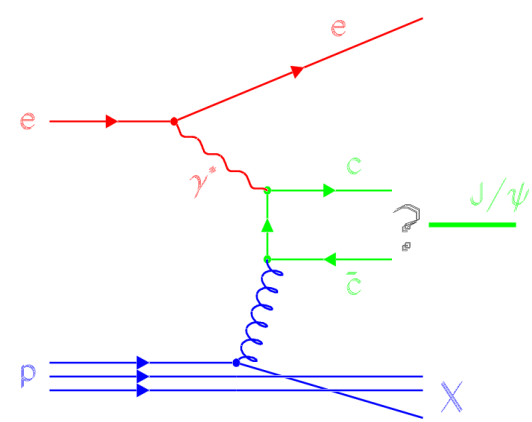
Charmonium Production

Arnd Meyer (Fermilab)
Quarkonium Workshop
CERN
November, 2002

- Introduction
- Tevatron - past, present, and future
  - Run I: cross section and polarization measurements (J/ψ, ψ')
  - Prospects for Run II
- HERA - past, present, and future
  - Inelastic production measurements (J/ψ, ψ')
  - Exclusive production: total and differential cross sections (J/ψ, ψ')
  - Prospects for HERA II
- Conclusions

Introduction

- Tevatron (Run 1 1992-96, $\int L\,dt \simeq 20\ pb^{-1}$ (1A) + $90\ pb^{-1}$ (1B)):
  - $p \rightarrow \leftarrow$ pbar at $\sqrt{s} = 1.8$ TeV
  - η, p_T, polarization
- HERA ("Run 1" , $\int L\,dt \simeq 100\ pb^{-1}$):
  - $e^{\pm}$ (27.5 GeV) $\rightarrow \leftarrow$ p (820/920 GeV) at $\sqrt{s} = 300/320$ GeV
  - Q^2, W, z, p_T, t, ..., polarization
  - overconstrained kinematics
- History
  - Inelastic J/ψ production at HERA: a golden way to extract gluon density
  - Elastic/diffractive J/ψ production to measure luminosity
- Variety of presumed production mechanisms:
  - Diffractive/elastic
  - Gluon-gluon-fusion, photon-gluon-fusion
  - Gluon fragmentation
  - "Resolved photon"-gluon/quark-fusion
  - + decays



Publications (Most Recent Only)

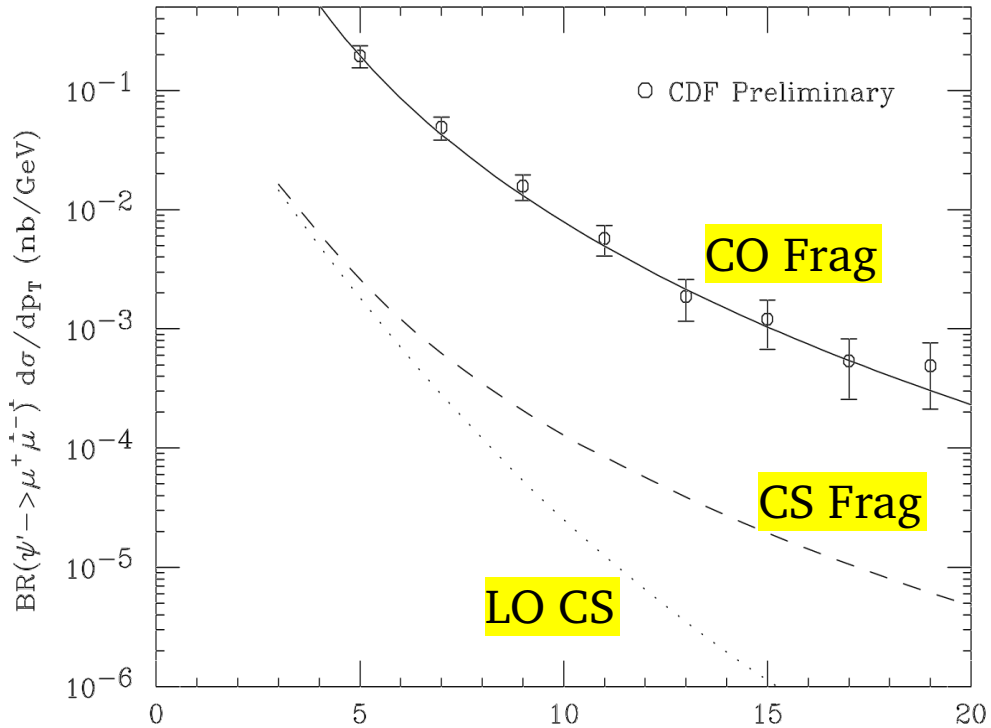
TEVATRON	J/ψ and $\psi(2S)$ cross section		CDF	(15 pb^{-1})	PRL 79 (1997) 572
	J/ψ cross section, $\chi_c \to J/\psi\gamma$		D0	(7 pb^{-1})	PL B370 (1996) 239
	$\chi_c \to J/\psi\gamma$		CDF	(18 pb^{-1})	PRL 79 (1997) 578
	χ_{c1}/χ_{c2}		CDF	(110 pb^{-1})	PRL 86(2001) 4472
	Polarization		CDF	(110 pb^{-1})	PRL 85 (2000) 2886
	"Forward" J/ψ		D0	(10 pb^{-1})	PRL 82 (1999) 35
			CDF	(74 pb^{-1})	FNAL-PUB-02/188-E ($\to$ PRD)
	Diffractive J/ψ		CDF	(80 pb^{-1})	PRL 87 (2001) 251803
HERA	Elastic/diffractive	J/ψ γp	ZEUS	(50 pb^{-1})	EJ C24 (2002) 345
			H1	(20 pb^{-1})	PL B483 (2000) 23
		J/ψ DIS	H1	(27 pb^{-1})	EJ C10 (1999) 373
			ZEUS	(6 pb^{-1})	EJ C6 (1999) 609
		J/ψ large|t|	ZEUS	(25 pb^{-1})	DESY-02-072 ($\to$ EJC)
		$\psi(2S)$ γp	H1	(77 pb^{-1})	PL B541 (2002) 251
		$\psi(2S)$ DIS	H1	(27 pb^{-1})	EJ C10 (1999) 373
	Inelastic	J/ψ γp	H1	(88 pb^{-1})	EJ C25 (2002) 25
		J/ψ DIS	H1	(77 pb^{-1})	EJ C25 (2002) 41
		J/ψ and $\psi(2S)$ γp	ZEUS	(38 pb^{-1})	DESY-02-163 ($\to$ EJC)

Direct $\psi(2S)$ Cross Section

- $\psi(2S) \to \mu\mu$, Run 1A data, 18 pb^{-1}
- "Central muons" ($|\eta| < 0.6$)
- Lifetime information from SVX used to extract prompt component
- *Prompt* ≡ *direct* for $\psi(2S)$
- Colour singlet fusion: α_s^3/p_T^8
- CS fragmentation (Braaten, Yuan, PRL 71(1993) 1673): α_s^5/p_T^4

$$g * \to 2g + c\bar{c}(^3S_1^{(1)}) \to \psi'$$

- NRQCD expansion
  - $d\sigma(H) = \sum_n d\sigma[c\bar{c}(n)] \langle O^H(n) \rangle$
  - n includes colour singlet and octet states
  - Expansion in α_s and v (relative velocity of quark and anti-quark)

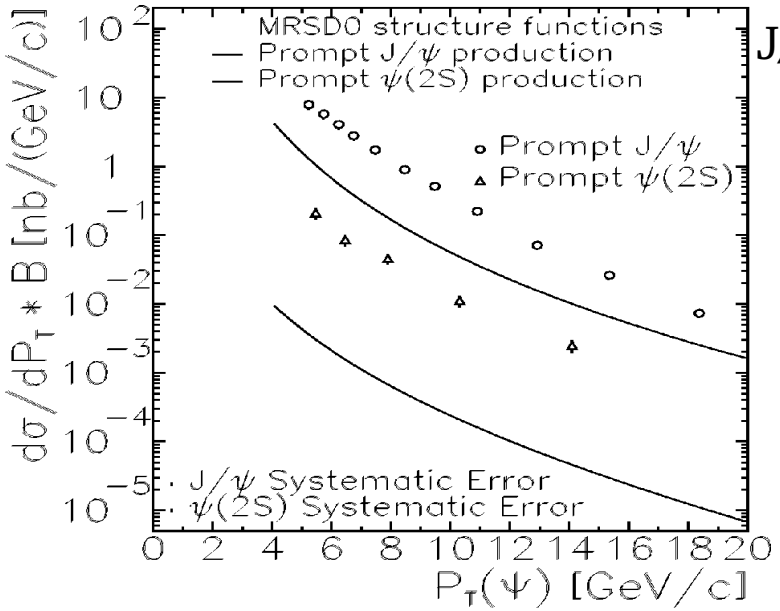


Braaten, Fleming PRL 74(1995) 3327

CDF Data: PRL 79(1997) 572

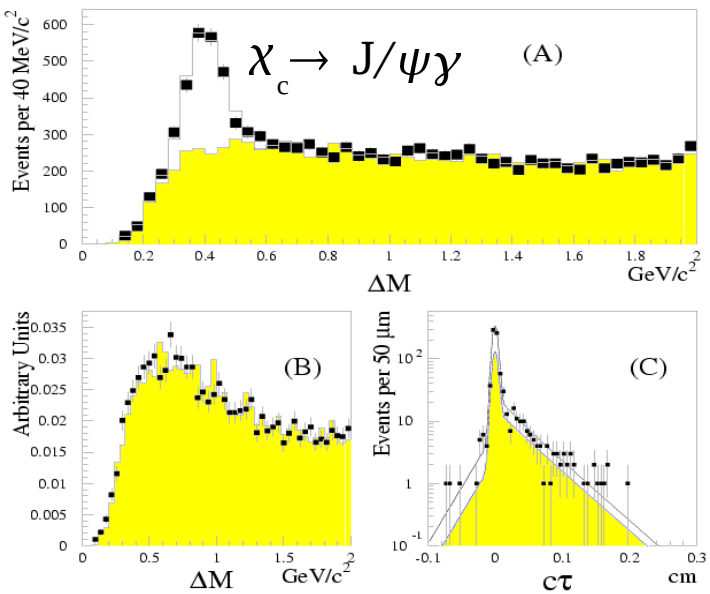
- Colour octet fragmentation (Braaten, Fleming, PRL 74(1995) 3327): $\alpha_s^3 v^4/p_T^4$ $\quad g * \to c\bar{c}(^3S_1^{(8)}) \to \psi'$
- *Fragmentation dominates at high p_T*

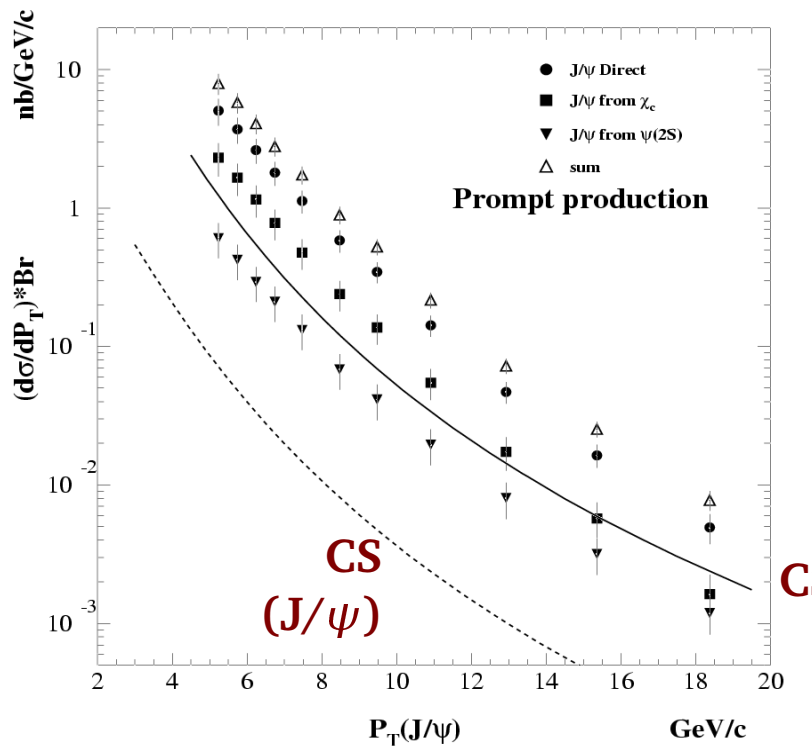
Prompt / Direct J/ψ Cross Section



$J/\psi \rightarrow \mu\mu$

- Prompt J/ψ cross section includes
  - χ_c decays ($\chi_c \rightarrow J/\psi\gamma$ measured)
  - ψ(2S) feed-down (measured)
  - Direct J/ψ (64±6%)

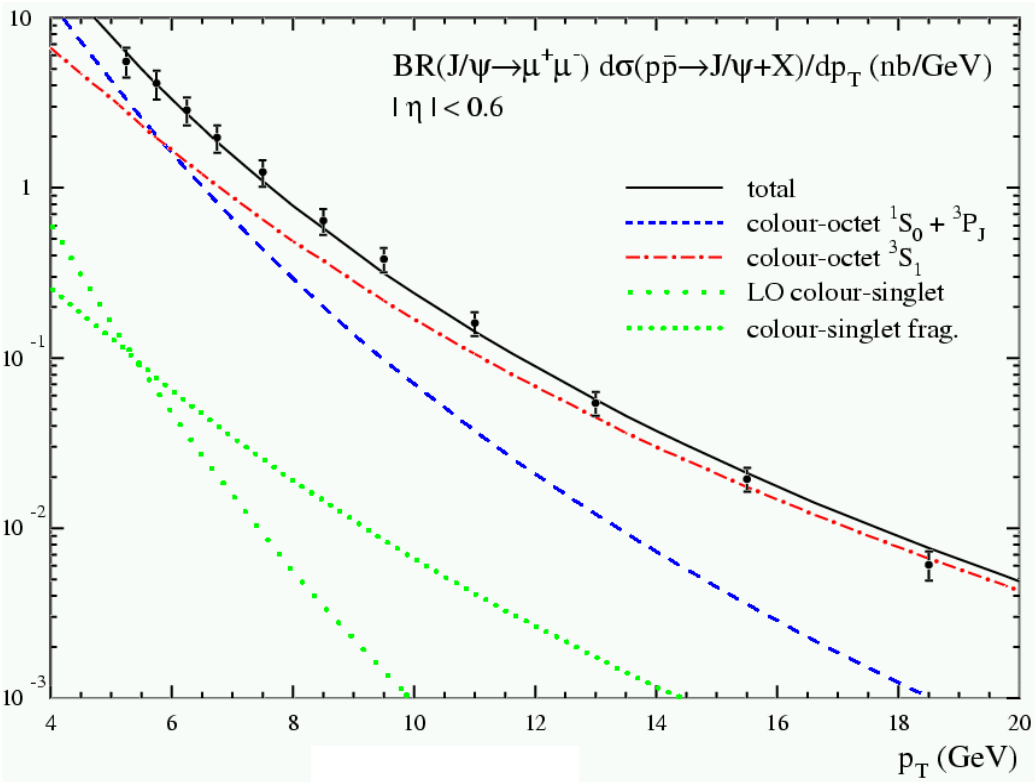




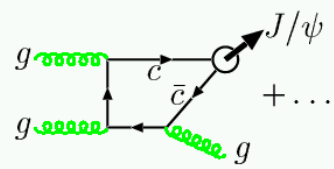
CDF, PRL 79(1997) 572, 578

Direct J/ψ Cross Section

- Large uncertainties in the extracted matrix elements
  - low p_T: effects of gluon k_t
  - parton density functions

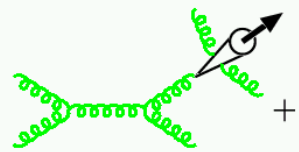


Beneke, Krämer, PRD 55(1997) 5269



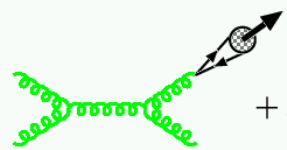
$+\ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$

colour-singlet fragmentation: $g + g \to [c\bar{c}[^3S_1^{(1)}] + gg] + g$



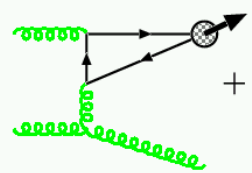
$+\ldots \qquad \sim \alpha_s^5 \frac{1}{p_t^4}$

colour-octet fragmentation: $g + g \to c\bar{c}[^3S_1^{(8)}] + g$



$+\ldots \qquad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$

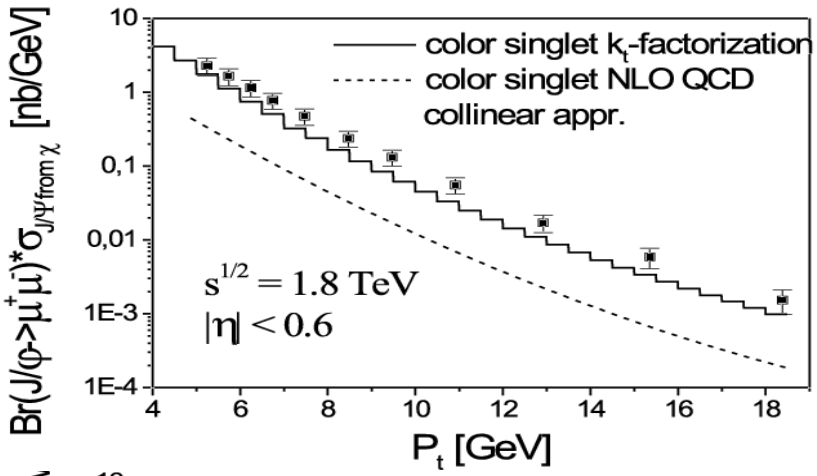
colour-octet fusion: $g + g \to c\bar{c}[^1S_0^{(8)}, ^3P_J^{(8)}] + g$



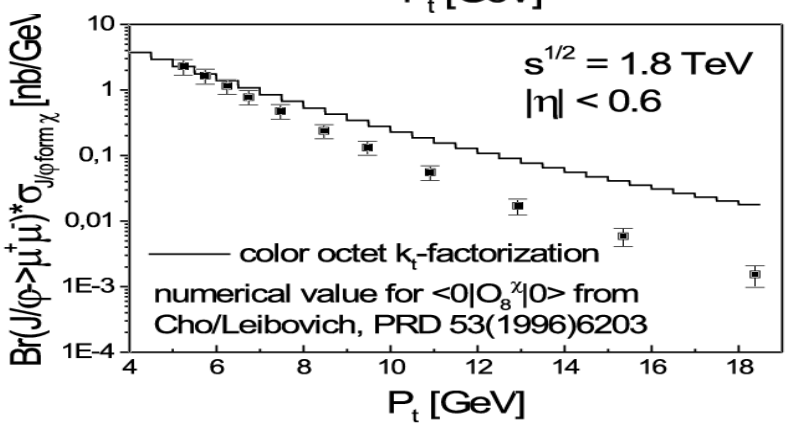
$+\ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4$

k_t Factorization

- Unintegrated gluon distribution + BFKL next-to-leading-log-approximation
- Little room for colour octet in χ_c production
- Changes values of extracted octet ME for $^3S_1^{(8)}$ by 1/30, but $^1S_0^{(8)}$ and $^3P_0^{(8)}$ not by much (see Hera-Tevatron anomaly)

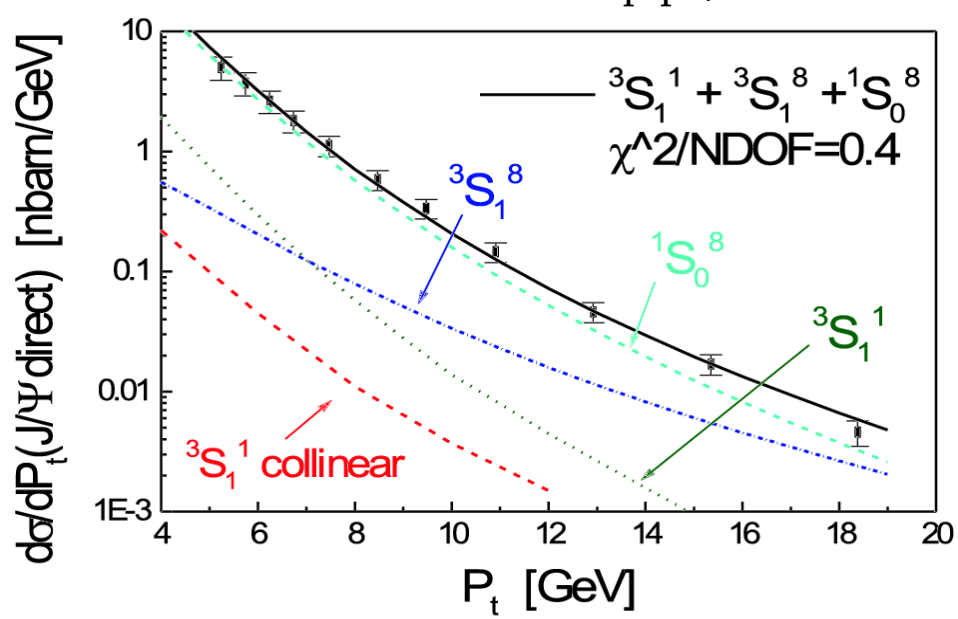


Hägler et al., hep-ph/0004263



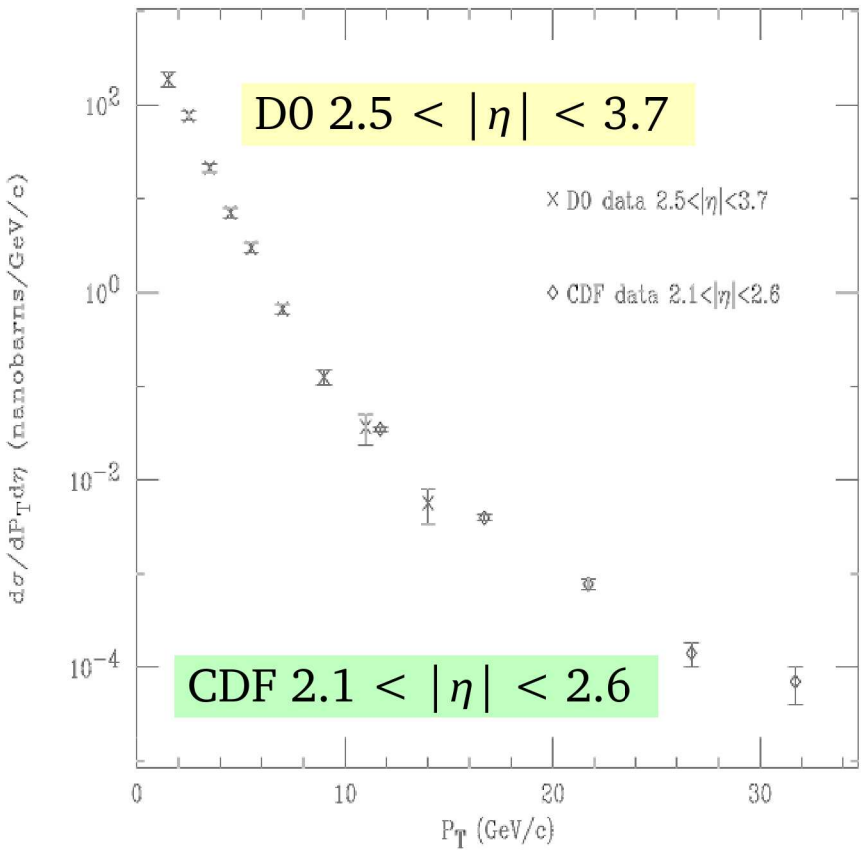
(also Yuan, Chao)

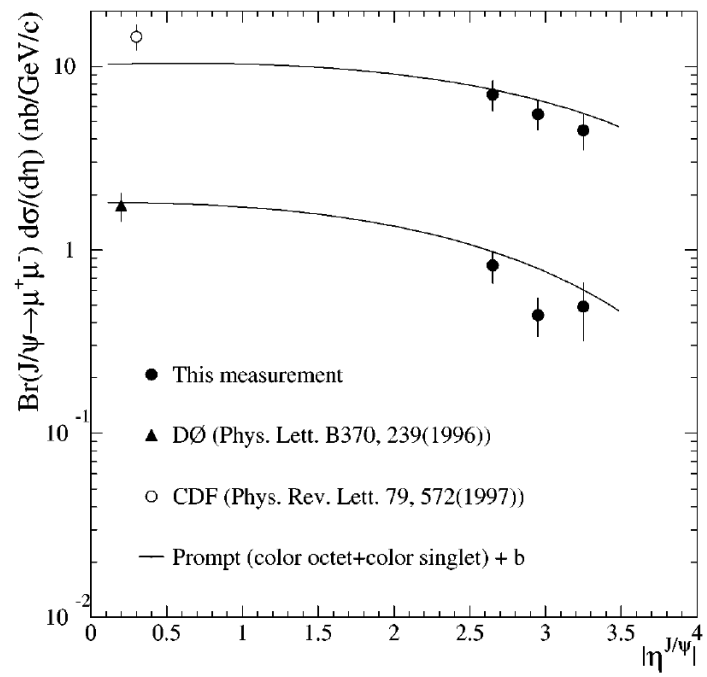
Hägler et al., hep-ph/0008316



Forward J/ψ Production

CDF: FNAL-PUB-02/188-E
D0: PRL 82(1999)35





p_T>5GeV

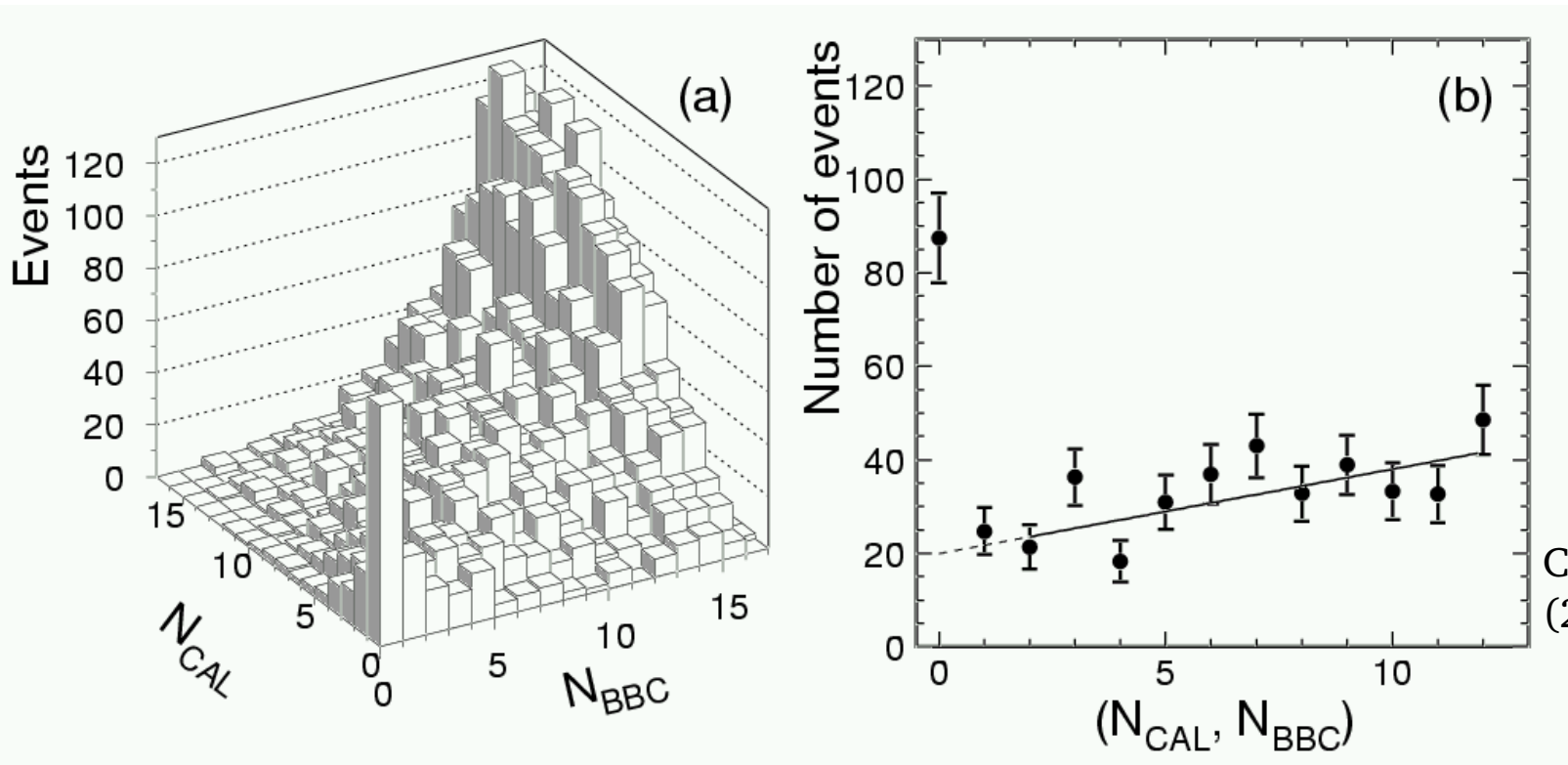
p_T>8GeV

Reasonable agreement between central and forward measurements

(CDF Run 2: intermediate coverage ($|\eta|$<1.5) replacing forward muon spectrometer)

Diffractive J/ψ Production

- Use Beam-Beam-Counters and forward calorimeter towers to “tag” diffractive events (gap in $2.4 < |\eta| < 5.9$)



$|\eta_\psi| < 1.0$

CDF, PRL 87 (2001) 251803

Ratio of diffractive to total production rate: $R_\psi = 1.45 \pm 0.25$ %

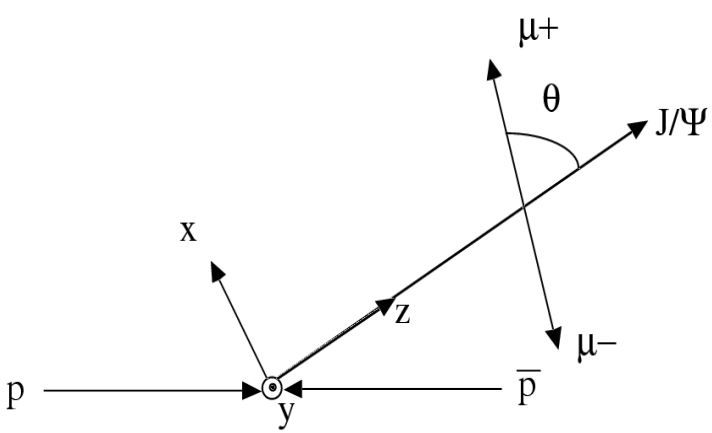
J/ψ Polarization

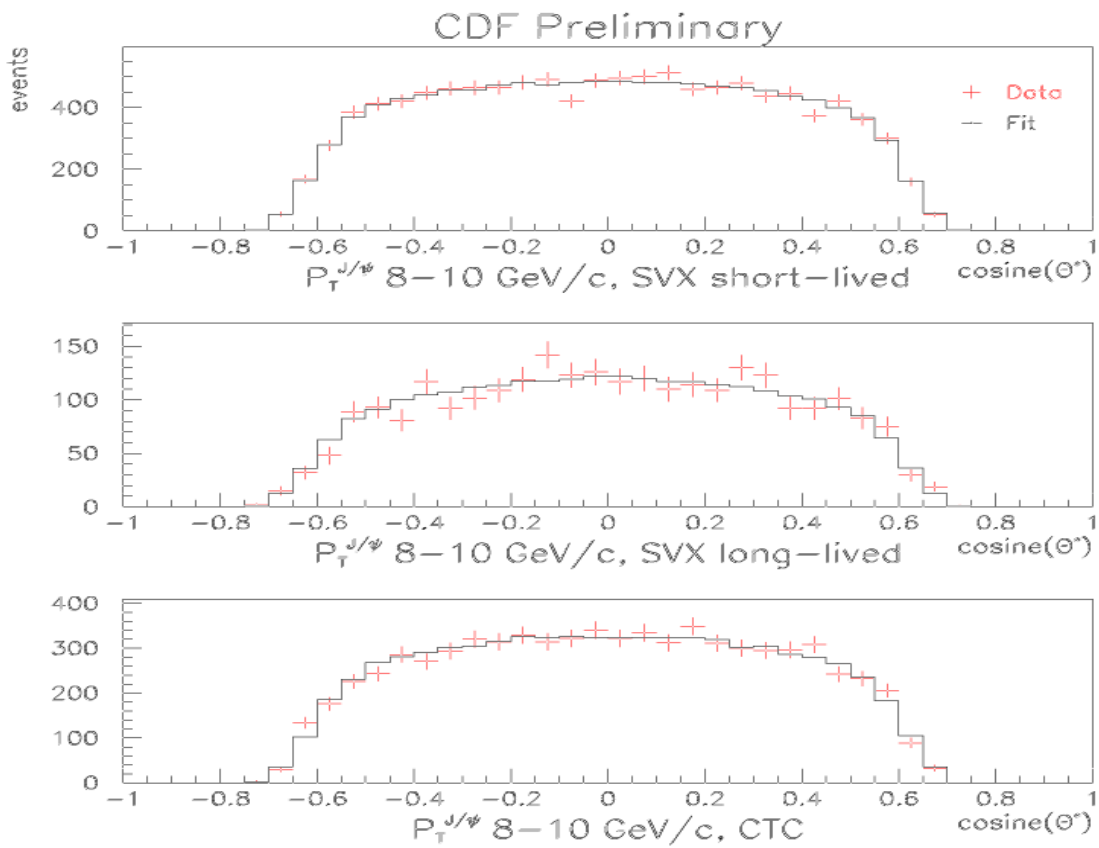
- All CDF Run 1 data, $\int L\,dt \simeq 110\ pb^{-1}$
- $p_T > 4$ GeV, $|y| < 0.6$
- Small acceptance at large $|\cos\theta|$
- χ^2 fit using templates for longitudinal and transverse polarization

$$d\Gamma / d\cos\theta \propto 1 + \alpha \cos^2\theta$$

$\alpha = 1$ transverse

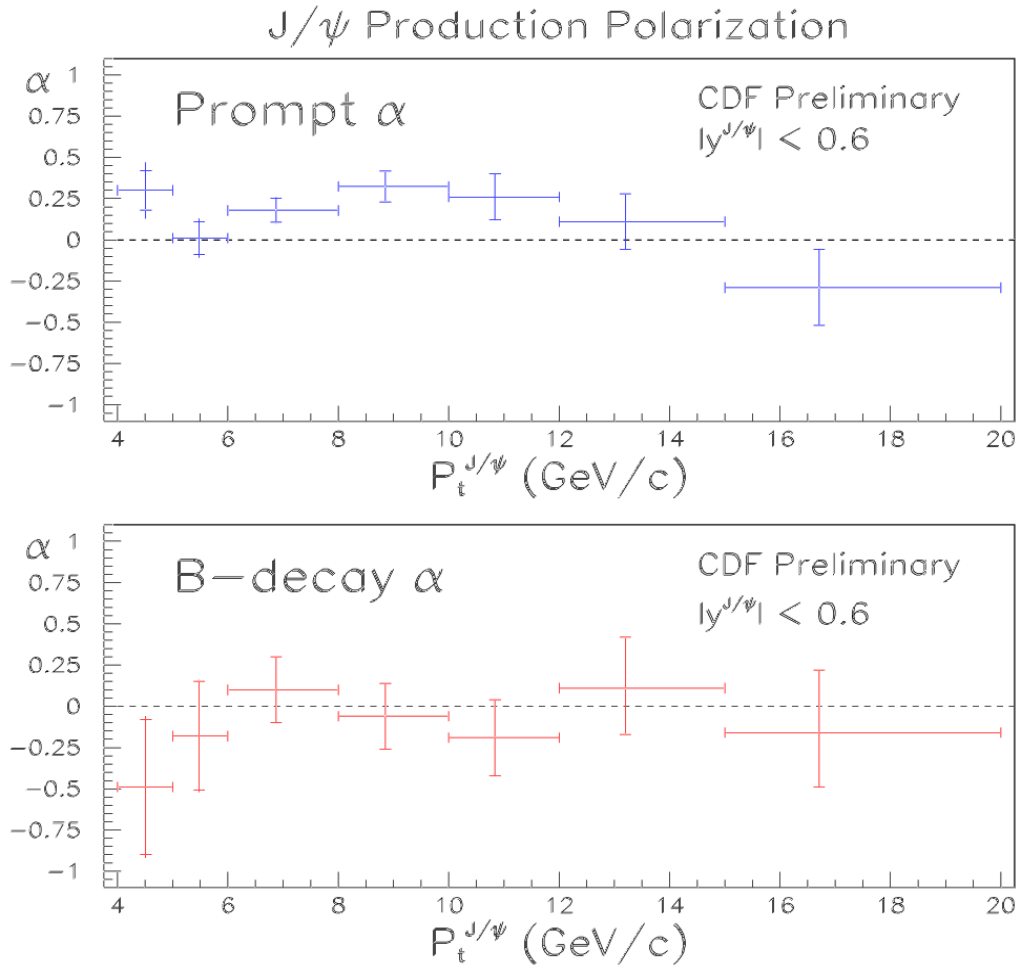
$\alpha = -1$ longitudinal





CDF, PRL 85 (2000) 2886

J/ψ Polarization

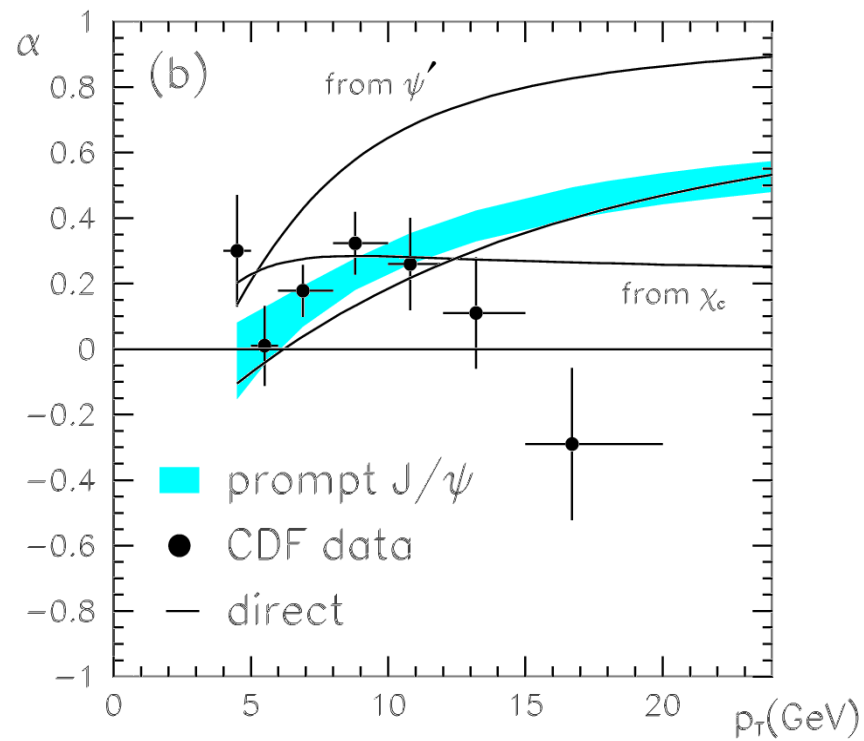


J/ψ from B decays essentially unpolarized

CDF, PRL 85 (2000) 2886

Prompt J/ψ Polarization

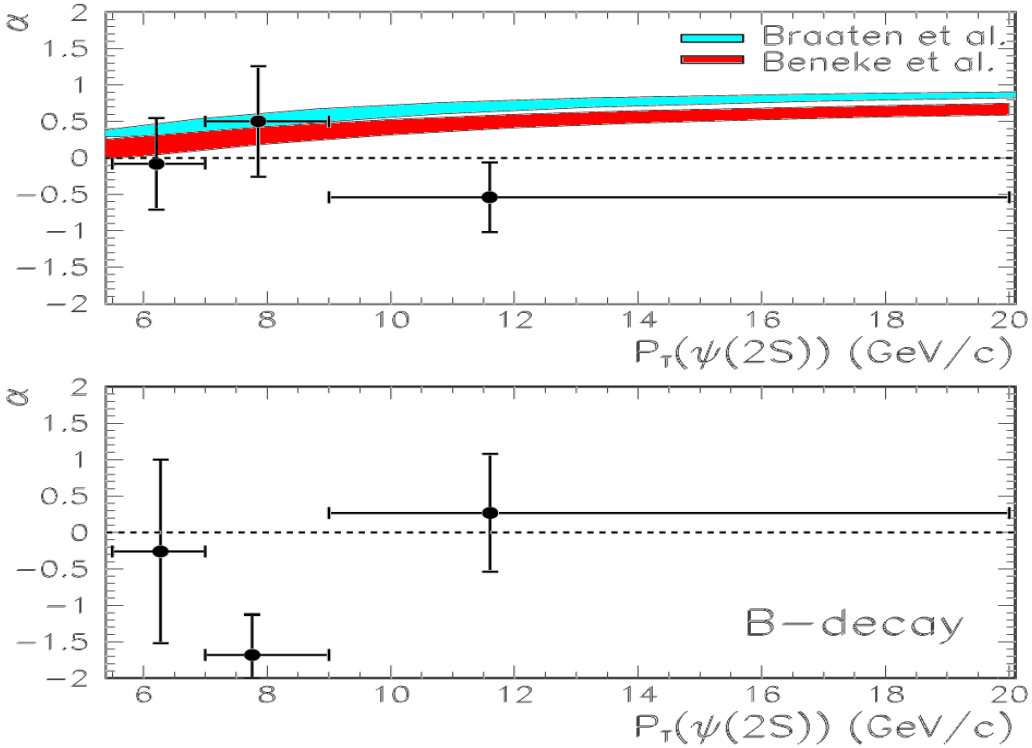
- Need to take into account ψ(2S) and χ_c contributions
- Data do not show a trend towards transverse polarization at large p_T
- Phenomenological models give better description
  - E.g. colour evaporation model: mostly unpolarized J/ψ at large p_T



Braaten, Kniehl, Lee
hep-ph/9911436

$\psi(2S)$ Polarization

- Same procedure, but limited statistics
- Preferable to J/ψ since no contamination from indirect production
- Inconclusive

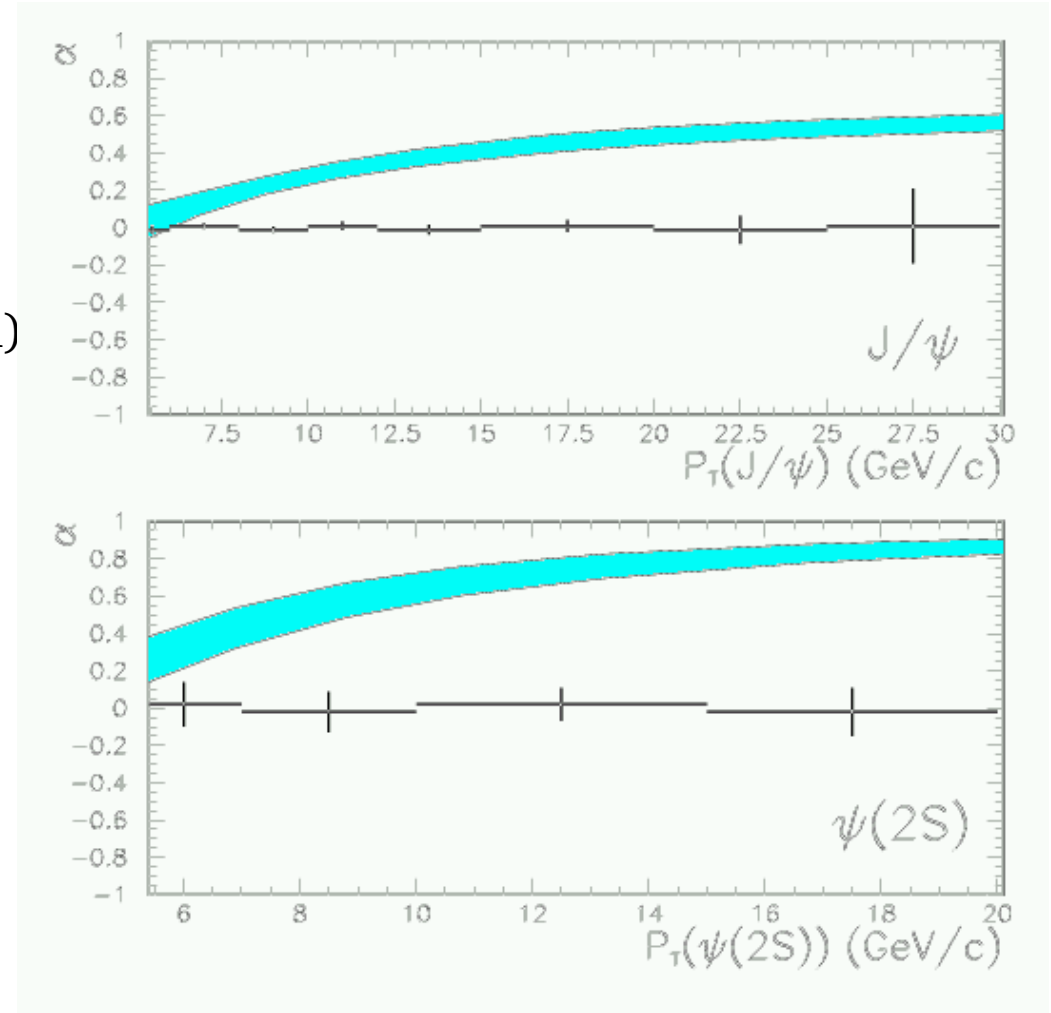


CDF, PRL 85 (2000) 2886

Polarization in Run II

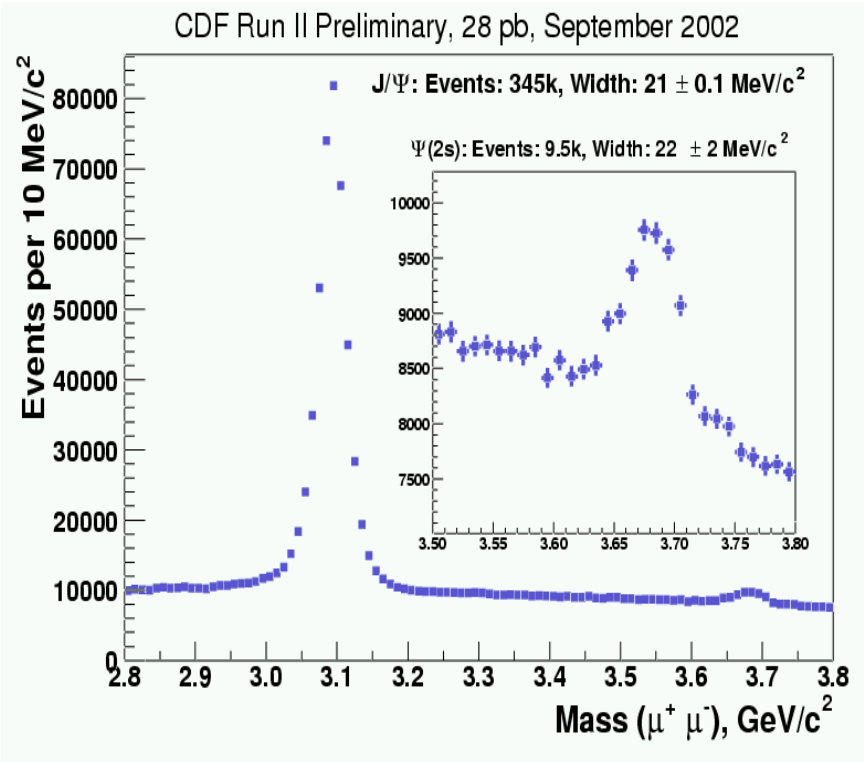
CDF study:

- Assume factor 50 in effective statistics
  - Integrated luminosity 2 fb^{-1} (Run 2a)
  - Better SVX coverage (separate prompt/B)
- Lower dimuon trigger threshold (1.5GeV)
  - Will be able to measure down to $p_T(\psi) \simeq 0$
- Systematic uncertainties still small at larger p_T

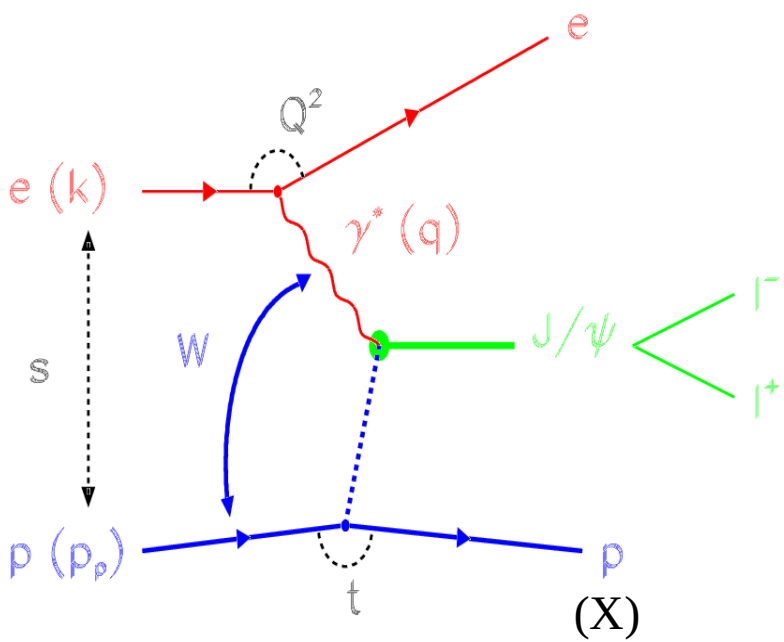


Prospects for Run II

- $\int L\,dt \simeq 2\ fb^{-1}$ in about 2-3 years, $\int L\,dt \simeq 10\text{-}15\ fb^{-1}$ by 20<*LHC*>
  - Run II is well underway, data samples comparable Run I now
- Will get many J/ψ's and $\psi(2S)$ for free, but
  - Is the charm system massive enough?
  - For J/ψ, will always have feed-down to J/ψ final states
- For most measurements, there are now 2 experiments
- Also better muon coverage, improved trigger capabilities, decays into e^+e^- (?)
- There will be other possible measurements that can shed light on the colour octet issue
  - h_c, η_c, ... production cross sections
  - Associated jets in direct production



Quarkonia at HERA

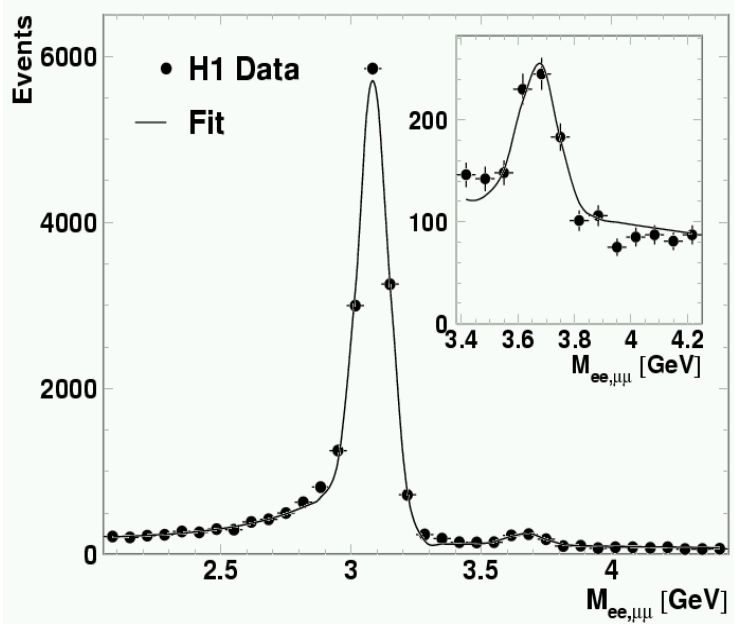


$$Q^2 := -q^2$$
$$W^2 := (p_p + q)^2 \simeq Q^2/x$$
$$Q^2 \simeq x\,y\,s$$

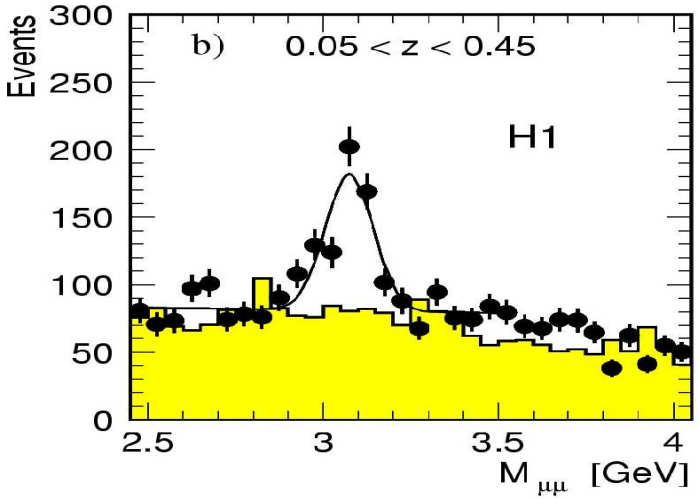
- DIS
  - $1 < Q^2 < 100$ GeV^2
- Tagged/untagged photoproduction
  - Scattered e not seen in main detector
  - Median $Q^2 \simeq 10^{-4}$ GeV^2
- Decays into e^+e^- and $\mu^+\mu^-$
- Central tracking ($|\eta| < 1.8$)
  - $30 < W < 180$ GeV
  - In addition, dedicated analyses with specific statistical and systematic limitations (forward muon spectrometer, backward calorimetry, ...)

J/ψ at HERA

$$z = \frac{P_p \cdot P_\Psi}{P_p \cdot P_\gamma} = \frac{E_\Psi}{E_\gamma} \quad \text{in p rest frame}$$

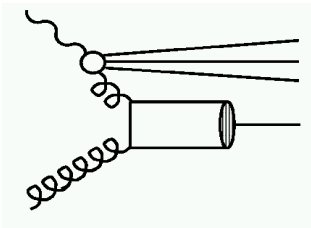


- Order of magnitude comparable
  - "Elastic" $z \simeq 1$ ($M_X = m_p$)
  - p diffractive dissociation $z \simeq 1$ ($\sigma \propto 1/M_X^2$)
  - "Inelastic" $z < 1$
- At small z contributions from
  - Resolved photon
  - B production
- Background increases with decreasing z

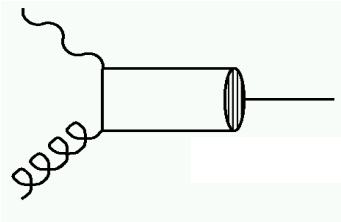


HERA Production Mechanisms

Inelastic

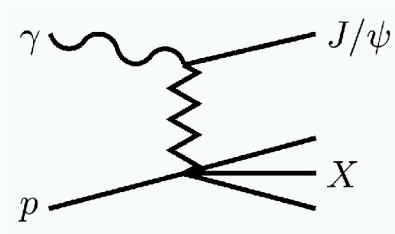


"resolved" (gg-fusion)
(z<0.3)

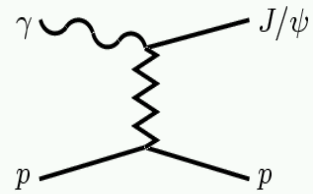


direct (γg-fusion)
(z>0.3)

p-dissociation



Elastic



J/ψ from $\psi(2S)$ decays ($\psi(2S) \to J/\psi\pi\pi$ and others)
(not subtracted, measured, ~ 15%)

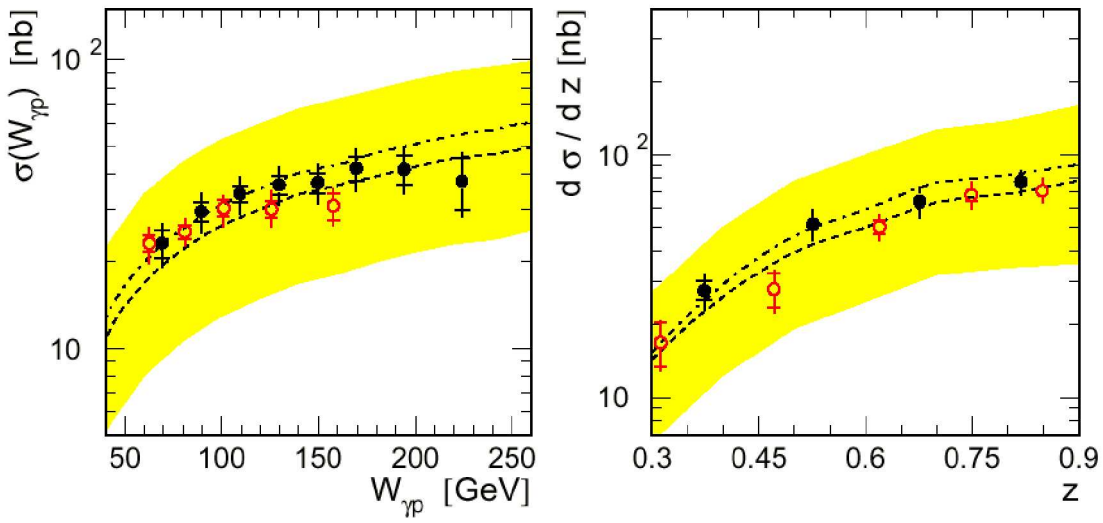
J/ψ from χ_c decays (not subtracted)
(1% of inelastic, up to 7% at lowest z)

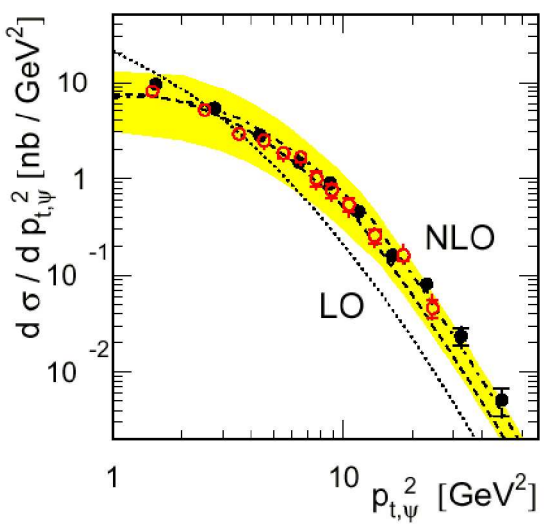
J/ψ from B decays (not subtracted)
(5% of inelastic, up to 25% at lowest z)

Cut on z, (fwd.) energy, add'l tracks, ...

"Forward tagging"

J/ψ Photoproduction: CSM





H1
CSM NLO
CSM LO
ZEUS (scaled)

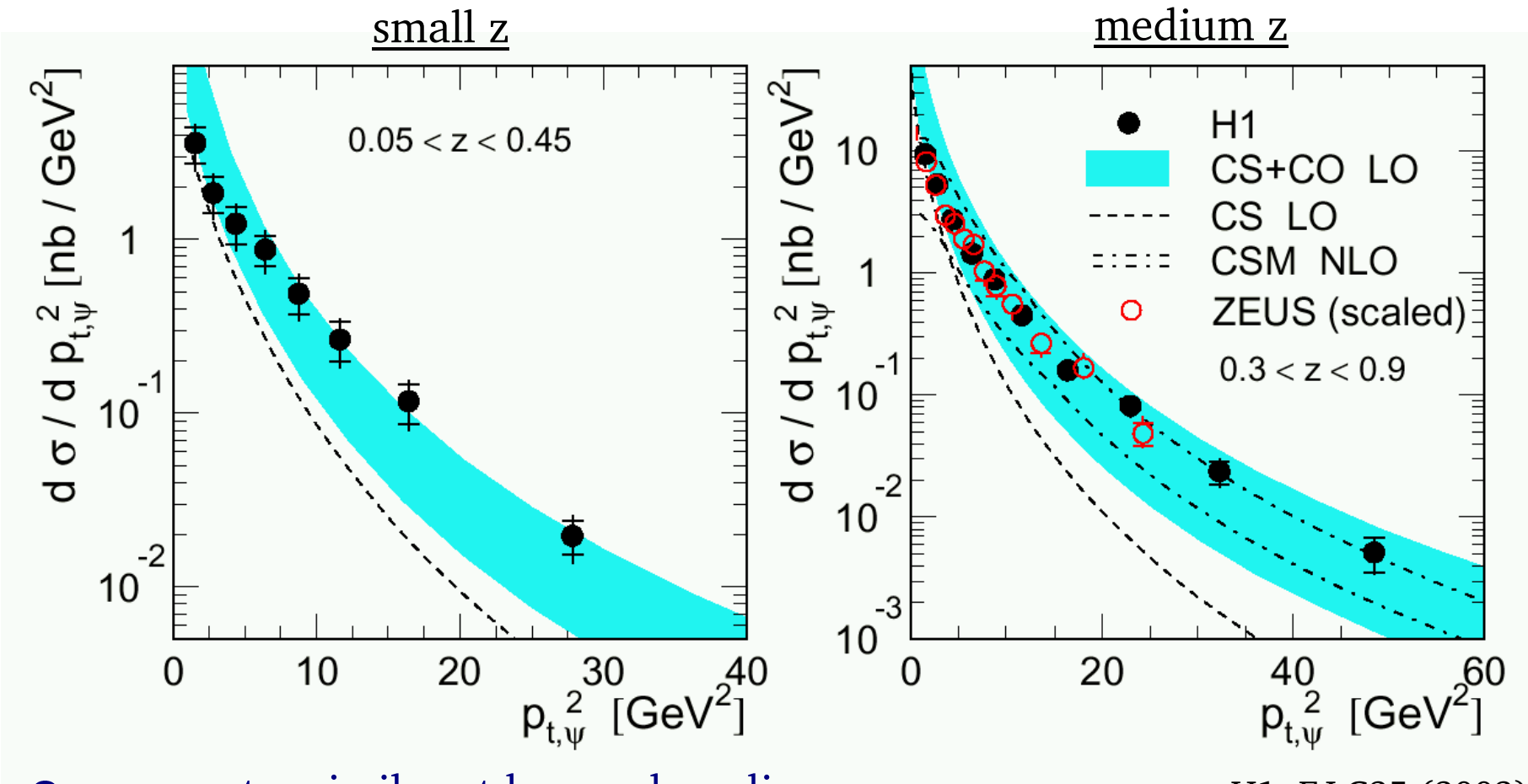
Colour Singlet Model: NLO calculation of direct photon gluon fusion process (M.Krämer)

LO: too steep
NLO: good agreement

Errorbands: $1.3 \leq m_c \leq 1.5$ GeV
$0.1175 \leq \alpha_s(M_Z) \leq 0.1225$

H1: EJ C25 (2002) 25
Zeus: DESY 02-163

J/ψ Photoproduction: NRQCD I

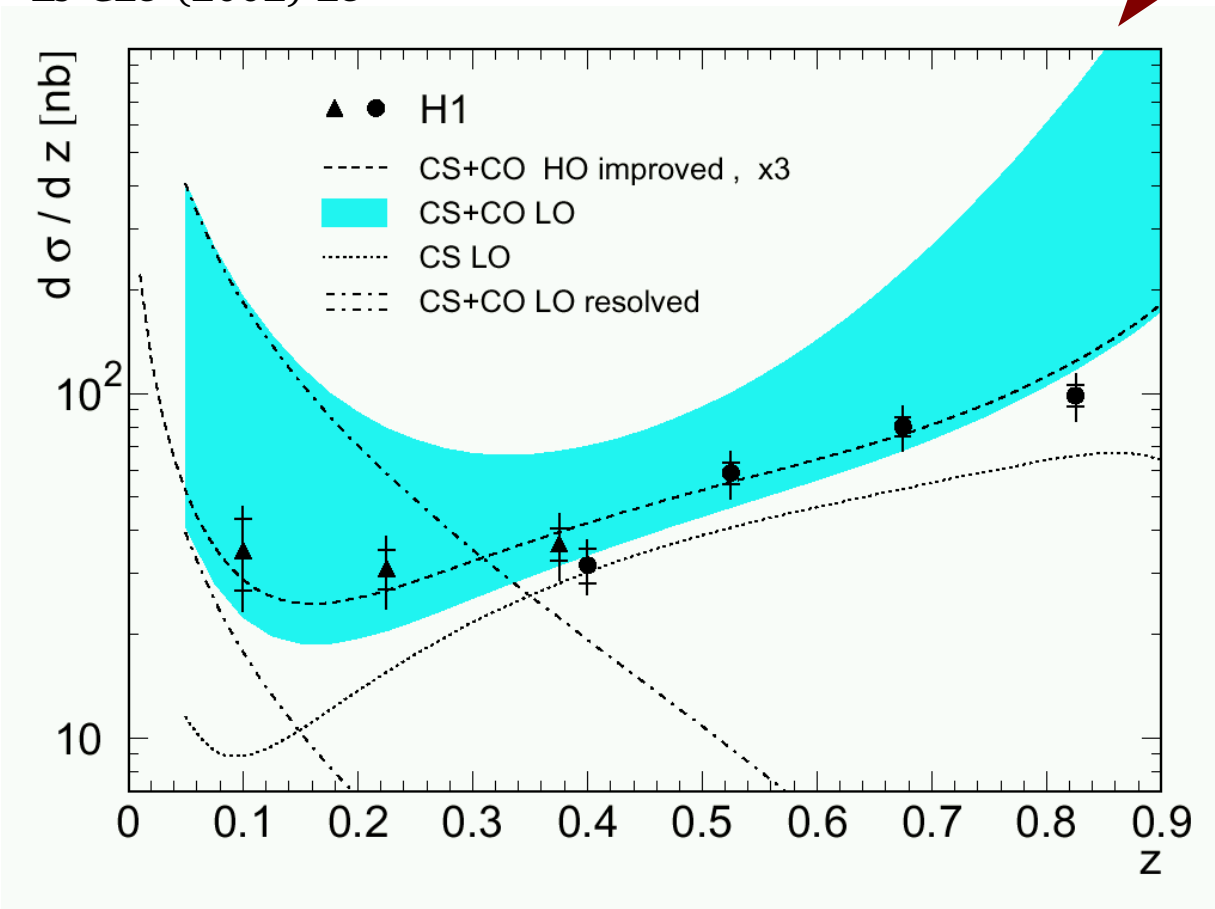


- p_T spectra similar at low and medium z
- NRQCD (including CS and CO): softer than data
  - Contributions from B decays in data?

H1: EJ C25 (2002) 25
Zeus: DESY 02-163

J/ψ Photoproduction: NRQCD II

EJ C25 (2002) 25



This used to be the "other" HERA anomaly

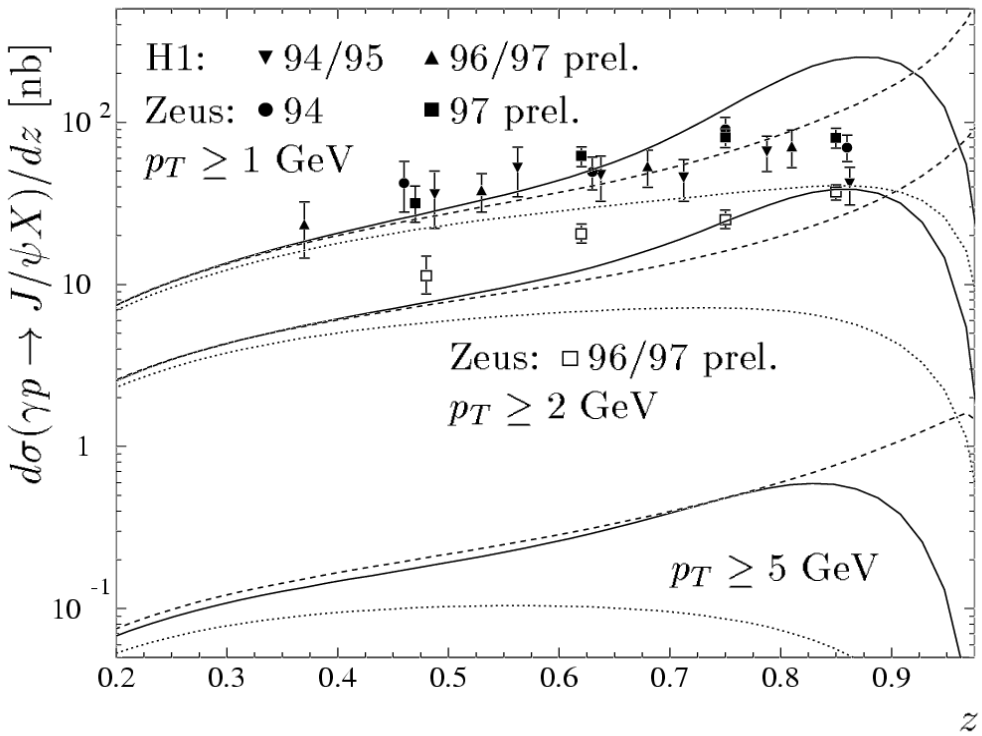
NRQCD (CS+CO): LO calculation including direct and resolved photon process (M.Krämer)

CO long-distance ME taken from fit to CDF data

Leading order NRQCD: fair description of the data
HERA data favor smaller value of LDME than Tevatron

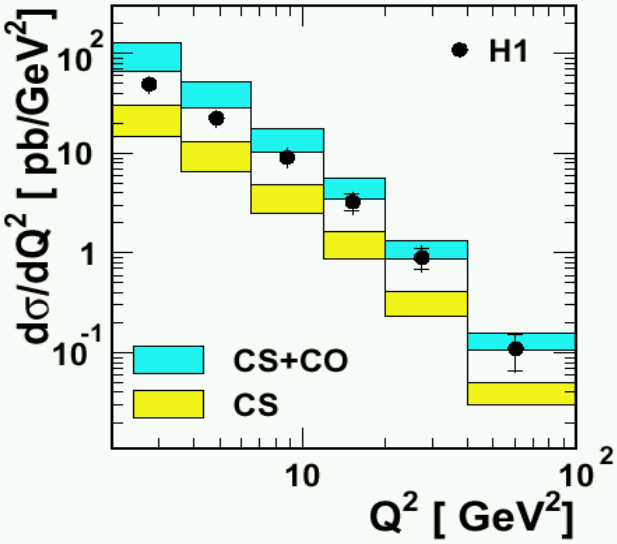
J/ψ Photoprod'n: Shape Functions

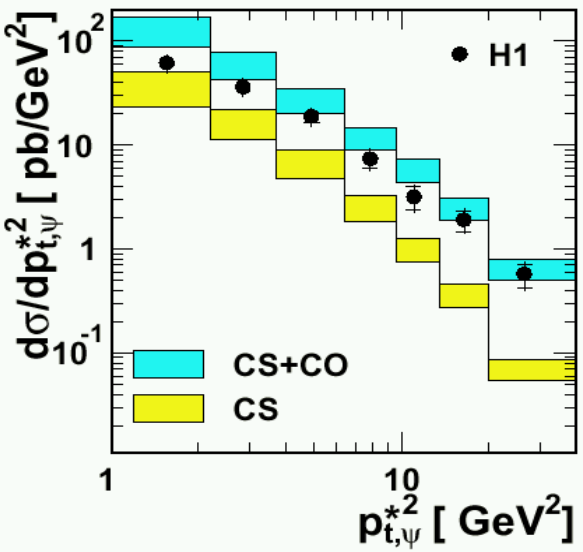
- Breakdown of NRQCD velocity expansion near the kinematic endpoint, when the J/ψ carries close to its maximal energy
  - $z > 1 - v^2 \simeq 0.7$
- Resummation of contributions from soft gluons at large z
  - Shape functions for each production channel
- Improved description of the data
- Less predictive power of theory
  - Need higher p_T



Beneke, Schuler, Wolf, PRD 62(2000)034004
Wolf, hep-ph/0008180

J/ψ Electroproduction





Data: $2 < Q^2 < 100$ GeV^2 EJ C25 (2002) 41
$0.3 < z < 0.9$
$50 < W < 225$ GeV
$p_T^* > 1$ GeV
$\int L\,dt = 77$ pb^{-1}

Theory: LO Colour Singlet Model
LO NRQCD (CS+CO)
(B.A.Kniehl, L.Zwirner, NP B621(2002) 337)

CS alone: normalization low, too steep in p_T

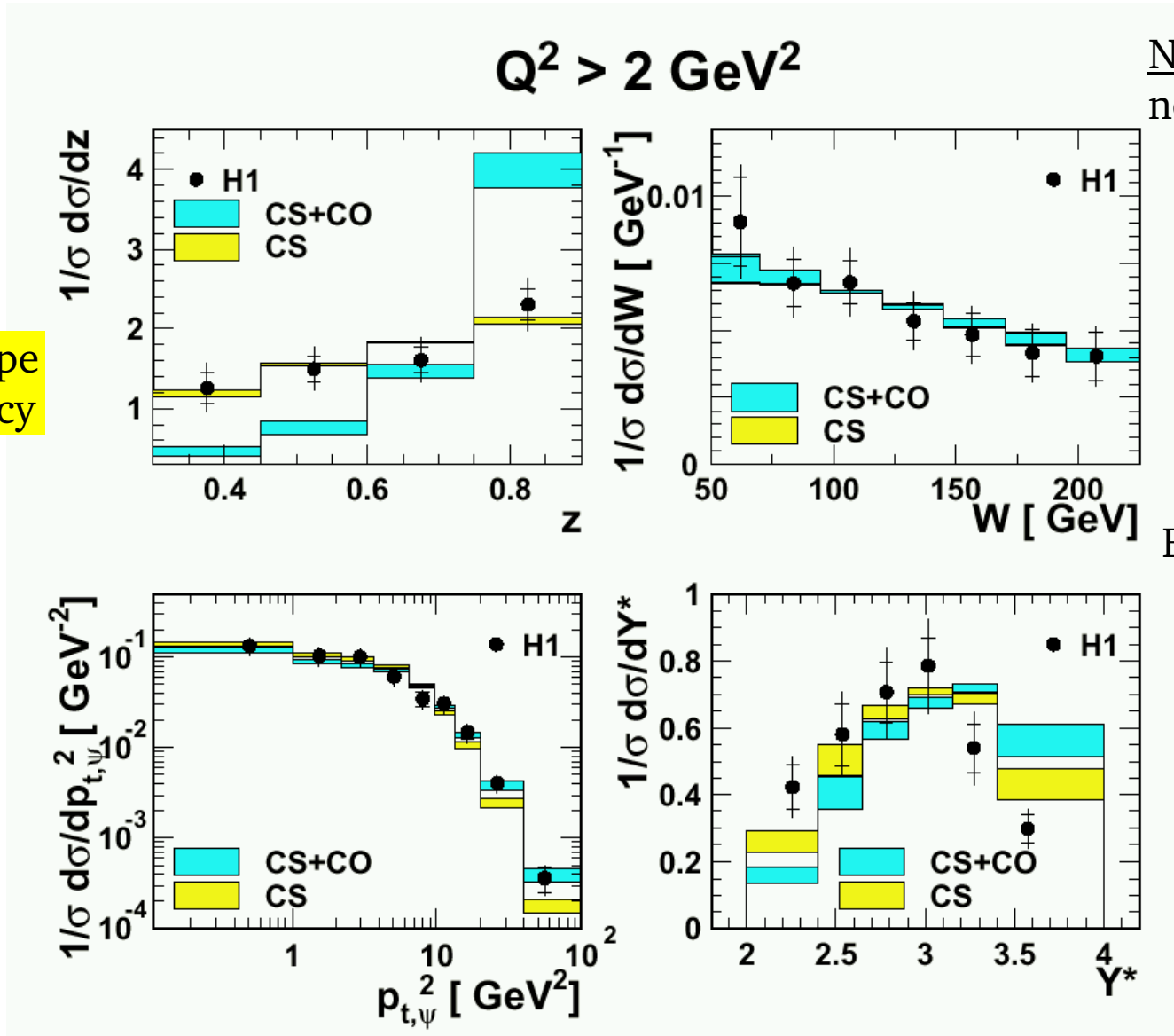
NRQCD (CS+CO): too high at low Q^2, p_T
better at high Q^2, p_T

Need: NLO calculations
More data at larger Q^2, p_T

J/ψ Electroproduction

Note: Theory normalized to data

Large shape discrepancy



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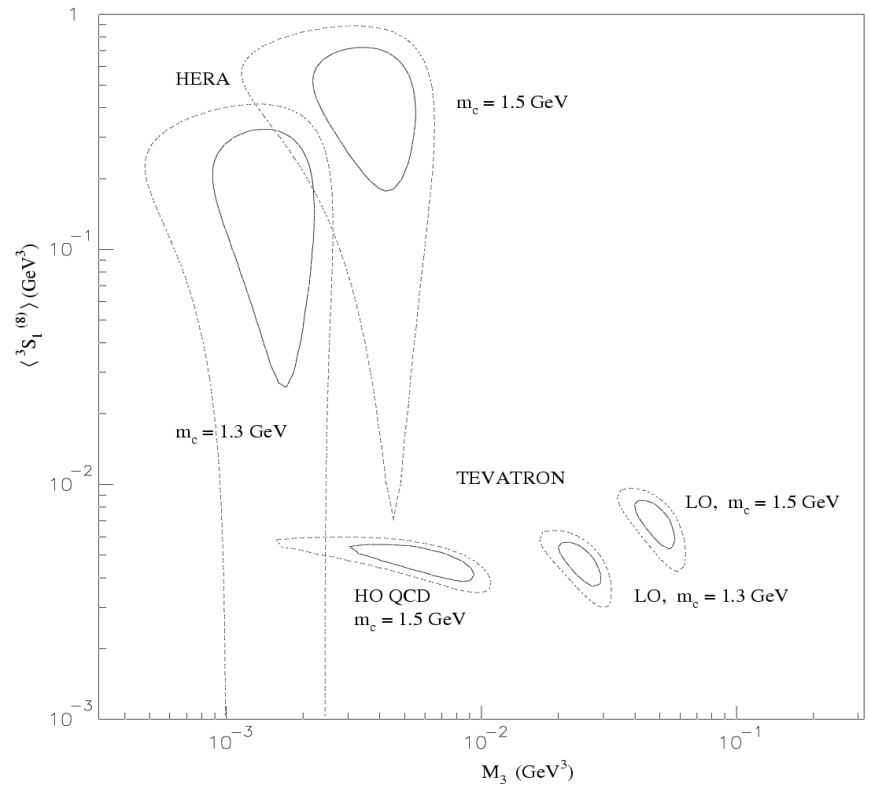
Rapidity in γp CMS

HERA vs. Tevatron ME

- Only use theoretically safe regime: p_T^2, $Q^2 > 4\ \mathrm{GeV}^2$, $M_X > 10$ GeV
  - Statistics limited in 1999
- Consistent description difficult
- Repeat including recent data?
- Common fit?



J.K.Mizukoshi,
hep-ph/9911384

J/ψ Polarization (γp)

$\cos\theta^*$: angle of μ^+ relative to proton in J/ψ rest frame

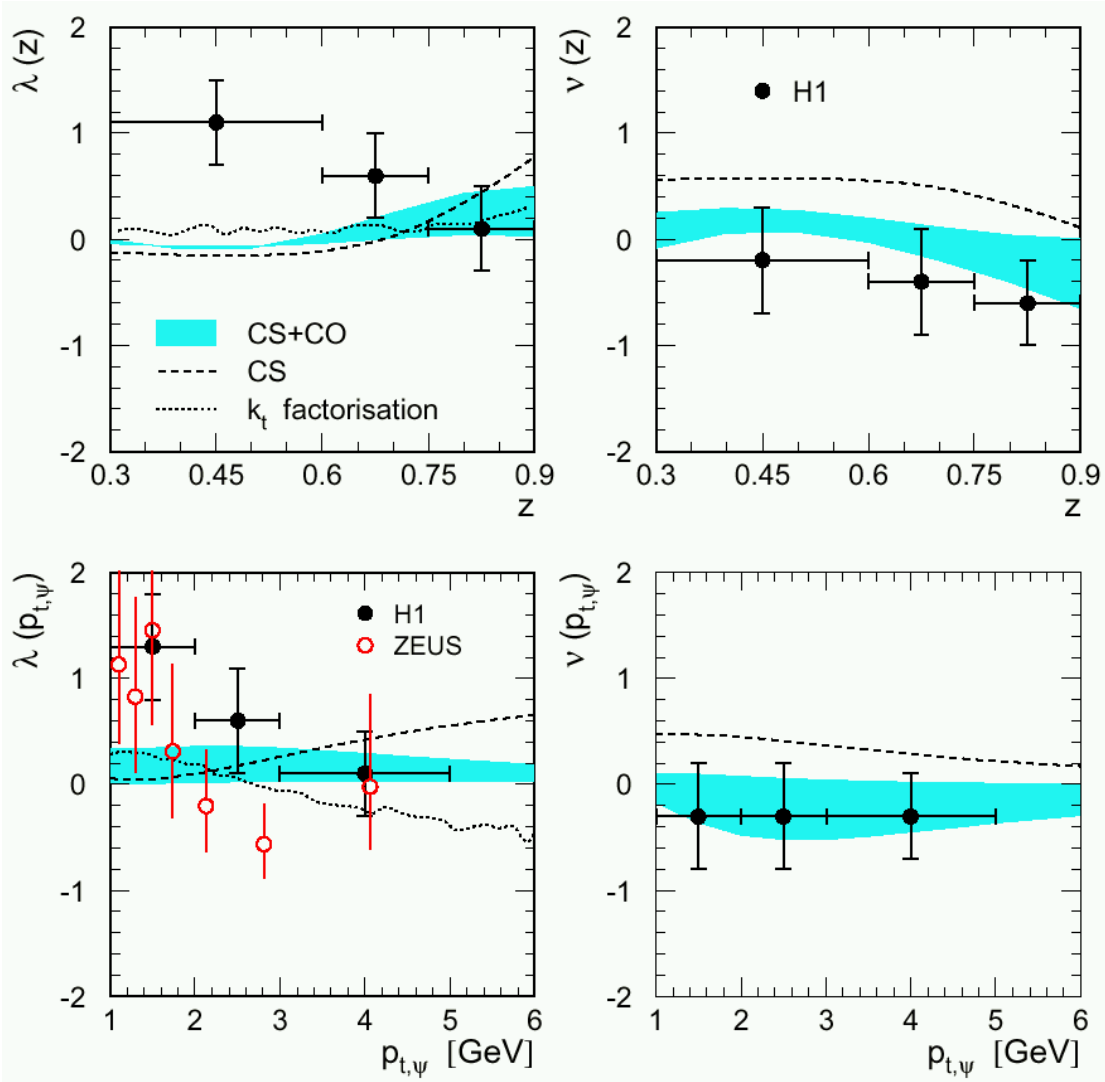
$\cos\phi^*$: angle of μ^+ in plane perp. to incoming photon

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

$$\frac{1}{\sigma}\frac{d\sigma}{d\Phi^*} \propto 1+\frac{\lambda}{3}+\frac{\nu}{3}\cos 2\Phi^*$$

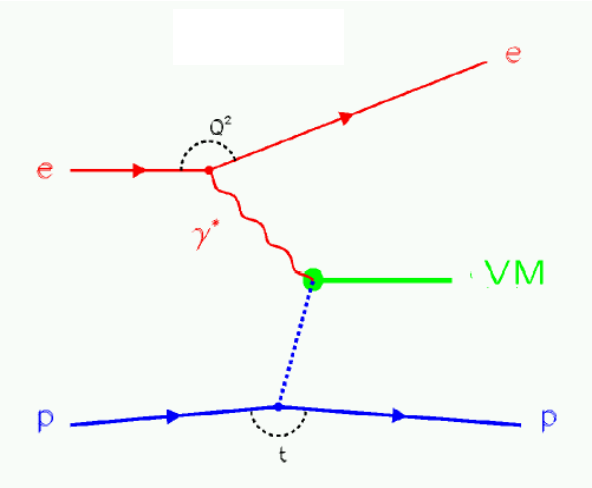
Uncertainties in data still large, more statistics at higher p_T required to discriminate between models

Similar conclusions in DIS



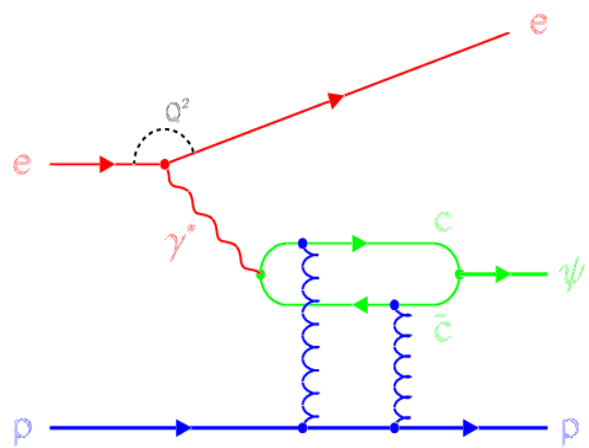
H1: EJ C25 (2002) 25
Zeus: DESY 02-163

Elastic VM Production



VM	Vector Meson	$\rho, \omega, \phi, J/\psi, \psi', \Upsilon$
Q^2	Photon virtuality	$0 < Q^2 < 100$ GeV^2
W	CM energy of γp system	$20 < W < 290$ GeV
t	(4-mom. transfer)^2	$0 < \lvert t \rvert < 20$ GeV^2

Can control all these variables at HERA



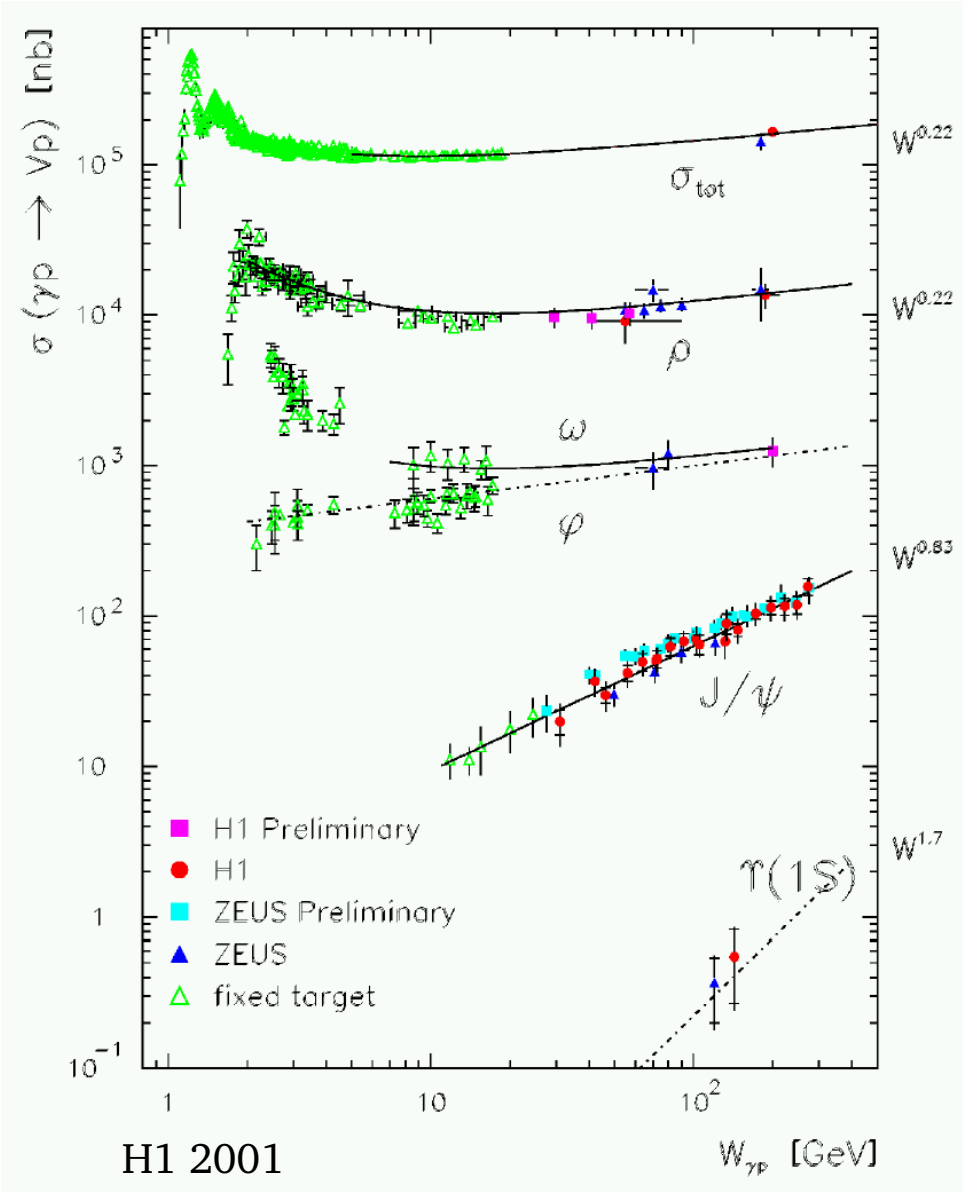
"soft"	**vs.**	**"hard" interaction**
soft Pomeron		two-gluon/gluon ladder
weak energy dep $\propto W^{0.22}$		steep energy dep $\propto W^{0.8}$
$\sigma \propto e^{bt}$ with $b \gg 5$ GeV^{-2}		$b \simeq 4$-5 GeV^{-2}
b energy dep ("shrinkage")		no/less shrinkage
...		...

$\Rightarrow$ **Testbed for QCD scales**
Sensitive to gluon density

Elastic VM Production: W

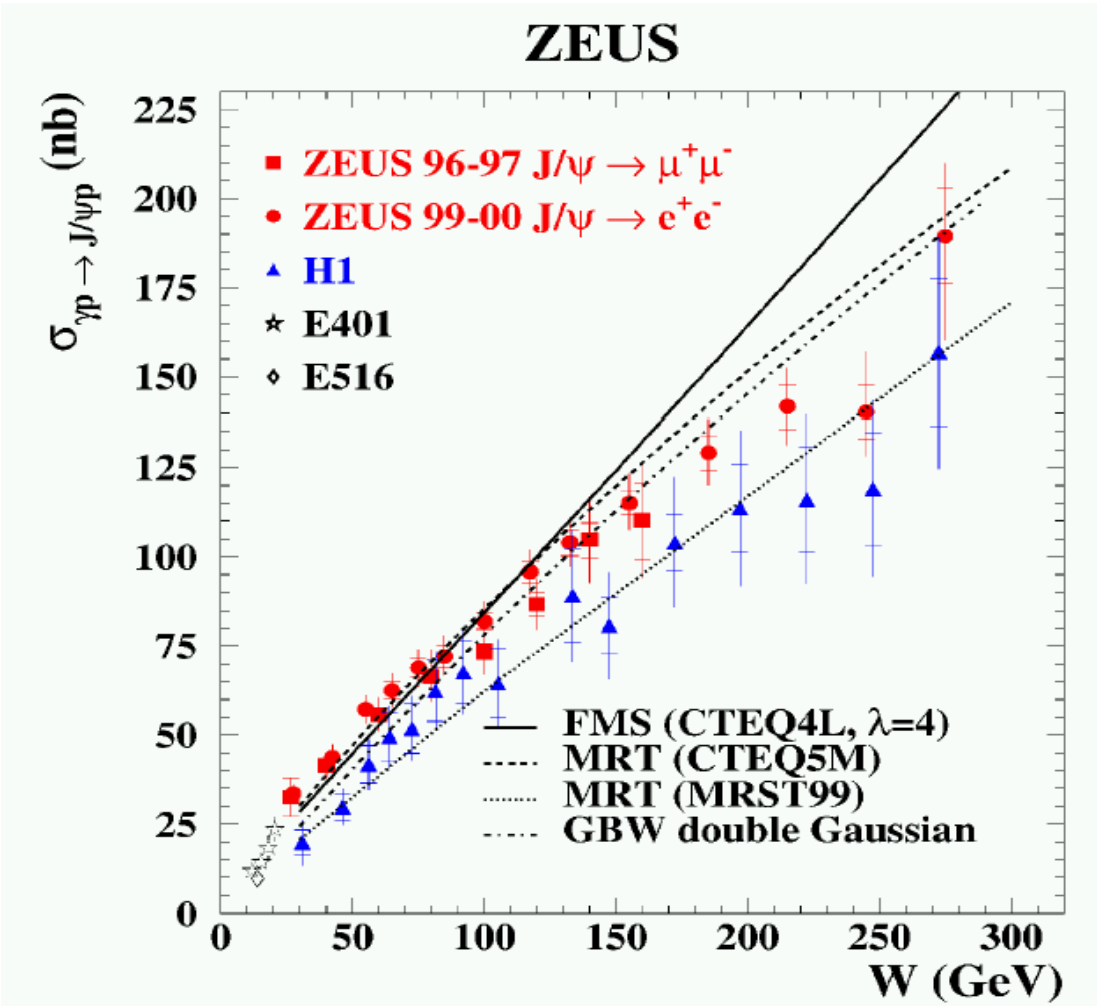
- "Soft" Pomeron exchange: slow rise of cross section $\propto W^{0.22}$
- Increasing M_{VM}: transition from "soft" to "hard" regime
- Strong rise of the cross section with W as signature for "hard" process
- "Hard" process (pQCD applicable) for J/ψ already in photoproduction
  - Steep rise of cross section driven by gluon density:

$$\sigma_{\gamma p} \propto \left[\alpha_s(Q^2_{eff})\, x\, g(x, Q^2_{eff}) \right]^2$$



H1 2001

Elastic J/ψ Photoproduction: W



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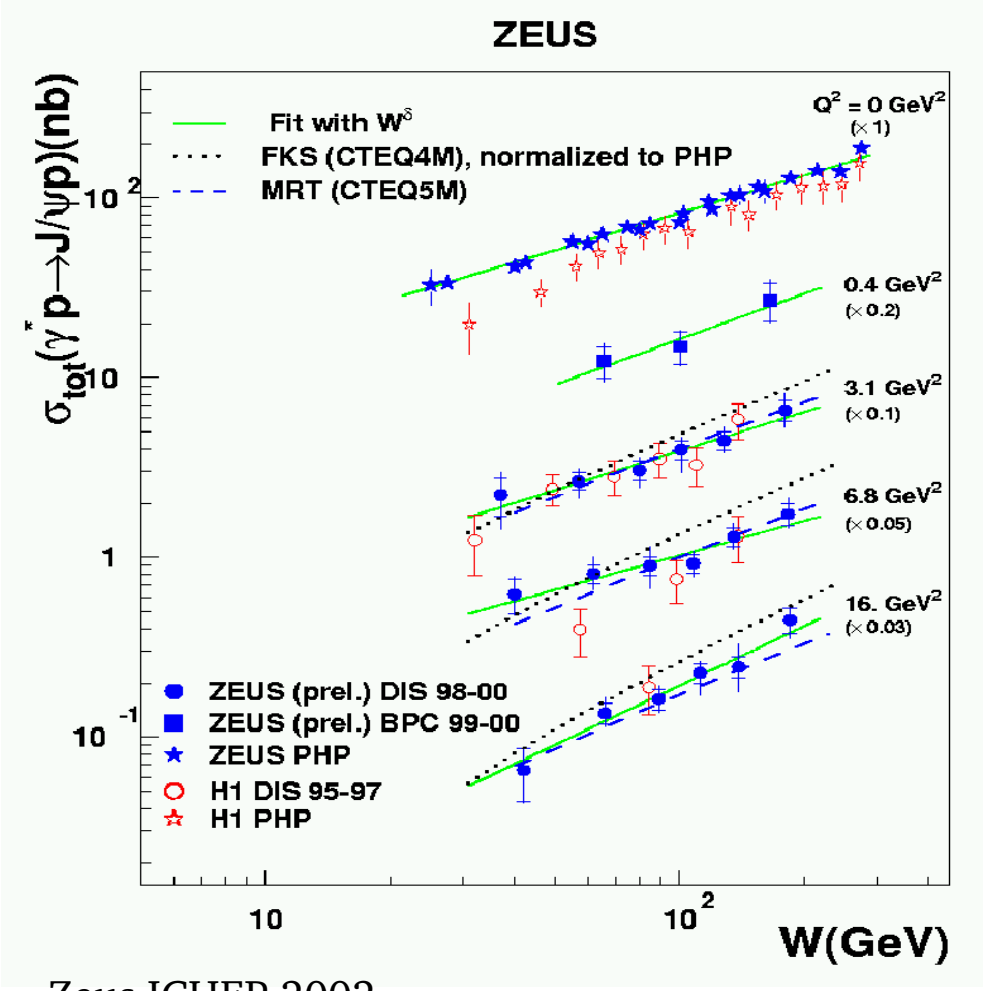
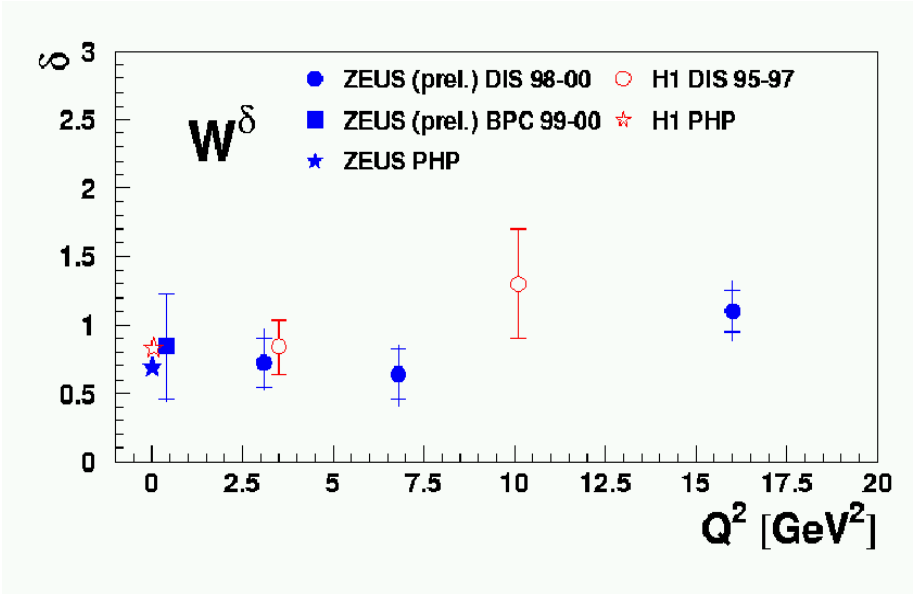
- pQCD-inspired models describe data
- Large spread in model predictions
  - Choice of wave function
  - Parton density functions
  - Charm quark mass
  - Fermi motion
- Normalization H1 ↔ Zeus?
- $\sigma \propto W^{\delta}$ with
  $\delta = 0.69 \pm 0.04$ (Zeus)
  $\delta = 0.83 \pm 0.07$ (H1)

Elastic J/ψ Electroproduction



Zeus ICHEP 2002



Steep rise of σ depends weakly on Q^2

Reasonable description by pQCD-based models

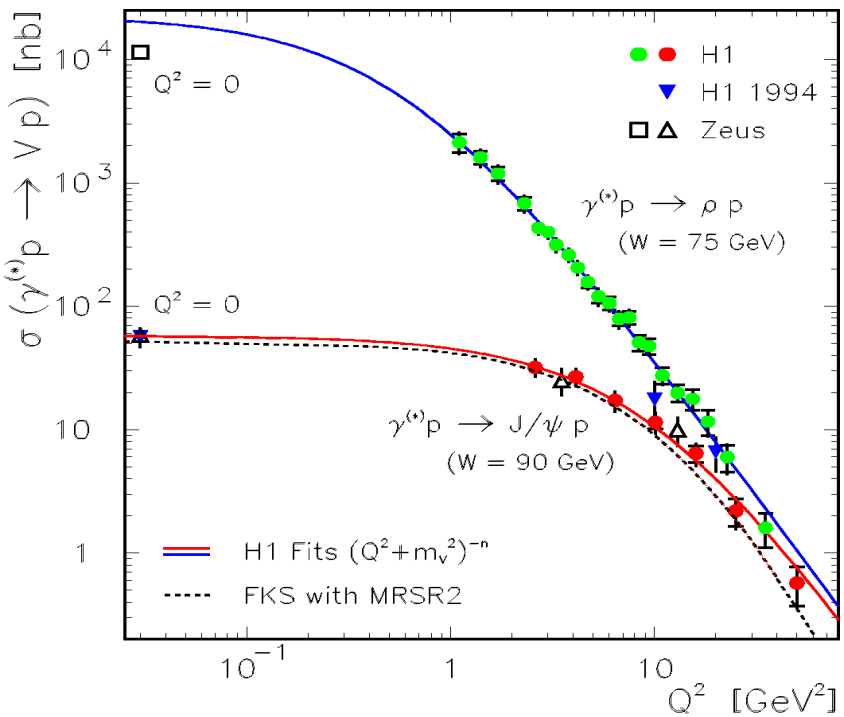
Elastic J/ψ Production: Q^2

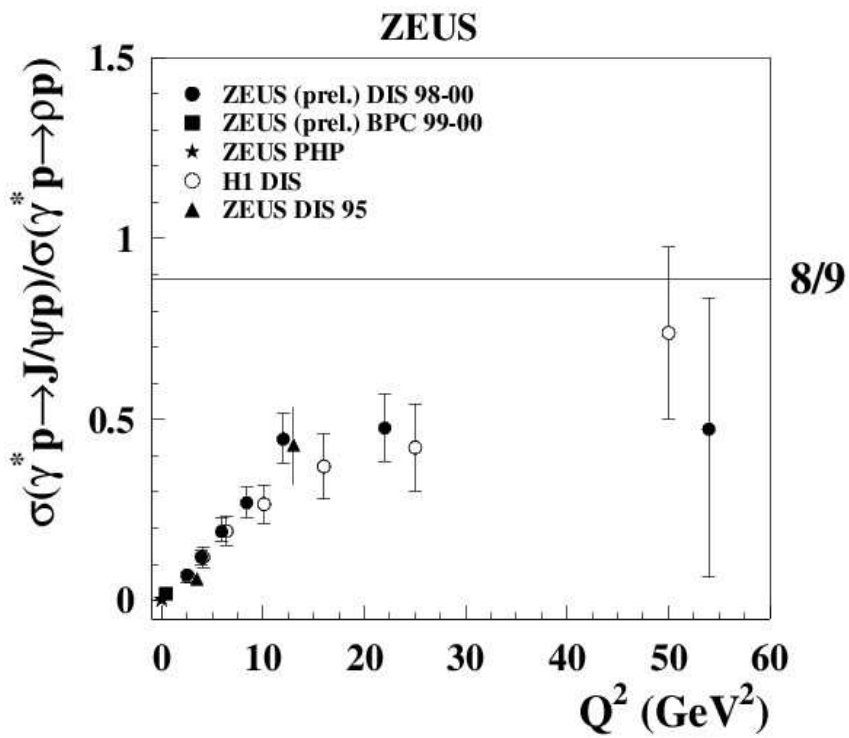
- Data are well described by the functional form

$$\sigma_{\gamma p \to J/\Psi p} \propto \left(\frac{1}{Q^2 + m_\Psi^2} \right)^n \quad \text{with} \quad n \simeq 2.4$$

- ρ and J/ψ cross sections comparable at large Q^2

Zeus ICHEP 2002
H1 EJ C10 (1999) 373



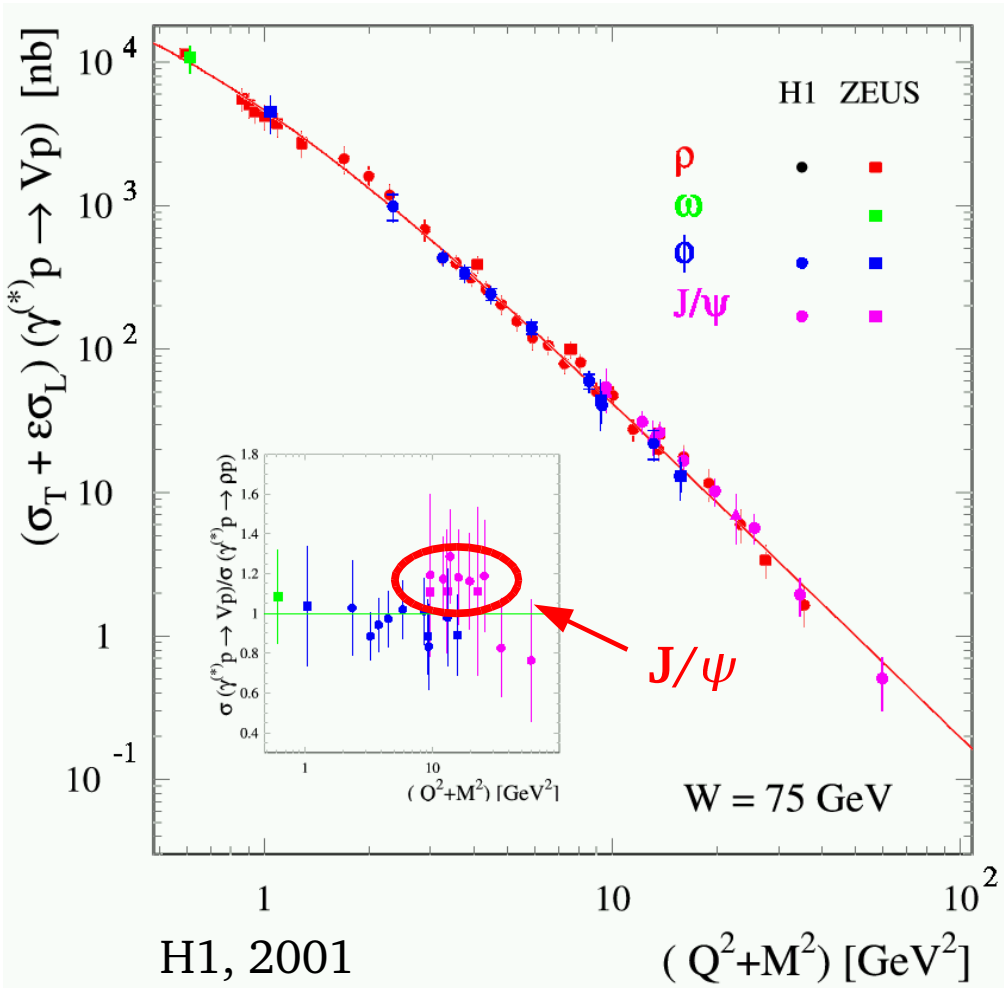


Universality in VM Production

- In search of the relevant scale
  - Q^2, m_V^2, t
- $(Q^2 + m_V^2) \sim$ universal?
- Photon couples to quarks, and VM - proton interaction is universal
- Fit to $(Q^2 + m_V^2 + a)^b$ (ρ data)
  - $a = 0.42 \pm 0.09$ GeV^2
  - $b = - 2.37 \pm 0.10$
- Measurements at large t
  - VM cross section ratios rise faster with t than with Q^2
  - t plays a different role

Cross sections scaled according to quark content

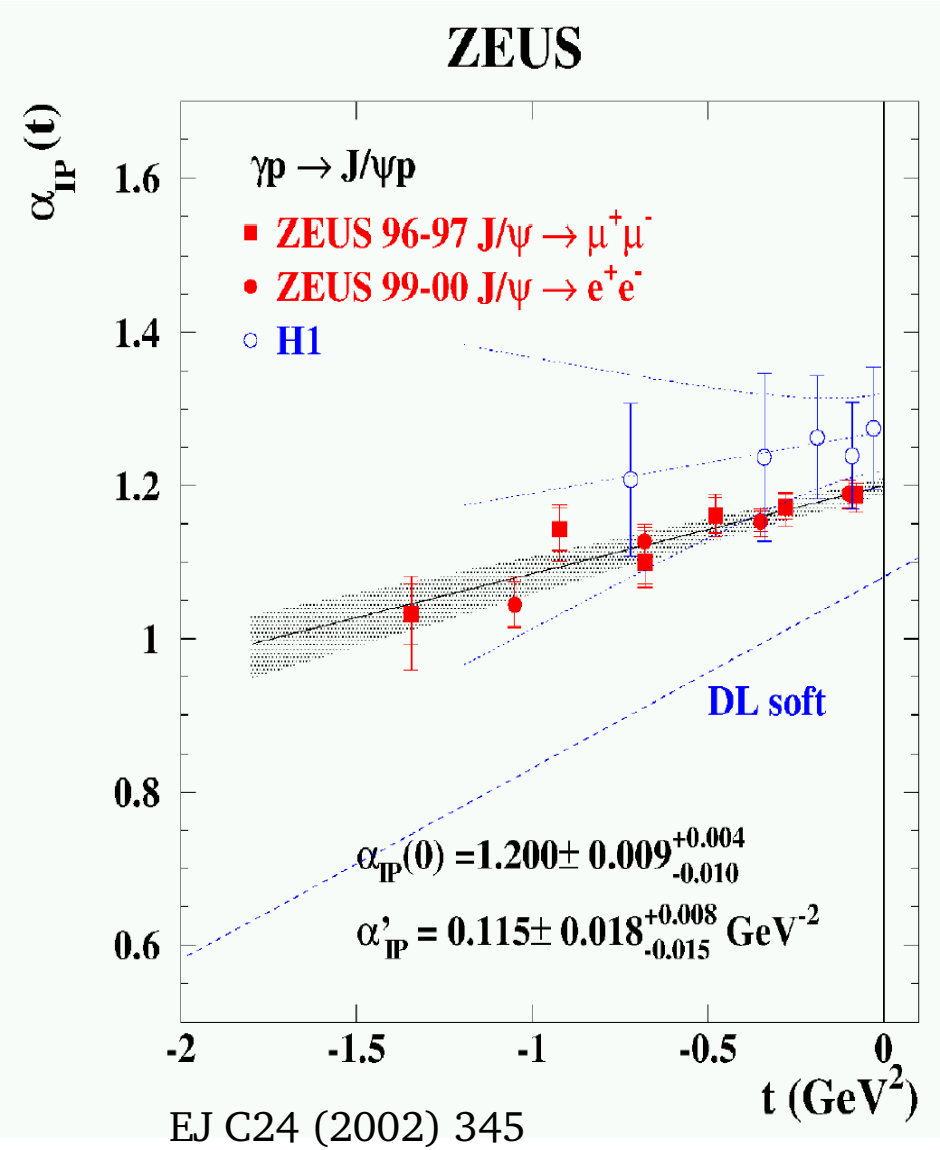
$$\rho : \omega : \phi : J/\psi : \Upsilon \;=\; 9:1:2:8:2$$



Elastic J/ψ Production: "Shrinkage"

$$\frac{d\sigma}{dt} = F(t) \cdot (W^2)^{2\alpha_P(t)-2}$$

- Usually assume $\alpha_P(t) = \alpha_P(0) + \alpha' t$
- $\alpha_P(0)$ is much larger for J/ψ than for the "soft" Pomeron trajectory
- Expect $\alpha' \simeq 0.25$ GeV^{-2} for "soft" Pomeron, but small for "hard" process
- Most direct determination: measure dσ/dt as a function of W for fixed t
- Shrinkage small in J/ψ photoproduction



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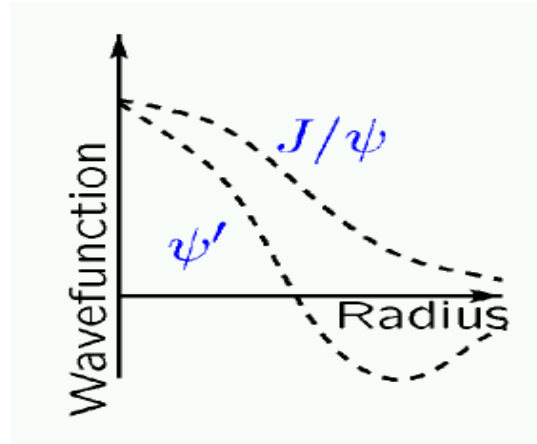
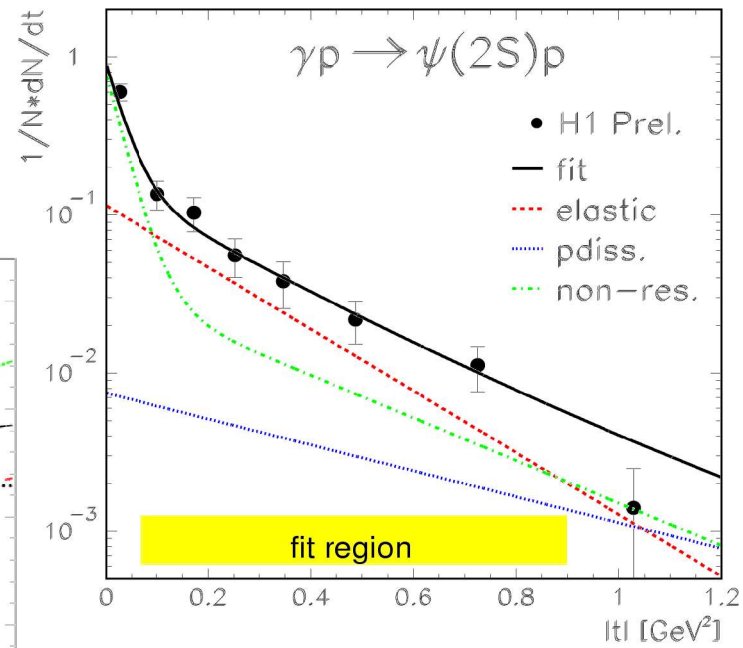
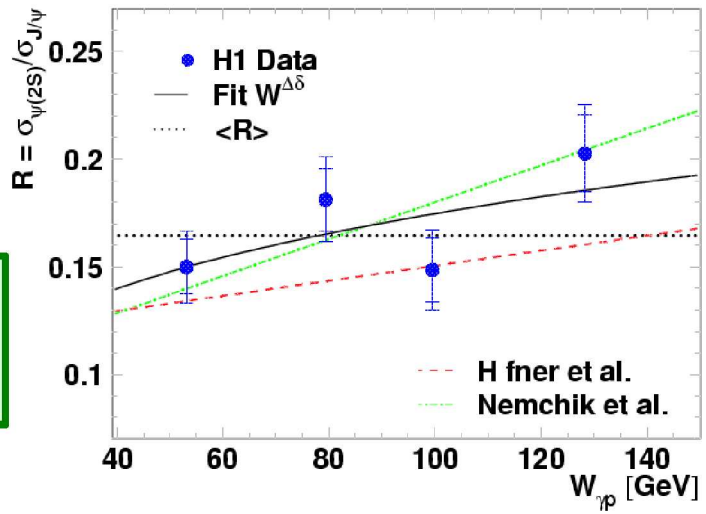
Elastic $\psi(2S)$ Photoproduction

- Important background to J/ψ production ($\rightarrow$ reduce systematic uncertainties)
- Interesting in itself due to node effect (wave function)
- H1 analysis: $\int L\,dt \simeq 77\ pb^{-1}$, all 4 channels
  $\psi(2S) \rightarrow (J/\psi \rightarrow l^+l^-)\pi^+\pi^-$ and $\psi(2S) \rightarrow l^+l^-$
- Assuming $d\sigma/dt \propto e^{-bt}$: $b = 4.3 \pm 0.6 \pm 0.5\,GeV^{-2}$
- Similar to J/ψ (compare $\sim 10\ GeV^{-2}$ for ρ)
  - Small size $q\,q$ configurations, $b \propto R_p^2 + R_V^2$







$$\sigma(\psi(2S))/\sigma(J/\psi) \simeq 0.16$$

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HERA Prospects

- "HERA I" running period ended in September 2000
  - Another > 50 pb^{-1} per experiment collected in 2000, giving a total of > 100 pb^{-1}
- Many analyses make use of the full data sets
- After the HERA upgrade:
  - $\int L\, dt \simeq 1\ fb^{-1}$ per experiment until ~2005-6
  - Polarized $e^{\pm}$ beams
- Various detector upgrades
  - ZEUS Silicon
  - New fast track trigger for H1
  - ...
- High Q^2/p_T will greatly benefit from increase in luminosity

Conclusions

- Tevatron Run 1 analyses done, most HERA-I analyses too
- Lots of results, many surprises
  - Large J/ψ and $\psi(2S)$ cross sections at the Tevatron
  - J/ψ and $\psi(2S)$ polarization from CDF
  - Steep rise of the elastic J/ψ cross section at HERA
  - Composition of inelastic J/ψ production at HERA
- Very fruitful interaction with theoretical developments
  - Non-relativistic QCD / colour octet contributions / ...
  - Soft Colour Interactions, Two Pomerons, ...
  - ...
- Tevatron Run 2 will provide 2-15 fb^{-1} (20-150x statistics, improved acceptance)
- HERA-II will deliver 1 fb^{-1} (10x statistics, measure at larger Q^2, p_T, polarization)