Quarkonium Physics
at the Tevatron

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High Energy Vector Meson Production Mechanisms

- Long history of theoretical models to try to match vector meson data from Tevatron and HERA
  - cross section problem $\Rightarrow$ CSM $\Rightarrow$ NRQCD
  - polarization problems with NRQCD $\Rightarrow$ multi-gluon models
  - recent theoretical considerations raise questions about $k_T$ factorization approach, Q fragmentation effects at Tevatron energies

- See recent review by J.-P. Lansberg for summary of theoretical situation (arXiv:0811.4005)
Experimental Results

- This talk’s focus: Tevatron experimental results on vector meson production and polarization
  - J/ψ and ψ(2S) cross section and polarization from CDF
  - Y(1S) and Y(2S) polarization from D0
  - new results on Y(1S) polarization from CDF
  - production issues

- CDF work on new charmonia X(3872) and Y(4140)

- Prospects for further Tevatron work will be given.
Measuring Polarization - I

- Polarization is an angular asymmetry:

\[ \frac{dN}{d(\cos \theta)} \propto 1 + \alpha \cos^2 \theta \]

  - what axis? The size of \( \alpha \) depends on frame.
    - (aside: think of electron polarized along z-axis. If you measure spin along some other direction with direction cosine \( \gamma \), the maximum polarization is \( \gamma \).)

  - historically, low \( p_T \) fixed target experiments have analyzed in Collins-Soper frame.
  - high \( p_T \) collider experiments have used s-channel helicity frame
Measuring Polarization - II

- Background control is essential! Good CDF mass resolution helps enormously.

- $J/\psi$ dominates; small background.

- Y region has higher background, varying with dimuon mass.
J/$\psi$ Analysis

- Classify J/$\psi$ candidates as *prompt* or b-decay
  - prompt candidates include feed-down from $\chi_c, \psi(2S)$ decays.
  - separate b-decay candidates by impact parameter cut (equivalent to proper time cut). Measure and correct leak-through.
  - divide data into bins of $p_T(\psi)$.
  - in each $p_T(\psi)$ bin define signal and sideband region. Assign events to bins of muon CM decay cosine $\cos\theta$. Use templates for pure L, T polarization to treat trigger and apparatus effects.
Prompt/b-decay Separation

- Mass and ct projections for two $p_T$ bins illustrating joint mass-lifetime fit to identify prompt and b-decay selection.
Prompt J/ψ Polarization

- Select Prompt Events based on decay length
  - in each p_T bin select prompt signal and sideband events from mass plot after cuts
  - make cos θ distribution for each: total, backgnd
  - make simultaneous fit to signal, backgnd distributions. \( \chi^2 \) can be minimized analytically for backgnd. Determine L fraction, template normalization.

- Analyze b-decay polarization in same way.
Sample Prompt J/ψ Polarization Fits

LEFT: background  CENTER: polarization-weighted template fit and data  RIGHT: same plot as center plus L and T template to illustrate sensitivity of measurement.

Typical plots; here $9 < p_T(J/ψ) < 12$ GeV/c. Background highly structured but small. Fitted templates give good description of data over whole angular region, esp. ends (tests efficiency function.).
Prompt J/ψ, ψ(2S) Polarization

- Prompt polarization in s-channel helicity frame is always longitudinal.

- Trend is to become more longitudinal as \( p_T(ψ) \) increases.

- Consistent with multi-gluon models but not NRQCD.
What About Y Polarization?

- Various theoretical papers about c quark being too light for factorization.
- Everyone agrees that Y(ns) polarization at high $m_T$ is the acid test for NRQCD.
- CDF Run I Measurement does not show trend to $T$ polarization, but $m_T$ is limited.
- Recent D0 publication suggests possible trend toward $T$ polarization.
- CDF has new Run II result.
CDF Y Analysis

- Follow methodology of J/$\psi$ analysis:
  - make templates for L, T polarization to incorporate trigger, acceptance conditions
  - Make MC-constrained mass fits in each $\cos \theta$ bin to identify signal yield and background
  - Make simultaneous fit to polarization parameter and background in $\cos \theta$ bins

- Check that $\cos \theta$ and $p_T$ resolutions are good enough that there are no bin-smearing corrections.
Y-region Dimuon Background

- Just as in J/ψ case, dimuon background has mass- and $p_T$-dependent angular variation

- Plots show angular dist. of fitted backgnd for Y(1S) in 8 $p_T$ bins

No prompt selection, so bkg includes heavy flavor + DY + junk
Y(1S) Polarization Fits

- Fitter is same as for J/ψ. Blue points are L template, green + are T template in 10 |cosθ| bins
- Solid line is best fit.
- All bins have good $\chi^2$. 
CDF Run II Y(1S) Polarization

- Y(1S) prompt polarization, including feed-down from $\chi_b$, Y(nS).
- Green is NRQCD (Braaten and Lee) including feeddown.
Good Agreement with CDF-I

- Polarization small for $p_T < 20 \text{ GeV/c}$
  ($m_T \sim 2.2 \text{ m}_Y$)
- Run II data
- L polarized at larger $p_T$
CDF Disagrees with D0

Trends are totally different.

D0: $|y| < 1.8$
CDF: $|y| < 0.6$

D0: polarization
Longitudinal for $p_T < m_T$

D0 paper: “We expect the CDF and D0 results to be similar and have no explanation for the observed difference.” Same remarks apply here – no explanation.
Check: Is low $p_T$ $\Upsilon(1S)$ data unpolarized?

- Generate unpolarized decays with Monte Carlo:
  - Processed in same way as fully-polarized template samples
  - Normalize to number of events in data and overlay – no fitting involved.

- See good agreement

- CDF data do not support D0 claim of longitudinal polarization at low $p_T$
CDF/ D0 Differences

D0: Smooth data-driven backgnd shape under all mass peaks for each angle, $p_T$ bin.

CDF: separate mass fits, backgnd for each $Y(nS)$ peak. Results for $Y(2S)$, $Y(3S)$ ready soon. D0-style mass fit in each angle bin gives same results as this analysis.
Prompt $J/\psi$, $\psi(2S)$ Polarization - II

- Recall that $Y(1S)$ polarization is longitudinal for $m_T(Y) > 2.2 \ m(Y)$

- Same feature seen in $J/\psi$ at $2.2 \ m(J/\psi)$
Polarization Summary

- CDF prompt vector meson polarizations show trend toward L polarization at high $p_T$ in s-channel helicity frame.
- Multi-gluon models predict this kind of behavior, but
  - models go L at lower $p_T$ than data
  - models are for direct production – data are prompt
  - multigluon models suggest Y(nS) states are not isolated – have to test in data
- Backgrounds have angular structure. How much is due to Drell-Yan? What is DY polarization?
D0 reported Y(1S) differential cross section, normalized to unit area, in 3 |y| regions: 0-.6, .6-1.2, 1.2-1.8. Some falloff in highest y-bin. For 0-.6, cross section agrees within uncertainties with CDF Run I result for 0-0.4. Shapes agree with model of Berger, Qui and Wang for $p_T \leq m_T$. 
CDF: $\psi(2S)$ Production

Prompt $\psi(2S)$ production falls off faster with $p_T$ than $b$-production

Comparing to Run I, see small shift to larger cross section at given $p_T$ for higher energy.
CDF has measured $J/\psi$ and $\psi(2S)$ production cross sections, both direct and B-decay cases.

Question: when the c-cbar pair at a given $p_T$ hadronizes into the 1S or 2S state, does it matter if it is directly produced or occurs in the B-decay environment?

Khoze, et al.: $R = d\sigma/dp_T(2S)/d\sigma/dp_T(1S) \propto \alpha(m_T)^5/m_T^6$ on dimensional grounds in direct production. Fix ratio in $p_T$ bin 8-9 GeV/c. Shape looks quite good at all other $p_T$. Is this fundamental?
In preceding R plot, b-decay result and direct production seemed to track in $p_T$. Take ratio of ratios:

Why should the ratio of b-decay hadronization to 2S and 1S charmonium have the same $p_T$-dependence as that of direct production?

A question to be explored with more data going to higher $p_T$. 
Onium Plans at Tevatron

- Now have ~2X as much data at CDF – double statistics for Y, quintuple for J/ψ.
- Measure Y(nS) production cross sections
- Study Y isolation in production
- Try to identify DY component of dimuon continuum and measure polarization vs m_T
- Measure χ_b, feed-down fractions for Y(1S)
- D0 J/ψ polarization result in process.
X(3872) Studies at CDF

- New charmonium states keep coming from Belle, BaBar, and (surprisingly) CDF.
- CDF uses natural calibration of $\psi(2S) \rightarrow J/\psi \pi\pi$ to set cuts, calibrate mass for $X(3872)$.
- Saw that $\pi\pi$ state prefers higher mass.
  - Right plot is cut at 500 MeV/c$^2$.
X(3872) - II

- Improving analysis takes multivariant selection
- Making NN selection requires careful study of discriminating variables, resolution – needs excellent detector understanding.
- Using B-decays and J/ψ decays to calibrate momentum scale is essential for precision. Material budget of detector also enters directly.
- Good vertex precision reduces number of fake candidates and lowers background.
X(3872) - III

- Measure $J^P$ at a hadron machine? Yes!
- $\pi\pi$ mass distribution sensitive to orbital angular momentum in decay and hence to parent’s spin-parity
- Top: fit to expected shape for $\psi(2S) \rightarrow \psi(1S)\pi\pi$ (validate)
- Bottom: fit to $L=0$ and $L=1$ for $X(3872) \rightarrow \psi(1S)\pi\pi$
Another New State – Y(4140)

- The X(3872) tries to decay to J/ψρ ... but it’s too light.
- Belle observes another threshold J/ψV state in B decays: Y(3930) → J/ψ ω
- CDF used its huge B → J/ψ X sample to look for a narrow J/ψ φ state near threshold
- No good theory for these objects, but interesting experimental pattern.
B$^+ \rightarrow \text{J}/\psi \phi$ Signal

- Very clean signal, using PID to tag three kaons
- Precise vertex definition keeps background low

CDF II Preliminary, 2.7 fb$^{-1}$

Candidates/5 MeV/c$^2$

75 ± 10
Is There $f^0$ Contamination?

- Make sideband-subtracted KK mass plot.
- Fit $J=1$ rel. BW
- Low-mass side of peak matches data
- No evidence for $f^0$
- signal is pure $\psi\phi$

![CDF II Preliminary, 2.7 fb$^{-1}$]
Evidence for a New State

Yield \( = 14 \pm 5 \)

\( \Delta m = 1046.3 \pm 2.9 \) (stat) MeV/c^2

Width = 11.7 \(\pm 8.3^{-5.0}\) (stat) MeV

Significance: > 3.8 \( \sigma \)

Studies with \(\sim 2x\) more data now underway
Summary - I

- Quarkonium studies at hadron colliders benefit from excellent mass resolution to handle complicated background angular behavior.
- Prompt production is readily measured. Determining the direct production fraction is much harder but was done at CDF-I. It’s important for comparing to theory.
- These methods can extend the $p_T$ reach of the measurements toward 100 GeV/c at LHC.
Summary - II

- Doing B-physics with \( \mu \mu \) trigger has been very profitable for J/\( \psi \)X and \( \mu \mu X \) at CDF.
- J/\( \psi \) trigger can also be entrée to new charmonium states
- Using well-understood vector meson systems to probe trigger and detector is the first step toward wisdom at LHC.
Backup Slides
Data Check – $\mu^+$ Spectra

- Compare sideband-subtracted $\mu^+$ spectra to polarization-weighted template
- Catches bad detector performance, trigger issues, etc.
- This plot identified period of COT trouble as bad for polarization
**μ pT distributions for Y(1S)**

- MC is weighted combination of T and L templates using $\alpha$ from polarization fit
- Edges and sharp structures are well-reproduced
- Reasonable $\chi^2$ for all bins.
- Data are sideband-subtracted (much more important here than for J/ψ.)