Latest Quarkonium results from HERA

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GSI, Darmstadt

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on behalf of H1 and ZEUS Collaborations

Outline:

- the HERA collider and the experiments H1 and ZEUS
- charmonium production at HERA
- charmonium measurements by H1 and ZEUS:
  - J/ψ double differential cross section measurements in γ p
  - J/ψ single differential cross section measurements in DIS
  - J/ψ helicity parameters in γ p
- conclusions

the HERA collider: a brief introduction

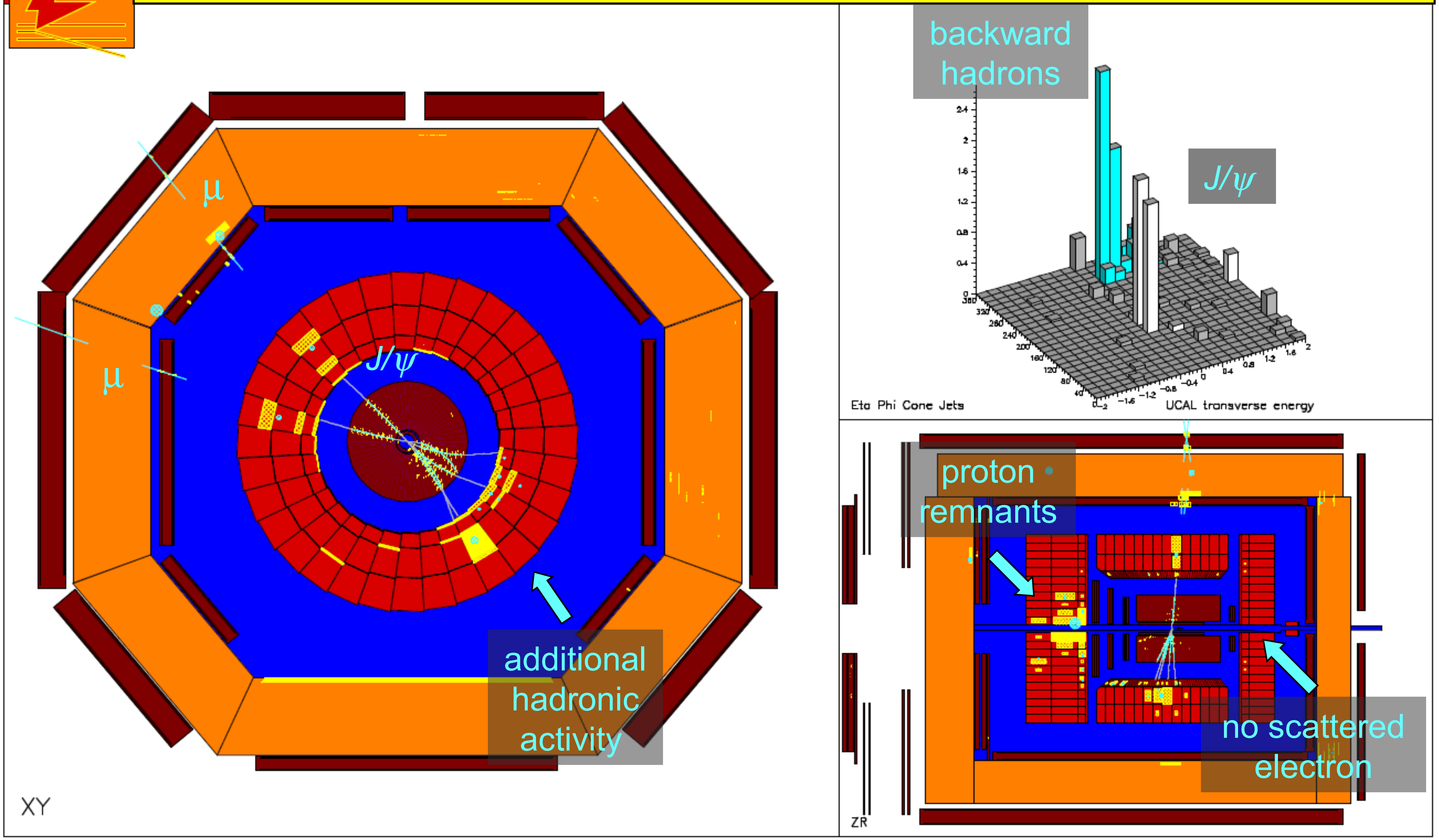
• HERA was an *e p* collider at high CMS energy (this was like having an about 50 TeV *e* beam on fixed target)

• H1 and ZEUS were large multipurpose experiments studying *e p* collisions

• "effective" running started in 1996 and ended mid 2007

• ZEUS lumi.: all data taken since 1996, 11 years of activity, 468 pb^{-1} of integrated lumi.; H1 lumi.: ranging between 165 and 315 pb^{-1} depending on the analysis ($\gamma\, p$ / DIS)

inelastic J/ψ event as seen in the ZEUS detector



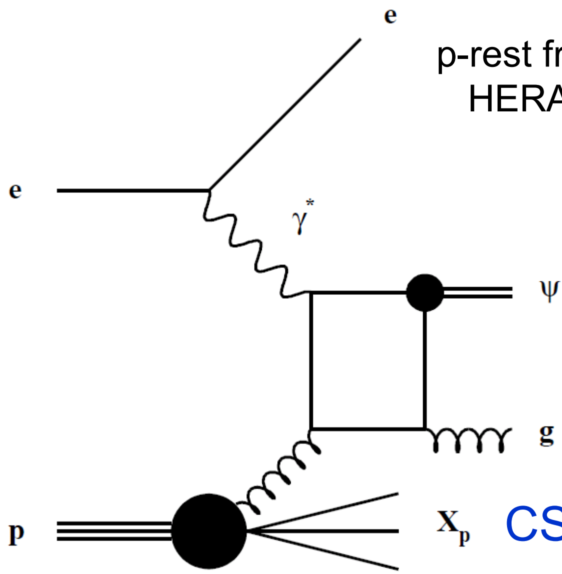
• proton remnant + additional hadronic activity: inelastic event

• no scattered electron: photoproduction (PHP) regime ($Q^2 < 1 – 2.5$ GeV^2); scattered electron seen: DIS regime ($Q^2 > 3.6$ GeV^2)

charmonium production at HERA (J/ψ and ψ(2S))

p-rest frame: $z = E(\psi) / E(\gamma^*)$

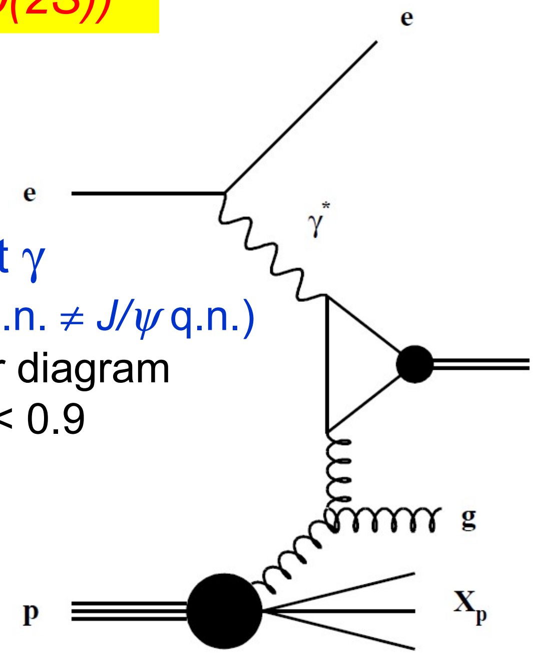
HERA frame $= E\text{-}P_z(\psi) / E\text{-}P_z(\psi) + E\text{-}P_z(\text{had})$



direct γ

CS model (cc q.n. = *J/ψ* q.n.)

$0.2 < z < 0.9$

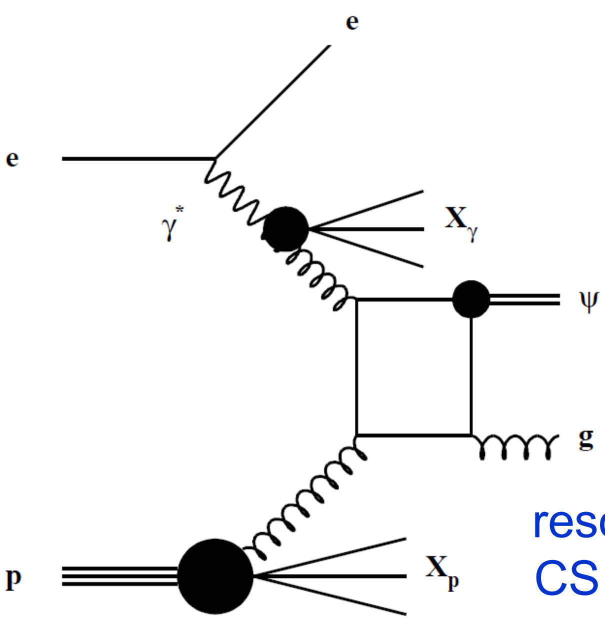


direct γ

CO model (cc q.n. ≠ *J/ψ* q.n.)

this particular diagram

$0.2 < z < 0.9$



resolved γ

CS model

$z < 0.2$

other contributions to the signal (decreasing size):

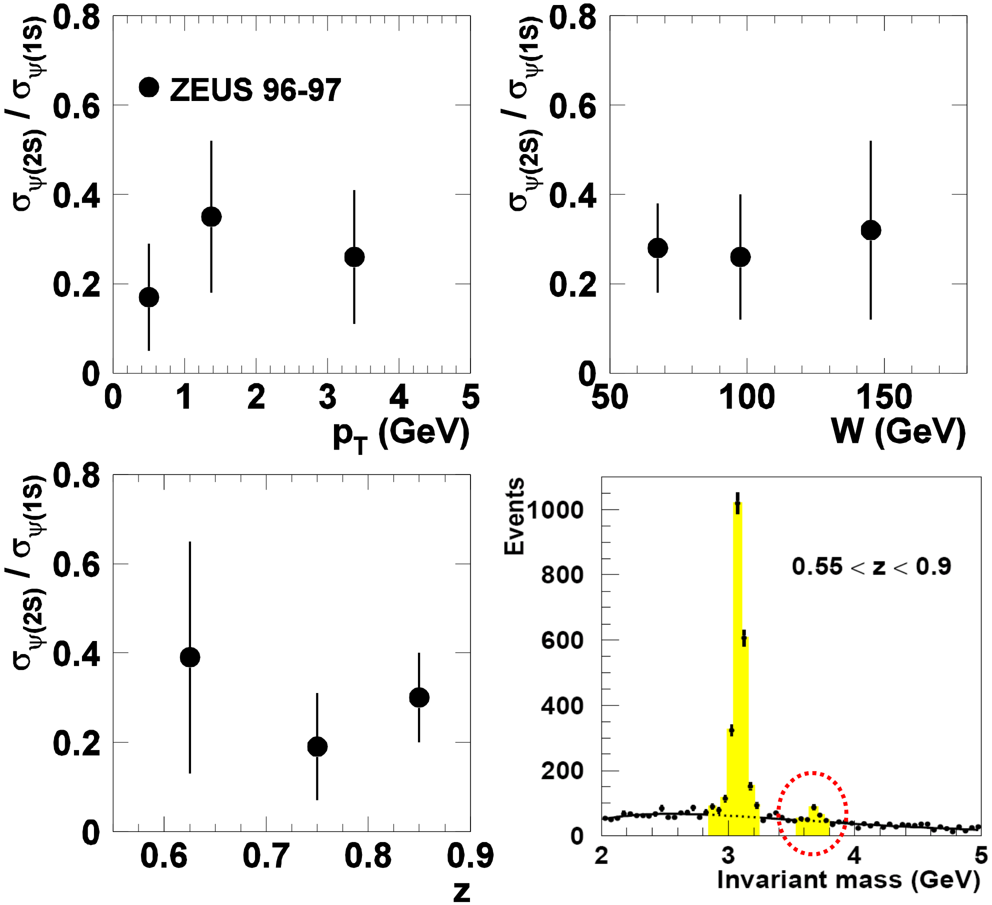
- $\psi(2S) \rightarrow J/\psi\,(\rightarrow \mu\,\mu)$ X decays
- *J/ψ* from B meson decays
- *J/ψ* from resolved photon processes

main background source:

- *J/ψ* from proton diffractive dissociation

other contributions to the signal

- inelastic $\psi(2S)$ production:



- < 1/10 of the total available luminosity
- $\psi(2S)$ to $\psi(1S)$ cross section ratio consistent with being flat, 0.33 ± 0.10 (stat), sys negligible (cancel when taking the cross section ratio)
- via $\psi(2S) \to J/\psi\,(\to \mu\,\mu)\,X$ this results in a 15 % increase of the J/ψ cross section

NOT subtracted by H1 and ZEUS

not possible experimentally … would need an inclusive reconstruction of the decay $\psi(2S) \to J/\psi\,(\to \mu\,\mu)\,X$

- ZEUS will try to update this measurement with the full available lumi.

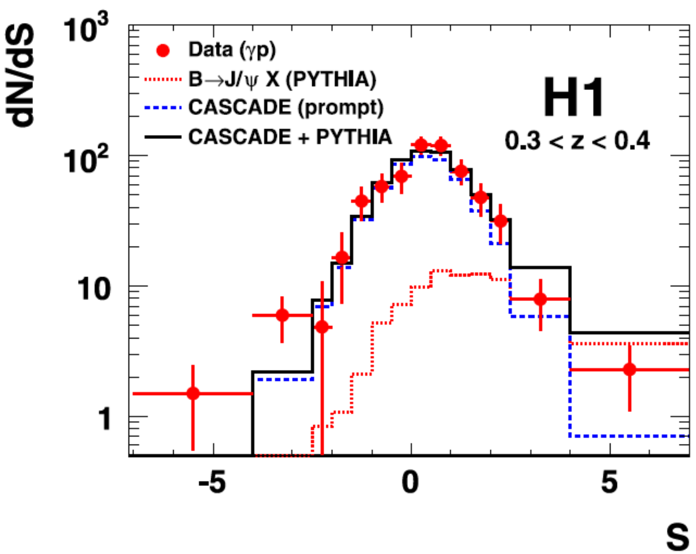
other contributions to the signal

• charmonium from B meson decays:

B production well tested at HERA, much smaller B cross section than at hadron colliders

• ZEUS: estimated via MC, properly normalized to the B cross section measured at HERA, within the ZEUS analysis cuts: overall < 1.7 % of the measured J/ψ are from B meson decays, < 9 % at low z

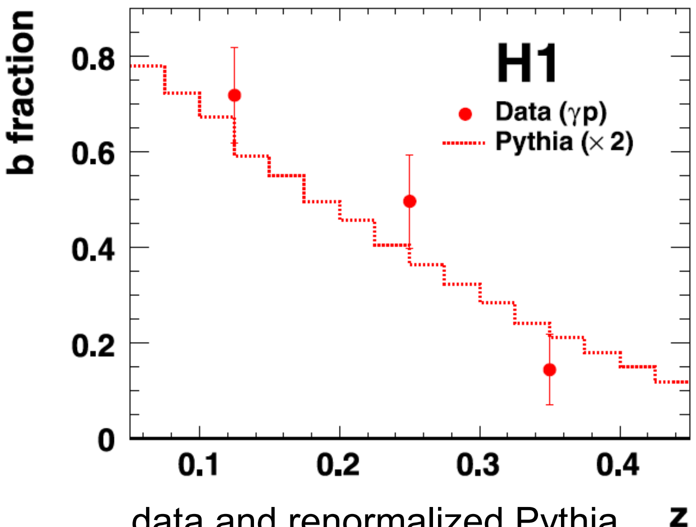
• H1: careful study based on data with secondary vertices measurements



$S = \delta / \sigma(\delta)$

δ: signed impact parameter of the decay μ

S: signed significance



data and renormalized Pythia MC in good agreement

NOT subtracted

• J/ψ from resolved γ processes (including $\chi_C \rightarrow J/\psi\,\gamma$): not well know in PHP, LO cross section is tiny at HERA: overall < 0.5 %, < 4 % at low z

NOT subtracted

main background

• charmonium from proton diffractive dissociation:

J/ψ produced at z > 0.9 but some are reconstructed with z < 0.9

can observe the proton remnants but have only a little chance of observing any additional hadronic activity (no color connection between the J/ψ and X_p)

- ZEUS (PHP):

2 μ + proton remnants + $\geq$ 1 track with $p_t > 0.125$ and $|\eta| < 1.75 \Rightarrow$ very strong suppression

remove 4 prong events with $| m(J/\psi\ \pi\pi) - m(J/\psi) - 0.59 | < 0.06$ i.e. diffractive $\psi(2S)$ events

remaining contribution: from a fit to the measured z distribution using the HERWIG MC for the signal and the EPSOFT MC for the diffractive background

overall: 6.9 % contribution, < 20 % for 0.75 < z < 0.9 $\Rightarrow$ strongly peaked at high z

subtracted

- H1 (PHP+DIS):

$\geq$ 5 track with $20° < \theta < 160°$

removes both diffractive J/ψ and $\psi(2S)$ events

nothing to subtract after this cut

these cuts to select inelastic events clearly also reduce the efficiency, they are then extrapolated for using HERWIG (ZEUS) / CASCADE (H1) MC

reminder: elastic charmonium: gone asking for the proton remnants

J/ψ measurements at HERA

PHP (H1 / ZEUS):

- 60 < W < 240 GeV
- 0.1 (ZEUS) - 0.3 (H1) < z < 0.9
- $p_t > 1$ GeV

double differential cross section in p_t and z as well as single differential cross sections as a function of W - z - p_t (not shown)

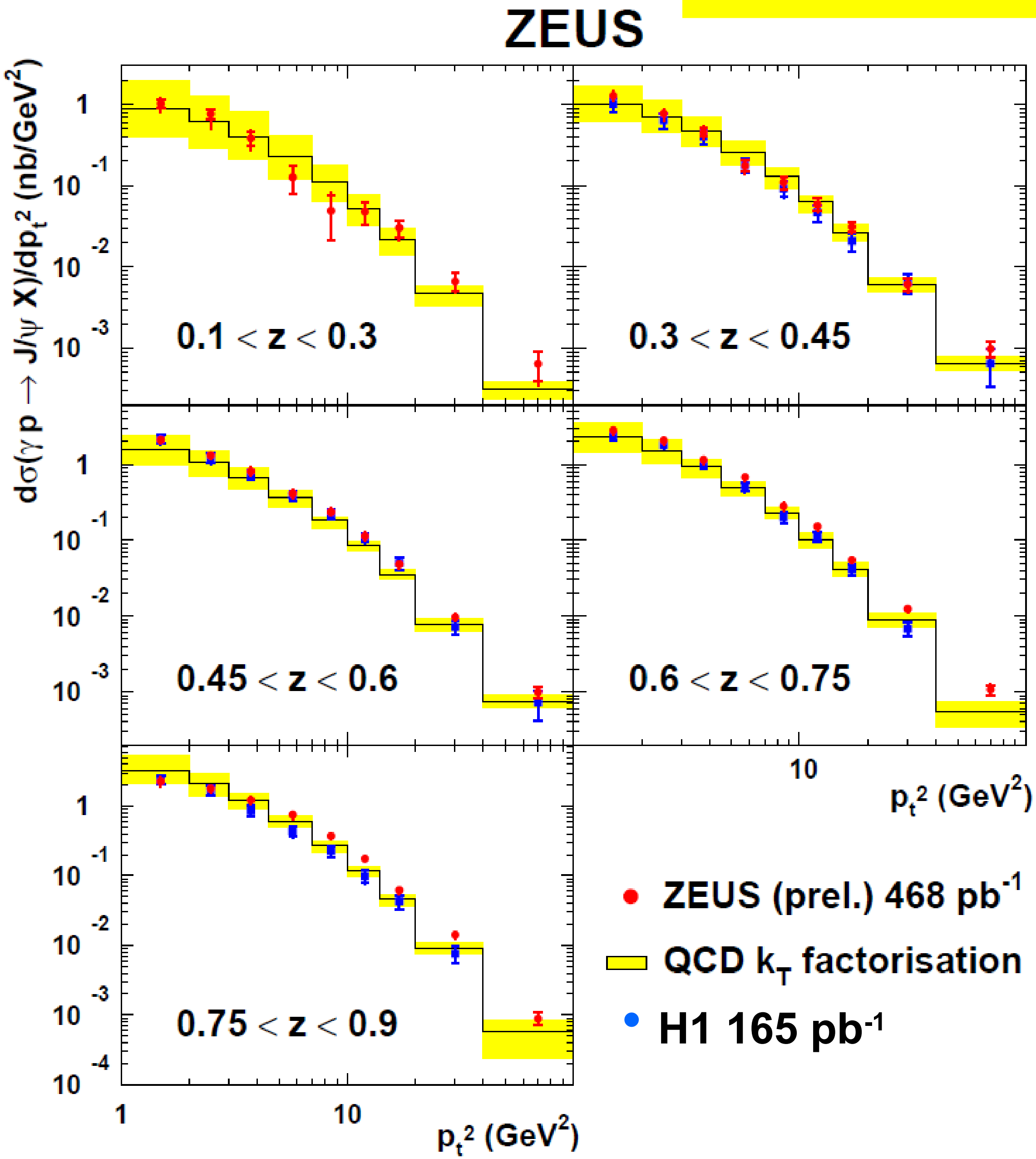
tried as much as possible to use the same binning to ease H1 – ZEUS comparisons

DIS (H1):

- $3.6 < Q^2 < 100$ GeV^2
- 60 < W < 240
- $p_t^* > 1$ GeV
- 0.3 < z < 0.9

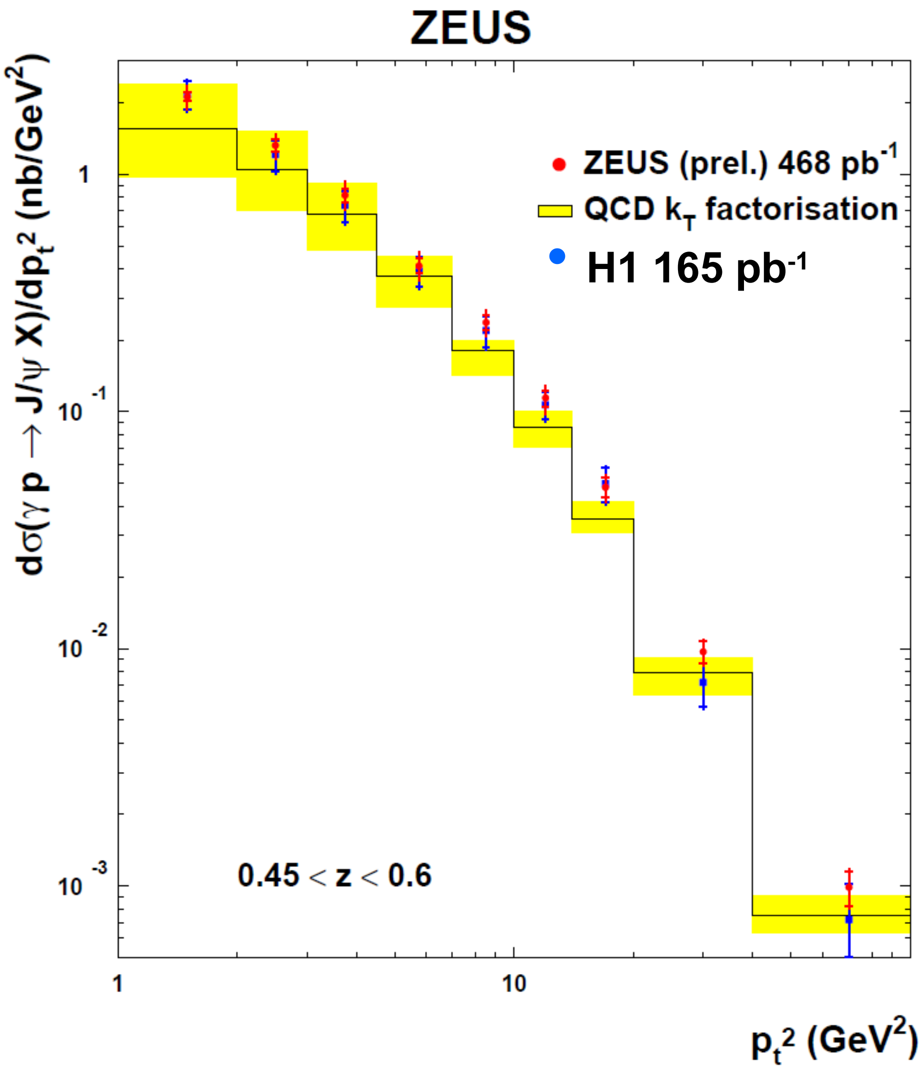
single differential cross sections in Q^2 - W - z - p_t^*

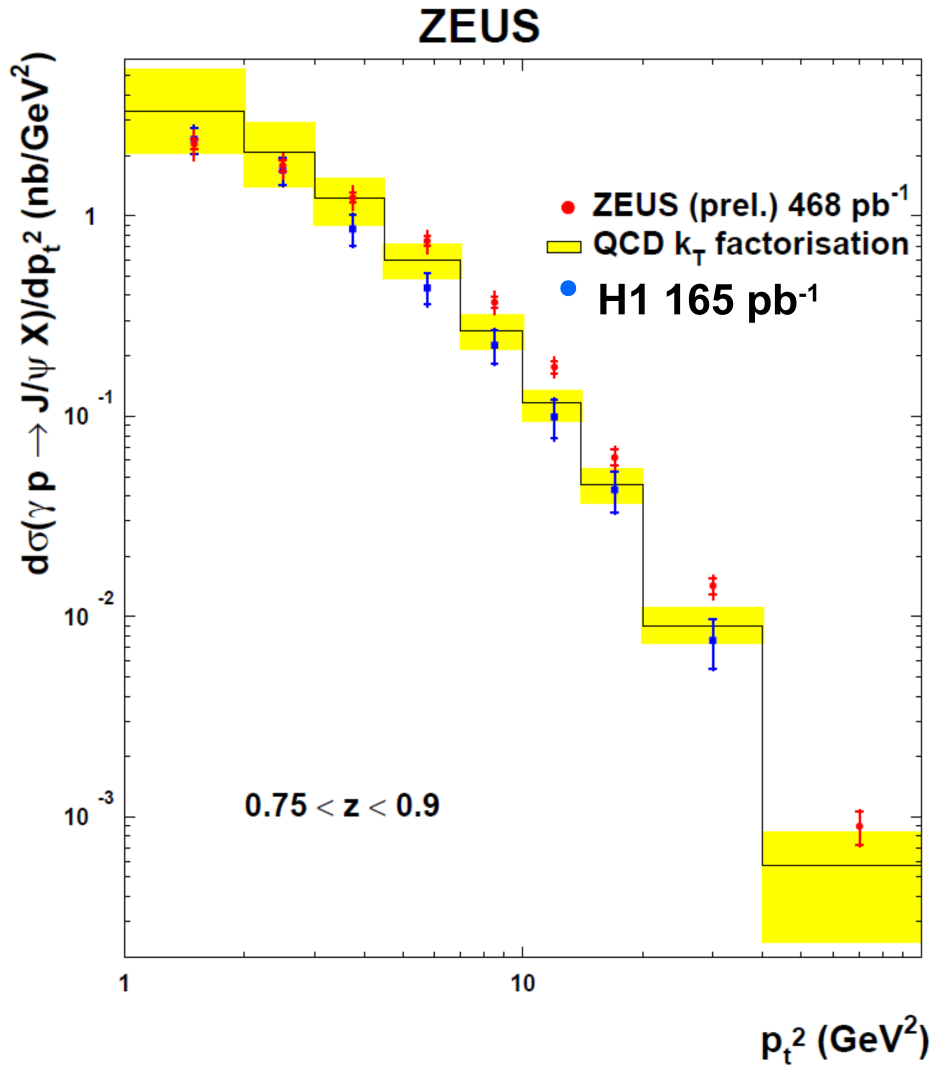
cross section differential in p_t^2 for different z ranges



- ZEUS data have a wider coverage (low z, high p_t^2) mostly due to the larger ZEUS stat. w.r.t. H1
- for the same reason ZEUS data have smaller uncertainties
- ZEUS and H1 data are in very good agreement except for high z high p_t^2
- HERA data are compared to k_T factorization predictions (see previous talk from S. Baranov), agreement is reasonable both in shape and normalization
- HERA data are much more precise than theory predictions

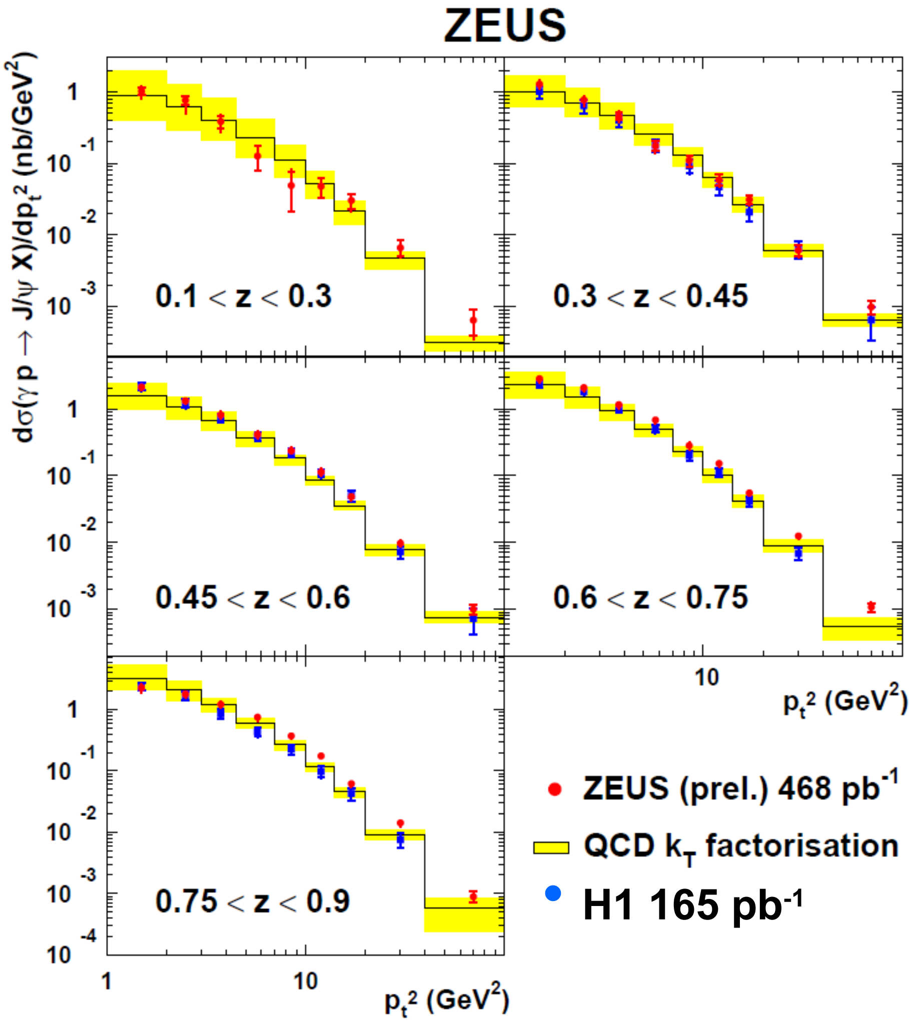
cross section differential in p_t^2 for different z ranges

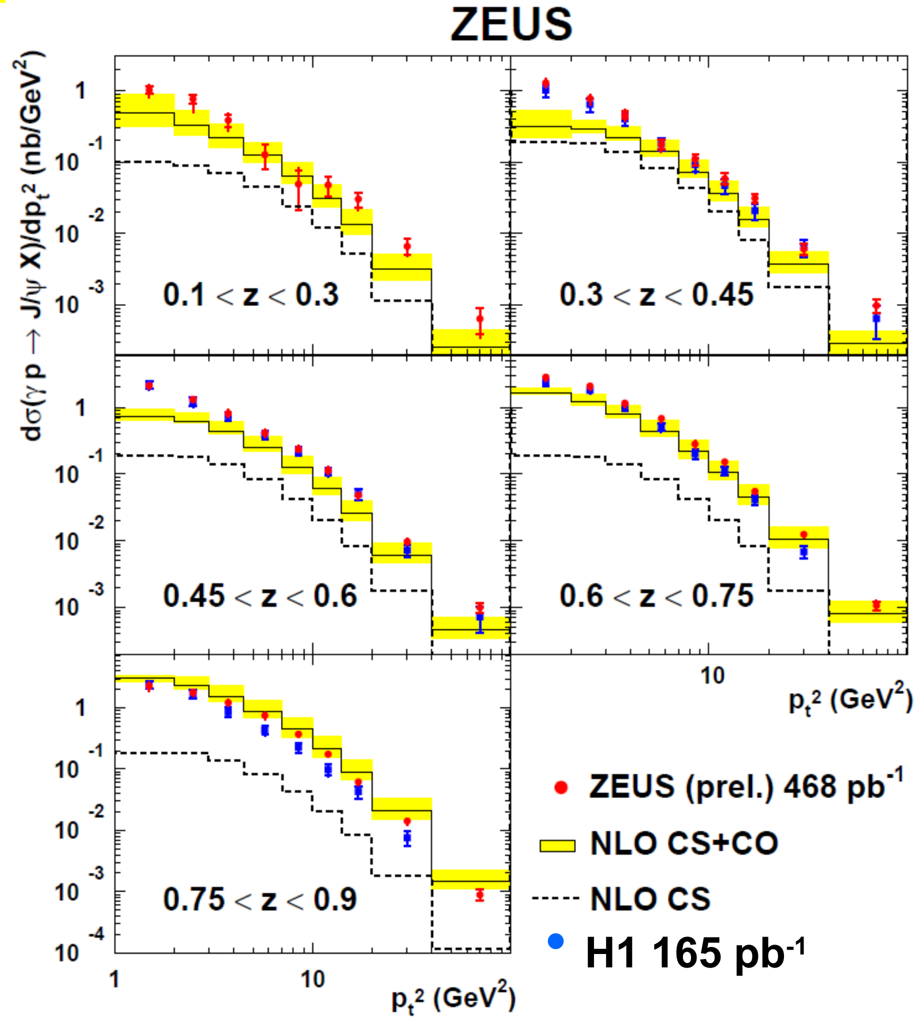




zoom in one of the 3 regions of good agreement and in the region of worse agreement … being investigated within ZEUS …

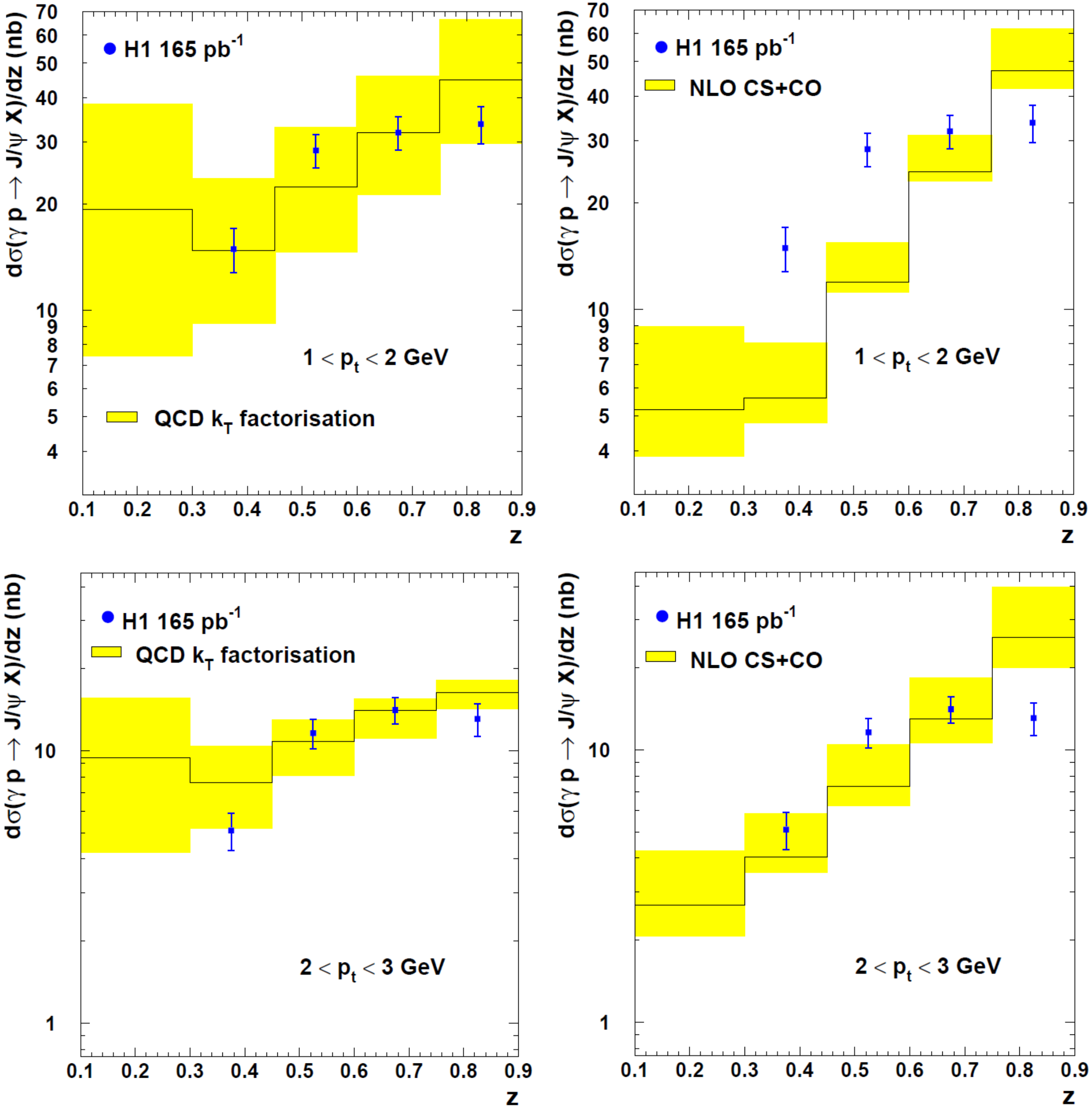
cross section differential in p_t^2 for different z ranges





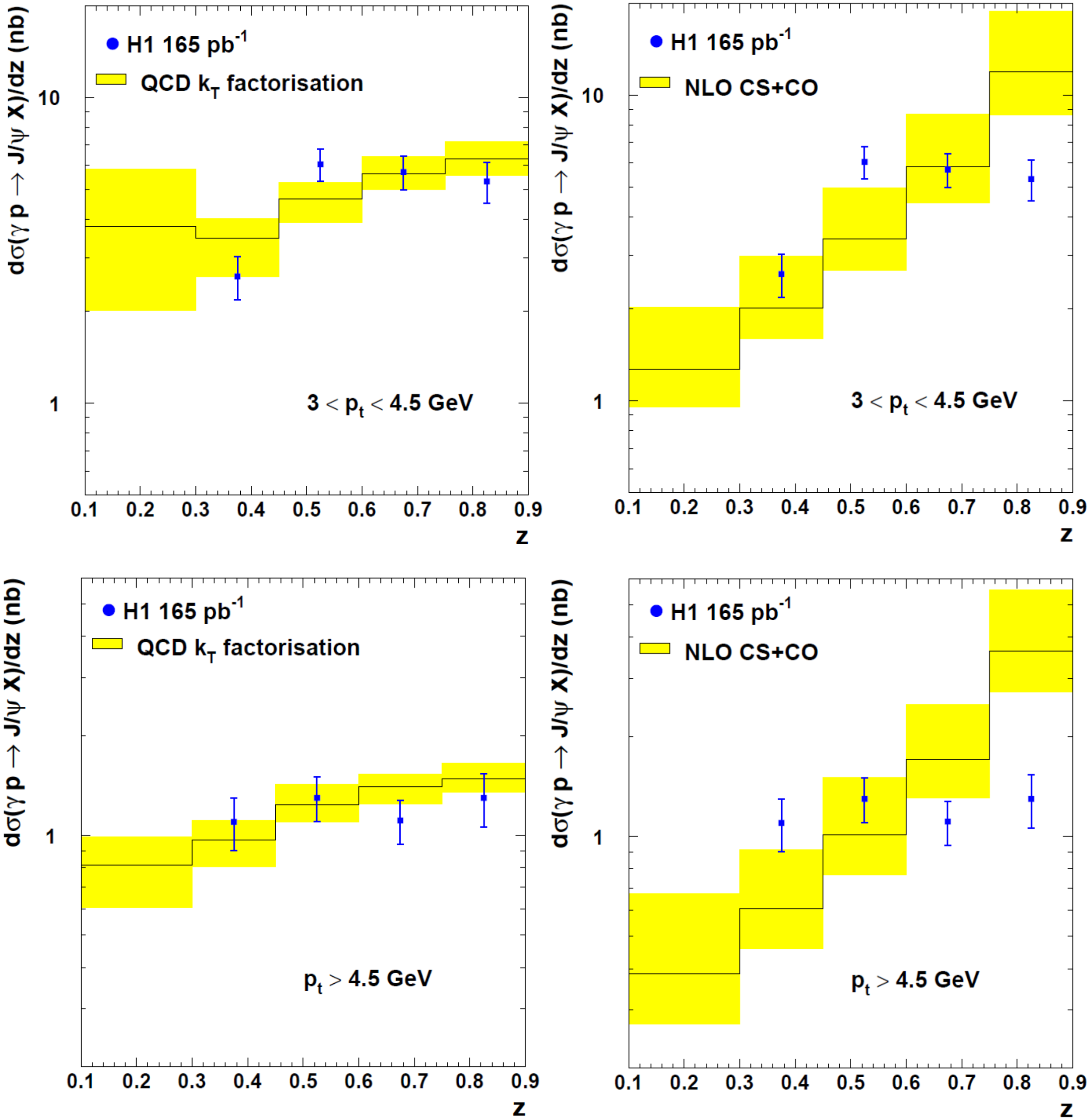
- same cross section, same HERA data
- k_T factorization (see S. Baranov) vs NLO CS+CO (see M. Butenschoen) … clearly the NLO CS+CO is an important achievement but as a naïve experimentalist k_T is better for now

cross section differential in z for different p_t slices



- clearly correlated with the previous measurement
- however few experimental differences, nice to measure also in this way
- left and right: same p_t slice, same H1 data, predictions are k_T and NLO CS+CO

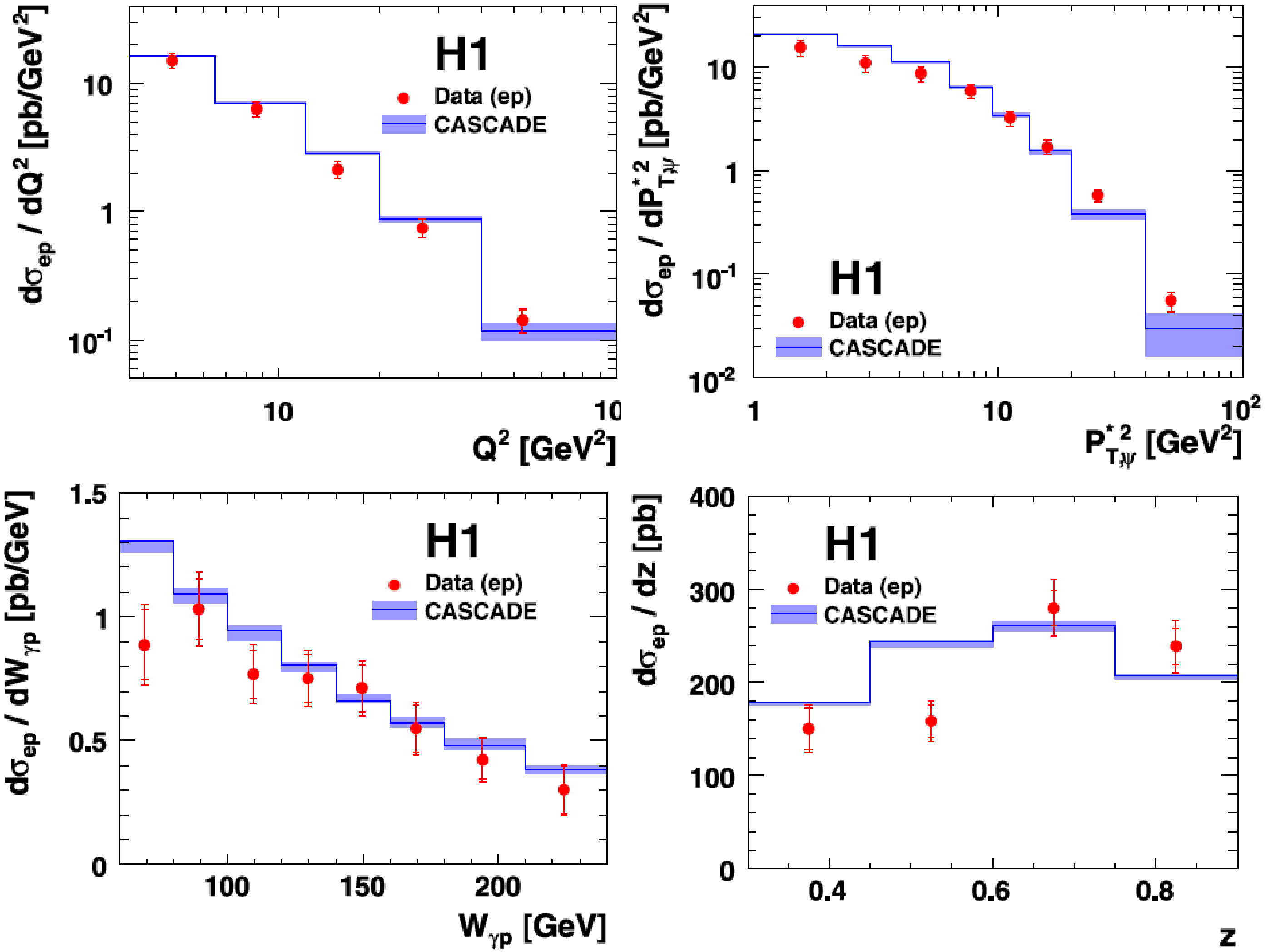
cross section differential in z for different p_t slices



observe significant differences in the k_T and NLO CS+CO predictions, up to a factor of 4, general better agreement with k_T

hopefully ZEUS data will be soon added to these plots

DIS cross sections



- H1 data (315 pb^{-1})
- CASCADE is a MC implementation of the QCD k_T factorization
- CASCADE band: ½ 2 scale variations
- may be "better" predictions are already available today …
- CASCADE MC gives a fair description of the H1 data

decay angular distributions in the J/ψ rest frame $\equiv$ helicity

- simplest example first: assume that all J/ψ originate from the spin-less state $^1S_0^{(8)}$ then the J/ψ will be unpolarized and the μ decay angular distributions will be the ones of a state with spin 1
- in general the μ decay angular distribution in the J/ψ rest frame is parameterized as:

$d^2\sigma/d\Omega dy \propto 1 + \lambda(y) \cos^2\theta + \mu(y) \sin 2\theta \cos\varphi + \frac{1}{2} \nu(y) \sin^2\theta \cos 2\varphi$

where y stands for a set of variables, z and $p_T(J/\psi)$ are good candidates

- λ, μ, ν are related to the different CS + CO matrix elements involved
- λ, μ, ν depend on the definition of a coordinate system

(what was the) main advantage:

"Since the decay angular distribution parameters are normalized, the dependence on parameters that affect the absolute normalization of cross sections, such as m_c, α_s, μ_R, μ_F and parton distribution, cancels to a large extent and does not constitute a significant uncertainty"

$\Rightarrow$ a source of theoretical uncertainties is gone

main disadvantage:

for every y bin we have to fit a distribution

$\Rightarrow$ unlikely requires large statistics

decay angular distributions in the J/ψ rest frame ≡ helicity

even using all the available luminosity we can not perform a double differential analysis without getting very large errors

but we can integrate the "helicity master formula"

- in φ

$1/\sigma\ d^2\sigma/d\cos\theta\ dy \propto 1 + \lambda(y)\cos^2\theta$

- in $\cos\theta$

$1/\sigma\ d^2\sigma/d\varphi\ dy \propto 1 + 1/3\ \lambda(y) + 1/3\ \nu(y)\cos 2\varphi$

can measure with good accuracy λ and ν (two out of three helicity parameters)

which frame ? frame accessible experimentally using PHP events: for ZEUS target frame

- ❑ z axis (quantization axis): along the opposite of the incoming proton direction in the J/ψ rest frame
- ❑ x and y axis: chosen to complete a right-handed coordinate system in the J/ψ rest frame according to some conventions we were given by the theorists
- ❑ θ: angle between the μ^+ vector in the J/ψ rest frame and the z axis
- ❑ φ: azimuthal angle in the x-y plane of the μ^+ vector in the J/ψ rest frame

target frame - ZEUS == recoil (or s-channel helicity) frame - H1, al least for PHP

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Inelastic photoproduction of polarized J/ψ

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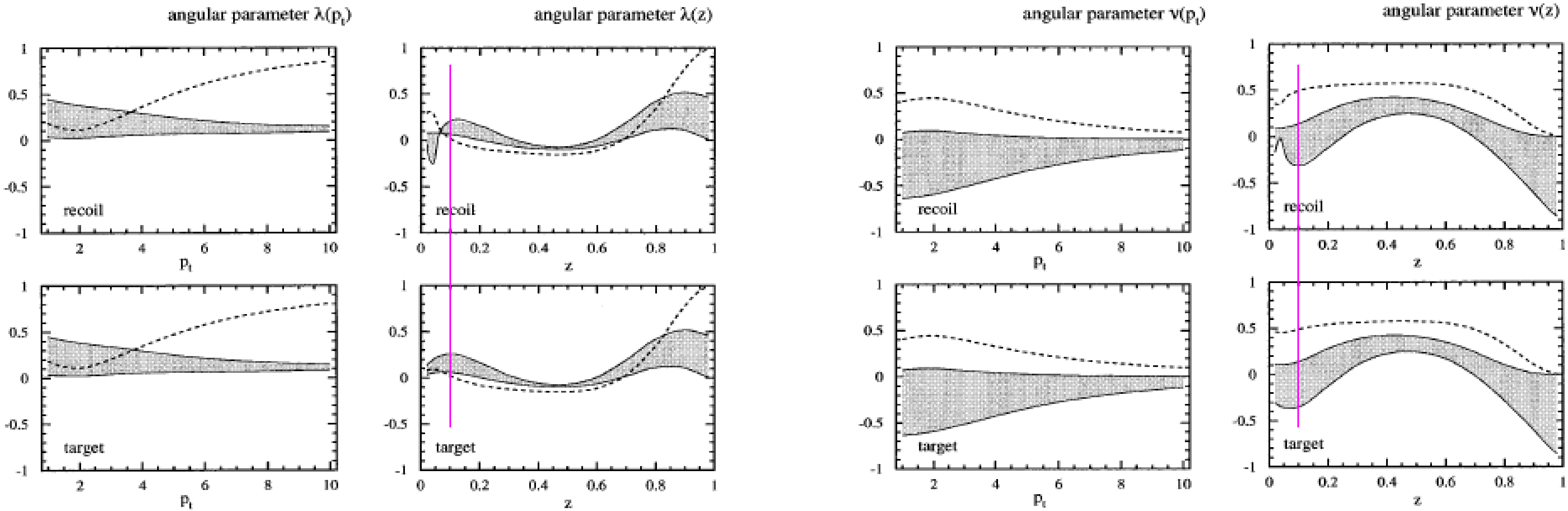
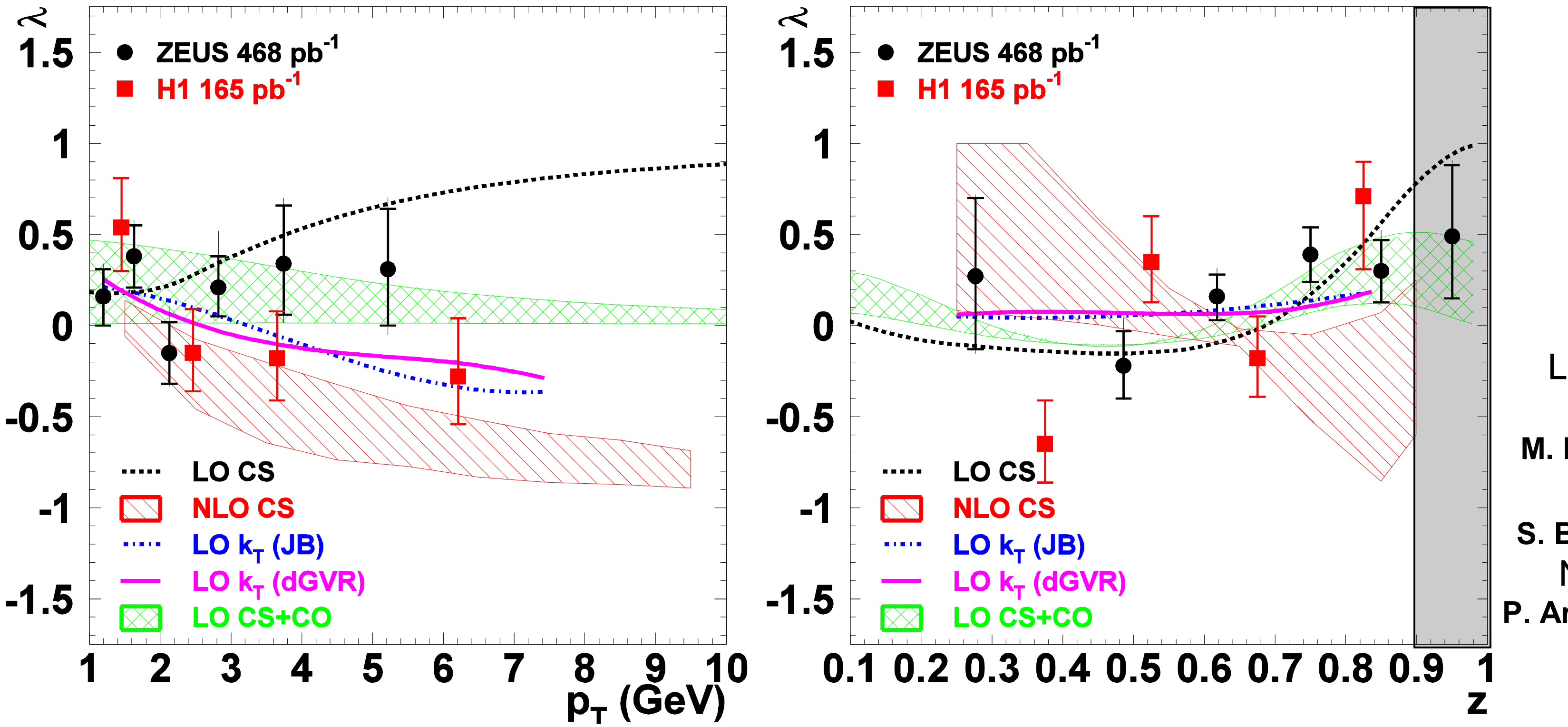


recoil == target

J/ψ helicity measurements at HERA



LO CS, LO CS+CO:
M. Beneke et al.
LO k_T:
S. Baranov et al.
NLO CS:
P. Artoisenet et al.

it would have been nicer to analyze the H1 and ZEUS data with the same binning …

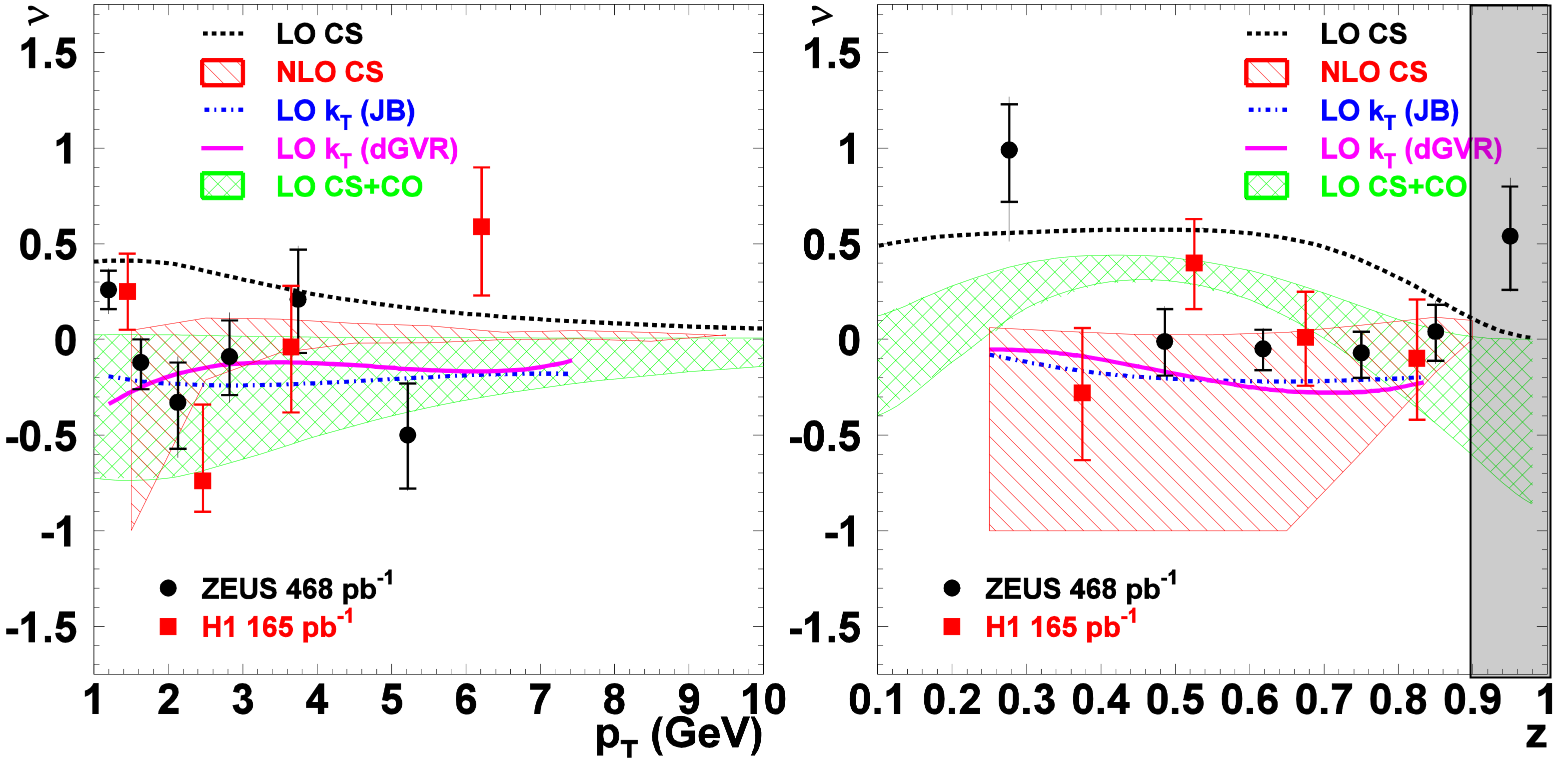
taking the large, mostly statistical, experimental errors into account data are generally consistent

what do we learn:

- little polarization seen in the probed p_T and z range
- NLO corrections are (unexpectedly) LARGE, see λ vs p_T; k_T factorization mimics NLO
- do we have better predictions by now ? NLO CS+CO ?

H1 published the same data analyzed also in the Collins Soper frame (not shown)

J/ψ helicity measurements at HERA



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LO k_T:
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NLO CS:
P. Artoisenet et al.

H1 published the same data analyzed in the Collins Soper frame (not shown)

λ: very similar to the hadroproduction polarization parameter α

in PHP can probe also the azimuthal parameter ν

what do we learn:

- little polarization seen in the probed p_T and z range
- NLO corrections are (unexpectedly) LARGE, see ν vs z; k_T factorization mimics NLO
- do we have better predictions by now ? NLO CS+CO ?

conclusions

- ZEUS double differential inelastic J/ψ cross section measurements are now also available, full luminosity is being used, data are limited by systematic except at low z and high p_t^2

- H1 and ZEUS double differential cross sections are compared: data are generally in good agreement

- differential cross section data are compared:

    - to a QCD k_T prediction: within the present uncertainties of this prediction an encouraging agreement is found

    - to a NLO CS+CO prediction: worse agreement w.r.t the k_T prediction

- H1 single differential cross section measurements in the DIS regime are fairly described by CASCADE, which is based on a MC implementation of the k_T predictions

- the polarization measurements performed by H1 and ZEUS are compared: data are generally in good agreement

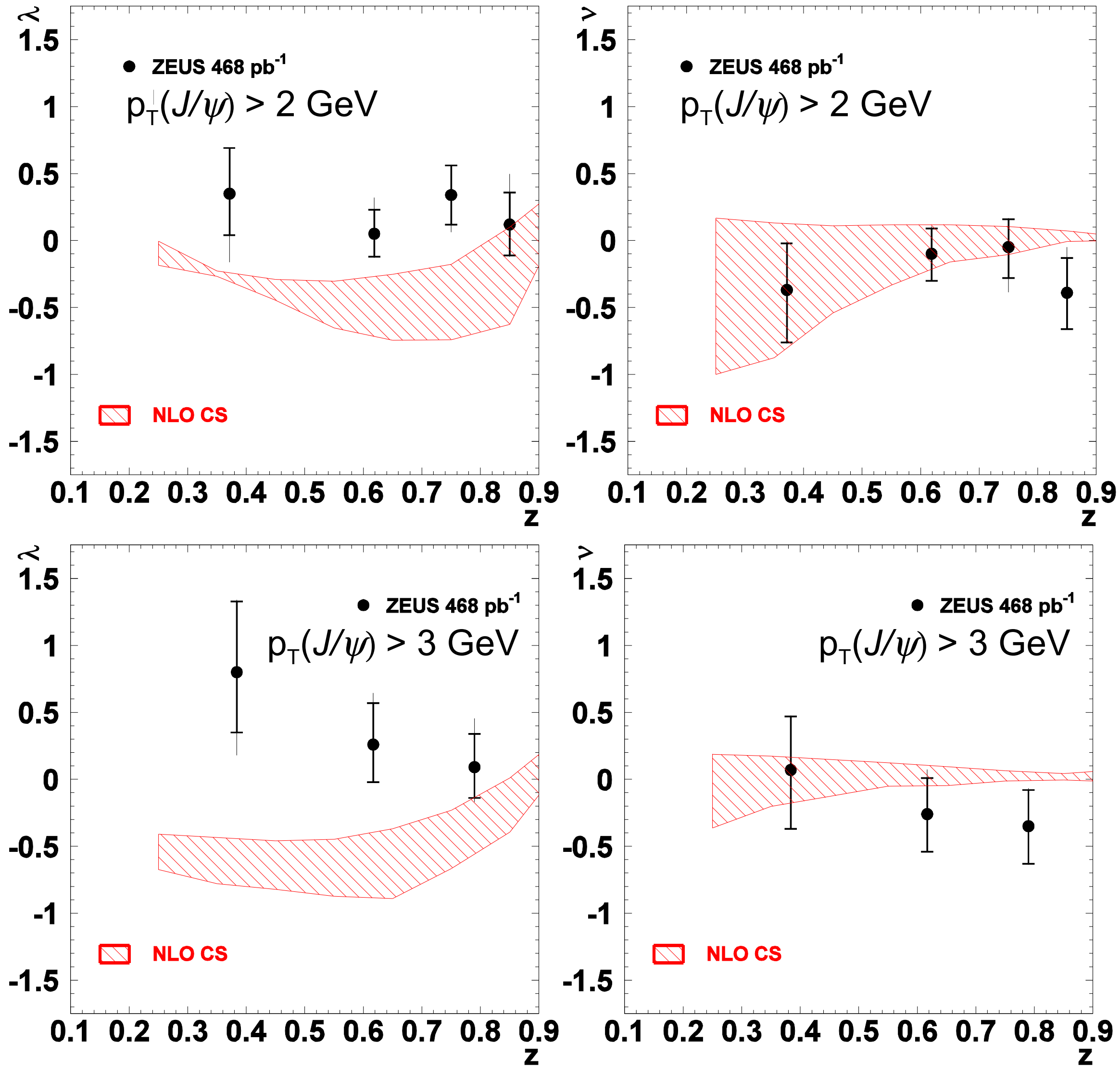
- the polarization data are compared to QCD LO CS / LO CS+CO / NLO CS and k_T factorization predictions, NLO CS and k_T provide the best description of the data

- from the H1 side there will be no further inelastic quarkonium activities

- from the ZEUS side a “final” paper on PHP double differential cross sections is in preparation

… backup slides …

J/ψ helicity measurements at HERA



NLO predictions for:

- $p_T(J/\psi) > 2$ GeV
- $p_T(J/\psi) > 3$ GeV

NLO has reduced uncertainties … but unlikely experimental errors grow … and the agreement between data and NLO does not really improve …

All differences for the helicity measurements:

- luminosity: ZEUS 468 pb^{-1}, H1 165 pb^{-1}
- W range: ZEUS [50,180] GeV, H1 [60,240] GeV
- pt(J/ψ) $>$ 1 GeV: same for both
- z range for the analysis vs pt(J/ψ) : ZEUS [0.4,1], H1 [0.3,0.9]

for ZEUS the difference between [0.4,1] and [0.4,0.9] in included in the sys. errors

Additional remarks:

- ZEUS requires at least 3 vertex tracks AND some hadronic energy in the forward direction (in the main calorimeter, this alone is equivalent to $M_N > 4.4$ GeV/c^2)
- H1 requires “only” at least 5 vertex tracks
- for ZEUS as a cross check we tried at least 5 vertex tracks but no significant variation of the results has been found

arXiv:1012.3022v1 [hep-ph] 14 Dec 2010

3 Numerical results

We now are in a position to present our numerical results. First we describe our input and the kinematic conditions. After we fixed the unintegrated gluon distributions, the cross sections (3) and (4) depend on the renormalization and factorization scales μ_R and μ_F. In the numerical calculations we set $\mu_R = \xi\sqrt{m_\psi^2 + \mathbf{p}_{\psi T}^2}$, $\mu_F = \xi\sqrt{\hat{s} + \mathbf{Q}_T^2}$, where $\mathbf{Q}_T$ is the transverse momentum of initial off-shell gluon or gluon pair (in the case of resolved photon production). In order to estimate the theoretical uncertainties of our calculations we vary the scale parameter ξ between 1/2 and 2 about the default value $\xi = 1$. The sensitivity of the predictions to the charmed quark mass has been investigated previously in [20, 21]. Here we set $m_c = 1.5$ GeV and use the LO formula for the coupling constant $\alpha_s(\mu^2)$ with $n_f = 4$ quark flavours at $\Lambda_{\rm QCD} = 200$ MeV, such that $\alpha_s(M_Z^2) = 0.1232$. Note that we apply another value $\Lambda_{\rm QCD} = 220$ MeV for the CCFM-evolved gluon densities (see discussion in Sect. 3.1). Finally, the J/ψ wave function at the origin of coordinate space is taken to be equal to $|\Psi(0)|^2 = 0.0876$ GeV^3 [31].