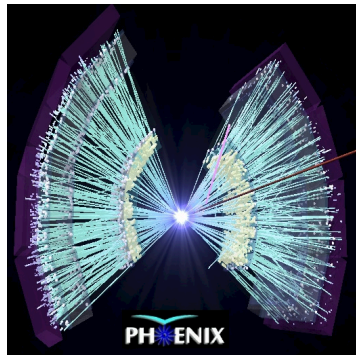


Highlights from RHIC (plus some earlier BNL highlights in subnuclear physics)

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

Intl. Symposium on Subnuclear Physics:
Past, Present and Future
Pontifical Academy of Sciences, The Vatican,
30 October--2 November 2011



Periodic Table of the Elements

19th century

Mendeleev 1871

H
Mendeleev 1871
B
C N O F
Li Be Na Mg Al Si P S Cl
K Ca Rb Sr Ti V Cr Mn Fe Co Ni Cu Zn As Se Br
Cs Ba ?Di Ce Er Ta W Os Ir Pt Au Hg In Sn Sb Te J
Th U Pb Bi

Periodic Table of the Elements

20th century

1A

1

H

¹

hydrogen

1.008

2A

3

Li

^{[He]2s¹}

lithium

6.941

4

Be

^{[He]2s²}

beryllium

9.012

11

Na

^{[Ne]3s¹}

sodium

22.99

12

Mg

^{[Ne]3s²}

magnesium

24.31

19

K

^{[Ar]4s¹}

potassium

39.10

20

Ca

^{[Ar]4s²}

calcium

40.08

37

Rb

^{[Kr]5s¹}

rubidium

85.47

38

Sr

^{[Kr]5s²}

strontium

87.62

55

Cs

^{[Xe]6s¹}

cesium

132.9

56

Ba

^{[Xe]6s²}

barium

137.3

87

Fr

^{[Rn]7s¹}

francium

(223)

88

Ra

^{[Rn]7s²}

radium

(226)

21

Sc

^{[Ar]4s²3d¹}

scandium

44.96

22

Ti

^{[Ar]4s²3d²}

titanium

47.88

23

V

^{[Ar]4s²3d³}

vanadium

50.94

24

Cr

^{[Ar]4s¹3d⁵}

chromium

52.00

25

Mn

^{[Ar]4s²3d⁵}

manganese

54.94

26

Fe

^{[Ar]4s²3d⁶}

iron

55.85

27

Co

^{[Ar]4s²3d⁷}

cobalt

58.93

28

Ni

^{[Ar]4s¹3d⁸}

nickel

58.69

29

Cu

^{[Ar]4s¹3d¹⁰}

copper

63.55

30

Zn

^{[Ar]4s²3d¹⁰}

zinc

65.39

31

Ga

^{[Ar]4s²3d¹⁰4p¹}

gallium

69.72

32

Ge

^{[Ar]4s²3d¹⁰4p²}

germanium

72.64

33

As

^{[Ar]4s²3d¹⁰4p³}

arsenic

74.92

34

Se

^{[Ar]4s²3d¹⁰4p⁴}

selenium

78.96

35

Br

^{[Ar]4s²3d¹⁰4p⁵}

bromine

79.90

36

Kr

^{[Ar]4s²3d¹⁰4p⁶}

krypton

83.79

39

Y

^{[Kr]5s²4d¹}

yttrium

88.91

40

Zr

^{[Kr]5s²4d²}

zirconium

91.22

41

Nb

^{[Kr]5s¹4d⁴}

niobium

92.91

42

Mo

^{[Kr]5s¹4d⁵}

molybdenum

95.94

43

Tc

^{[Kr]5s²4d⁵}

technetium

(98)

44

Ru

^{[Kr]5s¹4d⁷}

ruthenium

101.1

45

Rh

^{[Kr]5s¹4d⁸}

rhodium

102.9

46

Pd

^{[Kr]4d¹⁰}

palladium

106.4

47

Ag

^{[Kr]5s¹4d¹⁰}

silver

107.9

48

Cd

^{[Kr]5s²4d¹⁰}

cadmium

112.4

49

In

^{[Kr]5s²4d¹⁰5p¹}

indium

114.8

50

Sn

^{[Kr]5s²4d¹⁰5p²}

tin

118.7

51

Sb

^{[Kr]5s²4d¹⁰5p³}

antimony

121.8

52

Te

^{[Kr]5s²4d¹⁰5p⁴}

tellurium

127.6

53

I

^{[Kr]5s²4d¹⁰5p⁵}

iodine

126.9

54

Xe

^{[Kr]5s²4d¹⁰5p⁶}

xenon

131.3

57

La

^{[Xe]6s²5d¹}

lanthanum

138.9

58

Ce

^{[Xe]6s²4f¹5d¹}

cerium

140.1

59

Pr

^{[Xe]6s²4f³}

praseodymium

140.9

60

Nd

^{[Xe]6s²4f⁴}

neodymium

144.2

61

Pm

^{[Xe]6s²4f⁵}

promethium

(145)

62

Sm

^{[Xe]6s²4f⁶}

samarium

150.4

63

Eu

^{[Xe]6s²4f⁷}

euporium

152.0

64

Gd

^{[Xe]6s²4f⁷5d¹}

gadolinium

157.2

65

Tb

^{[Xe]6s²4f⁹}

terbium

158.9

66

Dy

^{[Xe]6s²4f¹⁰}

dysprosium

162.5

67

Ho

^{[Xe]6s²4f¹¹}

holmium

164.9

68

Er

^{[Xe]6s²4f¹²}

erbium

167.3

69

Tm

^{[Xe]6s²4f¹³}

thulium

168.9

70

Yb

^{[Xe]6s²4f¹⁴}

ytterbium

173.0

71

Lu

^{[Xe]6s²4f¹⁴5d¹}

lutetium

175.0

89

Ac

^{[Rn]7s²6d¹}

actinium

(227)

90

Th

^{[Rn]7s²6d²}

thorium

232.0

91

Pa

^{[Rn]7s²5f²6d¹}

protactinium

231

92

U

^{[Rn]7s²5f³6d¹}

uranium

238

93

Np

^{[Rn]7s²5f⁴6d¹}

neptunium

(237)

94

Pu

^{[Rn]7s²5f⁶}

plutonium

(243)

95

Am

^{[Rn]7s²5f⁷}

americium

(243)

96

Cm

^{[Rn]7s²5f⁷6d¹}

curium

(247)

97

Bk

^{[Rn]7s²5f⁹}

berkelium

(247)

98

Cf

^{[Rn]7s²5f¹⁰}

californium

(251)

99

Es

^{[Rn]7s²5f¹¹}

einsteinium

(252)

100

Fm

^{[Rn]7s²5f¹²}

fermium

(257)

101

Md

^{[Rn]7s²5f¹³}

mendelevium

(258)

102

No

^{[Rn]7s²5f¹⁴}

nobelium

(259)

103

Lr

^{[Rn]7s²5f¹⁴6d¹}

lawrencium

(262)

13

Al

^{[Ne]3s²3p¹}

aluminum

26.98

14

Si

^{[Ne]3s²3p²}

silicon

28.09

15

P

^{[Ne]3s²3p³}

phosphorus

30.97

16

S

^{[Ne]3s²3p⁴}

sulfur

32.07

17

Cl

^{[Ne]3s²3p⁵}

chlorine

35.45

18

Ar

^{[Ne]3s²3p⁶}

argon

39.95

5

B

^{[He]2s²2p¹}

boron

10.81

6

C

^{[He]2s²2p²}

carbon

12.01

7

N

^{[He]2s²2p³}

nitrogen

14.01

8

O

^{[He]2s²2p⁴}

oxygen

16.00

9

F

^{[He]2s²2p⁵}

fluorine

19.00

10

Ne

^{[He]2s²2p⁶}

neon

20.18

11B

29

Cu

^{[Ar]4s¹3d¹⁰}

copper

63.55

12B

30

Zn

^{[Ar]4s²3d¹⁰}

zinc

65.39

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12B

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zinc

65.39

In the 20th century, this table was understood using quantum mechanics, atomic, nuclear and subatomic physics and many elements were added

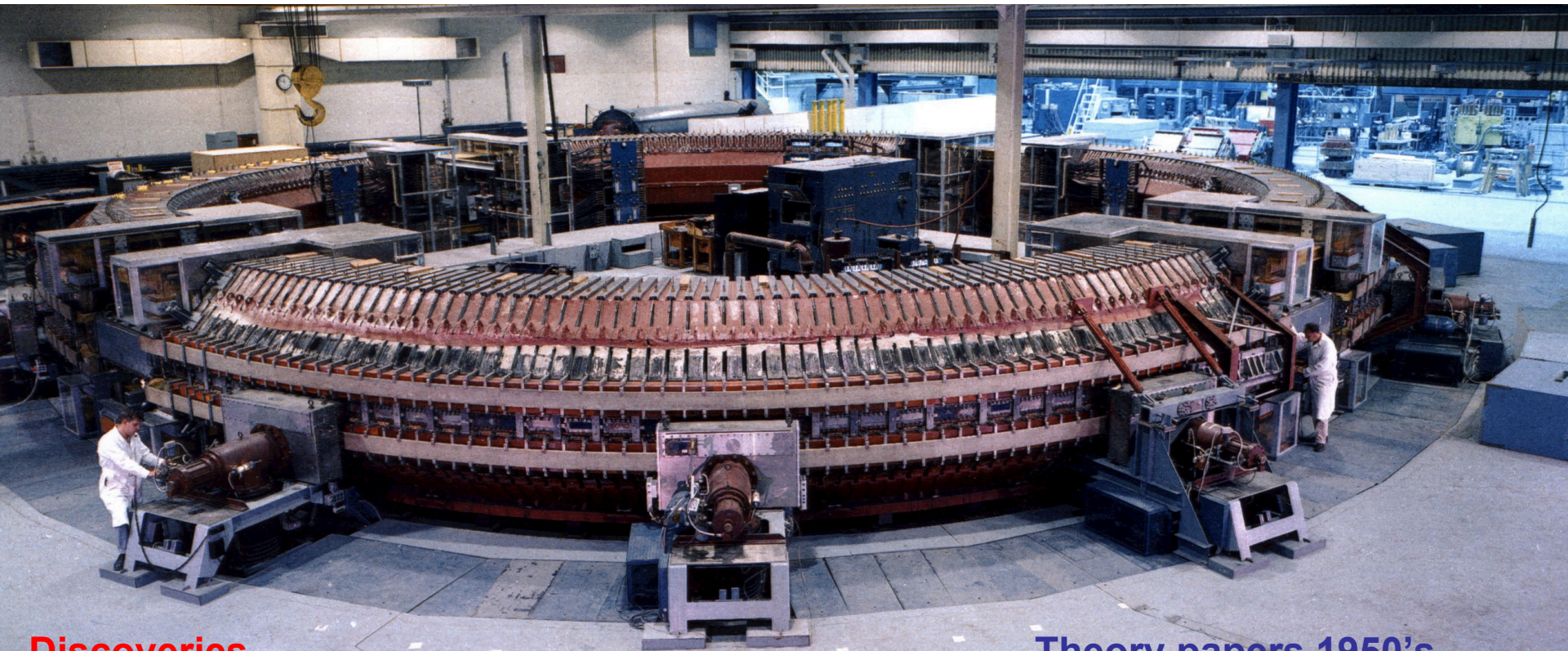
BNL/RHIC is visible from outer space







Cosmotron 3.3 GeV 1953-1966



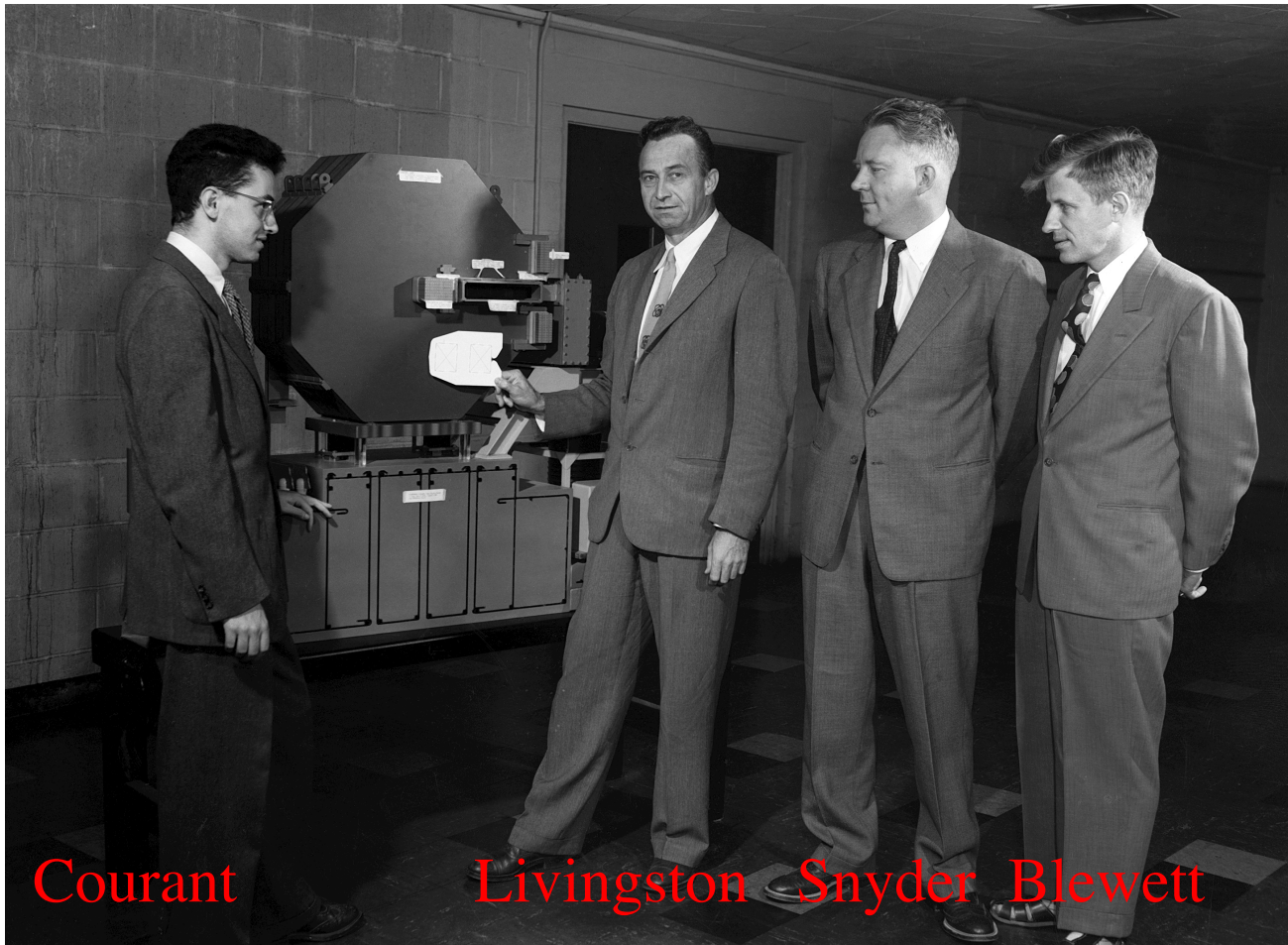
Discoveries

- (1954) Associated production of strange particles
- (1954) Multiparticle production in an n+p collision
- (1956) Long lived, CP-odd, K^0_2 . Limit $K^0_2 \rightarrow \pi^+\pi^- < 1\%$
- (1961) ρ vector meson.

Theory papers 1950's

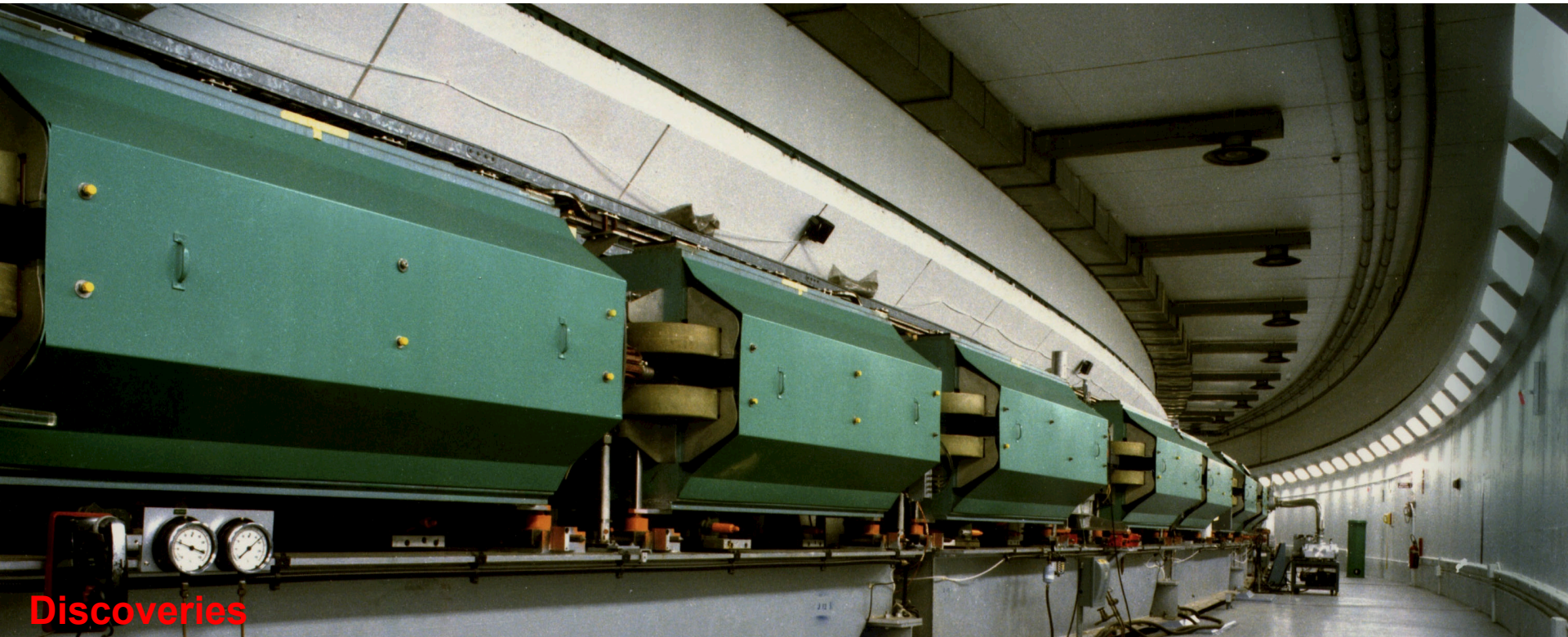
- (1954) Yang-Mills: Gauge field theory. Basis of Standard Model
- (1956) Lee & Yang: Parity Violation in Weak Interactions?

1952-Strong Focusing leads to AGS



“A sequence of alternately converging and diverging magnetic lenses of equal strength is itself converging, and leads to significant reductions in oscillation amplitude, both for radial and axial displacements. i.e much smaller magnets. Phys. Rev. **88**, 1190 (1952)

AGS 33 GeV 1960-(2002 for HEP)



Discoveries

- (1962) First neutrino beam experiment, μ -neutrino (ν_μ).
- (1963) ϕ -meson ($s\bar{s}$); (1964) Ω^- baryon (sss).
- (1964) CP violation $K_2^0 \rightarrow \pi^+ + \pi^- \approx 0.2\%$.
- (1970) Drell-Yan pairs, $p + p \rightarrow \mu^+ + \mu^- + X$.
- (1974) J/Ψ ($c\bar{c}$).

Other Neutrino Experiments

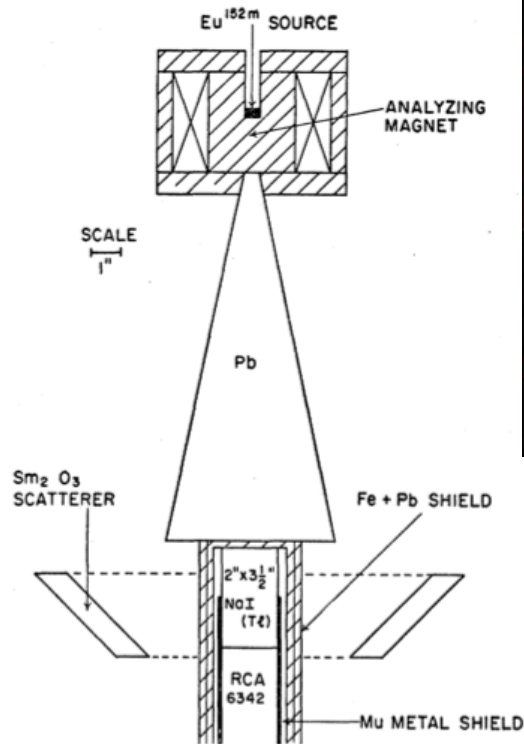
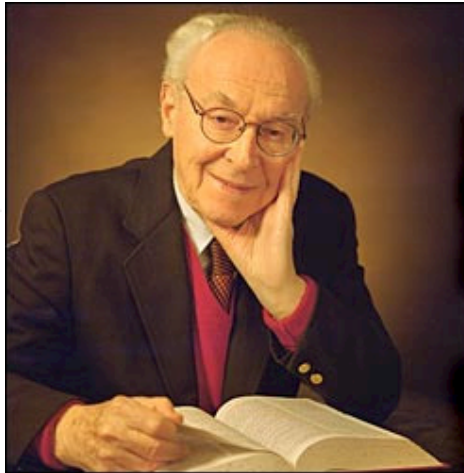
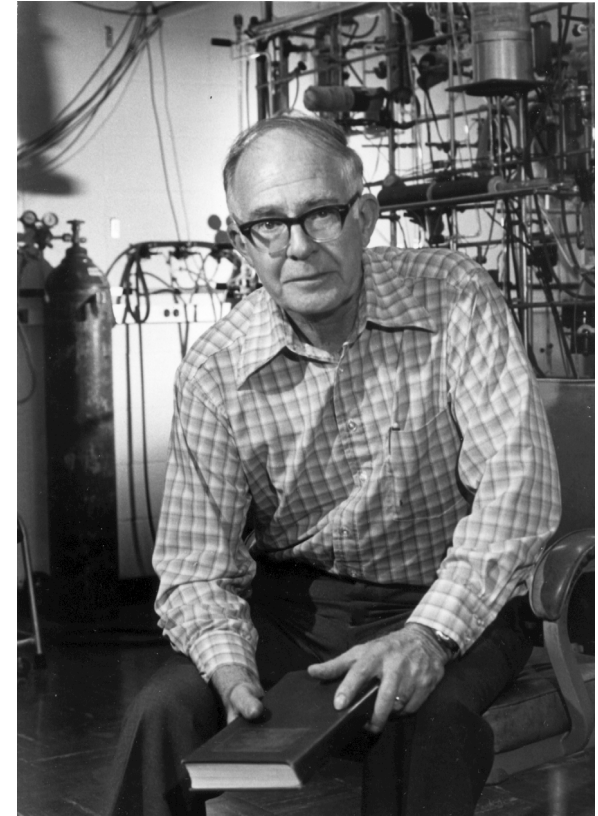


FIG. 1. Experimental arrangement for analyzing circular polarization of resonant scattered γ -rays. Weight of Sm_2O_3 scatterer: 1850 grams.



Goldhaber 1911-2011



Goldhaber, Grodzins, Sunyar
Phys.Rev. **109**, 1015--1017 (1958)

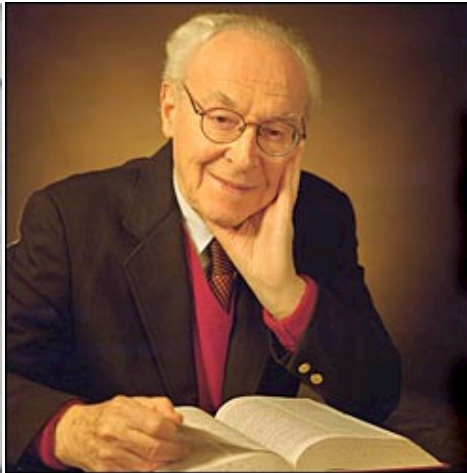
ν from β decay (actually electron capture) is left handed. Wolf Prize 1991

Ray Davis put a tank of cleaning fluid into a deep mine 1967-1988 and was first to detect neutrinos from the sun via $\nu + \text{Cl} \rightarrow \text{Ar} + e^-$. He found a deficit. Wolf Prize 2000, Nobel Prize 2002.

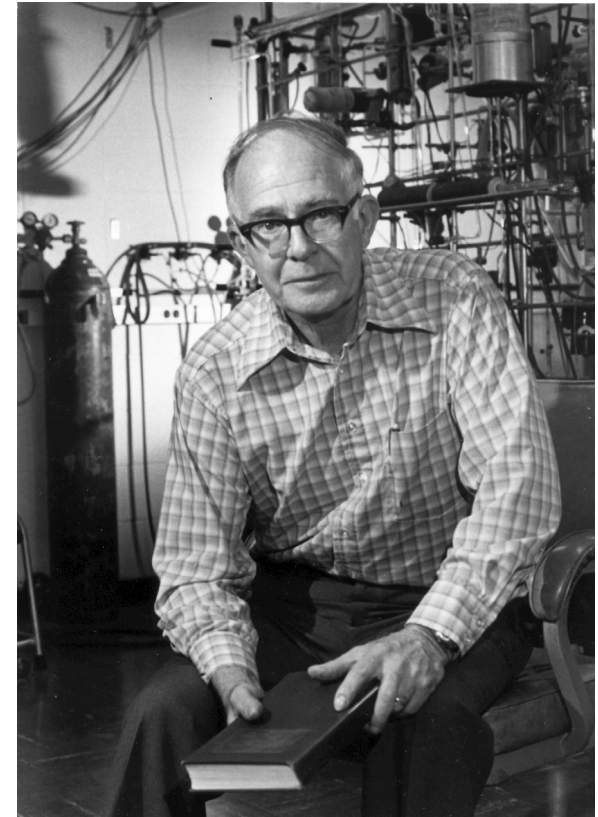
Other Neutrino Experiments



...ization of resonant scattered γ -rays. Weight of Sm_2O_3 scatterer: 1850 grams.



Goldhaber 1911-2011

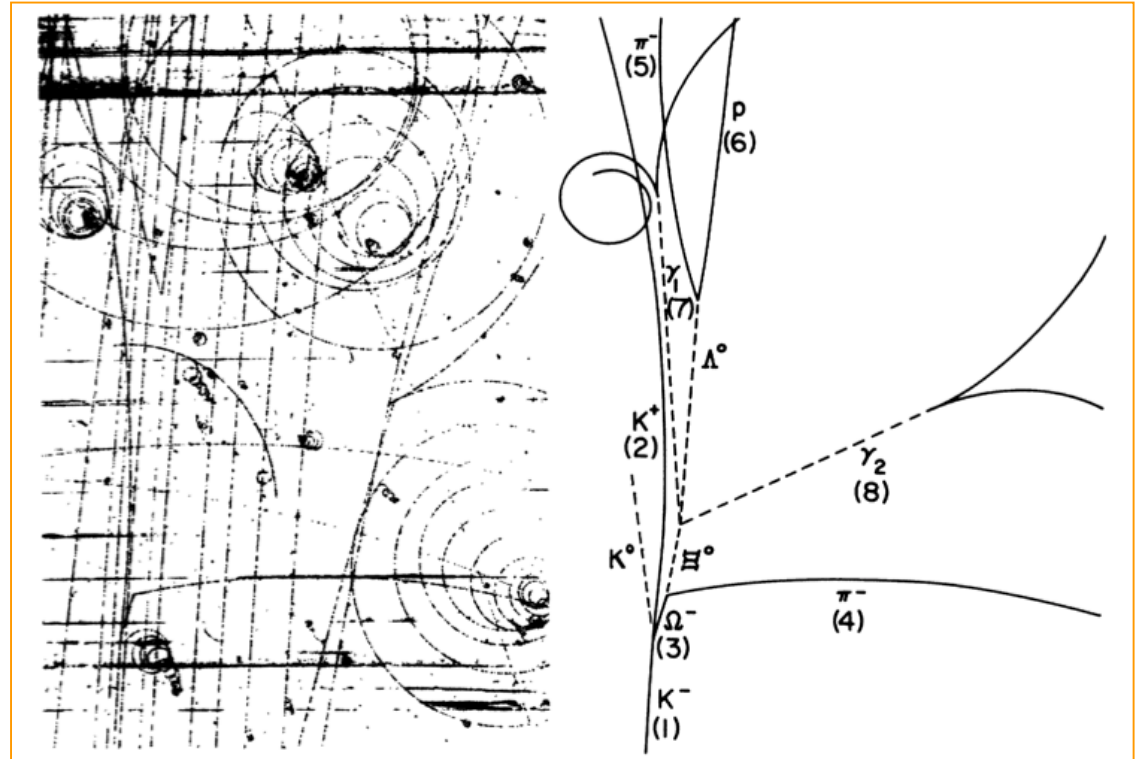
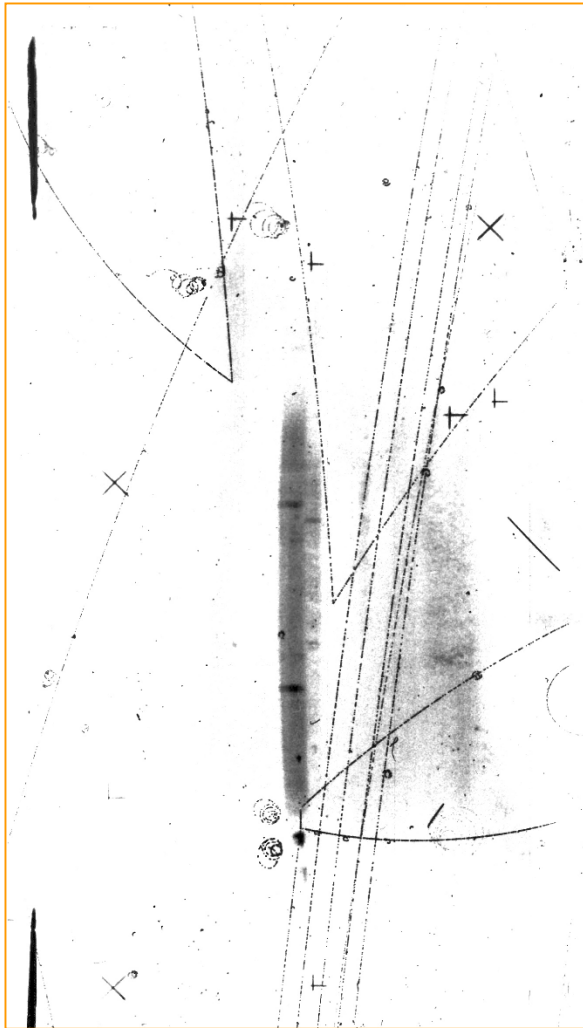


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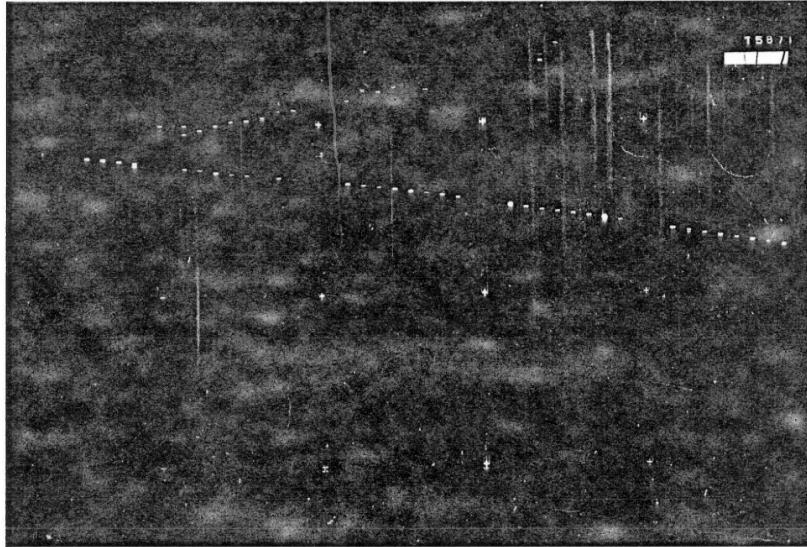
Discoveries evident in Photos



Ω^- (SSS)

Associated Production
(not the actual discovery)

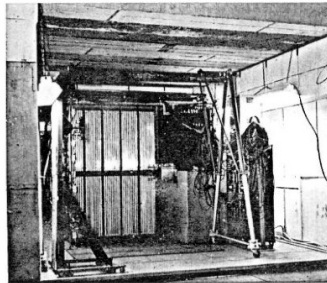
Discoveries evident in Photos



NEUTRINO EVENT



COLUMBIA (NEVIS)



BNL

*In Token of Our
Appreciation for
Your Contribution
to the Neutrino
Run September 1961-
June 1962.*

*"The
Neutrino
Group"*

Gordon Danby

Jean-Marc Guillard

Dino Goulanes

Warner Hayes

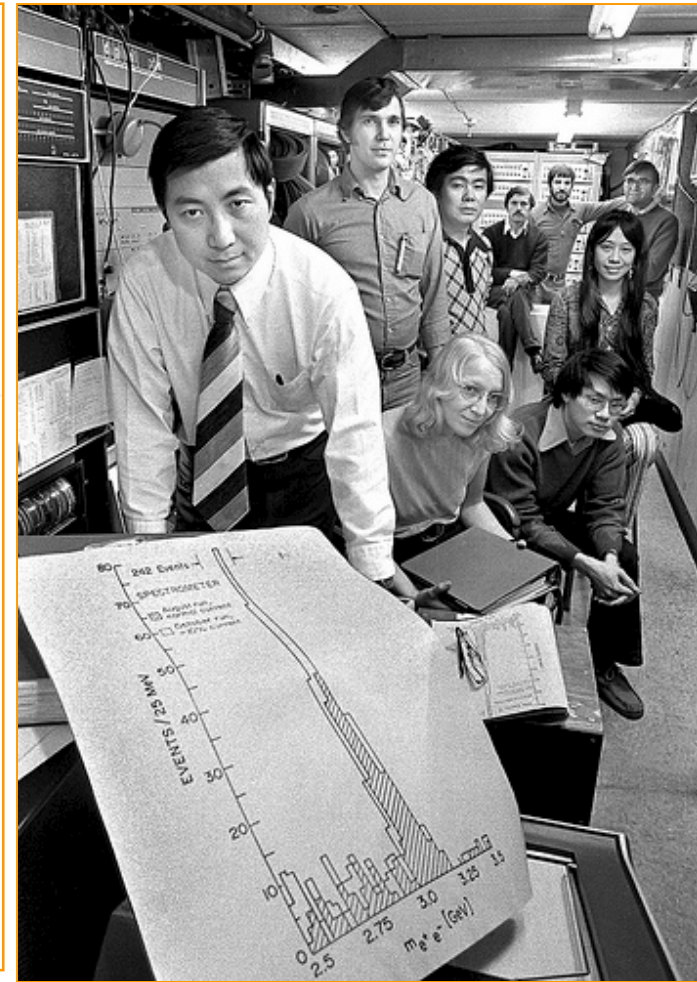
Leon Lederman

Nari Misley

Mel Schwartz

Jack Steinberger

*Raymond
Rein
Hyl
Joch*



ν_μ

J/ψ

Those were the
good old days!

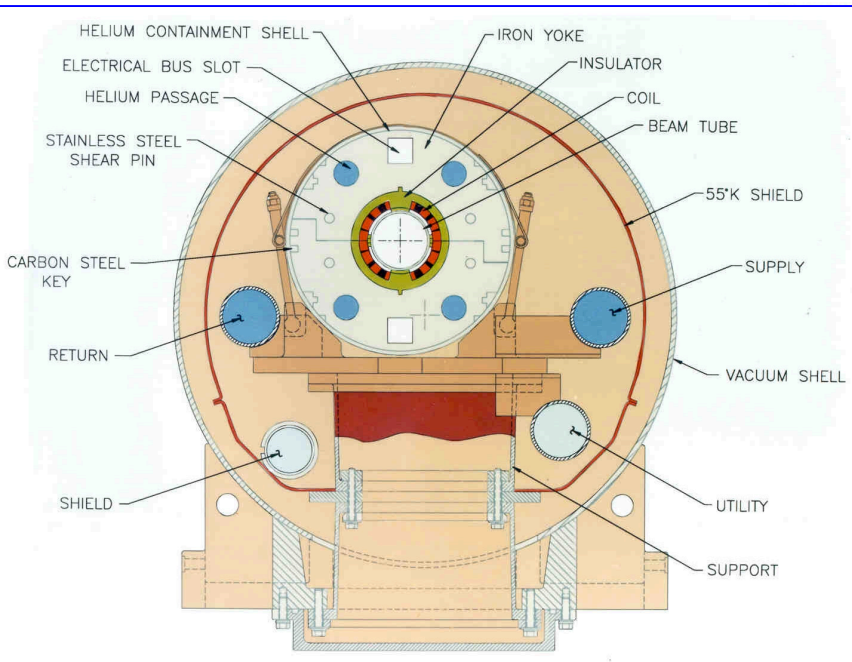


2000- RHIC-All Superconducting Magnets

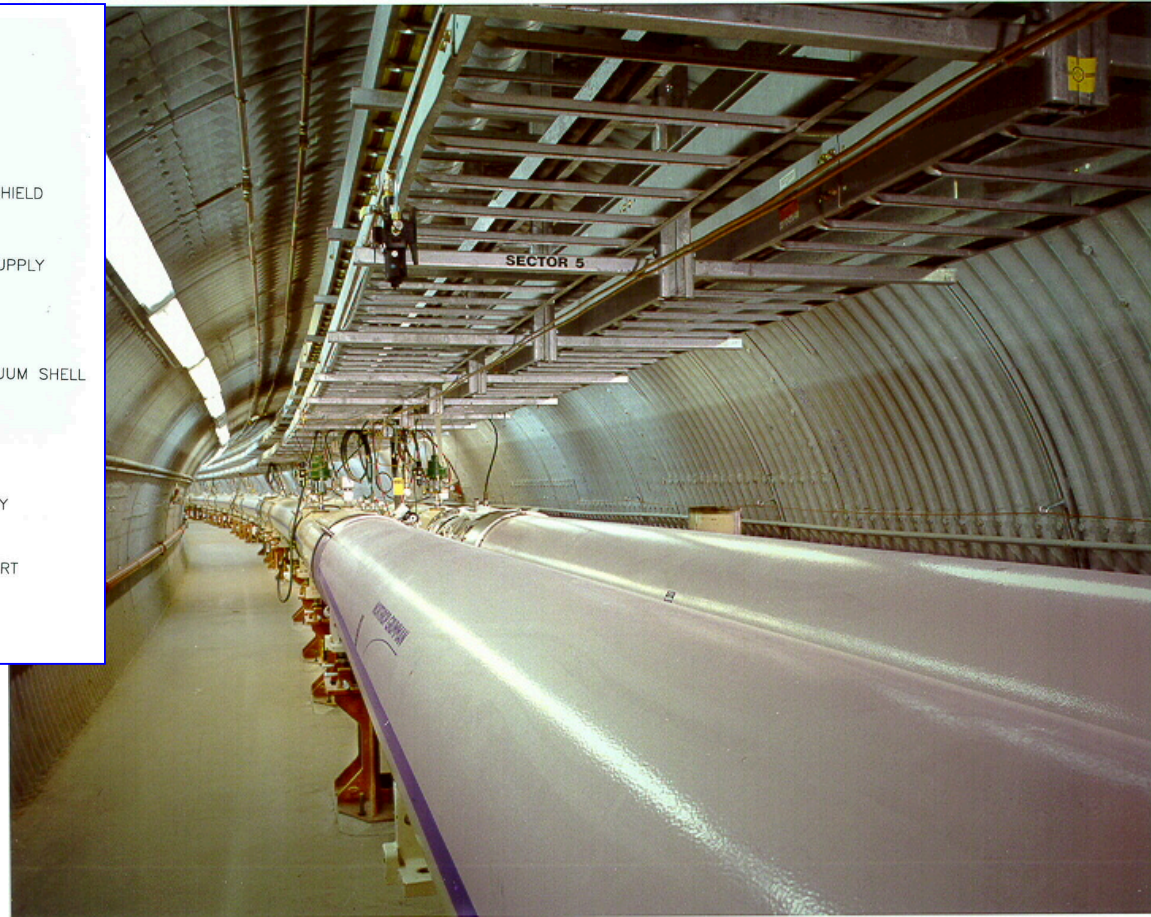
Two Rings 250 GeV (p)

1911-Superconductivity discovered by Kamerlingh-Onnes.

1970's practical large superconducting magnets



Palmer Magnet designed at BNL:
cold iron; superconducting coils
with Cu wedges for field shaping.
Basis of HERA and LHC design.

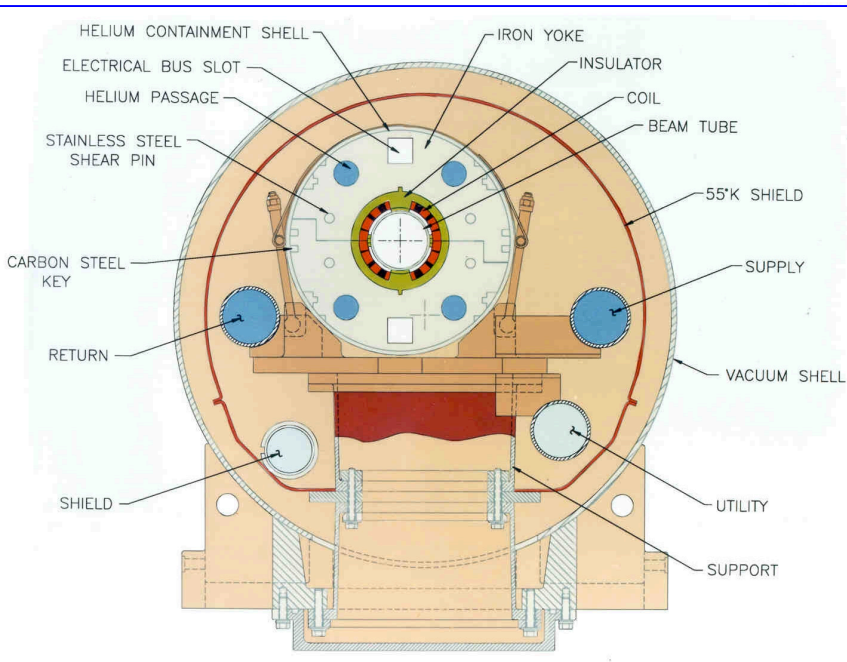


2000- RHIC-All Superconducting Magnets

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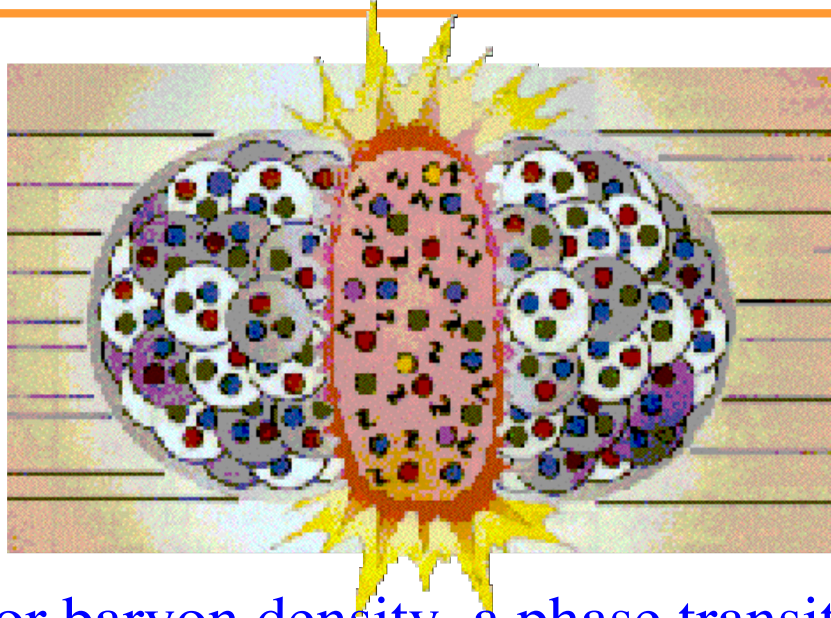


RHIC is versatile: has collided Au-Au, d-Au, Cu-Cu, polarized p-p (so far) at 12 different c.m. energies (so far) U+U, Cu+Au scheduled for 2012.



Palmer Magnet designed at BNL:
cold iron; superconducting coils
with Cu wedges for field shaping.
Basis of HERA and LHC design.

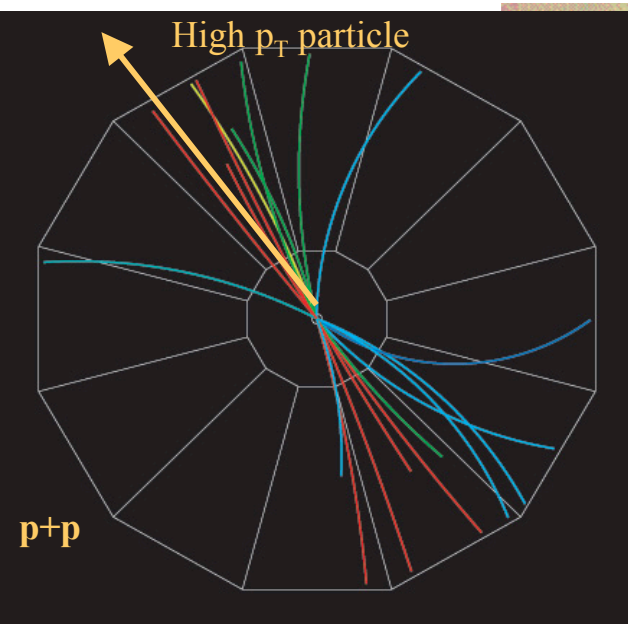
Collisions of High Energy Nuclei provide the means of creating Nuclear Matter in conditions of Extreme Temperature and Density



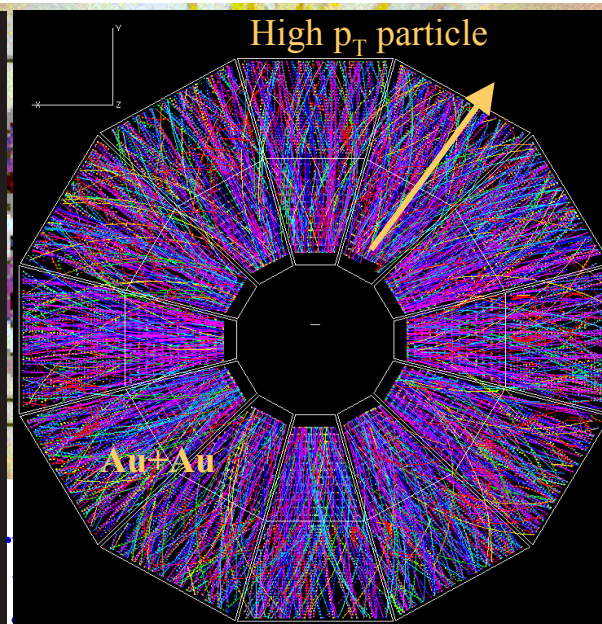
- At large energy or baryon density, a phase transition is expected from a state of nucleons containing confined quarks and gluons to a state of “deconfined” (from their individual nucleons) quarks and gluons, called the quark-gluon plasma or QGP, covering a volume that is many units of the confinement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

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

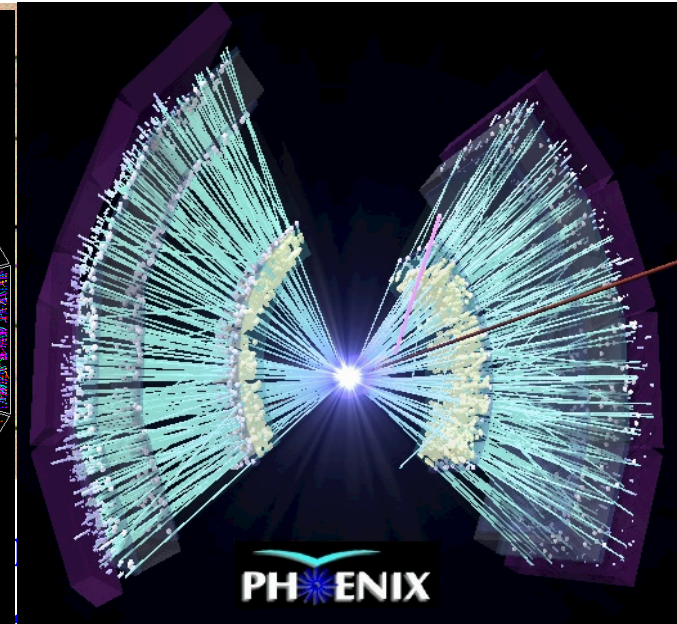
STAR-Jet event in pp



STAR Au+Au central

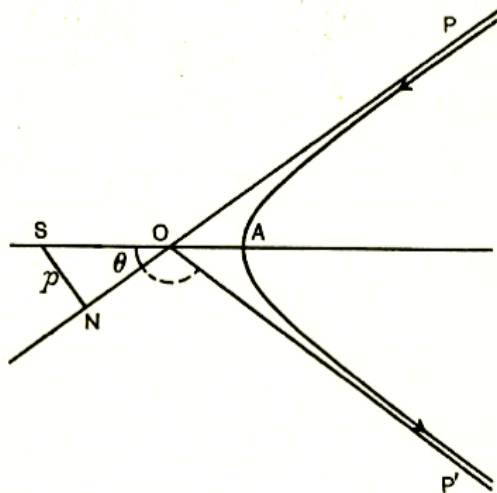


PHENIX Au+Au central

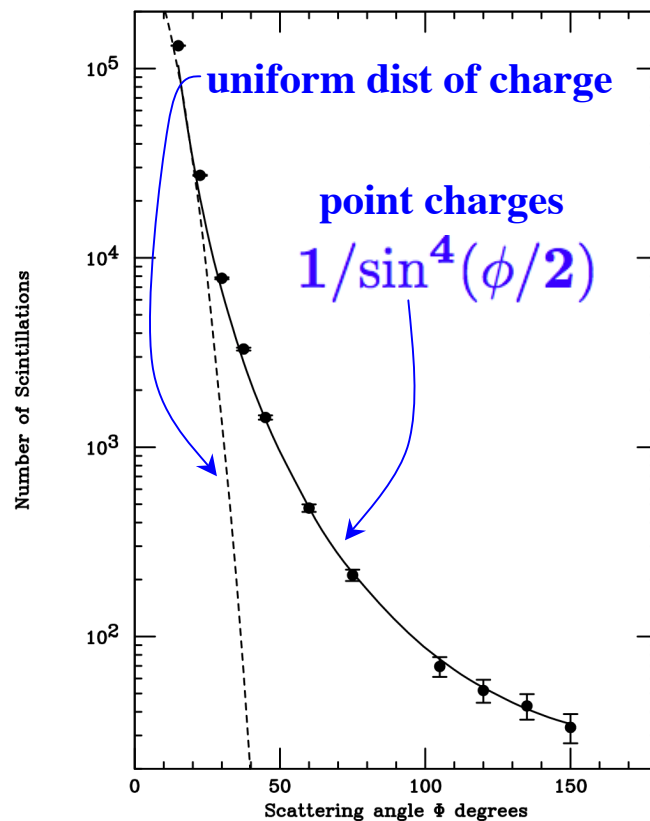


a state of nucleons containing confined quarks and gluons to a state of “deconfined” (from their individual nucleons) quarks and gluons, called the quark-gluon plasma or QGP, covering a volume that is many units of the confinement length scale.

Hard-Scattering: Rutherford to ISR to RHIC



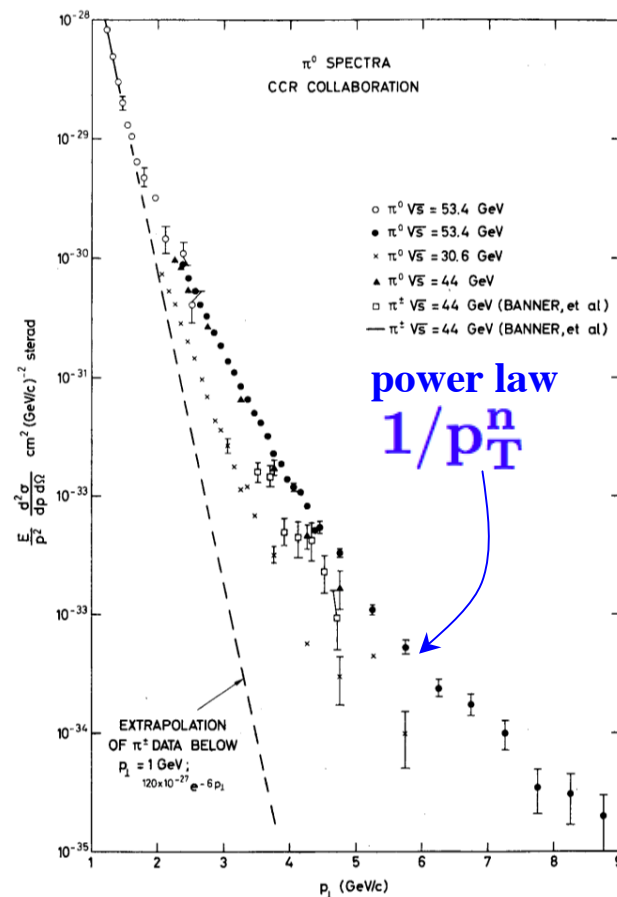
Rutherford scattering
Phil. Mag 21(1911)669
large angle scattering
implies close encounter



Geiger & Marsden

$\alpha + \text{Au} \rightarrow \alpha + \text{Au}$

Phil. Mag 25(1913)604

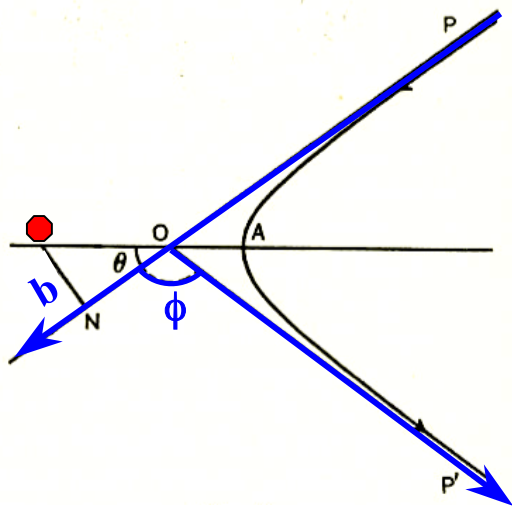


CCR CERN-ISR 1972

$p + p \rightarrow \pi^0 + X$

Hard scattering of partons
i.e constituents of proton

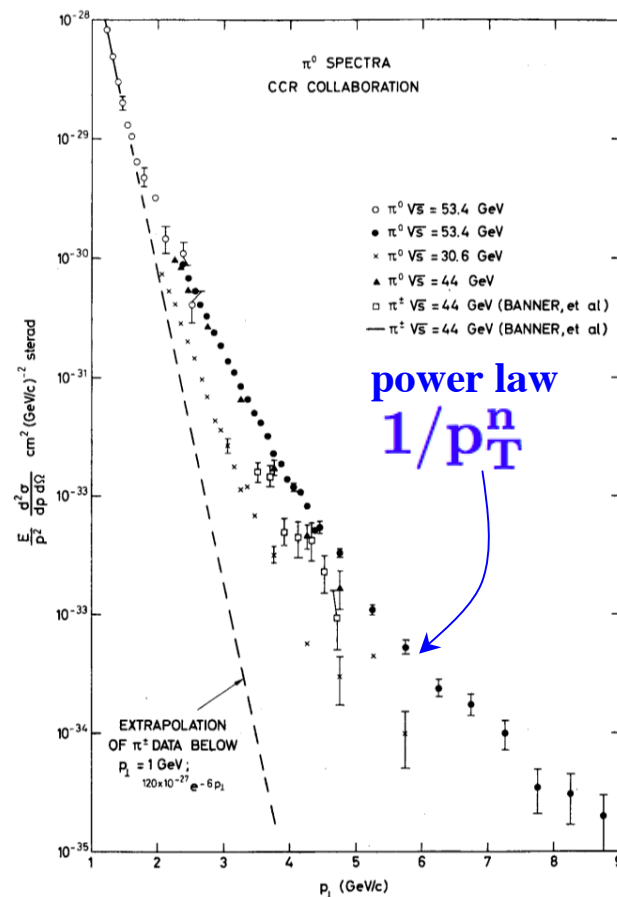
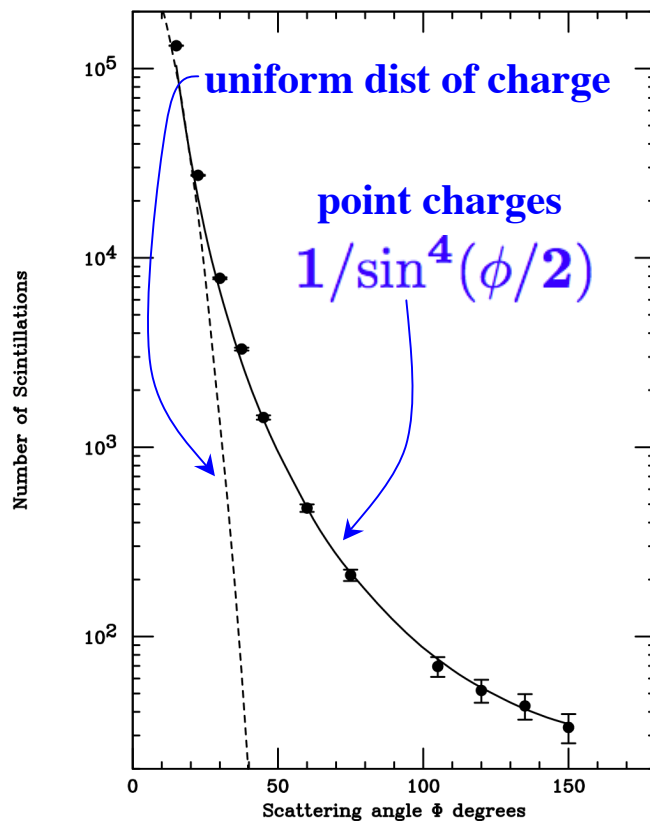
Hard-Scattering: Rutherford to ISR to RHIC



Rutherford scattering
Phil. Mag 21(1911)669
large angle scattering
implies close encounter

b =impact parameter

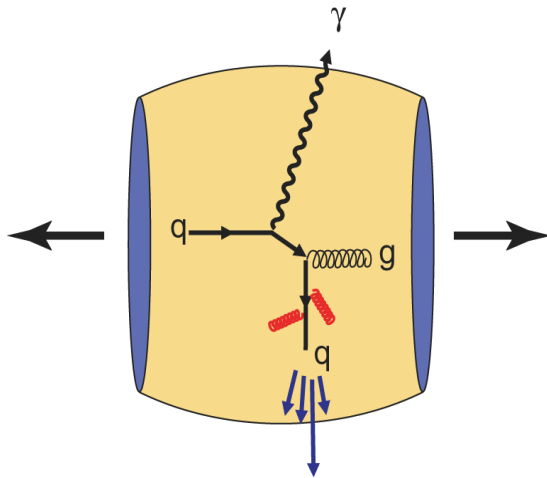
$$\tan(\phi/2) \propto \frac{1}{b}$$



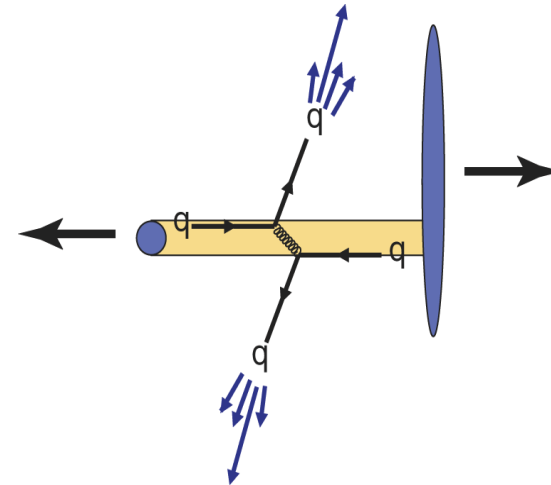
Geiger & Marsden
 $\alpha + \text{Au} \rightarrow \alpha + \text{Au}$
Phil. Mag 25(1913)604

CCR CERN-ISR 1972
 $p + p \rightarrow \pi^0 + X$
Hard scattering of partons
i.e constituents of proton

Hard scattering as a probe of the medium: Hot (AA) vs Cold pA Nuclear Matter Effects



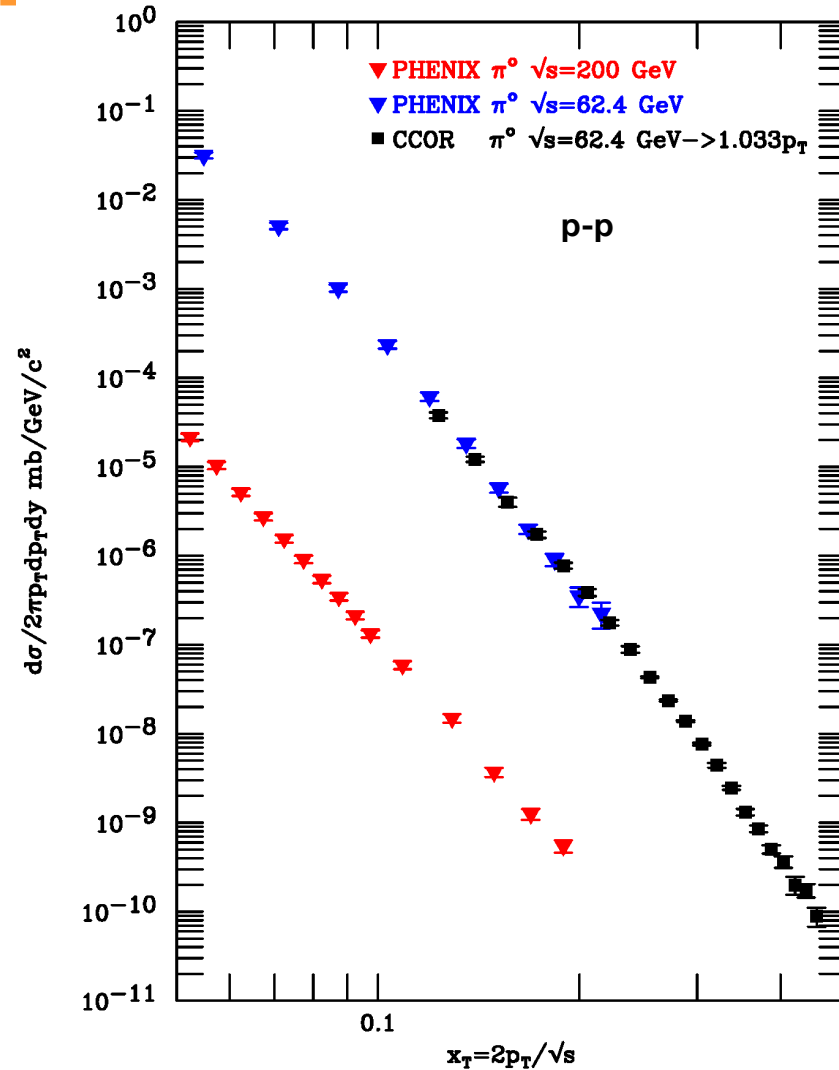
Hard scattering of partons in the initial collision is in-situ internal probe of medium. Do quarks and gluons lose energy in the medium? If so exactly how?



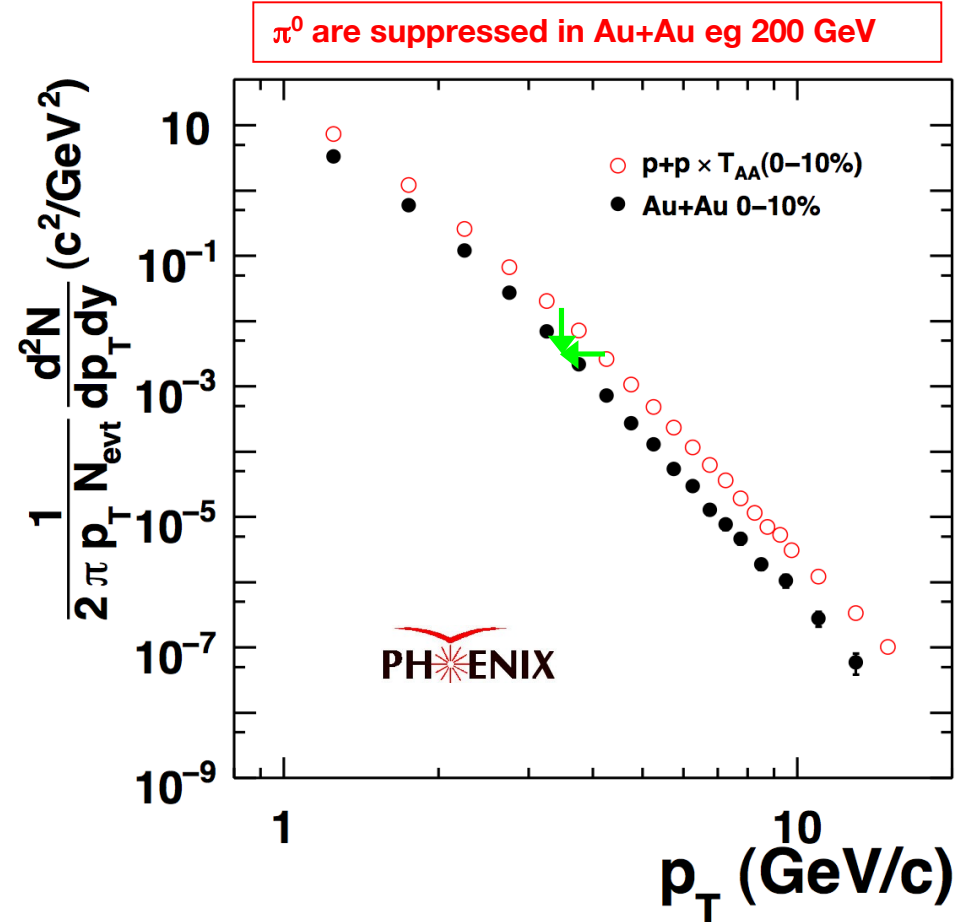
In p+A or d+A, medium is small, (1 nucleon wide) or non-existent. This is baseline for any cold nuclear matter effect in initial collision

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

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



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



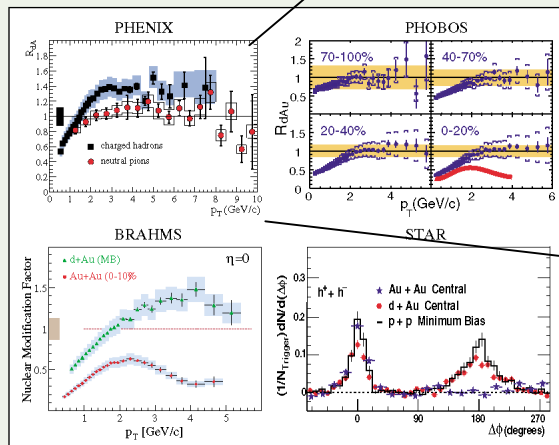
Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{d^2N_{AA}^\pi / dp_T dy N_{AA}^{\text{inel}}}{\langle T_{AA} \rangle d^2\sigma_{pp}^\pi / dp_T dy}$$

π^0 are suppressed in Au+Au but not in d+Au $\Rightarrow$ suppression is due to hot matter

PHYSICAL REVIEW LETTERS

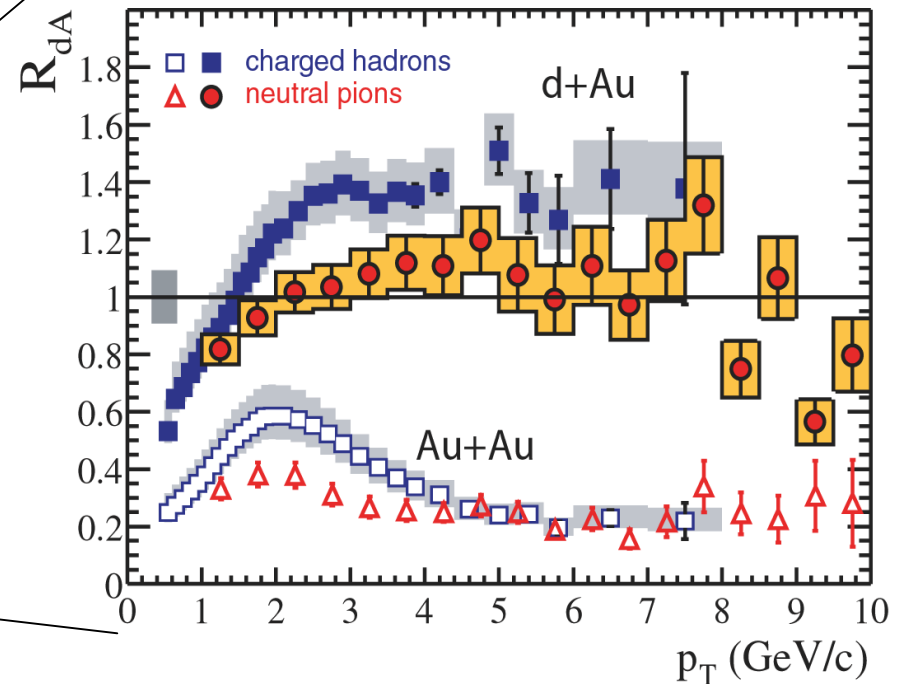
Articles published week ending
15 AUGUST 2003
Volume 91, Number 7



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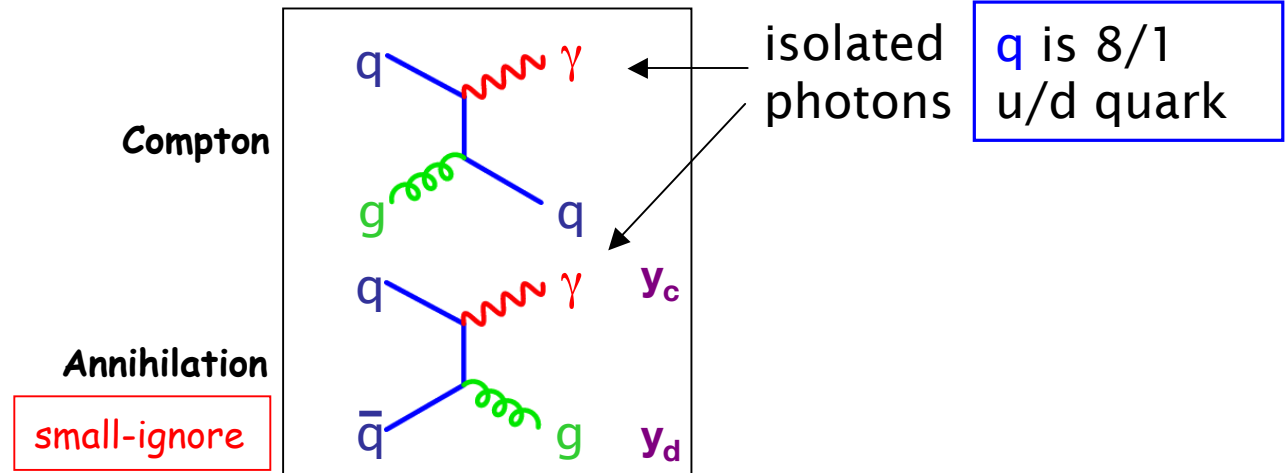
Published by The American Physical Society



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

Direct photon production-simple theory hard experiment

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



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

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

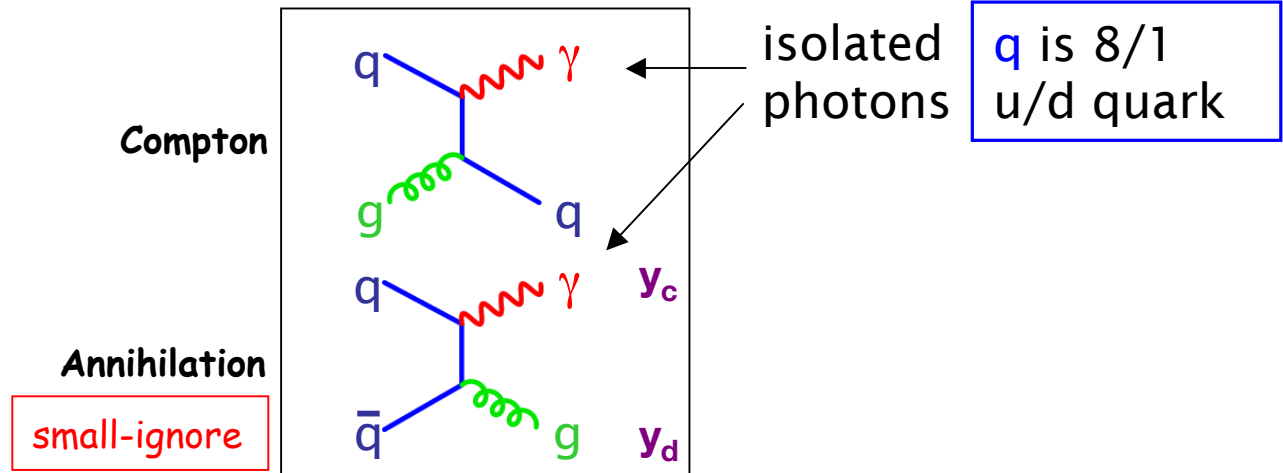
$$\cos\theta^* = \tanh\frac{(y_c - y_d)}{2}$$

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

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

Direct photon production-simple theory hard experiment

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



Analytical formula for γ -j

$$\frac{d^3\sigma}{dp_T^2 dy_c dy_d} = x$$

$$+ H$$

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



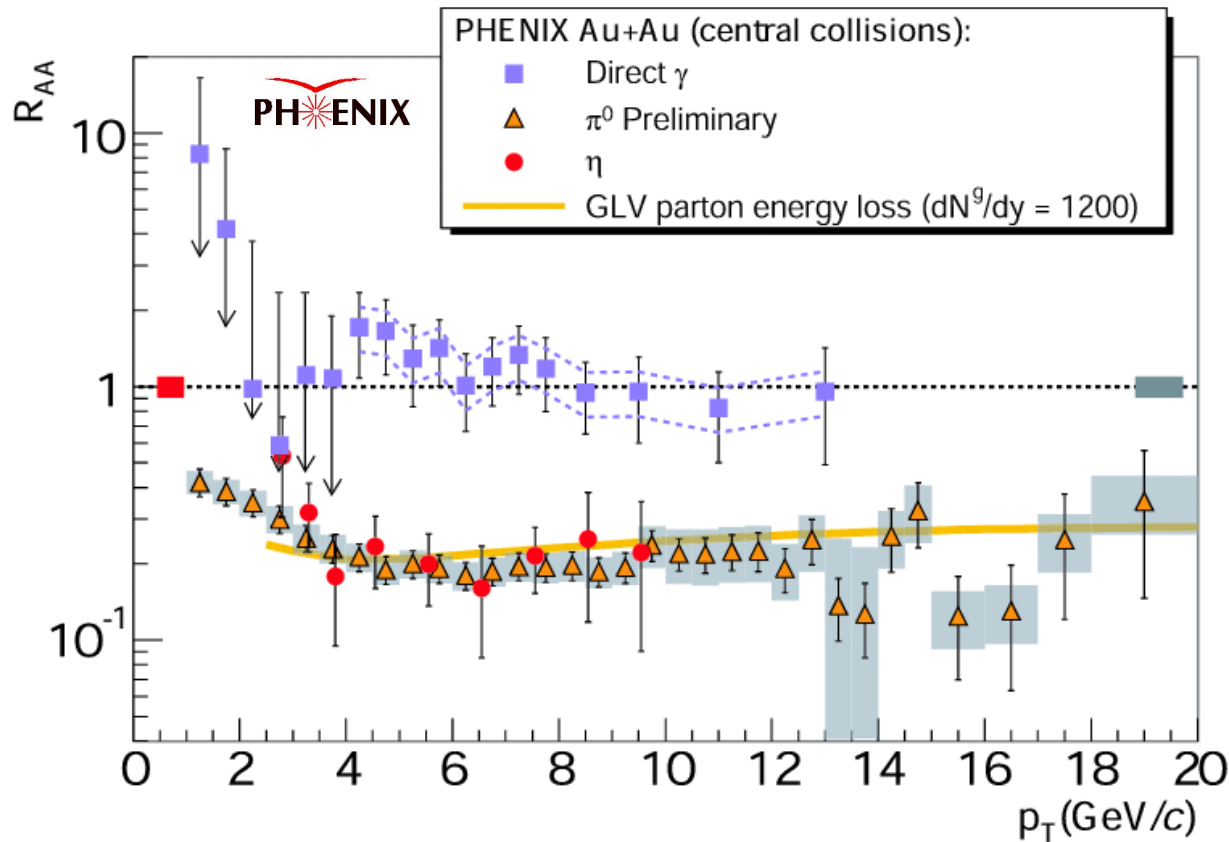
(and *parton* (jet) at p_T, y_d):

$$\left(\frac{1 + \cos \theta^*}{2} + \frac{2}{1 + \cos \theta^*} \right)$$

$$\left(\frac{1 - \cos \theta^*}{2} + \frac{2}{1 - \cos \theta^*} \right)$$

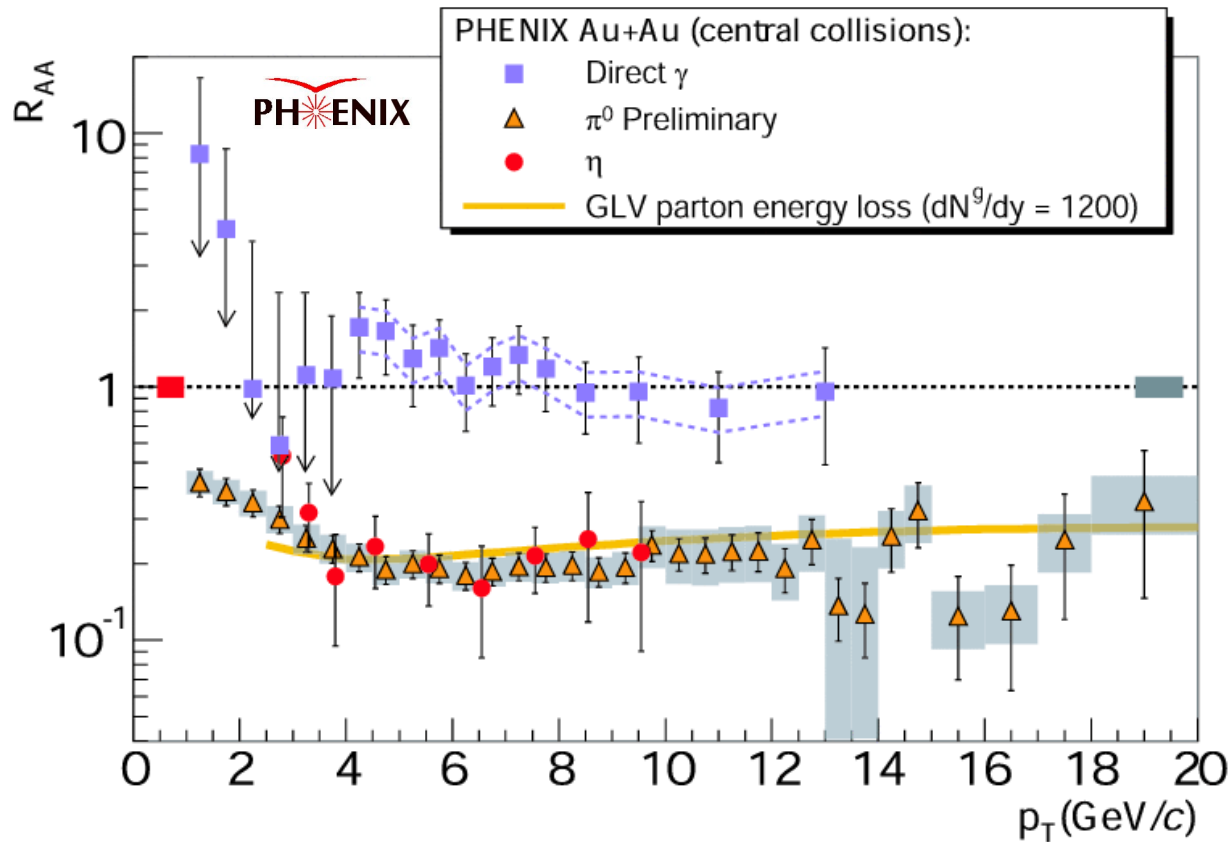
g and q pdf's in nuclei A,B

Direct photons, do not interact with the medium. They are not suppressed!



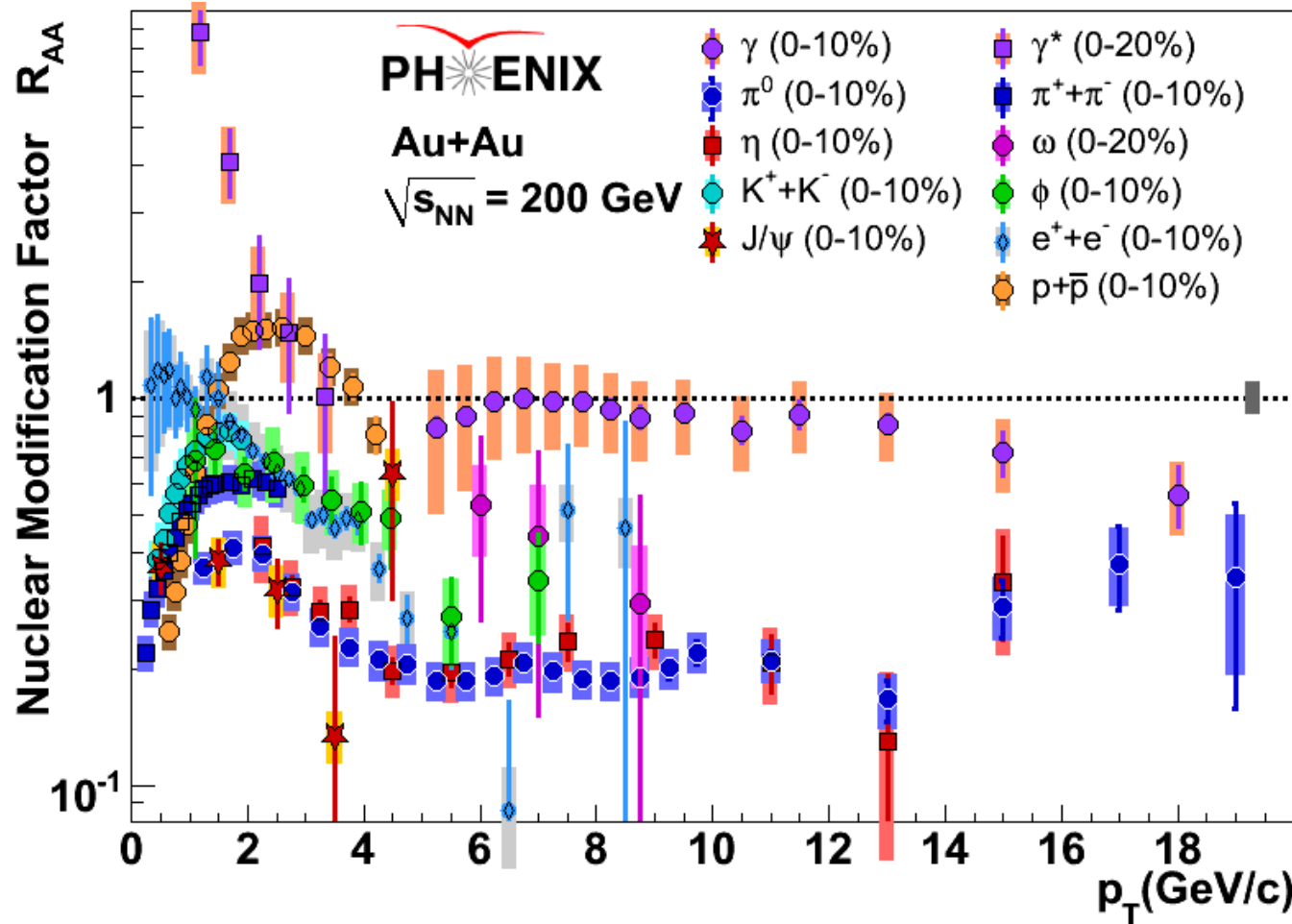
Direct γ are not suppressed. π^0 and η suppressed even at high p_T
Implies a strong medium effect (energy loss) since γ not affected.
Suppression is flat at high p_T . Theory predicts radiative energy loss

Suppression of π^0 is arguably the major discovery at RHIC. Energy loss in medium?



Direct γ are not suppressed. π^0 and η suppressed even at high p_T .
Implies a strong medium effect (energy loss) since γ not affected.
Suppression is flat at high p_T . Theory predicts radiative energy loss

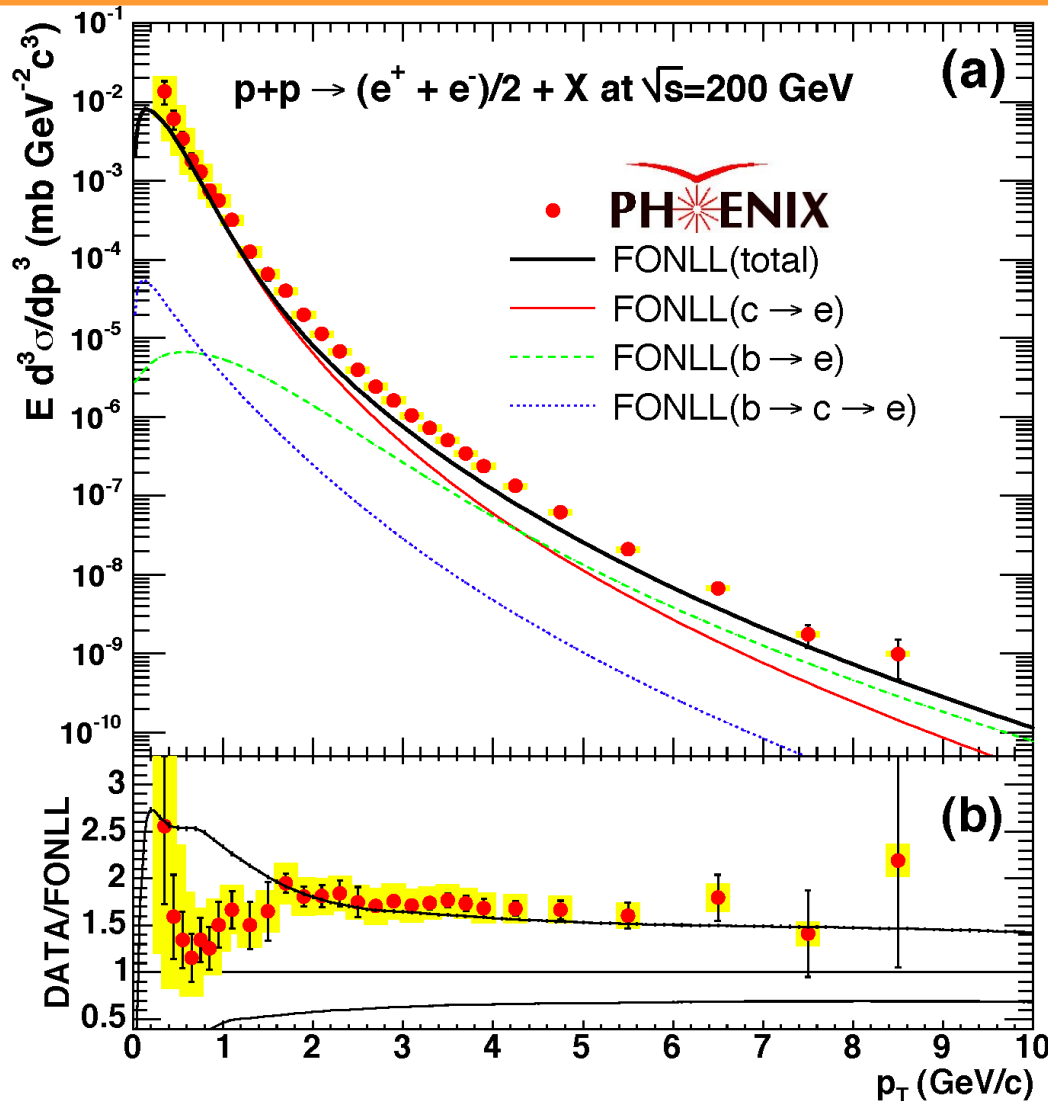
Status of R_{AA} in AuAu at $\sqrt{s_{NN}}=200$ GeV QM11



particle ID
is crucial.
different
particles
behave
differently.
some more
interesting
than others!

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- γ .

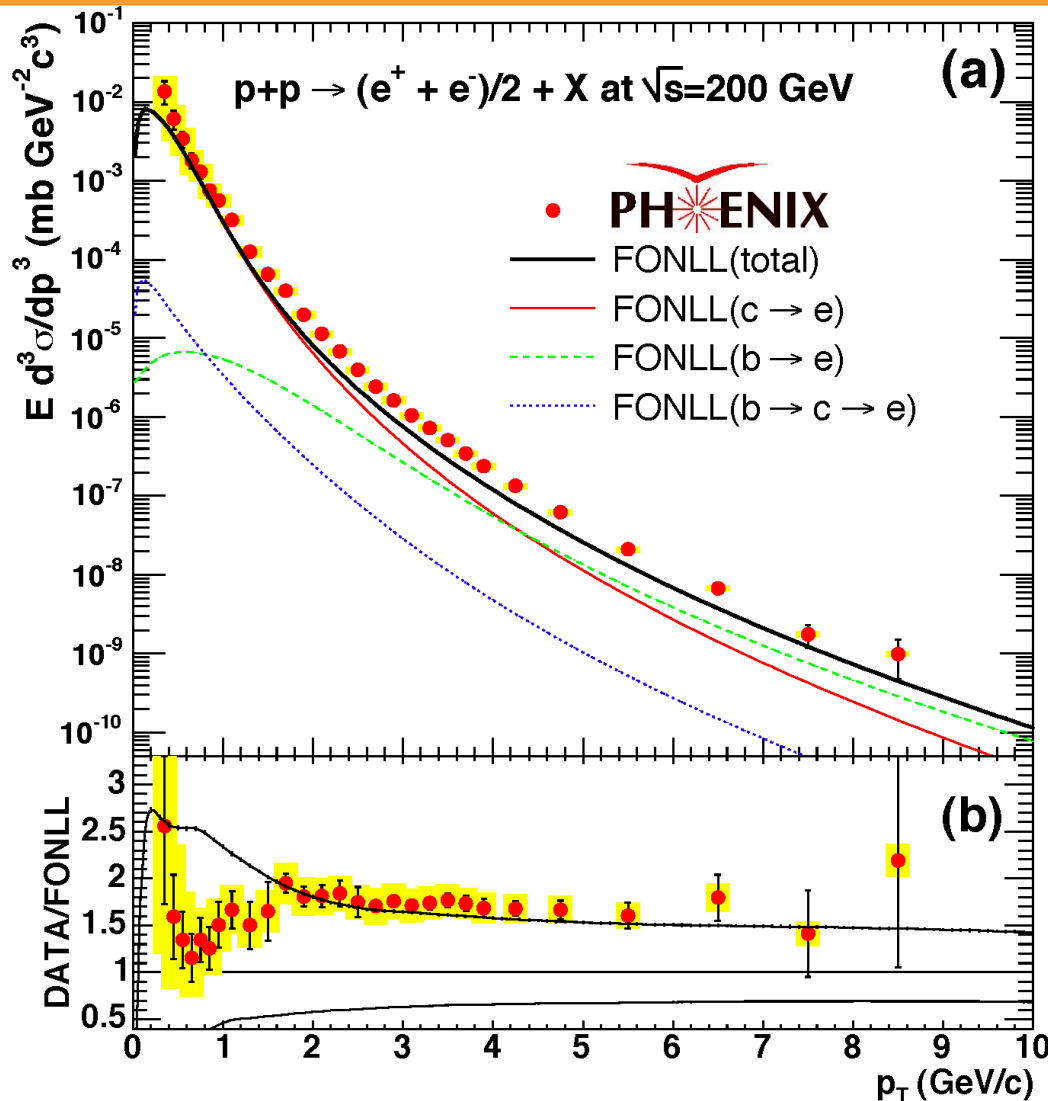
Charm via direct single $e^\pm$ in p-p collisions



PHENIX PRL97(2006)252002

Beautiful agreement of $e^\pm$ with c b production in p-p

Charm via direct single $e^\pm$ in p-p collisions



PHENIX PRL97(2006)252002

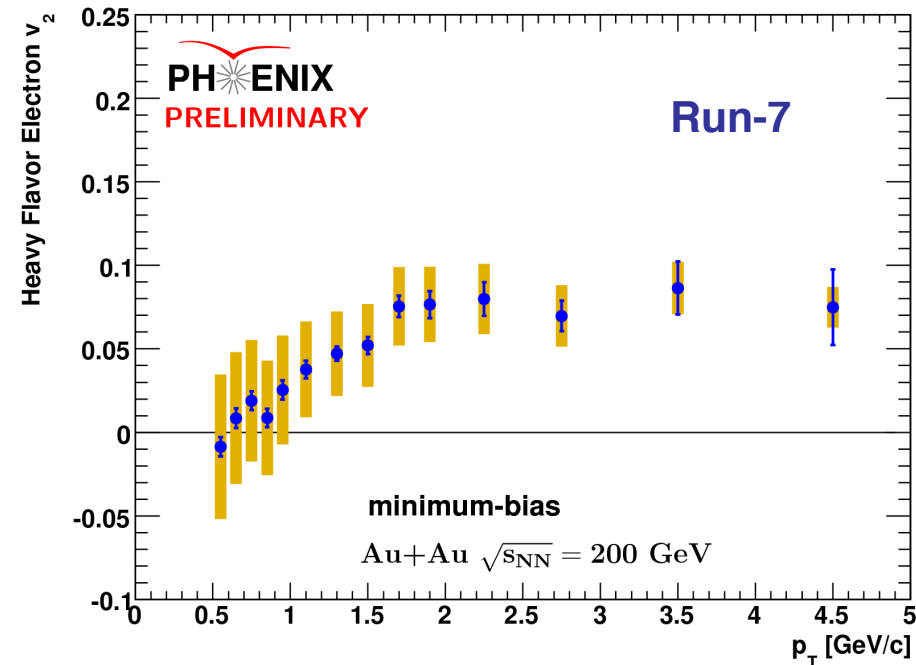
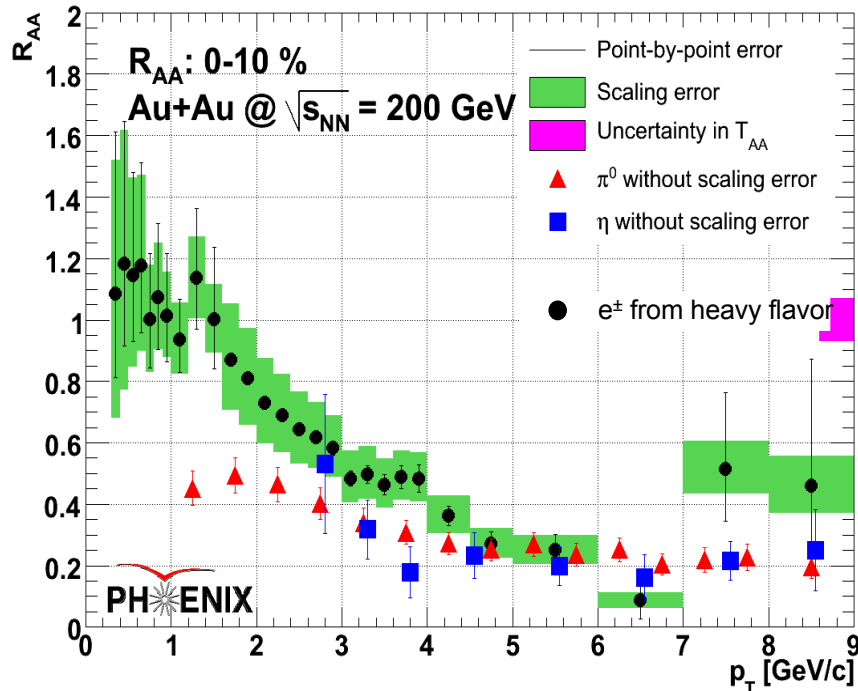
This reaction was discovered at the CERN-ISR in July 1974--before the J/Ψ , and was really the first evidence for the c -quark; but this was not understood until 1976 when “open charm” was discovered at SLAC.

Beautiful agreement of $e^\pm$ with c b production in p-p

Direct $e^\pm$ in Au+Au indicate a theoretical crisis

Au+Au PHENIX
PRL 98 (2007)172301

00-10 %



- 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.”
- 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.

From CERN Courier, September 2007

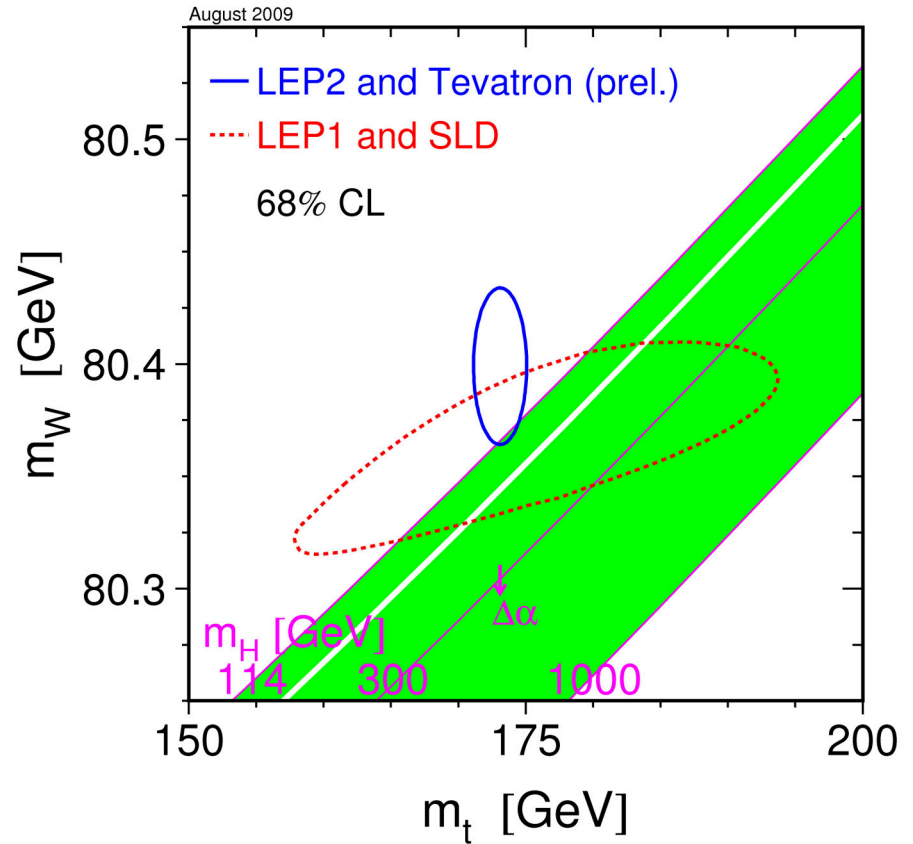
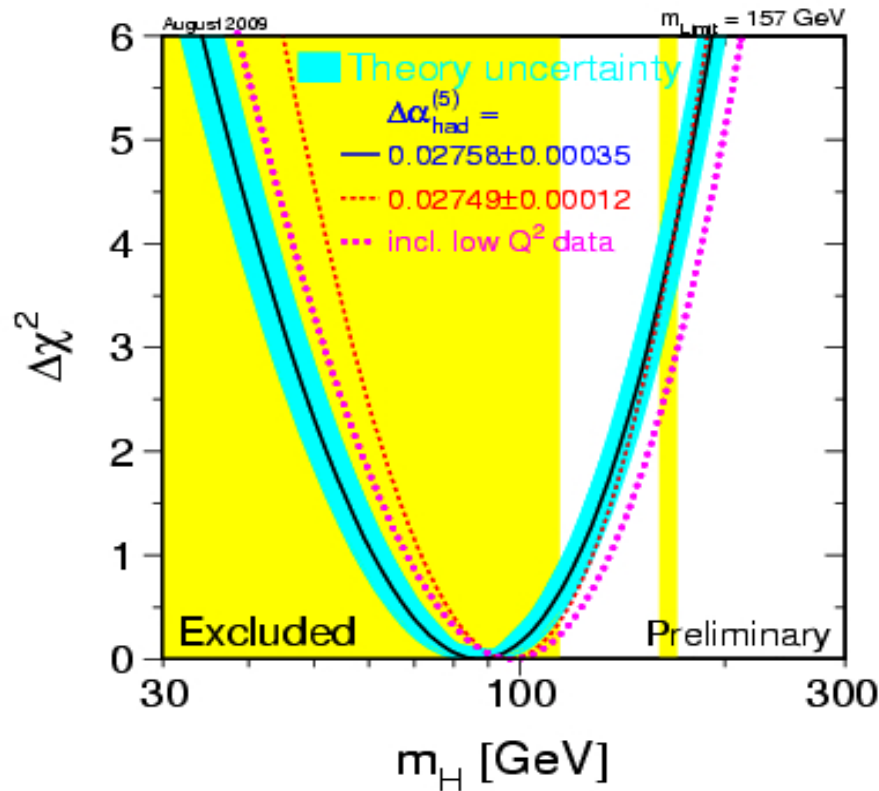
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 - Higgs doesn’t give quarks mass
 - QCD isn’t flavor-blind!!!
- MJT: “Wow! Massless b and c quarks in a color-charged medium would be the simplest way to explain the apparent equality of gluon, light and heavy quark suppression indicated by the equality 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?”

Does this affect the m_W - m_t - m_H relationship?

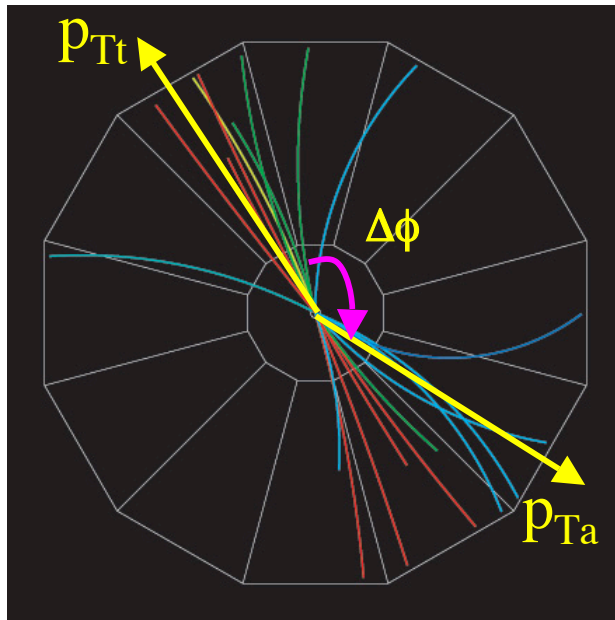


- Bill Marciano: “No change here if no Yukawa coupling; but there could be other changes” (?)

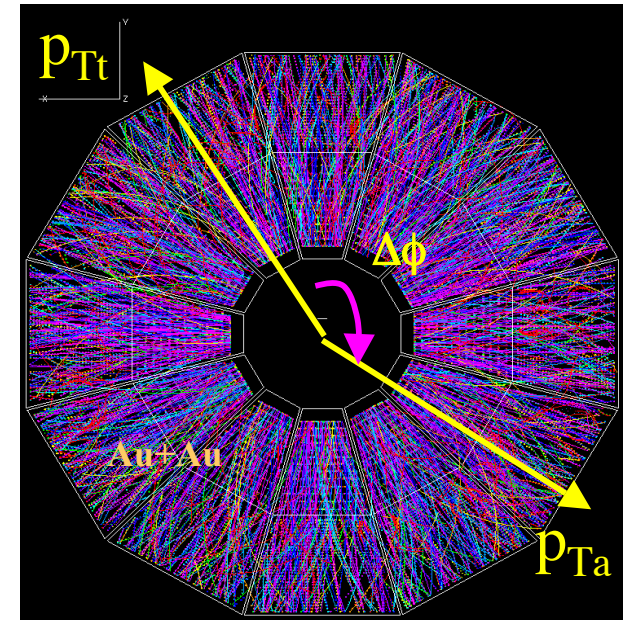
Opinions of distinguished physicists, cont'd

- 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.

Correlations

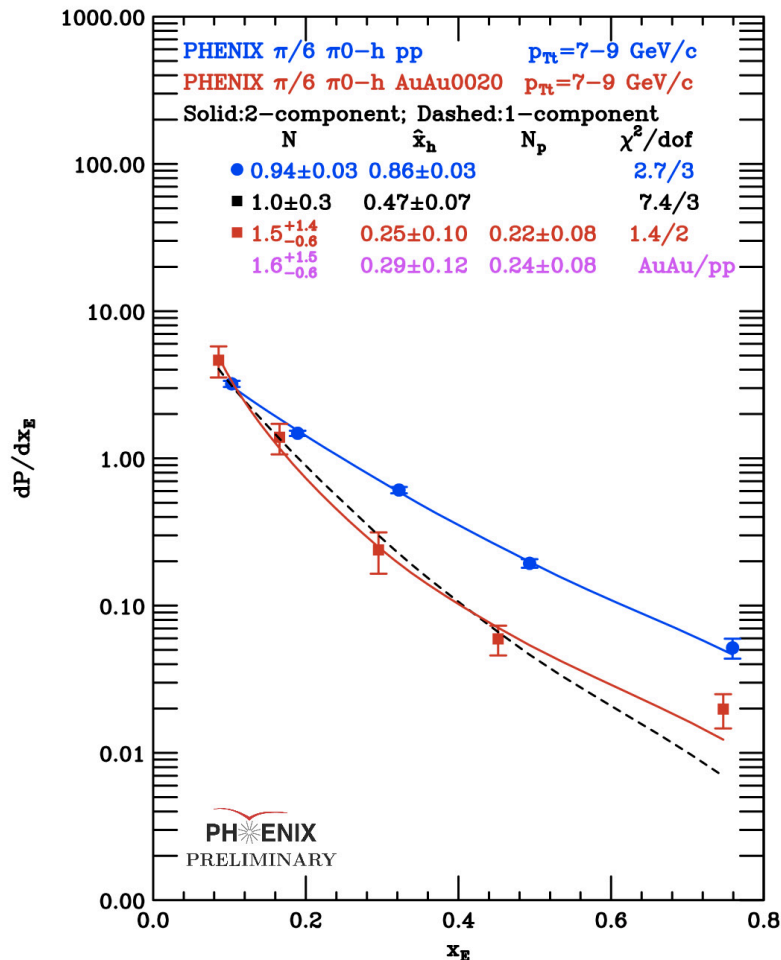


e.g. $p + p \rightarrow \text{jet} + \text{jet}$



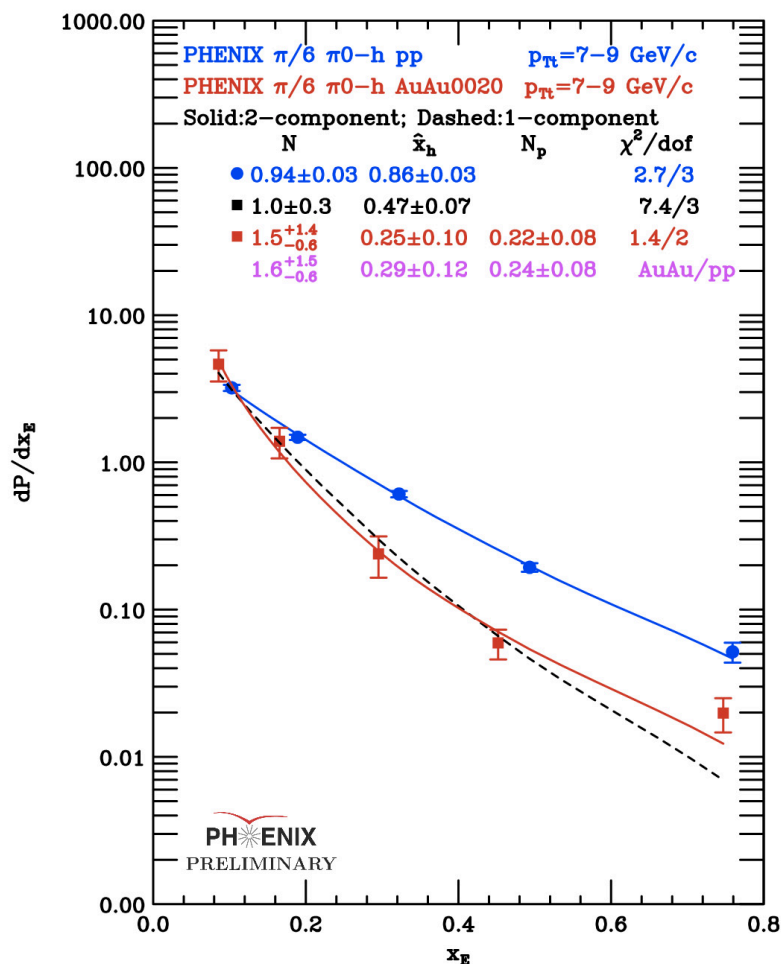
c.f. $\text{Au} + \text{Au} \rightarrow \text{jet} + \text{jet} + \text{flow}$

h-h or π^0 -h correlations in Au+Au: Away-side yield vs $x_E \approx p_{Ta}/p_{Tt}$ is steeper in Au+Au than p-p indicating energy loss

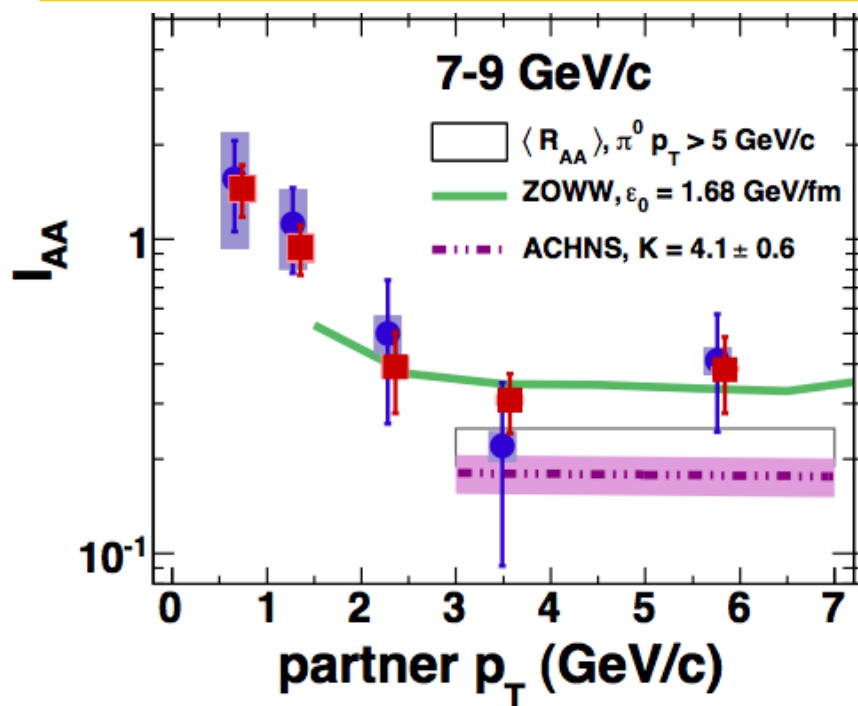


Steeper curve in Au+Au indicates that the away jet has lost energy relative to the trigger jet

h-h or π^0 -h correlations in Au+Au: Away-side yield vs $x_E \approx p_{Ta}/p_{Tt}$ is steeper in Au+Au than p-p indicating energy loss



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

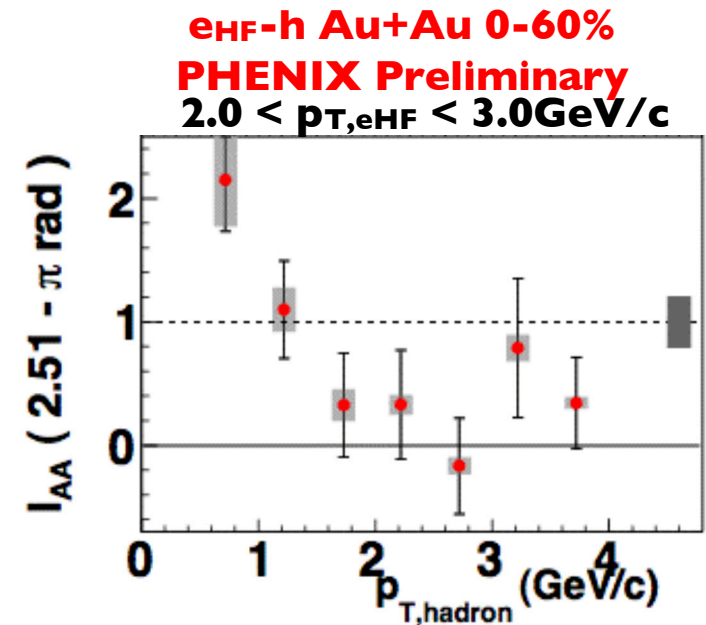
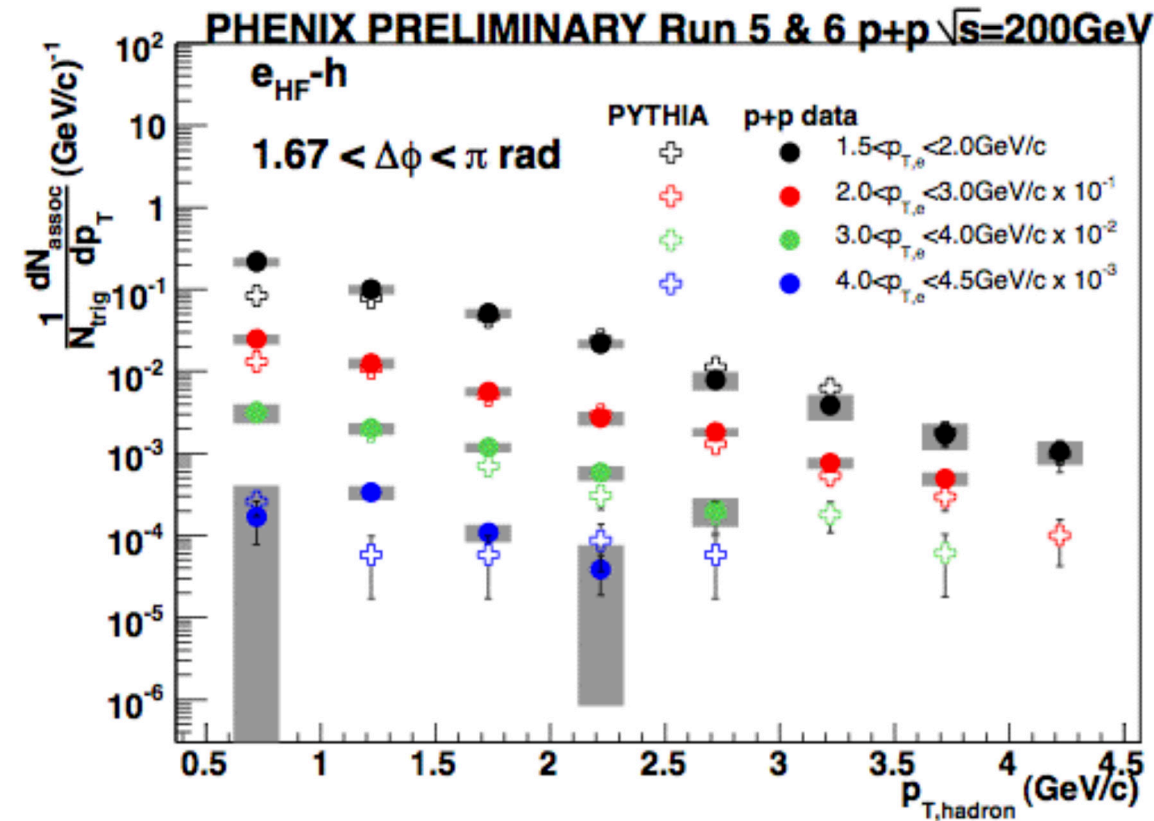


$$I_{AA} = [dN^{AA}/dx_E] / [dN^{pp}/dx_E]$$

Steeper curve in Au+Au indicates that the away jet has lost energy relative to the trigger jet

PHENIX π^0 -h correlations
 PRL104(2010)252301

First $e^\pm$ -h heavy flavor correlation-no VTX



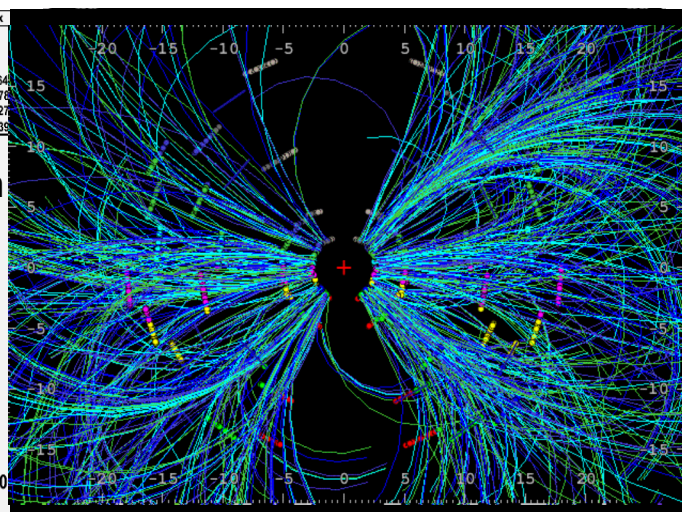
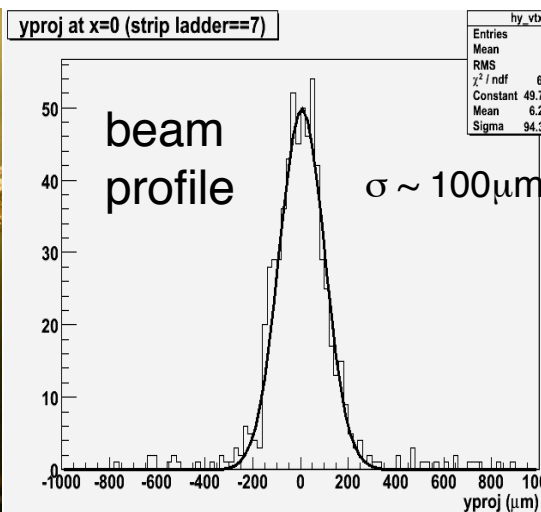
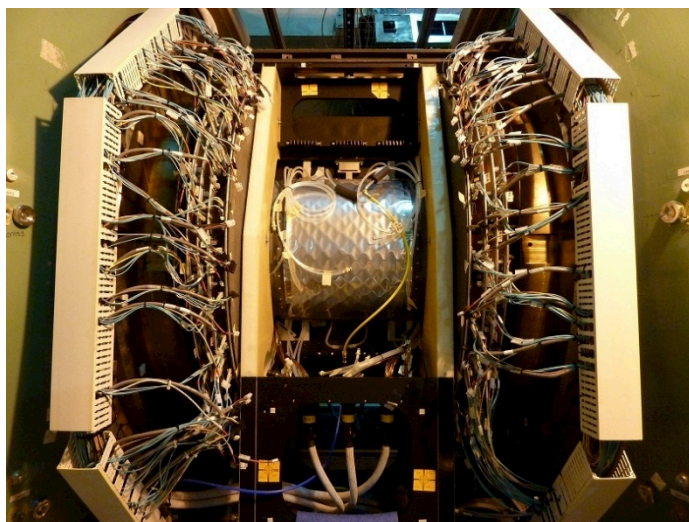
- heavy flavor tagged correlations: NLO important-- e_{HF} not necessarily balanced by back-to-back heavy quark

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)

Properties of QGP found at RHIC

The

hottest

densest

matter

ever studied in the laboratory

absorbs energy

flows

A (nearly) *perfect fluid!*

Not an ideal gas of free quarks and gluons !

Properties of QGP found at RHIC

The

hottest

$T \sim 200\text{--}400 \text{ MeV} = 2.3\text{--}4.6 \times 10^{12} \text{ K}$

$T \text{ center of sun} = 1.5 \times 10^7 \text{ K}$

densest

$\epsilon_i \sim 30\text{--}60 \times \text{nuclear density}$

matter

emits thermal (black body) radiation

ever studied in the laboratory

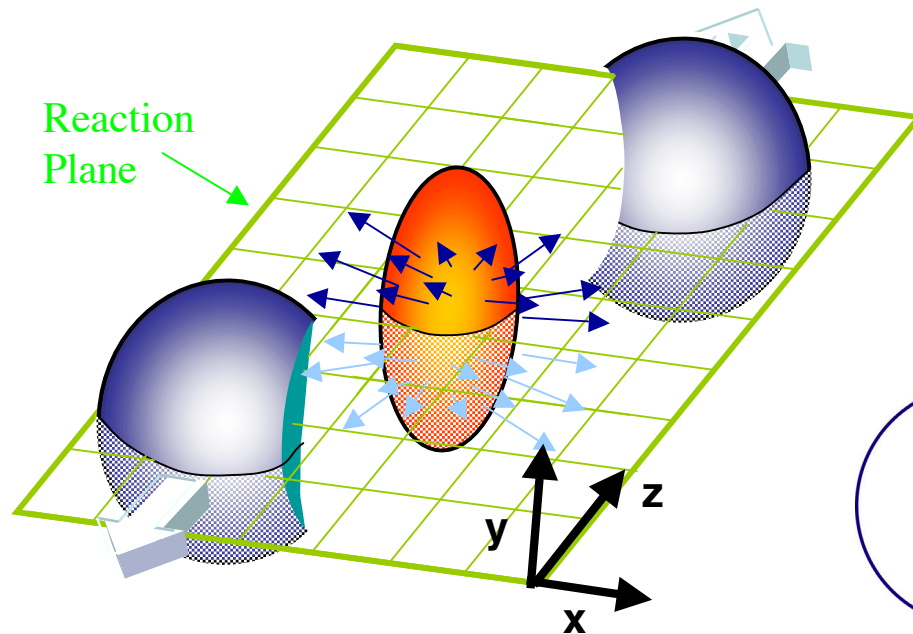
absorbs energy **stops high p_T quarks--“jet quenching”**

flows **large collective flow, viscosity~quantum lower limit**

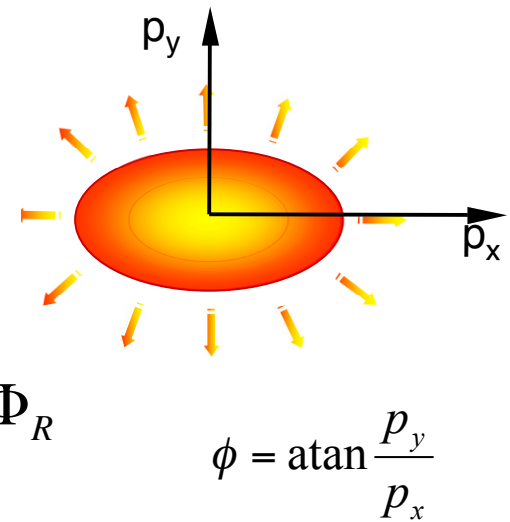
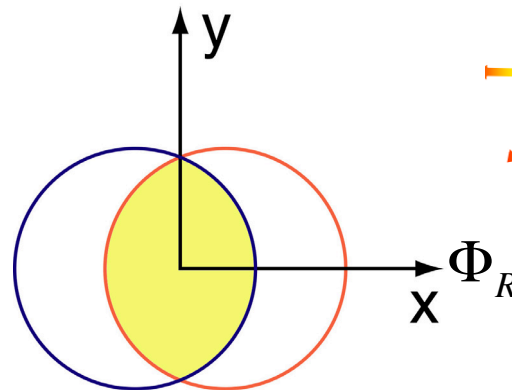
A (nearly) *perfect fluid!*

Not an ideal gas of free quarks and gluons !

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



- spatial anisotropy $\Rightarrow$ momentum anisotropy



$$\frac{Ed^3N}{dp^3} = \frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^3N}{2\pi p_T dp_T dy} \left[1 + \sum_n 2v_n \cos n(\phi - \Phi_R) \right]$$

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

✓ v_2 is the 2nd harmonic Fourier coefficient

Odd harmonics=0
due to symmetry of
“almond” $\phi \rightarrow \phi + \pi$

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

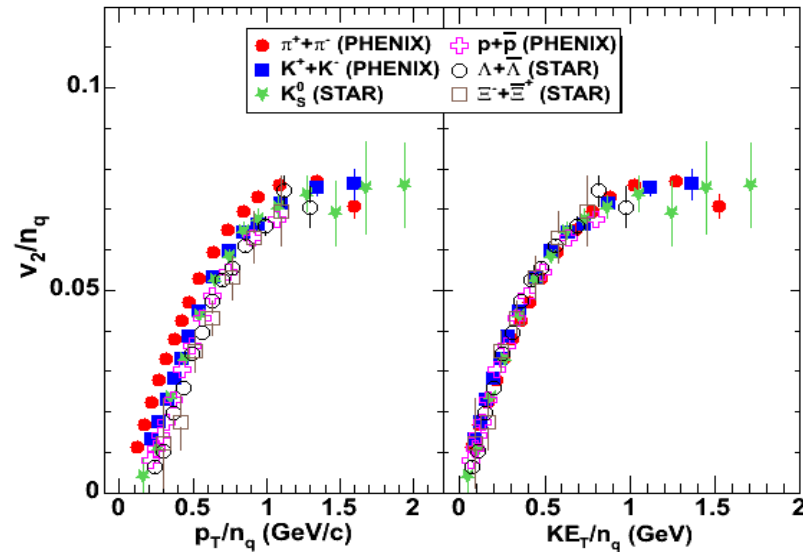
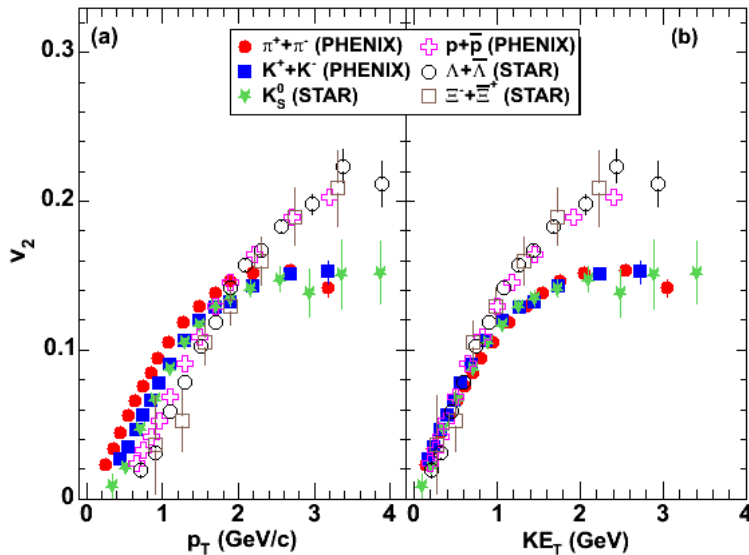
Elliptical flow
dominant at midrapidity

Elliptic Flow v_2 in AuAu Central 200 GeV

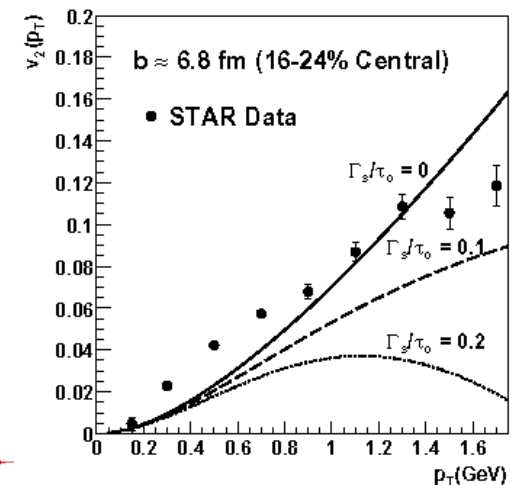
Universal in constituent quark Kinetic Energy

STAR-PRC72 (2005) 014904

PHENIX PRL98 (2007) 162301



- large v_2 for high and low p_T , plateaus for $p_T > 2$ GeV/c for mesons, scales in KE_T /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, PRC68 (2003) 034913, ``the perfect fluid''??
- Quantum Viscosity Bound from string theory reinforces this idea, Kotvun, Son, Starinets, PRL 94 (2005) 111601



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 due to fluctuations in the collision geometry on an event by event basis, the eccentricity of participants on any given event, did not respect the average symmetry, resulting in:

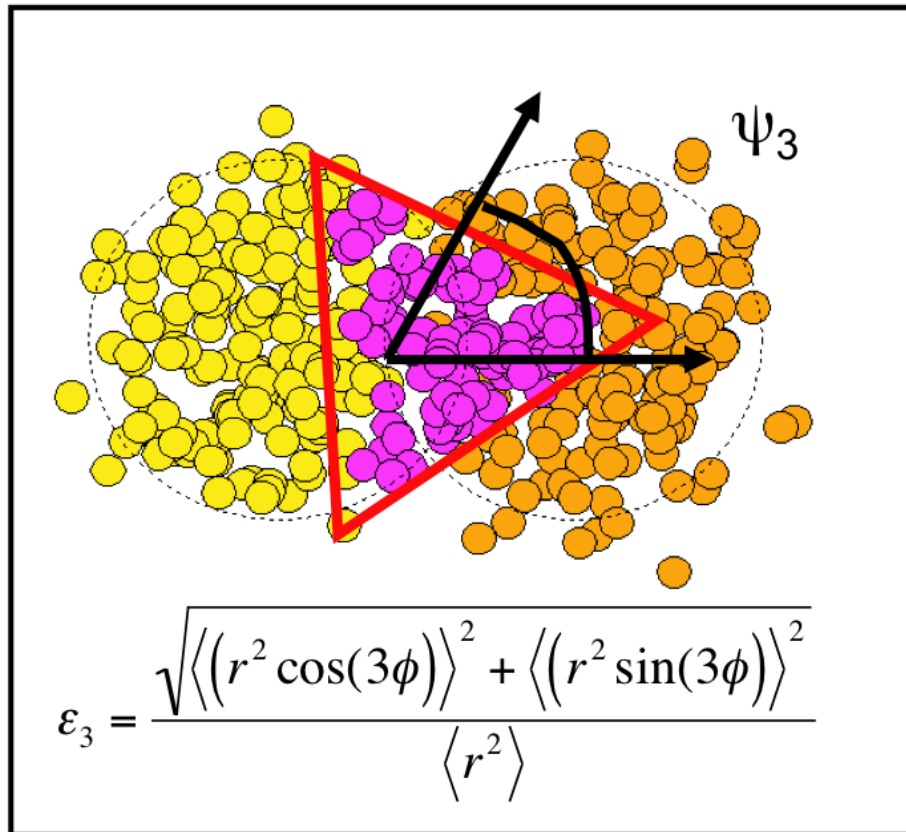
Another new ballgame-2010- v_3

- 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 due to fluctuations in the collision geometry on an event by event basis, the eccentricity of participants on any given event, did not respect the average symmetry, resulting in:

* In analogy to anisotropies in the Cosmic Microwave Background Radiation, an Indian group, A. P. Mishra, *et al.*, PRC77, 065902 (2008) suggested that $\sqrt{v_n^2} = v_n^{\text{r.m.s.}}$ including odd harmonics might show the same effect in A+A collisions. Then a Brazilian theory collaboration, J. Takahashi, *et al.*, PRL 103, 242301 (2009) who had an event-by-event hydrodynamics code showed that indeed odd harmonics v_3 exist in events with only soft-physics, no hard-scattering. The first measurement was made in 2010:

Triangular Flow- v_3

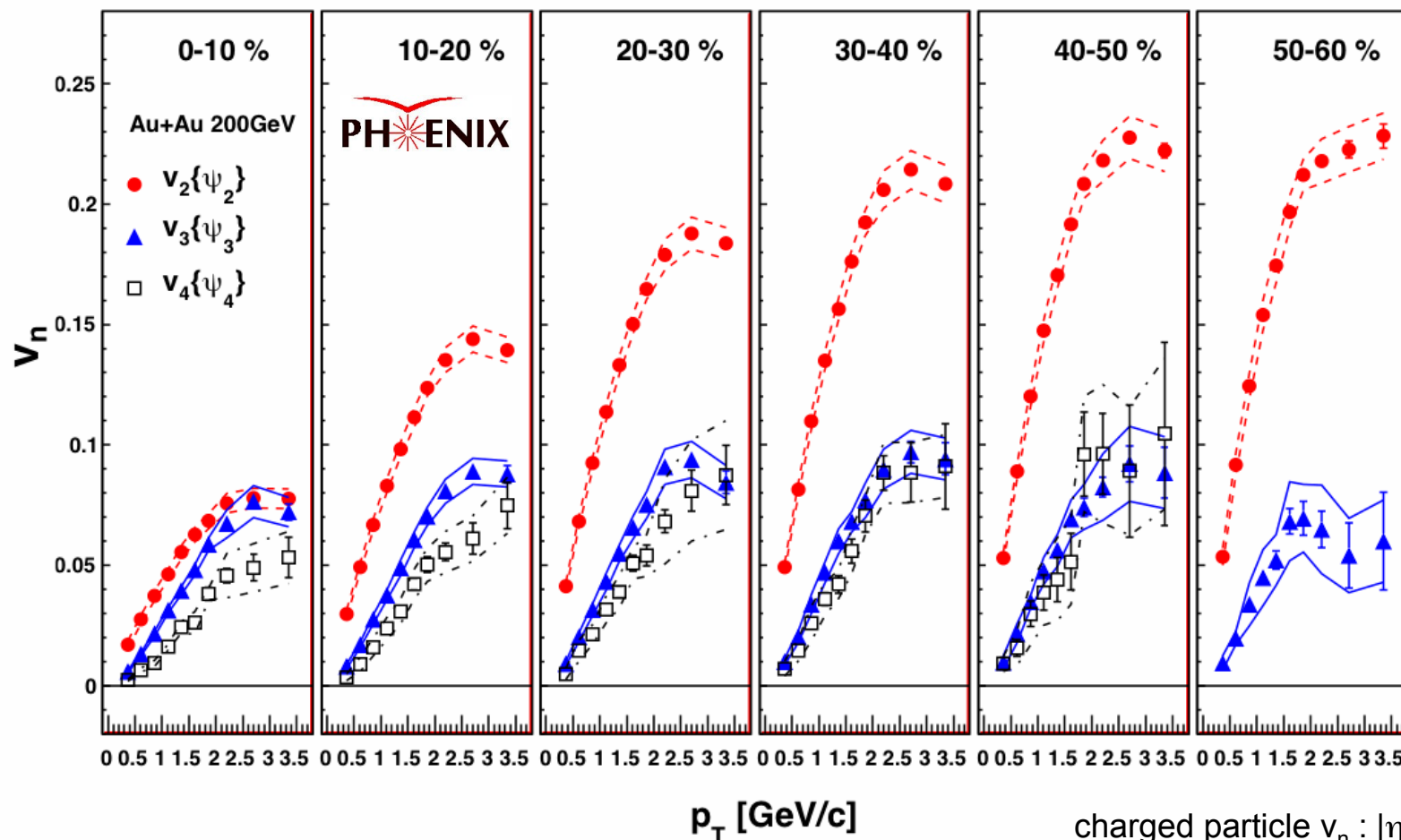
Participant Triangularity



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

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

arXiv:1105.3928



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

charged particle $v_n : |\eta| < 0.35$
 reaction plane $\Phi_n : |\eta| = 1.0 \sim 2.8$

All of these are consistent with initial fluctuation.

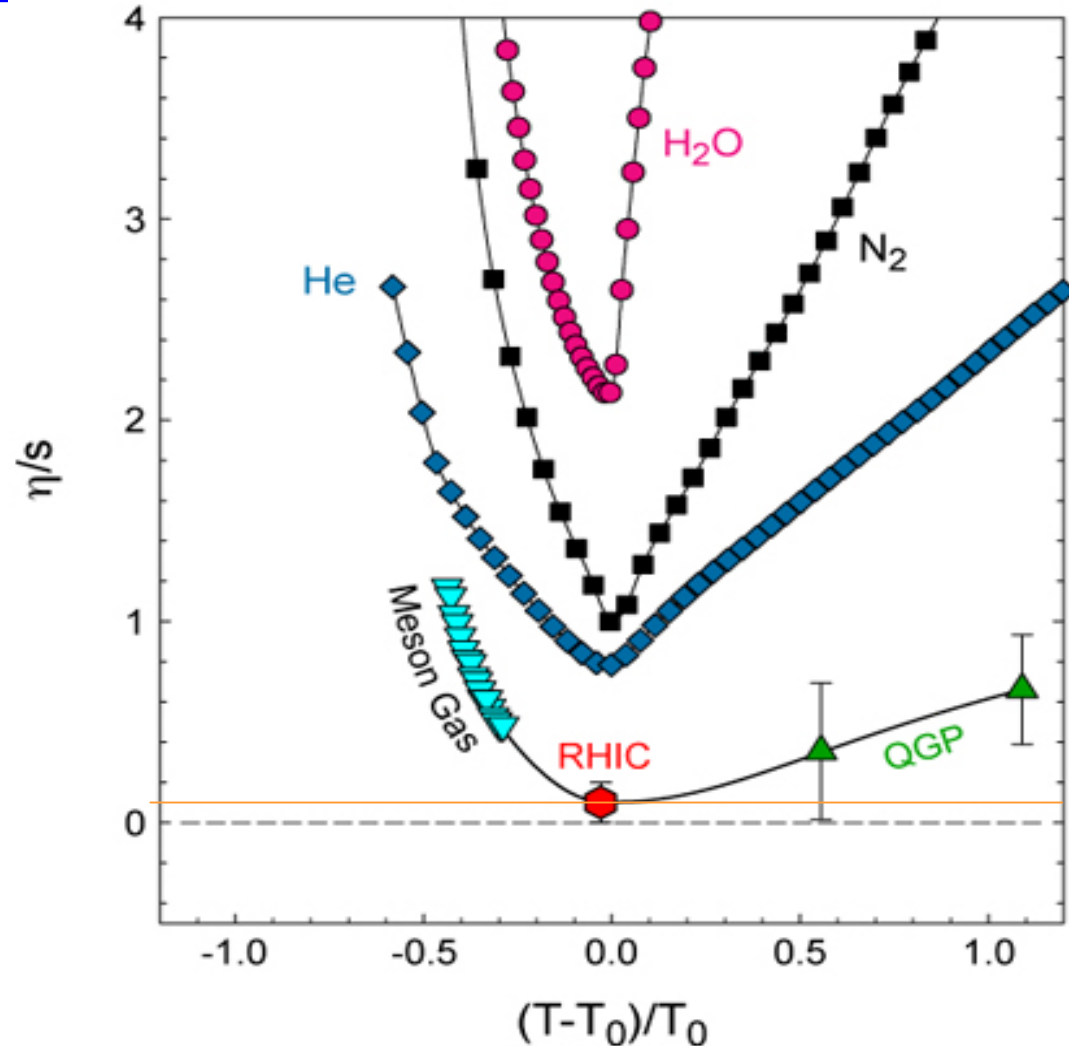
The constituent quark distribution after the medium thermalizes at time $\tau_0 \leq 1$ fm is converted by hydrodynamic expansion followed by fragmentation into the particle distributions that we measure in the laboratory. The fact that the particle distributions follow even the fluctuations in the initial state geometry points to real hydrodynamic flow of a nearly perfect fluid.

The viscosity bound---the perfect fluid

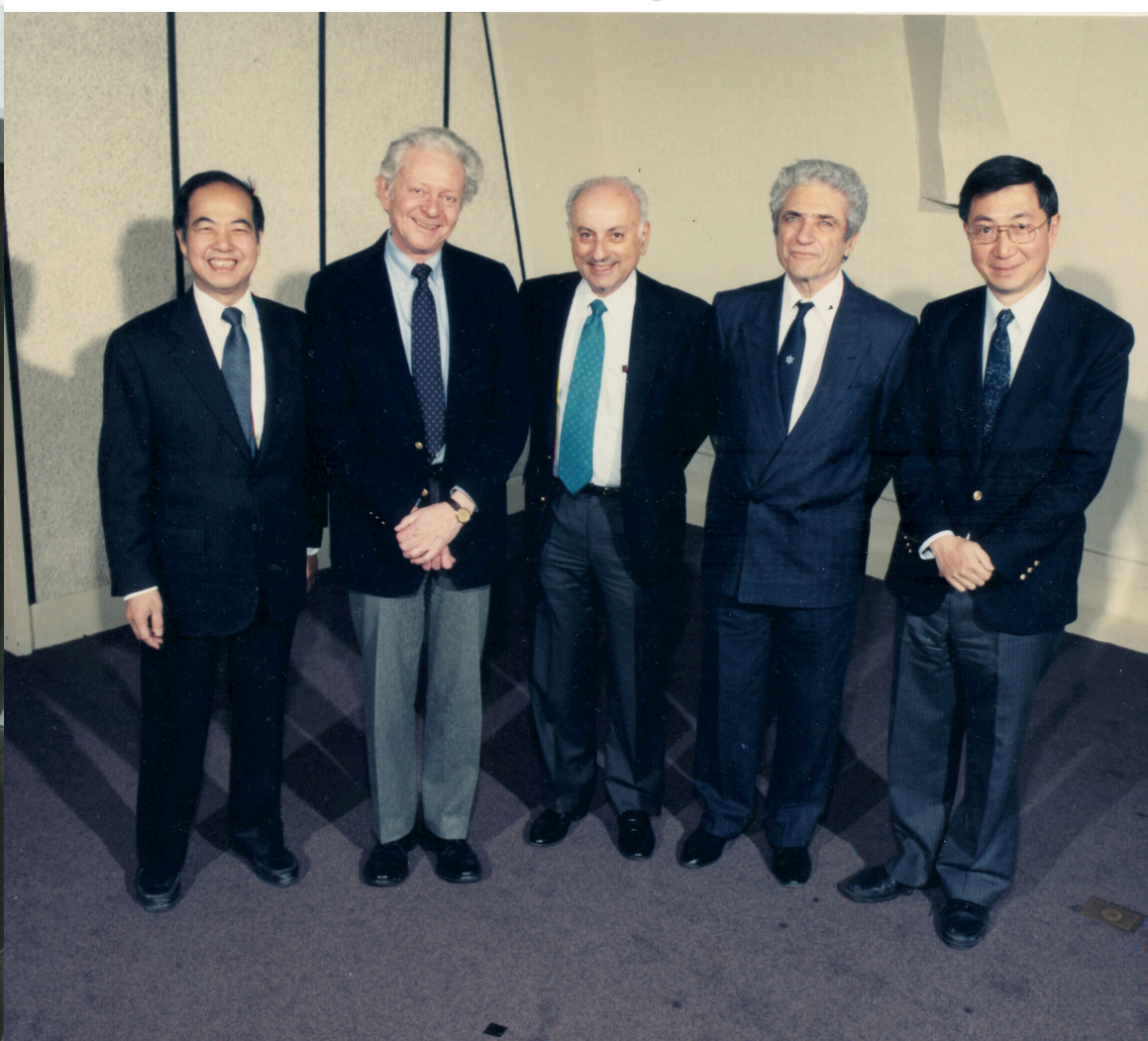
Kotvun, Son, Starinets, PRL **94** (2005) 111601

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

η = shear viscosity
 s =entropy density
 $\pi=3.1415927...$



BNL-Nobel Laureates in Physics



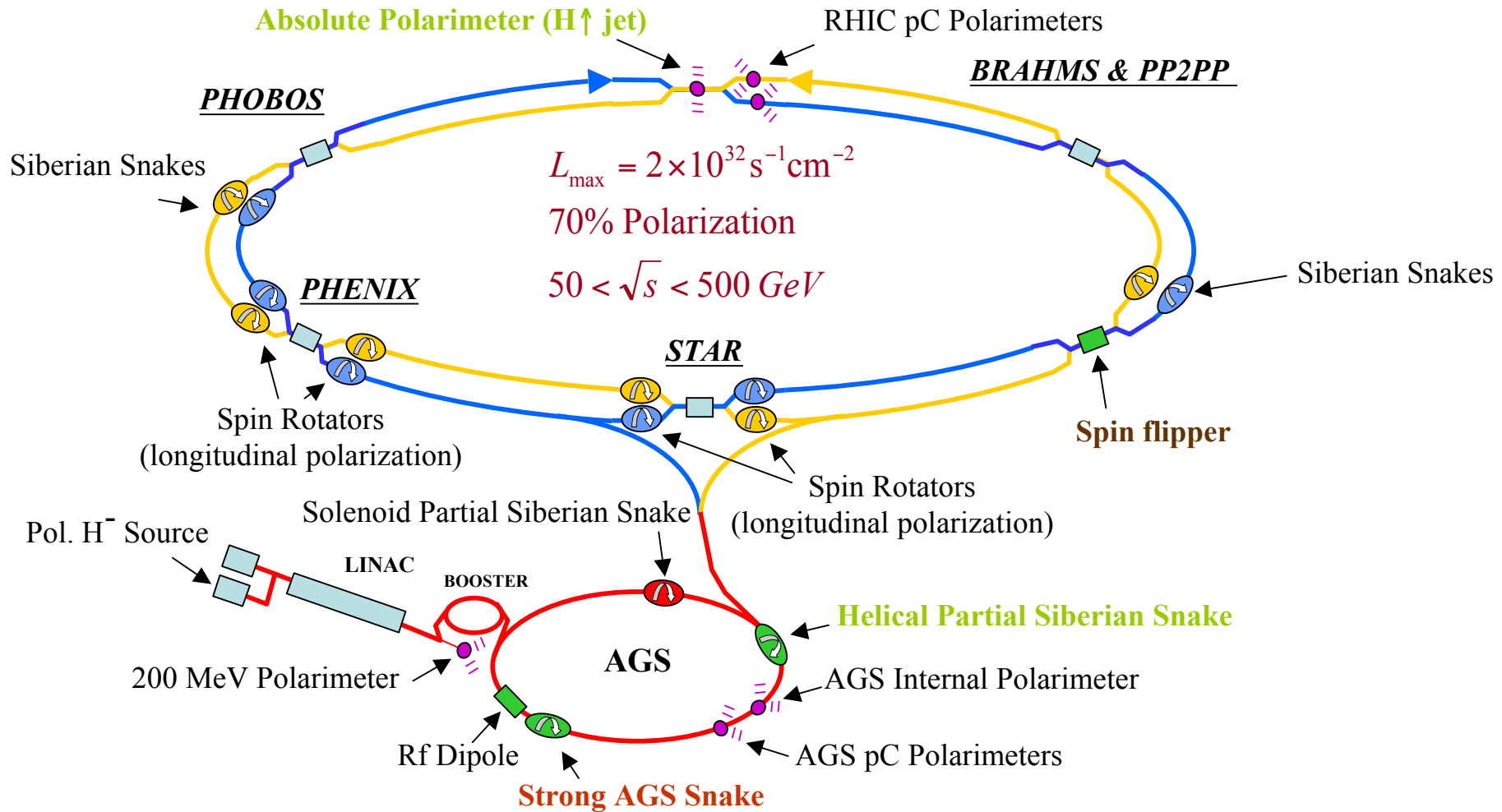
Fitch
Yang
Cronin
Rabi
Ting

Lee Lederman Schwartz Steinberger Ting

Gordon Danby-Jim Powell invented Maglev Trains



RHIC: RHI+polarized p-p collider



- Installed and commissioned during FY04 run
- Plan to be commissioned during FY05 run
- Installed and plan to be commissioned during FY05 run