# Measurement of the cross-section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in deep inelastic exclusive *ep* scattering at HERA

[ arXiv:1601.03699 ]

DESY

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on behalf of the **ZEUS Collaboration**

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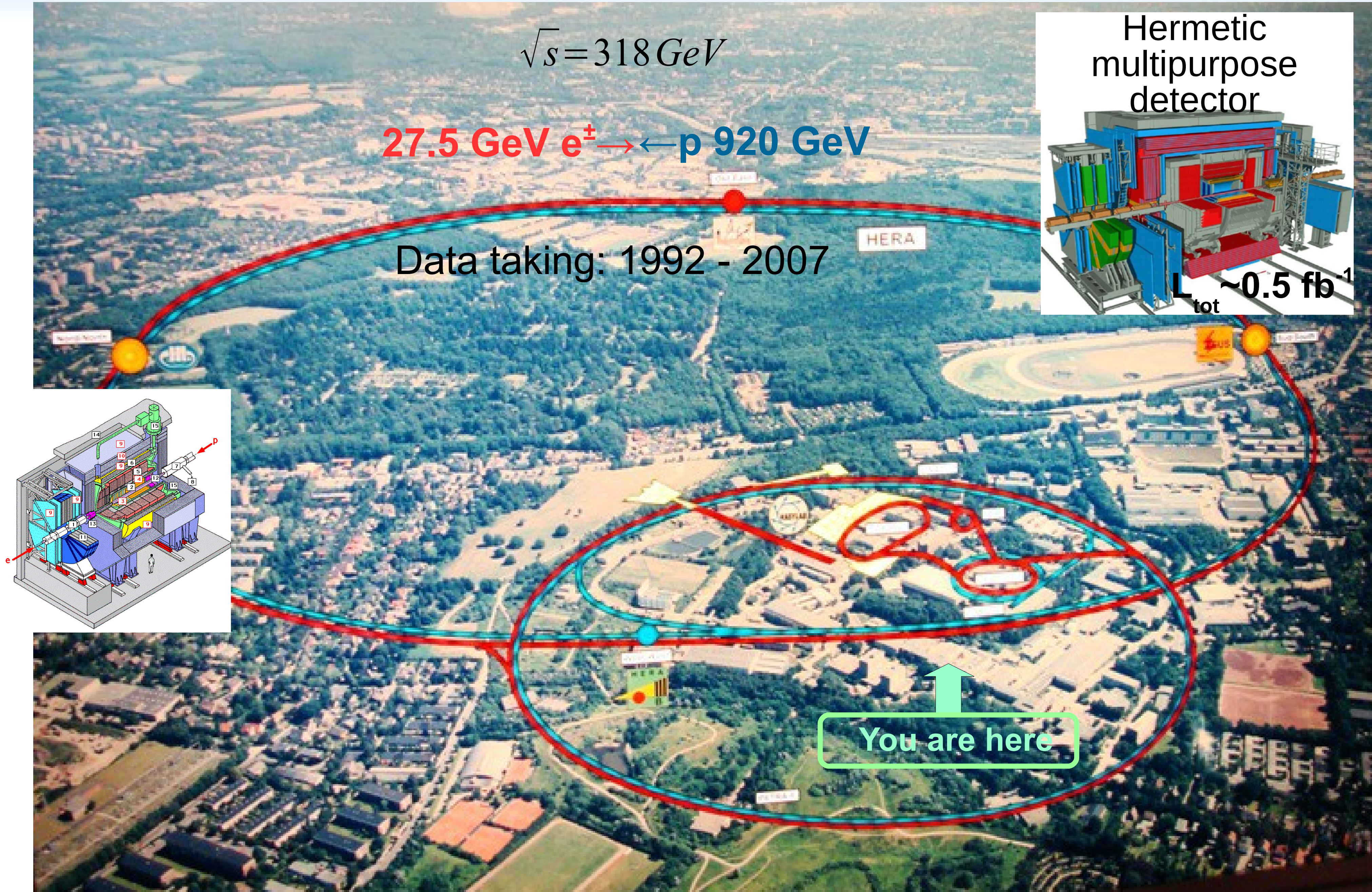
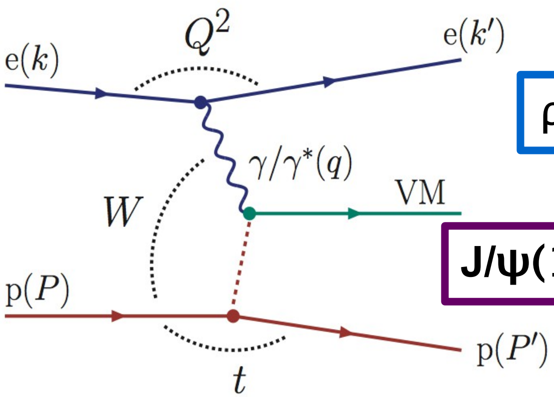
# HERA and ZEUS



# Diffractive vector meson (VM) production at HERA

elastic (exclusive)



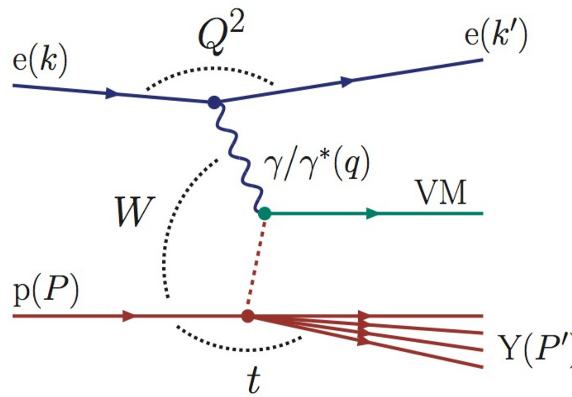

light

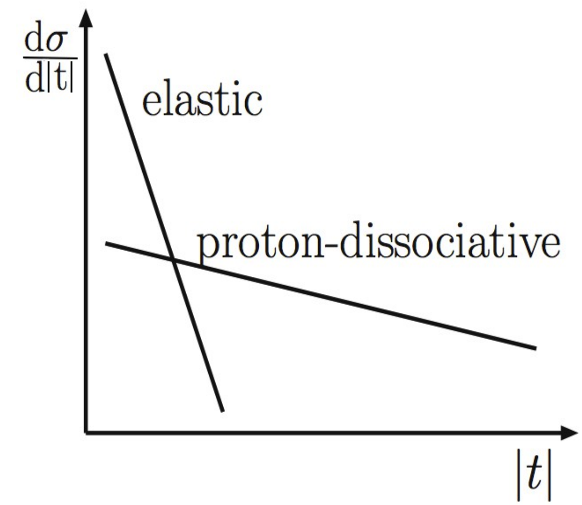
ρ, ω, φ

heavy

**J/ψ(1S), ψ(2S), ϒ**

proton-dissociative



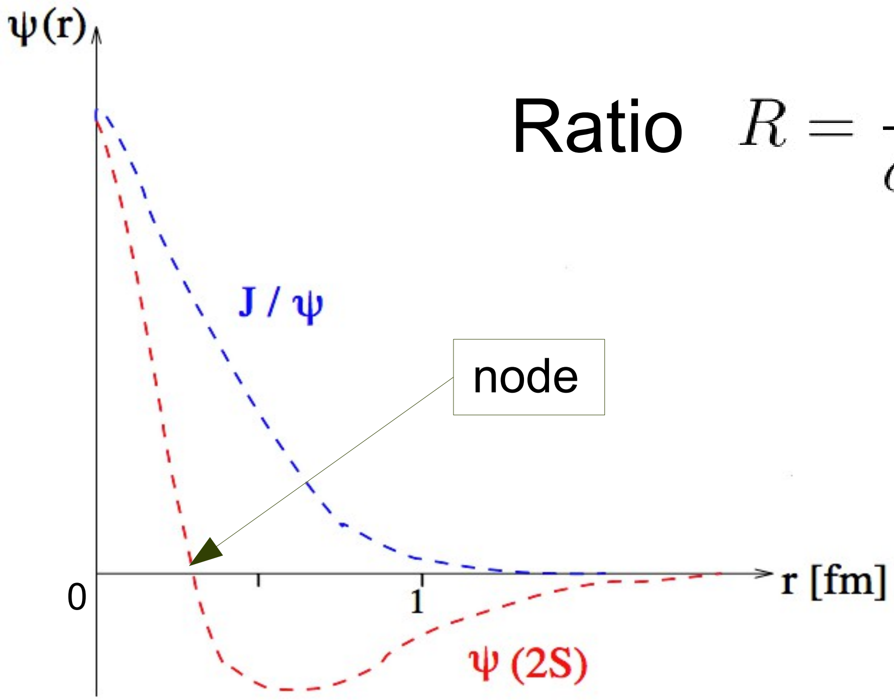

## Kinematics of the process

$Q^2$ — photon virtuality $Q^2 < 1$ GeV$^2$ — γp; $Q^2 \gtrsim 1$ GeV$^2$ — **DIS** $Q^2 = -q^2 = -(k - k')^2$

W — photon-proton CMS energy $W^2 = (q + P)^2$

t — 4-mom. transfer squared at proton vertex $t = (P - P')^2$

# $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in DIS




Ratio $R = \frac{\sigma_{\gamma p \to \psi(2S) p}}{\sigma_{\gamma p \to J/\psi\, p}}$ gives information about the dynamics of hard process

sensitive to radial wave function of charmonium

$\psi(2S)$ wave function different from $J/\psi$ wave function:

- Has a node at ≈ 0.35 fm
- $\langle r^2_{\psi(2S)} \rangle \approx 2 \langle r^2_{J/\psi(1S)} \rangle$

pQCD model calculations predicts R ~ 0.17 (PhP) and rise of R with $Q^2$ (DIS)

# Investigated channels and samples

$\psi(2S) \rightarrow J/\psi(1S)\, \pi^+ \pi^-;\ J/\psi(1S) \rightarrow \mu^+ \mu^-$

$\psi(2S) \rightarrow \mu^+ \mu^-$

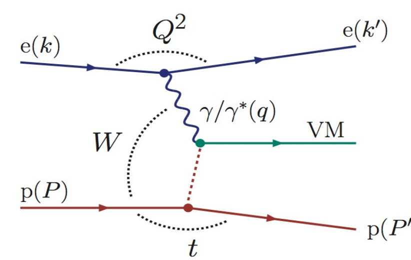
$J/\psi(1S) \rightarrow \mu^+ \mu^-$

## Data samples

HERA I + HERA II data (1996 — 2007)

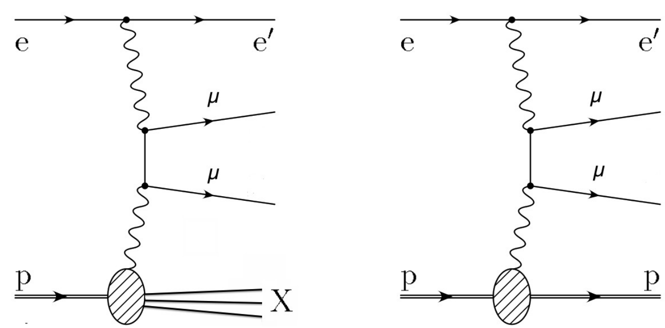
Integrated luminosity: 468 $pb^{-1}$

## MC-data samples




Signal MC: DIFFVM for exclusive VM production

Background MC: GRAPE for Bethe–Heitler mu–pair production

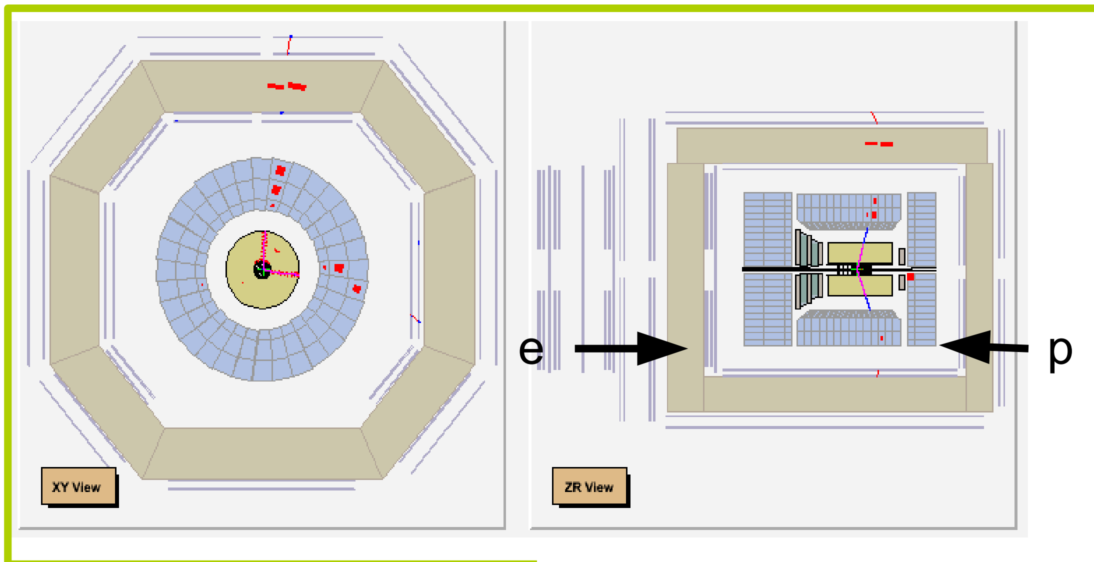


# Selection criteria

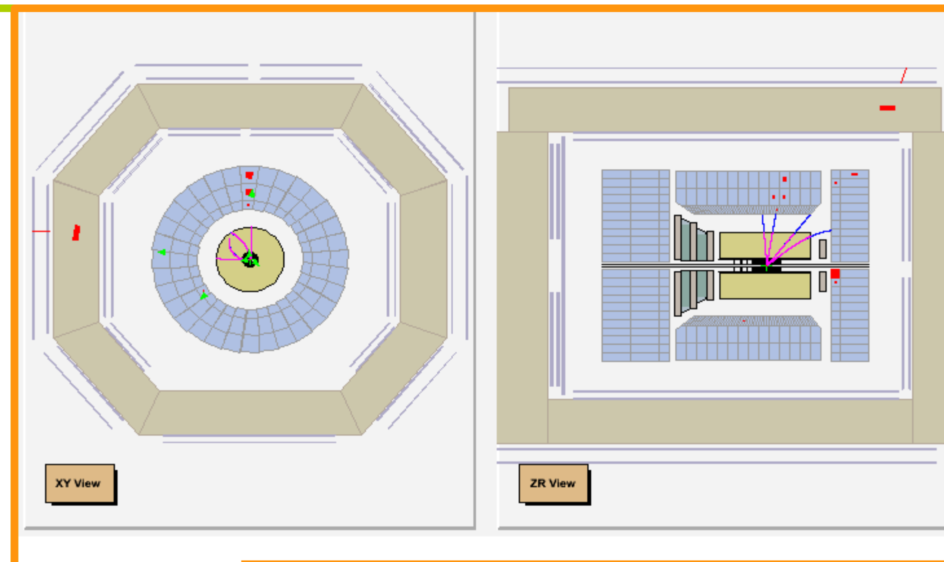
- Scattered *e* with E > 10 GeV reconstructed in CAL
- Scattered *p* undetected
- Two reconstructed tracks identified as muons

  and for $\psi(2S) \rightarrow J/\psi(1S)\,\pi^+\pi^-$ additionally two pion tracks from μμ vertex
- Nothing else in detector (above noise)

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

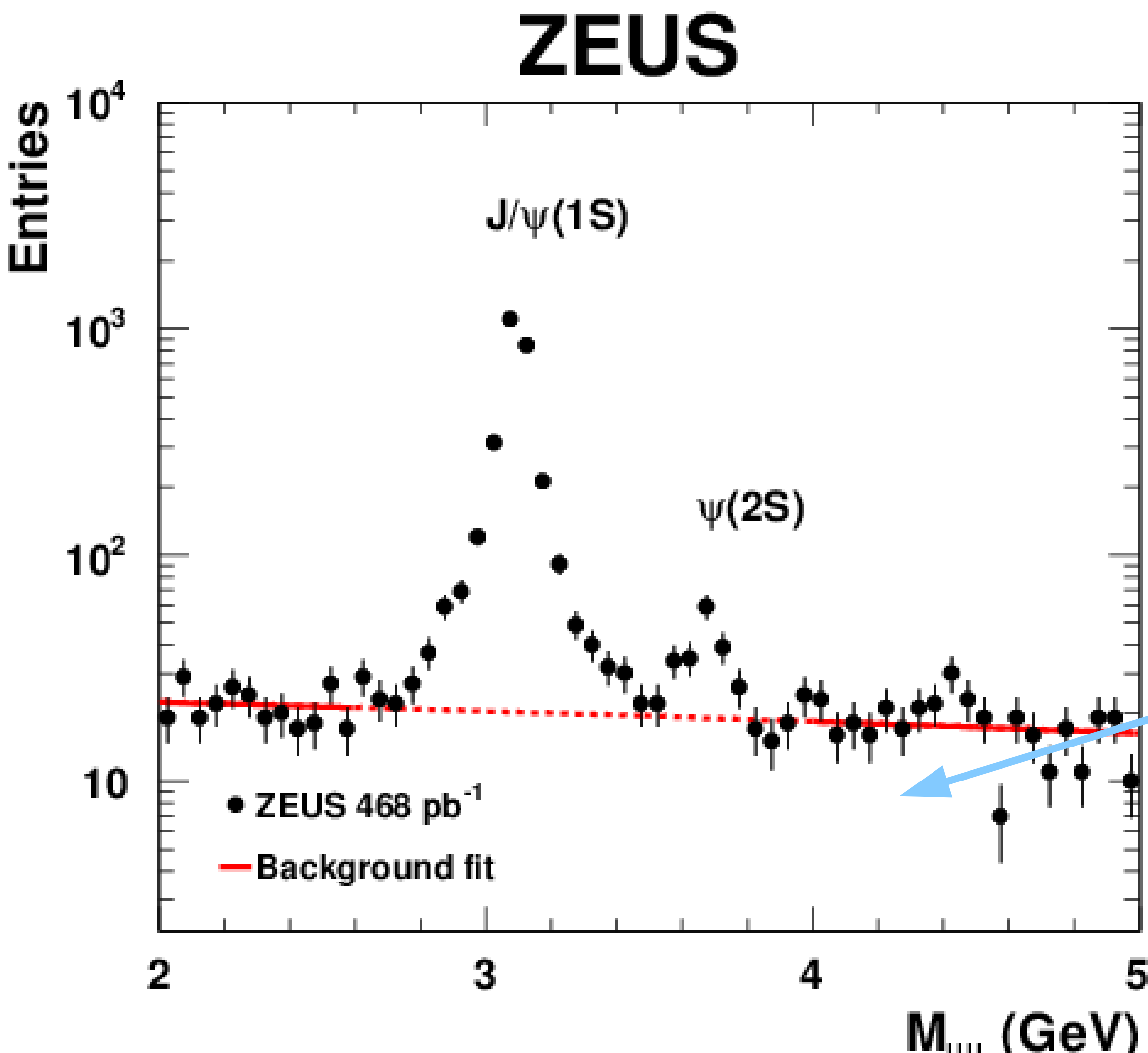



$J/\psi(1S) \rightarrow \mu^+\mu^-$



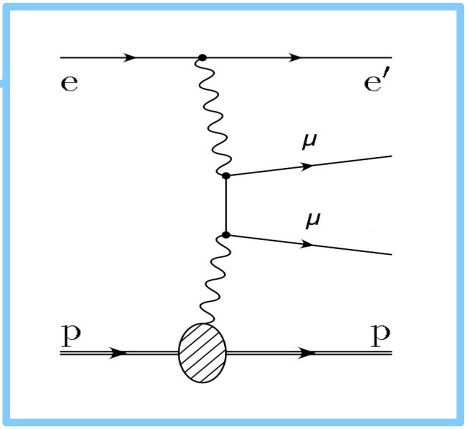

$\psi(2S) \rightarrow J/\psi(1S)\,\pi^+\pi^-$

# Background subtraction



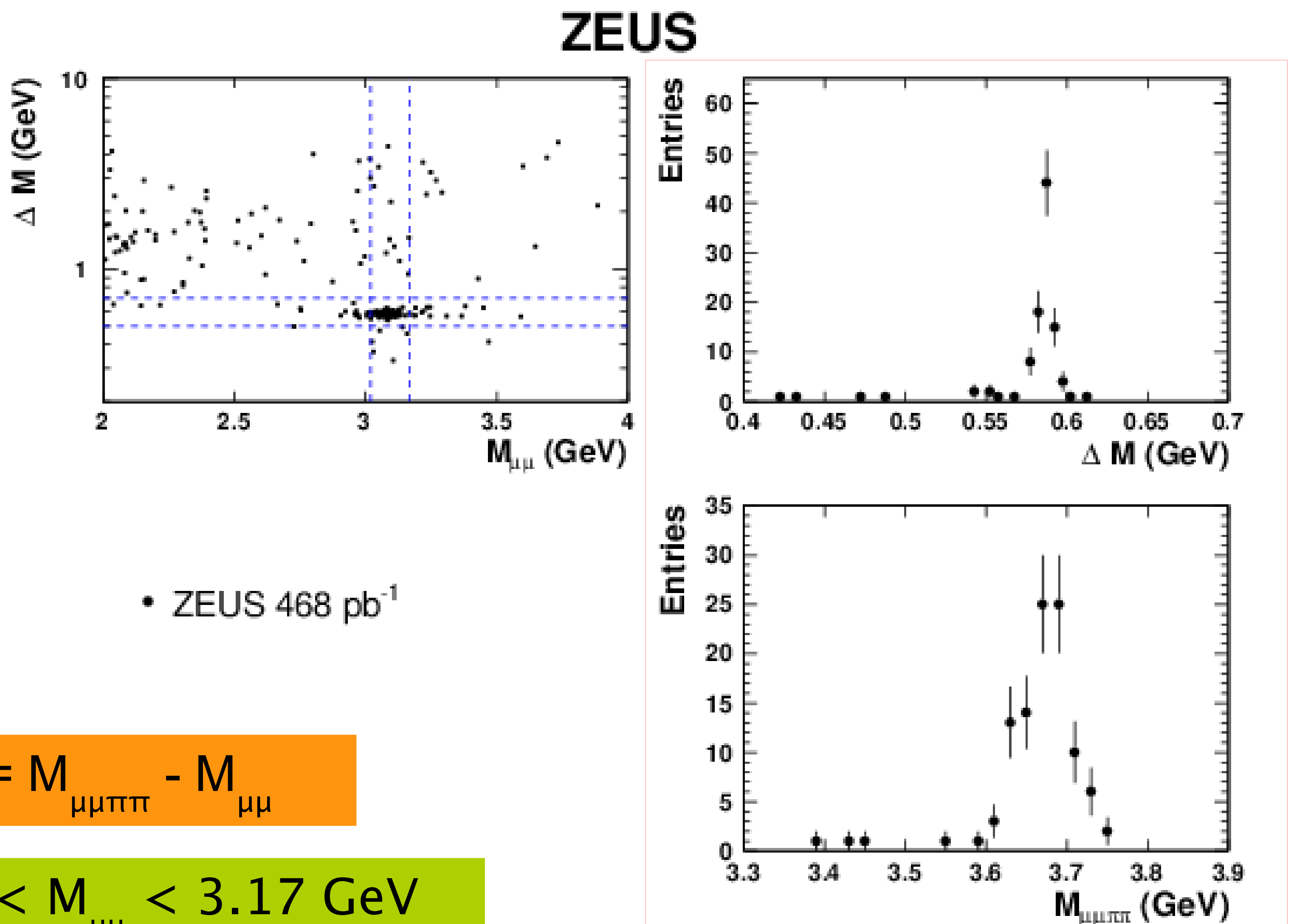

$J/\psi(1S) \rightarrow \mu^+\mu^-$

$\psi(2S) \rightarrow \mu^+\mu^-$




Sideband of the signal: $2.00 < M_{\mu\mu} < 2.62$ GeV and $4.05 < M_{\mu\mu} < 5.00$ GeV fitted by straight line

# $\psi(2S) \rightarrow J/\psi(1S)\ \pi^+\ \pi^-$




$\Delta M = M_{\mu\mu\pi\pi} - M_{\mu\mu}$

$3.02 < M_{\mu\mu} < 3.17$ GeV

$0.5 < \Delta M < 0.7$ GeV

After cut on $M_{\mu\mu}$

$\leq$ 3 events background

# $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ estimation

$$R_{J/\psi\pi\pi} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S)\to\mu^+\mu^-}}{Acc_{\psi(2S)\to J/\psi\pi^+\pi^-}} \cdot \frac{1}{BR_{\psi(2S)\to J/\psi\pi^+\pi^-}}$$

$$R_{\mu\mu} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S)\to\mu^+\mu^-}}{Acc_{\psi(2S)\to\mu^+\mu^-}} \cdot \frac{BR_{J/\psi(1S)\to\mu^+\mu^-}}{BR_{\psi(2S)\to\mu^+\mu^-}}$$

$$Acc_i = \frac{N_i^{reco}}{N_i^{true}}$$

| |
|---|
| BR($\psi(2S)\to J/\psi(1S)\pi^+\pi^-$) = (33.6 ± 0.4) % |
| BR($\psi(2S)\to\mu^+\mu^-$) = (7.7 ± 0.8)x$10^{-3}$ |
| BR($J/\psi(1S)\to\mu^+\mu^-$) = (5.93 ± 0.06)% |

# Results

| | |
|---|---|
| $R_{J/\psi\pi\pi}$ | $0.26 \pm 0.03^{+0.01}_{-0.01}$ |
| $R_{\mu\mu}$ | $0.24 \pm 0.05^{+0.02}_{-0.03}$ |
| $R_{\text{comb}}$ | $0.26 \pm 0.02^{+0.01}_{-0.01}$ |
| $R_{\psi(2S)}$ | $1.1 \pm 0.2^{+0.2}_{-0.1}$ |

30 ≤ W ≤ 210 GeV
2 ≤ $Q^2$ ≤ 80 $GeV^2$
|t| ≤ 1 $GeV^2$

$$R_{\psi(2S)} = R_{J/\psi\,\pi\pi}/R_{\mu\mu}$$

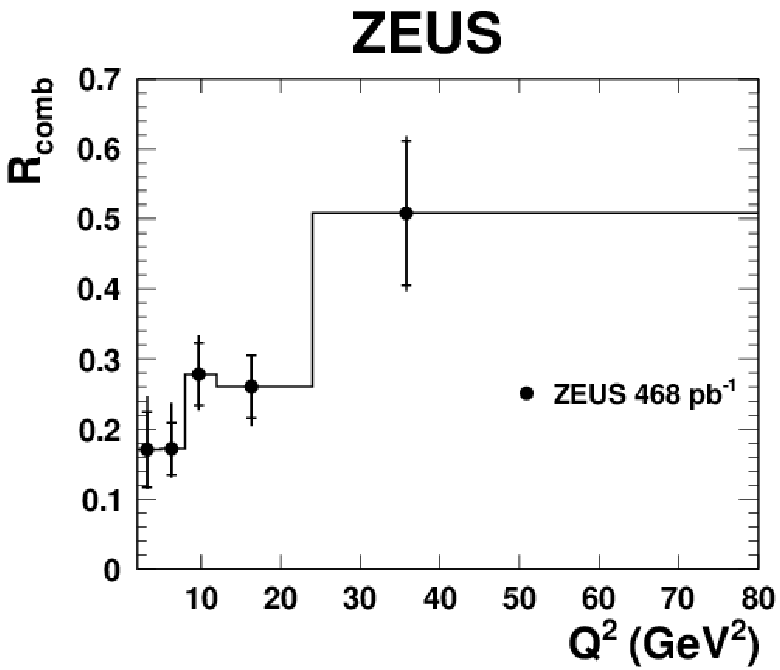
| $Q^2$ ($\text{GeV}^2$) | $R_{J/\psi\pi\pi}$ | $R_{\mu\mu}$ | $R_{\text{comb}}$ | $R_{\psi(2S)}$ |
|---|---|---|---|---|
| 2 – 5 | $0.21 \pm 0.07^{+0.04}_{-0.03}$ | $0.10 \pm 0.09^{+0.09}_{-0.09}$ | $0.17 \pm 0.05^{+0.05}_{-0.02}$ | – |
| 5 – 8 | $0.19 \pm 0.05^{+0.02}_{-0.02}$ | $0.13 \pm 0.06^{+0.12}_{-0.03}$ | $0.17 \pm 0.04^{+0.05}_{-0.02}$ | $1.5 \pm 0.8^{+0.4}_{-0.7}$ |
| 8 – 12 | $0.27 \pm 0.05^{+0.06}_{-0.01}$ | $0.29 \pm 0.08^{+0.03}_{-0.08}$ | $0.28 \pm 0.05^{+0.03}_{-0.03}$ | $0.9 \pm 0.3^{+0.4}_{-0.1}$ |
| 12 – 24 | $0.27 \pm 0.05^{+0.04}_{-0.03}$ | $0.24 \pm 0.08^{+0.01}_{-0.08}$ | $0.26 \pm 0.05^{+0.01}_{-0.03}$ | $1.1 \pm 0.4^{+0.6}_{-0.1}$ |
| 24 – 80 | $0.56 \pm 0.13^{+0.04}_{-0.09}$ | $0.42 \pm 0.17^{+0.12}_{-0.04}$ | $0.51 \pm 0.10^{+0.04}_{-0.04}$ | $1.3 \pm 0.6^{+0.3}_{-0.6}$ |

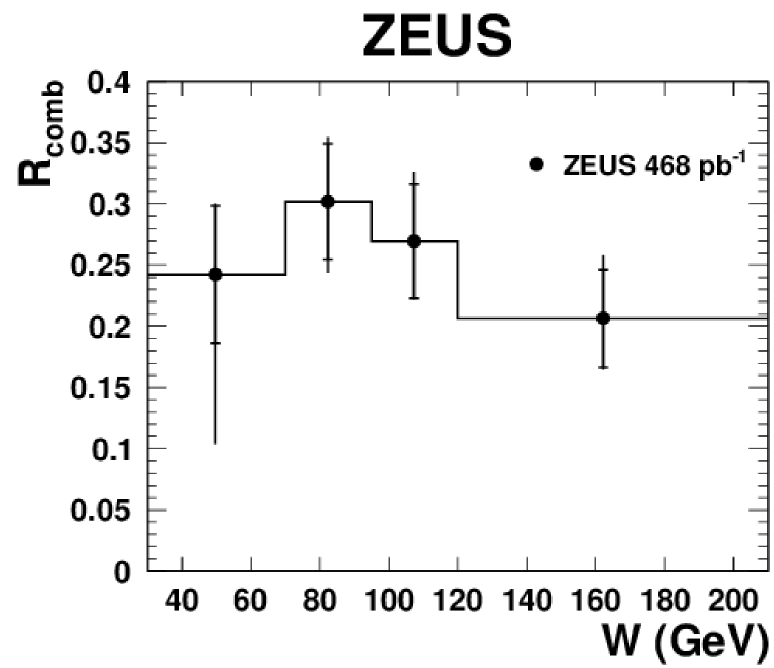
| $W$ (GeV) | $R_{J/\psi\pi\pi}$ | $R_{\mu\mu}$ | $R_{\text{comb}}$ | $R_{\psi(2S)}$ |
|---|---|---|---|---|
| 30 – 70 | $0.24 \pm 0.07^{+0.01}_{-0.13}$ | $0.24 \pm 0.10^{+0.03}_{-0.14}$ | $0.24 \pm 0.06^{+0.01}_{-0.13}$ | $1.0 \pm 0.5^{+0.5}_{-0.2}$ |
| 70 – 95 | $0.30 \pm 0.06^{+0.01}_{-0.04}$ | $0.31 \pm 0.09^{+0.09}_{-0.03}$ | $0.30 \pm 0.05^{+0.02}_{-0.03}$ | $1.0 \pm 0.3^{+0.1}_{-0.2}$ |
| 95 – 120 | $0.28 \pm 0.06^{+0.05}_{-0.01}$ | $0.24 \pm 0.08^{+0.04}_{-0.05}$ | $0.27 \pm 0.05^{+0.03}_{-0.01}$ | $1.2 \pm 0.5^{+0.5}_{-0.2}$ |
| 120 – 210 | $0.22 \pm 0.05^{+0.07}_{-0.01}$ | $0.17 \pm 0.07^{+0.02}_{-0.05}$ | $0.21 \pm 0.04^{+0.03}_{-0.01}$ | $1.3 \pm 0.6^{+0.7}_{-0.2}$ |

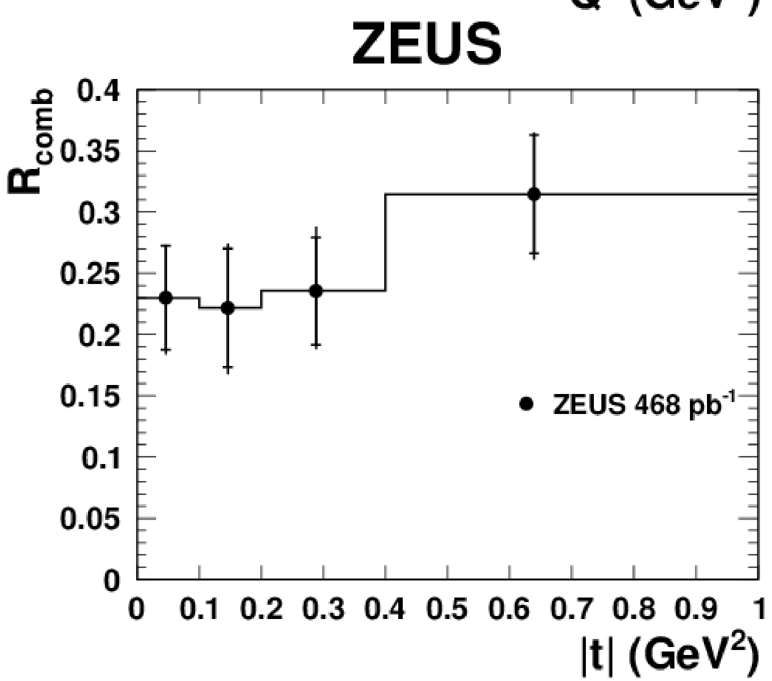
| $\|t\|$ ($\text{GeV}^2$) | $R_{J/\psi\pi\pi}$ | $R_{\mu\mu}$ | $R_{\text{comb}}$ | $R_{\psi(2S)}$ |
|---|---|---|---|---|
| 0 – 0.1 | $0.23 \pm 0.05^{+0.02}_{-0.02}$ | $0.23 \pm 0.09^{+0.04}_{-0.05}$ | $0.23 \pm 0.04^{+0.01}_{-0.02}$ | $1.0 \pm 0.4^{+0.3}_{-0.2}$ |
| 0.1 – 0.2 | $0.22 \pm 0.06^{+0.02}_{-0.03}$ | $0.23 \pm 0.09^{+0.02}_{-0.06}$ | $0.22 \pm 0.05^{+0.02}_{-0.02}$ | $0.9 \pm 0.4^{+0.5}_{-0.2}$ |
| 0.2 – 0.4 | $0.27 \pm 0.06^{+0.06}_{-0.01}$ | $0.18 \pm 0.07^{+0.05}_{-0.06}$ | $0.24 \pm 0.04^{+0.03}_{-0.02}$ | $1.5 \pm 0.6^{+0.5}_{-0.2}$ |
| 0.4 – 1 | $0.32 \pm 0.06^{+0.05}_{-0.03}$ | $0.30 \pm 0.08^{+0.02}_{-0.05}$ | $0.32 \pm 0.05^{+0.01}_{-0.02}$ | $1.1 \pm 0.3^{+0.3}_{-0.1}$ |

Consistent results

# $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ vs $Q^2$, W and |t|

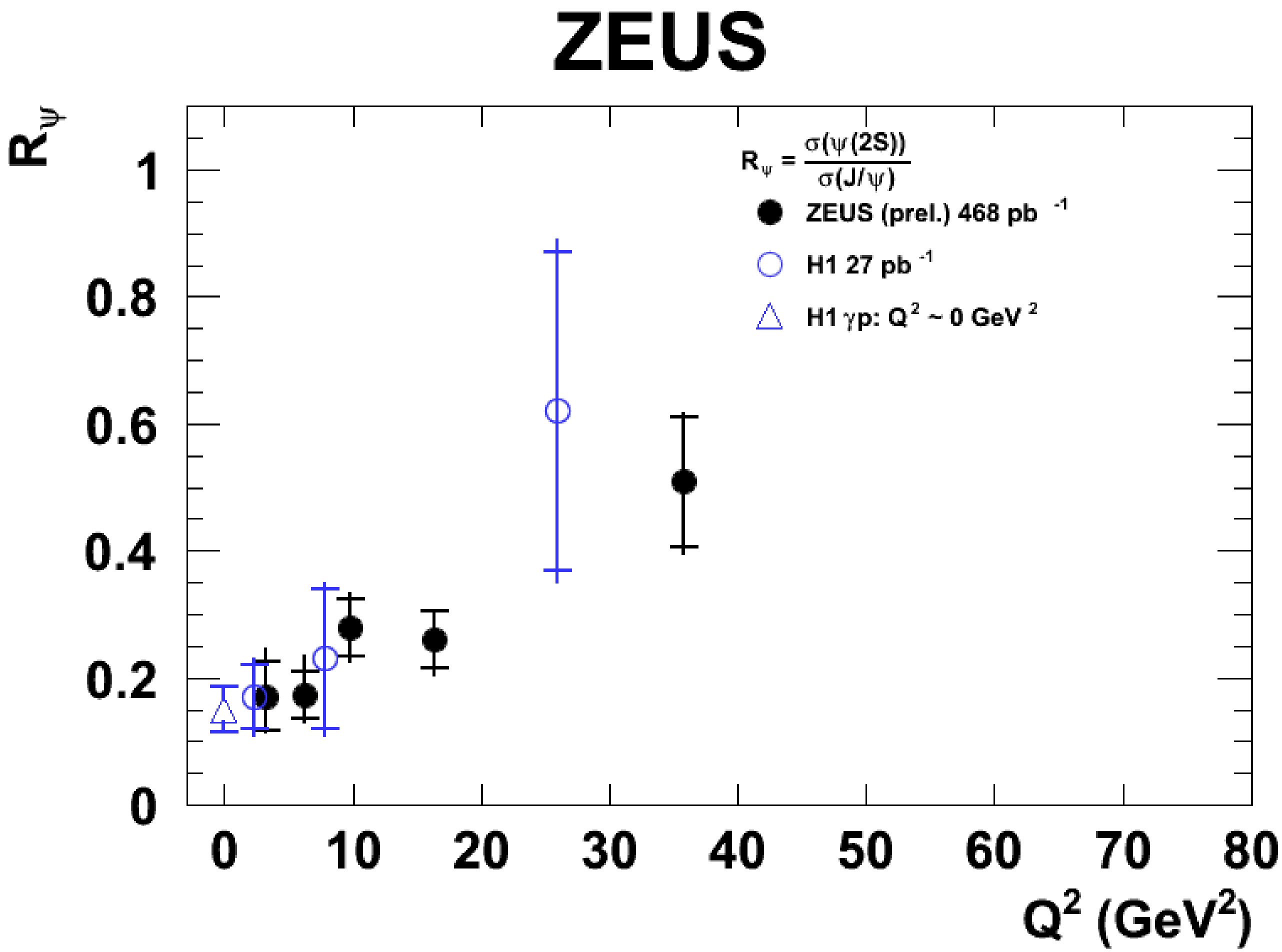



- Indication of an increase with $Q^2$
- Independent of W
- Independent of |t|

# ZEUS — H1 comparison

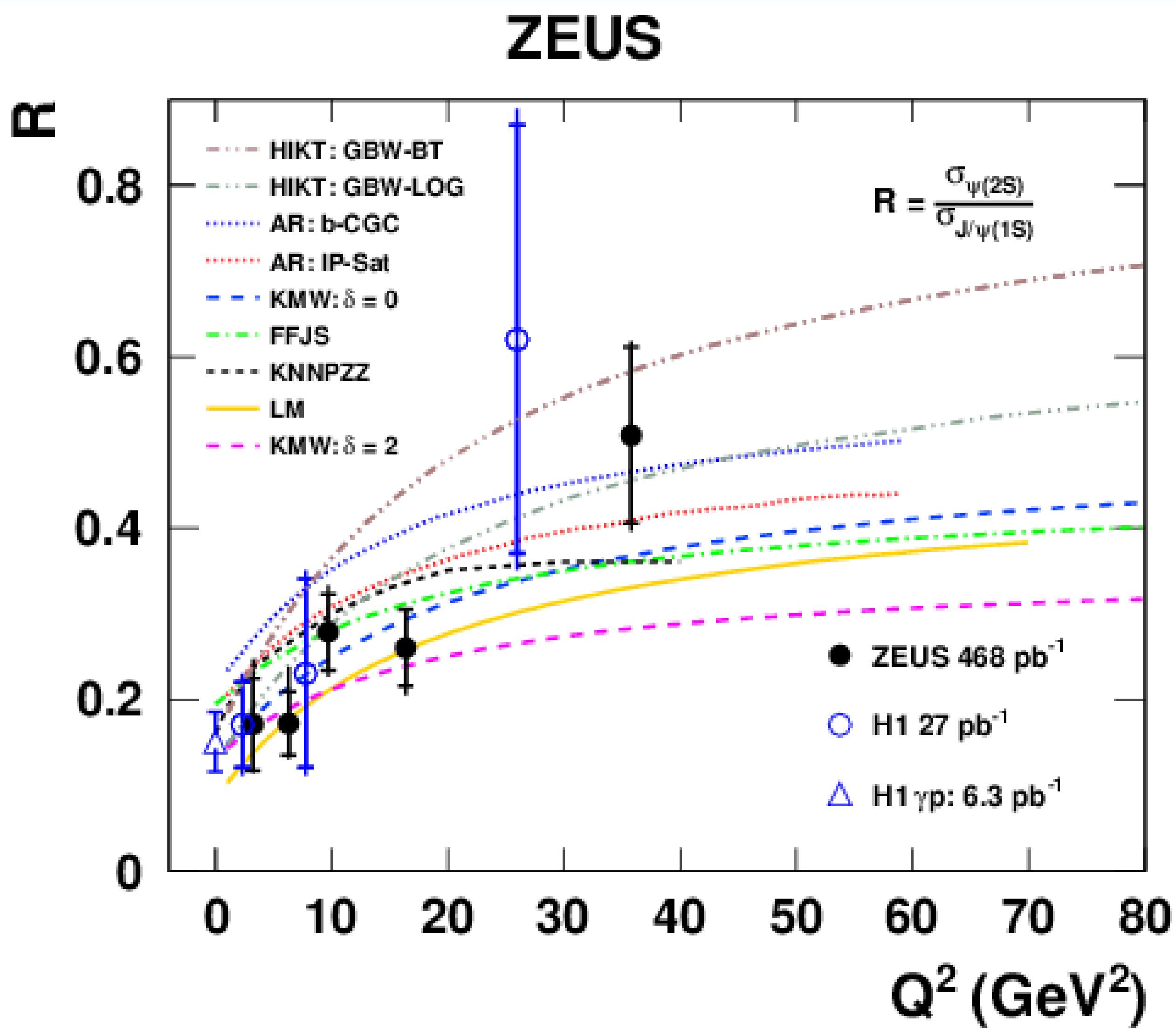



**H1 collaboration:**

**Eur.Phys.J.C10:373-393,1999**

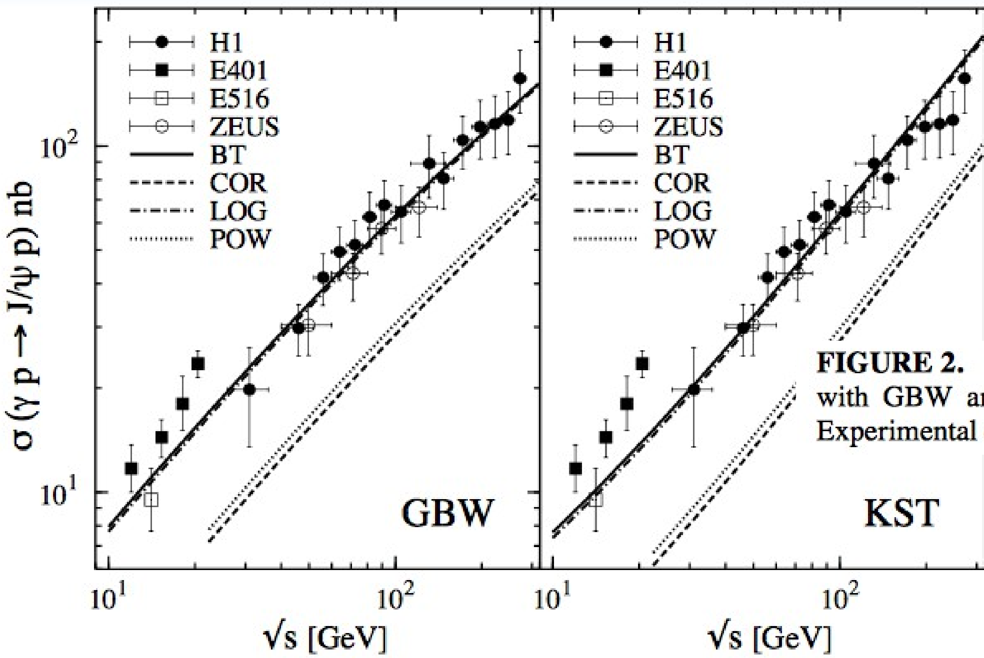
Results agree - $\sigma(\psi(2S))/\sigma(J/\psi(1S))$ increases with $Q^2$
Improved accuracy thanks to increased integrated luminosity

# Model predictions



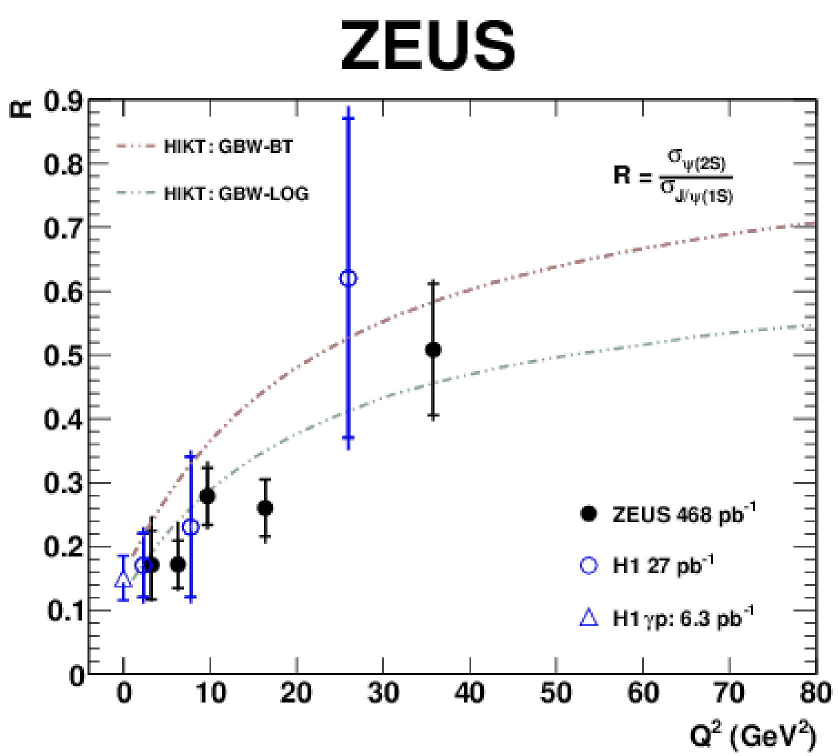

All models exhibit an increase of $\sigma(\psi(2S))/\sigma(J/\psi(1S))$ with increasing $Q^2$

# HIKT calculations




arXiv:hep-ph/0212322

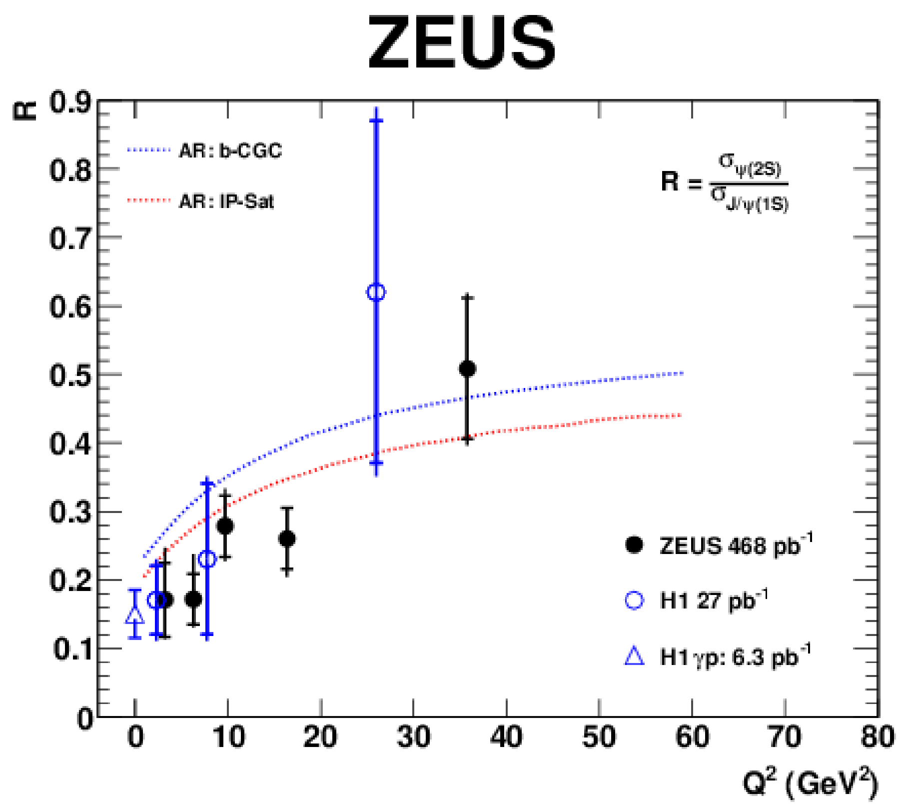
**FIGURE 2.** Integrated cross section for elastic photoproduction with real photons ($Q^2 = 0$) calculated with GBW and KST dipole cross sections and for four potentials to generate $J/\psi$ wave functions. Experimental data points from the H1 [20], E401 [21], E516 [22] and ZEUS [23] experiments.




**HIKT —** from Huefner et al., use two different form for the dipole cross section calculation and four different potentials to calculate the wave functions; BT and LOG use $m_c \approx 1.5$GeV, COR and POW use $m_c \approx 1.8$GeV

The predicted ratio values for the BT model are significantly larger compare to measured data

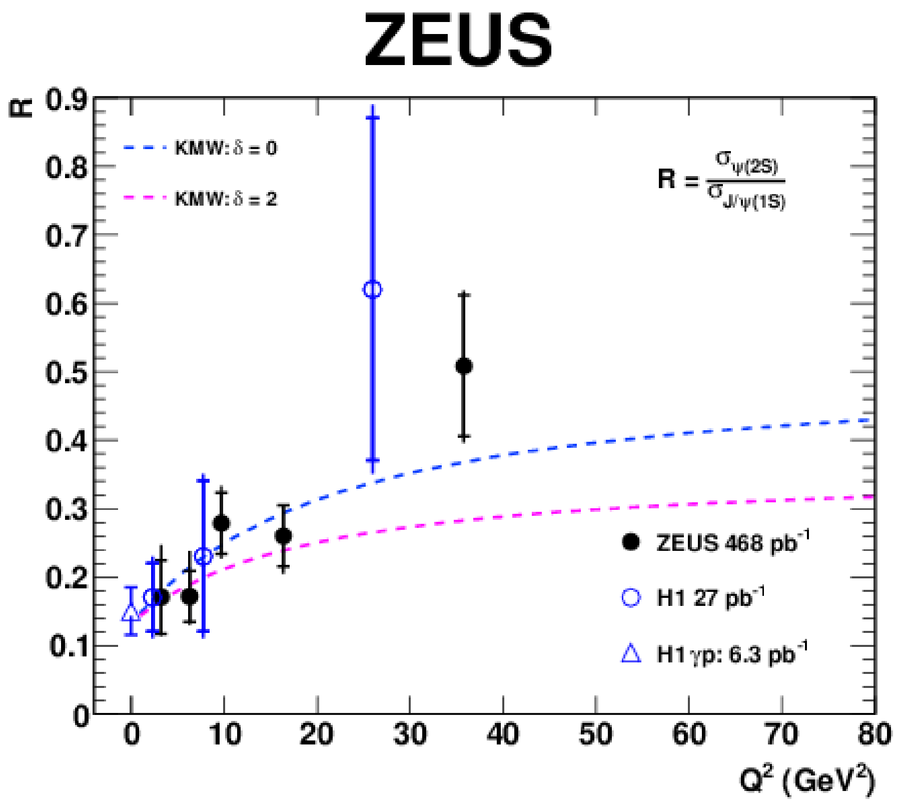
# AR calculations




The IP-Sat prediction is about 20% lower than that for b-CGC and gives a better description of the data

**AR —** from Armesto and Rezaeian,
calculate the dipole cross section using the Impact-Parameter dependent Color Glass Condensate (b-CGC) and the Saturation (IP-Sat) models

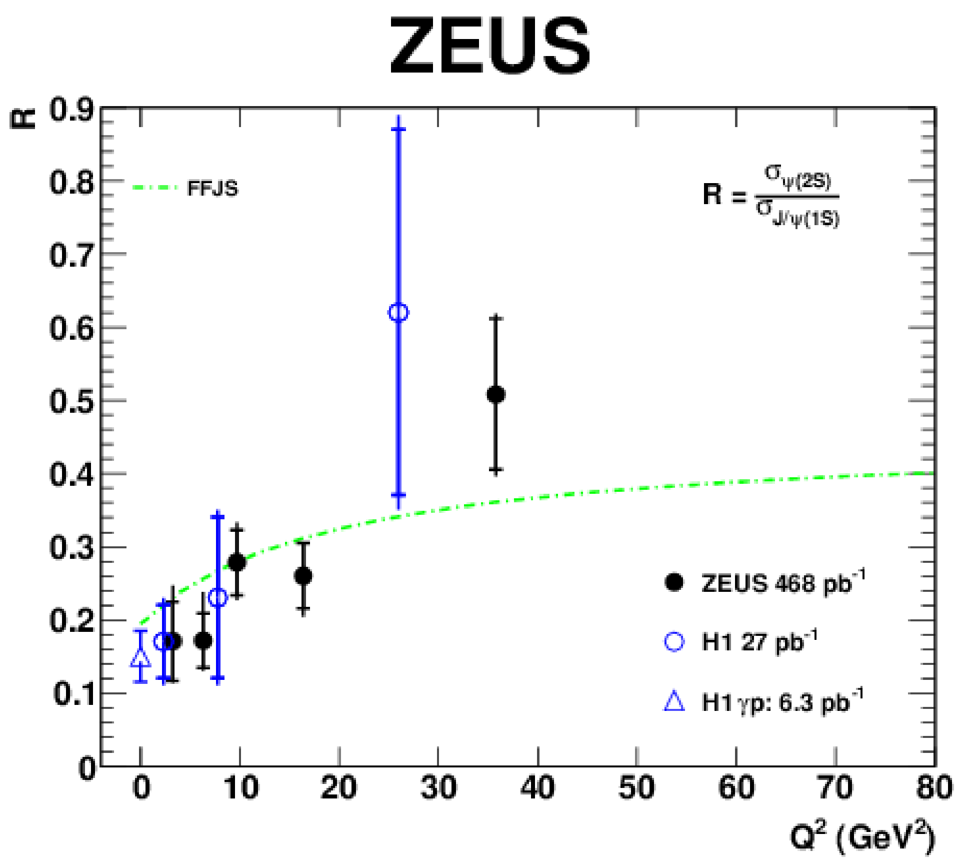
# KMW calculations




The prediction with δ = 0 gives a good description of the data and the prediction with δ = 2 is below the measured values at higer $Q^2$

**KMW** — from Kowalski, Motyka, Watt,
based on the QCD description and an assumption of universality of the quarkonia production mechanism
δ = 0 for non-relativistic wave functions
δ = 2 for relativistic boosted Gaussian model

# FFJS calculations

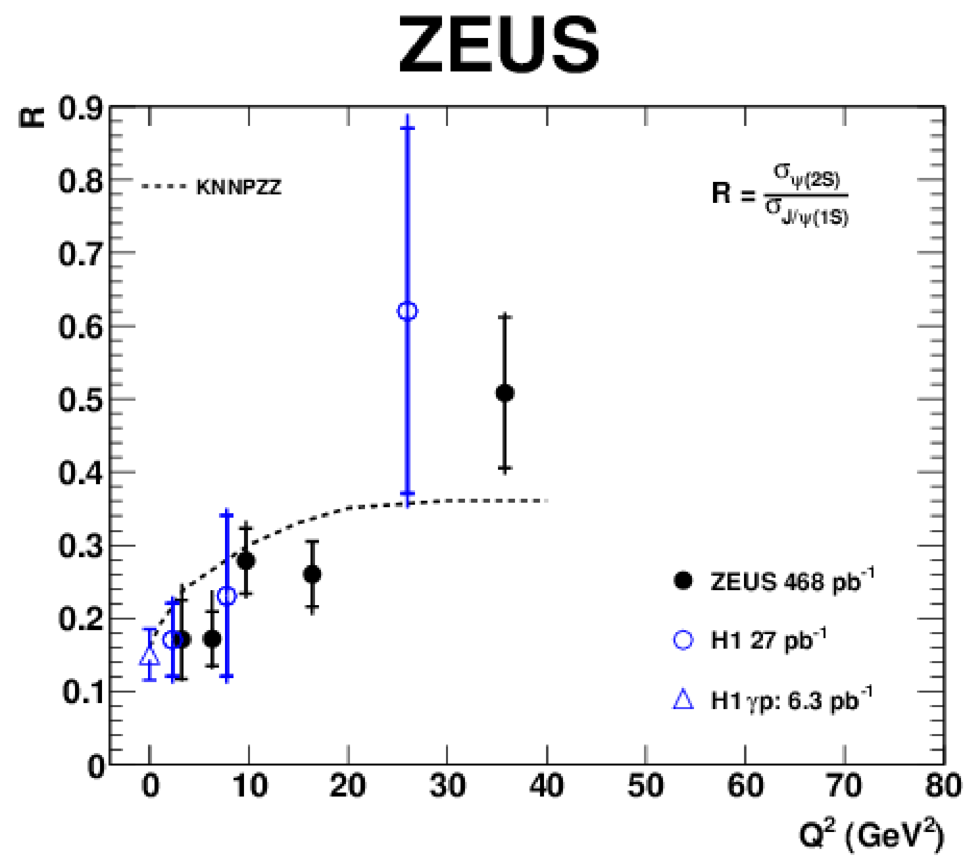



Describe the data reasonably well

**FFJS** — from Fazio et al.,
use a two component Pomeron model to predict the cross sections for VM production

# KNNPZZ calculations

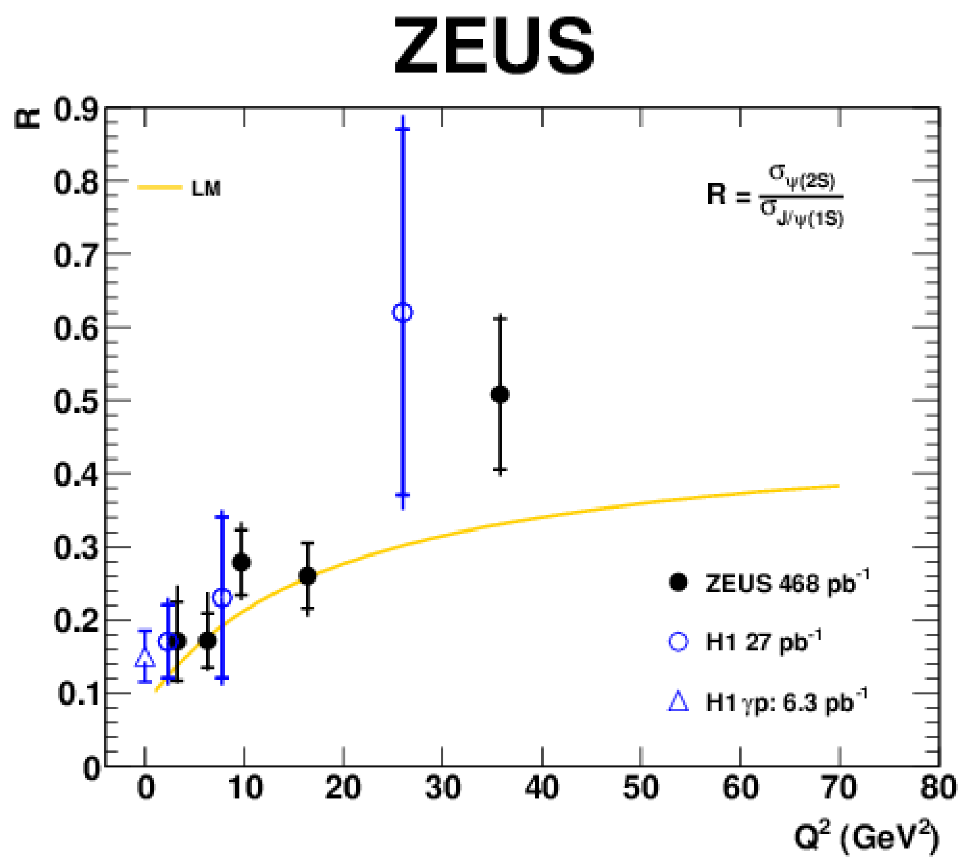
The model used in original H1 publication




Describe the data well

**KNNPZZ** — from Nemchik et al.,
describe the BFKL pomeron in terms of the colour-dipole cross section which is a solution of the generalised BFKL equations

# LM calculations




Good description of the data

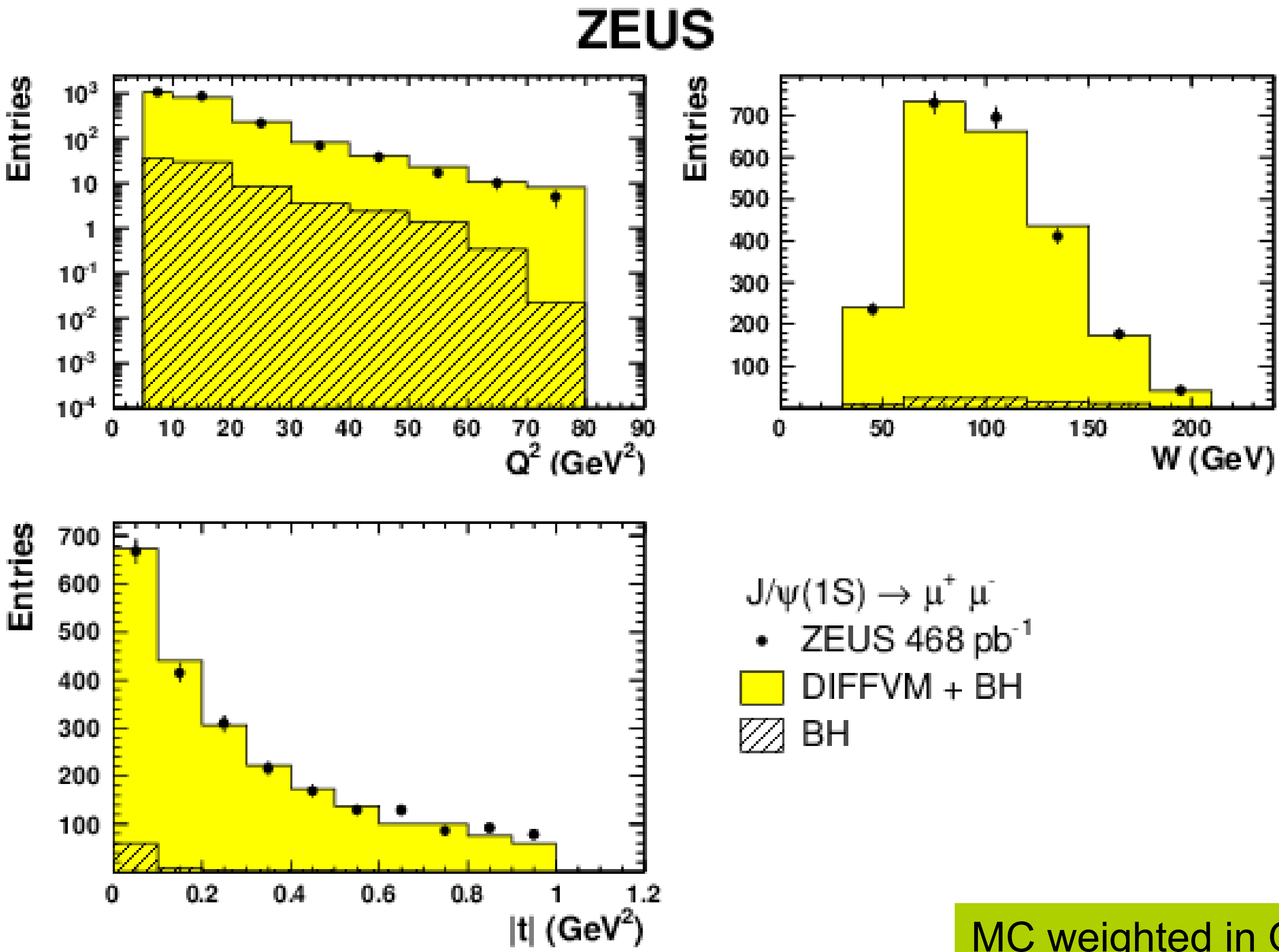
**LM** — from Lappi and Mäntysaari,
use dipole picture in the IP-Sat model to predict VM production

# Summary

- The pQCD prediction of σ(ψ(2S))/σ(J/ψ(1S)) ratio rise with $Q^2$ and is proved
- The accuracy of the result has been improved compared to the H1 HERA I results
- σ(ψ(2S))/σ(J/ψ(1S)) ratio is compared with models of VM production, some discrimination of the different models is possible
- σ(ψ(2S))/σ(J/ψ(1S)) independent of W and |t|
- arXiv:1601.03699

Thank you for your attention!

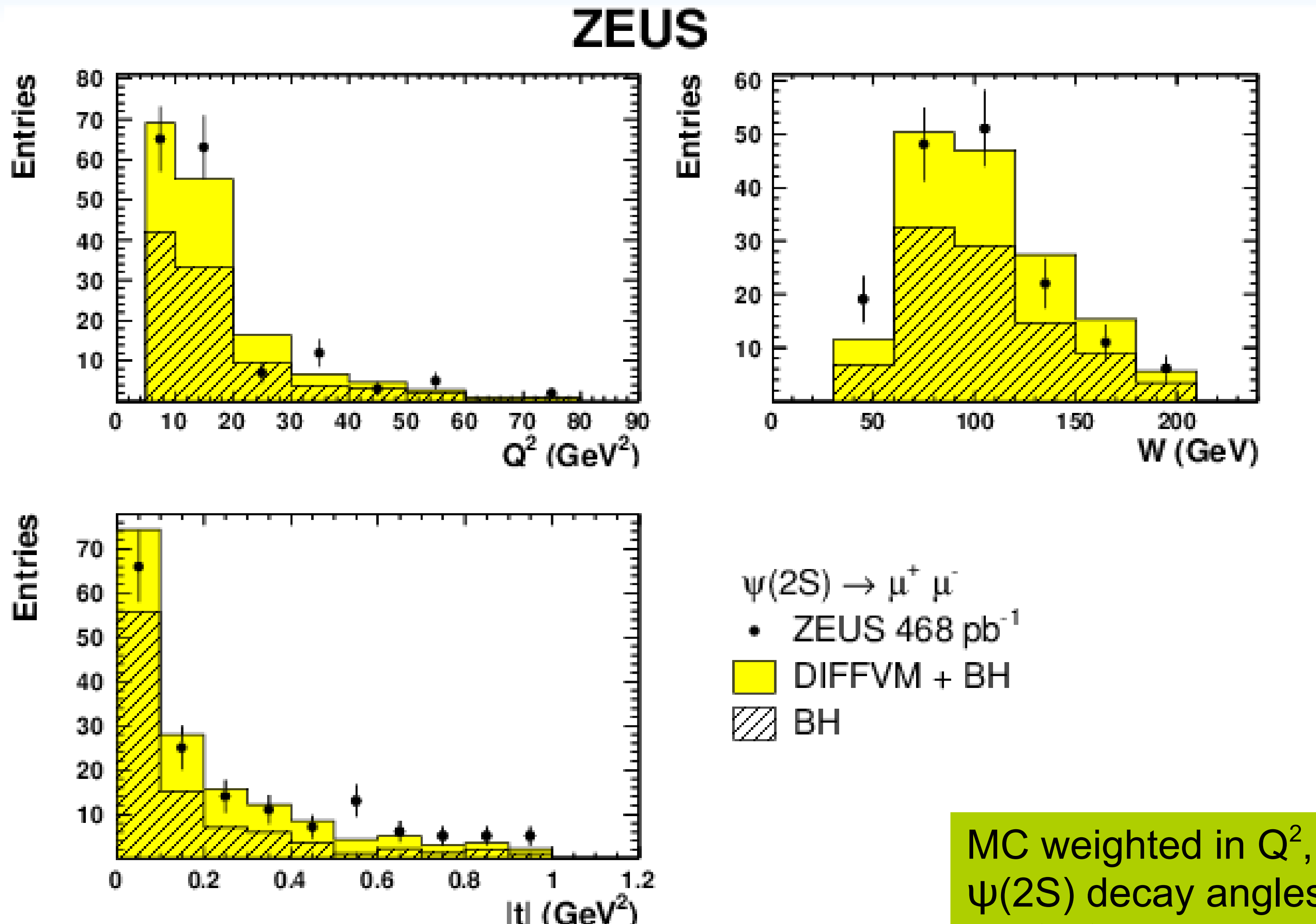
# Backup: Data-MC comparison for J/ψ(1S)




MC weighted in $Q^2$, |t| and J/ψ decay angles to match the data

Good description of the data by the weighted Monte Carlo

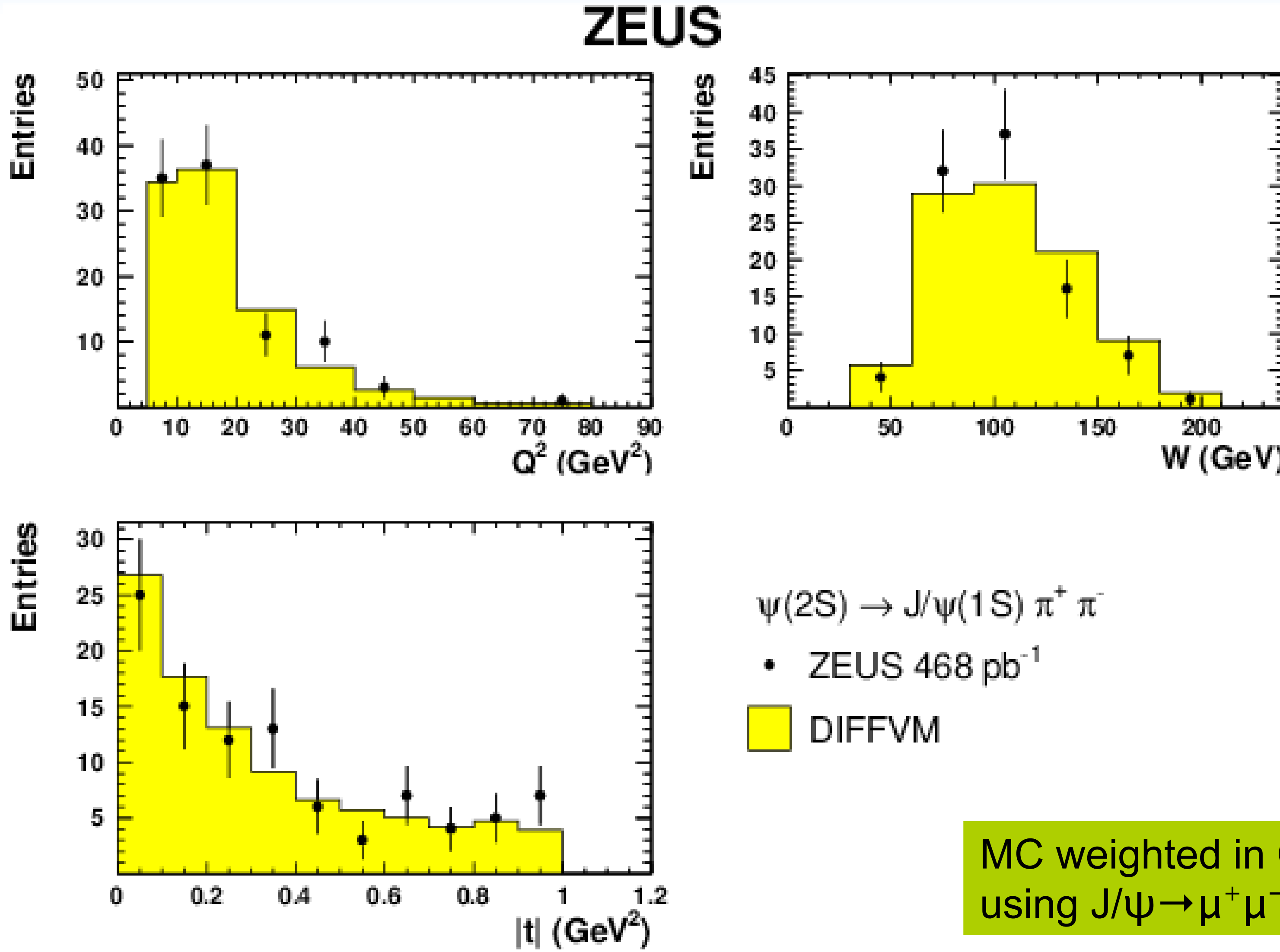
# Backup: Data-MC comparison for $\psi(2S) \rightarrow \mu^+\mu^-$




MC weighted in $Q^2$, |t| and $\psi(2S)$ decay angles using $J/\psi(1S) \rightarrow \mu^+\mu^-$ weights

Good description of the data by the weighted Monte Carlo

# Backup: Data-MC comparison for $\psi(2S) \rightarrow J/\psi(1S)\ \pi^+\pi^-$




MC weighted in $Q^2$ and |t| using $J/\psi \rightarrow \mu^+\mu^-$ weights

Good description of the data by the weighted Monte Carlo