Charmonium Production at HERA

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- Charmonium Production Mechanism
- Measurements of Charmonium Production:
  Photoproduction and Electroproduction
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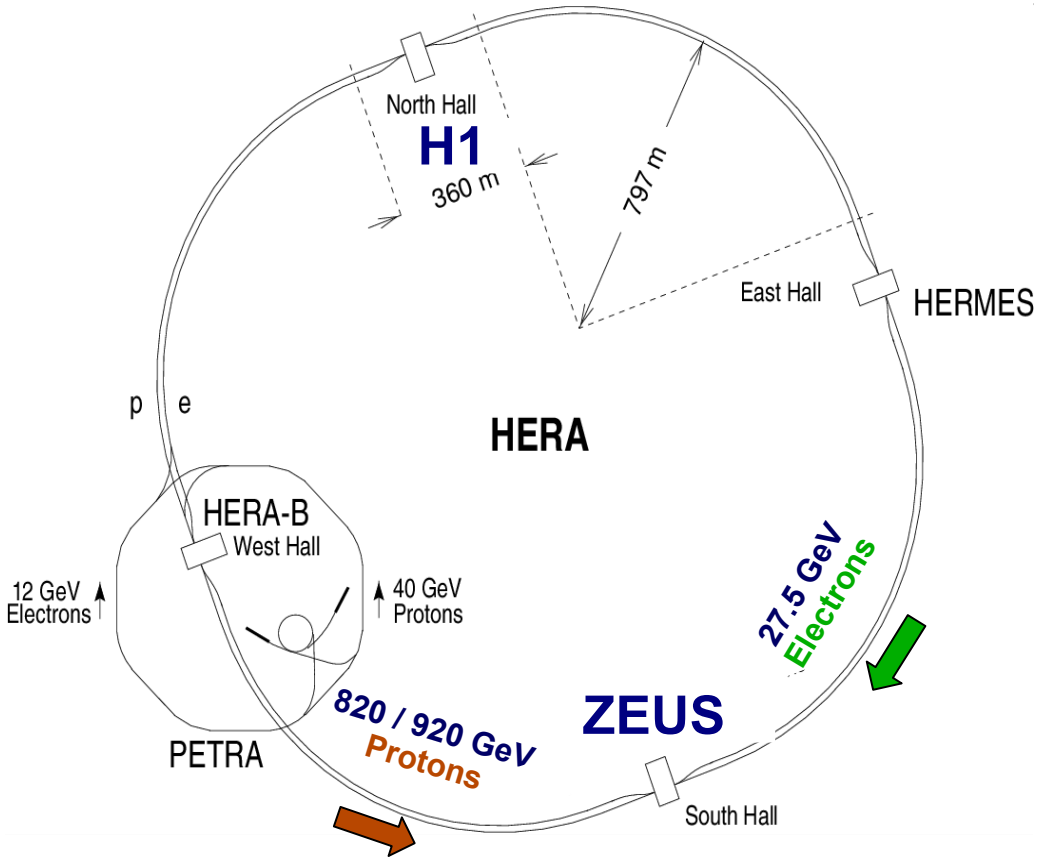
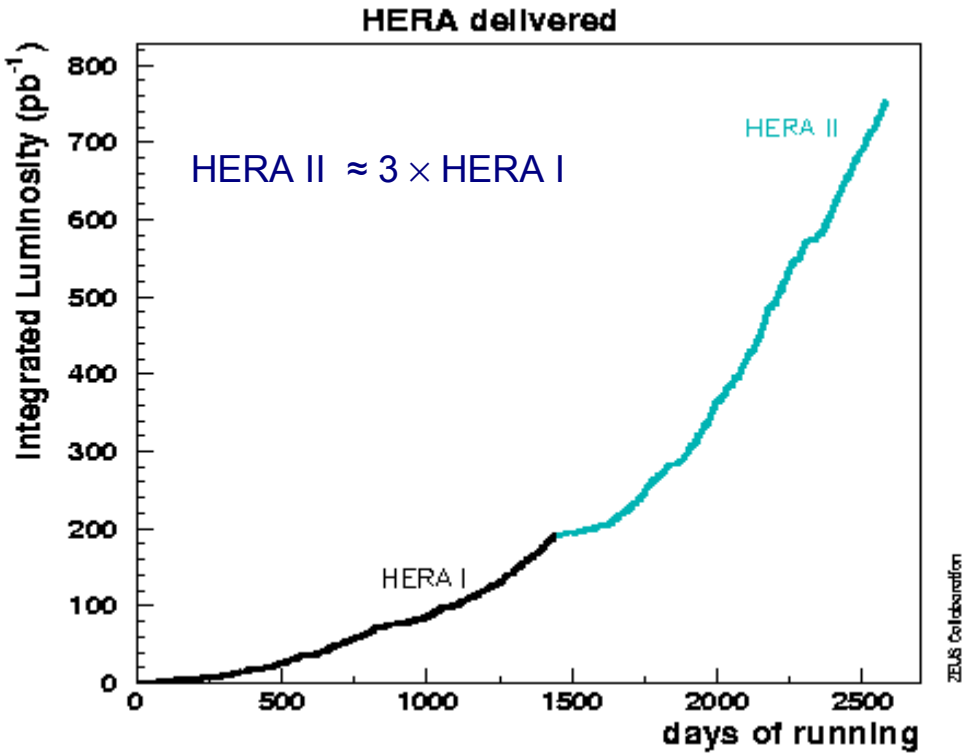
Electron-Proton Collider HERA and Experiments ZEUS and H1

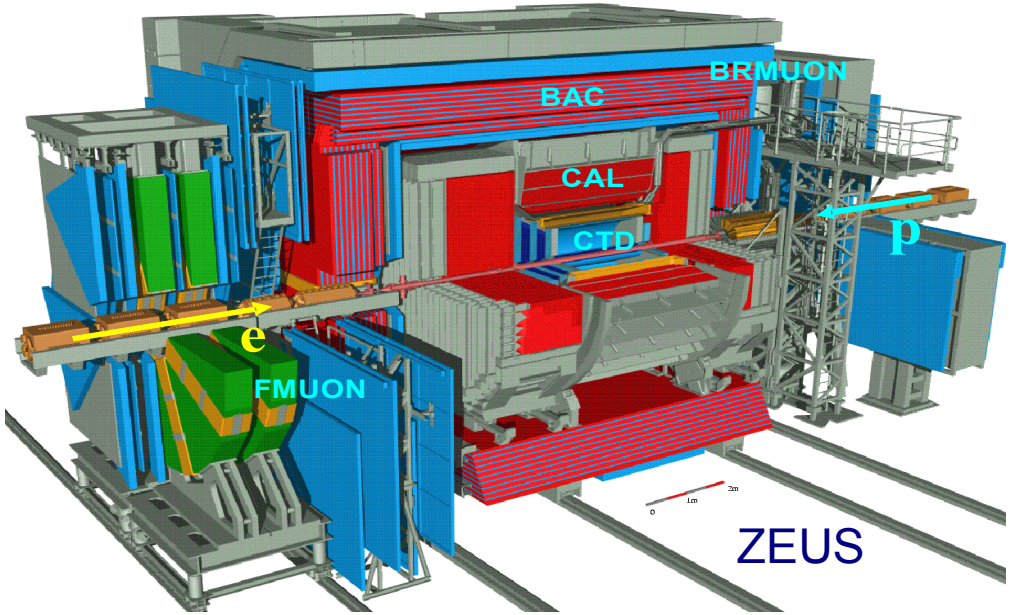




HERA *ep* CM energy of 300/318 GeV

ZEUS and H1 detectors are cylindrical multi-purpose devices with almost full solid angle coverage.

- Tracking system
- Calorimetry
- Muon system



Event Kinematics

Kinematic variables for $ep \rightarrow e' + J/\psi + X$ process:

CM energy:

$$s = (P + k)^2$$

Virtuality of exchanged photon:

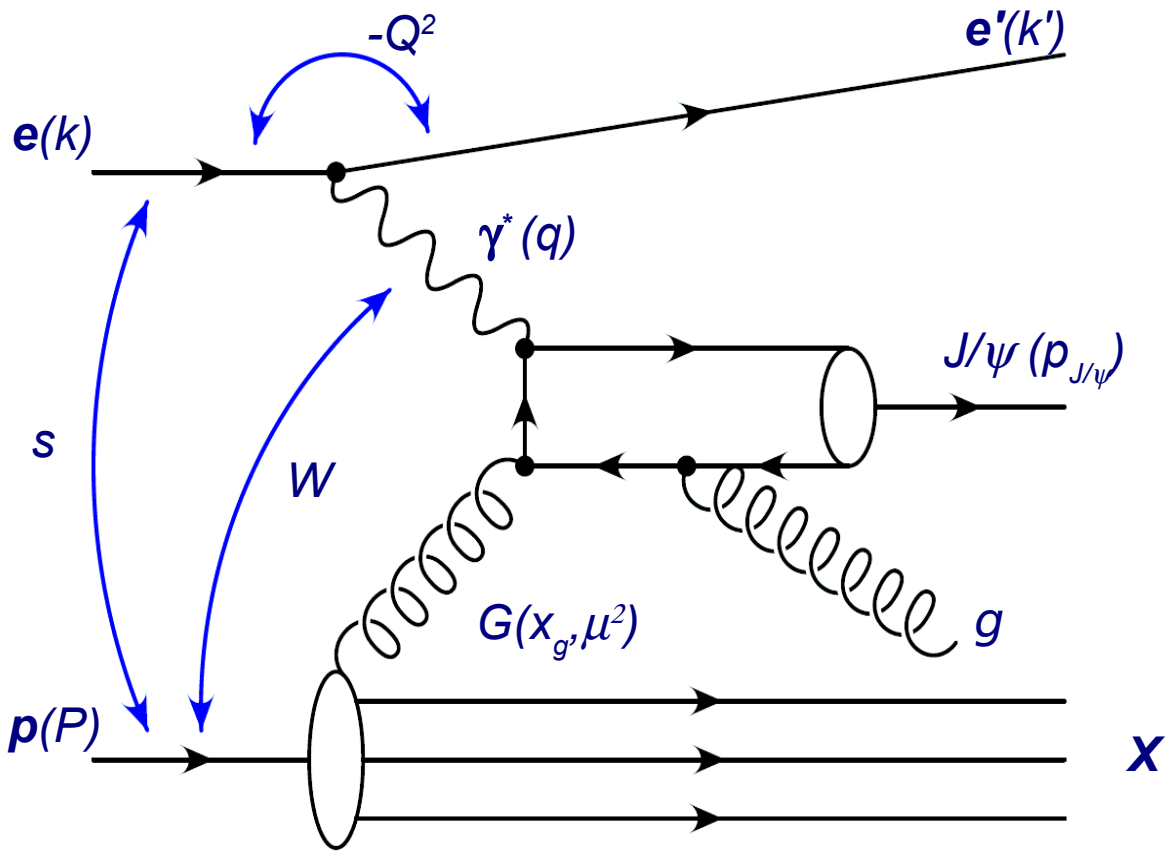
$$Q^2 = -q^2 = (k' - k)^2$$

Mass of $\gamma^* p$ system:

$$W^2 = (q + P)^2$$

Inelasticity: fraction of photon momentum transferred to J/ψ in proton rest frame:

$$z = p_{J/\psi} \cdot P \,/\, q \cdot P$$



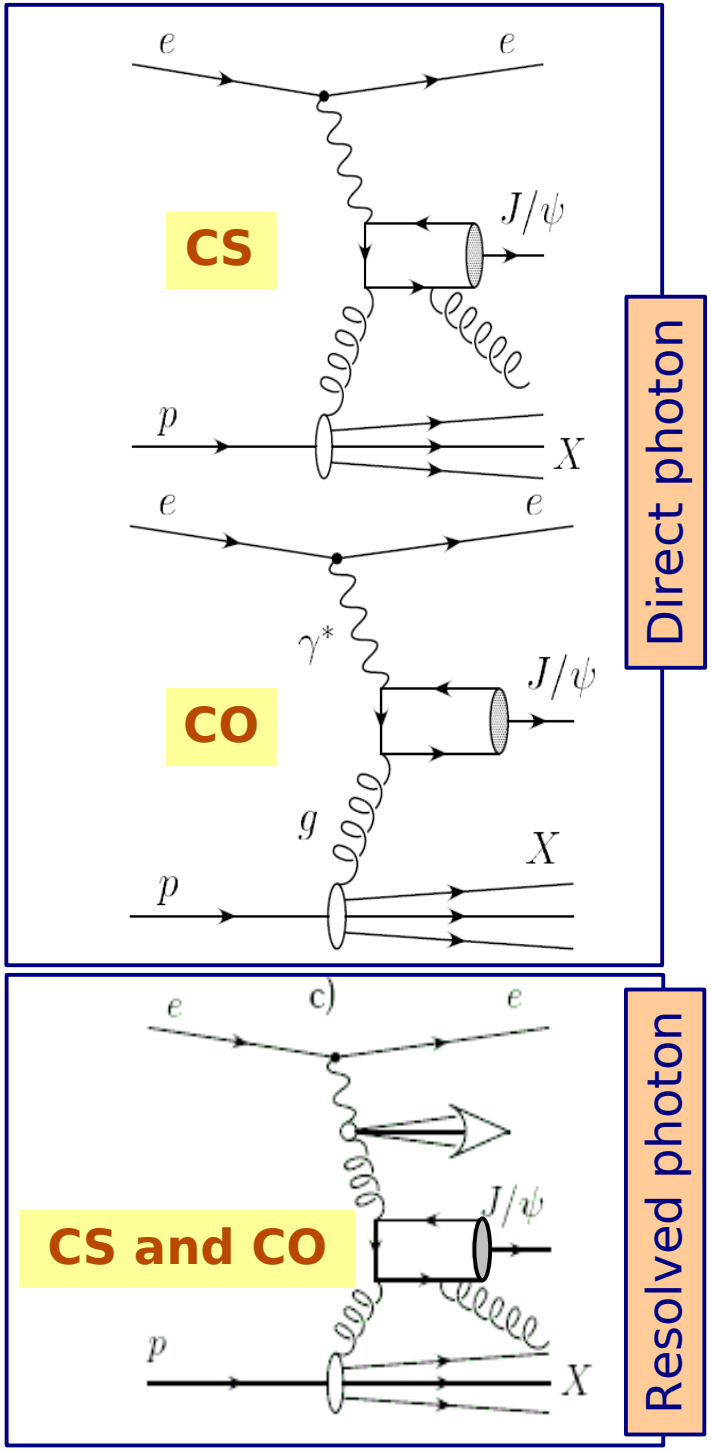
Inelastic ep process: $M_X >> m_p$, otherwise - elastic.

Two kinematic regimes:

- Photoproduction (PHP) with $Q^2 \sim 0$
- Electroproduction (DIS) with $Q^2 > 2$ GeV^2

Inelastic Charmonium Production Mechanism

- Charmonium at HERA $\Rightarrow$ mainly J/ψ production
- Dominant process: *BGF* $\Rightarrow$ sensitive to $G(x,\mu^2)$ (main contribution from direct photon processes)
- In photoproduction resolved photon processes contribute additionally. At high Q^2 these contributions are suppressed.
- According two different approaches, a produced charm quark pair can form:
  - a state with the same quantum numbers of J/ψ (color singlet state: CS)
  - a different state (color octet state: CO) with additional soft gluon emissions involved to build J/ψ



Inelastic Charmonium Production Mechanism

Theoretical models used in description of charmonium production:

- Factorization approach:

$$\sigma(J/\psi + X) = \Sigma\, \underbrace{\sigma(ep \to c\bar{c}[n] + X)}_{\text{calculated in pQCD}} \otimes \underbrace{\langle O_n^{J/\psi} \rangle}_{\text{non-perturbative part (N-P)}}$$

- CS model: charm quark pair produced in CS state.
  N-P $\Rightarrow$ one parameter fixed from $\Gamma(J/\psi \to \ell^+\ell^-)$.

  - LO calculations: for direct and resolved photon processes.
  - NLO calculations: only for direct photon processes and only for PHP.

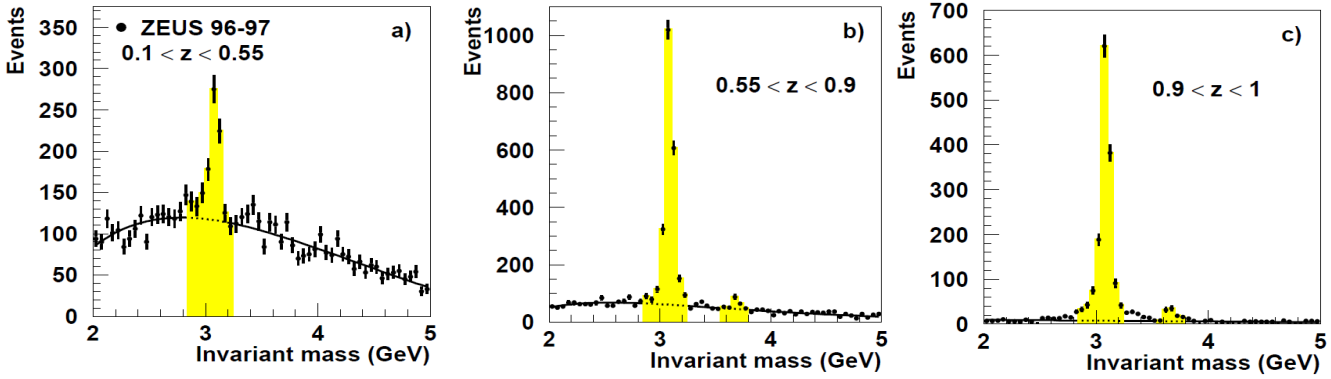
- CO model: charm quark pair produced in CO or CS state;
  N-P $\Rightarrow$ NRQCD approach: Long Distance Matrix Element (*LDME*) measured from NRQCD fit to Tevatron data and expected to be universal.

  - Only LO calculation. Direct and resolved processes included.
  - No NLO calculation.

- k_t factorization approach:
  Unintegrated gluon density convoluted with off-shell matrix element. Used in CO and CS model frameworks. Effectively taking into account higher order corrections at LO level.

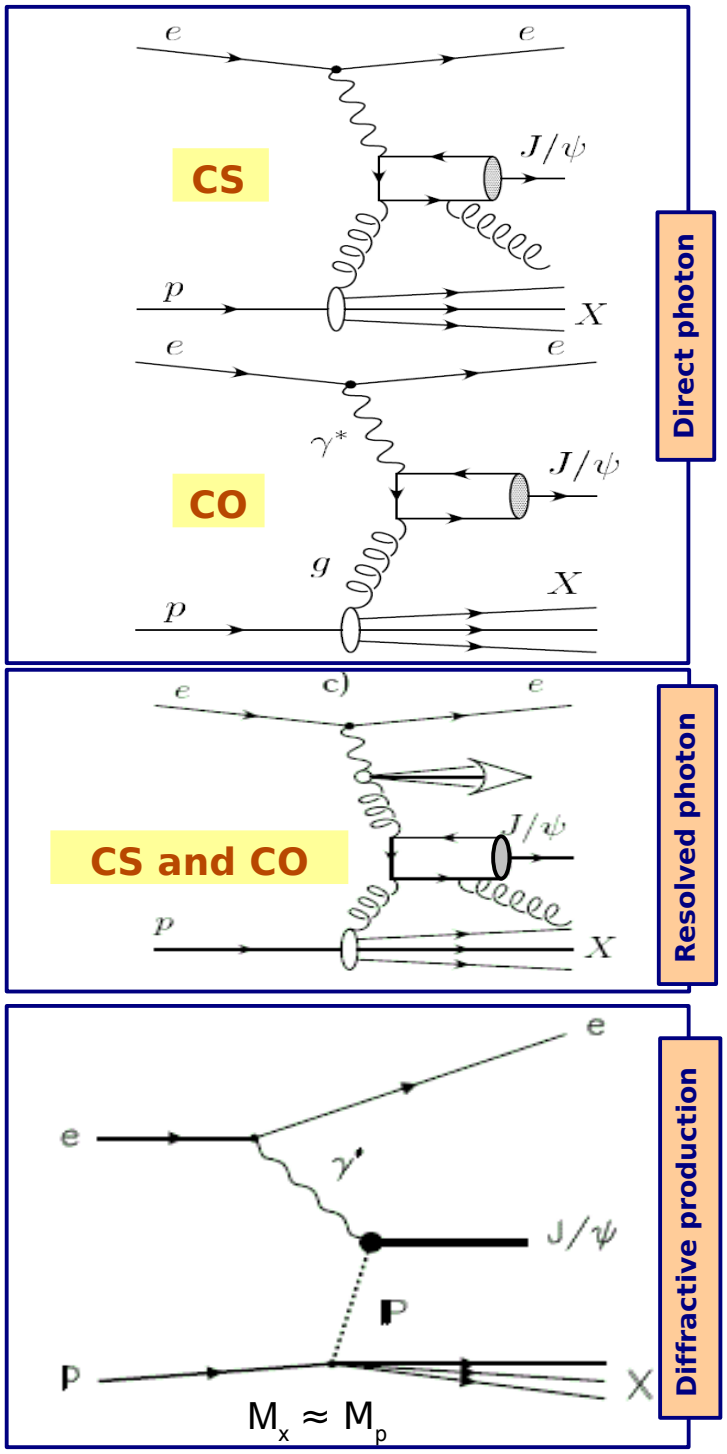
Event Selection

- Reconstruction technique is measurement of invariant mass of oppositely charged leptons.

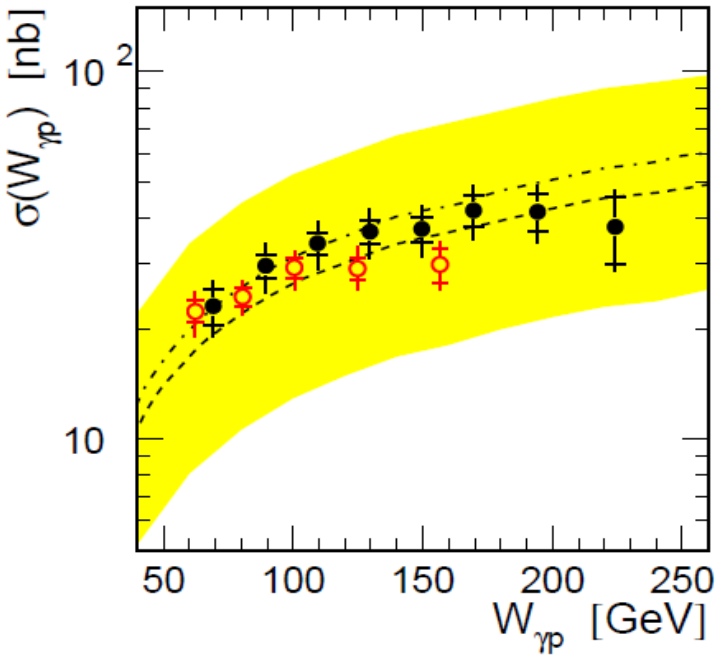


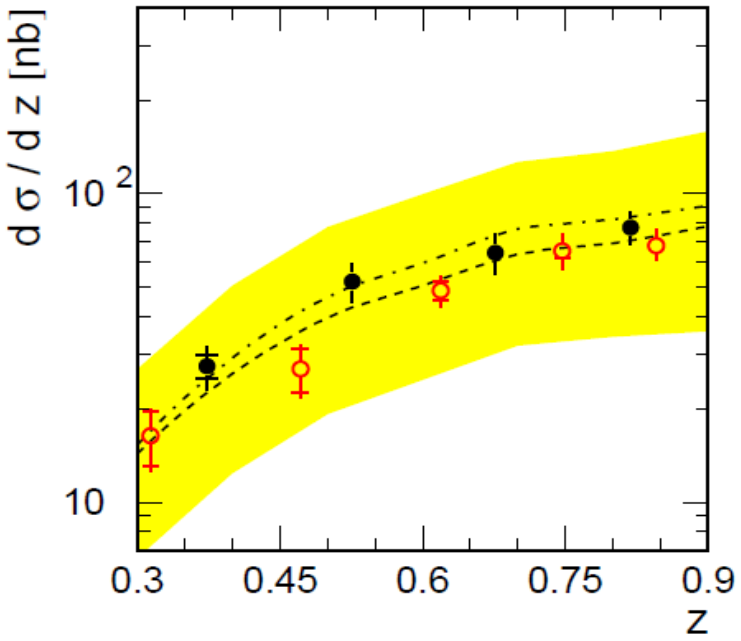
- Direct photon is dominant at middle z (0.4 - 0.9). At low z resolved photon contribution is significant. Diffractive production gives sizable contribution at high z.

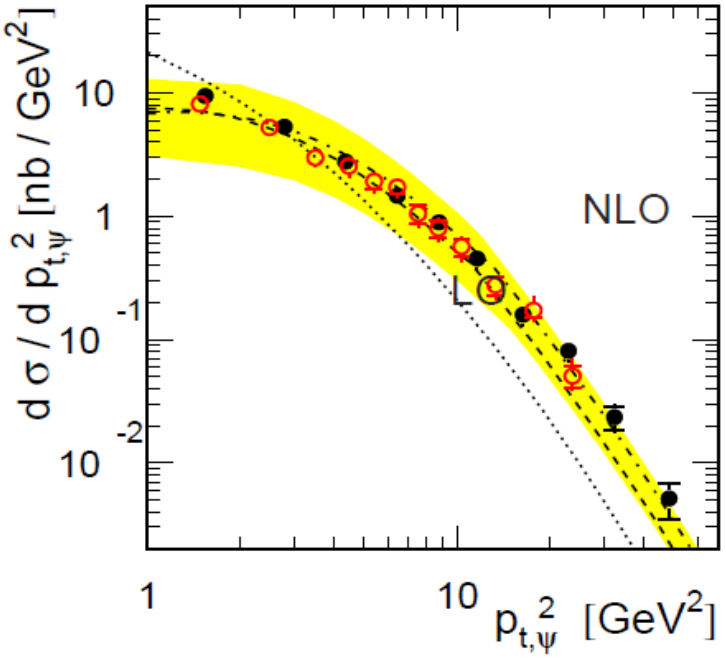
- Main Backgrounds:
  - Diffractive production (subtracted).
  - J/ψ from B (5%, up to 25% at low z, not subtracted).
  - J/ψ from χ_c(1%, up to 7% at low z, not subtracted).
  - J/ψ from ψ'(15%, not subtracted).

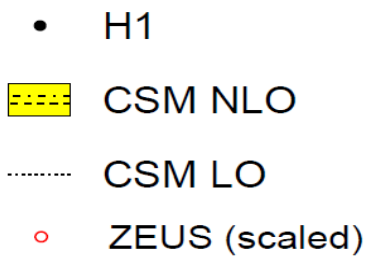


Photoproduction: Data vs NLO









HERA I data

H1 Data:

$60 < W < 240$ GeV

$0.3 < z < 0.9$

$p_T^2 > 1$ GeV^2

ZEUS Data:

$50 < W < 180$ GeV

$0.4 < z < 0.9$

$p_T > 1$ GeV

Error bands:

upper limit:

$m_c = 1.3$ GeV, $\alpha(M_Z) = 0.1225$

lower limit:

$m_c = 1.5$ GeV, $\alpha(M_Z) = 0.1175$

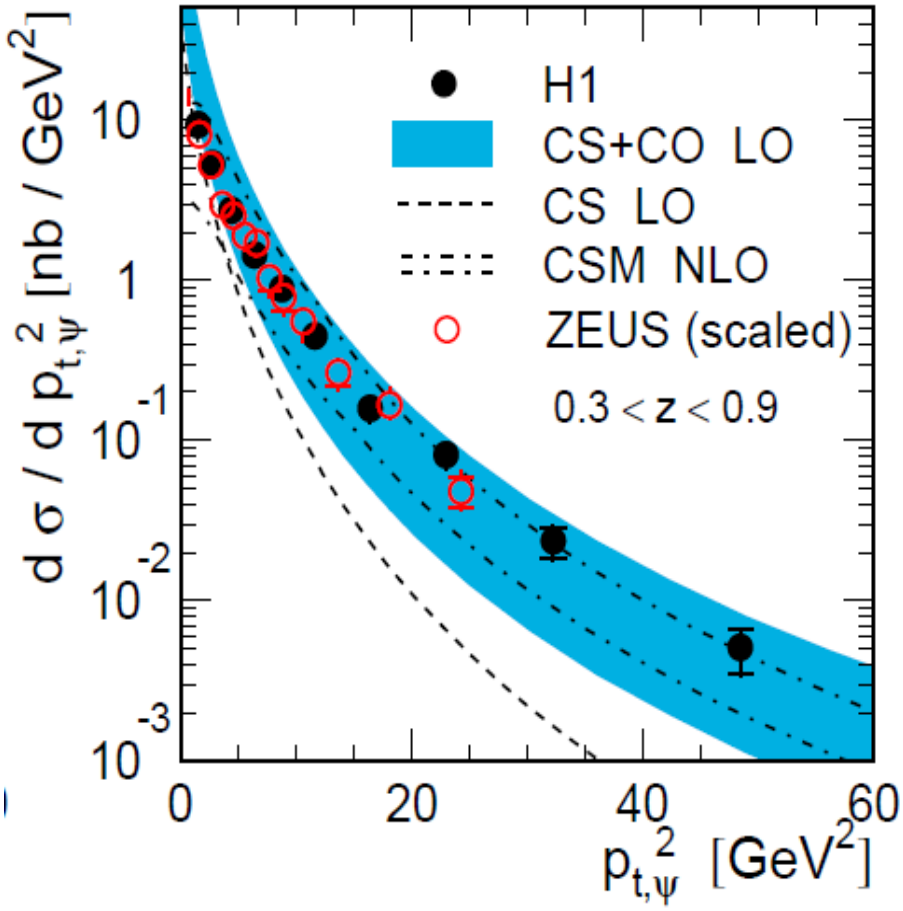
Good agreement between ZEUS and H1

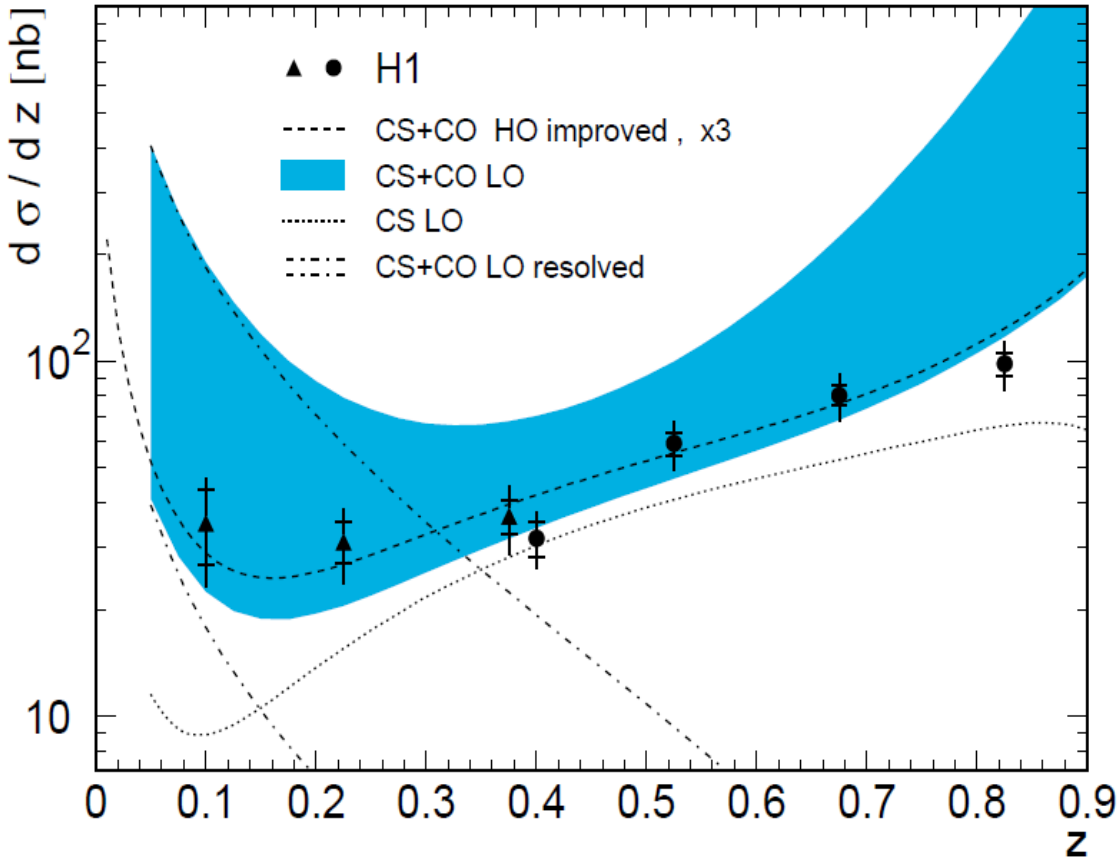
LO CSM ⇒ fails to describe data (too soft).

NLO CSM ⇒ provides good description within large normalization uncertainties.

Photoproduction: Data vs LO NRQCD

HERA I data

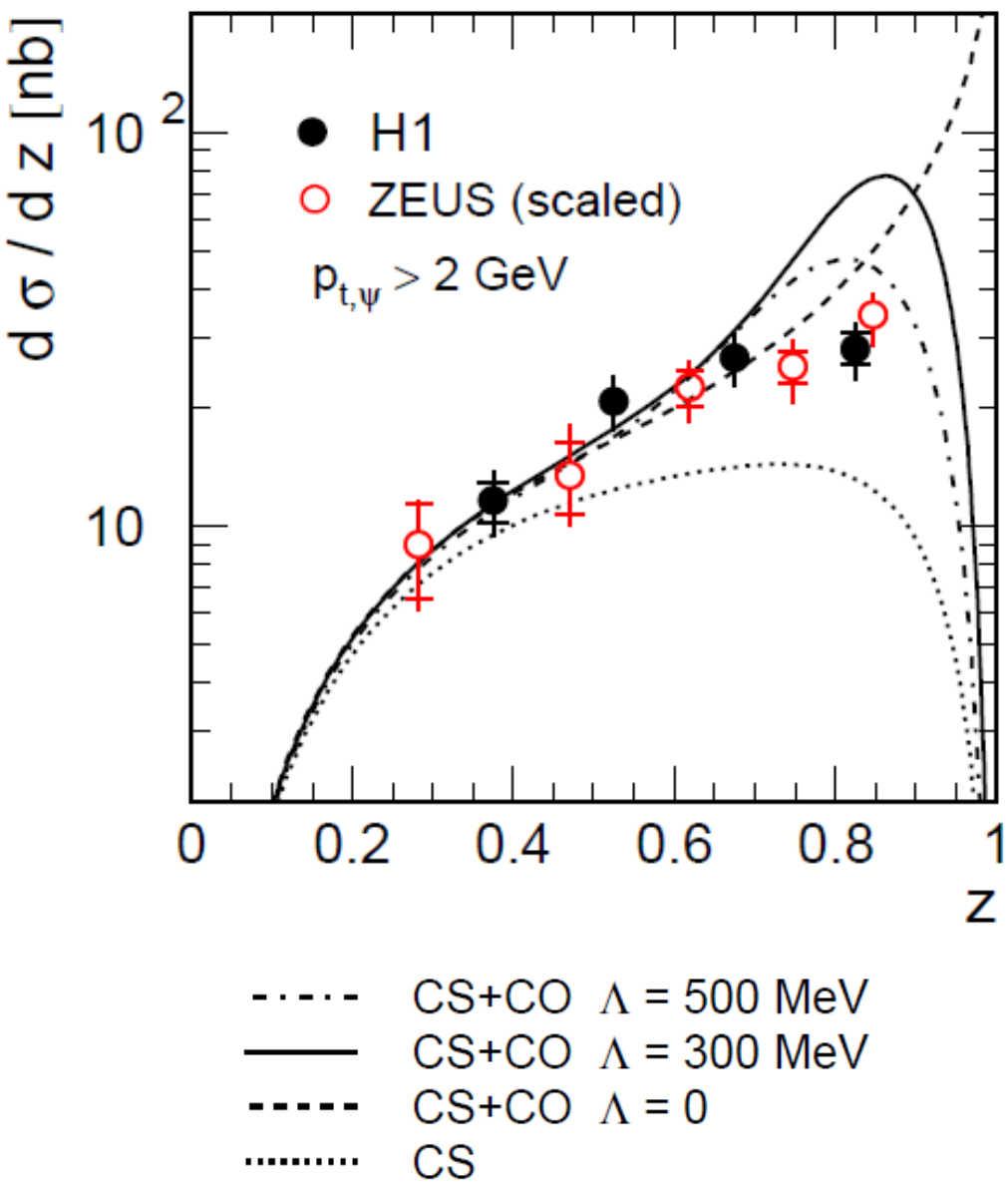




LO CS + CO NRQCD:

- Good description of J/ψ p_T spectrum within large uncertainties (coming from LDME).
- Good description of z spectrum by lower limit (LDME [NLO]) of error bands.
- Resolved photon contribution (CO included) improves shape agreements.
- Rise at high z $\Rightarrow$ delicate phase space: soft gluons.

Photoproduction: Data vs NRQCD



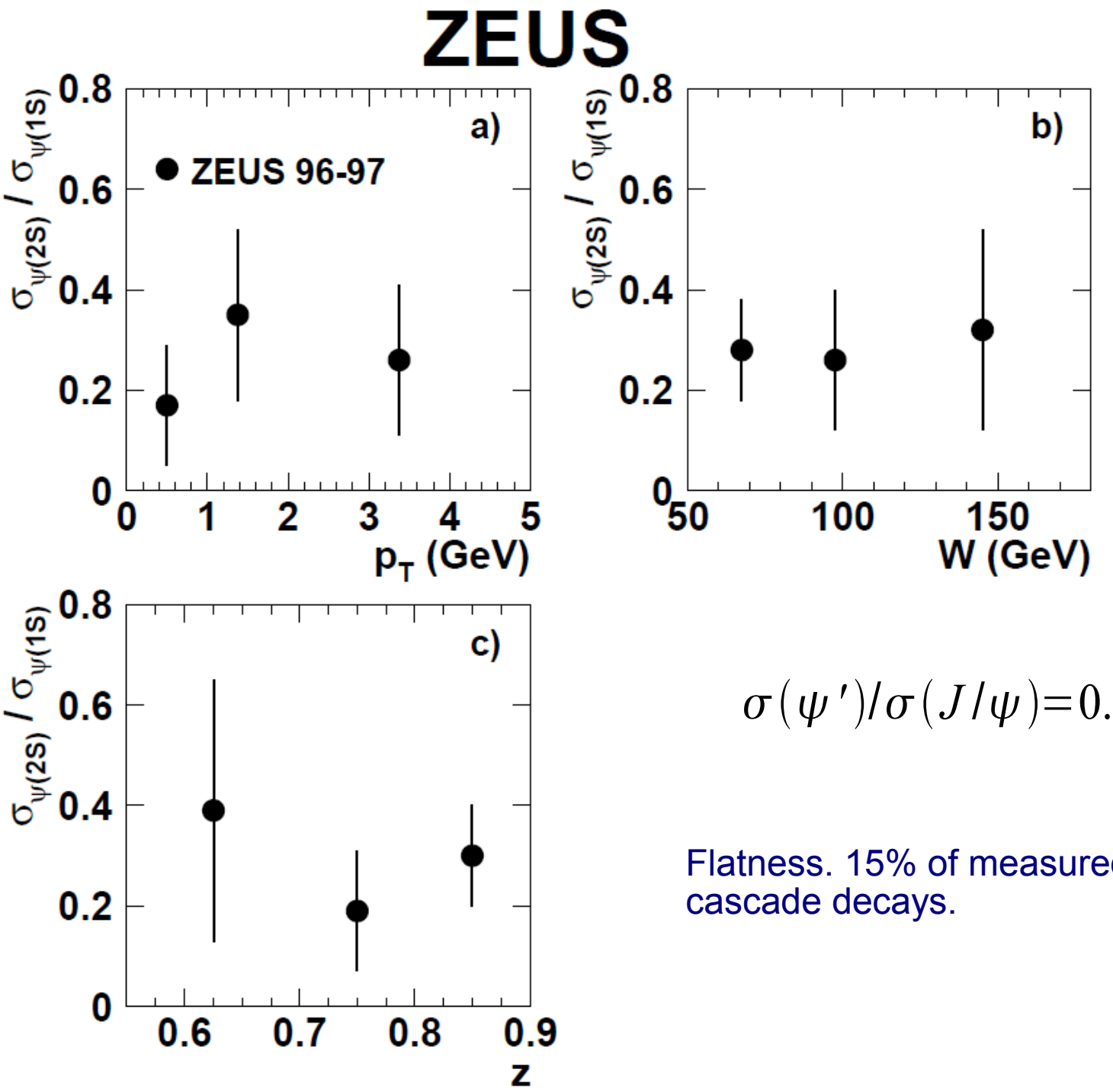
LO CS ⇒ falls down at high *z* due to hard gluon radiation.

LO CO ⇒ steep rise at high *z* due to soft gluon emission at high z: resummation!

Reasonable shape description by resummed NRQCD.

Photoproduction: ψ' Contribution

HERA I data

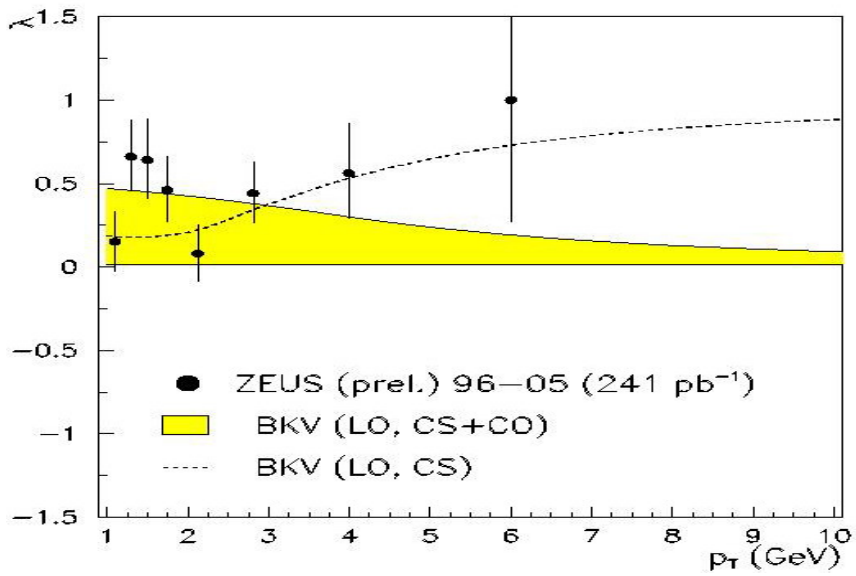


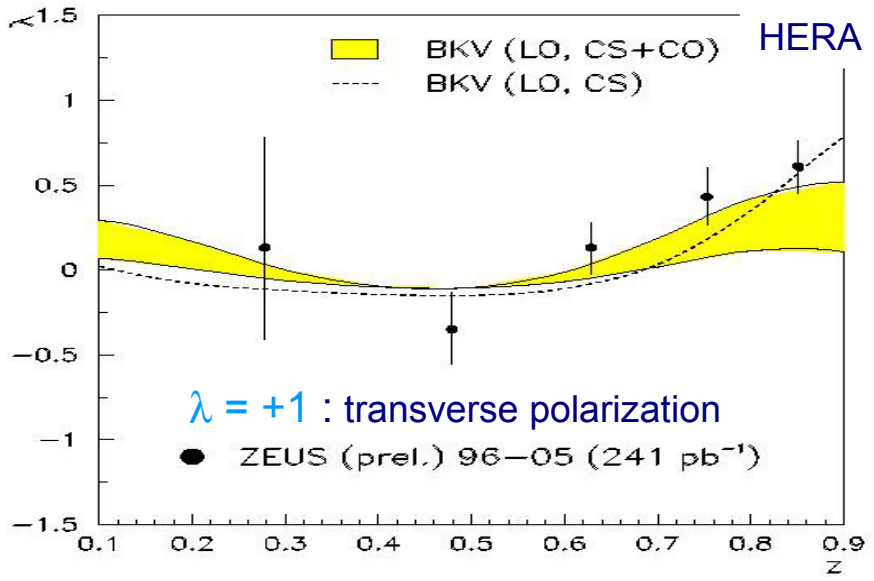
ZEUS Data:
$50 < W < 180$ GeV
$0.55 < z < 0.9$

$$\sigma(\psi')/\sigma(J/\psi) = 0.33 \pm 0.10^{+0.01}_{-0.02}$$

Flatness. 15% of measured J/ψ come from ψ' cascade decays.

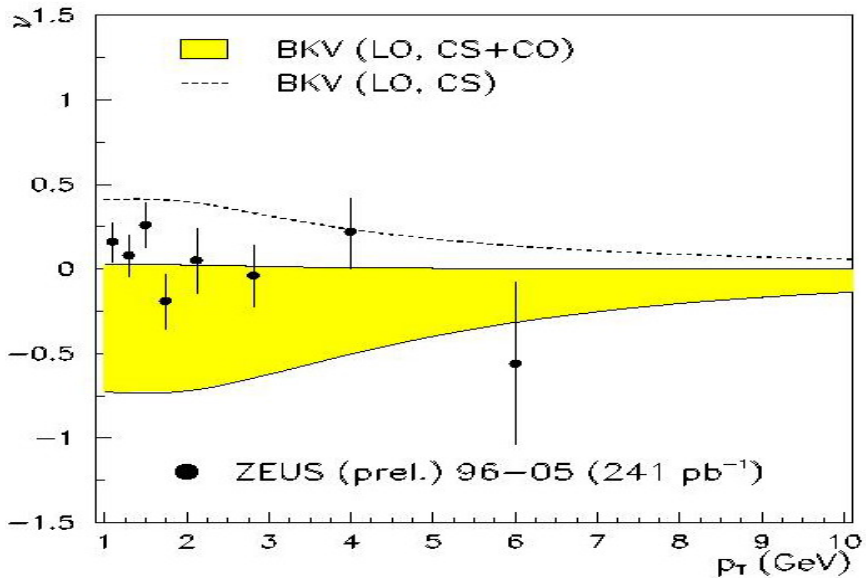
Photoproduction: J/ψ Polarization Measurement

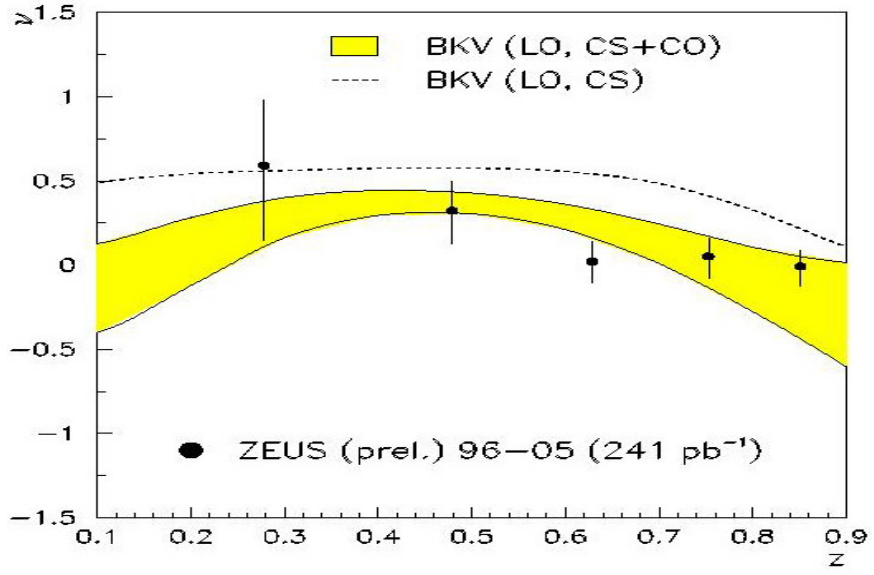




HERA I + HERA II data

$\mathcal{L}$ = 241 pb^{-1}





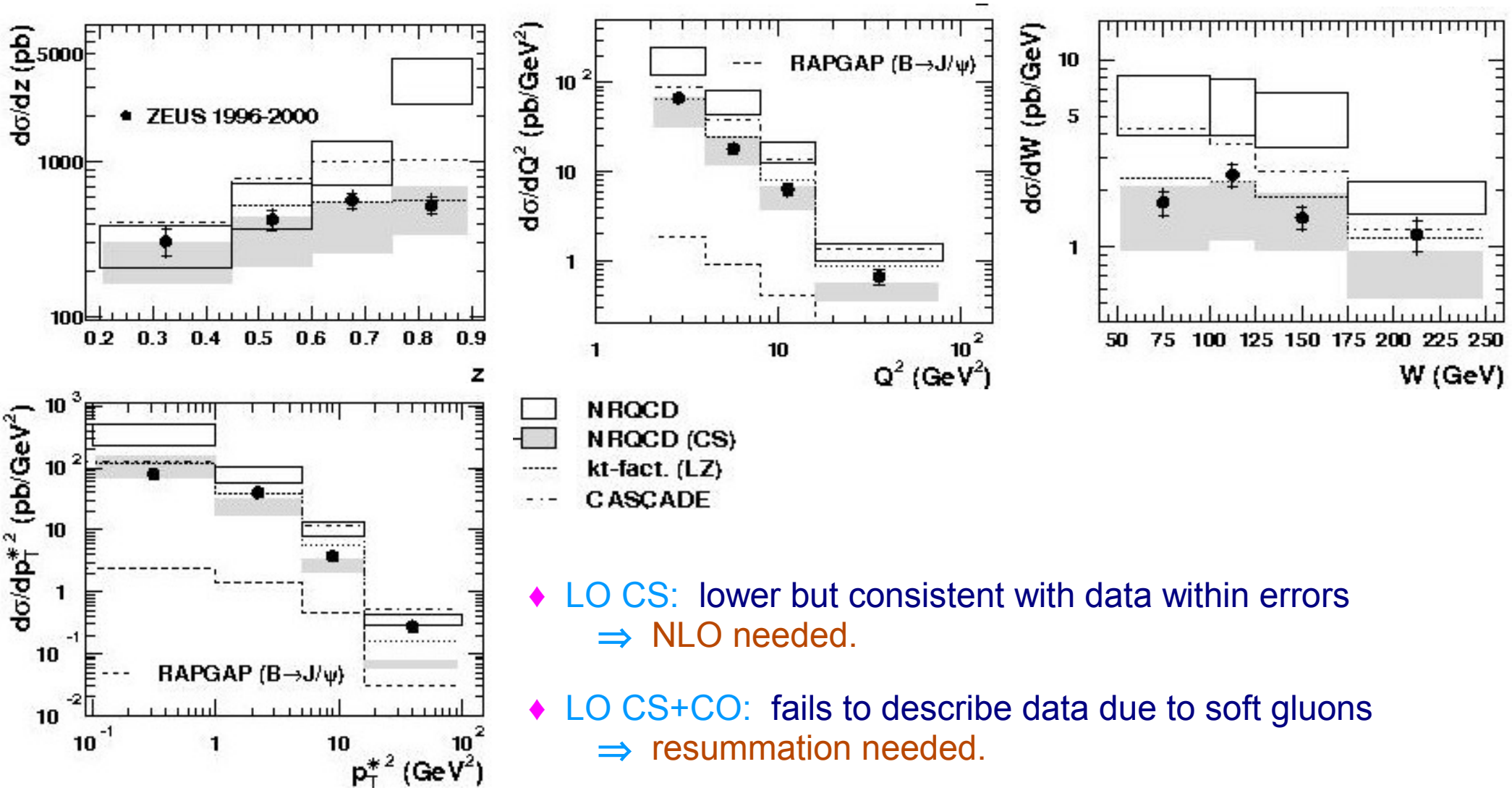
ZEUS Data:

$50 < W < 180$GeV
$0.1 < z < 0.9$
$p_T > 1$ GeV

- CS and CO + CS: fit data reasonably well within errors.
- CO + CS picture is preferable by data? ⇒ NLO needed !

Electroproduction: Data vs NRQCD

HERA I data



ZEUS Data:

$50 < W < 250$ GeV

$2 < Q^2 < 80$ GeV^2

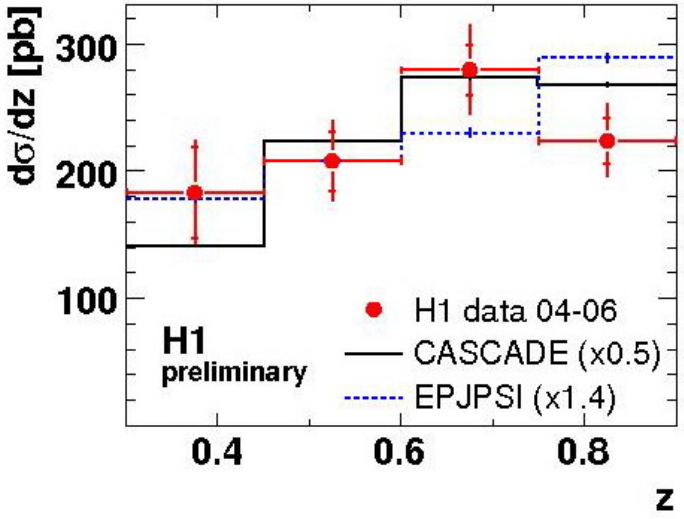
$0.2 < z < 0.9$

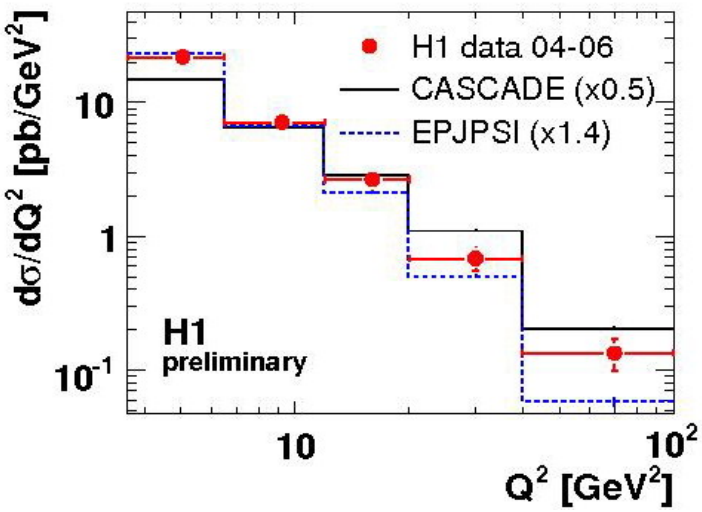
$-1.6 < Y_{lab} < 1.3$

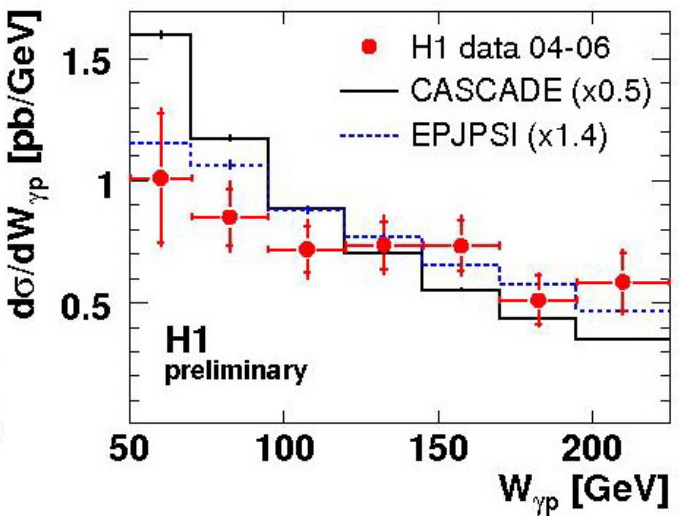
- LO CS: lower but consistent with data within errors
  ⇒ NLO needed.
- LO CS+CO: fails to describe data due to soft gluons
  ⇒ resummation needed.
- CASCADE MC: above data but shape is ok.
- LO CS with k_T factorization: reasonable description of data.

Electroproduction: Data vs CS MC

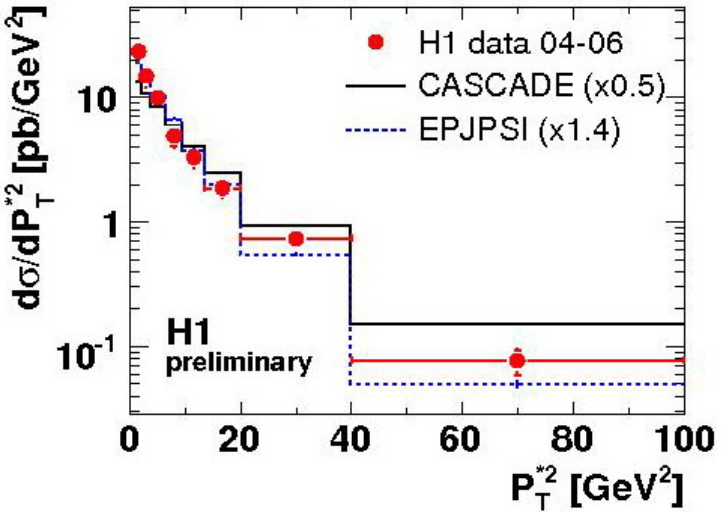
HERA II data







$\mathcal{L}$ = 285 pb^{-1}



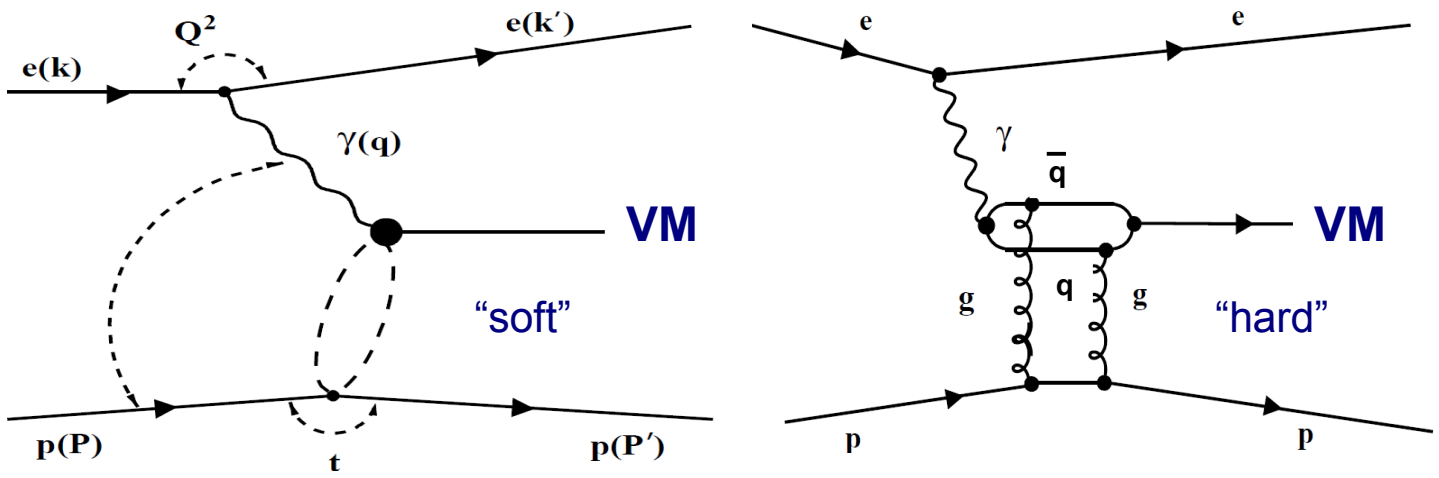
- CASCADE:
  ⇒ reasonable description of data but p_T spectrum is harder
- EPJPSI: (collinear factorization)
  ⇒ consistent with data but Q^2 distribution is soft

H1 Data:

50 < W < 225 GeV
3. 6 < Q^2 < 100 GeV^2
0.3 < z < 0.9
p_T^{*2} > 1 GeV^2

Elastic Bottomonium Photoproduction at HERA

- Production mechanism:



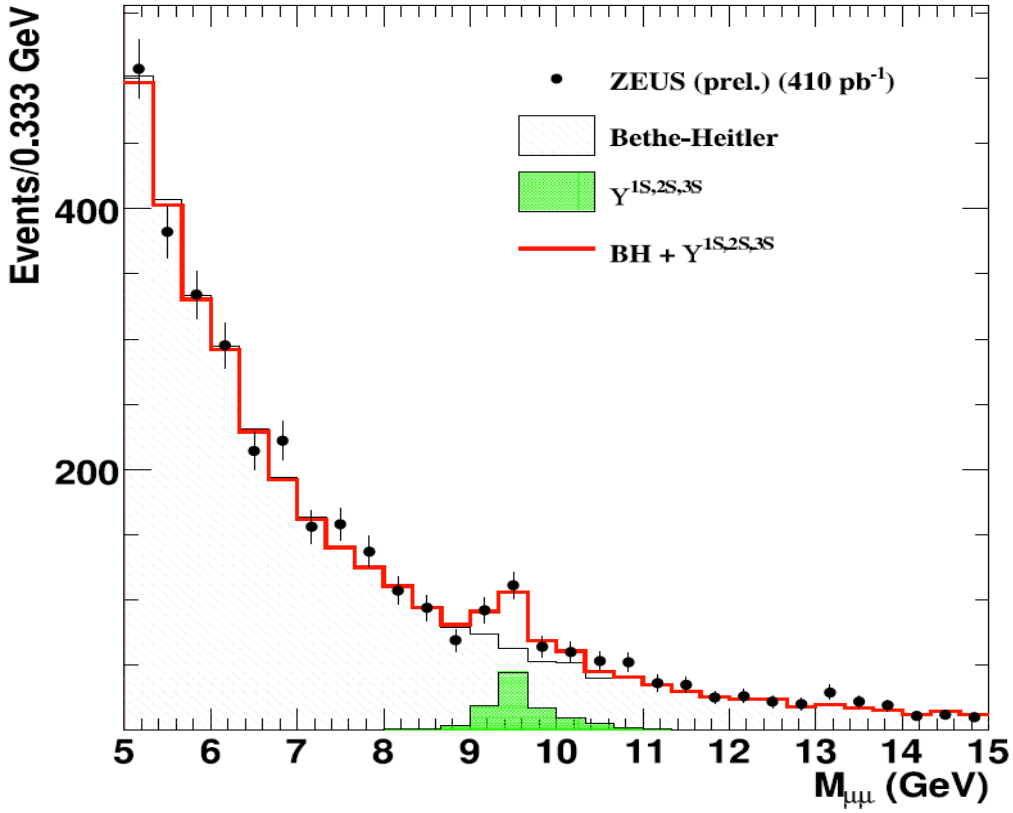
Two theoretical approaches:

- Pomeron exchange ⇒ soft interactions
- 2 gluon exchange ⇒ perturbative QCD

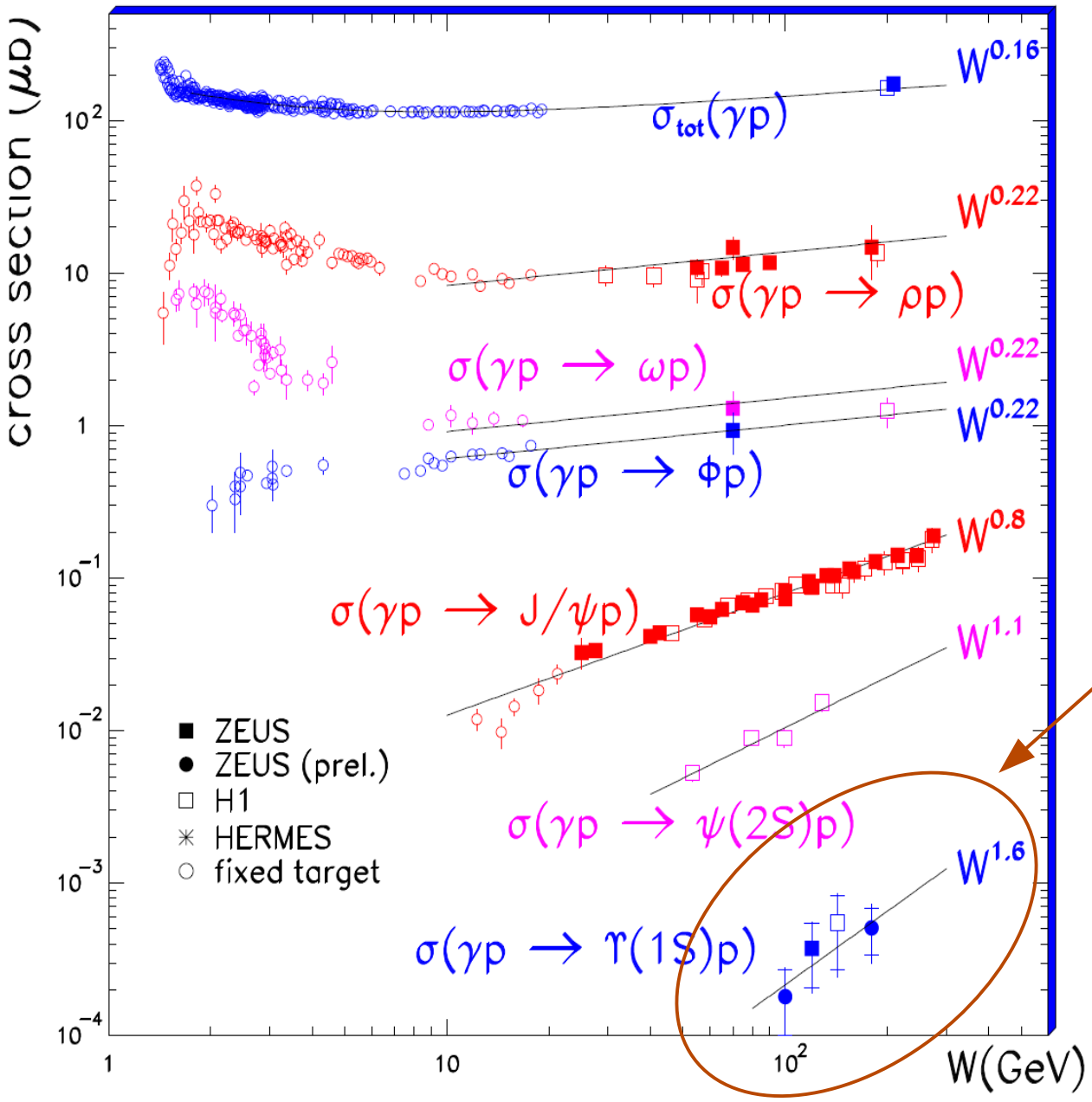
- Sensitive to gluon density $G(x,\mu_F^2)$: $W^2 \Leftrightarrow 1/x$

$$\sigma \propto W^{\delta} \text{ and } \sigma \propto G(x,\mu_F^2)^2$$

- δ is expected to increase with increasing hard scale ⇒ vector meson (VM) mass.



Elastic Vector Meson Photoproduction Measurements at HERA



- Cross section becomes steeper with W and hard scale (VM mass)
  $\Rightarrow$ pQCD in work: $\sigma \propto W^{\delta}$
- 4 points is available and used in fit
  $\Rightarrow$ $\sigma \propto W^{1.6}$

Conclusions

- Photoproduction:
  - LO CS model fails to describe the data, while ...
  - NLO CS calculations provide good description of data.
  - LO CO + CS NRQCD calculations with small LDME are also reasonable.
    ⇒ At low *z* resolved photon contribution improves agreement with data but contaminations of B meson decays and higher mass charmonium states are poorly know and not subtracted.
  - Helicity measurements looks to favor CO + CS picture but ...
    ⇒ Experimental and theoretical errors are large.
    ⇒ NLO calculations are needed to estimate theoretical uncertainties.
- Electroproduction:
  - LO CS predictions are below but consistent with data except high p_T range.
  - LO NRQCD predictions overshoot data.
    ⇒ NLO calculations for CS and CO are needed.
  - CS model with k_T factorization provides reasonable description of data.
  - MC predictions exhibit rather good agreement with data.
- Prospect with full HERA statistics:
  - Higher Q^2 and p_T.
  - Improvements in helicity measurements.