Quantifying the Properties of Hot QCD Matter
INT - Seattle
Friday May 28th 2010

Outline
- Data comparison
- Hard vs Soft
- Jet properties
- Constraining fragmentation functions
- Summary
Some samples from the p-p data at $\sqrt{s}=200$ GeV

Helen Caines – Yale University

PHENIX PRL 98, (2007) 012002
STAR arXiv:0912.3838

Friday, May 28, 2010
$\pi$ in p-p - Comparison

Data fit to:

$$\frac{A}{(e^{(-ap_T-bp_T^2)} + p_T/p_0)^n}$$

Not interested in parameters just want good fit to data
π in p-p - Comparison

- STAR $\pi^\pm$, PHENIX $\pi^0$ compared to a Tsallis fit
- New STAR data from run without SVT not published - presented at QM09

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K and $\phi$ in p-p - Comparison

Data in agreement within ~20%
$	ext{e}^+\text{e}^-$ invariant mass cocktail gives a good description of the PHENIX data - including charm and bottom predictions from PYTHIA

PHENIX

PRC 81, 034911 (2010)
Helen Caines – Yale University

**c/b in p-p - Comparison**

- $e^+e^-$ invariant mass cocktail gives a good description of the PHENIX data - including charm and bottom predictions from PYTHIA

**Long standing disagreement over NPE yield between STAR and PHENIX**
e^+e^- invariant mass cocktail gives a good description of the PHENIX data - including charm and bottom predictions from PYTHIA

Long standing disagreement over NPE yield between STAR and PHENIX

STAR removed inner silicon - less conversion contamination
Despite dramatically different background Run 8 low mass data and new analysis of Run 5 give consistent results
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**STAR and PHENIX p-p NPE consistent within errors**
Disentangling bottom and charm in NPE

Combined fit to data reveals the B meson contribution to NPE

\[ \Delta \phi_{e-h} = r_B \Delta \phi_{e-h}^B + (1 - r_B) \Delta \phi_{e-h}^D \]

\[ r_B = \frac{e_B}{e_D + e_B} \]

At \( p_T = 5 \text{ GeV/c} \) Bottom contribution is \( \sim 50\% \)

B wider than D due to decay kinematics and mass.

essentially from B decays only

\( \approx 75\% \) from charm

\( \approx 25\% \) from beauty
Combined fit to data reveals the B meson contribution to NPE

\[
\Delta \phi_{e-h} = r_B \Delta \phi^B_{e-h} + (1 - r_B) \Delta \phi^D_{e-h} \\
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Strange and multi-strange $p_T$ spectra

- PYTHIA Version 6.3 (TuneA)
  - Incorporated parameter tunes from CDF
  - Multiple parton interactions and shower algorithms
  - Fails to describe baryons with default parameters
Strange and multi-strange $p_T$ spectra

- PYTHIA Version 6.3 (TuneA)
  - Incorporated parameter tunes from CDF
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Necessary to tune: K-Factor (accounts for NLO contribution)
There are also resonance measurements

- Compare PYTHIA 6.3 to published STAR data on $\phi$, $K^*$, $\Sigma^*$

Resonance data also need $K=3$ for good description
Non-strange particles

- Good agreement for $\pi$ with $K=1$ but not for $K=3$
- Proton with $1 < K < 3$

Need different $K$ factors for different particles!
Anti-particle/particle ratios

At low $p_T$ ratios are: ~ flat
~ reasonably represented by PYTHIA

similar to Au-Au and d-Au

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Baryon-meson ratios

- Gluon jet B/M > quark jet B/M
- Cannot describe B/M ratio at intermediate $p_T$ even with tuned K-factors and/or di-quarks

"K-tuned" PYTHIA still under-predicts B/M ratio at 200 and 630 GeV

also fails for $p/\pi$ at ISR and FNAL: 19-53 GeV (not shown)
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Hadro-chemistry in p+p events

**p-p $\sqrt{s} = 200$ GeV**

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**Canonical ensemble**

- Statistical model fit OK but not as good as in A+A
Hadro-chemistry in p+p events

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STAR Preliminary

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$p_T > 5$ GeV/c

- Statistical model fit OK but not as good as in A+A
- High-$p_T$ ratios first step to looking at hadro-chemistry of jet FF
Hadro-chemistry in $p+p$ events

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Some ratios change significantly

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Measured particle spectra over large mass range

- Nice agreement with phenomenological curve established by ISR (23 GeV) for lower masses

- Linear dependence better description of data when all masses included

- $p$-$p$ data fits into A-A systematics

Mass dependence but don’t expect flow in $p$-$p$
HBT in p-p

Radii:
- ~1 fm (the size of a proton)
- all drop as a function of $m_T$

Slope of radii as function of $m_T$ same as in Au-Au

$m_T$ trend used as evidence of flow in Au-Au
Taking a closer look at the events

- Minimum-bias events: Hard + Soft
- Hard Scattering: Back-to-back jet
- Underlying Event: soft or semi-hard multiple parton interactions (MPI), initial & final state radiation, beam-beam remnants

What does each component contribute to an event?

Figure from Rick Field
Charged particle multiplicity distribution

PYTHIA + simulated trigger and detector acceptance

Minimum-bias distribution dominated by low multiplicity events

- Probability of high multiplicity events occurring very sensitive to NLO corrections

Modeling the collision - pQCD ansatz

\[ \frac{d\sigma^h_{pp}}{dyd^2p_T} = K \sum_{abcd} dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \left( \frac{d\sigma}{dt} (ab \otimes cd) \right) \frac{D_{h/c}^0}{\pi z_c} \]

Assume that the calculation is factorizable

Parton Distribution Function (non-pert.)

LO parton processes

Fragmentation Function (non-pert.)

K factor

RHIC

Pions

LO parton processes

NLO parton processes

Modeling the collision - pQCD ansatz

\[
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Parton Distribution Function (non-pert.)

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NLO parton processes

Pions

p-p collisions “messy”

Not all energy involved in the collision

Charged particle $p_T$ distribution

- At low $p_T$ spectra similar for all $\sqrt{s}$
- Power-law tails dependent on $\sqrt{s}$
Charged particle $p_T$ distribution

- At low $p_T$ spectra similar for all $\sqrt{s}$
- Power-law tails dependent on $\sqrt{s}$
- Shape dependent on multiplicity

“Hard” and “soft” contributions varying

$e^{-6p_T}$

mid-rapidity

$1/n_{ch} 1/p_t dn/dp_t [(GeV/c)^2]$
Mini-jet production in p+p

- Mini-jet - “Hardish” parton interaction (included in PYTHIA and HIJING)
  - jets occur in higher multiplicity events
  - produce higher $p_T$ final states
  - measure higher $<p_T>$

Evidence of jet production in high mult. events

---

$R_{pp}(p_T) = \frac{<N_{ch}(\text{minbias})> dN/dp_T(\text{mult}, p_T)}{<N_{ch}(\text{mult})> dN/dp_T(\text{minbias}, p_T)}$

---

$N_{\text{jet}} = 2$

XN. Wang et al (Phys Rev D45, 1992)
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$N_{jet}=2$

$N_{ch}$

$R_{pp}(p_T) = \frac{\langle N_{ch}(\text{minbias}) \rangle dN/dp_T(\text{mult}, p_T)}{\langle N_{ch}(\text{mult}) \rangle dN/dp_T(\text{minbias}, p_T)}$

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Where do hard scattering processes dominate?

High-$p_T$ particles are produced via hard scattering processes.

Rates calculable via pQCD:

$$E \frac{d^3 \sigma}{dp^3} = \frac{1}{\sqrt{s}^n} g(x_T) , \quad x_T = 2p_T/\sqrt{s}$$

$n \sim 4$ for basic (vector-gluon) scattering processes

In QCD:

$n \rightarrow n(x_T, \sqrt{s}) \sim 5-8$ depending on evolution of structure functions and fragmentation functions
Where do hard scattering processes dominate?

High-\(p_T\) particles are produced via hard scattering processes.

\[ x_T = 2p_T/\sqrt{s} \]

- \(n = 6.3 - 6.5\) for \(h^\pm, \pi, K\) and \(p\)
- \(n = 5.6 \pm 0.2\) for \(J/\psi\) at high \(p_T\)
- Color octet & evaporation (\(n=6\)), color singlet (\(n=8\))

Transition from soft to hard processes \(p_T \sim 2\) GeV/c \((x_T \sim 0.02)\)
Jets in p-p at RHIC

- Jet cross-section in p+p is well described by NLO pQCD calculations over 7 orders of magnitude.
- Excellent description when included in world data

All algorithms used give same result when same R used
Intrinsic properties - $k_T$ and $j_T$

$k_T = p_T(\text{Jet}) \sin(\Delta \Phi)$

$k_{T,\text{di-had}}(p-p) = 2.68 \pm 0.07 \pm 0.34$ GeV/c

$\sigma_{kT,\text{raw}} (p-p) = 2.8 \pm 0.1 \text{ (stat)}$ GeV/c

$k_T(\sqrt{s}=200) > k_T(\sqrt{s}=63)$
**Intrinsic properties - $k_T$ and $j_T$**

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\[ k_T(\sqrt{s}=200) > k_T(\sqrt{s}=63) \]

\[ j_T = p_T(\text{particle}) \sin(\Delta \Phi_2) \]

\[ j_{T,\text{di-had}}(p-p) = 585 \pm 6 \pm 15 \text{ MeV/c} \]

\[ j_T(\sqrt{s}=200) = j_T(\sqrt{s}=63) \]

$k_T$ and $j_T$ independent of $p_T$ over measured range
Fragmentation functions for charged hadrons

- Analysis details:
  - $Z_{\text{max}} \sim 0.81$
  - Electrons are rejected
  - FF scaled by successive factors of 10
- Reasonable agreement between data and PYTHIA
- Similar good agreement has been shown by STAR using $R=0.4$ and 0.7

NLO corrections small or accounted for in PYTHIA
Strange hadron FF

PYTHIA = PYTHIA+GEANT

- Data presented at detector level
- Errors - estimate from average of $k_T$, anti-$k_T$ and SISCones
- V0 $p_T > 1$ GeV/c - artificial cut in distribution

Description of $K^0_s$ seems better than for $\Lambda$

A. Timmins SQM2009

Friday, May 28, 2010
Extensive studies into jet properties have been done with $e^+e^-$ data

- Gluon jet fragmentation:
  - produces higher multiplicities
Quark and gluon jets

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- Gluon jet fragmentation:
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  - produces harder $p_T$ spectra
Extensive studies into jet properties have been done with $e^+e^-$ data

- **Gluon jet fragmentation:**
  - produces higher multiplicities
  - produces harder $p_T$ spectra

- **In p-p study:**
  - particle vs anti-particle
  - different species

Vary gluon vs quark sensitivities: constrain theory further.
Quark and gluon FF and PDFs

- Experimental data from different collisions systems have been fit with the same fragmentation function (FF)
- Constraints on Gluon FF and PDF were poor

Fragmentation function for Quarks

- OPAL
  - $\sqrt{s}=91.2$ GeV

Fragmentation function for Gluons

- ALEPH
- OPAL

3-jet events

- Experimental data from different collisions systems have been fit with the same fragmentation function (FF)
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- OPAL $\sqrt{s}=91.2$ GeV


Quark and gluon FF and PDFs

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Parton Distribution function for Gluons

Fragmentation function for Gluons

CTEQ6

CTEQ5


ALEPH

OPAL

3-jet events

Partonic hard scatterings in p+p at RHIC

At mid y:

Low $p_T$ particles come from gluon fragmentation

At forward y:

Add-mixture of quark and gluon but at high $z$

Significant information available about gluon FF from RHIC
$m_T$ scaling of identified particles

- First studied at ISR - In CGC picture $m_T$-scaling would be indicative of evidence of gluon saturation
- No absolute scaling (data shown are arbitrarily normalized)
- Baryon meson splitting above $m_T \sim 2$ GeV/c

STAR, PRC 75 (2007)
**m_T scaling of identified particles**

- First studied at ISR - In CGC picture m_T-scaling would be indicative of evidence of gluon saturation
- No absolute scaling (data shown are arbitrarily normalized)
- Baryon meson splitting above m_T ~2 GeV/c

PYTHIA and data show similar trends
$m_T$ scaling of identified particles

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- No absolute scaling (data shown are arbitrarily normalized)
- Baryon meson splitting above $m_T \sim 2$ GeV/c

PYTHIA and data show similar trends - comes from gluon jets
π cross-section - sensitivity to FF

- NLO pQCD calculations (factorization scale $\mu = p_t$) with different fragmentation functions

- Brahms forward $\pi$ and $K$ also used

RHIC data now sufficiently precise to be sensitive to different FF
Constraining the valence and sea parton FF

- New RHIC and Tevatron, as well as $e^+e^-$, data used
- Global fits to all data
- RHIC charged separated data used to constrain valence partons
- Calculations now include hadron mass effects since $p$, $K$, $\Lambda$ included
- AKK Shown but similar calculations/results from DSS

Mesons at mid-$y$ well represented, undershoot at forward-$y$
FF into baryons are also calculated

- (anti)p mid-rapidity described OK, undershoots as go forward
- (anti)Λ OK at high $p_T$ for CDF but miss at RHIC energies

**Baryons continue to be hard to describe collectively**
Contributions from gluon vs. quark jet

Contribution factor: \( N_g(i)/ (N_g(i) + N_q(i)) \); \( i = \pi, K, p \ldots \)

At \( p_T = 8 \text{ GeV/c} \): 50% for \( \pi \), 90% for \( p \)

At RHIC: baryons from glue, \( \pi \) both quark and glue contribution
Protons predominantly from glue?

- Both AKK08 and DSS give satisfactory descriptions of data
- FF calculations for light quarks similar
- FF of glue still poorly constrained - even after using RHIC data
  >factor 3 differences between AKK and DSS for glue

Need more precise data at high $p_T$ to finally resolve

K/π ratio at high p_T

- Charged and neutral K and π now extend up to 15 GeV/c
- Charged and neutral measurements are consistent
- Appears to be good fit to data

Ratio indicates how off the fits really are
Summary

- RHIC p+p data are extensive and can be used to constrain models.
- There is good agreement between experiments on 20% level.
- The STAR/PHENIX NPE difference has been resolved in p-p.
- $m_T(x_T)$-scaling show that hard processes (related to PDF and FF) dominate over soft process for min-bias collisions for $p_T \sim 2 \text{ GeV/c}$.
- OPAL and RHIC light-flavor separated measurements in $e^+e^-$ collisions provided significant improvement of FF for valence partons.
- RHIC data provides a unique tool for understanding gluon vs. quark jet contributions.
- FF have been improved but the details are still not correct (B/M ratios) and the add-mixture of quark and gluon still uncertain.