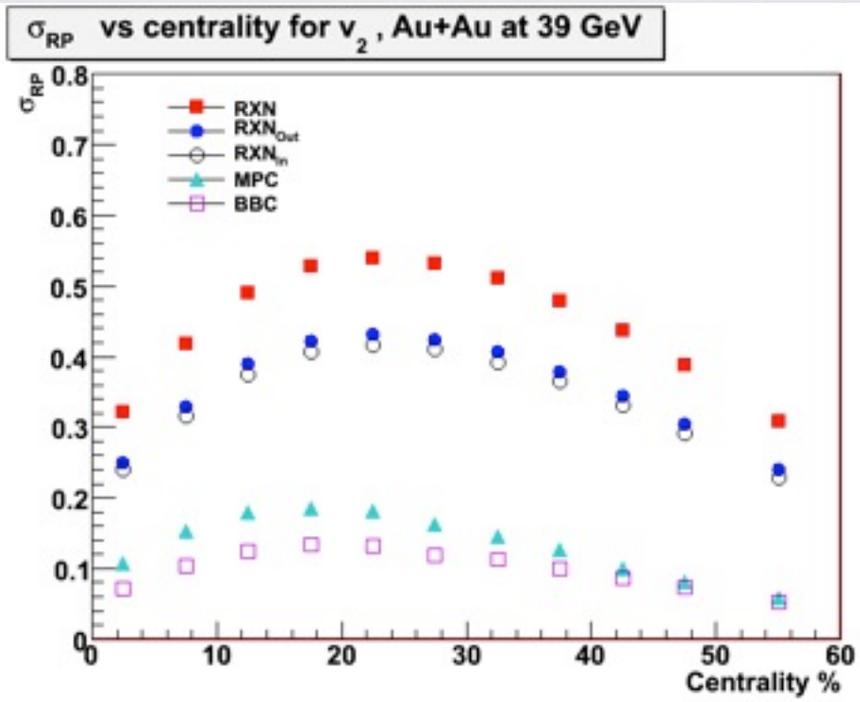
BBC ($3.1<|\eta|<3.9$)



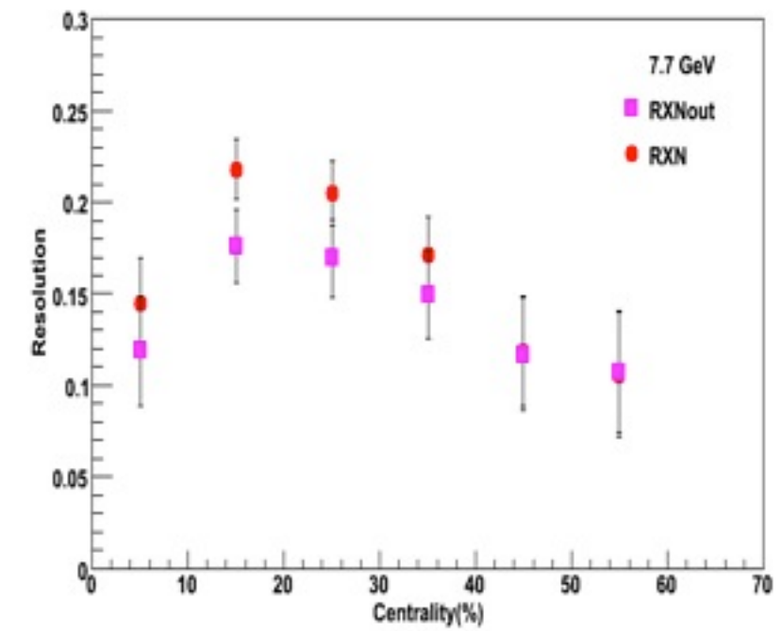
- **Large η gap away central arm $|\eta|<0.35$**
- **Systematic study the non-flow effect for the measurement of v_2 and v_4**

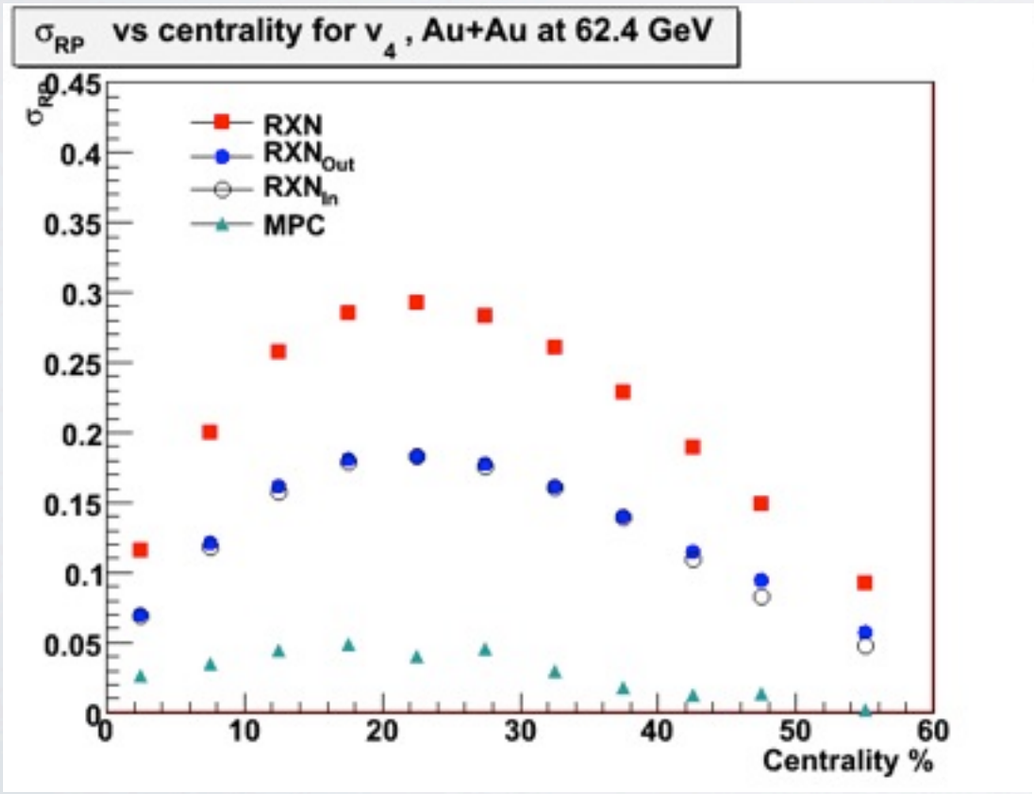
The event plane Resolution

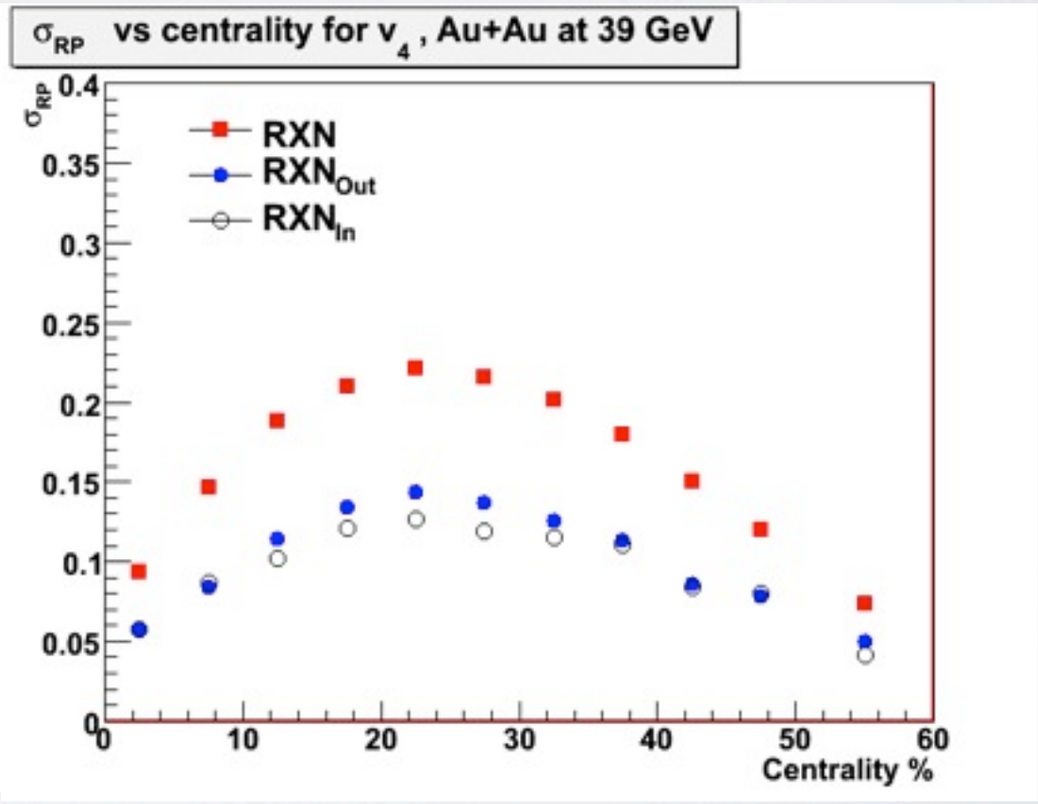




σ_{RP} for v_2, Au+Au at 7.7 GeV





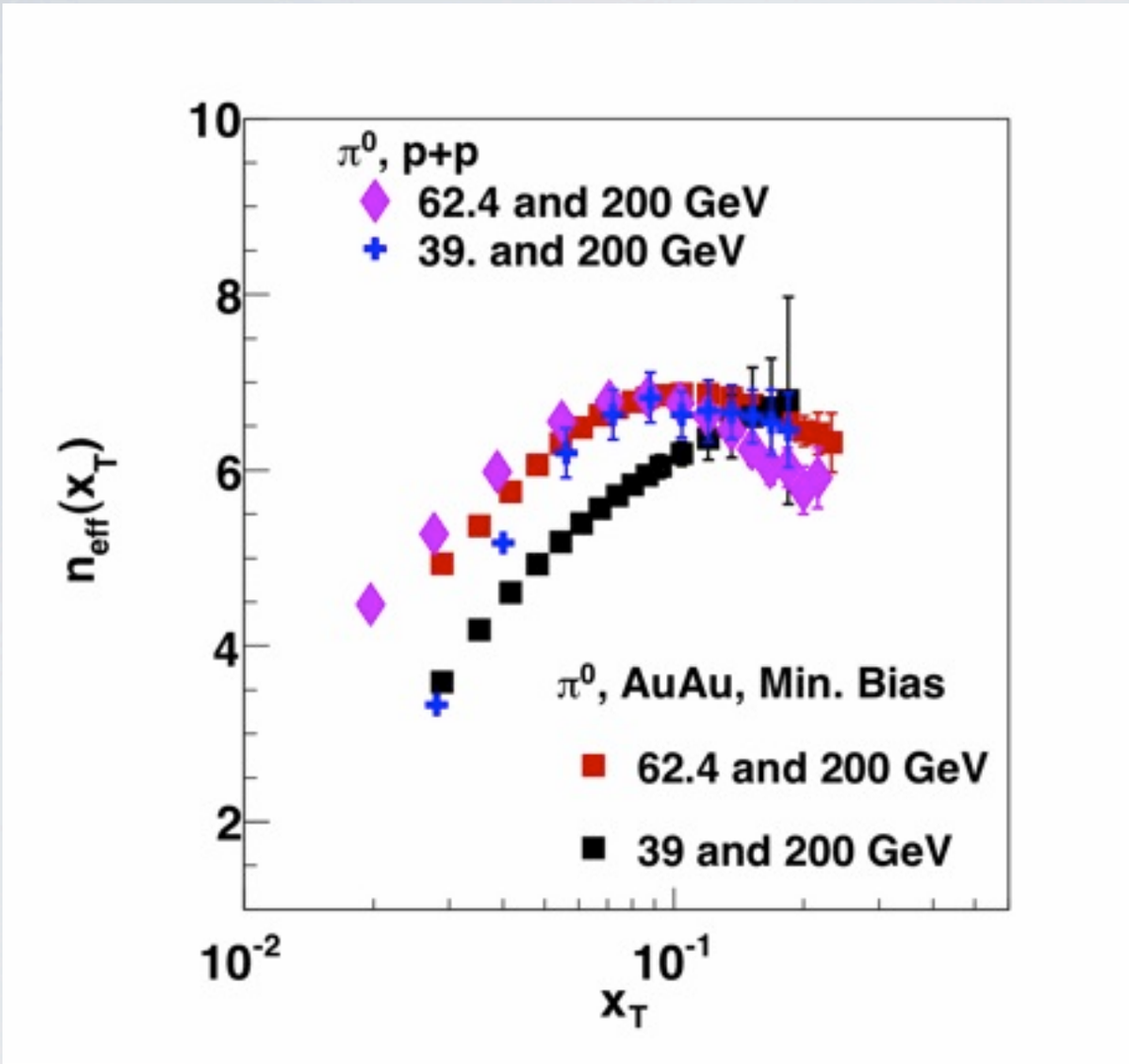


x_T scaling

$$x_T = \frac{2p_T}{\sqrt{s}}$$

$$n_{eff}(x_T) = \frac{log(\frac{Yield(x_T, \sqrt{s_1})}{Yield(x_T, \sqrt{s_2})})}{log(\frac{\sqrt{s_2}}{\sqrt{s_1}})}$$

x_T scaling



- All p+p data shows similar scaling behavior and the $n_{eff}(x_T)$ are comparable
- The 62.4 and 200 GeV Au+Au data agrees with the p+p data
- The $n_{eff}(x_T)$ of the 39 and 200 GeV Au+Au show the x_T scaling is not working below $x_T < 0.2$ (the end of overlapping region)

$$x_T = \frac{2p_T}{\sqrt{s}} \qquad n_{eff}(x_T) = \frac{log(\frac{Yield(x_T, \sqrt{s_1})}{Yield(x_T, \sqrt{s_2})})}{log(\frac{\sqrt{s_2}}{\sqrt{s_1}})}$$