Highlights from BNL-RHIC

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International School of Subnuclear Physics
“What we would like LHC to give us”
50th Course-Erice, Sicily, Italy
June 23- July 2, 2012
2nd of the 50th Anniversary Celebrations
High Energy Nucleus-Collisions provide the means of creating Nuclear Matter in conditions of Extreme Temperature and Density.

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

- The state should be in chemical (particle type) and thermal equilibrium \( <p_T> \sim T \)
- The major problem is to relate the thermodynamic properties, Temperature, energy density, entropy of the QGP or hot nuclear matter to properties that can be measured in the lab.
The QGP was discovered at RHIC, announced on April 19, 2005 (230th anniversary of Paul Revere’s Ride) as ‘the perfect fluid’, published NPA750,757(2005)1-171,1-283.

Results from the LHC Pb+Pb measurements confirm the RHIC discoveries and add some new information—notably with Jets.

http://www.nationalcenter.org/PaulRevere’sRide.html
That’s old news; but we start with this year’s news from BNL and RHIC.
Relativistic Heavy Ion Collider
1 of 2 ion colliders (other is LHC), only polarized p-p collider
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2 superconducting 3.8 km rings
2 large experiments
100 GeV/nucleon Au
250,255 GeV polarized protons

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

Au-Au, d-Au, Cu-Cu, polarized p-p (so far)
New in 2012 U+U, Cu+Au
15 different energies (so far)
Run12 polarized-p-p Integrated Luminosity

Objective: comparison data for Vertex detectors

Objective: flavor identified spin pdf’s using W parity violation
Run12 polarized-p-p Integrated Luminosity

\[ \sqrt{s} = 200 \text{ GeV} \]
\[ P = 61.8\% \]
\[ P = 56.6\% \]

\[ \sqrt{s} = 510 \text{ GeV} \]
\[ P = 50.3\% \]
\[ P = 53.5\% \]

Objective: comparison data for Vertex detectors
Objective: flavor identified spin pdf’s using W parity violation

Fantastic data-sets!
Areas to improve: Polarization, Luminosity (RHIC); Data-taking efficiency (exp.)
Ironically, the first measurement of the $W$ cross section in p-p collisions was from PHENIX at RHIC in polarized p-p collisions $\sqrt{s}=500$ GeV.

Method of Jacobian peak at mid-rapidity was originally proposed by Nino Zichichi

Proc. 12th ICHEP Dubna 1964 vol 3 p 35
Sampled Luminosity (U+U & Cu+Au) Run 12

Objective: Largest Nucleus American Football shaped

Goal: 60 $\mu$b$^{-1}$ for $|z|<10$ cm

Collected over 3 billion events (4/25 – 5/15). Far exceeded the requested goal by 150% !!!

Goal: 2.4 nb$^{-1}$ for $|z|<10$ cm

Goal achieved on Sunday June 24 during Erice Conference. Data taking continued until 8am, June 25.
“Mike, is there a ‘real collider detector’ at RHIC?”---J. Steinberger about PHENIX

- **PHENIX** is 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% X₀**
  ✓ **EMCAL RICH e± i.d. and lvl-1 trigger**
  
  • **γ π₀** separation up to **p_T ~ 25 GeV/c**
  • **EMCAL and precision TOF** for **h± pid**
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Comparison to scale with a wedge of CMS
STAR-more conventional collider detector

Original STAR detector c. 2000. Several incremental upgrades since.
Soft Physics Dominates
Particle production
in both p-p and A+A
(Relativistic Heavy Ion) collisions
Three things are dramatically different in Relativistic Heavy Ion Physics than in p-p physics

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

STAR-Jet event in pp

STAR Au+Au central

PHENIX Au+Au central

High p_T particle

Bj = 5.4 ± 0.6 GeV fm^{-2}

PRC 71 (2005) 034908

Central Collisions

High p_T particle

Central

Peripheral

Participants

Spectators

Maximum impact parameter ~ 15 fm

\[ E_{Bj} = \frac{1}{\pi R^2} \frac{1}{c \tau_0} \left( \frac{dE_T}{dy} \right) \]

\[ E_T \equiv \sum_i E_i \sin \theta_i \]

PHENIX \( E_T \) Transverse Energy corr to \( \Delta \eta = 1 \) and \( \Delta \phi = 2\pi \)

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All $dN_{ch}/d\eta$ distributions at $\sqrt{s_{NN}}=200$ GeV

Raw values-performance plot; not corrected for response, efficiency, acceptance. All B+A show typical elongation with increasing A
All $dN_{ch}/d\eta$ distributions at $\sqrt{s_{NN}}=200$ GeV

Raw values-performance plot; not corrected for response, efficiency, acceptance. All B+A show typical elongation with increasing A

For U+U no obvious effect from different possible orientations
From RHIC to LHC to RHIC

evolution of multiplicity with centrality, $N_{\text{part}}$

PHENIX $\sqrt{s_{NN}}=130$ GeV, PRL 86, 3500 (2001); ALICE $\sqrt{s_{NN}}=2.76$ TeV PRL 106,032301(2011)
From RHIC to LHC to RHIC evolution of multiplicity with centrality, $N_{\text{part}}$

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Identical shape of distributions indicates a nuclear-geometrical effect

New RHIC data for Au+Au at $\sqrt{s_{NN}} = 0.0077$ TeV show the same evolution with centrality

The geometry is the number of quark participants/nucleon participant

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Eremin & Voloshin, PRC 67, 064905 (2003); De & Bhattacharyya PRC 71; Nouicer EPJC 49, 281 (2007)
STAR measurement (AMS background) from A+A collisions-lots of $p\bar{p}$ to coalesce

$p/p$ ratio $\approx 0.85$ at mid-rapidity

**Discovery of anti-$^4\text{He}$ in Au+Au**

doi:10.1038/nature10079
QGP PHYSICS
Highlights from RHIC
Anisotropic (Elliptic) Transverse Flow--an Interesting complication in AA collisions

- spatial anisotropy $\Rightarrow$ momentum anisotropy

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" $\phi \rightarrow \phi + \pi$

Elliptical flow dominant at midrapidity
Elliptic Flow $v_2$ in AuAu Central 200 GeV
Universal in constituent quark Kinetic Energy

- $v_2$ for high and low $p_T$, plateaus for $p_T > 2$ GeV/c for mesons, scales in KE/constituent quark
- $\phi$-meson (not shown) follows same scaling: further implies flow is partonic not hadronic
- KE scaling suggests Hydrodynamic origin.
- $v_2$ for $p_T > 1$ GeV/c suggests low viscosity, D. Teaney, PRC 68 (2003) 034913, ``the perfect fluid''??
- Quantum Viscosity Bound from string theory reinforces this idea, Kotvun, Son, Starinets, PRL 94 (2005) 111601
A 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, in 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:
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* In analogy to anisotropies in the Cosmic Microwave Background Radiation, an Indian group, A. P. Mishra, et al., PRC77, 065902 (2008) suggested that $\sqrt{\nu_n^2} = \nu_n^{r.m.s.}$ 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-$\nu_3$

Participant Triangularity

\[ \varepsilon_3 = \frac{\sqrt{\langle r^2 \cos(3\phi) \rangle^2 + \langle r^2 \sin(3\phi) \rangle^2}}{\langle r^2 \rangle} \]

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

All of these are consistent with initial fluctuation.
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 most important innovation at RHIC was the use of hard-scattering as an in-situ probe of the medium in RHI collisions.
Hard-Scattering: Rutherford to ISR to RHIC

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

b=impact parameter
\[ \tan(\theta/2) \propto \frac{1}{b} \]

Geiger & Marsden
\[ \alpha + Au \rightarrow \alpha + Au \]
Phil. Mag 25(1913)604

CCR CERN-ISR 1972
\[ p + p \rightarrow \pi^0 + X \]
Discovery of strong, hard parton-parton scattering

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First prediction using ‘QCD’ 1975-wrong but


“Asymptotic freedom and the “absence” of vector-gluon exchange in wide-angle hadronic collisions”

Abstract: The naive, pointlike parton model of Berman, Bjorken and Kogut is generalized to scale-invariant and asymptotically free field theories. The asymptotically free field generalization is studied in detail. Although such theories contain vector fields, single vector-gluon exchange contributes insignificantly to wide-angle hadronic collisions. This follows from (1) the smallness of the invariant charge at small distances and (2) the breakdown of naive scaling in these theories. These effects should explain the apparent absence of vector exchange in inclusive and exclusive hadronic collisions at large momentum transfers observed at Fermilab and at the CERN ISR.

An interesting Acknowledgement: ... Two of us (J. K. and L. S. also thank S. Brodsky for emphasizing to us repeatedly that the present data on wide-angle hadron scattering show no evidence for vector exchange.

Nobody’s perfect, they get one thing right! They introduce the “effective index” \( n(x_T, \sqrt{s}) \) to account for ‘scale breaking’ in QCD; deviation from Bjorken scaling.

\[
E \frac{d^3 \sigma}{dp^3} = \frac{1}{p_T^{n(x_T, \sqrt{s})}} F(\frac{p_T}{\sqrt{s}}) = \frac{1}{\sqrt{s}^{n(x_T, \sqrt{s})}} G(\frac{p_T}{\sqrt{s}})
\]
PHENIX excellent in hard-scattering measurements via single-inclusive and two-particle correlations, STAR better with Jets.

In p-p collisions, since 1978, NLO pQCD agrees very well with all measurements.
Again agree very well with NLO pQCD in p-p collisions. But, I have known that QCD worked for hard scattering since 1978. What I learn from the CMS plot is that partons are pointlike up to $Q^2 \approx t \approx 2p_T^2 = 2,000,000 \text{GeV}^2$ i.e. $r \ll 1.4 \times 10^{-4} \text{fm}$.!!
• R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne and D. Schiff
  NPB484 (1997) 265-282 (and B. G. Zakharov in the same period, see
  Baier, Schiff, Zakharov Ann Rev Nucl Part Sci 50 (2000)37 for a
  review) studied radiative energy loss of energetic partons in hot and
cold QCD matter in pQCD.

• They concluded that “Numerical estimates of the loss suggest that it
  may be significantly greater in hot matter than in cold. This makes the
  magnitude of the radiative energy loss a remarkable signal for QGP
  formation”.

• A detector “designed and built to measure rare processes
  involving leptons and photons at the highest luminosities.” by
  some “old-timers” who had discovered high p_T physics at the CERN
  ISR had been prepared (not by accident) for such a possibility.
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
High $p_T$ in A+B collisions---$T_{AB}$ Scaling

- For point-like processes, the cross section in p+A or A+B collisions compared to p-p is simply proportional to the relative number of pointlike encounters
  - A for p+A, AB for A+B for the total rate
  - $T_{AB}$ the overlap integral of the nuclear profile functions, as a function of impact parameter $b$
In p-p at $\sqrt{s}=200$ GeV, $\pi^0$ invariant cross section is a pure power law for $p_T > 3$ GeV/c, $n=8.1\pm0.1$.
In p-p at $\sqrt{s}=200$ GeV, $\pi^0$ invariant cross section is a pure power law for $p_T > 3$ GeV/c, $n=8.1 \pm 0.1$
π^0 are suppressed in Au+Au but not in d+Au

⇒ suppression is due to hot matter

\[ R_{AA}(p_T) = \frac{d^2N_{\pi}^{AA}}{dp_T dy} \frac{N_{AA}^{inel}}{\langle T_{AA} \rangle d^2 \sigma_{pp}^{\pi} / dp_T dy} \]
One decade later--QuarkMatter2011

- 0-5% Au-Au central points at RHIC suppressed across the whole $p_T$ range

- PHENIX data reach out to 20GeV/c $p_T$. Consistent with constant $R_{AA} \approx 0.2$ in central Au+Au up to highest $p_T$ ($5 < p_T < 20$ GeV/c). Indicates constant fractional energy loss in power-law $p_T$ spectrum. Radiative, as suggested by BDMPSZ?
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- Despite more than a factor of 20 higher $\sqrt{s_{NN}}$, the $R_{AA}$ looks nearly identical for RHIC and LHC for 5<$p_T$< 20 GeV/c
- ALICE data show significant upward trend but PHENIX upward trend not significant.
Don't be tempted to conclude that the fractional jet energy loss is the same at RHIC and LHC in the range $5 < p_T < 20$ GeV/c. The inclusive invariant spectra are flatter at LHC $n \sim 6$ cf. RHIC $n = 8.1$, which implies 50% more $\Delta p_T/p_T$ shift at LHC than at RHIC.
Suppression of $\pi^0$ at RHIC is different from “Cronin” enhancement at lower $\sqrt{s_{NN}}=22.4$ GeV

\[ \text{CuCu central 10\% } \pi^0 R_{AA} \text{ vs } \sqrt{s_{NN}} \]

Suppression (QGP?) begins between $\sqrt{s_{NN}}=22.4$ and 39 GeV

PHENIX, PRL 101 (2008)162301

PHENIX, Au+Au 10\% $\pi^0 R_{AA}$

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

J/ψ suppression was predicted by Matsui and Satz PLB 178 (1986) 416 to be THE signature of deconfinement in a QGP. It drove the design of the detectors at both RHIC and at the LHC. Is it a valid signature (large suppression in pA)? We must wait for the LHC to settle this issue. Will Peter Higgs or Helmut Satz have to wait longer to find whether they are right?
Direct $e^\pm$ in Au+Au indicate a theoretical crisis

- 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.
- However, I think that Nino Zichichi had a better explanation.
Confirmed at LHC

D meson from c quarks (ALICE arXiv:1203.2160v1); non-prompt J/ψ from b quarks [CMS arXiv:1201.5069v1 suppressed the same as charged hadrons $R_{AA} \approx 0.3-0.4$
I read an article “Yukawa's gold mine” by Nino Zichichi taken from his talk at INPC 2007 in Tokyo, Japan, in which he noted that the Higgs doesn’t need to give Fermions mass for Electro-Weak unification, the Yukawa coupling is put in by hand.

S. Weinberg, PRD 19, 1277 (1979); L. Susskind, PRD20, 2619 (1979)

“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 $\pi^0$ and direct-single $e^{\pm}$ in regions where both $c$ and $b$ quarks dominate.” Test by measuring $b$-dijet imbalance in $b-\bar{b}$ correlations.
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Status of $R_{AA}$ in AuAu at $\sqrt{s_{NN}}=200$ GeV QM11

Particle ID is crucial, different particles behave differently.
Exponential enhancement of direct-$\gamma$ 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-$\gamma$.

For $p_T > 4$ GeV/c direct-$\gamma$ (color neutral) are not suppressed; all hadrons are suppressed, indicating that suppression is a medium-effect on outgoing color-charged partons.
There is also the issue that the direct-$\gamma$ appear to become suppressed for $p_T \sim 18$ GeV/c approaching the $\pi^0$ suppression. Impressive new data this year on direct-$\gamma$ production in p+p, d+Au and Au+Au by PHENIX at RHIC clarify the situation.
Direct photon production—simple theory hard experiment

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

\[ A + B \rightarrow \gamma + X \]

\[ \text{Compton} \]

\[ \text{Annihilation} \]

\[ \text{isolated photons} \]

\[ q \text{ is } 8/1 \text{ } u/d \text{ quark in } p+p \]

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

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

\[ \cos \theta^* = \tanh \left( \frac{y_c - y_d}{2} \right) \]

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

\( g(x) \) and \( F_2(x) \) are g and q pdf's in nuclei A,B
For AB collisions, taking the ratio to p-p cancels everything but the structure functions.

Near mid-rapidity, \( y_\gamma \approx 0 \) and the jacobian peak for fixed \( p_T \) is \( y_\gamma - y_d = 0 \) to minimize \( \sqrt{s} = 2p_T \cosh \left( \frac{y_c - y_d}{2} \right) \), which gives \( x_1 \approx x_2 \approx x_T = 2p_T / \sqrt{s} \).

\[
R_{AB} = \frac{d^2\sigma_{\gamma}^{AB}/dp_T^2}{AB} \frac{dy_\gamma}{dy_\gamma} \approx \frac{g_A(x_T) F_{2B}(x_T) + F_{2A}(x_T) g_B(x_T)}{AB \left( g_p(x_T) F_{2p}(x_T) + F_{2p}(x_T) g_p(x_T) \right)}
\]

For Au+Au minimum bias collisions:

\[
R_{AA} = \frac{d^2\sigma_{\gamma}^{AA}/dp_T^2}{AA} \frac{dy_\gamma}{dy_\gamma} \approx \left( \frac{F_{2A}(x_T)}{AF_{2p}(x_T)} \times \frac{g_A(x_T)}{A g_p(x_T)} \right)
\]

For d+Au minimum bias collisions (assuming \( g_d = 2g_p, \ F_{2d} = 2F_{2p} \)):

\[
R_{dA} = \frac{d^2\sigma_{\gamma}^{dA}/dp_T^2}{(2 \times A)} \frac{dy_\gamma}{dy_\gamma} \approx \frac{1}{2} \left( \frac{F_{2A}(x_T)}{AF_{2p}(x_T)} + \frac{g_A(x_T)}{A g_p(x_T)} \right)
\]
Experimental problem is HUGE background from $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, etc. But this is less of a problem in Au+Au due to suppression of $\pi^0$.

If \[ \frac{dn_{\pi^0}}{p_T dp_T} \propto p_T^{-\eta} \] then \[ \frac{\gamma}{\pi^0}(p_T) \bigg|_{\pi^0} = \frac{2}{(n - 1)} \times (1.19) = 0.335 \]

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

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

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

Comparison with other p-p data and pQCD

PHENIX direct-$\gamma$ in p-p
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New PHENIX p-p results this year arXiv:1205.5533 are even better!

JETPHOX
$M=\mu_R=M_T=p_T/2$

$\sigma_{pp}/pb/GeV^2$

$p_T$, GeV/c

D0 $p\bar{p}$ $\sqrt{s}=1.96$ TeV
CDF $p\bar{p}$ $\sqrt{s}=1.8$ TeV
D0 $pp$ $\sqrt{s}=630$ GeV
CDF $pp$ $\sqrt{s}=630$ GeV
UA2 $pp$ $\sqrt{s}=630$ GeV

PHENIX $pp$ 200 GeV prelim.
AFS $pp$ $\sqrt{s}=63$ GeV
R110 pp
R806 pp
E706 $pp$ $\sqrt{s}=38.8$ GeV
E706 $pp$ $\sqrt{s}=31.8$ GeV
UA6 $pp$
UA6 $pp$ $\sqrt{s}=24.3$ GeV
WA70 $pp$ $\sqrt{s}=22.9$ GeV

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PHENIX
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x_T scaling

For measurements of single particle or single jet inclusive $p_T$ distributions, $x_T$ scaling provides a totally data driven test of whether pQCD or some other underlying subprocess is at work, as well as providing a compact quantitative way to describe the data using the effective index, $n_{\text{eff}}(x_T, \sqrt{s})$:

$$E \frac{d^3\sigma}{dp^3} = \frac{d^3\sigma}{p_T dp_T dy d\phi} = \frac{1}{p_T^{n_{\text{eff}}(x_T, \sqrt{s})}} F \left( \frac{p_T}{\sqrt{s}} \right) = \frac{1}{\sqrt{s}^{n_{\text{eff}}(x_T, \sqrt{s})}} G(x_T)$$

where $E d^3\sigma/dp^3 = \sigma_{\text{inv}}(p_T, \sqrt{s})$ is the invariant cross section for inclusive particle production with transverse momentum $p_T$ at c.m. energy $\sqrt{s}$ and $x_T = 2p_T/\sqrt{s}$. It is important to emphasize that the effective power, $n_{\text{eff}}(x_T, \sqrt{s})$, is different from the power $n$ of the invariant cross section, which varies with $\sqrt{s}$ (which it must if $x_T$ scaling is to hold).

For pure vector gluon exchange, or without the evolution of $\alpha_s$ and the structure and fragmentation functions in QCD, $n_{\text{eff}} = 4$ as in Rutherford scattering (which can be seen for direct-$\gamma$ from slide 45). However, due to the non-scaling in QCD, the measured value of $n_{\text{eff}}$ depends on the $x_T$ value and the range of $\sqrt{s}$ used in the computation.
QCD in Action

x_T scaling with n_{eff}=4 (parton model) QCD non-scaling is visible

Collection of World’s direct-γ measurements (p+p/ p+pbar) including PHENIX low p_T msmt. to be described next.
x_T scaling with n_eff=4.5 works for direct-γ due to QCD non-scaling.

Collection of World’s direct-γ measurements (p+p/ p+pbar) including PHENIX low p_T msmt. to be described next.
Eliminates the apparent suppression of direct-$\gamma$ seen previously. Also suggests minimal nuclear modification of pdf’s $g_A(x)/A g_p(x)$, $F_{2A}(x)/A F_{2p}(x)$ but must wait for d+Au for confirmation.
Eliminating the $\pi^0$ background by going to $0.2 < m_{ee} < 0.3$ GeV enables direct $\gamma$ signal to be measured for $1 < p_T < 3$ GeV/c in Au+Au. It is exponential, does that mean it is thermal. We must see whether p-p direct $\gamma$ turns over as $p_T \rightarrow 0$ as in Drell-Yan or exponential like for $\pi^0$.
QM2008 direct $\gamma$ in $p$-$p$ via internal conversion

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

This is a major discovery, $p$-$p$ result turns over as $p_T \to 0$, follows the same function $B(1+p_T^2/b)^{-n}$ used in Drell Yan [Ito, et al, PRD23, 604 (1981)].

Fit to $Au+Au$ is $[A e^{-p_T/T} + \langle T_{AA} \rangle B_{pp}(1+p_T^2/b_{pp})^{-n_{pp}}]$. Significance of exponential (thermal?) is $> 3 \sigma$.

Temperature of medium is $> fitted T(MeV)$

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$dN/\gamma(p_T &gt; 1 GeV/c)$</th>
<th>$T(MeV)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20%</td>
<td>1.10 ± 0.20 ± 0.30</td>
<td>221 ± 23 ± 18</td>
</tr>
<tr>
<td>20-40%</td>
<td>0.52 ± 0.08 ± 0.14</td>
<td>215 ± 20 ± 15</td>
</tr>
<tr>
<td>MB</td>
<td>0.33 ± 0.04 ± 0.09</td>
<td>224 ± 16 ± 19</td>
</tr>
</tbody>
</table>
Three important points. 1) low $p_T$ exponential is only in Au+Au, a hot matter effect. Confirms thermal photon emission; 2) dAu data consistent with $R_{AA}=1$ for all $p_T$ shown, → no significant nuclear modification of pdf’s; 3) Low $p_T$ points in p-p lie on $x_T$ scaling curve.
2011 Direct-$\gamma$ $v_2$

- $v_2 \rightarrow 0$ where QCD hard direct-$\gamma$ dominate--no effect of the medium
- Initial $v_2$ large ($\sim 15\%$) at $p_T < 3$ GeV thermal region--$\gamma$'s from the medium

arXiv: 1105.4126, but still not accepted by PRL. If you want, you can ask why in question period. It’s due to using both real and virtual photon data at low $p_T$. 
Correlations

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

c.f. $\text{Au} + \text{Au} \rightarrow \text{jet} + \text{jet}$
$\quad + \text{flow}$
Direct-$\gamma$-$h$ correlation measures ($\sim$u quark) fragmentation function in p-p because its initial $p_T$ is known

- $x_E = p_T^h/p_T^\gamma \cos(\Delta \phi) \sim z_T$
- $\gamma$-$h$ is steeper than $\pi^0$-$h$!
- $x_E$ universal scaling vs. $p_Tt$ in $\gamma$-$h$
- $b = 8.2 \pm 0.3$

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

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

PHENIX PRD 82 (2010) 072001
Direct-\(\gamma\)-\(h\) correlation measures (\(\sim u\) quark) fragmentation function in \(Au+Au\)

\[\xi = \ln(1/z) = -\ln \left( \frac{p_{Th}}{p_{T\gamma}} \right)\]

- \(p+p\) consistent with \(e^+e^-\)
- \(Au+Au\) consistent with E loss model; but need more statistics to be definitive maybe by QM2012?

Tasso:
Braunschweig et al., Z. Phys. 320 C47, 187
MLLA:
Borghini, Wiedemann, hep-ph/0506218
Direct-γ-h correlation measures (~u quark) fragmentation function in Au+Au

\[ \xi = \ln(1/z) = -\ln \left( \frac{p_{Th}}{p_{T\gamma}} \right) \]

- \( p+p \) consistent with \( e^+e^- \)
- \( Au+Au \) consistent with E loss model; but need more statistics to be definitive maybe by QM2012?

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

Erice 2012

M. J. Tannenbaum 58/69/74
But a very interesting new formula for the $x_E$ distribution was derived by PHENIX in PRD74

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

Relates ratio of particle $p_T$

$$x_E = \frac{-p_{T_a} \cos \Delta \phi}{p_{T_t}} \approx \frac{p_{T_a}}{p_{T_t}} \text{ measured} \quad \text{aka } \frac{Z_T}{T}$$

Ratio of jet transverse momenta

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

Can be determined

If formula works, we can also use it in Au+Au to determine the relative energy loss of the away jet to the trigger jet (surface biased by large $n$)
h-h or $\pi^0$-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 $\pi^0$-h correlations in Au+Au: Away-side yield vs $x_E \approx p_T/a/p_{Tt}$ is steeper in Au+Au than p-p indicating energy loss

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

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

$I_{AA} = [dN_{AA}/dx_E]/[dN_{pp}/dx_E]$
h-h or $\pi^0$-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.

Also, in p-p the jets do not exactly balance due to $k_T$, trigger bias, cuts, so take the measured away-jet imbalance relative to p-p as:

$$1 - \hat{x}_{hAA}^{AA} / \hat{x}_{h}^{pp}$$

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Also, in p-p the jets do not exactly balance due to \(k_T\), trigger bias, cuts, so take the measured away-jet imbalance relative to p-p as:

\[
1 - \frac{\hat{x}^{AA}_h}{\hat{x}^{pp}_h}
\]

which is a quantitative measure that the away-jet has lost energy relative to the trigger jet in AuAu compared to pp collisions

Steeper curve in Au+Au indicates that the away jet has lost energy relative to the trigger jet
Comparison with CMS dijet imbalance

CMS PRC 84 (2011) 024906

Need to correct for the large non-zero effect in p-p collisions

\[
\frac{p_{T1} - p_{T2}}{p_{T1}} = 1 - \hat{x}_h
\]

\[
\begin{align*}
130: & \quad pp = 0.255, \quad PbPb=0.36 \\
\Rightarrow & \quad \hat{x}_h: pp = 0.745, \quad PbPb=0.64 \\
1 - \frac{\hat{x}_h^{AA}}{\hat{x}_h^{pp}} & = 0.141 \\
\Leftarrow & \quad \frac{\hat{x}_h^{AA}}{\hat{x}_h^{pp}} = 0.64/0.745 = 0.859
\end{align*}
\]
Big difference between RHIC and LHC in this analysis. What I wanted from the LHC was to check this analysis, and they did!
Big difference between RHIC and LHC in this analysis. What I wanted from the LHC was to check this analysis, and they did!
New CMS result confirms my idea

\[ \hat{x}_h = \frac{\hat{p}_{T,a}}{\hat{p}_{T,t}} \]

CMS PLB 712 (2012) 176
PHENIX cf. CMS corrected for pp
PHENIX cf. CMS corrected for pp

Emphasizes the need to understand the mechanism of energy loss by extending both the RHIC and LHC measurements to overlapping regions of \( p_T \).
I proposed that the heavy quark energy loss could be measured the same way $b - \bar{b}$ correlations using a Silicion vtx detector to identify the $b$’s via displaced vertices.
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; must identify both b-quarks

PHENIX Preliminary Run 5 & 6 $p+p \sqrt{s}=200\text{GeV}$

e$_{HF}$-h $1.67 < \Delta \phi < \pi \text{ rad}$

$1.5<p_{T, e_{HF}}<2.0\text{GeV/c}$

$2.0<p_{T, e_{HF}}<3.0\text{GeV/c} \times 10^{-1}$

$3.0<p_{T, e_{HF}}<4.0\text{GeV/c} \times 10^{-2}$

$4.0<p_{T, e_{HF}}<4.5\text{GeV/c} \times 10^{-3}$

$2.0 < p_{T, \text{hadron}} < 3.0\text{GeV/c}$

Quark Matter 2009
Anne M. Sickles
March 31, 2009

PHENIX
Erice 2012

M. J. Tannenbaum 67/69/74
Run 12 FVTX and VTX in place
Still lots to learn!!

For the future, super PHENIX (sPHENIX) “4\pi” detector for di-jet and \(\gamma\)-jet measurements using a superconducting solenoid, Si tracking EM and Hadron calorimeters
Remember CMS cf. PHENIX
CMS cf. sPHENIX

[Diagram of the CMS and sPHENIX detectors with labels for SOLENOID, INNER HCAL, OUTER HCAL, EMCAL, and Iron return yoke interspersed with Muon chambers.]
Properties of QGP found at RHIC

The

*hot*test

densest

*mat*ter

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 densest matter ever studied in the laboratory absorbs energy flows

A (nearly) perfect fluid!

Not an ideal gas of free quarks and gluons!

T ~ 200- 400 MeV=2.3-4.6 x 10^{12} K
T center of sun=1.5 x 10^7 K
ε_i ~ 30-60 × nuclear density
emits thermal (black body) radiation

large collective flow, viscosity~quantum lower limit

stops high p_T quarks--“jet quenching”