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

[arXiv:1601.03699]

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HERA and ZEUS

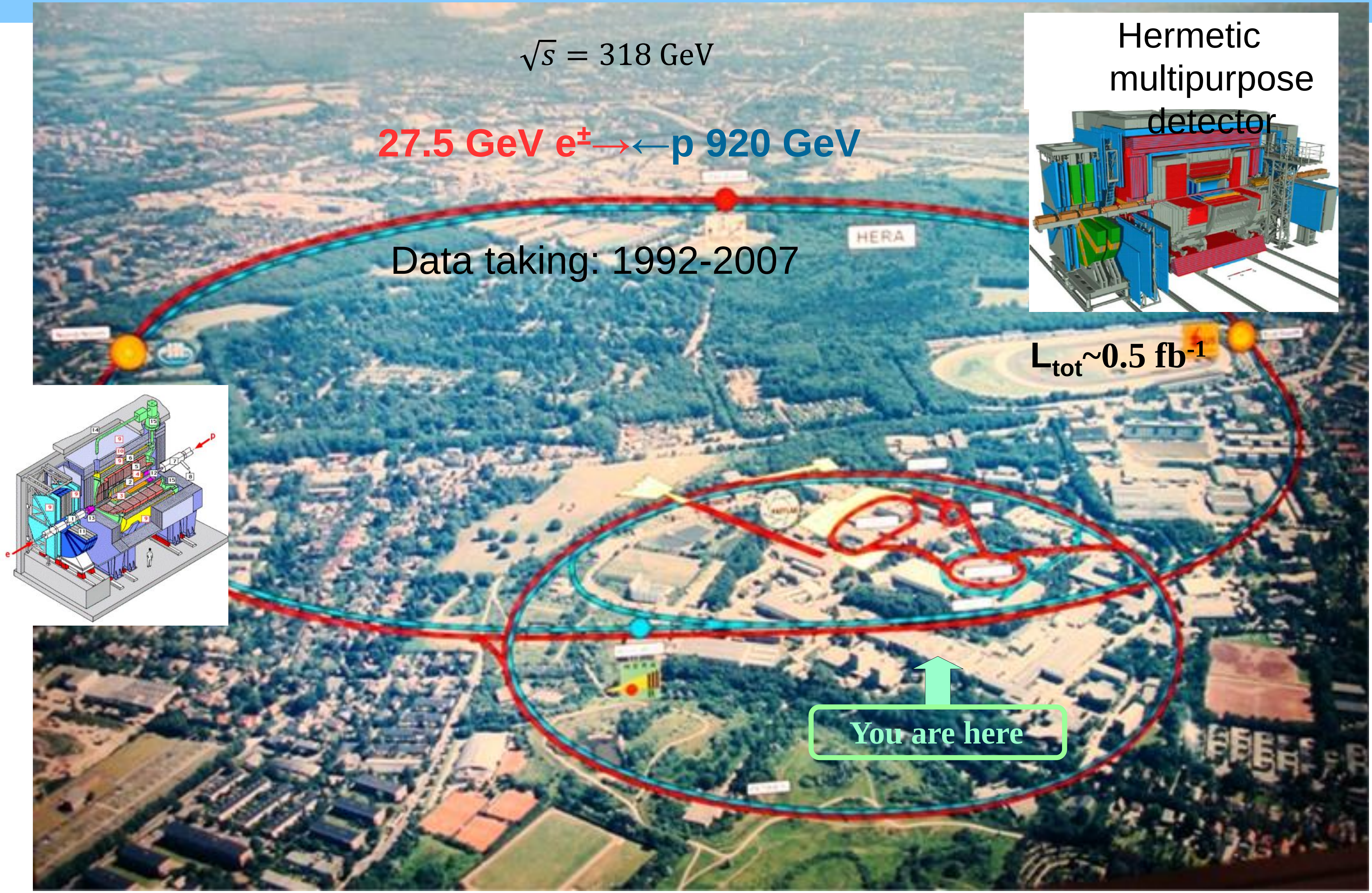
$\sqrt{s} = 318\ \text{GeV}$

27.5 GeV e$^{\pm}$→←p 920 GeV

Data taking: 1992-2007

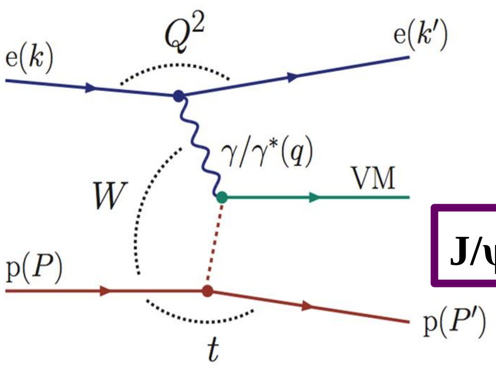
Hermetic multipurpose detector

L_{tot}~0.5 fb^{-1}



Diffractive vector meson (VM) production at HERA

elastic (exclusive)



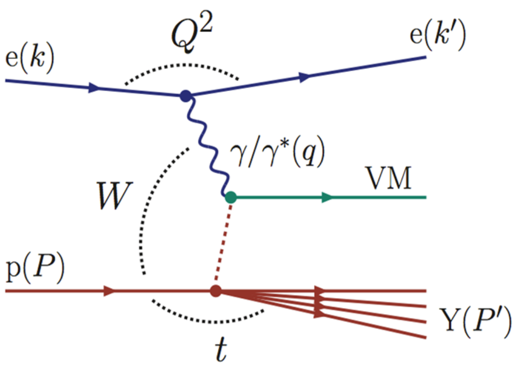
light

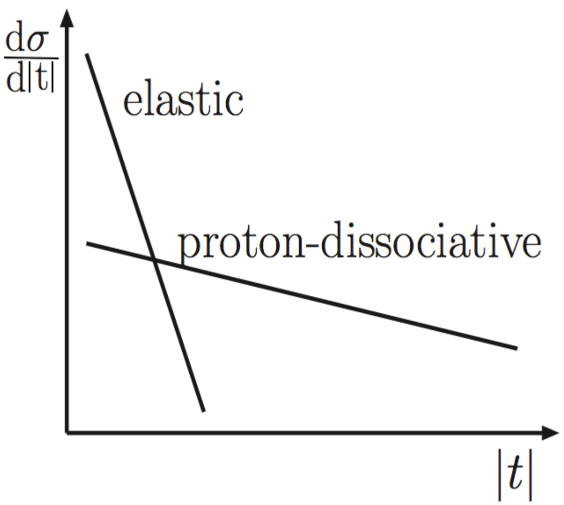
ρ, ω, φ

heavy

J/ψ(1S), ψ(2S), ϒ

proton-dissociative





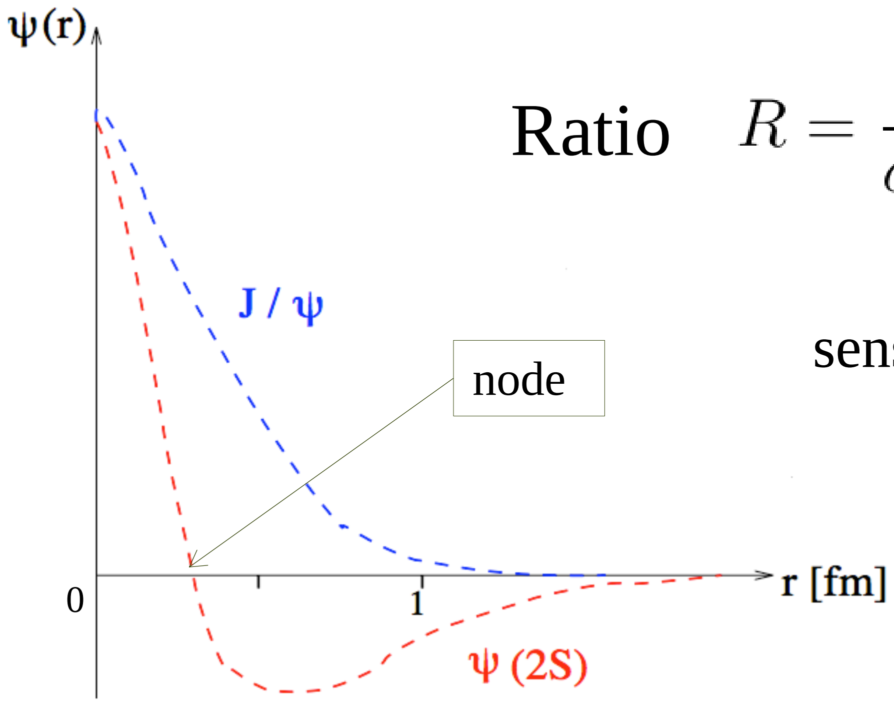
Kinematics of the process

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 the proton vertex $t = (P - P')^2$

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



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

sensitive to radial wave function of charmonium

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

- 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

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

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

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

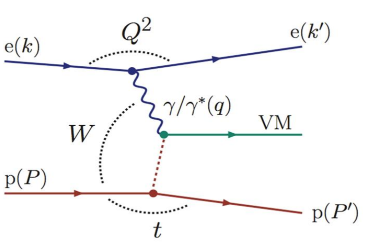
Data samples

HERA I + HERA II data (1996 — 2007)

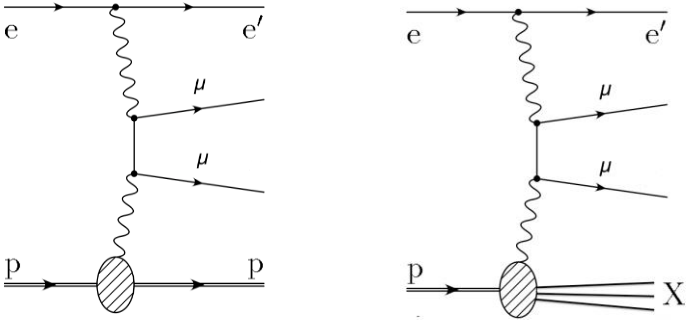
Integrated luminosity: 468 pb^{-1}

MC-data samples

Signal MC: DIFFVM for exclusive VM production



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



Selection criteria

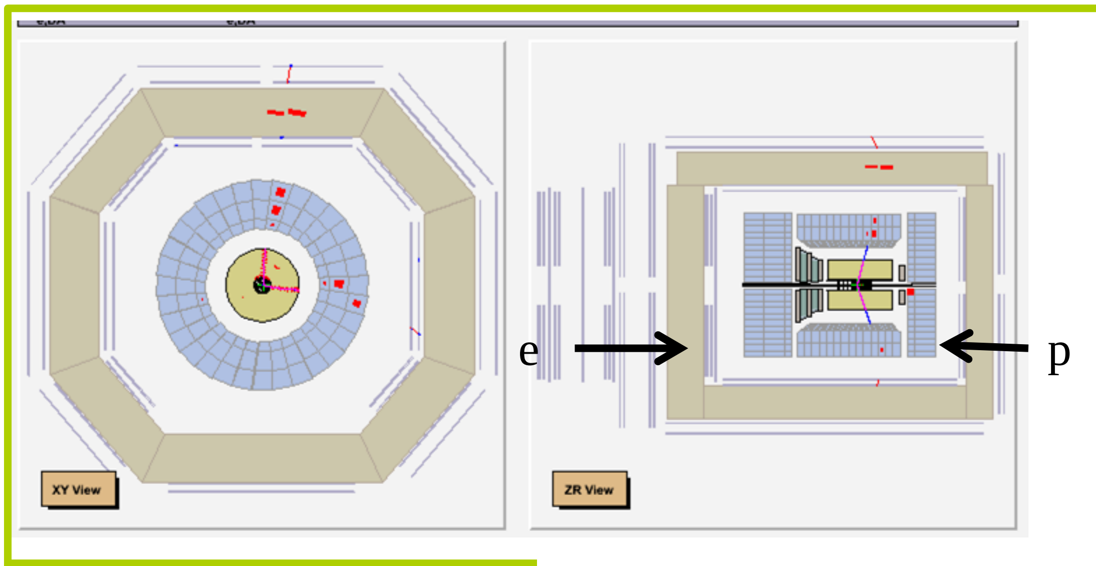
- Scattered *e* with E > 10 GeV reconstructed in CAL
- Scattered *p* undetected
- Two reconstructed tracks identified as muons

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

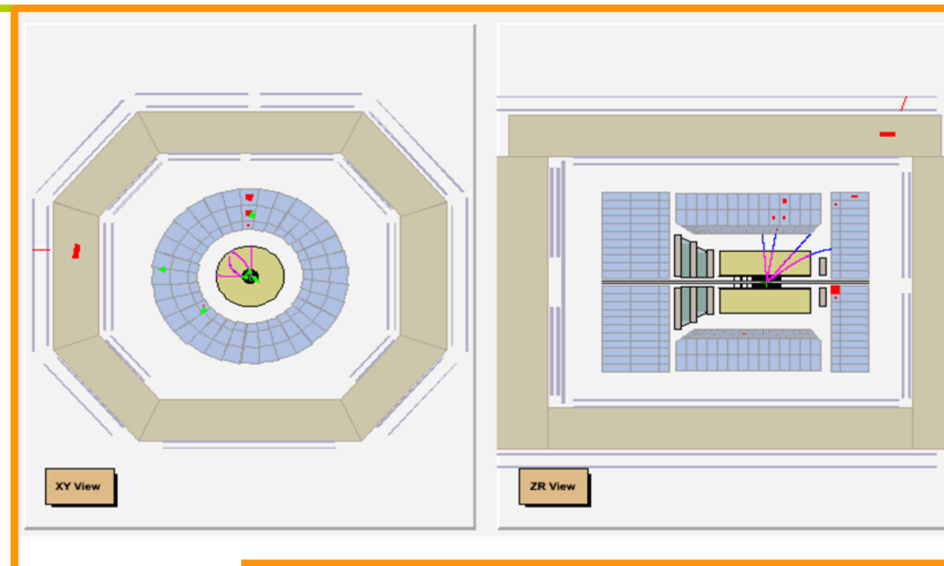
$30 \leq W \leq 210$ GeV

$2 \leq Q^2 \leq 80$ GeV^2

$|t| \leq 1$ GeV^2

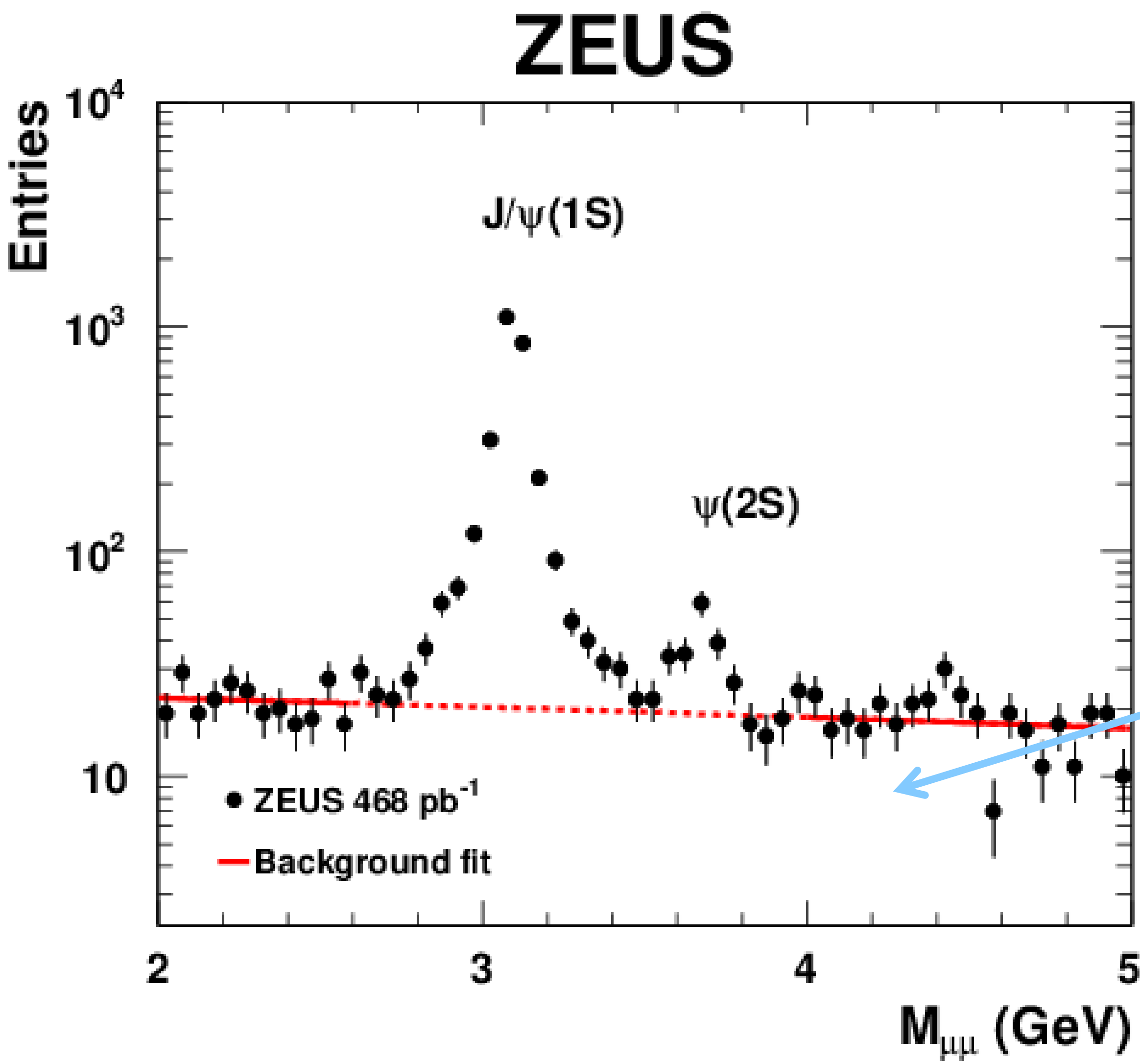


$J/\psi(1S) \rightarrow \mu^+\mu^-$



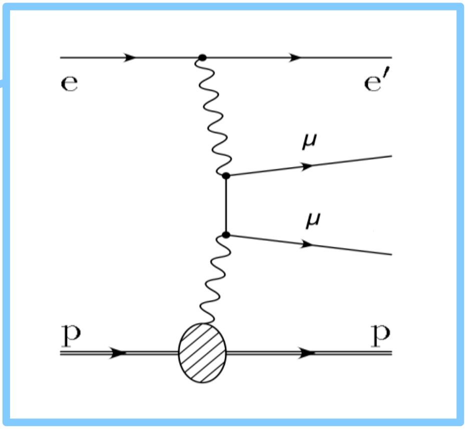
$\psi(2S) \rightarrow J/\psi(1S)\, \pi^+\pi^-$

Background subtraction



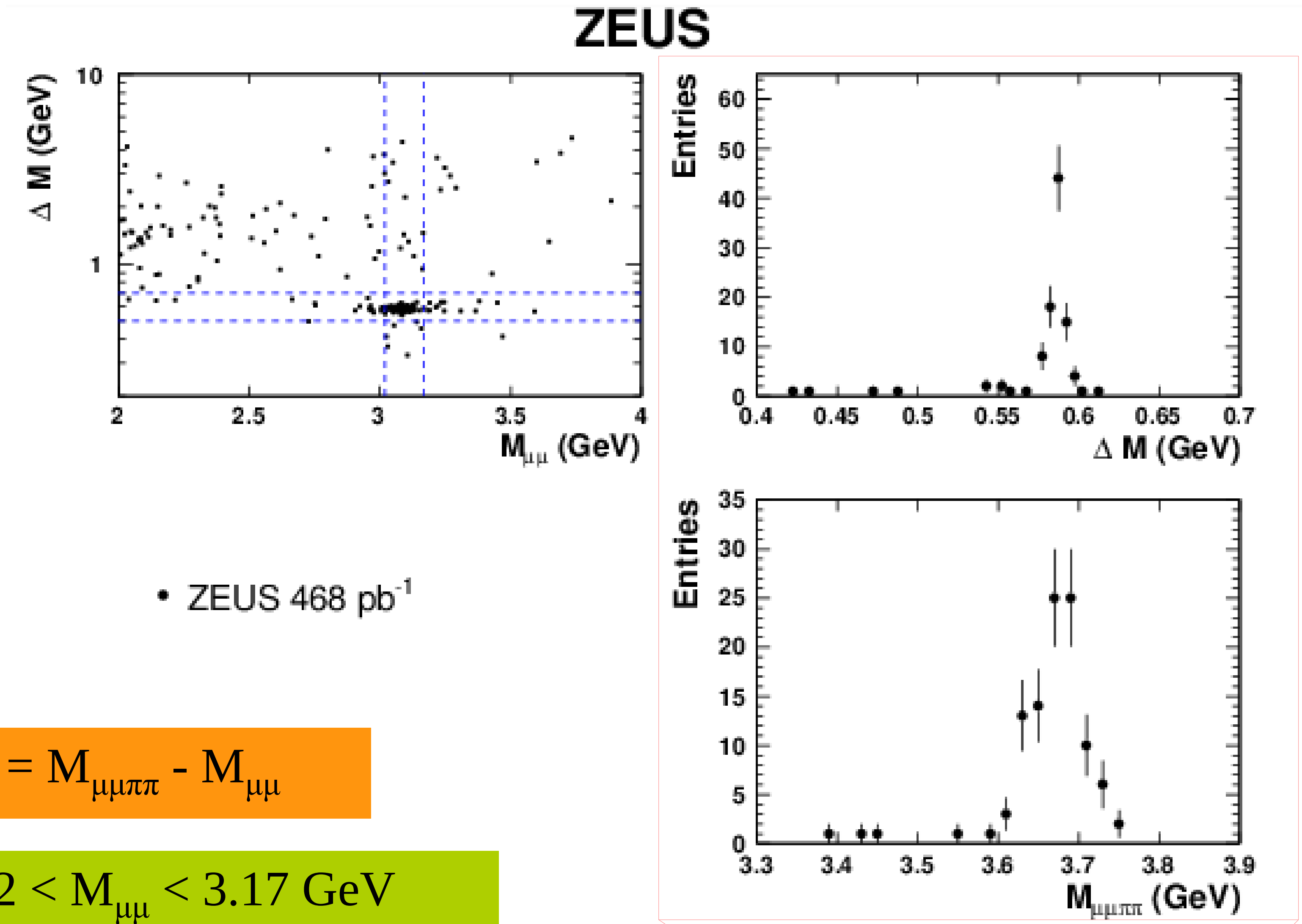
$J/\psi(1S) \rightarrow \mu^+\mu^-$

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



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

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



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

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

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

≤ 3 events background

Determination of $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$

$$R_{\mu\mu} = \left(\frac{N_{\mu\mu}^{\psi(2S)}}{B(\psi(2S) \to \mu^+\mu^-) \cdot A_{\mu\mu}^{\psi(2S)}} \right) \Big/ \left(\frac{N_{\mu\mu}^{J/\psi(1S)}}{B(J/\psi(1S) \to \mu^+\mu^-) \cdot A_{\mu\mu}^{J/\psi(1S)}} \right)$$

$$R_{J/\psi\,\pi\pi} = \left(\frac{N_{J/\psi\,\pi\pi}^{\psi(2S)}}{B(\psi(2S) \to J/\psi(1S)\,\pi^+\pi^-) \cdot A_{J/\psi\,\pi\pi}^{\psi(2S)}} \right) \Big/ \left(\frac{N_{\mu\mu}^{J/\psi(1S)}}{A_{\mu\mu}^{J/\psi(1S)}} \right),$$

Combined result: weighted average

- MC sample DIFFVM J/ψ, $\psi(2S)$ no cuts for Q2, |t|, W]
- Data sample CN v06a

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_{comb}	$0.26 \pm 0.02^{+0.01}_{-0.01}$
$R_{\psi(2S)}$	$1.1 \pm 0.2^{+0.2}_{-0.1}$

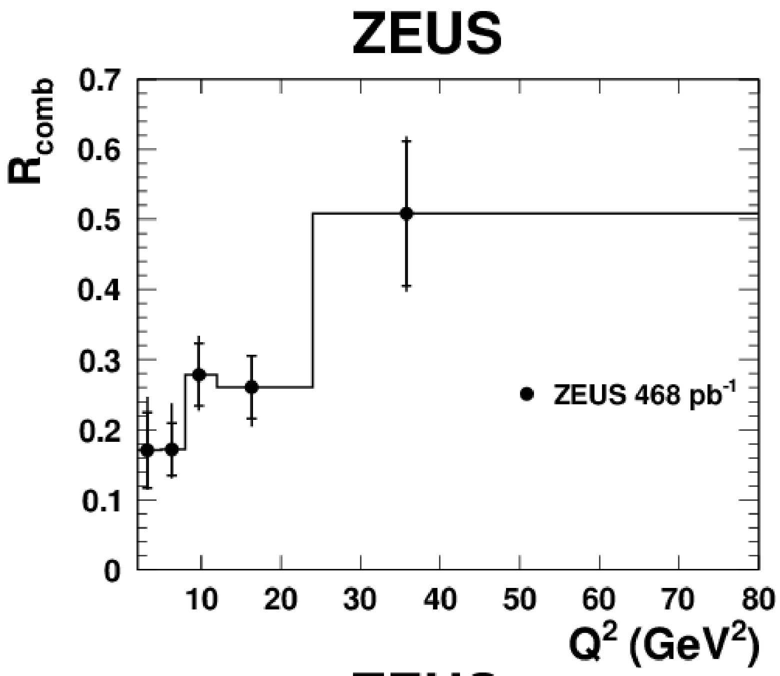
$$R_{\psi(2S)} = R_{J/\psi\,\pi\pi}/R_{\mu\mu}$$

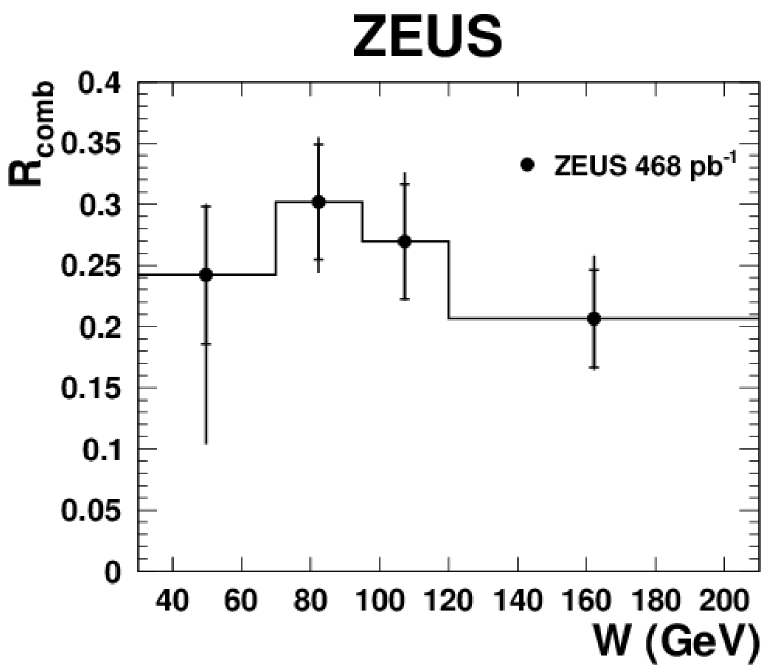
$30 \leq W \leq 210$ GeV
$2 \leq Q^2 \leq 80$ GeV^2
$|t| \leq 1$ GeV^2

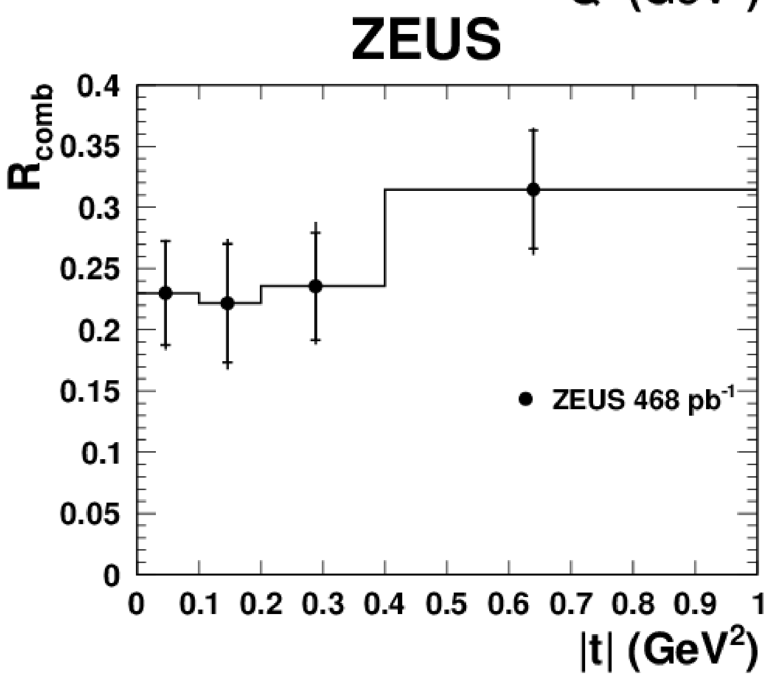
Q^2 (GeV^2)	$R_{J/\psi\pi\pi}$	$R_{\mu\mu}$	R_{comb}	$R_{\psi(2S)}$
$2-5$	$0.21 \pm 0.07^{+0.04}_{-0.03}$	$0.10 \pm 0.09^{+0.09}_{-0.09}$	$0.17 \pm 0.05^{+0.05}_{-0.02}$	–
$5-8$	$0.19 \pm 0.05^{+0.02}_{-0.02}$	$0.13 \pm 0.06^{+0.12}_{-0.03}$	$0.17 \pm 0.04^{+0.05}_{-0.02}$	$1.5 \pm 0.8^{+0.4}_{-0.7}$
$8-12$	$0.27 \pm 0.05^{+0.06}_{-0.01}$	$0.29 \pm 0.08^{+0.03}_{-0.08}$	$0.28 \pm 0.05^{+0.03}_{-0.03}$	$0.9 \pm 0.3^{+0.4}_{-0.1}$
$12-24$	$0.27 \pm 0.05^{+0.04}_{-0.03}$	$0.24 \pm 0.08^{+0.01}_{-0.08}$	$0.26 \pm 0.05^{+0.01}_{-0.03}$	$1.1 \pm 0.4^{+0.6}_{-0.1}$
$24-80$	$0.56 \pm 0.13^{+0.04}_{-0.09}$	$0.42 \pm 0.17^{+0.12}_{-0.04}$	$0.51 \pm 0.10^{+0.04}_{-0.04}$	$1.3 \pm 0.6^{+0.3}_{-0.6}$
W (GeV)	$R_{J/\psi\pi\pi}$	$R_{\mu\mu}$	R_{comb}	$R_{\psi(2S)}$
$30-70$	$0.24 \pm 0.07^{+0.01}_{-0.13}$	$0.24 \pm 0.10^{+0.03}_{-0.14}$	$0.24 \pm 0.06^{+0.01}_{-0.13}$	$1.0 \pm 0.5^{+0.5}_{-0.2}$
$70-95$	$0.30 \pm 0.06^{+0.01}_{-0.04}$	$0.31 \pm 0.09^{+0.09}_{-0.03}$	$0.30 \pm 0.05^{+0.02}_{-0.03}$	$1.0 \pm 0.3^{+0.1}_{-0.2}$
$95-120$	$0.28 \pm 0.06^{+0.05}_{-0.01}$	$0.24 \pm 0.08^{+0.04}_{-0.05}$	$0.27 \pm 0.05^{+0.03}_{-0.01}$	$1.2 \pm 0.5^{+0.5}_{-0.2}$
$120-210$	$0.22 \pm 0.05^{+0.07}_{-0.01}$	$0.17 \pm 0.07^{+0.02}_{-0.05}$	$0.21 \pm 0.04^{+0.03}_{-0.01}$	$1.3 \pm 0.6^{+0.7}_{-0.2}$
$\|t\|$ (GeV^2)	$R_{J/\psi\pi\pi}$	$R_{\mu\mu}$	R_{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|

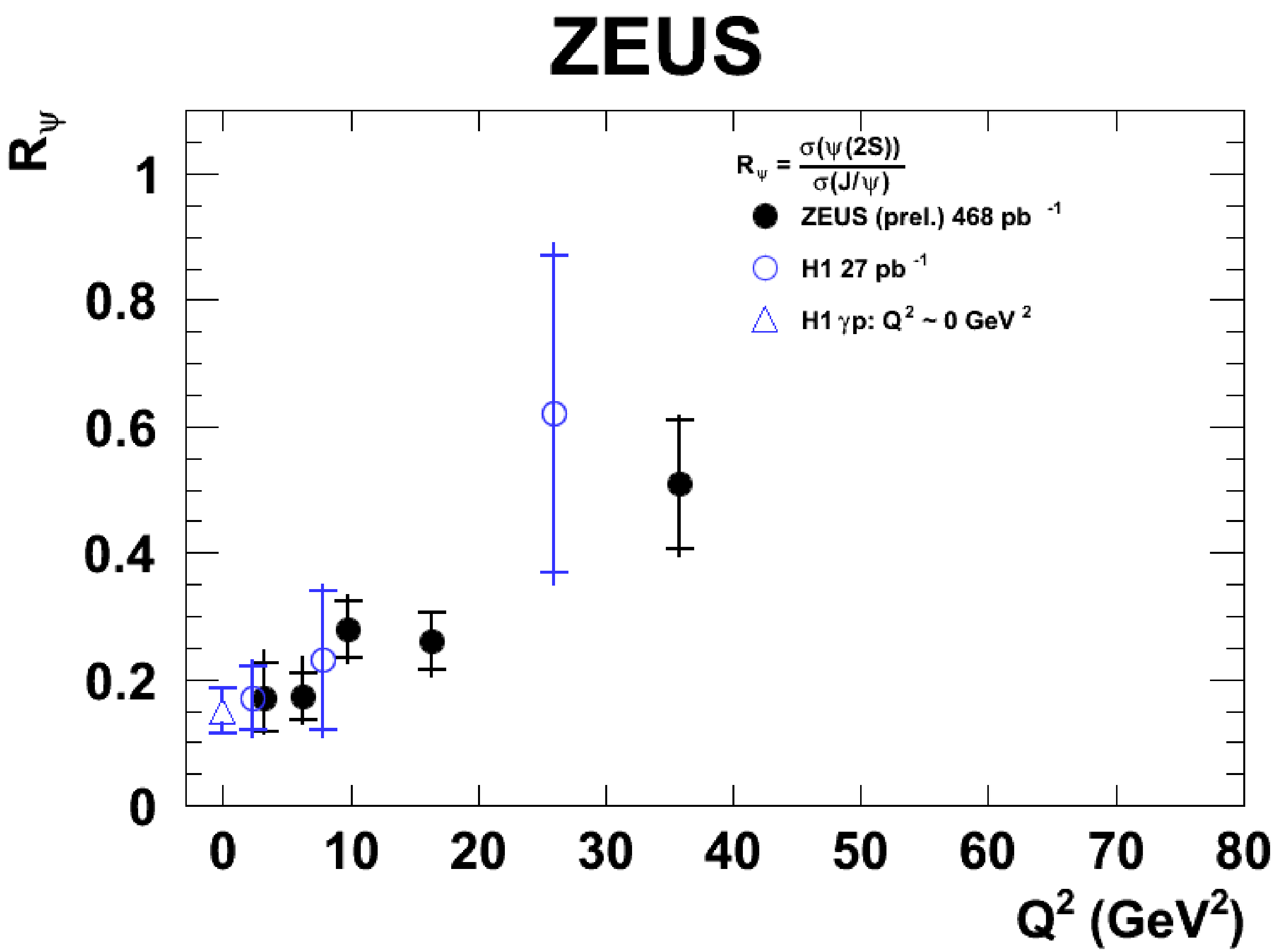






- Indication of an increase with Q^2
- Independent of W
- Independent of |t|

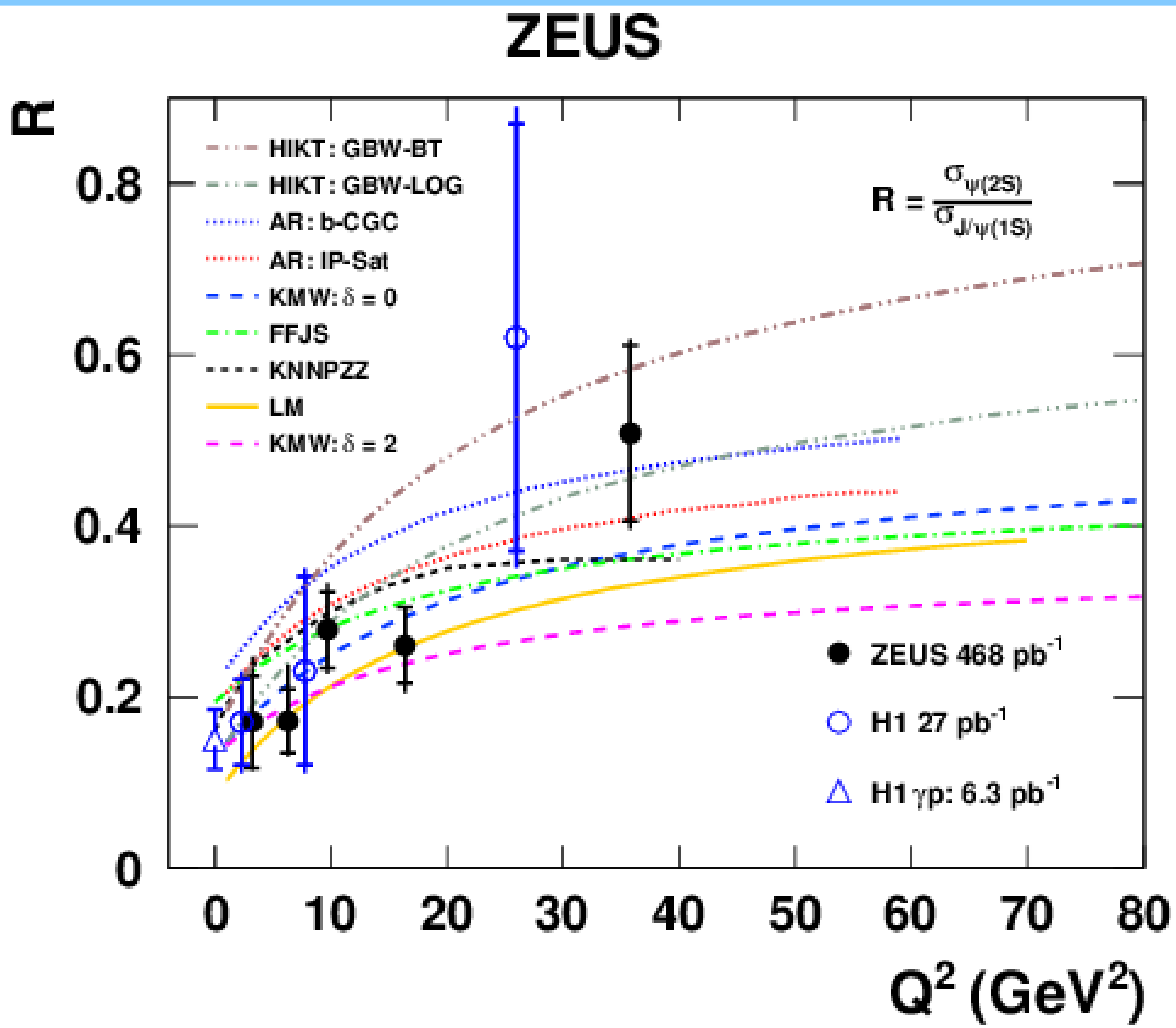
ZEUS — H1 comparison



H1 collaboration: data 95-97, Eur.Phys.J. C10 (1999) 373

Good agreement - σ(ψ(2S))/σ(J/ψ(1S)) increases with Q^2
ZEUS smaller uncertainties owing to 17x higer integrated luminosity

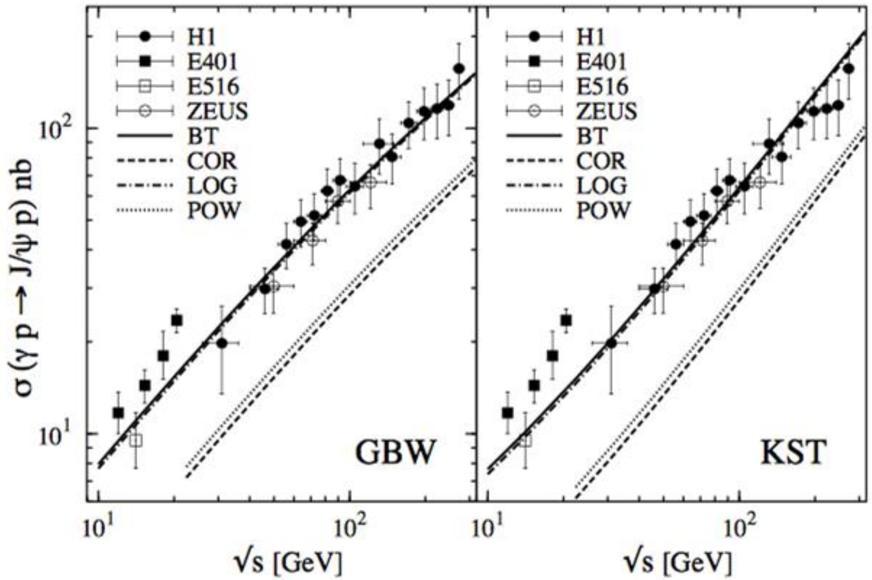
Model predictions



All models predict an increase of σ(ψ(2S))/σ(J/ψ(1S)) with Q^2

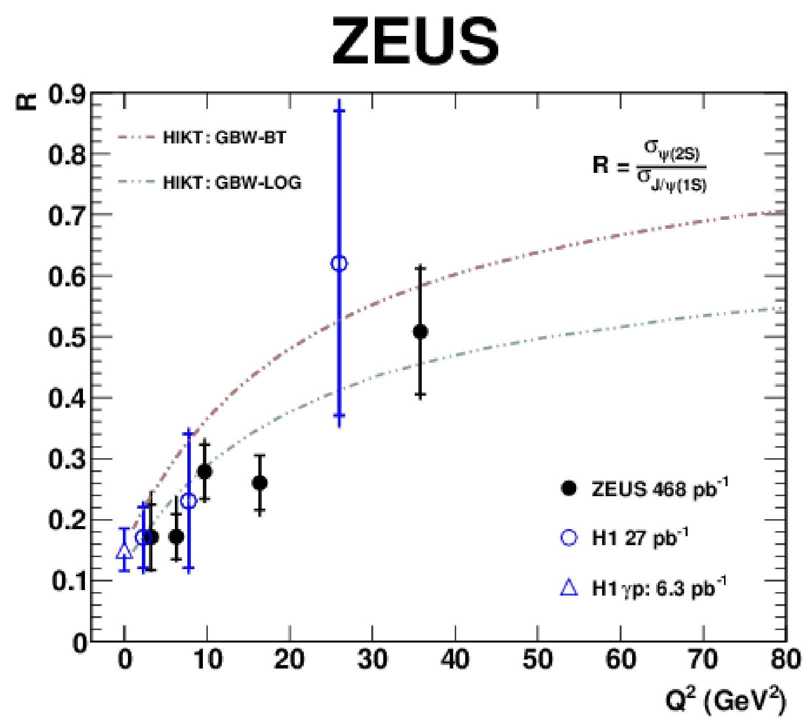
HIKT calculations

ıon oı energy.



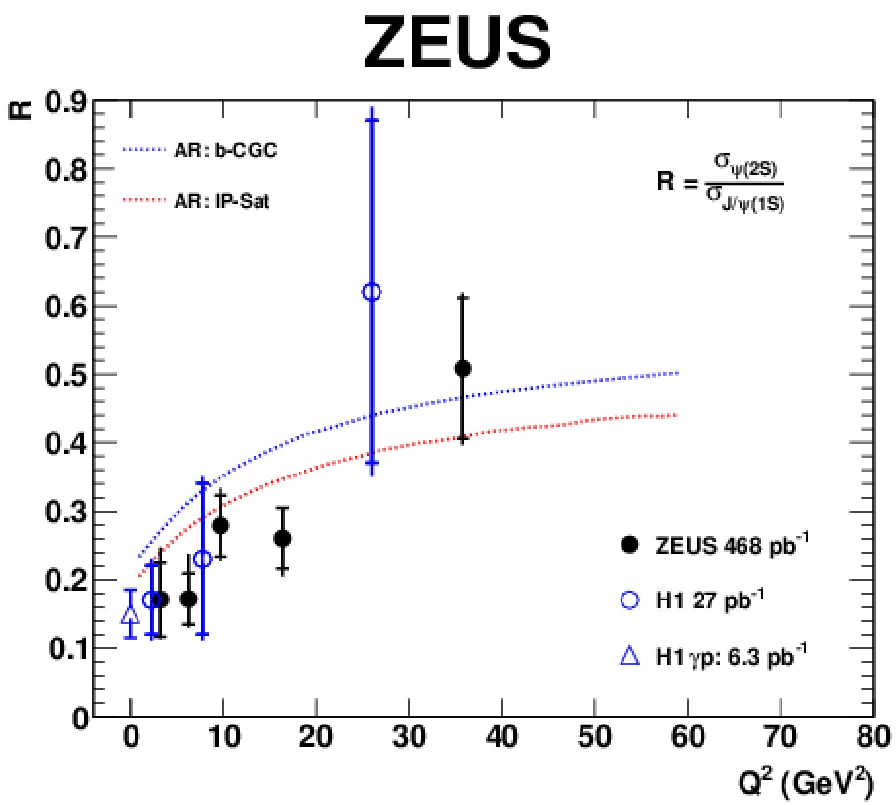
RE 2. Integrated cross section for elastic photoproduction with real photons ($Q^2 = 0$) calc

HIKT — from Huefner et al.,
use 2 forms for the dipole cross section calculation and 4 forms of 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 compared to measurements

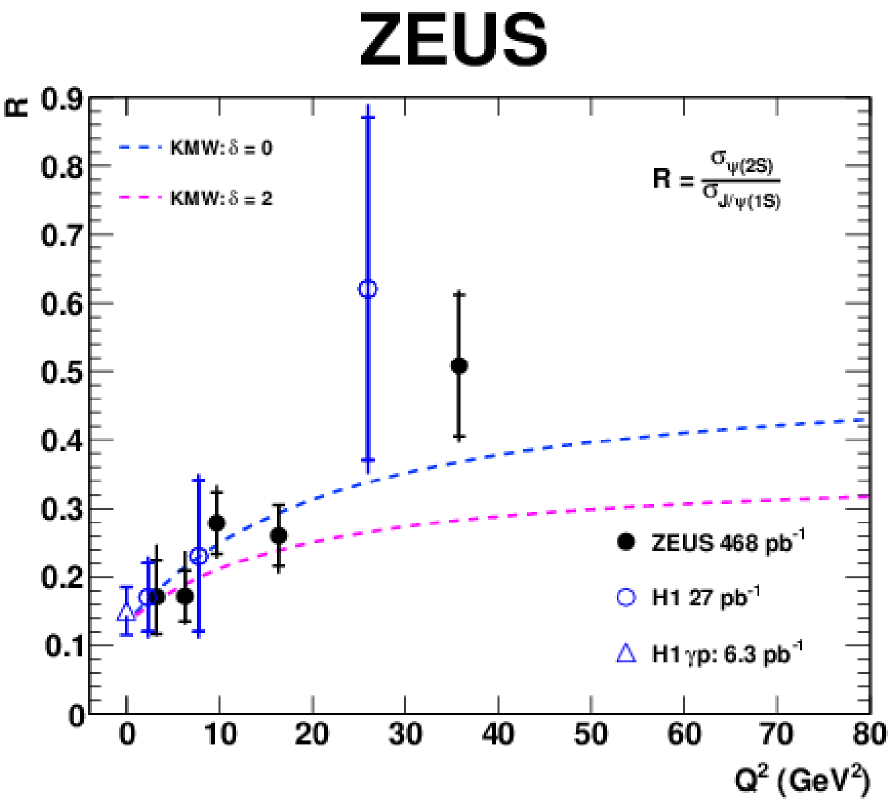
AR calculations



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

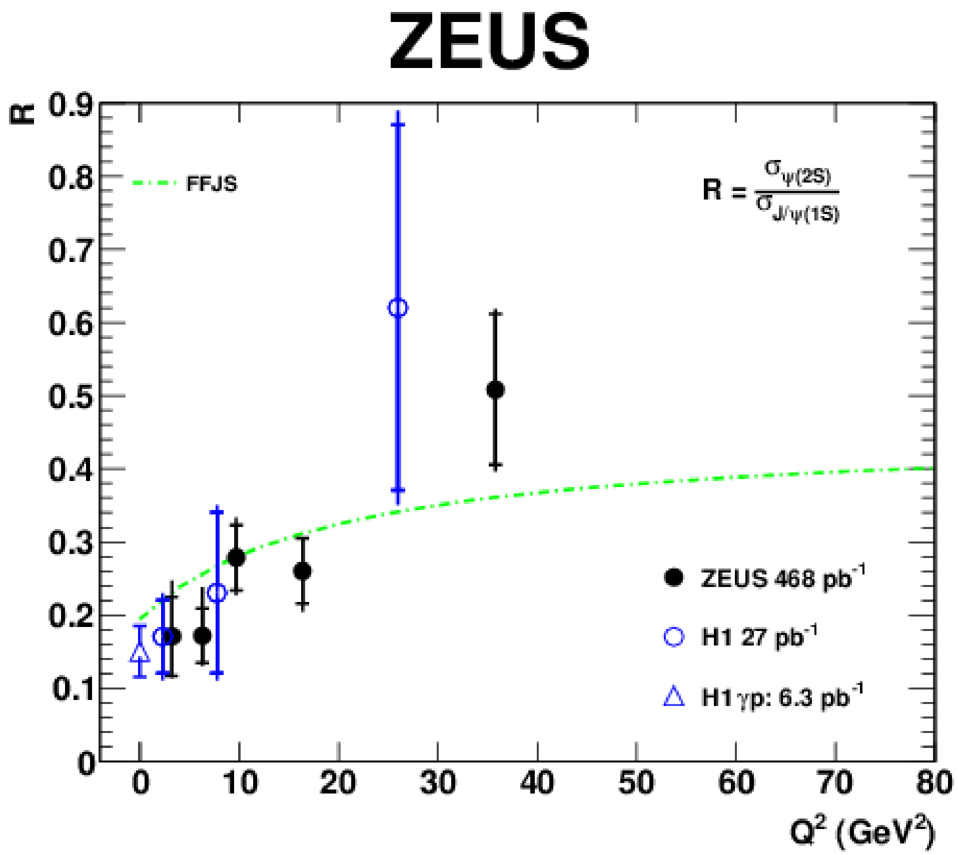
KMW calculations



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

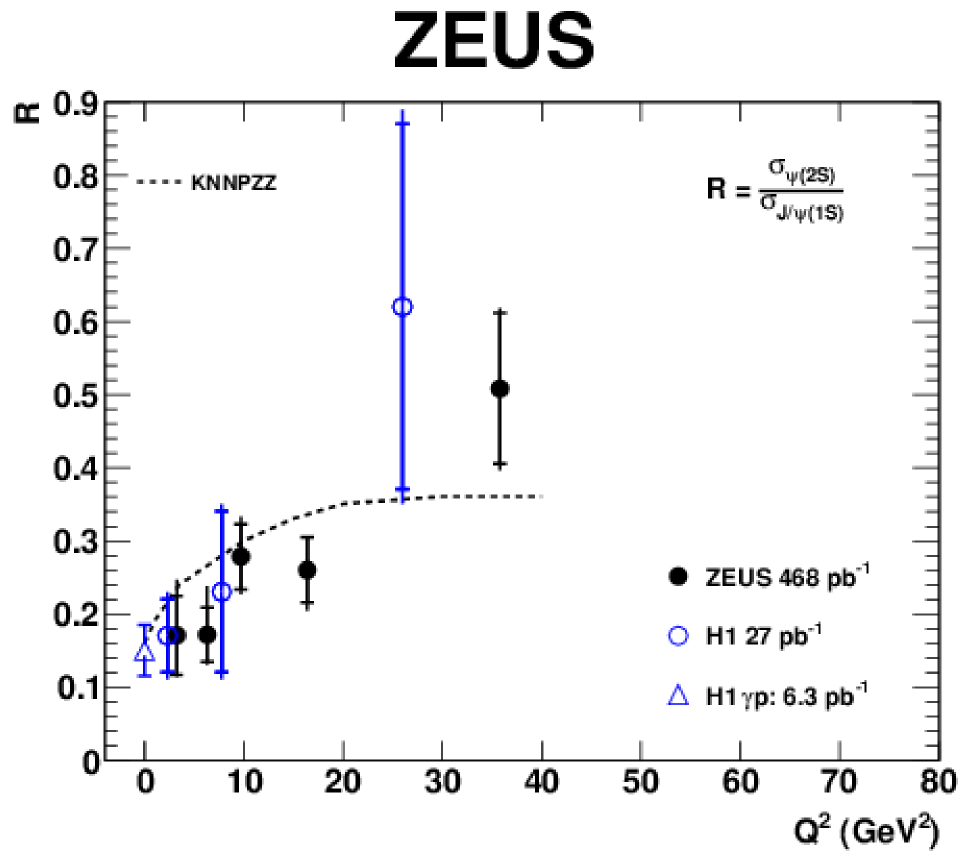
FFJS calculations



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

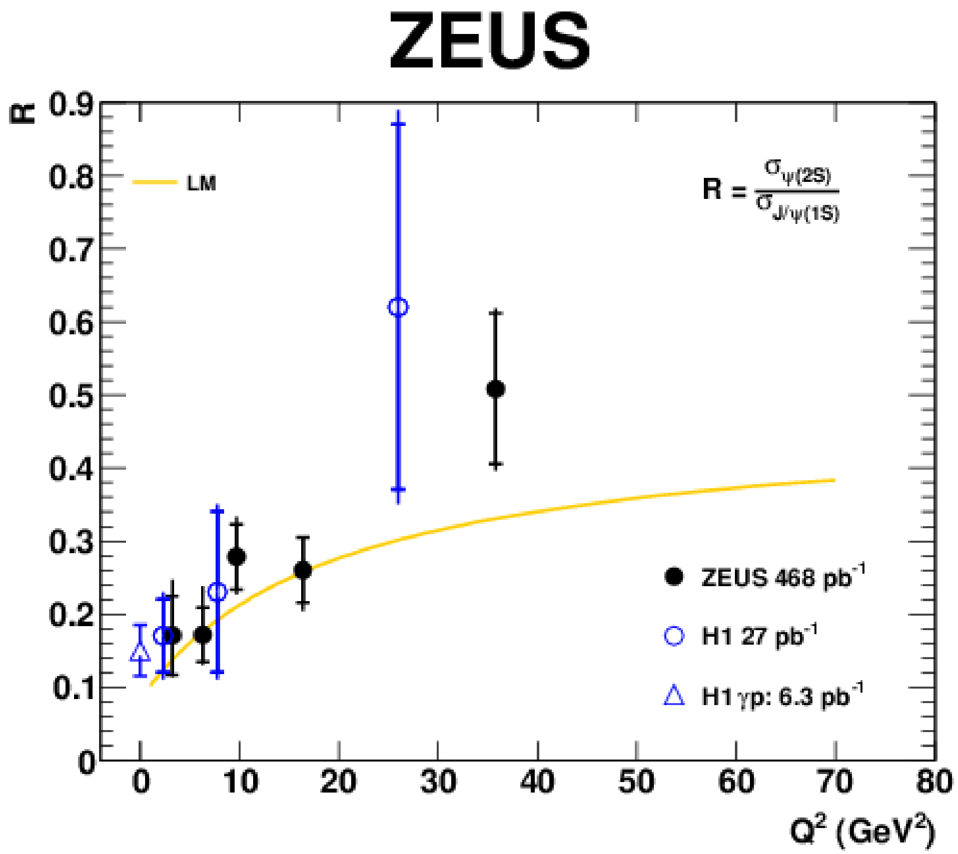


The model used in original H1 publication

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



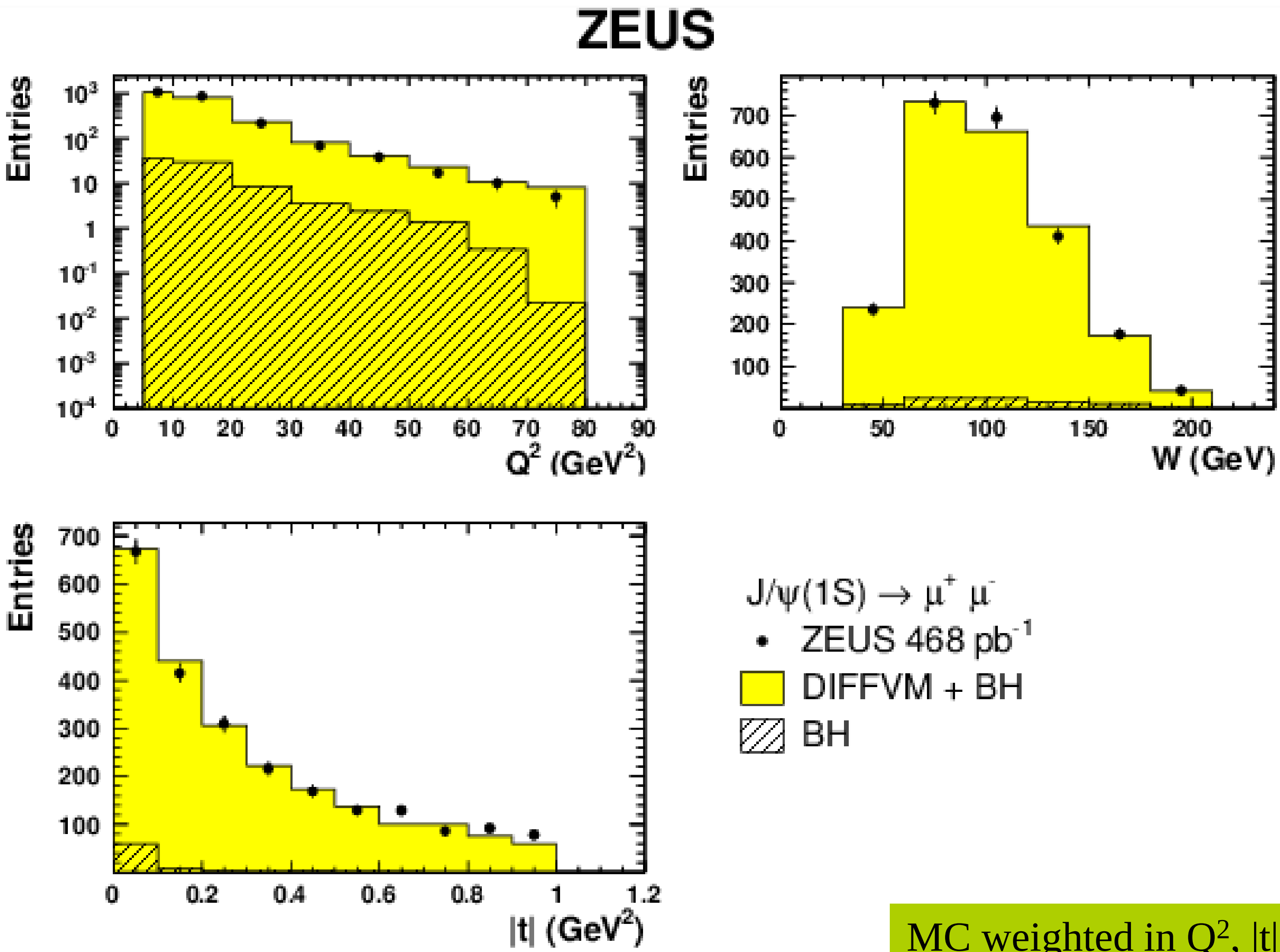
Good description of the data

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

Summary

- The pQCD prediction of $\sigma(\psi(2S))/\sigma(J/\psi(1S))$ ratio rise with Q^2 and is demonstrated by data
- Uncertainties smaller compared to the H1 HERA I (1999) results
- $\sigma(\psi(2S))/\sigma(J/\psi(1S))$ ratio compared to models of VM production, some discrimination of the different models possible
- $\sigma(\psi(2S))/\sigma(J/\psi(1S))$ independent of W and |t|
- arXiv:1601.03699

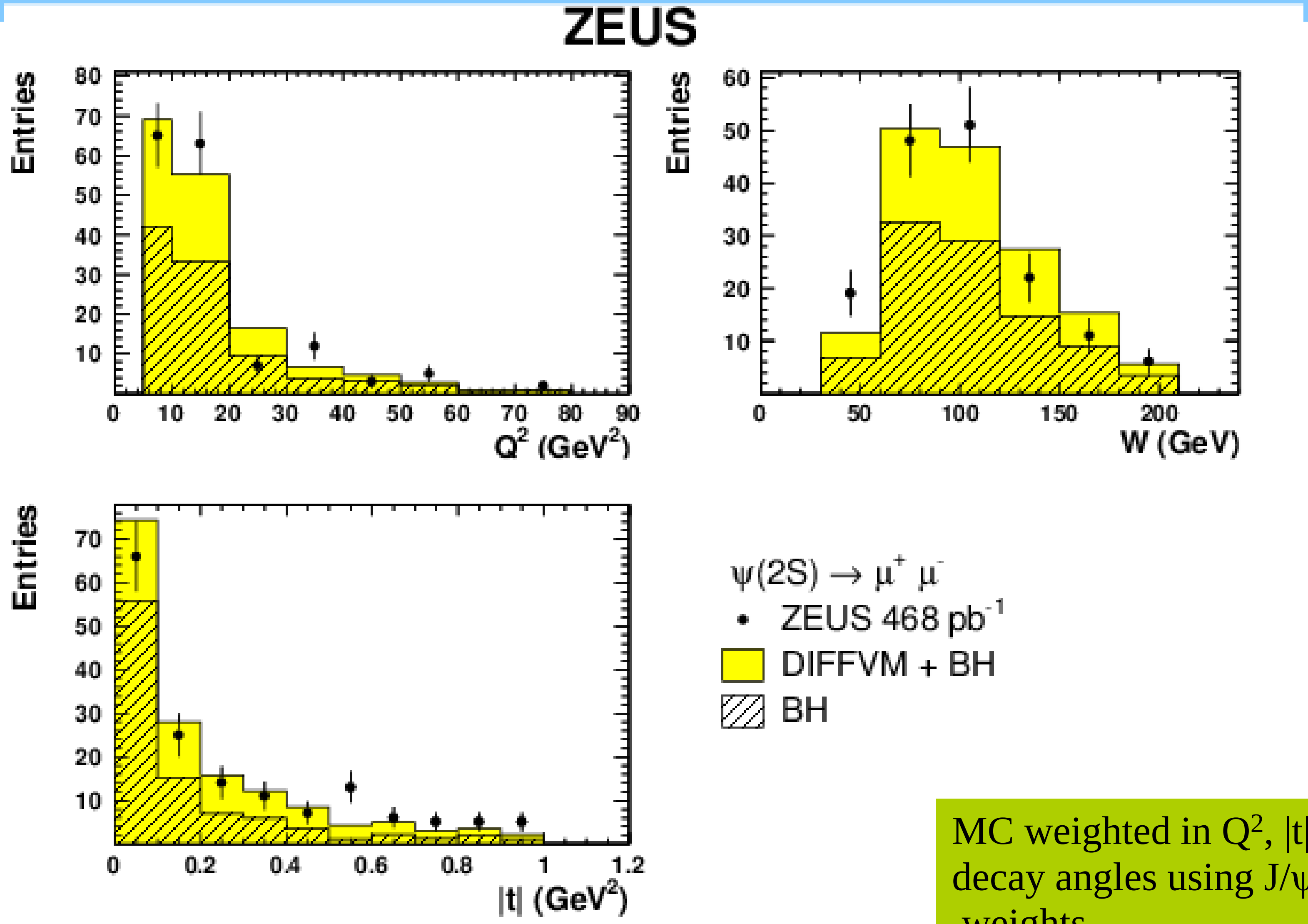
Backup: Data-MC comparison for J/ψ(1S)



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

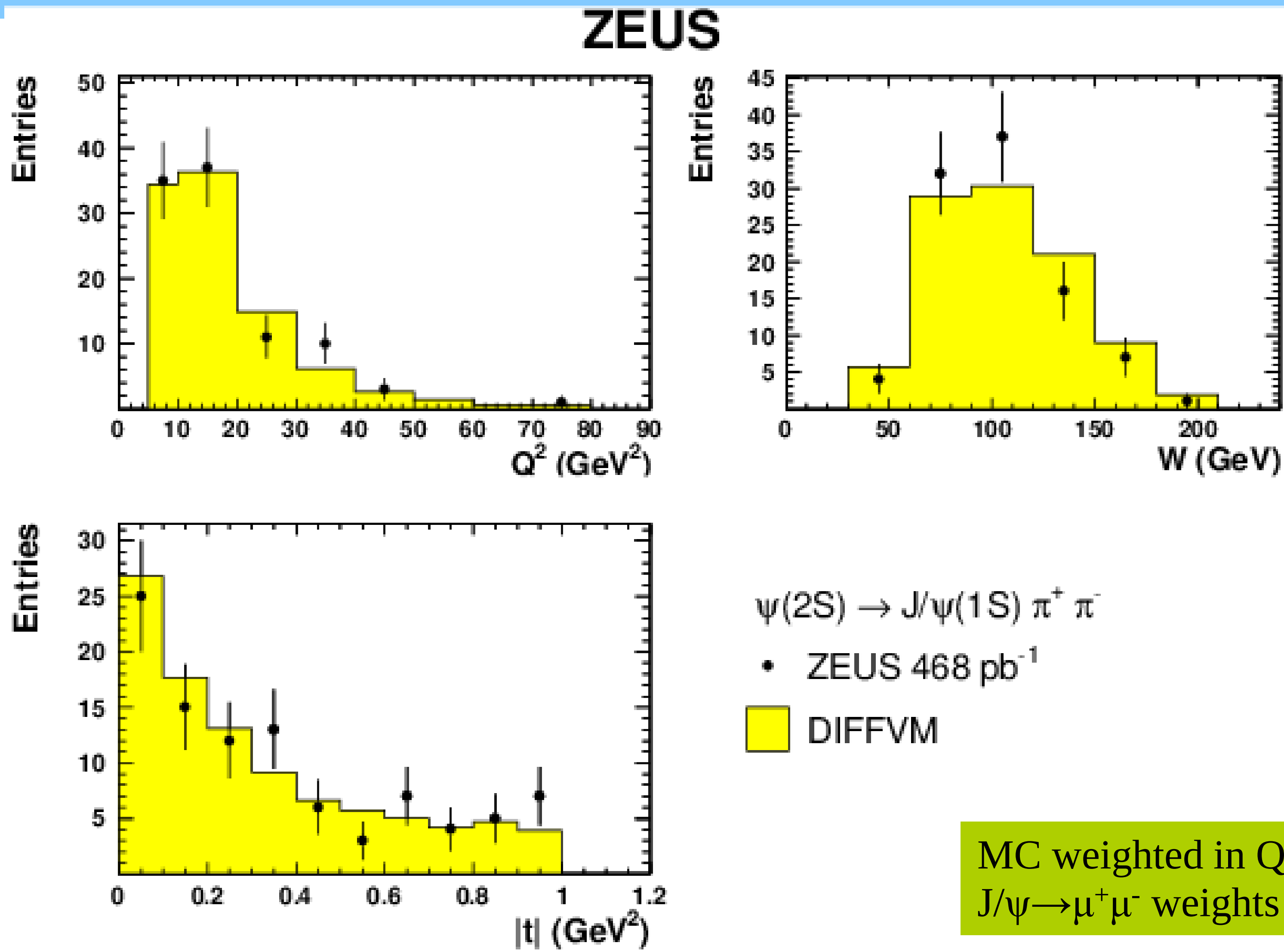
Backup: Data-MC comparison for $\psi(2S) \rightarrow \mu^+\mu^-$



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