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

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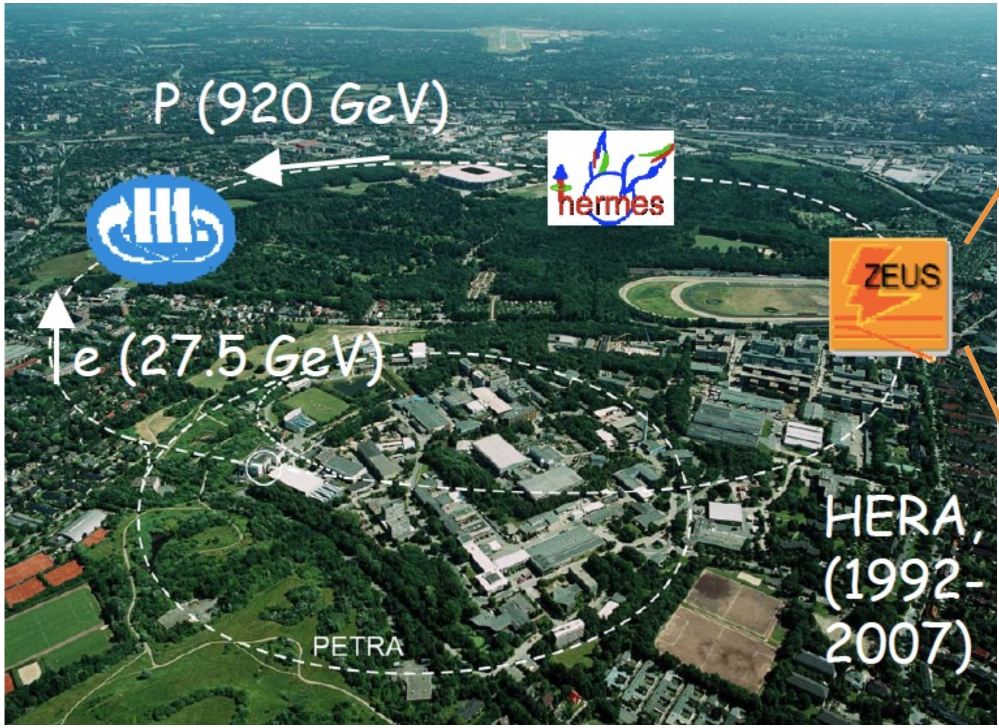
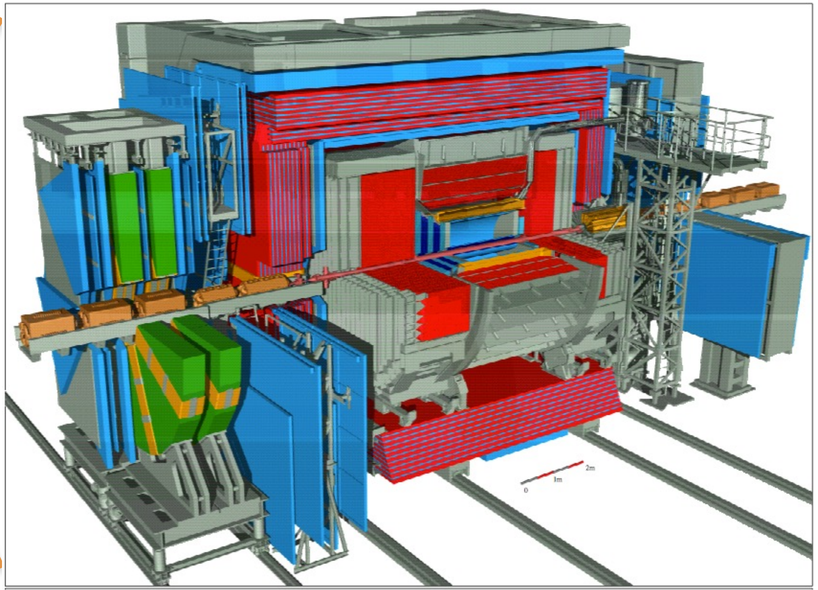
HERA and the ZEUS detector





ZEUS detector: multipurpose, hermetic, asymmetric with extended coverage in the proton beam direction

HERA-II : 2001-2007

p : 920 GeV $\quad e^+/e^-$: 27.5 GeV

575 GeV

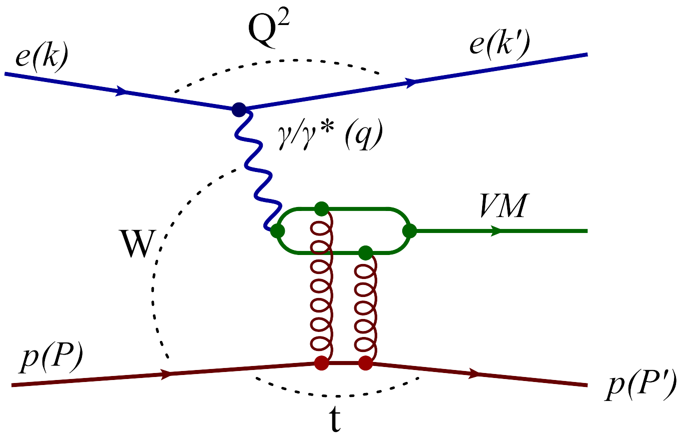
460 GeV

Most of the collected data are at $\sqrt{s}$ = 318 GeV

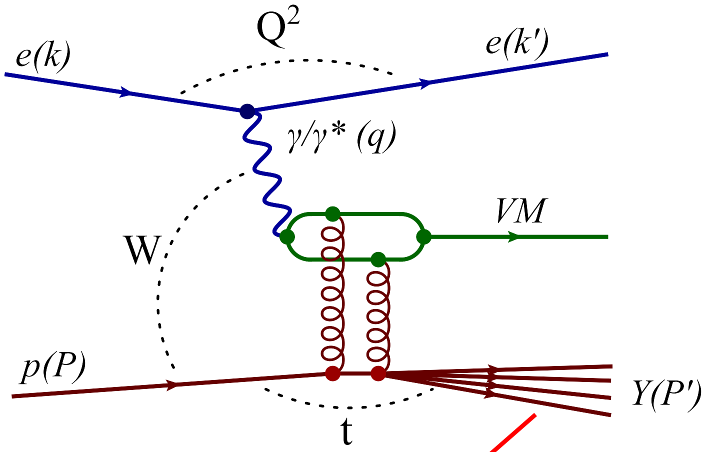
This analysis uses HERA II data 2003-2007
at $\sqrt{s}$ = 318 GeV: L = 373 pb^{-1}

Exclusive production of vector mesons in ep

Exclusive (elastic):



Proton-dissociative:



Kinematic variables: $(M_V)^2$, Q^2, W, |t|

Q^2 = virtuality of exchanged photon

- **Q^2 ~ 0, PHP** (Photoproduction) [this analysis]
- Larger Q^2, DIS (Deep inelastic scattering)

W = invariant mass of γp system

$W \approx \sqrt{[2E_p(E-p_Z)_V]}$

|t| = 4-momentum exchanged at p vertex

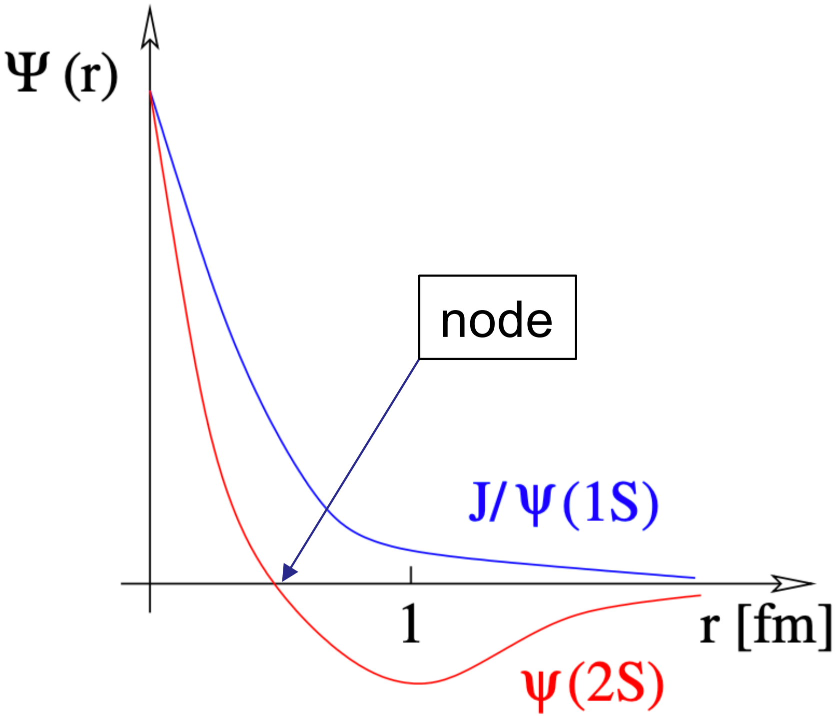
$|t| \approx (p_{T,V})^2$

As $Q^2 \sim 0$ GeV^2, the **hard QCD scale is provided by the squared mass of the vector meson $(M_V)^2$**

The scattered proton is not measured → when the system Y is not detected, **proton-dissociative events form a significant background**

Cross-section ratio ψ(2S) / J/ψ(1S)

Motivation:



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

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

- J/ψ(1S) and ψ(2S) have the same quark composition but different wave functions
- ψ(2S) has a node at ≈ 0.4 fm
- $\langle r^2 (\psi(2S)) \rangle \approx 2 \langle r^2 (J/\psi(1S)) \rangle$
- QCD models predict R ~ 0.17 in PHP and rise of R with Q^2 in DIS

Samples and event selection

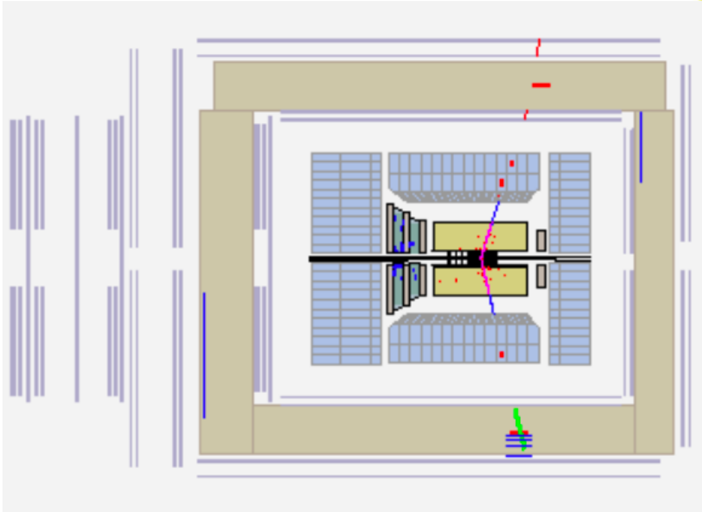
2- and 4-prong final states:

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

Data : HERA II (2003 - 2007) → **L = 373 pb^{-1}**

MC :
- **Signal** – exclusive VM production with **DIFFVM**
- **Background** – Bethe-Heither $\mu^+\mu^-$ production with **GRAPE**

(both including proton-dissociative events)



Event display $J/\psi \rightarrow \mu^+\mu^-$

Event selection :
- No scattered electron measured in CAL (corresponding to $Q^2 < 1$ GeV^2)
- Scattered proton undetected
- Exactly two reconstructed tracks identified as muons and
  for $\psi(2S) \rightarrow J/\psi\ \pi^+\pi^-$ additionally two pion tracks from $\mu\mu$ vertex
- Nothing else in the detector above noise → very clean events!
- **Proton-dissociative events removed above masses M_Y ~ 5 GeV**

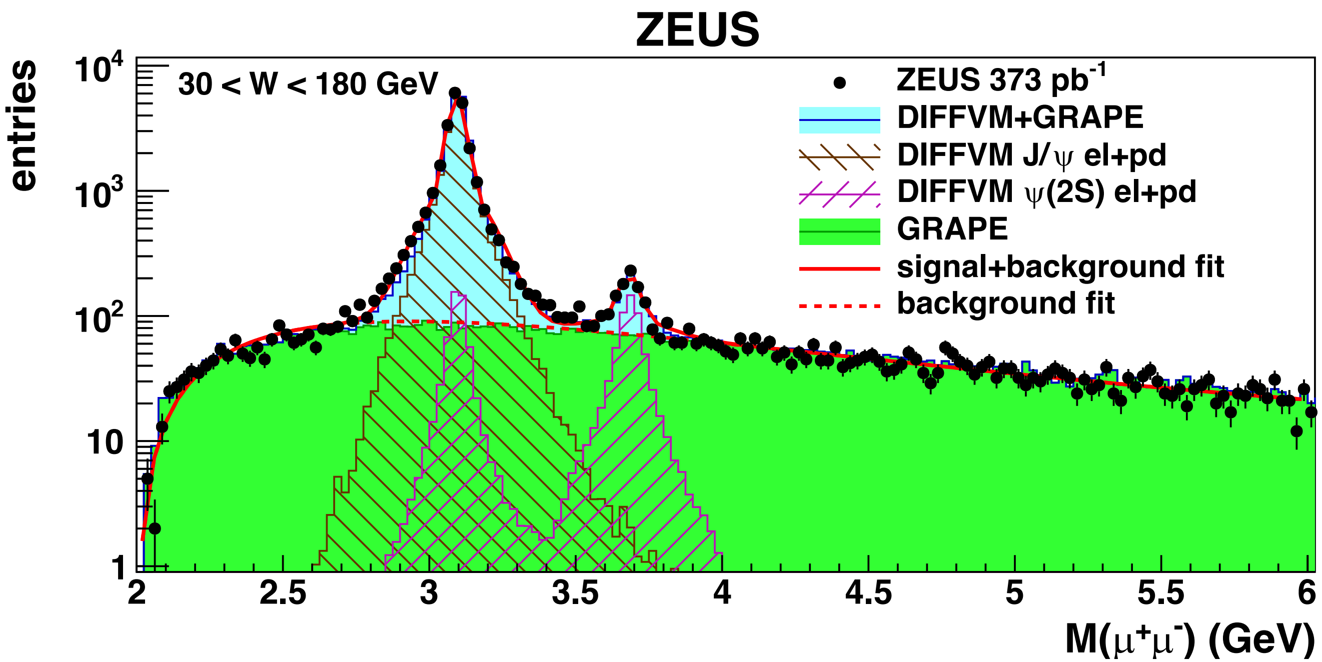
Kinematic range :

30 < W < 180 GeV; |t| < 1 GeV^2
$Q^2 < 1$ GeV^2. (median $Q^2 \sim 5 \cdot 10^{-5}$ GeV^2)

5 bins in W
5 bins in |t|

Mass spectra: 2-prong events

Signal extraction: 2-prong final states ($\mu^+\mu^-$)



Full phase space:

30 < W < 180 GeV;

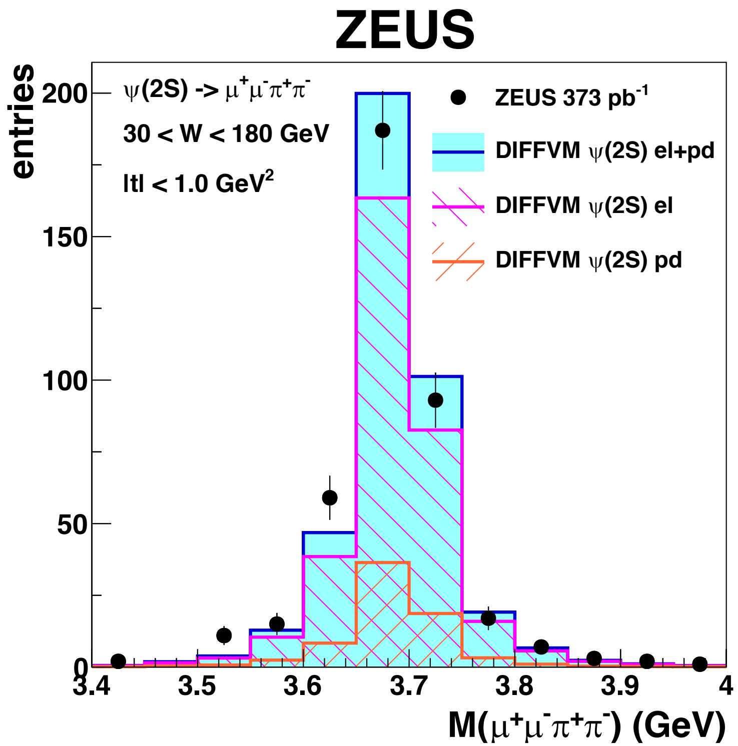
$|t| < 1$ GeV^2

- Sum of MC distributions normalized to data; relative contribution of each process obtained from a fit to the data. Good agreement between data and MC.
- Numbers of J/ψ and ψ(2S) obtained from a fit to the data describing peaks and backgrounds: **~23000 J/ψ and ~700 ψ(2S)**
- Resonant background under J/ψ peak from ψ(2S) decays: ~2.4% and subtracted
- Non-resonant background (Bethe-Heitler): ~9% under the J/ψ peak,
  2.5 higher than the signal under the ψ(2S) peak

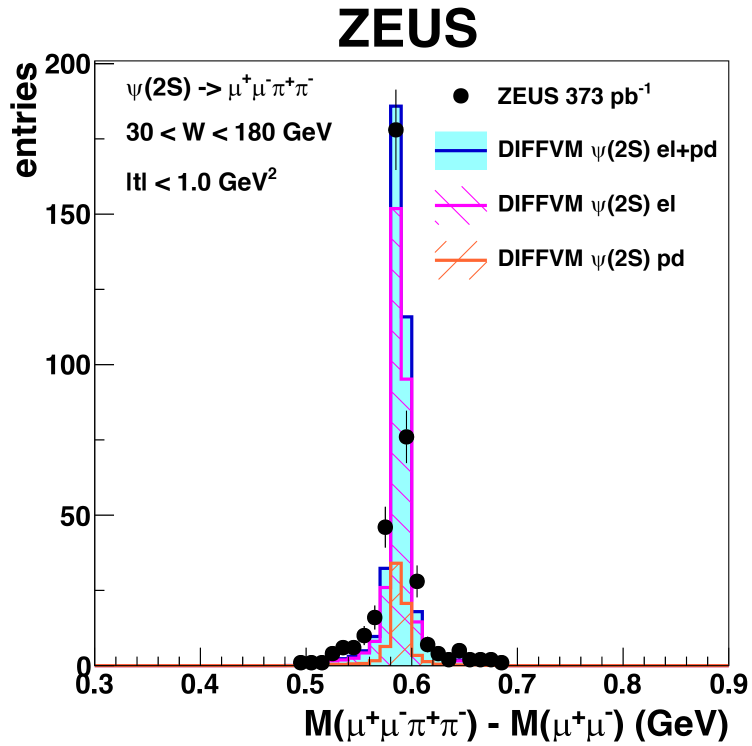
Mass spectra: 4-prong events

Signal extraction: **4-prong final states ($\mu^+\mu^-\ \pi^+\pi^-$)**

$M(\mu^+\mu^-\ \pi^+\pi^-)$



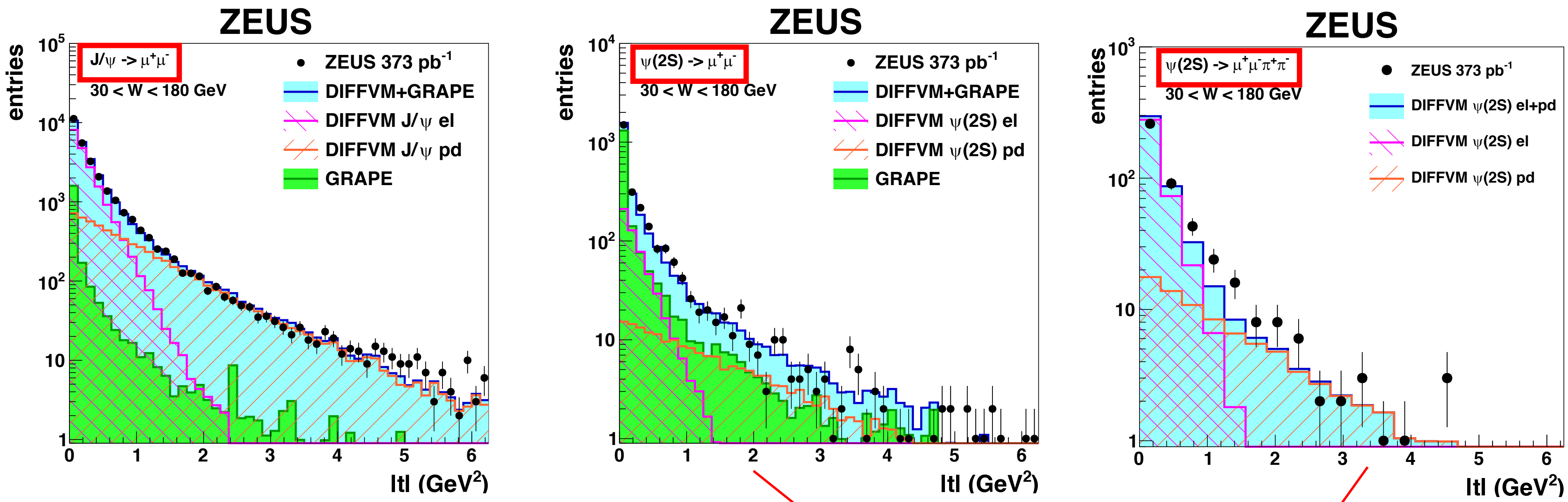
$M(\mu^+\mu^-\ \pi^+\pi^-) – M(\mu^+\mu^-)$



- Number of background events from data in side-bands in $M(\mu^+\mu^-\ \pi^+\pi^-) – M(\mu^+\mu^-)$, assuming a uniform distribution: very small number
- Event yield after background subtraction: **~400 ψ(2S)**
- **Fraction of proton-dissociative events from t-spectra fits**

|t| distributions

Evaluation of **proton dissociation fraction:**



$f_{pdiss}(J/\Psi) = 0.17 \pm 0.01$ **$f_{pdiss}(\Psi') = 0.16 \pm 0.01$**

- **f_{pdiss} is found independent of W and strongly dependent on |t|**
- Proton-dissociative events dominate above 1 GeV² → analysis range: |t| < 1 GeV²
- f_{pdiss} from ~7% for |t| < 0.1 GeV² to ~45% for 0.6 < |t| < 1 GeV²
  → corresponding values used for measuring the ratio R as a function of |t|
- **Little difference between mean values of $f_{pdiss}(J/\Psi)$ and $f_{pdiss}(\Psi')$ in full range**
  → final factor in the calculation of R is approximately 1
- **But variation of t dependence (b slopes) is one of the largest systematics: ± 0.01 in R**

Cross-section ratios R in full kinematic range

$\psi(2S)$ decay mode	$R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$
$\mu^+\mu^-$	0.154 ± 0.012
$J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$	0.125 ± 0.019
combined	$0.146 \pm 0.010^{+0.016}_{-0.020}$

30 < W < 180 GeV

|t| < 1 GeV^2

Q^2 < 1 GeV^2

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

$$R_{\mu\mu} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S)\rightarrow\mu^+\mu^-}}{Acc_{\psi(2S)\rightarrow\mu^+\mu^-}} \cdot \frac{BR_{J/\psi(1S)\rightarrow\mu^+\mu^-}}{BR_{\psi(2S)\rightarrow\mu^+\mu^-}} \cdot \frac{1-f^{\psi(2S)}_{pdiss}}{1-f^{J/\psi(1S)}_{pdiss}}$$

$Acc_i = \frac{N_i^{reco}}{N_i^{true}}$, $f^i_{p.diss}$ - fraction of proton dissociative events

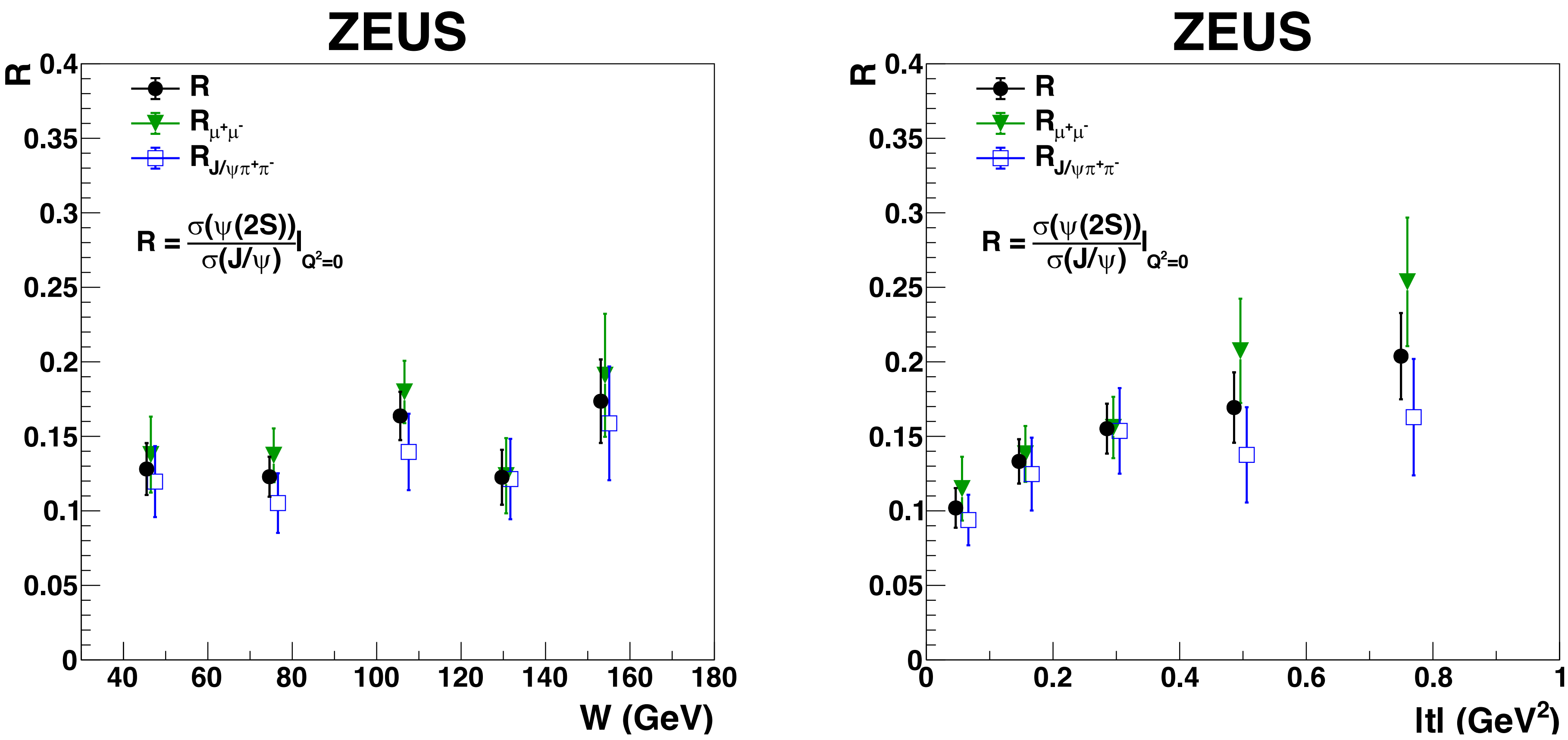
$BR(\psi(2S) \rightarrow J/\psi\pi^+\pi^-) = (34.68 \pm 0.3)\%$, $BR(\psi(2S) \rightarrow \mu^+\mu^-) = (0.80 \pm 0.06)\%$,

$BR(J/\psi \rightarrow \mu^+\mu^-) = (5.961 \pm 0.033)\%$, $BR(\psi(2S) \rightarrow \mu^+\mu^-\pi^+\pi^-) = (2.07 \pm 0.02)\%$ (PDG 2020)

Both channels have similar precision and provide consistent results

Cross-section ratios R as function of W and |t|

Comparison of 2-prong and 4-prong decay channels:

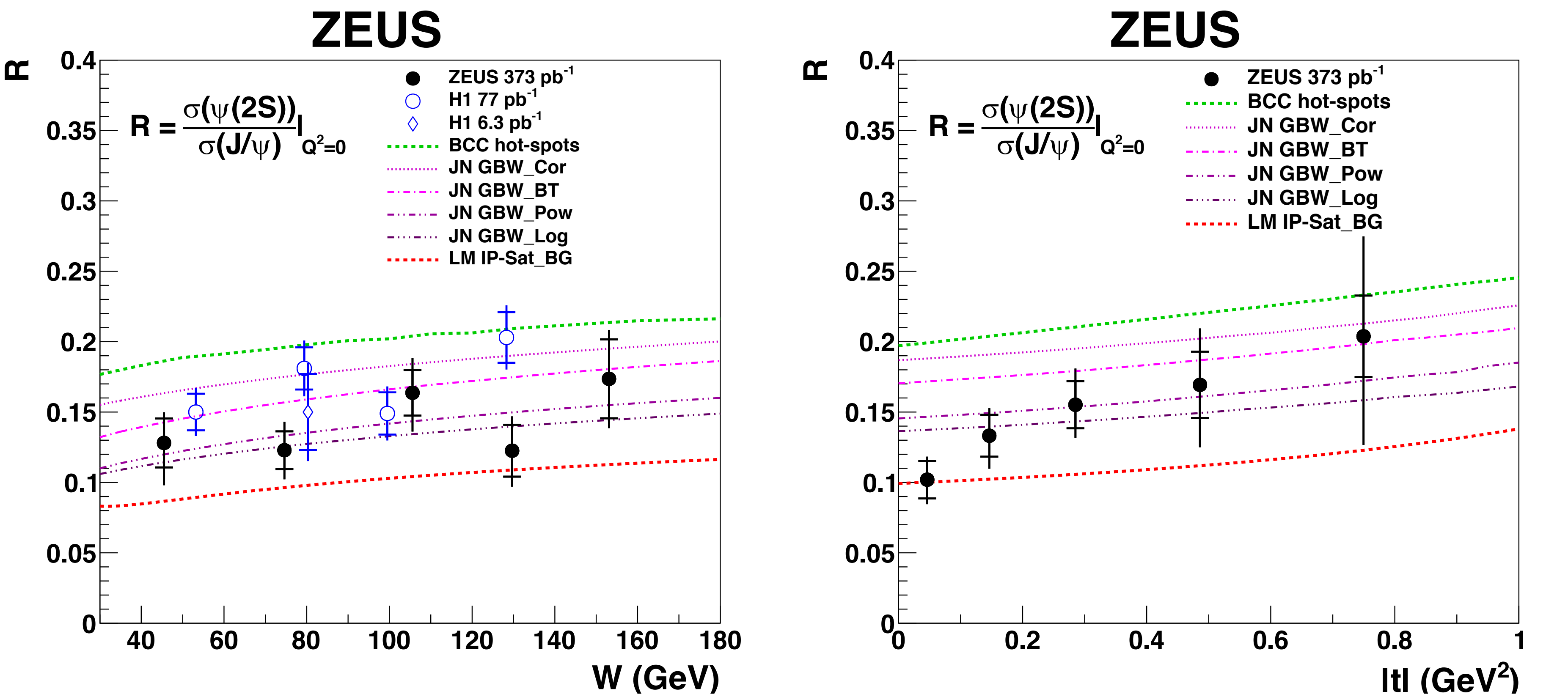


Good agreement between the two channels independent measurements

→ Combined ratio obtained using the weighted average with statistical errors only

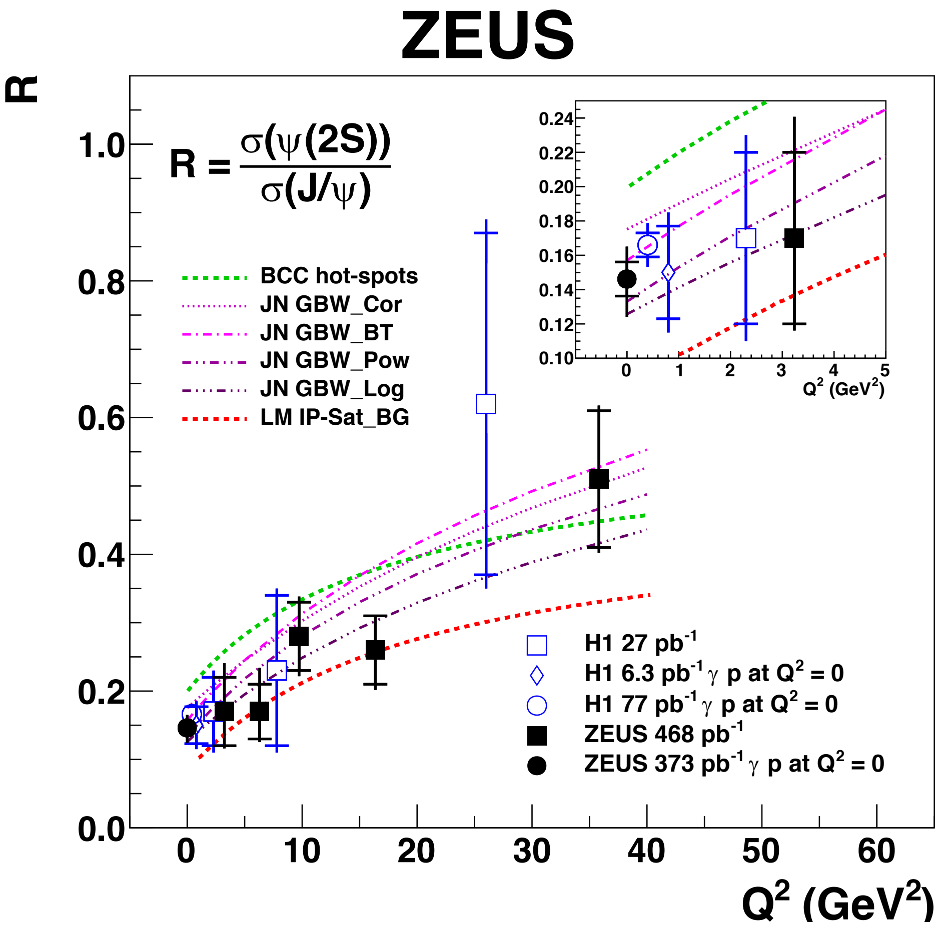
Cross-section ratios R – final results

Comparison with H1 and theoretical models:



- For R vs. W, **ZEUS (full dots)** and **H1 (open markers)** are compared
- **No clear W dependence observed, moderate increase in |t|**
- Errors at **high-|t| dominated by systematics** (proton-dissociative background)
- **Theoretical models:** no uncertainties provided and values differing by up to a factor 2
- In general, **reasonable agreement between data and theoretical models**

Cross-section ratio R as a function of Q^2



Theoretical models:

- Bendova, Cepila and Contreras (BCC hot-spots):
  - Phys. Rev. **D 99**, 034025 (2019).
- Jan Nemchik et al. (JN):
  - Eur. Phys. J. **C 79**, 154 (2019).
  - Eur. Phys. J. **C 79**, 495 (2019).
  - Phys. Rev. **D 103**, 094027 (2021).
- Lappi and Mäntysaari (LM IP-Sat):
  - Phys. Rev. **C 83**, 065202 (2011).
  - Phys. Rev. **D 87**, 034002 (2013).
  - PoS (DIS2014), 069 (2014).

- **Photoproduction results** (ZEUS, H1) are presented **together with DIS ones**
- Models predict a strong increase in R with increasing Q^2, compatible with data
- The good precision of PHP data has the potential of constraining the models further

Summary

- **Cross-section ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ in exclusive PHP** with HERA II data has been measured by ZEUS in the range $30 < W < 180$ GeV , $|t| < 1$ GeV^2
- **First ZEUS measurement of R at $Q^2 = 0$**:

$$R = 0.146 \pm 0.01(stat.)^{+0.016}_{-0.022}(syst.)$$

- Consistent results for 2- and 4-prong decay channels and comparable precision
- **First HERA results for R vs. |t| in photoproduction**
- Data show a **slow rise of cross-section ratio as a function of |t|**
- **No W dependence observed** within the experimental errors
- Data start to exhibit constraining power
- Overall, theoretical predictions give a reasonable description of the W, |t| and Q^2 dependence of R

Backup slides

Theory predictions: BCC hot-spots model

- **Bendova, Cepila and Contreras (BCC hot-spots) :**
- Phys. Rev. D **99**, 034025 (2019).
- model with hot spots randomly sampled in the transverse plane bound by the size of the proton
- The slope parameter b is 4.72 GeV^{-2} and it is fixed by the combined H1 and ZEUS data from 2013 for JPsi photoproduction t-distribution.
- the same b-slope for both JPsi and Psi2s

Theory predictions: JN model

- **Jan Nemchik (JN) et al. :**
- Eur. Phys. J. C **79**, no.6, 495 (2019).
- Eur. Phys. J. C **79**, no.2, 154 (2019).
- calculations have been performed for various combinations of quarkonium wave functions:
  - **Cor** (Cornell potential)
  - **BT** (Buchmüller-Tye)
  - **Pow** (Power-law potential)
  - **Log** (Logarithmic potential)

  and models for the dipole cross sections:
  - BGBK, **GBW** ← **used on the plots**
  - for each combinations calculations are performed with and w/o skewness in the gluon density
- the same *b*-slope parameters for both quarkonium states

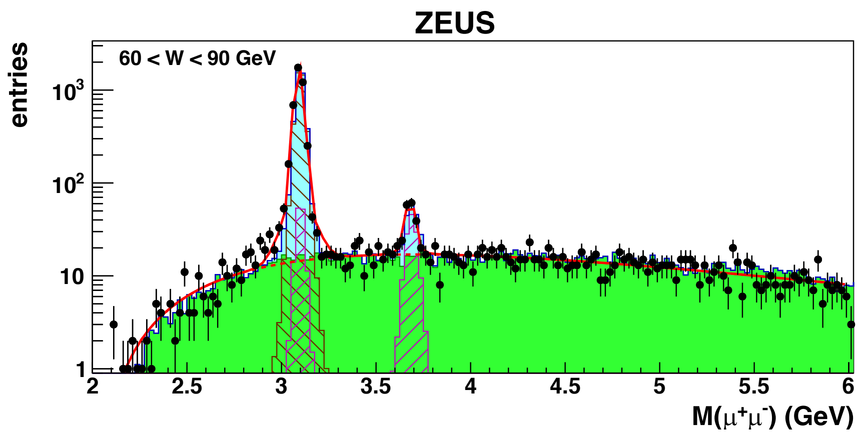
Theory predictions: LM IP-Sat_BG model

- **Lappi and Mntysaari (LM IP-Sat) :**
- the BFKL evolution plus the IP-Sat model to predict vector-meson production in ep and electronion collisions in the dipole picture
- 2S parameters from arXiv:1406.2877 (PoS DIS2014 (2014) 069)
- 1S parameters from hep-ph/0606272 (Phys.Rev. **D74** (2006) 074016)
- Calculation described in (Phys.Rev. **C83** (2011) 065202)
- **IP-Sat** dipole from fit (Phys.Rev. **D87** (2013) no.3, 034002)
- Wave function: Boosted Gaussian (**BG**), $Q^2 = 0$ GeV^2
- Skewedness and real part corrections included

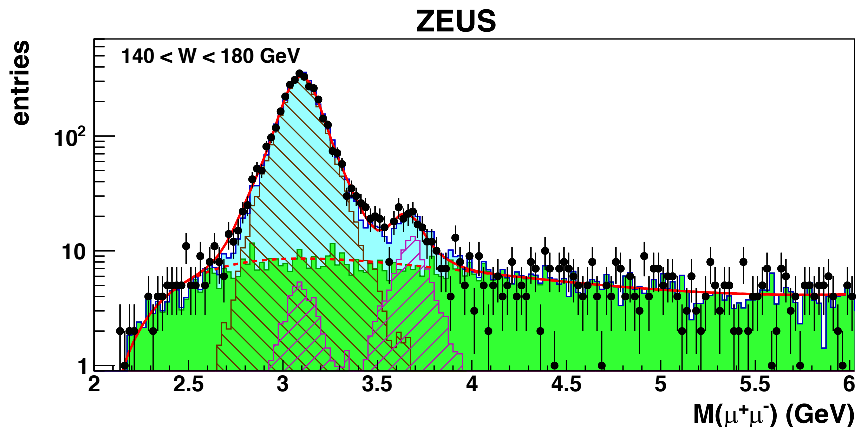
Tuning of DIFFVM MC sample

- Reweighting of MC sample at generator level
- $|t|$ dependence: $\sim \exp(-b|t|)$, generated with $b_{el} = 4.0$, $b_{pd} = 1.0$
  reweighted to:
  $b_{el} = 4.6 \pm 0.3$, $b_{pd} = 1.0 \pm 0.1$ (JPSI)
  $b_{el} = 4.3 \pm 0.7$, $b_{pd} = 0.7 \pm 0.2$ (PSI2S)
- shrinkage added by reweighting: $b = b_0 + 4.0\alpha' \log(W/W_0)$;
  $\alpha' = 0.12 \pm 0.04$ GeV^{-2}, $W_0 = 90$ GeV (elastic only)
- W dependence: $\sigma \sim W^{\delta}$,
  generated with $\delta = 0.88$ for both elastic and p.diss
  reweighted to:
  $\delta_{el} = 0.67 \pm 0.10$, $\delta_{pd} = 0.42 \pm 0.15$ (JPSI)
  $\delta_{el} = 1.10 \pm 0.20$, $\delta_{pd} = 0.70 \pm 0.30$ (PSI2S)
- M_Y dependence: $\sim \frac{1}{M_Y^{\beta}}$, generated with $\beta = 2.5$
  reweighted to $\beta = 2.4 \pm 0.3$ (both JPSI and PSI2S, p.diss only)
- **all parameters are subject to systematics checks**

Mass spectra: 2-prong events

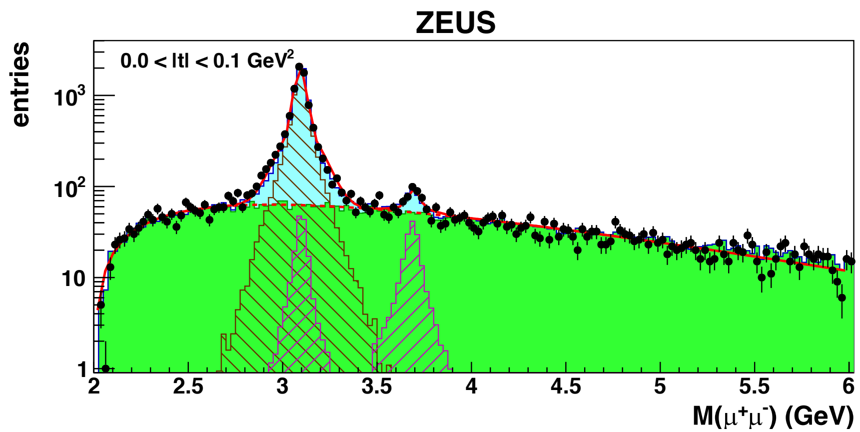


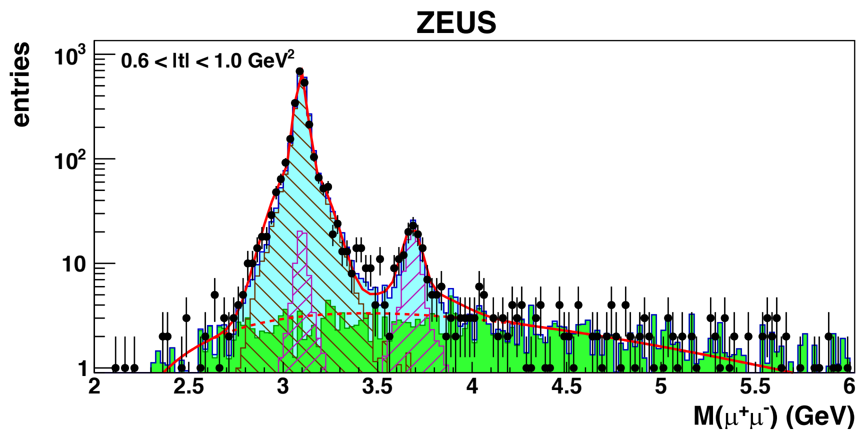
Central rapidity: σ(M) ~ 22 MeV



Backward region: σ(M) ~ 73 MeV

- Different M(μμ) resolutions with W well reproduced by the detector MC simulation





- Widths of the peaks do not change with |t|
- Bethe-Heitler background decreases significantly with increasing |t|