
Review on Charmonium Production

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Why Study Charmonium Production?

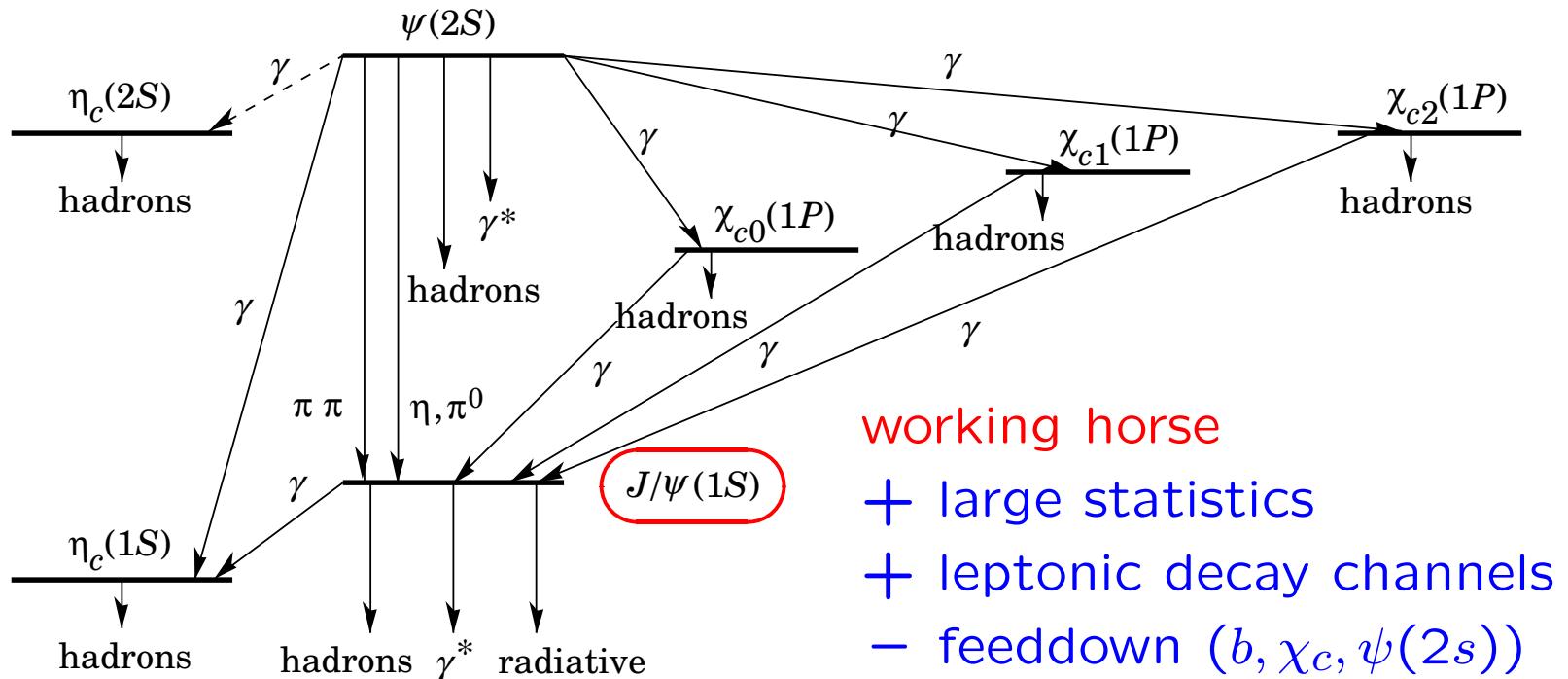
Why Charm?

- m_c large, pQCD applicable
- large fraction of cross section
- sensitive to gluon density
- b tagging

Why Charmonium?

- clean and easy to reconstruct (large branching fraction to leptons)
- understanding of the interplay between perturbative and non-perturbative effects

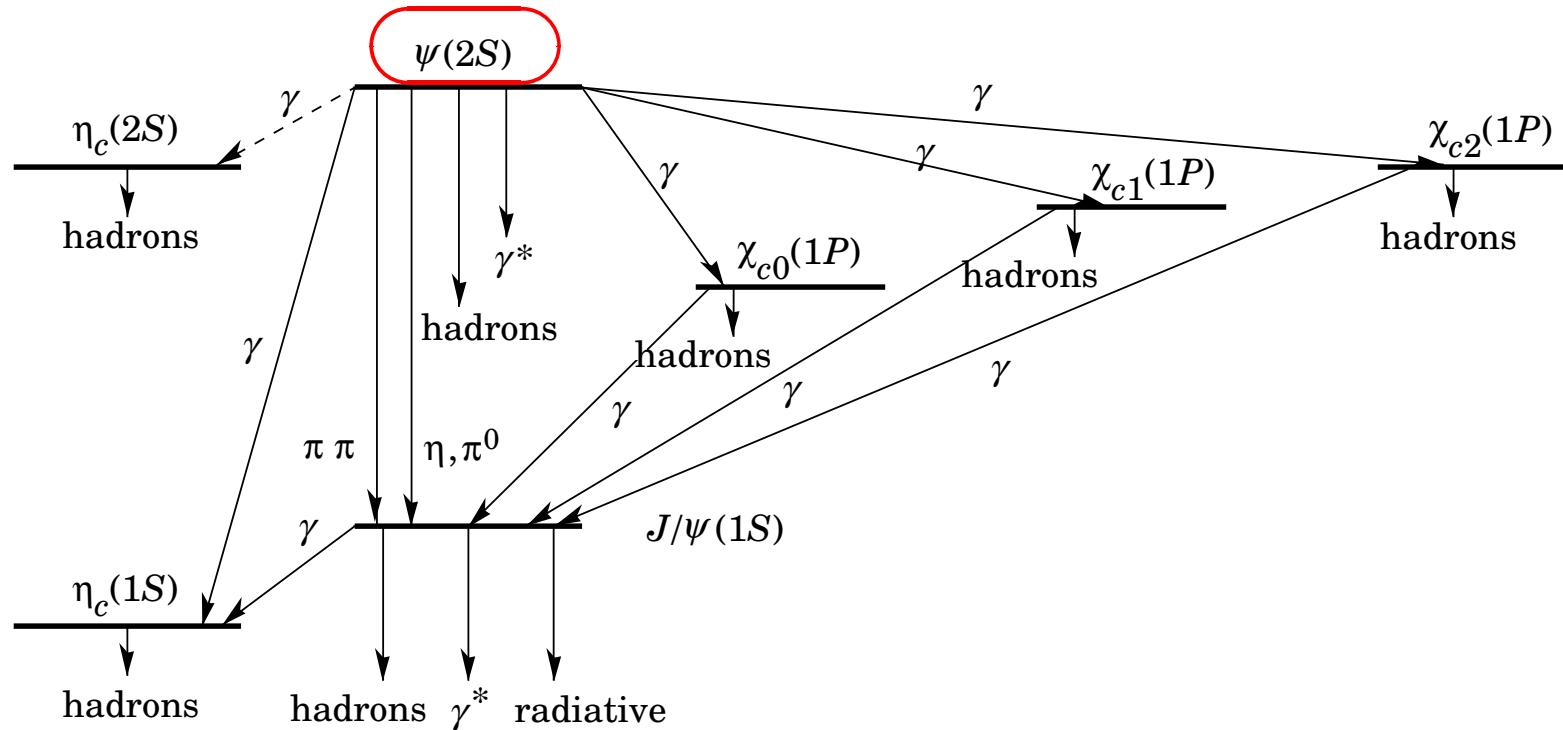
Charmonium



$J^{PC} = \quad 0^{-+} \quad \quad \quad 1^{--} \quad \quad \quad 0^{++} \quad \quad \quad 1^{++} \quad \quad \quad 2^{++}$

Charmonium

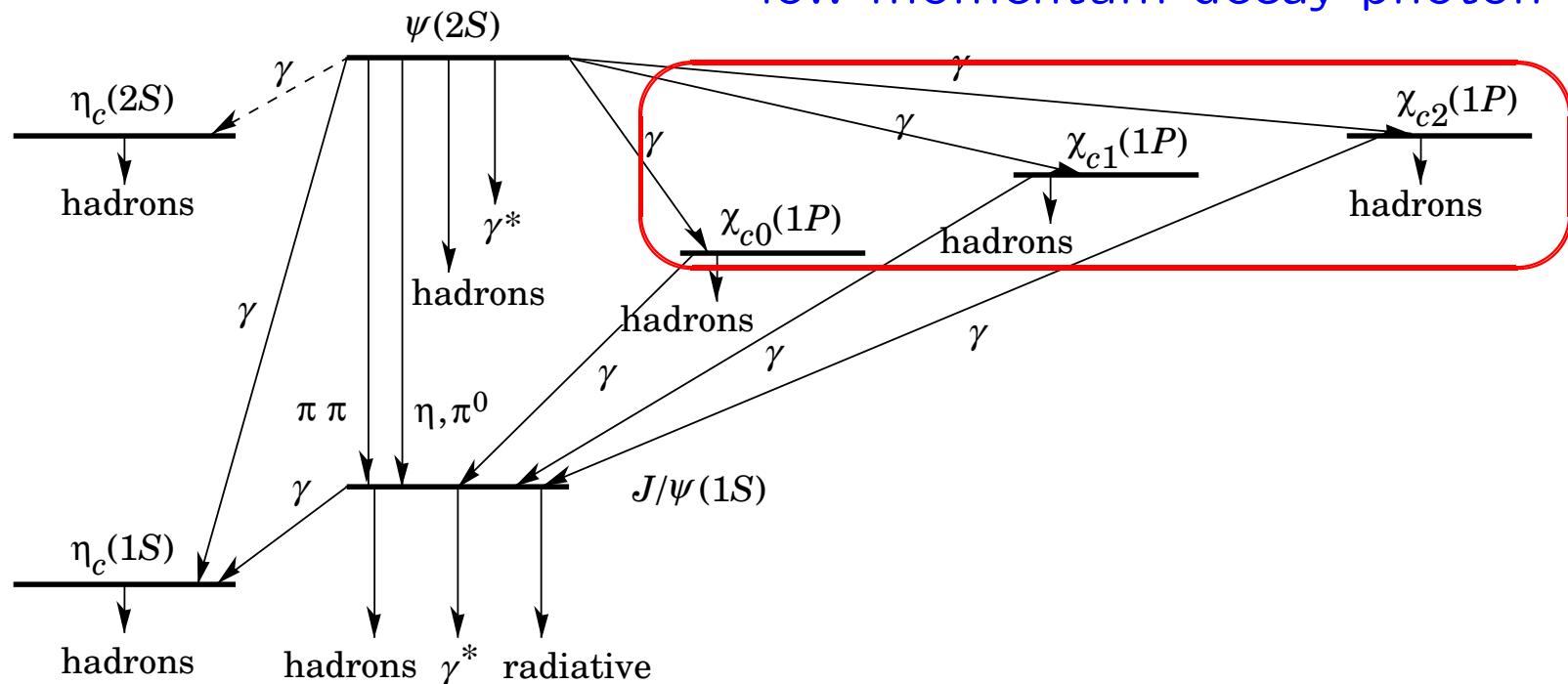
- + less feeddown (b)
- less statistics



$$J^{PC} = \quad 0^{-+} \qquad \qquad 1^{--} \qquad \qquad 0^{++} \qquad \qquad 1^{++} \qquad \qquad 2^{++}$$

Charmonium

- + less feeddown ($b, \psi(2s)$)
- + different angular momentum
- low momentum decay photon

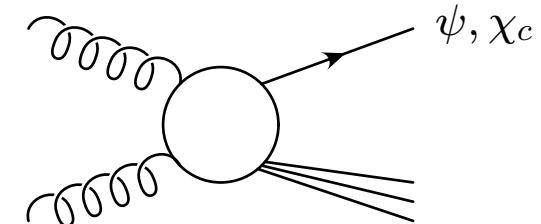


$$J^{PC} = \quad 0^{-+} \qquad \qquad 1^{--} \qquad \qquad 0^{++} \qquad \qquad 1^{++} \qquad \qquad 2^{++}$$

Charmonium Production Reactions

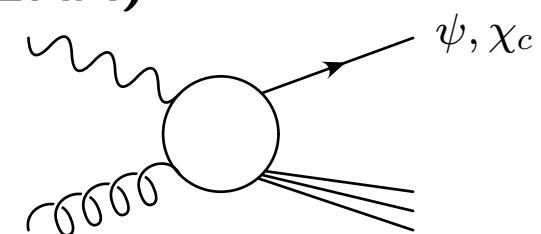
- **Hadroproduction (Tevatron)**

- 'prompt' production
- (B meson decays)



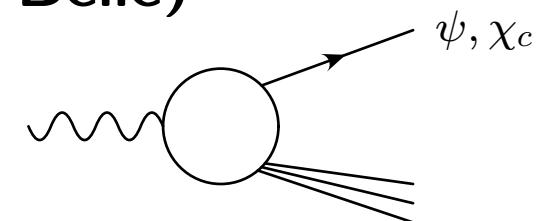
- **Photoproduction, Electroproduction (HERA)**

- 'inelastic' production
- (diffractive production)
- (B meson decays)



- **Electron-Positron-Annihilations (BaBar, Belle)**

- 'prompt' production
- double Charmonium production
- (B meson decays)



- **(Fixed Target Experiments)**

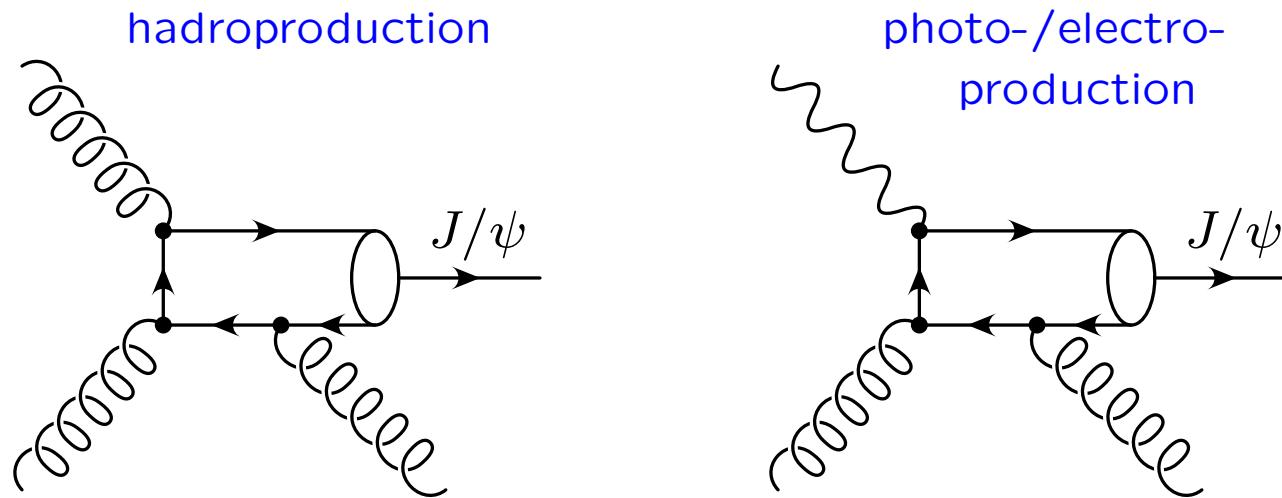
Models for Charmonium Production

- idea: $c\bar{c}$ production can be calculated in pQCD
- different models for transition from $c\bar{c}$ to charmonium
- **Colour Singlet Model CSM** Berger, Jones; Baier, Rückl
 $c\bar{c}$ has to be produced in the colour and angular momentum state of the charmonium
- **Non-Relativistic QCD NRQCD** Bodwin, Braaten, Lepage
 $c\bar{c}$ loses its colour according to its colour and angular momentum state, colour singlet and colour octet contributions
- **Gluon Rescattering** Khoze et al.
 $c\bar{c}$ scatters with gluons from parton shower
- **(Colour Evaporation Model)** Halzen et al.
 $c\bar{c}$ loses its colour independent of other quantities

Colour Singlet Model

Berger, Jones, Phys.Rev. D23 (1981) 1521
Baier, Rückl, Phys. Lett. B102 (1981) 364

- transition $c\bar{c} \rightarrow J/\psi$ known from leptonic decay width
 \Rightarrow no free parameters
- divergencies for P wave states



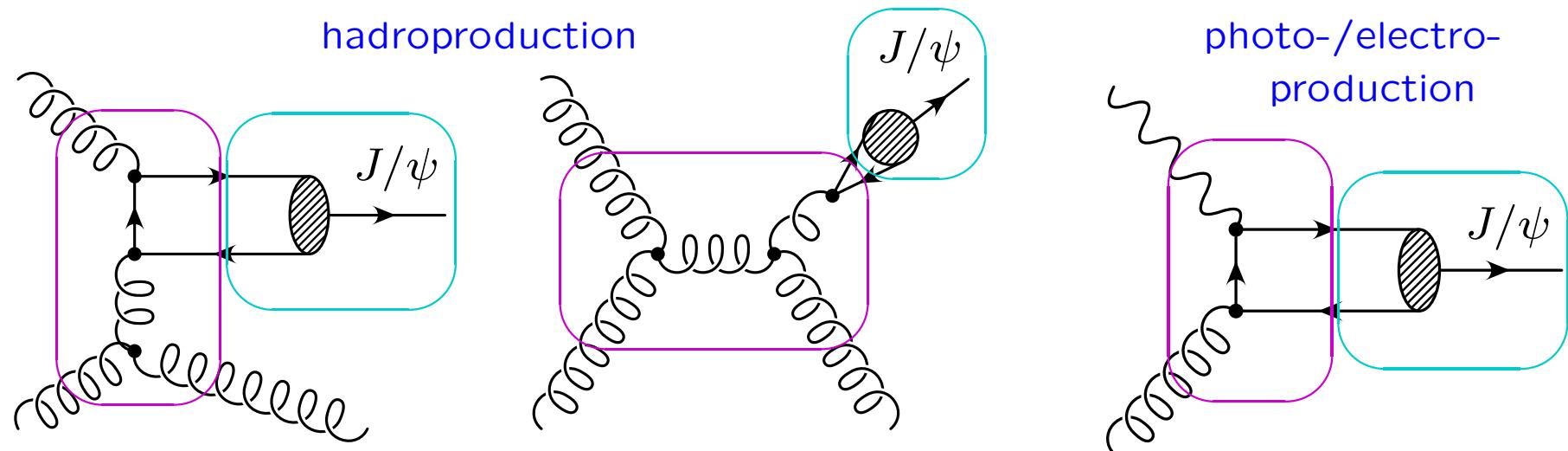
- LO calculations for most processes
- NLO calculation available only for photoproduction

Non-Relativistic QCD

Bodwin, Braaten, Lepage, Phys. Rev. D51 (1995) 1125

$$\text{factorization ansatz: } d\sigma(H) = \sum_n d\hat{\sigma}(c\bar{c}[n]) \langle O^H[n] \rangle$$

- [n] colour and angular momentum state
- $\hat{\sigma}$ perturbative cross section
- $\langle O^H \rangle$ non-perturbative transition $c\bar{c} \rightarrow H$
Long Distance Matrix Elements (LDME) (free parameters)
universal, relative sizes predicted

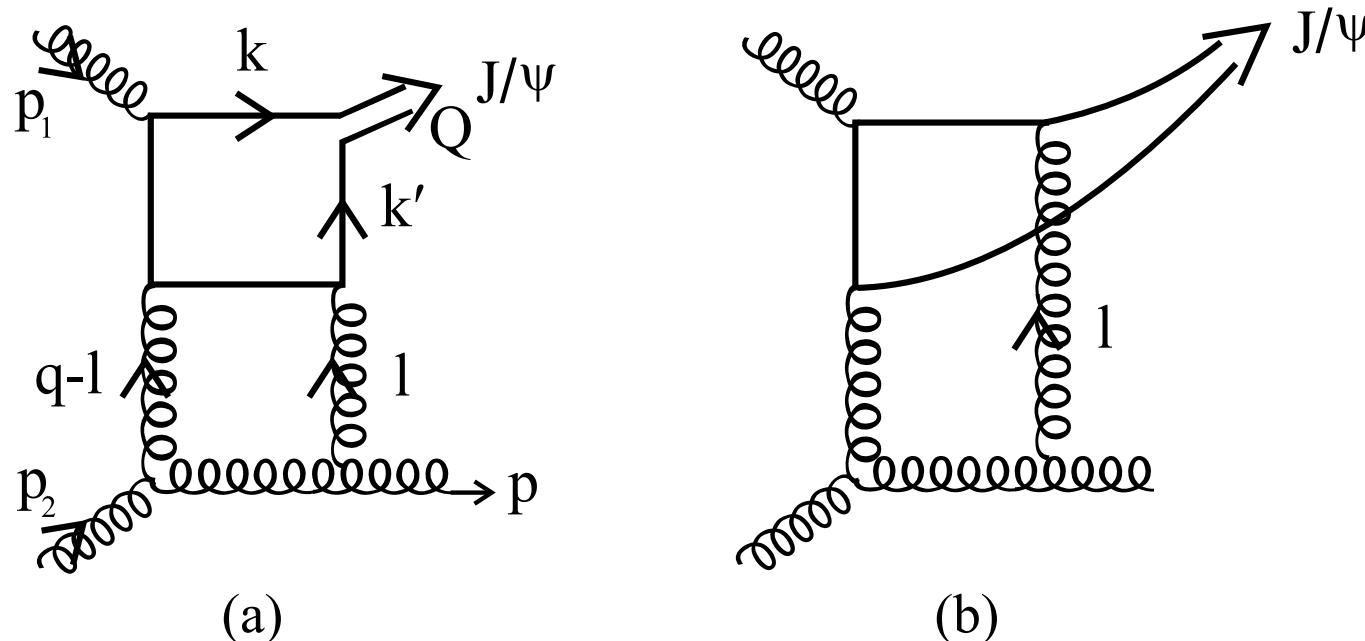


LO calculations available

Gluon Rescattering

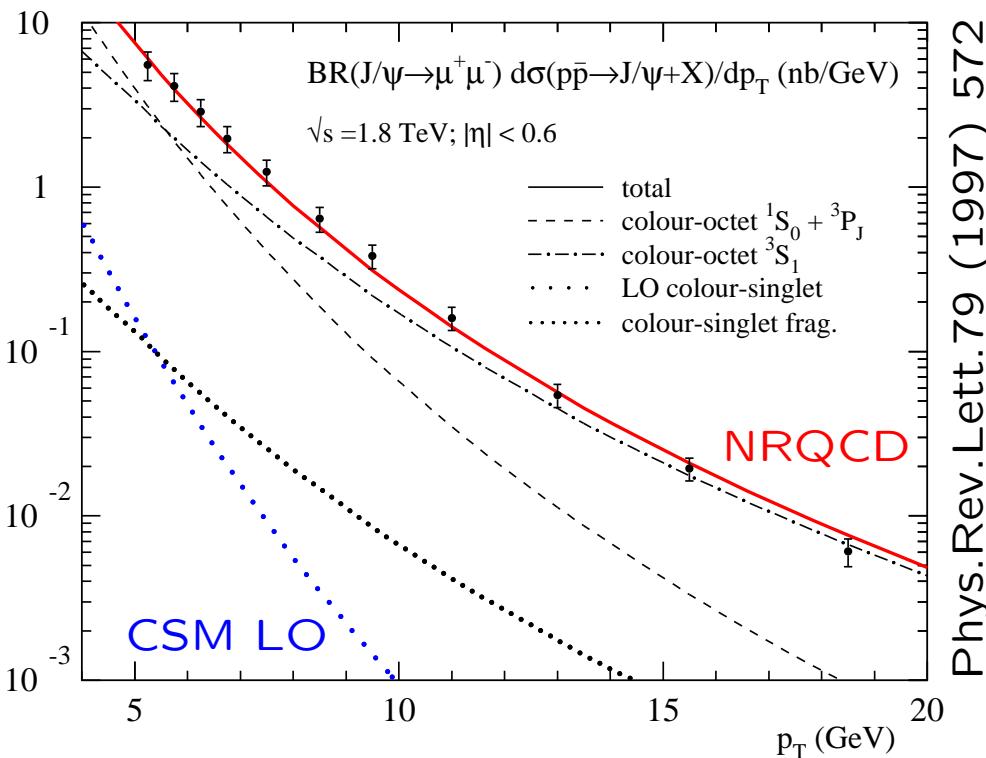
Khoze, Martin, Ryskin, Stirling, Eur.Phys.J. C39 (2005) 163

- scattering with gluons from parton shower
⇒ fusion of symm. colour-octet state $(gg)_{8s}$ and additional gluon
- free param.: effective gluon mass, cut-off to suppress large x
- 'NNLO' contribution in α_s

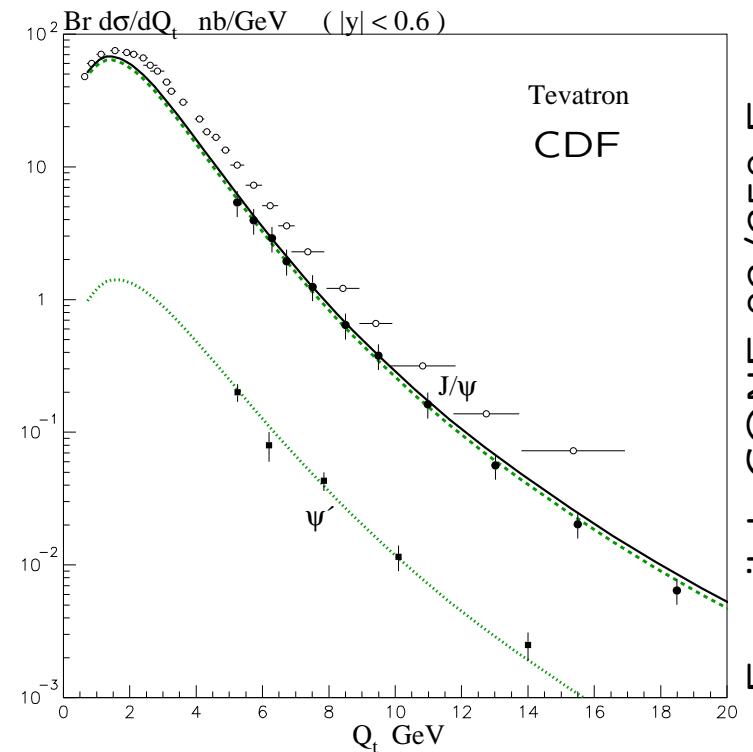


- calculation available for J/ψ and $\psi(2s)$ hadroproduction

Hadroproduction: J/ψ and $\psi(2s)$ Transverse Momentum



CSM LO much too low
NRQCD LDMEs fitted
to this distribution

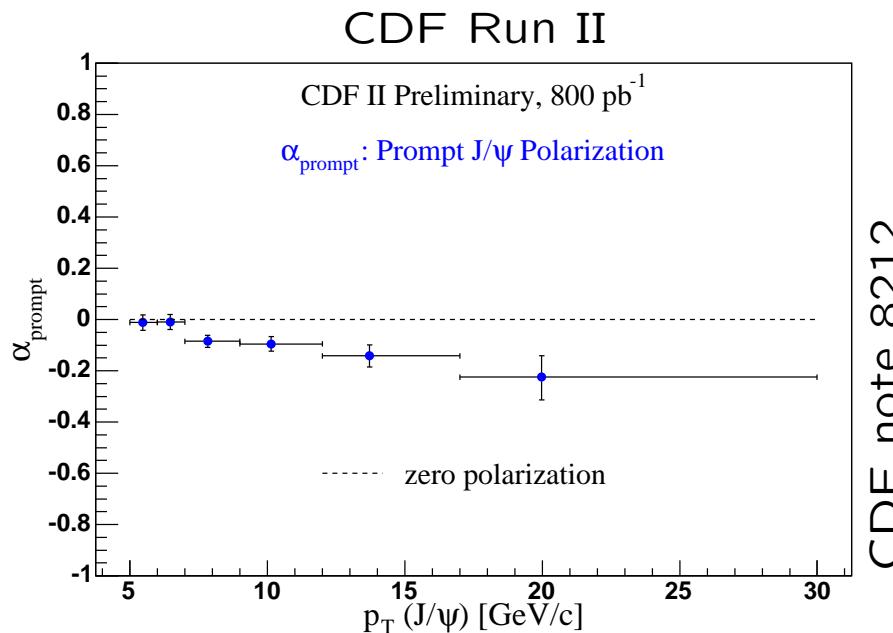
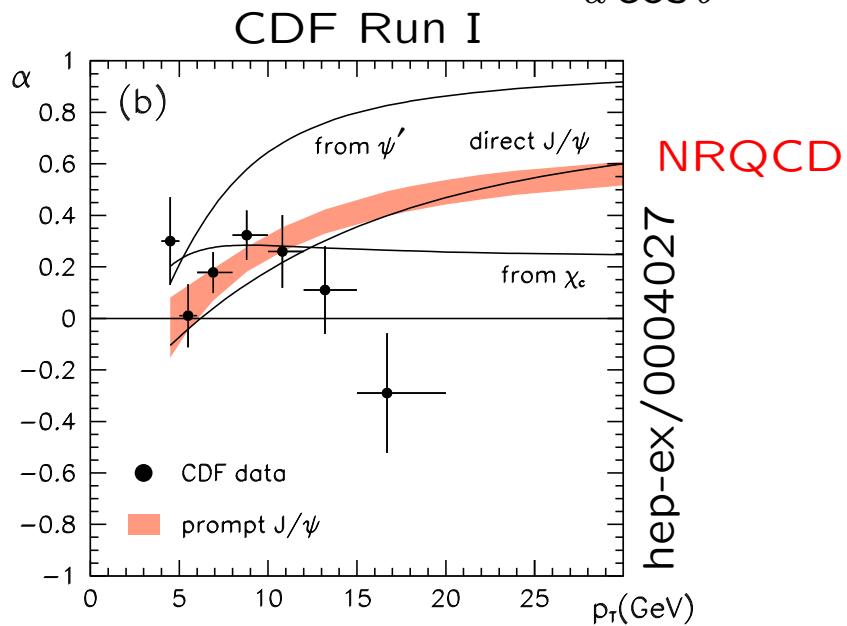


gluon rescattering
describes prompt
 J/ψ and $\psi(2s)$

Hadroproduction: Prompt J/ψ Polarization

- + no normalization uncertainty
- huge statistics needed for precise measurement

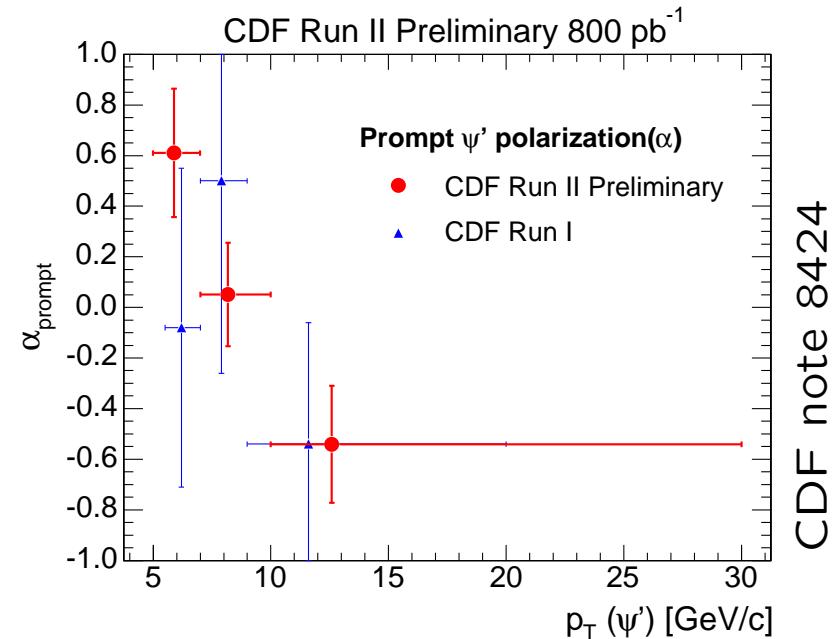
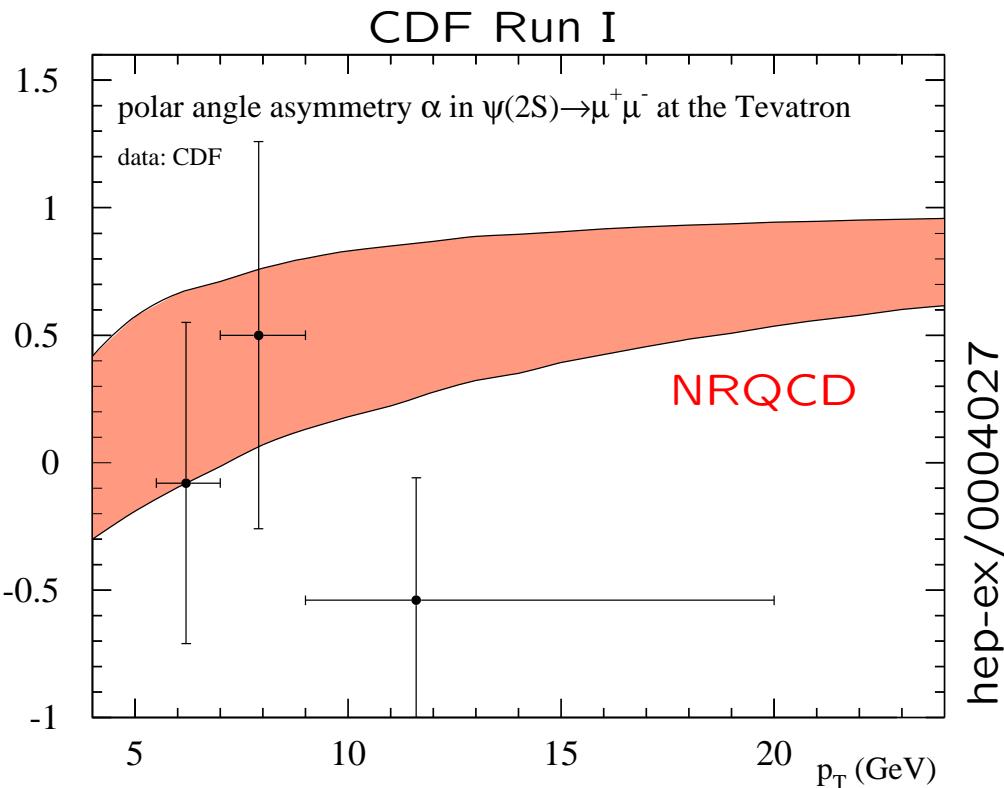
$$\frac{d\sigma}{d\cos\theta} \propto 1 + \alpha \cos^2\theta$$



- NRQCD: transverse polarization ($\alpha > 0$) at large p_t
 - gluon rescattering: longitudinal polarization ($\alpha < 0$) at large p_t
 - clear preference for longitudinal polarization
- ⇒ no room for large gluon fragmentation contribution

Hadroproduction: Prompt $\psi(2s)$ Polarization

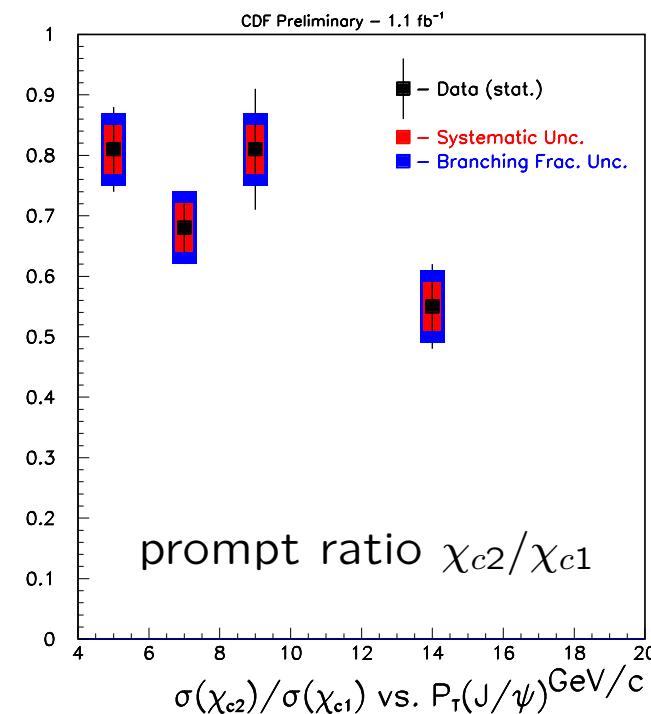
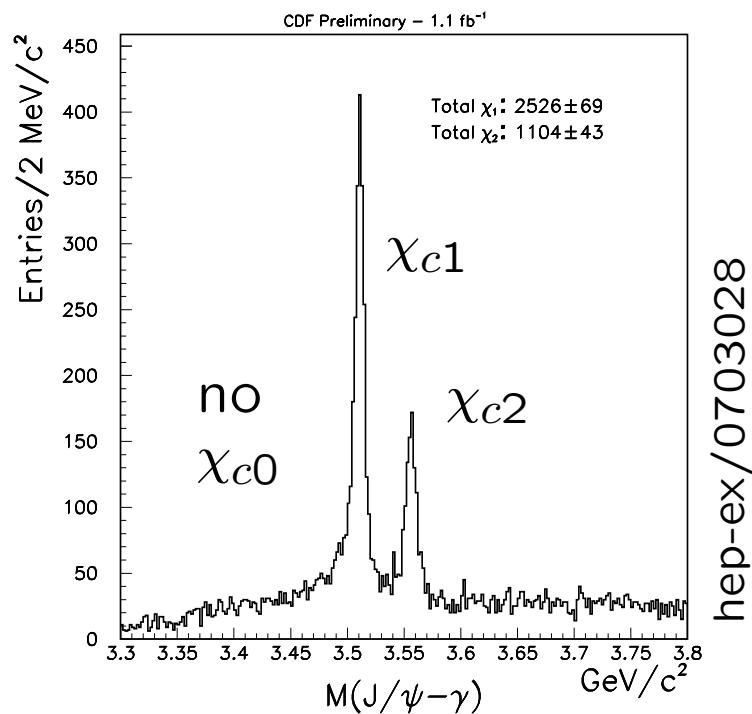
- + no feeddown from higher charmonium states
- less statistics available



⇒ same tendency as in J/ψ polarization

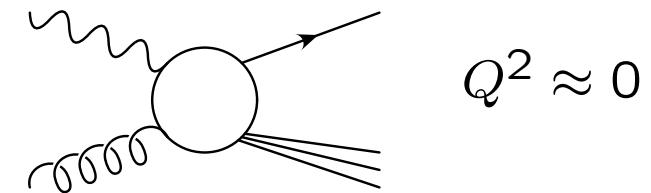
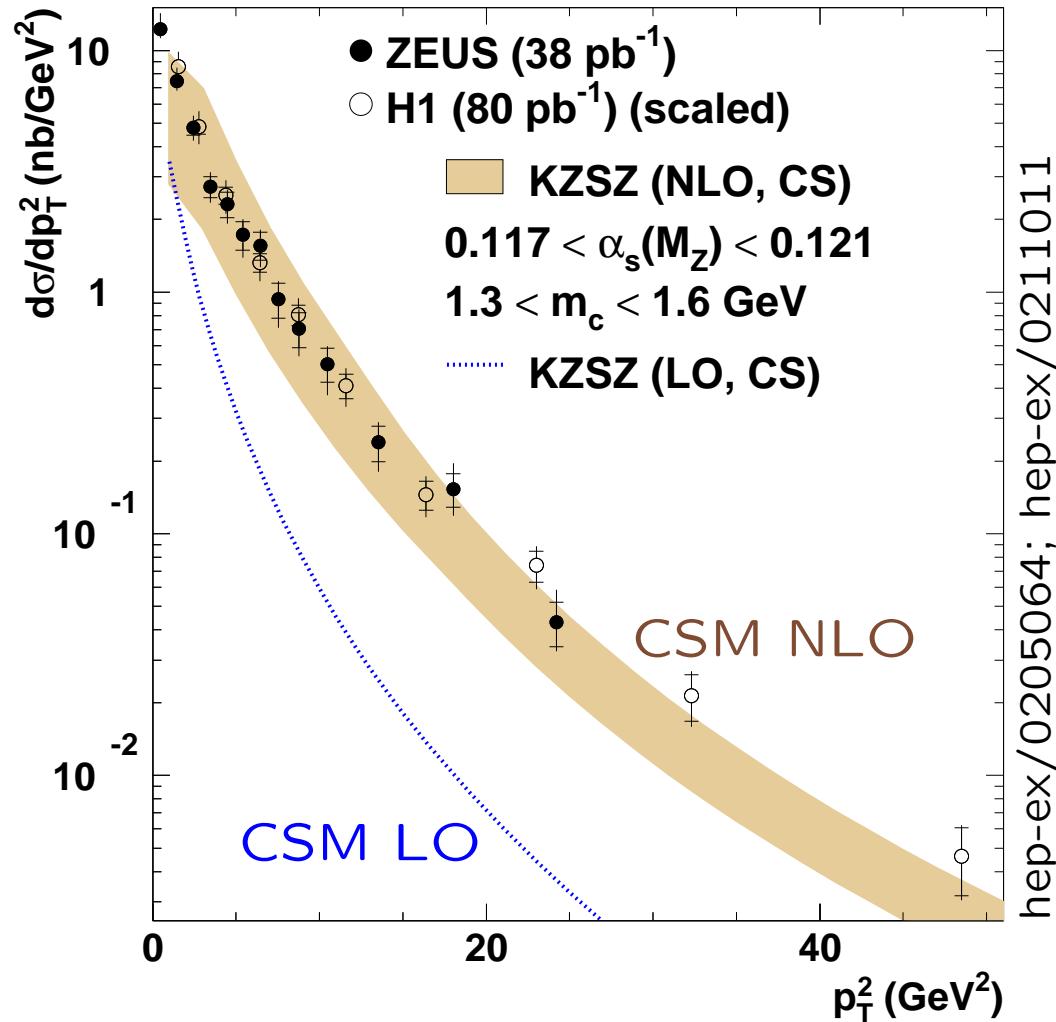
Hadroproduction: χ_c Ratios

- experimentally difficult: low momentum photon $\chi_c \rightarrow J/\psi \gamma$
⇒ first precise measurement



- prompt: $\chi_{c2}/\chi_{c1} = 0.70 \pm 0.04(stat.) \pm 0.04(sys.) \pm 0.06(B.F.)$
- NRQCD expectation: $\chi_{c2} : \chi_{c1} : \chi_{c0} = 5 : 3 : 1$

Photoproduction: J/ψ Transverse Momentum



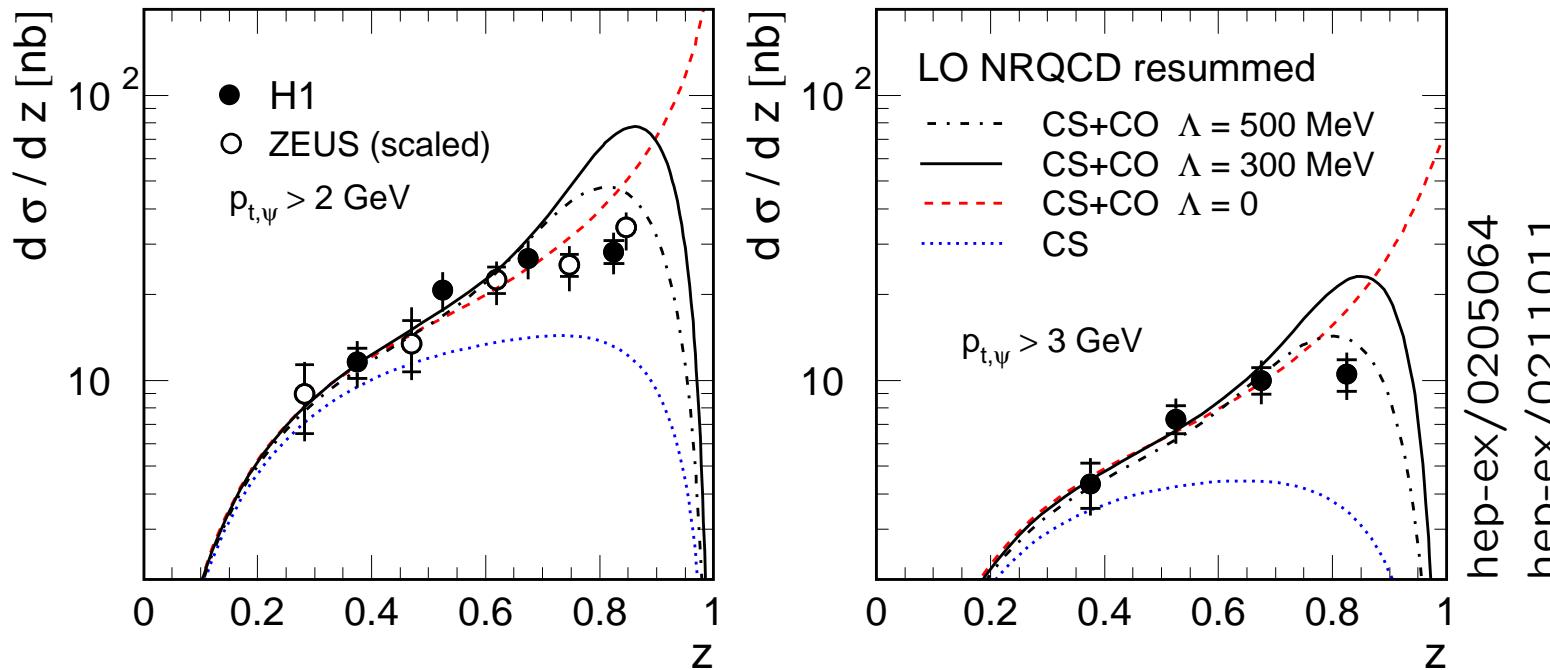
discrepancy to CSM LO
at large p_T^2 similar
to hadroproduction

CSM NLO describes shape
and normalization

⇒ no need for large
colour octet contributions

Photoproduction: J/ψ Elasticity

- elasticity $z = E_\psi^*/E_\gamma^*$:
fractional energy transfer from γ to J/ψ in proton rest frame

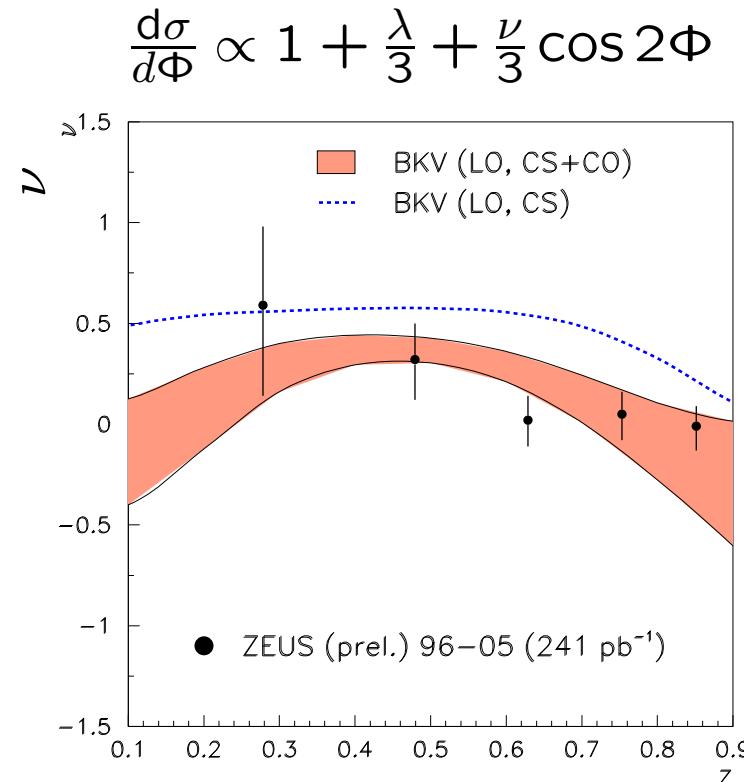
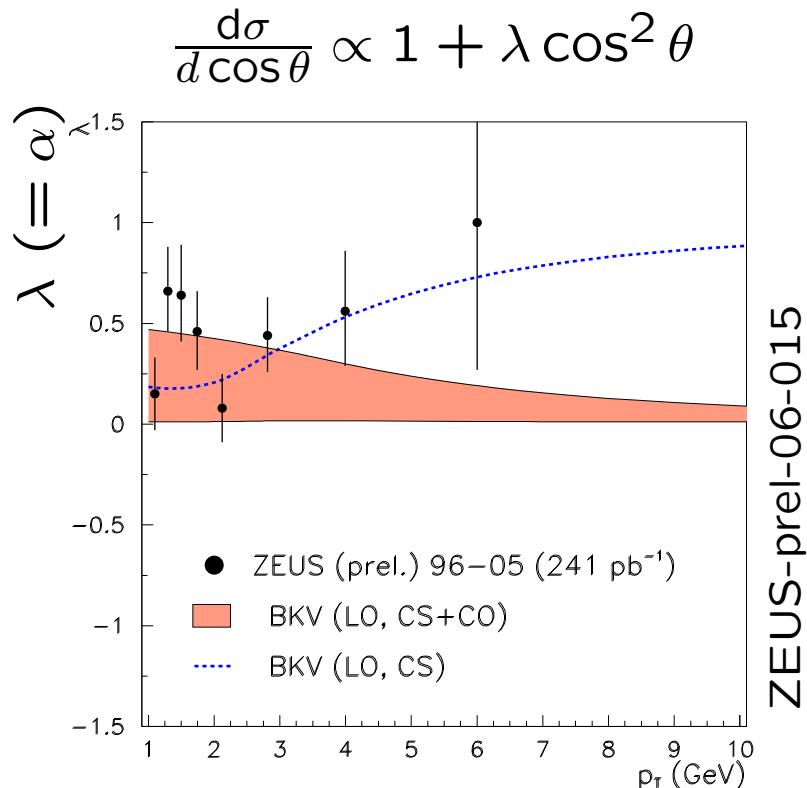


- NRQCD resummed: soft gluons carry energy and momentum
purely non-perturbative resummation, apply as shape function
additional free parameter Λ : related to gluon energy in J/ψ rest frame

⇒ resummation dampens rise towards large z

Photoproduction: J/ψ Polarization

- statistically limited, HERA II data improve situation

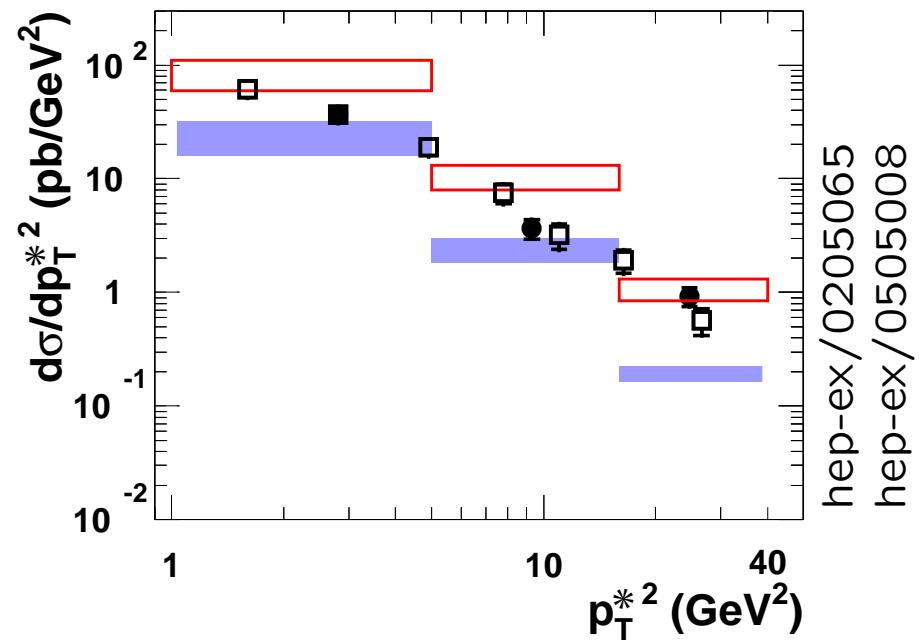
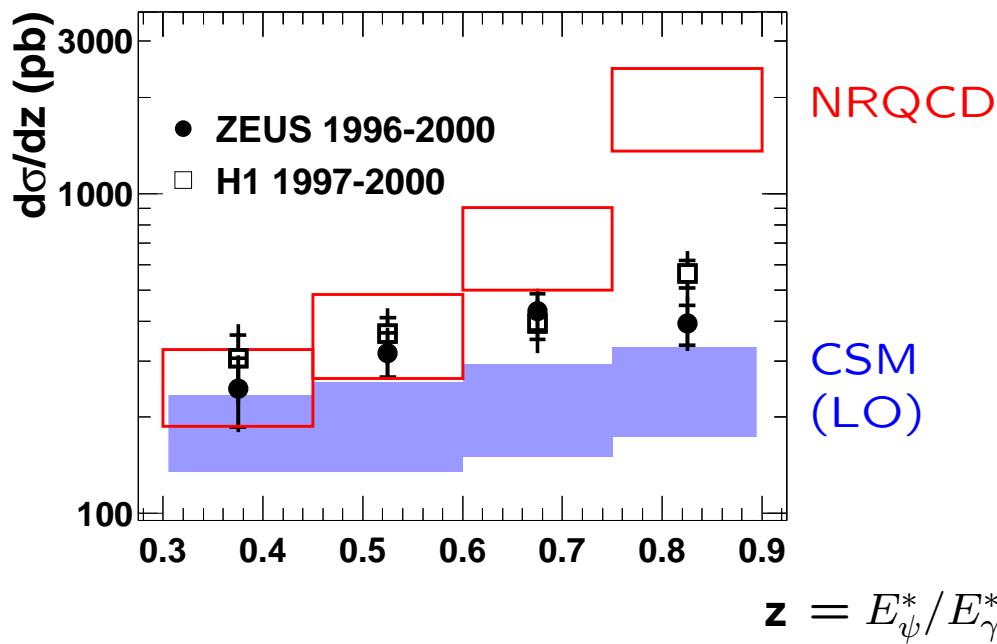
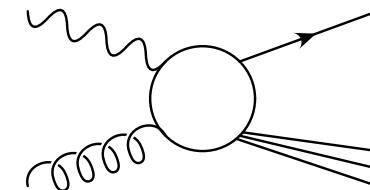


- errors still too large to clearly decide between **CSM** and **NRQCD**
- deviation from CSM LO at large z**
- influence on theory from missing NLO corrections?

Electroproduction: J/ψ Elasticity and Transverse Momentum

- photon virtuality Q^2 provides another scale
 \Rightarrow predictions more reliable?

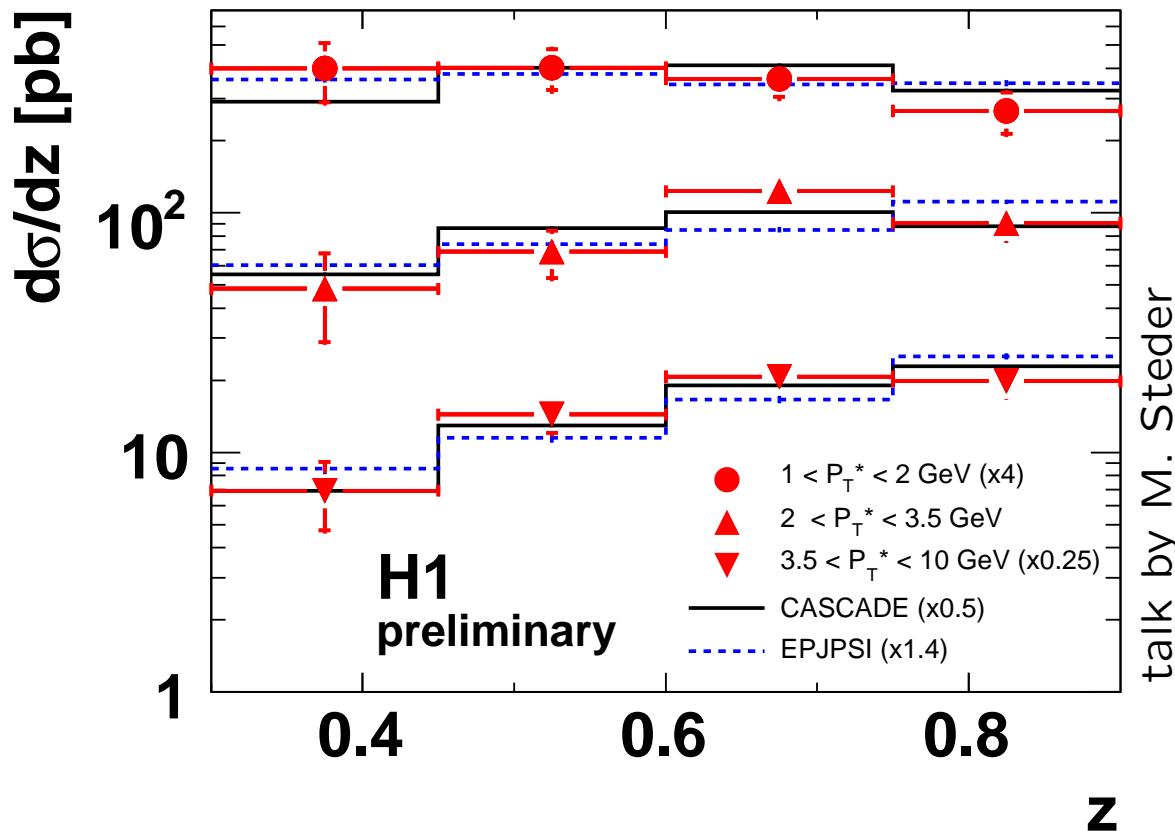
$$2 < Q^2 < 80 \text{ (100) GeV}^2$$



- CSM only to LO available, normalization too low, $p_t^*{}^2$ too steep
- NRQCD (w/o resummation) rises too strongly towards large z

Electroproduction: J/ψ Double-Differential

HERA II statistics allow more differential measurement

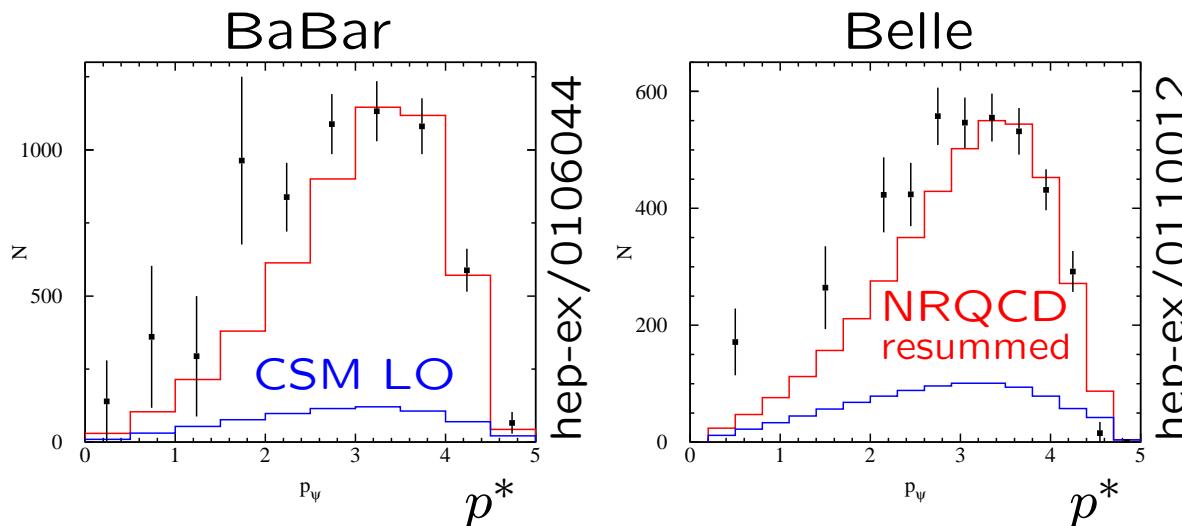
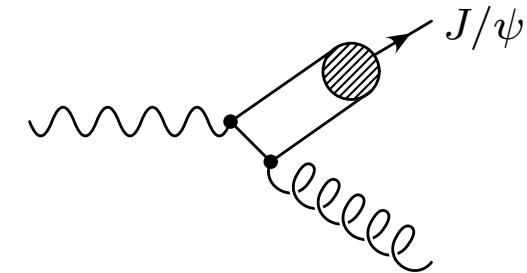


both MC models
(CSM LO) describe
shapes of data
EPJPSI: DGLAP evolution
CASCADE: CCFM evolution

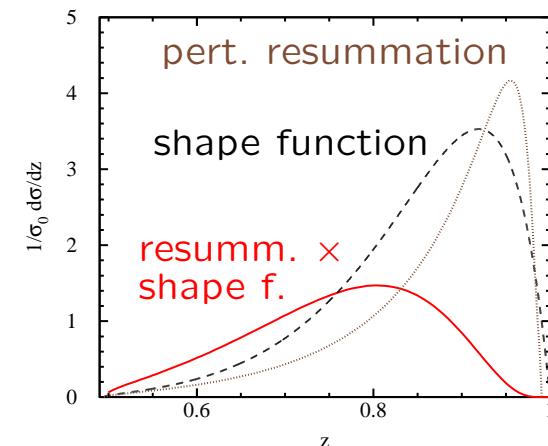
⇒ additional con-
tributions must be
very similar to
CSM LO

e^+e^- Annihilation at 10.6 GeV: Prompt J/ψ Momentum

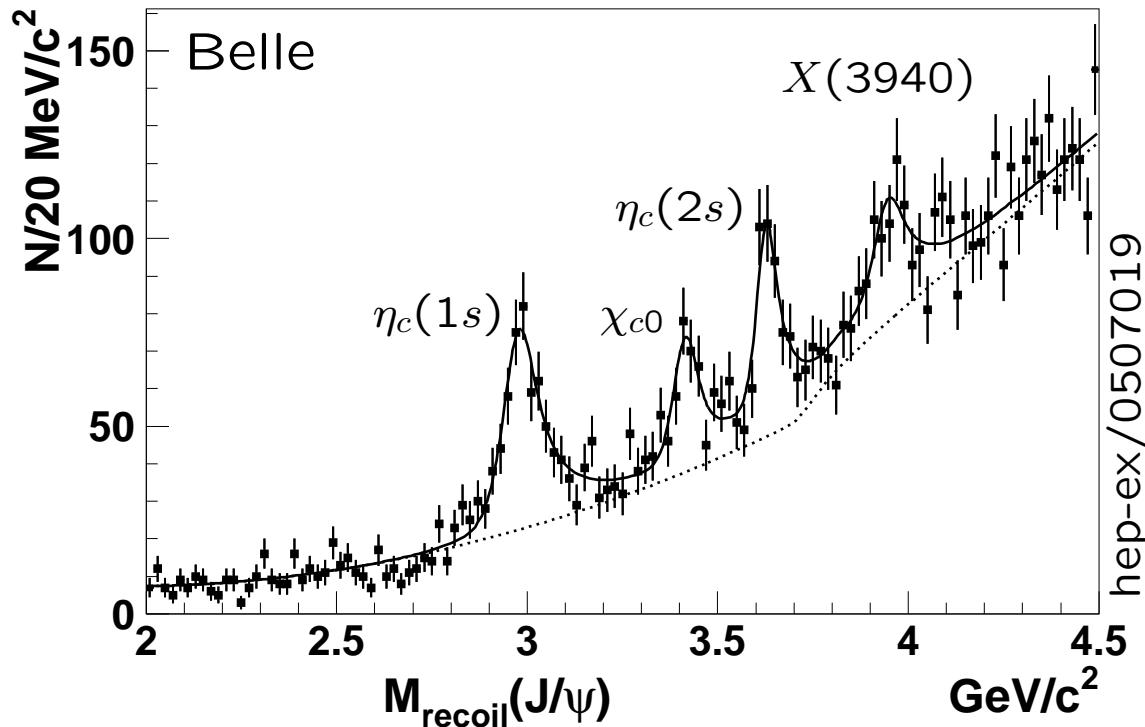
- p^* : J/ψ momentum in the center-of-mass frame



- CSM LO cannot describe normalization
- NRQCD needs resummation (perturbative and non-perturbative) to describe shape



e^+e^- Annihilation at 10.6 GeV: Double Charmonium Production



x-sect. (fb)	$\eta_c(1s)$	χ_{c0}	$\eta_c(2s)$
BaBar	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
Belle	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
NRQCD	$\approx 1 - 6$	$\approx 1 - 7$	$\approx 0.5 - 4$

hep-ex/0506062 hep-ex/0407009

reconstruct recoil mass
from J/ψ quantities

observe new charmonium
state $X(3940)$

cross sections and
ratio to inclusive
prompt J/ψ pro-
duction much higher
than expected
by NRQCD

Conclusions

- wealth of experimental data on charmonium production available
- more data (full statistics of Tevatron Run II, HERA II) expected soon
- theoretical situation not so clear:
 - not many NLO calculations available
 - CSM describes HERA and Tevatron data (with gluon rescattering), fails for BaBar & Belle
 - NRQCD fails some crucial tests
 - ⇒ colour octet terms much different from expectation?
 - ⇒ LDMEs not universal?
 - suggestions to solve some points exist, but no coherent picture