ZEUS measurement of the cross-section ratio $\sigma(\Psi(2S))/\sigma(J/\Psi)$ in exclusive ep scattering at HERA

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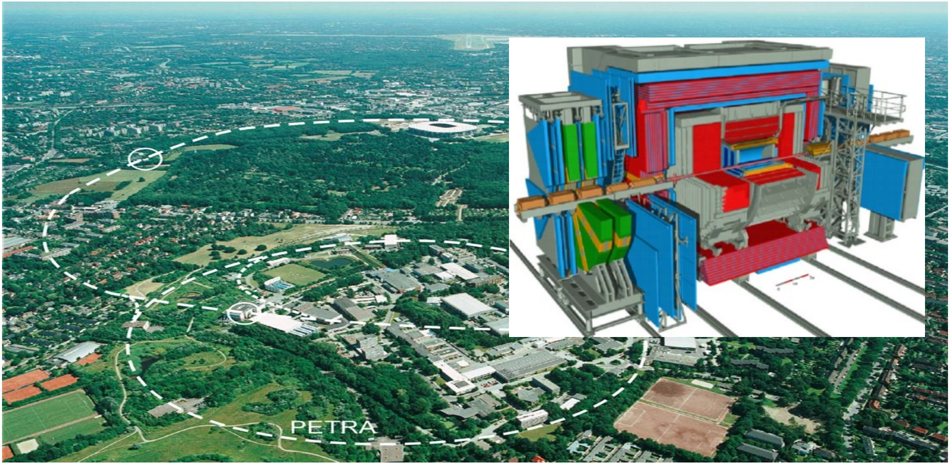
Outlook

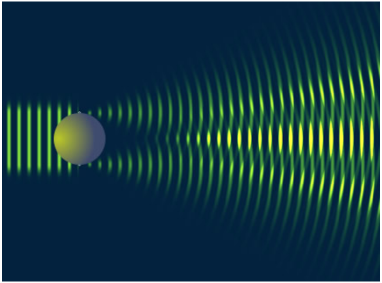
1. Experimental apparatus: the HERA accelerator and the ZEUS detector
2. Introduction: Vector Meson Production in Exclusive Diffraction in *ep* Scattering
3. Analysis: Events selection and extraction of the signal
4. Results: Cross section ratio $\psi(2S)/J/\psi(1S)$ in DIS (electroproduction)
5. Results: Cross section ratio $\psi(2S)/J/\psi(1S)$ in photoproduction
6. Summary

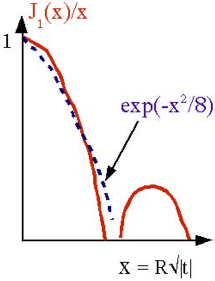
HERA and ZEUS: 1992 – 2007, DESY, Hamburg

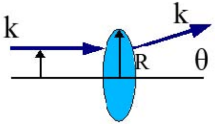
HERA: world's first and only $e^{\pm}p$ collider, $\mathbf{E_e = 27.5\ GeV, E_p = 920\ GeV}$ ($\sqrt{s} = 318$ GeV)



ZEUS: multipurpose, hermetic detector (MVD, CTD, CAL, F/B/RMUON, BAC, ...)
Total luminosity: $\int \mathcal{L} \sim \mathbf{500\ pb^{-1}}$ collected during HERA I + II running periods



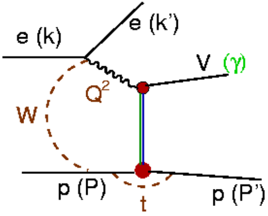


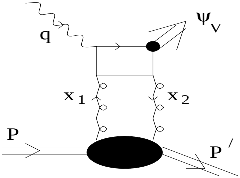


Light Scattering in Fraunhofer approximation (wavelength $\lambda \sim 1/k << R$)

- $|t| = 4k^2 sin^2(\theta/2)$
- $d\sigma/dt \sim e^{-b|t|}$ (first diffractive peak approximated from Bessel function)
- $b = (R/2)^2 \rightarrow$ transverse size of the target
- in the presented studies: target $\equiv$ proton and photon energy $\gg 1$ GeV

Production of Vector Mesons in Exclusive Diffraction in *ep* Scattering





Exclusive process: proton stays intact

Proton dissociation also possible → background

Kinematics: $\mathbf{M_V^2}$, $\mathbf{Q^2}$, **W**, $|\mathbf{t}|$

M_V^2 - vector meson mass squared

Q^2 $(= -q^2 = -(k - k')^2)$ - the photon virtuality (emitted by the incoming electron):

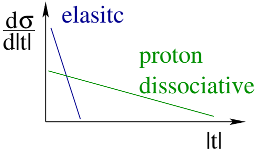
- $Q^2 \approx 0$ GeV^2 PHP (*Photoproduction*)
- larger Q^2 for DIS (*Deep Inelastic Scattering*)

$W = (q + P)^2$ - invariant mass of the γp system

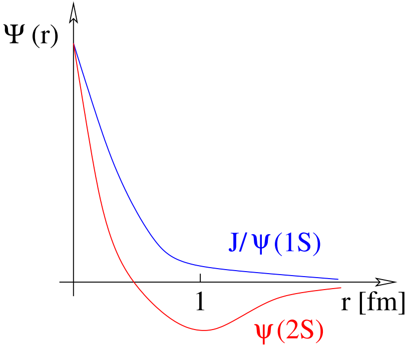
Process sensitive to the **gluon density** in the proton

$|t|$ - 4-momentum transfer at the proton vertex

$t = (P - P')^2$



pQCD: M_V^2 and Q^2 - set the scale at which the W and $|t|$ are probed



$$\text{Ratio } R = \frac{\sigma_{\gamma p \to \psi(2S)p}}{\sigma_{\gamma p \to J/\psi(1S)p}}$$

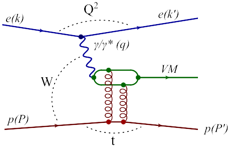
- sensitive to radial wave function of charmonium
- provides insight into the dynamics of the hard process

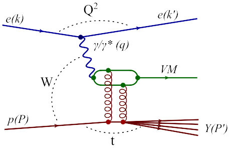
- $J/\psi(1S)$ and $\psi(2S)$ have distinctive wave functions
- $\psi(2S)$ has a node at $\approx$ 0.4 fm
- $\langle r^2_{\psi(2S)} \rangle \approx 2 \langle r^2_{J/\psi(1S)} \rangle$
- pQCD models predict $R \sim 0.17$ in PHP and moderate rise of R with Q^2 in DIS
- ψ' cross section is expected to be suppressed w.r.t. the J/ψ production

Analyzed channels and DATA/MC samples

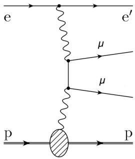
- Investigated decay channels:
  - $\psi(2S) \to J/\psi + \pi^+\pi^-, \quad \psi(2S) \to \mu^+\mu^-, \quad J/\psi(1S) \to \mu^+\mu^-$
- HERA I+II: $\mathcal{L} = 468$ pb^{-1} (1996 - 2007) with $5 < Q^2 < 80$ GeV (DIS)
- subsample of 114 pb^{-1} (HERA I) with $2 < Q^2 < 5$ GeV (DIS)
- HERA II: $\mathcal{L} = 333$ pb^{-1} (2003 - 2007) $Q^2 < 1$ GeV (PHP)
- MC Samples: Signal: DIFFVM for exclusive VM production (J/ψ and ψ')

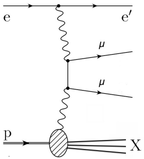
- $\frac{d\sigma}{dQ^2} \sim \frac{1}{(1+Q^2/M_V^2)^{1.5}}$
- $\frac{d\sigma}{d|t|} \sim \exp(-b|t|)$, $b = 4.0$ GeV^{-2}





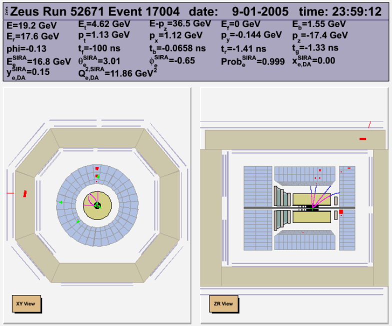
- Background: GRAPE for non resonant muon pair production (Bethe-Heitler process)





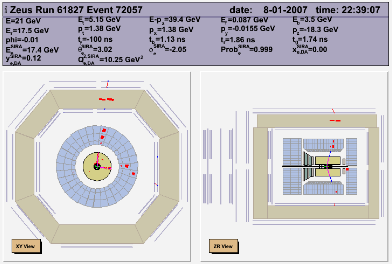
Events selection (DIS channel)

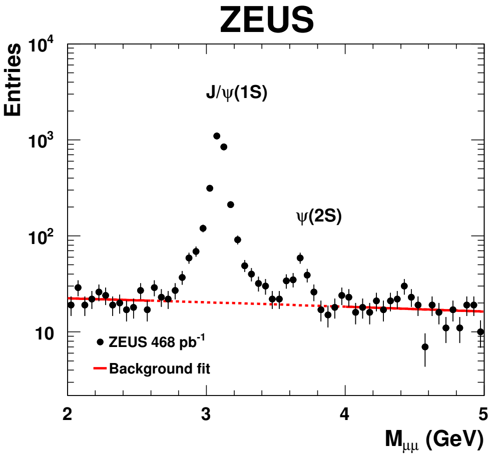
$$\psi(2S) \to \mu^+\mu^-\pi^+\pi^- \quad \Rightarrow$$



- Event selection:
  - scattered electron $E_{e'} > 10$ GeV in CAL
  - 2 (4 for $\psi(2S)$ 4-prongs decay) non-electron tracks from primary vertex, net charge $= 0$
  - two tracks identified as muons (CAL, F/B/R/MUO, BAC)
  - no other deposits not matched to tracks (above CAL noise) $\to$ proton remains undetected
- Kinematic range:
  - (2) $5 \le Q^2 \le 80$ GeV^2
  - $30 \le W \le 210$ GeV
  - $|t| \le 1$ GeV^2

$$J/\psi(1S) \to \mu^+\mu^- \quad \Rightarrow$$

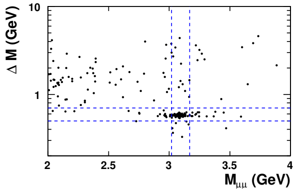




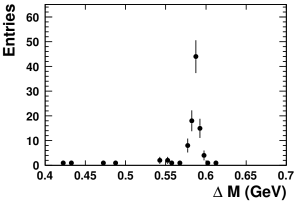
- $J/\psi(1S) \to \mu^+\mu^-$
- $\psi(2S) \to \mu^+\mu^-$
- BG (BH): $\gamma\gamma \to \mu^+\mu^-$

- mass intervals for side-band straight-line background fit and signal extraction:
  BG: 2.00 – 2.62 GeV and 4.05 – 5.00 GeV
  Signal $J/\psi(1S)$: 3.02 – 3.17 GeV , Signal $\psi(2S)$: 3.59 – 3.79 GeV

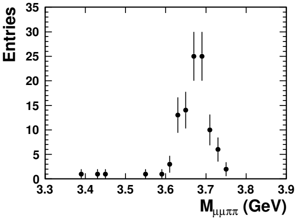
Selection specific for $\psi(2S) \to \mu^+\mu^-\pi^+\pi^-$ channel



- ΔM vs. $M_{\mu^+\mu^-}$
  $\Delta M = M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$
  cascade decay of $\psi(2S)$



- $0.5 < \Delta M < 0.7$ GeV
  $3.02 < M_{\mu^+\mu^-} < 3.17$ GeV



- $M(\mu^+\mu^-\pi^+\pi^-)$ after cleanup
  very clean signature
  (≤ 3 background events at 90% CL)

Cross section ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ (DIS) for full kinematic range

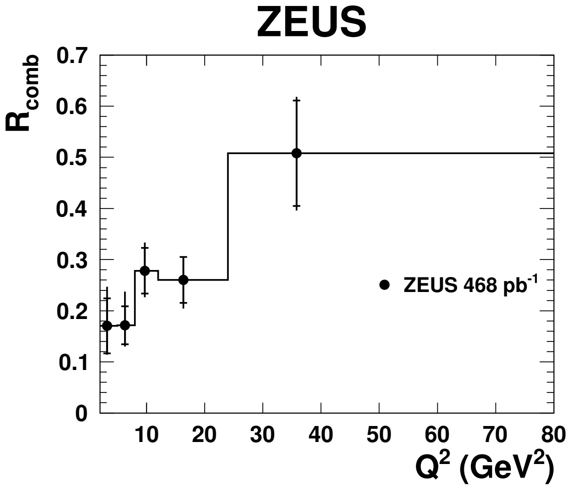
For $30 \leq W \leq 210$ GeV, $5 \leq Q^2 \leq 80$ GeV^2, $|t| \leq 1$ GeV^2

$\psi(2S)$ decay mode	$R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$
$\to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$	$0.26 \pm 0.03^{+0.01}_{-0.01}$
$\to \mu^+\mu^-$	$0.24 \pm 0.05^{+0.02}_{-0.03}$
combined	$0.26 \pm 0.02^{+0.01}_{-0.01}$

Nucl. Phys. **B 909** (2016) 934.

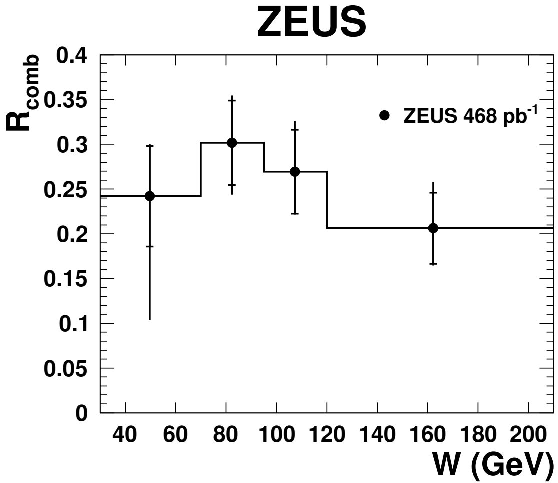
- both channels provide consistent results
- $R_{\psi(2S)\to J/\psi\pi^+\pi^-} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S)\to\mu^+\mu^-}}{Acc_{\psi(2S)\to J/\psi\pi^+\pi^-}} \cdot \frac{1}{BR_{\psi(2S)\to J/\psi\pi^+\pi^-}}$
- $R_{\psi(2S)\to\mu^+\mu^-} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S)\to\mu^+\mu^-}}{Acc_{\psi(2S)\to\mu^+\mu^-}} \cdot \frac{BR_{J/\psi(1S)\to\mu^+\mu^-}}{BR_{\psi(2S)\to\mu^+\mu^-}}$
- $Acc_i = \frac{N_i^{reco}}{N_i^{true}}$
- $BR(\psi(2S) \to J/\psi\pi^+\pi^-) = (33.6 \pm 0.4)\%$, $BR(\psi(2S) \to \mu^+\mu^-) = (7.7 \pm 0.8) \times 10^{-3}$, $BR(J/\psi \to \mu^+\mu^-) = (5.93 \pm 0.06)\%$

Ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ vs. Q^2 (DIS: combined 2- and 4-prong channels)



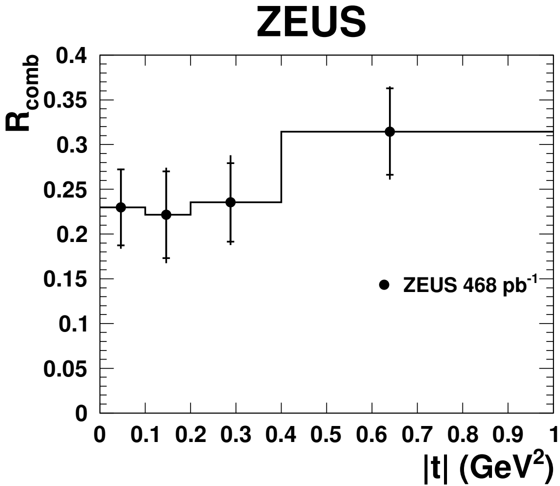
- *R* rises with Q^2

Ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ vs. W (DIS: combined 2- and 4-prong channels)



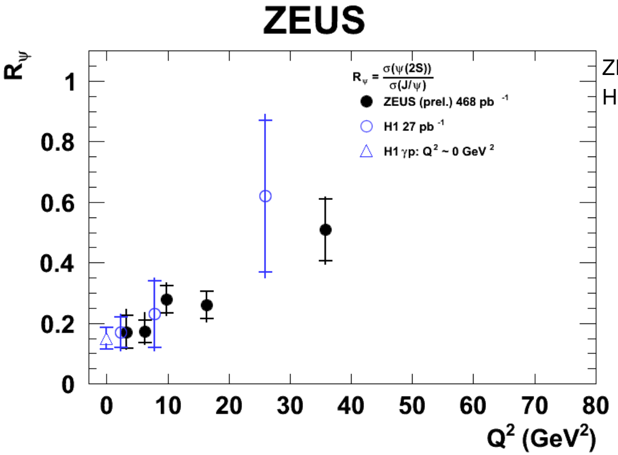
- *R* independent of *W*

Ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ vs. $|t|$ (DIS: combined 2- and 4-prong channels)



- *R* independent of $|t|$

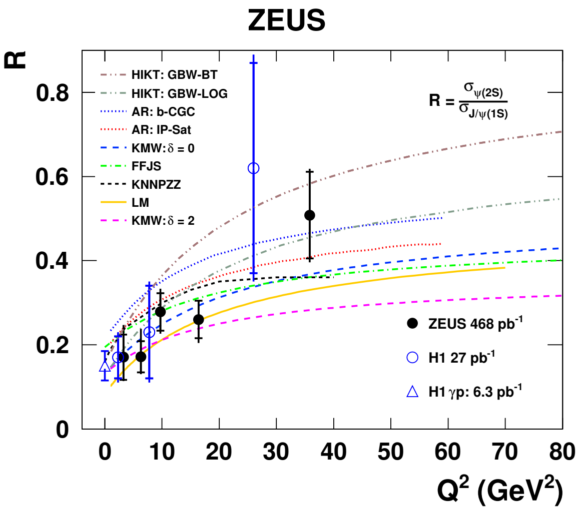
ZEUS to H1 comparison: (DIS) full data sample 468 pb^{-1}



ZEUS: Nucl. Phys. **B 909** 934 (2016)
H1: EPJ **C10** 373 (1999)

- ZEUS: full HERA I + HERA II data sample (468 pb^{-1}) (incl. low-Q^2 point)
- both ZEUS and H1 measurements are in agreement: R increases with Q^2
- ZEUS improved accuracy due to the increased statistic of HERA I+II data

Q^2 dependence: comparison with theoretical models



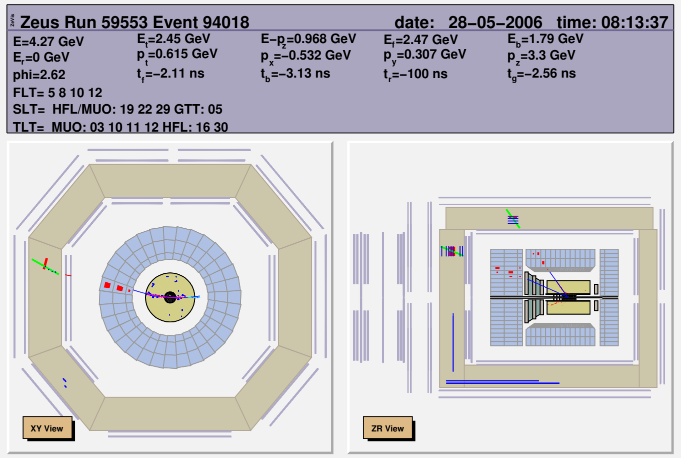
theoretical models:

- HIKT: J. Hüfner et al., Phys. Rev. **D 62**, 094022 (2000).
- KNNPZZ: B.Z. Kopeliovich, et al., Phys. Rev. **D 44**, 3466 (1991), Phys. Lett. **B 324**, 469 (1994), Phys. Lett. **B 341**, 228 (1994), J. Exp. Theor. Phys. **86**, 1054 (1998).
- AR: N. Armesto and A.H. Reazeian, Phys. Rev. **D 90**, 054003 (2014).
- LM: T. Lappi and H. Mäntysaari, Phys. Rev. **C 83**, 065202 (2011).
- FFJS: S. Fazio et al., Phys. Rev. **D 90**, 016007 (2014).
- KMW: H. Kowalski, L. Motyka and G. Watt, Phys. Rev. **D 74**, 074016 (2006).

- All models predict the rise of $\sigma(\psi(2S))/\sigma(J/\psi)$ with Q^2
- ...data begin to discriminate some models (see also backup plots for more details)

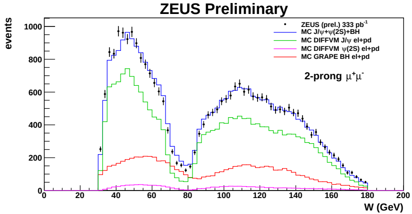
- Cross section ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ in photoproduction

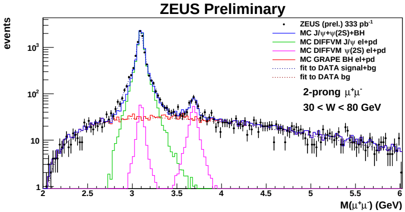
Event selection (photoproduction channel)

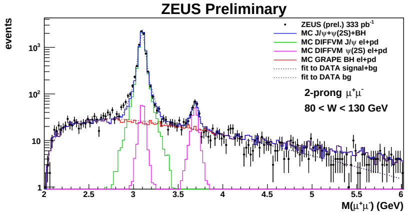


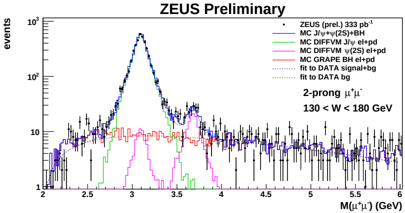
- no scattered electron observed in the calorimeter, otherwise selection very similar to DIS channel
- very clean signature, selection entirely driven by muons starting from trigger
- $30 < W < 180$ GeV (limited by muon chambers)
- experimental challenge: very good understanding of muon efficiency for all components

2-prong sample: $\psi(2S) \to \mu^+\mu^-$ (photoproduction)





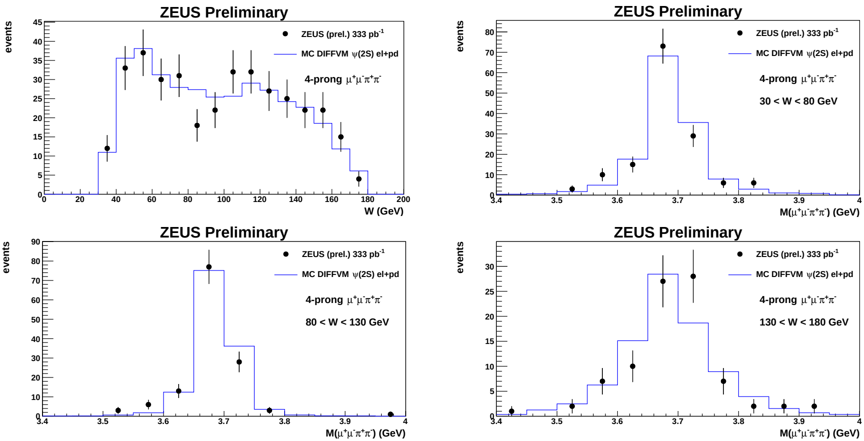




- W and $M(\mu^+\mu^-)$ distributions for 3 W intervals (30-80), (80-130), (130-180) GeV
- DIFFVM J/ψ, $\psi(2S)$ and GRAPE BH MC normalized to data (fractional fit)
- double Gaussian fit to data for signal extraction

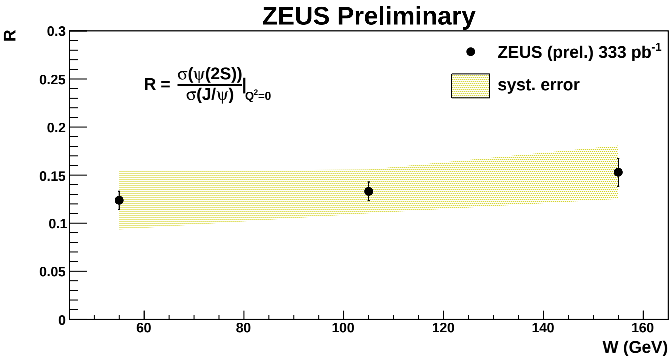
- $W = \sqrt{2E_P(E_{TOT} - P_Z)}$, $P_Z = p^{\mu^+}\cos(\theta^{\mu^+}) + p^{\mu^-}\cos(\theta^{\mu^-})$

4-prong sample: $\psi(2S) \to \mu^+\mu^- \pi^+\pi^-$ (photoproduction)



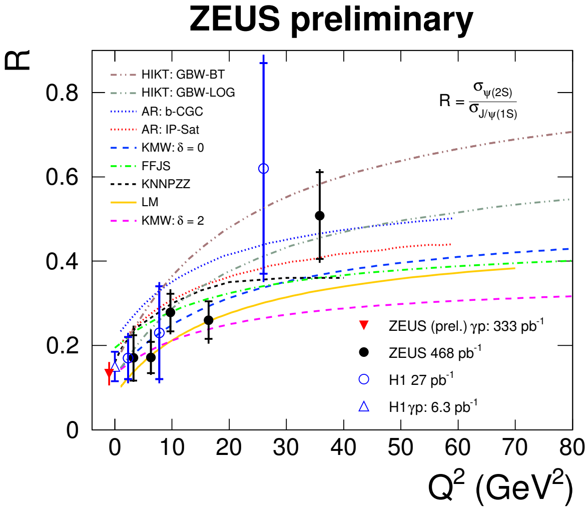
- W, $M(\mu^+\mu^-\pi^+\pi^-)$ distributions for 3 W intervals (30-80), (80-130), (130-180) GeV
- very clean (almost) background free channel
- DiffVM $\psi(2S)$ MC normalized to data
- $W = \sqrt{2E_P(E_{TOT} - P_Z)}$,
  $P_Z = p^{\mu^+}\cos(\theta^{\mu^+}) + p^{\mu^-}\cos(\theta^{\mu^-}) + p^{\pi^+}\cos(\theta^{\pi^+}) + p^{\pi^-}\cos(\theta^{\pi^-})$

$R = \frac{\sigma_{\gamma p \to \psi(2S)p}}{\sigma_{\gamma p \to J/\psi(1S)p}}$ vs. W at $Q^2 = 0$ GeV^2 (photoproduction)



- average *R* values over 2- and 4-prong channels
- moderate rise of R with photon-proton centre-of-mass W
- systematics dominated by 2- and 4-prong channel difference

$R = \frac{\sigma_{\gamma p \to \psi(2S) p}}{\sigma_{\gamma p \to J/\psi(1S) p}}$ vs. Q^2 including new $Q^2 = 0$ measurement



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- highest precision $Q^2 = 0$ GeV^2 measurement
- $R = 0.1332 \pm 0.0065(stat.) \pm 0.0270(syst.)$ (average over full phase space)

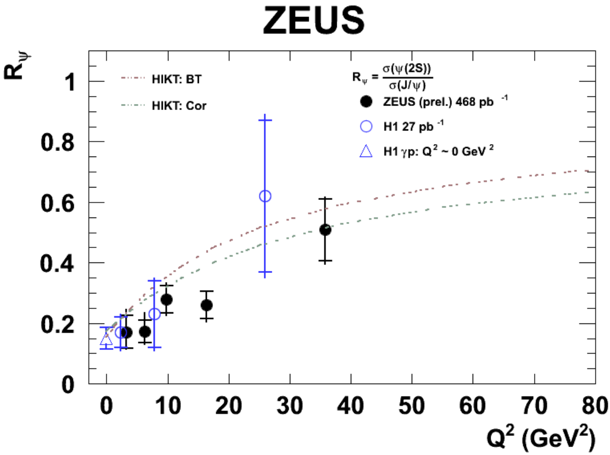
Summary

- Ratio of $\frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ using HERA I+II data was measured for the first time by ZEUS in the kinematic range: $30 \leq W \leq 210$ GeV, $2 \leq Q^2 \leq 80$ GeV^2, $|t| \leq 1$ GeV^2 for exclusive DIS and in $30 \leq W \leq 180$ GeV for photoproduction ($Q^2 \approx 0$)
- The accuracy has been improved compared to the H1 HERA I results
- The ratio increases with Q^2 and is constant as a function of W and $|t|$
- Theoretical calculations of the ratio $\frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ for exclusive vector-meson production has been compared to the experimental data
  $\rightarrow$ majority of the predictions are consistent with the data
- **data start to exhibit constraining power**

Thank You For Your Attention

BACKUP PLOTS

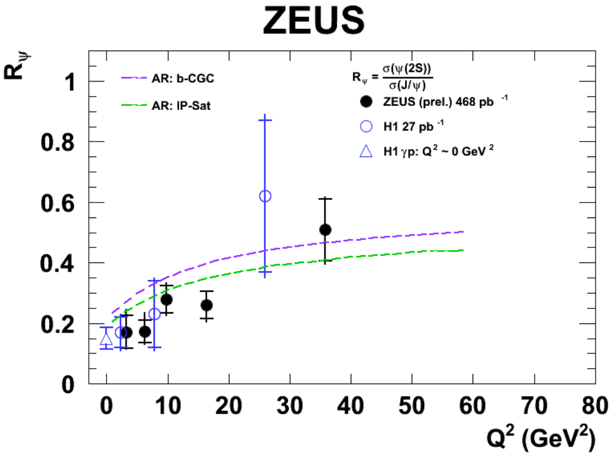
BACKUP PLOTS FOLLOW...



Phys. Rev. **D 62** 094022 (2000)
Phys. Rev. **D 59** 14017 (1999)
Phys. Rev. **D 62** 054022 (2000)

$$V(r) \sim -\frac{k}{r} + \frac{r}{a^2}$$

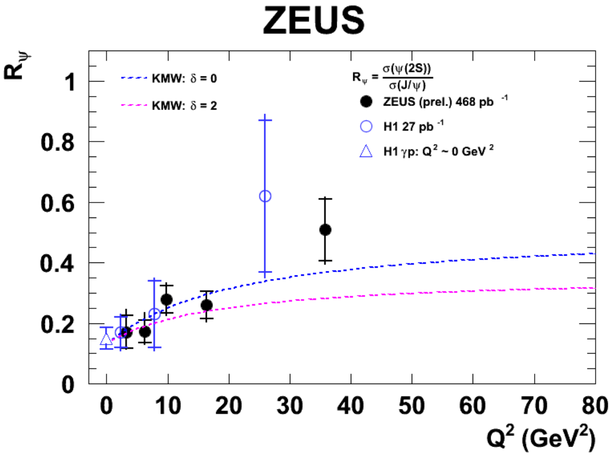
- HIKT: Hüfner et al. $\rightarrow$ adopt the light-cone dipole formalism to describe VM production, the dipole - proton interaction cross section is constrained by inclusive low-x DIS data from HERA (BT and Cor: different charmonium potentials with $m_c \approx 1.5$ GeV)
- HIKT - BT: overestimates lower Q^2 points



Phys. Rev. **D 90** 054003 (2014)

- AR: Armesto and Rezaeian $\rightarrow$ two predictions are presented: results from the Impact-Parameter dependent Color Glass Condensate (b-CGC) and the gluon Saturation (IP-Sat) dipole models
- b-CGC overestimates lower Q^2 points

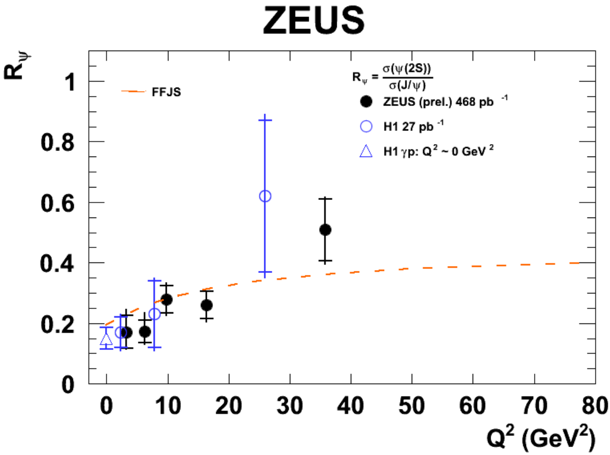
Comparison with theoretical models: KMW



Phys. Rev. **D 74** 074016 (2006)

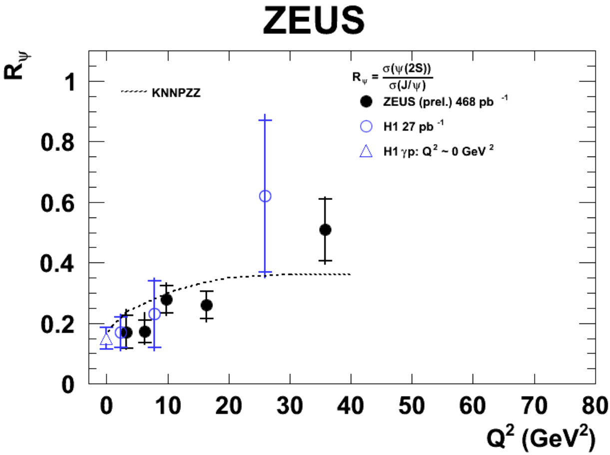
- KMW: Kowalski, Motyka, Watt $\rightarrow$ impact parameter dependent saturated dipole model, based on the QCD description and an assumption of universality of the gluon distribution and proton shape: $\delta = 0$ non-relativistic wave functions, $\delta = 2$ relativistic boosted Gaussian model

Comparison with theoretical models: FFJS



Phys. Rev. **D 90** 016007 (2014)

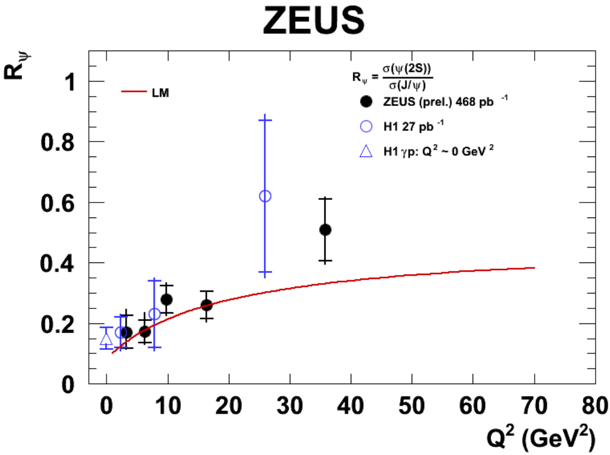
- FFJS: Fazio et al. $\rightarrow$ two component Pomeron model to predict the cross sections for Vector Meson production. The Pomeron is universal, containing two terms, a "soft" and a "hard" one: relative weights: $\sim \tilde{Q}^2 = Q^2 + M_V^2$.



Phys. Lett. **B 342** 228 (1994)

- KNNPZZ: Kopeliovich et al. $\rightarrow$ describe the BFKL Pomeron in terms of the colour-dipole cross section which is a solution of the generalized BFKL equations

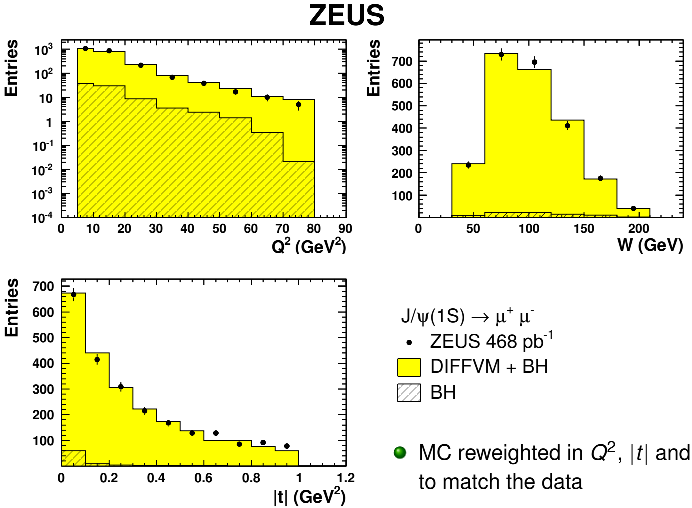
Comparison with theoretical models: LM



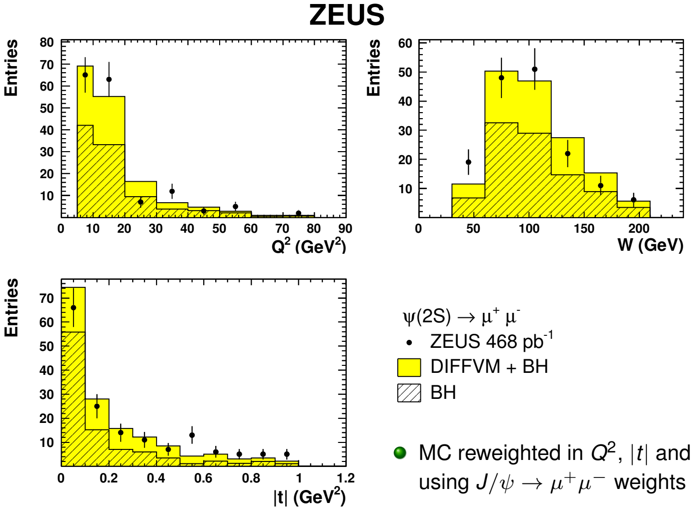
Phys. Rev. **C 83** 065202 (2011)

- LM: Lappi and Mäntysaari $\rightarrow$ use the BFKL evolution as well as the dipole picture in the IP-Sat model to predict VM production

Control plots for $J/\psi \to \mu^+\mu^-$ channel

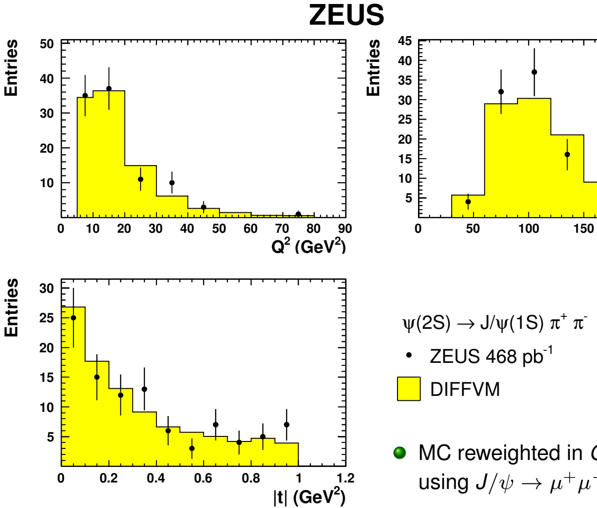


- MC reweighted in Q^2, $|t|$ and J/ψ decay angles to match the data
- good description → detector efficiency calculation



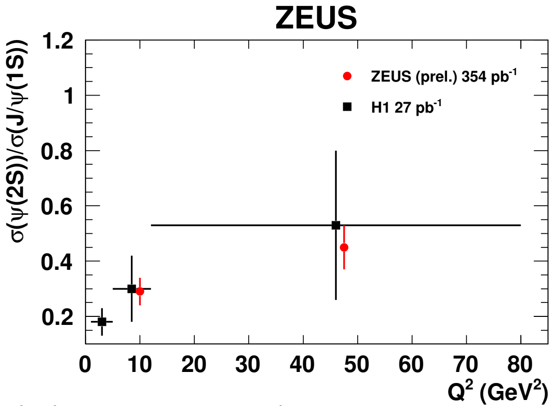
- MC reweighted in Q^2, $|t|$ and $\psi(2S)$ decay angles using $J/\psi \to \mu^+\mu^-$ weights
- good description $\to$ detector efficiency calculation

Control plots for $\psi(2S) \to \mu^+\mu^-\pi^+\pi^-$ channel



- MC reweighted in Q^2 and $|t|$ using $J/\psi \to \mu^+\mu^-$ weights
- good description $\to$ detector efficiency calculation

- cross check: ZEUS data analyzed in Q^2 bins used by H1: [EPJ **C10** (1999) 373.] $(5-12)\ \mathrm{GeV}^2$ and $(12-80)\ \mathrm{GeV}^2$
- $40 < W < 180\ \mathrm{GeV}$ and $1 < Q^2 < 80\ \mathrm{GeV}^2$



- both measurements are in agreement
- improved accuracy due to the increased statistic of HERA II data

Systematics checks (2-prongs and 4-prongs channels)

- varying the $M_{\mu\mu}$ window for signal event counting:
  - for $J/psi(1S)$: from $3.02 - 3.17$ GeV to $3.05 - 3.15$ GeV and $2.97 - 3.19$ GeV
  - for $\psi(2S)$: from $3.59 - 3.79$ GeV to $3.62 - 3.75$ GeV and $3.55 - 3.80$ GeV

  changes the values of $R_{\mu\mu}$ by 6% and $R_{J/\psi\pi\pi}$ by 2%
- varing the cut on pions transverse momenta p_T from 0.12 GeV to 0.15 GeV changes the $R_{J/\psi\pi\pi}$ by 4.5%
- changing the background fit function from linear to quadratic changes the values of $R_{\mu\mu}$ by 11% and $R_{J/\psi\pi\pi}$ by 0.5%
- changing the reconstruction of kinematic variables from "constrained" to "electron" method changes the values of $R_{\mu\mu}$ and $R_{J/\psi\pi\pi}$ by 1.5%
- not reweighting the MC samples changes the values of $R_{\mu\mu}$ by 3% and $R_{J/\psi\pi\pi}$ by 1%
- applying more restrictive cuts on the number of (soft/noisy) tracks not associated with the event vertex changes the values of $R_{\mu\mu}$ by 5% and $R_{J/\psi\pi\pi}$ by 3%

Total systematic uncertainties are: $\delta R_{\mu\mu} =^{+7}_{-14}$**%,** $\delta R_{J/\psi\pi\pi} =^{+4}_{-5}$**% and** $\delta R =^{+3}_{-5}$**%**

PHP: Event selection

$\psi(2S) \to \mu^+\mu^-$ channel:

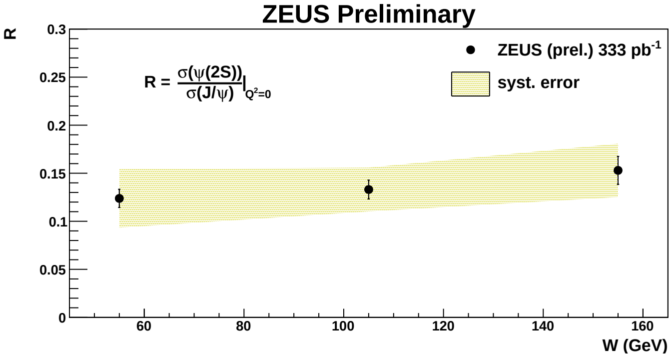
- exclusive muon triggers
- vertex consistent with *ep* interaction
- $N_{track} = 2$ (oppositely charged)
- $p_T > 1$ GeV (of each track)
- muon identification:
  at least one track identified by muon detectors or BAC
  both tracks matched to MIP clusters in CAL
- no scattered beam-electron in the CAL
- $\cos(\mu^+, \mu^-) > -0.9$ (cosmic rejection)
- elasticity cut (no CAL clusters other then 2 MIPs)
- $30 < W < 180$ GeV, $|t| < 5$ GeV^2, $2 < M(\mu^+, \mu^-) < 6$ GeV.

$\psi(2S) \to \mu^+\mu^- \pi^+\pi^-$ channel:

(differences w.r.t. the 2-prong channel)

- $N_{track} = 4$ (two oppositely charged pairs, sorted by p_T)
- highest momentum pair: muon candidates
  lowest momentum pair: pion candidates
- transverse momentum of pion candidates: $p_T^{\pi} > 0.12$ GeV;
- $2.8 < M(\mu^+\mu^-) < 3.4$ GeV (J/ψ window)
- $M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$ in $(0.5 - 0.7)$ GeV window
  (cascade decay of $\psi(2S)$)

$R = \frac{\sigma_{\gamma p \to \psi(2S)p}}{\sigma_{\gamma p \to J/\psi(1S)p}}$ vs. W at $Q^2 = 0$ GeV^2



- $R_{\psi(2S)\to J/\psi\pi^+\pi^-} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S)\to\mu^+\mu^-}}{Acc_{\psi(2S)\to J/\psi\pi^+\pi^-}} \cdot \frac{1}{BR_{\psi(2S)\to J/\psi\pi^+\pi^-}}$
- $R_{\psi(2S)\to\mu^+\mu^-} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S)\to\mu^+\mu^-}}{Acc_{\psi(2S)\to\mu^+\mu^-}} \cdot \frac{BR_{J/\psi(1S)\to\mu^+\mu^-}}{BR_{\psi(2S)\to\mu^+\mu^-}}$
- $BR(\psi(2S) \to J/\psi\pi^+\pi^-) = (34.49 \pm 0.3)\%$, $BR(\psi(2S) \to \mu^+\mu^-) = (7.9 \pm 0.9) \times 10^{-3}$, $BR(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033)\%$