Quarkonium Polarization: Recent Results from NuSea/E-866

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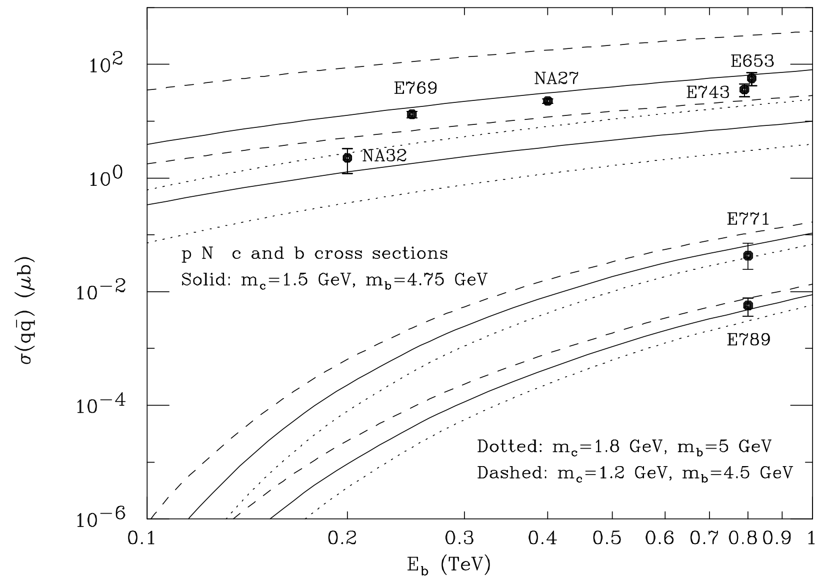
Outline

- Review of charmonium production in QCD
- An effective field theory for heavy quarkonia: non-relativistic QCD
- Charmonium production and polarization at high energy and large p_T
- Fermilab E-866: a high-statistics study of J/ψ polarization at fixed target
- Where we stand
- Implications for other studies

Charm Production in QCD

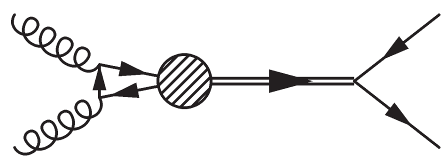
Inclusive charm production is fairly well understood in perturbative QCD
Charm quark mass is thought large enough for pQCD to be reliable



Total cross sections from fixed target and theory curves from `hep-ph/9702287`
But total cross section requires measuring many final states and good vertexing
➪ *It is experimentally advantageous to measure specific final states*

Charmonium Production

Charmonium states easy to detect through decay to lepton pairs
However, cross section involves a *short-distance* and a *long-distance* part



Long-distance part not calculable perturbatively
May be taken from experiment — but this can be model-dependent
One of the early guesses: the $c\bar{c}$ pair must be in a color-singlet state in order to bind into a physical J/ψ or ψ' state — the *Color-Singlet Model*

The Color-Singlet Model

The most economical idea: only $c\bar{c}$ pairs produced in the right color and spin state can bind into charmonium
For J/ψ this is $c\bar{c}_1(^3S_1)$ (subscript for singlet/octet)

Production cross section: $\sigma(J/\psi) = \widehat{\sigma}[c\bar{c}_1(^3S_1)]\frac{|R_{J/\psi}(0)|^2}{4\pi}$

Short-distance $\widehat{\sigma}[c\bar{c}_1(^3S_1)]$: production rate of color-singlet $c\bar{c}$ in $^3S_1$ at threshold — calculable in pQCD due to small value of $\alpha_S(m_c)$

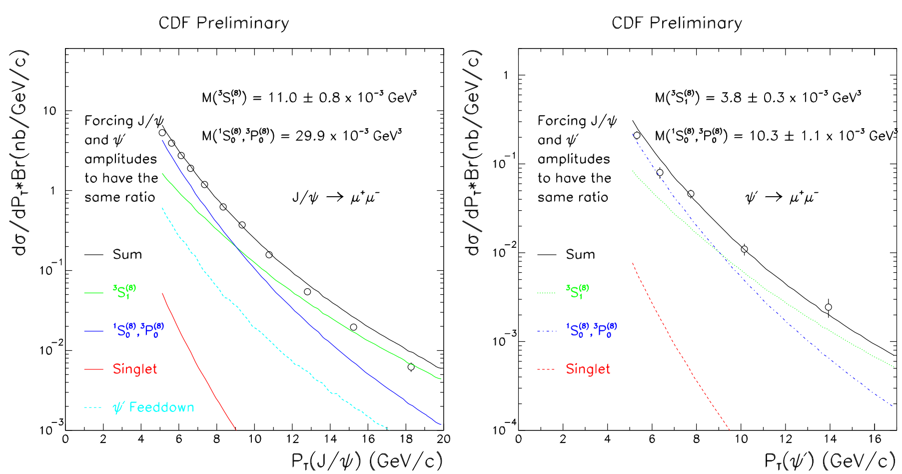
Long-distance $R_{J/\psi}(0)$: radial wavefunction at origin — taken directly from leptonic decay width

Well-defined prediction — and *it accounts for only 2–3% of the direct ψ production*, whether $1S$ or $2S$
☛ The rest must come from something else

Direct ψ Production at $\sqrt{s} = 1.6$ TeV

ψ production can be prompt or from b decays
Prompt production is direct or from decays of higher-mass quarkonium states
For ψ', all prompt production is direct — no feed-down

Direct J/ψ production measured by separating the contribution from radiative χ_c decays — also from ψ' decays



☛ Inescapable conclusion: both singlet and octet $c\bar{c}$ production must contribute — and various spin states as well

✝ <u>Color Singlet Model (1980–1995) R.I.P.</u>

Factorization of Quarkonium Production Cross Section

Factorization formula: production of quarkonium state H given by

$$d\sigma^H = \sum_n d\widehat{\sigma}_{Q\overline{Q}[n]} < \mathcal{O}_n^H >$$

Infinite number of terms for all possible $Q\overline{Q}_n$ states (index n refers to both color and angular momentum)

Not a model: factorization into short- and long-distance parts was shown to be a consequence of QCD (Bodwin, Braaten, Lepage; Qui, Vary, Zhang)
Universality of long-distance matrix elements still an open question
➪ True for the inclusive cross section at high p_T

Short-distance part (process-dependent) calculable due to smallness of $\alpha_S(M)$
➪ must be convoluted with the "known" parton distribution functions

✎ <u>*Note:*</u> Same approach can be applied to decays and mass spectra

Non-Relativistic QCD as an Effective Field Theory

Basic idea: for heavy $Q\overline{Q}$ systems the relative velocity is $v \ll 1$

➪ Use Pauli spinors ψ (χ) for Q ($\overline{Q}$) instead of a single Dirac spinor Ψ_Q

Separate QCD Lagrangean in *light* and *heavy* parts: $\mathcal{L} = \mathcal{L}_{\text{light}} + \mathcal{L}_{\text{heavy}} + \delta\mathcal{L}$ where

$$\mathcal{L}_{\text{light}} = -\frac{1}{2}\text{tr}G_{\mu\nu}G^{\mu\nu} + \sum_q \overline{\Psi}_q i \not{D} \Psi_q \quad \text{(relativistic)}$$

$$\mathcal{L}_{\text{heavy}} = \psi^\dagger(iD_0 + \frac{\mathbf{D}^2}{2M})\psi + \chi^\dagger(iD_0 - \frac{\mathbf{D}^2}{2M})\chi \quad \text{(non-relativistic)}$$

and $\delta\mathcal{L}$ are the remaining terms of the fully-relativistic Lagrangean (corrections)

It includes terms like $\mathbf{D}^2$, $\mathbf{D}\cdot\mathbf{E}$, $\mathbf{D}\times\mathbf{E}\cdot\sigma$, *etc.*

Full QCD Lagrangean can be approximated by including as many terms as desired

❄ But which are the most important ones?

Non-Relativistic QCD Factorization

The NRQCD factorization approach is an attempt to classify the relative importance of the long-distance matrix elements in terms of a *second small parameter*: the velocity v of the quarks in the quarkonium rest frame

Estimate: Take Mv^2 from mass splittings ➠ $v^2 \simeq 1/3$ **Not too small!**

➪ Expand as a series in v

Example: Scaling of leading matrix elements for J/ψ production

$< \mathcal{O}_1^{J/\psi}(^3S_1) >$	$< \mathcal{O}_8^{J/\psi}(^1S_0) >$	$< \mathcal{O}_8^{J/\psi}(^3S_1) >$	$< \mathcal{O}_1^{J/\psi}(^3P_J) >$
v^3	v^6	v^7	v^7

First one taken from leptonic width — others must be obtained from fits to data
Good fits obtained to CDF $d\sigma/dp_T$ cross sections *(Fig.)*

☛ Should be able to use extracted ME's to predict other processes

Polarization

Polarization defined as

$$\lambda = \frac{\sigma - 3\sigma_L}{\sigma + \sigma_L}$$

where $\sigma = \sigma_T + \sigma_L$

Transverse: $\sigma = \sigma_T$, $\lambda = 1$ (helicity ± 1 — indistinguishable due to parity)

Longitudinal: $\sigma = \sigma_L$, $\lambda = -1$ (helicity 0)

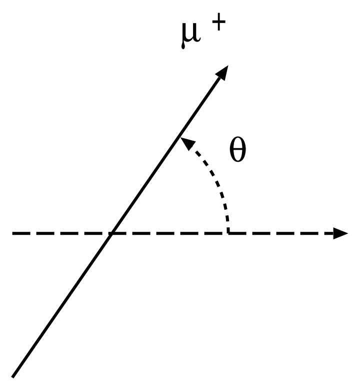
Unpolarized: $\sigma_T = 2\sigma_L$, $\lambda = 0$ (equal probabilities for $+1$, 0, and -1)

$Q\overline{Q}$ pairs turn into quarkonium through multiple soft-gluon emission.
Heavy-Quark Symmetry predicts that spin-flip transitions are suppressed
➠ Polarization of the $Q\overline{Q}$ state survives as the polarization of the quarkonium

- ☛ Prediction of the polarization comes for free

Measurement of Polarization

Polarization λ determined from angular distribution of the dimuon vector in the quarkonium rest frame



$\lambda>0$ Longitudinal

$\lambda=0$ Unpolarized

$\lambda<0$ Transverse

ϑ is measured with respect to
either the beam direction (*Gottfried-Jackson* frame)
or the bisector of the angle of the two initial-state hadrons (*Collins-Soper* frame)
— it only makes a difference at high p_T

✎ *Note:* Often α is used instead of λ for polarization

Polarization Predictions at High Energy

At $p_T \gtrsim 2M$ production is dominated by fragmentation of (transverse) gluons

At lower p_T, it is a mixture of parton fusion and gluon fragmentation

Scaling laws used to pick out the leading matrix elements:
$< \mathcal{O}_\alpha^H({}^{2S+1}L_J) >$ scales as $v^{3+2L+2E+4M}$
$E(M)$: min. number of color electric (magnetic) dipole transitions $Q\overline{Q} \to H$

Spin-symmetry relationships used to reduce the number of ME's to fit, *e.g.*
$< \mathcal{O}_1^{\chi_{cJ}}({}^3P_J) >= (2J+1) < \mathcal{O}_1^{\chi_{c0}}({}^3P_0) >$
$< \mathcal{O}_8^{\psi}({}^3P_J) >= (2J+1) < \mathcal{O}_8^{\psi}({}^3P_0) >$
$< \mathcal{O}_8^{\chi_{cJ}}({}^3S_1) >= (2J+1) < \mathcal{O}_8^{\chi_{c0}}({}^3S_1) >$ *etc.*

Also, $< \mathcal{O}_1^{\psi}({}^3S_1) >= \frac{9}{2\pi}|R_\psi(0)|^2$ (same as in the CSM)

Predictions for ψ polarization obtained by using ME's from fits to $d\sigma/dp_T$.

Determination of NRQCD Matrix Elements from $d\sigma/dp_T$

Determined using two different sets of Parton Distribution Functions: *MRST98LO* and *CTEQ5L*

For $\psi(1S)$:

Matrix Element	*MRST98LO*	*CTEQ5L*	*Unit*
$<\mathcal{O}_1(^3S_1)>$	1.34 ± 0.10	1.38 ± 0.10	10^0 GeV^3
$<\mathcal{O}_8(^3S_1)>$	4.42 ± 0.73	3.95 ± 0.66	10^{-3} GeV^3
M_r	8.75 ± 0.87	6.59 ± 0.69	10^{-2} GeV^3
r	3.44	3.55	

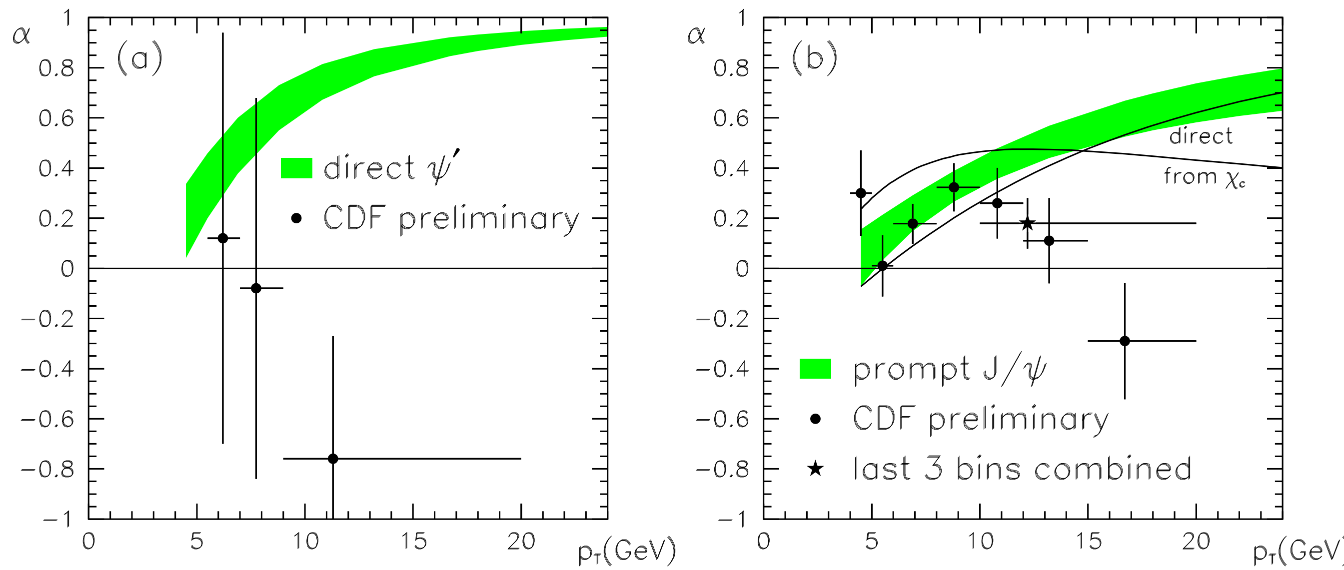
where $M_r \equiv <\mathcal{O}_8(^1S_0)> + \frac{r}{m_c^2} <\mathcal{O}_8(^3P_0)>$

Similarly for $\psi(2S)$ and χ_c — also needed to calculate contributions to $\psi(1S)$

Quarkonium Polarization at the Tevatron Collider

Polarization of prompt $\psi(1S)$ and $\psi(2S)$ measured by CDF

Calculation for $\psi(1S)$ includes both prompt and decay components (mainly χ_c)



Behavior at large p_T very hard to understand — no easy way out
— *unless one is willing to blame statistics and/or systematics*

❄ Low-energy experiments can provide additional tests with high statistics

Charmonium Production at Fixed-Target Energies

Proton and pions beams on nuclear targets at $\sqrt{s}$ up to ~ 40 GeV

From inclusive cross section, we can conclude that pQCD describes the short-distance part even at these energies

Main advantage: large event samples

One can study x_F as well as p_T dependence of λ

At low energies parton-fusion processes dominate

Small x_F: Mostly $g - g$ fusion

Large x_F: Mostly $q - \overline{q}$ annihilation

Gluon fragmentation not important even at the highest p_T ($\simeq 4$ GeV)

Expectations at Fixed-Target Energies

Polarization of the J/ψ calculated by Beneke and Rothstein (1996) using earlier fits to cross sections from the collider

From spin symmetry ➠ spin of charmonium aligned with spin of $c\bar{c}$ pair
➪ Ratio of longitudinal-to-transverse final state for different intermediate states

State	${}^3S_1^{(1)}$	${}^1S_0^{(8)}$	${}^3P_J^{(8)}$	${}^3S_1^{(8)}$
L/T	$1:3.35$	$1:2$	$1:6$	$0:1$

Calculation includes direct production as well as feed-down from ψ' and χ_{cJ}

Expect sizable transverse polarization: $0.31 < \lambda < 0.63$

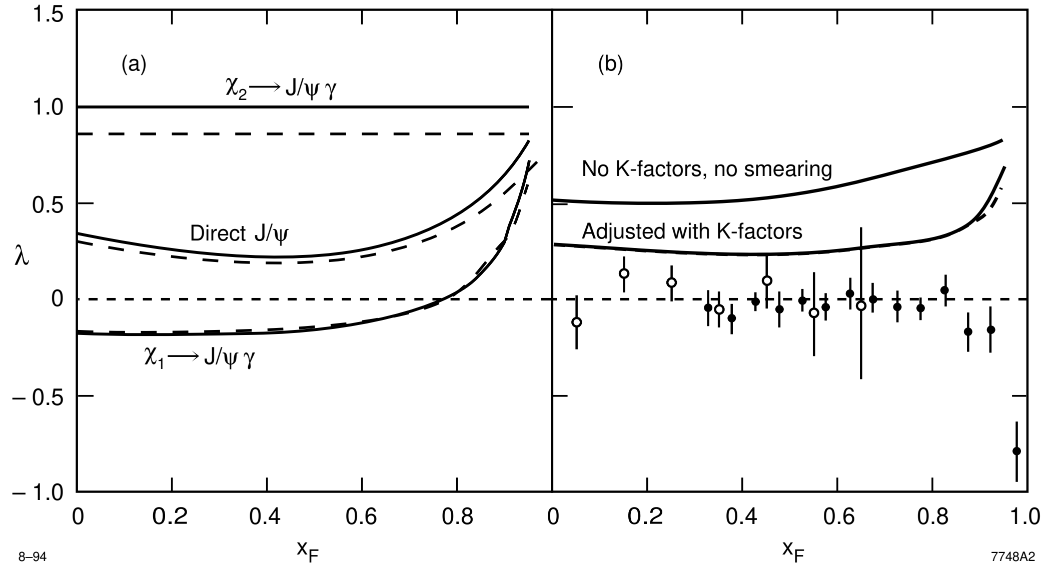
A significant part of that is due to χ_{c2} feed-down (produced with helicity ± 2)

Range reflects uncertainty in relative strength of ${}^1S_0^{(8)}$ and ${}^3P_0^{(8)}$ matrix elements (different linear combination from that in the cross section)

More Predictions: Color-Singlet Model

Very similar to the predictions of NRQCD

Polarization measurements do not discriminate between the two

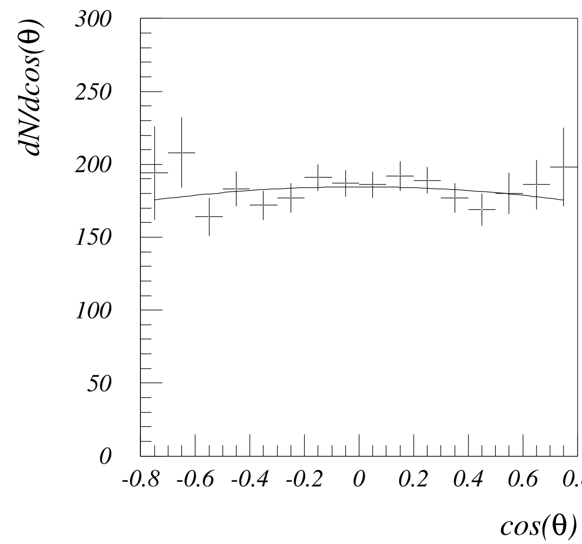


And they are also in disagreement with experiments — no polarization seen

Data are from two πW experiments at 125-250 GeV (E-537 and CIP)

Calculation by Vänntinen, Hoyer, Brodsky, and Tang [*Phys. Rev.* **D51**, 3332 (1995)]

More Recent Results: pA Interactions at the Tevatron



E-771 pSi interactions at 800 GeV

Kinematic range: $p_T < 3.5$ GeV

$-0.05 < x_F < 0.25$

Polarization: $\lambda = -0.09 \pm 0.12$

T. Alexopoulos *et al.*, *Phys. Rev.* ***D55***, 3927 (1997)

E-672/706 pBe interactions at 530 and 800 GeV

Kinematic range: $p_T < 3.5$ GeV

$0 < x_F < 0.55$

Polarization: $\lambda = 0.01 \pm 0.12 \pm 0.09$ (535 GeV)

and $-0.11 \pm 0.12 \pm 0.09$ (800 GeV)

A. Gribushin *et al.*, *Phys. Rev.* ***D62***, 012001 (2000)

Not enough statistics to study the x_F and p_T dependence of λ

The Fermilab E-866/NuSea Experiment

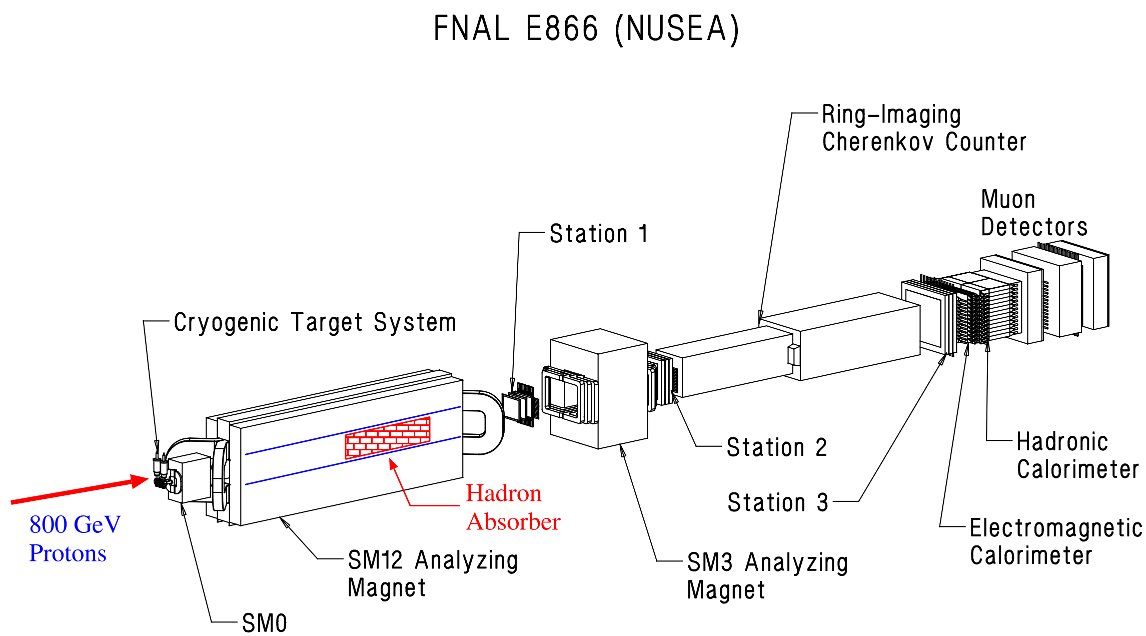
A fixed-target dimuon experiment

Used 800-GeV proton beam on H_2, D_2, Be, Fe, and W targets

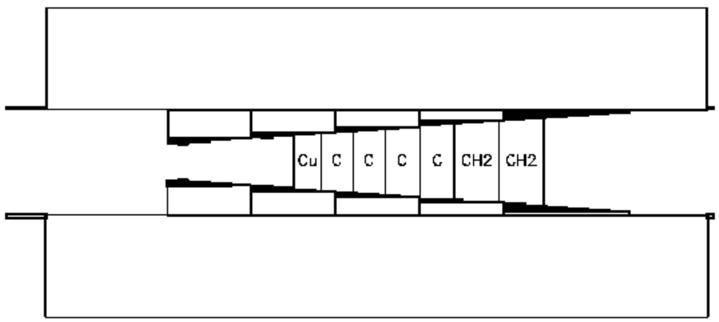
Equivalent to ∼20-GeV beams

Studied both Drell-Yan and quarkonium production

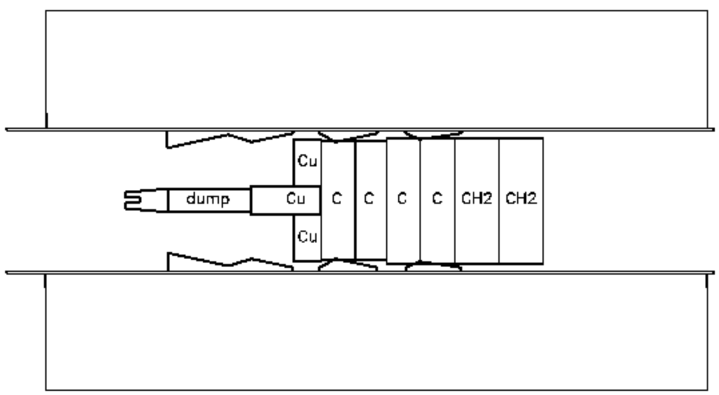
Spectrometer



SM1/2 Analysis Magnet and Beam Dump



Plan View (X)



Elevation View (Y)

Entire beam interacts in the target maximizing statistics

Trade-offs:

- Multiple scattering and energy loss before muons are detected
- Vertex position and production angle not known event-by-event

Angular-Distribution Data

Dedicated run in April 1997 using the beam dump instead of target
Collected ~ 400 M triggers — mostly J/ψ and Drell-Yan background
Downside: loss of mass resolution from not having point-like target due to multiple Coulomb scattering and energy loss before detection

Peaks and background fitted in individual x_F, p_T, and ϑ bins

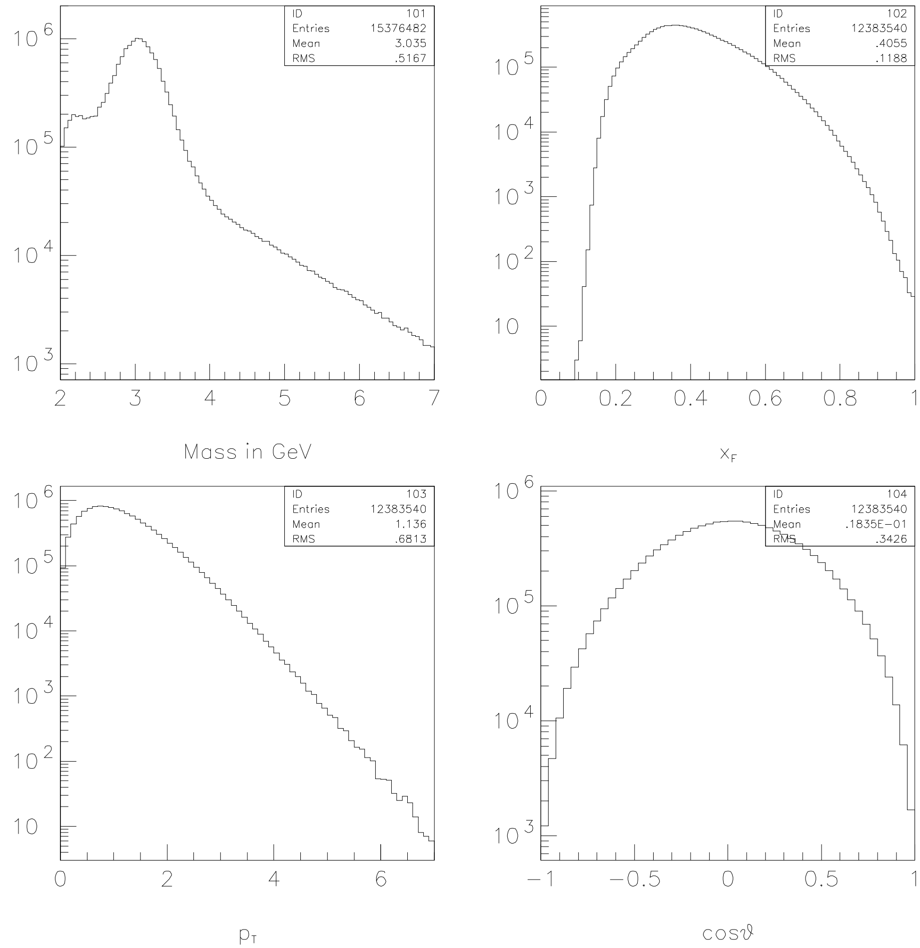
Cannot separate $\psi(2S)$ — contributes only about 1% to the peaks

Monte-Carlo corrected angular distributions in (x_F, p_T) bins fitted to $1+\lambda^2 \cos\vartheta$

Data taken with two different magnet settings and two different polarities

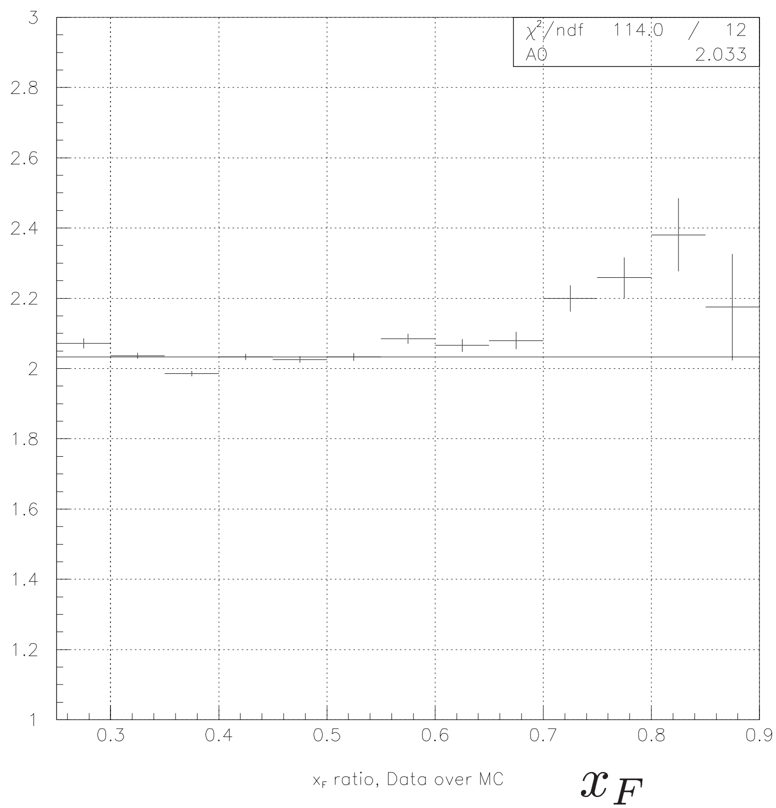
- Total: about 10^7 reconstructed J/ψ events used in fits

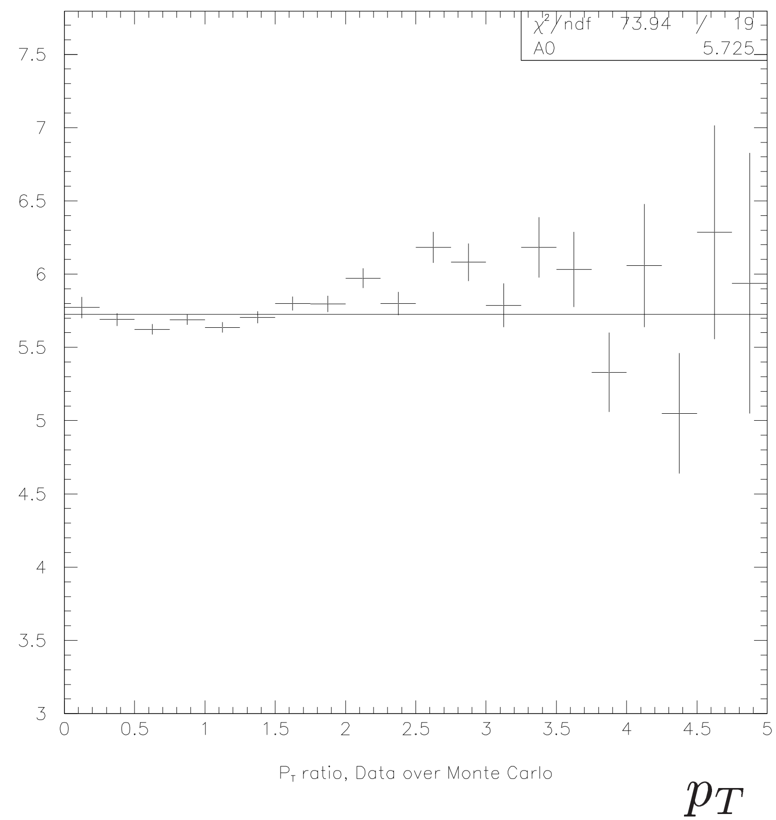
Kinematic coverage



Good coverage in $\cos\vartheta$ and more extended p_T range than earlier fixed-target experiments; x_F range somewhat higher than other p experiments

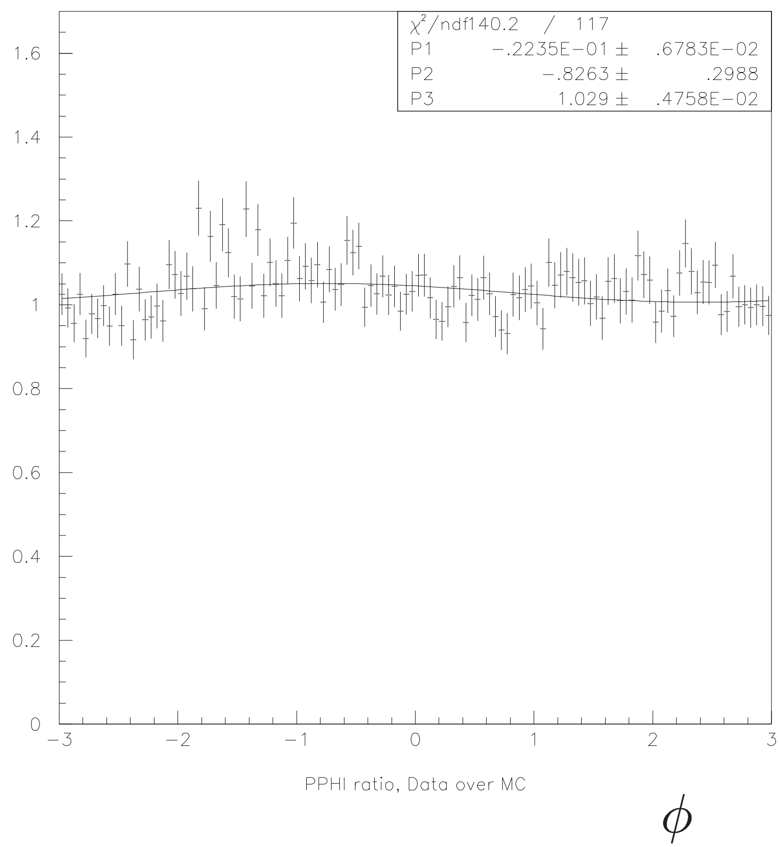
Data-Monte Carlo Comparison





p_T plot is after re-weighing Monte Carlo events to bring in agreement with experimental p_T distributions in x_F bins

Uncertainty in the Beam Angle



Error in beam angle can distort *decay* angular distributions — must be calculated from data and put into Monte Carlo

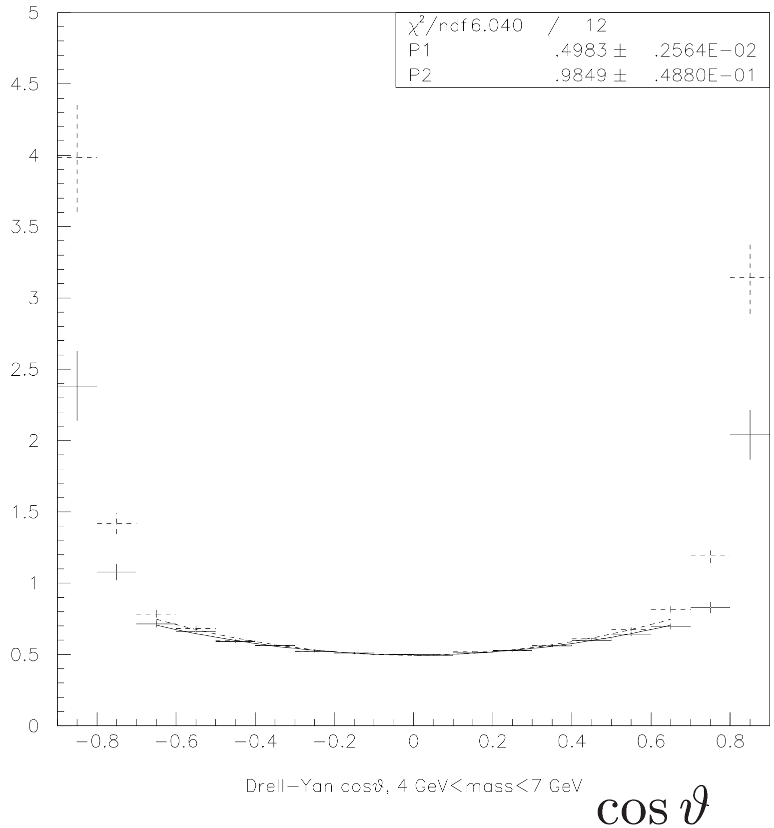
Check: *production* angle ϕ is very sensitive to incoming beam angle — corrected distribution should be flat

Beam angles vary from dataset to dataset and even from run to run

Residual uncertainty in average beam angle is small: $\sim 2\%$

Cross-Check: Angular Distribution of Drell-Yan Events

Expected to be 100% transverse due to helicity conservation



Consistent with $\lambda = 1$ with small statistical errors

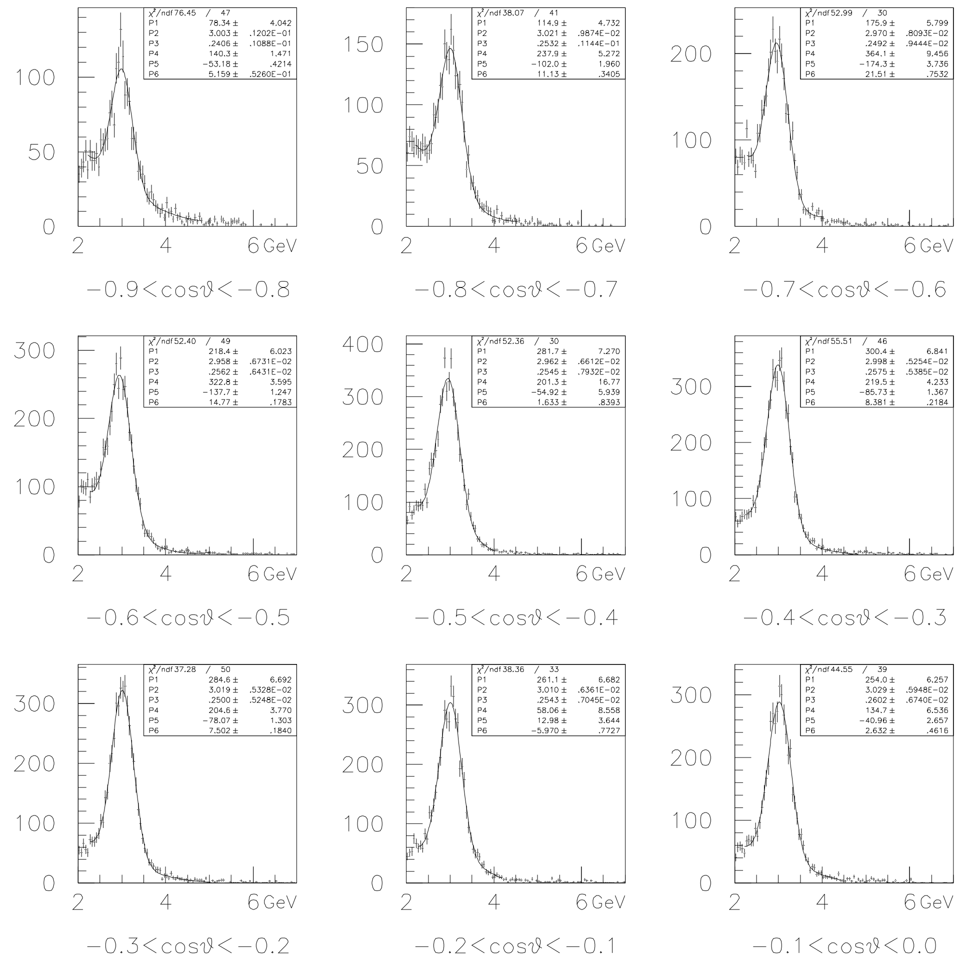
Not enough statistics to study x_F and p_T dependence

Deviations at large $|\cos\vartheta|$ due to incomplete subtraction of random coincidences

Caveat: Different kinematics from J/ψ data: $4 < M_{\mu\mu} < 7$ GeV

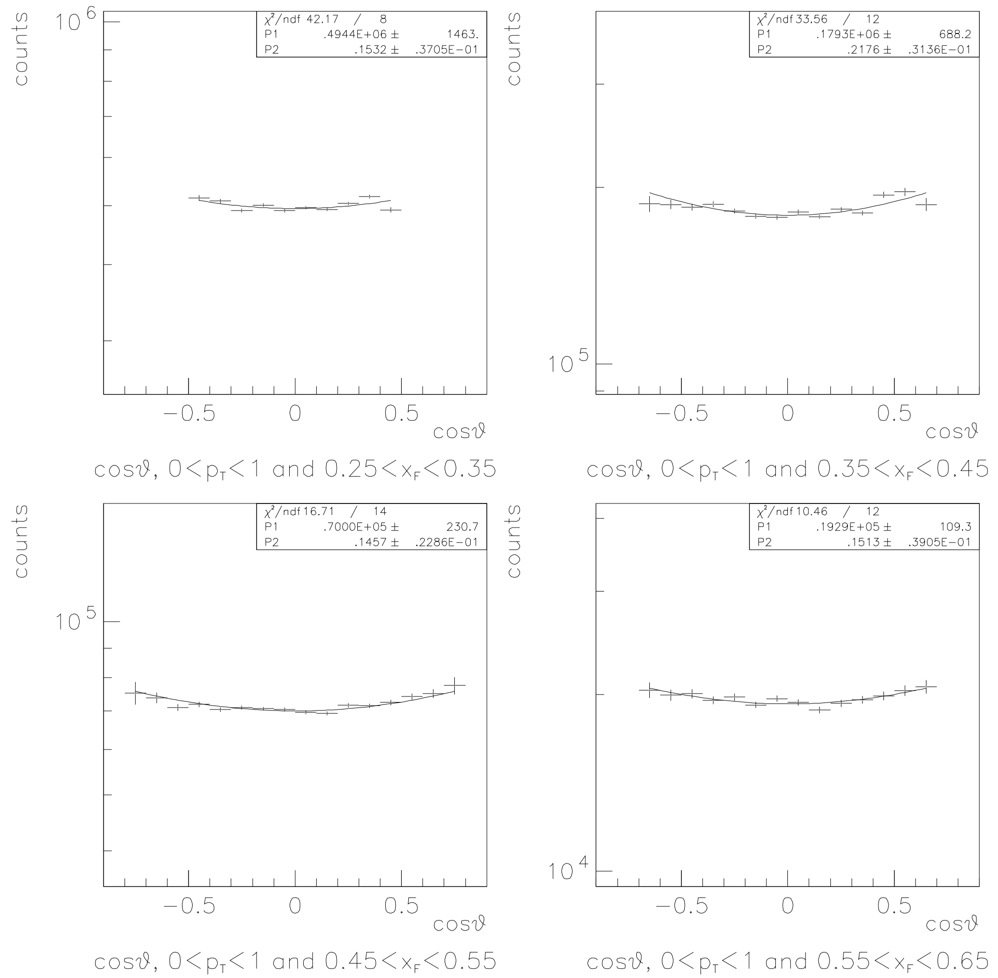
Gives confidence in the following analysis of the charmonium data

Example: mass plots for $2 < p_T < 3$ GeV, $0.55 < x_F < 0.64$, $\pi/2 < \vartheta < \pi$



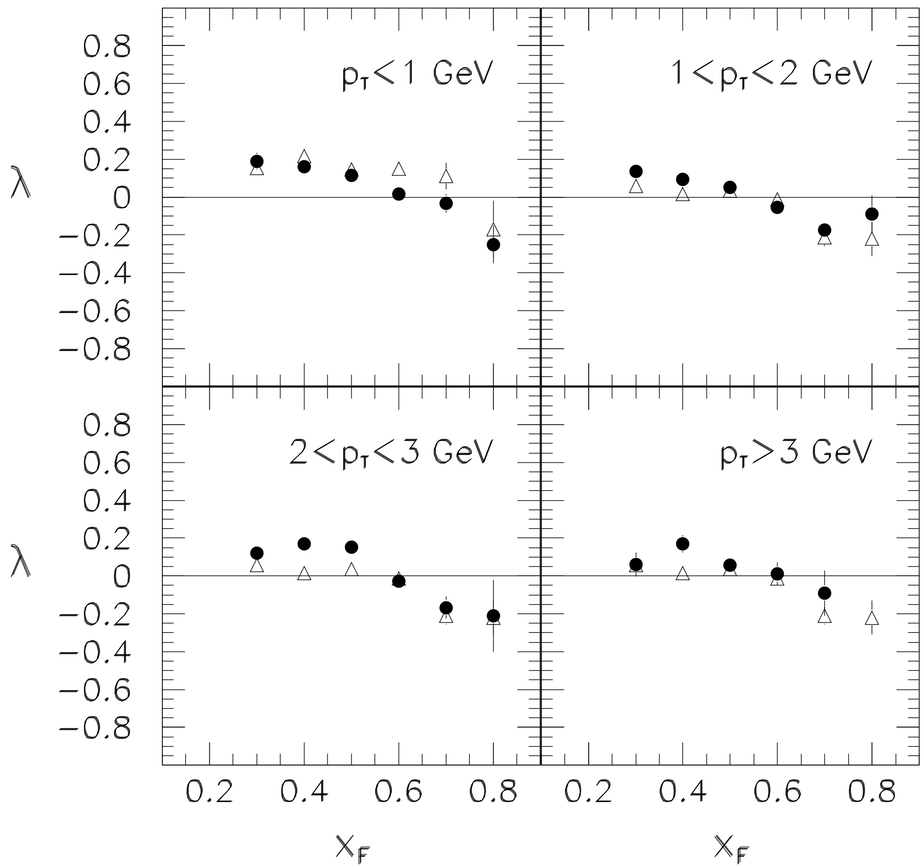
About 1% contamination from ψ'

Example: fits to corrected angular distributions for $0 < p_T < 1$ GeV



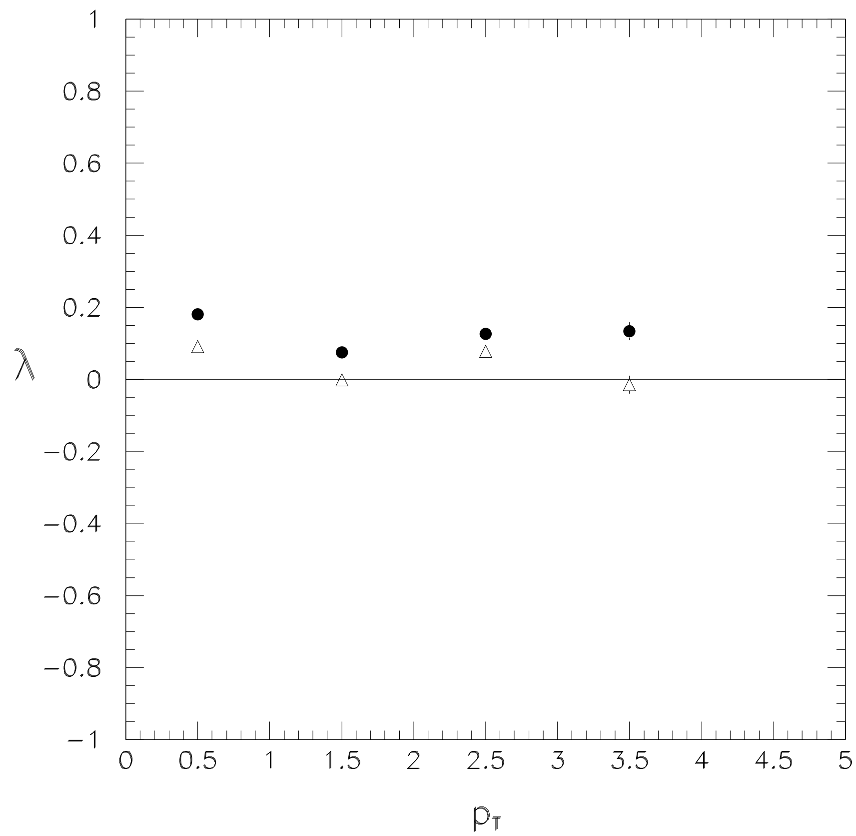
E-866: J/ψ Polarization vs. x_F in p_T Bins

Two sets of points are from the two magnet settings averaged over polarity



Statistical errors only

E-866: J/ψ Polarization vs. p_T in Two x_F Ranges



● $x_F < 0.45$
△ $x_F > 0.45$

Statistical errors only

No obvious dependence on p_T in either range up to $p_T \approx 4$ GeV

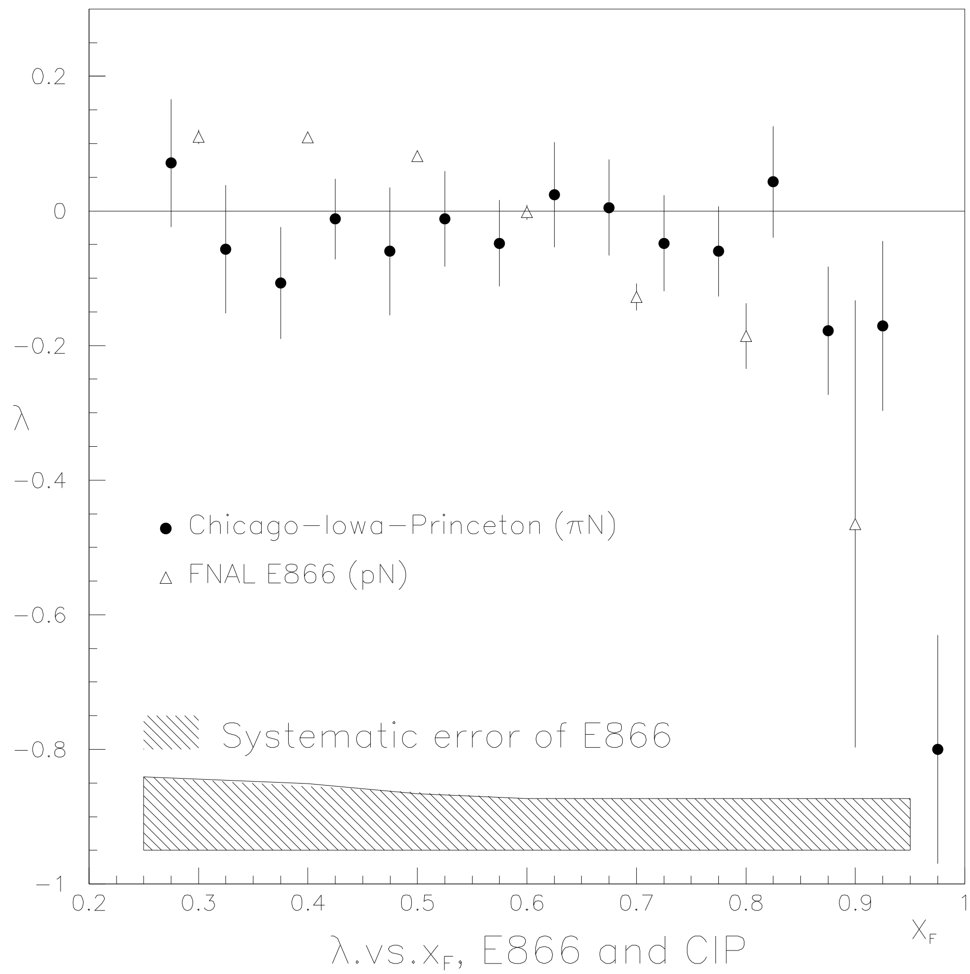
Systematic Uncertainties

Main sources: Uncertainties in fitting of background and the p_T spectrum

x_F	SM12	SM3	angle	centroid	$< p_T >$	fit limit	background	overall
0.3	0.01	0.01	0.04	0.02	0.06	0.05	0.06	0.109
0.4	0.01	0.01	0.04	0.02	0.06	0.04	0.05	0.099
0.5	0.01	0.01	0.02	0.02	0.06	0.04	0.03	0.084
0.6	0.01	0.01	0.02	0.02	0.06	0.03	0.02	0.077
0.7	0.01	0.01	0.02	0.02	0.06	0.03	0.02	0.077
0.8	0.01	0.01	0.02	0.02	0.06	0.03	0.02	0.077
0.9	0.01	0.01	0.02	0.02	0.06	0.03	0.02	0.077

Systematic precision does not match statistical — partly due to extended target

J/ψ Polarization vs. x_F Integrated over p_T



NRQCD prediction: $\lambda \simeq 0.3 - 0.6$ (CSM: $0.25 - 0.5$)

Conclusions from Fixed-Target Results

Results not in agreement with NRQCD calculations

- Polarization at all x_F is much smaller than predicted, both for proton and pion beams
- The highest-statistics proton experiment sees change in polarization from transverse to longitudinal roughly at the x_F point where mechanism changes from $g-g$ fusion to $q-\overline{q}$ annihilation
- The highest-statistics pion experiment sees no polarization except at highest x_F — possible higher-twist effects (not necessarily the same for different beams)

Results also not in agreement with the Color-Singlet Model — but calculations within its latest incarnation are not yet available

- Possibly lower J/ψ polarization due to larger contribution from χ_{c1} decay?

Conclusions from Fixed-Target Results — Caveats

Not ready to conclude that the NRQCD factorization formula fails

- Systematic errors are significant
- Possible additional theoretical uncertainty from nuclear effects
- Relative strength of feed-down from different χ_{cJ} states still uncertain
- Energy may be too low for validity of factorization formula
- Need to keep more terms in v expansion?

The high-p_T collider data present a much more immediate challenge to the theory

Summary of the Theoretical Situation

Where we stand

- Quarkonium production theory much more rigorous than even 5-6 years ago
- Still outstanding issues
  - Factorization still not proved in all cases of interest
  - Higher-order corrections are $\propto \frac{1}{p_T^2}$ — but are they $\frac{M^2}{p_T^2}$ or $\frac{\Lambda_{QCD}^2}{p_T^2}$?
  - Need to keep higher powers of v in matrix-element expansion?
- If high-p_T behavior of ψ polarization is confirmed, whole picture is in trouble
  - Perhaps m_c is not large enough after all
  - Detailed data on Υ polarization from FNAL Run II might help a great deal
    - Also coming: Υ data from NuSea
  - PHENIX at BNL will also study quarkonium production, using polarized beams

Reported Sightings

The Color-Singlet Model is dead — but so is he

Last seen at `hep-ph/0004263`

Latest suggestion: recalculate the pointlike cross section using the unintegrated (*i.e.*, k_T-dependent) gluon distribution and k_T factorization à la BFKL.

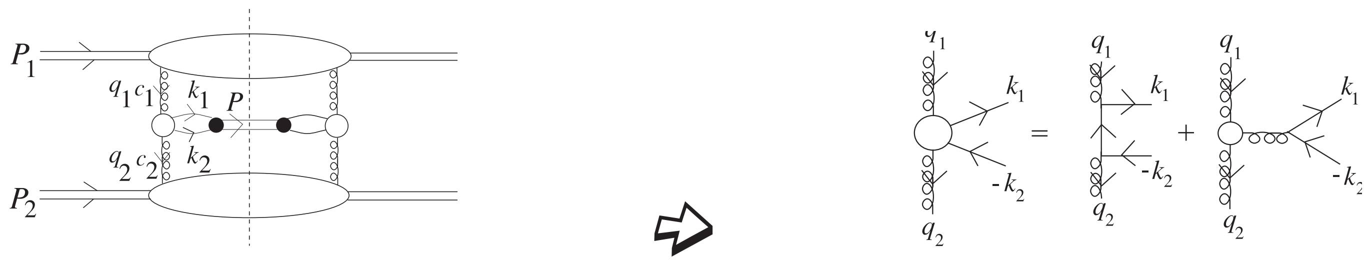
Not yet done for direct J/ψ production
— it involves a three-particle $q\bar{q}g$ production vertex

The χ_{cJ} only involves $c\bar{c}$ production and can be calculated

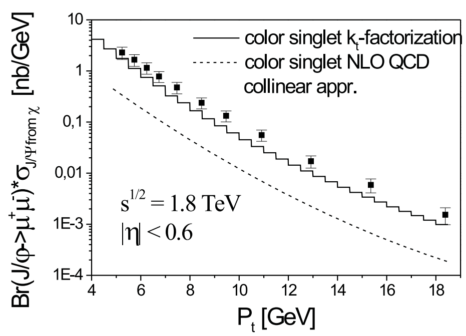
Result: Large contribution from $\chi_{c1} \to J/\psi\,\gamma$ using only CS matrix elements
Production of χ_{c1} can violate the Landau-Young theorem ($\rho \not\to 2\gamma$) because the gluons are *off-shell* ➠ increase by one order of magnitude

Production of χ_{c1} in the k_T Factorization Approach

Basic diagram:



Calculated $B(\chi_{c1} \to J/\psi\,\gamma)B(J/\psi \to \mu^+\mu^-)d\sigma_{x_{c1}}/dp_T$ in k_T factorization approach using only color-singlet matrix elements



Dotted line is the standard collinear approximation result — Data from CDF

Naive question: *what does this do to the two-jet cross section?*

Footnote on Large-x_F Behavior and Higher Twists

Pion experiment sees sudden transition to large *longitudinal* polarization at the highest x_F where higher-twist terms may dominate - both valence quarks in beam contributing

- ❒ Indication of intrinsic charm in pion?
  A pre-existing $c\bar{c}$ pair in the pion would retain the spin-0 state

Proton experiment sees a more gradual transition to longitudinal polarization

- ❒ Similar mechanism possible, but not clear what the $c\bar{c}$ spin would be in this case — could be either 0 or 1 (three valence quarks in p)

Implications for Other Physics Studies

In addition to improving understanding of QCD, charmonium production is also a valuable tool in other physics studies — not in small part due to its convenient *experimental* signature

Example: The new *Relativistic Heavy-Ion Collider* at BNL

- ❒ The heavy-ion program at RHIC is looking at J/ψ suppression as a signal for quark-gluon plasma formation
  - ▷ Calculations need a better understanding of the production mechanism
- ❒ The spin program could benefit greatly from looking at J/ψ production asymmetries, as they depend on gluon polarization inside the proton
  - ▷ Parton-level asymmetries well understood, but need to know the relative importance of various terms