Leptons, Photons, and Heavy Quarks

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Outline

- **Low and Intermediate-Mass Dileptons**
  - open questions
  - pending answers

- **Direct Photons**
  - controlling jets

- **Heavy Flavor**
  - charmonia
    - news from SPS
    - preparing the case for RHIC
  - open charm at RHIC
    - reference and probe

- **Summary**
SPS dilepton experiments: open questions

- low-mass dielectrons
  - excess established by NA45/CERES
  - vector mesons, i.e. $\omega$, $\phi$?
    - where are they?
    - medium modifications of yield, mass, width?
SPS dilepton experiments: open questions

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  - discrepancy between NA49 ($\phi \to K^+K^-$) and NA50 ($\phi \to \mu^+\mu^-$)
  - physics ($\phi$ in-medium vs. $\phi$ at freeze-out)?
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  - dimuon excess observed at intermediate masses (NA50)
    - charm enhancement?
    - thermal dimuons?
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SPS dilepton experiments: answers?

NOT YET!
SPS dilepton experiments: perspectives!

- NA45/CERES (talks by A. Marin, A. Cherlin)
  - improved mass resolution (TPC)
  - possibility for $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ in one experiment
  - work in progress
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- **NA60** (talks by P. Sonderegger, A. David)
  - DESIGNED to answer open questions!
    - high statistics due to selective trigger
    - good mass resolution (~20 MeV for \(\omega,\phi\))
    - good phase-space coverage (down to zero \(p_T\))
    - 50 \(\mu m\) secondary vertex resolution (prompt \(\mu\) vs. \(\mu\) from charm decays)
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- Indium+Indium at 158 AGeV (2003)
  - >$10^6$ low-mass dimuons!
  - S/B: $1/2 - 1$ (depending on centrality)
  - >$10^5$ $\phi \rightarrow \mu^+\mu^-$
  - $\phi \rightarrow K^+K^-$ feasible as well
Low-mass dileptons at RHIC

- **PHENIX (talk by R. Seto):** resonance measurements in leptonic and hadronic channels in ONE experiment
- Look forward to results from large statistics Au+Au Run04 at RHIC
  - $\rho$, $\omega$, $\phi$
  - Continuum (low and intermediate mass)
- **RHIC upgrades (talk by A. Drees):**
  - Electron identification $\Rightarrow$ Dalitz / Conversion rejection (poster by I. Ravinovich)
  - Silicon vertex spectrometers $\Rightarrow$ resolve secondary vertices (heavy flavor physics)
- PHENIX Preliminary
- Posters by C. Maguire, D. Pal, Y. Tsuchimoto
Virtual photons → real photons

- real photon sources in AA collisions
  - “trivial” ⇔ background
    - decays of light hadrons ($\pi^0 \rightarrow \gamma \gamma$)
    - dominant at low / intermediate $p_T$ (few GeV/c)
  - “thermal” ⇔ black body radiation from hot medium
    - partonic and/or hadronic medium
    - expected at low $p_T$ on top of huge background
  - “direct” ⇔ photons from initial state hard scattering
    - Compton scattering dominates, i.e. probe for gluon distribution
    - calculable in pQCD
    - no fragmentation of photon!
    - photon “shines through” hot and dense medium!

- direct photons “calibrate” hard scattering processes
  ⇒ IDEAL CONTROL EXPERIMENT FOR JET SUPPRESSION!

- how-to measure direct photons
  - subtraction of “background” photons (WA98 / PHENIX)
  - photon correlations (WA98 talk by D. Peressounko)
Virtual photons $\rightarrow$ real photons

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  $\Rightarrow$ IDEAL CONTROL EXP

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Correlation method:
- The lowest yield ($R_o=0$)
- Most probable yield ($R_o=6$ fm)

Subtraction method, upper limit

Predictions
- hadronic gas
- QGP
- pQCD
- sum

Most probable yield (Ro=6 fm)
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Direct photons from 200 GeV pp collisions

- evaluation of excess above background: double ratio
  - $\frac{\gamma/\pi^0_{\text{measured}}}{\gamma/\pi^0_{\text{background}}} \rightarrow \frac{\gamma_{\text{measured}}}{\gamma_{\text{background}}}$
- (small) direct photon signal observed!
  (PHENIX talk by J. Frantz, posters by G. David, K. Reygers, T. Sakaguchi)

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2004
Direct photons from 200 GeV pp collisions


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\[ \frac{[\gamma/\pi]_{\text{measured}}}{[\gamma/\pi]_{\text{background}}} \rightarrow \frac{\gamma_{\text{measured}}}{\gamma_{\text{background}}} \]

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Direct photons from 200 GeV AuAu collisions

- strong suppression of high $p_T$ pions in central AuAu collisions
- VERY significant background reduction!
Comparison with NLO pQCD calculation

- nice agreement with unsuppressed, binary scaled pp NLO pQCD calculation!
Direct photons: centrality dependence

\[ \frac{\gamma}{\pi^0}_{\text{measured}} / \frac{\gamma}{\pi^0}_{\text{sim}} = 1 + \left( \frac{\gamma_{\text{pQCD}} \times N_{\text{coll}}}{\gamma_{\text{phenix background}}} \right) \]

PHENIX Preliminary PbGI / PbSc Combined

80-92% Central AuAu 200 GeV

- Vogelsang NLO

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Direct photons: centrality dependence

PHENIX Preliminary PbGl / PbSc Combined
70-80% Central AuAu 200 GeV

\[ 1 + \left( \gamma_{pQCD} \times N_{\text{coll}} \right) / \gamma_{\text{phenix backgrd}} \] Vogelsang NLO

\( \frac{(\gamma / \pi^0)_{\text{measured}}}{(\gamma / \pi^0)_{\text{sim}}} \) vs. \( p_T \) (GeV/c)
Direct photons: centrality dependence

\begin{align*}
\frac{\gamma/\pi^0}{\text{measured}} &= 1 + \frac{\gamma_{\text{QCD}} \times N_{\text{coll}}}{\gamma_{\text{phenix background}}} \\
\text{Vogelsang NLO}
\end{align*}
Direct photons: centrality dependence

\[
1 + \frac{\gamma_{\text{QCD}} \times N_{\text{coll}}}{\gamma_{\text{phenix backgrd}}} \]

\[
\text{PHENIX Preliminary PbGl / PbSc Combined 50-60\% Central AuAu 200 GeV}
\]

\[
\begin{align*}
\text{(\gamma/\pi^0)_\text{measured} / (\gamma/\pi^0)_\text{sim}}
\end{align*}
\]

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Direct photons: centrality dependence

\[ 1 + \left( \frac{\gamma_{pQCD} \times N_{\text{coll}}}{\gamma_{\text{phenix backgrd}}} \right) \]

PHENIX Preliminary  PbGl / PbSc Combined
40-50% Central AuAu 200 GeV

Vogelsang NLO

\[ \frac{\langle \gamma/T^0 \rangle_{\text{measured}}}{\langle \gamma/T^0 \rangle_{\text{sim}}} \]
Direct photons: centrality dependence

\[ 1 + \left( \gamma_{pQCD} \times N_{\text{col}} \right) / \gamma_{\text{phenix backgrd}} \]  

Vogelsang NLO

PHENIX Preliminary  PbGj / PbSc Combined

30-40% Central AuAu 200 GeV
Direct photons: centrality dependence

\[ \frac{\gamma}{\pi^0} \text{measured} / \frac{\gamma}{\pi^0} \text{sim} \]

PHENIX Preliminary PbGl / PbSc Combined

20-30% Central AuAu 200 GeV

\[ 1 + \left( \gamma_{pQCD} \times N_{\text{coll}} \right) / \gamma_{\text{phenix backgrd}} \]

Vogelsang NLO
Direct photons: centrality dependence

\[ \frac{(\gamma / \pi^0)}{\text{measured}} / \frac{(\gamma / \pi^0)}{\text{sim}} = 1 + \frac{\gamma_{\text{pQCD}} \times N_{\text{coll}}}{\gamma_{\text{phenix backgrd}}} \]

10-20% Central 200 GeV AuAu

Vogelsang NLO
Direct photons: centrality dependence

- direct photons are not inhibited by hot/dense medium and shine through consistent with pQCD!

thermal photons: reduction of systematic uncertainties is essential!!

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Another hard probe: heavy flavor production

- a (very) complex playground
  - cc production in hard scattering
    - sensitive to PDF
  - propagation
  - hadronization
- medium modifications
  - modification of PDF in nuclei (shadowing, antishadowing)
  - multiple scattering $\Rightarrow p_T$ broadening
  - initial state parton energy loss
  - charmonia:
    - “normal” nuclear absorption
    - “anomalous” suppression ("Debye" screening)
      - enhancement via "coalescence"?
  - additional “thermal” production?
  - energy loss by induced gluon radiation? “Dead-cone effect”?
  - how to disentangle this?
- measure charmonium states and open charm
  - in pp, pA, AA collisions
  - in various kinematic regions
  - at various energies
    - news from SPS
    - news from RHIC

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J/ψ suppression in PbPb at SPS

- updated analysis of J/ψ (and ψ’) absorption in cold nuclear matter (NA50 pA run at 400 GeV (2000) + combined fit of ALL data sets) (NA50 talk by G. Borges)
- \( \sigma_{\text{J/ψ}}^{\text{abs}} = 4.3 \pm 0.3 \text{ mb} \)
- J/ψ suppression with respect to this expected “normal” nuclear absorption (relative to Drell-Yan): a familiar pattern
- what is new?
  - \( \psi' \) measurement
  - challenging because of
    - small dimuon cross section
    - small S/B
    - large suppression (weaker bound state than J/ψ)
\( \psi' \) suppression at SPS

- NA50 talk by H. Santos
- \( \psi' \) absorption in pA is stronger than J/\( \psi \) absorption
- significantly stronger absorption in AA going from peripheral to central collisions
- no apparent difference in absorption pattern between SU and PbPb collisions

\[ \sigma_0 e^{-\langle \rho L \rangle \sigma_{abs}} \]

- \( \psi' \) suppression relative to Drell-Yan and J/\( \psi \) increases with centrality in PbPb collisions
Open questions at SPS

- what fraction of $J/\psi$ comes from $\chi_c$ feed down ($\chi_c \rightarrow J/\psi + \gamma$)?
- what is the nuclear dependence of $\chi_c$ production/absorption in pA?
- is open charm enhanced in AA?

will be answered by NA60

- $\chi_c$ measurement at HERA-B (huge statistics dilepton data sample from pA collisions at $\sqrt{s_{NN}} = 42$ GeV)
  (HERA-B talks by J. Spengler, A. Gorisek)

$\chi_c/J/\psi = 0.21 \pm 0.05$

from 15% of available statistics
### J/ψ suppression / enhancement at RHIC?

- **PHENIX: preparing the case**

<table>
<thead>
<tr>
<th>Year</th>
<th>Ions</th>
<th>(\sqrt{s_{NN}})</th>
<th>Detectors</th>
<th>J/ψ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Au-Au</td>
<td>130 GeV</td>
<td>Central (electrons)</td>
<td>0</td>
</tr>
<tr>
<td>2001</td>
<td>Au-Au</td>
<td>200 GeV</td>
<td>Central</td>
<td>13 + 0</td>
</tr>
<tr>
<td>2002</td>
<td>p-p</td>
<td>200 GeV</td>
<td>+ 1 muon arm</td>
<td>46 + 66</td>
</tr>
<tr>
<td>2002</td>
<td>d-Au</td>
<td>200 GeV</td>
<td>Central</td>
<td>300+800+600</td>
</tr>
<tr>
<td>2003</td>
<td>p-p</td>
<td>200 GeV</td>
<td>+ 2 muon arms</td>
<td>100+300+120</td>
</tr>
<tr>
<td>2004</td>
<td>Au-Au</td>
<td>200 GeV</td>
<td>! ready !</td>
<td>~400+2x1600</td>
</tr>
</tbody>
</table>

- **QM2002** first observation
- **QM2004** first sizeable pp & dAu samples

**study J/ψ modifications in cold nuclear medium**

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**J/ψ in dAu collisions at RHIC**

- J/ψ produced by gluon fusion
- Sensitivity to gluon pdf
- 3 rapidity ranges in PHENIX probe different momentum fraction of Au partons
  - South (y < -1.2) : large $X_2$ (in gold)
  - Central (y ~ 0) : intermediate
  - North (y > 1.2) : small $X_2$ (in gold)

From Eskola, Kolhinen, Vogt
**J/ψ in pp and dAu collisions at RHIC**

- rapidity distributions: improved pp / first dAu measurements

**PHENIX talk by R. G. de Cassagnac, posters: J.M. Burward-Hoy, S. Kametani, D. Kim, D. Silvermyr**

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J/$\psi$ dAu/pp versus rapidity at RHIC

- indication for (weak) shadowing and absorption
- centrality dependence studied as well!
- more statistics desirable to disentangle nuclear effects (and distinguish models)
J/ψ dAu/pp versus rapidity at RHIC

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J/$\psi$ dAu/pp versus rapidity at RHIC

STAGE IS SET

Look forward to high statistics AuAu run!

- indication for (weak) shadowing and absorption
- centrality dependence studied as well!
- more statistics desirable to disentangle nuclear effects (and distinguish models)
Open charm: reference and probe

- physics motivation for open charm measurements
  - reference for $J/\psi$ suppression / enhancement
  - production mainly via gluon fusion ⇒ interesting probe itself
    - sensitive to gluon structure function (and nuclear modification of this)
    - heavy quark energy loss
      - induced gluon radiation
      - “dead cone” effect
    - does charm flow?

- open charm measurements at RHIC

  direct reconstruction
  
  ideal, difficult in HI, doable
  
  200 GeV dAu: STAR (mb)

  indirect measurements
  
  electrons from semileptonic decays
  
  130 GeV AuAu: PHENIX (cent.)
  200 GeV pp: PHENIX & STAR
  200 GeV dAu: PHENIX (cent.) & STAR (mb)
  200 GeV AuAu: PHENIX (cent)
First direct charm measurement (STAR)

- reconstruction of D mesons in minimum bias dAu collisions
  - $D^0$
  - $D^±$
  - $D^*$

- STAR talks by A. Tai, L. Ruan, A. Suaide

\[
\sigma_{c\bar{c}}^{NN} = 1.12 \pm 0.20 \pm 0.37 \text{ mb from D data}
\]
\[
(1.36 \pm 0.20 \pm 0.39 \text{ mb with electrons})
\]
Open charm in pp: the baseline

- two single electron measurements

\[ \sigma_{cc} = 709 \, \mu b \pm 85_{\text{stat}} \pm 332_{\text{sys}} \]

- three methods to subtract photonic background (PHENIX talk by S. Kelly)

- three methods to identify electrons (STAR talk by A. Suaide)

- charm cross sections (barely) agree!

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Consistency between electron data sets

\( \frac{e^+ + e^-}{2} \)

PHENIX

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

\( p_T \) [GeV/c]
Consistency between electron data sets

\[ \frac{(e^+ + e^-)}{2} \]

- PHENIX
- STAR TOF

\[ E \frac{d\sigma^3}{dp^3} \text{[mb GeV}^2/c^3] \]

\[ p_T \text{[GeV/c]} \]
Consistency between electron data sets

\[ \frac{(e^+ + e^-)}{2} \]

- PHENIX
- STAR TOF
- STAR EMC

\[ E d^3N/dp^3 \text{ [mb GeV}^2/c^3] \]

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

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Consistency between electron data sets

\[ \frac{(e^+ + e^-)}{2} \]

- PHENIX
- STAR TOF
- STAR EMC
- STAR D2e

\[ E \frac{d\sigma}{dp^3} \text{ [mb GeV}^2 c^3] \]

\[ p_T \text{ [GeV/c]} \]
Consistency between electron data sets

- STAR systematically (slightly) above PHENIX
- beware: error bars are meant to be taken seriously!

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Does the PYTHIA extrapolation work?

- PYTHIA tuned to available data ($\sqrt{s_{NN}} < 63$ GeV) BEFORE RHIC results

PHENIX PRELIMINARY

- spectra are harder than PYTHIA extrapolation from low energies! (hard fragmentation function, charm quark recombination ...?)
- PYTHIA can’t be used to extract bottom cross section!
- bottom measurement requires PRECICE D measurement first!
Centrality dependence in dAu (PHENIX)

Single electrons from non-photonic sources agree well with pp fit and binary scaling (posters: S. Butsyk, X. Li)

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Centrality dependence in dAu (PHENIX)

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Centrality dependence in AuAu (PHENIX)

- uncertainties too large for definite statements regarding (small) deviations from binary scaled pp results (poster: T. Hachiya)

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Binary collision scaling in AuAu (PHENIX)

- binary collision scaling of pp result works VERY WELL for non-photonic electrons in AuAu (PHENIX talk by S. Kelly)
- open charm is a good CONTROL, similar to direct photons!
Binary collision scaling in AuAu (PHENIX)

- Binary collision scaling of pp result works VERY WELL for non-photonic electrons in AuAu (PHENIX talk by S. Kelly)
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\[
\frac{dN}{dy} = A \left( N_{\text{coll}} \right)^{\alpha}
\]

Integrated 0.8 < \(p_t\) < 4.0 (GeV/c)

0.906 < \(\alpha\) < 1.042
Does charm flow?

- is partonic flow realized?
- $v_2$ of non-photonic electrons indicates non-zero charm flow in AuAu collisions
- uncertainties are large
- definite answer: AuAu RUN-04 at RHIC!

PHENIX poster by S. Sakai
Summary

- low and intermediate-mass dileptons
  - looking forward to
    - solutions of SPS puzzles
    - data from RHIC
- direct photons as jet control measurement
  - pQCD at work
- charmonia
  - improvements at SPS
  - preparing the reference for RHIC
- open charm
  - a second player joined the game
- what next?
  - LUMINOSITY!!
  - back to work