Latest results from BNL and RHIC + Progress on determining q-hat in RHI collisions using di-hadron correlations

For previous years with more details see:

2009: IJMPA **26** (2011)5299 1406.0830

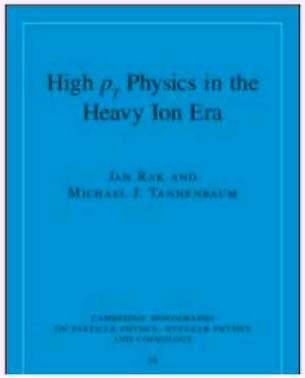
2011-2013: IJMPA **29** (2014)1430017 1406.1100

2014: arXiv1504.02771

2015: arXiv1604.08550

2016: arXiv1705.07925

2017: arXiv1805.02692



High-pT Physics in the Heavy Ion Era
Jan Rak, University of Jyväskylä, Finland
Michael J. Tannenbaum, Brookhaven National Laboratory, New York

Hardback

Series: Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology (No. 34)

ISBN:9780521190299

396pages
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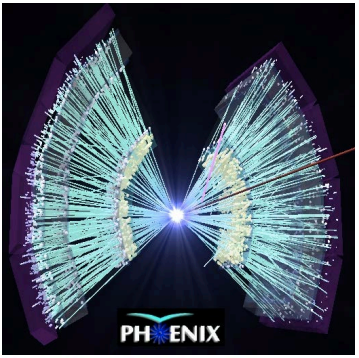
How hadron collider experiments contributed to the development of QCD arXiv:1801.08969

M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973 USA



18th Zimanyi School
Budapest, Hungary
December 3-7, 2018

The Relativistic Heavy Ion Collider (RHIC) at BNL is 1 of the 2 remaining hadron colliders and the first and only polarized p+p collider

New York City region nurtures science
Many Nobel Prize winners from NYC High Schools

Nobel Prize winners from NYC High Schools

Number of laureates by secondary school		Class	Name of laureate	Award and year		University
8	The Bronx High School of Science, Bronx, New York City, NY	1947	Leon N. Cooper[1]	Physics	1972	Brown University
		1950	Sheldon Glashow[1][2]	Physics	1979	Columbia University
		1950	Steven Weinberg[1]	Physics	1979	Cornell University
		1949	Melvin Schwartz[1][3]	Physics	1988	Columbia University
		1966	Russell Hulse[1][4]	Physics	1993	Princeton University
		1966	H. David Politzer[1]	Physics	2004	California Institute of Technology
		1941	Roy Glauber[1][5]	Physics	2005	Harvard University
		1959	Robert Lefkowitz[6]	Chemistry	2012	Columbia University
4	James Madison High School, Brooklyn, New York City, NY	1939	Stanley Cohen[15]	Medicine	1986	Vanderbilt University
		1940	Robert Solow[16]	Economics	1987	Massachusetts Institute of Technology
		1943	Martin Lewis Perl[17]	Physics	1995	University of Michigan
		1947	Gary Becker[18]	Economics	1992	University of Chicago
4	Stuyvesant High School, Manhattan, New York City, NY	1941	Joshua Lederberg[19][20]	Medicine	1958	Rockefeller University
		1954	Roald Hoffmann[20][21]	Chemistry	1981	Cornell University
		1944	Robert Fogel[20][22]	Economics	1993	Cornell University
		1963	Richard Axel[20][23]	Medicine	2004	Columbia University
3	Abraham Lincoln High School, Brooklyn, New York City, NY	1933	Arthur Kornberg[31]	Medicine	1959	Stanford University
		1943	Paul Berg[31]	Chemistry	1980	Stanford University
		1933	Jerome Karle[31][32]	Chemistry	1985	City College of New York
3	Far Rockaway High School, Queens, New York City, NY	1935	Richard Feynman[33][34]	Physics	1965	California Institute of Technology
		1948	Burton Richter[34][35]	Physics	1976	Stanford University

Nobel Prize winners from NYC High Schools

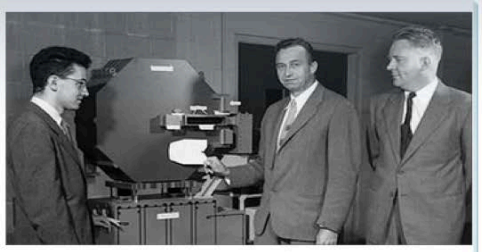
		1942	Baruch Blumberg[34]	Medicine	1976	University of Pennsylvania
3	Townsend Harris High School, Queens, New York City, NY originally Manhattan, New York City, NY	1933	Herbert A. Hauptman[45]	Chemistry	1985	City College of New York
		1933	Julian Schwinger[45]	Physics	1965	Harvard University
		1936	Kenneth Arrow[45]	Economics	1972	City College of New York
2	Brooklyn Technical High School, Brooklyn, New York City, NY	1954	Arno Penzias	Physics	1978	City College of New York
		1922	George Wald	Biology	1987	Harvard University
2	Erasmus Hall High School, Brooklyn, New York City, NY	1919	Barbara McClintock[52]	Medicine or Physiology	1983	Cold Spring Harbor Laboratory
		1944	Eric Kandel[53]	Medicine or Physiology	2000	Columbia University
2	Hastings High School (New York)	1951	Edmund S. Phelps	Economics	2006	Columbia University
	Hastings High School (New York)	1962	Robert C. Merton	Economics	1997	MIT Sloan School of Management
2	Martin Van Buren High School, Queens, New York	1967	Frank Wilczek[57]	Physics	2004	University of Chicago Princeton University
		1967	Alvin Roth[58]	Economics	2012	Columbia University Stanford University
2	Walton High School, Bronx, New York City, NY	1941	Rosalyn Sussman Yalow[45]	Medicine and Physiology	1977	Hunter College
		1933	Gertrude B. Elion[45]	Medicine and Physiology	1988	Duke University
1	Manual Training HS, Brooklyn NY	1916	Issidor Isaac Rabi	Physics	1944	Columbia University
1	DeWitt Clinton HS, Bronx, NY	1931	Robert Hofstadter	Physics	1961	Stanford University
1	James Monroe High School, Bronx NY	1939	Leon Max Lederman	Physics	1988	Columbia University
1	New Trier High School, Winnetka, Illinois	1938	Jack Steinberger[90]	Physics	1988	Columbia University
1	Regis High School, Manhattan, New York City, NY	1957	John O'Keefe	Medicine	2014	City College of New York McGill University

Add another to the list

One of this year's Nobel Prize winners in Physics

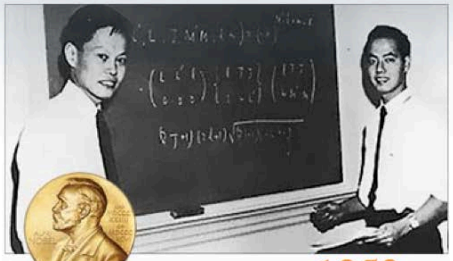
Arthur Ashkin graduated James Madison High school in 1940,
Columbia College in 1947 [delay because of WWII] and PhD from Cornell in 1952

Also many Discoveries & Nobel Prizes at BNL



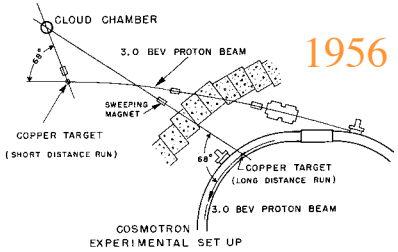
1952 **Strong Focusing**

Brookhaven physicists—including Ernst Courant and Hartland



1953

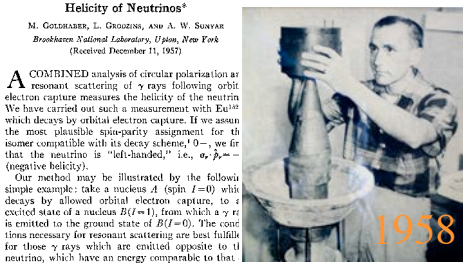
Nobel Prize-winning Discovery: Parity Violation



1956

FIG. 1. Experimental arrangement, showing disposition of the beams in both the long and short distance exposures.

K_L discovered



Helicity of Neutrinos*

M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

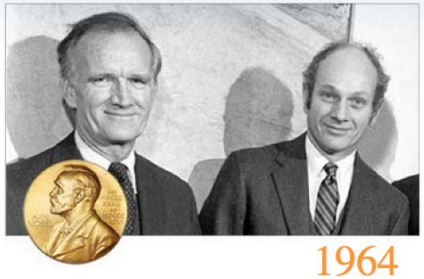
A COMBINED analysis of circular polarization ar resonant scattering of γ rays following orbit electron capture measures the helicity of the neutrin We have carried out such a measurement with Eu^{152} which decays by orbital electron capture. If we assun the most plausible spin-parity assignment for th isomer compatible with its decay scheme,[1] 0−, we fir that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -$ (negative helicity).

Our method may be illustrated by the followi simple example: take a nucleus A (spin $I=0$) whic decays by allowed orbital electron capture, to a excited state of a nucleus $B(I=1)$, from which a γ ra is emitted to the ground state of $B(I=0)$. The cond tions necessary for resonant scattering are best fulfille for those γ rays which are emitted opposite to th neutrino, which have an energy comparable to that

1958

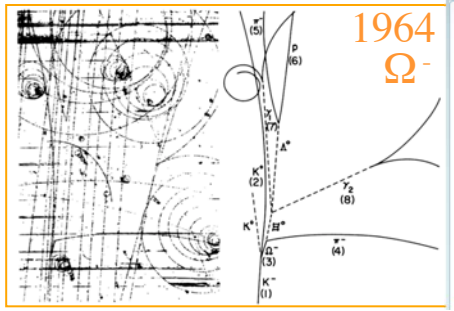
1962

Nobel Prize-winning Discovery: The Muon-Neutrino



1964

Nobel Prize-winning Discovery: CP Violation



1964

Ω^-

1974

Nobel Prize-winning Discovery: The J/Psi Particle

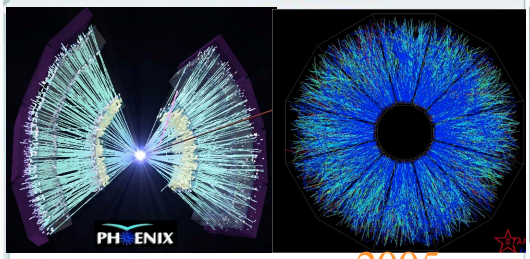
2002

Nobel Prize-winning Discovery: Cosmic Neutrinos

2003

Nobel Prize-winning Discovery: Chemistry of the Cell

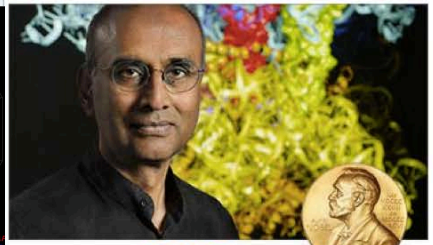
Roderick MacKinnon, M.D., a visiting researcher at Brookhaven



The 'Perfect' Fluid sQGP

2005

Scientists discover quark-gluon plasma, a "perfect" liquid 100,000 times hotter than the center of the sun and so hot that protons and

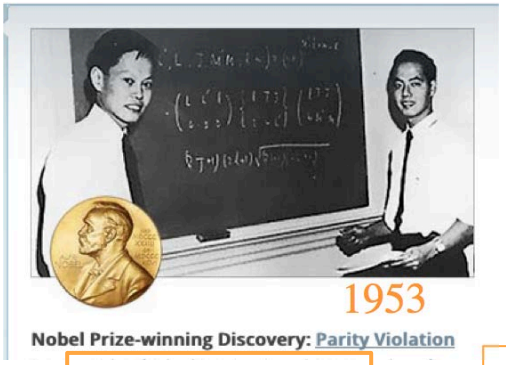


2009

Nobel Prize-winning Discovery: Atomic-Level 'Pictures' of Protein

Leon Lederman died this year at the age of 96

Leon was the most creative and productive high-energy physics experimentalist of his generation and also the physicist with the best jokes. He was also my PhD thesis Professor



PR104 (1956) 254

PR103 (1956) 1901

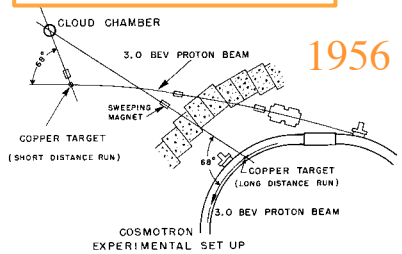


FIG. 1. Experimental arrangement, showing disposition of the beams in both the long and short distance exposures.

1956

K_L discovered

Discovered by Lederman at BNL Nobel to Fitch&Cronin for CP violation

PR105 (1957) 1415

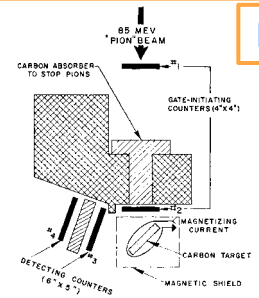
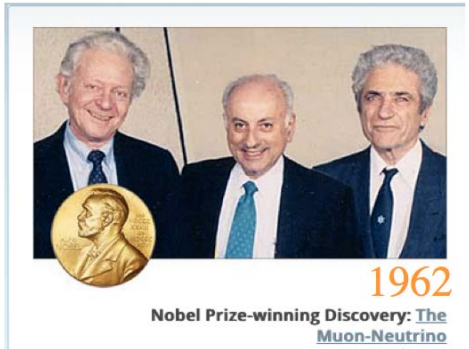


FIG. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

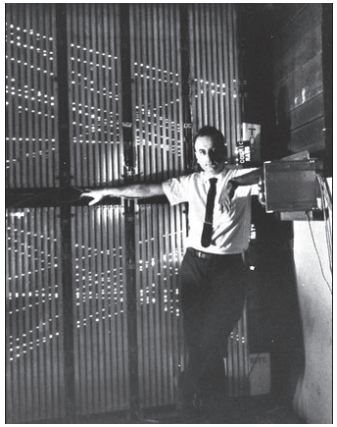
1957

Discovered by Garwin Lederman at Nevis Cyclotron-parity violation in muon decay Nobel to Lee and Yang



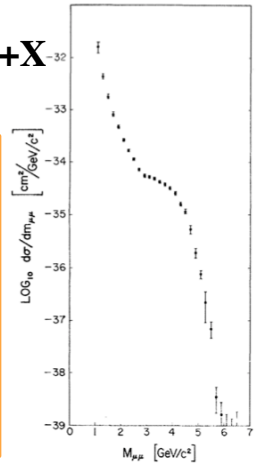
PRL9 (1962) 36

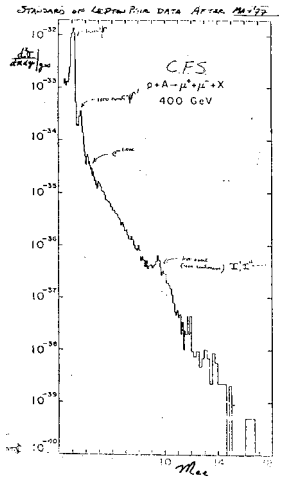
The muon neutrino discovered at BNL--Nobel Prize in 1988



DrellYan
$p+U \rightarrow \mu^+\mu^- + X$
BNL 1970

PRL25 (1970) 1523



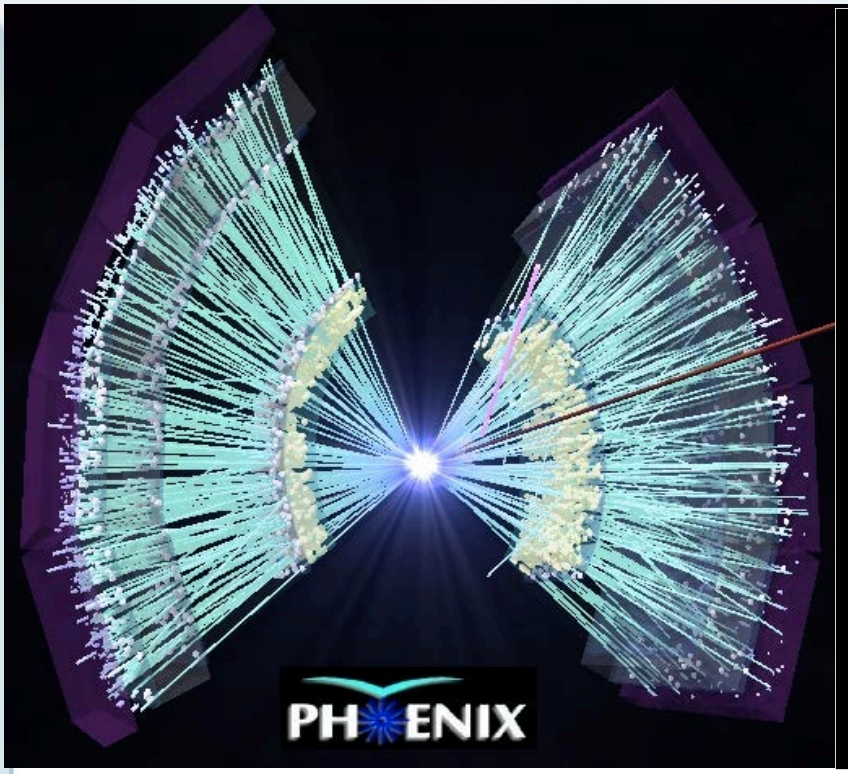


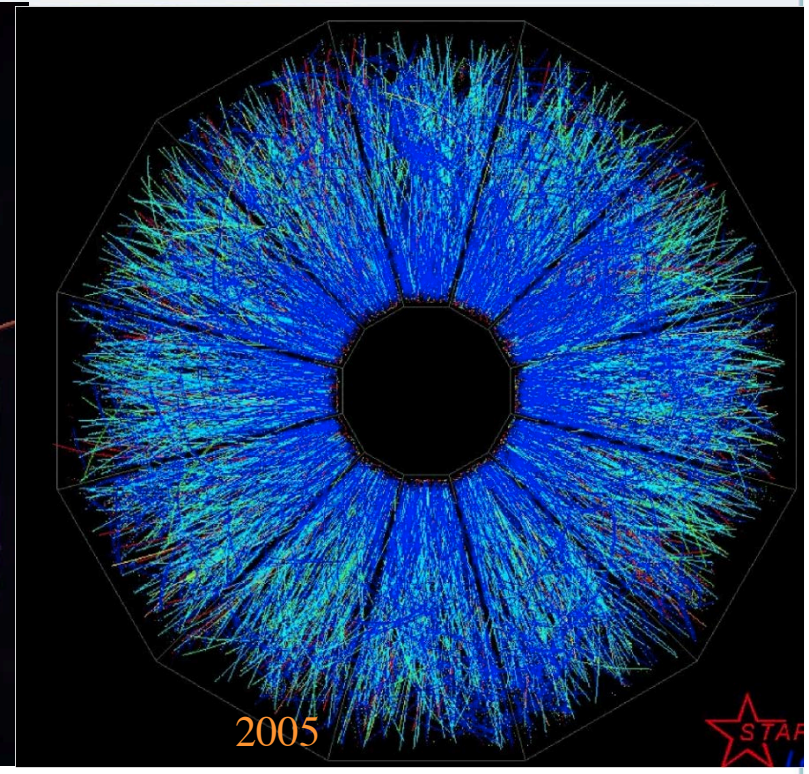
Upsilon at FNAL
1977

PRL39 (1977) 252

For more details see https://physicstoday.scitation.org/do/10.1063/PT.6.4.20181010a/full/

Discovery of the QGP: Why RHIC was built
The surprise is that it is a perfect liquid





Fluid sQGP

The 'Perfect'

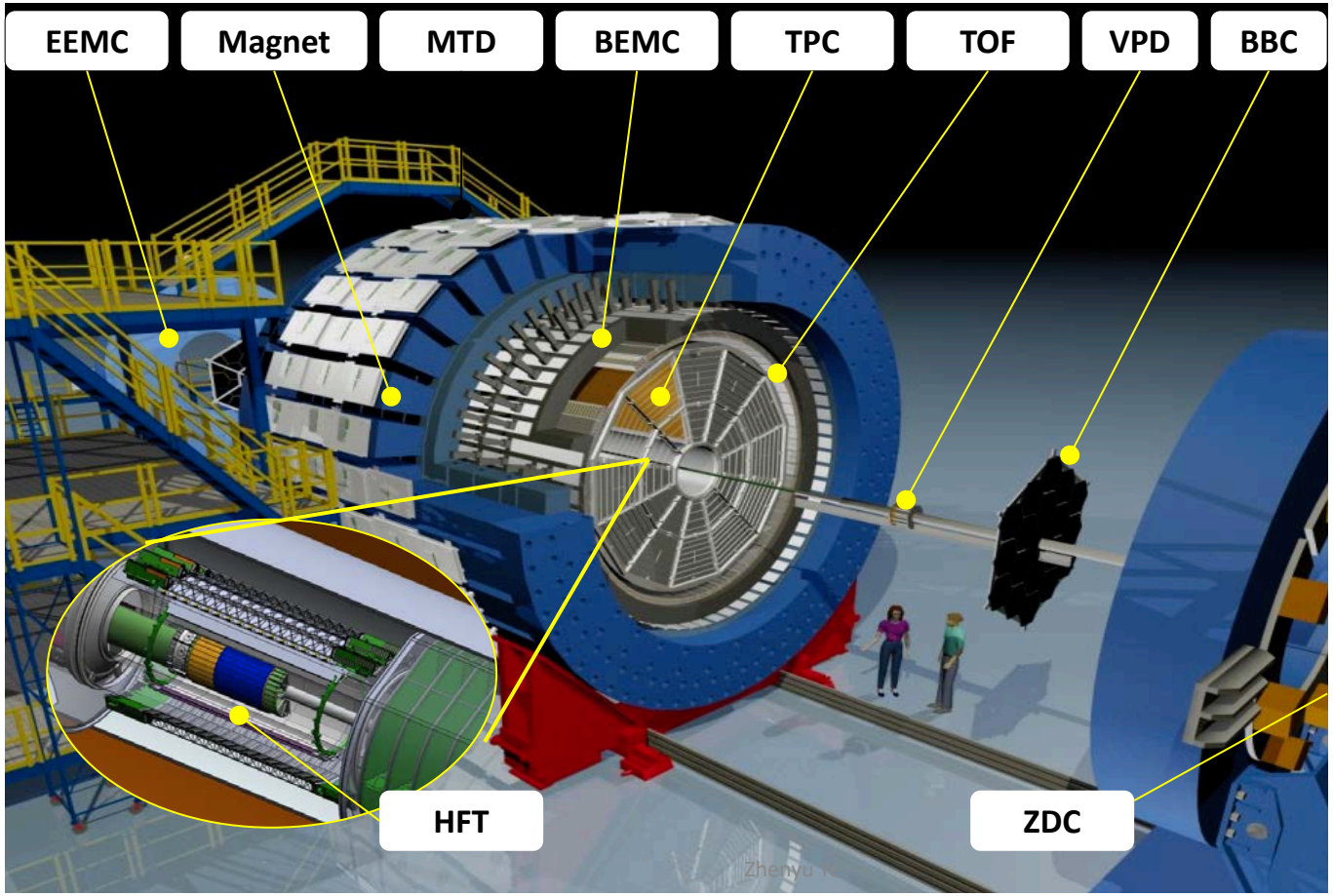
Scientists discover quark-gluon plasma, a "perfect" liquid 100,000 times hotter than the center of the sun and so hot that protons and

Brookhaven National Laboratory (BNL)

Brookhaven National Laboratory (BNL)

Now only one experiment at RHIC: STAR

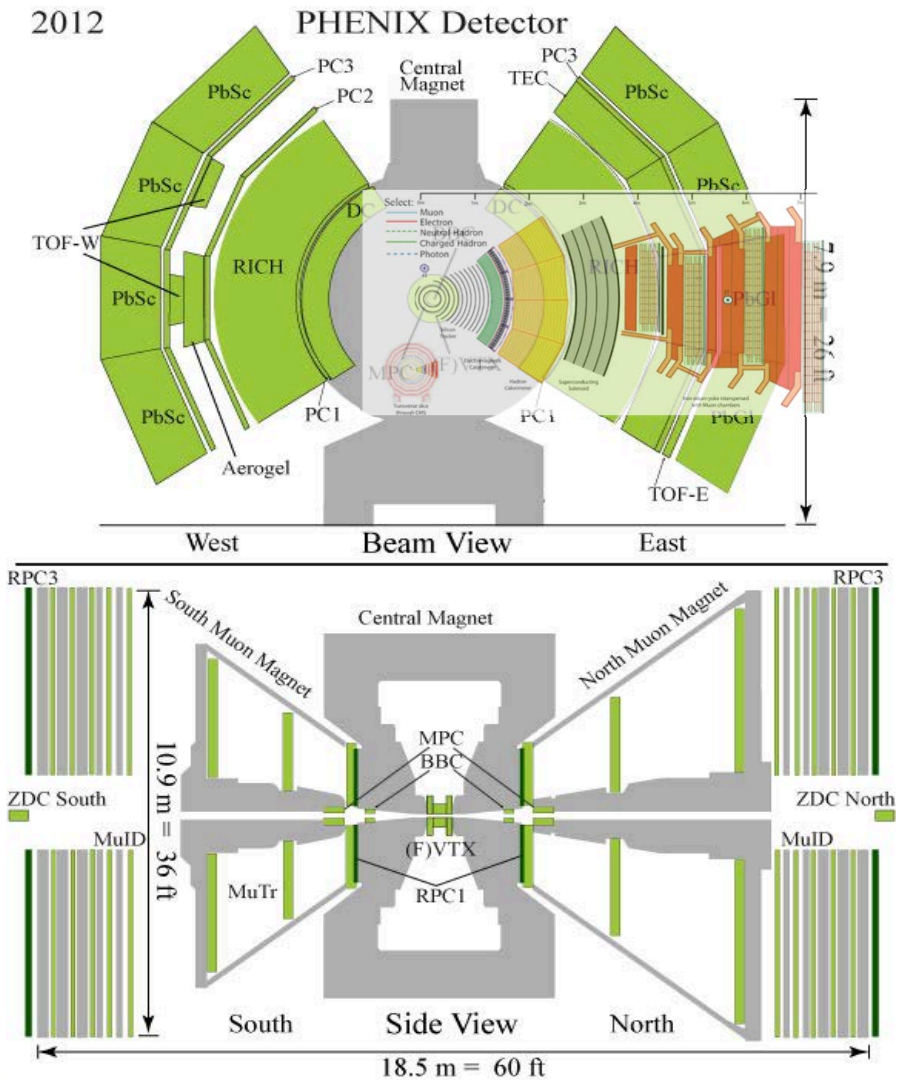
STAR Detector



- **Tracking and PID (full 2π)**
  TPC: $|\eta| < 1$
  TOF: $|\eta| < 1$
  BEMC: $|\eta| < 1$
  EEMC: $1 < \eta < 2$
  HFT (2014-2016): $|\eta| < 1$
  MTD (2014+): $|\eta| < 0.5$
- **MB trigger and event plane reconstruction**
  BBC: $3.3 < |\eta| < 5$
  EPD (2018+): $2.1 < |\eta| < 5.1$
  FMS: $2.5 < \eta < 4$
  VPD: $4.2 < |\eta| < 5$
  ZDC: $6.5 < |\eta| < 7.5$
- **On-going/future upgrades**
  iTPC (2019+): $|\eta| < 1.5$
  eTOF (2019+): $-1.6 < \eta < -1$
  FCS (2021+): $2.5 < \eta < 4$
  FTS (2021+): $2.5 < \eta < 4$

Normal Solenoid, TPC, TOF, EMCalorimeter, VTX detctor, μ detector

"Mike, is there a 'real collider detector' at RHIC?"---J. Steinberger about PHENIX 2002



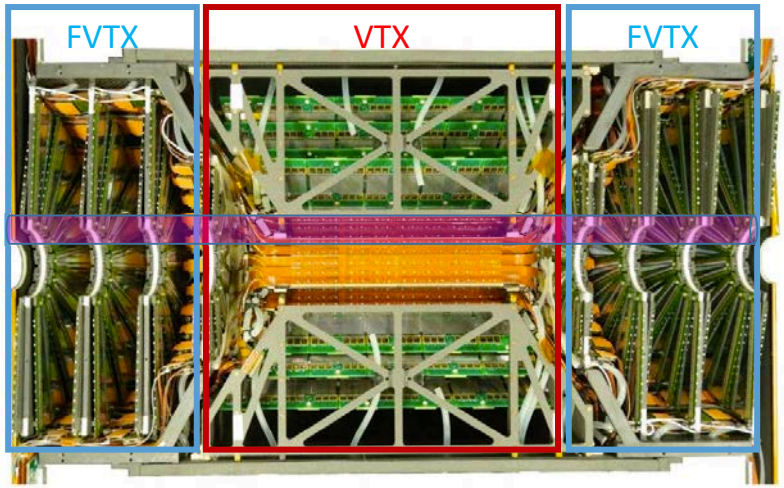
- **PHENIX was a special purpose detector designed and built to measure *rare processes* involving *leptons and photons* at the *highest luminosities*.**
  - ✓ *possibility of zero magnetic field on axis*
  - ✓ *minimum of material in aperture 0.4% X_o*
  - ✓ *EMCAL RICH $e^{\pm}$ i.d. and lvl-1 trigger*
  - *$\gamma\ \pi^0$ separation up to $p_T \sim 25$ GeV/c*
  - *EMCAL and precision TOF for $h^{\pm}$ pid*

Comparison to scale with a wedge of CMS

Last PHENIX run was 2016

PHENIX has Silicon Vertex Detector upgrade
Separate c from b with single e trigger

PHENIX Silicon Vertex Detector, VTX & FVTX

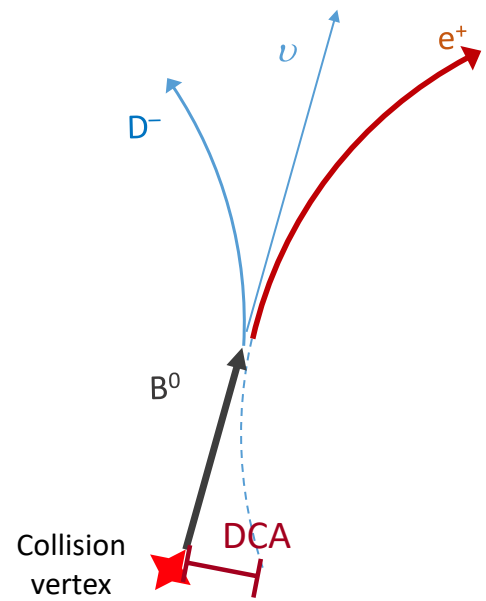


VTX installed in 2011

$|y|<1.2$, $\phi\sim2\pi$: 4 layers (2 pixels + 2 strips)

FVTX installed in 2012

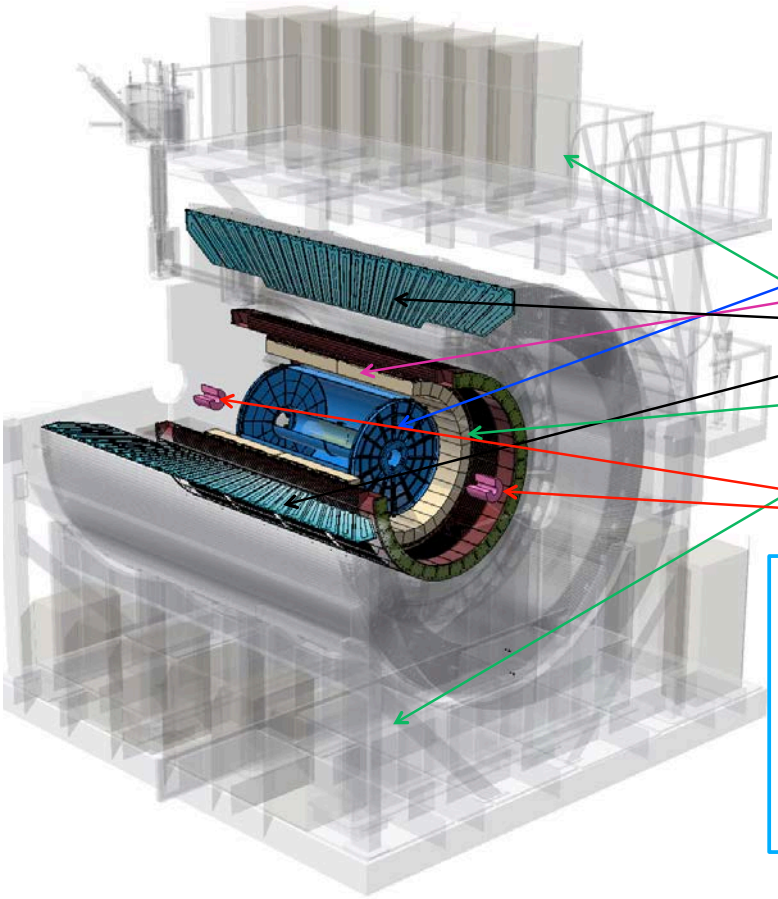
$1.2<|y|<2.2$, $\phi=2\pi$: 4 layers



- Purpose
  - Measure DCA for charm-bottom separation
    - Proportional to decay length
    - B^0 : 455 μm, D^0 : 123 μm
  - VTX : Collision vertex determination
  - FVTX: Event plane :twice higher resolution

The new experiment sPHENIX is moving along well
Successful DOE Major Item of Equipment review

sPHENIX MIE



WBS	sPHENIX MIE Project Elements
1.1	Project Management
1.2	Time Projection Chamber
1.3	Electromagnetic Calorimeter
1.4	Hadron Calorimeter
1.5	Calorimeter Electronics
1.6	DAQ-Trigger → To counting house
1.7	Minimum Bias Trigger Detector

The conceptual design of sPHENIX is based on 3 principles:

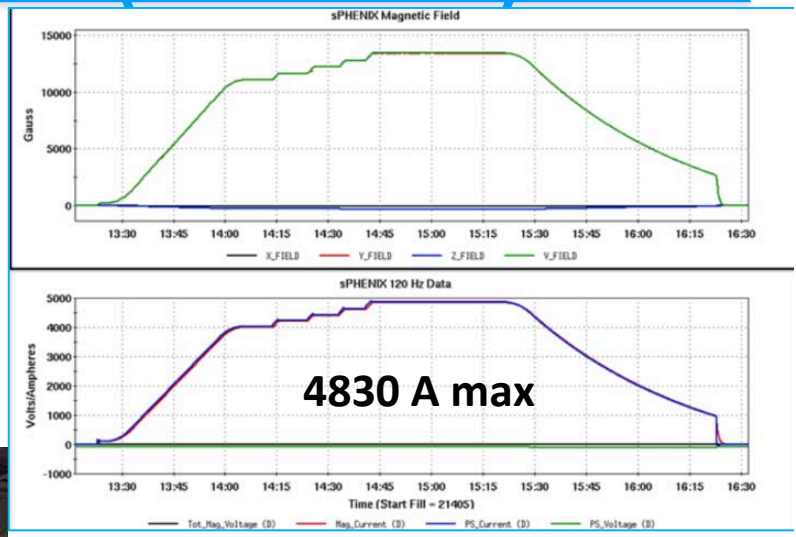
- **Design a detector to meet the Science Mission of measurements of Jets and Upsilons in RHIC environment**
- **Maximize cost effectiveness and utilize modern technologies where appropriate (SiPM, fast TPC readout)**
- **Build on existing $20M+ PHENIX infrastructure**

Ansaldo-Babar-sPHENIX superconducting Soleniod ramped to 105% full current

sPHENIX SC-Magnet Test (off-MIE)

The SC-Magnet has last been operated 10 years ago and has since been moved from SLAC to BNL.
The full current cold test in Jan-Feb 2018 tested:

- Magnet Integrity
- The Power Supply to be used by sPHENIX
- The Quench Protection and Magnet controls that will be used by sPHENIX
- The new extension to the cryo chimney



SC-Magnet ramped and held at 105% Full Current

DOE approves with a few minor issues 05/25/18

Critical Decision Level 1 MIE Schedule

U.S. DEPARTMENT OF ENERGY
Office of Science

Milestone	Schedule Date	
CD-0, Approve Mission Need	9/27/2016	✔
CD-1/3A, Approve Alternative Selection and Cost Range. Long Lead Procurements	Q4 FY 2018	✔
CD-2/3, Approve Performance Baseline	Q4 FY 2019	
CD-4, Approve Project Completion	Q1 FY 2023	

Multi-year run plan for sPHENIX

sPHENIX

	Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
2023	Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
2024	Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
2024	Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
2025	Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
2026	Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
2027	Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

Also See Gunther Roland's talk at Hard Probes 2018

sPHENIX collaboration: 70 institutions and counting

Augustana University
Banaras Hindu University
Baruch College, CUNY
Brookhaven National Laboratory
CEA Saclay
Central China Normal University
Chonbuk National University
Columbia University
Eötvös University
Florida State University
Georgia State University
Howard University
Hungarian sPHENIX Consortium
Insititut de physique nucléaire d'Orsay
Institute for High Energy Physics, Protvino
Institute of Nuclear Research, Russian Academy of Sciences, Moscow
Institute of Physics, University of Tsukuba
Iowa State University
Japan Atomic Energy Agency
Joint Czech Group
Korea University
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Lehigh University
Los Alamos National Laboratory
Massachusetts Institute of Technology
Muhlenberg College
Nara Women's University
National Research Centre "Kurchatov Institute"
National Research Nuclear University "MEPhI"
New Mexico State University
Oak Ridge National Laboratory
Ohio University
Petersburg Nuclear Physics Institute
Purdue University
Rice University
RIKEN
RIKEN BNL Research Center
Rikkyo University
Rutgers University
Saint-Petersburg Polytechnic University
Stony Brook University
Temple University
Tokyo Institute of Technology
Universidad Técnica Federico Santa María
University of California, Berkeley
University of California, Los Angeles
University of California, Riverside
University of Colorado, Boulder
University of Debrecen
University of Houston
University of Illinois, Urbana-Champaign
University of Jammu
University of Maryland
University of Michigan
University of New Mexico
University of Tennessee, Knoxville
University of Texas, Austin
University of Tokyo
Vanderbilt University
Wayne State University
Weizmann Institute
Yale University
Yonsei University

Next meeting: BNL, June '18

Santa Fe, Dec '17

BNL, June '17

GSU (Atlanta), Dec '16

BNL, June '16

Rutgers, Dec'15

If you are interested in joining/contributing contact Dave Morrison (BNL) or Gunther Roland (MIT)

Next U.S. Nuclear Physics Facility Electron-Ion Collider Need for EIC approved by U.S. National Academy of Sciences July24,2018

Statement by Brookhaven Lab, Jefferson Lab, and the Electron-Ion Collider Users Community on National Academy of Sciences Electron-Ion Collider Report

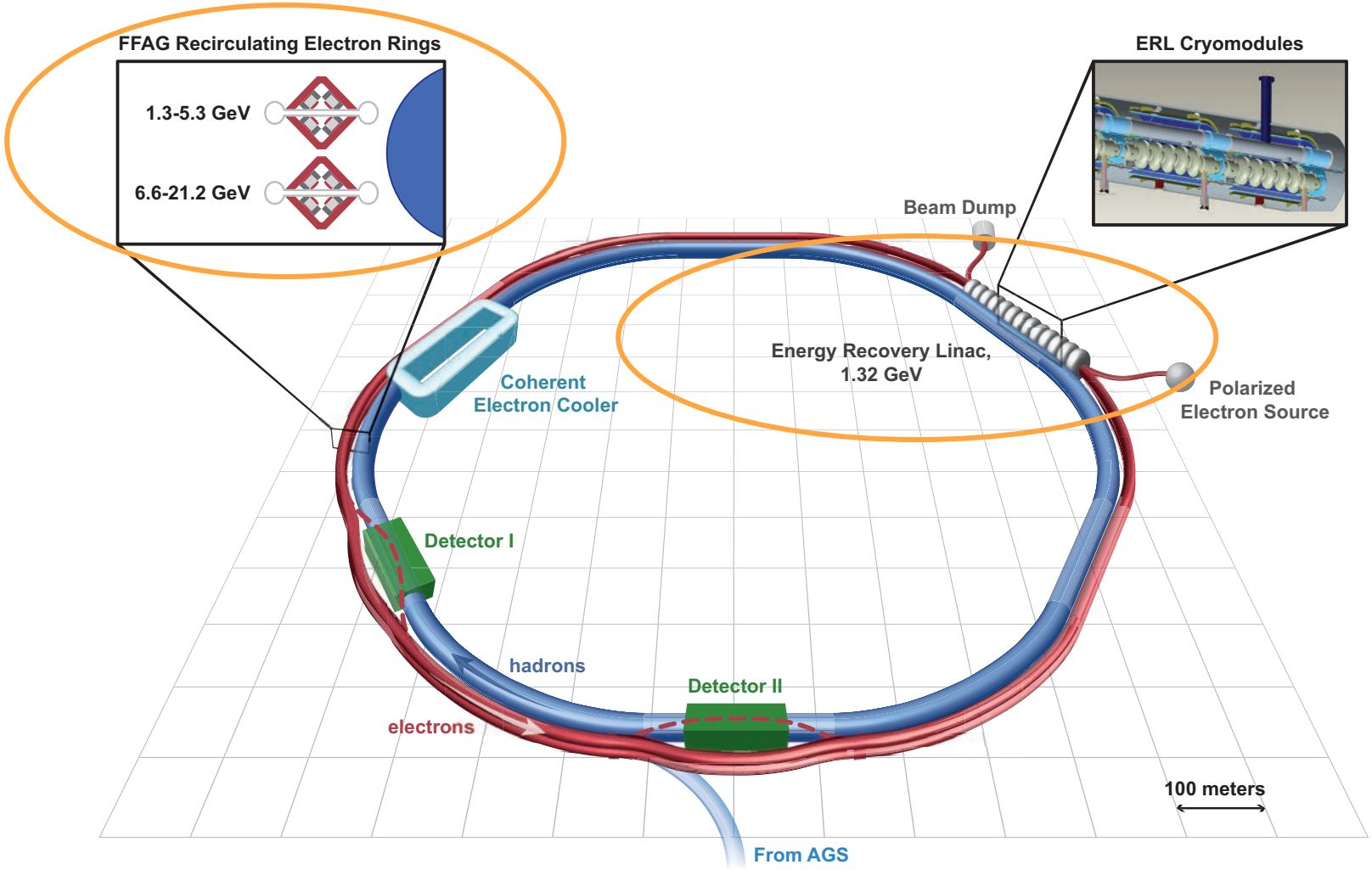
July 24, 2018

On July 24, 2018, a National Academy of Sciences (NAS) committee issued a report of its findings and conclusions related to the science case for a future U.S.-based Electron-Ion Collider (EIC) and the opportunities it would offer the worldwide nuclear physics community.

The committee's report—commissioned by the U.S. Department of Energy (DOE)—comes after 14 months of deliberation and meetings held across the U.S. to gather input from the nuclear science community. The report's conclusions include the following:

- The committee concludes that the science questions regarding the building blocks of matter are compelling and that an EIC is essential to answering these questions.
- The answers to these fundamental questions about the nature of the atoms will also have implications for particle physics and astrophysics and possibly other fields.
- Because an EIC will require significant advances and innovations in accelerator technologies, the impact of constructing an EIC will affect all accelerator-based sciences.
- In summary, the committee concludes that an EIC is timely and has the support of the nuclear science community. The science that it will achieve is unique and world leading and will ensure global U.S. leadership in nuclear science as well as in the accelerator science and technology of colliders.

eRHIC first BNL design—(ISSP2014)



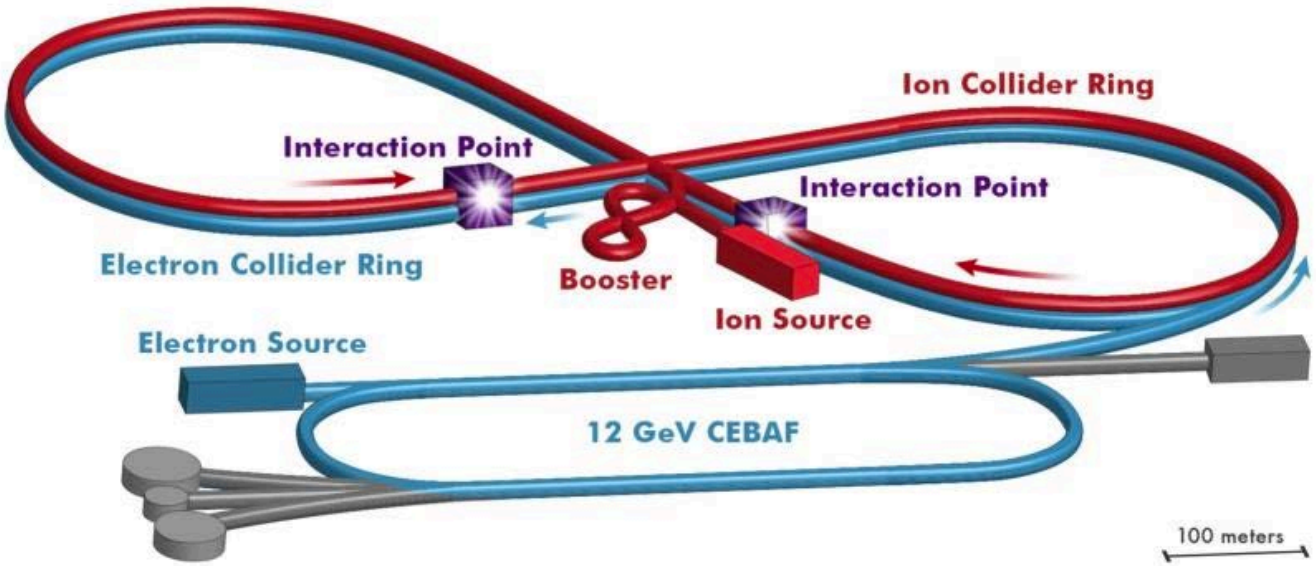
NSAC Sub-Committee Review of the EIC (Electron Ion Collider) Cost Estimates

L Edward Temple, Jr. Chairman Review Conducted 1/26-28/2015 Report Given to NSAC 4/3/2015

Cost estimates
BNL $755.9M
NSAC $1.5B

Jefferson Lab Design

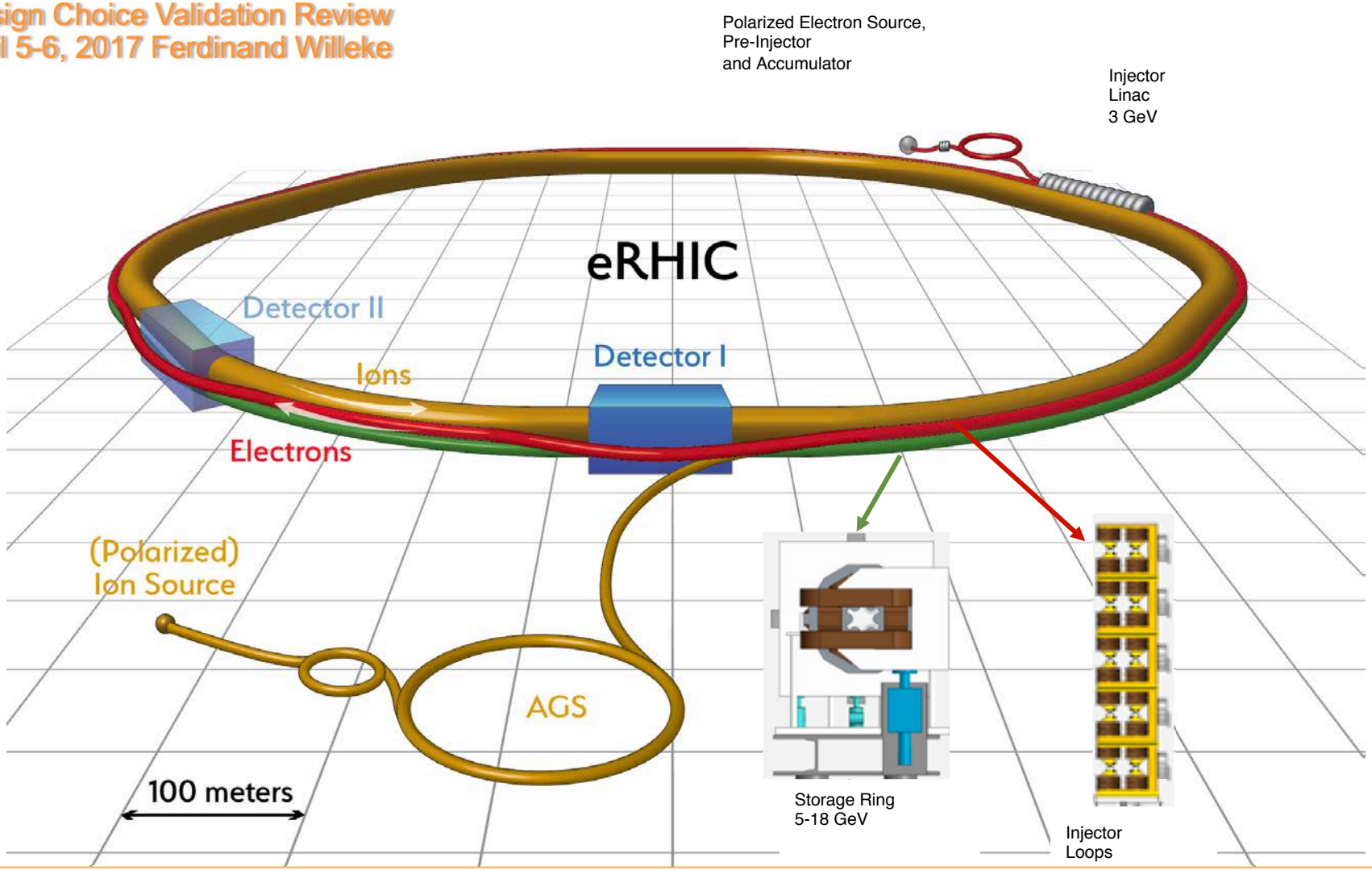
JLEIC Concept, Jefferson Lab, VA



Temple committee cost estimate also $1.5B
but no new accelerator technology required

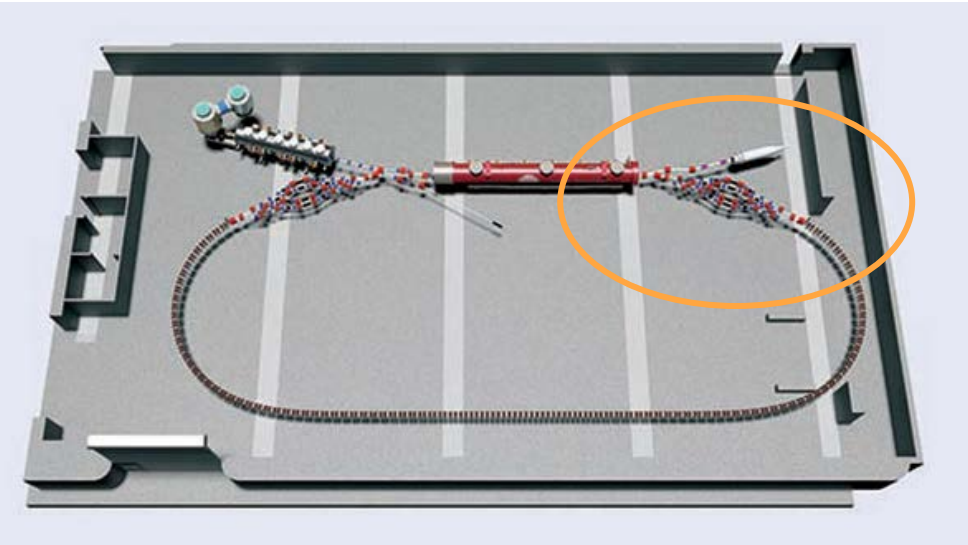
eRHIC design progress 2017

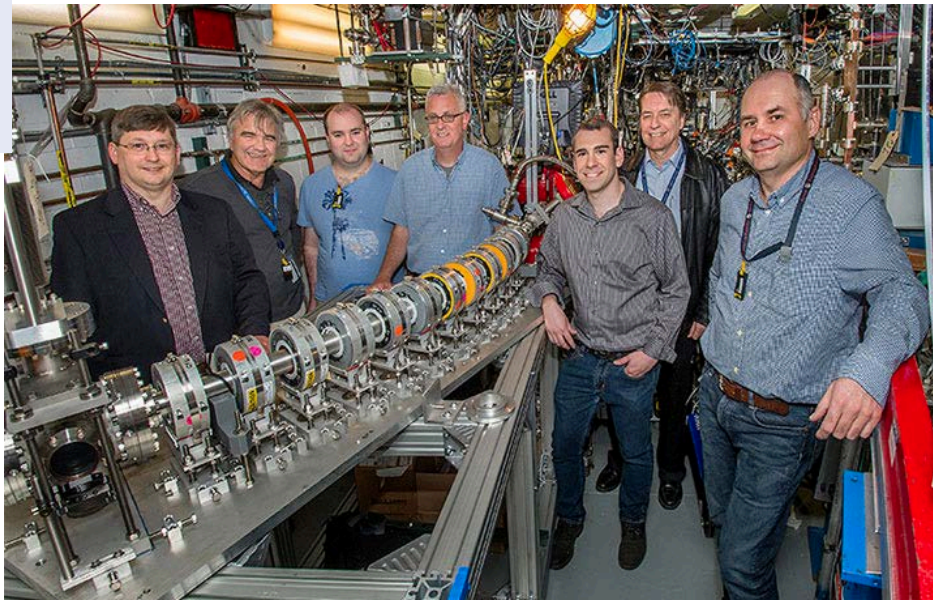
Design Choice Validation Review
April 5-6, 2017 Ferdinand Willeke



National Academy of Sciences: US based electron ion collider Science Assessment 2/1/17-7/31/18
http://www8.nationalacademies.org/cp/projectview.aspx?key=49811

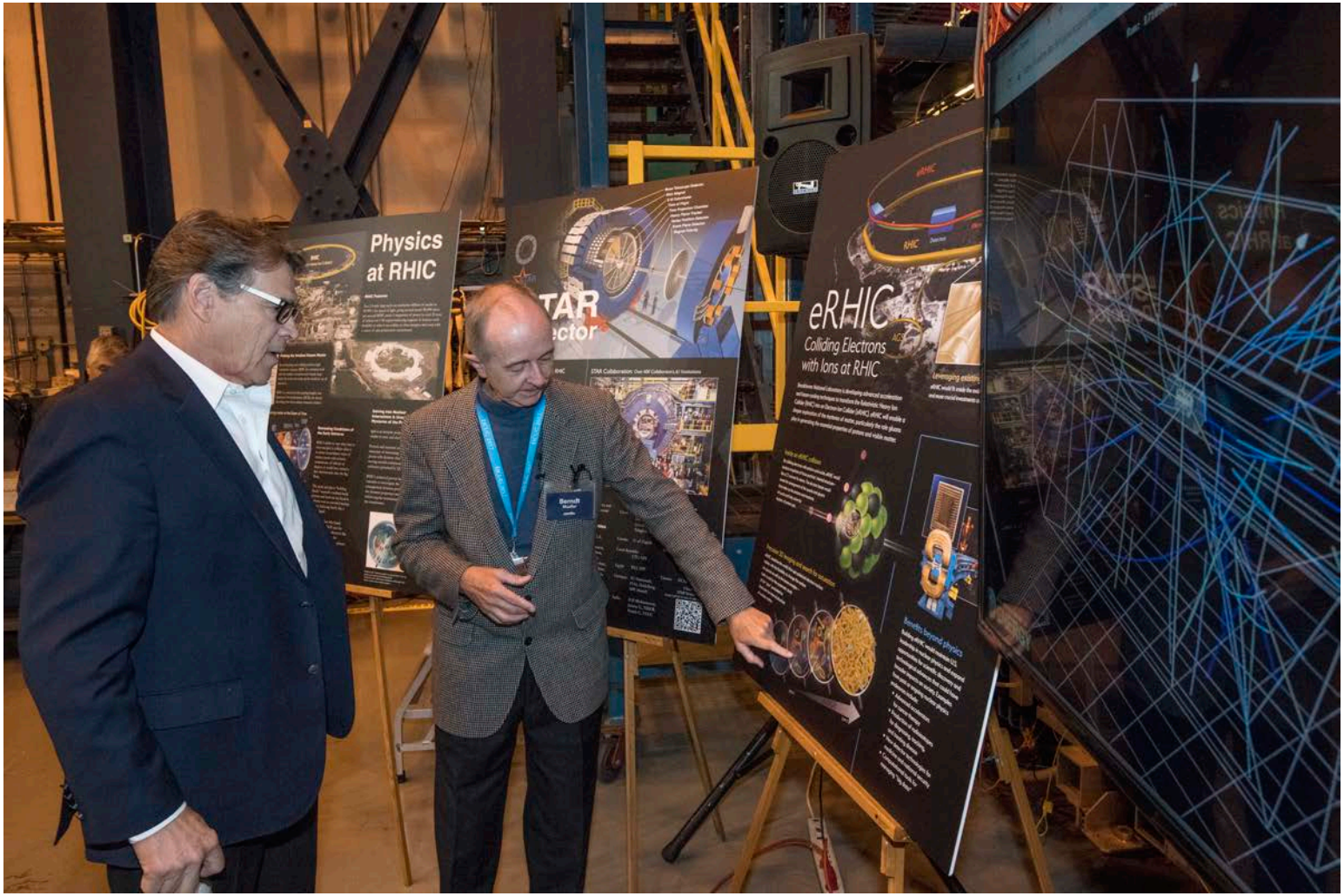
Novel design not idle: BNL-Cornell study of energy recovery linac (ERL), superconducting RF cavities and FFAG return loop which uses permanent magnets





Members of the team testing a fixed-field, alternating-gradient beam transport line made with permanent magnets at Brookhaven Lab's Accelerator Test Facility (ATF), left to right: Mark Palmer (Director of ATF), Dejan Trbojevic, Stephen Brooks, George Mahler, Steven Trabocchi, Thomas Roser, and Mikhail Fedurin (ATF operator and experimental liaison).

Berndt Mueller showing Secretary of Energy eRHIC plan at BNL Oct. 26,2018

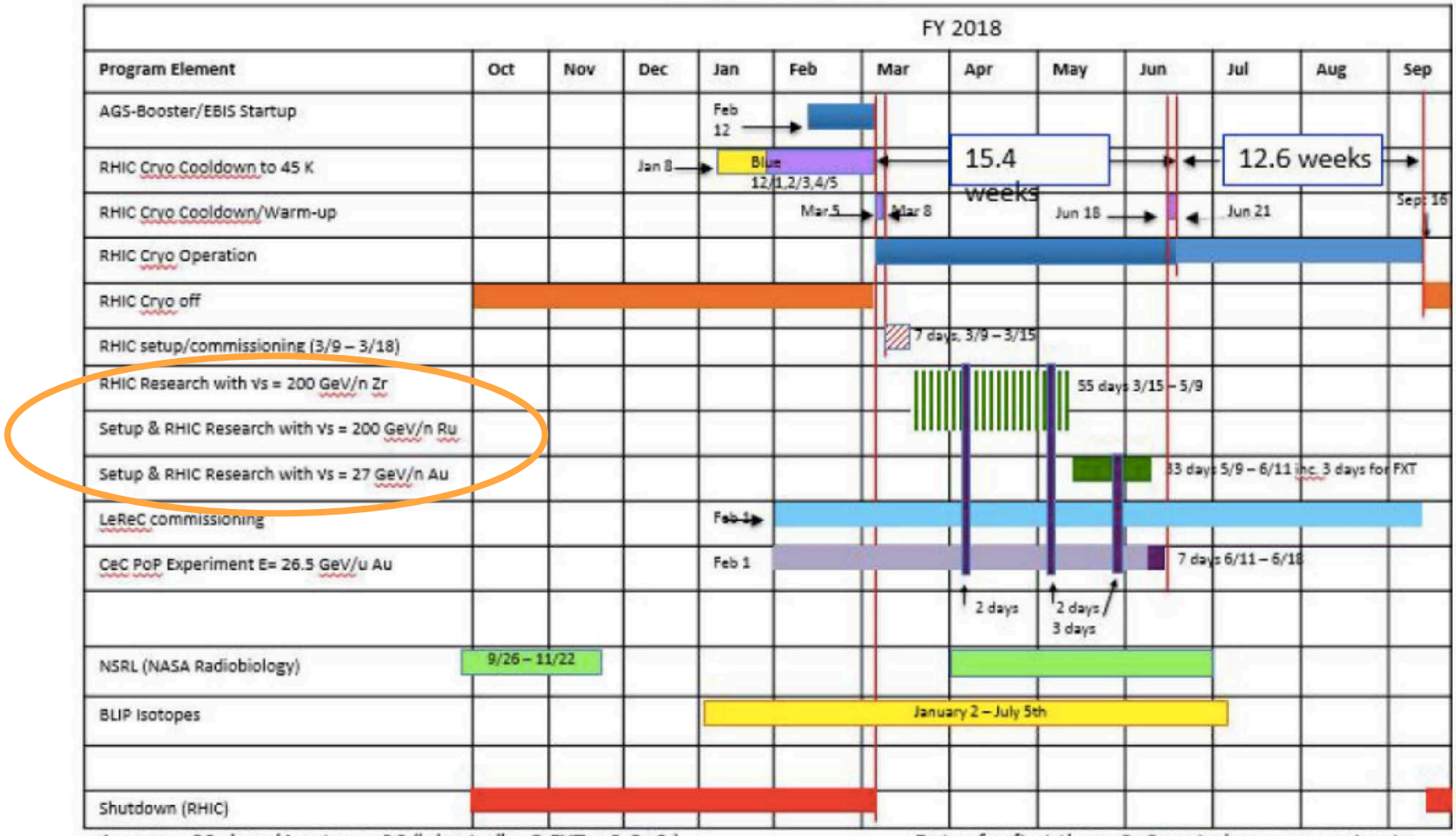


BNL's future plan 2017 still works in 2018

Years	Beam Species and	Science Goals	New Systems
2014	Au+Au at 15 GeV Au+Au at 200 GeV ^{3}He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p↑+p↑ at 200 GeV p↑+Au, p↑+Al at 200 GeV High statistics Au+Au ~~Au+Au at 62 GeV ?~~ d+Au @ 200, 62, 39, 20 GeV	Extract η/s(T) + constrain initial quantum fluctuations Complete heavy flavor studies Sphaleron tests Parton saturation tests	PHENIX MPC-EX STAR FMS preshower Roman Pots Coherent e-cooling test
2017	p↑+p↑ at 510 GeV	Transverse spin physics Sign change in Sivers function	Coherent e-cooling final
2018	~~No Run~~ isobars	96Zr+96Zr and 96Ru+96Ru to test chiral magnetic effect on observed Au+Au charge separation effects	Low energy e-cooling install. STAR iTPC upgrade
2019-20	Au+Au at 5-20 GeV (BES-2)	Search for QCD critical point and onset of deconfinement	Low energy e-cooling
2022-23 ~~2021-22~~	Au+Au at 200 GeV p↑+p↑, p↑+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia Forward spin & initial state physics	sPHENIX Forward upgrades ?
2024-26 ≥ 2023 ?	Factor of 10 increase Au+Au ~~No Runs~~ Factor of 4 increase p+p	Complete above measurements	Transition to eRHIC

This color is sPHENIX proposed run plan

RHIC running FY2018



Au run = 33 days (1 setup + 26 "physics" + 3 FXT + 3 CeC)
"physics" = physics + APEX + maintenance

Dates for first three CeC periods are approximate (early April, early and late May)
CeC parasitic commissioning =
CeC Dedicated running = (Total of 14 days)

N.B. "Physics" running was declared on 3/14, STAR started Physics data on 3/15.

WHY Isobars

$_{40}Zr^{96} + {}_{40}Zr^{96}$

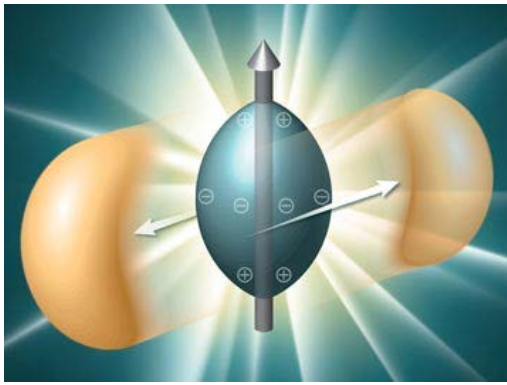
$_{44}Ru^{96} + {}_{44}Ru^{96}$

Dates Back to 2015 result and press release

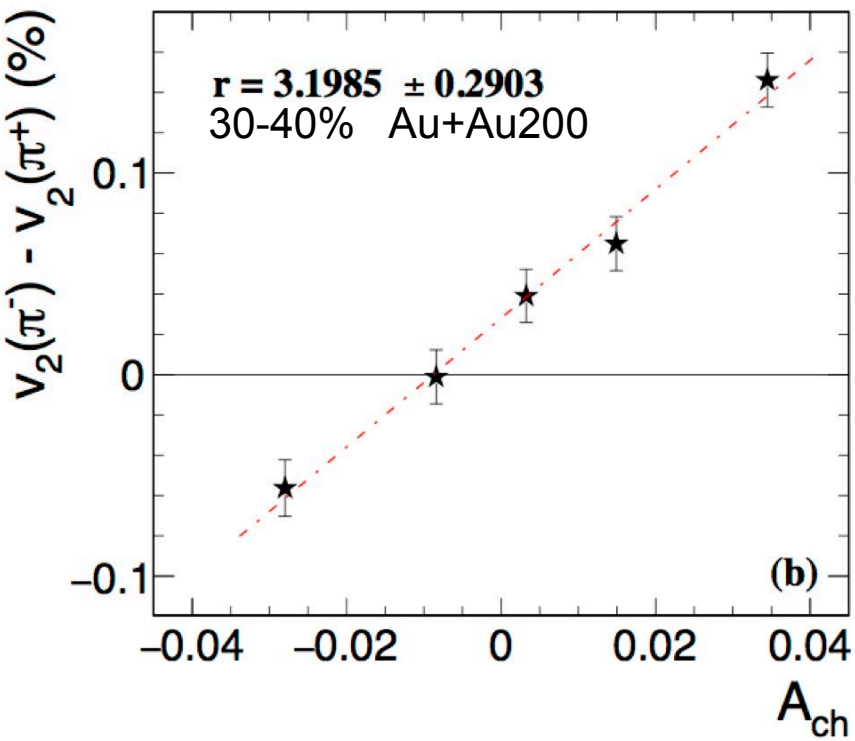
By Karen McNulty Walsh | June 8, 2015

Scientists See Ripples of a Particle-Separating Wave In Primordial Plasma

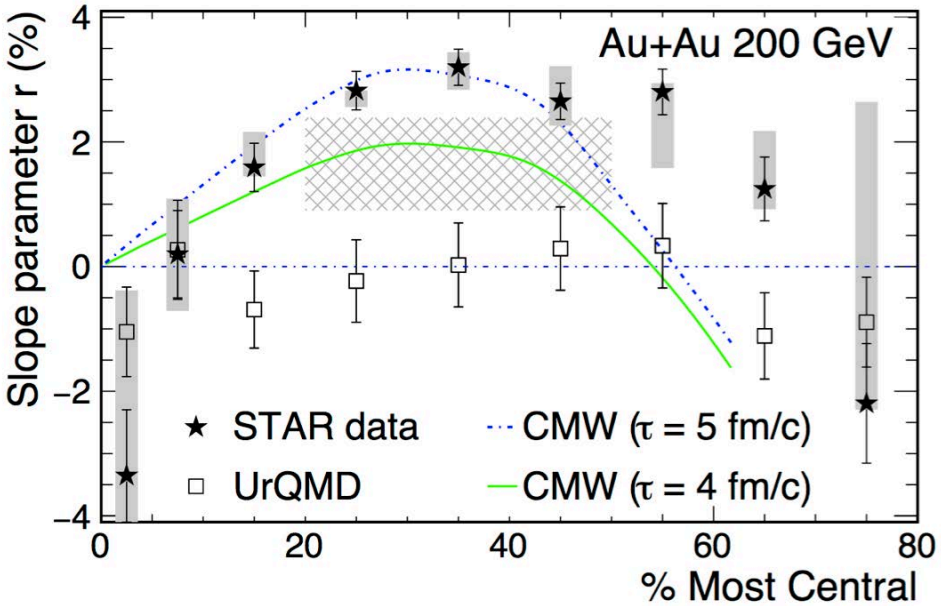
Key sign of quark-gluon plasma (QGP) and evidence for a long-debated quantum phenomenon



v_2 is elliptical transverse flow



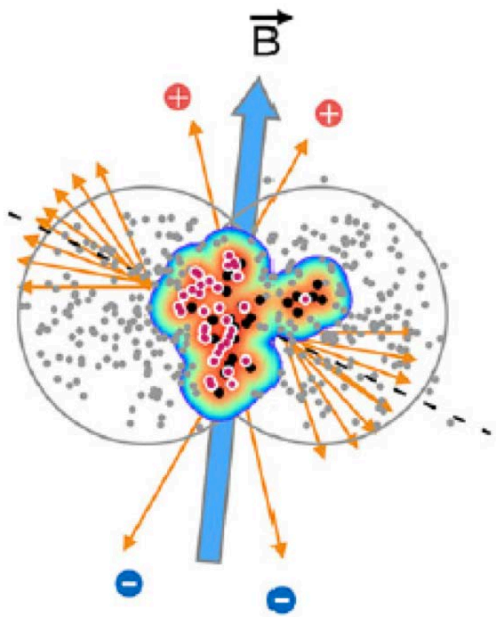
STAR PRL114(2015)252302

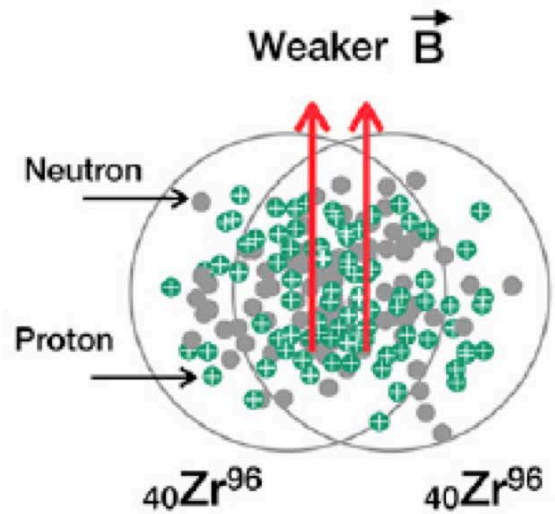


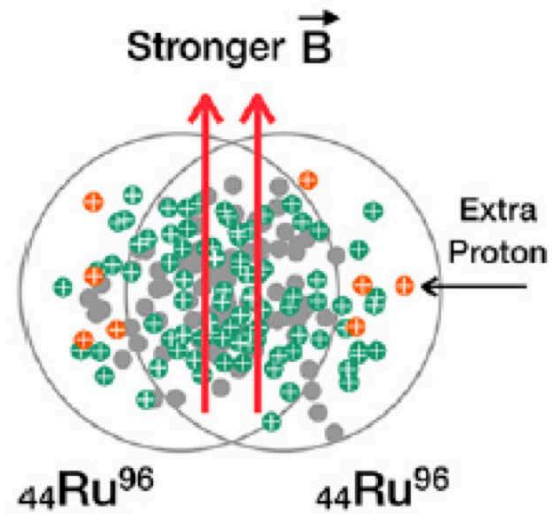
How does one prove what it is?

$$A_{ch} = (N_+ - N_-)/(N_+ + N_-)$$

Present Run 2018: Isobars





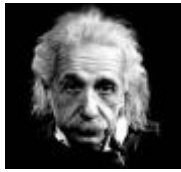


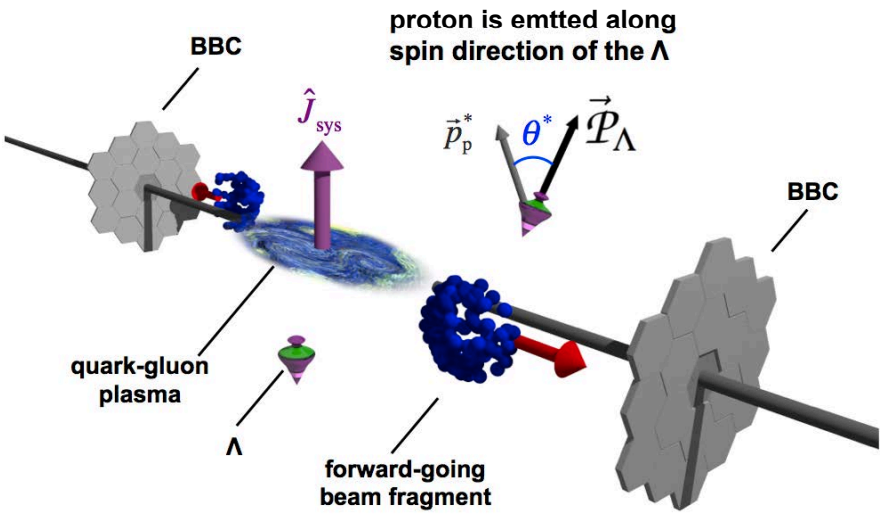
Separation of charges in v_2 of π^+ π^- in previous run. Is this a Chiral Magnetic effect?

Is the v_2 asymmetry a Chiral Magnetic effect which depends on the electric charge or a nucleon effect. This run is now in progress.

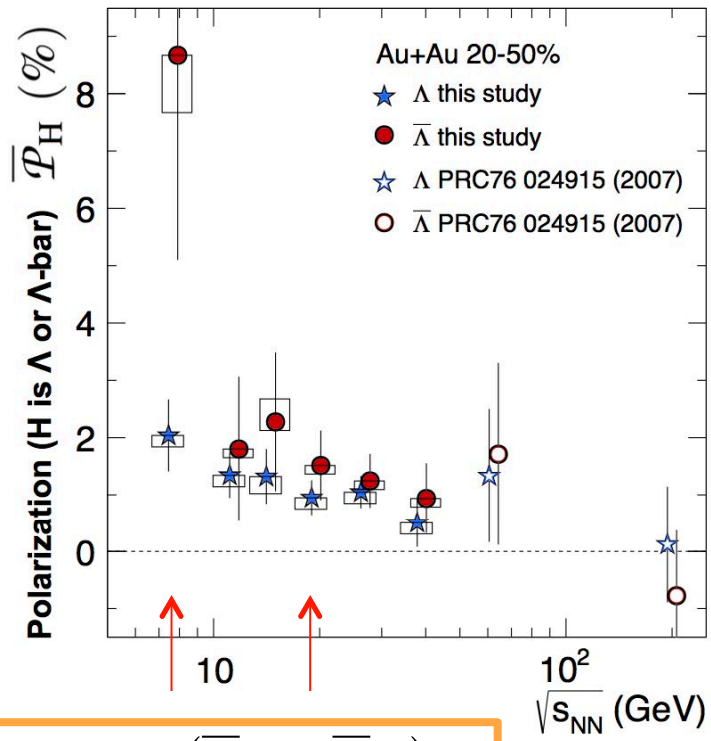
New or Improved Physics Results 2017-2018

Au+Au Vorticity: something for a plumber or Hydrodynamics theorist to love





STAR-arXiv:1701.06657 Nature **548** (2017) 62-65



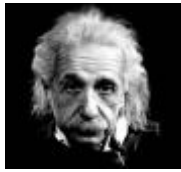
$$\omega = k_B T \left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\bar{\Lambda}'}\right)/\hbar$$

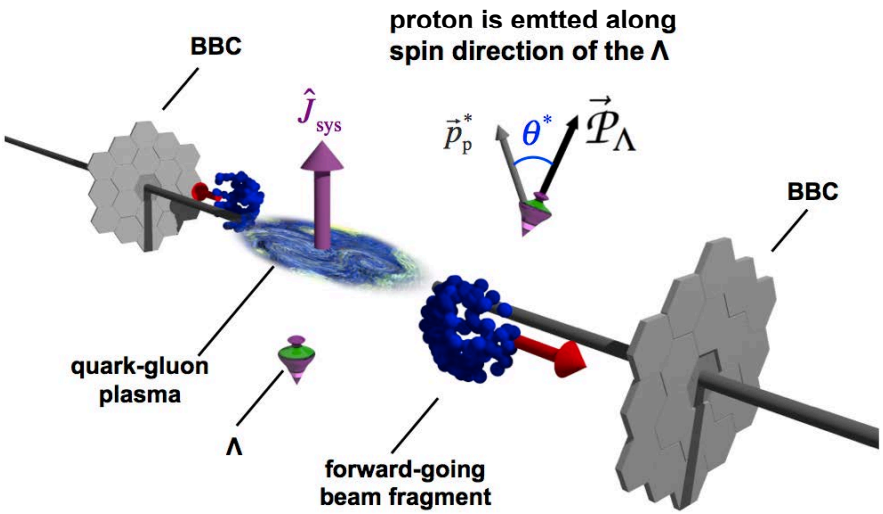
Forward Λ are polarized in p+Be collision Bunce, et al PRL 36(1976)1113.
STAR claims that this effect in Au+Au is new because Λ polarization is parallel to the angular momentum of the QGP ***J***sys everywhere

See CERN 86-07 for T.D.Lee's story of how Jack Steinberger missed parity violation of Λ decay

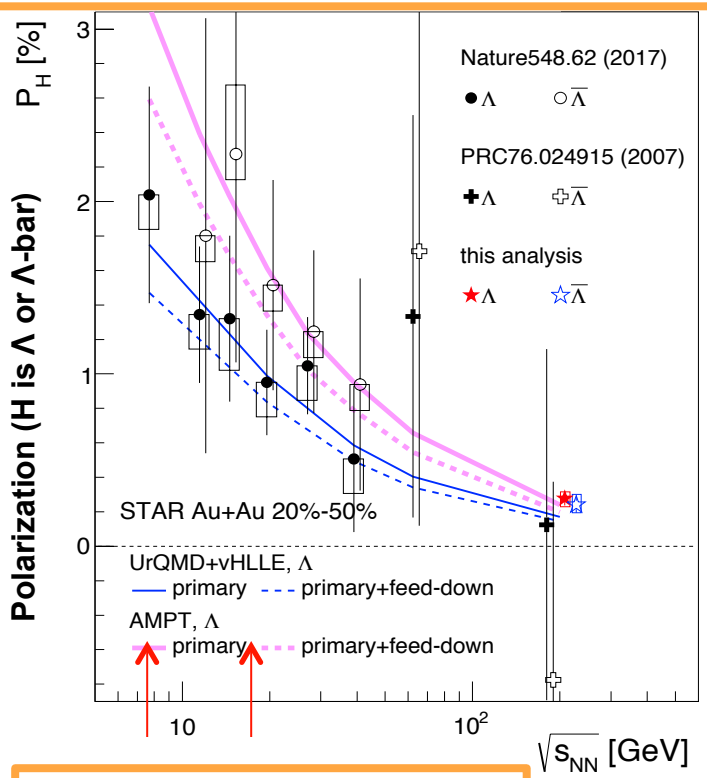
Vorticity Formula. See if you can get $\omega \sim 10^{22}$/s, 10^{15} times larger than any other fluid. But note, largest vorticity is at $\sqrt{s_{NN}}$=7.6--19GeV where CERN fixed target measures---is their fluid also perfect or ???

Au+Au Vorticity: something for a plumber or Hydrodynamics theorist to love 2018





STAR-arXiv:1805.04400 Submitted to PRC



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STAR receives an award for vorticity BUT Michael Lisa isn't there

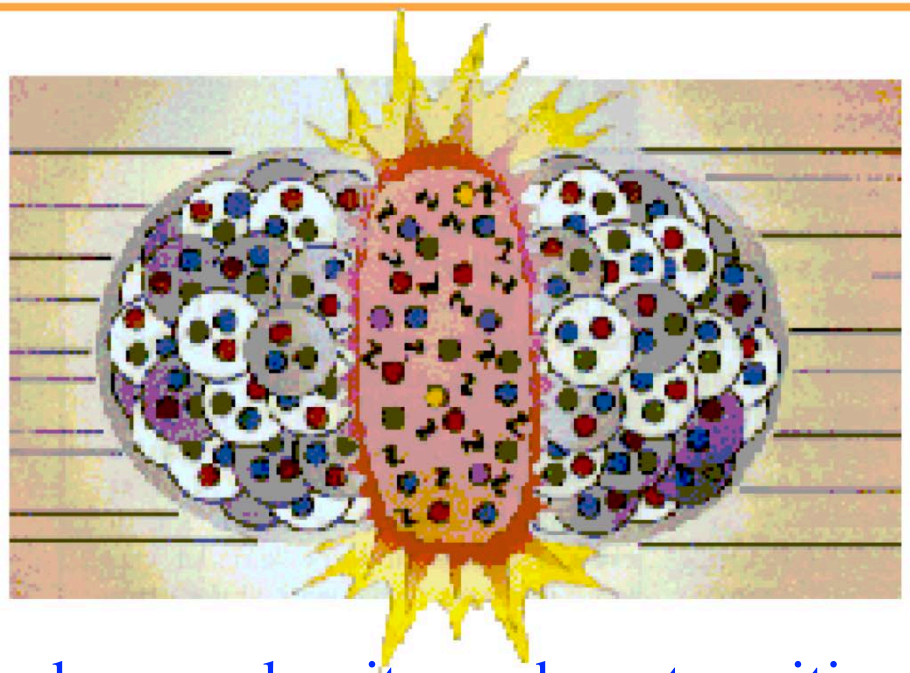
STAR Team Receives Secretary's Achievement Award

Recognition for role in enabling discovery of fastest swirling matter at U.S. Departmei of Energy Office of Science user facility for nuclear physics research

+ENLARGE Members of the STAR team at the awards ceremony (l to r): William Christie, Zhangbu Xu, Victor Perevoztchikov, Dmitry Arkhipkin, Paul Sorensen, Energy Secretary Rick Perry, Jerome Lauret, James Dunlop, Gene Van Buren, Rachel Nieves, Flemming Videbaek, Robert Scheetz, Michael Poat, Dmitri Smirnov. Not shown: Elke-Caroline Aschenauer, Wayne Betts, Leslie Bland, Timothy Camarda, Zilong Chang, Lidia Didenko, Oleg Eyser, Salvatore Fazio, Yuri Fisyak, Wlodek Guryn, Levente Hajdu, John Hammond, Jiangyong Jia, Hongwei Ke, Alexander Kiselev, Jeffery Landgraf, Alexei Lebedev, Jeong-Hun Lee, Tonko Ljubic Rongrong Ma, Liz Mogavero, Akio Ogawa, Brian Page, Robert Pak, Lijuan Ruan, John Scheblein, Bill Schmidke, Rahul Sharma,

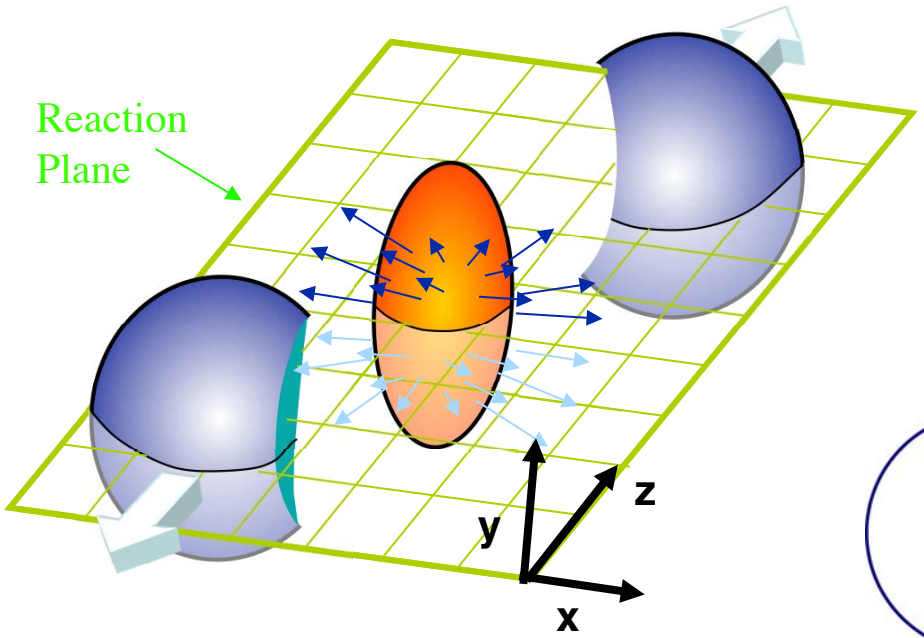
PHENIX and Collectivity but first why we are doing A+A experiments at RHIC: Searching for the Quark Gluon Plasma

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

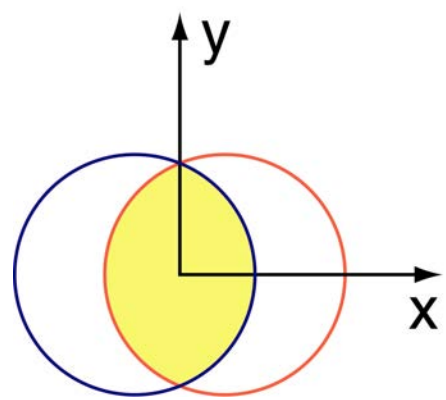


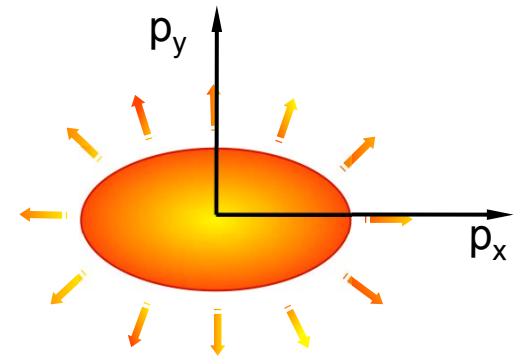
- At large energy or baryon density, a phase transition is expected from a state of nucleons containing confined quarks and gluons to a state of "deconfined" (from their individual nucleons) quarks and gluons covering a volume that is many units of the confinement length scale.

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



- spatial anisotropy⇒ momentum anisotropy





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

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

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

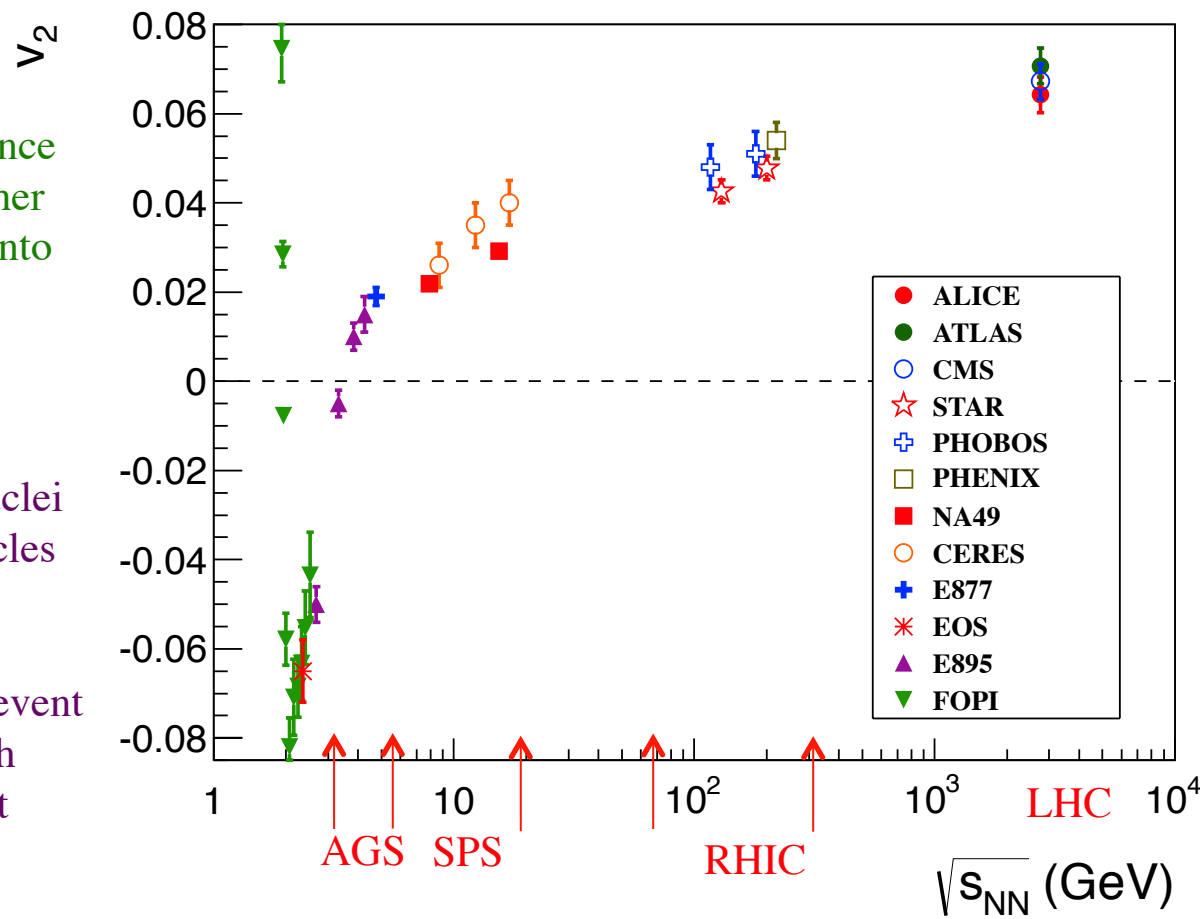
- Perform a Fourier decomposition of the momentum space particle distributions in the x-y plane
  - ✓ v_2 is the 2nd harmonic Fourier coefficient

Directed flow zero at midrapidity	Elliptical flow dominant at midrapidity

Flow exists in all A+A collisions: evidence of a collective effect of nucleons (quarks ?) Is this an indication of indication of QGP ?

Nuclei bounce off each other and break into fragments

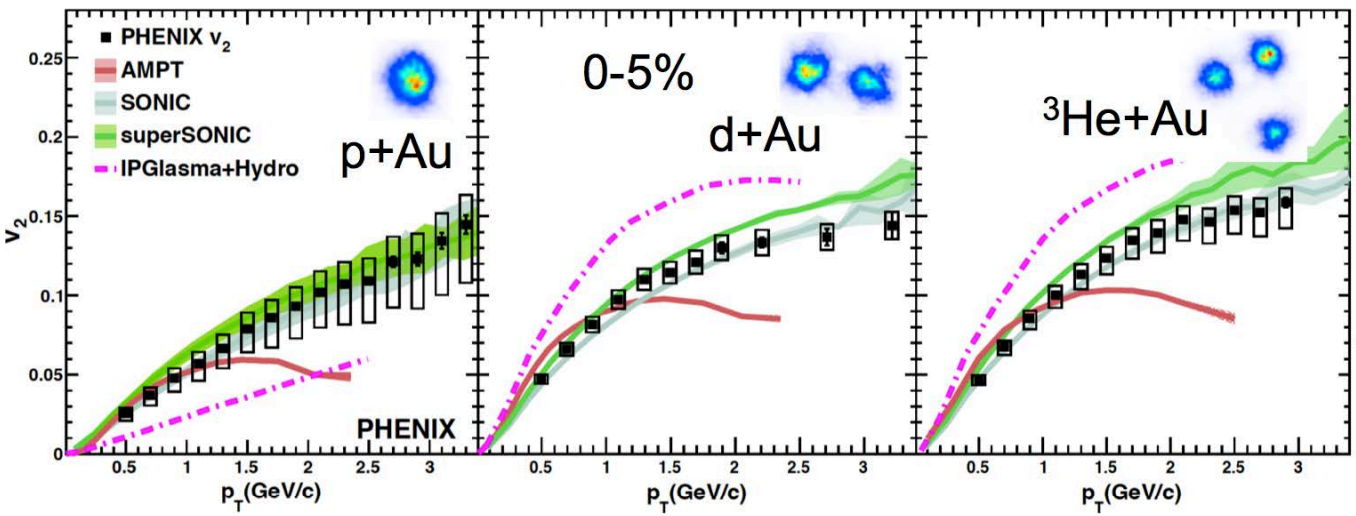
Here slow moving Nuclei make particles but block particles emitted in event plane which squeeze out vertically

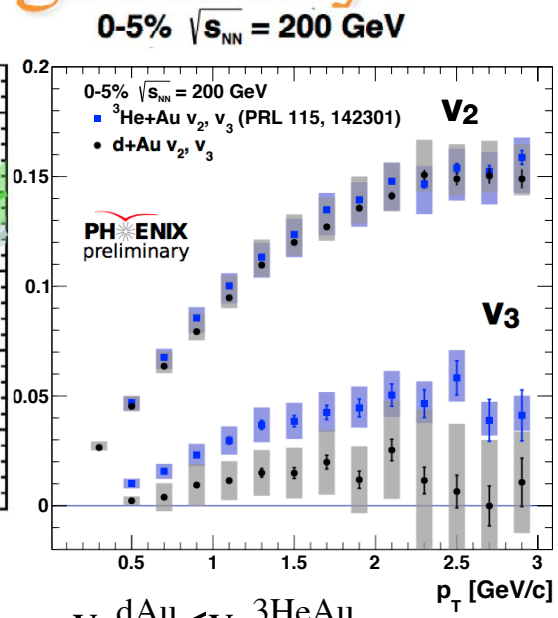


Heinz, Snellings ARNPS **63** (2013) 123-151

Flow is sensitive to the initial geometry

PRC 95 (2017) 034910 *PRL 114, 192301, (2015)* *PRL 115, 142301, (2015)*

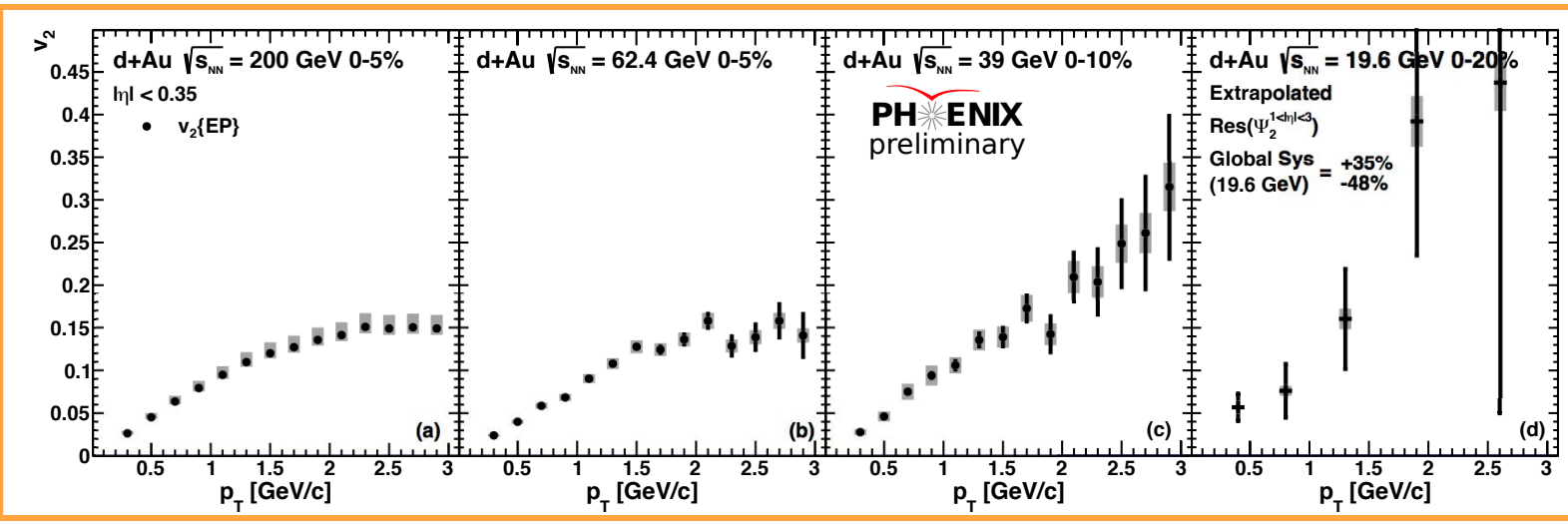




large non-flow systematic error

$v_2^{pp} < v_2^{dAu} \approx v_2^{3HeAu}$

$v_3^{dAu} < v_3^{3HeAu}$



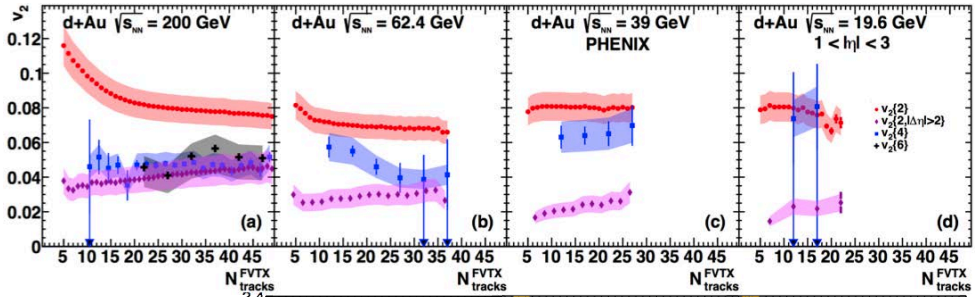
v_2^{dAu} central vs $\sqrt{s}$
Non-flow effects increase with decreasing $\sqrt{s}$

Conclusion: Flow in small systems 2018

PHENIX

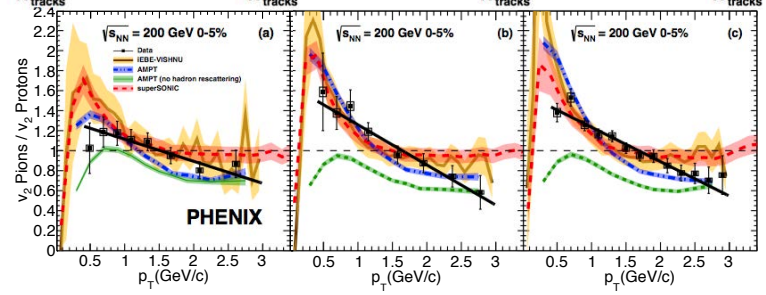
Final state correlations in lowest energy suggests short-lived QGP droplets

PRC 96, 064905 (2017) and PRL 120, 062302 (2018)



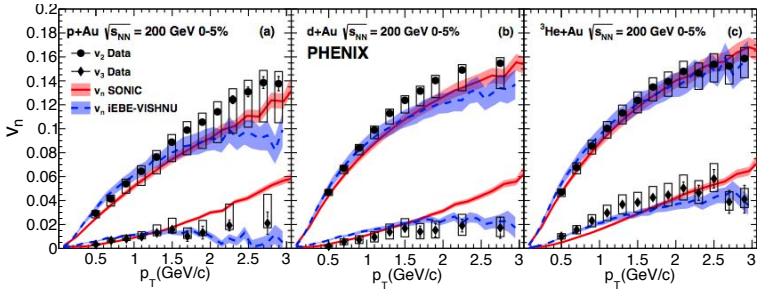
Mass ordering strengthens case for QGP droplets

arXiv:1710.09736



Flow is geometric

arXiv:1805.02973



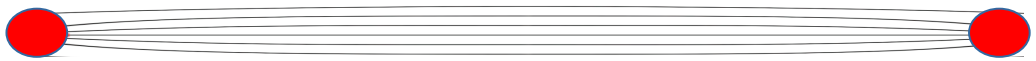
- **The collection of measurements best description is by hydro which includes QGP**
- **Strong evidence for QGP in small systems**

"It takes two to tango" Nagle, et al

PRC **97** (2018) 024909

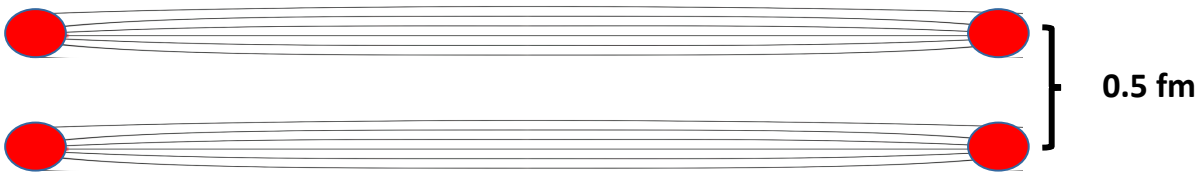
What are the minimal conditions for collectivity?

$e^+e^- \rightarrow Z_0 \rightarrow q\bar{q}$



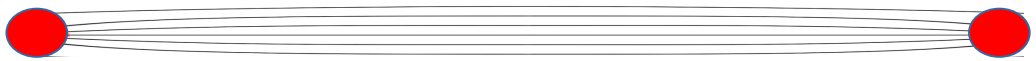
For the case of e+e– collisions utilizing the AMPT framework and a single color string. The results indicate only a modest number of parton-parton scatterings and no observable collectivity signal.

Additional Special Case – 2 Strings



However, a simple extension to two color strings which represent a simplified geometry in p + p collisions predicts finite long-range two-particle correlations (i.e., the ridge) and a strong v2 with respect to the initial parton geometry.

A fundamental point about QCD and the string tension



Unlike an electric or magnetic field between two sources which spreads over all space, in QCD as proposed by Kogut and Susskind PRD9(1974)3501 the color flux lines connecting two quarks or a q-qbar pair are constrained in a thin tube-like region because of the three-gluon coupling. Furthermore if the field contained a constant amount of color-field energy stored per unit length, this would provide a linearly rising confining potential between the q-q or q-qbar pair. This led to the Cornell potential PRL 34(1975)369 which combined the Coulomb 1/r

$$V(r) = -\frac{\alpha_s}{r} + \sigma r$$

dependence at short distances from vector-gluon exchange with a linearly rising string-like potential at large distances which provided confinement. Fragmentation is produced by the string breaking.

OK since the latest discovery claims ‘flow’ in small systems is from the QGP, how did we find the QGP in the first place

The gold-plated signature for the QGP J/ψ Suppression-1986

- 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.

With increasing temperature, T, in analogy to increasing Q^2, the strong coupling constant $\alpha_s(T)$ becomes smaller, reducing the binding energy, and the string tension, $\sigma(T)$, becomes smaller, increasing the confining radius, effectively screening the potential[Satz 2000]:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma\, r \rightarrow -\frac{4}{3}\frac{\alpha_s}{r} e^{-\mu_D\, r} + \sigma\, \frac{(1 - e^{-\mu_D\, r})}{\mu_D}$$

where $\mu_D = \mu_D(T) = 1/r_D$ is the Debye screening mass [Satz 2000]. For $r < 1/\mu_D$ a quark feels the full color charge, but for $r > 1/\mu_D$, the quark is free of the potential and the string tension, effectively deconfined. The properties of the QGP can not be calculated in QCD perturbation theory but only in Lattice QCD Calculations [Soltz 2015].

This eventually didn't work because the free c and c-bar quarks recombined to make J/ψ's. Ask somebody from ALICE for more details

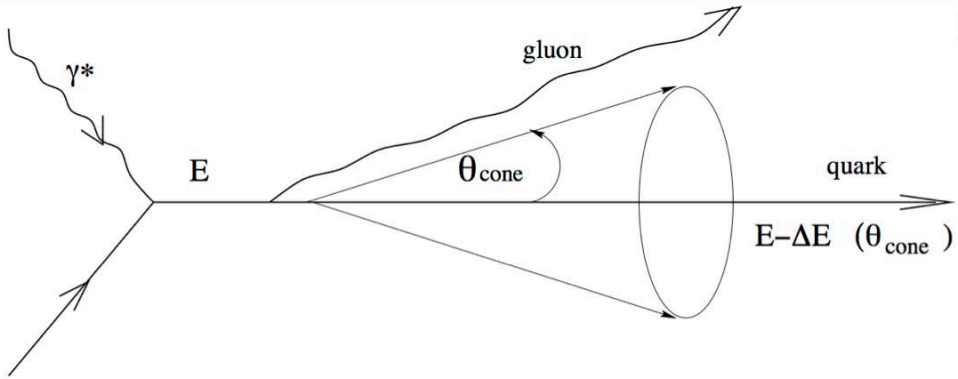
Jet Quenching: by coherent LPM radiative energy loss of a parton in the QGP-1997

In 1997, Baier, Dokshitzer, Mueller Peigne, Schiff also Zakharov, see ARNPS **50**, 37 (2000), said that the energy loss from coherent LPM radiation for hard-scattered partons exiting the QGP would "result in an attenuation of the jet energy and a broadening of the jets"

As a parton from hard-scattering in the A+B collision exits through the medium it can radiate a gluon; and both continue traversing the medium. It is important to understand that "Only the gluons radiated outside the cone defining the jet contribute to the energy loss." . In the angular ordering of QCD, the angular cone of any further emission will be restricted to be less than that of the previous emission and will end the energy loss once inside the jet cone. This doesn't work in the QGP So no energy loss occurs only when all gluons emitted by a parton are inside the jet cone. In addition to other issues this means that defining the jet cone is a BIG ISSUE—watch out for so-called trimming.

BDMPSZ-the cone, the energy loss, azimuthal broadening-QGP signature 1997

BSZ arXiv:hep-ph/0002198v2



The energy loss of the original outgoing parton, $-dE/dx$, per unit length (x) of a medium with total length L, is proportional to the total 4-momentum transfer-squared, $q^2(L)$, with the form:

$$\frac{-dE}{dx} \simeq \alpha_s \langle q^2(L) \rangle = \alpha_s \, \mu^2 \, L/\lambda_{\rm mfp} = \alpha_s \, \hat{q} \, L$$

where μ, is the mean momentum transfer per collision, and the transport coefficient $\hat{q} = \mu^2/\lambda_{\rm mfp}$ is the 4-momentum-transfer-squared to the medium per mean free path, $\lambda_{\rm mfp}$.

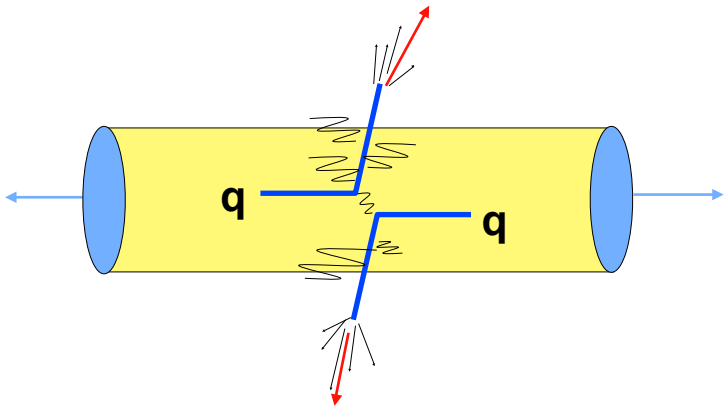
Additionally, the accumulated momentum-squared, $\langle p^2_{\perp W} \rangle$ transverse to the parton from its collisions traversing a length L in the medium is well approximated by

$$\langle p^2_{\perp W} \rangle \approx \langle q^2(L) \rangle = \hat{q} \, L.$$

Jet Quenching: a parton-medium effect
First QCD-based prediction BDMPSZ c. 1997

See Baier, Schiff, Zakharov, Ann. Rev. Nucl. Part. Sci. **50**, 37 (2000).

- Energy loss of an outgoing parton with color charge fully exposed in a medium with a large density of similarly exposed color charges (i.e. a QGP) from LPM coherent radiation of gluons is predicted in QCD by BDMPSZ.



Hard scattered partons lose energy going through the medium so that there are fewer partons or jet fragments at a given p_T The ratio of measured AA to scaled pp cross section which=1 for no energy loss is:

Lots of evidence for jet Quenching, discovered at RHIC for π^0 and $h^{\pm}$

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

PHENIX PRL 88, 022301 (2002) >1000 cites

<N_{coll}> is the number of collisions

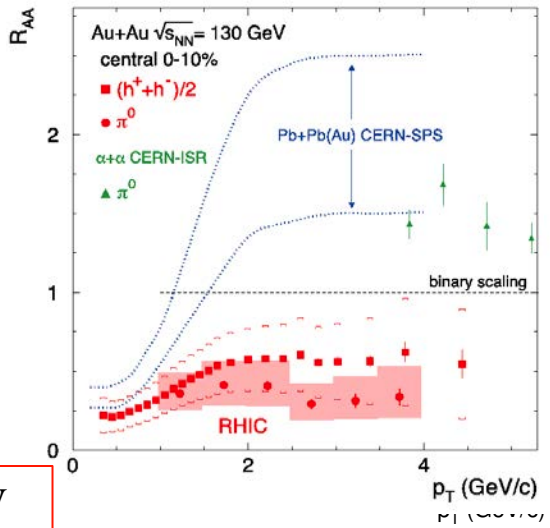
PHENIX discovered Jet Quenching at RHIC 2001

PHENIX at Quark Matter 2018

Our third paper (now well over 200 papers) Phys. Rev. Lett. 88, 022301 (2002)

HEP 1 records found Search to

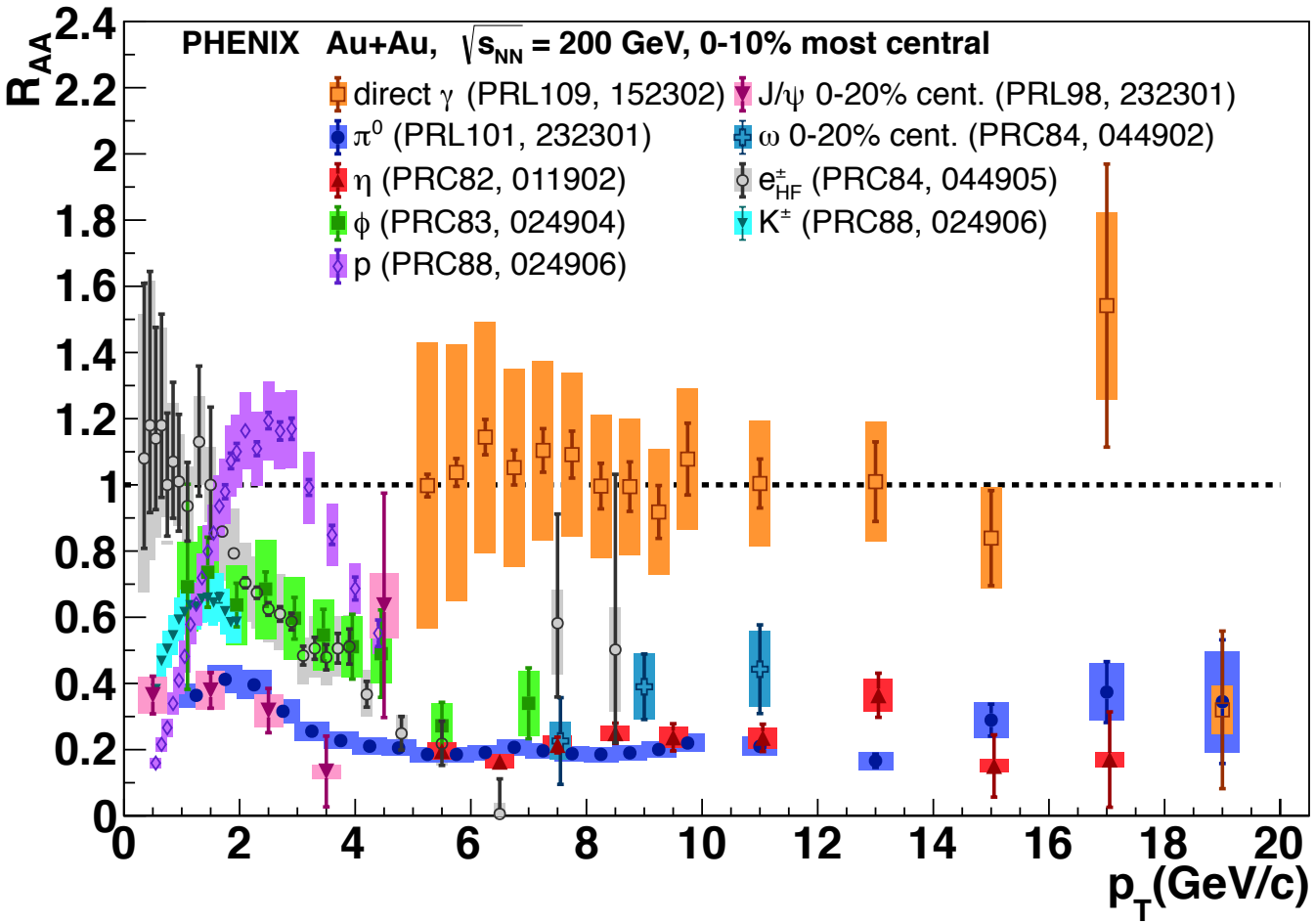
1. **Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130-GeV**
PHENIX Collaboration (K. Adcox (Vanderbilt U.) *et al.*). Sep 2001. 6 pp.
Published in **Phys.Rev.Lett. 88 (2002) 022301**
DOI: 10.1103/PhysRevLett.88.022301
e-Print: **nucl-ex/0109003** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 1000 records 1000+



First regular paper from RHIC experiment to reach 1000 citations

Pions at large $p_T > 2.5$ GeV/c suppressed in Au+Au at $\sqrt{s_{NN}}$=130 GeV compared to enhancement at CERN SpS $\sqrt{s_{NN}}$=17 GeV

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



particle ID is crucial: different particles behave differently

Notable are that ALL particles are suppressed for p_T>2 GeV/c (except for direct-γ), even electrons from c and b quark decay; with one notable exception: the protons are enhanced-(baryon anomaly)

Back to Jet Quenching and BDMPSZ.

The BDMPSZ model has 2 predictions

(1) The energy loss of the outgoing parton, $-dE/dx$, per unit length (x) of a medium with total length L, is proportional to the total 4-momentum transfer-squared, $q^2(L)$, and takes the form:

$$\frac{-dE}{dx} \simeq \alpha_s \langle q^2(L) \rangle = \alpha_s \, \mu^2 \, L/\lambda_{\rm mfp} = \alpha_s \, \hat{q} \, L$$

where μ, is the mean momentum transfer per collision, and the transport coefficient $\hat{q} = \mu^2/\lambda_{\rm mfp}$ is the 4-momentum-transfer-squared to the medium per mean free path, $\lambda_{\rm mfp}$.

(2) Additionally, the accumulated momentum-squared, $\langle p^2_{\perp W} \rangle$ transverse to a parton traversing a length L in the medium is well approximated by

$$\langle p^2_{\perp W} \rangle \approx \langle q^2(L) \rangle = \hat{q} \, L \qquad \boxed{\langle \hat{q} L \rangle = \langle k_T^2 \rangle_{AA} - \left\langle k_T'^2 \right\rangle_{pp}}$$

Although only the component of $\langle p^2_{\perp W} \rangle \perp$ to the scattering plane affects k_T, the azimuthal broadening of the di-jet is caused by the random sum of the azimuthal components $\langle p^2_{\perp W} \rangle /2$ from each outgoing di-jet or $\langle p^2_{\perp W} \rangle = \hat{q} \, L$

The BDMPSZ model has 2 predictions

(1) The energy loss of the outgoing parton, $-dE/dx$, per unit length (x) of a medium with total length L, is proportional to the total 4-momentum transfer-squared, $q^2(L)$, and takes the form:

$$\frac{-dE}{dx} \simeq \alpha_s \langle q^2(L) \rangle = \alpha_s \, \mu^2 \, L/\lambda_{\rm mfp} = \alpha_s \, \hat{q} \, L$$

where μ, is the mean momentum transfer per collision, and the transport coefficient $\hat{q} = \mu^2/\lambda_{\rm mfp}$ is the 4-momentum-transfer-squared to the medium per mean free path, $\lambda_{\rm mfp}$.

(2) Additionally, the accumulated momentum-squared, $\langle p^2_{\perp W} \rangle$ transverse to a parton traversing a length L in the medium is well approximated by

$$\langle p^2_{\perp W} \rangle \approx \langle q^2(L) \rangle = \hat{q} \, L \qquad \boxed{\langle \hat{q} L \rangle = \langle k_T^2 \rangle_{AA} - \langle k'^2_T \rangle_{pp}}$$

From R_{AA} observed at RHIC (after 12 years) the JET Collab. PRC **90** (2014) 014909 has found that $\hat{q}$ = 1.2±0.3 GeV^2/fm at RHIC, 1.9± 0.7 at LHC at initial time τ_0=0.6 fm/c but nobody has yet measured the azimuthal broadening predicted in (2) !

The key new idea (k'_T) gives elegant Solutions

The di-hadron correlations of p_{Tt} with p_{Ta} are measured in p+p and Au+Au collisions. The parent jets in the original Au+Au collision as measured in p+p will both lose energy passing through the medium but the azimuthal angle between the jets should not change unless the medium induces multiple scattering from $\hat{q}$. Thus the calculation of k'_T from the dihadron p+p mesurement to compare with Au+Au measurements with the same di-hadron p_{Tt} and p_{Ta} must use the value of $\hat{x}_h$ and $\langle z_t \rangle$ of the parent jets in the A+A collision. $x_h = p_{Ta}/p_{Tt} \quad \hat{x}_h = \hat{p}_{Ta}/\hat{p}_{Tt} \quad \langle z_t \rangle = p_{Tt}/\hat{p}_{Tt}$

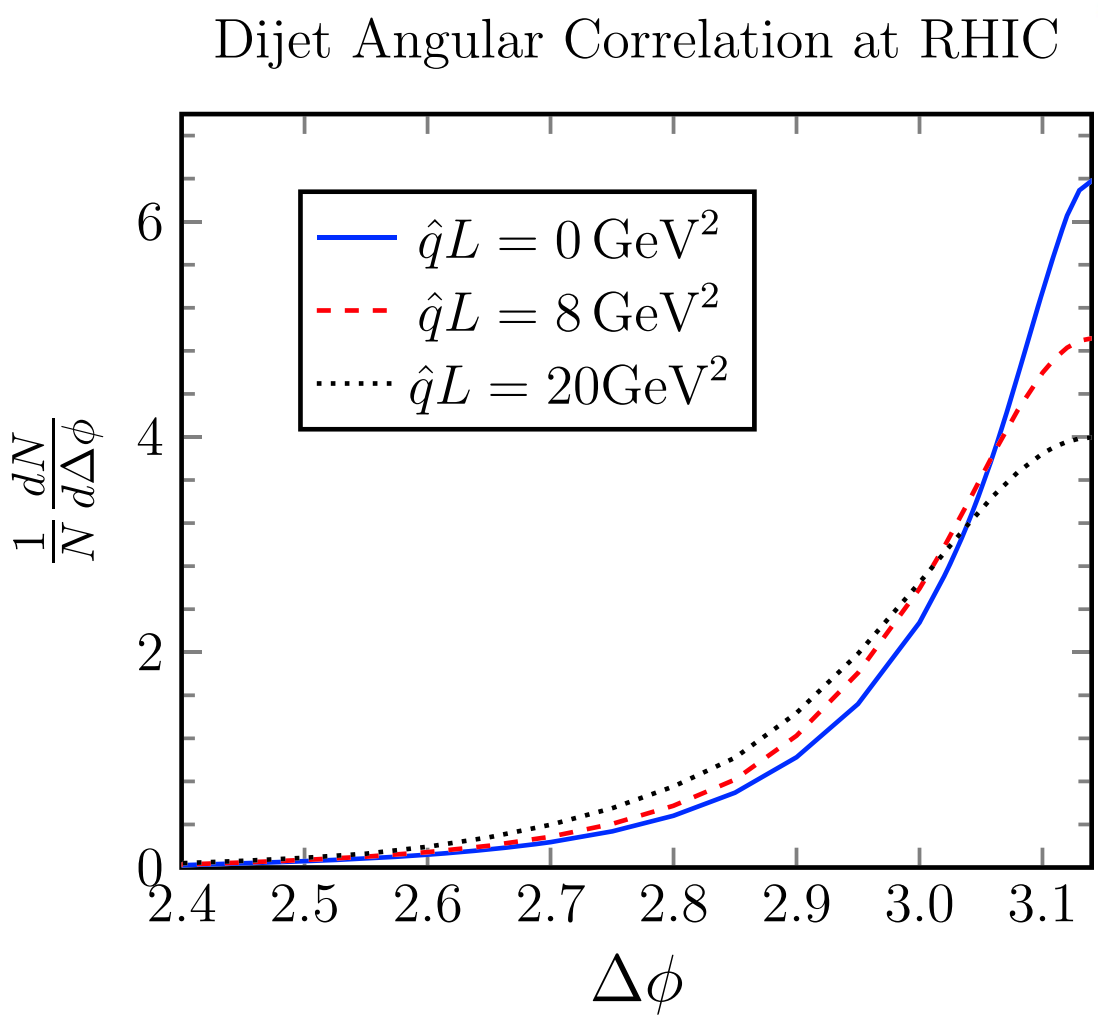
The same values of $\hat{x}_h$, and $\langle z_t \rangle$ in Au+Au and p+p gives the cool result:

$$\langle \hat{q}L \rangle = \left[\frac{\hat{x}_h}{\langle z_t \rangle}\right]^2 \left[\frac{\langle p^2_{\rm out}\rangle_{AA} - \langle p^2_{\rm out}\rangle_{pp}}{x_h^2}\right]$$

For di-jet measurements, the formula is even simpler:
i) $x_h \equiv \hat{x}_h$ because the trigger and away 'particles' are the jets; ii) $\langle z_t \rangle \equiv 1$ because the trigger 'particle' is the entire jet not a fragment of the jet;
iii) $\langle p^2_{\rm out}\rangle = \hat{p}^2_{Ta}\sin^2(\pi - \Delta\phi)$. This reduces the formula for di-jets to:

$$\langle \hat{q}L \rangle = \left[\langle p^2_{\rm out}\rangle_{AA} - \langle p^2_{\rm out}\rangle_{pp}\right] = \hat{p}^2_{Ta}\left[\langle \sin^2(\pi - \Delta\phi)\rangle_{AA} - \langle \sin^2(\pi - \Delta\phi)\rangle_{pp}\right]$$

Homework



A.Mueller et al PLB **763** (2016) 208
predictions for 35 GeV/c Jets at RHIC

$$\langle \hat{q}L \rangle = \left[\langle p^2_{\mathrm{out}} \rangle_{AA} - \langle p^2_{\mathrm{out}} \rangle_{pp} \right]$$

Does the formula give the same answer for qhatL from $\langle p^2_{out} \rangle$ of the above predictions at RHIC for 35 GeV Jets?
I got 9.7 GeV^2 and 21.5 GeV^2 respectively for the 8 GeV^2 and 20 GeV^2 plots

Find di-jet info from di-hadrons and $\langle z_t \rangle$

$$\langle \hat{q}L \rangle = \left[\frac{\hat{x}_h}{\langle z_t \rangle} \right]^2 \left[\frac{\langle p^2_{\rm out} \rangle_{AA} - \langle p^2_{\rm out} \rangle_{pp}}{x_h^2} \right]$$

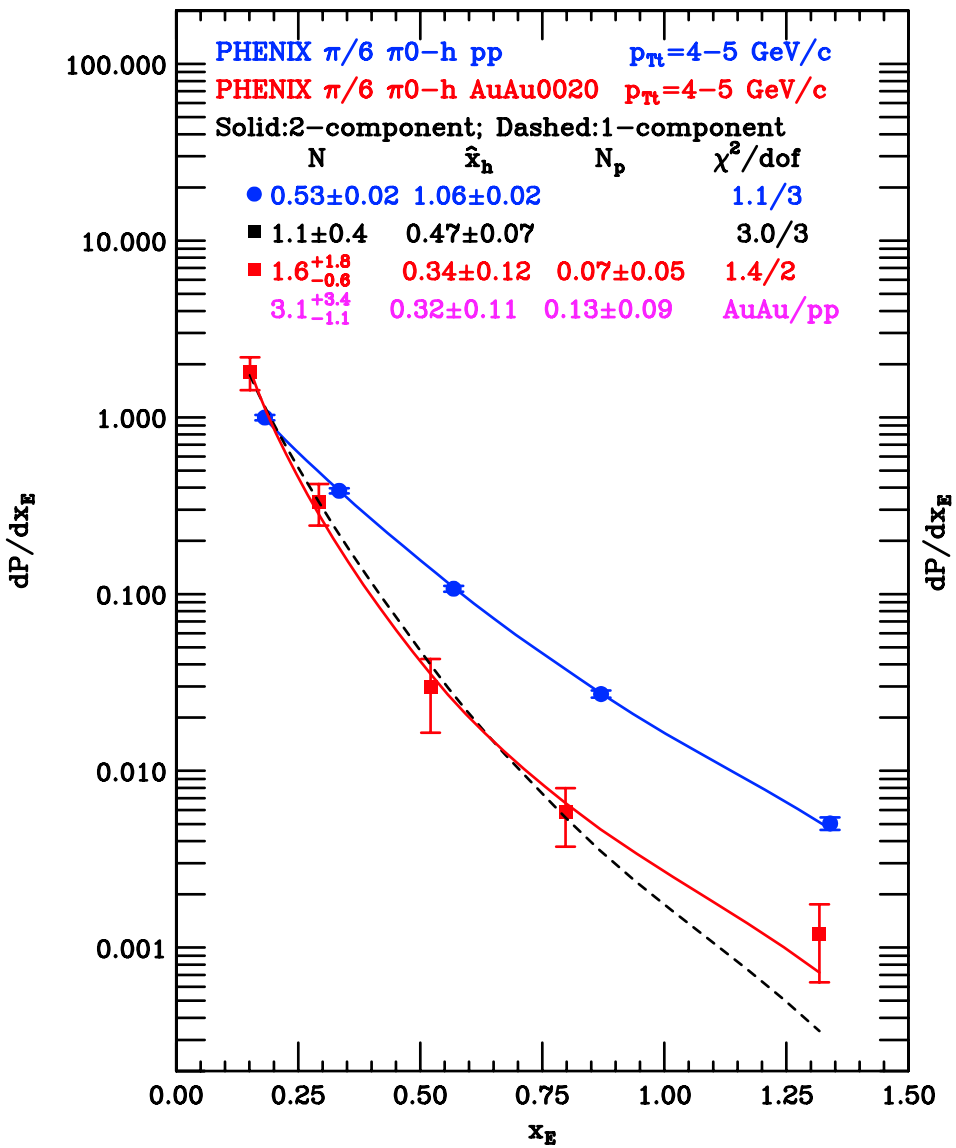
This is well known to older PHENIXians who have read PRD74(2006)072002, or my book [Rak & Tannenbaum, High pT physics in the Heavy Ion Era –Cambridge 2013] as outlined below

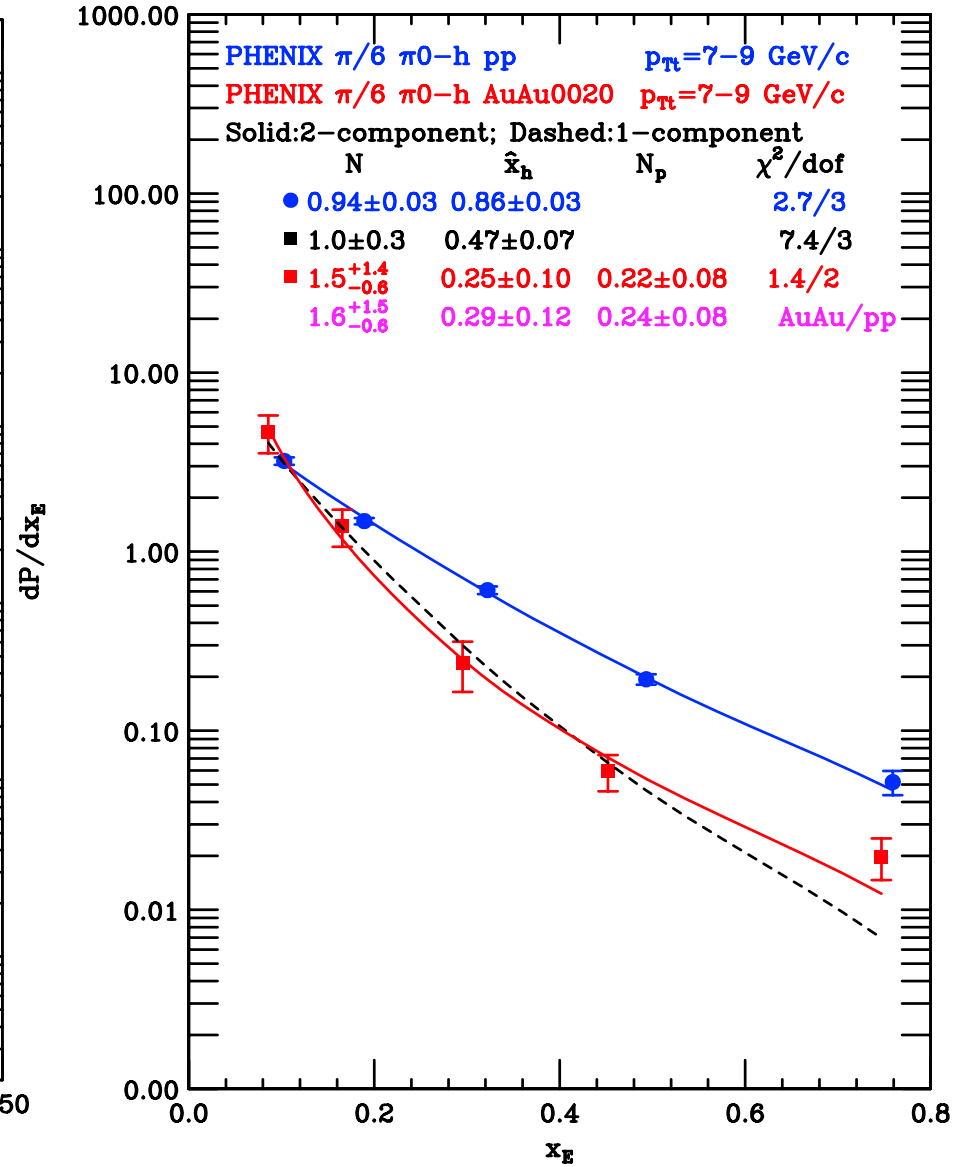
- A) Bjorken parent-child relation and `trigger-bias' gives $\langle z_t \rangle$
- B) The energy loss of the trigger jet from p+p to Au+Au can be measured by the shift PRC87(2013) 034911
- C) \hat{x}_h the ratio of the away-jet to the trigger jet transverse moments can be measured by the away particle p_{Ta} distribution for a given trigger particle p_{Tt}

n=8.1 for 200 GeV

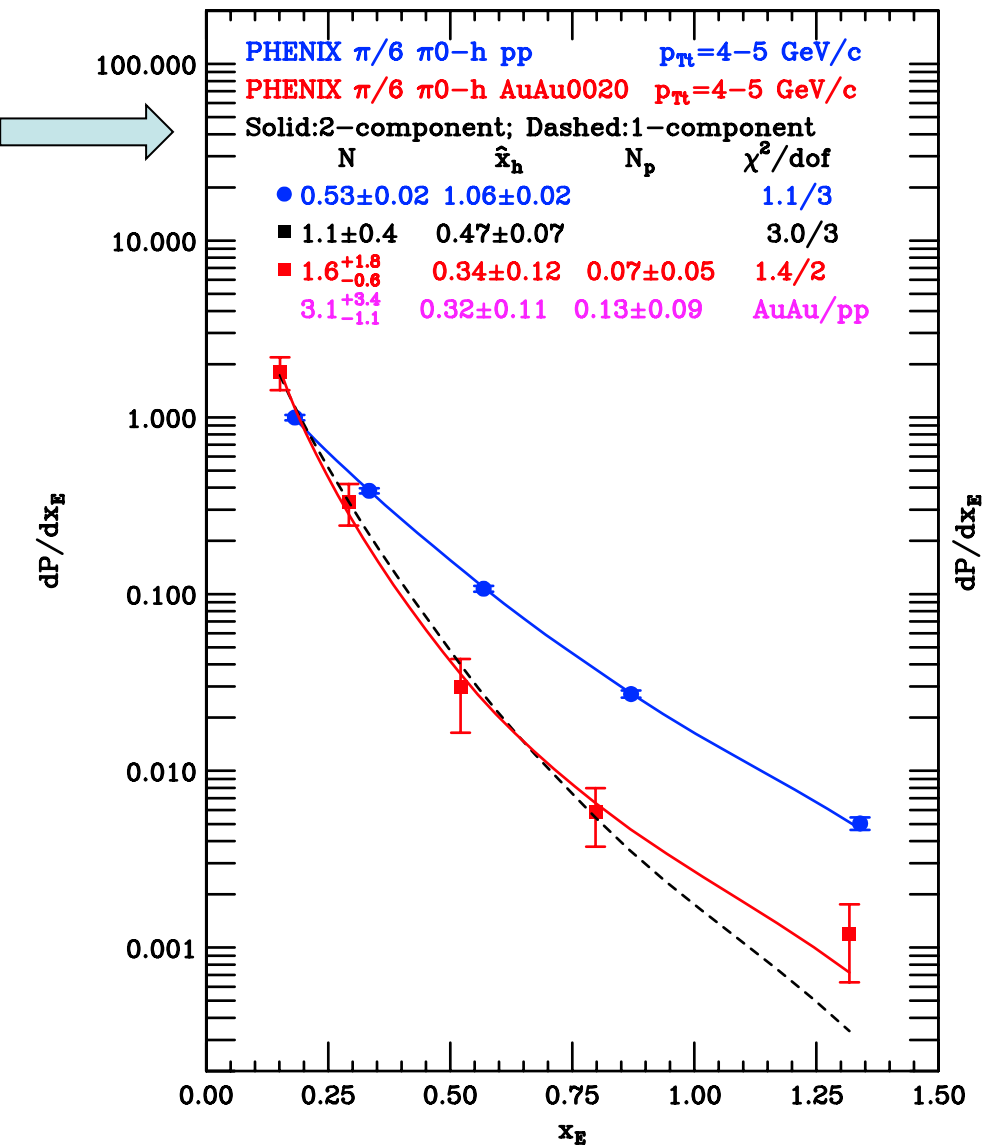
$$\left. \frac{dP_\pi}{dx_E} \right|_{p_{T_t}} \approx N(n-1) \frac{1}{\hat{x}_h} \frac{1}{(1 + \frac{x_E}{\hat{x}_h})^n}$$

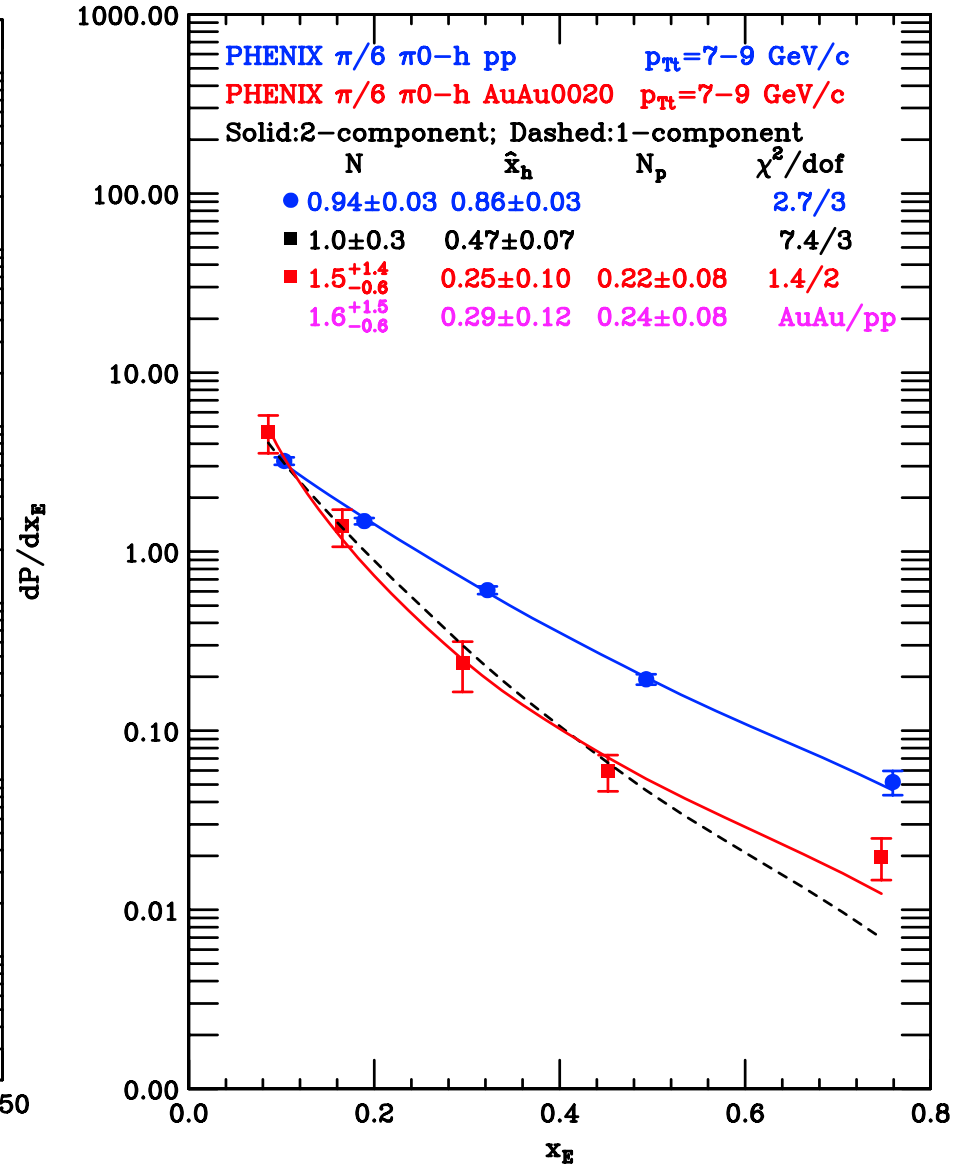
\hat{x}_h from fits to the PX PRL104 data





\hat{x}_h from fits to the PX PRL104 data





Results from STAR PLB760(2016)689 as given by MJT in PLB771(2017)553

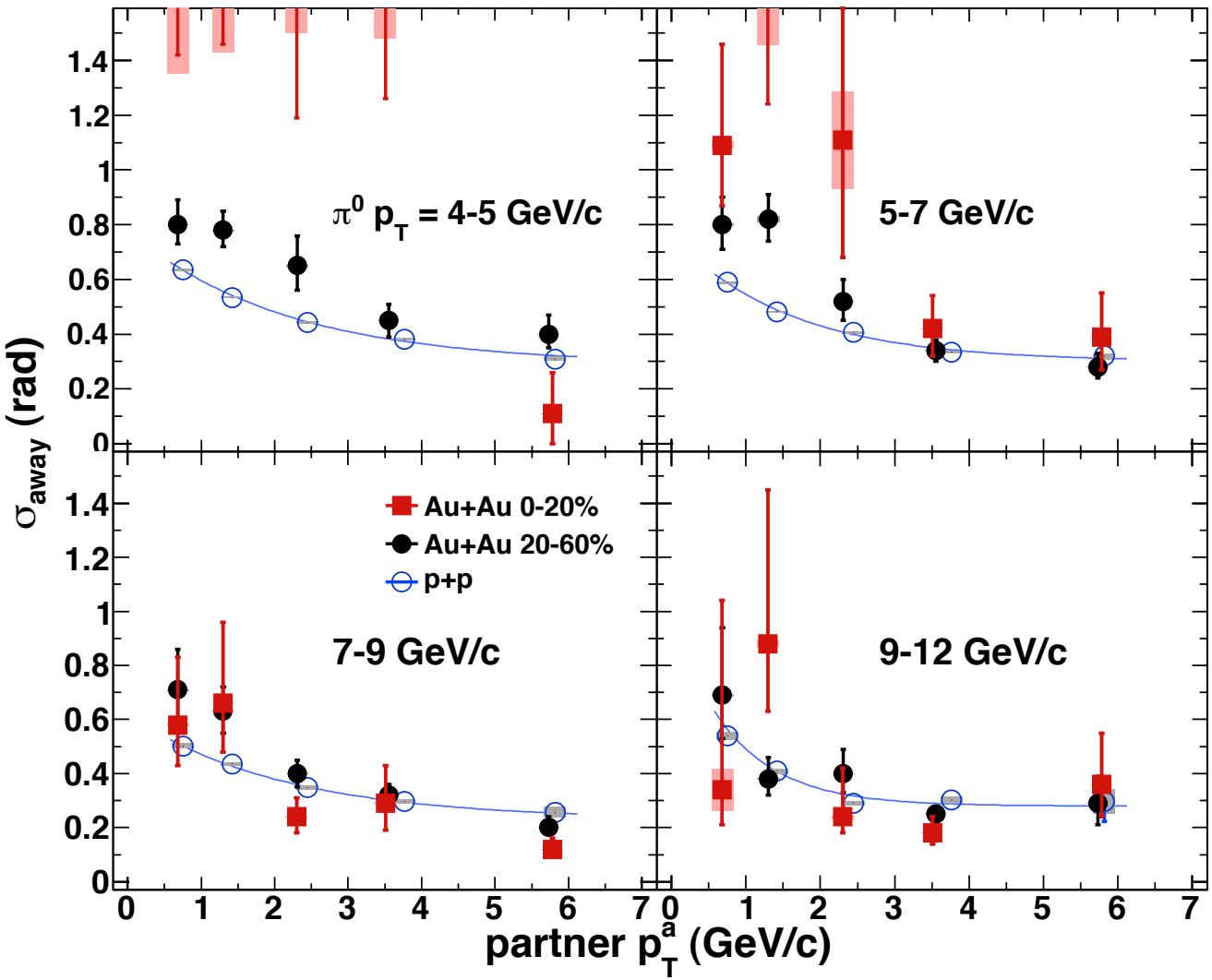
with a few corrections

Table 18: Tabulations for $\hat{q}$–STAR π^0-h: $12 < p_{Tt} < 20$ GeV/c 00-12% Centrality

STAR PLB771						
$\sqrt{s_{NN}} = 200$	$\langle p_{Tt} \rangle$	$\langle p_{Ta} \rangle$	$\langle z_t \rangle$	$\hat{x}_h$	$\langle p^2_{\rm out} \rangle$	$\sqrt{\langle k^2_T \rangle}$
Reaction	GeV/c	GeV/c		GeV/c		GeV/c
p+p	14.71	1.72	0.80 ± 0.05	0.84 ± 0.04	0.263 ± 0.113	2.34 ± 0.34
p+p	14.71	3.75	0.80 ± 0.05	0.84 ± 0.04	0.576 ± 0.167	2.51 ± 0.31
Au+Au 00-12%	14.71	1.72	0.80 ± 0.05	0.36 ± 0.05	0.547 ± 0.163	2.28 ± 0.35
Au+Au 00-12%	14.71	3.75	0.80 ± 0.05	0.36 ± 0.05	0.851 ± 0.203	1.42 ± 0.22
p+p comp	14.71	1.72	0.80 ± 0.05	0.36 ± 0.05	0.263 ± 0.113	1.006 ± 0.18
p+p comp	14.71	3.75	0.80 ± 0.05	0.36 ± 0.05	0.576 ± 0.167	1.076 ± 0.18
						$\langle \hat{q}L \rangle$ GeV^2
Au+Au 00-12%	14.71	1.72				4.21 ± 3.24*
Au+Au 00-12%	14.71	3.75				0.86 ± 0.87*

The errors on the STAR $\langle \hat{q}L \rangle$ GeV^2 are much larger than stated in my publication using the STAR data [15] because I made an error by incorrectly calculating Eq. 44 which is correct. Interestingly neither referee caught this because all they had to do was use Eq. 5 since the necessary information with correct errors was given in the Tables. For the present work, the errors are correct. Also, the new values reflect that Eq. 5 defines $\langle \hat{q}L \rangle$ not $\langle \hat{q}L \rangle /2$.

Fig 2 from PHENIX PRL104,252301(2010) shows the away widths



Some qhatL results from PRL104 Fig2

Table 8: Tabulations for $\hat{q}$–PHENIX π^0-h: $5 < p_{Tt} < 7$ GeV/c 20-60% Centrality (Fig. 13)

PHENIX PRL104						
$\sqrt{s_{NN}} = 200$	$\langle p_{Tt} \rangle$	$\langle p_{Ta} \rangle$	$\langle z_t \rangle$	$\hat{x}_h$	$\langle p^2_{\rm out} \rangle$	$\sqrt{\langle k^2_T \rangle}$
Reaction	GeV/c	GeV/c		GeV/c		GeV/c
p+p	5.78	1.42	0.60 ± 0.06	0.96 ± 0.02	0.434 ± 0.010	3.13 ± 0.37
p+p	5.78	2.44	0.60 ± 0.06	0.96 ± 0.02	0.934 ± 0.031	3.18 ± 0.34
p+p	5.78	3.76	0.60 ± 0.06	0.96 ± 0.02	1.523 ± 0.061	2.74 ± 0.29
p+p	5.78	5.82	0.60 ± 0.06	0.96 ± 0.02	3.339 ± 0.351	2.73 ± 0.32
Au+Au 20-60%	5.78	1.30	0.62 ± 0.06	0.69 ± 0.05	0.867 ± 0.116	4.04 ± 0.61
Au+Au 20-60%	5.78	2.31	0.62 ± 0.06	0.69 ± 0.05	1.291 ± 0.308	2.88 ± 0.54
Au+Au 20-60%	5.78	3.55	0.62 ± 0.06	0.69 ± 0.05	1.370 ± 0.249	1.90 ± 0.32
Au+Au 20-60%	5.78	5.73	0.62 ± 0.06	0.69 ± 0.05	2.562 ± 0.620	1.66 ± 0.31
p+p comp	5.78	1.30	0.62 ± 0.06	0.69 ± 0.05	0.434 ± 0.010	2.39 ± 0.32
p+p comp	5.78	2.31	0.62 ± 0.06	0.69 ± 0.05	0.934 ± 0.031	2.34 ± 0.29
p+p comp	5.78	3.55	0.62 ± 0.06	0.69 ± 0.05	1.522 ± 0.061	2.03 ± 0.25
p+p comp	5.783	5.73	0.62 ± 0.06	0.69 ± 0.05	3.339 ± 0.351	1.93 ± 0.26
					$\langle \hat{q}L \rangle$ .01	$\langle \hat{q}L \rangle$ GeV^2
Au+Au 20-60%	5.78	1.30			6.9 ± 3.6	10.6 ± 3.8
Au+Au 20-60%	5.78	2.31			2.3 ± 2.1	2.8 ± 2.4
Au+Au 20-60%	5.78	3.55			0.35 ± 0.93	-0.5 ± 0.9
Au+Au 20-60%	5.78	5.73			-0.75 ± 1.0	-1.0 ± 0.9

More qhatL results from PRL104 Fig2

Table 10: Tabulations for $\hat{q}$–PHENIX π^0-h: $7 < p_{Tt} < 9$ GeV/c 20-60% Centrality (Fig. 13)

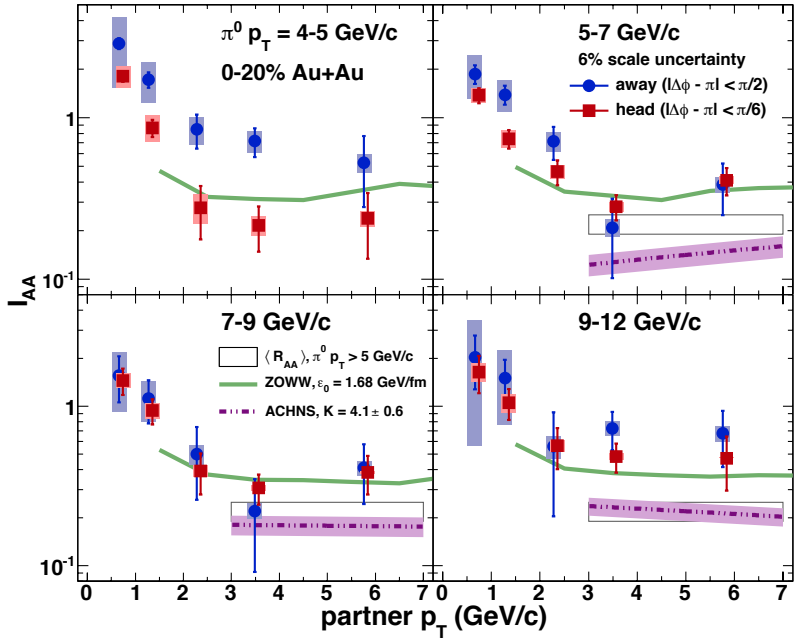
PHENIX PRL104						
$\sqrt{s_{NN}} = 200$	$\langle p_{Tt} \rangle$	$\langle p_{Ta} \rangle$	$\langle z_t \rangle$	$\hat{x}_h$	$\langle p^2_{\rm out} \rangle$	$\sqrt{\langle k^2_T \rangle}$
Reaction	GeV/c	GeV/c		GeV/c		GeV/c
p+p	7.83	1.42	0.64 ± 0.06	0.86 ± 0.03	0.360 ± 0.017	2.98 ± 0.41
p+p	7.83	2.44	0.64 ± 0.06	0.86 ± 0.03	0.694 ± 0.048	2.99 ± 0.34
p+p	7.83	3.76	0.64 ± 0.06	0.86 ± 0.03	1.213 ± 0.109	2.76 ± 0.32
p+p	7.83	5.82	0.64 ± 0.06	0.86 ± 0.03	2.177 ± 0.424	2.48 ± 0.38
Au+Au 20-60%	7.83	1.30	0.66 ± 0.06	0.62 ± 0.04	0.548 ± 0.107	3.35 ± 0.64
Au+Au 20-60%	7.83	2.31	0.66 ± 0.06	0.62 ± 0.04	0.803 ± 0.177	2.45 ± 0.46
Au+Au 20-60%	7.83	3.55	0.66 ± 0.06	0.62 ± 0.04	1.237 ± 0.232	2.08 ± 0.34
Au+Au 20-60%	7.83	5.73	0.66 ± 0.06	0.62 ± 0.04	1.300 ± 0.350	1.29 ± 0.27
p+p comp	7.83	1.30	0.66 ± 0.06	0.62 ± 0.04	0.360 ± 0.017	2.28 ± 0.33
p+p comp	7.83	2.31	0.66 ± 0.06	0.62 ± 0.04	0.694 ± 0.048	2.22 ± 0.28
p+p comp	7.83	3.55	0.66 ± 0.06	0.62 ± 0.04	1.213 ± 0.109	2.05 ± 0.26
p+p comp	7.83	5.73	0.66 ± 0.06	0.62 ± 0.04	2.177 ± 0.424	1.76 ± 0.28
					$\langle \hat{q}L \rangle$ .01	$\langle \hat{q}L \rangle$ GeV^2
Au+Au 20-60%	7.83	1.30			9.3 ± 6.3	6.0 ± 3.7
Au+Au 20-60%	7.83	2.31			2.4 ± 2.2	1.1 ± 1.9
Au+Au 20-60%	7.83	3.55			1.0 ± 1.2	0.11 ± 1.1
Au+Au 20-60%	7.83	5.73			-1.2 ± 1.0	-1.4 ± 1.0

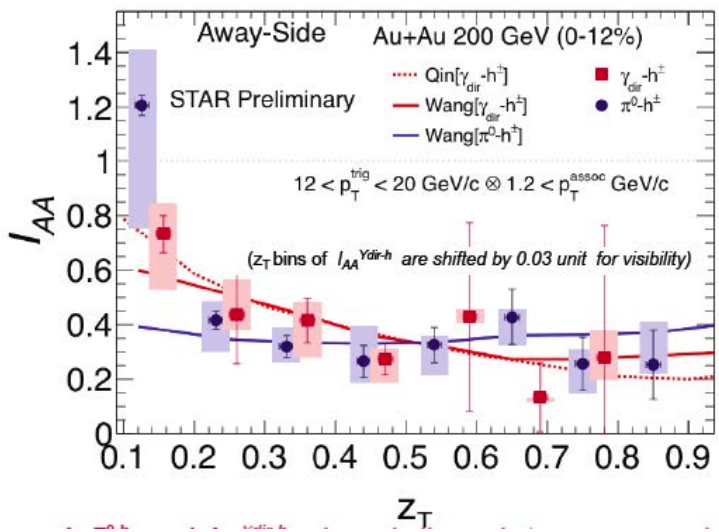
Conclusion

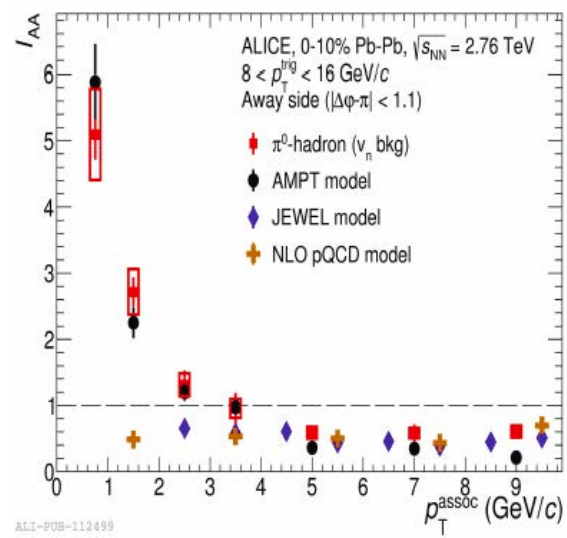
It appears that the method works and gives consistent results for all the data shown. In the lowest $p_{Ta} \sim 1.5$ GeV/c bin the results are all consistent with the JET collaboration [Phys. Rev. C**90**, 014909 (2014)] result, $\hat{q} = 1.2 \pm 0.3$ GeV^2/fm or $\hat{q}L \approx 8.4 \pm 2.1$ GeV^2 for $L = 7$fm, the diameter of an Au nucleus. However for $p_{Ta} > 2.0$ GeV/c all the results are consistent with $\hat{q}L = 0$. Personally I think that this is where the first gluon emitted in the medium was inside the jet cone, so that there is no evident suppression; or that jets with hard fragments close to the axis don't lose energy in the QGP. I think that this also agrees with the observation that three orders of magnitude down in the x_E aka (STAR z_T) distributions the A+A best fit is parallel to the p+p measurement which means no energy loss from the jets beyond this value. This is consistent with all the $I_{AA} = p_{Ta}/p_{Tt}$ distributions ever measured which decrease with increasing p_{Ta} until $p_{Ta} \approx 3$ GeV/c and then become constant because the A+A and p+p distributions are parallel.

PHENIX PRL104,252301(2010)

Some I_{AA} distributions all flat for p_{Ta}>3 GeV/c



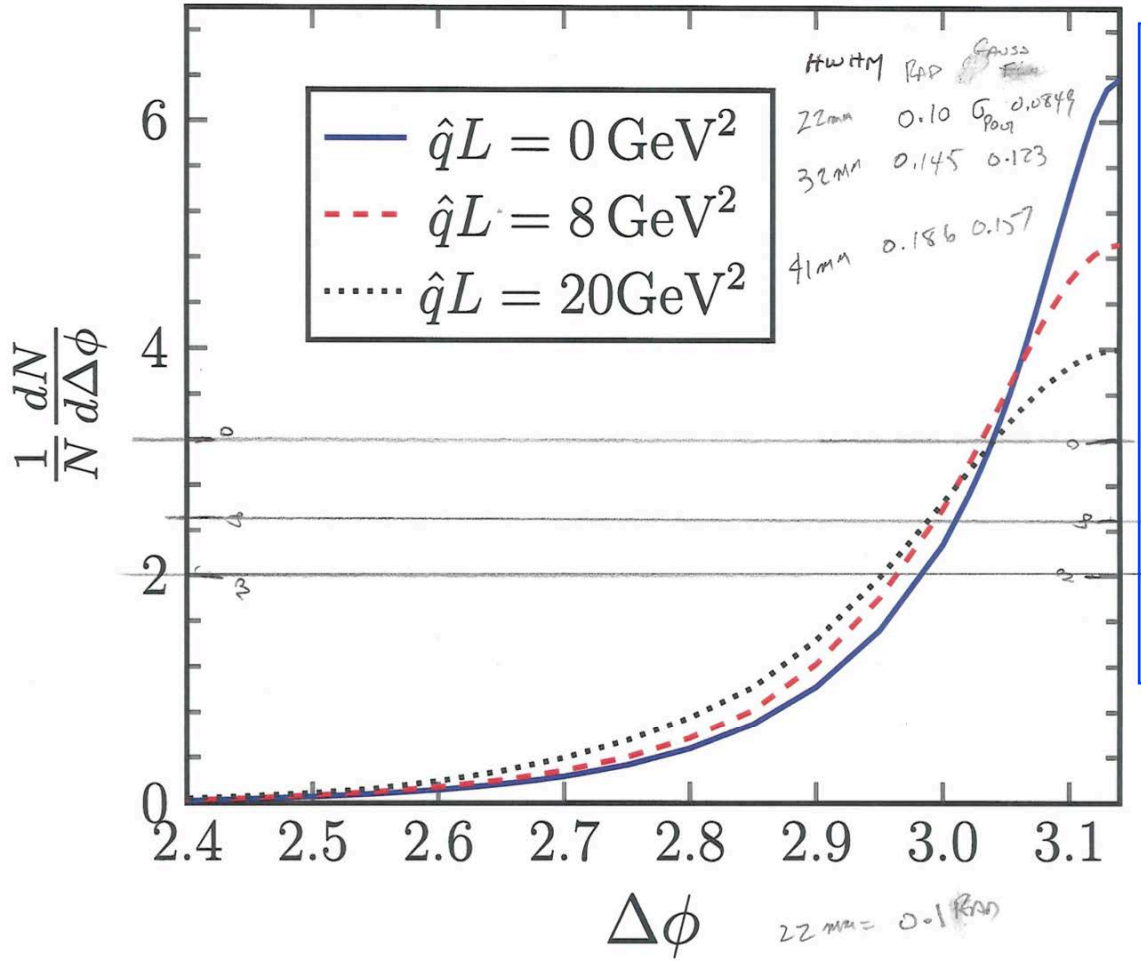




THE END

For More Info on the latest BNL results check Quark Matter 2018 https://qm2018.infn.it

My method and answer



A.Mueller et al PLB **763** (2016) 208 predictions for 35 GeV/c Jets at RHIC

The theorists don't give numbers for the curves, so I assumed gaussians and measured the half width at half maximum, which for a gaussian is 1.177 σ. i.e. σ=hwhmax/1.177.

Assuming that the peak is symmetric about π, I calculated $\langle p_{out}^2\rangle=(35*\sin\sigma)^2$ and used

$$\langle \hat{q}L\rangle = \left[\langle p_{\mathrm{out}}^2\rangle_{AA} - \langle p_{\mathrm{out}}^2\rangle_{pp}\right]$$

I got 9.7 GeV^2 and 21.5 GeV^2 for the 8 GeV^2 and 20 GeV^2 plots

Δ Pout RMS = 8 9.68 20 21.5

$\hat{q}L = \times$ Δ Pout RMS

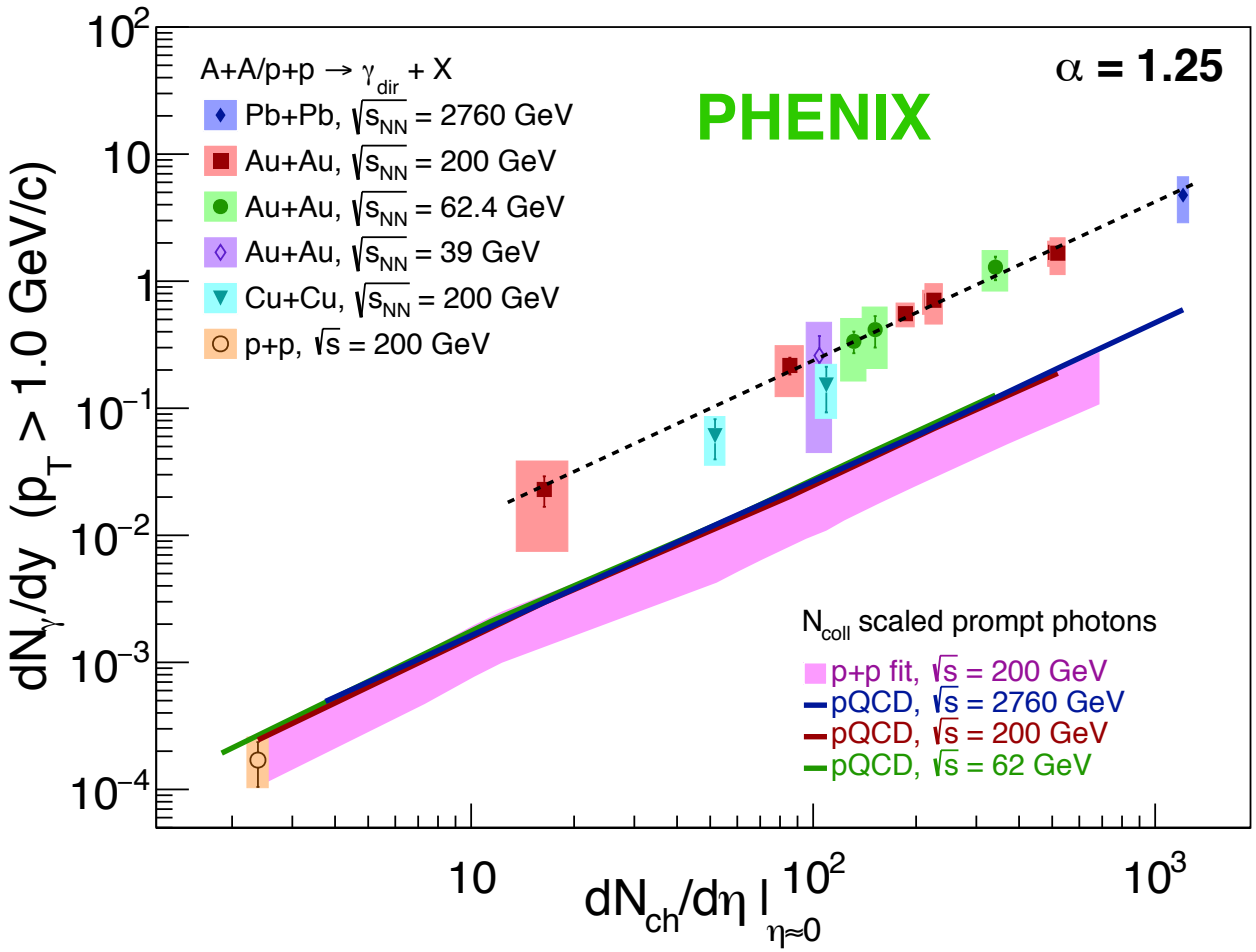
$\lambda_h = x_h \langle z_h \rangle = 1$

(QGP) Discoveries at RHIC

- Suppression of high p_T hadrons from hard-scattering of initial state partons; also modification of the away-side jet
- Elliptic Flow at the Hydrodynamic limit as a near ideal fluid with shear viscosity/entropy density at or near the quantum lower bound $\eta/s \approx 1/(4\pi)$
- Elliptic flow of particles proportional to the number of the valence (constituent) quark count.
- Charged particle multiplicity proportional to the number of constituent quark participants
- Higher order flow moments proportional to density fluctuations of the initial colliding nuclei
- Suppression and flow of heavy quarks roughly the same as that of light quarks; QCD hard direct photons not suppressed, don't flow.
- Production and flow of soft photons not seen in p+p collisions

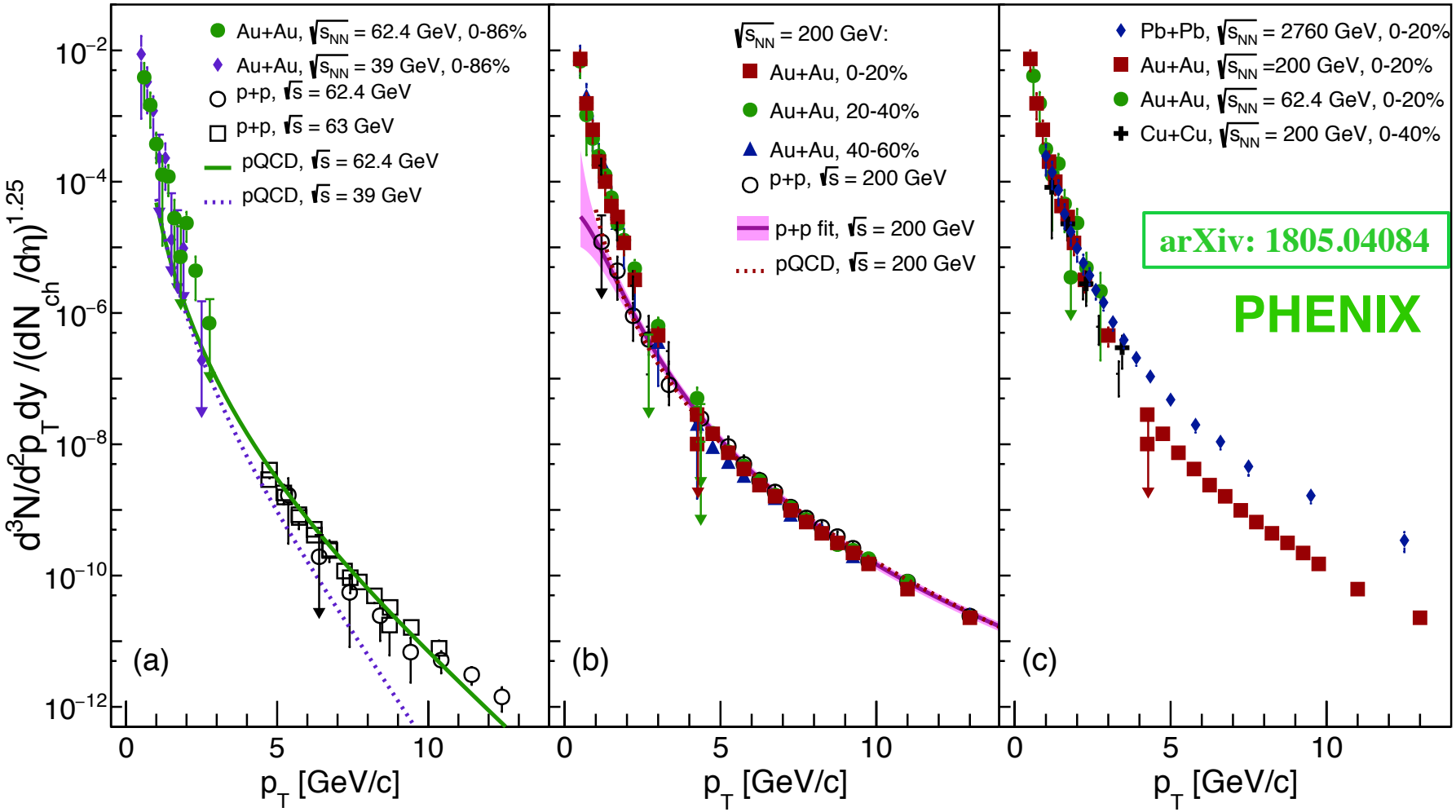
The big discovery is that the soft photons, p_T>1.0 GeV/c, also follow Ncoll scaling, but without the SY($\sqrt{s_{NN}}$) i.e. they scale with $(dN_{ch}/d\eta)^{1.25}$ as a function of centrality for all $\sqrt{s_{NN}}$ measured

The exponential soft photons, p_T>1 GeV/c scale with $(dNch/d\eta)^{1.25}$ as a function of centrality for all $\sqrt{s_{NN}}$ measured.

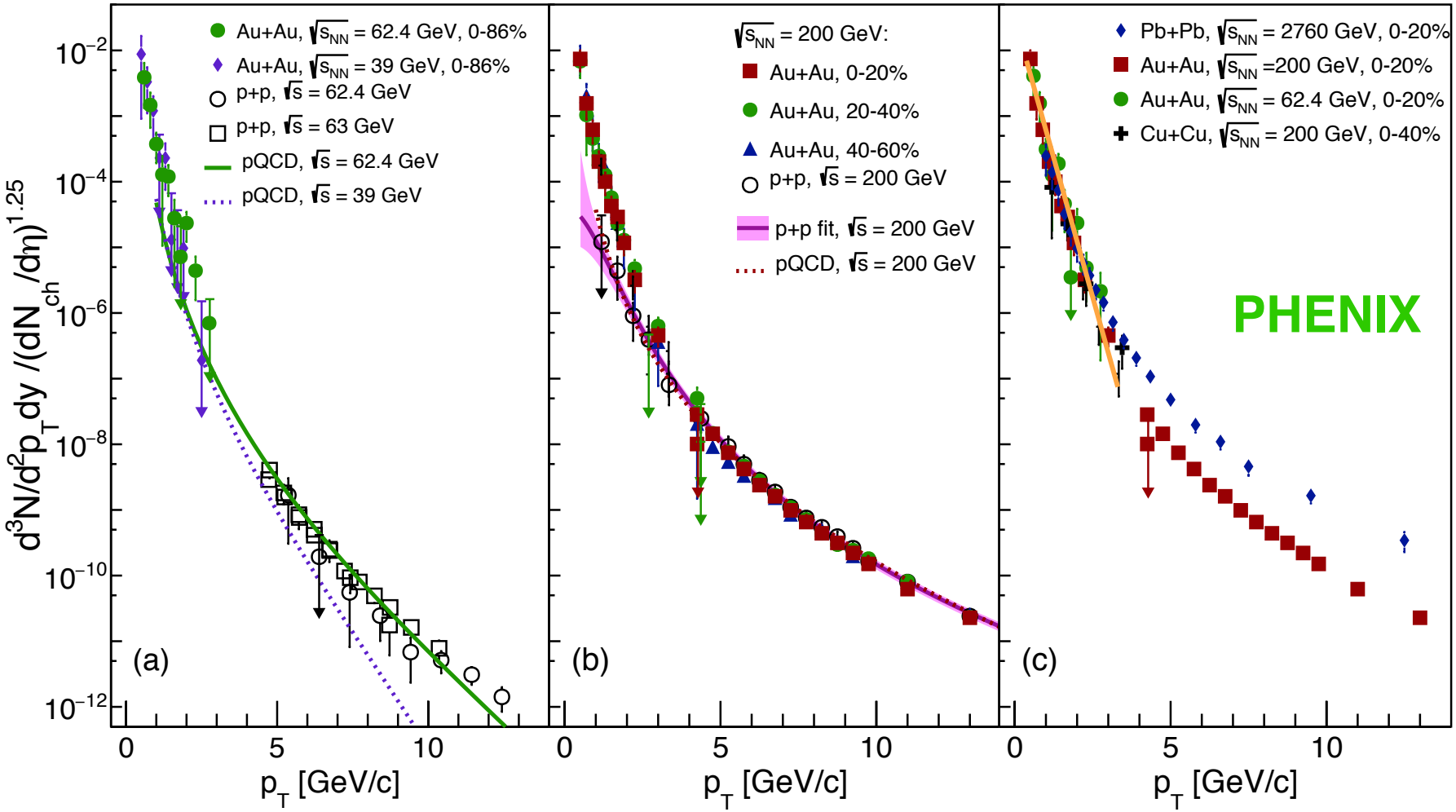


arXiv: 1805.04084

AuAu & PbPb Direct single photon p_T spectra normalized by $(dNch/d\eta)^{1.25}$



AuAu & PbPb Direct single photon p_T spectra normalized by $(dNch/d\eta)^{1.25}$



The very big discovery

PHENIX arXiv: 1805.04084

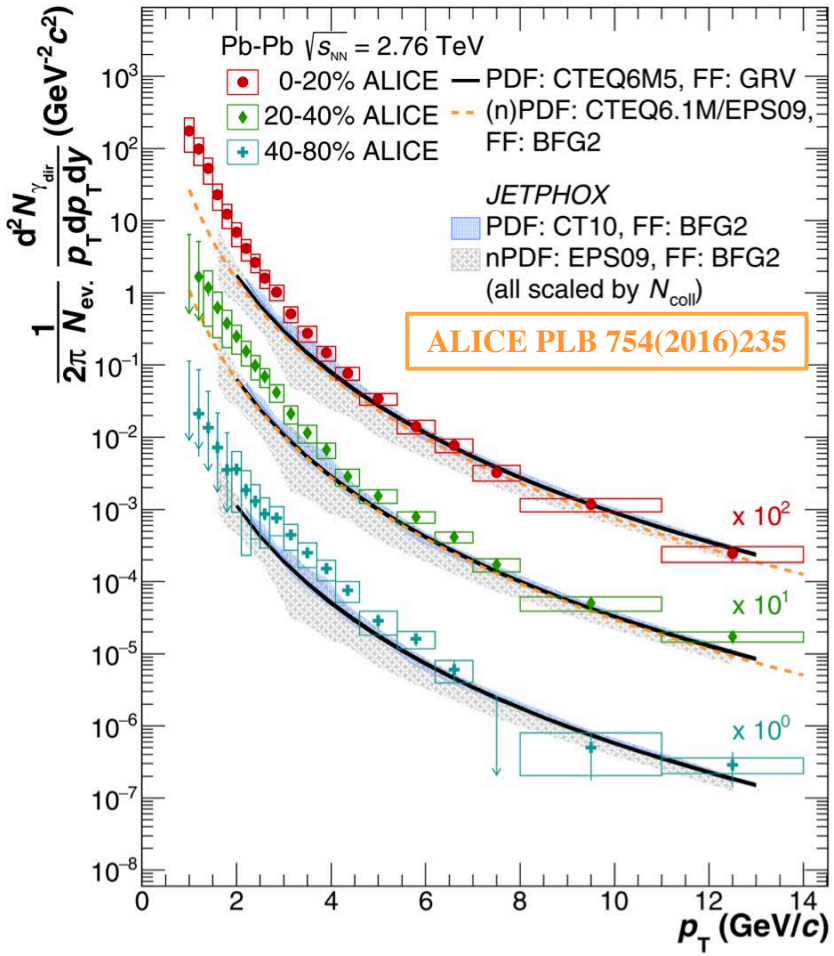
1) the soft photons, p_T=1-3 GeV/c, scale with Ncoll as a function of centrality like the hard photons.

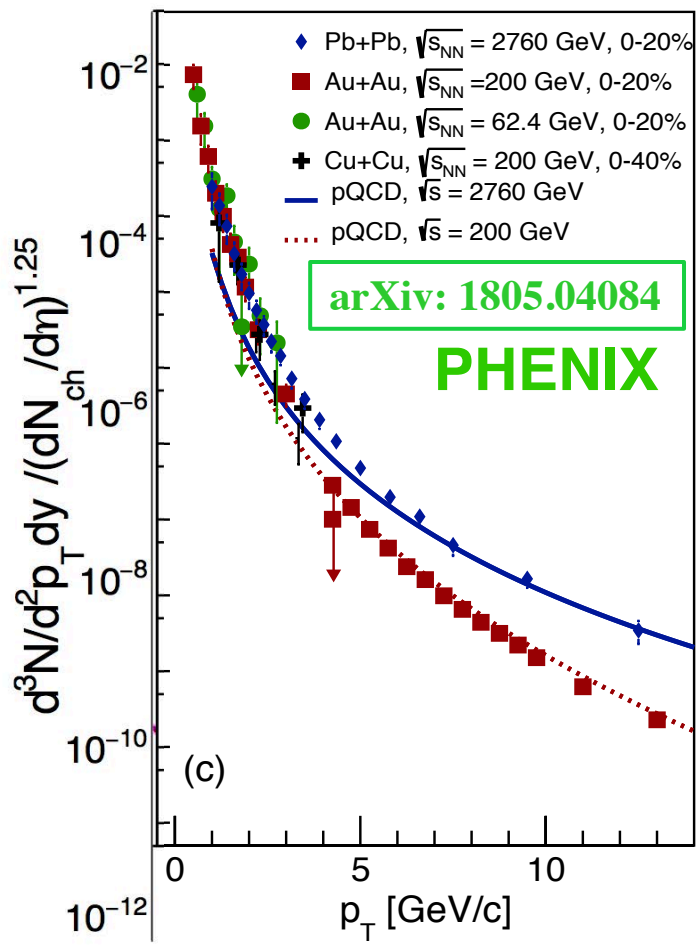
2) the scaling is identical at all $\sqrt{s_{NN}}$ in the variable $(dNch/d\eta)^{1.25}$ as a function of centrality

3) the soft photons flow $v_2>0$, but the hard photons don't flow (old news)

PHENIX PRL109(2012)122302

Note: ALICE QCD good down to 4 GeV/c



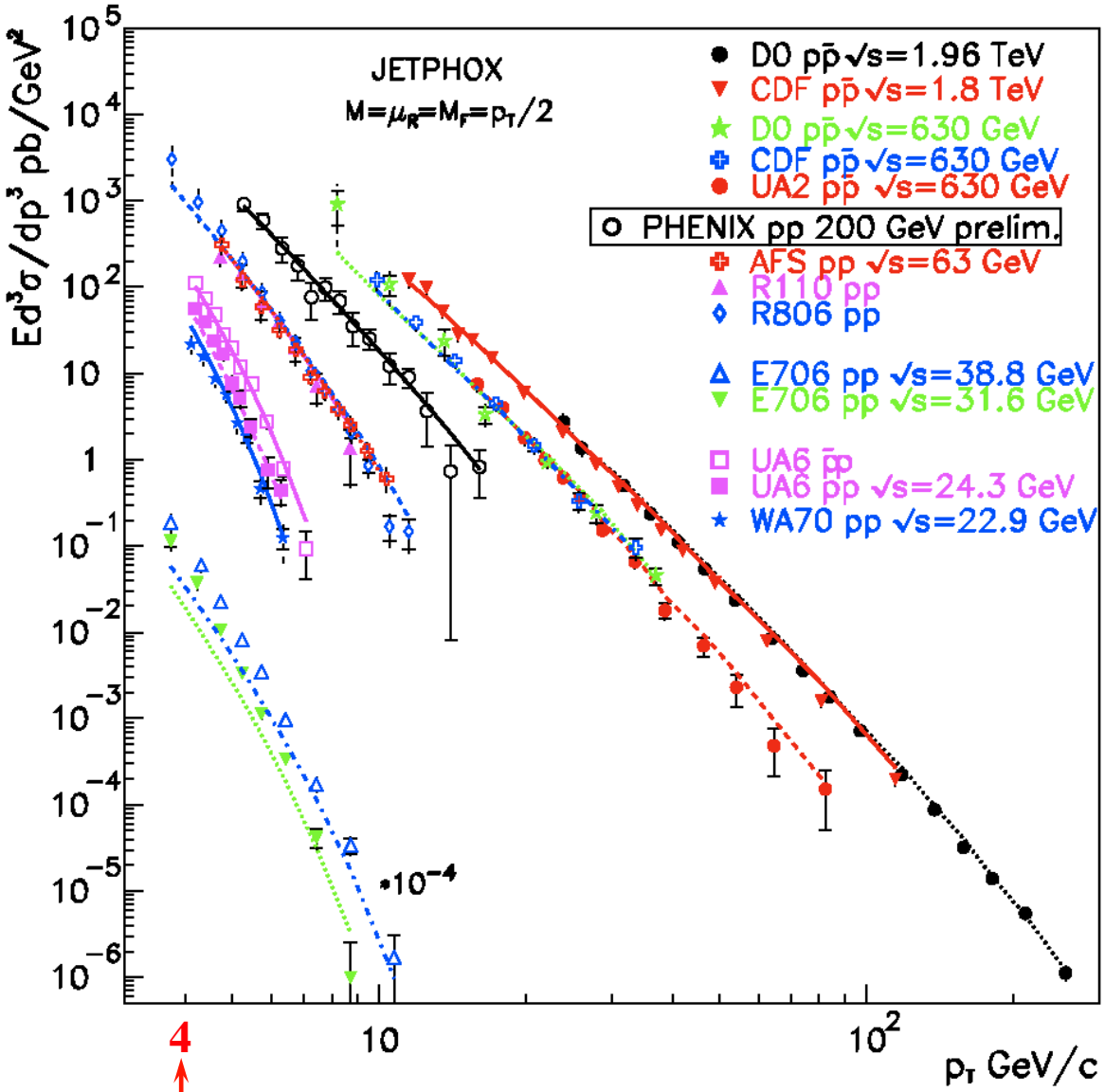


I don't believe the so called QCD calculation used by PHENIX and the dashes from ALICE which has a 30% to 60% systematic error not shown but I do believe in JETPHOX

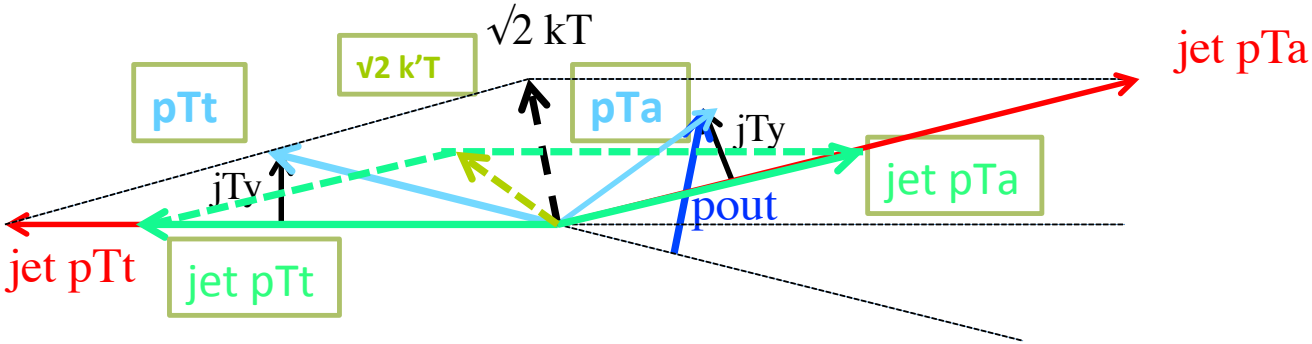
All Direct γ p-p data and pQCD c. 2007

PHENIX direct-γ in p-p
PRL **98** (2007) 012002

P. Aurenche et al Phys. Rev. D **73**, 094007 (2006) QCD JETPHOX fits all existing direct γ data for p_T>4 GeV/c plus the new 2.76 TeV data



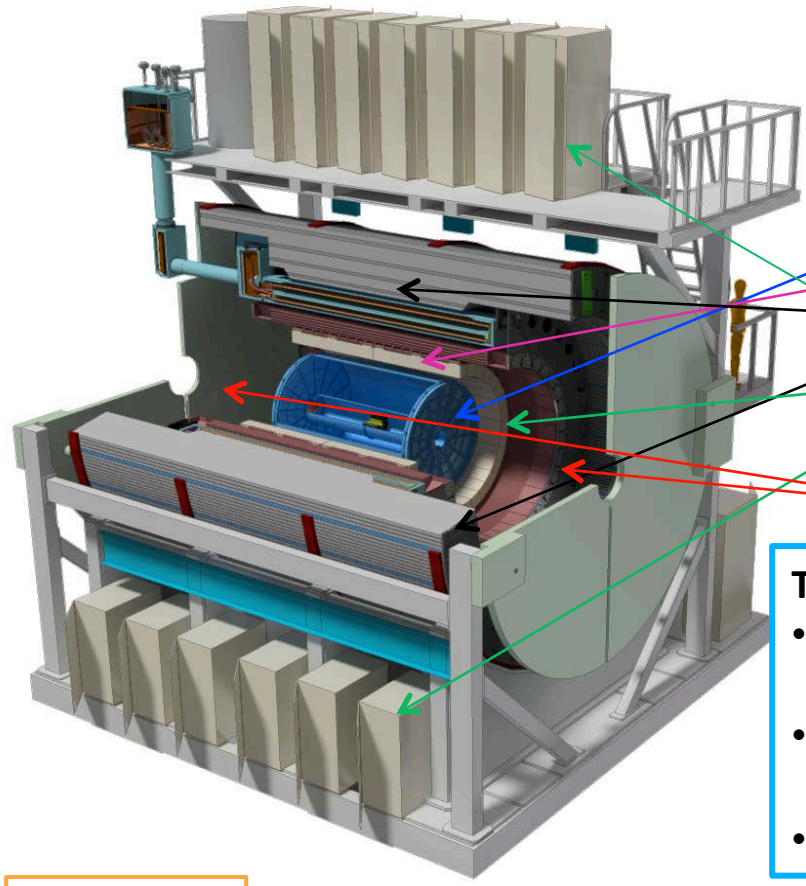
The solution in pictures



Final configuration a di-jet with k'_T and fragments with p_{out} .

The new experiment sPHENIX is moving along well
Successful DOE Major Item of Equipment review

sPHENIX MIE



WBS	sPHENIX MIE Project Elements
1.1	Project Management
1.2	Time Projection Chamber
1.3	Electromagnetic Calorimeter
1.4	Hadron Calorimeter
1.5	Calorimeter Electronics
1.6	DAQ-Trigger → To counting house
1.7	Minimum Bias Trigger Detector

The conceptual design of sPHENIX is based on 3 principles:

- Design a detector to meet the Science Mission of measurements of Jets and Upsilons in RHIC environment
- Maximize cost effectiveness and utilize modern technologies where appropriate (SiPM, fast TPC readout)
- Build on existing $20M+ PHENIX infrastructure