Highlights from BNL-RHIC

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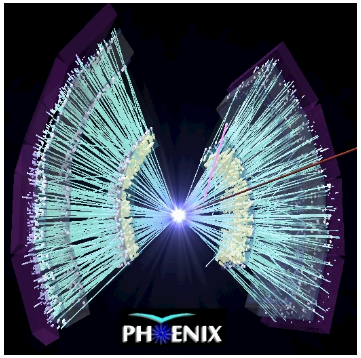
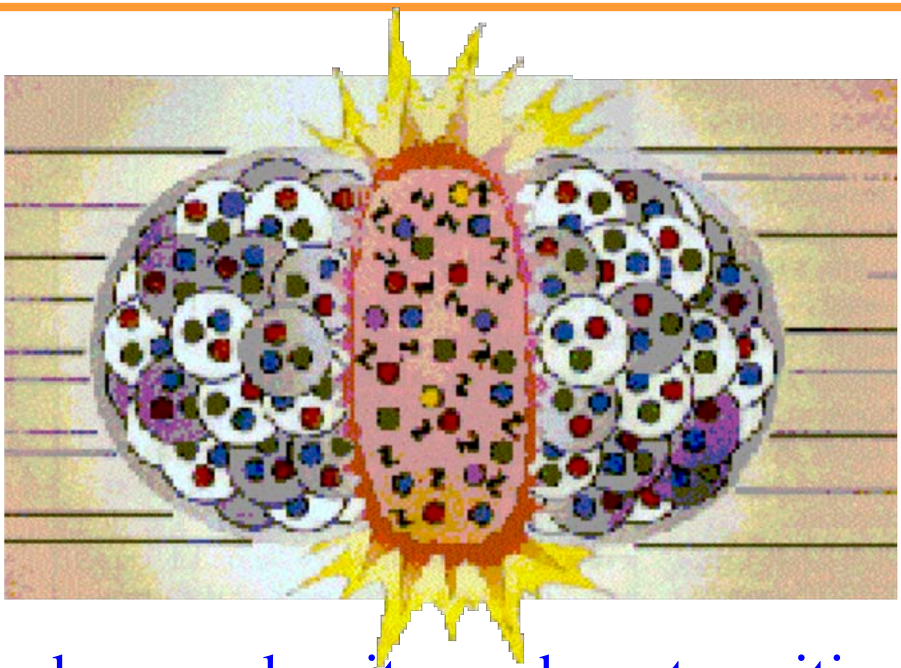
International School of Subnuclear Physics
"Searching for the Unexpected at LHC and the Status of our Knowledge"
49th Course-Erice, Sicily, Italy
June 24- July 3, 2011
1st of the 50th Anniversary Celebrations



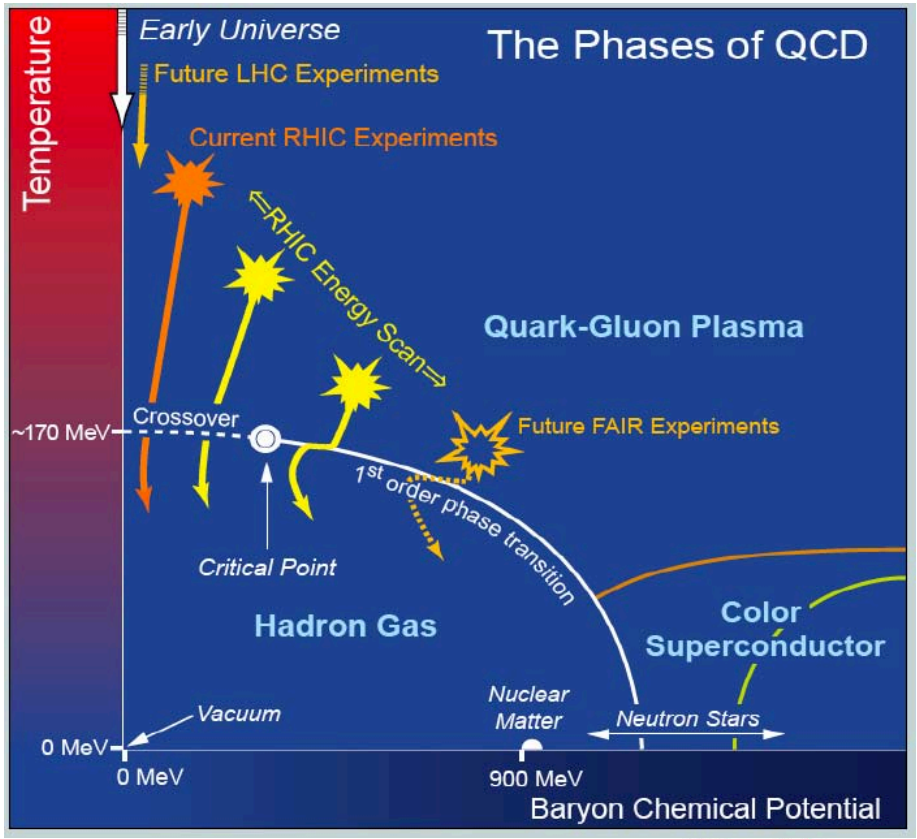
High Energy Nucleus-Collisions provide the means of creating Nuclear Matter in conditions of Extreme Temperature and Density



- At large energy or baryon density, a phase transition is expected from a state of nucleons containing confined quarks and gluons to a state of "deconfined" (from their individual nucleons) quarks and gluons covering a volume that is many units of the confinement length scale.

The Quark Gluon Plasma (QGP)

- The state should be in chemical (particle type) and thermal equilibrium $\langle p_T \rangle \sim T$
- The major problem is to relate the thermodynamic properties, Temperature, energy density, entropy of the QGP or hot nuclear matter to properties that can be measured in the lab.



The QGP was discovered at RHIC, announced on April 19, 2005 (230th anniversary of Paul Revere's Ride) as 'the perfect fluid', published NPA750,757(2005)1-171,1-283 with properties quite different from the 'new state of matter claimed' by the CERN fixed target heavy ion program on February 10, 2000 ("unpublished")

http://www.nationalcenter.org/PaulRevere'sRide.html

Mortadella-NYTimes 2/10/2000


"All the News That's Fit to Print"

The New York Times

Late Edition

NEW YORK, THURSDAY, FEBRUARY 10, 2000

75 CENTS

Spread of Attacks on Web Sites Is Slowing Traffic on the Internet

Attorney General Says There Are No Solid Leads

CLINTON IS RAISING MILLIONS TO PUSH EARLY 'ISSUE ADS'

EFFORT TO HELP NOMINEE

Paige and Louise's Big Interview

DIALLO TESTIMONY: A MAN CRIED 'GUN'

Democrats Drawn to McCain Are Unsettling Republicans

Mayor Unfairly Using Religion, First Lady Says

More Hostages Freed

Lobbyists for McCain

A Trade Truce, Over Lunch

Particle Physicists Getting Closer To the Bang That Started It All

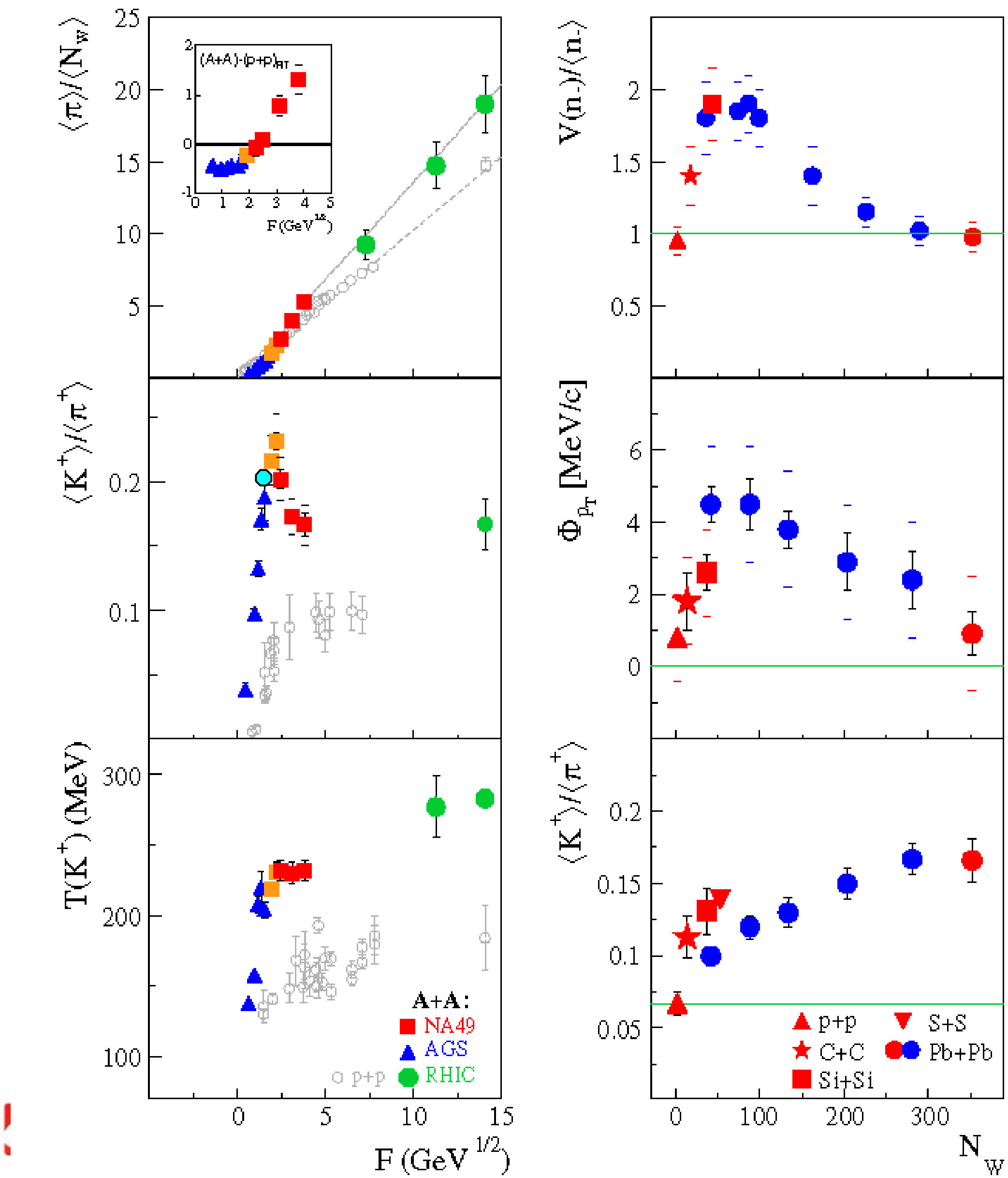
In Britain's Health Service, Sick Itself, Cancer Care Is Dismal

INSIDE

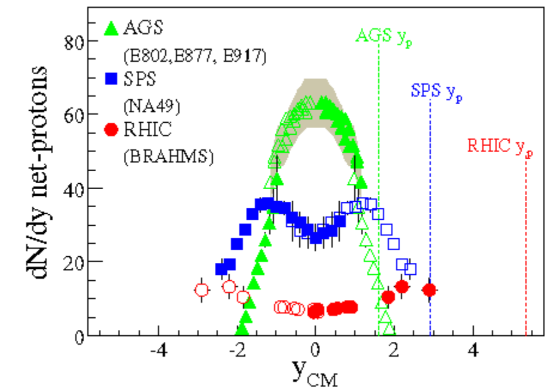
Summary---Mortadella Redux

SpS fixed target RHI

M Gaździcki (for the NA49 Collaboration)

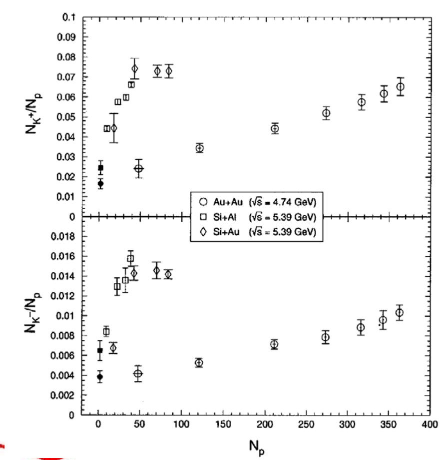


- No matter how you slice it---it's still ....
..**resonance matter** for $\sqrt{s_{NN}}$=3-20 GeV



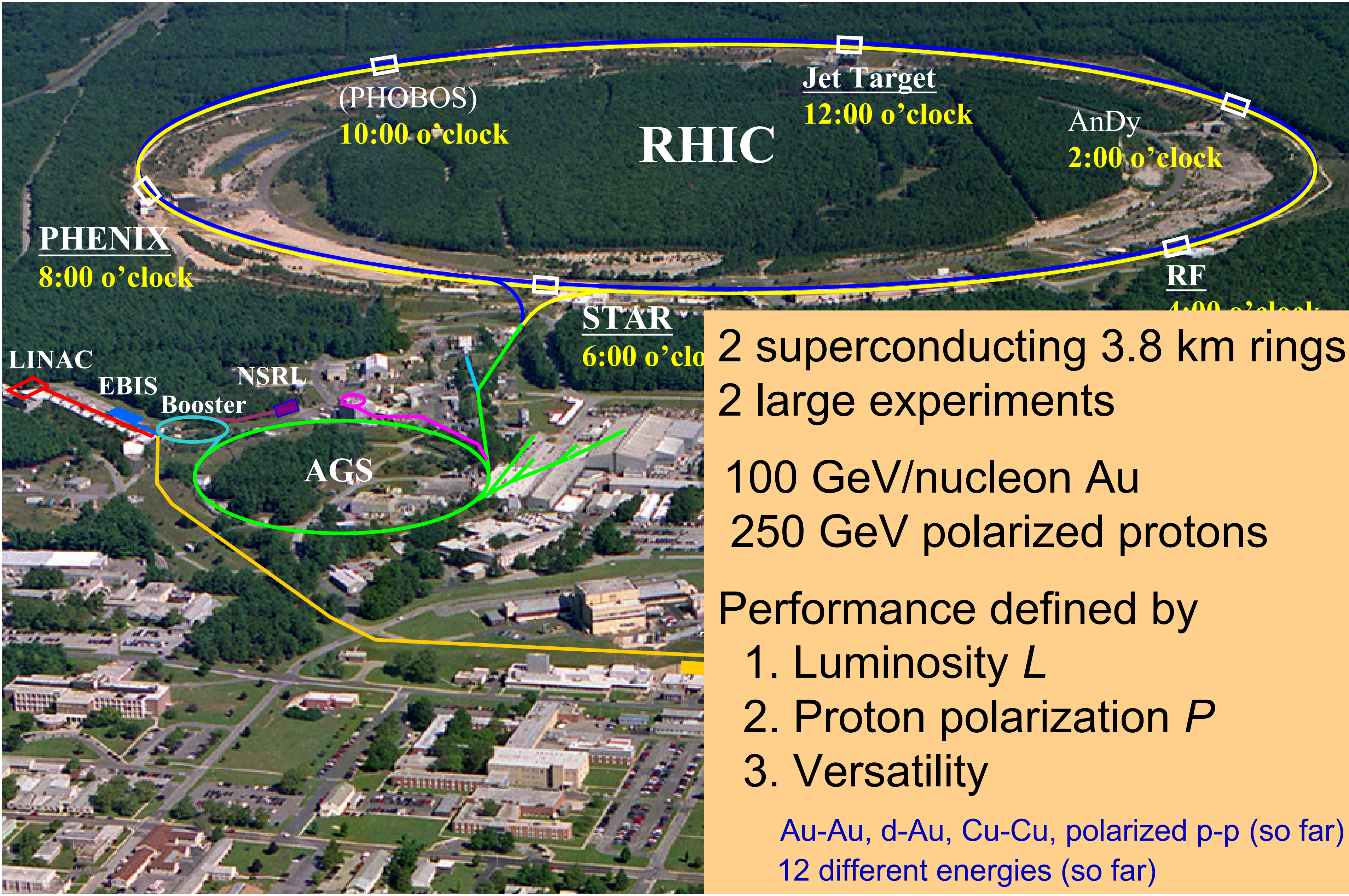
AGS RHI

PHYSICAL REVIEW C **60** 044904



That's old news; but we start with news from BNL and RHIC this year.

Relativistic Heavy Ion Collider
1 of 2 ion colliders (other is LHC), only polarized p-p collider



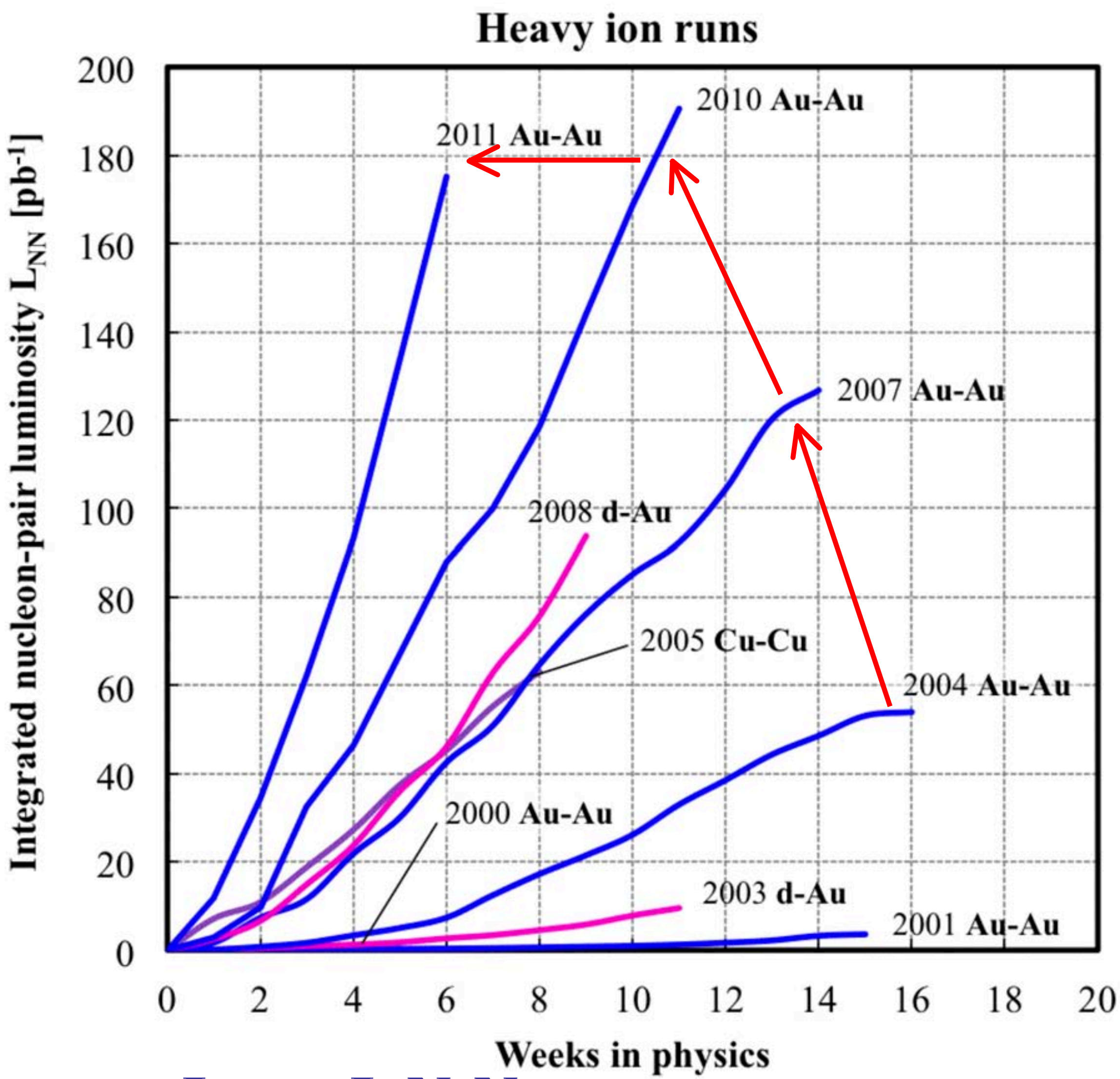
2 superconducting 3.8 km rings
2 large experiments

100 GeV/nucleon Au
250 GeV polarized protons

Performance defined by
1. Luminosity L
2. Proton polarization P
3. Versatility

Au-Au, d-Au, Cu-Cu, polarized p-p (so far)
12 different energies (so far)

RHIC heavy ions – luminosity evolution to date



<L> = 15x design in 2011

About 2x increase in L_{int}/week each
- Run-4 to Run-7
- Run-7 to Run10
- Run-10 to Run-11

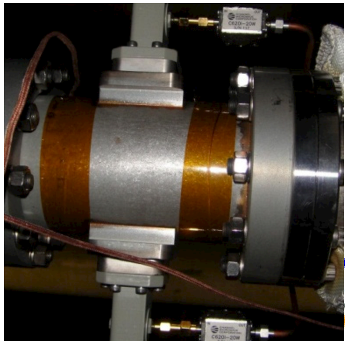
Rate of progress will slow down – burn off 50% of beam in collisions already

Wolfram Fischer

$L_{NN} = L\, N_1 N_2$ (= luminosity for beam of nucleons, not ions)

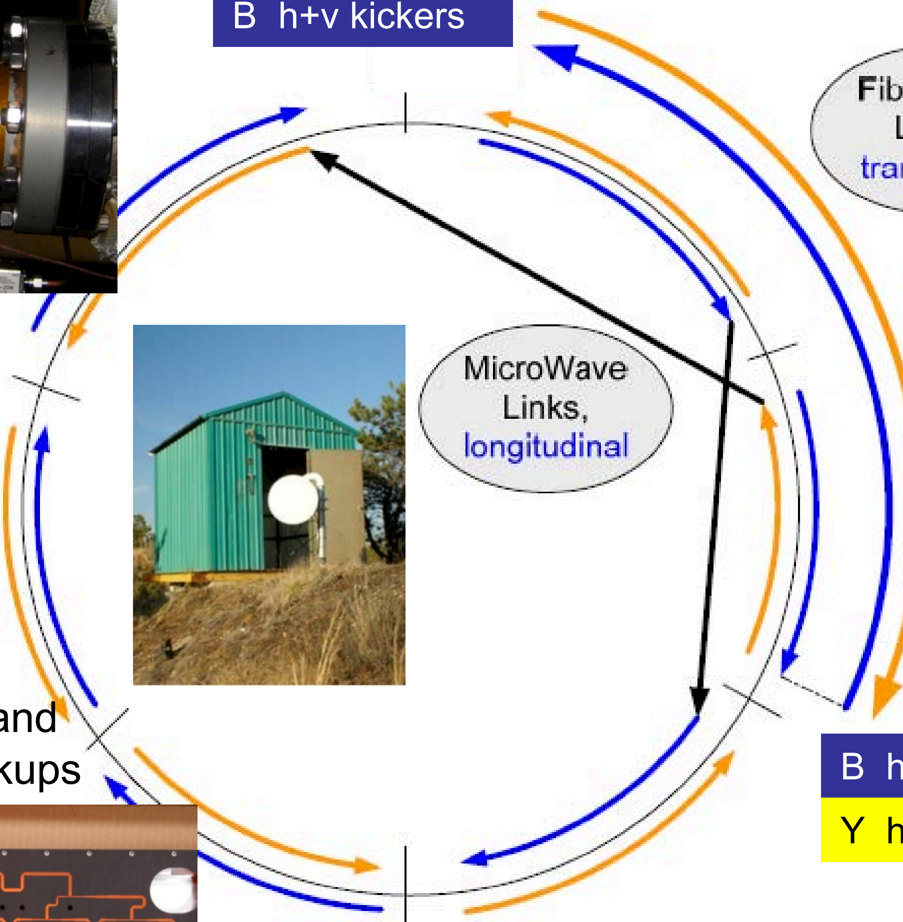
RHIC – 3D stochastic cooling for heavy ions

longitudinal pickup

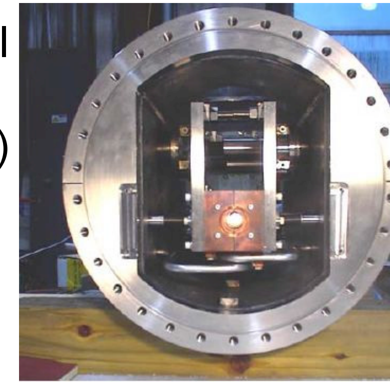


Y h+v pickups

B h+v kickers

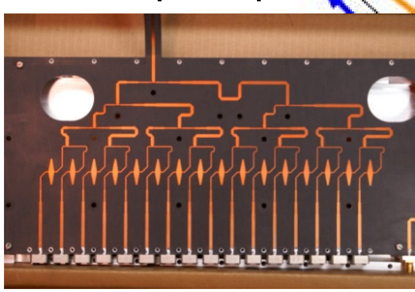


longitudinal kicker (closed)



Last missing planes: B+Y horizontal installation in summer 2011

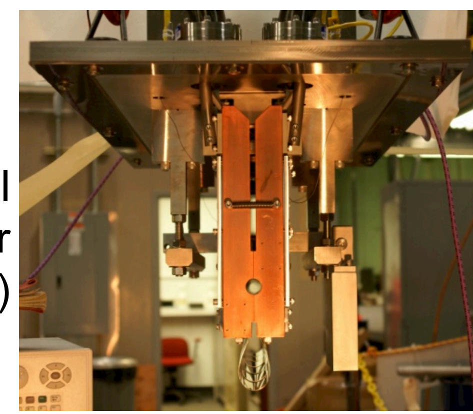
horizontal and vertical pickups



B h+v pickups

Y h+v kickers

vertical kicker (closed)

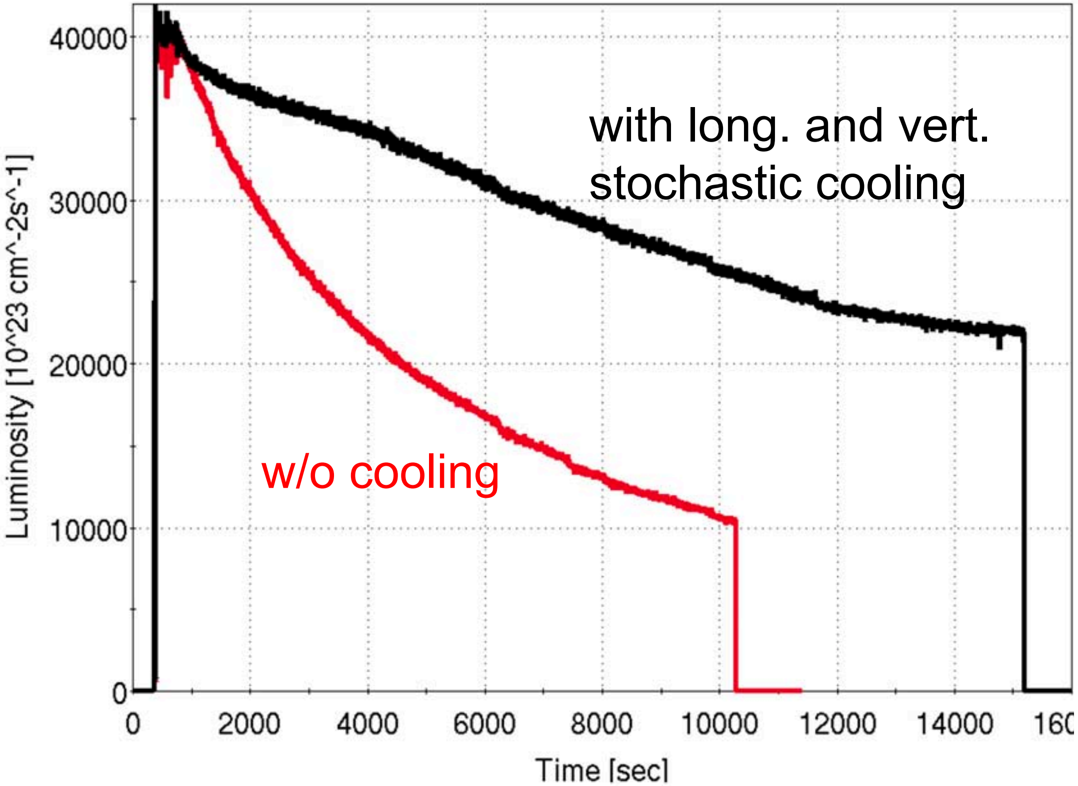


5-9 GHz, cooling times ~1 h

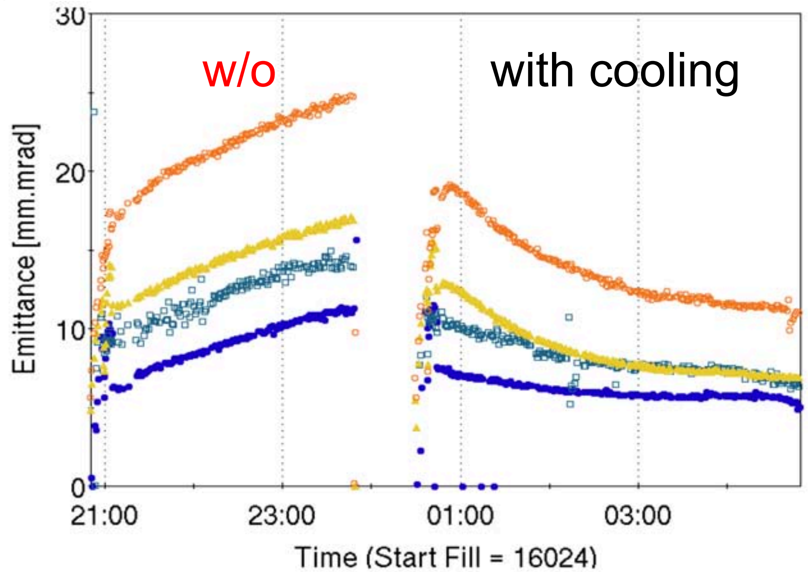
M. Brennan, M. Blaskiewicz, F. Severino, Phys. Rev. Lett. **100** 174803 (2008); PRST-AB, PAC, EPAC

RHIC – effect of stochastic cooling in Run-11

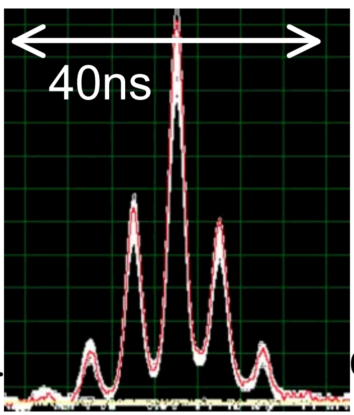
luminosity in 2 consecutive stores



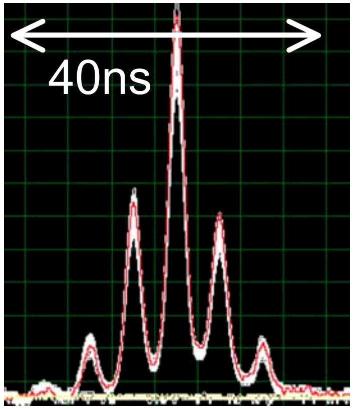
Factor 2 gain in average luminosity from stochastic cooling so far



strong transverse cooling makes longitudinal cooling less efficient, i.e. these longitudinal profiles at the end of a store with be more pronounced with horizontal cooling next year

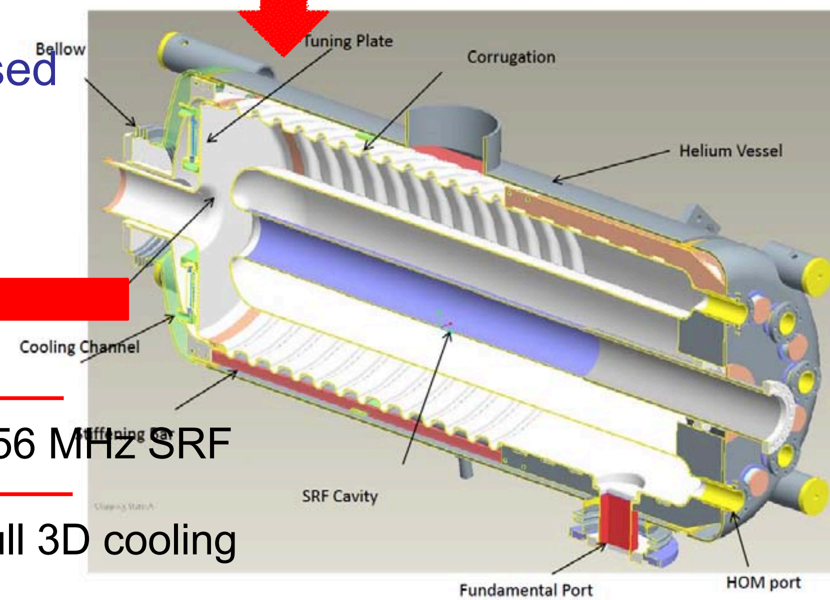


56 MHz SRF for heavy ions – under construction (I. Ben-Zvi et al.)

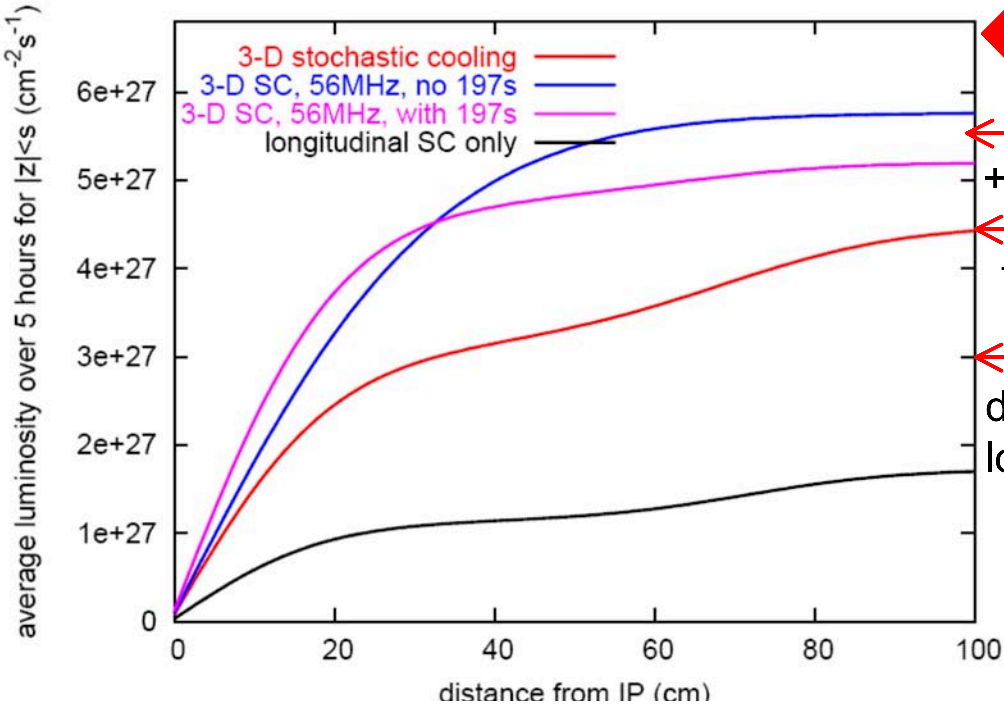


Longitudinal profile at end of store
- even with cooling, ions migrate into neighboring buckets
- can be reduced with increased longitudinal focusing

Commissioning planned for Run-14



Average luminosity vs. vertex size



+ 56 MHz SRF

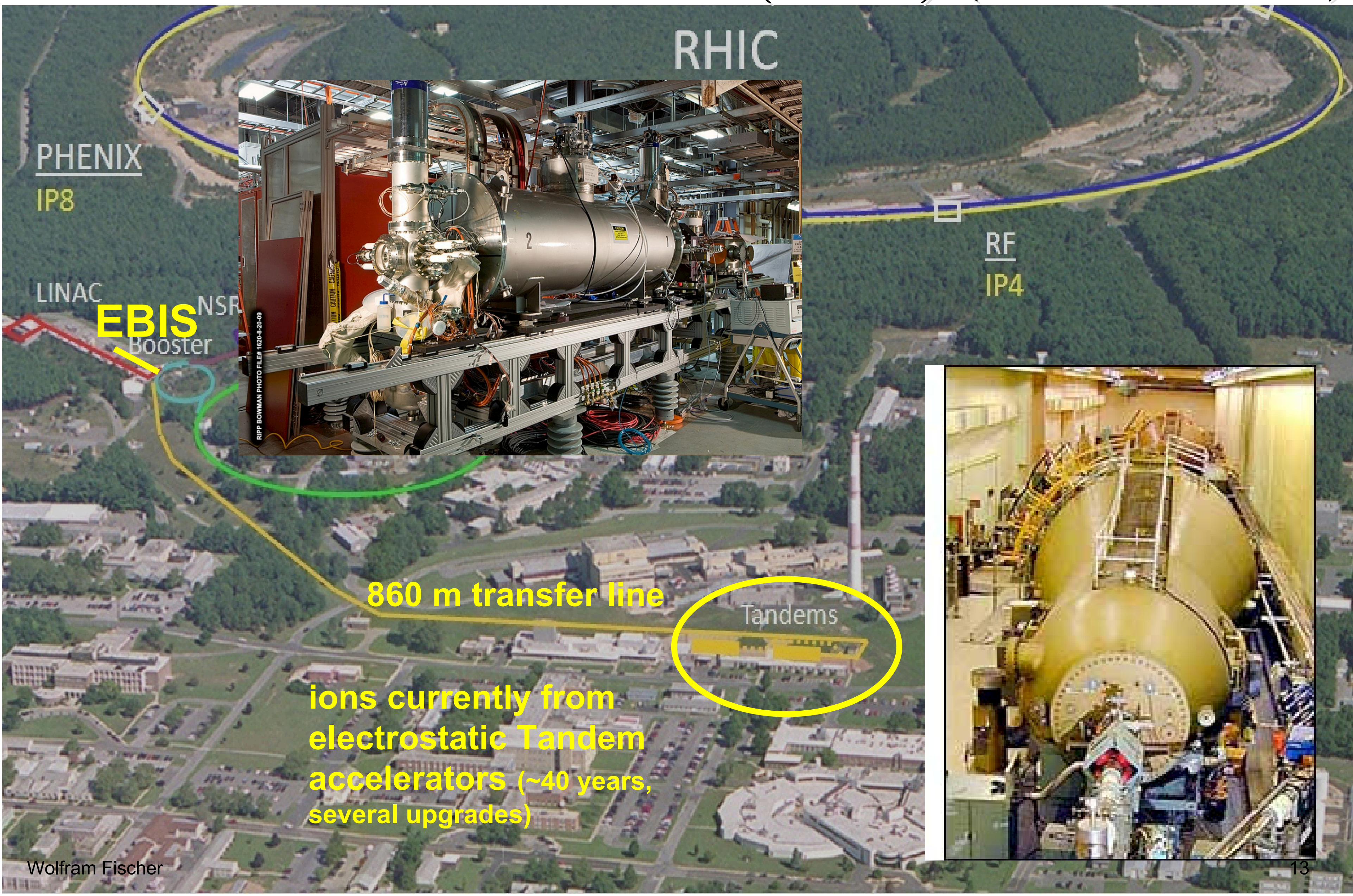
full 3D cooling

demonstrated 2011
long. + ver. cooling

- $\lambda/4$ Ni resonator
- common to both beams
- beam driven
- 56 MHz, 2 MV

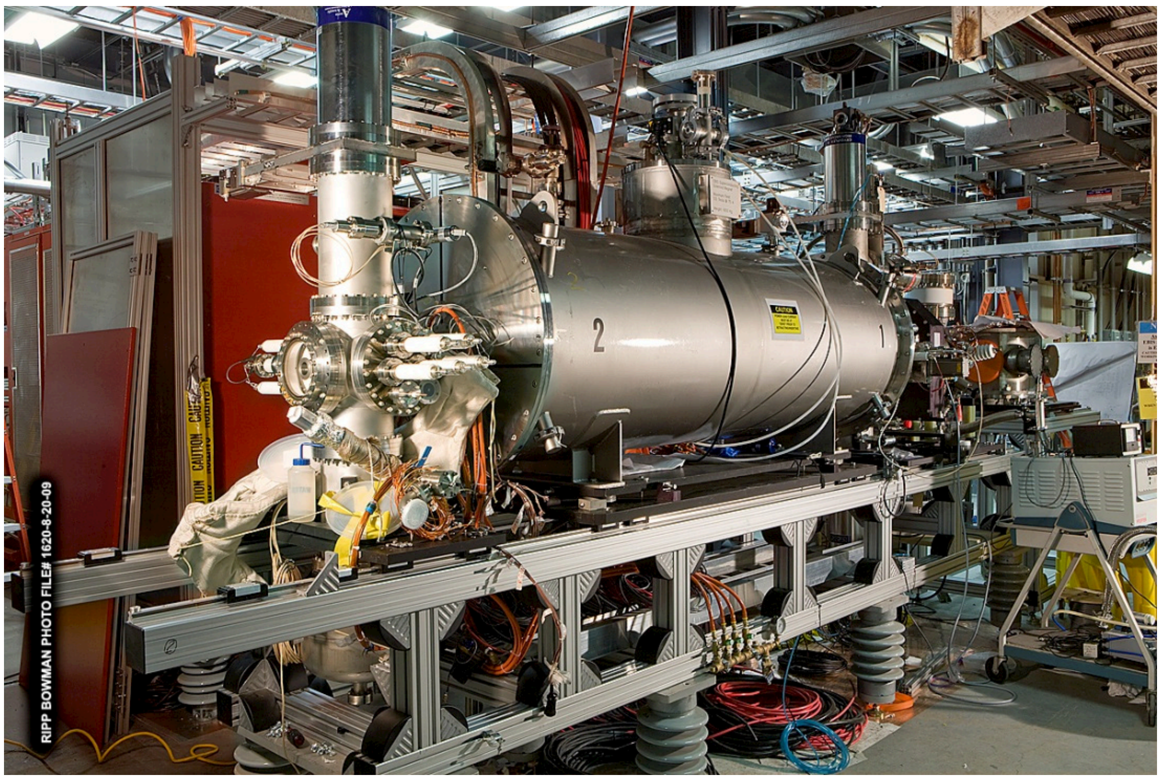
Calculation by M. Blaskiewicz

Electron Beam Ion Source (EBIS) (J. Alessi et al.)



Electron Beam Ion Source (EBIS)

- 10 A electron beam creates desired charge state(s) in trap within 5 T superconducting solenoid
- Accelerated through RFQ and linac, injected into AGS Booster
- All ion species incl. noble gas, uranium and polarized ^3He



Operated for NSRL with
- He^+, He^{2+}, Ne^{5+}, Ne^{8+}, Ar^{11+}, Ti^{18+}, Fe^{20+}

Commissioning for RHIC under way
- Work on 4x Au^{32+} increase to design intensity
  2x from electron current,
  2x from transmission
- Received U cathode
- Tandem still available as backup next year

Asymmetric collisions (p-Au)

- p-Au was considered in RHIC design (D. Trbojevic), no operation yet

  100.8 GeV p on 100.0 GeV/nucleon Au ($\gamma_p = \gamma_{Au} = 107.4$)

- **Need to translate DX magnets horizontally by 4.33 cm**

  p are bent stronger than Au^{79+}

- For energy scan need to match Lorentz factor γ of both beams

Parameter	unit	p-Au		p-Au	
No of bunches	…	111	111	111	111
Ions/bunch, initial	10^9	100	1.0	200	1.2
Average beam current/ring	mA	139	110	278	132
Stored energy per beam	MJ			0.36	0.42
β^*	m	0.85		0.60	
Hour glass factor	…	1.00		0.91	
Beam-beam parameter ξ/IP	10^{-3}	4.3	1.7	5.2	3.5
Peak luminosity	10^{28} cm^{-2}s^{-1}	30		95	
Average / peak luminosity	%	60		60	
Average store luminosity	10^{28} cm^{-2}s^{-1}	18		57	
Time in store	%	55		55	
Maximum luminosity/week	nb^{-1}			189	
Minimum luminosity/week	nb^{-1}	60			

Low energy collider operation

Au-Au energy scan with E = 3.85, 5.75, 9.8, 13.5, 19.5, 31.2, 100 GeV/nucleon

Up to nominal injection energy (9.8 GeV/nucleon) luminosity can be enhanced by electron cooling, use of Fermilab Pelletron possible (other options exist)

Have moved back by 2 year possible start of this upgrade due to manpower demand and needed guidance from experiment (completion ≥Run-17)

Cooling into space charge limit ΔQ_{sc} ~ 0.05 **(new collider regime)**

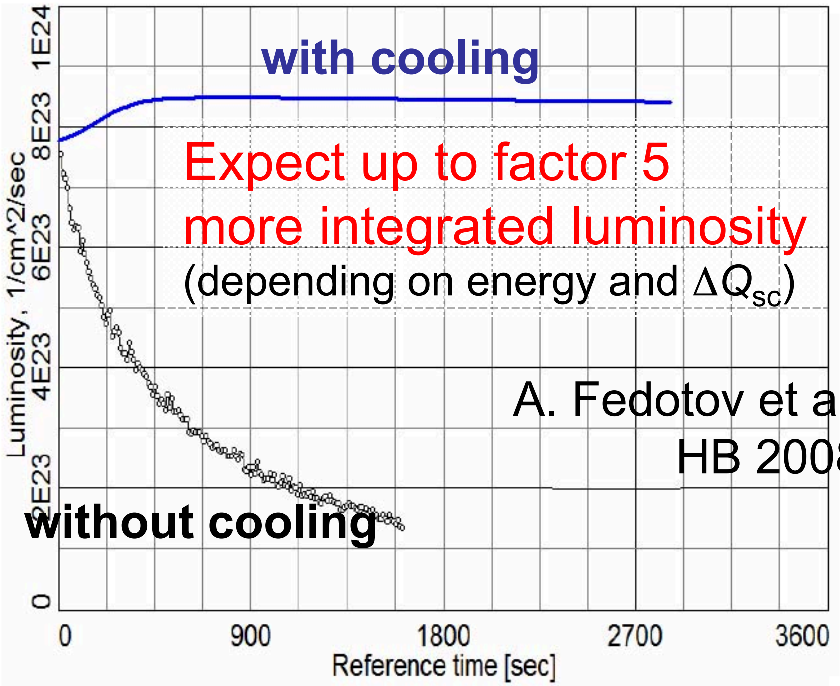
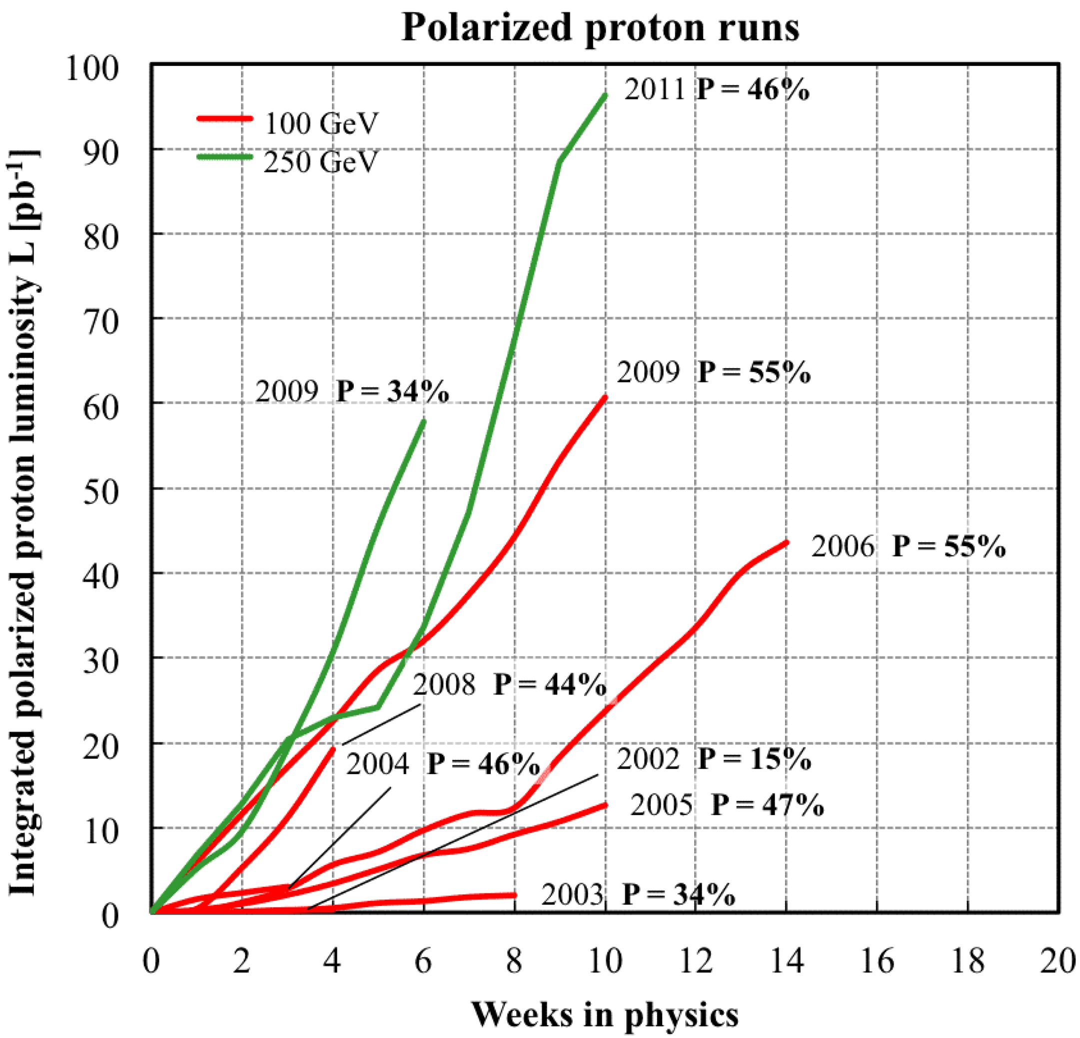


Figure 4. Simulation of luminosity with (blue line) and without (black dots) electron cooling at γ=2.7.

RHIC polarized protons – luminosity and polarization



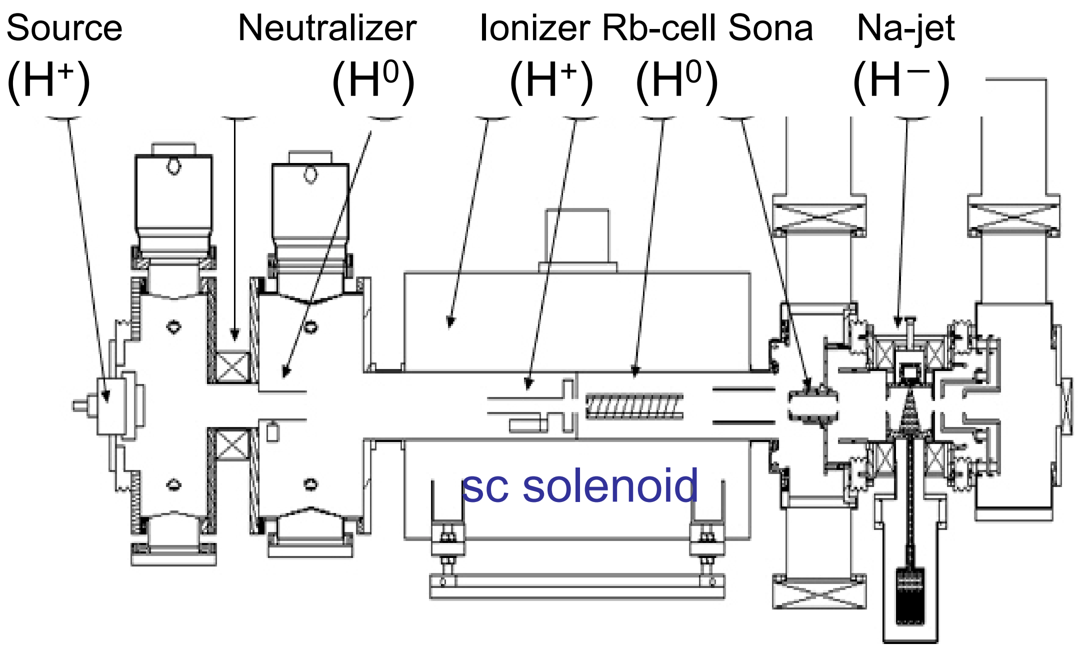
Wolfram Fischer

- <P> increased from 37% to 46% at 250 GeV in Run-11
  still significant effort needed to reach goal of 70%
- Building blocks for pp design luminosity at 250 GeV demonstrated in Run-9 and Run-11
  need to be put together
  plans to go beyond
- Expect no large increase in luminosity at 100 GeV before electron lenses

Luminosity and Polarization Goals

Parameter	unit	Achieved	With full stoch. cooling and 56 MHz cavity	
Au-Au operation		**2011**	**≥ 2012**	
Energy	GeV/nucleon	100	100	
No of bunches	…	111	111	
Bunch intensity	10^9	1.3	1.1	
Average Luminosity	10^{26} cm^{-2} s^{-1}	**30**	**40**	
p↑- p↑ operation		**2011**	**≥ 2012**	**≥ 2014**
Energy	GeV	100 / 250	100 / 250	250
No of bunches	…	109	109	109
Bunch intensity	10^{11}	1.3 / 1.65	1.3 / 1.7	2.0
Average Luminosity	10^{30} cm^{-2} s^{-1}	**24 / 90**	**30 / 150**	**300**
Polarization	%	**56 / 46**	**65**	**70**

Upgraded Optically Pumped Polarized H⁻ source (OPPIS) (run 13)– A. Zelenski



10x intensity increase was demonstrated in a pulsed operation by using a very high-brightness Fast Atomic Beam Source instead of the ECR source

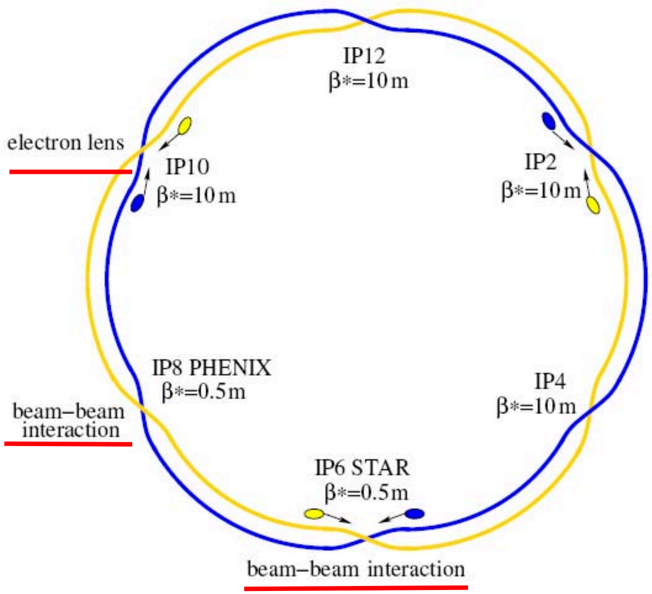
Goals:

1. H⁻ beam current increase to 10mA (order of magnitude)
2. Polarization to 85-90% (~5% increase)

Upgrade components:

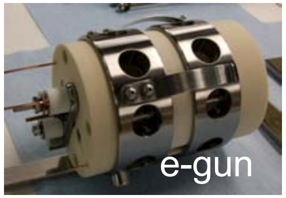
1. Atomic hydrogen injector (collaboration with BINP Novosibirsk)
2. Superconducting solenoid (3 T)
3. Beam diagnostics and polarimetry

Electron lenses – partial head-on beam-beam compensation



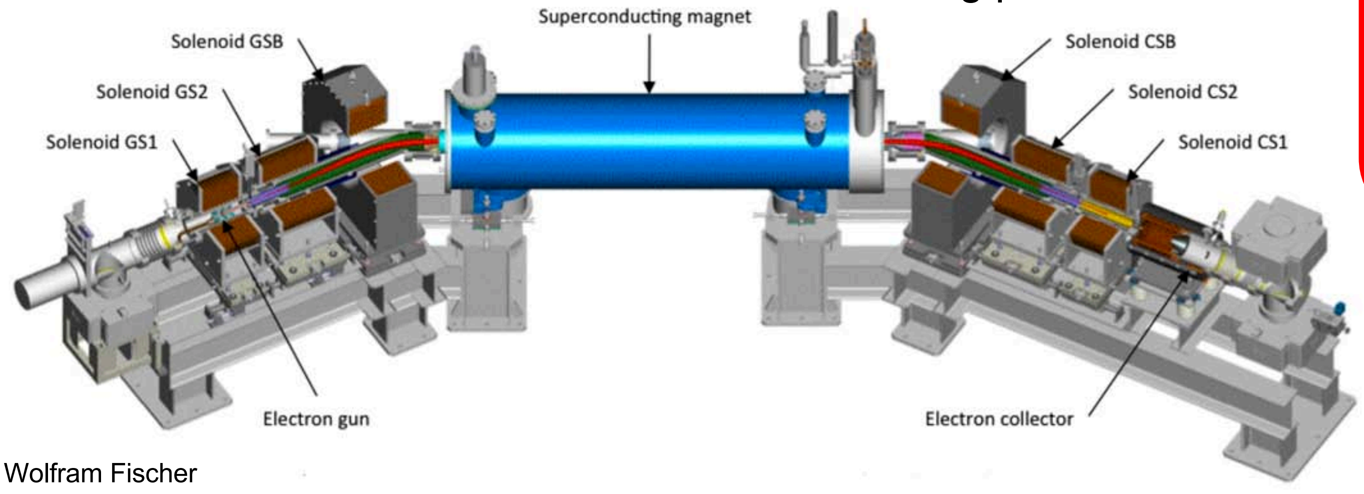
Polarized proton luminosity limited by head-on beam-beam effect ($\Delta Q_{bb,max}$ ~ 0.02)

Basic idea:
In addition to 2(3) beam-beam collisions with **positively** charged beam have another collision with a **negatively** charged beam with the same amplitude dependence.



Exact compensation for:
- short bunches
- $\Delta\psi_{x,y}$ = $k\pi$ between p-p and p-e collision
- no nonlinearities between p-p and p-e
- same amplitude dependent kick from p-p, p-e
- only approximate realization possible

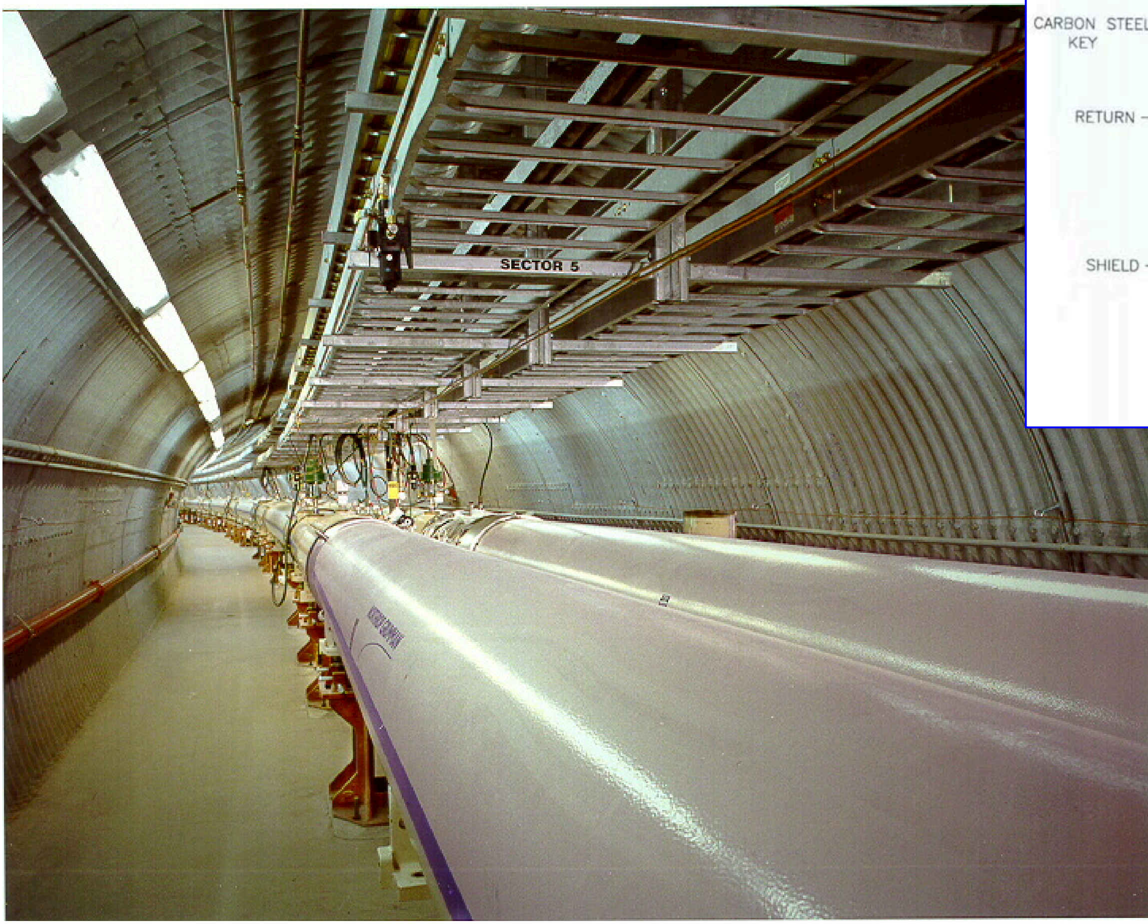
Expect up to 2x more luminosity
with OPPIS upgrade
Commissioning planned for Run-13

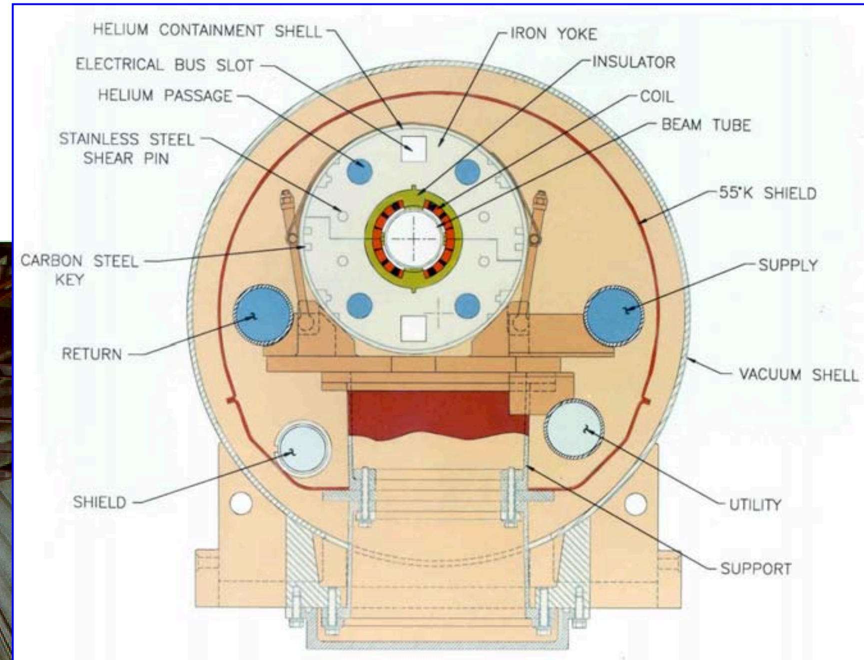


M. J

RHIC-All Superconducting Magnets

1911-Superconductivity discovered by Kamerlingh-Onnes. **1970's** practical large superconducting magnets





RHIC magnets designed at BNL (Palmer Magnet). BNL superconducting magnet division is a world treasure.

The Importance of another Phase Diagram at RHIC--that of Fe+C i.e. magnet steel

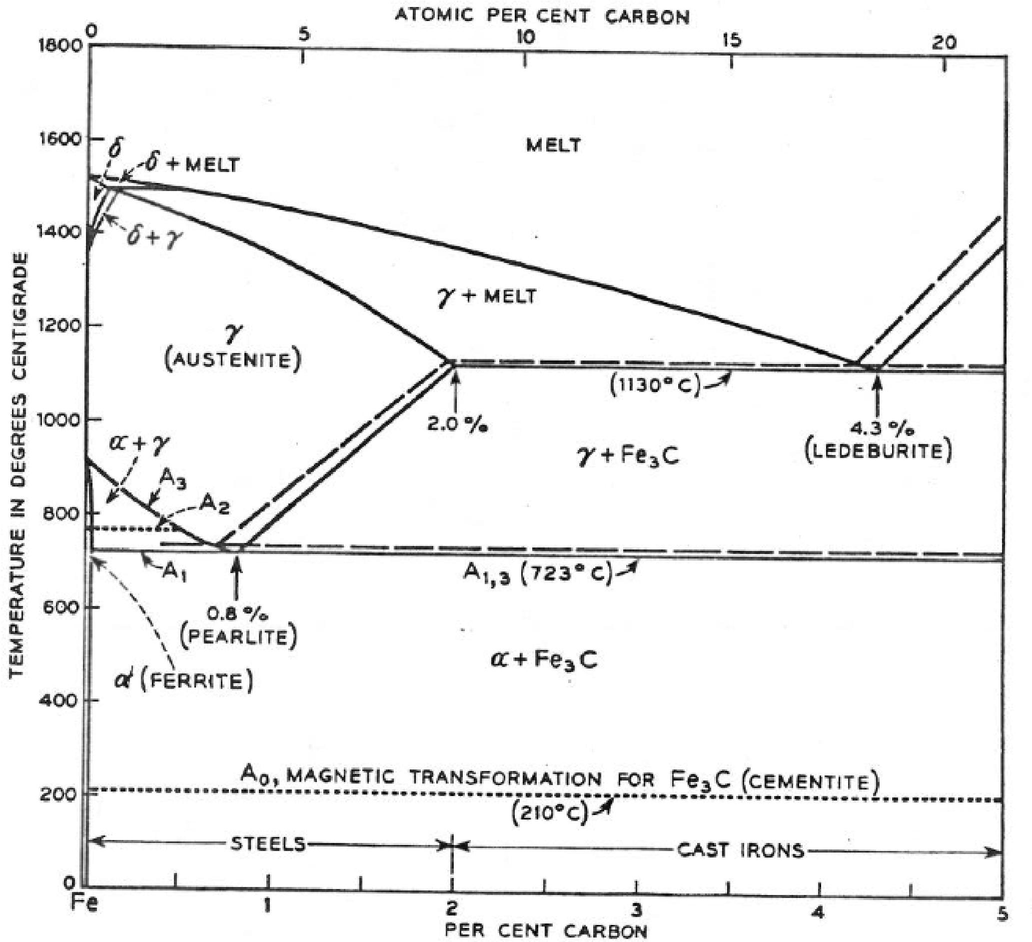
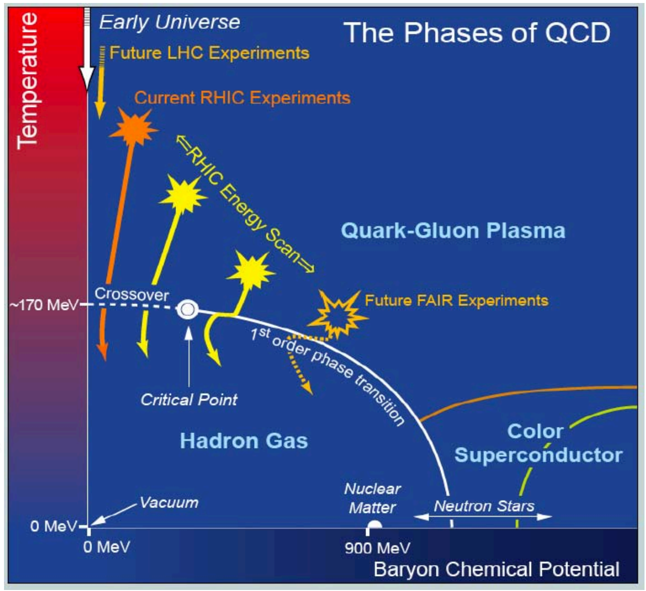


FIG. 9–17. Phase diagram of iron-carbon alloys.

quite complicated, well known



perhaps simpler but largely unknown

BNL Magnet Division-Latest Results

NIM A566(2006)746--756

Antimatter-catching BNL-built Magnet Featured in CERN Courier

The March edition of the CERN Courier has a familiar magnet on its cover. The octupole (eight-magnetic-pole) magnet — fabricated in Brookhaven Lab's Superconducting Magnet Division (SMD) in 2006 — recently helped an international team of scientists working on the ALPHA collaboration at CERN trap and store a significant amount of antimatter atoms for the first time. The magnet is the main component of the bottle-like, anti-matter-catching device, which is called a minimum magnetic field trap. The octupole's magnetic fields keep the antimatter away from the walls of the trap, preventing them from annihilating. As part of the fabrication, the Brookhaven team used a specially developed 3D winding machine in the SMD to build the magnet directly onto the outside of the trap.

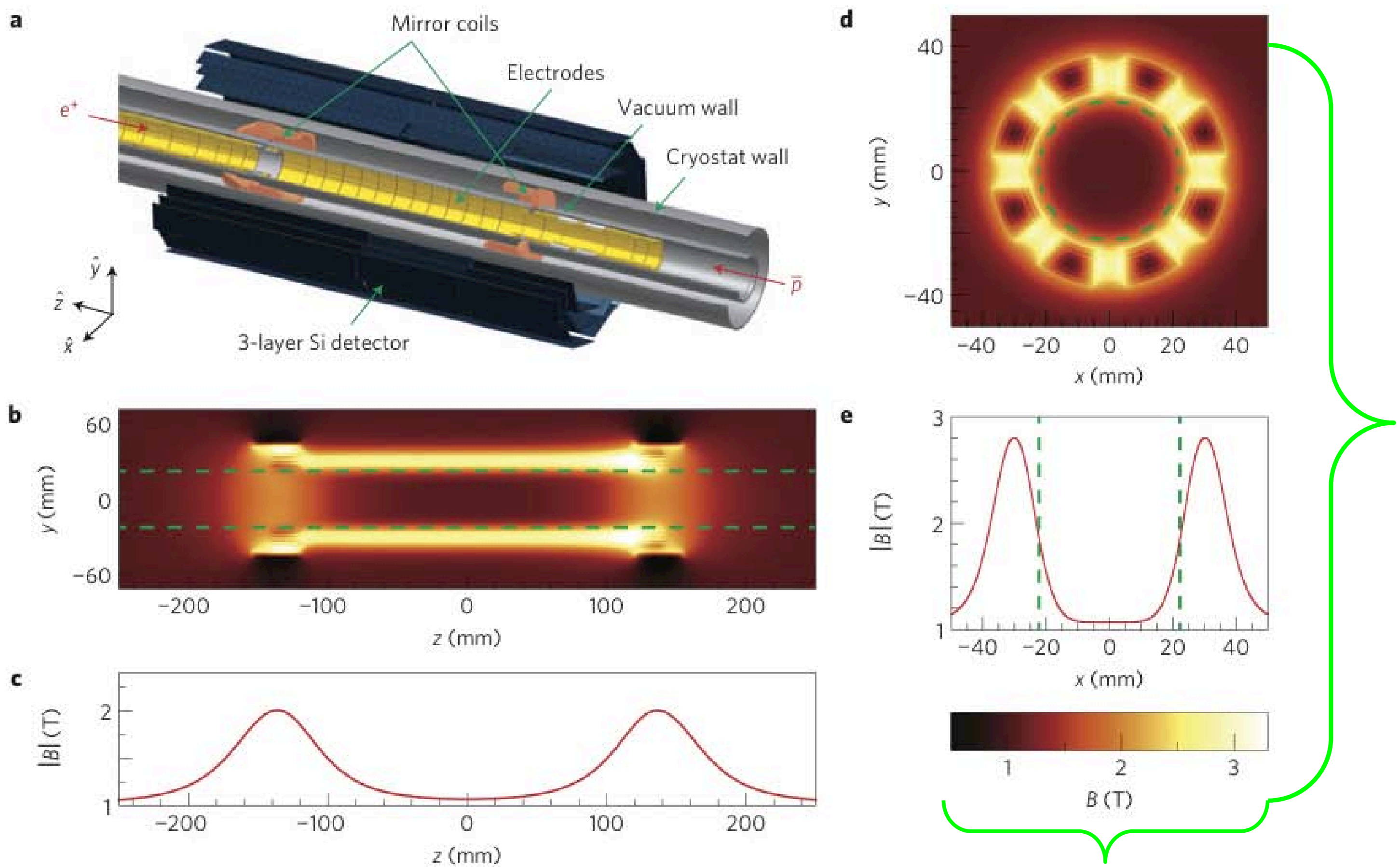
Said Peter Wanderer, SMD Head, "Several special features of the coil design and winding machine contributed to the success of this magnet. For example, the magnet generates a very pure octupole field. Also, the materials of the support structure provide a minimal barrier between the region where the antihydrogen is stored and the detectors. We were surprised but pleased that the magnet has withstood so many cycles of rapid quenching."

— Kendra Snyder

Is truth stranger than fiction?

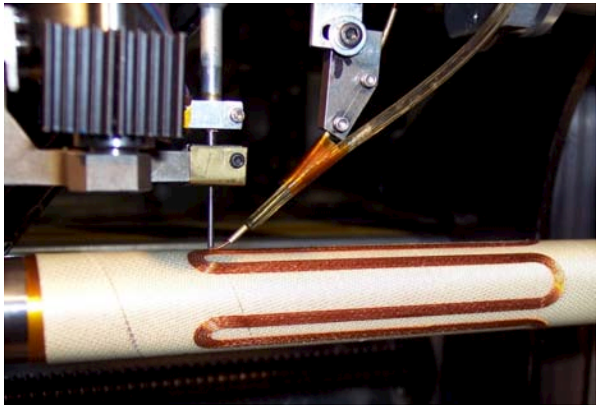
Confinement of antihydrogen for 1000 seconds

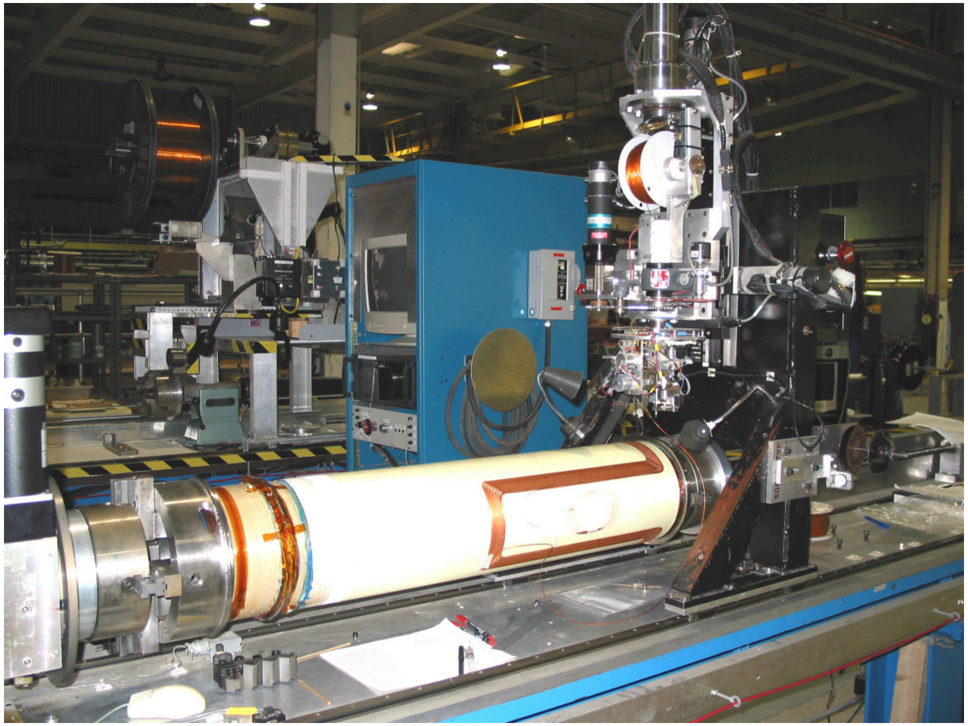
ARTICLES NATURE PHYSICS DOI:10.1038/NPHYS2025

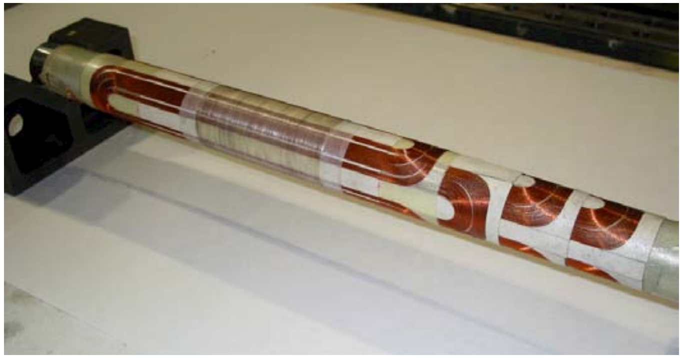


Complicated B-field, zero on axis

Direct Wind machine

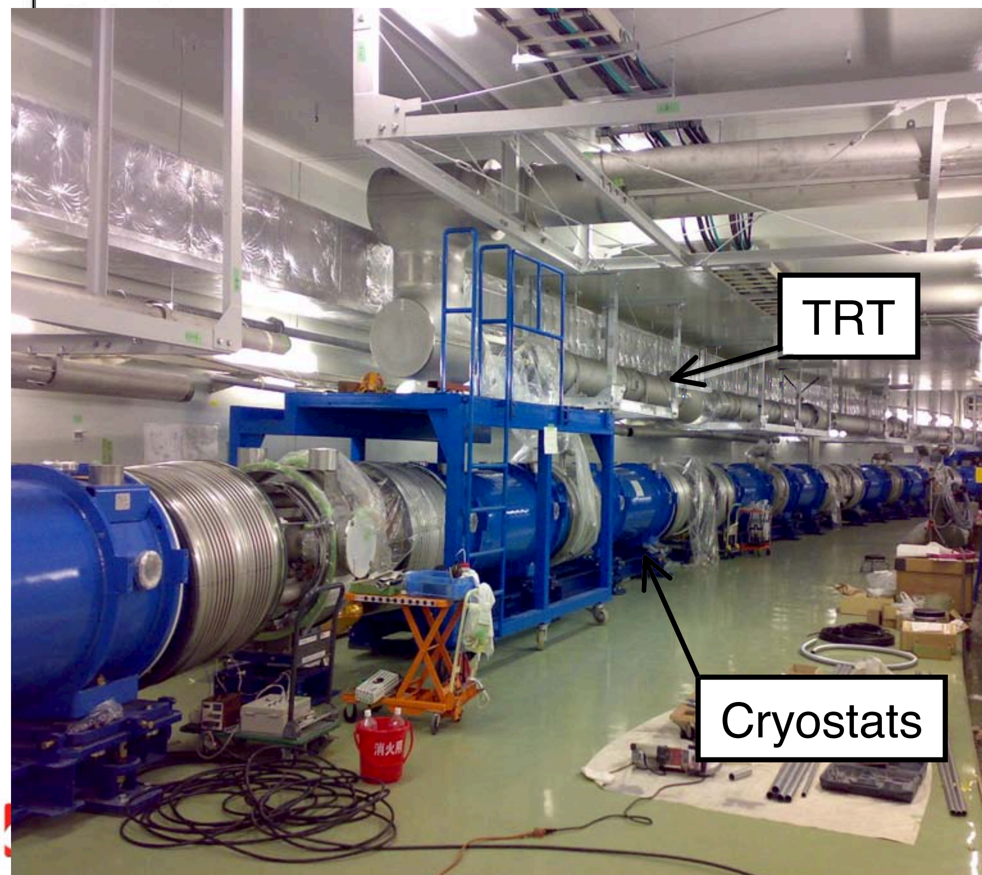


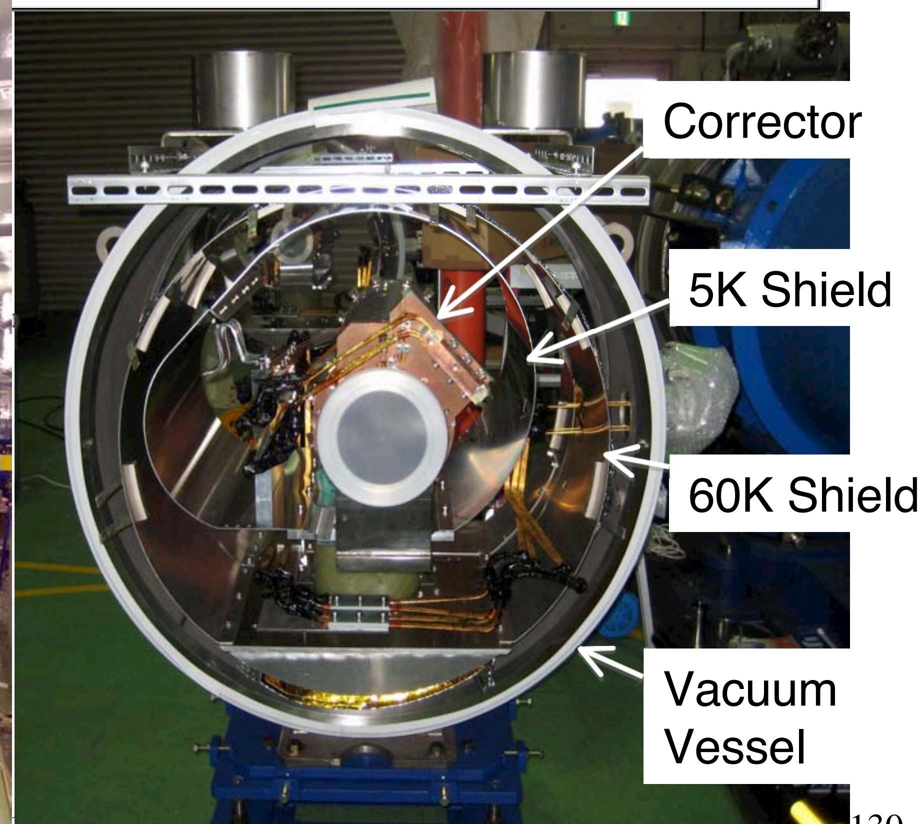




June 14, 2011-New Type of Neutrino Oscillation at the T2K Experiment

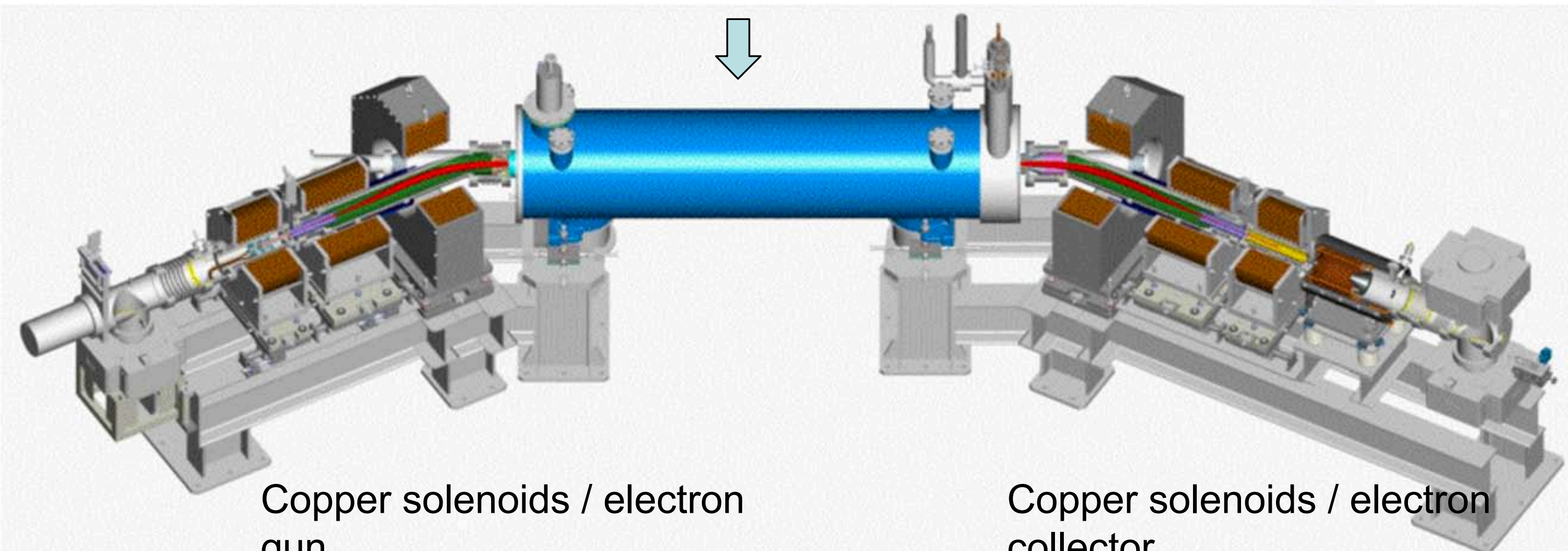
The following news release is being issued by the U.S. T2K collaboration at the Japan Proton Accelerator Research Complex (J-PARC). The experiment has found evidence for a new type of transformation between neutrinos, ghostlike elementary particles that zip through the Earth at a rate of 400 billion per second. Scientists at the U.S. Department of Energy's Brookhaven National Laboratory built a key part of the T2K experiment: five dipole (two-pole) "corrector" magnets. Made with a special 3-D winding machine – technology that allowed BNL engineers to use smaller and more efficient cable – these superconducting magnets are sandwiched between 28 "bending" magnets that drive an intense beam of protons into a stationary target. This high-speed impact creates a shower of particles, some of which decay to neutrinos. Together, the two types of magnets keep the protons tightly packed as they speed toward the target. Weighing about 500 pounds each, the meter-long corrector magnets were shipped to Japan from Brookhaven in 2008. For more information about Brookhaven's role, contact Kendra Snyder, ksnyder@bnl.gov, 631-344-8191, or Peter Genzer, genzer@bnl.gov, 631-344-3174.





NbTi magnets for RHIC Electron Lens system

- **Electron Lens system** will increase integrated luminosity of polarized protons colliding in RHIC



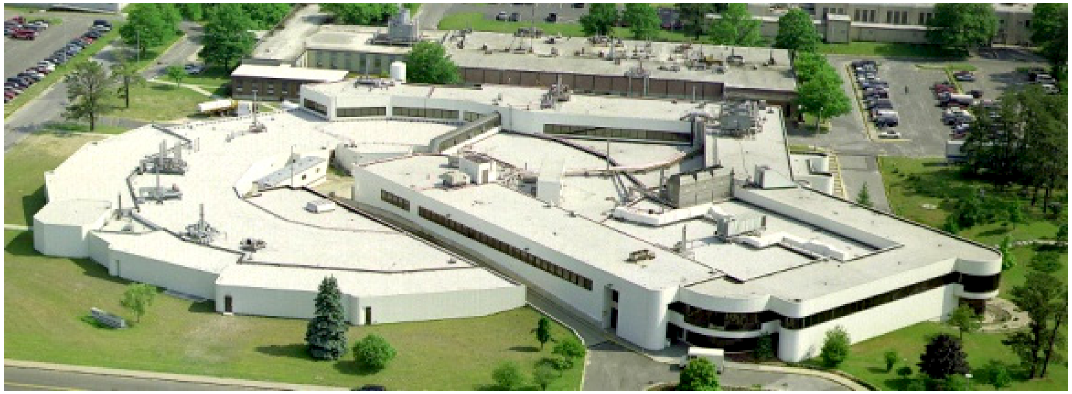
Ongoing projects

- NbTi final focus quad for ILC
- Nb_3Sn for LHC Luminosity Upgrade
  - ✓11.5 Tesla, 1.2-1.5kA Nb_3Sn Strand Test Barrel
  - ✓Coil for 3.4m, 90 mm quad
  - ✓Coil for 1m, 120 mm quad
- HTS for FRIB Quadrupole -Facility for Rare Isotope Beams (MSU)
  - ✓First quad after target → 220mm aperture, 600 mm L_{mag}, high heat and radiation loads.
  - ✓From Industry: 2G HTS (YBCO) - tape: SuperPower, American Superconductor

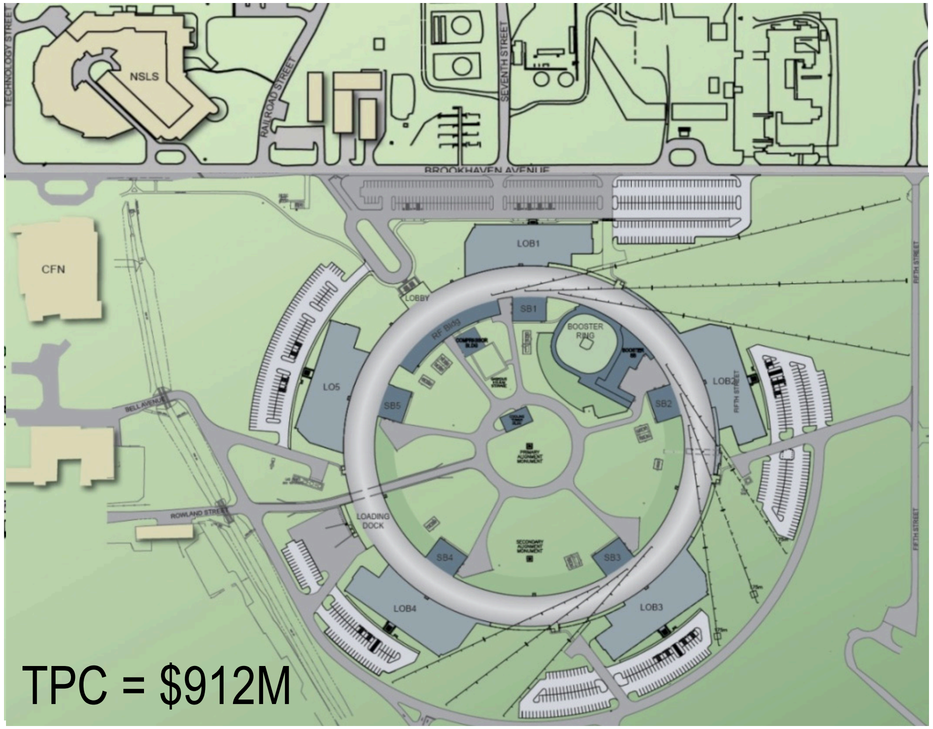
Other projects underway

- NbTi: APUL – spare dipole for LHC
- HTS (2G – YBCO) high-field solenoid R&D
  - ✓ Muon collider solenoids (subcontractor under SBIR)
  - ✓ Superconducting Magnetic Energy Storage (SMES), ARPA-E grant with BNL Materials Science, SuperPower, ABB
- HTS (1G – BSCCO cable) conductor R&D
  - ✓ ARRA-funded R&D – Very High Field Superconducting Magnet Collaboration (VHFSMC) – Muon collider
- Nb_3Sn Open Midplane Dipole for Muon Collider
  - ✓ subcontractor under SBIR
  - ✓ High field / large energy deposition / high radiation environment

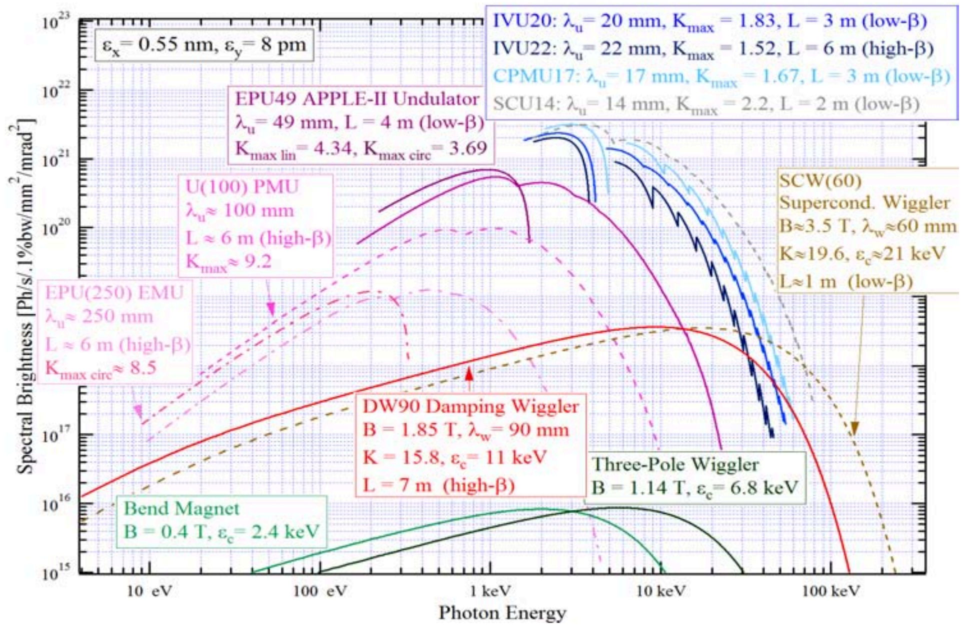
NSLS-II Current Status and Plans



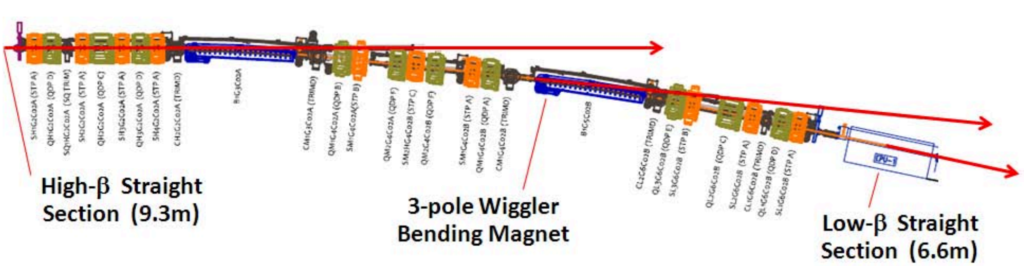
NSLS-II: Optimized 3rd Generation SR



TPC = $912M



- 3 GeV, 500 mA, Circumference 791 m
- Emittance: ε_x= 0.55, ε_y= 0.008 nm-rad
- High brightness from soft to hard x-rays
- Small beam size: σ_y=2.6 μm, σ_x=28 μm
- Pulse length (rms) ~15 psec
- 27 insertion device beamlines
- 31 BM / 3PW / IR beamlines
- High brightness, small source size, long beamlines – unique design features



NSLS-II Construction Progress

- Ring building construction progressing on budget and ahead of schedule
- LOB construction started
- Pentant 1 beneficial occupancy received; Accelerator installation in progress

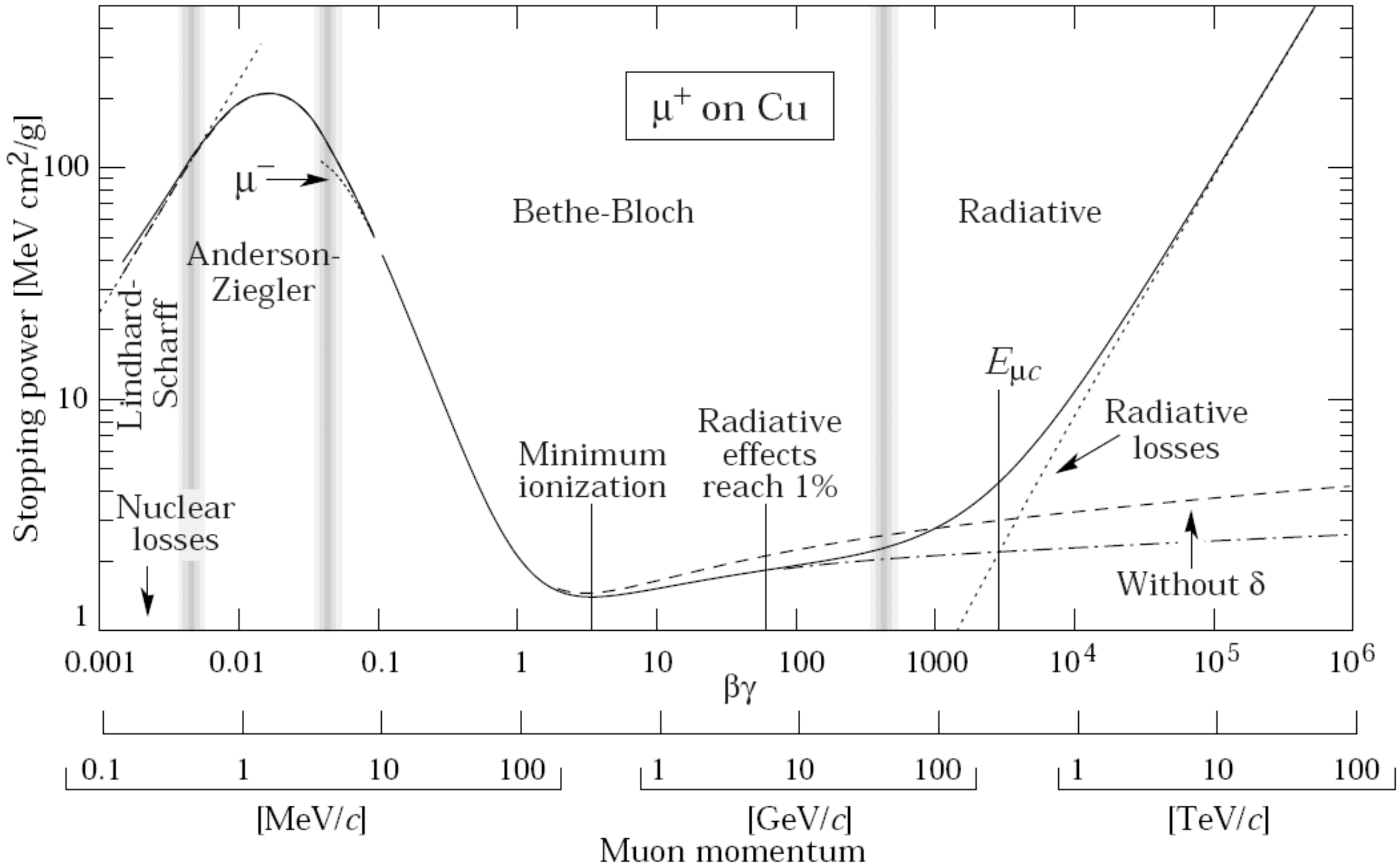
NSLS-II-Summary

- NSLS-II construction project (including 6 project BLs) progressing well
- Additional beamline projects getting started (NEXT, NIH, Type-II)
- Photon Sciences staff are excited to work with the community to define and pursue cutting-edge beamlines and science programs at NSLS-II
- Active, innovative, and engaged BNL/SBU community crucial to successful NSLS-II
- Thanks to **Qun Shen Photon Division Director, Photon Sciences Directorates, BNL for slides**

QGP PHYSICS Highlights from RHIC

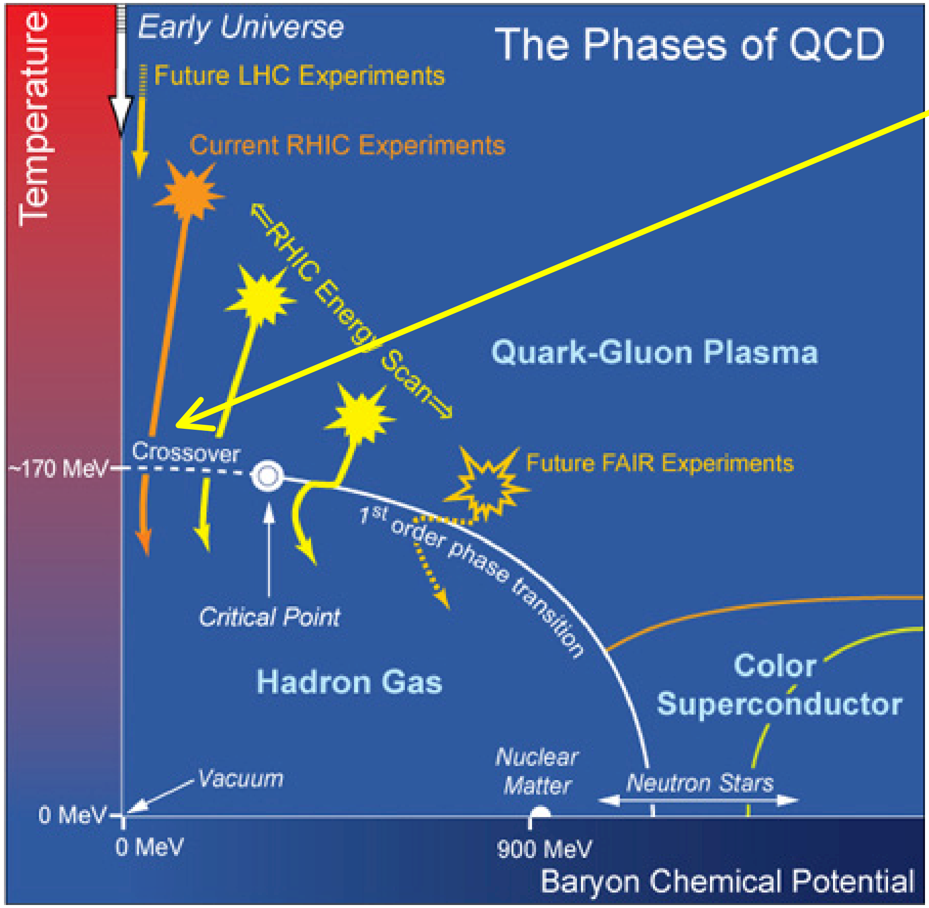
Given the QGP, what is my interest?

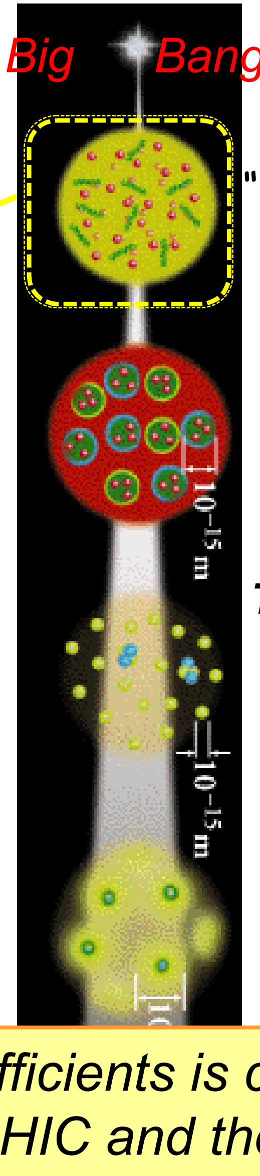
The QGP is the only place in the universe where we can in principle and in practice understand QCD for color-charged quarks in a color charged medium. How long will it take before we understand this as well as we understand a muon in Cu in QED?



slide by Jamie Nagle from PDG following a discussion with me.

Also quantitative study of the phases of QCD is a central goal of our field





Roy Lacey QM2011

"The major discoveries in the first five years at RHIC must be followed by a broad, quantitative study of the fundamental properties of the quark gluon plasma …"

The Frontiers of Nuclear Science
A Long Range Plan - 2007

Characterization requires

T, c_s, η/s, etc

The extraction of transport coefficients is central to the heavy ion programs at RHIC and the LHC

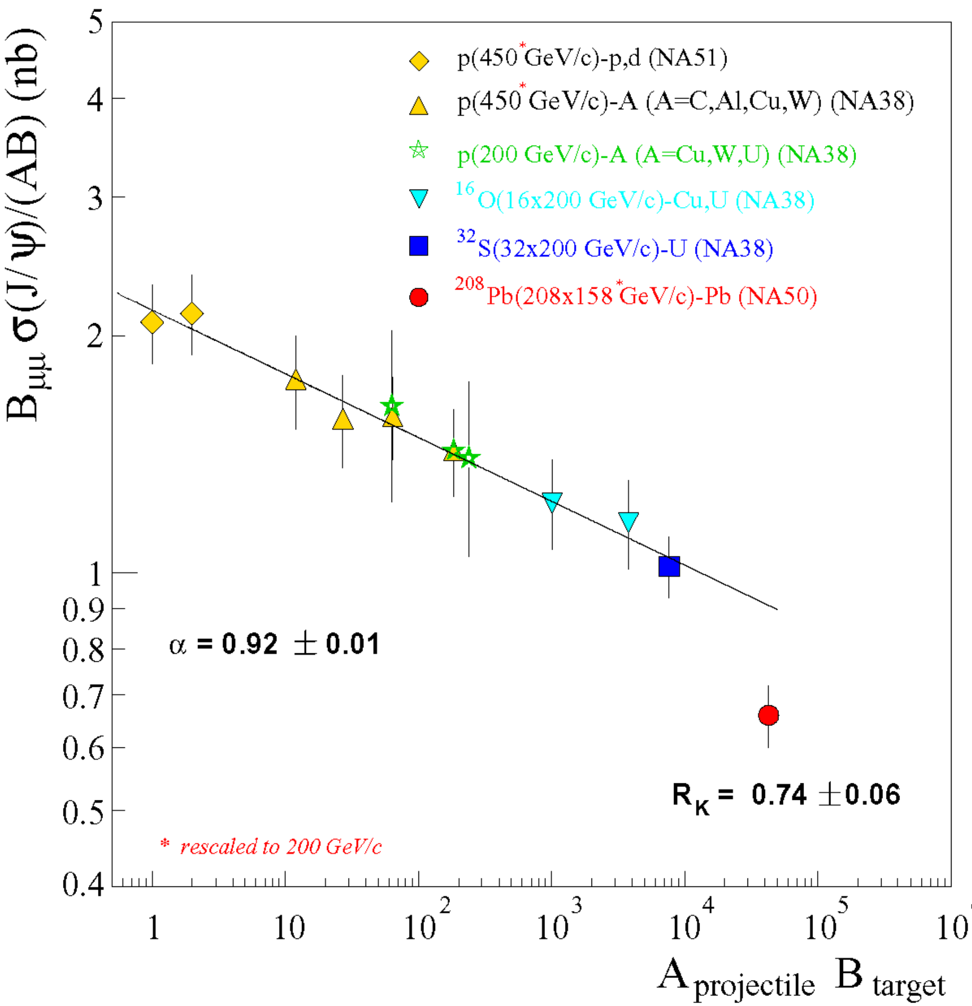
How to find the QGP Key signatures c.1990 influenced RHIC detector design

The gold-plated signature for the QGP J/ψ Suppression

- In 1986, T. Matsui & H. Satz PL **B178**, 416 (1987) said that due to the Debye screening of the color potential in a QGP, charmonium production would be suppressed since the cc-bar couldn't bind.

- This is CERN's Heavy Ion's claim to fame: but the situation is complicated because J/ψ are suppressed in p+A collisions.

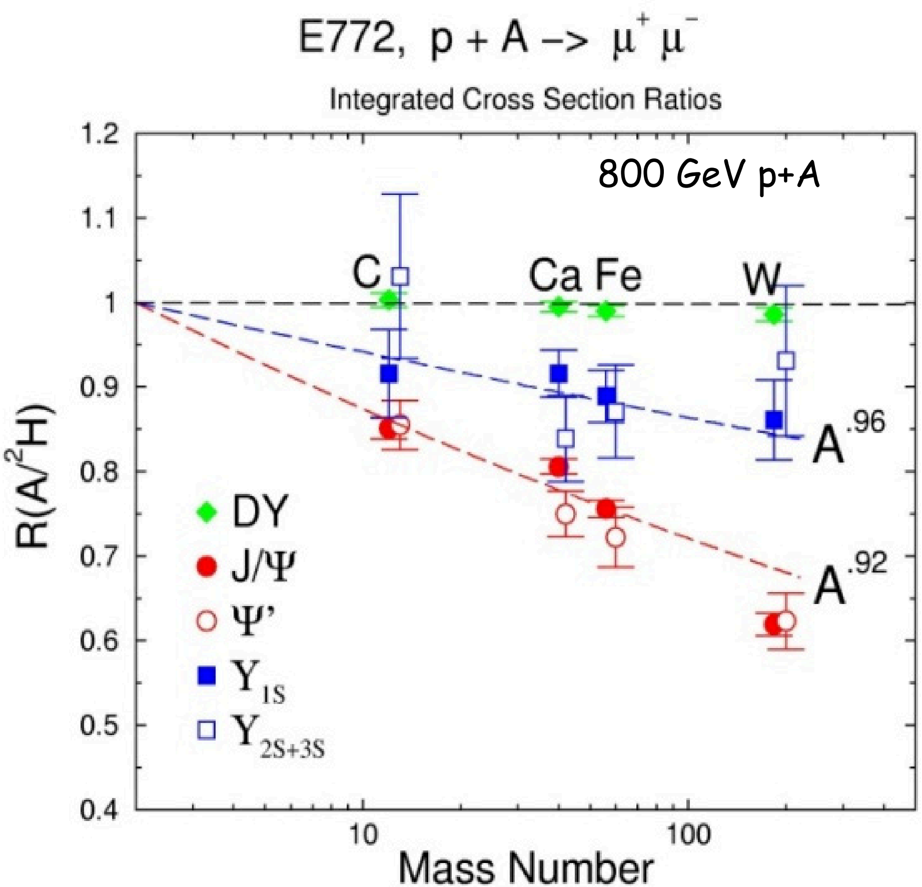
[NA50 collaboration, M.C. Abreu, et al., PL**B 477**, 28 (2000)]



Cold Nuclear Matter p+A (CNM) for J/ψ

Also Other Quarkonia – the ψ', the Υ

CNM effects on ψ' in fixed target measurements same as J/ψ except for backwards rapidity. Need to check CNM for J/ψ, ψ' and Υ at RHIC/LHC establish if baseline for A+A



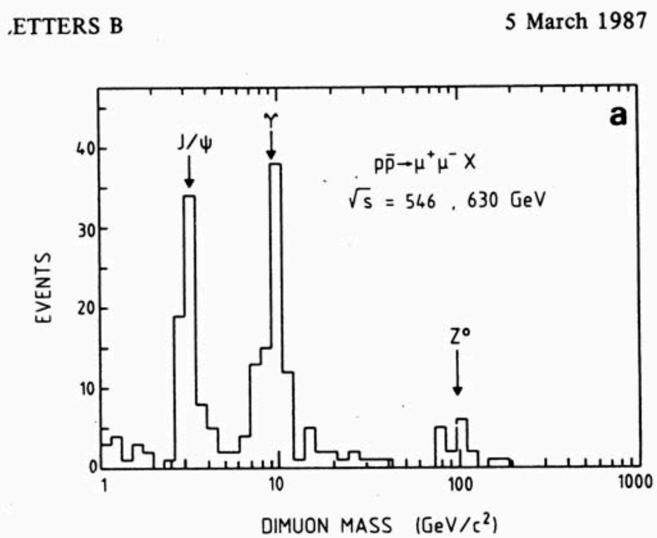
Υ_{1s} $197^{2\times0.92}/197^2$=0.66

J/ψ: $197^{2\times0.92}/197^2$=0.43

How to discover the QGP-1990-91

- The Classical road to success in RHI Physics: J/Ψ Suppression

The Road To Success in HEP



$p_T(\mu) \geq 3$ GeV/c, UA1 Phys. Lett. B**186**, 237 (1987)

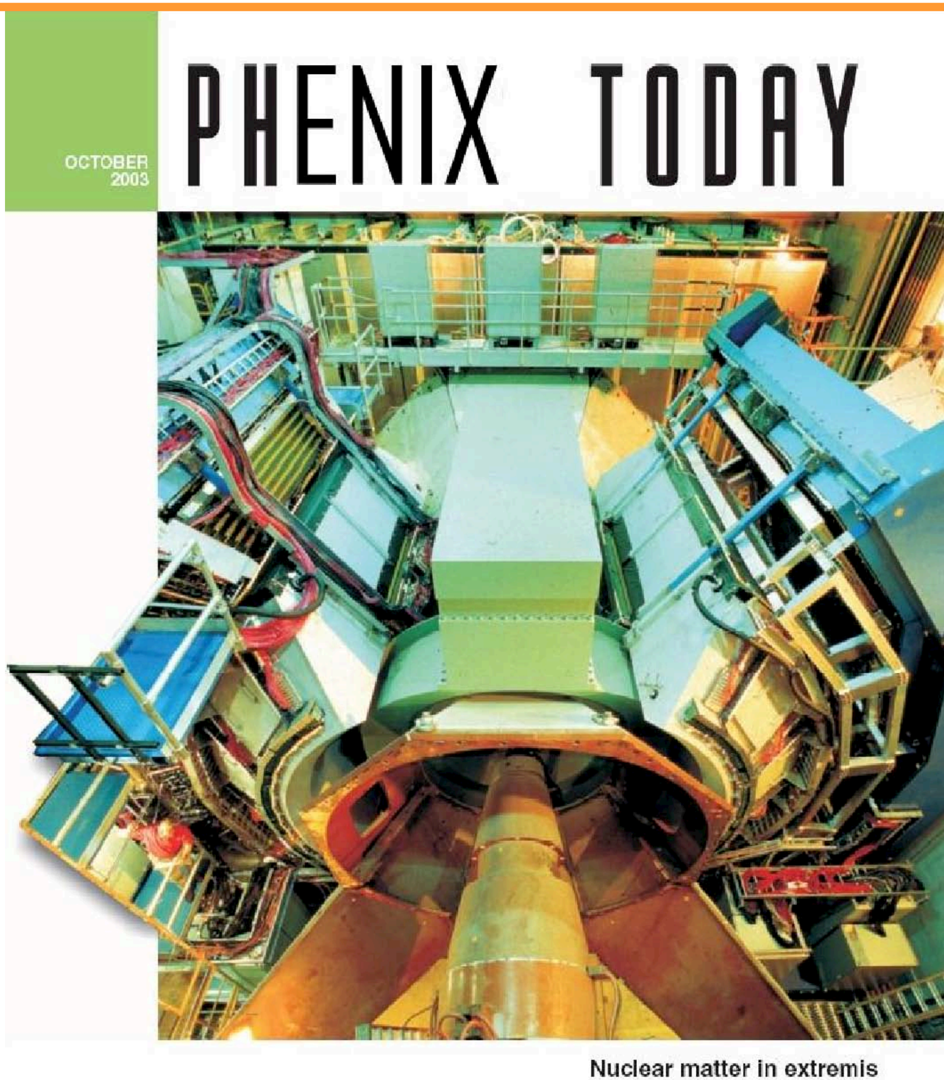
The Road To Success in HIP

•Need to to go p_T=0 for the J/Psi (p_{Te}<<1.5 GeV/c) in order to observe the desired suppression effect.

•This means electron identification is required at the trigger level to avoid being swamped by background from photons and charged hadrons. But the trigger provides

- Charm measurement via single $e^{\pm}$ (Discovered by CCRS experiment at CERN ISR)
- So we designed PHENIX to make these measurements

"Mike, is there a 'real collider detector' at RHIC?"---J. Steinberger

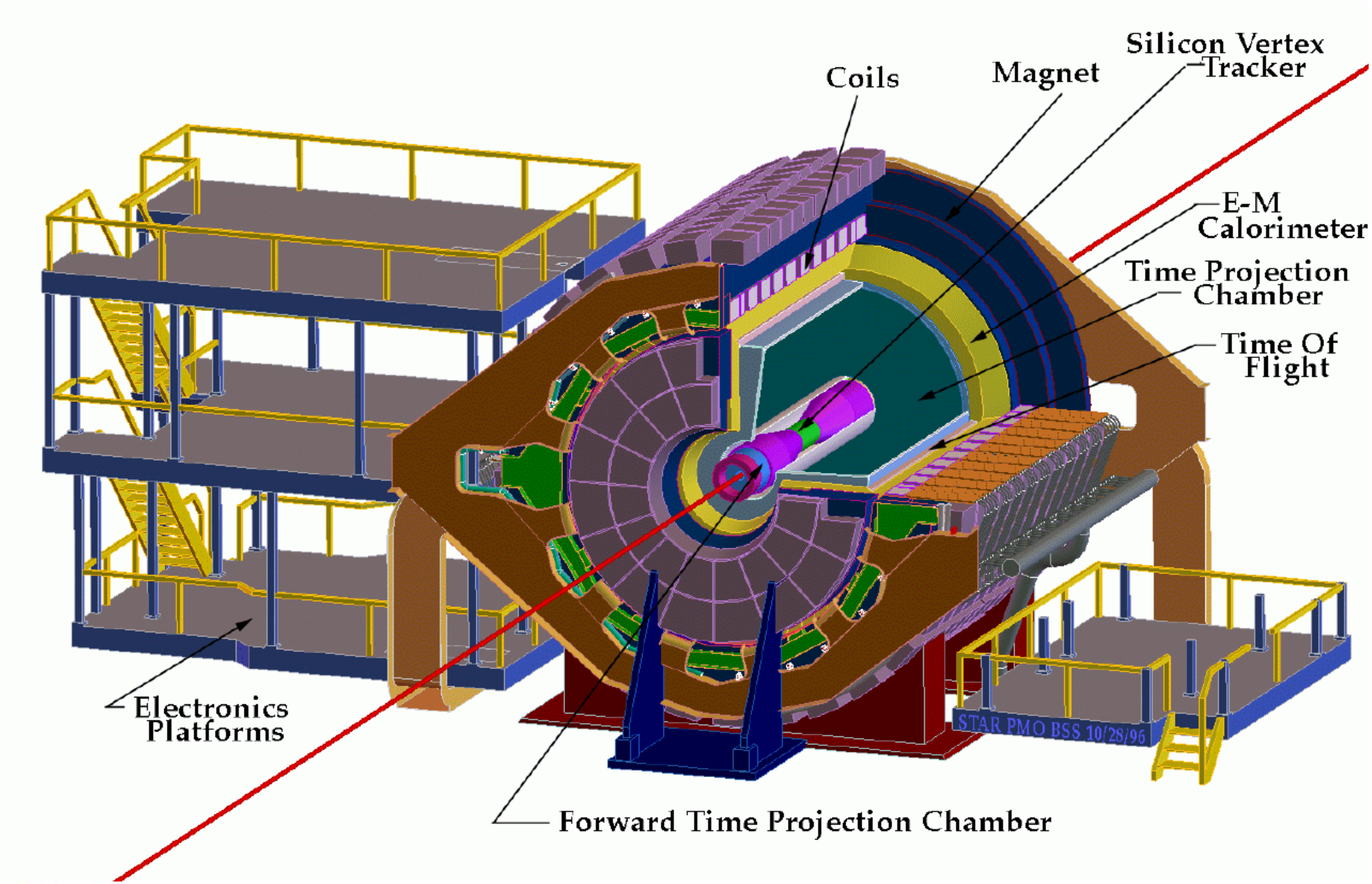


- **PHENIX is picturesque because it is not your father's solenoid collider detector**
- **Special purpose detector designed and built to measure *rare processes* involving *leptons and photons* at the *highest luminosities*.**

✓ ***possibility of zero magnetic field on axis***
✓ ***minimum of material in aperture 0.4% X_o***
✓ ***EMCAL RICH $e^{\pm}$ i.d. and lvl-1 trigger***
- ***γ π^0 separation up to $p_T \sim 25$ GeV/c***
- ***EMCAL and precision TOF for $h^{\pm}$ pid***

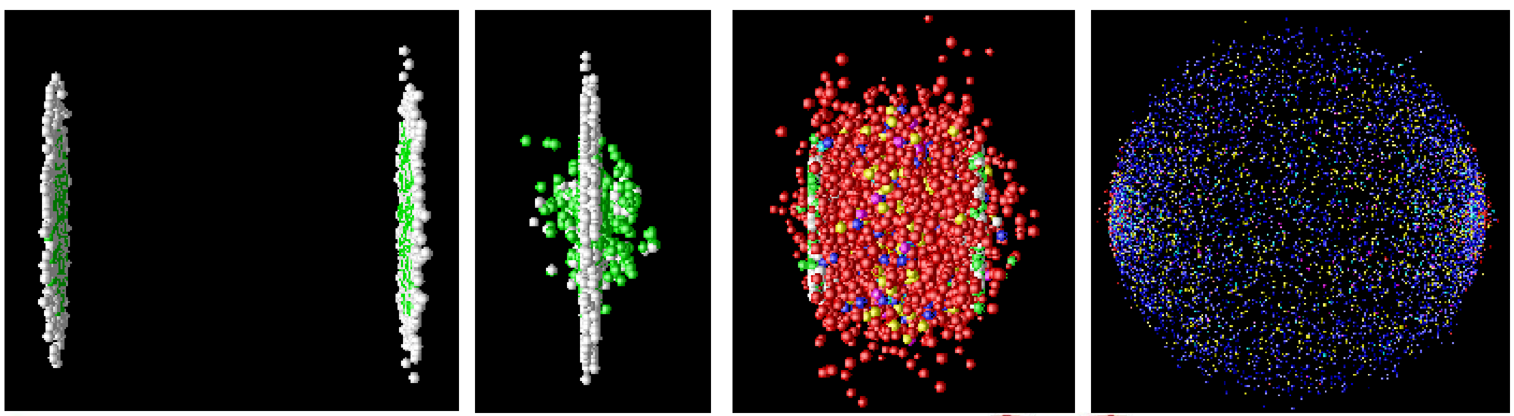
STAR-more conventional collider detector

Original STAR detector c. 2000. Several incremental upgrades since.



Three things are dramatically different in Relativistic Heavy Ion Physics than in p-p physics

- the multiplicity is ~A~200 times larger in AA central collisions than in p-p ⇒huge energy in jet cone: 300 GeV for R=1 at $\sqrt{s_{NN}}$=200 GeV
- huge azimuthal anisotropies which don't exist in p-p which are interesting in themselves, and are useful, but sometimes troublesome.
- space-time issues both in momentum space and coordinate space are important in RHI : for instance what is the spatial extent of parton fragmentation, is there a formation time/distance?



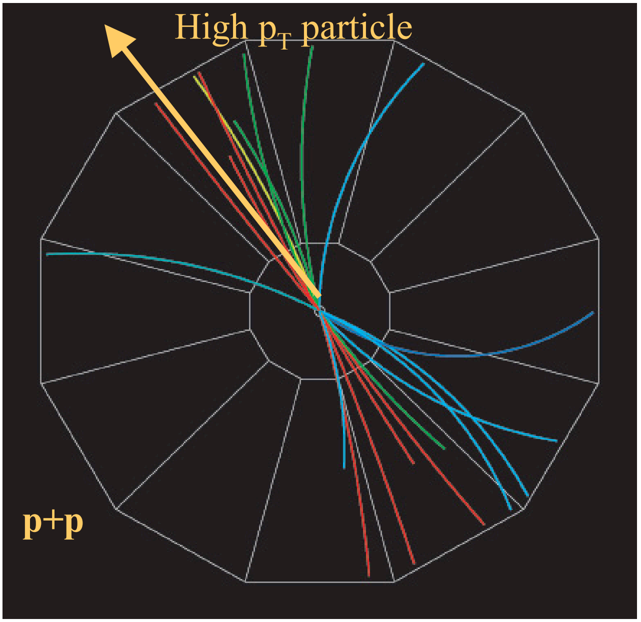
Example of space-time issues

- When in time and space does a parton fragment? Is this different for light and heavy quarks? When are particles formed?
- Dokshitser textbook formula: $\tau_F = ER^2 \Rightarrow t_F = \gamma R = ER/M = ER\lambda_c$
- Would a proton embedded in a QGP dissolve? How long does this take? How is this related to J/Psi suppression?

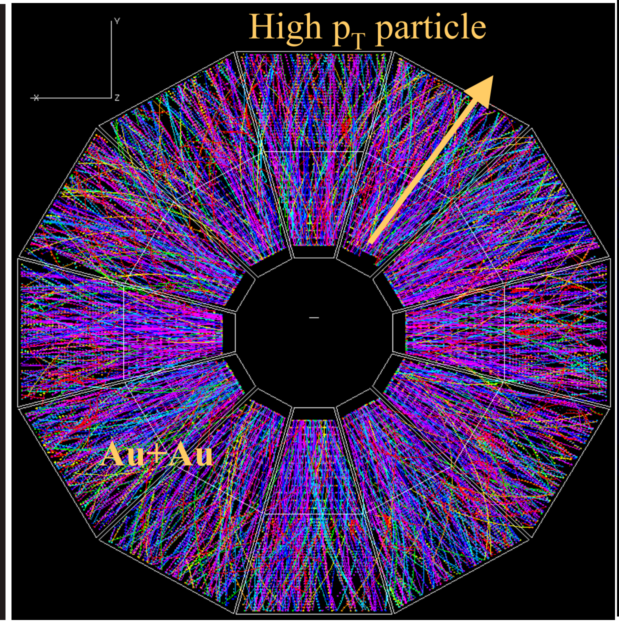
Soft Physics Dominates Particle production in both p-p and A+A (Relativistic Heavy Ion) collisions

AuAu Central Collisions cf. p-p

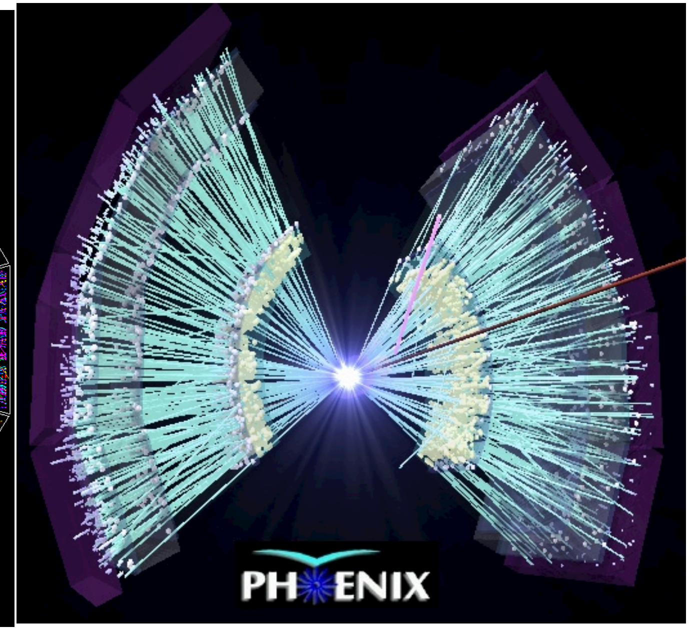
STAR-Jet event in pp

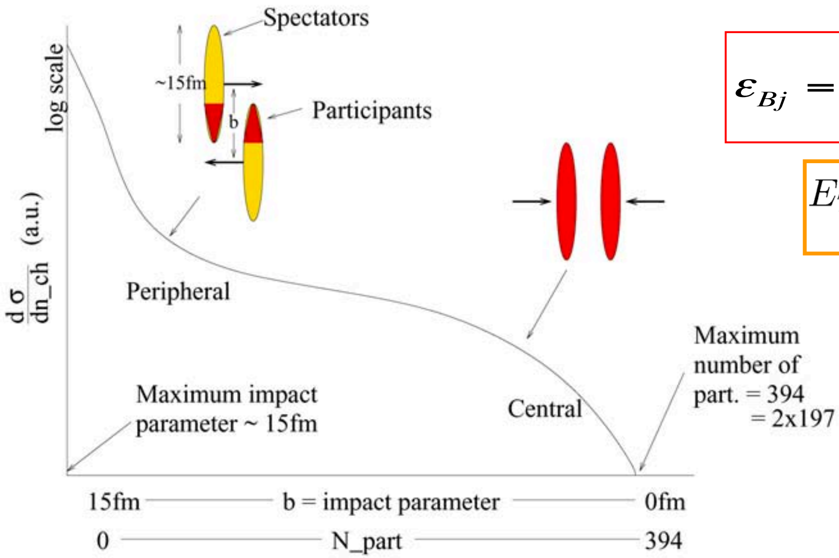


STAR Au+Au central



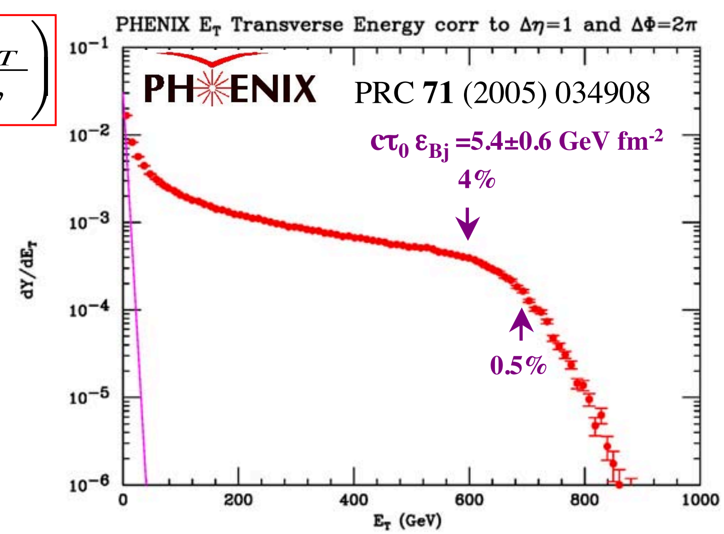
PHENIX Au+Au central





$$\boxed{\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{c\tau_0}\left(\frac{dE_T}{dy}\right)}$$

$$\boxed{E_T \equiv \sum_i E_i \sin\theta_i}$$



Dependence of $dN_{ch}/d\eta$ and $dE_T/d\eta$ on centrality

S. S. ADLER *et al.* PHYSICAL REVIEW C **71**, 034908 (2005)

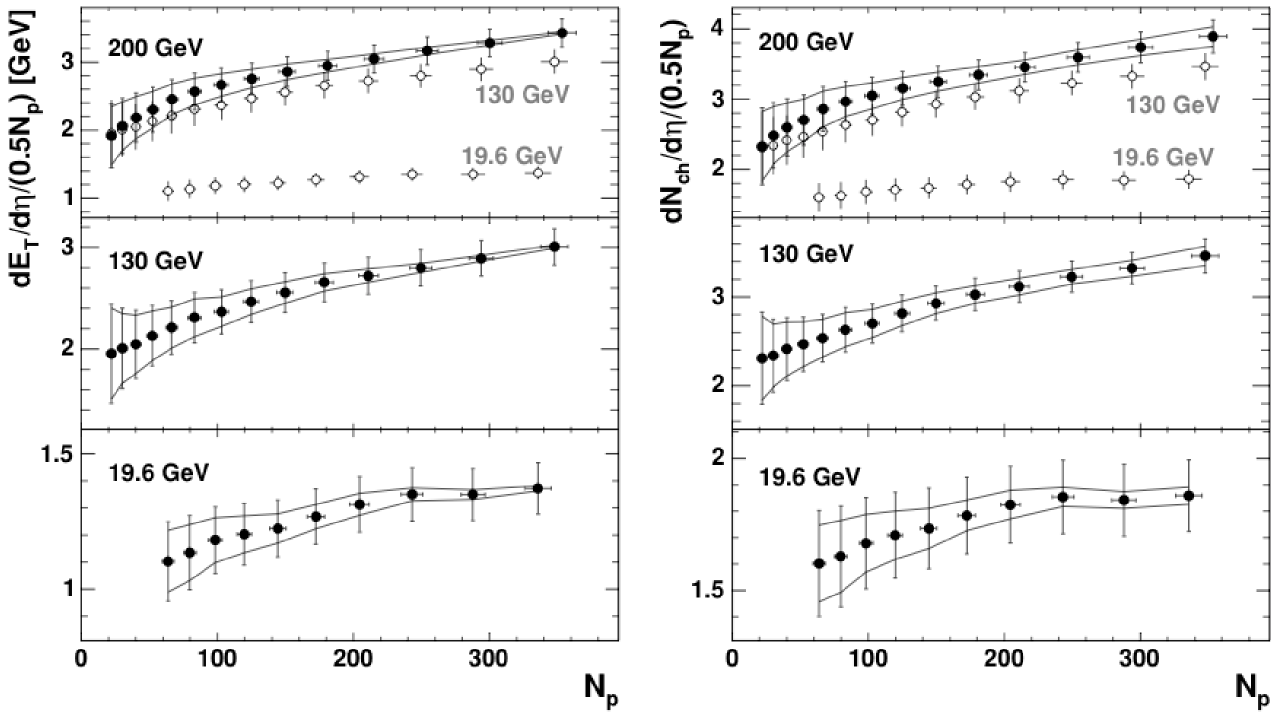


FIG. 5. $dE_T/d\eta$ (left) and $dN_{ch}/d\eta$ (right) divided by the number of participant pairs at three RHIC energies. Errors shown with vertical bars are full systematic errors. Lines show the part of the systematic error that allows bending or inclination of the points. Horizontal errors denote the uncertainty in determination of N_p.

$dN_{ch}/d\eta/(\mathrm{Npart}/2)$ allows direct comparison to p-p (2 participants)
Mulitplicity increase is larger than the number of participant pairs.

Dependence on centrality reminds me of an old radio commercial for sausage: “No matter how you slice it, it’s still baloney”

I have said this many times about a few results from the CERN Fixed-Target SpS Heavy Ion Program, notably the claim to have discovered the Quark Gluon Plasma

See MJT, Rep. Prog. Phys. **69** (2006) 2005-2059 for details

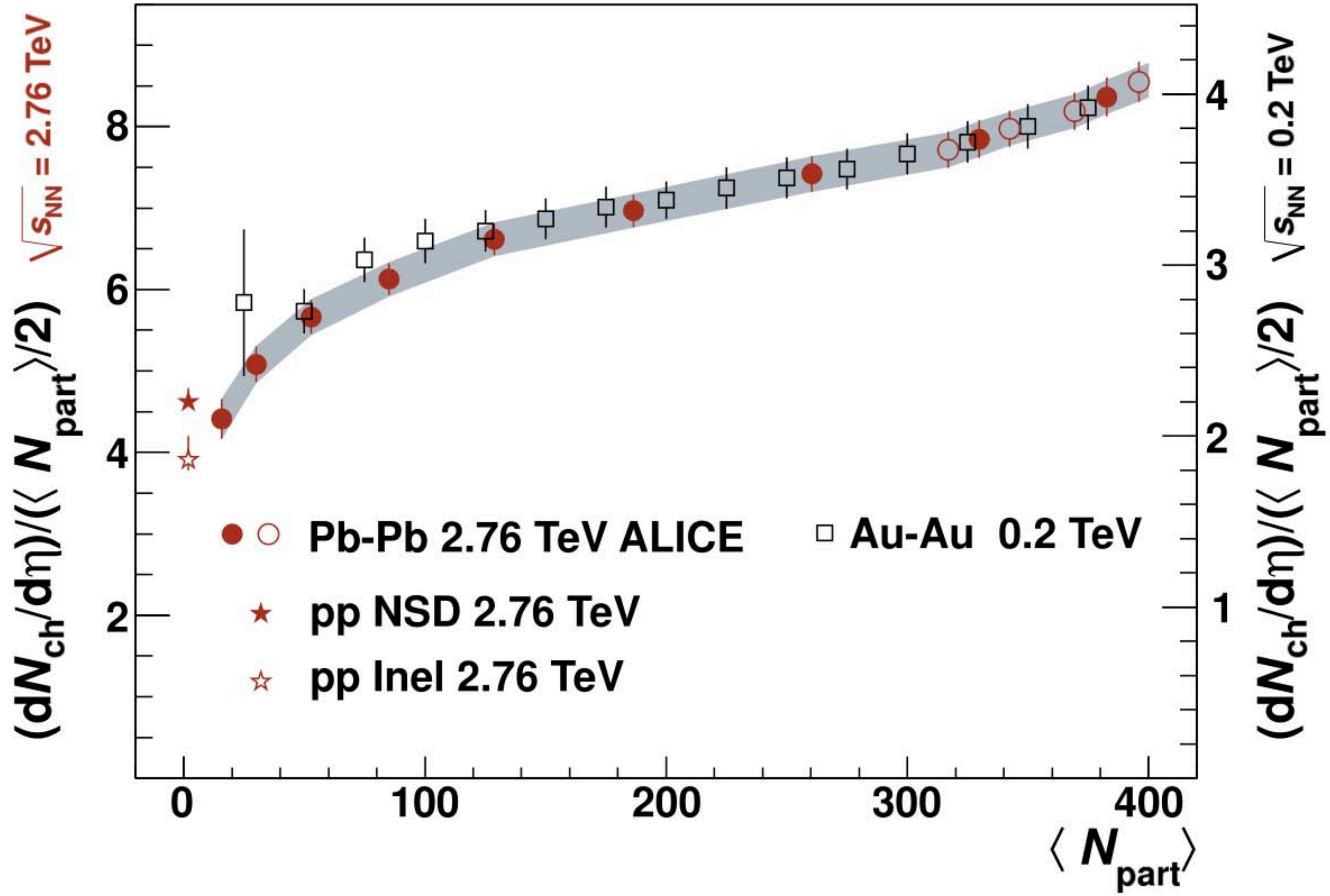
BUT

Its a new ballgame at the LHC

Dependence of multiplicity on centrality
Beautiful ALICE result---it's not baloney

LHC scale

RHIC scale

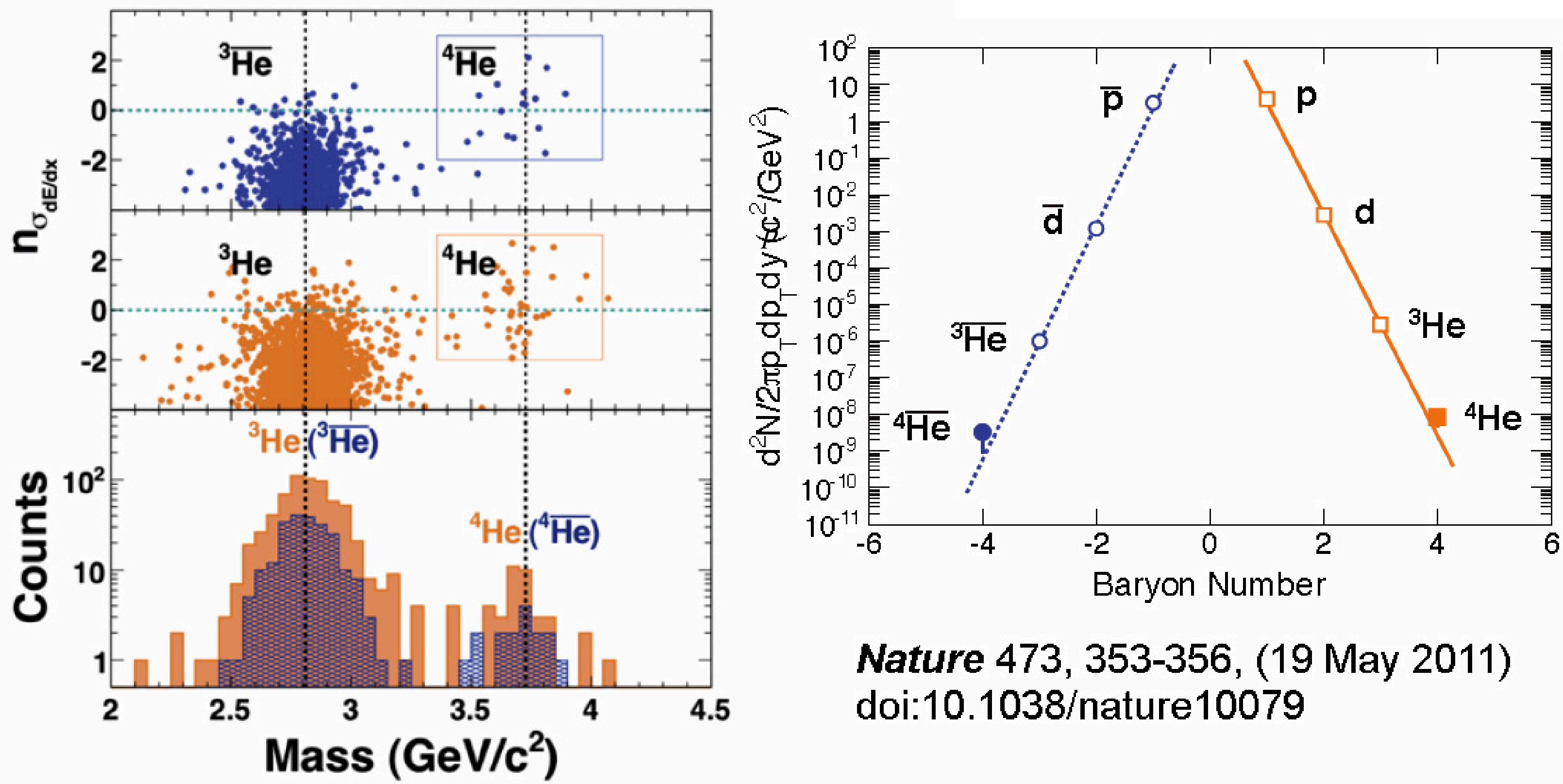


ALICE, PRL **106**, 032301 (2010)

Dependence of $dN_{ch}/d\eta/(Npart/2)$ on Npart, the same at RHIC and LHC

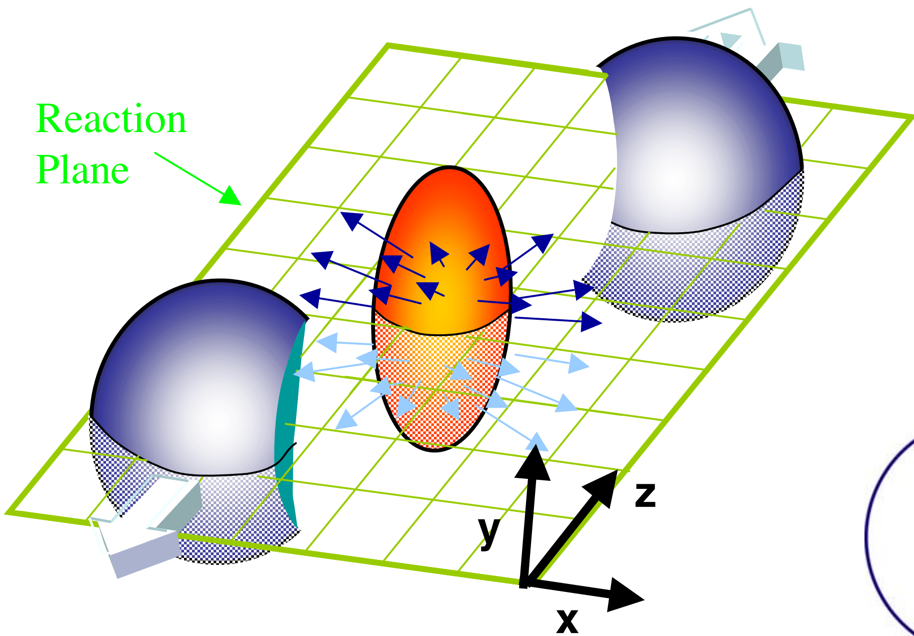
STAR and AMS background from A+A collisions-lots of $\bar{p}$ $\bar{n}$ to coalesce

Discovery of anti-^{4}He in Au+Au

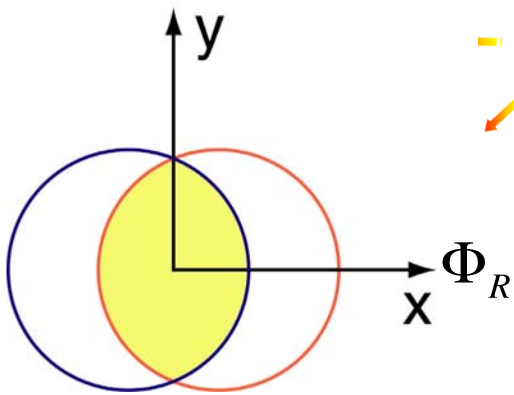


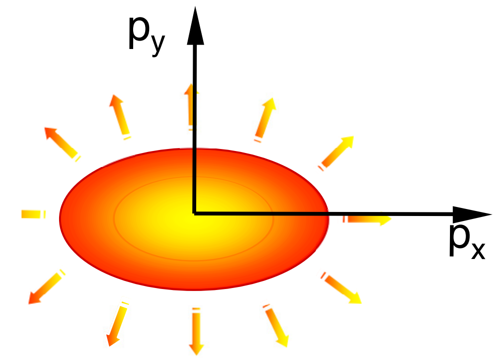
Nature 473, 353-356, (19 May 2011)
doi:10.1038/nature10079

Anisotropic (Elliptic) Transverse Flow--an Interesting complication in AA collisions



• spatial anisotropy⇒ momentum anisotropy





$$\phi = \operatorname{atan}\frac{p_y}{p_x}$$

$$\frac{Ed^3N}{dp^3} = \frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^3N}{2\pi\, p_T dp_T dy}[1+2v_1\cos(\phi-\Phi_R)+2v_2\cos 2(\phi-\Phi_R)+\cdots]$$

$$v_1 = \langle\cos\phi\rangle \qquad v_2 = \langle\cos 2\phi\rangle$$

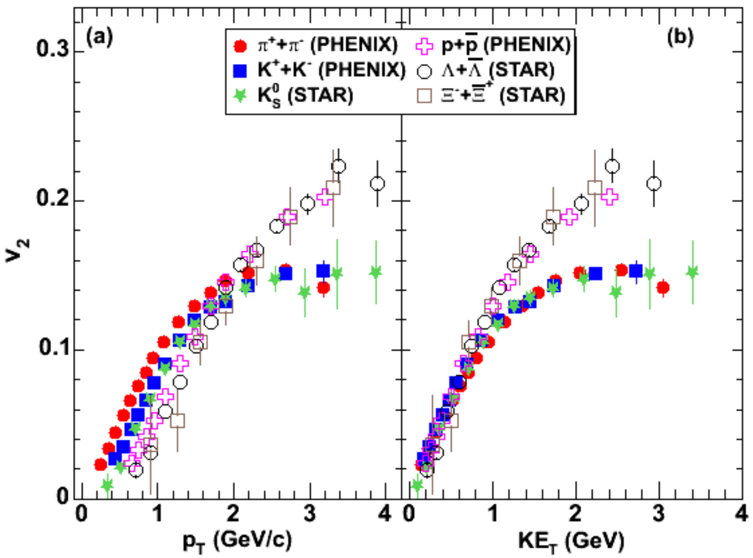
Directed flow zero at midrapidity	Elliptical flow dominant at midrapidity

•Perform a Fourier decomposition of the momentum space particle distributions in the x-y plane

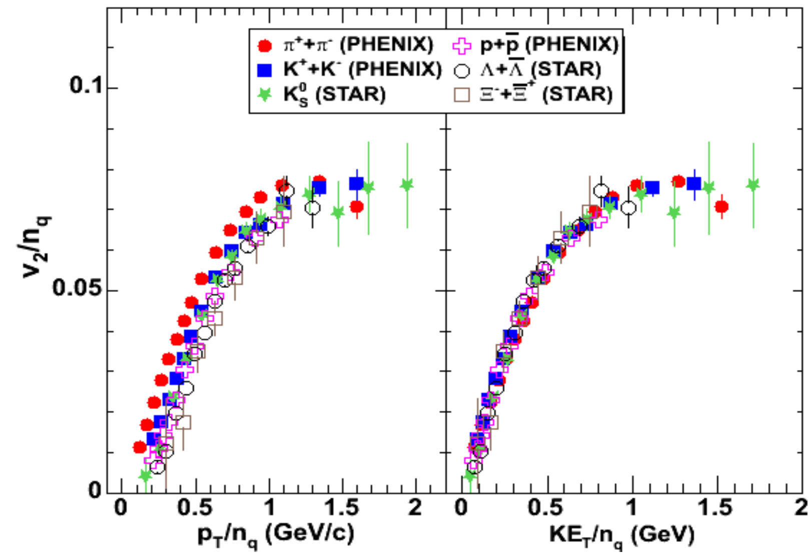
✓ v_2 is the 2nd harmonic Fourier coefficient

Elliptic Flow v_2 in AuAu Central 200 GeV Universal in constituent quark Kinetic Energy

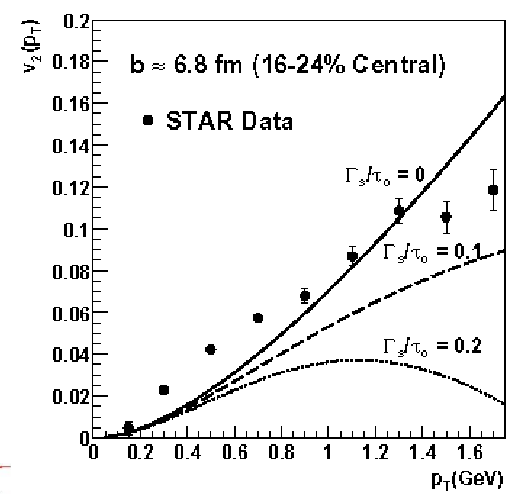
STAR-PRC**72** (2005) 014904



PHENIX PRL**98** (2007) 162301



- large v_2 for high and low p_T, plateaus for p_T>2 GeV/c for mesons, scales in KE/constituent quark
- ϕ-meson (not shown) follows same scaling: further implies flow is partonic not hadronic
- KE scaling suggests Hydrodynamic origin.
- v_2 for p_T> 1 GeV/c suggests low viscosity, D.Teaney, PRC**68** (2003) 034913, ``the perfect fluid''??
- Quantum Viscosity Bound from string theory reinforces this idea, Kotvun, Son, Starinets, PRL **94** (2005) 111601



U.S. DEPARTMENT OF ENERGY

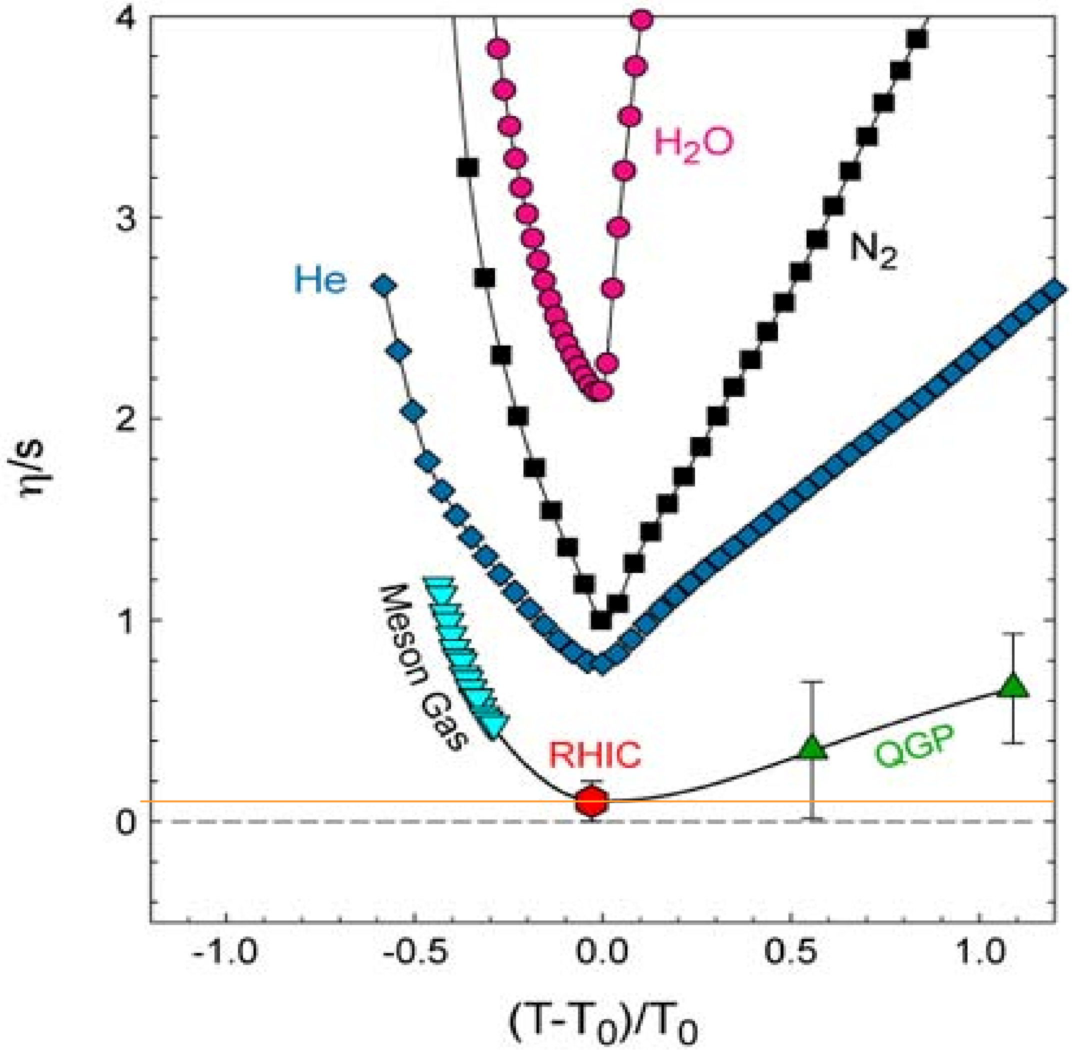
ENIX

The viscosity bound---the perfect fluid

Kotvun, Son, Starinets, PRL **94** (2005) 111601

$$\frac{\eta}{s} \geq \frac{1}{4\pi} = 0.08$$

η= shear viscosity
s=entropy density
π=3.1415927...



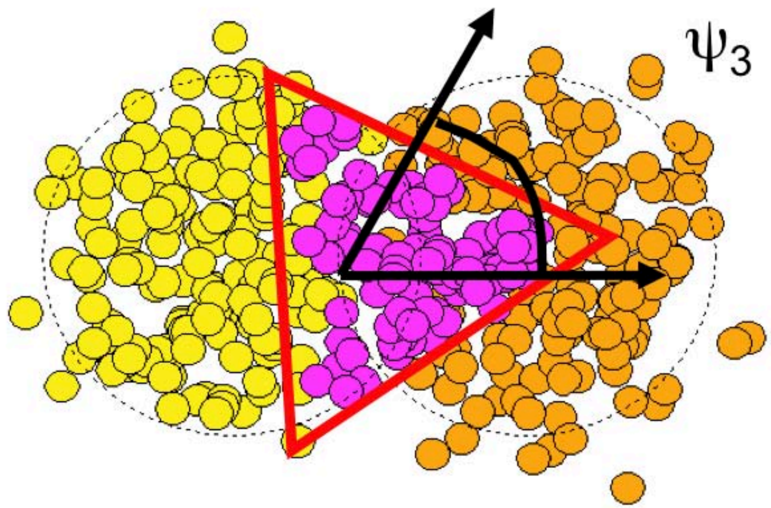
Another new ballgame-2010-v_3

- For the first 10 years of RHIC running and dating back to the Bevalac, all the experts thought that the odd harmonics vanished at mid-rapidity due to the symmetry of the source for $\phi \rightarrow \pi - \phi$

- But last year, 2010, an MIT graduate student and his Professor in experimental physics, seeking (at least since 2006) how to measure the fluctuations of v_2 in PHOBOS at RHIC realized that fluctuations in the collision geometry on an event by event basis, the eccentricity of participants from event to event, did not respect the average symmetry, resulting in:

Triangular Flow-v_3

Participant Triangularity



$$\varepsilon_3 = \frac{\sqrt{\left\langle \left(r^2 \cos(3\phi) \right) \right\rangle^2 + \left\langle \left(r^2 \sin(3\phi) \right) \right\rangle^2}}{\left\langle r^2 \right\rangle}$$

B. Alver and G. Roland, Phys. Rev. C 81, 054905 (May 2010)

This had been seen in 2-particle correlations: v_n-without a reaction plane; but not recognized

Single particle w.r. reaction plane Ψ_n

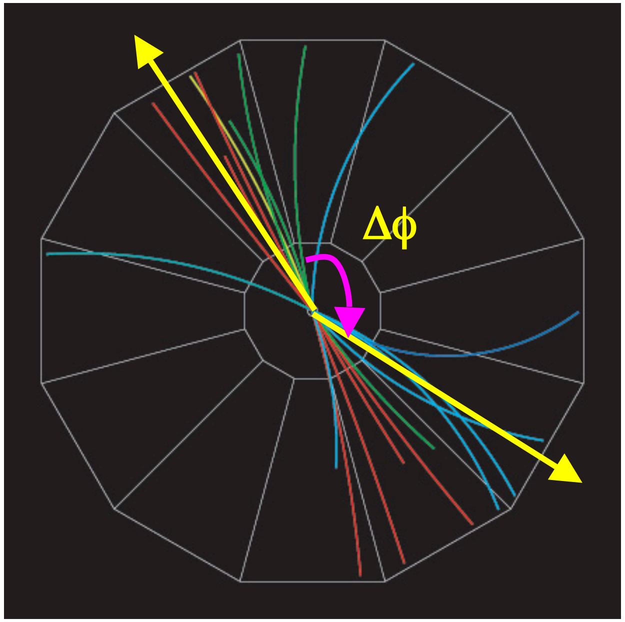
$$\frac{dN^A}{d\phi^A} \propto 1 + \sum 2 v_n^A \cos\left(n(\phi^A - \Psi_n)\right)$$

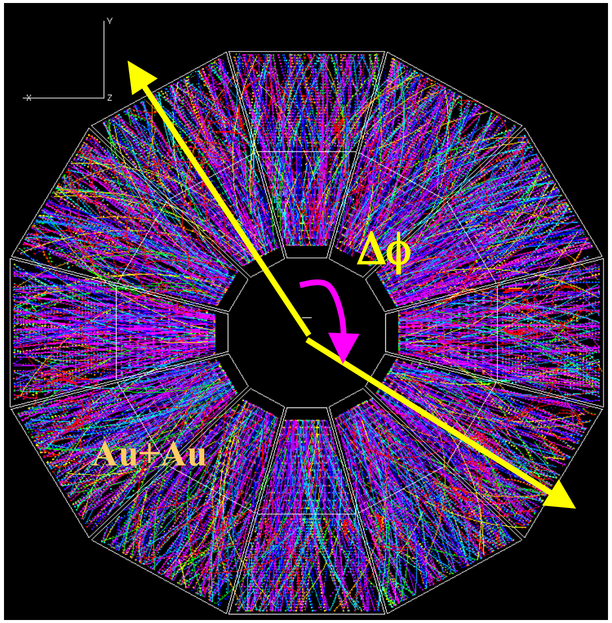
$$\frac{dN^B}{d\phi^B} \propto 1 + \sum 2 v_n^B \cos\left(n(\phi^B - \Psi_n)\right)$$

Two particles w.r. to each other

$$\frac{d^2 N^{AB}}{d\phi^A d\phi^B} \propto \left[1 + 2 v_2^A v_2^B \cos 2\left(\phi^A - \phi^B \right) + 2 v_3^A v_3^B \cos 3\left(\phi^A - \phi^B \right) + \ldots \right]$$

Correlations

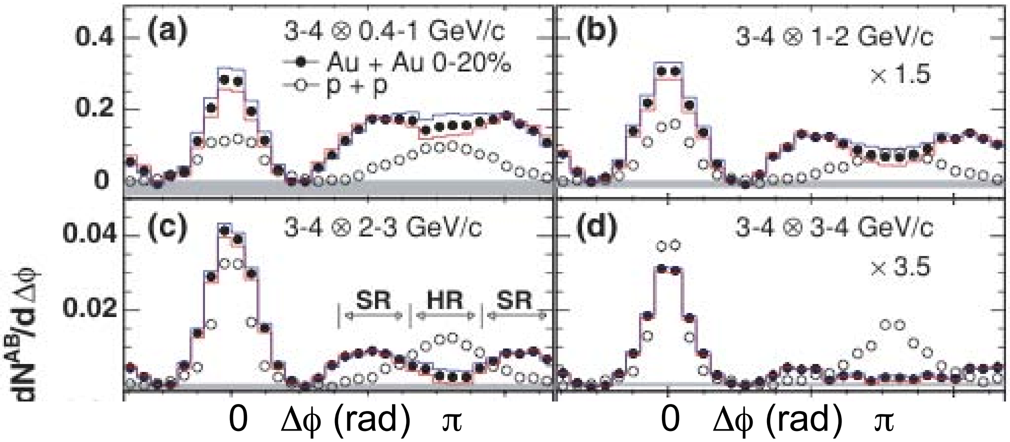


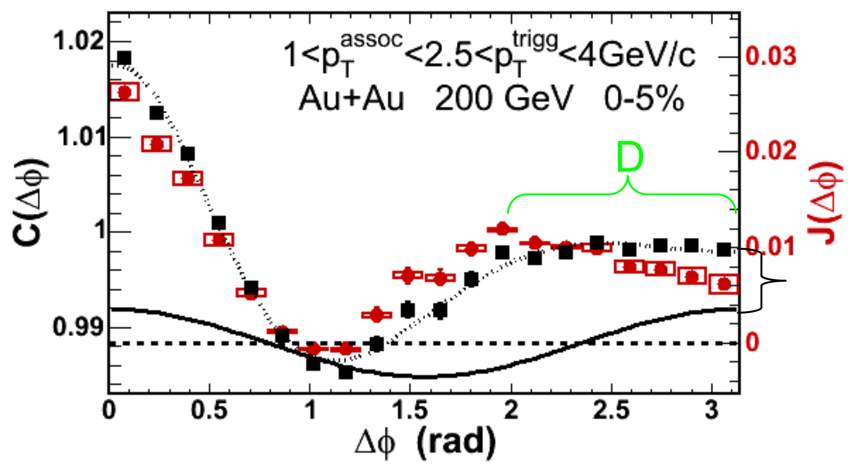


e.g. p + p → jet + jet

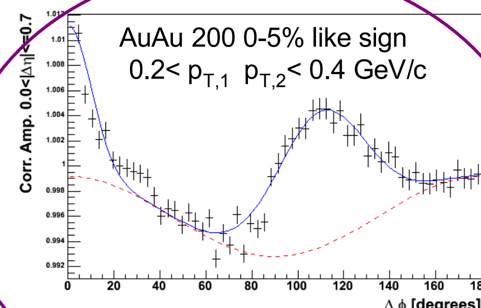
c.f. Au + Au → jet + jet
+ flow

Away side correlations in Au+Au much wider than in p-p

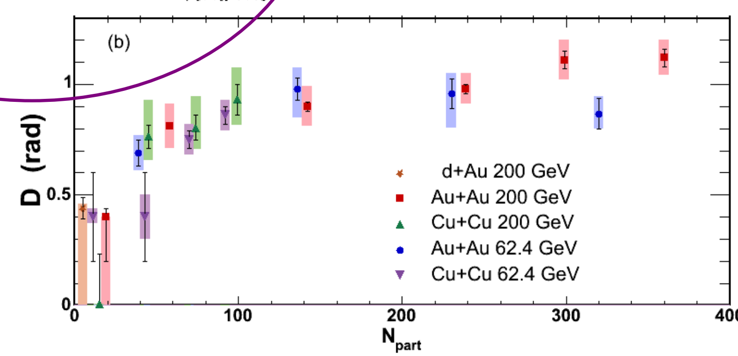




Away side distribution much wider in A+A than p-p in correlation fn. $C(\Delta\phi)$ Subtraction of v_2 (flow?) effect→ $J(\Delta\phi)$ causes a dip at 180^o which gives 2 peaks at $\pi \pm D \sim 1$ radian independent of system and centrality for $N_{part} > 100$. This is also seen for (auto) correlations of low p_T particles. Is this the medium reaction to the passage of a color-charged parton? Why no dependence on centrality? "Stay tuned, much more study needed"-MJT ERICE ISSP 2009. The answer is v_3

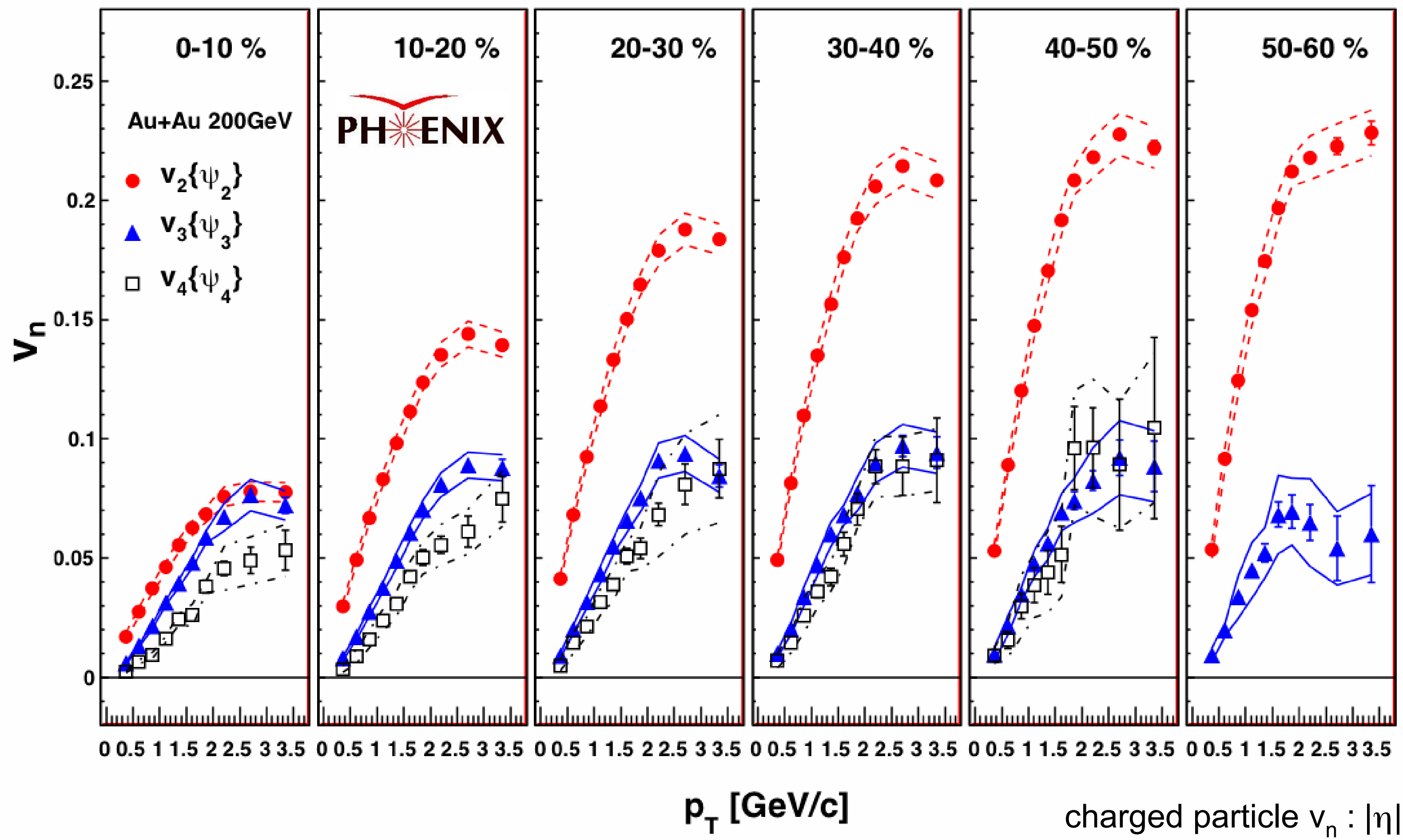


PHENIX AuAu PRC **77** (2008) 011901(R)



$v_2\{\Phi_2\}$, $v_3\{\Phi_3\}$, $v_4\{\Phi_4\}$ at 200GeV Au+Au

arXiv:1105.3928

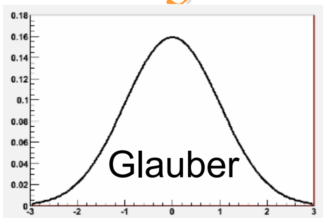


charged particle v_n : $|\eta|<0.35$
reaction plane Φ_n : $|\eta|=1.0\sim2.8$

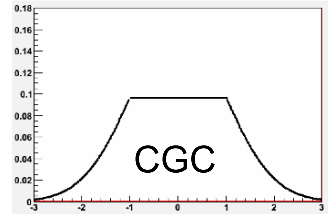
(1) v_3 is comparable to v_2 at 0~10%
(2) weak centrality dependence on v_3
(3) $v_4\{\Phi_4\} \sim 2 \times v_4\{\Phi_2\}$

All of these are consistent with initial fluctuation.

v_3 disentangles initial state and η/s

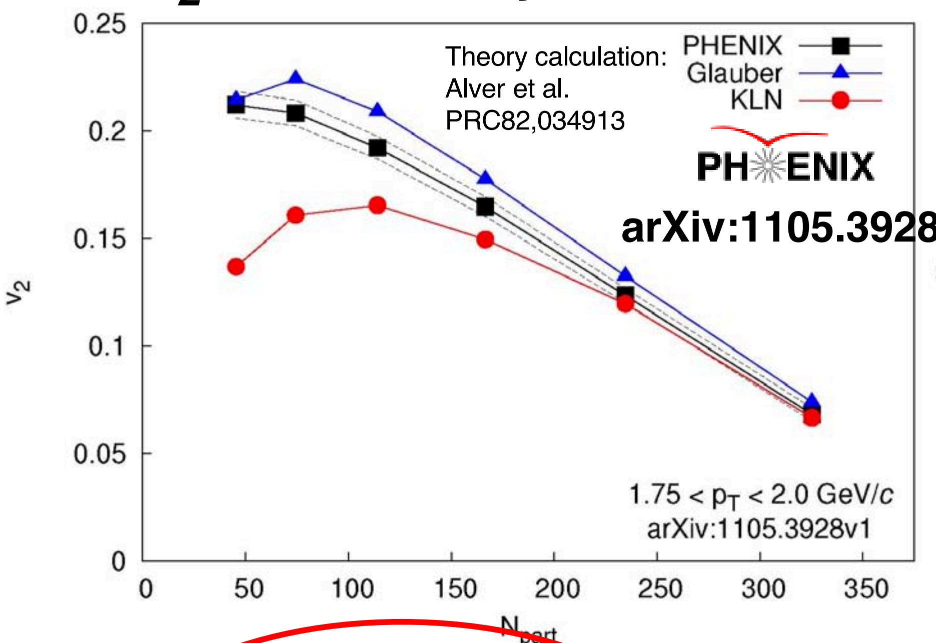


Smaller eccentricity

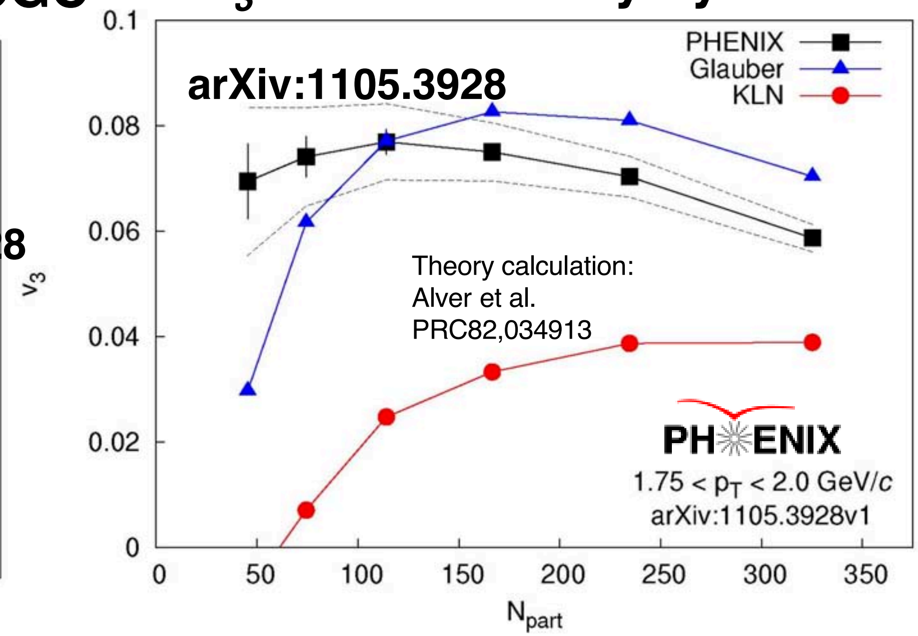


gluon saturation→ Larger eccentricity

v_2 described by Glauber and CGC



v_3 described only by Glauber



Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

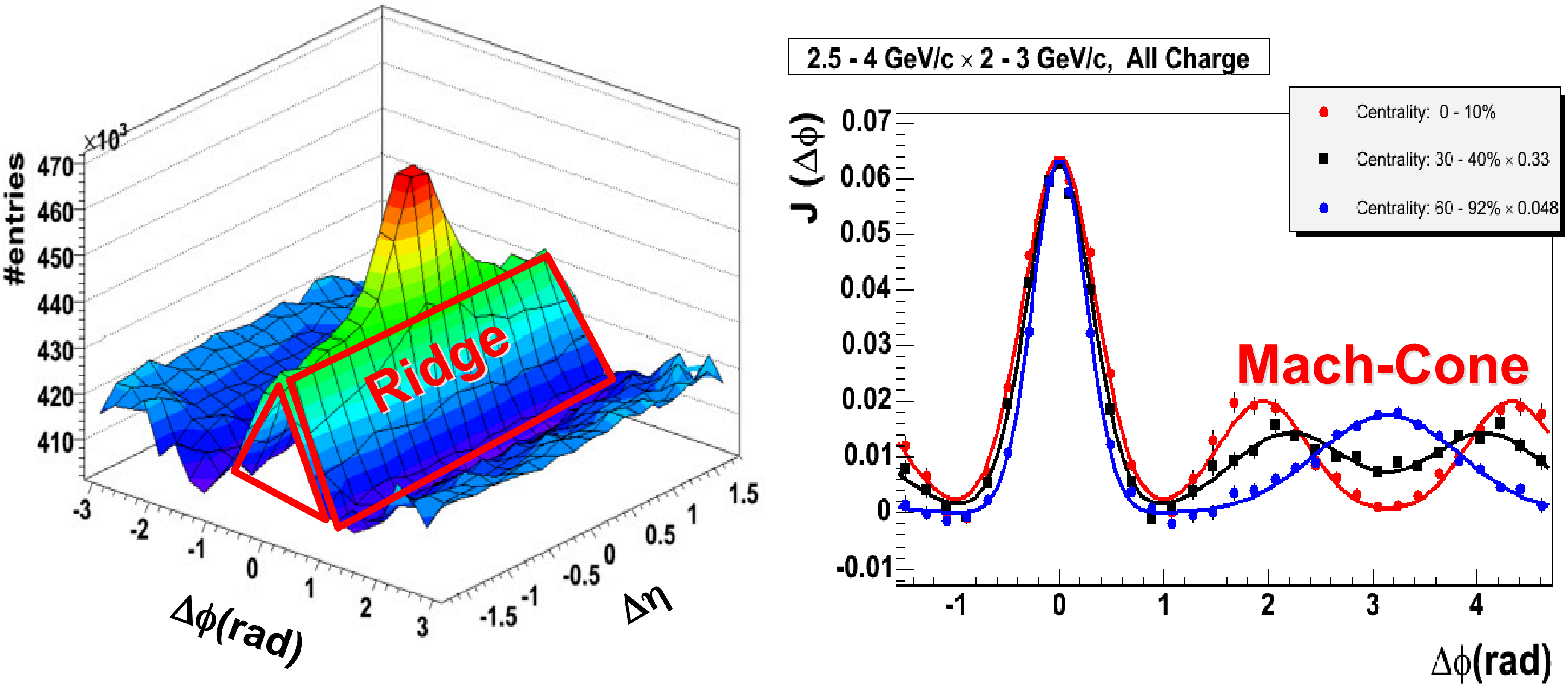
favored

- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

← Two models →

- MC-KLN
  - CGC initial state
  - $\eta/s = 2/4\pi$

v_3 Explains Ridge and Mach-Cone

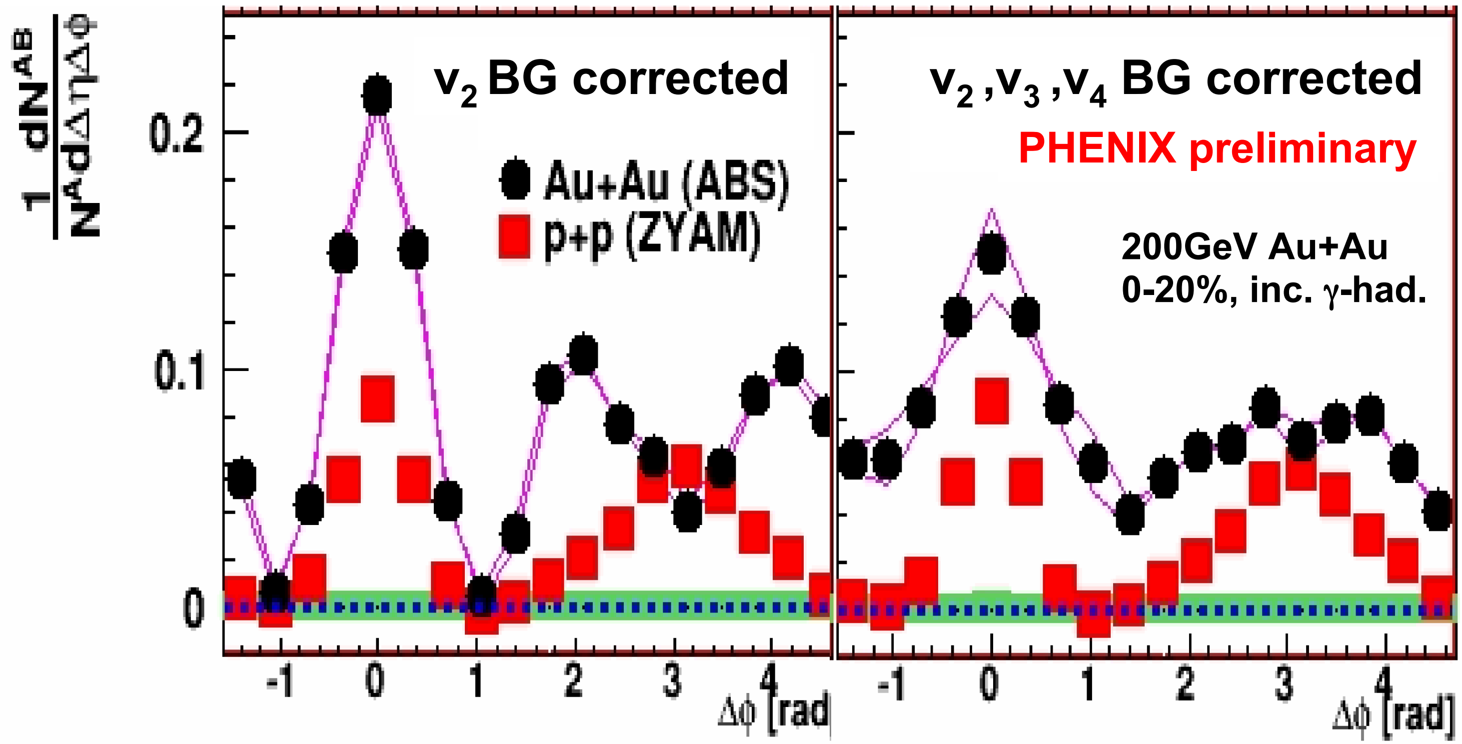


Ridge : long range $\Delta\eta$ correlation at near-side

Cone : double peak/shoulder at away-side (long in $\Delta\eta$)

v_3 : initial fluctuation is common over wide range of η

Flow subtraction/correction with measured v_n for central-central 2-particle correlation

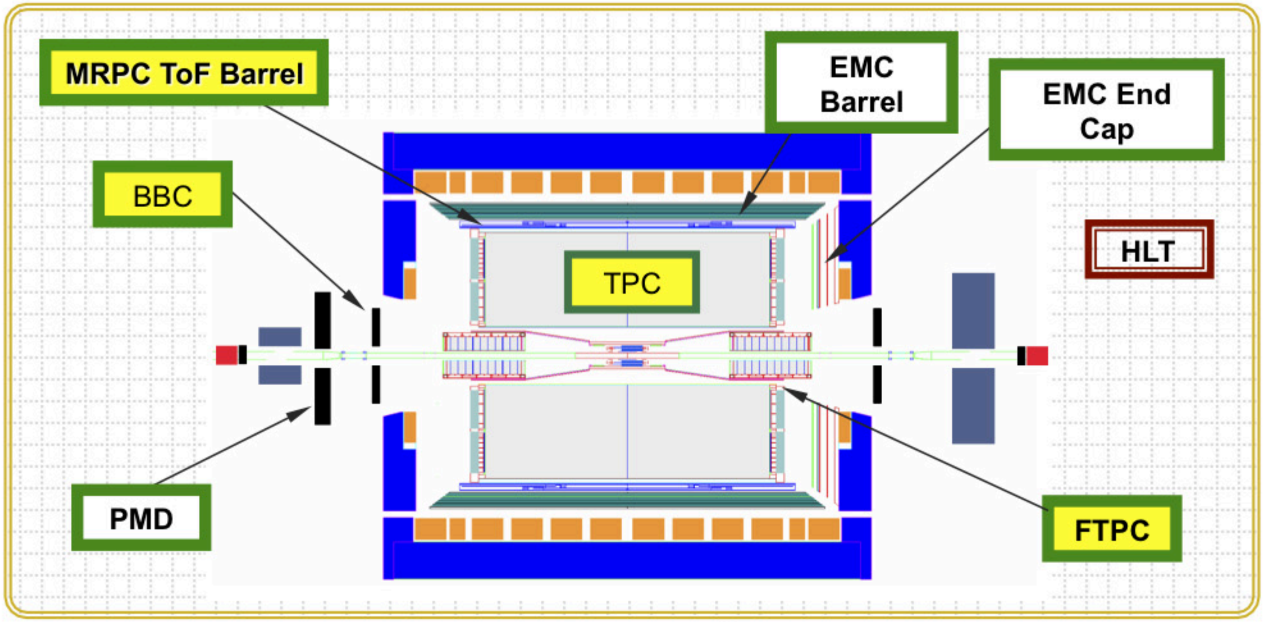


- v_2 correction only
  - double-hump
- v_2, v_3, v_4 correction
  - double-hump disappeared
  - Peak still broadened

Highlights from BNL-RHIC
Second Lecture

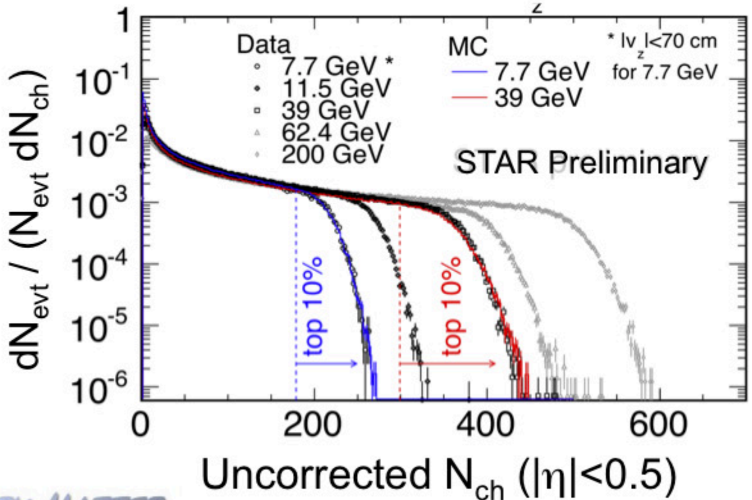
RHIC BEAM ENERGY SCAN
STAR RESULTS

Data Set and Detectors Used



Particle identification over 2π in azimuthal angle and more than two units in rapidity

Au+Au Collisions:
7.7, 11.5 and 39 GeV
$|y| < 0.1$
$p_T > 0.1$ GeV/c
Centrality: 0-80%

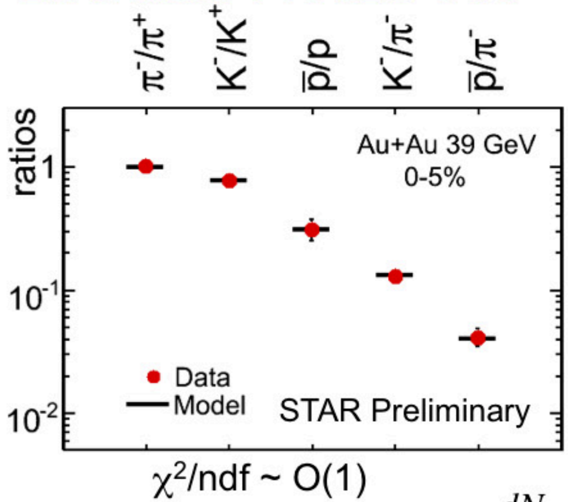


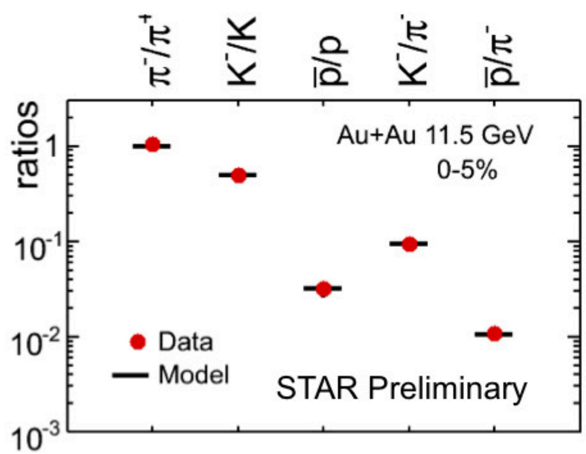
$\sqrt{s_{NN}}$ (GeV)	Good events (proposed) Million MB
5.0	
7.7	~5(5)
11.5	~11 (5)
19.6	~17 (15)
27	(150 @ 400 Hz)
39	~170 (25)

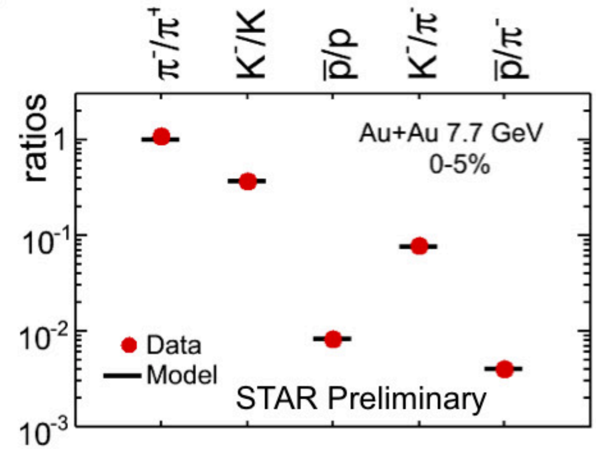
Freeze-out Conditions

Chemical Freeze-out:

$$n_i(T,\mu_i) \sim \exp\left(\frac{\mu_i - m_i}{T}\right) \qquad \frac{N_i}{N_j} \sim \exp\left(\frac{\mu_{i,\text{ch.}} - \mu_{j,\text{ch.}}}{T_{\text{ch.}}} - \frac{m_i - m_j}{T_{\text{ch.}}}\right)$$







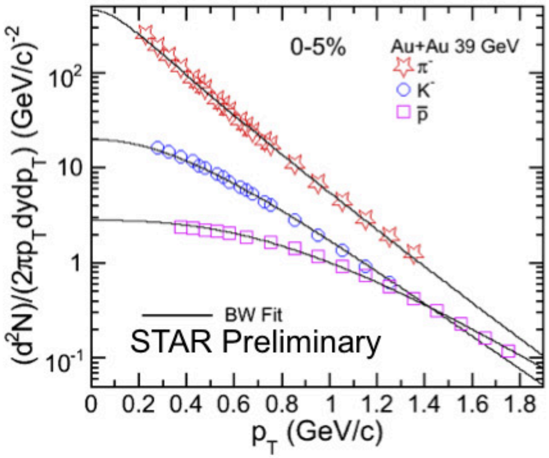
χ^2/ndf ~ O(1)

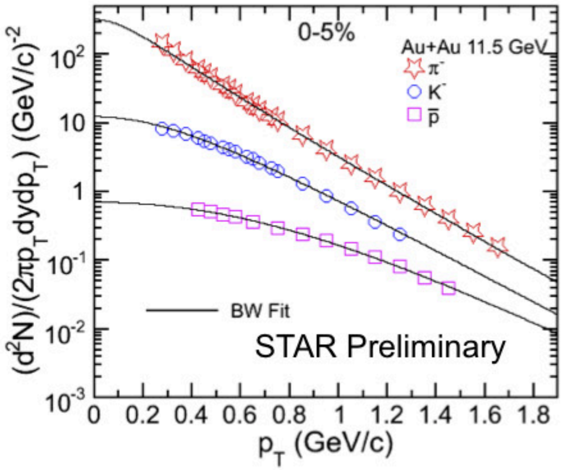
STAR : PRC 79, 034909 (2009) and ref. therein
STAR : NPA 757, 102 (2005).
P. Braun-Munzinger et al. PLB 344, 43 (1995).
E. Schnedermann et al. PRC 48, 2462 (1993).

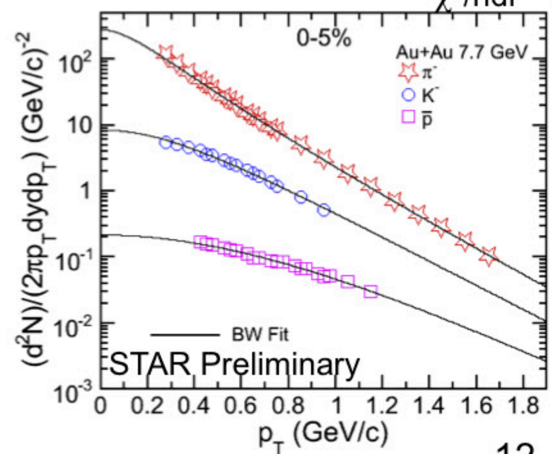
Kinetic Freeze-out:

$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

χ^2/ndf ~ O(1)



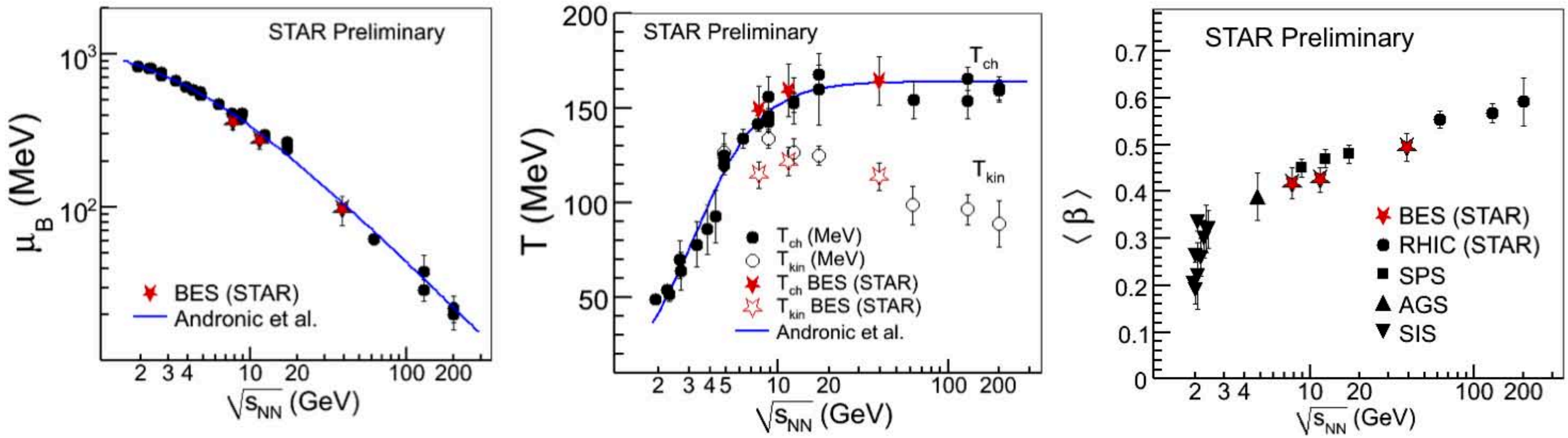




QUARK MATTER ANNECY 2011

Lokesh Kumar

Energy Dependence of Freeze-out Parameters



STAR : PRC 79 (2009) 034909 and references therein
STAR : NPA 757 (2005) 102
Andronic et al. NPA 834 (2010) 237

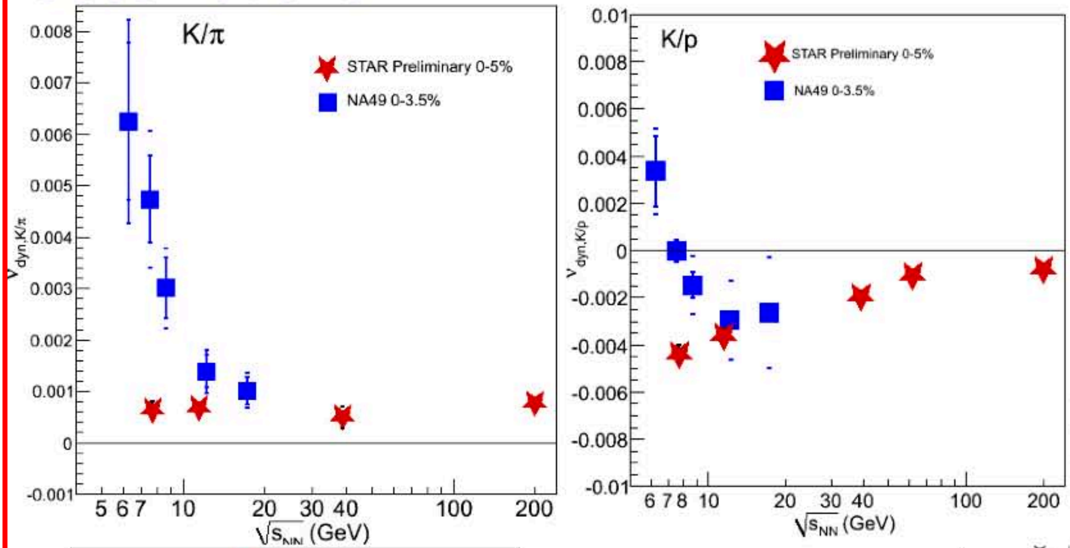
- Baryon chemical potential decreases with energy
- Chemical freeze-out temperature increases with energy at low energies and becomes almost similar at higher energies
- Kinetic freeze-out temperature decreases with energy after $\sqrt{s_{NN}}$ ~ 7.7 GeV
- Average flow velocity increases with energy

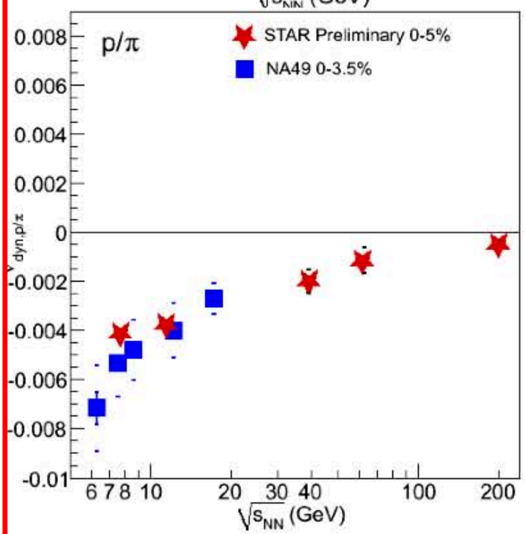
MJT-model dependent!

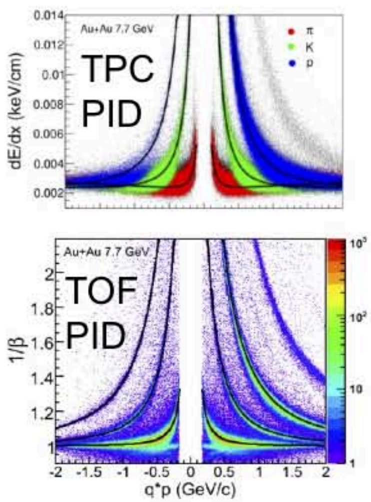
MJT-3 new points: smooth behavior as previous data.

Particle Ratio Fluctuations

Observations:



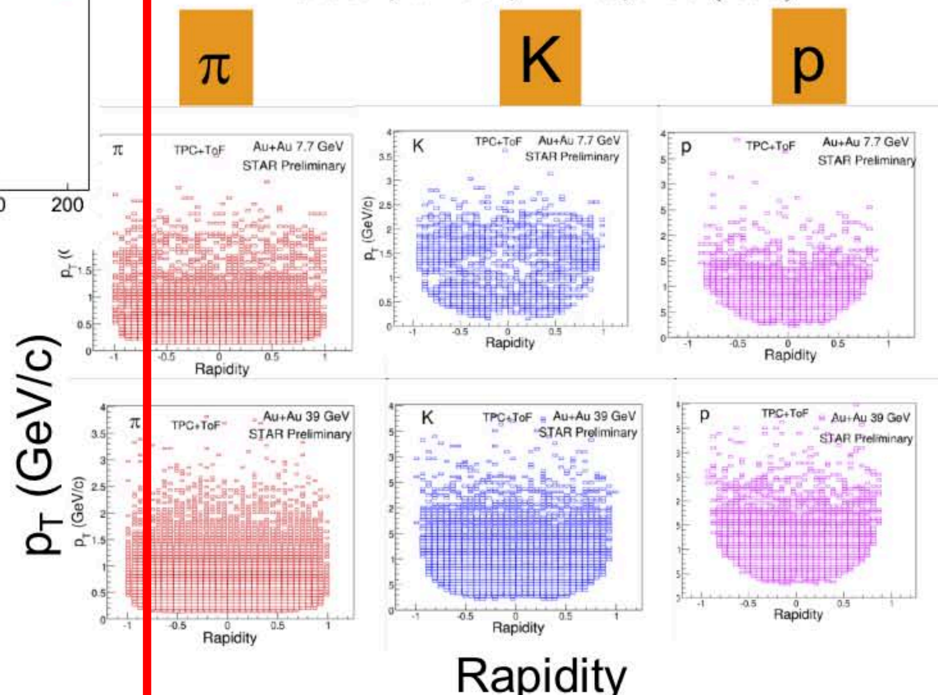




Constant or monotonic trends observed
Apparent differences (results with Kaons) with SPS

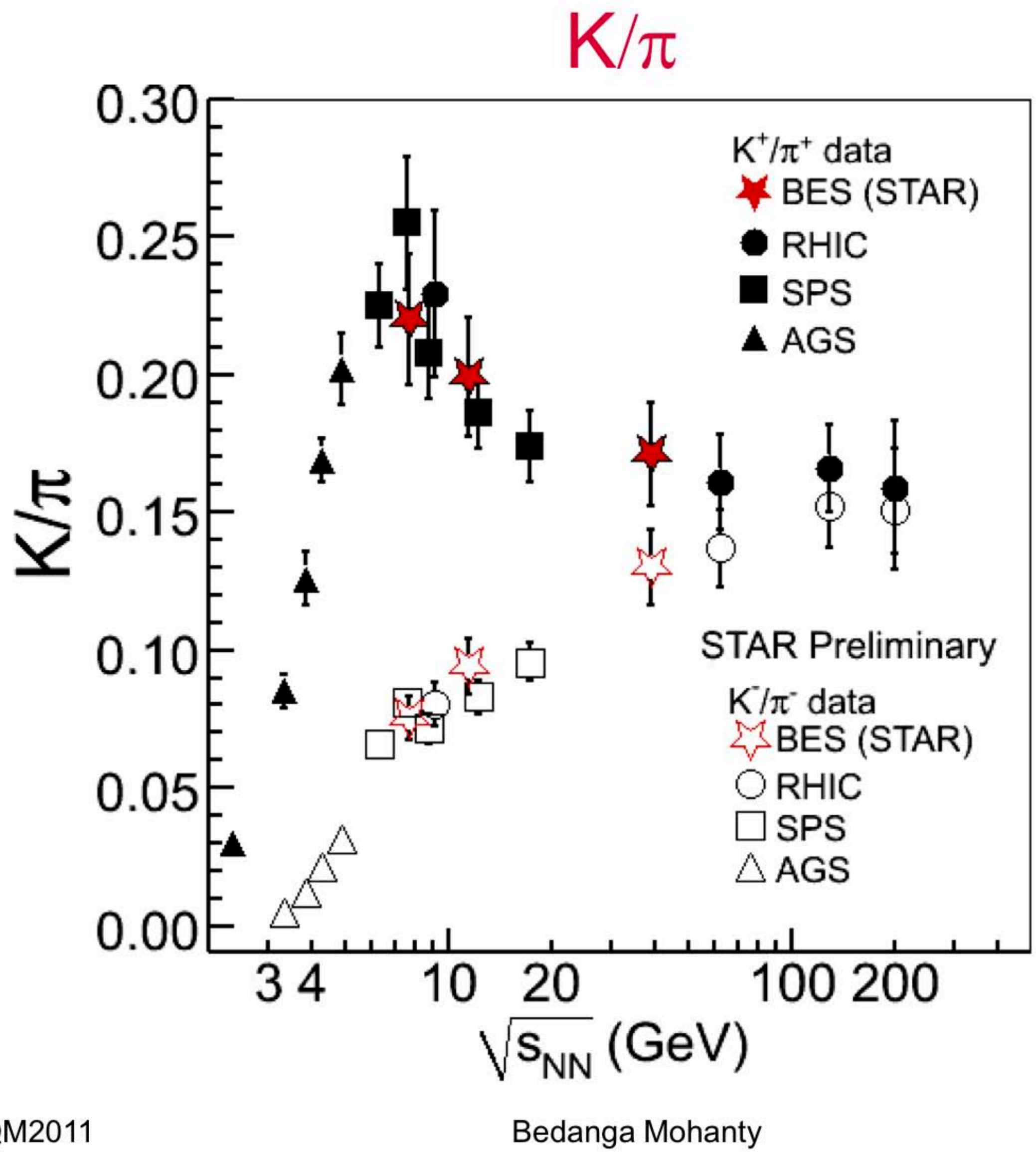
Fluctuations in particle ratios
-- Sensitive to particle numbers at chemical FO not kinetic FO
-- Volume effects may cancel

S. Jeon, V. Koch, PRL 83, 5435 (1999)



Differences could be due to difference in acceptance and/or PID selections --- under discussion

SpS K/π-Horn is Dubious (a 1σ effect)



Change in shape of K^+/π^+ near $\sqrt{s_{NN}}$=8 GeV naturally explained in many models by change in dominant strangeness production from $K^+ \Lambda$ to $K^+ K^-$

STAR's opinion of phase diagram c. 2011

http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
arXiv:1007.2613

The QCD Phase Diagram

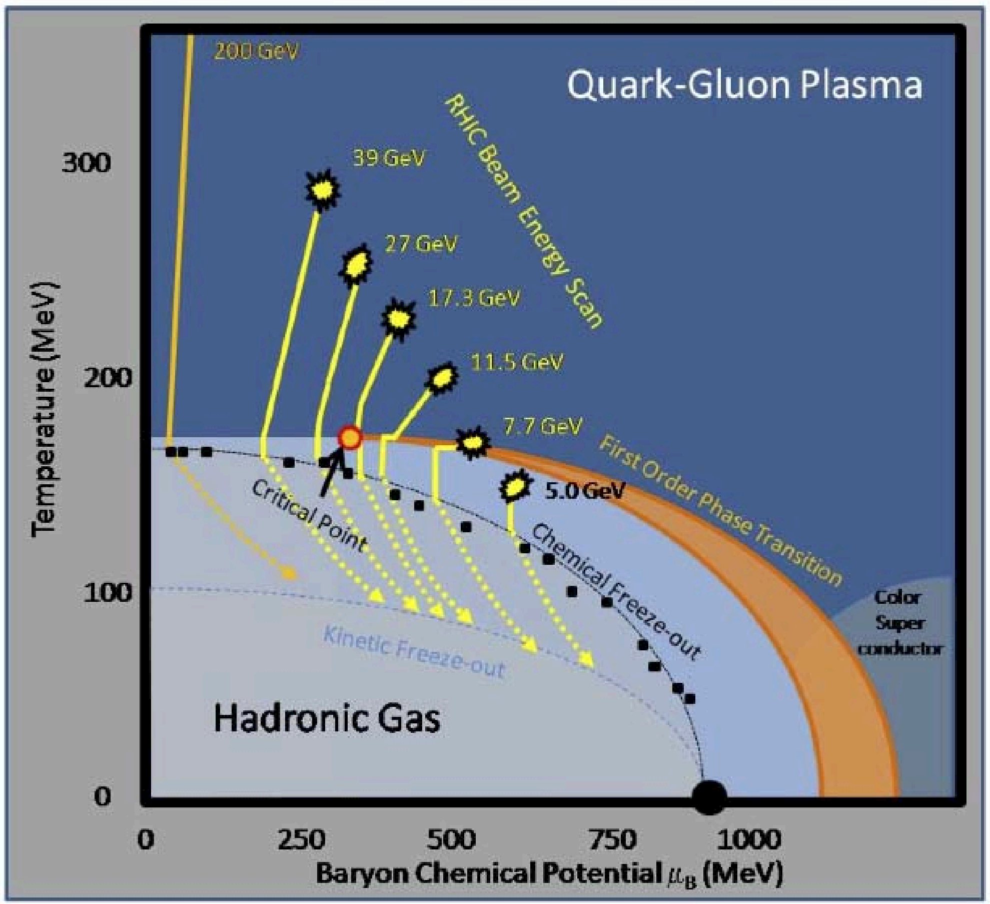


Fig. 1: A schematic representation of the QCD Phase Diagram. The location of the critical point, the separation between the 1st-order transition and chemical freeze-out, and the focusing of the event trajectories towards the critical point, are not based on specific quantitative predictions, but are all chosen to illustrate plausible possibilities.

Hot off the presses-LBL Press release June 24

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY
A-Z INDEX | PHONE BOOK | JOBS | SEARCH

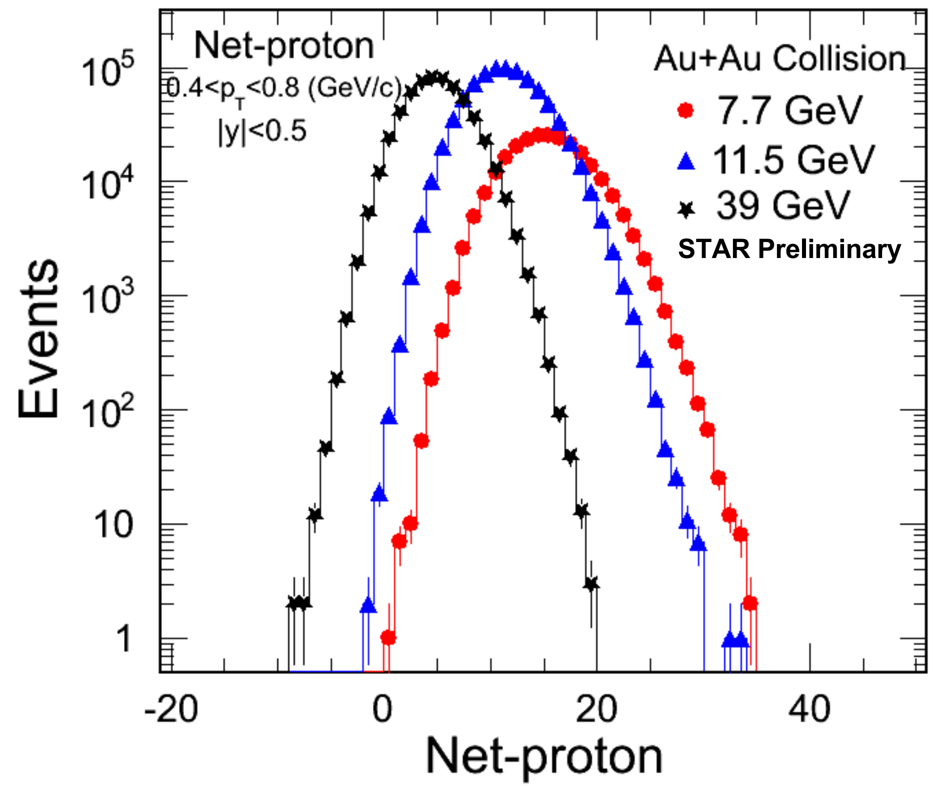
When Matter Melts

By comparing theory with data from STAR, Berkeley Lab scientists and their colleagues map phase changes in the quark-gluon plasma

June 23, 2011

Hot off the presses-LBL Press release June 24 Higher Moments of Net-Proton Distributions

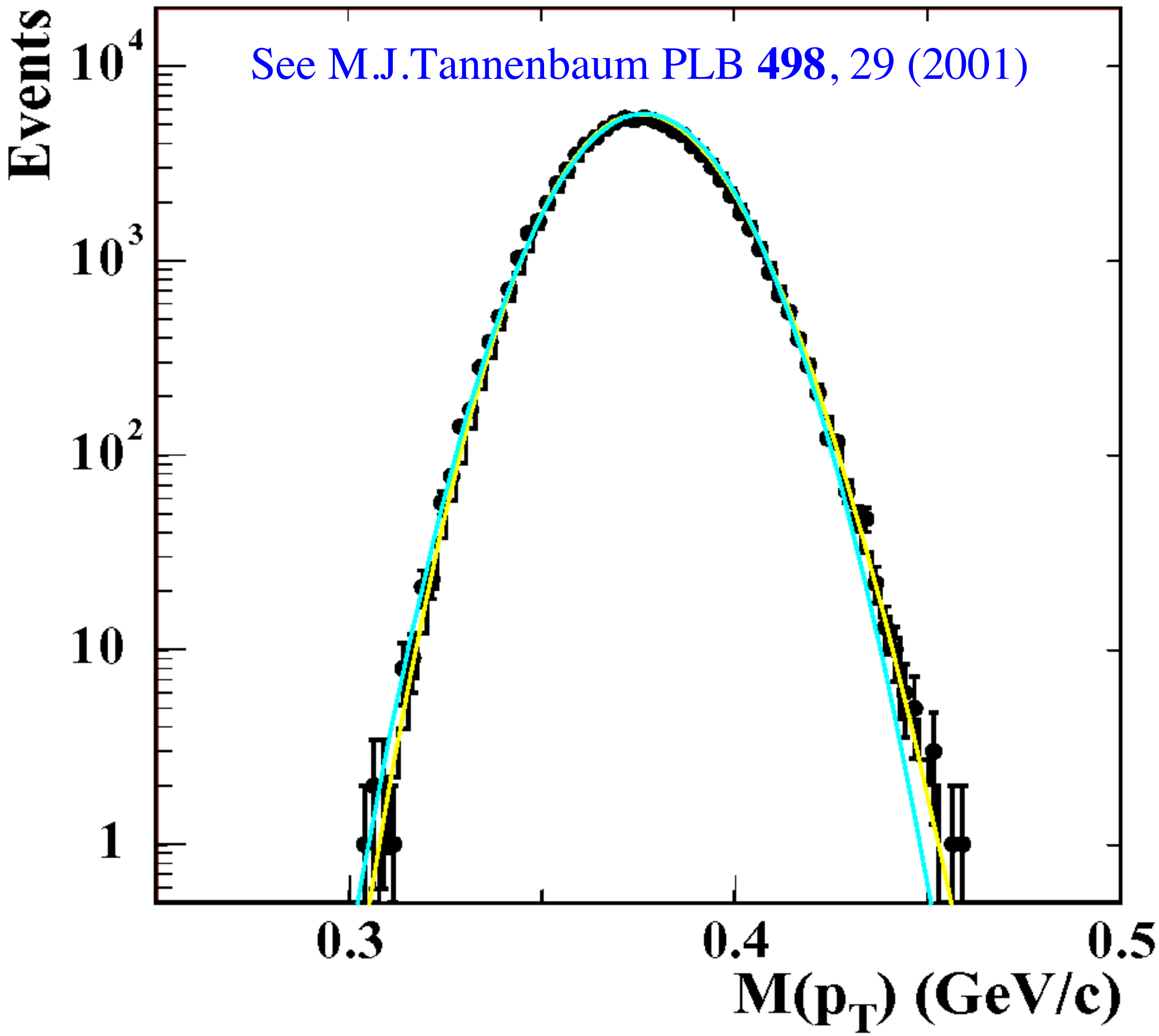
- 1^{st} moment: mean = $\mu=\langle x\rangle$
- 2^{nd} cumulant: variance = $\sigma^2=\langle(x-\mu)^2\rangle$
- 3^{rd} standardized cumulant: skewness = $S=\langle(x-\mu)^3\rangle/\sigma^3$
- 4^{th} standardized cumulant: kurtosis = $\kappa=\{\langle(x-\mu)^4\rangle/\sigma^4\}-3$
- Calculate moments from the event-by-event net proton distribution.
  - ✓ Have similar plots for net-charge and net-kaon distributions.



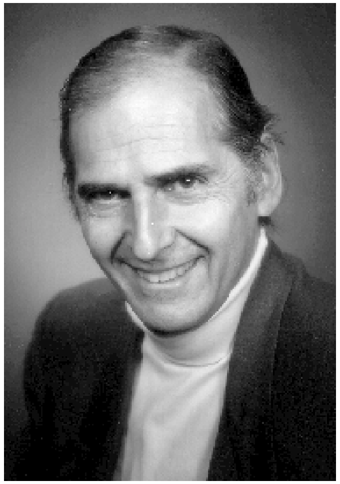
MJT-If you know the distribution, you know all the moments, but statistical mechanics and Lattice Gauge like Taylor expansions, hence moments/cumulants

From one of Jeff Mitchell's talks 2001: "Average p_T Fluctuations"

NA49 Pb+Pb central PLB **459**, 679 (1999)



It's not a Gaussian…it's a Gamma distribution!



Also: It's not Poisson, it's negative binomial

Lattice and Experiment Compared-a first?

Sourendu Gupta, et al., Science 332,1525 (2011)-LBL press release

- Calculate QGP-QCD on Lattice. Find P/T^4 as a function of T/T_c and μ_B/T, (Tc is critical temp) (μ_B Baryon chemical potential). Take derivatives to find cumulants, B^n (just terms in the series expansion). V is volume.

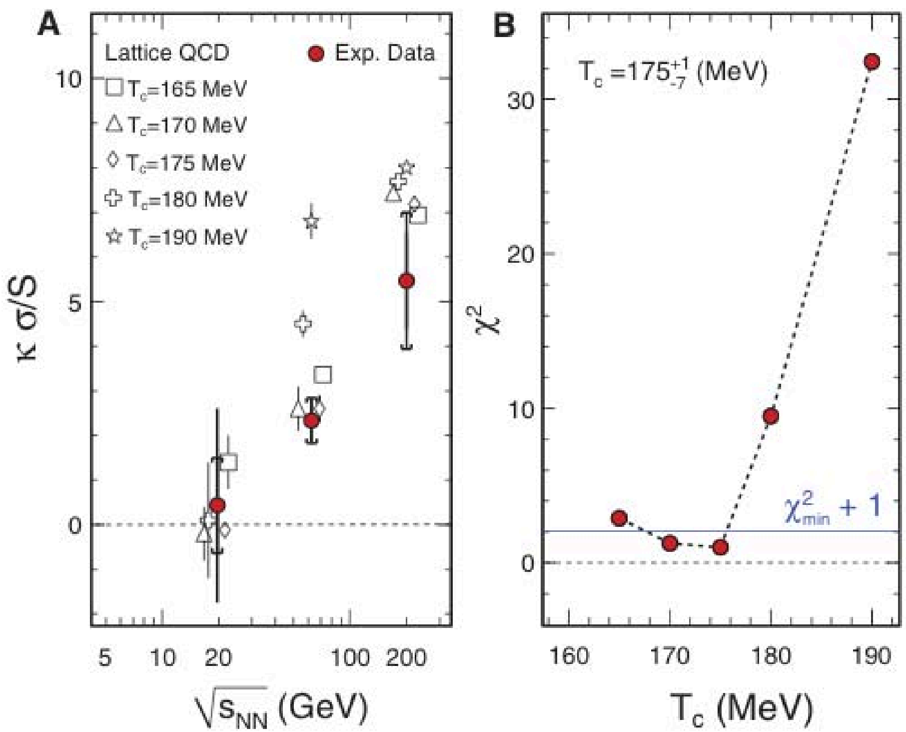
$$T^{n-4}\chi_B^{(n)}\left(\frac{T}{T_c},\frac{\mu_B}{T}\right) = \frac{1}{T^4}\frac{\partial^n}{\partial(\mu_B/T)^n}P\left(\frac{T}{T_c},\frac{\mu_B}{T}\right)\Big|_{T/T_c}$$

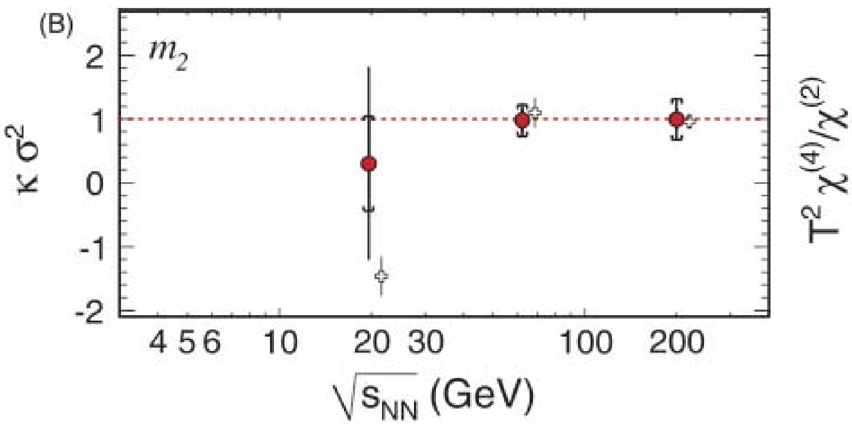
$$[B^n] = VT^3T^{n-4}\chi_B^{(n)}\left(\frac{T}{T_c},\frac{\mu_B}{T}\right)$$

- Higher moments of net-proton distribution can be related to thermodynamic susceptibilities, B^n, but take ratios so that Volume and other factors cancel:
$(\kappa\sigma^2)_B = \langle(x-\langle x\rangle)^4\rangle/\sigma^2 - 3\sigma^2 = B^4/B^2 = T^2\,\chi_B^{(4)}/\chi_B^{(2)}$
$(\kappa\sigma/S)_B = \{\langle(x-\langle x\rangle)^4\rangle/\sigma^3 - 3\sigma\}/\langle(x-\langle x\rangle)^3\rangle/\sigma^3 = B^4/B^3 = T\,\chi_B^{(4)}/\chi_B^{(3)}$
- Hadron Resonance Gas Calculations: M.Cheng et al, Phys. Rev. D 79, 074505 (2009), F. Karsch and K. Redlich, Phys. Lett. B 695, 136 (2011))\
- Predictions that critical fluctuations contribute to higher moments and are strongly dependent on correlation length (ζ) of the system:
4th order moments go as ζ^7. (M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009))
- For net-charge, change index from B to Q. For net-kaons, change B to S.

Following T. Tarnowsky QM2011

Results and Conclusions





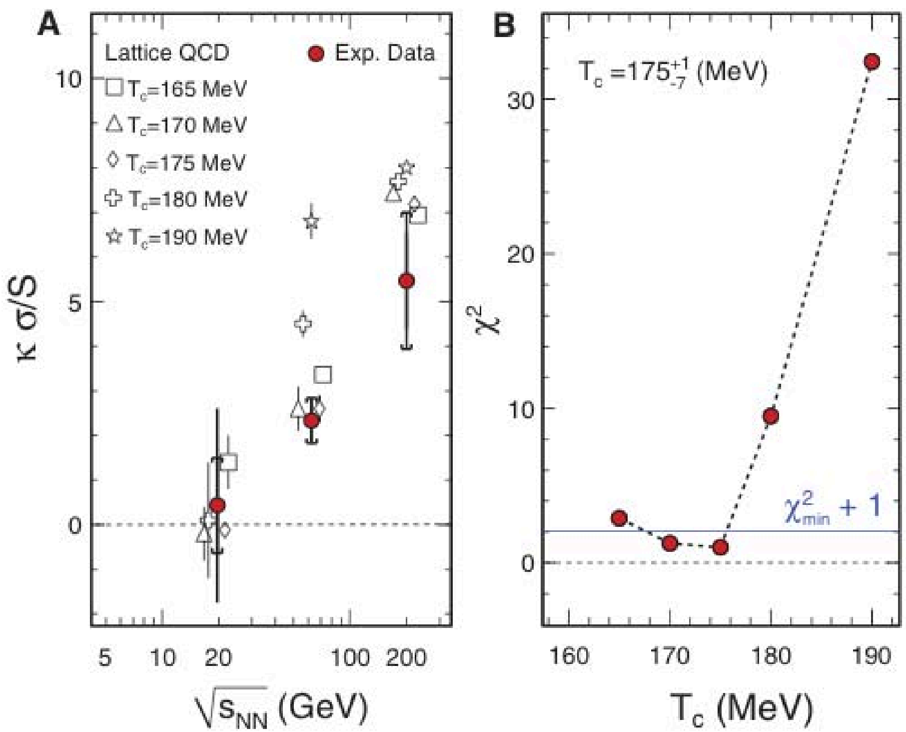
$$\chi^2(T_c) = \sum_{\sqrt{s_{NN}}} \frac{[Expt(\sqrt{s_{NN}}) - Lattice(\sqrt{s_{NN}}, T_c)]^2}{Error^2_{Expt} + Error^2_{Lattice}}$$

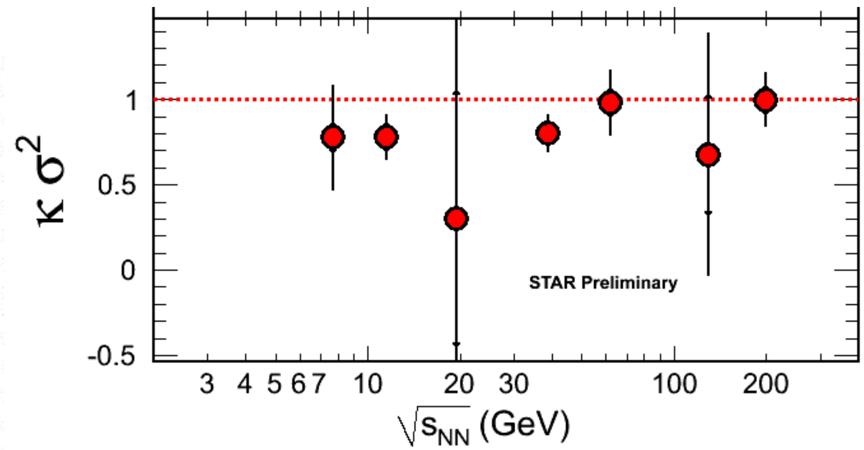
Lattice shows huge deviation of $T^2\,\chi^{(4)}/\,\chi^{(2)}$ from 1 near 20 GeV, suggesting critical fluctuations. Expt $\kappa\sigma^2$ suggests not; but with big errors. Need more data.

Evidence for phase transition from resonance gas to QGP at T_c=175 MeV

Poison: $\kappa\sigma^2=1$
NBD: $\kappa\sigma^2=1+6\mu/k+6\mu^2/k^2$
Do you think they know?

Results and Conclusions





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Evidence for phase transition from resonance gas to QGP at T_c=175 MeV

Poison: $\kappa\sigma^2$=1
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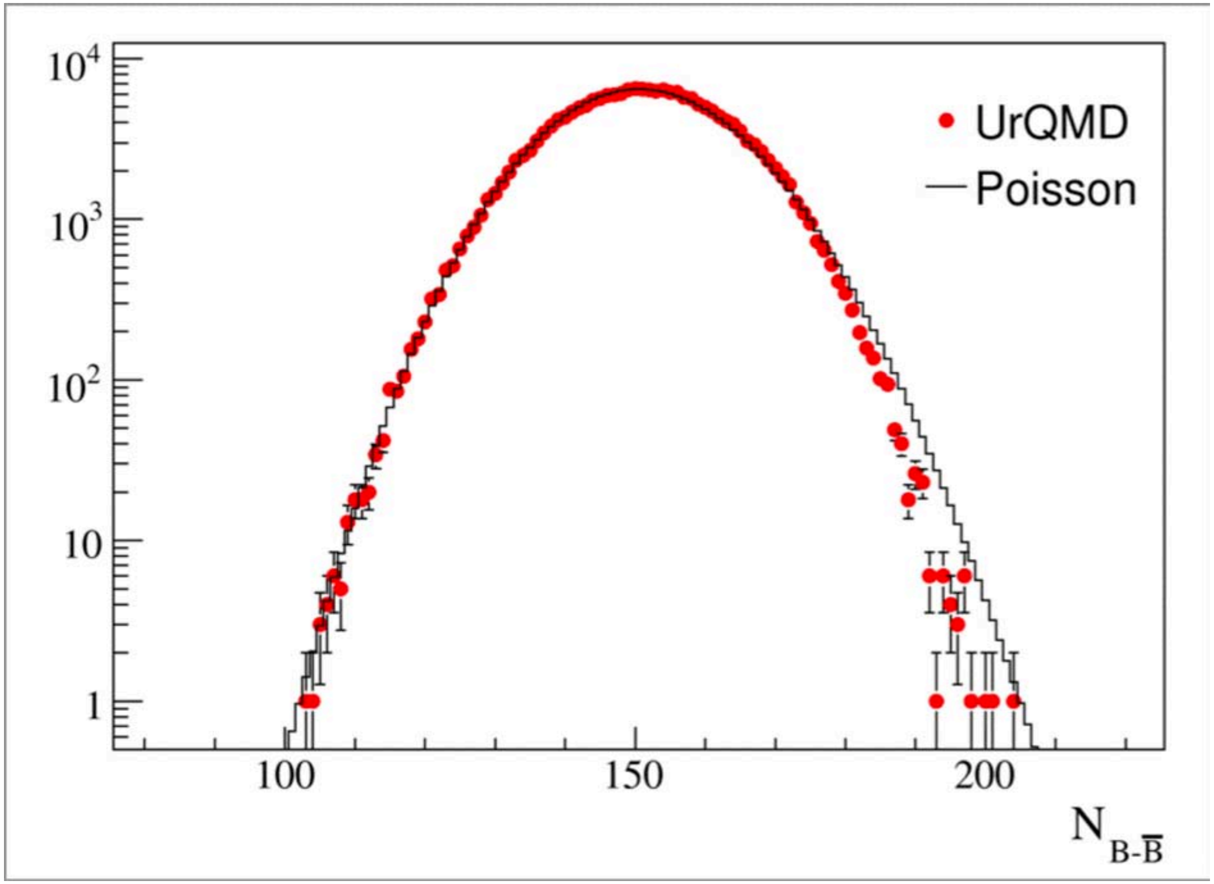
Do you think they know?

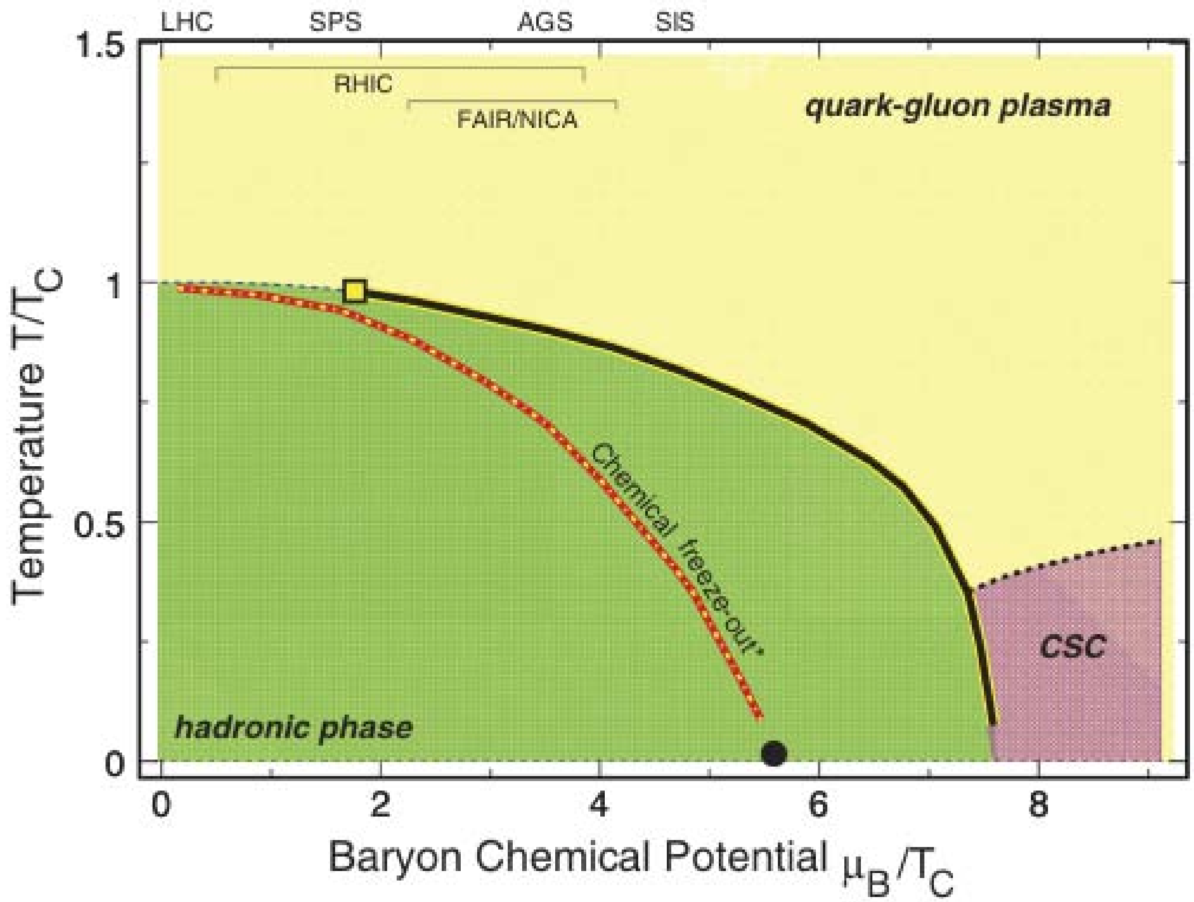
But cuts can distort the distribution



Centrality cut distorts the poisson distribution. Leads to negative $\kappa\sigma^2$, see Nahrgang, QM2011, arXiv:0903.2911

Thanks for Viktor Begun for pointing this out to me.

Quoting the LBL Press Release

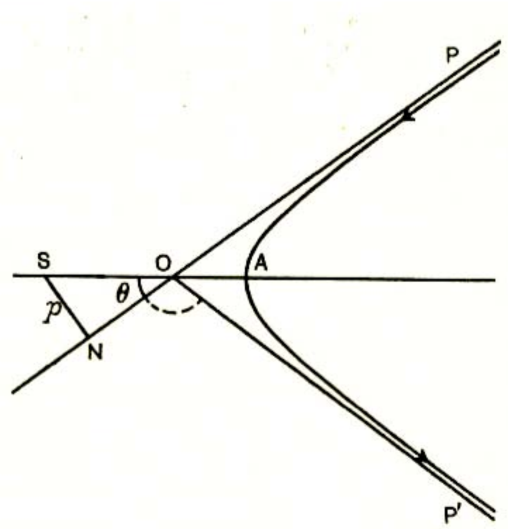


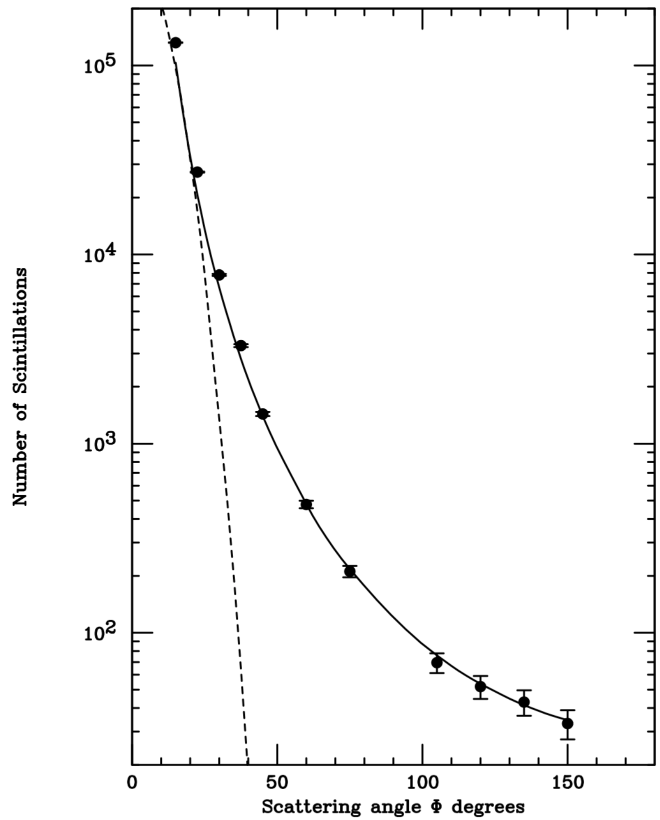
"Among the world's heavy-ion colliders, only RHIC can tune the energy of the collisions through the region of the QCD phase diagram where the critical point is most likely to be found"

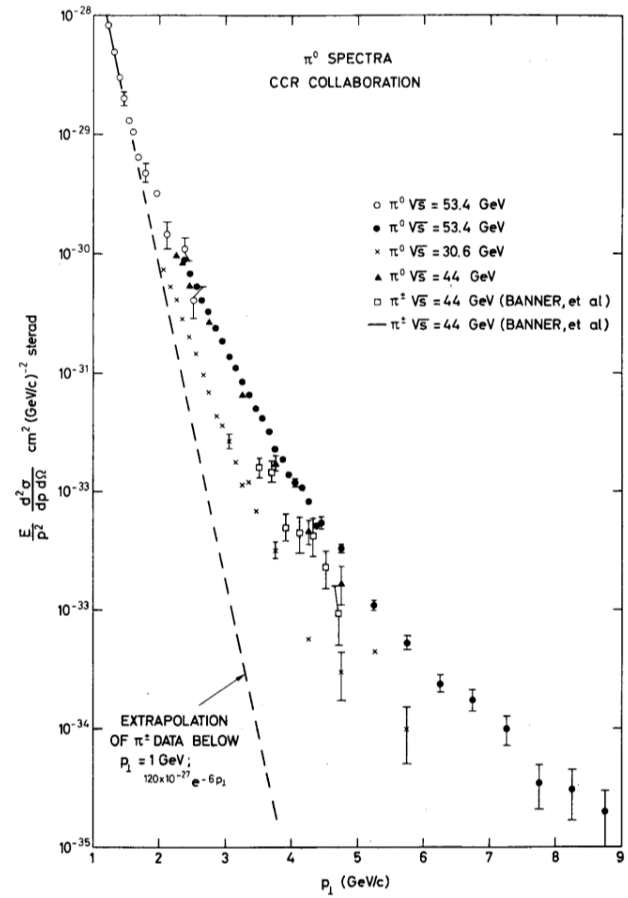
MJT--or this could be the next 'Ridge/MachCone'

Hard-Scattering at RHIC provided the most dramatic new effects

Rutherford to ISR to RHIC







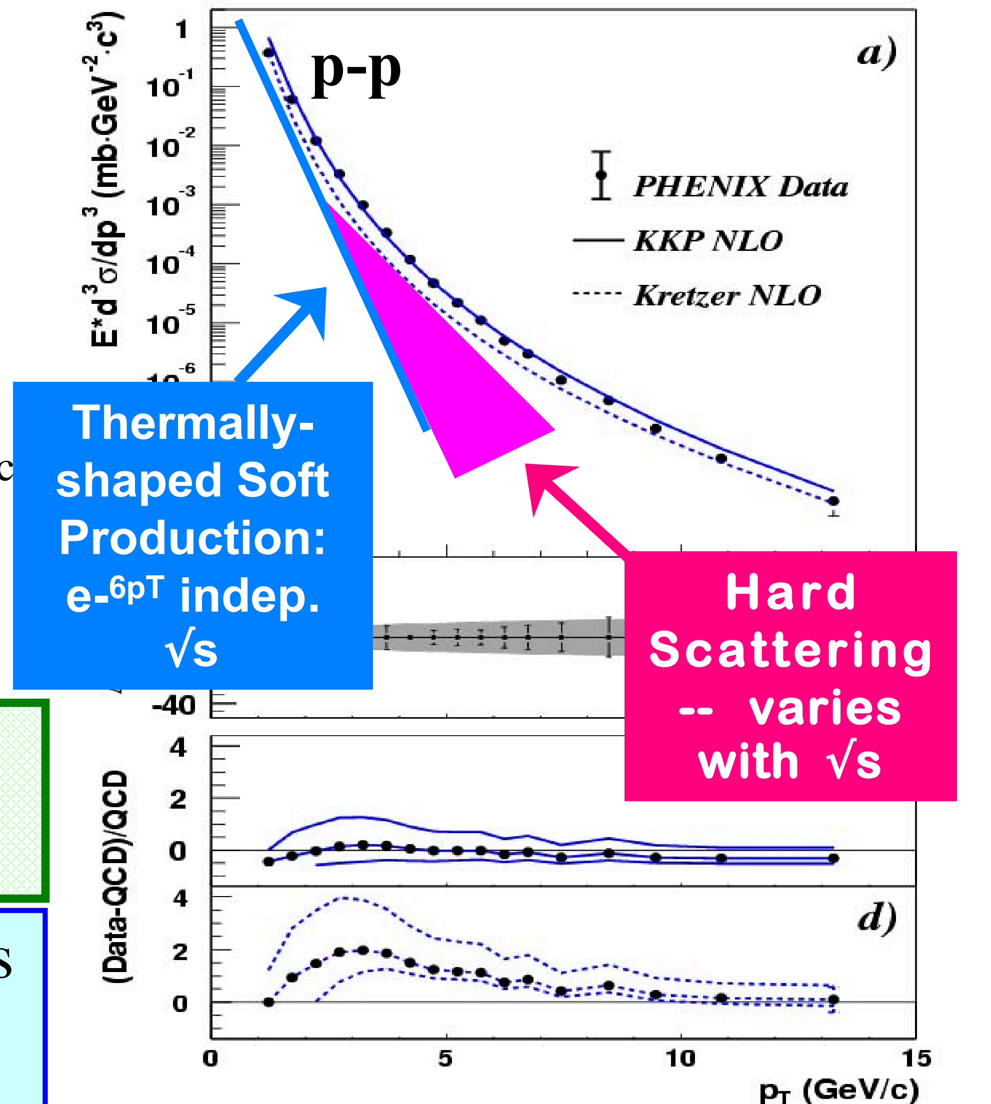
Rutherford scattering
Phil. Mag 21(1911)669

Geiger & Marsden
α+Au→ α+Au
Phil.Mag 25(1913)604

CCR ICHEP 1972
p+p→π^0+X
Hard scattering of partons

π^0's in p+p $\sqrt{s}$=200 GeV: Data vs. pQCD

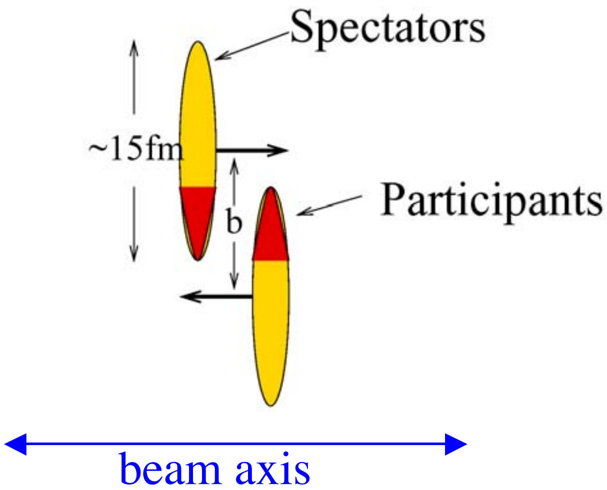
- Result from run2 published-a classic
  - ✓ PRL91 (2003) 241803
- New result from run5
  - ✓ preliminary
- Comparison of π^0 cross section
  - ✓ Next-to-leading order(NLO) pQCD
    - CTEQ6M + KKP or Kretzer
    - Matrix calculation by Aversa, et. al.
    - Renormalization and factorization sc
      are set to be equal and set to
      $1/2p_T$, p_T, $2p_T$
    - Calculated by W.Vogelsang

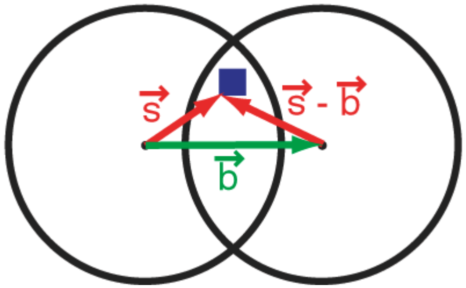


NLO-pQCD described very well down even to $p_T \sim 1$ GeV/c

Inclusive invariant π^0 spectrum is pure power law for $p_T \geq 3$ GeV/c
n=8.1±0.1

High p_T in A+B collisions---T_{AB} Scaling

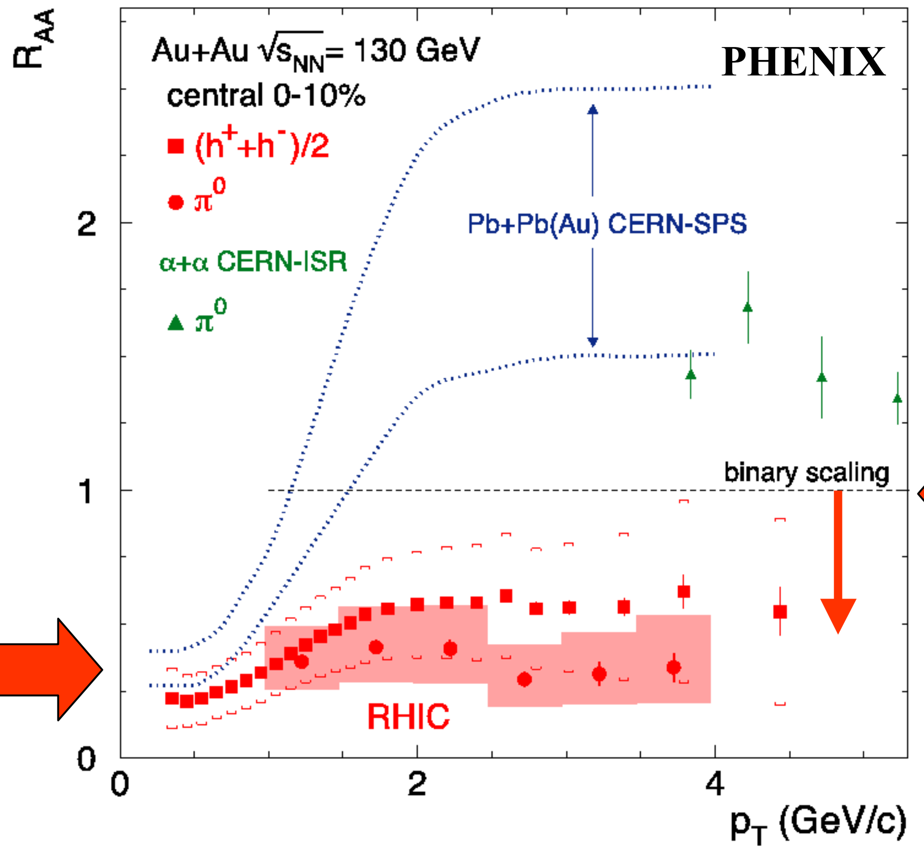


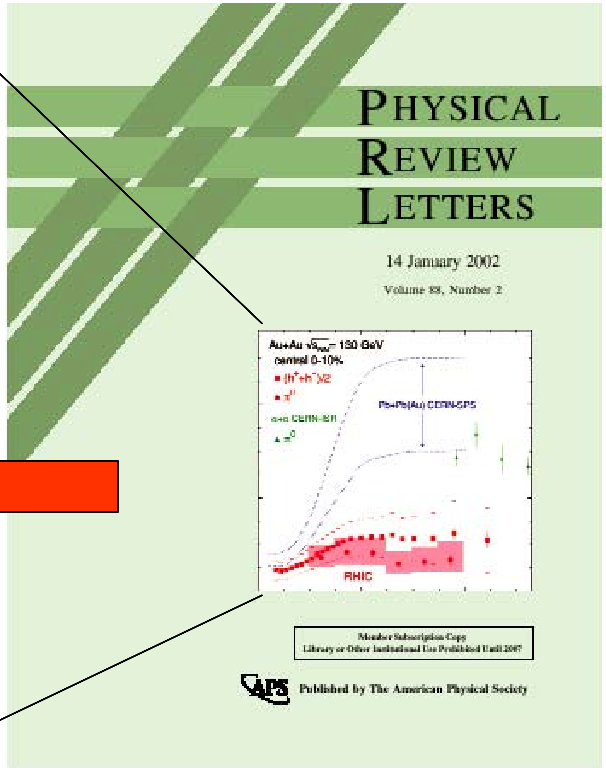


view along beam axis

- For point-like processes, the cross section in p+A or A+B collisions compared to p-p is simply proportional to the relative number of pointlike encounters
  - ✓ A for p+A, AB for A+B for the total rate
  - ✓ T_{AB} the overlap integral of the nuclear profile functions, as a function of impact parameter b

10 Years Ago--QM2001 we discovered π^0 suppression… First results $\sqrt{s_{NN}}$=130 GeV



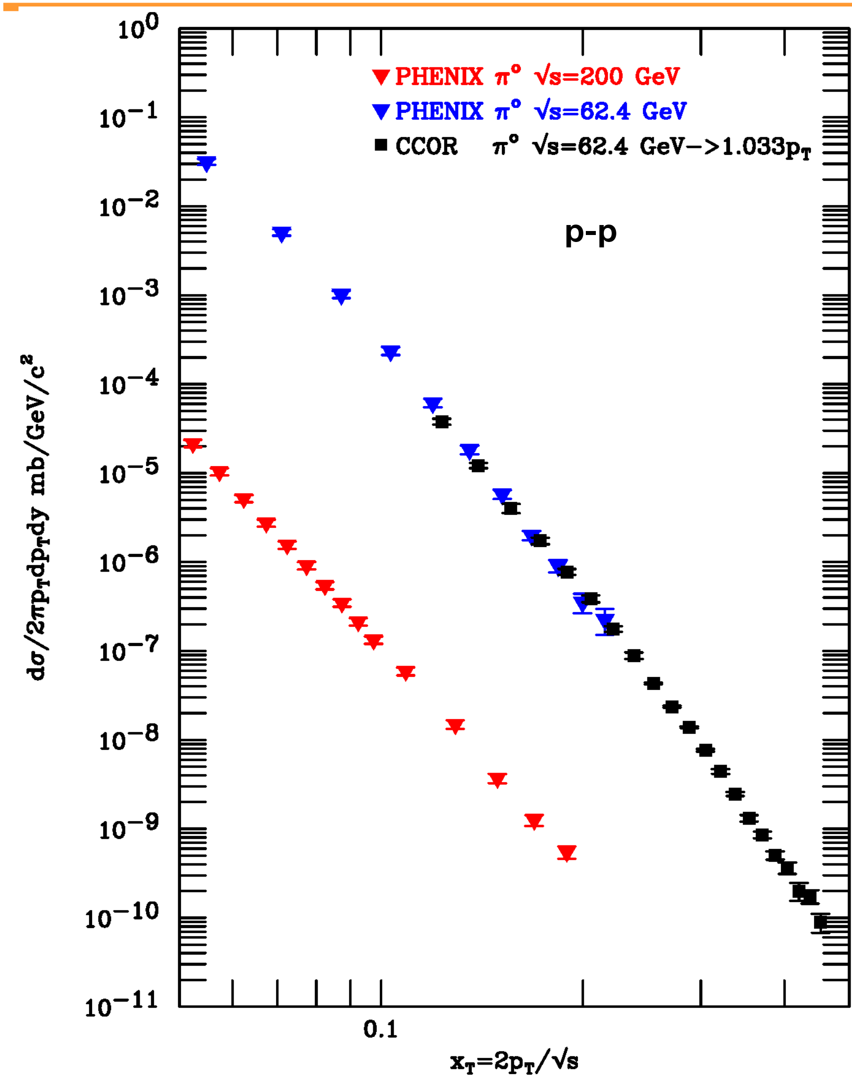


PHENIX PRL 88, 022301 (2002)

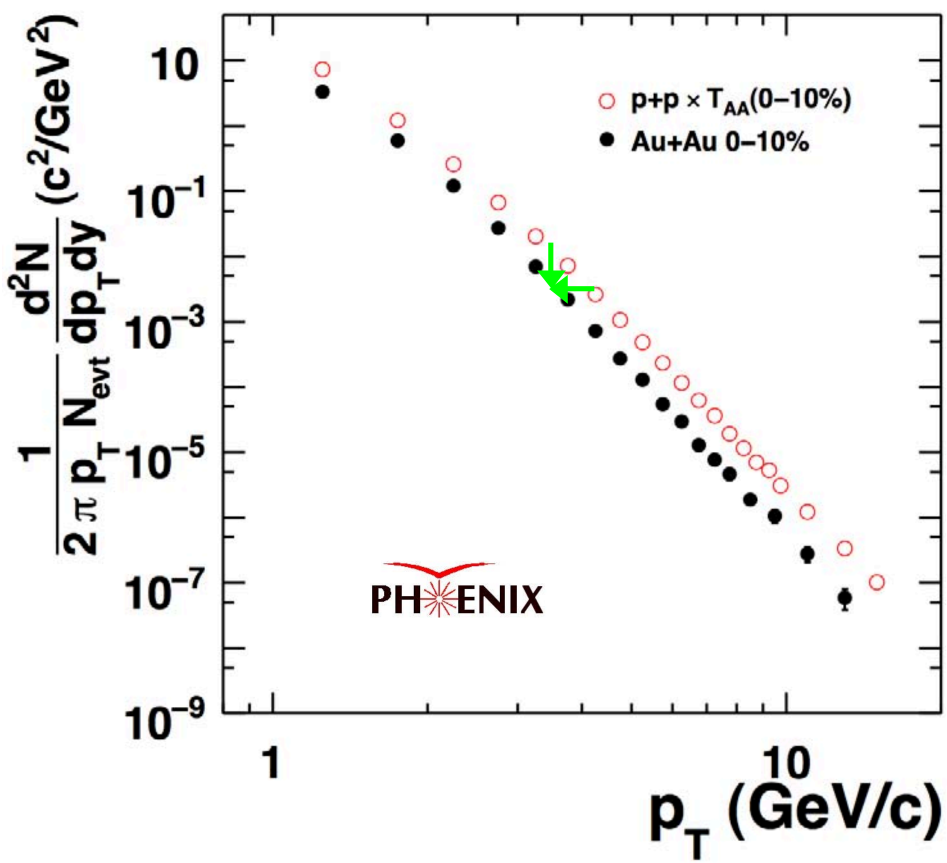
First observation of *large* suppression of high p_T hadron yields

"Jet Quenching"? == Quark Gluon Plasma?

ISR π^0 vs RHIC p-p $\Rightarrow$ RHIC pp vs AuAu



π^0 are suppressed in Au+Au eg 200 GeV

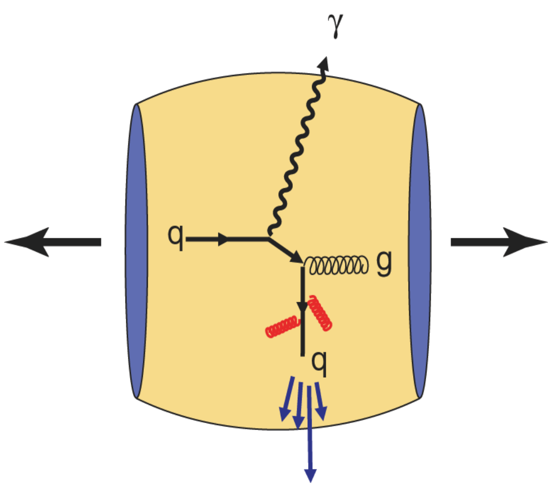


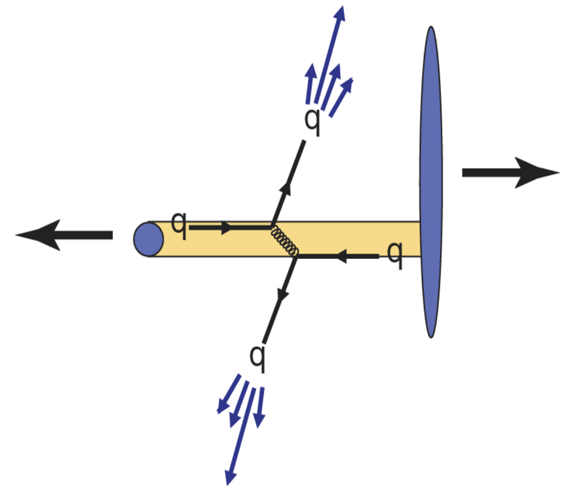
π^0 invariant cross section in p-p at $\sqrt{s}$=200 GeV is a pure power law for $p_T > 3$ GeV/c, n=8.1±0.1

Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{d^2N^{\pi}_{AA}/dp_T dy N^{inel}_{AA}}{\langle T_{AA}\rangle d^2\sigma^{\pi}_{pp}/dp_T dy}$$

Hot (AA) vs Cold pA Nuclear Matter Effects



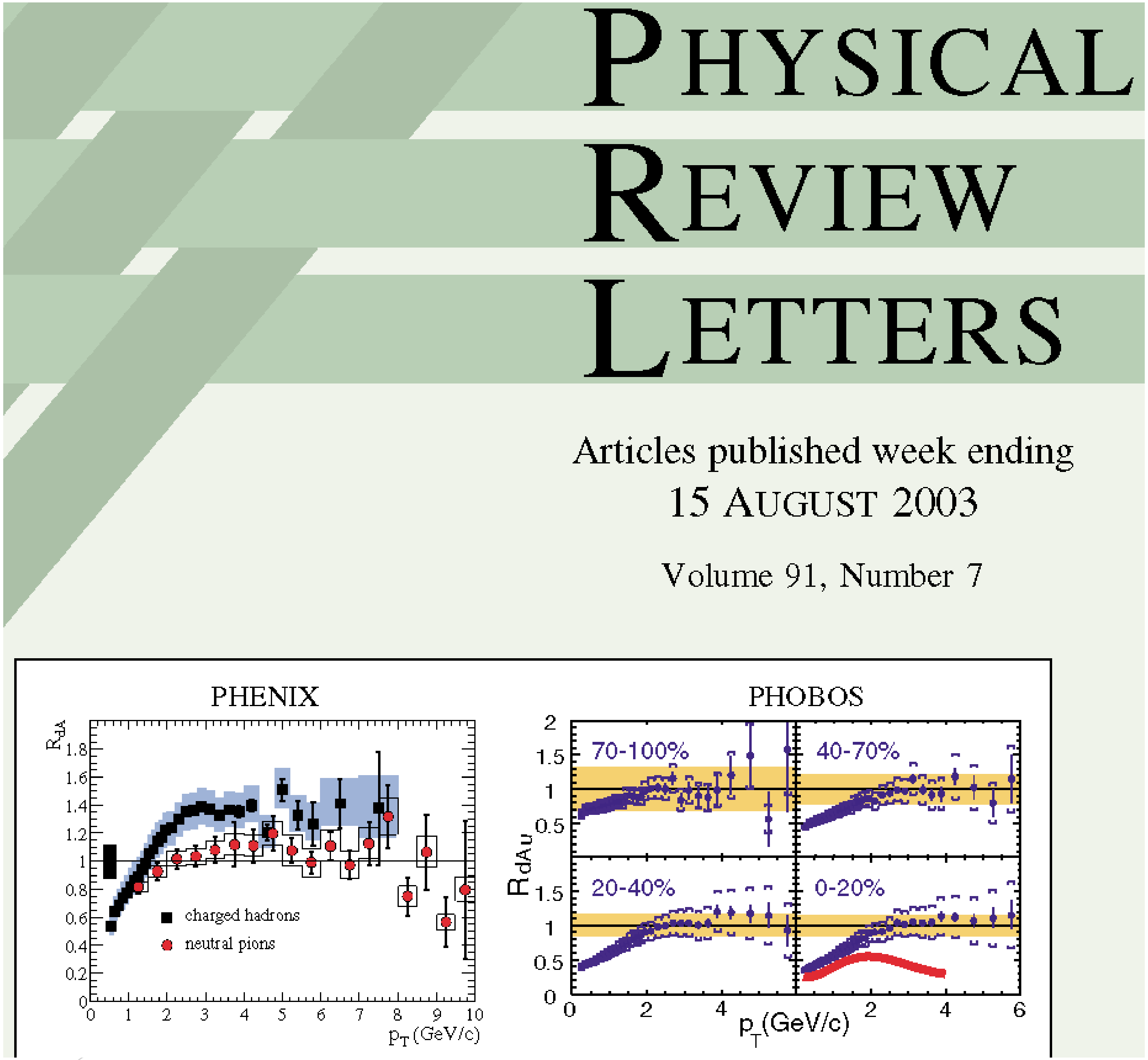


Hard scattering of partons in the initial collision is in-situ internal probe of medium

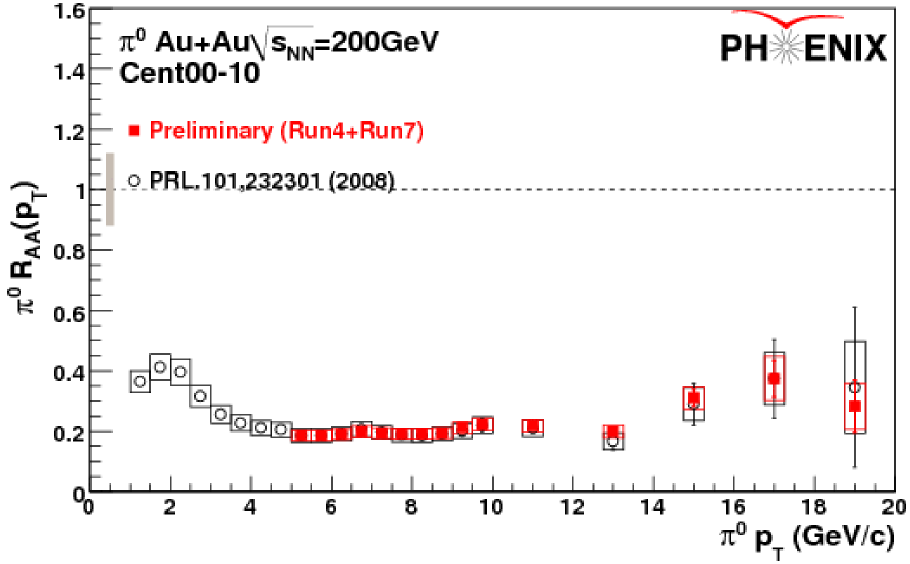
In p+A or d+A, medium is small, (1 nucleon wide) or non-existent. This is baseline for any cold nuclear matter effect in initial collision

- RHIC is versatile
  - ✓ Can collide any nuclear species on any other

No effect in dAu: suppression is medium effect

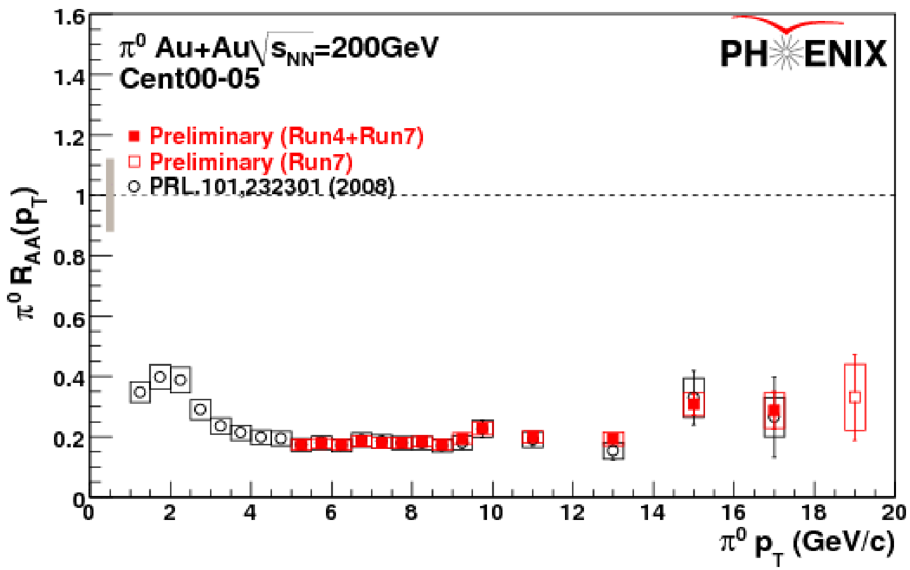


One decade later--QM2011



0-5%,0-10% Au-Au central points suppressed across the whole p_T range

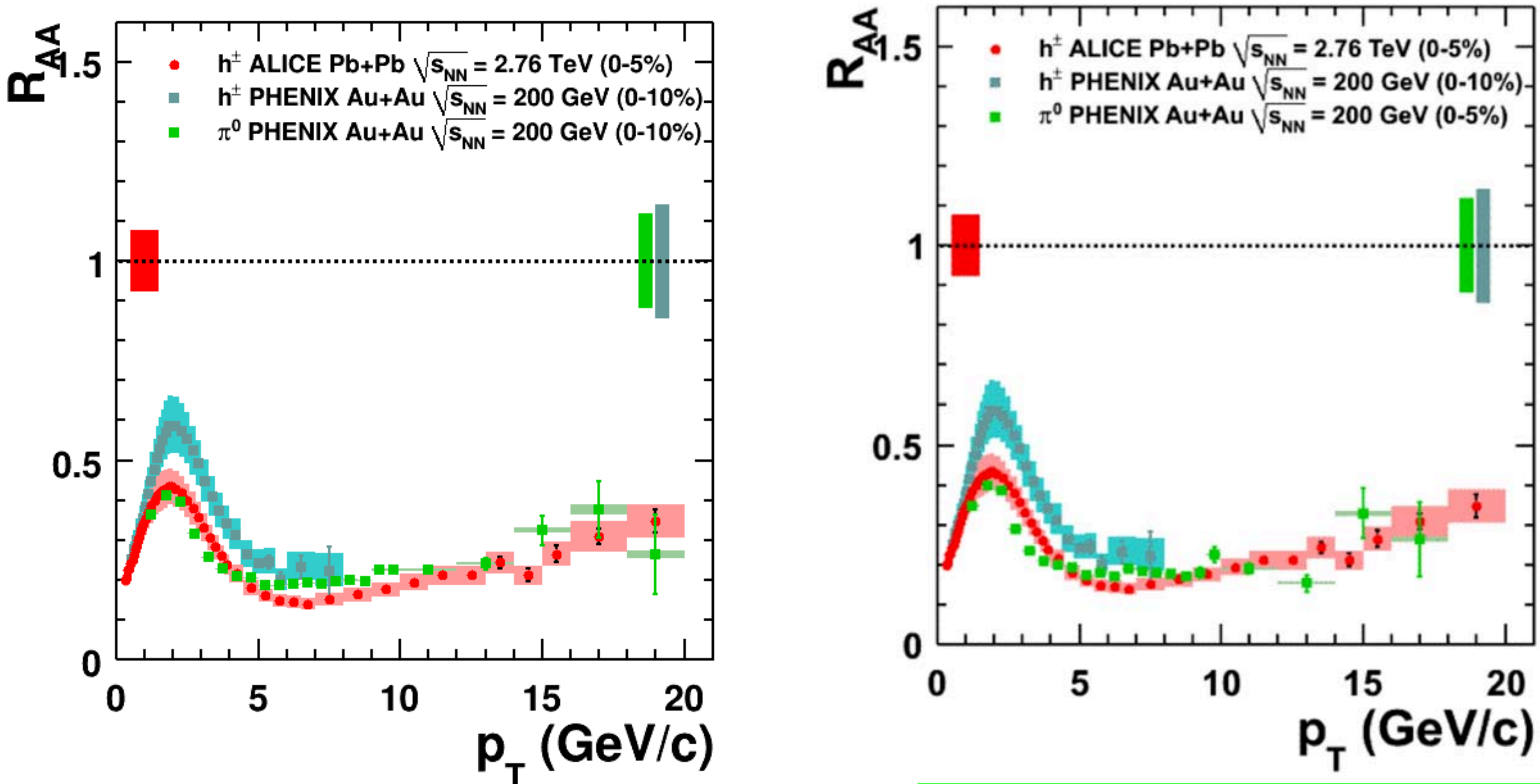
PHENIX data reach out to 20GeV/c p_T Consistent with constant $R_{AA} \approx 0.2$ in central Au+Au up to highest p_T ($5 < p_T < 20$ GeV/c)



For the past decade, R_{AA} has been one of the workhorse variables

A wealth of results available from different probes

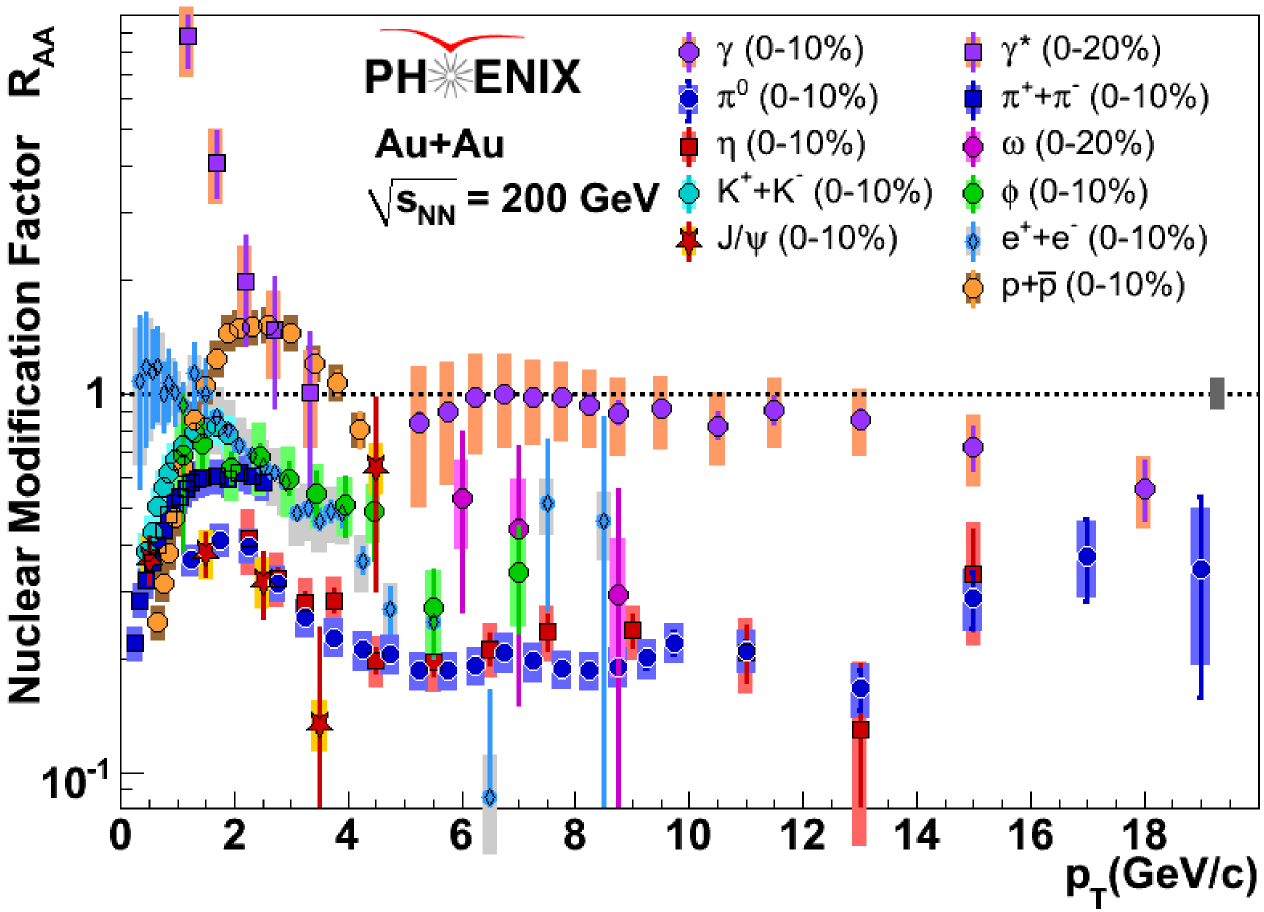
Comparison to ALICE at LHC



- Despite more than a factor of 20 higher $\sqrt{s_{NN}}$, the R_{AA} looks nearly identical for RHIC and LHC for 5<pT< 20 GeV/c
- ALICE data show significant upward trend but PHENIX upward trend not significant.

Don't be tempted to conclude that the fractional jet energy loss is the same at RHIC and LHC: the inclusive spectra are flatter at LHC n~6 cf. RHIC n=8.1, which implies 50% more $\Delta E/E$ at LHC than at RHIC

Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV QM11



Exponential enhancement of direct-γ as $p_T \rightarrow 0$ is unique. No other particle is enhanced except in the region of the 'baryon anomaly'. This suggests new physics, *i.e*. thermal photons.

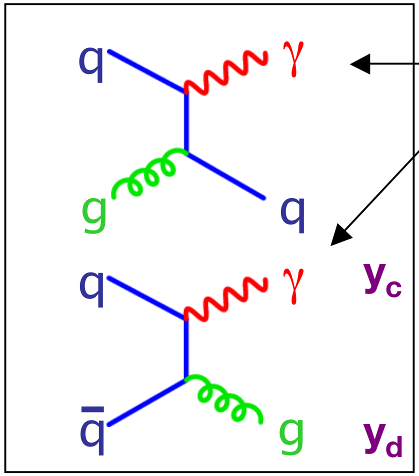
Direct photon production-simple theory hard experiment

See the classic paper of Fritzsch and Minkowski, PLB **69** (1977) 316-320

Compton

Annihilation

small-ignore



isolated photons

q is 8/1 u/d quark

Analytical formula for γ-jet cross section for a photon at p_T, y_c (and *parton* (jet) at p_T, y_d):

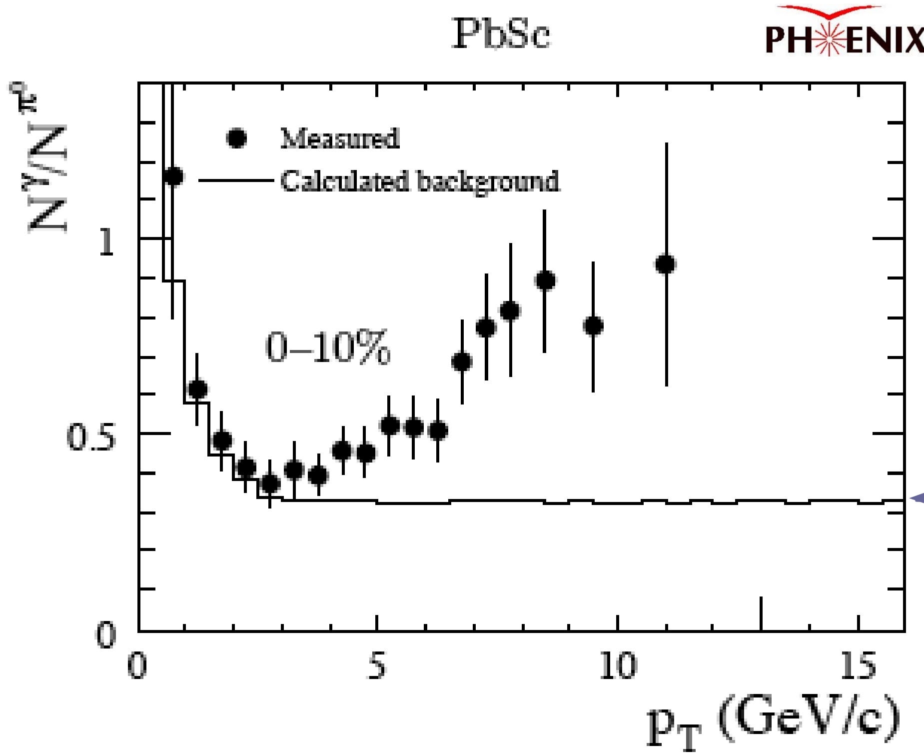
$$\frac{d^3\sigma}{dp_T^2\, dy_c\, dy_d} = x_1 f_g^A(x_1)\, F_{2B}(x_2,Q^2) \frac{\pi\alpha\alpha_s(Q^2)}{3\hat{s}^2}\left(\frac{1+\cos\theta^*}{2}+\frac{2}{1+\cos\theta^*}\right)$$
$$+\ F_{2A}(x_1,Q^2)\, x_2 f_g^B(x_2) \frac{\pi\alpha\alpha_s(Q^2)}{3\hat{s}^2}\left(\frac{1-\cos\theta^*}{2}+\frac{2}{1-\cos\theta^*}\right)$$

$$\cos\theta^* = \tanh\frac{(y_c-y_d)}{2}$$

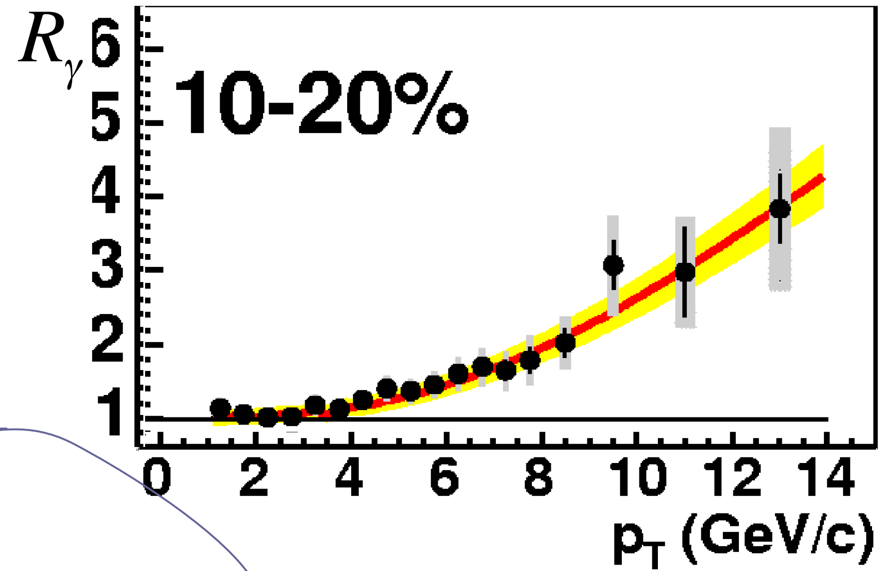
$$x_{1,2} = x_T\frac{e^{\pm y_c}+e^{\pm y_d}}{2}$$

$f_g(x)$ and $F_2(x)$ are g and q pdf's in nuclei A,B

Experimental problem is HUGE background from $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, etc. But this is less of a problem in Au+Au due to suppression of π^0



PHENIX PRL**94** (2005) 232301



$$R_\gamma = \frac{(\gamma/\pi^0)_{\text{Measured}}}{(\gamma/\pi^0)_{\text{Background}}} \approx \frac{\gamma_{\text{Measured}}}{\gamma_{\text{Background}}}$$

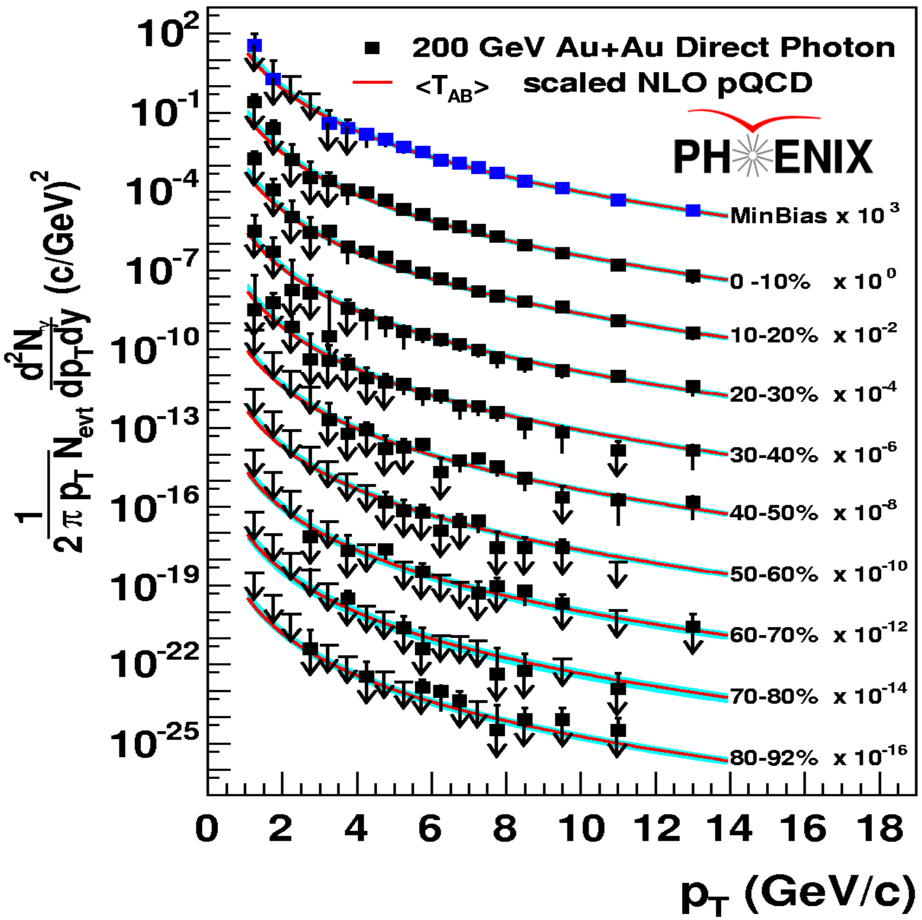
If $\dfrac{dn_{\pi^0}}{p_T dp_T} \propto p_T^{-n}$ then $\left.\dfrac{\gamma}{\pi^0}\right|_{\pi^0}(p_T) = 2/(n-1)$ x (1.19)=0.335

η/π^0=0.50

Since the the photons from $\pi^0 \rightarrow \gamma+\gamma$, $\eta \rightarrow \gamma+\gamma$ and similar decays are the principal background to direct photon production, the importance of a precise estimate of this background can not be overstated.

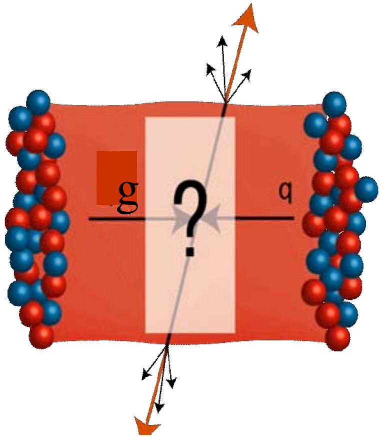
2004--Direct Photons in Au+Au 200 GeV: follow T_{AB} scaling from p-p for all centralities-no suppression

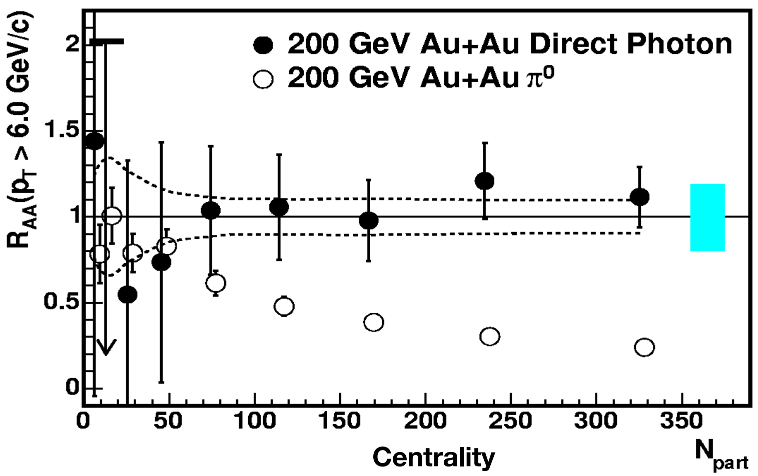
1) Proves that initial state Au structure function is simply a superposition of p-p structure functions including g(x).



PHENIX PRL**94** (2005) 232301

Au+Au





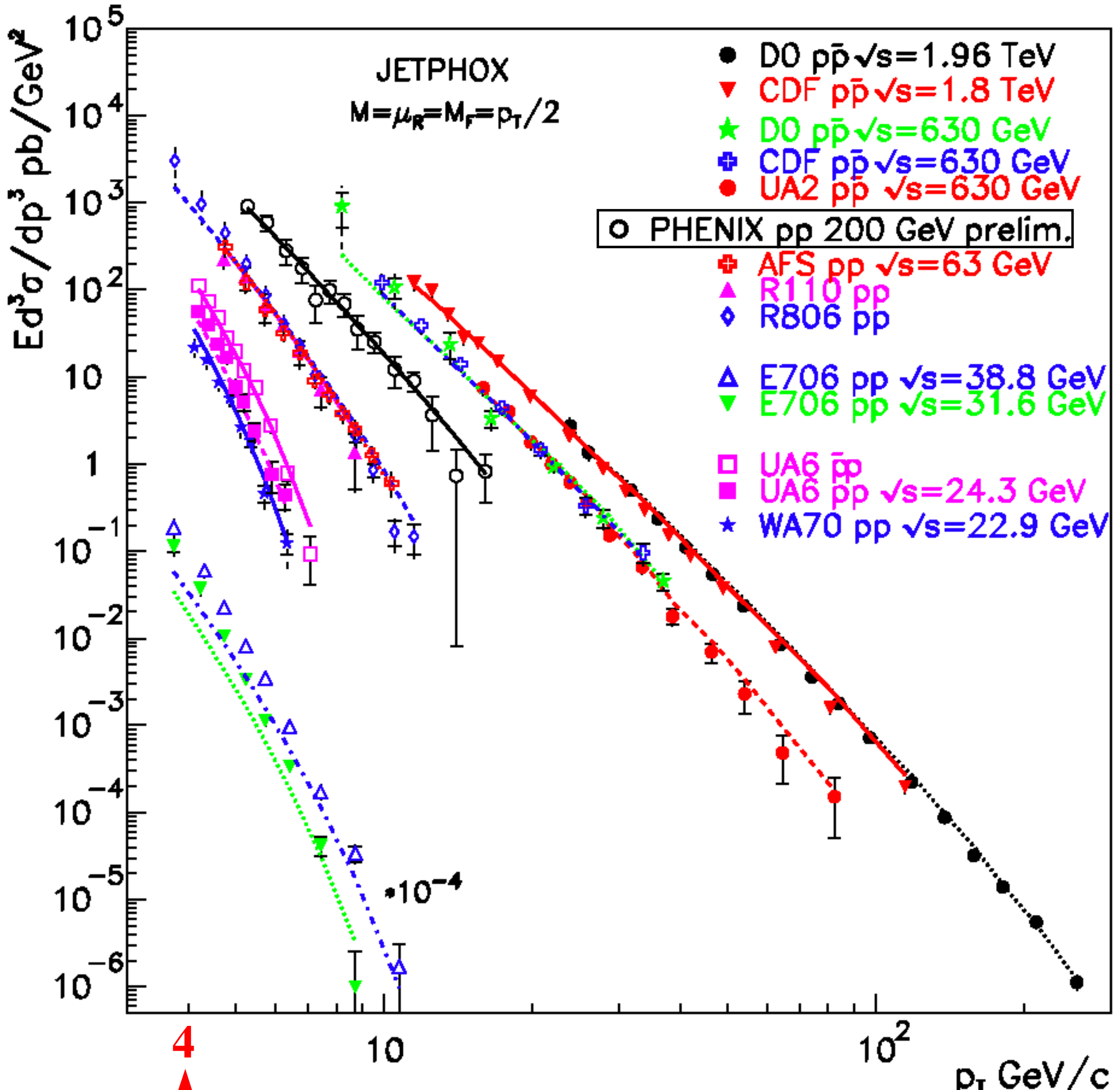
2)Direct photons unaffected by QCD medium in Au+Au →
π^0 suppression is medium effect

Comparison with other p-p data and pQCD

P. Aurenche et al Phys. Rev. D **73**, 094007 (2006)

PHENIX direct photon p-p data clarifies longstanding data/theory puzzle

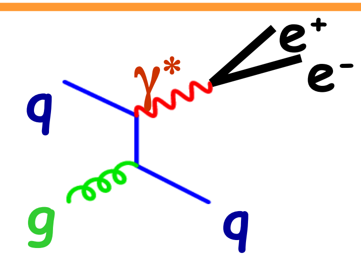
PHENIX PRL **98** (2007) 012002



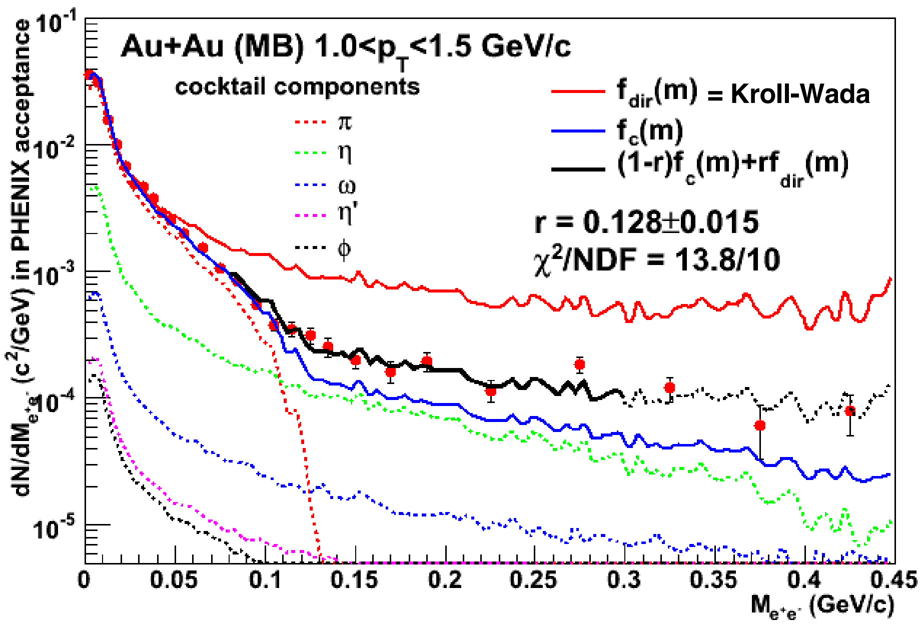
QM2005-direct γ in AuAu via internal conversion

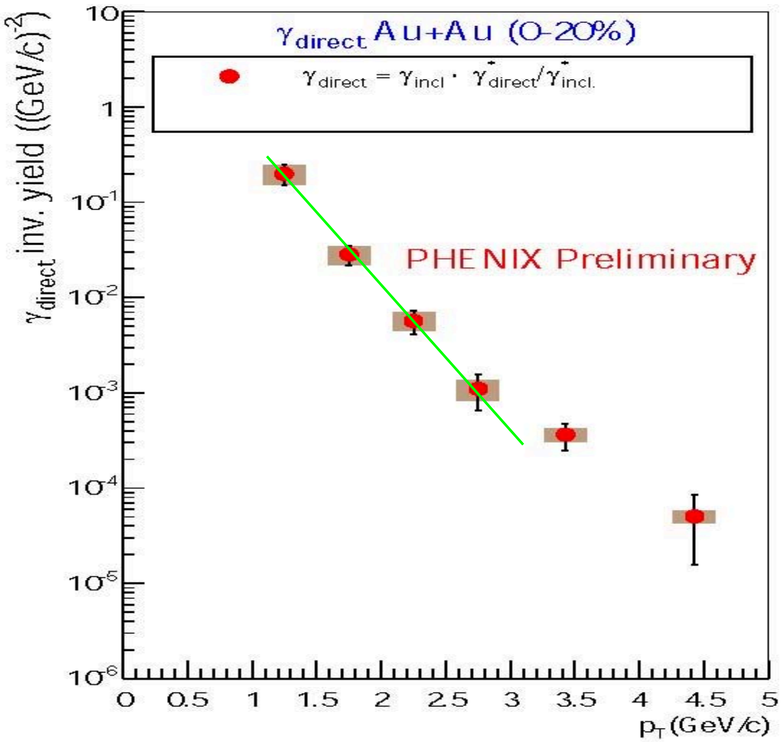
Kroll Wada PR**98**(1955) 1355

PHENIX NPA**774**(2006)403



$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\left(1-\frac{m_{ee}^2}{M^2}\right)^3 \mid F(m_{ee}^2)\mid^2 \sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)$$

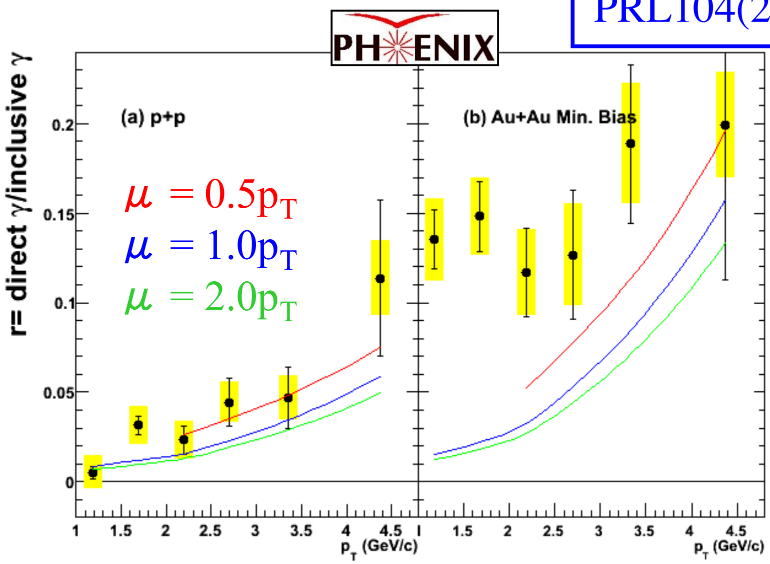




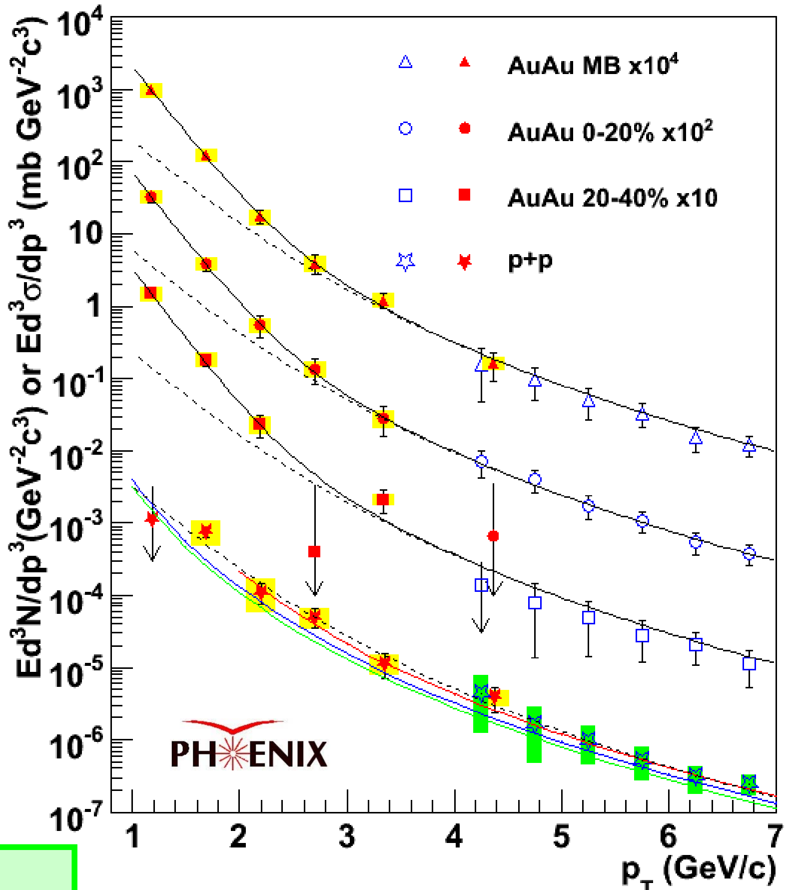
Eliminating the π^0 background by going to $0.2<m_{ee}<0.3$ GeV enables direct γ signal to be measured for $1<p_T<3$ GeV/c in Au+Au. It is exponential, does that mean it is thermal. We must see whether p-p direct γ turns over as $p_T \rightarrow 0$ as in Drell-Yan or exponential like for π^0

QM2008 direct γ in p-p via internal conversion

PRL104(2010)132301



Lowest p_T direct γ ever measured in p-p (and Au+Au). Curves are pQCD extrapolated (W.Vogelsang)

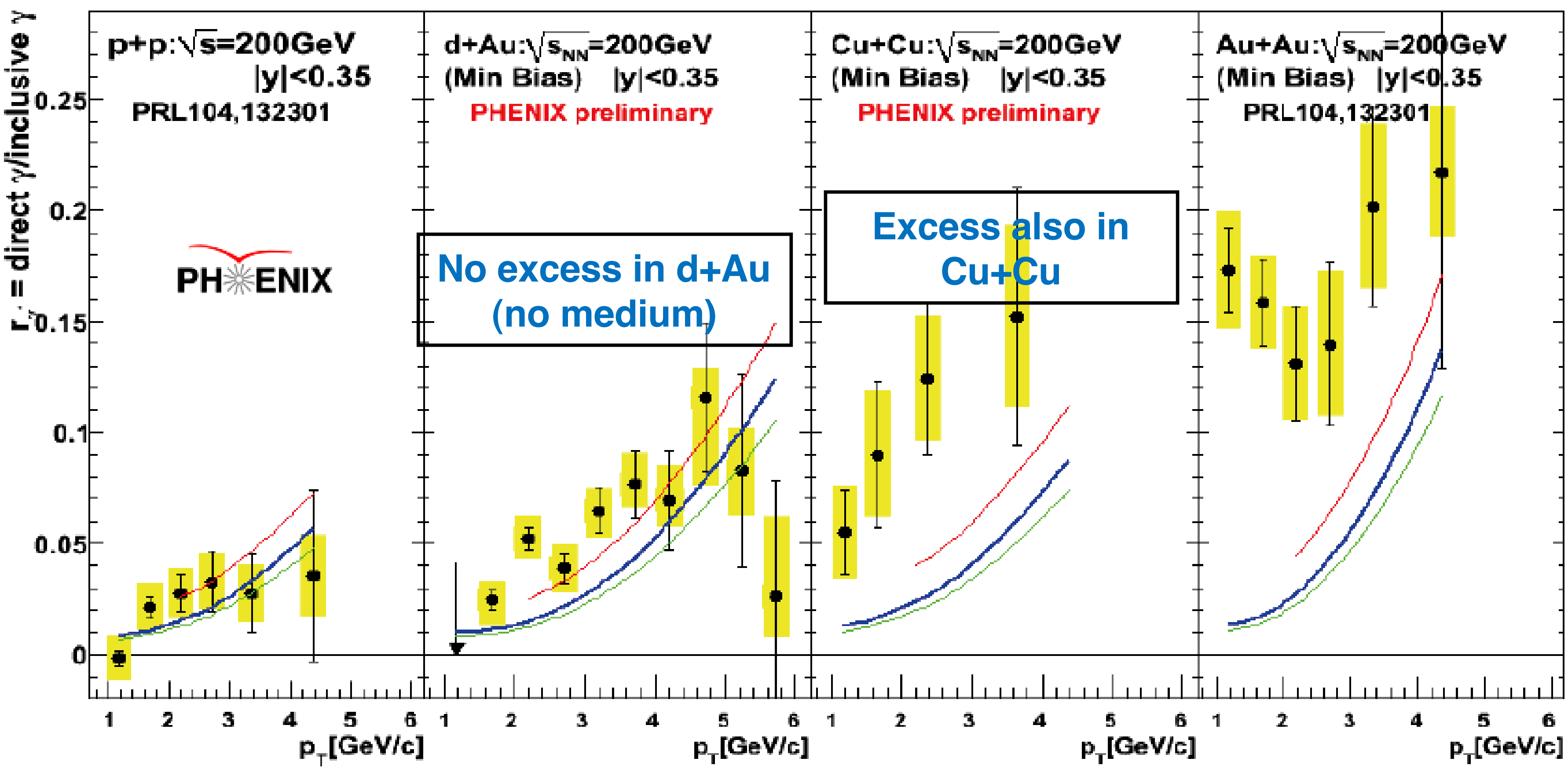


This is a major discovery, p-p result turns over as $p_T \rightarrow 0$, follows the same function $B(1+p_T^2/b)^{-n}$ used in Drell Yan [Ito, et al, PRD23, 604 (1981)] .
Fit to Au+Au is $[A\, e^{-p_T/T} + \langle T_{AA}\rangle\, B_{pp}(1+p_T^2/b_{pp})^{-n_{pp}}]$.
Significance of exponential (thermal?) is > 3 σ

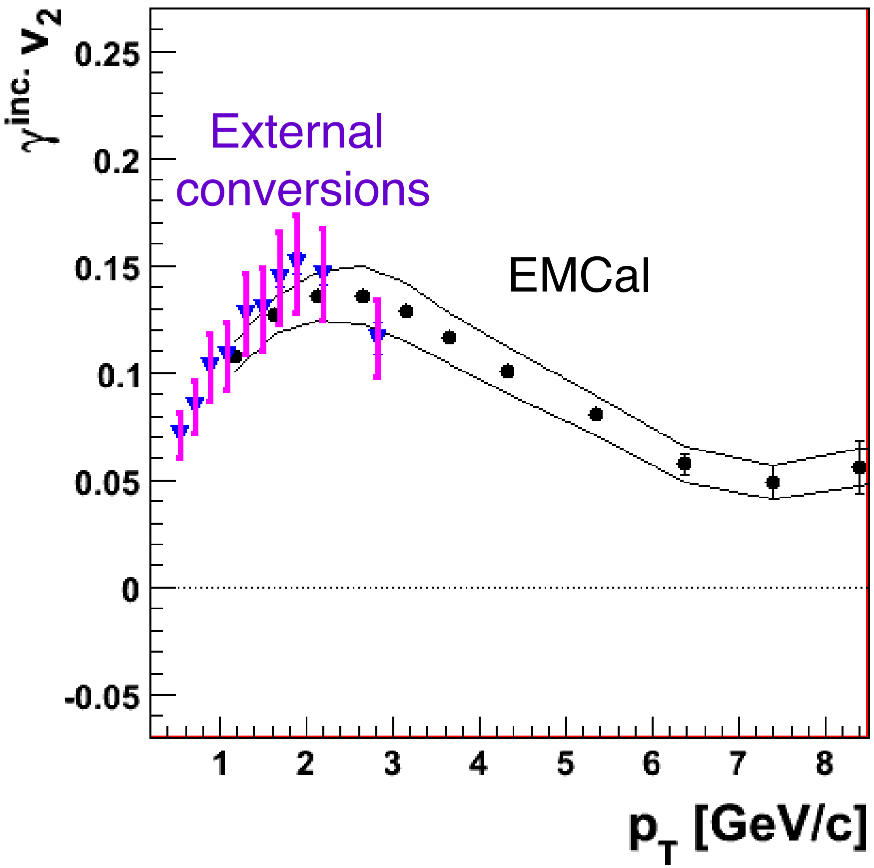
centrality	$dN/dy(p_T > 1\mathrm{GeV}/c)$	T(MeV)
0-20%	$1.10 \pm 0.20 \pm 0.30$	$221 \pm 23 \pm 18$
20-40%	$0.52 \pm 0.08 \pm 0.14$	$215 \pm 20 \pm 15$
MB	$0.33 \pm 0.04 \pm 0.09$	$224 \pm 16 \pm 19$

Confirmation from *d*+Au and Cu+Cu-QM2011

- Fraction of direct photons compared to pQCD

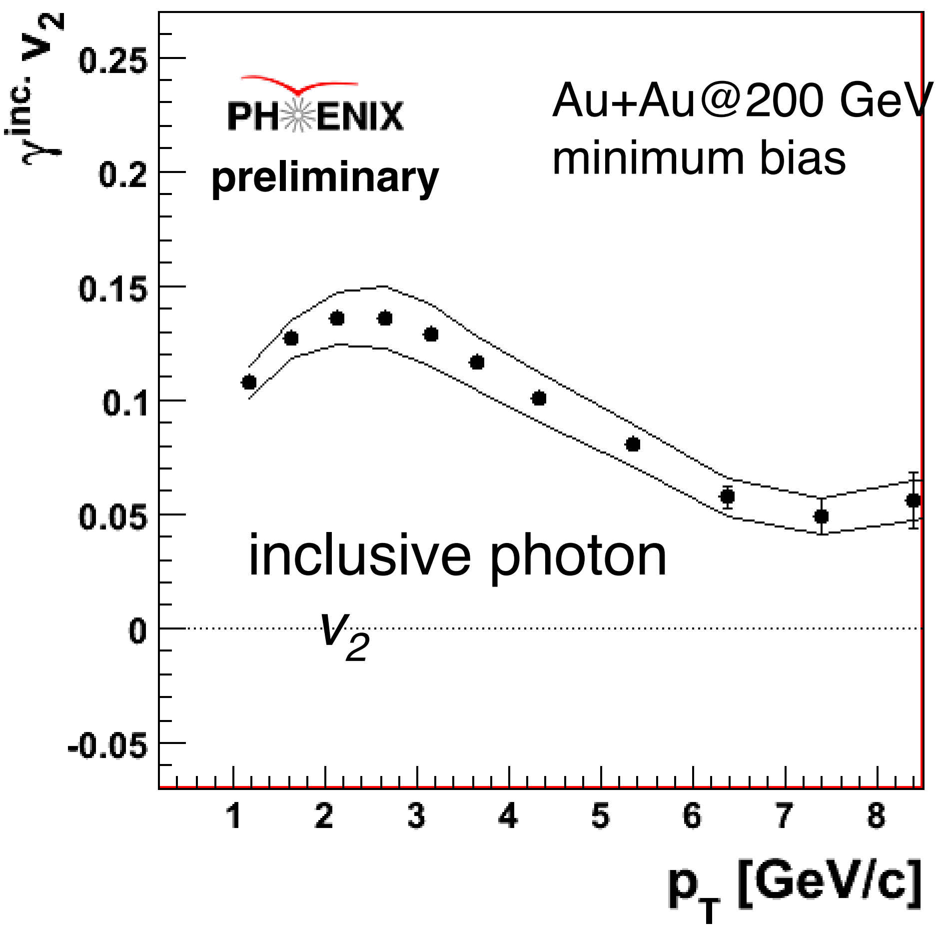


Direct single photon v_2
Start with Inclusive photon v_2



- Measured with EMCal
- Issue:
  - ✓ Hadronic contamination at low pT
    - Hadrons deposit only fraction of energy
    - depends on hadron species
    - Difficult to estimate
- Confirmed with external conversion
  - ✓ No hadronic contamination

Subtract decay photon v_2



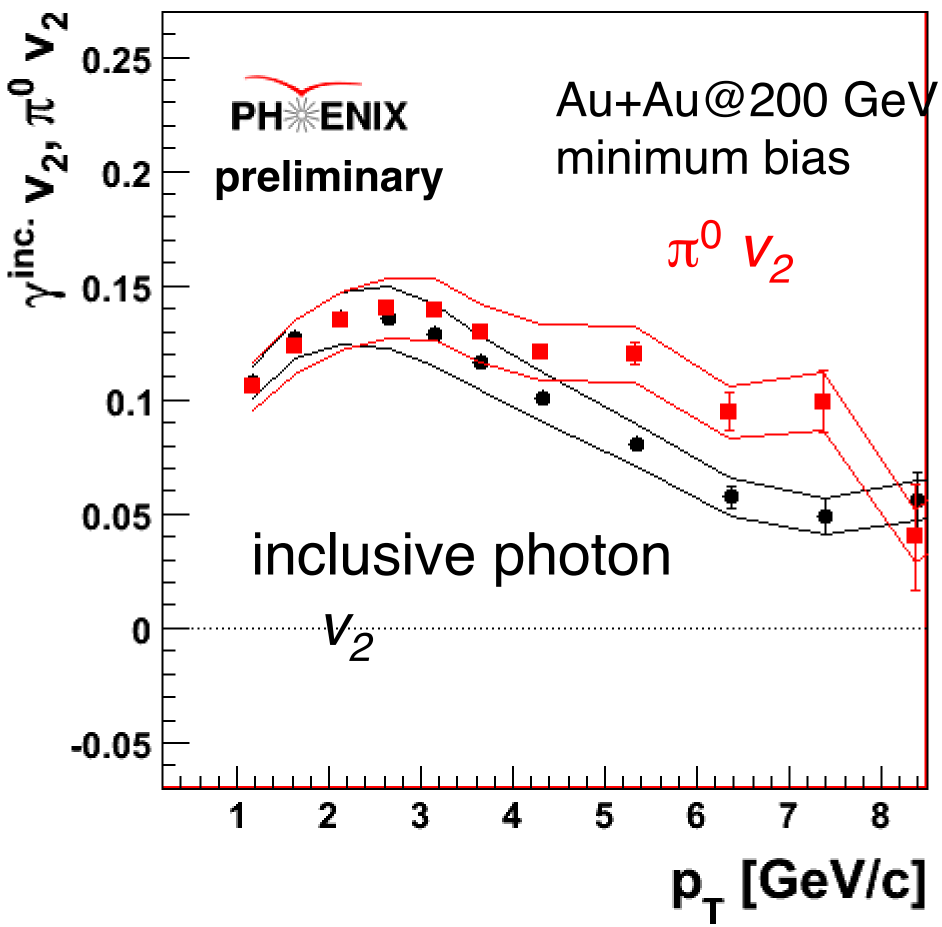
Statistical subtraction

inclusive photon v_2
- decay photon v_2

= direct photon v_2

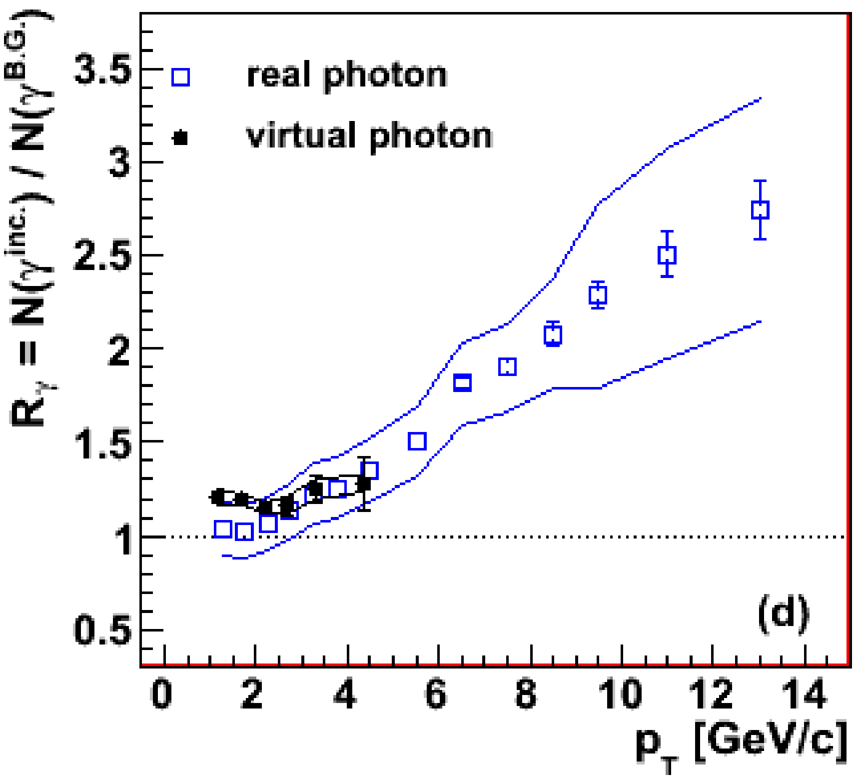
$$v_2^{dir.} = \frac{R_\gamma v_2^{inc} - v_2^{BG}}{R_\gamma - 1}$$

π^0 and inclusive photon v_2 very similar



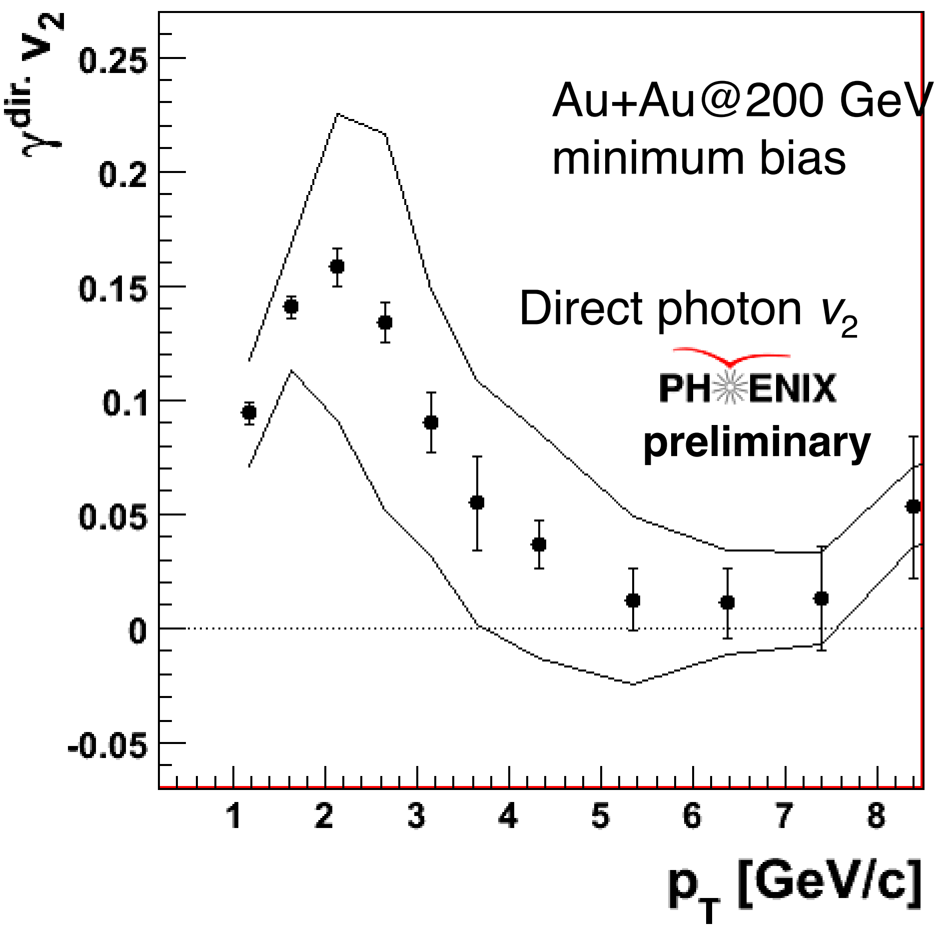
- π^0 v_2 similar to inclusive photon v_2
- Two possibilities
  - ✓ A: there are no direct photons
  - ✓ B: direct photon v_2 similar to inclusive photon v_2
- Key: precise measurement of direct photon excess

Direct photon excess R_γ



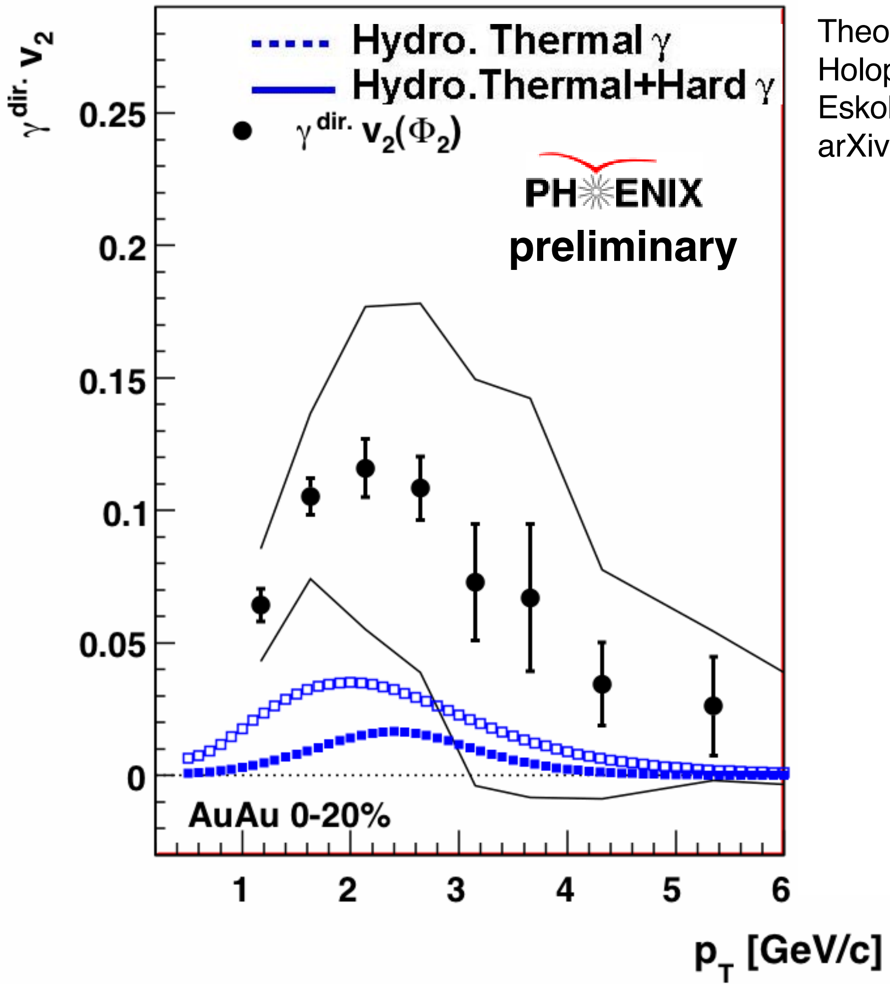
- Key to this analysis
  - ✓ Precise measurement of R_γ through internal conversion
- 20 % direct photon fraction
- => direct photon similar to inclusive photon v_2 (or π^0 v_2)

Direct Photon v_2



- direct photon v_2 large (~15 %) at p_T =2.5 GeV
- $v_2 \rightarrow 0$ where prompt photons dominate

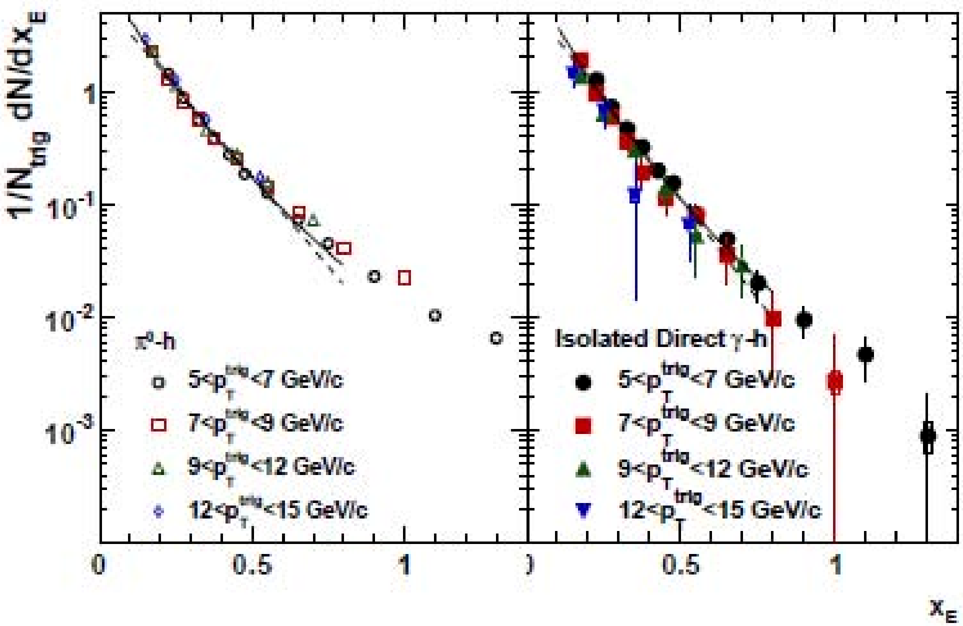
Theory Comparison: Direct Photon v_2

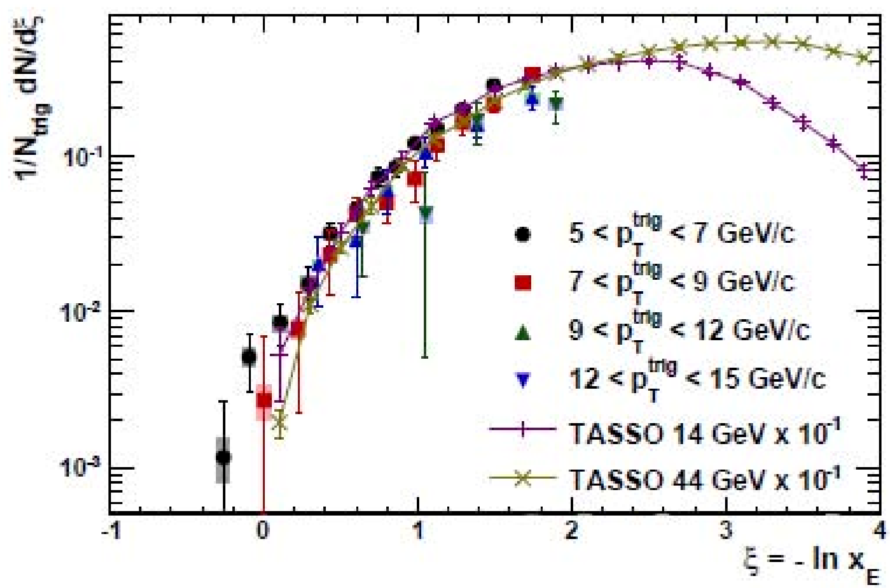


Theory calculation:
Holopainen, Räsänen, Eskola
arXiv:1104.5371v1

- Models under-predict direct photon v_2
- Measurement further constrains T_i and τ_i
- Challenge to theorists

Direct-γ-h correlation measures (~u quark) fragmentation function in p-p





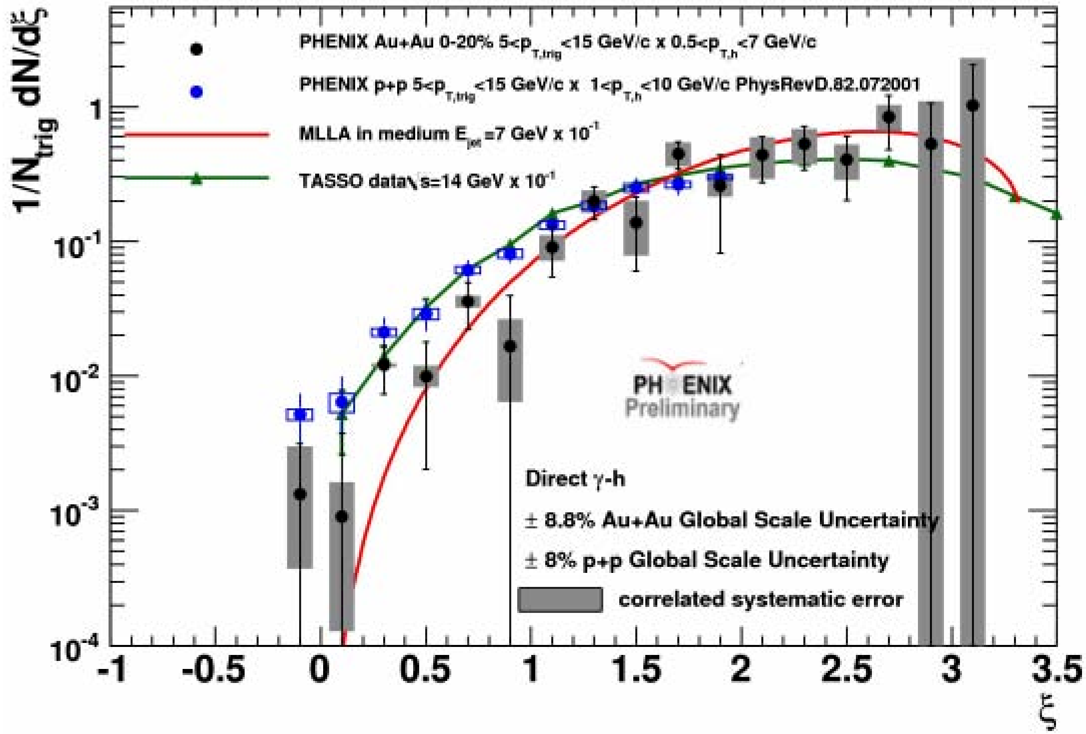
- $x_E = p_T{}^h/p_T{}^\gamma \cos(\Delta\phi) \sim z_T$
- γ-h is steeper than π^0-h!
- x_E universal scaling vs. p_{Tt} in γ-h
- b=8.2±0.3

$$\frac{dN}{dx_E} = Ne^{-bx_E}$$

- Plot with MLLA variable $\xi = -\ln x_E$
- Good agreement with TASSO measurement (e^+e^-)
- Baseline for E-loss in Au+Au

Matt Nguyen's PhD thesis, PRD 82 (2010) 072001

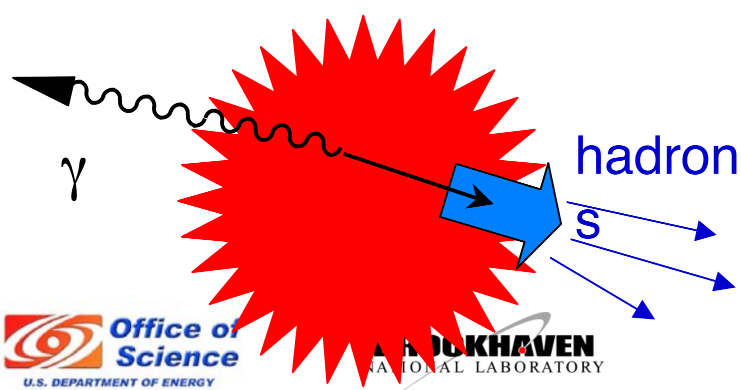
Direct-γ-h correlation measures (~u quark) fragmentation function in Au+Au



Tasso:
Braunschweig et al. , Z. Phys. 320 C47, 187
MLLA:
Borghini, Wiedemann, hep-ph/0506218

$$\xi=\ln(1/z)=-\ln\,(p_{Th}/p_{T\gamma})$$

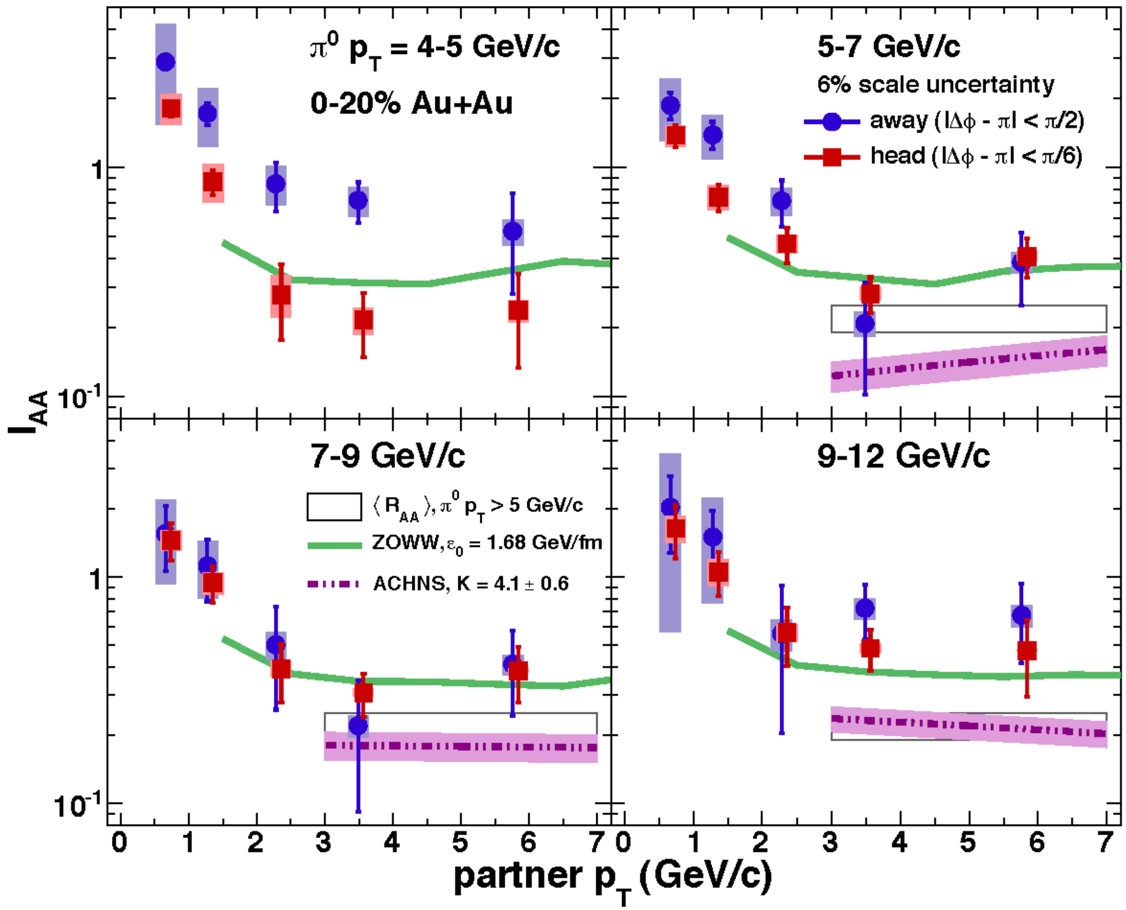
- $p+p$ consistent with e^+e^-
- Au+Au consistent with E loss model; but need more statistics to be definitive



N.B. h-h correlations where both h are jet fragments does NOT measure the fragmentation function

PHENIX π^0-h-I_{AA} PRL**104**,252301(2010)

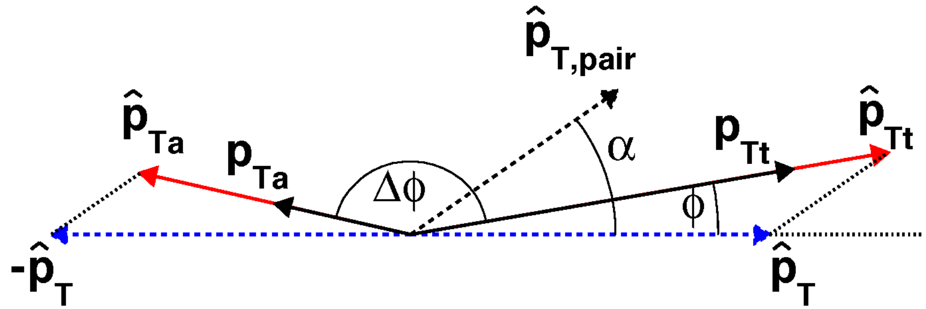
Typically experiments just show I_{AA}, the ratio of AA and pp $x_E \approx z_T = p_{Ta}/p_{Tt}$ distributions



$I_{AA}=[dN^{AA}/dx_E]/\ [dN^{pp}/dx_E] \approx [dN^{AA}/dz_T]/\ [dN^{pp}/dz_T]$

A very interesting new formula for the x_E distribution was derived by PHENIX in PRD74

$$\boxed{\left.\frac{dP_\pi}{dx_E}\right|_{p_{T_t}} \approx \langle m\rangle (n-1)\frac{1}{\hat{x}_h}\frac{1}{(1+\frac{x_E}{\hat{x}_h})^n}}$$



Relates ratio of particle p_T

$$x_E = \frac{-p_{T_a}\cos\Delta\phi}{p_{T_t}} \simeq \frac{p_{T_a}}{p_{T_t}}$$

measured

aka Z_T

Ratio of jet transverse momenta

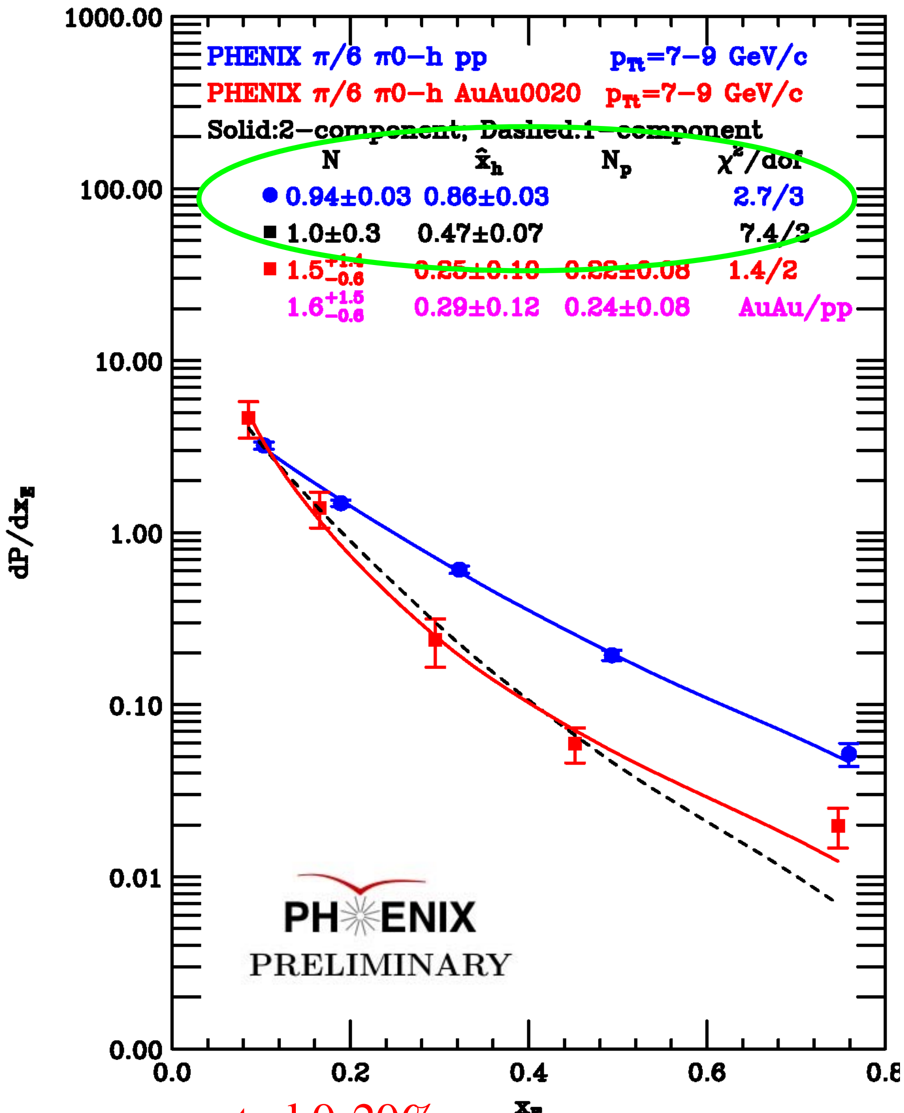
$$\hat{x}_h = \frac{\hat{p}_{T_a}}{\hat{p}_{T_t}}$$

Can be determined

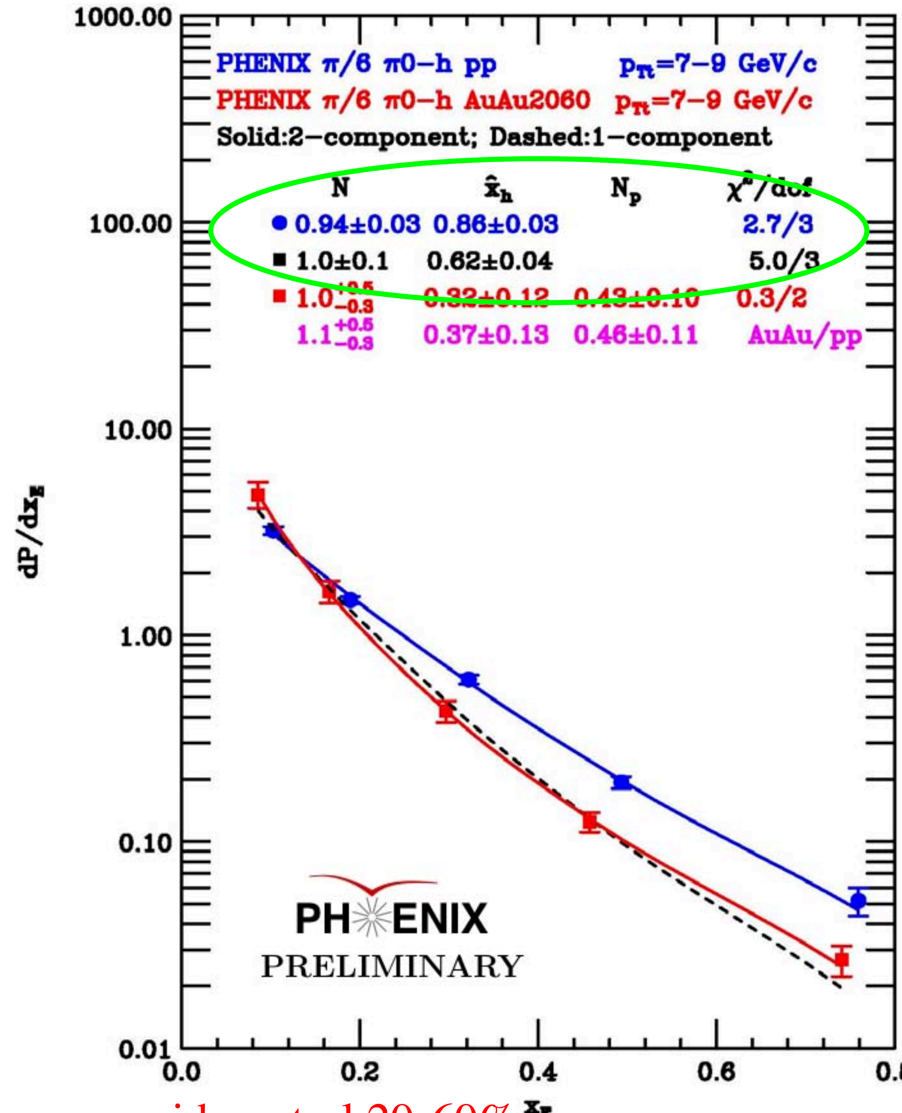
If formula works, we can also use it in Au+Au to determine the relative energy loss of the away jet to the trigger jet (surface biased by large *n*)

Separately fit pp and AuAu $x_E(z_T)$ distributions

First, use 1 component fit



central 0-20%

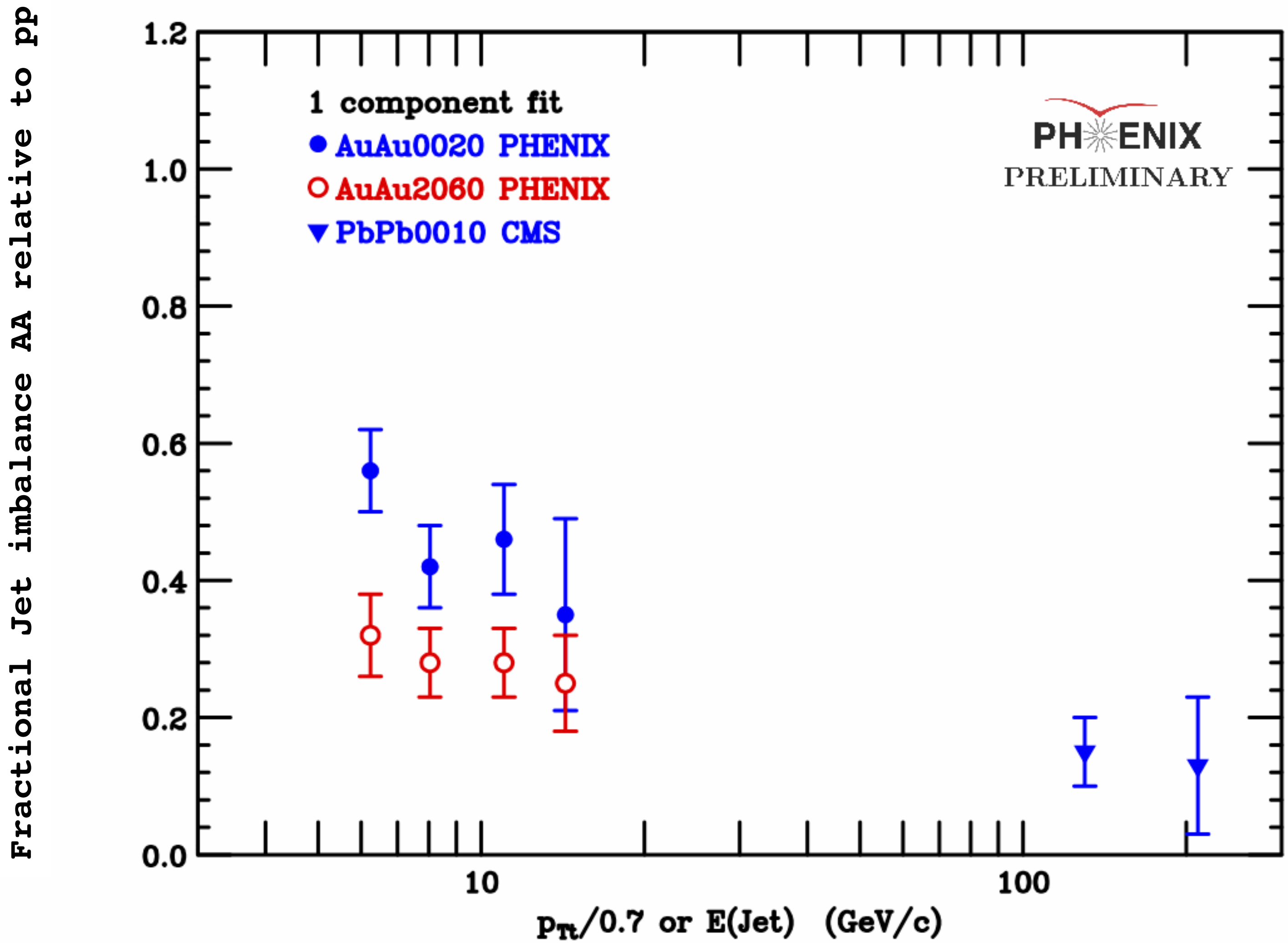


mid-central 20-60%

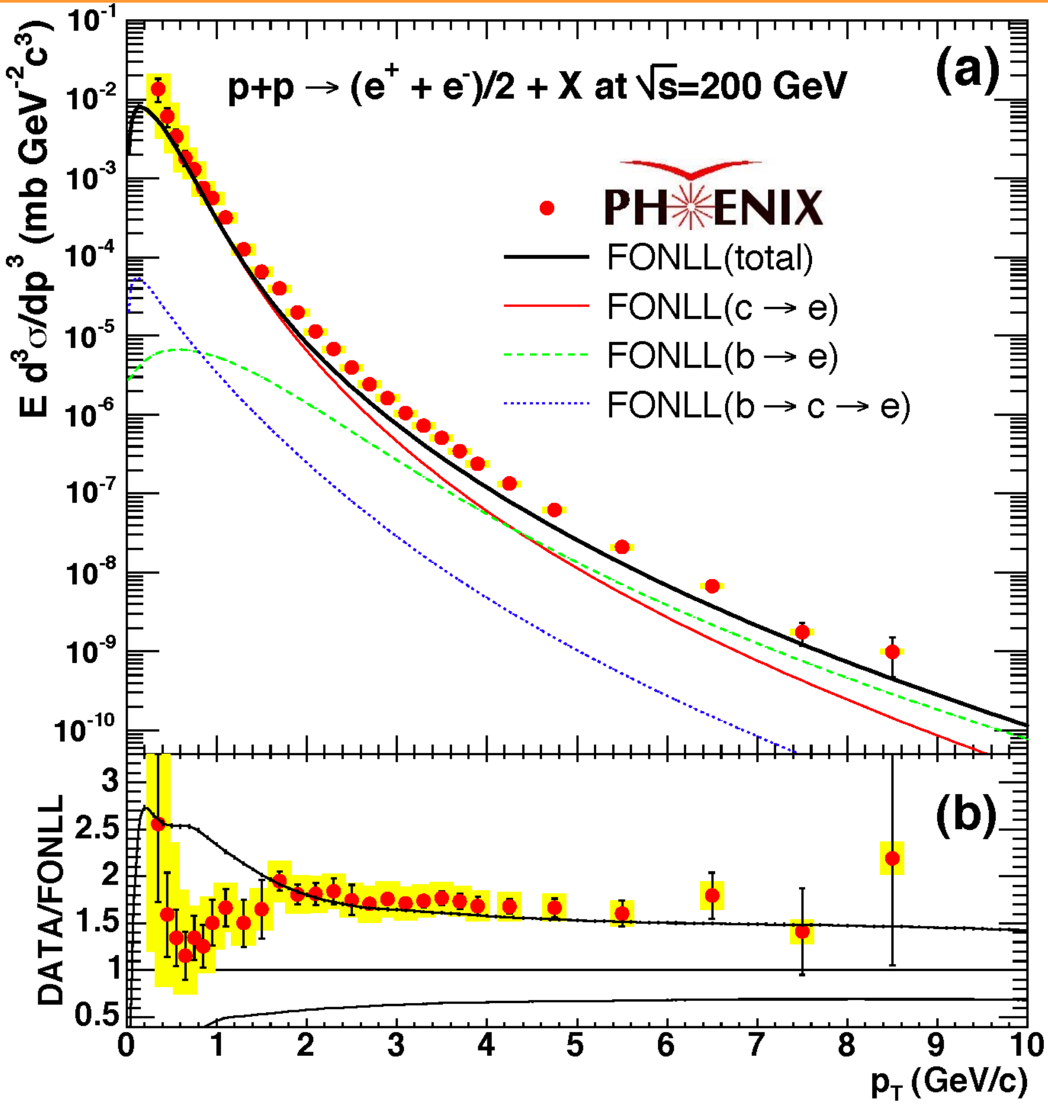
$$\left.\frac{dP_\pi}{dz_T}\right|_{p_{T_t}} = N_{pp}\,(n-1)\,\frac{1}{\hat{x}_h^{pp}}\,\frac{1}{(1+\frac{z_T}{\hat{x}_h^{pp}})^n}$$

$$\left.\frac{dP_\pi}{dz_T}\right|_{p_{T_t}} = N_{1AA}\,(n-1)\,\frac{1}{\hat{x}_h^{AA}}\,\frac{1}{(1+\frac{z_T}{\hat{x}_h^{AA}})^n}$$

See my QM2011 Poster



Charm via direct single e in p-p collisions

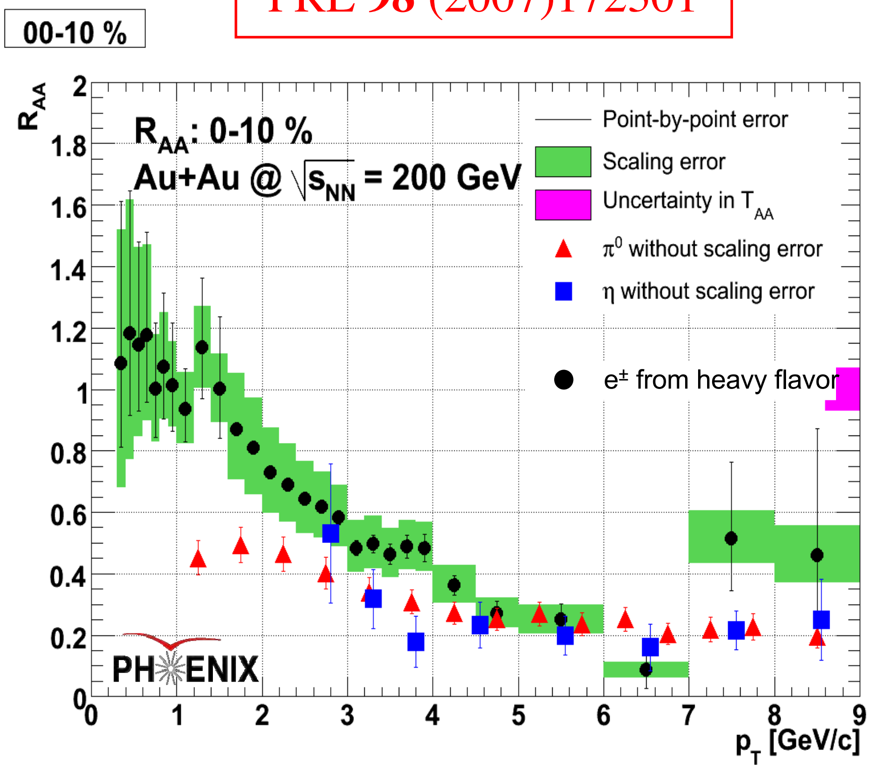


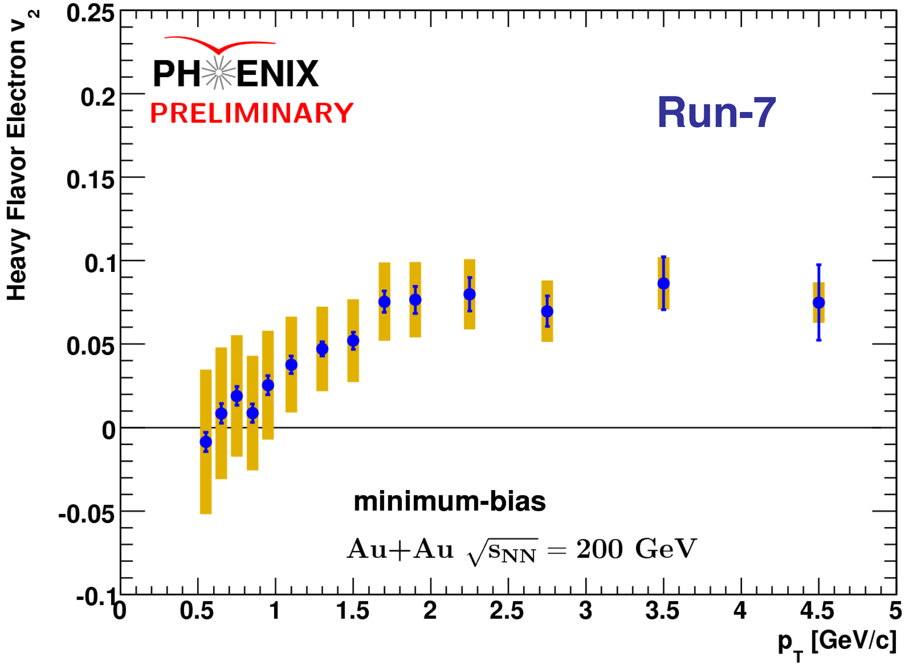
PHENIX PRL**97**(2006)252002

Beautiful agreement of e± with *c b* production in p-p

Direct e± in Au+Au indicate a theoretical crisis

Au+Au PHENIX
PRL **98** (2007)172301





- heavy quarks suppressed the same as light quarks, and they flow, but less.
- This disfavors the hypothesis of energy loss by gluon bremsstrahlung in medium
- but brings string theorists into the game, see references in PRL 98 (2007) 172301.

From CERN Courier, September 2007

- I read an article “Yukawa's gold mine” by Nino Zichichi taken from his talk at INPC 2007 in Tokyo, Japan, in which he proposed: “We know that confinement produces masses of the order of a GeV. Therefore, according to our present understanding, the QCD ‘colourless’ condition could not explain the heavy quark mass. However, since the origin of the quark masses is still not known, it cannot be excluded that in a QCD coloured world (i.e. QGP), the six quarks are all nearly massless and that the colourless condition is ‘flavour’ dependent.”

  - Higgs doesn’t give quarks mass
  - QCD isn’t flavor-blind

  !!!

- MJT: “Wow! Massless *b* and *c* quarks in a color-charged medium would be the simplest way to explain the apparent equality of gluon, light and heavy quark suppression indicated by the equality of R_{AA} for π^0 and direct-single $e^{\pm}$ in regions where both *c* and *b* quarks dominate.” Test by measuring b-dijet imbalance.

In my opinion Zichichi's idea is much more reasonable than AdS/CFT! How to prove it?

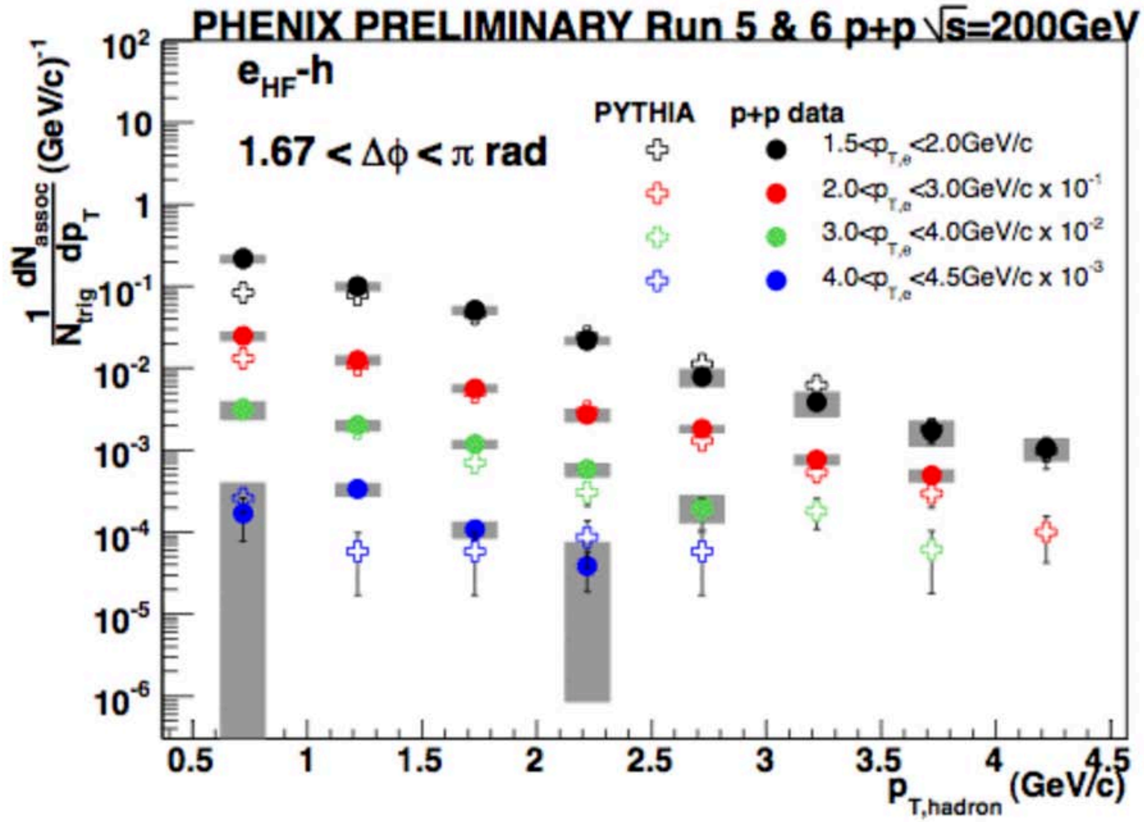
First, comments from some distinguished physicists:

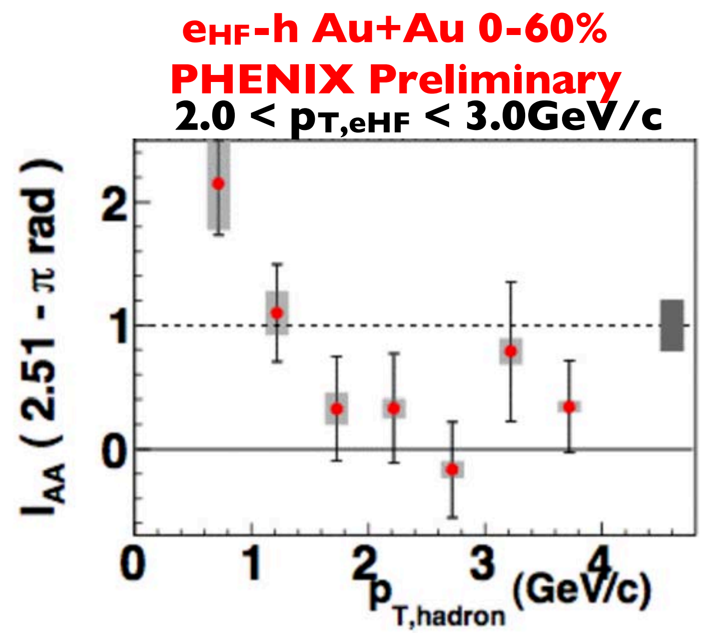
- Stan Brodsky:"Oh, you mean the Higgs Field can't penetrate the QGP."
- Rob Pisarski: "You mean that the propagation of heavy and light quarks through the medium is the same"
- Chris Quigg (Moriond 08): "The Higgs coupling to vector bosons γ, W, Z is specified in the standard model and is a fundamental issue. One big question to be answered by the LHC is whether the Higgs gives mass to fermions or only to gauge bosons? The 'Yukawa' couplings to fermions are put in by hand and are not required." "What sets fermion masses, mixings?"

Opinions of distinguished physicists, cont'd

- I asked Steve Weinberg (4/15/10) whether the standard model would still work in the vector boson sector if the Higgs didn't couple to Fermions, or the Higgs Yukawa coupling was much smaller than now considered standard; and could this possibly explain the absence of the Higgs detected in the $b-\bar{b}$ and $\tau^+ \tau^-$ decay modes.
- He didn't say yes, He didn't say no.
- But he did say that he and Lenny Suskind had a model, Technicolor, that worked well in the vector boson sector but didn't give mass to the Fermions.
- Hmm.

First e±-h heavy flavor correlation-no VTX





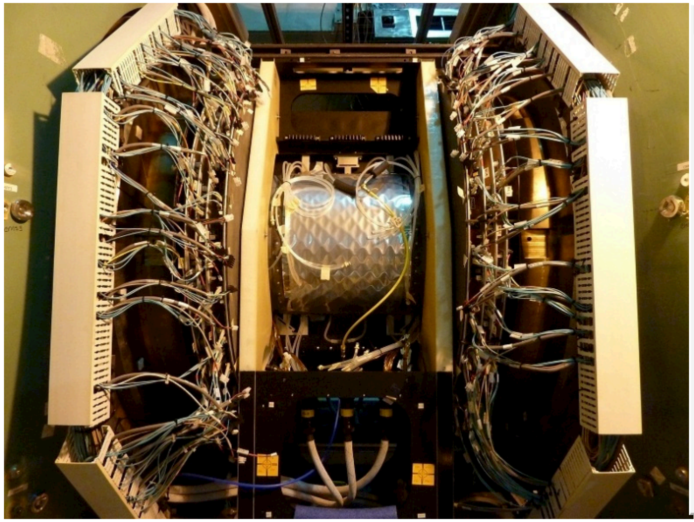
- heavy flavor tagged correlations: NLO important--e_{HF} not necessarily balanced by back-to-back heavy quark

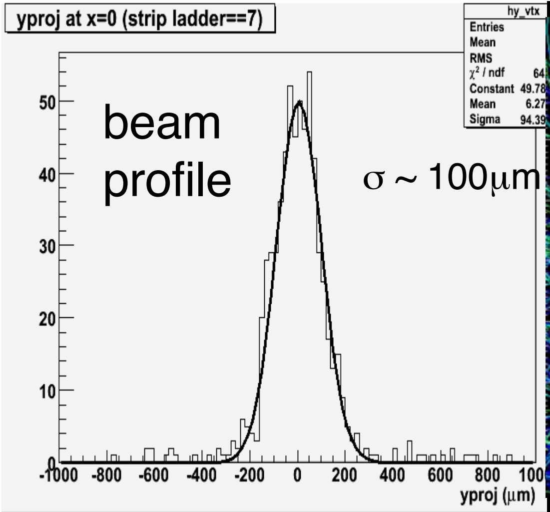
New for 2011: Silicon Vertex Detector

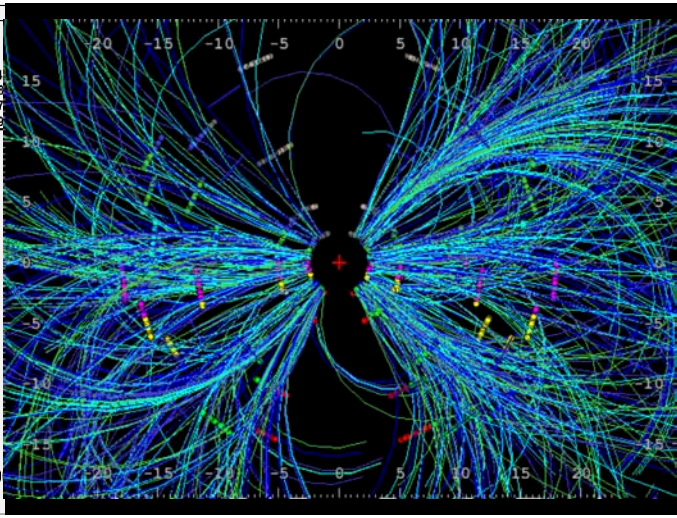
Status

- VTX successfully commissioned in 2011 *p+p* run
- VTX taking data in Au+Au now!

Data: Au+Au@200 GeV, 20







Physics

- R_{AA} of *c*, *b* separately
- v_2 of *c*, *b* separately
- Jet tomography (di-hadron, γ-*h*, *c*-*h*, *c*-*c*, *b*-*b*, for energy loss)

Why would I be so quick to believe Zichichi?

Proc. 12th ICHEP, Dubna 1964

MUON-PROTON ELASTIC SCATTERING AT HIGH MOMENTUM TRANSFERS *

R. Cool, A. Maschke
Brookhaven National Laboratory, USA
L. Lederman, M. Tannenbaum
Columbia University, USA
R. Ellsworth, A. Melissinos, J. Tinlot, T. Yamanouchi
University of Rochester, USA
(Presented by J. TINLOT)

We have studied the elastic scattering of negative muons from liquid hydrogen at momentum transfers of 550 MeV/c to 1050 MeV/c ($q^2 = 7$ to 26 fermi^{-2}), using a detecting array of spark chambers and scintillation counters. The experiment was performed at the AGS accelerator of the Brookhaven National Laboratory, and the runs were divided into three stages, of the proton in an aluminum plate spark chamber. One also measures the directions of the recoil proton and the recoil muon. This is equivalent to measuring three independent angles, from which one can infer for each event the value of k, and still overdetermine the scattering event by two degrees of freedom. This redundancy is used to select true scattering

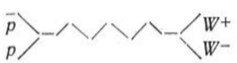
ДИСКУССИЯ — DISCUSSION

A. Zichichi

In connection with the problem of observing the production of intermediate bosons, I would like to mention that we have been studying at CERN two schemes:

1) $\bar{p}+p \to W^+ + W^-$, with $W \to e^- + \nu_e$ and $W \to \mu^+ + \nu_\mu$, $\to \mu^\pm, e^\mp$.

This process is described by the following Feynman diagram



Notice that this process is proportional to α^2 where α is the electromagnetic coupling constant.

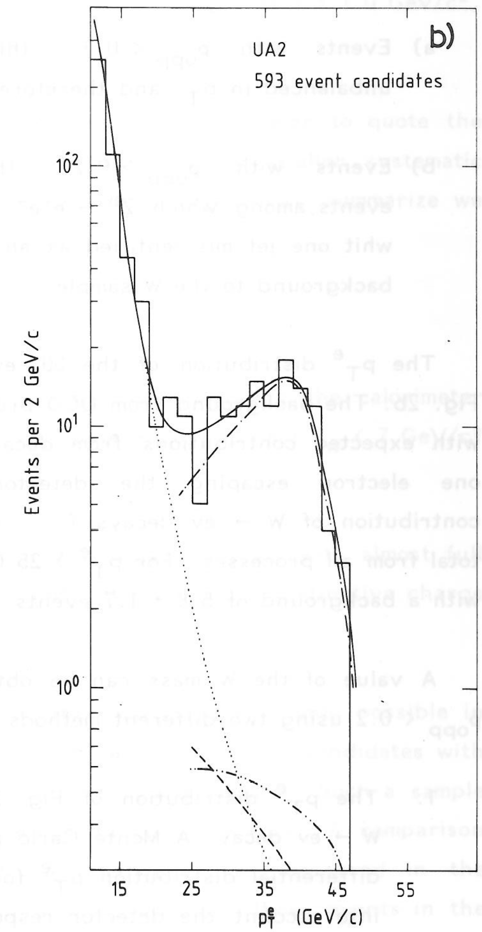
2) The second proposal studied would use the internal target of the proton synchrotron with 10^{12} protons per pulse incident onto the target. The process would be $p + \left(\frac{p}{n}\right) \to W^\pm +$ anything. We would observe the μ's from W-decays. By measuring the angular and momentum distribution at large angles of K and π's, we can predict the corresponding μ-spectrum. We then see if the μ's found at large angles agree with or exceed the expected number. A supplementary check can be made by measuring the polarization of these μ's. The polarization indicates the origin of these μ's. Notice that the cross section for this process goes with $\sqrt{g}$, where g is the β-decay coupling constant.

B. Pontecorvo

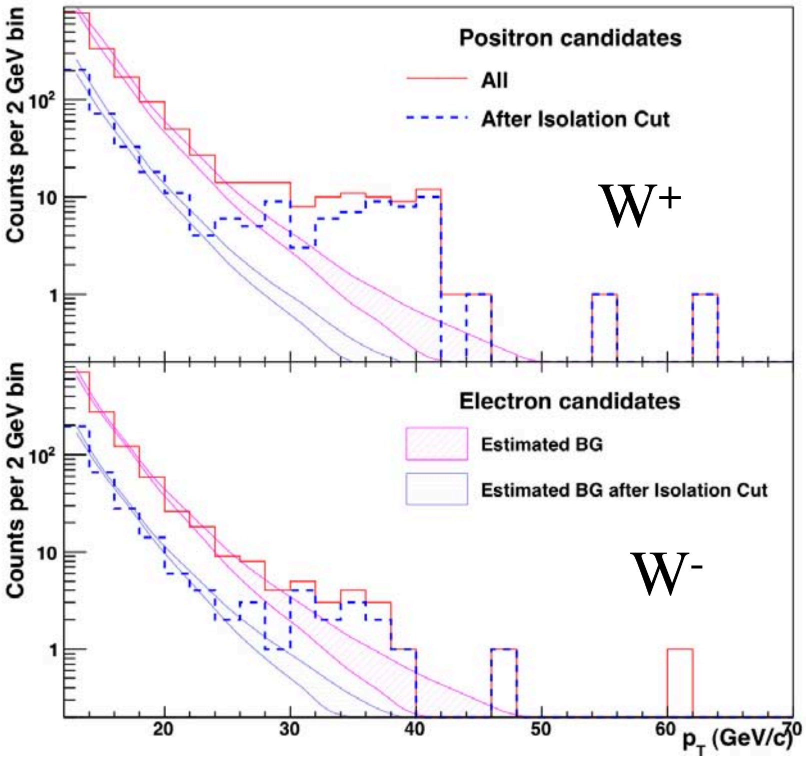
I would like to use the fact that you are all tired in order to make a remark of linguistic rather than scientific character. All the speakers used as notations for neutral leptons the letters ν_e and ν_μ. This seems to be a very convenient notation. On the other hand, the terms which are usually used for neutral leptons-electron and muon neutrinos (and even «electron and muon type of neutrino!»), are too cumbersome. True, sometimes for ν_e the word «neutrino» is used and for ν_μ, the word «neutretto». The last term, however, is not very satisfactory since the last thirty years lost of particle including strong interacting particles had been called that way. In addition, it seems to me that both types of leptons should conserve in their «name» the root «neutrino», which is widely associated with the unique

3* 35

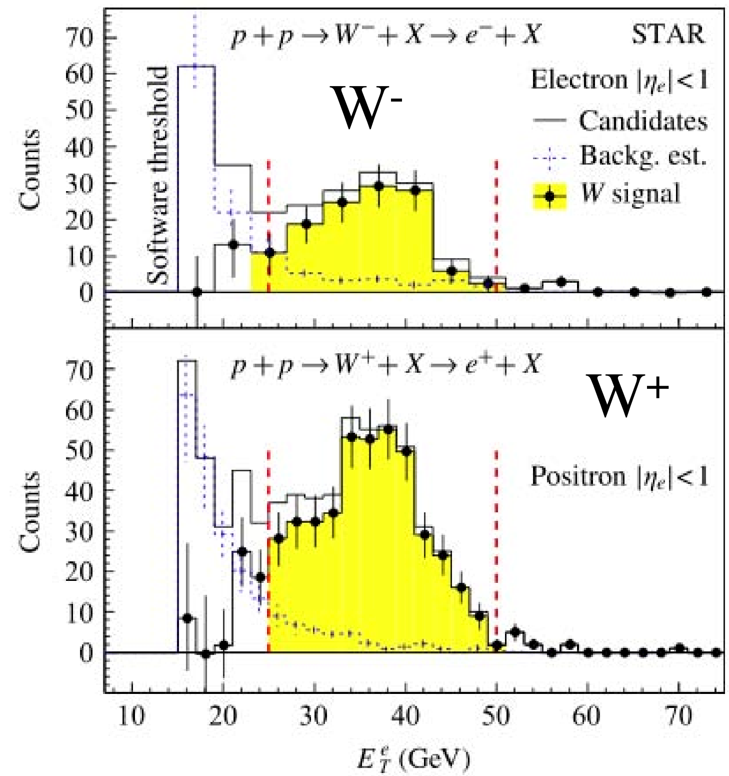
UA1,UA2, CERN 1983
W boson discovery



First measurement of W's at RHIC in polarized p-p collisions √s=500 GeV

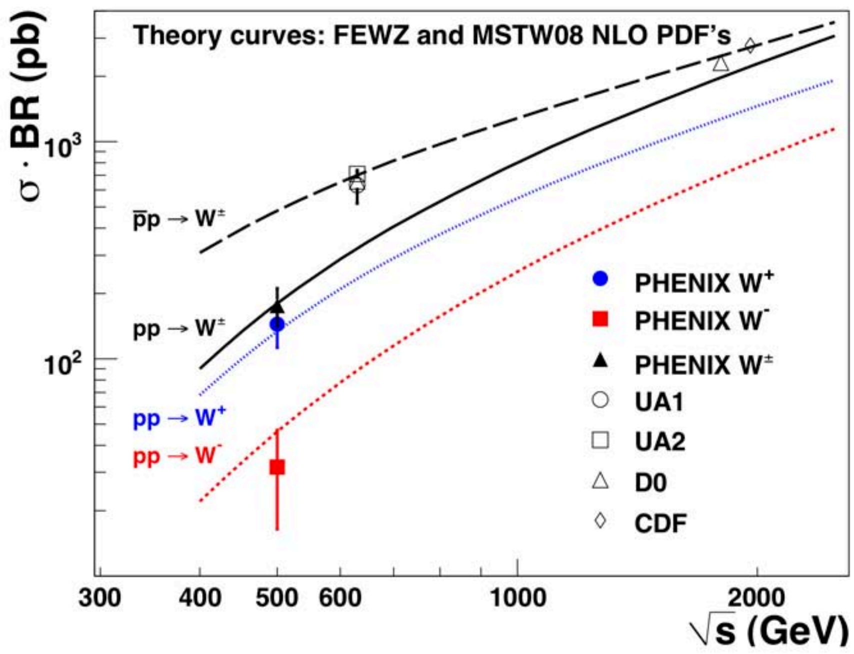


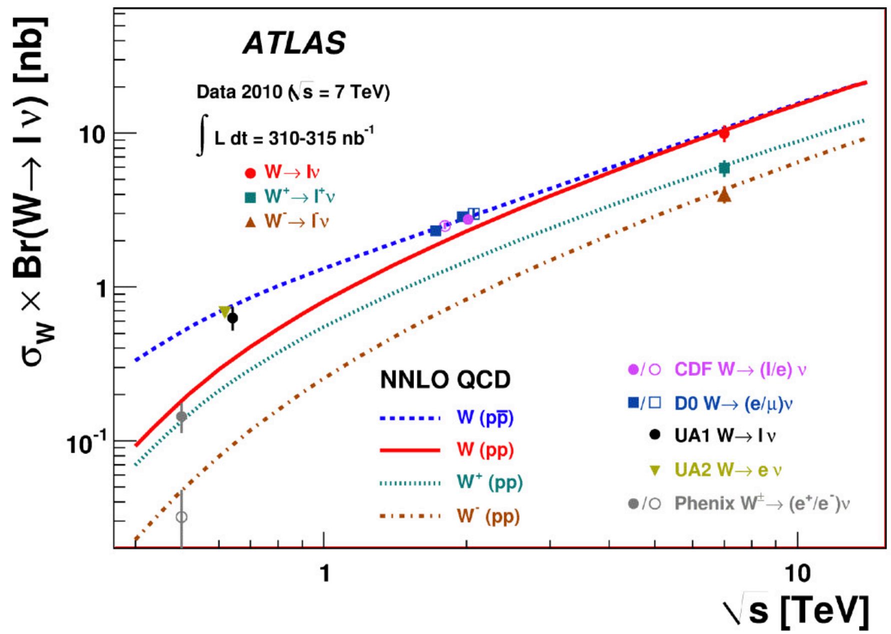
PHENIX PRL106(2011)062001



STAR PRL 106 (2011) 62002

RHIC-First measurement of W cross sect in pp





ATLAS, JHEP 1012:060,2010 (arXiv/1010.2130v1)

PHENIX PRL106(2011)062001

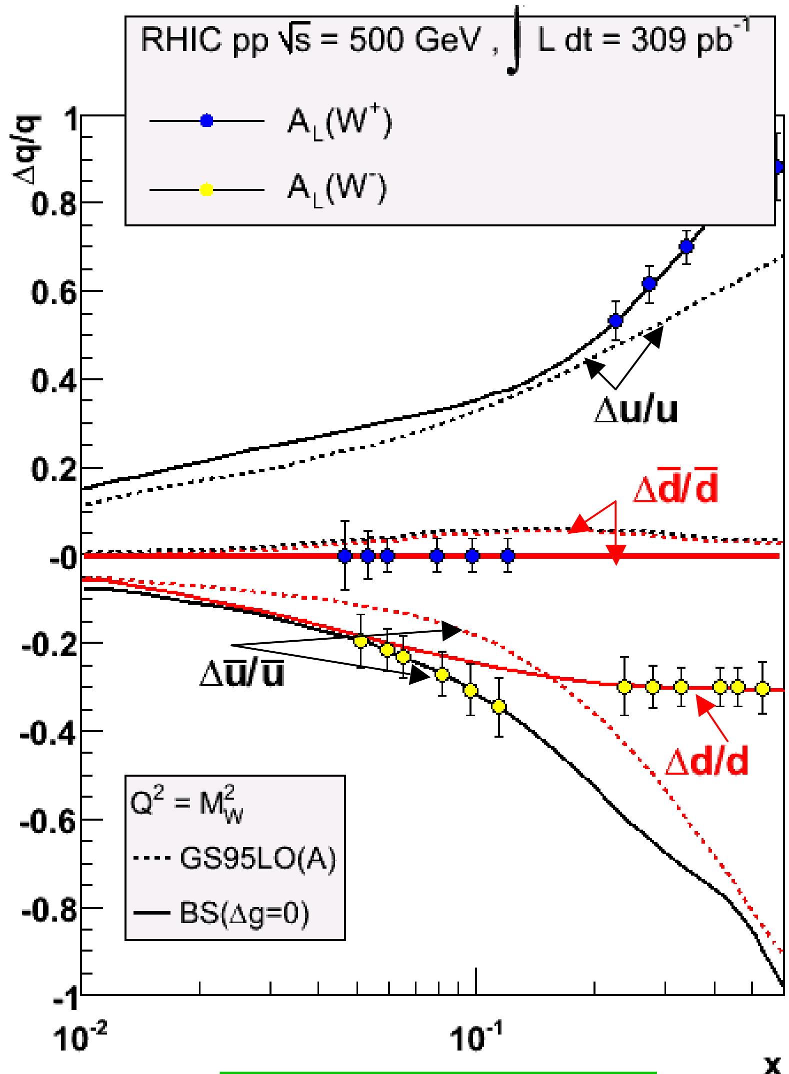
W in polarized pp – quark flavor

- A_L (parity violating)
- u + $\bar{d}$ →W⁺ leads to $\bar{d}$, u polarized pdf's

$$A_L^{W^+} = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

$$A_L^{W^-} = \frac{\Delta d(x_a)\bar{u}(x_b) - \Delta\bar{u}(x_a)d(x_b)}{d(x_a)\bar{u}(x_b) + \bar{u}(x_a)d(x_b)}$$

- Measure via decay to muons y>1.5 for x from single μ → trigger upgrade in operation

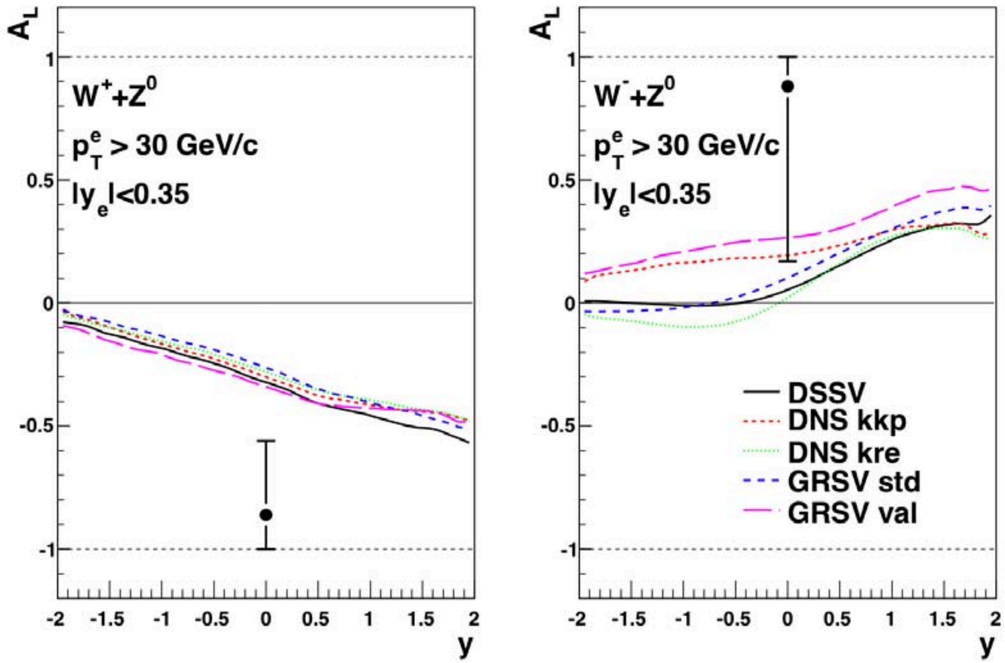


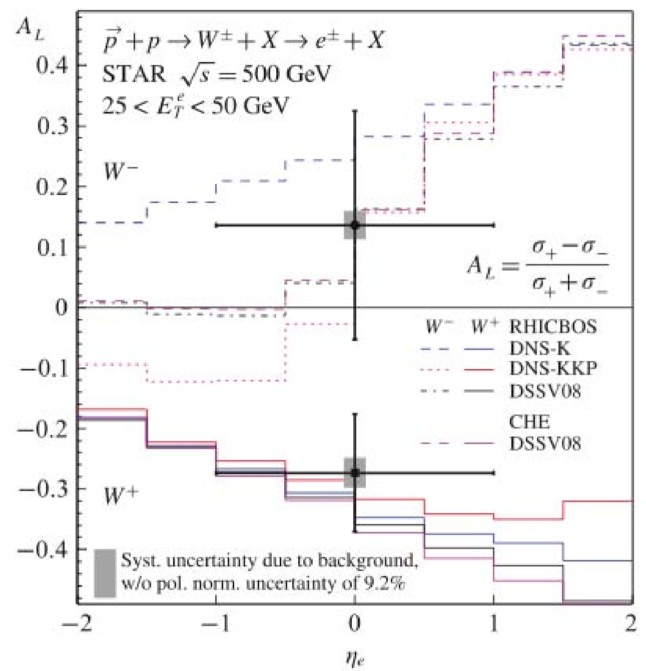
N. Saito 1995

First parity violation of on-shell W's

PHENIX PRL106(2011)062001

STAR PRL 106 (2011) 62002



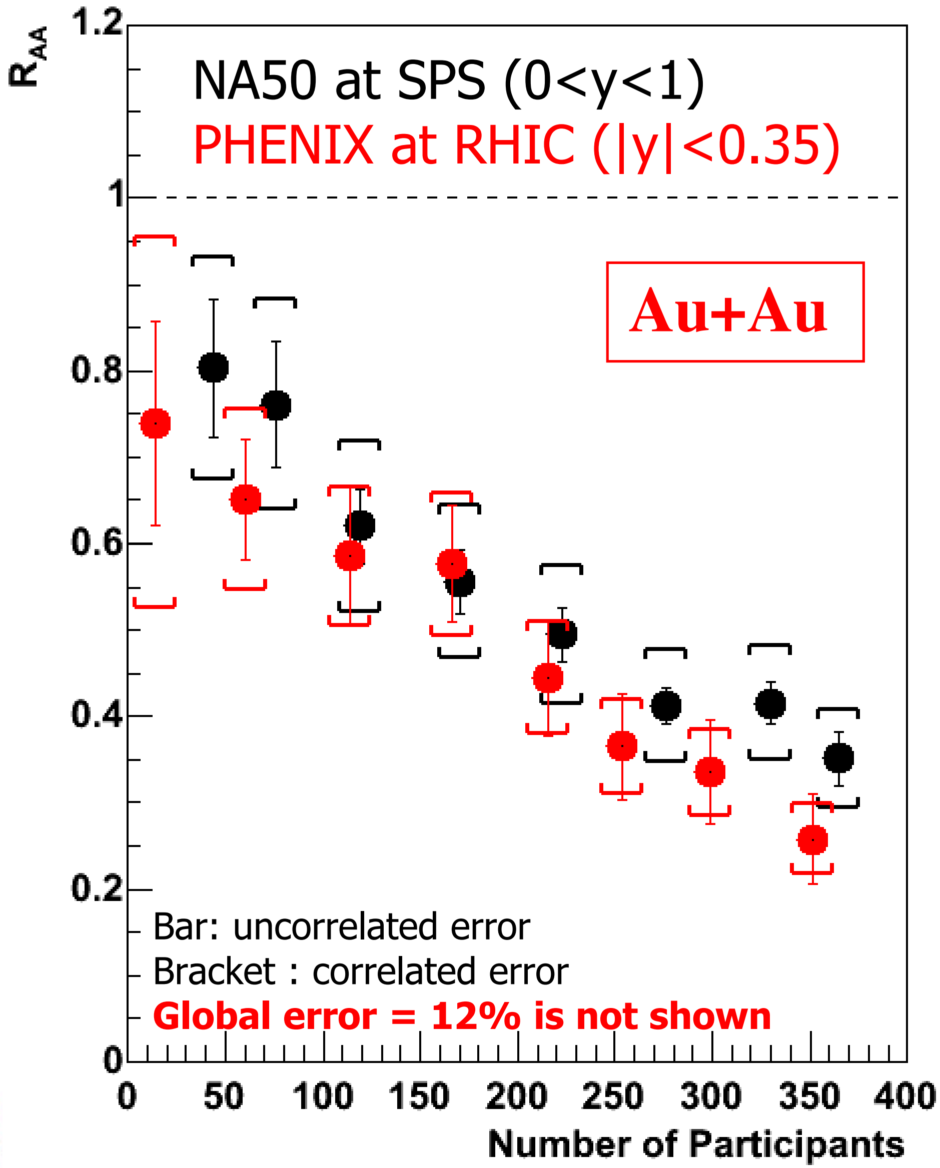


A_L=parity violating spin asymmetry.
Parity Violation is ~ 4σ from 0, with
- sign in W^+: + sign in W^- as expected

Good Betting Opportunity at LHC

Will Peter Higgs or Helmut Satz have to wait longer to find whether they are right?

J/ψ Suppression (R_{AA}) is the **same** at mid-rapidity (PHENIX e^+e^-) as at lower $\sqrt{s_{NN}}$!!!

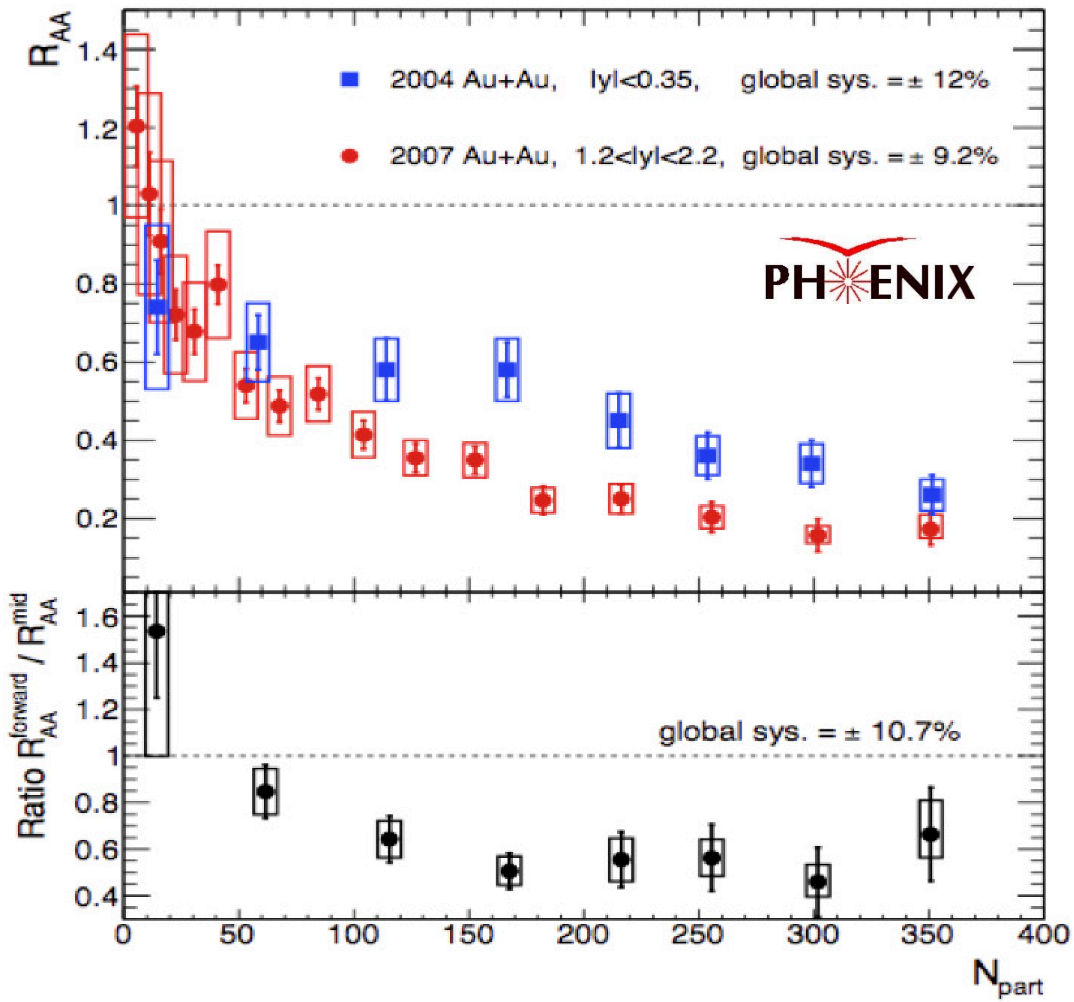


- R_{AA} vs. N_{part} integrated over p_T
  - ✓ NA50 at SPS
    - 0<y<1
  - ✓ PHENIX at RHIC
    - |y|<0.35

PHENIX PRL **98**, 232301 (2007)

This was CERN-Heavy Ion's main claim to fame in the infamous press conference of 2000 claiming observations ``consistent with the predicted signatures of a QGP.'' Will have to wait for LHC to find out whether J/ψ merely act like ordinary hadrons low p_T or whether they are actually probes of deconfinement as predicted by Matsui and Satz PLB**178**(1986)416. Also see discussion by MJT in Rep.Prog.Phys. **69** (2006)2005

But J/ψ Suppresson larger at forward rapidity

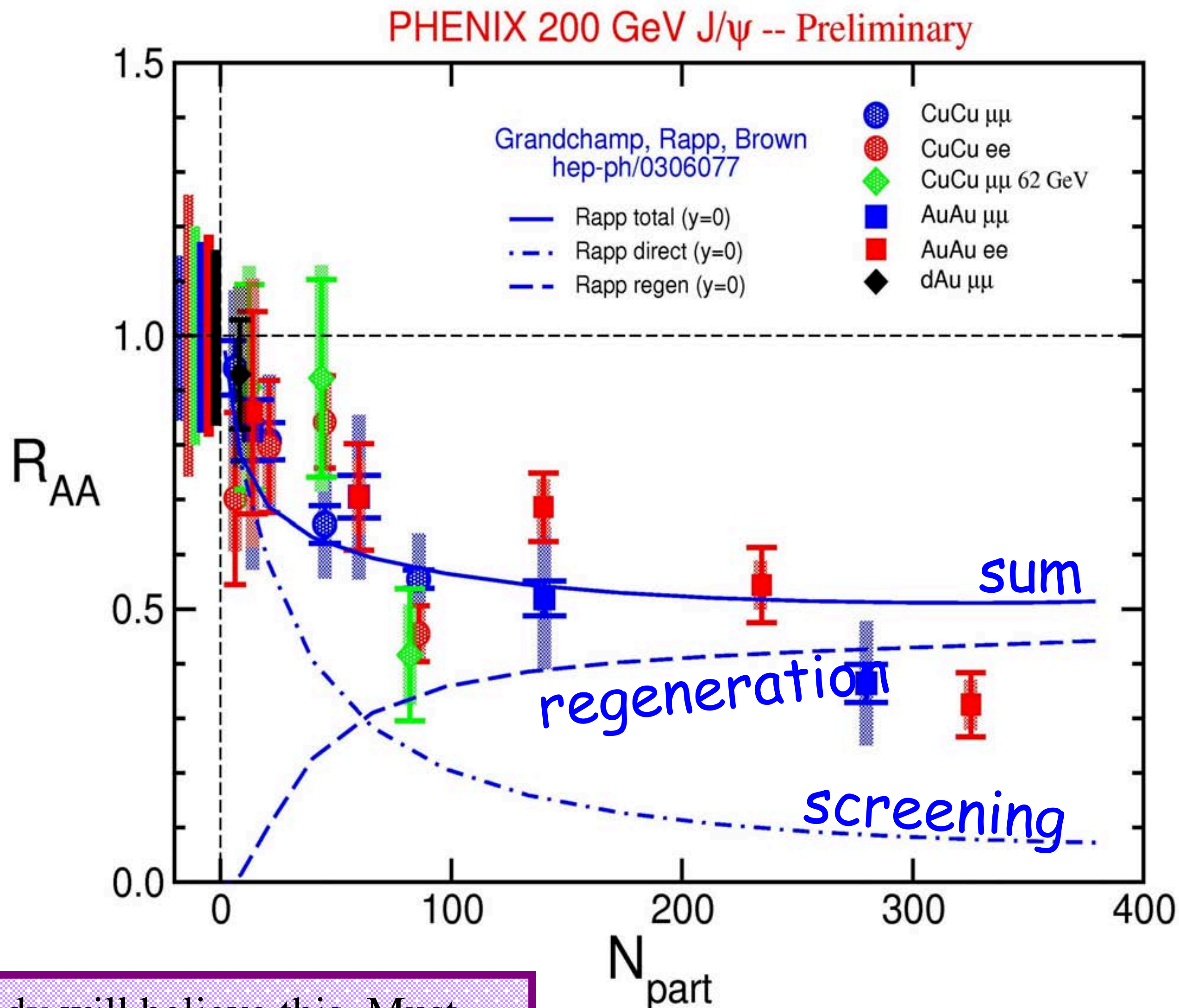


Recently Helmut Satz told me that he thinks that J/ψ are suppresed at all c.m. energies, the only J/ψ that we see are from the corona. How to test?

e.g. see arXiv:1103.6269

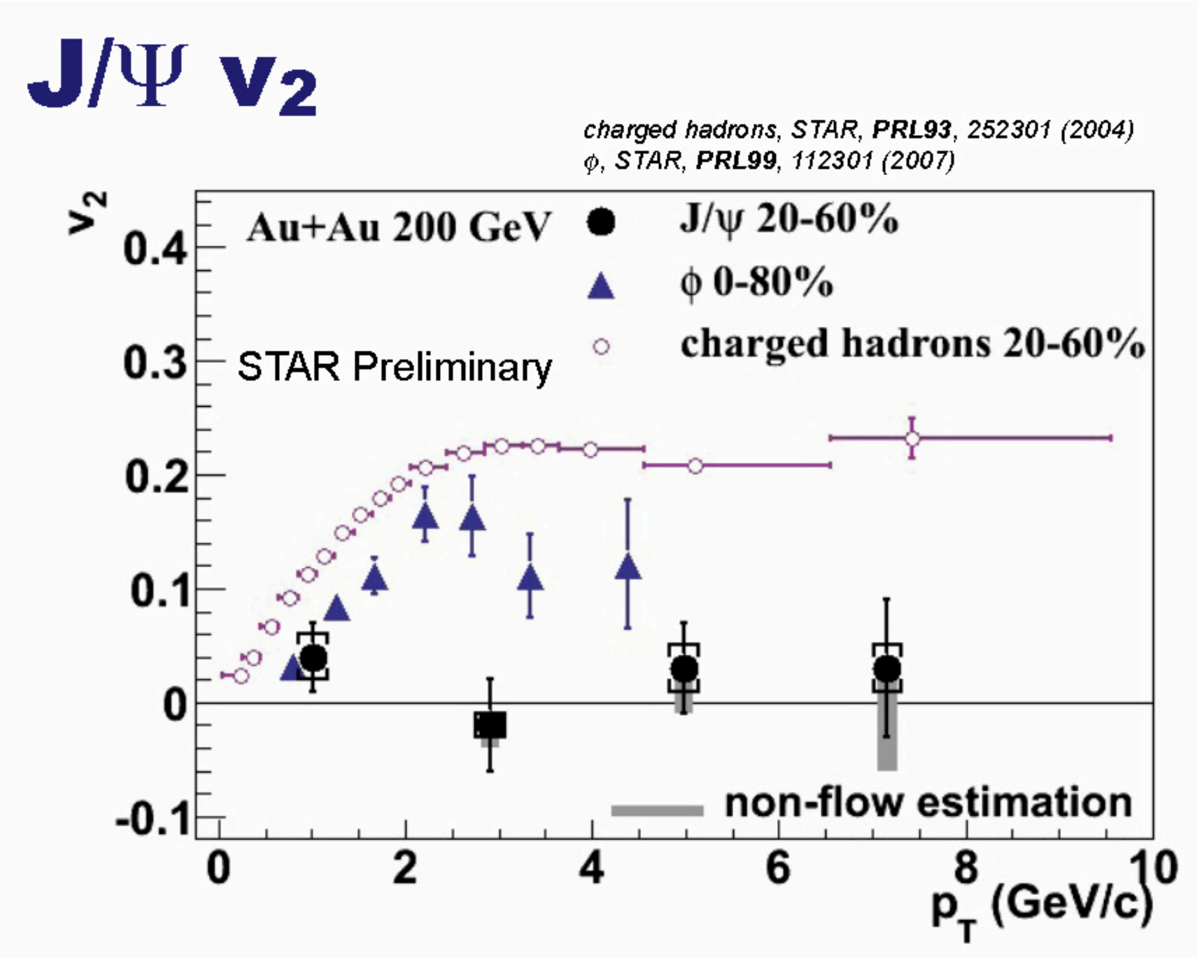
J/ψ Suppression--My Nightmare Scenario

- Many new Explanations.
- One example: Grandchamp, Rapp, Brown; [PRL 92, 212301 (2003)]
  - ✓ In-media dissolution
  - ✓ Plus regeneration from "off-diagonal" c-cbar pairs



The Nightmare is that nobody will believe this. Must see J/ψ enhancement to believe⇒Wait for LHC result

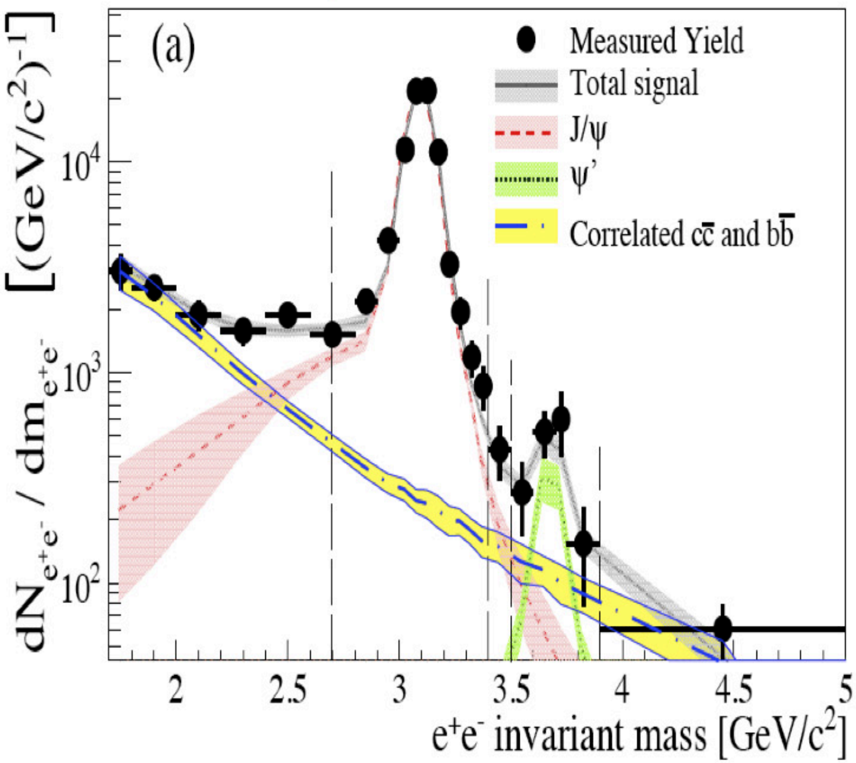
Surprise!



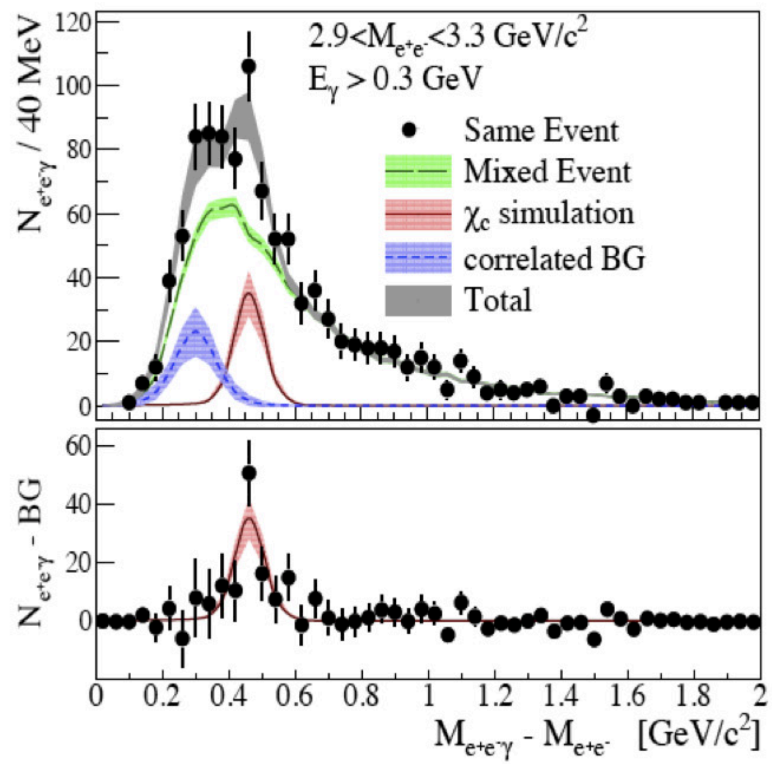
- STAR says J/Psi does not flow.

PHENIX new arXiv:1105.1966

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



$\chi_C \rightarrow J/\psi + \gamma \rightarrow e^+e^-$

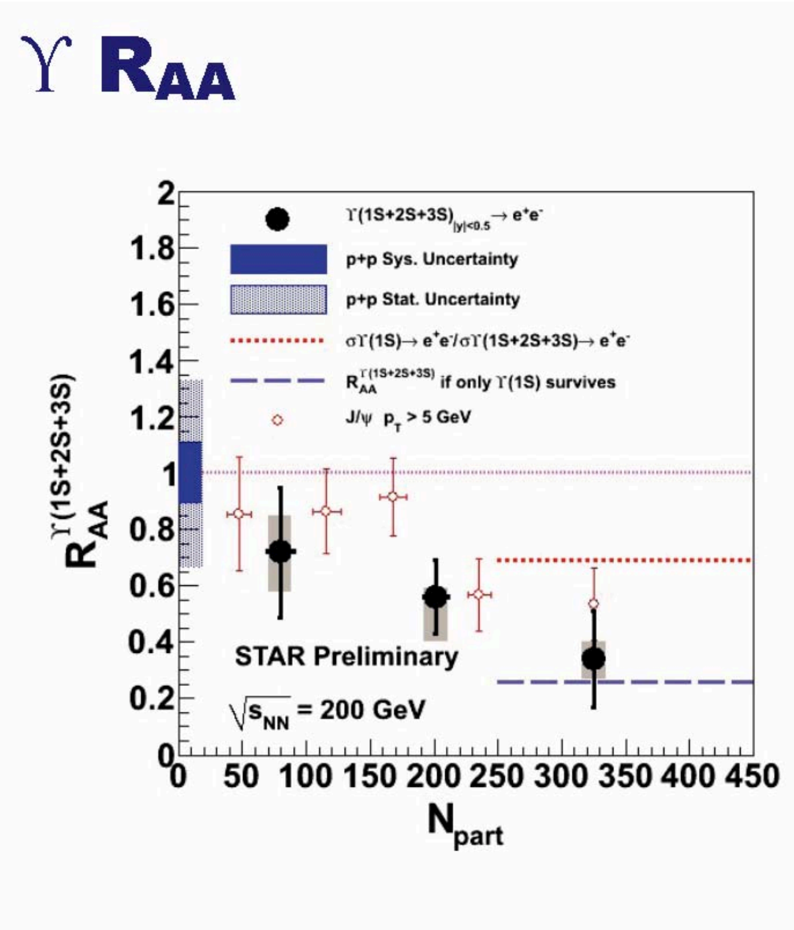


$$F_{\psi'}^{J/\psi} = \frac{B_{J/\psi}^{\psi'}\sigma_{\psi'}}{\sigma_{J/\psi}} = (9.6 \pm 2.4)\%$$

$$F_{\chi_C}^{J/\psi} = \frac{N_{\chi_C}}{N_{J/\psi}} \frac{1}{\epsilon_{\chi_C/\epsilon_{J/\psi}}} = (32 \pm 9)\%$$

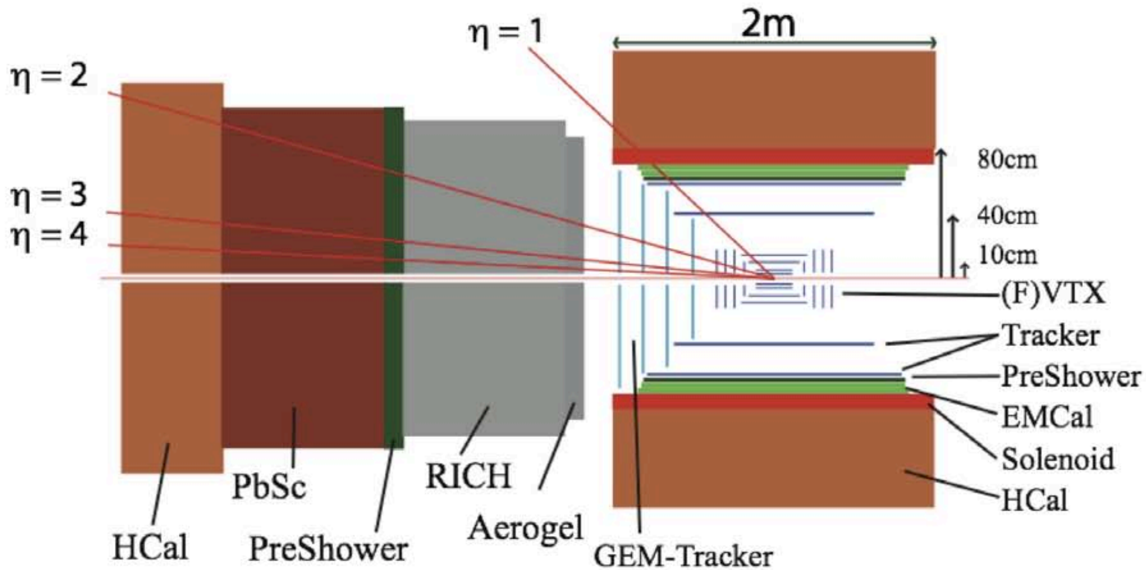
STAR QM2011shows Upsilon Suppression.

- 1s state should be too large to melt in the plasma.
- 2s/3s could be melted.
- Data are above blue-dashed which would be consistent with only 1s survival and removal of nearly all 2s/3s.



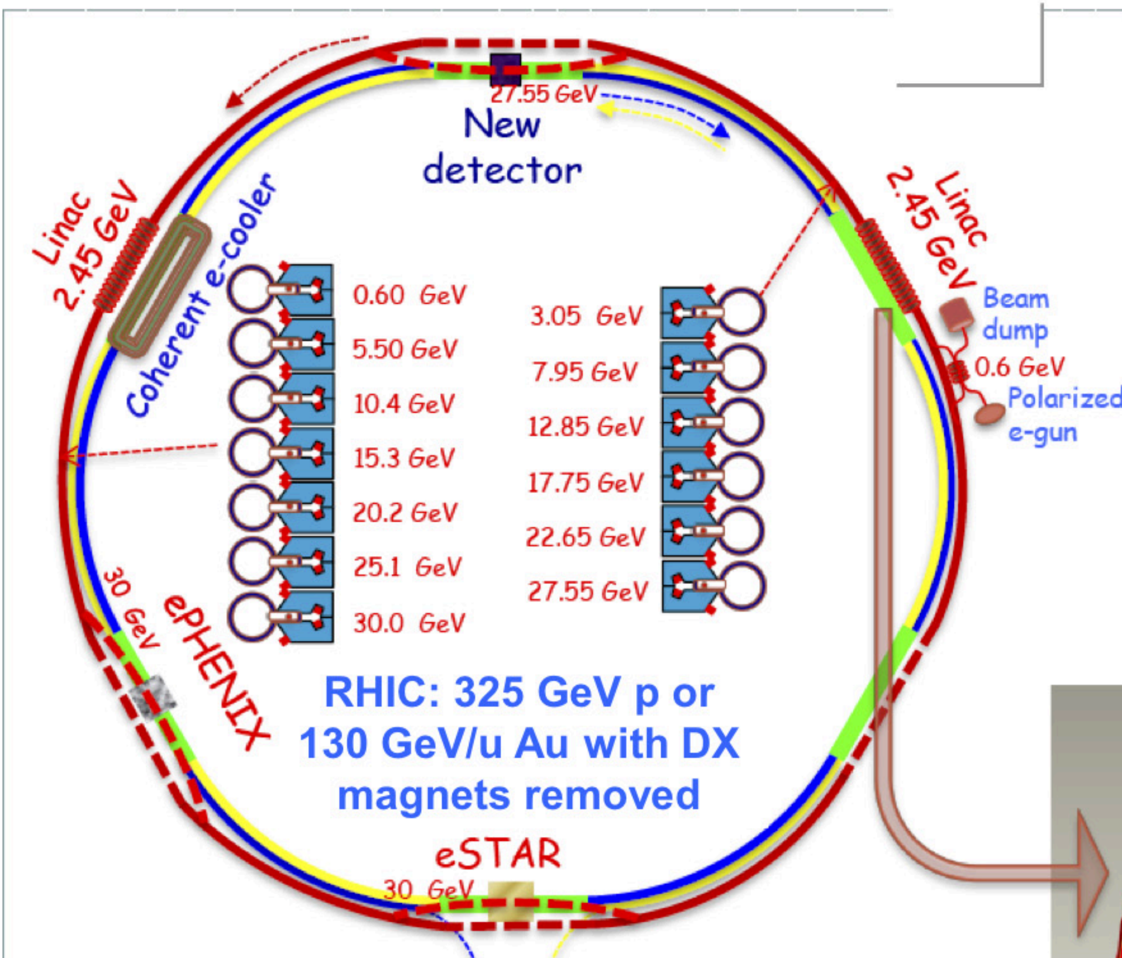
10 year Future: Retire everything but Silicon Vertex Detector. Emphasize Hadron Calorimeter, large solid angle and forward measurements compatible with eRhic AA, pA,pp, ep eA in same detector

sPHENIX strawman

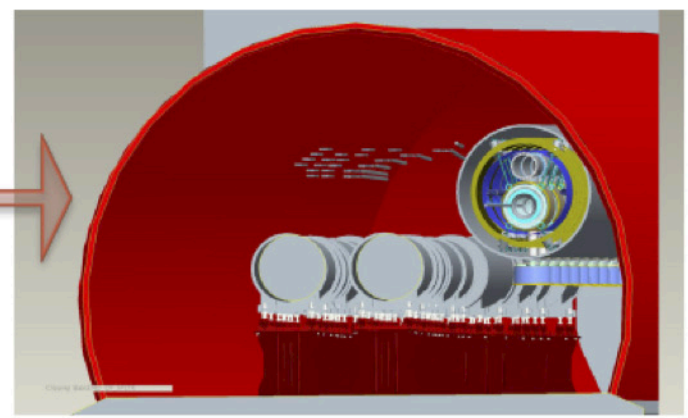


dimensions, technology, additional capabilities still under investigation

eRHIC Design Under Active Consideration



- ✓All-in tunnel staging approach uses two energy recovery linacs and 6 recirculation passes to accelerate the electron beam.
- ✓Staging: the electron energy will be increased in stages, from 5 to 30 GeV, by increasing the linac lengths .
- ✓Up to 3 experimental locations



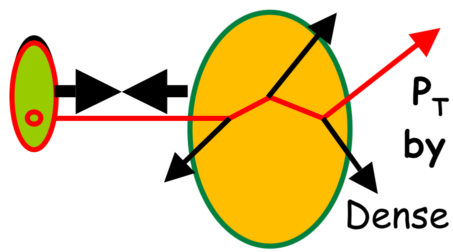
Vis-à-vis earlier MeRHIC design, this allows for:

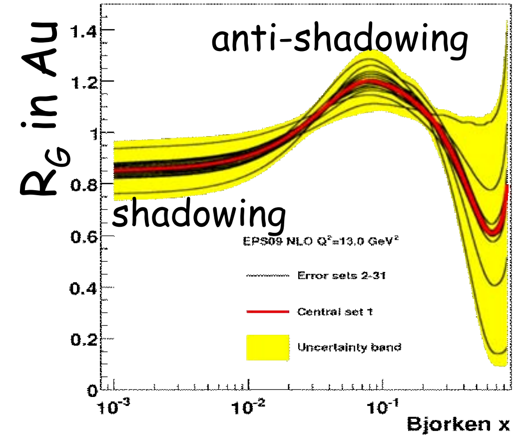
- ***more IP's***
- ***reduced cost***
- ***reusing infrastructure + det. components for STAR, PHENIX***
- ***easier upgrade path from 5 GeV eRHIC-I***
- ***minimal environmental impact concerns***
- ***IR design to reach 10^{34} luminosity***

v_3 has made a major change for the better in our understanding. Thermal photon flow opened a new window on the system evolution. What is next?

Cold Nuclear Matter (CNM) and Low-x Partons in Nuclei

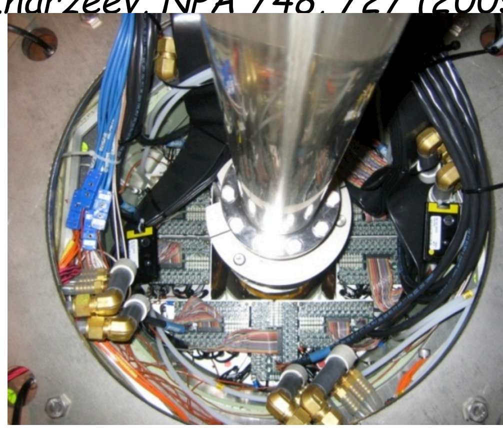
Other probes of shadowing & gluon saturation – forward hadrons



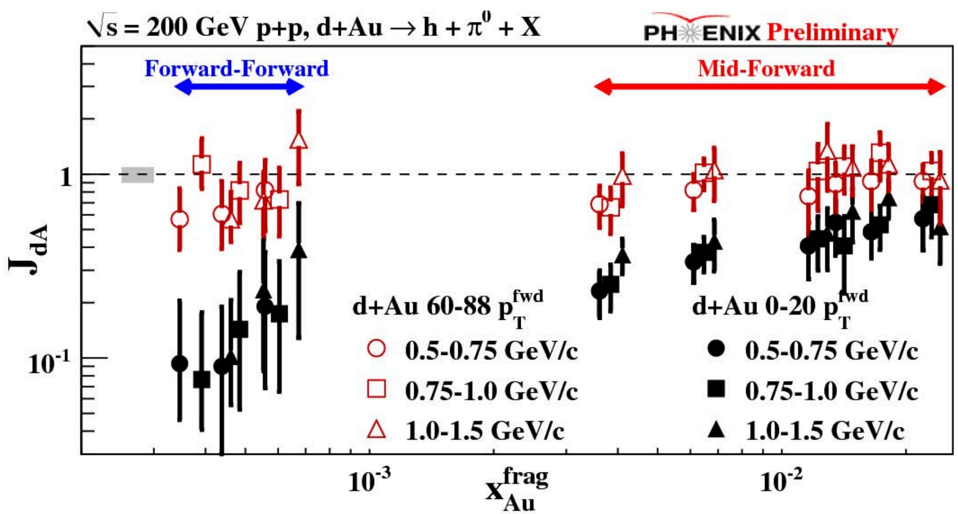


Mono-jets in the gluon saturation (CGC) picture give suppression of pairs per trigger and some broadening of correlation

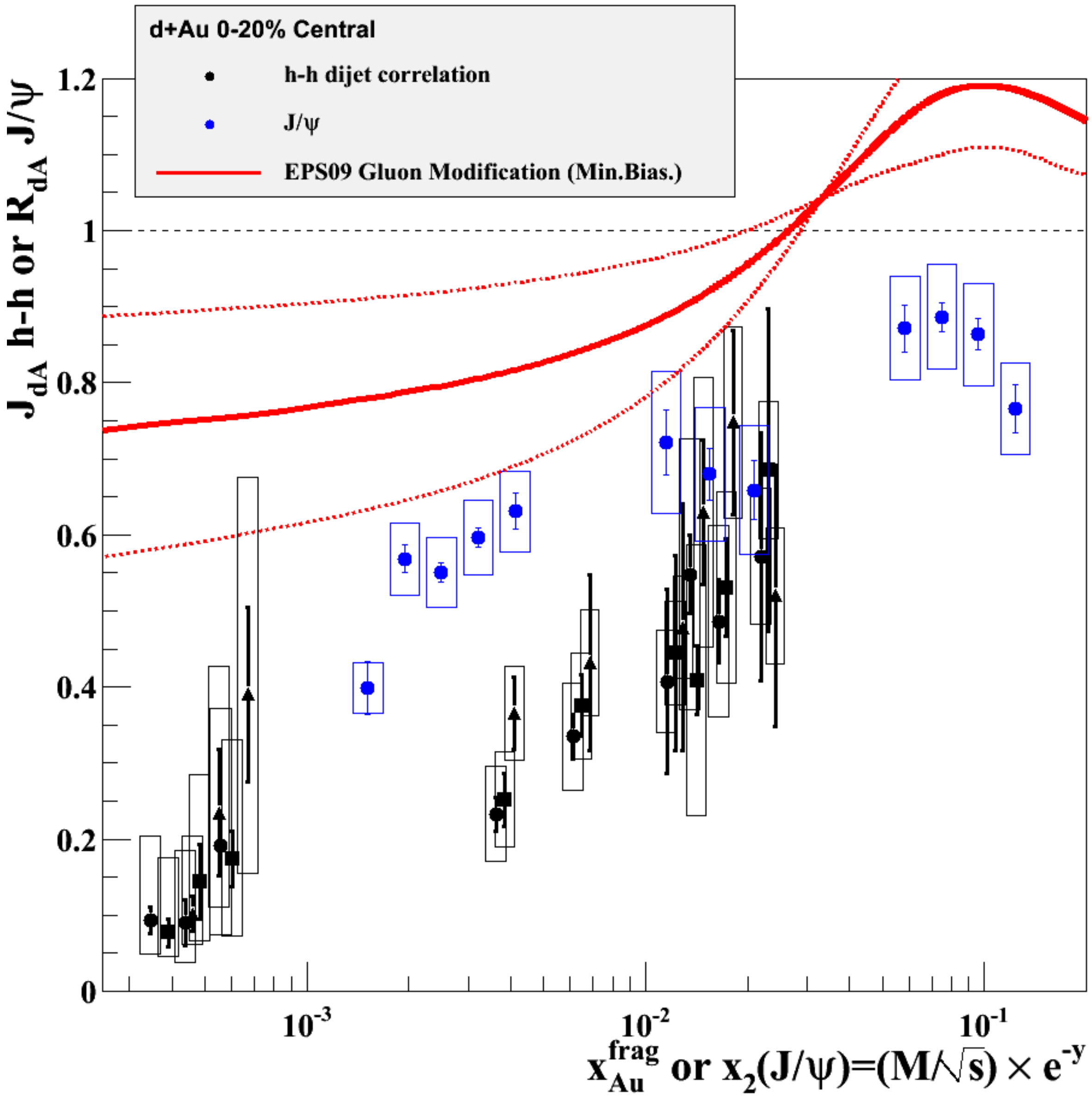
Kharzeev, NPA 748, 727 (2005)



PHENIX MPC



$$x_{Au}^{frag} = \frac{<p_{T1}> e^{-<\eta_1>} + <p_{T2}> e^{-<\eta_2>}}{\sqrt{s}}$$


d+Au 0-20% Central
h-h dijet correlation
J/ψ
EPS09 Gluon Modification (Min.Bias.)
J_{dA} h-h or R_{dA} J/ψ
x_{Au}^{frag} or $x_2(J/\psi)=(M/\sqrt{s}) \times e^{-y}$