International Workshop "e^+e^- Collisions from ϕ to ψ"

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LFV and charmonium production at HERA

M. Turcato (ZEUS)

Padova University and INFN

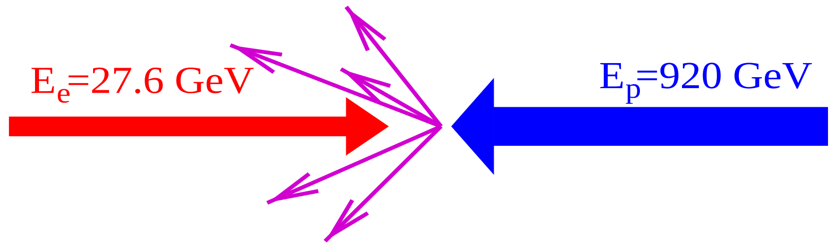
on behalf of the H1 and ZEUS collaborations

Outline

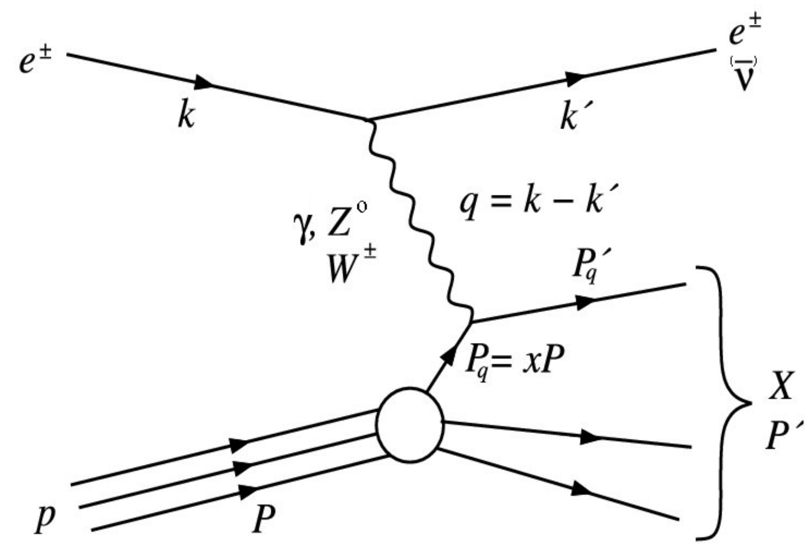
- Physics at HERA.
- HERA Physics program, topics of interest for this conference.
- Lepton flavour violation at HERA.
- FCNC processes in sigle top production.
- Charmonium production.

Physics at HERA

- HERA is a lepton-proton collider operating at a centre-of-mass energy of ~318 GeV (protons of 920 GeV on 27.6 GeV electrons or positrons).



- HERA-I: data taking up to 2000. HERA-II: afterwards.
  - Centre-of-mass energy: $s = (P+k)^2$.
  - Transferred 4-momentum, squared: $Q^2 = -(k-k')^2$.
  - Bjorken-x: $x = Q^2/(2P \cdot q)$.
  - Inelasticity: $y = (P \cdot q)/(P \cdot k)$.
  - Proton-photon mass, squared: $W^2 = (P+q)^2$.



PHP: low Q^2 (~< 1 GeV^2), DIS otherwise

ZEUS and H1 detectors are multipurpose detectors designed to study the various Physics phenomena occuring at HERA.

HERA and the Workshop Physics

The Physics that comes out from ep interactions is rich and various. Here some topics are presented, the ones mostly related to the program of the conference:

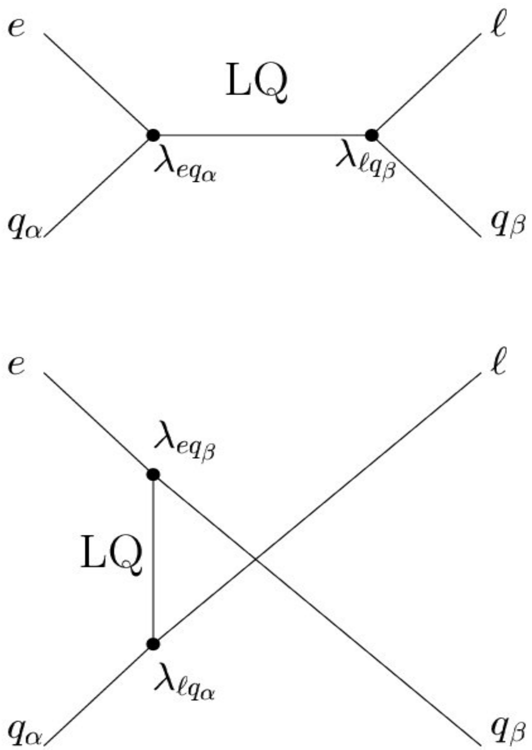
- *Symmetries:* LFV is studied at HERA...
- *Flavour Physics:* FCNC phenomena are searched for at HERA...
- *Charmonium:* is produced in *ep* interactions, mainly via photon gluon fusion process...

But many other interesting Physics phenomena studied at HERA have not been shown here.

Results presented here have been obtained using the data collected by HERA-I, up to 2000.

LFV at HERA

- LFV exists in the neutrino sector, but LFV induced in the charged lepton sector due to neutrino oscillation is too small to be observed at detectors.
- Several extensions of the SM, as SUSY, GUT..., predict detectable rates for $e \to \mu$ and $e \to \tau$ transitions.

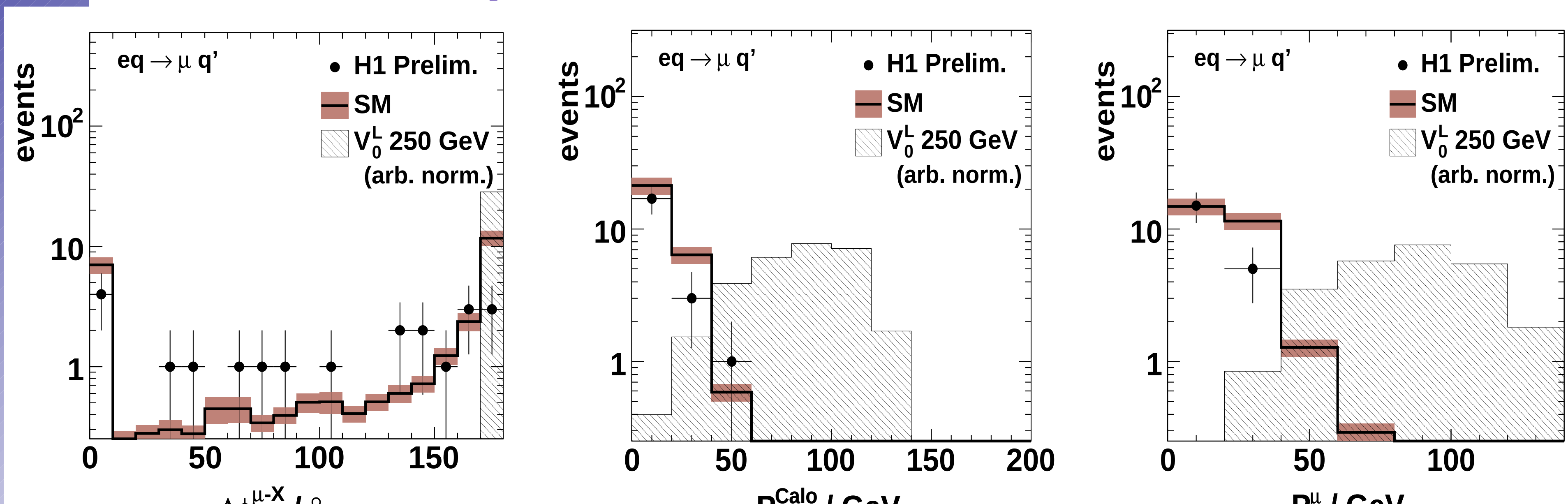


- LFV violation is thought to happen with the exchange of a leptoquark (LQ), a scalar or vector boson which couples to both leptons and quarks. The fermion number F is defined as $F = 3B+L$, and can be 0 or ±2.
- The process under search is $ep \to lX$, l being a μ or a τ. Typical signature of the events are the isolated lepton or the lepton decay products, and a jet.

LFV search, $e \to \mu$

Muon channel:

Signature is an isolated high-p_T muon balanced in p_T by a jet. Since muon releases not so much energy in the calorimeter, an apparent missing p_T in the calorimeter (p_T^{calo}) is observed in the event, in the muon direction.



$\mathscr{L}$ = 66 pb^{-1}

Main SM contribution is the di-muon production in QED ($ep \to \mu^+\mu^- X$)

M. Turcato

LFV search, e → τ

Tau channel, leptonic decay of the τ:

Signature is similar to the muon channel if τ decays into a muon.

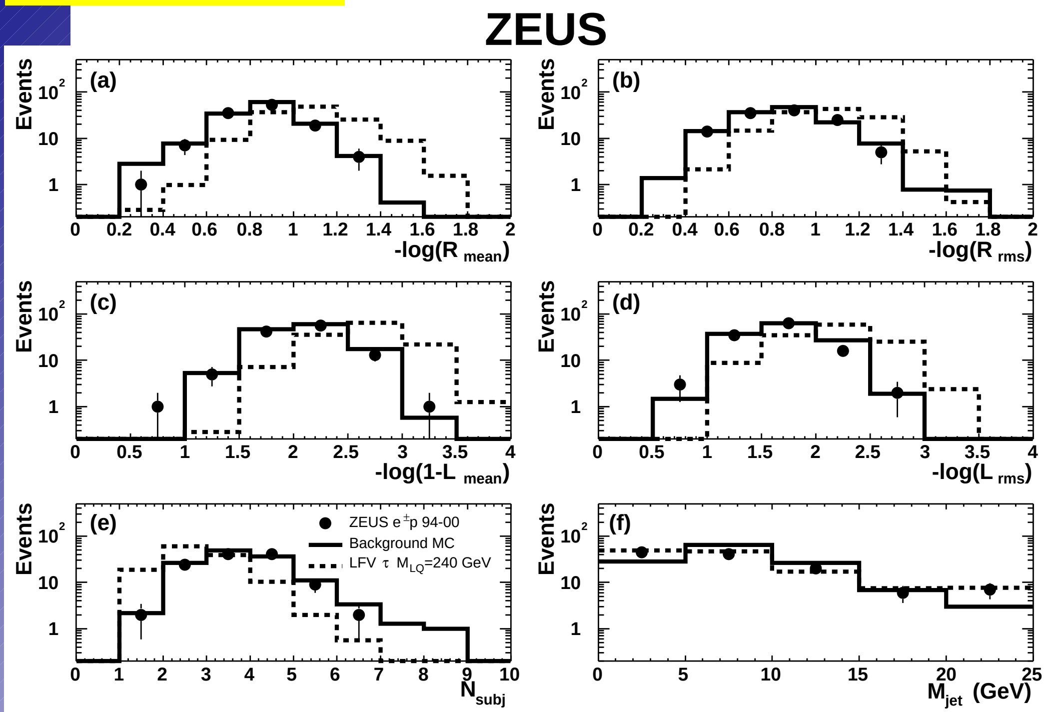
If τ goes into an electron, signature is similar: high p_T electron and missing p_T in the electron direction due to the presence of the two neutrinos.

Tau channel, hadronic decay of the τ:

Signature is a jet, as in the previous case, balanced in p_T with a τ jet, i.e. a jet made by the τ decay products. In order to distinguish this jet from usual QCD jets, we should consider that this jet has small radial dimension, few tracks inside, and small intrinsic p_T. ZEUS used these characteristics to develope a τ-finder to identify τ 's.

LFV search, e → τ

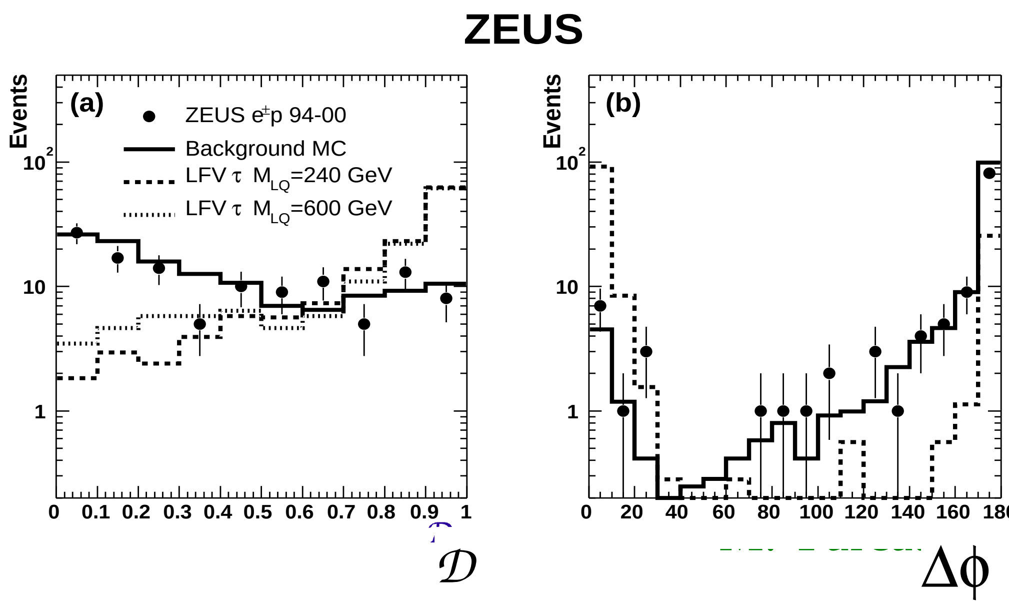
$\mathscr{L} = 130\ pb^{-1}$



Variables related to the jet longitudinal and transverse dimension, mass and number of subjets are used to distinguish between τ-jets and *q*-jets.

$$\mathcal{D}(\vec{x}) = \frac{\rho_{\rm sig}(\vec{x})}{\rho_{\rm sig}(\vec{x}) + \rho_{\rm bkg}(\vec{x})}$$

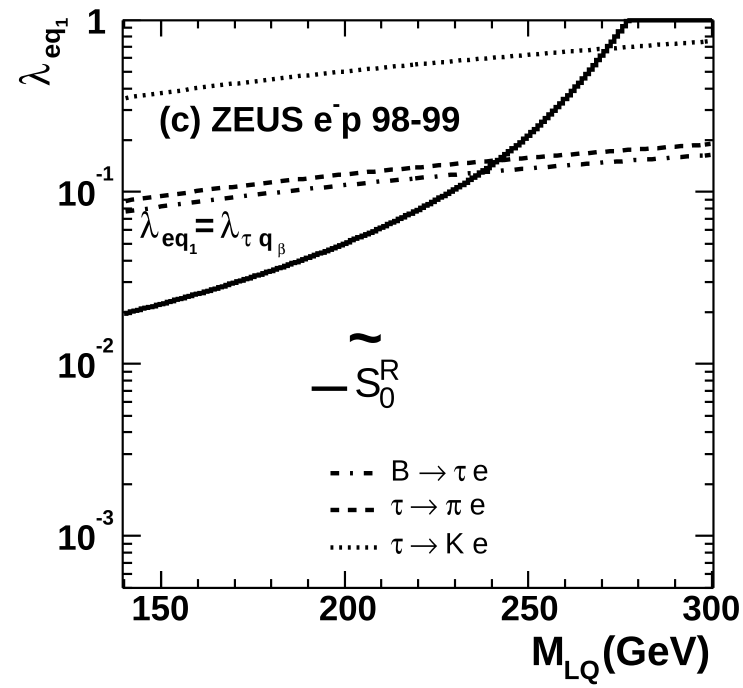
τ events have discriminant values close to 1, NC DIS are close to 0. Moreover, the Δϕ angle between the jet and the missing p_T is close to 0 for signal events.



Main SM contribution is the QCD di-jet production.

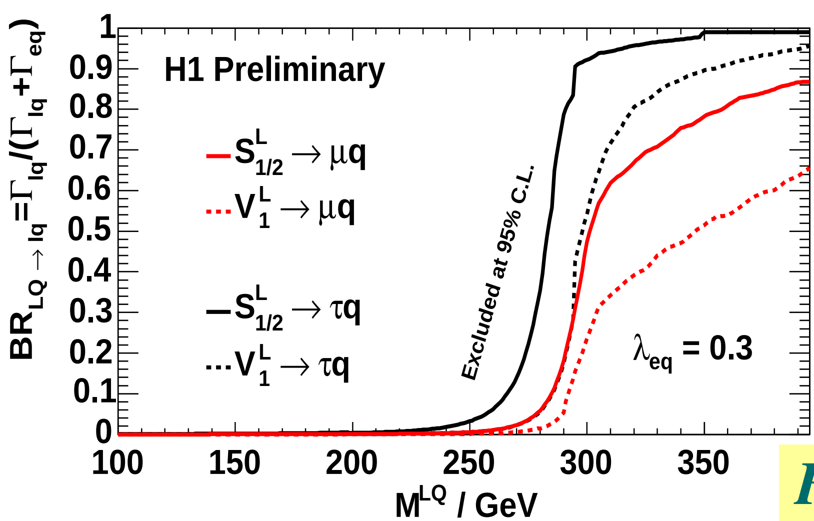
LFV: results, resonant production (m_{LQ} < 300 GeV)

- No candidate LQ was found by ZEUS, expectation was (2.3 ±0.5). H1 found 1 candidate in the hadronic channel, SM predicts (0.56 ±0.16).
- Limits are extracted by both experiments on coupling times *BR*, $\lambda_{eq1}\sqrt{\beta}_{\mu q2}$ and $\lambda_{eq1}\sqrt{\beta}_{\tau q2}$, and, fixing the couplings to $\lambda_{eq1} = \lambda_{lq2} = 0.3$, on the LQs masses.



F = 2, e^-p data

Limits on $\lambda_{eq1}\sqrt{\beta}_{\tau q2}$ for a scalar LQ coupling to a right-handed e^- and a τ.



F = 0, e^+p data

LFV: results, virtual LQ exchange (m_{LQ} > 300 GeV)

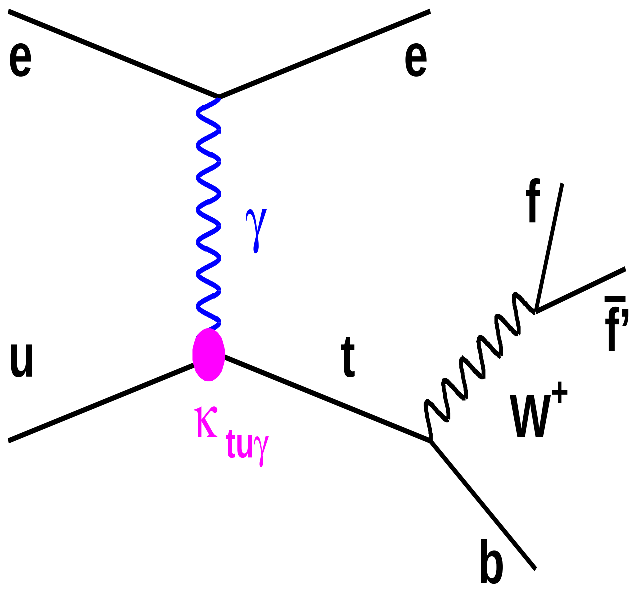
- Limits on $(\lambda_{eq\alpha}\lambda_{lq\beta} / M^2_{LQ})$ are extracted. In the τ channel, most limits are the best up to date.
- Some limits can be applied also to R-parity-violating squarks.

Limit on $(\lambda_{1j\alpha}\lambda_{ij\beta}/ M^2_{u})$ for a *u*-type squark of generation j, i=μ,τ being the final state lepton.

$e \to \tau$			ZEUS $e^{\pm}p$ 94-00				$F=0$
$\alpha\beta$	$S^L_{1/2}$ $e^-\bar{u}$ e^+u	$S^R_{1/2}$ $e^-(\bar{u}+\bar{d})$ $e^+(u+d)$	$\tilde{S}^L_{1/2}$ $e^-\bar{d}$ e^+d	V^L_0 $e^-\bar{d}$ e^+d	V^R_0 $e^-\bar{d}$ e^+d	$\tilde{V}^R_0$ $e^-\bar{u}$ e^+u	V^L_1 $e^-(\sqrt{2}\bar{u}+\bar{d})$ $e^+(\sqrt{2}u+d)$
1 1	$\tau\to\pi e$ 0.4 **1.8**	$\tau\to\pi e$ 0.2 **1.5**	$\tau\to\pi e$ 0.4 **2.7**	$\tau\to\pi e$ 0.2 **1.7**	$\tau\to\pi e$ 0.2 **1.7**	$\tau\to\pi e$ 0.2 **1.3**	$\tau\to\pi e$ 0.06 **0.6**
1 2	**1.9**	$\tau\to Ke$ 6.3 **1.6**	$K\to\pi\nu\bar{\nu}$ 5.8×10^{-4} **2.9**	$\tau\to Ke$ 3.2 **2.1**	$\tau\to Ke$ 3.2 **2.1**	**1.6**	$K\to\pi\nu\bar{\nu}$ 1.5×10^{-4} **0.8**
1 3	*	$B\to\tau\bar{e}$ 0.3 **3.2**	$B\to\tau\bar{e}$ 0.3 **3.3**	$B\to\tau\bar{e}$ 0.13 **2.6**	$B\to\tau\bar{e}$ 0.13 **2.6**	*	$B\to\tau\bar{e}$ 0.13 **2.6**
2 1	**6.0**	$\tau\to Ke$ 6.3 **4.1**	$K\to\pi\nu\bar{\nu}$ 5.8×10^{-4} **5.2**	$\tau\to Ke$ 3.2 **2.3**	$\tau\to Ke$ 3.2 **2.3**	**2.1**	$K\to\pi\nu\bar{\nu}$ 1.5×10^{-4} **0.9**
2 2	$\tau\to 3e$ 5 **10**	$\tau\to 3e$ 8 **5.6**	$\tau\to 3e$ 17 **6.5**	$\tau\to 3e$ 9 **3.4**	$\tau\to 3e$ 9 **3.4**	$\tau\to 3e$ 3 **5.5**	$\tau\to 3e$ 1.6 **2.1**
2 3	*	$B\to\tau\bar{e}X$ 14 **8.1**	$B\to\tau\bar{e}X$ 14 **7.8**	$B\to\tau\bar{e}X$ 7.2 **5.5**	$B\to\tau\bar{e}X$ 7.2 **5.5**	*	$B\to\tau\bar{e}X$ 7.2 **5.5**
3 1	*	$B\to\tau\bar{e}$ 0.3 **7.8**	$B\to\tau\bar{e}$ 0.3 **7.2**	V_{ub} 0.12 **2.5**	$B\to\tau\bar{e}$ 0.13 **2.5**	*	V_{ub} 0.12 **2.5**
3 2	*	$B\to\tau\bar{e}X$ 14 **11**	$B\to\tau\bar{e}X$ 14 **10**	$B\to\tau\bar{e}X$ 7.2 **4.2**	$B\to\tau\bar{e}X$ 7.2 **4.2**	*	$B\to\tau\bar{e}X$ 7.2 **4.2**
3 3	*	$\tau\to 3e$ 8 **15**	$\tau\to 3e$ 17 **14**	$\tau\to 3e$ 9 **8.1**	$\tau\to 3e$ 9 **8.1**	*	$\tau\to 3e$ 1.6 **8.1**

Single top production

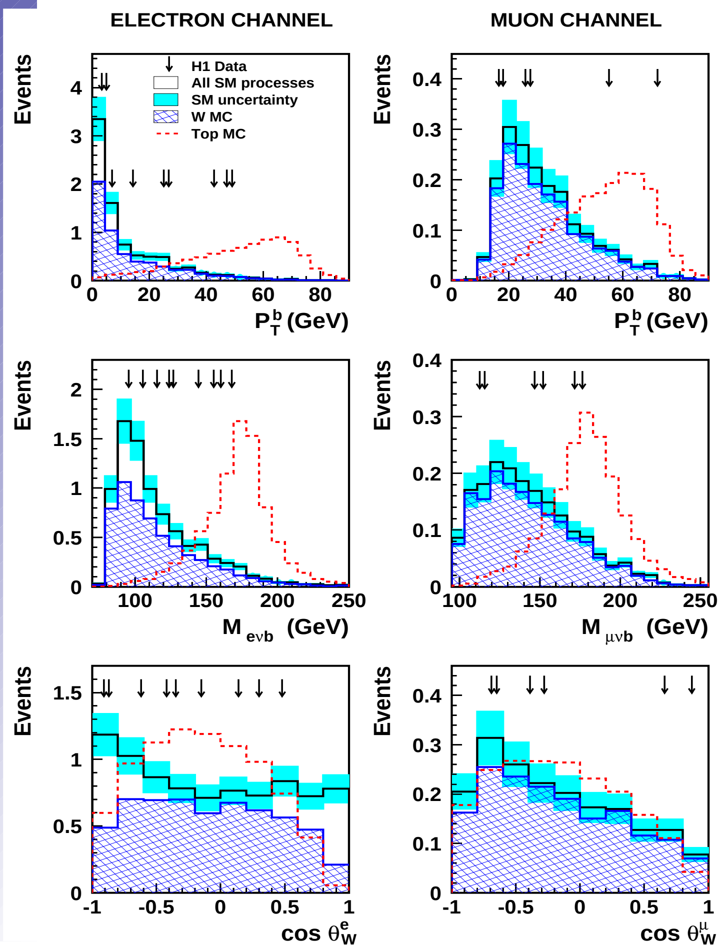
- At HERA, the SM process leading to single top production is $ep \to t\bar{b}\nu X$, but this has a very low cross section.
- Single top production can occur through FCNC processes, $ep \to etX$, with a γ or a Z interacting with a u-type quark in the proton.
- FCNC processes are an insight into beyond the SM processes. They have been searched for at CDF ($t \to uV$) and at LEP ($e^+e^- \to t\bar{u}, t\bar{c}$). No events were found and limits were put on the branching fractions $B(t \to u\gamma)$, $B(t \to Zq)$.
- At HERA the dominant contribution comes from the exchange of the γ; moreover, a large x is required to create top, so the dominant coupling is $tu\gamma$.



The single top decays into bW^+. W^+ can decay into $l^+\nu$ or into quarks.

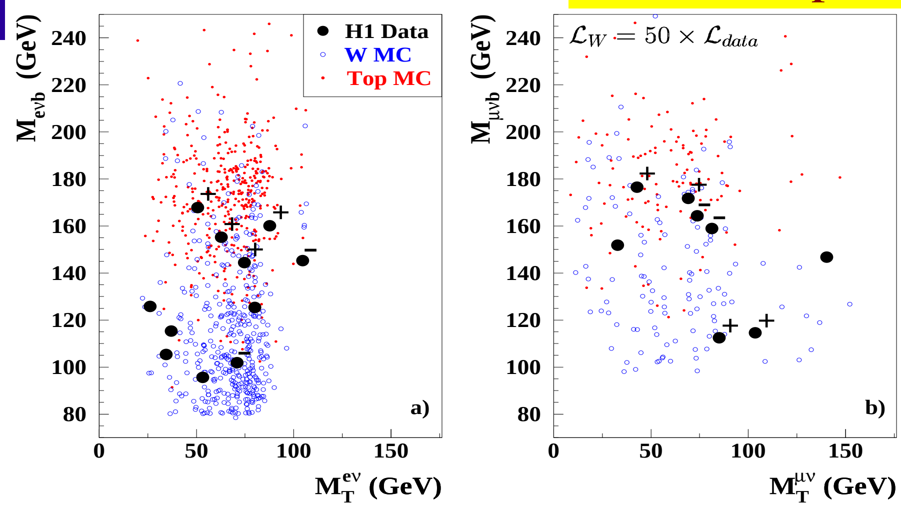
Event selection, leptonic channel: $t \to W^+ b \to l^+ \nu_l\ jet$

- Events are characterized by a isolated high-p_T lepton, large missing p_T and a jet from the b hadronization.
- ZEUS finds no candidate in the leptonic channel. H1 finds 9 e^+ (8.40±1.06) and 6 μ^+ (1.88±0.32) events after the preselection.



H1

$\mathscr{L} = 132\ pb^{-1}$

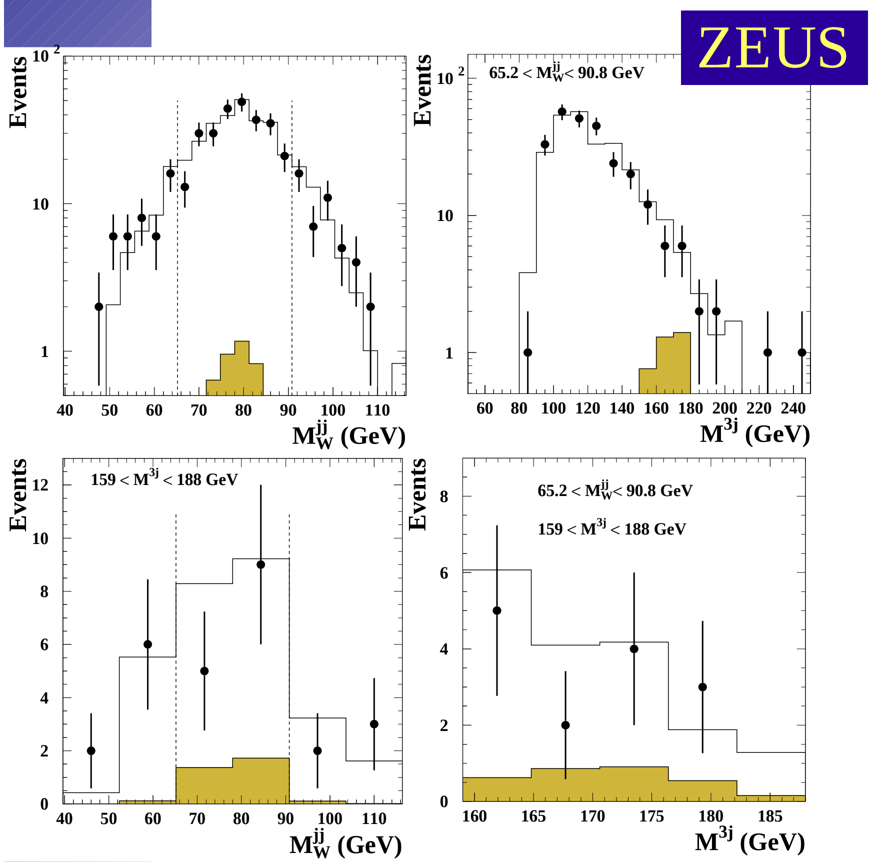


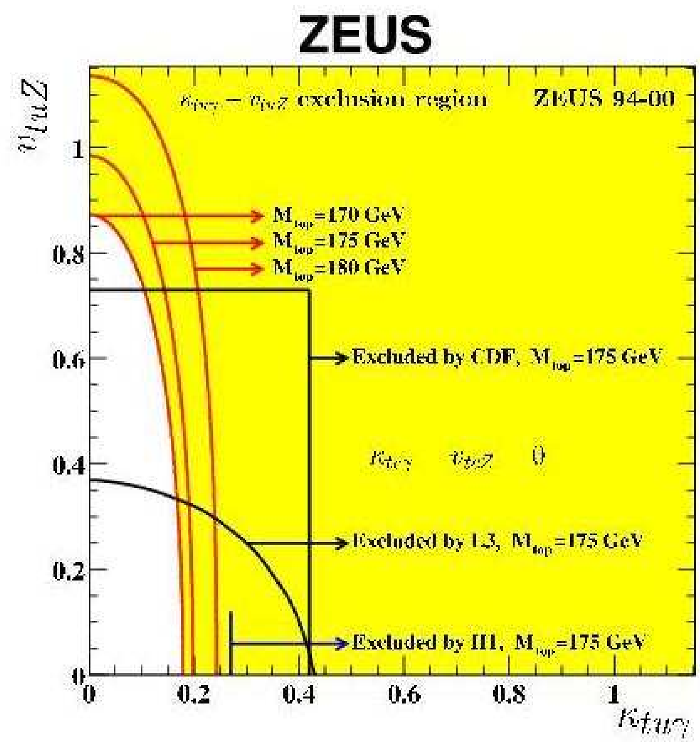
After tighter cut on $p_T^{\ b}$ and mass of the system, $3e^+$ (0.67±0.13) and $2\mu^+$ (0.65±0.10) survive.

Wait for HERA-II data...

Event selection, hadronic channel: $t \rightarrow W^{+}b \rightarrow 3jet$

- Single top signature is less clear and background from QCD is high. Signature are high p_T jets, with invariant masses giving the W and the t mass.
- Both experiments find agreement with SM expectations.





$\mathscr{L} = 130\ pb^{-1}$

Limits are set on the coupling $\kappa_{tu\gamma}$ by both experiments. These are competitive with the world's best.

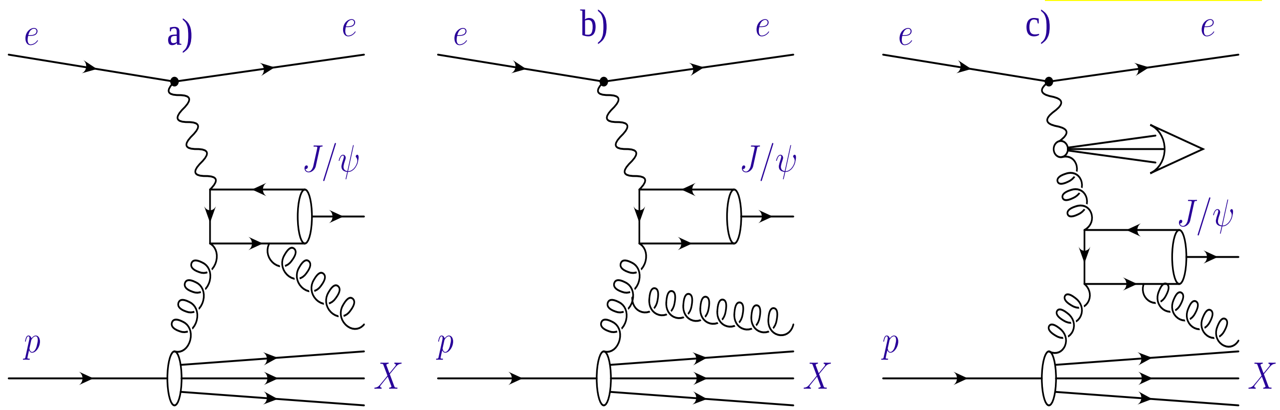
Charmonium production at HERA

- Charmonium production is studied, mainly J/ψ production is analysed. The aim is to investigate the production mechanism (i.e. identify colour singlet and colour octet contributions) in both the high (DIS) and low Q^2 (photoproduction, PHP) regimes.
- PHP analyses: H1 uses ~87 pb^{-1} of data, ZEUS ~38 pb^{-1}.
- DIS analyses: H1 uses ~77 pb^{-1} of data, ZEUS ~109 pb^{-1}.

J/ψ production

- Dominant process for inelastic charmonium production in *ep* collisions is photon-gluon fusion.

CS or CO | CO | CS or CO



Direct γ processes | Resolved γ process

- In the photoproduction regime, $Q^2 < 1\ GeV^2$, also resolved processes contribute. Those contributions are suppressed at high Q^2.
- The c-$\bar{c}$ pair can be produced in a state having the quantum numbers of the J/ψ (color singlet) or in a different state (color octet). In this last case, the transition to J/ψ proceeds through the emission of soft gluons.

J/ψ production -2-

Available theoretical models:

- CS in perturbative QCD. NLO calculations for the direct γ part in photoproduction are available.
- CS and CO in NRQCD: the J/ψ production amplitude is factorized in a short distance part, calculable in pQCD, and long distance terms, (LDME) that have to be extracted by the data (hadronic J/ψ production or B decay to J/ψ). Calculations are available at LO. If we consider the CS part in NRQCD, colour singlet model at LO is recovered.
- The (CS+CO) contribution describes the rates of J/ψ in $p\bar{p}$ and $\gamma\gamma$ collisions. LDME used for the calculations are extracted using data collected in $p\bar{p}$ collisions.

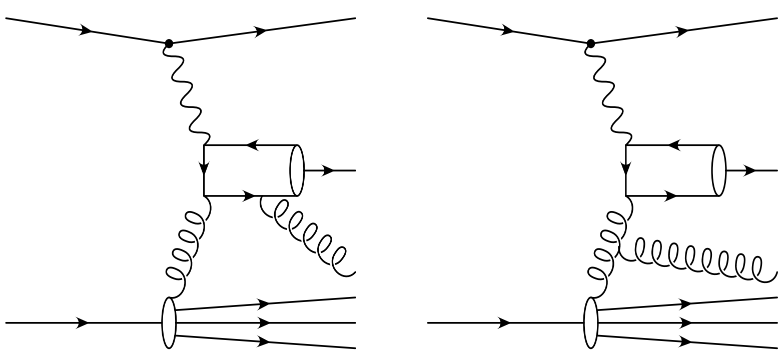
Event selection

- *J/ψ* mesons are identified through their decay into muons. There is also a measurement by H1 in the DIS regime where *J/ψ* is selected through the decay into e^+e^-.

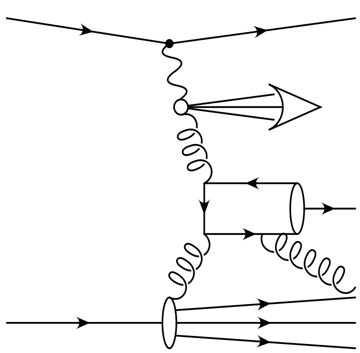
- An important variable is the inelasticity, z, which is the fraction of the photon momentum transferred to the *J/ψ*:

$$z = \frac{p_\psi \cdot p}{q \cdot p}, \qquad z = \frac{(E - p_z)_{J/\psi}}{2\,y\,E_e},$$

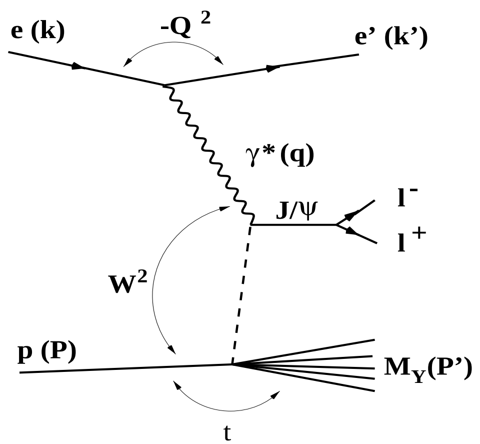
- At low z (< 0.2) resolved photon processes dominate, at medium z direct processes are the most important, but for $z > 0.9$ diffractive proton-dissociative processes give a sizeable contribution. This is the reason why the analyses are limited to the region $z < 0.9$.



Direct γ processes



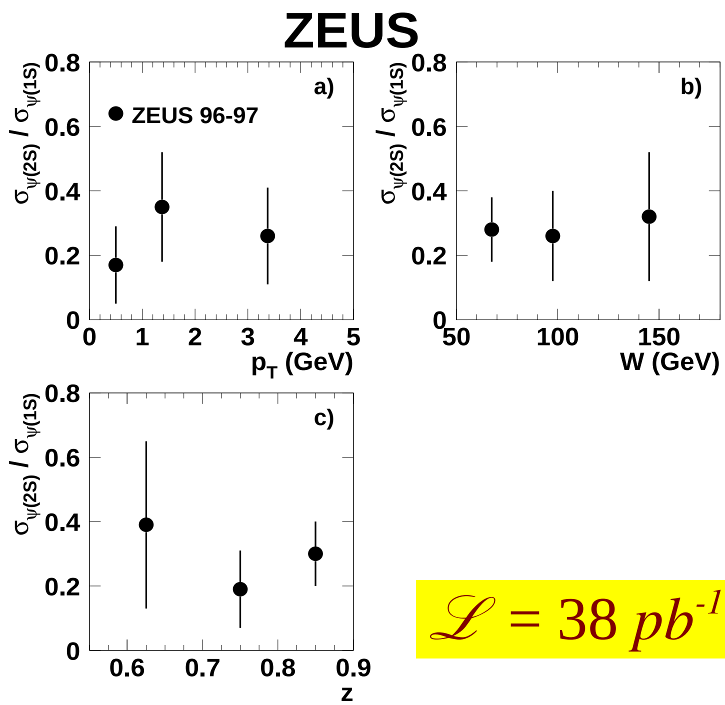
Resolved γ process



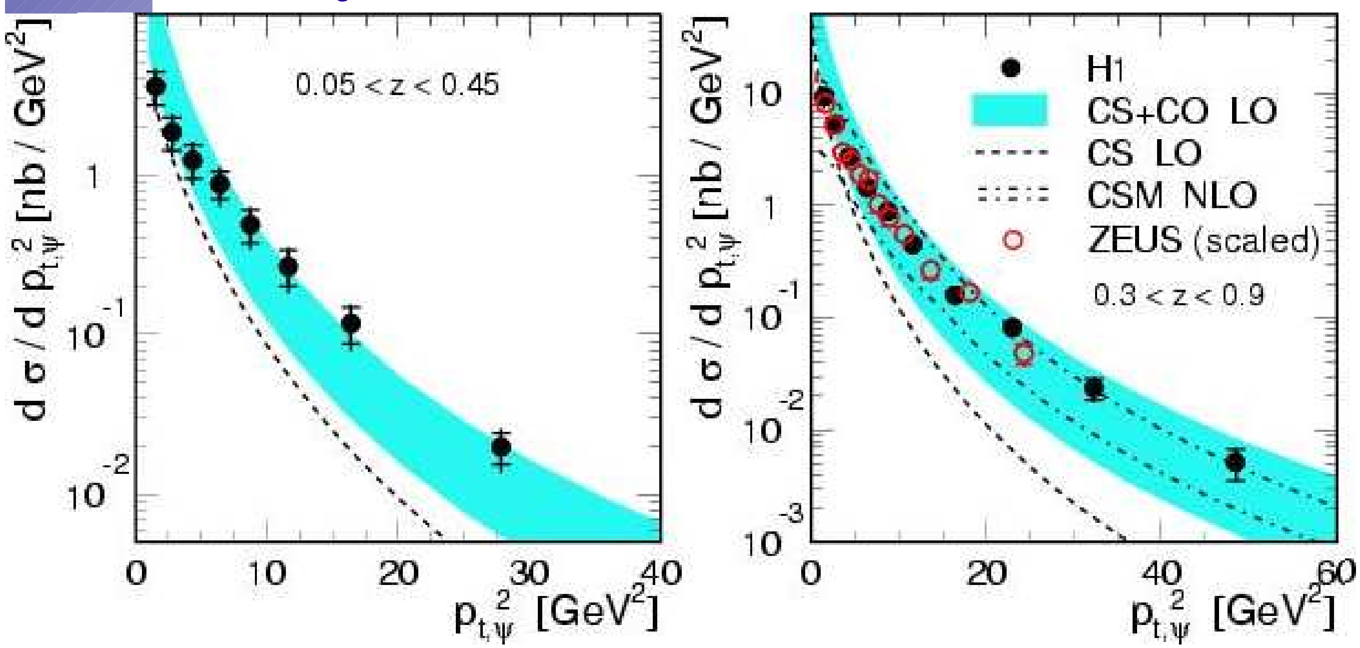
Diffractive process

PHP regime

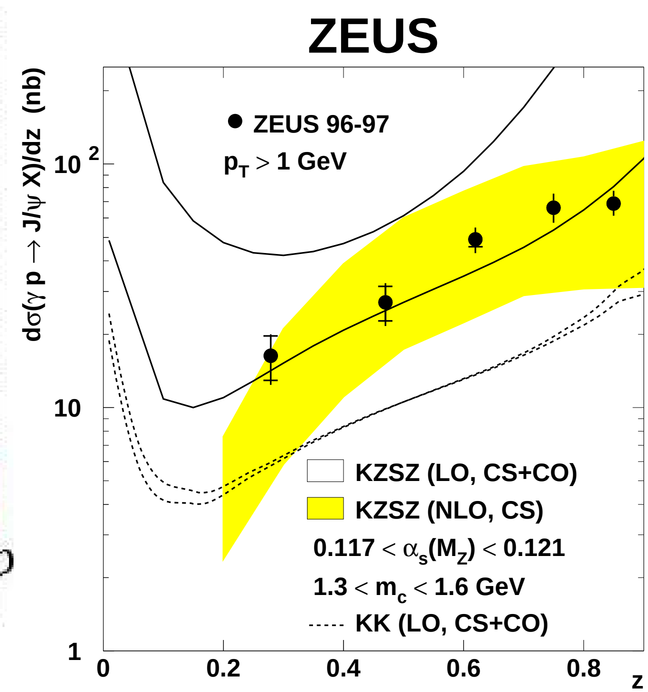
- The ratio of the cross sections of $\psi(2s)$ and J/ψ is evaluated as a function of p_T, W and z. This is found flat, and, keeping branching ratios into account, ~18%.
- Differential cross sections are compared with CS and (CS+CO) calculations, in pQCD and NRQCD.



$\mathscr{L} = 38\ pb^{-1}$



$\mathscr{L} = 87\ pb^{-1}$

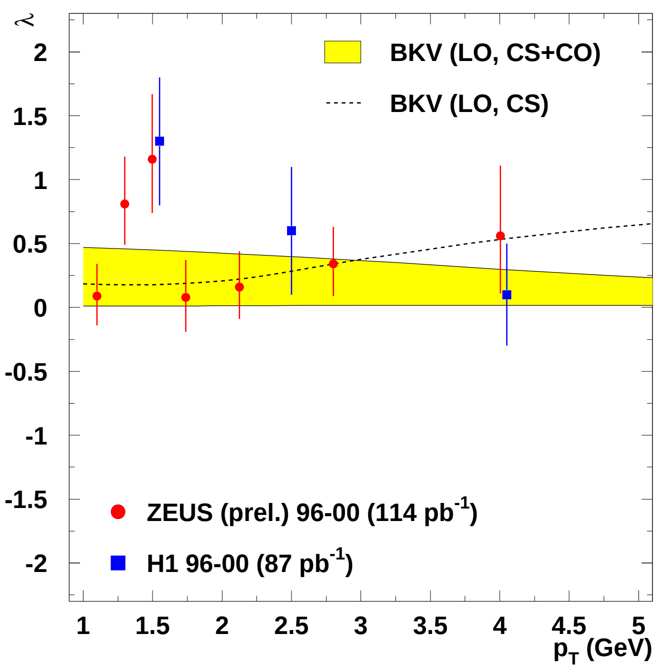


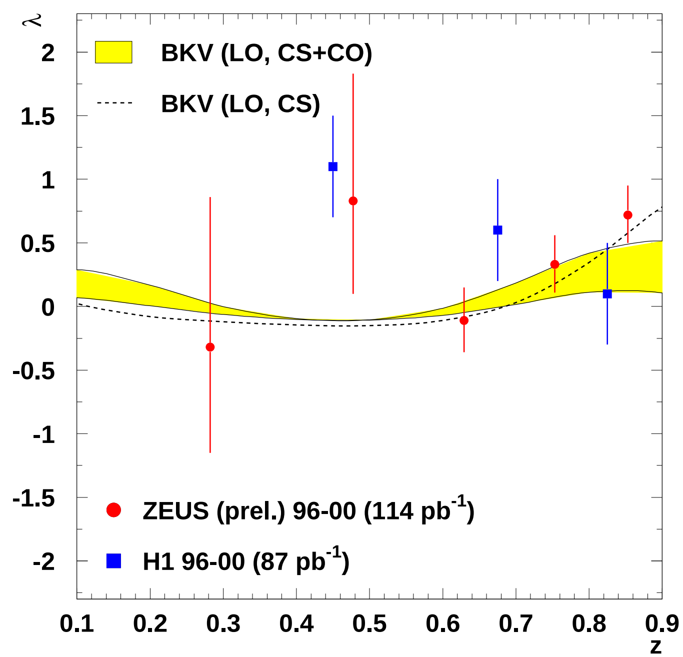
Polarisation measurement

- The polarisation of the J/ψ is different in the different theoretical models and can be used to distinguish between them. In this case normalisation uncertainties are avoided.
- The cross section as a function of ϑ^* can be parametrised as

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

- The dependence of from p_T can give hints on the production mechanism.





No firm conclusions with the present statistics.

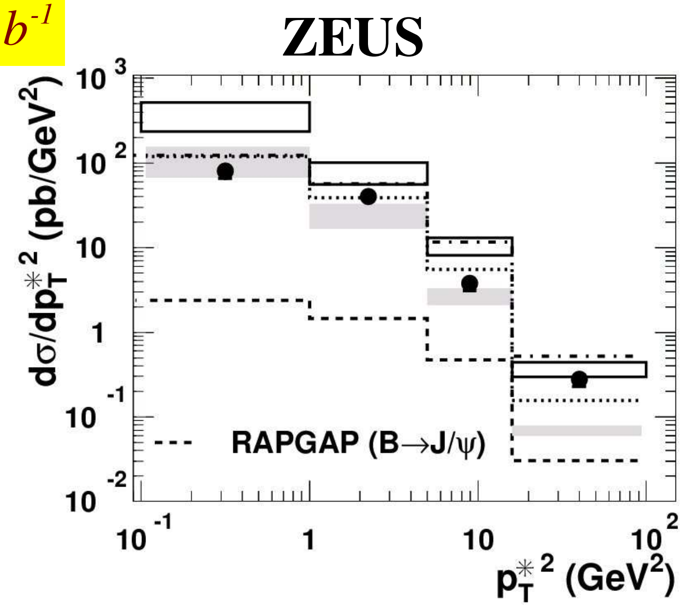
CDF has recently reported a result on J/ψ polarisation showing disagreement between data and (CS+CO) NRQCD

DIS regime

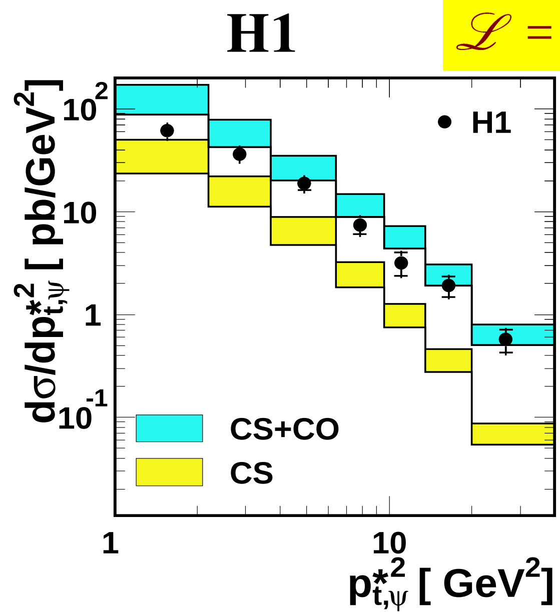
- *Advantages:* the contribution from CO is expected to be more significant, the predictions should be more accurate, background from diffractive processes is suppressed at high Q^2, resolved processes are suppressed and so the analysis is cleaner.

Data are compared with NRQCD, CS and (CS+CO), at LO.

$\mathscr{L}$ = 109 pb^{-1}



$\mathscr{L}$ = 77 pb^{-1}



H1 agrees with LO NRQCD, (CS+CO), while ZEUS agrees better with CS at LO. This is due to the fact that H1 ask the J/ψ to have $p_T{}^{*2} > 1$ GeV^2, and in the higher p_T region higher order corrections to CS are important.

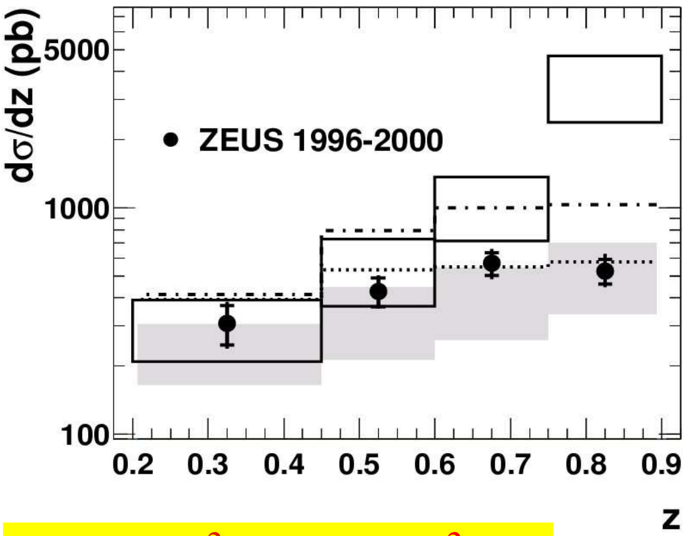
ZEUS-H1 comparison

2nd March 2006

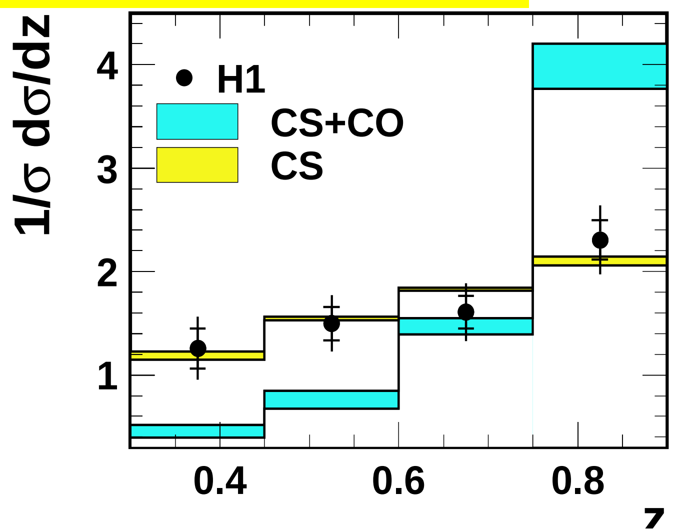
In the $p_T{}^{*2} > 1\ GeV^2$ region the data are not in agreement with CS.

In the same kinematic region H1 and ZEUS data are in agreement.

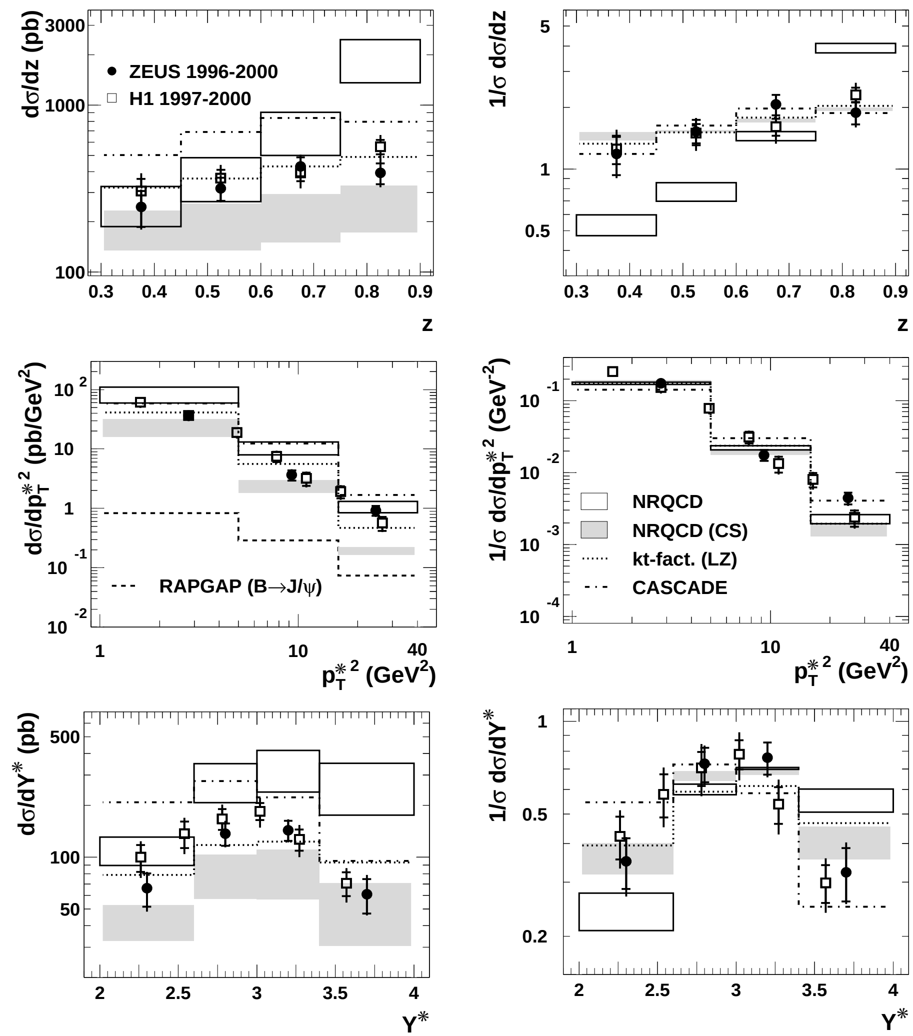
ZEUS, no $p_T{}^{*2}$ cut



H1, $p_T{}^{*2} > 1\ GeV^2$ cut



$p_T{}^{*2} > 1\ GeV^2$ cut



z distribution in CS+CO is difficult to be calculated (singularity at z=1)

Conclusions

- Search of LFV at HERA with the whole HERA-I statistics has found no deviation from the SM.
- Some possible candidates for single top production have been found by H1 but not by ZEUS: anyway, the number is small and more statistics is needed to draw conclusions. Wait for HERA-II data.
- Inelastic charmonium production is studied in both high and low Q^2 regimes. Differential cross sections and polarisation distribution are investigated in order to distinguish between CO and CS model. No firm conclusion is drawn, but when NLO is available the data are well described by the CS.
- Hints on the CO mechanism can come from the observation of $\chi_c \to J/\psi\,\gamma$ in direct photon processes, i.e. in the medium z region.

HERA-II data taking is going well since 2004, in 2005 more luminosity than the whole HERA-I sample has been collected. 5 times the HERA-I statistic is expected at the end, in middle 2007. *Stay tuned!*

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LFV:

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Single top:

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