Measuring high pT single electrons from open heavy flavor in pp collisions at sqrt(s) = 200GeV using the PHENIX detector
Why do we study heavy quarks?

• RHIC was built to produce and study the Quark Gluon Plasma
  – Medium is small 1000fm$^3$
  – Short lived 100 fm/c
  – Must be probed with particles produced in collision

• Hard Probe
  – Charm and especially Bottom, will only be created at beginning
  – Will propagate through and be modified by the medium
Open Charm (Bottom)

- Dominant production mechanism is gluon fusion (LO)
  - possibility of studying gluon density as a function of system density
- Modification of transverse momentum spectra
  - energy loss -> look for suppression
  - Azimuthal anisotropy or flow
  - di leptons
- Cold and Hot nuclear matter
- J/ψ regeneration
- To make the best measurement of these things you need a pp reference in the same detector
PHENIX Detector

- High Rate, High Multiplicity Spectrometer
- Central arms
  - cover $\pi$ in azimuth
  - $|\eta|<0.35$
  - central solenoidal field
  - carefully managed material budget
- Writing events at 6+ kHz
Beam Beam Counter

- Provide minimum bias trigger
- Determine z of collision vertex
- Set $t_0$ for all of PHENIX

- Two arrays of hexagonal Cerenkov radiators
- Phototubes have intrinsic resolution of 50ps
- 1.44m from center, $3.1<\eta<4.0$

\[
t_0^{BBC} = \frac{(t_N^{BBC} + t_S^{BBC})}{2}
\]

\[
z_{vtx}^{BBC} = \frac{(t_N^{BBC} - t_S^{BBC})}{2c}
\]

\[
\sigma_{pp} \approx 1.2 \text{ cm}
\]
Drift Chamber

Sector, side view

Electron drift lines from a track

- Cell: New wire configuration
- Gas: C₂H₆, 50%, Ar 50%, T=300 K, p=1 atm
- Particle: 300 equally spaced points

Printed at 05:31 AM Sun 14/04/03 with CorelDraw version 6.0.

7/7/2011 Harry Themann Stony Brook
Drift Chamber

- Accurate determination of charged track transverse momentum $p_T$.
- Measure, in concert together with PC1 and BBC, $z$ at the DC and, consequently, the angle of a particle track w.r.t. beam axis, $\phi$.
- Determine the tracks of charged particles though PHENIX.

FYI $p_T = 92/\alpha$
Pad Chambers

- Reinforce the tracking of charged particles in r-\( \theta \) plane
- In particular, PC1 provides \( z \) coordinate at the DC
- \( \sigma_z = 1.7 \text{mm (PC1)} \)
Ring Imaging CHERENKOV

- Primary electron identification subsystem
- Threshold Cherenkov
- \(\pi\)'s begin to emit Cherenkov light at 4.2 GeV

Most hadrons do not emit Cherenkov light

Cerenkov photons are detected by array of PMTs

Electrons emit Cerenkov photons in RICH.
RICH Variables

- \( n_0 \) & \( n_1 \) are both number of phototubes fired
- There are variables that use pulse height
- \( n_1 \) was chosen
  - alignment issue
  - easier to simulate
ElectroMagnetic Calorimeter

- **PbGI**
  - Better Energy Resolution
  - Better Granularity
  - Proven system (WA98)

- **PbSc**
  - Better Timing Resolution
  - Better Linearity
  - response to hadrons better understood (in principle)
Data Analysis

• Selection Cuts
• Run QA
• Trigger efficiency
• Acceptance Efficiency Correction
• Final Inclusive Spectrum
• Cocktail
• Background subtraction
Selection Cuts

• z vertex, |z|<20cm
• Quality X1/X2 unambiguous
  – 31 PC1 found/ambiguous, UV found
  – 51 PC1 found/unique, UV not found
  – 63 PC1 found/unique, UV found/unique
• EMC
  – matching -> Track to energy cluster
  – shower shape -> EM showers narrower than Hadronic
• RICH, n_1 ≥ 5
• E/p
  – Centered about one, fixed window
  – Basis of new technique
• Fiducial Cuts -> fine tune matching of simulation to real detector
E/p

E/p n1 (6.0-7.0)

hep_phc_n121
Entries 218
Mean 0.6039
RMS 0.2911
RunQA

• Data consists of two sets,
  – Min Bias
  – Triggered E > 1.4GeV

• For MB data
  – plot electron candidate yield per event vs run number
  – remove outliers
  – look for variations indicating changes in detector performance

• Make list of matching ERT runs
• Merge sets
Trigger Efficiency

e^+ + e^- (raw inclusive)(n1>=5) all emc Run6pp200

$\frac{1}{p_T} \frac{dN}{dp_T}$ [a.u.]

$\frac{1}{p_T}$ $p_T$ [GeV/c]

MB triggered events, mb file
ERT triggered events, mb file
ERT triggered events, ert file
Trigger Efficiency

\[
\chi^2 / \text{ndf} = 7.763 / 17
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.8211 ± 0.05138</td>
</tr>
<tr>
<td>Numerator</td>
<td>1.534 ± 0.04898</td>
</tr>
<tr>
<td>Denominator</td>
<td>0.2589 ± 0.04418</td>
</tr>
</tbody>
</table>

\[
\text{constant} \left(1 + \exp \left(\frac{-(p_T - \text{numerator})}{\text{denominator}}\right)\right)
\]

- \(p_T\) - numerator
- denominator

4x4c Trigger eff n1>=5 all emc Run6pp200
Trigger Efficiency

\( e^+ + e^- \) (scaled raw inclusive)(n1>=5) all emc Run6pp200

\[
\frac{1}{N_{\text{event}}} \frac{1}{p_T} \frac{dN}{dp_T} \text{ [a.u.]} \]

- MB triggered events, mb file
- ERT triggered events, ert file, eff corr

scale MB data by \( N_{\text{MB}}^{\text{recorded}} \)

scale ERT data by \( N_{\text{MB}}^{\text{live}} \)

\[
N_{\text{MB}}^{\text{live}} = \frac{\text{scaledown}_{\text{ERT}}}{N_{\text{MB}}^{\text{recorded}} \times \text{scaledown}_{\text{MB}}} \]

\( p_T \) [GeV/c]
Trigger Efficiency

ERT 4x4 corr phc/mb ratio n1>=5 all emc Run6pp200

\[ df \quad 2.773 / 6 \]

\[ p_0 \quad 1.009 \pm 0.022 \]
Acceptance Efficiency Correction

- Correct for
  - cut efficiencies
  - acceptance limitations
  - resolution effects -> Steeply falling spectra
- PHENIX Integrated Simulation Application (PISA)
- Generate simulated electrons and propagate through PHENIX with all cuts
- Divide what you get out by what you put in
Steeply Falling Spectrum

[Graph showing a typical pT spectrum with logarithmic scaling on the y-axis and a linear scale on the x-axis. The graph depicts a steeply falling spectrum with quantiles 1, 2, 3, and 4 indicated.]
Acceptance Efficiency Correction

- dN/dphi plot
  - all eID cuts
  - 0.6<p_T<4.0GeV straight tracks below pion threshold
- check to make sure PISA version of PHENIX is the same as the real version
Acceptance Efficiency Correction

\[ \frac{p_0 + p_1 p_T}{1 + \exp \left( \frac{p_1 - p_2}{p_4} \right)} \]

\( \chi^2/\text{ndf} = 2.5060 \)

- \( p_0 = 0.21 \)
- \( p_1 = 0.00080 \)
- \( p_2 = -0.00029 \)
- \( p_3 = 0.01666 \)
- \( p_4 = 0.38224 \)
Final Inclusive Spectrum

- Divide raw inclusive by acc/eff curve
- Scale 0.5 (\((e^+ + e^-)/2\))
- Scale 1/2\(\pi\)
- Scale 1/0.1 (bin width)
- Scale 0.516/0.75 MB trig eff/trig bias
- Scale 42.2 (pp inelastic cross section)
Pions in the EMC

- Most are MIPs, some shower
- Hadronic shower
  - smaller cross sections
  - much larger fluctuation of energy deposit in active medium
- EMC $<1\lambda$ => never get to shower max
- 30% of any shower are $\pi^0$'s

Assert that the energy distribution, scaled by the momentum, is the same for any $p_T$ bin

Cartoon of the longitudinal development of a shower
The Principle

- The hadron E/p shape is pT independent.

- Plot the hadron E/p distribution for each pT bin.

- Divide the E/p plot into two regions.

- Form the ratio

\[
R_\pi = \frac{\int_{\text{II}} E/p}{\int_{\text{I}} E/p}
\]

- Then \( N_e = N_{\text{II}} - R_\pi N_{\text{I}} \)
IEEE paper

Fig. 7 Top: EMCal response to 1 GeV/c π’s, p’s and electrons.

The PHENIX Lead-Scintillator Electromagnetic Calorimeter: Test Beam and Construction Experience

G.David, Y.Goto, E.Kistenev, S.Stoll, S.White, C.Woody
Brookhaven National Laboratory, Upton, New York

A.Bazilevsky, S.Belikov, S.Chernichenkov, A.Denisov, V.Kochetkov, Y.Melnikov, V.Onuchin, V.Semenov,
V.Shelikhov, A.Soldatov, A.Usachev Institute for High Energy Physics, Protvino, Russia
Background Function

- **Ke3, Pions & Electrons**
  - Generate Ke3 OSCAR files with modified EXODUS
  - propagate through PISA
  - Plot E/p p_T bin by p_T bin, fit with a function
- The resulting function is a sum of all three, the fit to data will have all parameters fixed except the three normalization constants.
- Use the resulting fits to:
  - Show π’s are the only background
  - Demonstrate that MC accurately models π’s
- As part of this process
  - wrote a “FastMC” to model π’s in the RICH
  - wrote a recalibrator for energy and momentum for PISA
- Final
  - incorporate FastMC result and recalibrator into PISA
  - weight all species in PISA with fits to real data
  - extract R_π from PISA
Final Fit
Does PISA produce $R_\pi$ Accurately?
Does PISA produce $R_\pi$ Accurately?
Cocktail of Electrons

- Primary ingredient is π data

\[
E \frac{d^3 \sigma}{dp^3} = f(c(e^{-(f_{ap} + f_{bp}^2) + p_T / p_0})^{-f_n} \sqrt{(p_T/c)^2 - m_{\pi_0}^2 + m_h^2},
\]

\[
\text{invariant cross section of some hadrons after correction}
\]
Cocktail of Electrons

$p+p \at \sqrt{s} = 200 \text{ GeV Run-6}$

cocktail: $(e^+e^-)/2$

- $\pi^0 \rightarrow \gamma ee$
- $\gamma$ conversion
- $\eta \rightarrow \gamma ee$
- $\eta' \rightarrow \gamma ee$
- $\rho \rightarrow ee$
- $\phi \rightarrow ee$ and $\phi \rightarrow \pi^0 ee$
- $\phi \rightarrow ee$ and $\phi \rightarrow \eta ee$
- direct $\gamma$ contributions
- $J/\psi \rightarrow ee$
- $K_{e3}$
- $\eta \rightarrow ee$
- all electrons

$E^3\sigma/d^3p \text{ [mb GeV}^2c^3]$
Final Spectrum

- Re bin & Bin shift correct
  - inclusive
  - cocktail
  - $R_\pi$
- Subtract Cocktail & Background
- Calculate Systematic Errors
Comparison to Published PHENIX Data

\((e^+ + e^-)/2\) non-photonic ratio pp077/fit to pp077

\((e^+ + e^-)/2\) non-photonic ratio Run 6/fit to pp077

\((e^+ + e^-)/2\) non-photonic ratio Run 6/pp077

7/7/2011  Harry Themann Stony Brook
Conclusion

• Successfully demonstrated a new technique for subtraction of hadron contamination
• Significantly extended the PHENIX pp reference for single electrons from open heavy flavor
• Hope to add Run5 and Run8 statistics
• SVTX and displaced vertex -> check my work
Problem with PISA

R$_{\pi}$ \_CuCu \_cuts

PbGI only

$R_x$

$P_T$ [GeV/c]

CuCu n1 ignored prob<0.01 PbGI
MCx n1 ignored prob<0.01 PbGI
CuCu n1 ignored prob<0.10 PbGI
MCx n1 ignored prob<0.10 PbGI
PbSc Only

Run6pp200 Single Electron Invariant Cross Section n1>=5

Graph showing the invariant cross section for single electron production in PbSc collisions at n1>=5. The graph includes data points and curves from various sources, such as arXiv:1005.1627v2 (ppg077) and D meson, arXiv:hep-ph/0511257v1 22 Nov 2005. The x-axis represents the transverse momentum (pT) in GeV/c, and the y-axis shows the cross section in units of 1/2π.”
backup
Overall Systematic Error

- Cocktail
- $R_\pi \rightarrow +/- 25\%$
- Acc/eff -> +/- 10\%
- Three separate final spectra are created and added in quadrature to get final error boxes
Systematic Error in Cocktail

• Pions
  - Move pion data points up(down) by their sys errors
  - re fit hagedorn, feed parameters into EXODUS
  - calculate fractional change in total

• Other Elements
  - change weights by their fractional uncertainties
  - put into EXODUS
  - calculate fractional change in total
Fit to Latest $\pi$ Data

\[ E \frac{d^3\sigma}{dp^3} = f_c \left( e^{- (f_a p_T + f_b p_T^2)} + \frac{p_T}{p_0} \right)^{-f_n} \]

- $f_c = 300.00$
- $f_a = 0.452546$
- $f_b = 0.0730125$
- $f_{p_0} = 0.70128$
- $f_n = 8.1714$
Ratio

Data Divided by Fit (stat and sys errors added in quadrature)

\[ \frac{E \cdot d^3 \sigma}{d^3 p} (\text{mb/GeV}^2 \text{c}^3) \]

\[ p_T [\text{GeV/c}] \]

\[ \pi^0 \text{ AN567} \]
\[ \pi^+ \text{ ppg101} \]
\[ \pi^- \text{ ppg101} \]
m_T Scaling

invariant cross section of some hadrons

\[ \sqrt{(p_T/c)^2 - m_{\pi^0}^2 + m_h^2}, \]
Additional Normalization Constant

data divided by hagedorn

Ratio

$10^{-2}$

$10^{-1}$

$1$
Final Fit

invariant cross section of some hadrons after correction

- $\pi^0 \times 5.00e+01$
- $\pi^- \times 5.00e+01$
- direct $\gamma$ (AN741 iso) $\times 5.00e+05$
- $\eta \rightarrow 2\gamma \times 1.00e+01$
- $\eta$ prelim $\times 1.00e+01$
- $\omega \times 1.00e+00$
- $\omega \rightarrow 3\gamma \times 1.00e+00$
- $J/\psi \times 1.00e-01$
- $K^{'0} \times 1.00e+01$
- $\phi \times 1.00e+00$

$E_d \sigma/d^3 p$ (mb/GeV²c³) vs $p_T$ [GeV/c]
\[ \frac{d^3\sigma}{dp^3} = \frac{1}{2\pi} \frac{1}{p_T} \sigma_{\text{inel}} \frac{dN}{dy} \frac{dN}{dp_T} = Hagedorn \]

\[ \frac{dN}{dy} = \frac{2\pi}{\sigma_{\text{inel}}} \int_0^\infty p_T Hagedorn(p_T) \]

- 1.01653 \(\frac{dN}{dy}\) \(\pi\)
- 0.107884 \(\eta\)
- 0.0161826 \(\eta'\)
- 0.08953762 \(\rho \rightarrow \sigma_\rho/\sigma_\omega = 1.15\)
- 0.0778588 \(\omega\)
- 0.00946404 \(\phi\)
- 0.0000170768 \(J/\psi\)
- 0.000000111960 \(Y \rightarrow d\sigma_{Y}/dy / Bd\sigma_{J/\psi}/dy = 0.006556291\)
- 0.0000025 \(\psi' \rightarrow \sigma_{\psi'}/\sigma_{J/\psi} = 0.14\)
- 0.0262 Direct Photon
- 0.00162 Ke3

\(\int_0^\infty \frac{dN}{dy} = 0\)

\(\frac{d\sigma}{dy} \frac{1}{B} \frac{d\sigma_{J/\psi}}{dy} = 0.006556291\)

\(\frac{\sigma_{\psi'}}{\sigma_{J/\psi}} = 0.14\)
Systematic Error in Cocktail

\[ \text{sys.error}[\%] = p0 \times \exp(p1 \times p_T) + p2 + p3 \times p_T + p4 \times p_T^2 + p5 \times p_T^3 \]
Systematic Error in Cocktail

• Pions
  – Move pion data points up(down) by their sys errors
  – re fit hagedorn, feed parameters into EXODUS
  – calculate fractional change in total
• Mesons
  – change meson/pion ratio by fractional uncertainty in normalization factor
  – put into EXODUS
  – calculate fractional change in total
• Conversions
  – change convprob +/- 10%
  – convprob is ratio of pi/pi dalitz
• Direct Photons
  – sys error from AN goes from 20-10% pT dependent
  – for now using 15%
Yield Fraction

\[ \int \frac{E}{p} - R\pi \int \frac{E}{p} \]

\[ \int \frac{E}{p} \]

\( n1 \geq 5 \)
Model The Background

• From data

\[ \int_{0.8}^{1.2} \frac{E}{p} - \int_{0.6}^{0.8} \frac{E}{p} \]

• This can be re written

\[ \frac{N_e}{N_e + N_\pi} \rightarrow \frac{N_e}{N_e + N_\pi} \]

• To Calculate

\[ \frac{N_\pi}{N_e} = \frac{\pi}{e} \frac{\int_{0.0}^{2.0} \frac{E}{p(\pi)} \frac{\text{frac}_\pi{n}_1 >= 5}{\text{frac}_e{n}_1 >= 5}}}{\int_{0.0}^{1.2} \frac{E}{p(\pi)}} \]
Terms

• $\pi/e$
  – Got most recent $\pi^0$ data from AN567 K. Boyle, A. Bazilevsky, A. Deshpande, Y. Fukao
  – Fit with Hagedorn function
  – For electrons got FONLL function from ppg065
  – Divided two functions (plots)

• Fraction in E/p window
  – Integrals done on MC $\pi$ E/p distributions

$$\int_{0.0}^{2.0} \int_{0.8}^{1.2} \frac{E}{p(\pi)}$$
Model The RICH

- Cerenkov Turn On -> Frank-Tamm

\[
\frac{dE}{dx} = \frac{q^2}{4\pi} \int_{\omega > \gamma c/n} \mu(\omega) \omega \left(1 - \frac{c^2}{v^2 n^2(\omega)}\right) d\omega
\]

# photons \(350 - 500\text{nm} = 390 \sin^2 \theta_c \times n_{CO_2} \times \text{path\_length}\)

\[
\frac{\pi}{n_1} \geq 5
\]

\[
\frac{e}{n_1} \geq 5
\]
n₁ turn on

- Normalize Cerenkov curve to asymptotic electron n₁ mean
- Generate a \( \pi \) with random \( p_T \)
- Determine n₁ mean for pion from the Cerenkov curve
- Generate pion n₁ from poisson distribution with this mean
- \( \frac{dN}{dp_T} \) vs \( p_T \) normalized to one is the turn on
- Close but not good enough (plot)
- Then used reconstructed \( p_T \)
- Think of a better way to model RICH
  - n1 is number of PMT’s not PE’s
Toy MC

- Generate track
  - Cerenkov angle
  - # photons from poisson with mean from Cerenkov curve
  - Distribute randomly in 2pi azimuth
- Propagate the resulting ring to an array of phototubes
RICH focal plane

$e^{+/-}$ ring has $r = 5.9$ cm

Kept mask centered on tube hit by track projection
Match Toy to Data by Varying the Asymptotic Value of the Number of Cerenkov Photons in Curve for e+/-. 

![Graph showing n1 mean vs electron mean](image)

**n1 mean vs electron mean**

- **Entries**: 0
- **Mean**: 0
- **RMS**: 0
Money Plot

![Graph showing yield fraction vs. electron fraction and pT]
Before
Better Way to Smear

Run8dAu dielectrons. 600 MeV trigger. [fcn=gaus+pol1]

<table>
<thead>
<tr>
<th>h1_FG12_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
</tr>
<tr>
<td>Prob</td>
</tr>
<tr>
<td>$p_0$</td>
</tr>
<tr>
<td>$p_1$</td>
</tr>
<tr>
<td>$p_2$</td>
</tr>
<tr>
<td>$p_3$</td>
</tr>
<tr>
<td>$p_4$</td>
</tr>
</tbody>
</table>
Run8dAu dielectrons. 600 MeV trigger. [fcn=gaus+pol2]

<table>
<thead>
<tr>
<th>h1_FG12_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
</tr>
<tr>
<td>Prob</td>
</tr>
<tr>
<td>p0</td>
</tr>
<tr>
<td>p1</td>
</tr>
<tr>
<td>p2</td>
</tr>
<tr>
<td>p3</td>
</tr>
<tr>
<td>p4</td>
</tr>
<tr>
<td>p5</td>
</tr>
</tbody>
</table>

$m_{ee}$ [GeV/c$^2$]
Then The Miracle Occurs

\[
\sqrt{2} \frac{\delta m}{m} = \frac{\delta p}{p}
\]

\[
J/\Psi \rightarrow \frac{\delta m}{m} = \frac{51.1}{3082} = 1.66\% \rightarrow \frac{\delta p}{p} = 2.34\% 
\]

\[
\phi \rightarrow \frac{\delta m}{m} = \frac{9.59}{1012} = 0.95\% \rightarrow \frac{\delta p}{p} = 1.34\%
\]

\[
\left( \frac{\delta p}{p} \right)^2 = C_1^2 + C_2^2 p^2
\]

\[
J/\Psi \rightarrow 2.34^2 = C_1^2 + C_2^2 (1.774)^2
\]

\[
\phi \rightarrow 1.34^2 = C_1^2 + C_2^2 (0.650)^2
\]

\[
C_2^2 = \frac{(2.34^2 - 1.34^2)}{(1.774^2 - 0.650^2)}
\]

\[
C_2 = 1.16\% \text{ and } \Rightarrow C_1 = 1.1\%
\]
After