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

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XXIII LOW-X MEETING
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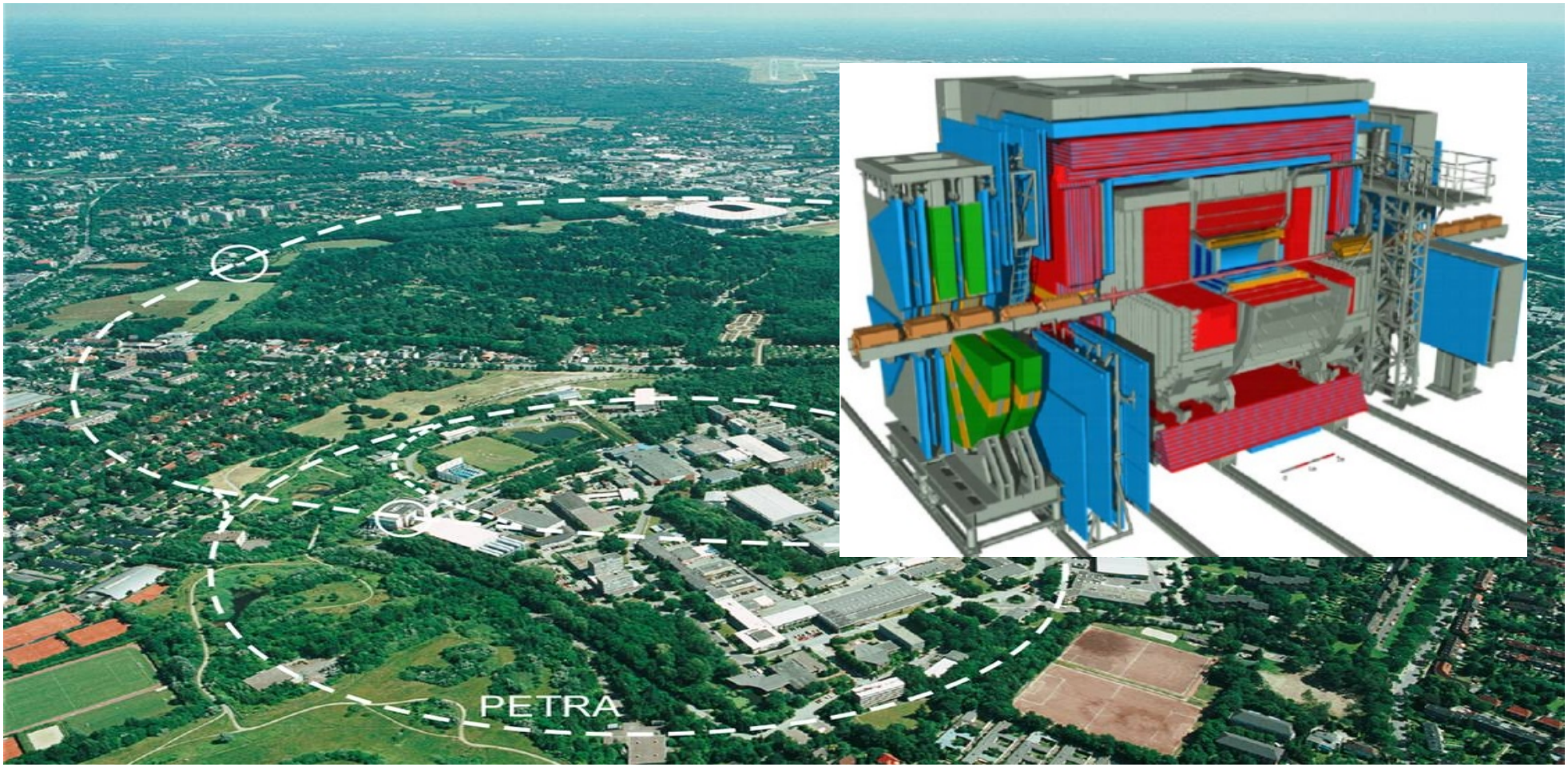
Outlook

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
5. Summary

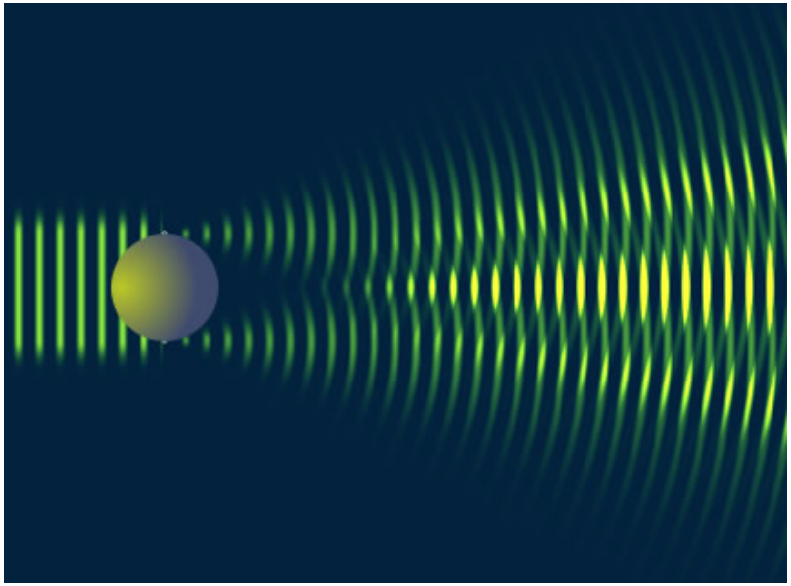
HERA and ZEUS: 1992 – 2007, DESY, Hamburg

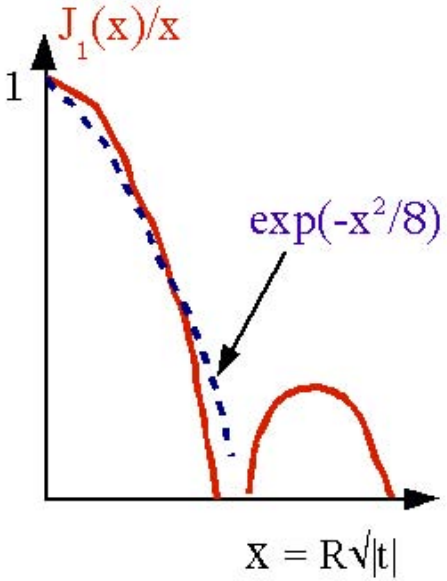
HERA: world's first and only $e^{\pm}p$ collider, $\mathbf{E_e = 27.5\ GeV}$, $\mathbf{E_p = 920\ GeV}$ ($\sqrt{s} = 318$ GeV)

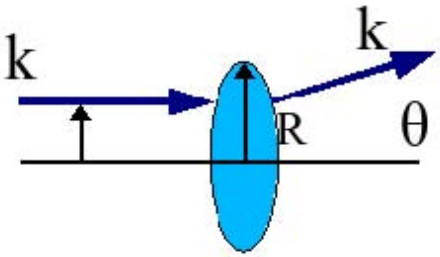


ZEUS: multipurpose, hermetic detector
Total luminosity: $\int \mathcal{L} \sim \mathbf{500\ pb^{-1}}$ collected during HERA I + II running periods

Diffraction of Light



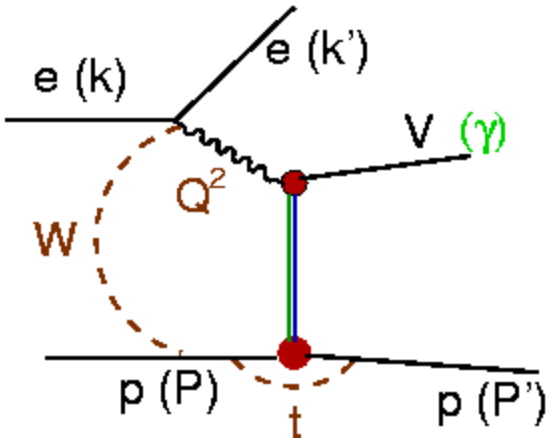


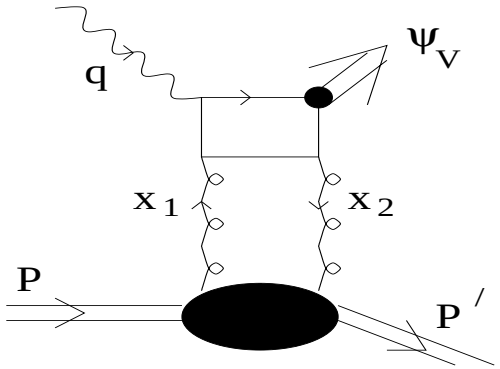


Light Scattering in Fraunhofer approximation (wavelength $\lambda \sim 1/k << R$)

- $|t| = 4k^2 sin^2(\theta/2)$
- $d\sigma/dt \sim e^{-b|t|}$ (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: $\mathbf{M_V^2}$, $\mathbf{Q^2}$, $\mathbf{W}$, $\mathbf{|t|}$

M_V^2 - vector meson mass squared

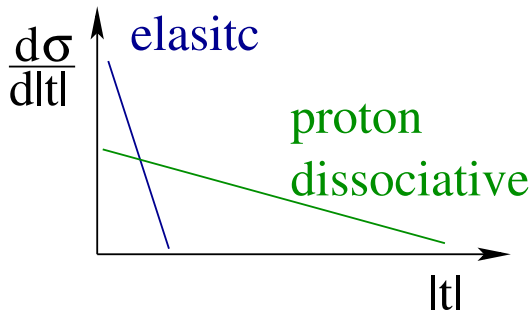
Q^2 $(= -q^2 = -(k - k')^2)$ - the photon virtuality (emitted by the incoming electron):

- $Q^2 \approx 0$ 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

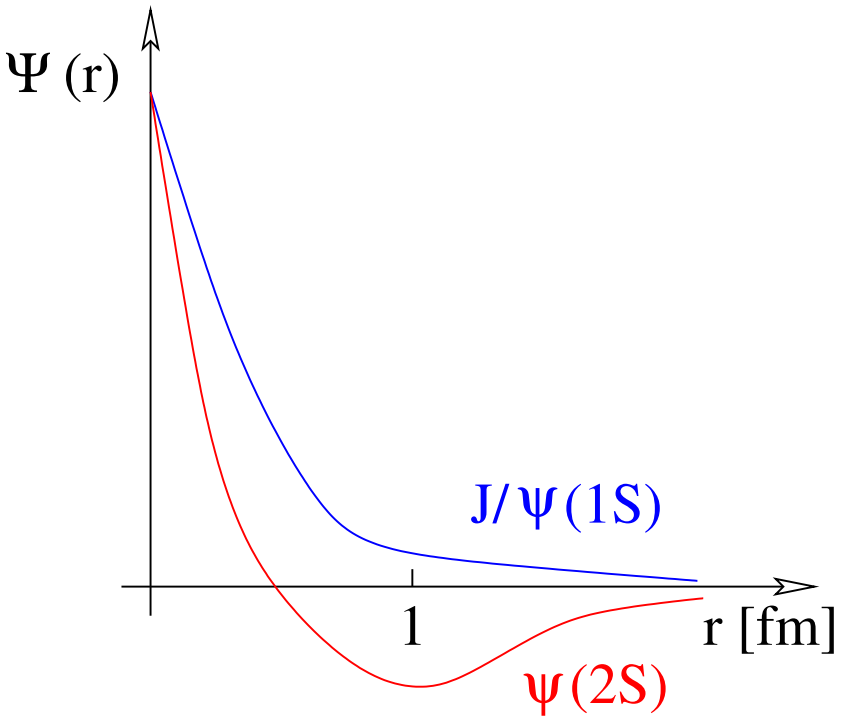
$|t|$ - 4-momentum transfer at the proton vertex

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



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

Cross section ratio $\psi(2S)/J/\psi(1S)$ in DIS



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

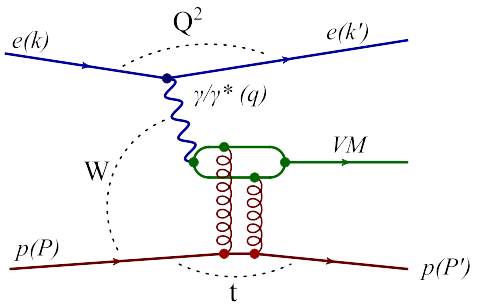
- sensitive to radial wave function of charmonium
- provides insight into the dynamics of the hard process

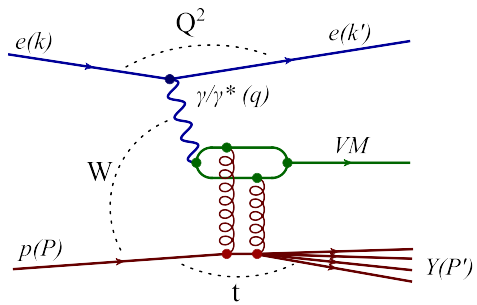
- $J/\psi(1S)$ and $\psi(2S)$ have distinctive wave functions
- $\psi(2S)$ has a node at ≈ 0.4 fm
- $\langle r^2_{\psi(2S)} \rangle \approx 2 \langle r^2_{J/\psi(1S)} \rangle$
- pQCD models predict $R \sim 0.17$ in PHP and moderate rise of R with Q^2 in DIS
- ψ' cross section is expected to be suppressed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

Analyzed channels and DATA/MC samples

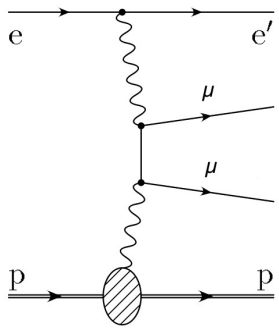
- Investigated decay channels:
  - $\psi(2S) \to J/\psi + \pi^+\pi^-, \quad \psi(2S) \to \mu^+\mu^-, \quad J/\psi(1S) \to \mu^+\mu^-$
- HERA I+II DATA: $\mathcal{L} = 468\ \text{pb}^{-1}$ (1996 - 2007) with $5 < Q^2 < 80\ \text{GeV}$
- subsample of $114\ \text{pb}^{-1}$ (HERA I) with $2 < Q^2 < 5\ \text{GeV}$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

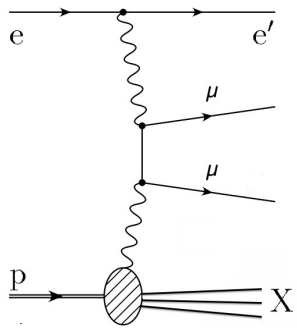
- $\frac{d\sigma}{dQ^2} \sim \frac{1}{(1+Q^2/M_V^2)^{1.5}}$
- $\frac{d\sigma}{d|t|} \sim \exp(-b|t|)$, $b = 4.0\ \text{GeV}^{-2}$





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

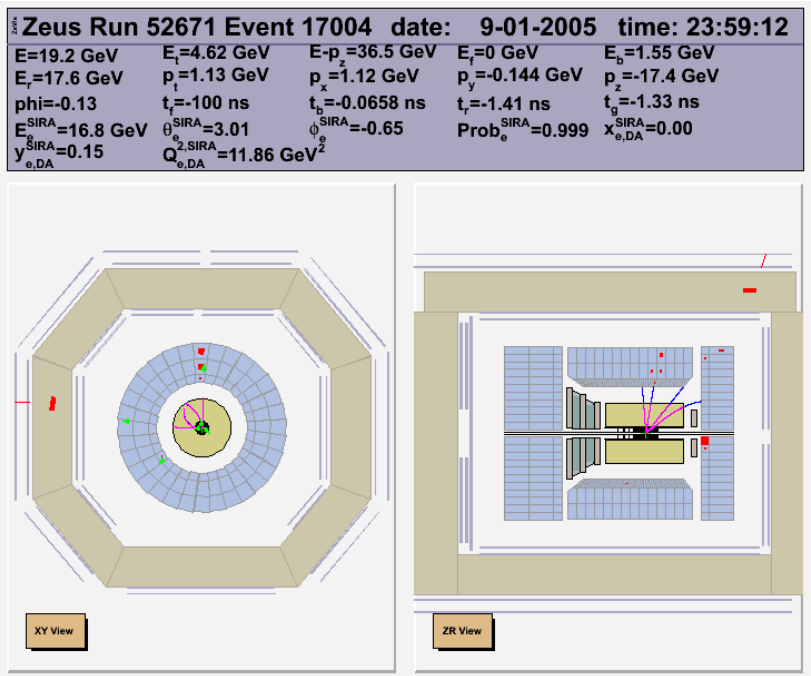


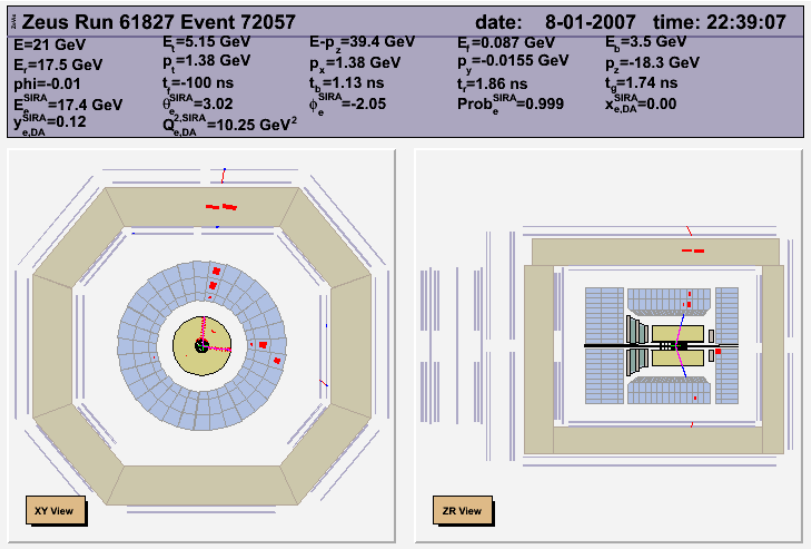


Events selection

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

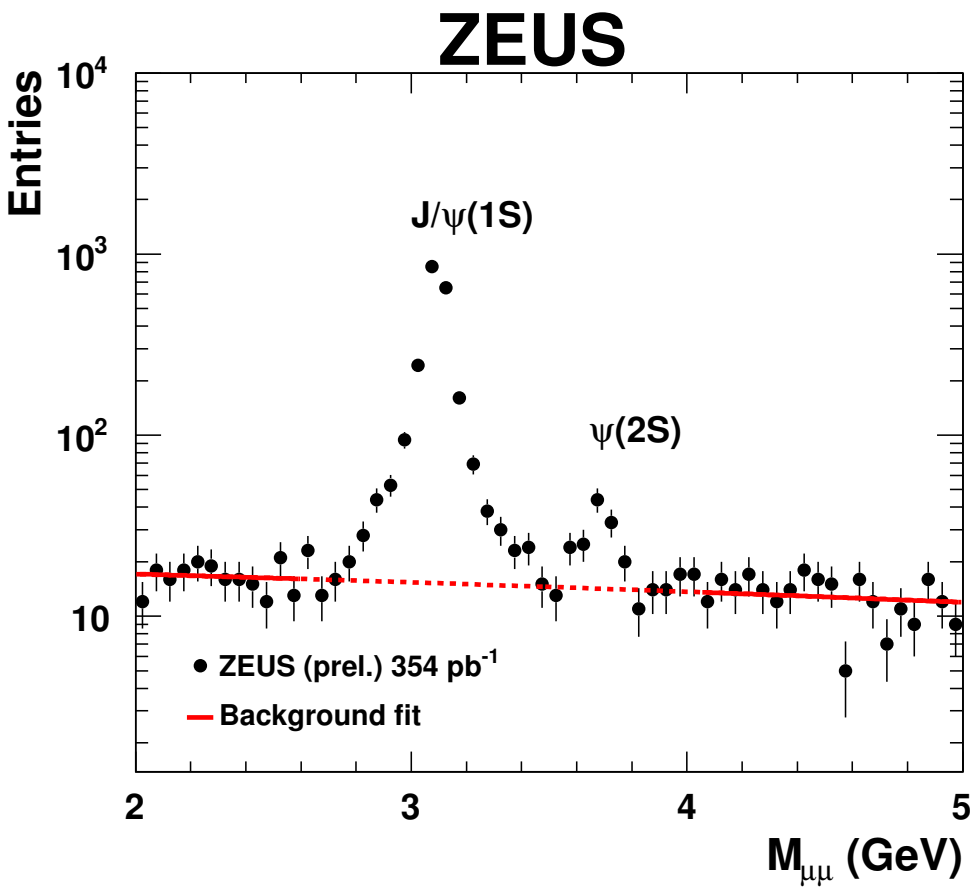
- Event selection:
  - scattered electron $E_{e'} > 10$ GeV in CAL
  - 2 (4 for $\psi(2S)$ 4-prongs decay) non-electron tracks from primary vertex, net charge $= 0$
  - two tracks identified as muons (CAL, F/B/R/MUO, BAC)
  - no other deposits not matched to tracks (above CAL noise) $\to$ proton remains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





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

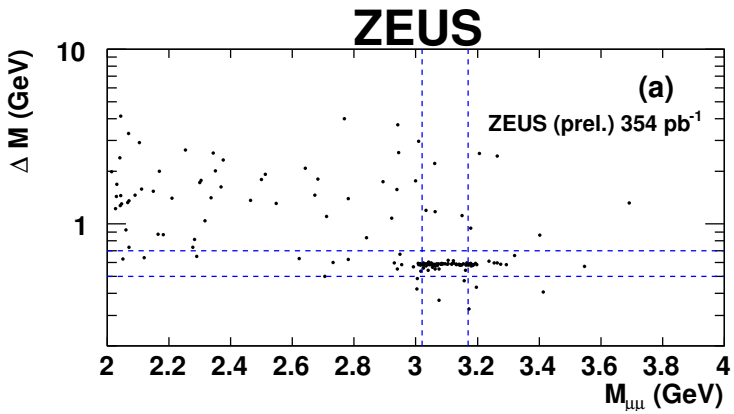
di-muon channel: mass distribution $M_{\mu^+\mu^-}$



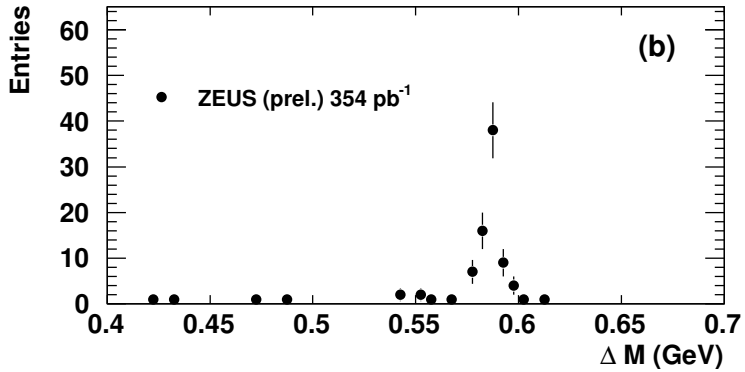
- $J/\psi(1S) \to \mu^+\mu^-$
- $\psi(2S) \to \mu^+\mu^-$
- BG (BH): $\gamma\gamma \to \mu^+\mu^-$

- 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

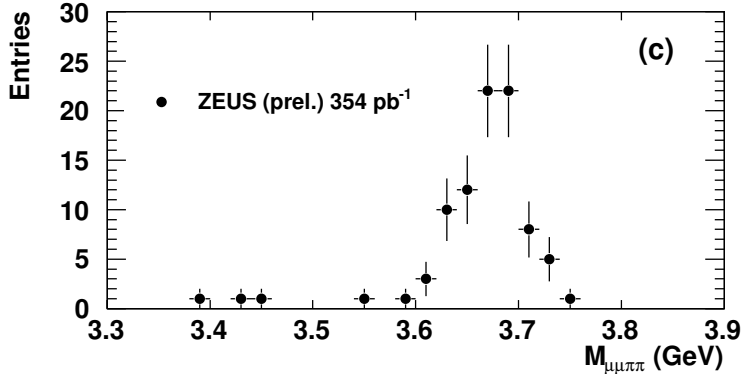
Selection specific for $\psi(2S) \to \mu^+\mu^-\pi^+\pi^-$ channel



- 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
  ($\leq$ 3 background events at 90% CL)

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

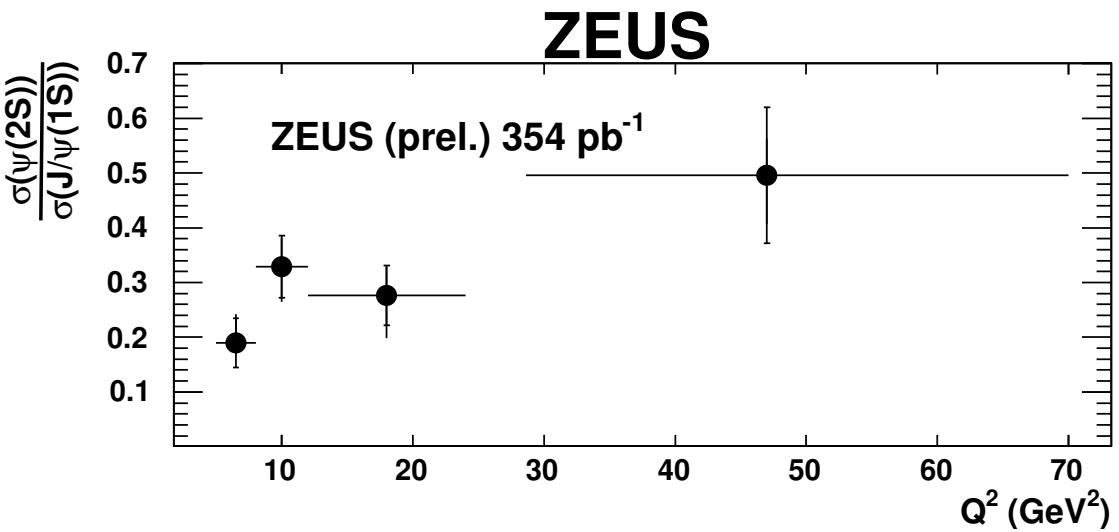
For $30 \leq W \leq 210$ GeV, $5 \leq Q^2 \leq 80$ GeV^2, $|t| \leq 1$ GeV^2

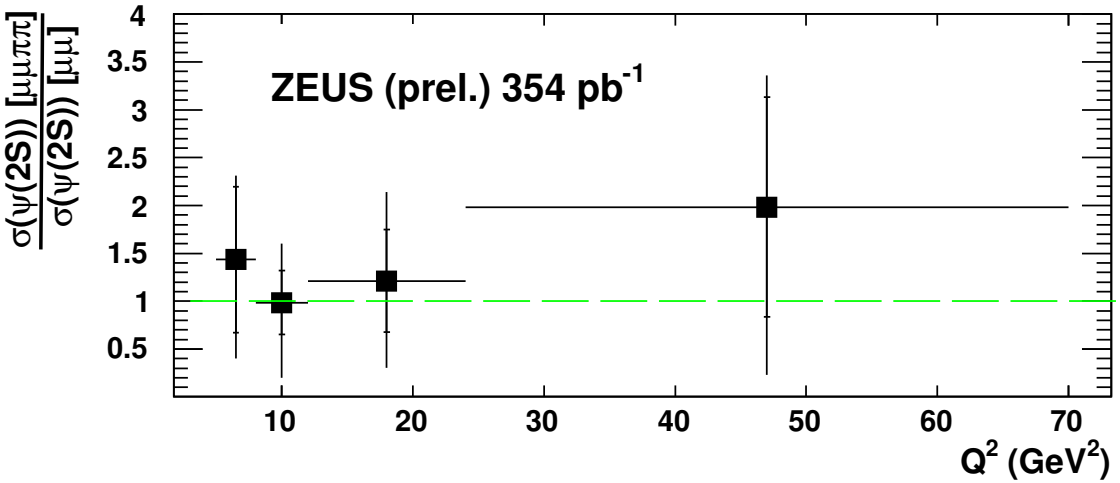
$\psi(2S)$ decay mode	$R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$
$\rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$	$0.29 \pm 0.04^{+0.02}_{-0.01}$
$\rightarrow \mu^+\mu^-$	$0.25 \pm 0.05^{+0.04}_{-0.02}$
combined	$0.28 \pm 0.03^{+0.02}_{-0.01}$

ZEUS Preliminary

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

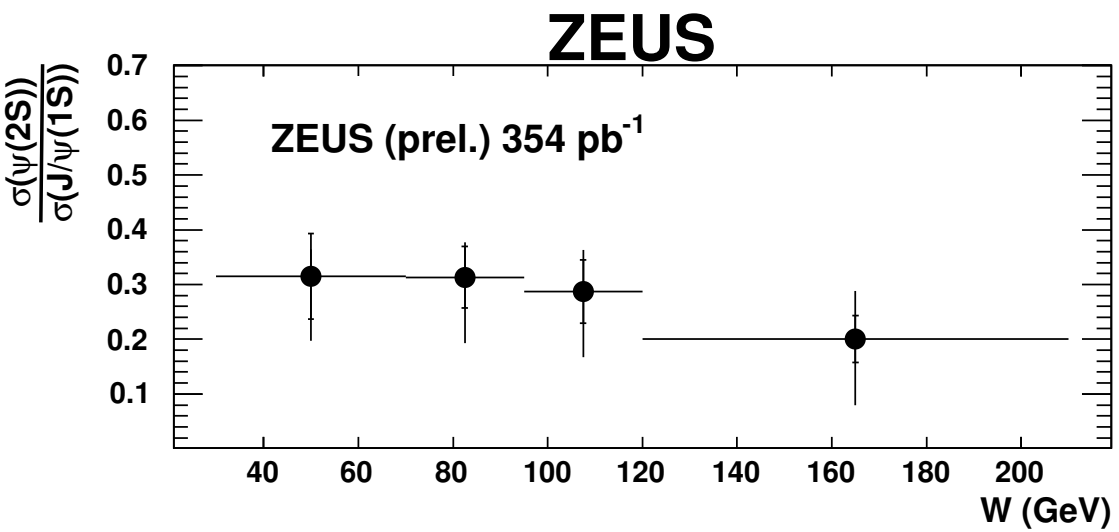
Ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ vs. Q^2



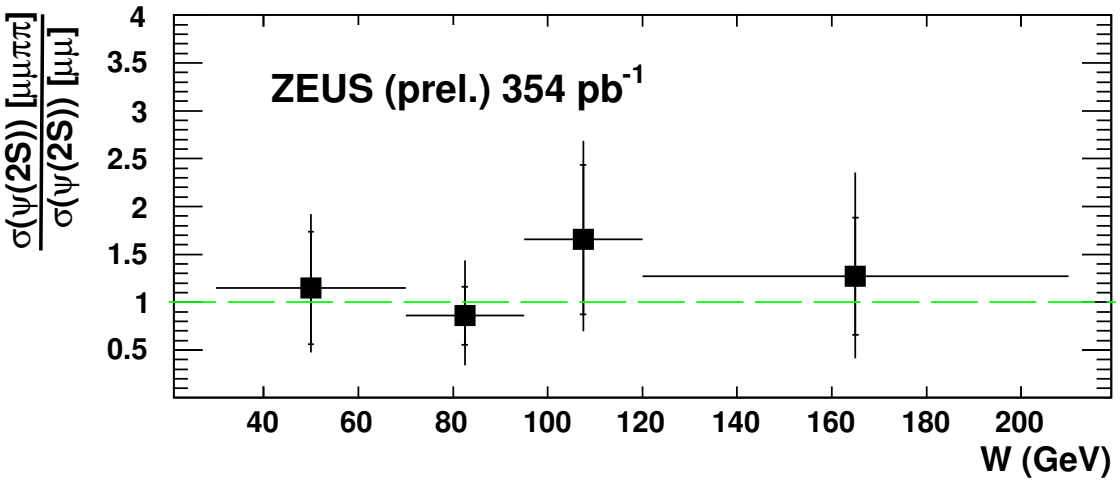


- R rises with Q^2
- $\frac{\sigma(\psi(2S)\to\mu^+\mu^-\pi^+\pi^-)}{\sigma(\psi(2S)\to\mu^+\mu^-)}$

Ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ vs. W

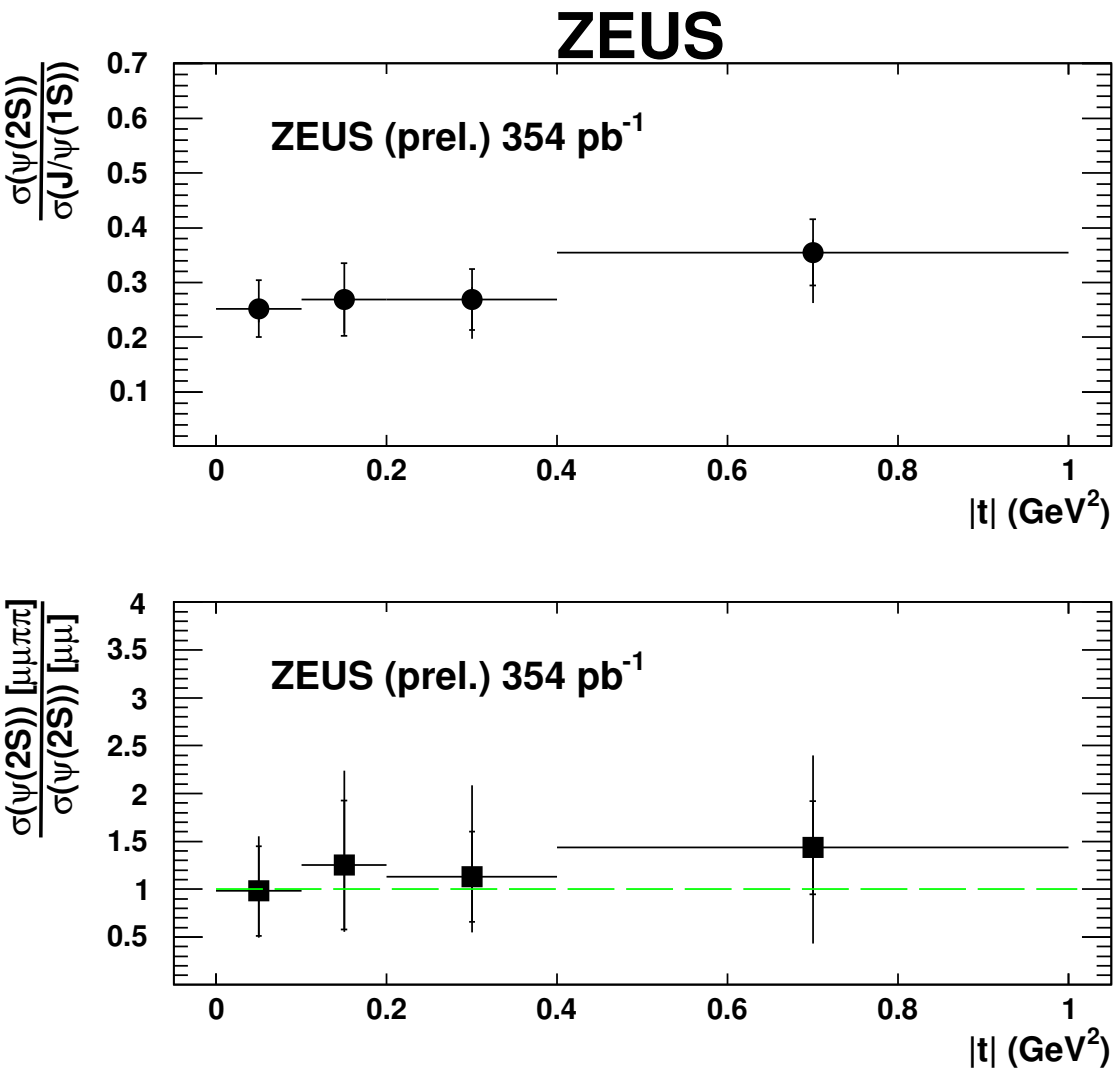


- *R* independent of *W*



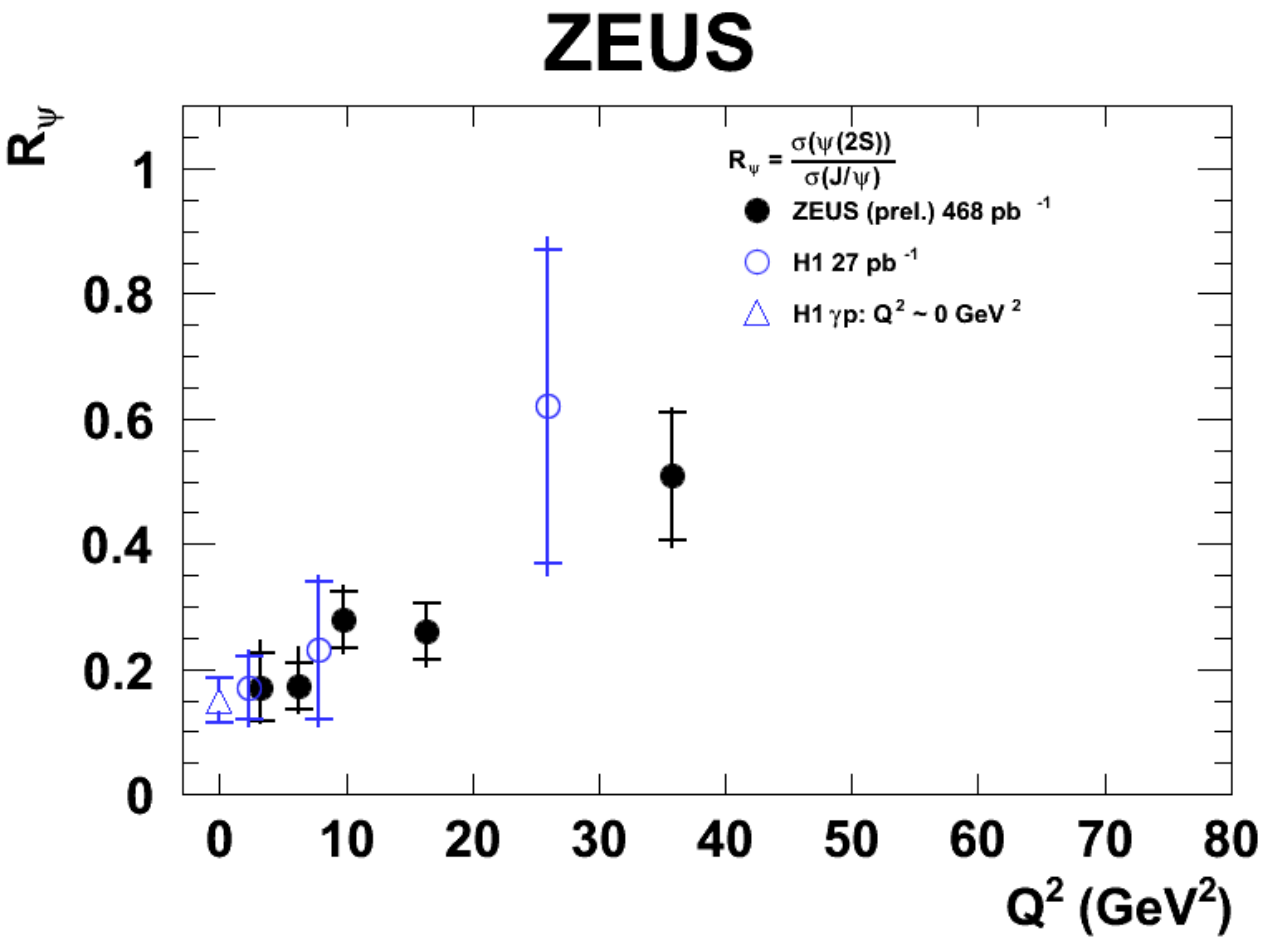
- $\frac{\sigma(\psi(2S)\to\mu^+\mu^-\pi^+\pi^-)}{\sigma(\psi(2S)\to\mu^+\mu^-)}$

Ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ vs. $|t|$



- R independent of $|t|$
- $\frac{\sigma(\psi(2S)\to\mu^+\mu^-\pi^+\pi^-)}{\sigma(\psi(2S)\to\mu^+\mu^-)}$

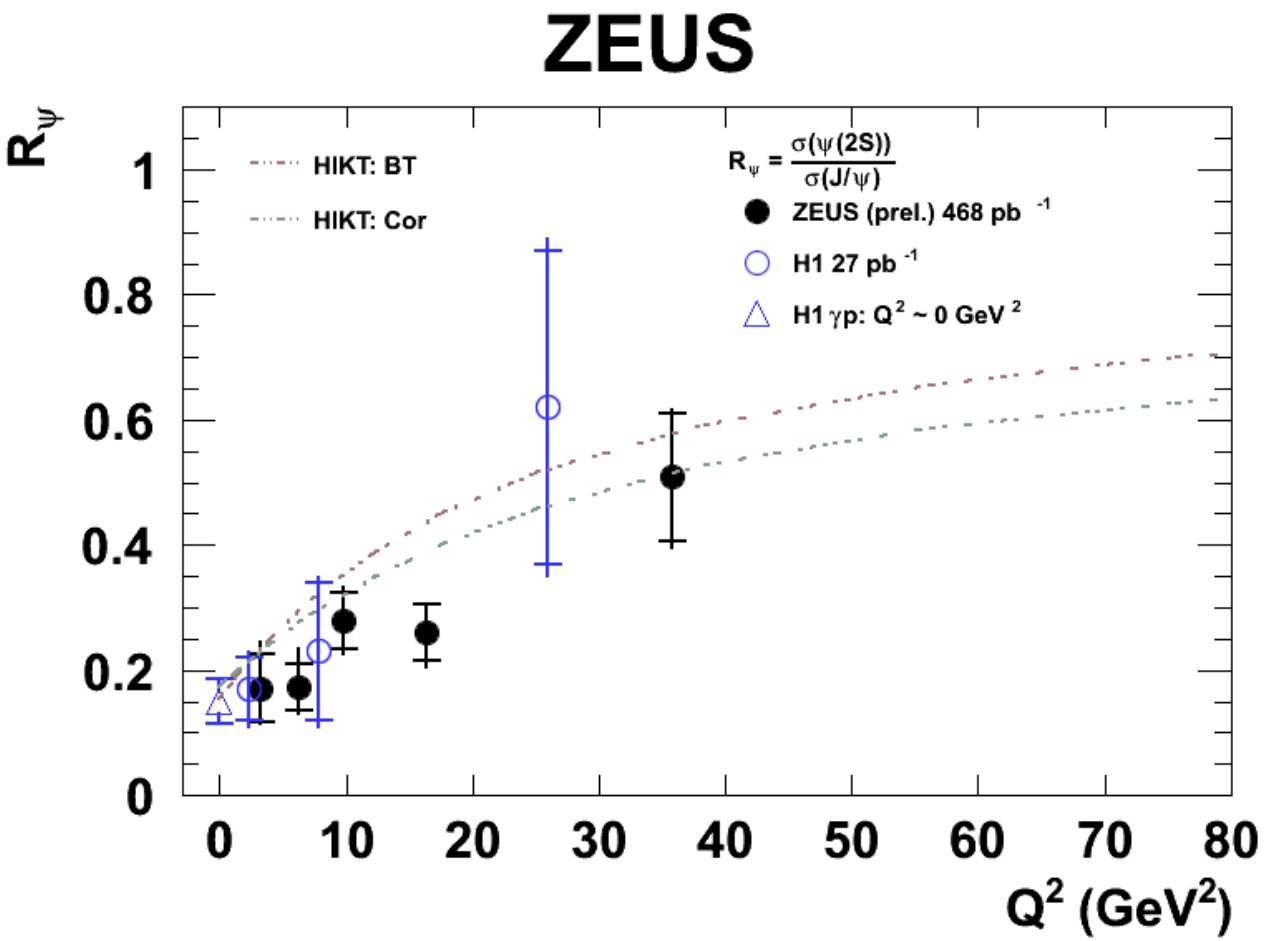
ZEUS to H1 comparison: full data sample 468 pb^{-1}



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

Comparison with theoretical models: HIKT

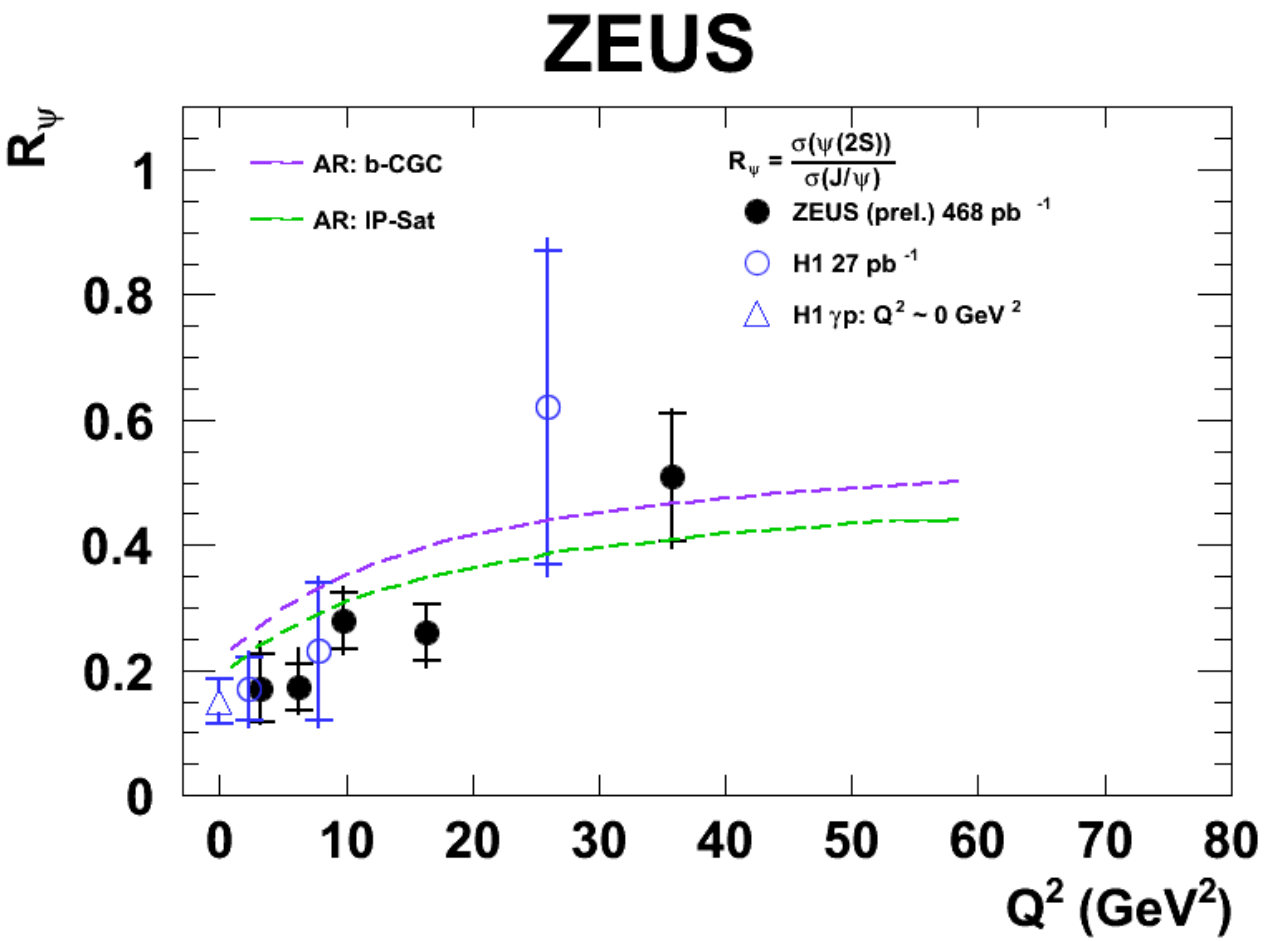


Phys. Rev. **D 62** 094022 (2000)
Phys. Rev. **D 59** 14017 (1999)
Phys. Rev. **D 62** 054022 (2000)

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

- 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

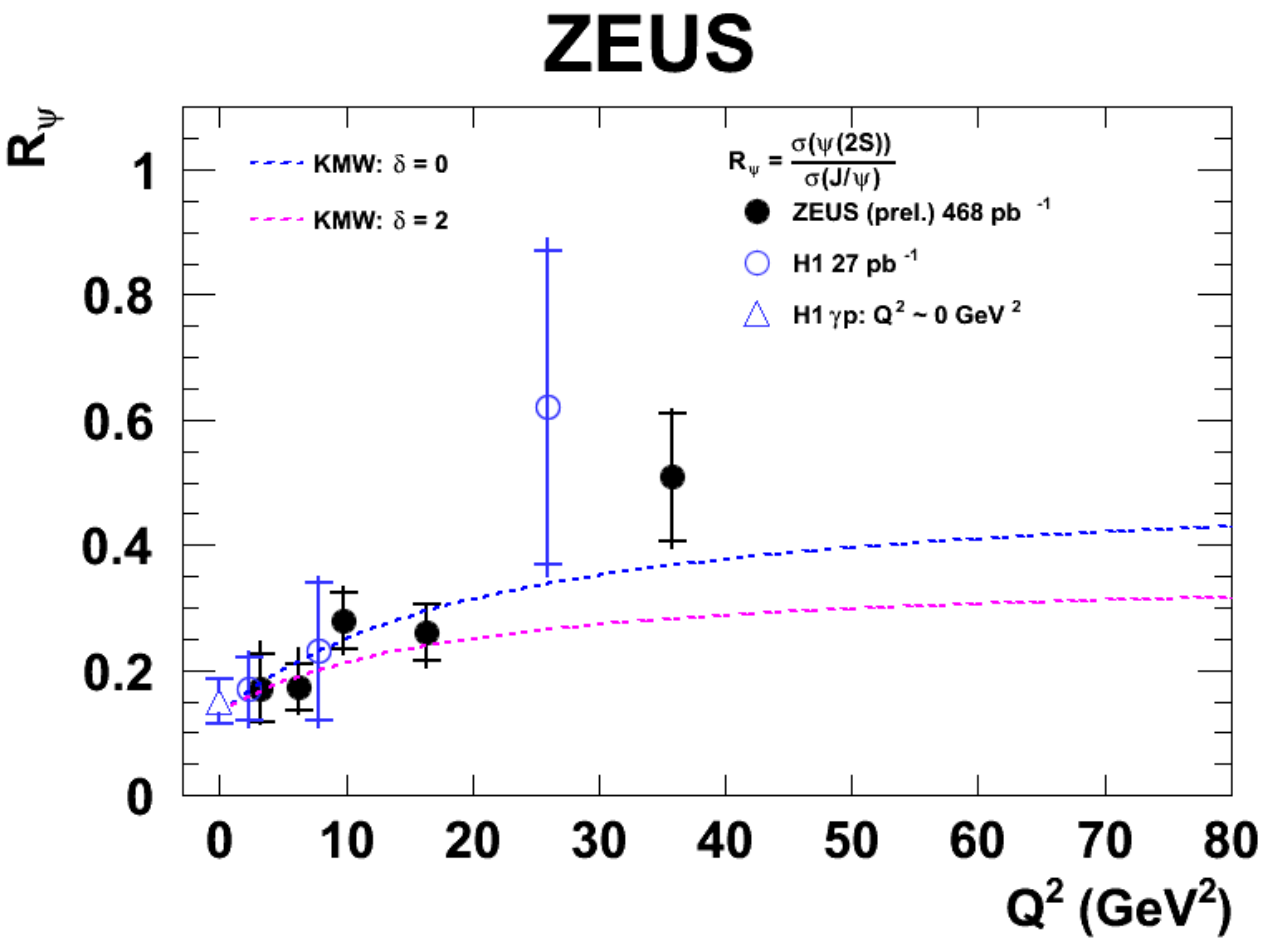
Comparison with theoretical models: AR



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

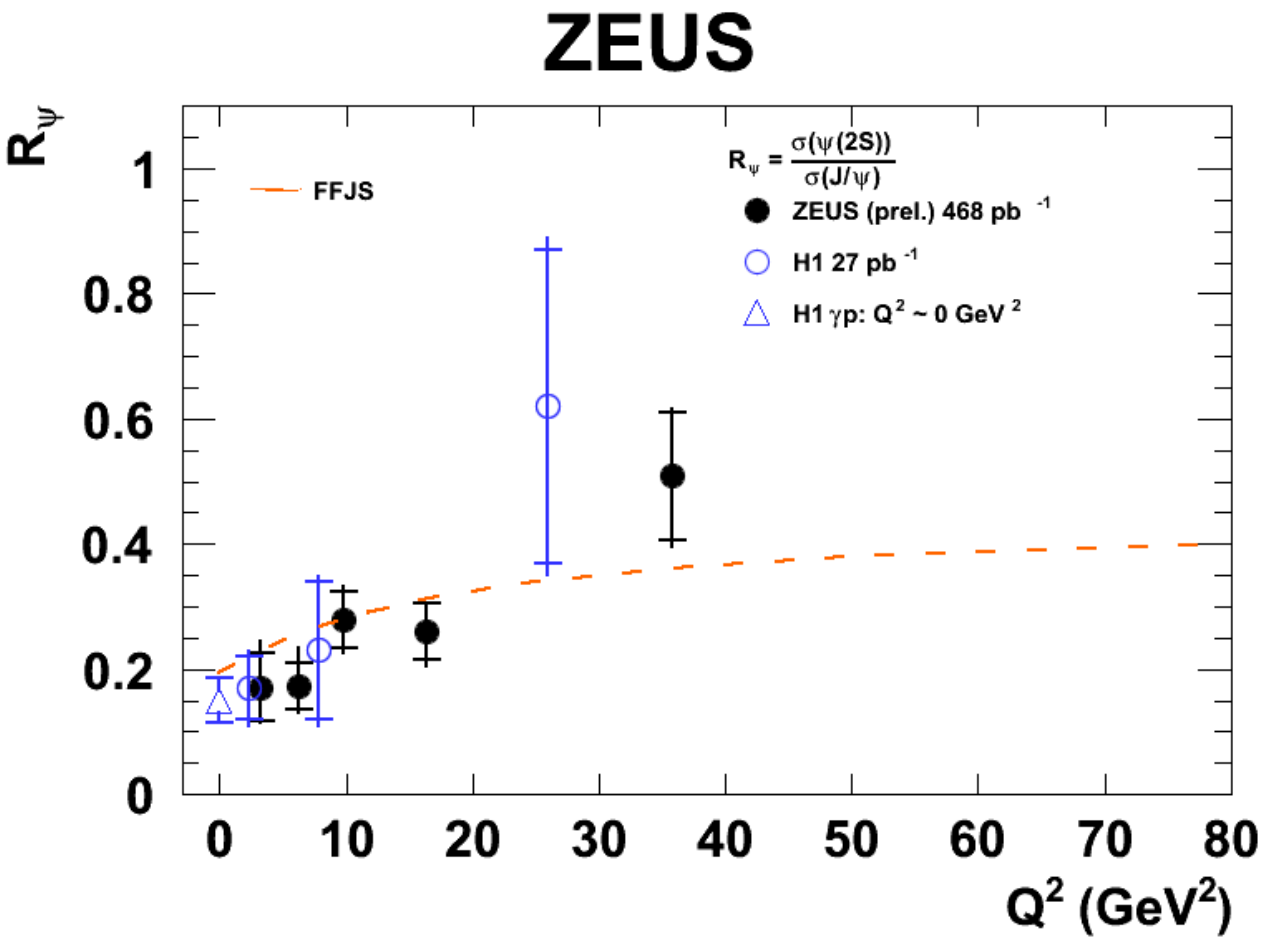
Comparison with theoretical models: KMW



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

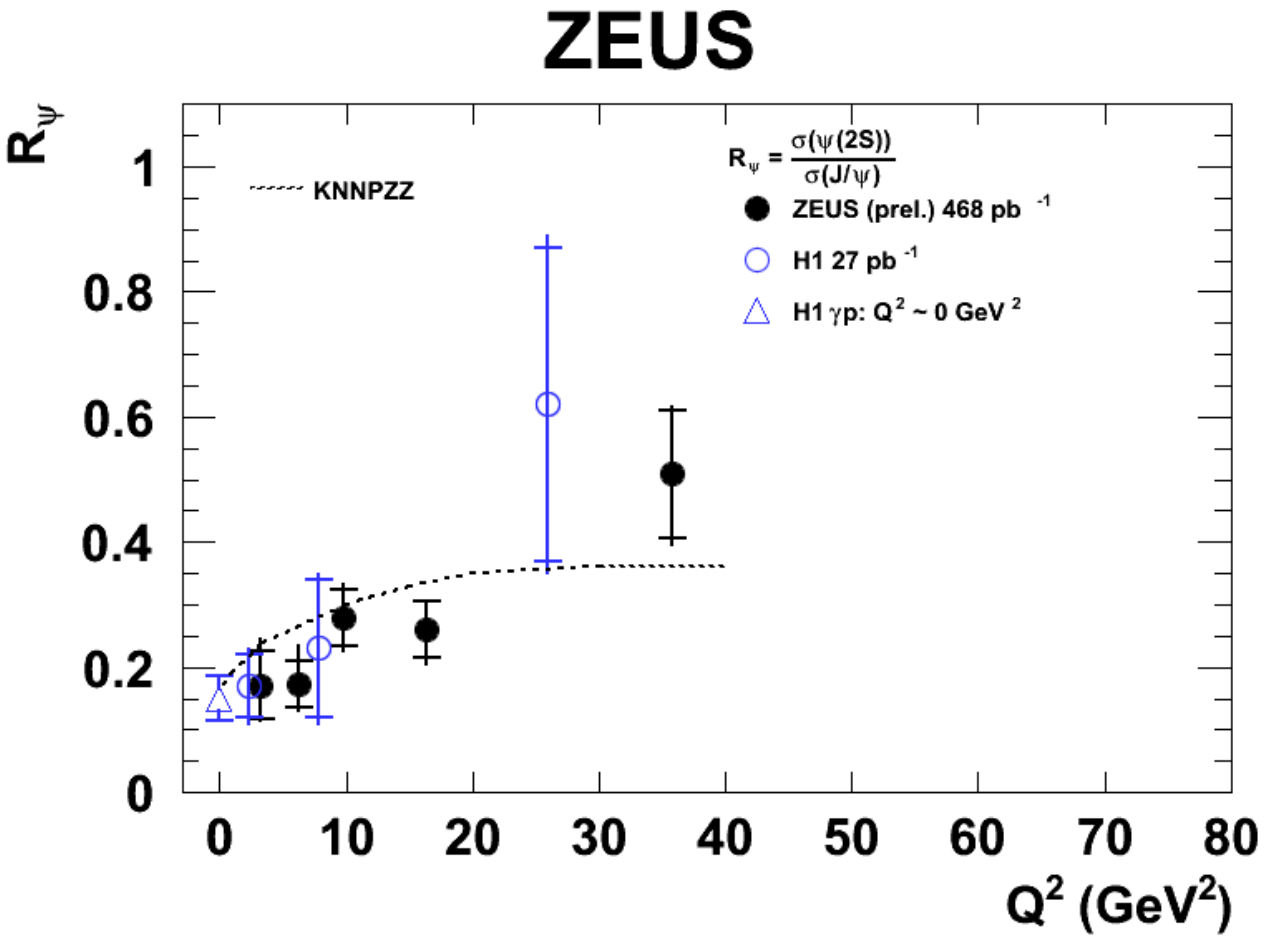
Comparison with theoretical models: FFJS



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: $\sim \tilde{Q}^2 = Q^2 + M_V^2$.

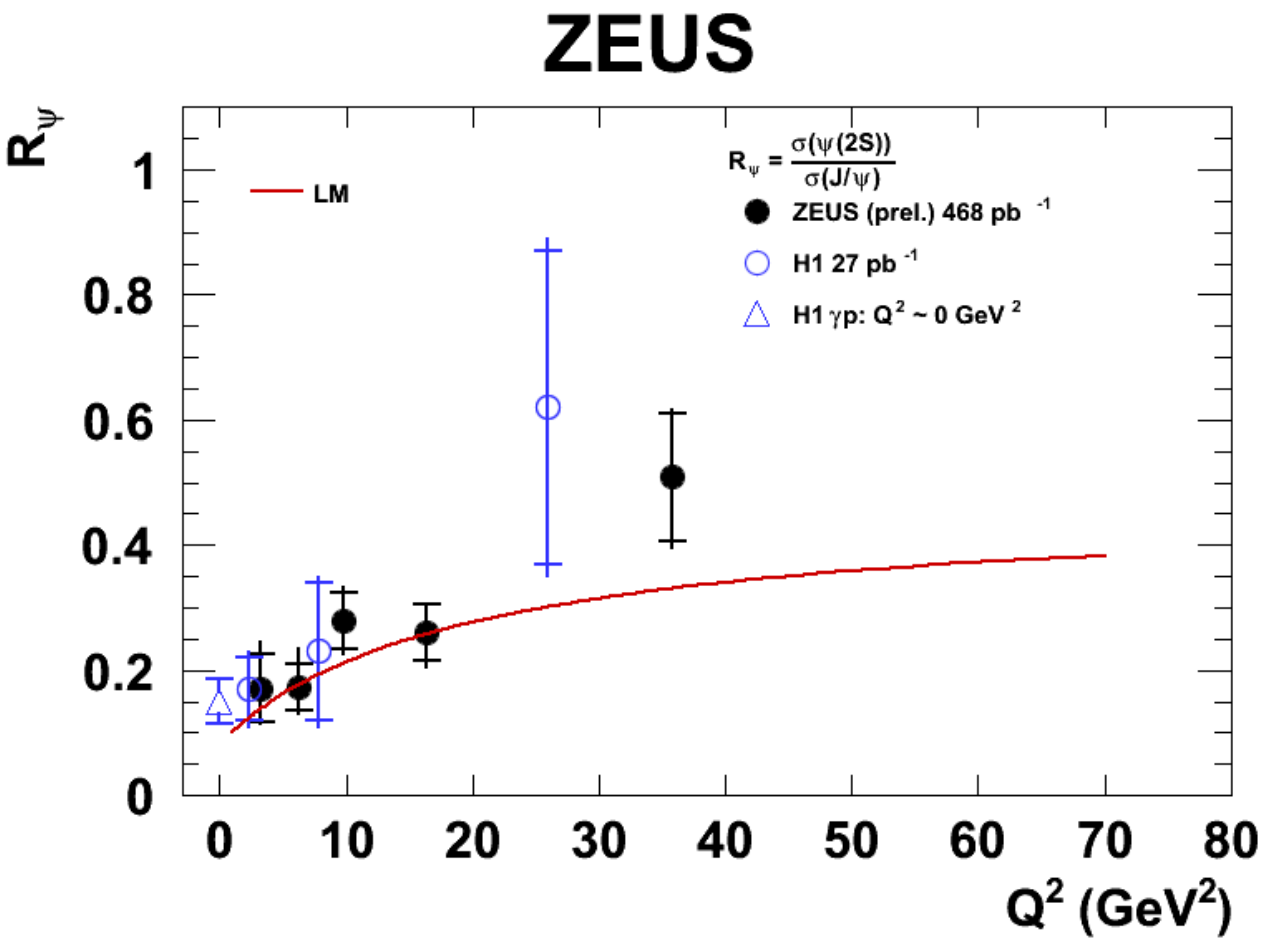
Comparison with theoretical models: KNNPZZ



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

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

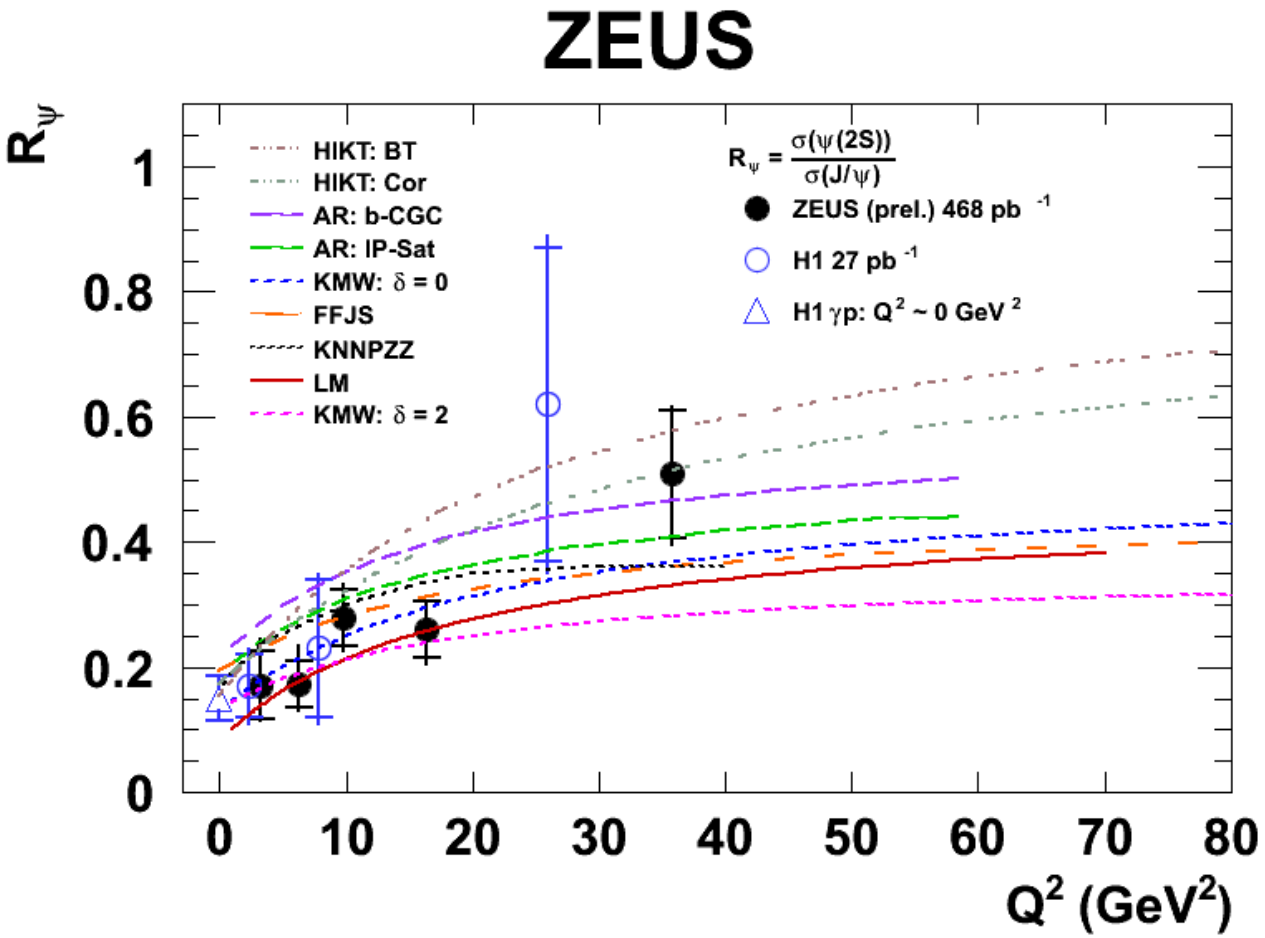
Comparison with theoretical models: LM



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

Comparison with theoretical models: OVERALL PICTURE



- All models predict the rise of $\sigma(\psi(2S))/\sigma(J/\psi)$ with Q^2, many theoretical predictions are consistent with data within current precision, but...
- ...data begin to discriminate some models

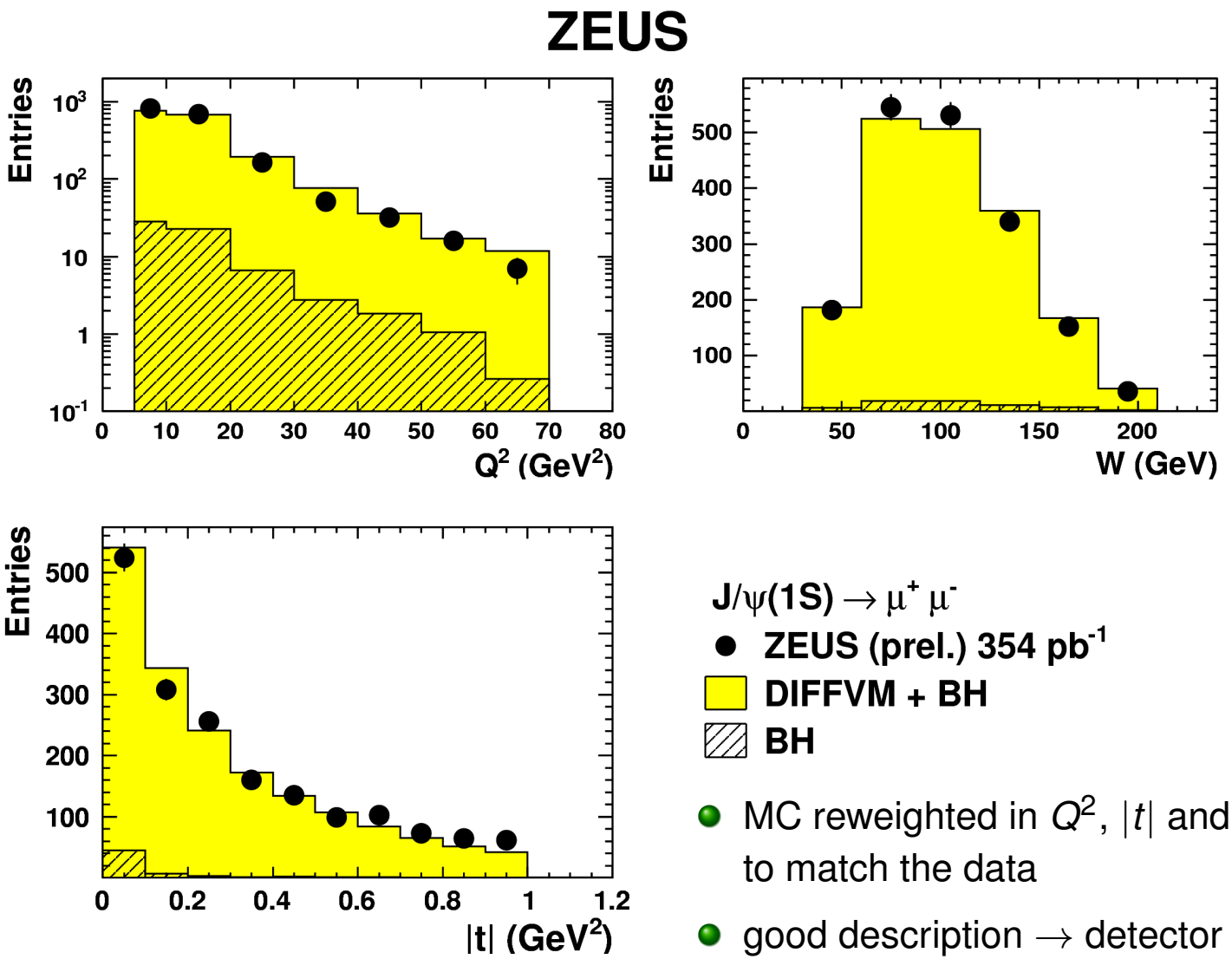
Summary

- 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
- 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

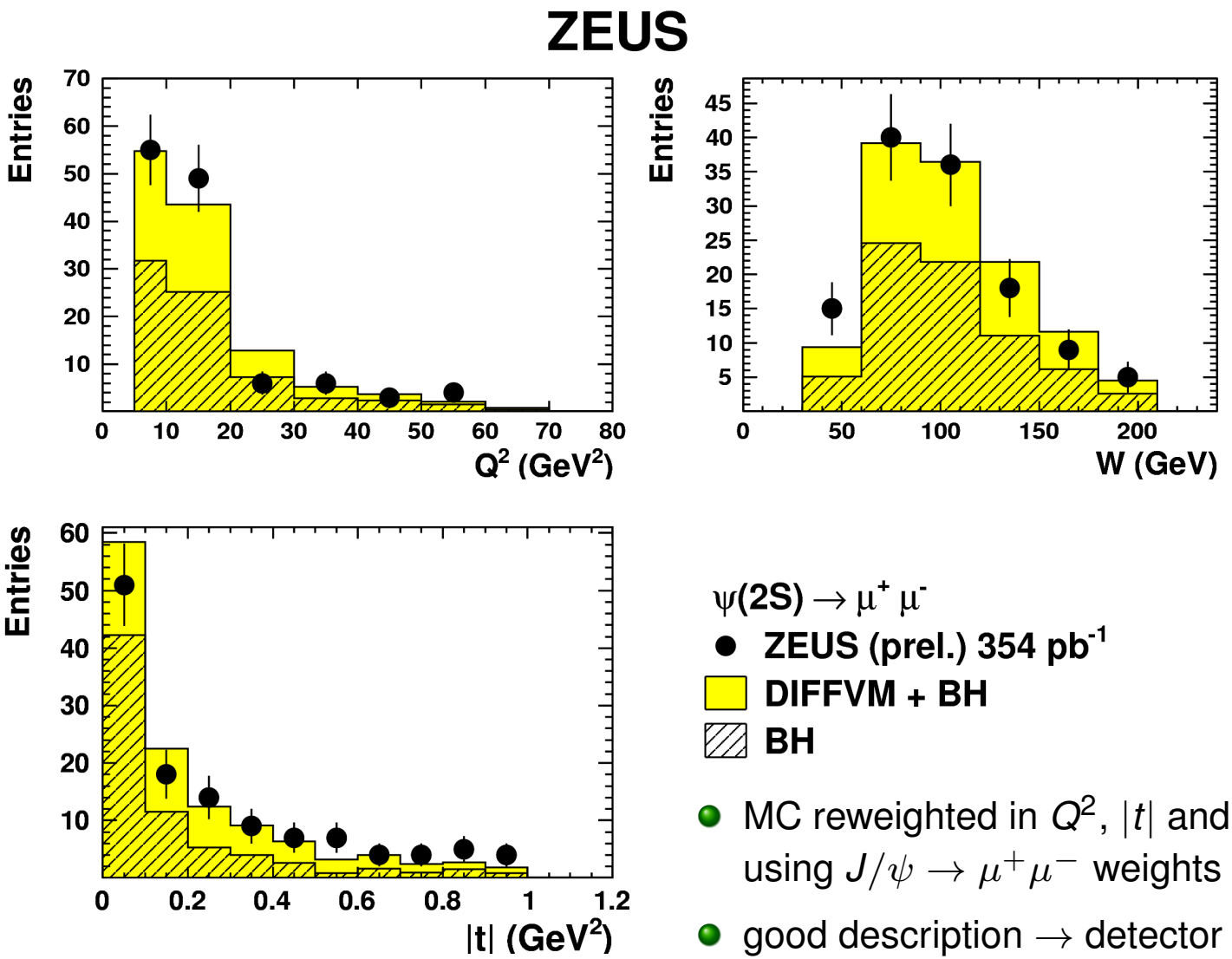
BACKUP PLOTS FOLLOW...

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



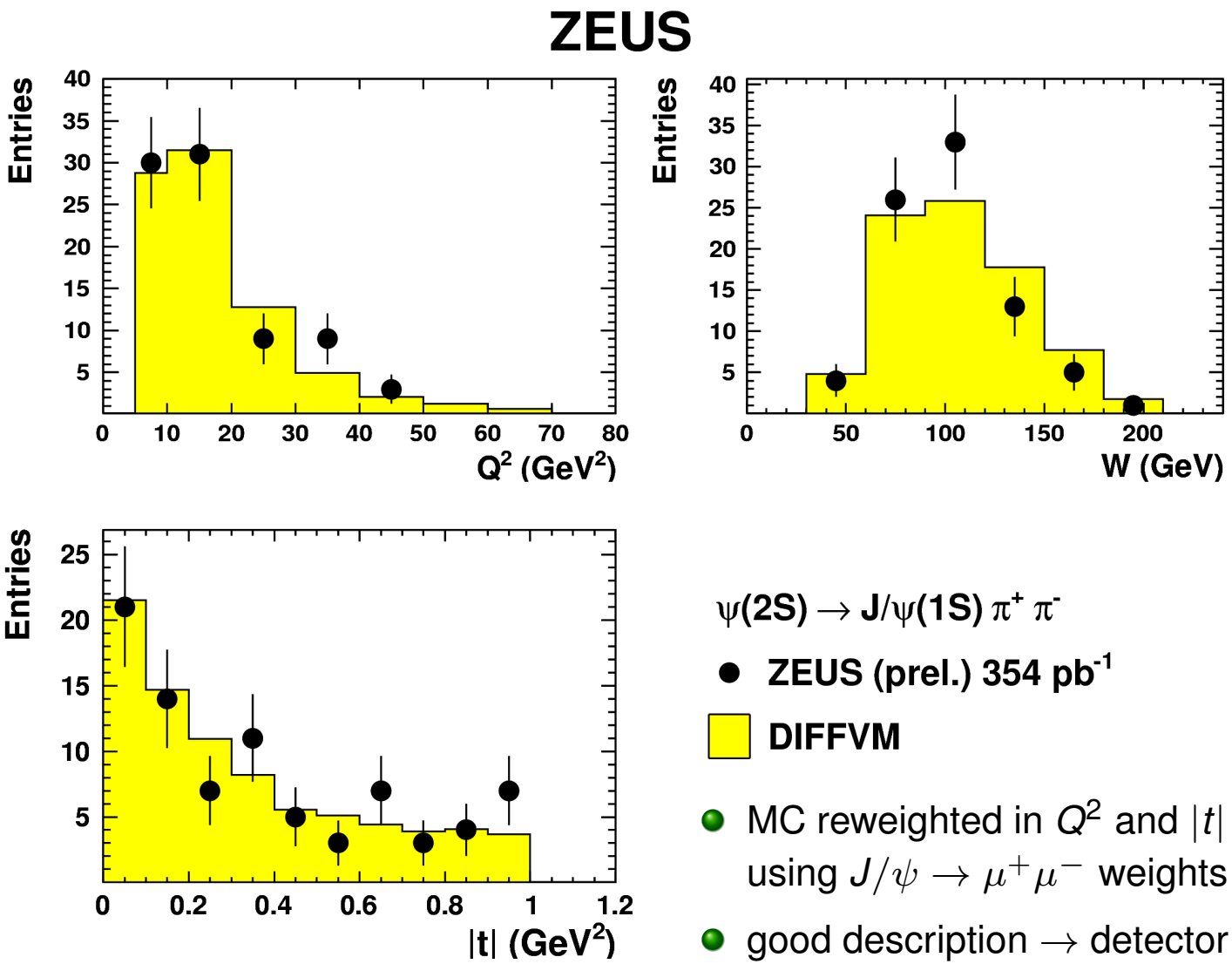
- MC reweighted in Q^2, $|t|$ and J/ψ decay angles to match the data
- good description $\rightarrow$ detector efficiency calculation

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



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

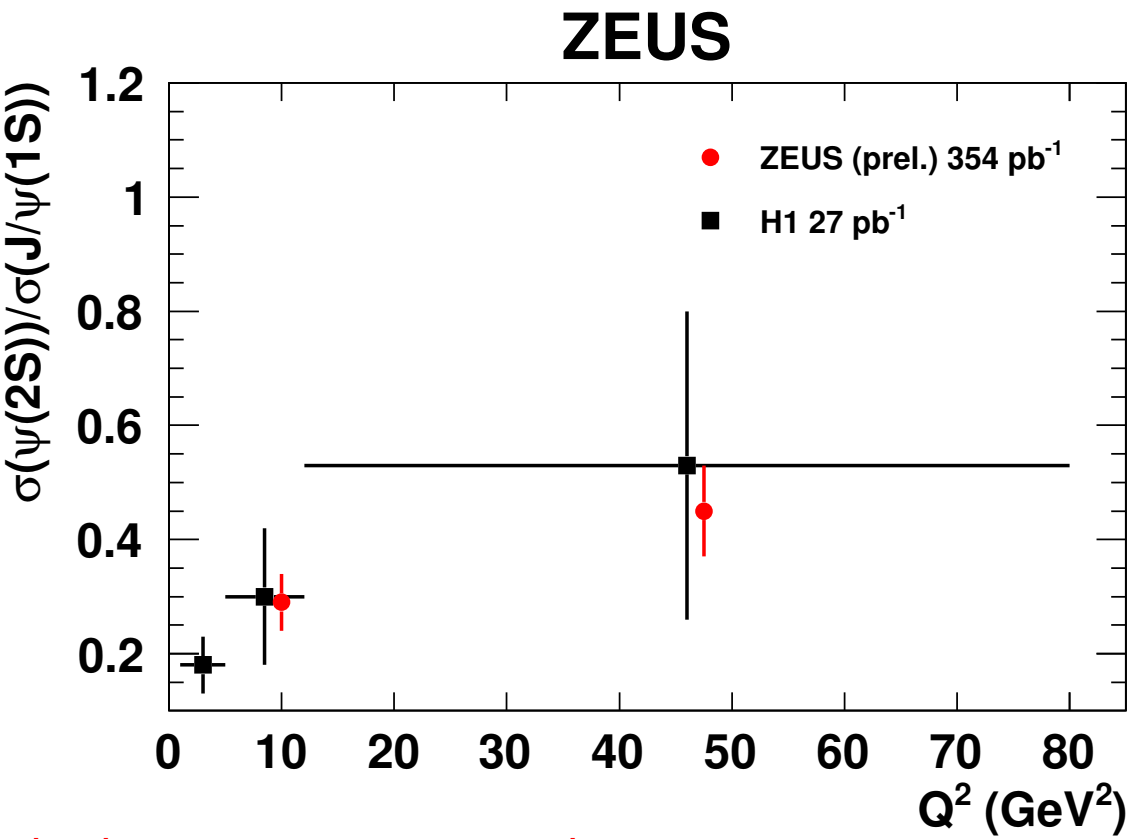
Control plots for $\psi(2S) \to \mu^+\mu^-\pi^+\pi^-$ channel



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

ZEUS to H1 comparison (in H1 phase space and H1 bins)

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



- 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 5% 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 12% 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 3.5% 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** $\delta R = ^{+3}_{-5}$**%**