Heavy Flavor Production in Hadron Collisions
(with a few leptons & photons thrown in)

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Columbia University

XXIV Physics in Collision
Boston, MA June 28, 2004
Why Study QCD at All?

QCD is *the* Theory of the Strong Force
So why aren’t we still at lunch?

1. Because of non-perturbative effects we can’t make accurate predictions using QCD for a large range of observables

2. This is Bad…
   a. on an intellectual level
   b. because QCD proc’s are intimately entwined with other SM effects
      * backgrounds, corrections to EW observables,…

3. Fortunately, QCD can be studied using many processes
   – this talk will review how heavy flavor production helps
What’s so Great about Q Production?

Arbitrary Definitions: Heavy Flavor c and b
Obese Flavor t

see talk by Andy Hocker

\[ \sigma(AB \rightarrow H_Q X) = \sum_{ij} \int dx_1 \int dx_2 \int dz \, f_i(x_1, \mu) f_j(x_2, \mu) \hat{\sigma}_{ij}(x_1, x_2, z, \mu, \alpha_s(m)...) \, D_{Q}^{H,Q}(z, \mu) \]
Problem: Too many New Results!

Concentrate on

- Hera, Tevatron, some Fixed Target
- very recent results
- areas where our understanding has changed substantially
- surprises

Focus of Talk

- previous status of
  - what we (thought) understood
  - problems
- how this has changed recently
  - improvements in understanding
  - remaining problems
- where we go from here
  - how new exp’s can help

Tragically Ignore

- nearly all e^+e^- results
  - feeble excuse: no hadrons in initial state
- cursory view of fixed target
  - mainly as it overlaps collider
- detailed survey of advances in theory

Outline

1. Open b & c Production
2. Heavy Quarkonia
3. New Resonances
4. The Future

My Apologies if I’ve Left Out your Favorite Topic
Acknowledgements & Warnings

Many Thanks to

- all those whose work I am presenting
- and of course, the conference organizers!

Some Warnings

1. I blithely combine results and make Data vs Theory comp’s
   - these always assume no error correlations
   - often use spread in theoretical predictions as error
2. This is not the fault of those listed above
### Heavy Quarks in the Wild

<table>
<thead>
<tr>
<th>Exp. or Facility</th>
<th>Beams (GeV)</th>
<th>√s / N [GeV]</th>
<th>Runs</th>
<th>Recorded Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOCUS/E831</td>
<td>γ(175) – BeO</td>
<td>18</td>
<td>96-97</td>
<td></td>
</tr>
<tr>
<td>NuSea/E866</td>
<td>P(800) – Cu</td>
<td>38</td>
<td>96-97</td>
<td>9M J/ψ</td>
</tr>
<tr>
<td>SELEX/E781</td>
<td>Σ⁻,π⁻(600) – C,Cu</td>
<td>33</td>
<td>96-97</td>
<td>15B int’s</td>
</tr>
<tr>
<td>Hera-B</td>
<td>P(920) – C,Al,Ti,W</td>
<td>41</td>
<td>00,02-03</td>
<td>308K J/ψ</td>
</tr>
<tr>
<td>HERA I</td>
<td>e±(27.6) – p(820,920)</td>
<td>300/318</td>
<td>93-00</td>
<td>130 pb⁻¹</td>
</tr>
<tr>
<td>HERA II</td>
<td>e±(27.6) – p(920)</td>
<td>318</td>
<td>03-04</td>
<td>~70 pb⁻¹</td>
</tr>
<tr>
<td>Tevatron I</td>
<td>p(900) - p̅(900)</td>
<td>1800</td>
<td>92-96</td>
<td>125 pb⁻¹</td>
</tr>
<tr>
<td>Tevatron II</td>
<td>p(980) - p̅(980)</td>
<td>1960</td>
<td>02-04</td>
<td>~400 pb⁻¹</td>
</tr>
<tr>
<td>LEP</td>
<td>e⁺(45,~100) – e⁻(45,~100)</td>
<td>90–210</td>
<td>89-00</td>
<td>3.6M bb</td>
</tr>
</tbody>
</table>
Issues in b & c Production

Heavy Q Prod in hadron-hadron

(a) (b) (c) (d)

Leading Order

Next to LO

Heavy Q Prod in ep

PhP: $Q^2 < 1 \text{ GeV}^2$

DIS: $Q^2 > 1 \text{ GeV}^2$

γ structure

$p$ structure

Perturbative Worries

1. NLO terms are important, NNLO ~impossible
   - vary factorization, renormalization scales ⇒ est NNLO effects
2. Q mass definition / uncertainties
   - generally: $m_b = 4.5–5.0 \text{ GeV}$  $m_c = 1.2–1.8 \text{ GeV}$
3. Large log($p_T/m$) resummation
   - must be matched to NLO calc (e.g. FONLL)
4. Soft gluon corrections near threshold
   - require some NNLO + NNNLL
5. Non-Perturbative parts
   - Structure Functions & Fragmentation Functions consistent w/ perturb calc.

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some History – b,c Cross-Sections

CDF, DØ Run I

b Production vs NLO QCD
- shape in good agreement
- norm off by factors of 2–3 (nearly within exp & theory errors)

DØ Forward b

ZEUS D* prod in DIS
ZEUS 1996–97

charm

γγ at LEP

Data / Theory

b cross section at HERA

- H1 μ pT
- H1 μ impact param. (prel.)
- ZEUS e pT
- ZEUS μ pT (prel.)
- ZEUS D μ (prel.)

γγ at LEP

charm

γγ at LEP

QCD

dε e+ e− → c c bar b b

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b Production vs NLO QCD
- agreement much better

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# New b,c-Production Results Reported

## b Production

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Result Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>b-Hadron inclusive cross-section in Run II using $H_b \rightarrow J/\psi X$</td>
<td>Preliminary (2003)</td>
</tr>
<tr>
<td>H1</td>
<td>Beauty photoproduction using semi-muonic decays</td>
<td>Preliminary (2003)</td>
</tr>
<tr>
<td>ZEUS</td>
<td>Beauty photoproduction using muon + dijet events</td>
<td>hep-ex/0312057</td>
</tr>
<tr>
<td>H1</td>
<td>Beauty production in DIS</td>
<td>Preliminary (2004)</td>
</tr>
<tr>
<td>H1</td>
<td>Charm &amp; beauty production in DIS at high $Q^2$</td>
<td>Preliminary (2004)</td>
</tr>
<tr>
<td>ZEUS</td>
<td>Beauty production in DIS</td>
<td>hep-ex/0405069</td>
</tr>
</tbody>
</table>

## c Production

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<tbody>
<tr>
<td>CDF</td>
<td>Prompt charm production cross-section at $\sqrt{s} = 1.96$ TeV</td>
<td>PRL 91, 241804 (2003)</td>
</tr>
<tr>
<td>Hera-B</td>
<td>Open charm production using D-mesons</td>
<td>Preliminary (2004)</td>
</tr>
<tr>
<td>H1</td>
<td>Inclusive $D^*$ + dijet production in DIS</td>
<td>Preliminary (2003)</td>
</tr>
<tr>
<td>ZEUS</td>
<td>$D^*$ production in DIS</td>
<td>PRD 69, 0120004 (2004)</td>
</tr>
<tr>
<td>H1</td>
<td>Photoproduction of $D^*$</td>
<td>Preliminary (2003)</td>
</tr>
<tr>
<td>ZEUS</td>
<td>Charm jet photoproduction</td>
<td>Preliminary (2004)</td>
</tr>
</tbody>
</table>
1. B-hadrons instead of b-quarks

2. FONLL Calculation
   Cacciari, Greco, Nason: 1998
   a. full, massive NLO calc.
   b. NLL resum of \( \log(p_T/m) \)

   Binnewies, Kniehl, Kramer: 1998
   Cacciari, Nason: 2002
   a. FONLL framework used to extract FF from \( e^+e^- \) data
   b. Tevatron data sensitive to \( N=3–5 \) moments of FF
      \( \Rightarrow \) param’s of FF change

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The Road to Enlightenment?

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Physics in Collision: 28 June, 2004
CDF $H_b \rightarrow J/\psi$ Cross Section

Run II $J/\psi \rightarrow \mu^+ \mu^-$ Data  37 pb$^{-1}$  
  - Feb-Sep 2002

$H_b \rightarrow J/\psi$ fract. vs. $P_T(J/\psi)$  
  - pos. of $J/\psi$ vtx w.r.t. prim vtx
  - $1.25 < P_T(J/\psi) < 17$ GeV

$\frac{d\sigma(H_b)}{dP_T(H_b)}$ from $\sigma_{incl}(J/\psi)$  
  - unfold $P_T(H_b)$ from $P_T(J/\psi)$
  - to $P_T(H_b) = 0$

Main Systematics  
  - acc., $\sigma_{incl}(J/\psi)$, vtx res.

Total x-section corr. to quark level

$\sigma(p\bar{p} \rightarrow bX, |y_b| < 1.0) = 29.4 \pm 0.6 \pm 6.2$ μb

Good agreement w/ FONLL pred  

$\sigma = 25.0^{+12.6}_{-8.1}$ μb

large error dominated by $\mu_{R,F}$ dependence

Cacciari,Frixione,Mangano,Nason,Ridolfi: hep-ph/0312132
Other Possible Explanations

From good Old Friends…
Intrinsic $K_T$

…To exotic New Ones
Light gluinos

Shabelski, Shuvaev: hep-ph/0406157

Berger, Harris, Kaplan, Sullivan, Tait, Wagner: 2001
Open Beauty at Hera-B

Use displaced vertices to extract b-comp from \( J/\psi \) (ee,\( \mu\mu \)) sample

<table>
<thead>
<tr>
<th>Run</th>
<th>prompt J/( \psi )'s</th>
<th>b's</th>
<th>Total x-sect [nb/nucleon]</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>ee</td>
<td>5.7K</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>( \mu\mu )</td>
<td>2.9K</td>
<td>1.9</td>
</tr>
<tr>
<td>02/03*</td>
<td>ee</td>
<td>150K</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>( \mu\mu )</td>
<td>170K</td>
<td>38</td>
</tr>
</tbody>
</table>

* prelim: 35% of 02/03 data

Soft g corr’s important near thresh

- new calculation: NNLO soft-g + NNNLL terms
- kinematics & scale dep. reduced

Kidonakis, Vogt: hep-ph/0405212

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Physics in Collision: 28 June
H1 & ZEUS look for b’s in $\mu + \text{jet(s)}$ data

H1 finds b’s with:
- $P_t^{\text{rel}}$ & $\delta$
- DIS: $Q^2 > 1 \text{ GeV}^2$
- PhP: $Q^2 < 1 \text{ GeV}^2$

ZEUS uses
- $P_t^{\text{rel}}$
- DIS
- PhP
### b Photoproduction

**Process**
\[ ep \rightarrow e b \bar{b} X \rightarrow e j j \mu X \]

<table>
<thead>
<tr>
<th></th>
<th>Years</th>
<th>Lumi [pb⁻¹]</th>
<th>Sample [evts]</th>
<th>Main Systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 (prelim)</td>
<td>99-00</td>
<td>48</td>
<td>446 ± 36</td>
<td>(\mu)-ID, trk &amp; vtx res.</td>
</tr>
<tr>
<td>ZEUS</td>
<td>96-00</td>
<td>110</td>
<td>820 ± 62</td>
<td>(\mu)-ID, (P_T^{rel}), dijet sel.</td>
</tr>
</tbody>
</table>

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**Graph**
- **H1 Preliminary**
  - Data
  - NLO QCD \(\otimes\) Had
  - NLO QCD

**Legend**
- Q^2 < 1 GeV^2; 0.2 < y < 0.8
- \(p_T^{rel} > 7(6)\) GeV; \(|y|^{obs} < 2.5\)
- \(p_T > 2.5\) GeV; -0.55 < \(y^{obs}\) < 1.1

**Notes**
- Systematics limited
- Data-NLO agreement quite good
- But problems at low \(P_T\) & low \(x\)?

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*Physics in Collision: 28 June, 2004*
**Deep Inelastic Scattering**

\[ ep \rightarrow e b \bar{b} X \rightarrow e j \mu X \]

<table>
<thead>
<tr>
<th></th>
<th>Years</th>
<th>Lumi [pb(^{-1})]</th>
<th>Sample [evts]</th>
<th>Main Systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 (prelim)</td>
<td>99-00</td>
<td>50</td>
<td>243 ± 29</td>
<td>(\mu)-ID, trk res., phys. model</td>
</tr>
<tr>
<td>ZEUS</td>
<td>98-00</td>
<td>72</td>
<td>284 ± 36</td>
<td>sel. cuts, (\mu)-ID, signal extr.</td>
</tr>
</tbody>
</table>

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Physics in Collision: 28 June, 2004
Measuring $F_2^{cc}$ & $F_2^{bb}$ at H1 (prelim)

- Intrinsic c and b in proton
  - Inclusive Data Sample
  - track $\delta$-tagging
  - high $Q^2 (>150 \text{ GeV}^2$)

- X-Sect ($Q^2>150 \text{ GeV}^2$, $0.1<y<0.7$)
  $\sigma(\bar{c}c) = 431 \pm 59 \pm 69 \text{ pb}$
  $\sigma(b\bar{b}) = 45 \pm 11 \pm 11 \text{ pb}$

- Good agreement w/ $F_2^{cc}$ from D*

- Extend b-prod data to higher $Q^2$
Improved Data-Theory at CDF

1. use B-hadrons 20%
2. FONLL calc 20%
3. consist fragm 20%
4. fragm params 20%

Agreement slightly worse at HERA
   — but no huge prob’s

Experiments largely syst dominated
   — scale w/ stat’s?

Theory err’s > Exp err’s
   — exp constrains theory
Charm Production at CDF

- Run II $J/\psi \rightarrow \mu^+ \mu^-$ Data
  - Feb-Mar 2002 5.8 pb$^{-1}$
  - uses SVT 2-Track-Trigger

- Separate prompt-c from $b \rightarrow c$
  - Imp. par. of c-candidate

- Main Systematics
  - 1-track eff., 2-track eff. corr’s

| $P_T > X$ | cand’s | $\sigma(D, P_T > X, |y|<1)$ [µb] |
|-----------|--------|-------------------------------|
| $D^0$     | 5.5    | 36804                         |
| $D^{*+}$  | 6.0    | 5515                          |
| $D^+$     | 6.0    | 28361                         |
| $D_s$     | 8.0    | 851                           |

| $D^0 \rightarrow K^- \pi^+$ | $D^{*+} \rightarrow D^0 \pi^+$ | $D^+ \rightarrow K^- \pi^+ \pi^+$ | $D_s \rightarrow \phi \pi^+$ |

- Reasonable agreement w/ FONLL theory

syst. limited

3% of curr data
Open Charm at Hera-B

- 2002/03 Min Bias data 210M evts

<table>
<thead>
<tr>
<th>D^+ → K^- π^+ π^+</th>
<th>N</th>
<th>σ(-0.1&lt;xF&lt;0.05) [µb/N]</th>
<th>σ(all x_F) [µb/N]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>98±12</td>
<td>11.5 ± 1.7 ± 2.2</td>
<td>30.2 ± 4.5 ± 5.8</td>
</tr>
<tr>
<td>D^0 → K^- π^+</td>
<td>189±20</td>
<td>20.4 ± 3.2 ± 3.6</td>
<td>56.3 ± 8.5 ± 9.5</td>
</tr>
<tr>
<td>D^*+ → D^0 π^+</td>
<td>43±8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- D^+/D^0 x-section ratio expect ~ 1/3
  - diff. largely due to feed-down from D^*
    - BR(D^*0 → D^0 X) ~ 100%
    - BR(D^*+ → D^0 X) ~ 70%
  - prev. meas’s not entirely compatible (with large uncertainties)
  - new Hera-B meas
    D^+/D^0 = 0.54 ± 0.11 ± 0.14
Charm Baryon Asymmetries at FOCUS

Perturb. QCD $\Rightarrow$ small charm asym in Fixed Target exp’s

$$A \equiv \frac{\sigma_c - \sigma_{\bar{c}}}{\sigma_c + \sigma_{\bar{c}}} = \frac{N_c - N_{\bar{c}}}{N_c + N_{\bar{c}}}$$

“Leading Particle” effects can change this

Leading particle: common valence q’s w/ target/projectile

$\Sigma^-$ (dds) $\rightarrow$ N $\rightarrow$ $\Lambda_c^+$ (udc) $\rightarrow$ $\Sigma_c^0$ (ddc) $\rightarrow$ $\Sigma_c^{++}$ (uuc)

<table>
<thead>
<tr>
<th>focus</th>
<th>Meas Asymmetry</th>
<th>PYTHIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c^+$</td>
<td>0.111±0.018±0.012</td>
<td>0.073</td>
</tr>
<tr>
<td>$\Sigma_c^{++}$</td>
<td>0.136±0.073±0.036</td>
<td>0.126</td>
</tr>
<tr>
<td>$\Sigma_c^0$</td>
<td>0.005±0.089±0.024</td>
<td>0.128</td>
</tr>
<tr>
<td>$\Sigma_c^{++}$</td>
<td>0.181±0.105±0.033</td>
<td>0.133</td>
</tr>
<tr>
<td>$\Sigma_c^0^{*}$</td>
<td>0.298±0.165±0.023</td>
<td>0.132</td>
</tr>
<tr>
<td>$\Lambda_c^{+2625}$</td>
<td>−.075±0.087±0.021</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Heavy-Q Recomb. $\Rightarrow$ better descr. of prev. data also describes $A(D)$

Braaten, Kusunoki, Jia, Mehen: hep-ph/0304280

FOCUS 2003
D* Production in DIS

<table>
<thead>
<tr>
<th>Years</th>
<th>Lumi [pb⁻¹]</th>
<th>Sample [evts]</th>
<th>Main Systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 (prelim) 99-00</td>
<td>47</td>
<td>2604 ± 77</td>
<td>track reco. eff.</td>
</tr>
<tr>
<td>ZEUS    98-00</td>
<td>82</td>
<td>5545 ± 129</td>
<td>D* reco, accept.</td>
</tr>
</tbody>
</table>

\[ \text{ep} \to eD^*X \to e(K^{\pm} \pi^\pm \pi_s^\pm)X \]

Open Charm contrib to \( F_2 \) useful to constrain gluon density in proton!

good agreement w/ NLO QCD

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D* (+jets) Photoproduction

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<th>Main Systematics</th>
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</thead>
<tbody>
<tr>
<td>H1 prelim</td>
<td>99-00</td>
<td>49</td>
<td>1117 ± 76</td>
</tr>
<tr>
<td>ZEUS prelim</td>
<td>98-00</td>
<td>79</td>
<td>10350 ± 190</td>
</tr>
</tbody>
</table>

Jet X-Sect: ZEUS 99-00
- less sens. to hadr. effects
- extend further forward
- mild discrep’s remain

Data – NLO Discrepancies
- mid-Pt & high η
c-Production Scorecard

FONLL calc agrees very well with CDF data
- but theory errs large

Latest HERA meas’s ~agree with NLO
- no improve w/ FONLL

Experiments largely syst dominated
- scale w/ stat’s ?

Theory err’s > Exp err’s
  - especially for newest calc’s (CDF)

n.b. PYTHIA ⇒ poor descrip of FOCUS Asym
- Q-recombination models much better
We should Understand J/ψ & Υ

cc in color singlet
- quarkonium meson retains quantum numbers of hard scatter QQ

cc in color octet
\[ \sigma(ij \rightarrow Q\bar{Q}[n] \rightarrow HX) = \sum \sigma(ij \rightarrow Q\bar{Q}[n]) \langle O^H(n) \rangle \]
- for any S/color/L state n
- (non-perturb) NRQCD matrix elements \( <O^H(n)> \) from fits to data

Other production mechanisms also possible…

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Physics in Collision: 28 June, 2004
The $J/\psi$ Production Crisis

CDF 1997
the CSM doesn’t work!

COM to the Rescue!

and Tevatron Run II B Working Group

PhP – H1,ZEUS 2003

DIS – H1 2002

maybe in ep too?

So we all feel fairly Smug
…but things get confusing!
COM Means Polarization

CDF sees no Polarization in J/ψ or ψ(2S) (largely from data at high P_T)

Fixed Target meas’s also lower than COM

<table>
<thead>
<tr>
<th>Exp</th>
<th>Int</th>
<th>E [GeV]</th>
<th>Pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>COM</td>
<td></td>
<td>0.35 – 0.65</td>
<td></td>
</tr>
<tr>
<td>E672/E706 π⁻ Be</td>
<td>515</td>
<td></td>
<td>−0.01±0.08</td>
</tr>
<tr>
<td>p Be</td>
<td>530</td>
<td></td>
<td>+0.01±0.15</td>
</tr>
<tr>
<td>p Be</td>
<td>800</td>
<td></td>
<td>−0.11±0.15</td>
</tr>
<tr>
<td>E711 p Si</td>
<td>800</td>
<td></td>
<td>−0.09±0.12</td>
</tr>
<tr>
<td>WA92 π⁻ Cu</td>
<td>350</td>
<td></td>
<td>−0.01±0.19</td>
</tr>
</tbody>
</table>

Caution: most exp results include large contrib from decay J/ψ’s, which have NO polarization

Υ situation even less clear

- CDF consist w/ NRQCD (large errors)
- NuSea finds: pol Υ(1S) ~ 0  pol Υ(2S,3S) ~ 1

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New Quarkonium Results Reported

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<td>Inclusive $J/\psi$ cross-section (start point of $H_b$ result)</td>
<td>Preliminary (2003)</td>
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see talk by Rich Galik for more on Quarkonia
**J/ψ Polarization at NuSea**

**NuSea meas: 800 GeV p on Cu**
- 9M J/ψ → µ⁺µ⁻
- 1st proton meas with enough stat’s meas. x_F dep
- no sep of direct & decay J/ψ

**Systematics limited**
- P_T dep of production x-sect
- P_T dep of acc vs. decay ang

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<td>E672/E706</td>
<td>π Be</td>
<td>515</td>
<td>−0.01±0.08</td>
</tr>
<tr>
<td></td>
<td>p Be</td>
<td>530</td>
<td>+0.01±0.15</td>
</tr>
<tr>
<td></td>
<td>p Be</td>
<td>800</td>
<td>−0.11±0.15</td>
</tr>
<tr>
<td>E711</td>
<td>p Si</td>
<td>800</td>
<td>−0.09±0.12</td>
</tr>
<tr>
<td>WA92</td>
<td>π Cu</td>
<td>350</td>
<td>−0.01±0.19</td>
</tr>
<tr>
<td>NuSea/E866</td>
<td>p Cu</td>
<td>800</td>
<td>0.069±0.004±0.080</td>
</tr>
<tr>
<td>My Ave.</td>
<td></td>
<td></td>
<td>0.00±0.04</td>
</tr>
</tbody>
</table>

**NuSea consistent w/ prev meas’s of J/ψ pol at F.T.**
- significantly more accurate

All point to small J/ψ pol
- n.b. most include significant contrib from decay J/ψ’s

Disagreement w/ COM should be regarded w/ Caution
DIS Production of J/ψ

<table>
<thead>
<tr>
<th></th>
<th>Years</th>
<th>Lumi [pb⁻¹]</th>
<th>N(J/ψ)</th>
<th>Main Systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>97-00</td>
<td>77 (ee,µµ)</td>
<td>458 ± 30</td>
<td>Non-res bgrd, acc. &amp; eff.</td>
</tr>
<tr>
<td>ZEUS (prelim)</td>
<td>98-00</td>
<td>73 (µµ)</td>
<td>203 ± 19</td>
<td>MC model of acc, diffr evts</td>
</tr>
</tbody>
</table>

Shape of ZEUS and H1 Data favor CSM but model uncertainties are large.

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Physics in Collision: 28 June, 2004
**J/ψ Helicity at HERA**

<table>
<thead>
<tr>
<th></th>
<th>Years</th>
<th>Lumi [pb⁻¹]</th>
<th>N(Jψ)</th>
<th>Main Systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>96-00</td>
<td>87 (µµ)</td>
<td></td>
<td>Non-res bgrd, acc. &amp; eff.</td>
</tr>
<tr>
<td>ZEUS (prelim)</td>
<td>96-00</td>
<td>114 (µµ)</td>
<td>203 ± 19</td>
<td>MC model of acc, diffr evts</td>
</tr>
</tbody>
</table>

\[
polar \ angle: \quad \frac{1}{\sigma} \frac{d\sigma}{d\cos\theta^*} \ dy \propto 1 + \lambda(y)\cos^2\theta^*
\]

\[
azimuthal: \quad \frac{1}{\sigma} \frac{d\sigma}{d\phi^*} \ dy \propto 1 + \frac{\lambda(y)}{3} + \frac{\nu(y)}{3} \cos 2\phi^*
\]

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**not statistically significant – yet !**
Subjective Comparison of Results w/ Models

Production
- COM required by Tevatron
- but not by HERA

Polarization
- no signif J/ψ pol obs
- few Υ meas’s
- prompt vs non-prompt an issue in some meas’s

Experiments largely syst dominated
- scale w/ stat’s?

Theory uncert’s very larg
- quantitative statements difficult
# New Particles with Heavy Flavor

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Observation</th>
<th>Report</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>X(3872)</td>
<td>hep-ex/0312021</td>
</tr>
<tr>
<td>CDF</td>
<td>Charmed pentaquark search</td>
<td>Preliminary (2004)</td>
</tr>
<tr>
<td>DØ</td>
<td>X(3872)</td>
<td>hep-ex/0405004</td>
</tr>
<tr>
<td>H1</td>
<td>Charmed pentaquark search</td>
<td>hep-ex/0403017</td>
</tr>
<tr>
<td>ZEUS</td>
<td>Charmed pentaquark search</td>
<td>Preliminary (2004)</td>
</tr>
<tr>
<td>SELEX</td>
<td>Double charm baryon</td>
<td>hep-ex/0406033</td>
</tr>
<tr>
<td>SELEX</td>
<td>First observation of a narrow charm-strange meson</td>
<td>hep-ex/0406045</td>
</tr>
</tbody>
</table>

see talks by Rich Galik & Takashi Nakano for more on New Particles
The X(3872) in p-pbar

$X(3872) \rightarrow J/\psi \pi^+ \pi^-$ 1st obs by Belle: $M = 3872.0 \pm 0.5 \pm 0.6$ MeV
(Previous hints at E705, E706, E672: 1994-95)

Open question – what is it?
cc-bar? D$^0$-D* “molecule”? ccghybrid? something else?

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>220</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$</td>
<td>y</td>
<td>&lt; 1$</td>
<td>3871.3 ± 0.7 ± 0.3</td>
<td>4.9</td>
</tr>
<tr>
<td>DØ</td>
<td>230</td>
<td>$</td>
<td>y</td>
<td>&lt; 2$</td>
<td>3871.8 ± 3.1 ± 3.0</td>
<td>17</td>
</tr>
</tbody>
</table>

Prod. characteristics similar to $\psi(2S)$ but low stat’s

$M(\pi\pi) > 500$ MeV

$M(\pi\pi) > 520$ MeV

$P_T(\psi) > 15$ GeV

$|y| < 1$
$|y| < 2$
$\text{hel. } \pi\pi < 0.4$
$\text{dec len} < 100 \mu$m
Isolated X
$\text{hel. } \mu\mu < 0.4$
Charmed Pentaquarks

Strange Pentaquark: $\Theta^+ = (uudd\bar{s}) \rightarrow K^+ n, K_S^0 p$
- observations by
  - LEPS, DIANA, CLAS-1/2, SAPHIR, Asratyan, et al, HERMES, SVD, COSY-TOF, ZEUS, Spring-8
- not seen by
  - BaBar, BES, Hera-B, PHENIX
- $<M> = 1530.5 \pm 2.0$ MeV
  - but not all meas’s consistent

Charm Pentaquark: $\Theta_c^0 = (uudd\bar{c}) \rightarrow D^* - p$
- critical issue: $p/K/\pi$ separation: $D^{**} \rightarrow D^* \pi$

<table>
<thead>
<tr>
<th></th>
<th>Years</th>
<th>Lumi [pb^{-1}]</th>
<th>N(D^*)</th>
<th>N(\Theta_c)</th>
<th>Signif</th>
<th>Mass [MeV]</th>
<th>M res</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>96-00</td>
<td>75</td>
<td>8.5K</td>
<td>51 ± 11</td>
<td>5.4 (\sigma)</td>
<td>3099 ± 3 ± 5</td>
<td>12</td>
</tr>
<tr>
<td>ZEUS</td>
<td>95-00</td>
<td>127</td>
<td>43K</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>CDF</td>
<td>02-04</td>
<td>240</td>
<td>500K</td>
<td>&lt; 29 (90%CL)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>FOCUS</td>
<td>96-97</td>
<td>36K</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

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**H1 DIS & Photo-Prod**

**DIS**
- $D^+ p + D^{*+} b$
- Signal + bg. fit
- Bg. only fit

**PhP**
- $D^+ p + D^{*+} p$
- Wrong charge $D$

**CDF Run II Preliminary**
- Use ToF
- $M(D^{*+} p)$
- $N/2$ MeV/c$^2$
- Use $dE/dx$
- $M(D^{*+} p)$
- $N/2$ MeV/c$^2$

**FOCUS Preliminary**
- $D^\star p$
- Location of H1 penta quark

**ZEUS Inclusive**
- $\Theta_c^0$ Search Results
- $\varphi$ search results
- H1 DIS & Photo-Prod
- $\gamma p$ H1
- $D^+ p + D^{*+} p$
- Wrong charge $D$

**H1 Signal not observed by other exp’s with similar or greater sensitivity**

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**New Particles at SELEX**

**confirm obs of \( \Xi^{+}_{cc}(3520) \)**

**1st obs of \( D_{sJ}^{+}(2632) \)**

**see talk by Peter Cooper**

<table>
<thead>
<tr>
<th>State</th>
<th>Events</th>
<th>Mass [MeV]</th>
<th>Signif</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Xi^{+}_{cc}(3520) \rightarrow \Lambda^{+} c K^{-} \pi^{+} )</td>
<td>15.9</td>
<td>3519 ± 1</td>
<td>6.3 ( \sigma )</td>
</tr>
<tr>
<td>( \Xi^{+}_{cc}(3520) \rightarrow p D^{+} K^{-} )</td>
<td>5.4</td>
<td>3518 ± 3</td>
<td>~4 ( \sigma )</td>
</tr>
<tr>
<td>( D_{s}^{+}(2573) \rightarrow D^{0} K^{+} )</td>
<td>14 ± 9</td>
<td>2569.9 ± 4.3</td>
<td>5.4 ( \sigma )</td>
</tr>
<tr>
<td>( D_{s}^{+}(2632) \rightarrow D_{s}^{+} \eta )</td>
<td>45 ± 9.3</td>
<td>2635.9 ± 2.9</td>
<td>7.2 ( \sigma )</td>
</tr>
<tr>
<td>( D_{s}^{+}(2632) \rightarrow D^{0} K^{+} )</td>
<td>14 ± 4.5</td>
<td>2631.5 ± 1.9</td>
<td>5.3 ( \sigma )</td>
</tr>
</tbody>
</table>

\( \Xi^{+}_{cc}(3520) \)

- \( \Gamma(pDK)/\Gamma(\Lambda K\pi) = 0.078\pm0.045 \)
  - phase space \( \Rightarrow \sim0.22 \)
- lifetimes appear lower than expect

\( D_{sJ}(2632) \)

- \( \Gamma(D_{s}\eta)/\Gamma(D^{0}K) \sim 6 \)
  - phase space \( \Rightarrow \sim0.5 \)
- very narrow: \( \Gamma < 17 \text{ MeV} \)

**not obs in FOCUS or E791**
**What’s Next ?**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam</th>
<th>E [TeV]</th>
<th>Runs</th>
<th>Lumi [fb⁻¹]</th>
<th>$\sigma_{tot}(bb)$</th>
<th>Sample Stat’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1,ZEUS I</td>
<td>e± p</td>
<td>0.30/0.32</td>
<td>93-00</td>
<td>0.13</td>
<td></td>
<td>D$^*$: 5x10⁴</td>
</tr>
<tr>
<td>H1,ZEUS II</td>
<td>e± p</td>
<td>0.318</td>
<td>03-07</td>
<td>~0.7</td>
<td></td>
<td>D$^*$: 3.5x10⁵</td>
</tr>
<tr>
<td>CDF,DØ I</td>
<td>p $\bar{p}$</td>
<td>1.8</td>
<td>92-96</td>
<td>0.125</td>
<td>100 $\mu$b</td>
<td>J/$\psi$: 1.8x10⁵</td>
</tr>
<tr>
<td>CDF,DØ II</td>
<td>p $\bar{p}$</td>
<td>1.96</td>
<td>02-08</td>
<td>4–9</td>
<td>+10-15%</td>
<td>J/$\psi$: 3.1–6.9x10⁷</td>
</tr>
<tr>
<td>BTeV</td>
<td>p $\bar{p}$</td>
<td>1.96</td>
<td>09–</td>
<td>2 / y</td>
<td>~100 $\mu$b</td>
<td>Reco B: ~10⁷/y</td>
</tr>
<tr>
<td>Atlas,CMS</td>
<td>pp</td>
<td>14</td>
<td>07-09</td>
<td>10 / y</td>
<td>500 $\mu$b</td>
<td>B→J/$\psi$: ~2x10⁶/y</td>
</tr>
<tr>
<td>LHCb</td>
<td>pp</td>
<td>14</td>
<td>07–</td>
<td>2 / y</td>
<td>500 $\mu$b</td>
<td>B→J/$\psi$(µµ): ~2x10⁶/y</td>
</tr>
</tbody>
</table>

**Fixed Target: continuing analysis of existing data**

- possibility of new runs beyond 2009 ?

**New collider exp’s aim mainly at EW aspects of B-Physics**

- Production studies will use exclusive final states
- Triggers are the critical issue ⇒ Muon PT
  - but keep an eye on the BTeV displaced vertex trigger !

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Physics in Collision: 28 June, 2004
A Taste of What’s to Come

**Atlas: pp → J/ψ X**

Panikashvili, Smizanska: 2003

**CMS: B → J/ψφ**

Silvestris: 2004

**LHCb: evt yields**

Ruiz: 2004

**DØ J/ψ - 200 pb⁻¹**

DØ Run II Preliminary

Cheung: 2004 (n.b. low stat’s)

**BTeV: flat B trigg accept**
Where do We Stand?

1. b-Production
   - big steps forward in understanding recently
     - especially at the Tevatron, Fixed Target
     - mild data-theory disagreement at HERA
   - exp meas’s syst limited, theory errors quite large

2. c-Production
   - data-theory agreement remains fairly good
   - but some discrepancies developing in new measurements
   - again exp and theory uncertainties are large

3. Heavy Quarkonia Production
   - confusion regarding details of prod mechanism remains
     - inconsistent(?) results for both production and polarization

4. New Particles
   - studies of their existence/properties starting
Where are We Going (soon) ?

New Data is rolling in CDF, DØ, H1, ZEUS
New Analyses are Proceeding Fixed Target

1. b,c Production
   - use new theoretical and analysis tools more widely
   - extend kinematic reach of studies
   - study correlations in production
   - use production measurements to constrain PDFs

2. Quarkonia
   - better polarization measurements (prompt vs. non-prompt)
   - more $\Upsilon$ studies

3. New Particles
   - confirm/refute observations in question
   - understand properties of those particles that survive
and Further Down the Road

• **Upcoming collider exp’s** Atlas, CMS, LHCb, BTeV
  - superb detector capabilities
  - huge heavy flavor samples

• **But…**
  - focus mainly on EW measurements in Q-sector
  - rely critically on aggressive triggers

• **Nevertheless…**
  - there is an active heavy flavor effort (Hera-LHC Workshops)

---

Look for Exciting Heavy Flavor Reviews for many *Physics in Collisions* to come