Where Feynman, Field and Fox Failed and How we Fixed it at RHIC

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XLIII Rencontres de Moriond
(recent Super Bowl was XLII)
QCD and High Energy Interactions
La Thuile, Italy, Mar 8-15, 2008
Il y’avait une fois

Many results in p-p collisions that were new and exciting in 1979 are relevant for RHIC 2008
**π⁰ production in p-p collisions at RHIC**

**PHENIX, PRD76(2007)051006(R)**

- Hard scattering dominates after ~3 orders of magnitude power-law.
- NLO-pQCD precision agreement
  - Stratmann Vogelsang hep-ph/0702083

No surprise (to me) that NLO pQCD agrees with data.
$\pi^0$ invariant cross section in p-p at $\sqrt{s}=200$ GeV is a pure power law for $p_T > 3$ GeV/c, $n=8.10\pm0.05$. Power at 62.4 ISR ($x_T>0.27$ is $n=11.03\pm0.16$)
Au+Au Central Collisions cf. p-p

STAR-Jet event in pp

STAR Au+Au central

PHENIX Au+Au central

High $p_T$ particle

p+p

High $p_T$ particle

Au+Au

PHENIX $E_T$ Transverse Energy corr to $\Delta\eta=1$ and $\Delta\Phi=2\pi$

0.5%  4%
Latest $\pi^0$ Au+Au arXiv:0801.4020

Power Law $p_T > 3\text{GeV/c}$ all centralities $n = 8.10 \pm 0.05$

Table 5: Fit parameters for $p_T > 3\text{GeV/c}$

<table>
<thead>
<tr>
<th>System</th>
<th>$A$</th>
<th>$n$</th>
<th>$\chi^2/NDF$</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p</td>
<td>14.61±1.45</td>
<td>8.12±0.05</td>
<td>5.68/17</td>
</tr>
<tr>
<td>Au+Au 0-5%</td>
<td>81.18±10.30</td>
<td>8.20±0.07</td>
<td>9.66/16</td>
</tr>
<tr>
<td>Au+Au 0-10%</td>
<td>75.28±8.89</td>
<td>8.18±0.06</td>
<td>10.62/17</td>
</tr>
<tr>
<td>Au+Au 10-20%</td>
<td>64.62±7.64</td>
<td>8.19±0.06</td>
<td>10.04/17</td>
</tr>
<tr>
<td>Au+Au 20-30%</td>
<td>49.33±5.78</td>
<td>8.18±0.06</td>
<td>6.63/16</td>
</tr>
<tr>
<td>Au+Au 30-40%</td>
<td>30.85±3.53</td>
<td>8.10±0.06</td>
<td>10.63/16</td>
</tr>
<tr>
<td>Au+Au 40-50%</td>
<td>22.58±2.61</td>
<td>8.13±0.06</td>
<td>3.50/15</td>
</tr>
<tr>
<td>Au+Au 50-60%</td>
<td>12.40±1.48</td>
<td>8.06±0.07</td>
<td>8.09/15</td>
</tr>
<tr>
<td>Au+Au 60-70%</td>
<td>6.25±0.78</td>
<td>8.03±0.07</td>
<td>2.89/14</td>
</tr>
<tr>
<td>Au+Au 70-80%</td>
<td>3.38±0.45</td>
<td>8.12±0.08</td>
<td>8.42/13</td>
</tr>
<tr>
<td>Au+Au 80-92%</td>
<td>1.19±0.18</td>
<td>8.03±0.09</td>
<td>9.84/13</td>
</tr>
<tr>
<td>Au+Au 0-92%</td>
<td>29.31±3.07</td>
<td>8.17±0.05</td>
<td>6.83/17</td>
</tr>
</tbody>
</table>
Suppression of $\pi^0$ is arguably the major discovery at RHIC. Energy loss in medium?

Original $\pi^0$ discovery, PHENIX PRL 88 (2002)022301

\[
R_{AA}(p_T) = \frac{d^2N_{AA}^\pi}{dp_T dy N_{AA}^{inel}} / \left(\frac{T_{AA}}{T_{pp}}\right) \frac{d^2\sigma_{pp}^\pi}{dp_T dy}
\]
Direct $\gamma$ are not suppressed. $\pi^0$ and $\eta$ suppressed even at high $p_T$.
Implies a strong medium effect (energy loss) since $\gamma$ not affected.
Suppression is flat at high $p_T$. Are data flatter than theory?
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Trigger on a particle e.g. $\pi^0$ with transverse momentum $p_{T\pi}$. Measure azimuthal angular distribution w.r.t the trigger azimuth of associated (charged) particles with transverse momentum $p_{Ta}$. The strong same and away side peaks in p-p collisions indicate di-jet origin from hard-scattering of partons. For the away distribution calculate the conditional yield in the peak as a function of $x_E \sim p_{Ta}/p_{T\pi}$.
\[ z = \frac{p_T}{\hat{p}_T} \] is the jet fragmentation variable: \( z_t \) and \( z_a \)

\[ D^q_\pi(z) = Be^{-bz} \] is a typical Fragmentation Function, \( b \approx 8-11 \) at RHIC

Due to the steeply falling spectrum, the trigger \( \pi^0 \) are biased towards large \( z_t \), \( \langle z_t \rangle \approx (n-1)/b \) while unbiased \( \langle z \rangle \approx 1/b \)

\[ x_E = \left| \frac{\vec{p}_{Ta} \cdot \vec{p}_{Tt}}{p_{Tt}^2} \right| = \frac{-p_{Ta} \cos \Delta \phi}{p_{Tt}} \approx \frac{p_{Ta}}{p_{Tt}} = \frac{p_{Ta}/\hat{p}_{Tt}}{p_{Tt}/\hat{p}_{Tt}} \approx \frac{z_a}{\langle z_t \rangle} \]

From Feynman, Field and Fox: the \( x_E \) distribution corrected for \( \langle z_t \rangle \) measures the unbiased fragmentation function

\[ \frac{dP_{\text{FFF}}}{dx_E} \approx \langle z_t \rangle B \exp -b \langle z_t \rangle x_E \]
Kinematics-Figure is from Moriond 1979

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\[ \frac{dP_{\text{FFF}}}{dx_E} \approx \langle z_t \rangle B \exp \left( -b \langle z_t \rangle x_E \right) \]
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\[ \frac{dP_{FFF}}{dx_E} \approx \langle z_t \rangle B \exp -b \langle z_t \rangle x_E \]
There is a simple relationship between experiments done with single-particle triggers and those performed with jet triggers. The only difference in the opposite side correlation is due to the fact that the ‘quark’, from which a single-particle trigger came, always has a higher $p_\perp$ than the trigger (by factor $1/z_{\text{trig}}$). The away-side correlations for a single-particle trigger at $p_\perp$ should be roughly the same as the away side correlations for a jet trigger at $p_\perp (\text{jet}) = p_\perp (\text{single particle})/ <z_{\text{trig}}>$.
PHENIX-compared measured $x_E$ distribution in p-p to numerical integral using LEP fragmentation functions

PHENIX PRD 74 (2006) 072002. The $x_E$ distribution triggered by a leading fragment ($\pi^0$) is not sensitive to the shape of the fragmentation function!!! Disagrees with FFF!!
A very interesting new formula for the $x_E$ distribution was derived by PHENIX in PRD74.

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

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 $n$).

Relates ratio of particle $p_T$

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

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 $n$).
Exponential Frag. Fn. and power law crucial

\[
\frac{d^2 \sigma_{\pi}(\hat{p}_T, z_t)}{dp_T dz_t} = \frac{d\sigma_q}{dp_T} \times D^q_{\pi}(z_t) = \frac{A}{\hat{p}^{n-1}_T} \times D^q_{\pi}(z_t)
\]

Fragment spectrum given \( \hat{p}_T \)

Power law spectrum of parton \( \hat{p}_T \)

Let \( \hat{p}_T = p_T/z_t \) \( \frac{d\hat{p}_T}{dp_T}\big|_{z_t} = 1/z_t \)

\[
\frac{d^2 \sigma_{\pi}(p_T, z_t)}{dp_T dz_t} = \frac{A}{p^n_T} \times z_t^{n-2} D^q_{\pi}(z_t)
\]

Fragment spectrum given \( p_T \) is weighted to high \( z_t \) by \( z_t^{n-2} \)

where \( z_{t_{\min}}|_{p_T} = x_T \)

\[
D^q_{\pi}(z_t) = B e^{-bz_t}
\]

Incomplete gamma function

\[
\frac{1}{p_T} \frac{d\sigma_{\pi}}{dp_T} = AB \int_{x_T}^{1} dz_t \ z_t^{n-2} \exp(-bz_t)
\]

Good approximation \( x_T \rightarrow 0 \) upper limit \( \rightarrow \infty \)

\[
\frac{1}{p_T} \frac{d\sigma_{\pi}}{dp_T} \approx \frac{\Gamma(n-1)}{b^{n-1}} \frac{AB}{p_T^n}
\]

Bjorken parent-child relation: parton and particle invariant \( p_T \) spectra have same power \( n \), etc.
Shape of $x_E$ distribution depends on $\hat{x}_h$ and $n$ but not on $b$—i.e. FFF failed.

$$n = 8.1$$

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

$\hat{x}_h$

1.0

0.8

0.6

0.4

0.2

Moriond 2008
Shape of $x_E$ distribution depends on $\hat{x}_h$ and $n$ but not on $b$-i.e. FFF failed

$$n = 8.1$$

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

$\hat{x}_h$

1.0

0.8

0.6

0.4

0.2
Fit works for PHENIX p+p PRD 74, 072002

Calculation from Fragmentation Fn.

New fits. Very nice!
Excellent $\chi^2$ in most cases
\( \hat{\chi}_h \sim 0.75 \) due to \( k_T \) smearing in p-p, dAu

\( k_T \) and \( k_T \) smearing was a big topic at Moriond 1979
Define Head region (HR) and Shoulder regions (SR) for wide away side correlation.

Away side correlation in Au+Au is generally wider than p-p with complicated structure.
Fit H+S and HO (head only)
4<p_T<5 GeV/c
Statistical two-component distribution (⇒punch-through) for Head-Only
Formula works in Au+Au: Away-side $x_E$ distribution is steeper in Au+Au than p-p indicating energy loss

Since the trigger jet is surface biased, the away jet must cross through nearly the entire medium except in the case of tangential emission. The decrease of $\hat{x}_h = \hat{p}_{Ta} / \hat{p}_{Tt}$ in Au+Au central collisions relative to p-p by a factor of ~0.5-0.6 indicates that the away jet has lost energy by traversing the medium and gives a quantitative measurement.
Two-component distribution (punch-through) is now clear for $6 < p_T < 10 \text{ GeV/c}$
Two-component distribution (punch-through) is now clear for $6 < p_T^{\text{trig}} < 10$ GeV/c
The End
Away side correlations in Au+Au much wider than in p-p

Away side distribution much wider in A+A than p-p in correlation fn. C(Δφ)
Subtraction of v2 (flow?) effect → J(Δφ) causes a dip at 180° which gives 2
peaks at π±D~1 radian independent of
system and centrality for N_{part} >100.
This is also seen for (auto) correlations
of low p_T particles. Is this the medium
reaction to the passage of a color-
charged parton? Stay tuned, much more
study needed.
STAR dAu, AuAu

STAR-PRL 97 (2006) 162301
8 < pTt < 15 GeV/c

STAR-PRL 95 (2005) 152301

PHENIX dAu PRC73 π–h Fig.30
N
2.45
\bar{x}_h
0.74

★ STAR dAu PRL97 h–h p_T=9.38 GeV/c

Moriond 2008
The leading-particle effect a.k.a. trigger bias

- Due to the steeply falling power-law spectrum of the scattered partons, the inclusive particle $p_T$ spectrum is dominated by fragments biased towards large $z$. This was unfortunately called trigger bias by M. Jacob and P. Landshoff, Phys. Rep. 48C, 286 (1978) although it has nothing to do with a trigger.

$$\frac{d^2\sigma_\pi(\hat{p}_T, z_t)}{d\hat{p}_Tdz_t} = \frac{d\sigma_q}{d\hat{p}_T} \times D^q_\pi(z_t)$$

Fragment spectrum given $\hat{p}_T$

\[\frac{A}{\hat{p}_T^{n-1}} \times D^q_\pi(z_t)\]

Power law spectrum of parton $\hat{p}_T$

\[\frac{1}{z_t(p_T/z_t)^{n-1}} \times D^q_\pi(z_t)\]

Fragment spectrum given $p_T$ is weighted to high $z_t$ by $z_t^{n-2}$

where \(z_{t_{\text{min}}}|_{p_T} = x_{T_t}\)

\[D^q_\pi(z_t) = Be^{-b z_t}\]  \(\langle z_t \rangle = 1/b\)

Moriond 2008

PHOENIX

M. J. Tannenbaum 29/23
We can integrate over the trigger jet $z_t$ and find the inclusive pion cross section:

$$\frac{1}{p_{T_t} \, dp_{T_t}} \frac{d\sigma_{\pi}}{dp_{T_t}} = \frac{AB}{p_{T_t}^{n}} \int_{x_{T_t}}^{1} dz_t z_t^{n-2} \exp -b z_t ,$$  \hspace{1cm} (8)

which can be written as:

$$\frac{1}{p_{T_t} \, dp_{T_t}} \frac{d\sigma_{\pi}}{dp_{T_t}} = \frac{AB}{p_{T_t}^{n}} \frac{1}{b^{n-1}} [\Gamma(n - 1, bx_{T_t}) - \Gamma(n - 1, b)] \hspace{1cm} (9)$$

where

$$\Gamma(a, x) \equiv \int_{x}^{\infty} t^{a-1} e^{-t} dt$$ \hspace{1cm} (10)

is the Complementary or upper Incomplete Gamma function, and $\Gamma(a, 0) = \Gamma(a)$ is the Gamma function, where $\Gamma(a) = (a - 1)!$ for $a$ an integer.

A reasonable approximation for small $x_T$ values is obtained by taking the lower limit of Eq. 8 to zero and the upper limit to infinity, with the result that:

$$\frac{1}{p_{T_t} \, dp_{T_t}} \frac{d\sigma_{\pi}}{dp_{T_t}} \approx \frac{\Gamma(n - 1) AB}{b^{n-1} p_{T_t}^{n}}$$

Bjorken parent-child relation: parton and particle invariant $p_T$ spectra have same power $n$

$$\langle z_t(p_{T_t}) \rangle = \frac{1}{x_{T_t}} \int_{x_{T_t}}^{1} dz_t z_t^{n-1} \exp -b z_t = \frac{1}{b} \frac{[\Gamma(n, bx_{T_t}) - \Gamma(n, b)]}{[\Gamma(n - 1, bx_{T_t}) - \Gamma(n - 1, b)]} \approx \frac{n - 1}{b}$$

Inclusive high $p_T$ particle has $n-1$ times larger $\langle z \rangle$ than unbiased fragmentation, $\langle z \rangle = 1/b$
2 particle Correlations

\[ \frac{d^2 \sigma_\pi(\hat{p}_{T_t}, z_t)}{d\hat{p}_{T_t} dz_t} = \frac{d\sigma_q}{d\hat{p}_{T_t}} \times D^q_\pi(z_t) \]

Also detect fragment with \( z_a = \frac{p_{T_a}}{\hat{p}_{T_a}} \)

from away jet with \( \frac{\hat{p}_{T_a}}{\hat{p}_{T_t}} \equiv \hat{x}_h \)

\[ \frac{d^3 \sigma_\pi(\hat{p}_{T_t}, z_t, z_a)}{d\hat{p}_{T_t} dz_t dz_a} = \frac{d\sigma_q}{d\hat{p}_{T_t}} \times D^q_\pi(z_t) \times D^q_\pi(z_a) \]

\[ z_a = \frac{p_{T_a}}{\hat{p}_{T_a}} = \frac{p_{T_a}}{\hat{x}_h \hat{p}_{T_t}} = \frac{z_t p_{T_a}}{\hat{x}_h p_{T_t}} \]

\[ \frac{d\sigma_\pi}{dp_{T_t} dz_t dp_{T_a}} = \frac{1}{\hat{x}_h p_{T_t}} \frac{d\sigma_q}{d(\frac{p_{T_t}}{z_t})} D^q_\pi(z_t) D^q_\pi(\frac{z_t p_{T_a}}{\hat{x}_h p_{T_t}}) \]

 Appears to be sensitive to away jet Frag. Fn.
Amazingly, I got a neat analytical result

\[
\frac{d^3\sigma_\pi}{dp_{T_t}dz_tdp_{T_a}} = \frac{1}{\hat{x}_h p_{T_t}} \frac{d\sigma_q}{d(p_{T_t}/z_t)} D_q^{\pi}(z_t) D_q^{\pi}(\frac{z_t p_{T_a}}{\hat{x}_h p_{T_t}})
\]  

(1)

Take: \(D(z) = B \exp(-bz)\)  
\(\frac{d\sigma_q}{dp_{T_t}} = A \frac{\hat{\rho}_{T_t}^{n-1}}{\hat{\rho}_{T_t}^{n-1}} = A\frac{z_t^{n-1}}{\hat{x}_h p_{T_t}}\)

(2)

\[
\frac{d^2\sigma_\pi}{dp_{T_t}dp_{T_a}} = \frac{B^2}{\hat{x}_h p_{T_t}^n} \int_{x_{T_t}}^{x_{T_t}p_{T_a}} dz_t z_t^{n-1} \exp[-b z_t(1 + \frac{p_{T_a}}{\hat{x}_h p_{T_t}})]
\]

\[
\frac{d\sigma_\pi}{dp_{T_t}} = \frac{AB}{p_{T_t}^{n-1}} \int_{x_{T_t}}^{1} dz_t z_t^{n-2} \exp -b z_t
\]

Using: \(\Gamma(a, x) \equiv \int_{x}^{\infty} t^{a-1} e^{-t} \, dt\)  
Where \(\Gamma(a,0)= \Gamma(a)=(a-1) \Gamma(a)\)
The final result

\[ \frac{d^2 \sigma_\pi}{dp_{Tt} dp_{Ta}} \approx \frac{\Gamma(n) B^2 A}{b^n \hat{x}_h p_T^n (1 + \frac{p_{Ta}}{\hat{x}_h p_{Tt}})^n} \]

\[ \frac{d\sigma_\pi}{dp_{Tt}} \approx \frac{\Gamma(n - 1) AB}{b^{n-1} p_T^{n-1}} \]

\[ \frac{dP_\pi}{dp_{Ta}} \bigg|_{p_{Tt}} \approx \frac{B(n - 1)}{b p_{Tt}} \frac{1}{\hat{x}_h (1 + \frac{p_{Ta}}{\hat{x}_h p_{Tt}})^n} \]

In the collinear limit, where \( p_{Ta} = x_E p_{Tt} \):

\[ \frac{dP_\pi}{dx_E} \bigg|_{p_{Tt}} \approx \frac{B(n - 1)}{b} \frac{1}{\hat{x}_h (1 + \frac{x_E}{\hat{x}_h})^n} \]

Where \( B/b \approx \langle m \rangle \approx b \) is the mean charged multiplicity in the jet
Why dependence on the Frag. Fn. vanishes

• The only dependence on the fragmentation function is in the normalization constant $B/b$ which equals $\langle m \rangle$, the mean multiplicity in the away jet from the integral of the fragmentation function.

• The dominant term in the $x_E$ distribution is the Hagedorn function $1/(1 + x_E/\hat{x}_h)^n$ so that at fixed $p_{Tt}$ the $x_E$ distribution is predominantly a function only of $x_E$ and thus exhibits $x_E$ scaling, as observed.

• The reason that the $x_E$ distribution is not sensitive to the shape of the fragmentation function is that the integral over $z_t$ in (1, 2) for fixed $p_{Tt}$ and $p_{Ta}$ is actually an integral over jet transverse momentum $\hat{p}_{Tt}$. However since the trigger and away jets are always roughly equal and opposite in transverse momentum (in p+p), integrating over $\hat{p}_{Tt}$ simultaneously integrates over $\hat{p}_{Ta}$. The integral is over $z_t$, which appears in both trigger and away side fragmentation functions in (1).
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 $b$
As measured at the ISR by Darriulat, etc.


Figures from P. Darriulat, ARNPS 30 (1980) 159-210 showing that Jet fragmentation functions in vp, e⁺e⁻ and pp (CCOR) are the same with the same dependence of $b$ (exponential slope) on $\hat{s}$.
Three things are dramatically different in Relativistic Heavy Ion Physics than in p-p physics

• the multiplicity is \( \sim A \sim 200 \) times larger in AA central collisions than in p-p \( \Rightarrow \) huge energy in jet cone: \( 300 \text{ GeV} \) for \( R=1 \) at \( \sqrt{s_{\text{NN}}}=200 \text{ GeV} \)
• 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?