Recent results on charmonium production at HERA

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on behalf of

Diffraction 2014

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Recent results from H1 and ZEUS

Elastic and Proton-Dissociative Photoproduction of J/ψ Mesons at HERA.

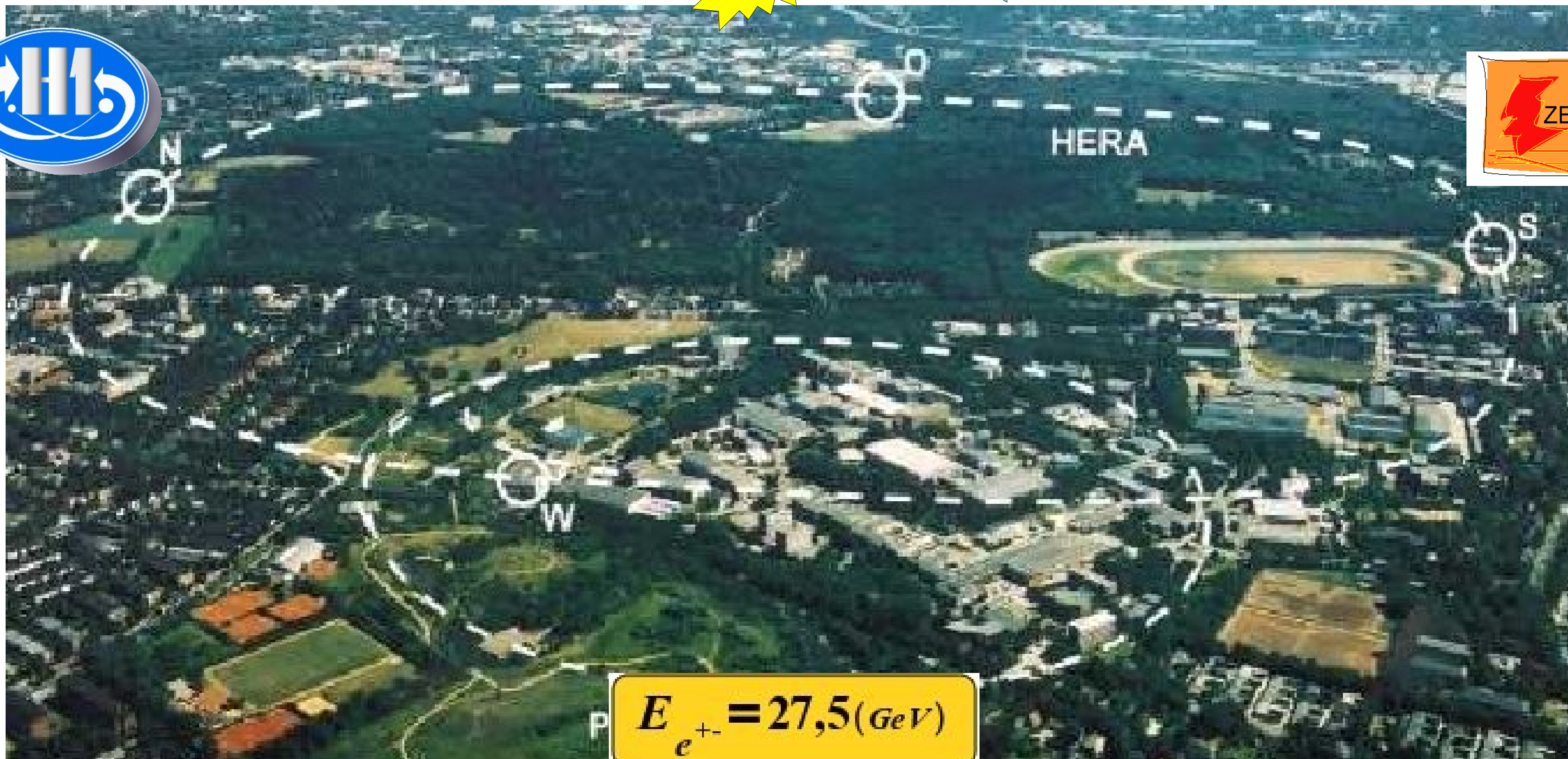
Eur. Phys. J C73 (2013) 2466, [arXiv:1304.5162]

Measurement of the cross section ratio σ(ψ(2S))/σ(J/ψ(1S)) in deep inelastic exclusive *ep* scattering at HERA.

ZEUS-prel-14-003

H1 and ZEUS experiments at HERA

e^{+-} → ← p

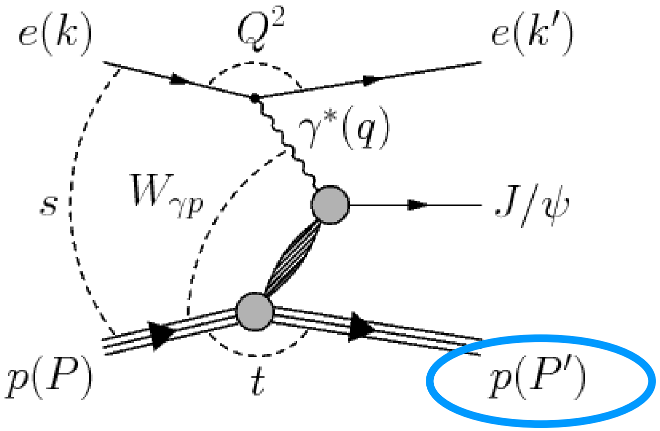


$E_{e^{+-}} = 27{,}5\,(GeV)$

	$E_p\,(GeV)$	$\sqrt{s}\,(GeV)$
high energy	820 / 920	300/318
medium energy	575	250
low energy	460	225

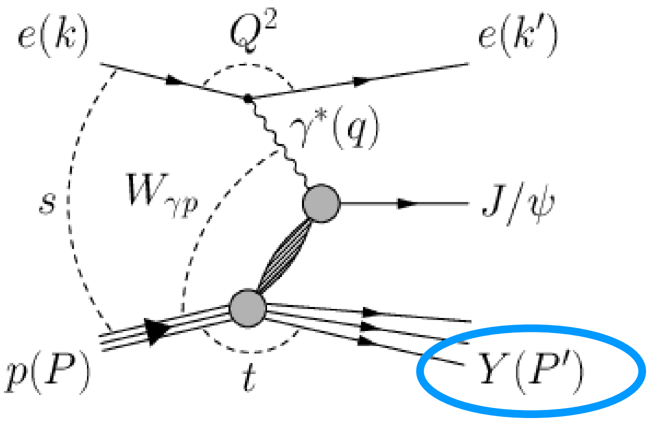
Diffractive Vector Meson production at HERA

elastic (exclusive)



$|t| < 1$ GeV²

proton dissociative



dominates at high |t|

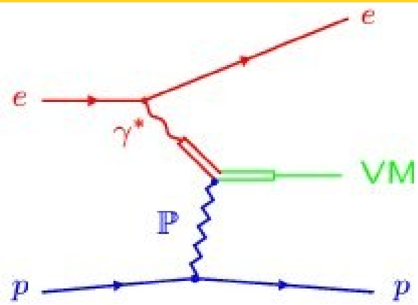
Q^2	proton virtuality	$Q^2 = -q^2 = -(k - k')^2$
W	CMS energy of the γp system	$W^2 = (q + P)^2$
t	4-mom. transfer squared at proton vtx.	$t = (P - P')^2$
x	parton momentum fraction (Bjorken *x*)	$x \approx Q^2/W^2$

HERA makes it possible, within a single experiment, to study diffractive vector meson production over a large $W_{\gamma p}$ interval with a wide range of several scales:

$$Q^2, t, M_{VM}$$

Expectations for diffractive Vector Meson production

- Regge Approach



Soft Pomeron exchange

$$\alpha_P(t) = \alpha_0 + \alpha' t$$

$$\alpha_0 = 1.08, \alpha' = 0.25\, GeV^{-2} \quad \text{(DL)}$$

$$\frac{d\sigma}{dt} \propto e^{bt} \left(\frac{W_{\gamma p}}{W_0} \right)^{\delta} \qquad \delta = 4(\alpha_0 - 1)$$

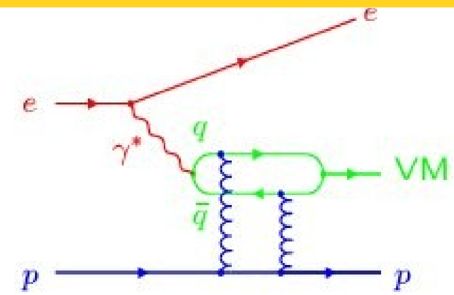
$$b = b_0 + 4\alpha' \ln\left(\frac{W_{\gamma p}}{W_0} \right)$$

For light VM at $Q^2 \approx 0, t \approx 0$ expect

Slow rise of $\sigma \propto W_{\gamma p}^{0.22 \ldots 0.32}$

Shrinkage $b = b(W_{\gamma p})$

- pQCD Approach



Exchange of ≥ 2 gluons

1. Photon fluctuates into $q\bar{q}$ dipole
2. Dipole proton interaction through a gluon ladder
3. $q\bar{q}$ recombines into VM

$$\sigma \propto [x g(x, Q^2)]^2$$

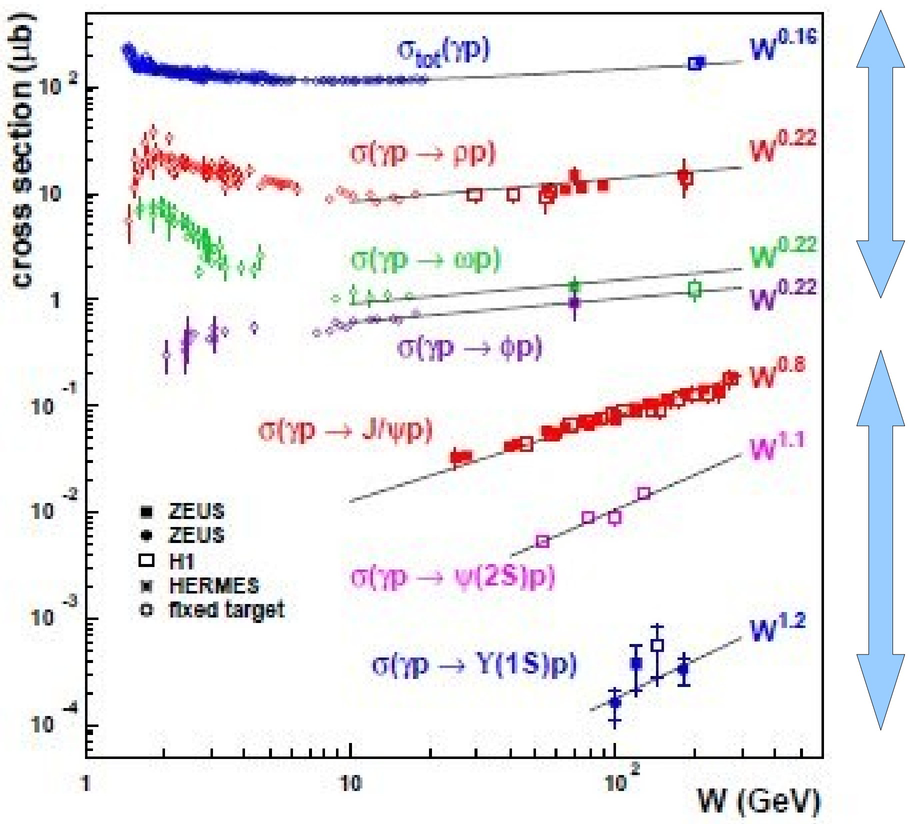
Expected to work if hard scale present

Steep rise with increasing $W_{\gamma p}$ due to gluon density increase at low x

No shrinkage

Energy dependence in Photoproduction

$$\sigma(\gamma p \to V p) \; vs \; W_{\gamma p}$$



$$\sigma \sim W^{\delta}$$

- Low mass VM $(\rho, \omega, \phi, M_V^2 \simeq 1\, GeV^2)$:
  no perturbative scale
  ==> weak energy dependence

  soft regime

- High mass VM $(J/\psi, \psi', \Upsilon)$:
  perturbative scale
  ==> strong energy dependence

  hard regime

VM production at HERA: transition between soft and hard regimes

Elastic and Proton-Dissociative Photoproduction of J/ψ Mesons at HERA ***[arXiv:1304.5162]***

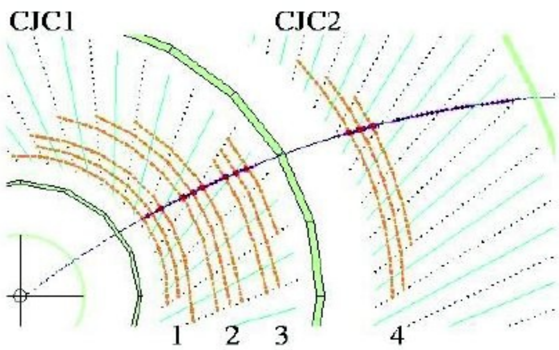
Motivation and experimental technique

- Extend energy range to lower $W_{\gamma p}$

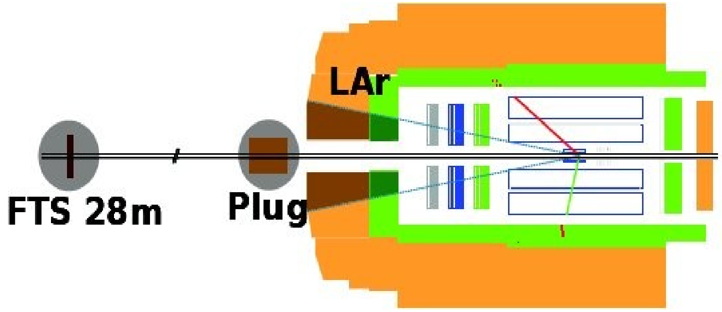
  Use data from HERA low energy run, $E_p = 460\, GeV$

- Use H1 Fast Track Trigger (FTT)

  * purely based on track information
  * trigger both decay channels: $J/\psi \dashrightarrow \mu^+\mu^-$, $J/\psi \dashrightarrow e^+e^-$
  * measure elastic and p-diss. processes with the same trigger



- Use forward detectors FTS, Plug, LAr to tag p-diss. process



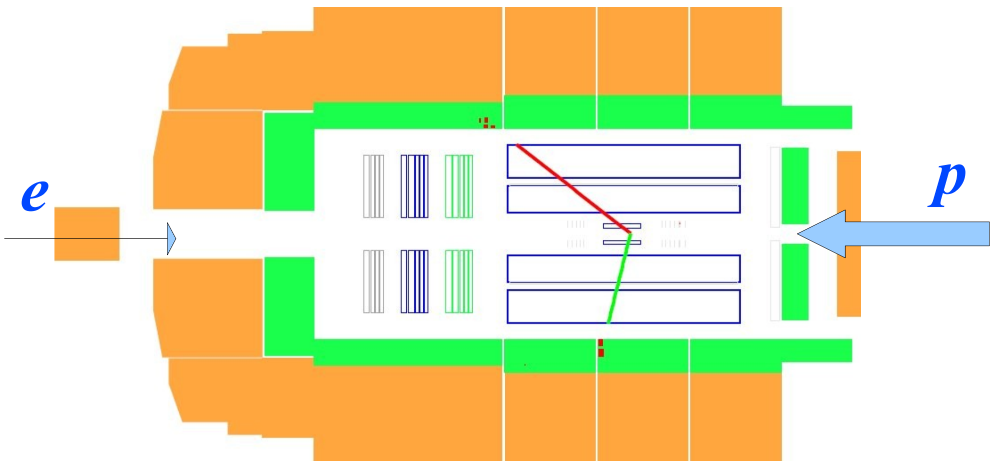
- Measure proton dissociation precisely at low |t| values :

  use Regularised Unfolding technique to disentangle elastic and p-diss. processes

Analysis data samples

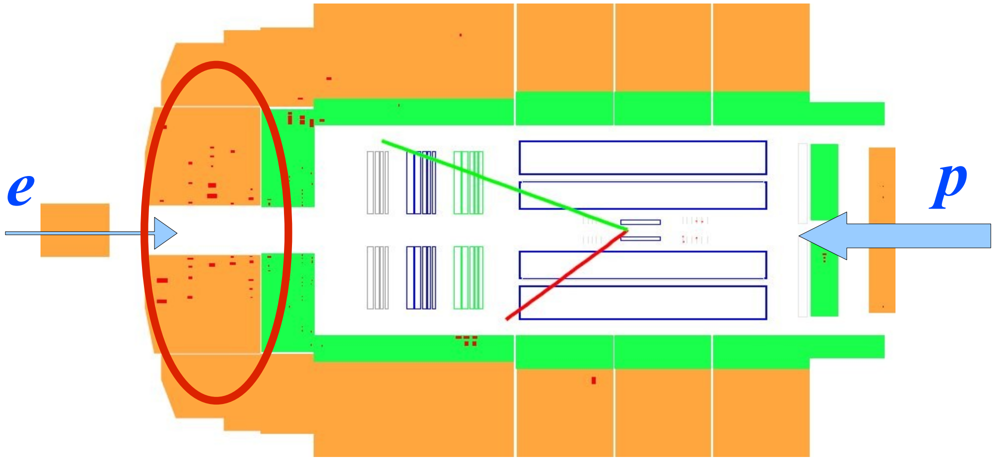
Data Set	E_p	Process	M_Y	$<Q^2>$	|t|	$W_{\gamma p}$	L
HE	920 GeV	*elastic* *p−diss*	m_p $m_p - 10\,GeV$	$0.1\,GeV^2$	$<8\,GeV^2$	$40-110\,GeV$	$130\,pb^{-1}$
LE	460 GeV	*elastic* *p−diss*	m_p $m_p - 10\,GeV$	$0.1\,GeV^2$	$<8\,GeV^2$	$25-80\,GeV$	$11\,pb^{-1}$

Elastic process



$M_Y = m_p$

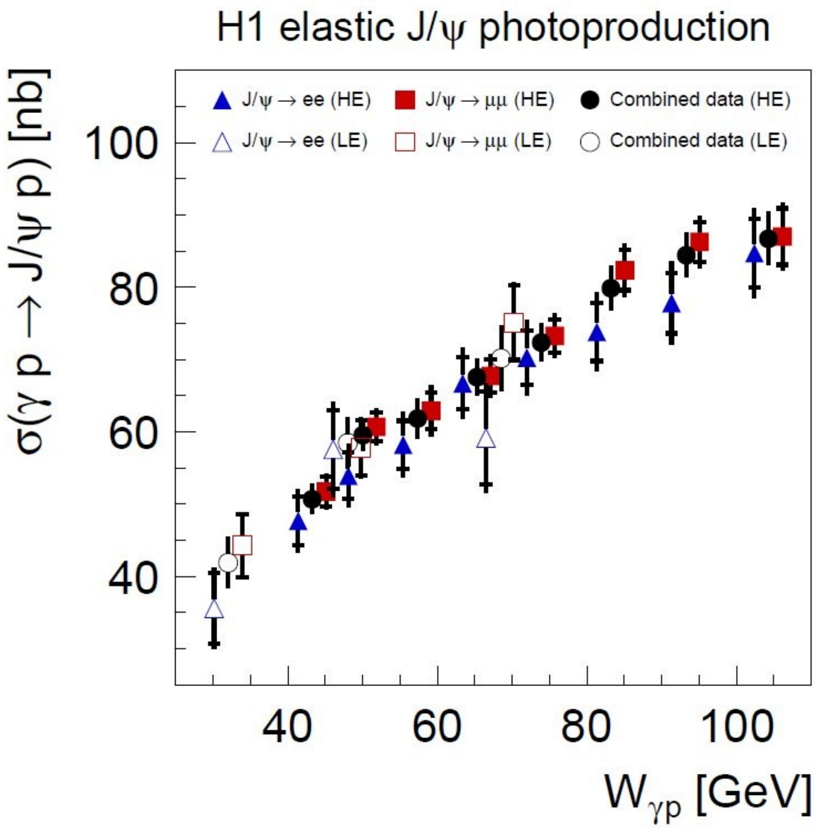
Proton dissociation process

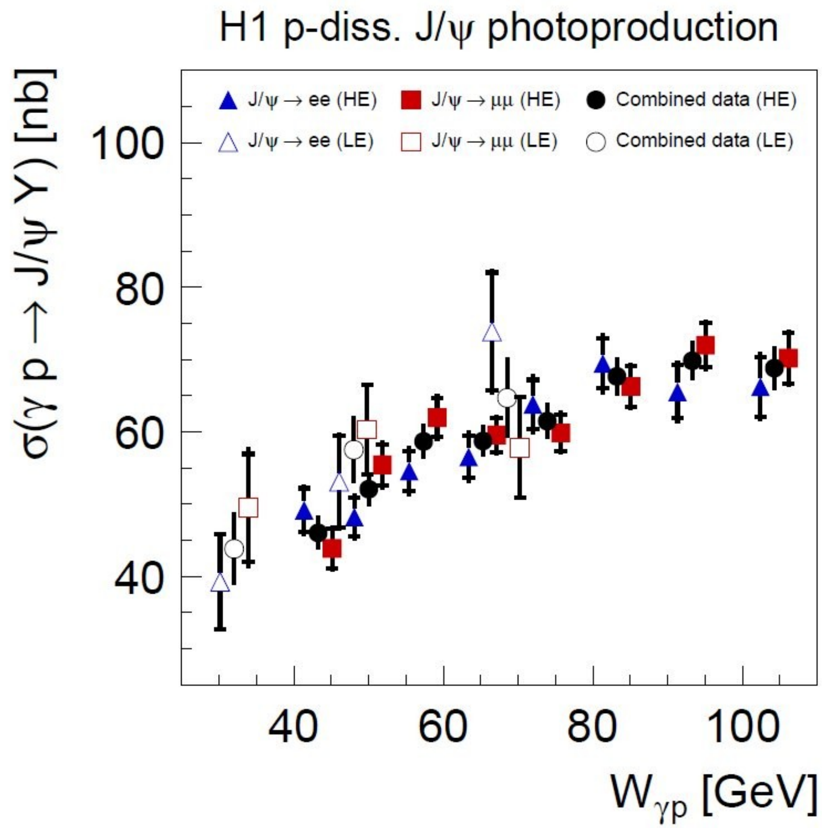


$m_p < M_Y < 10\,GeV$

Combined $J/\psi \rightarrow e^+e^-, \mu^+\mu^-$ cross sections

Elastic and p-diss. Cross Sections measured **simultaneously** using Regularised Unfolding

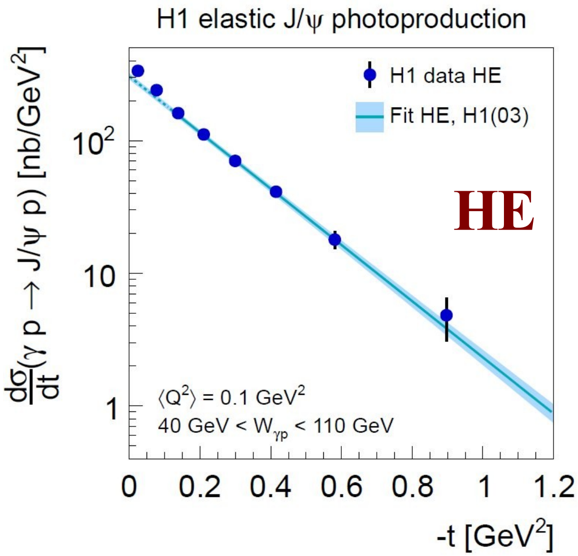


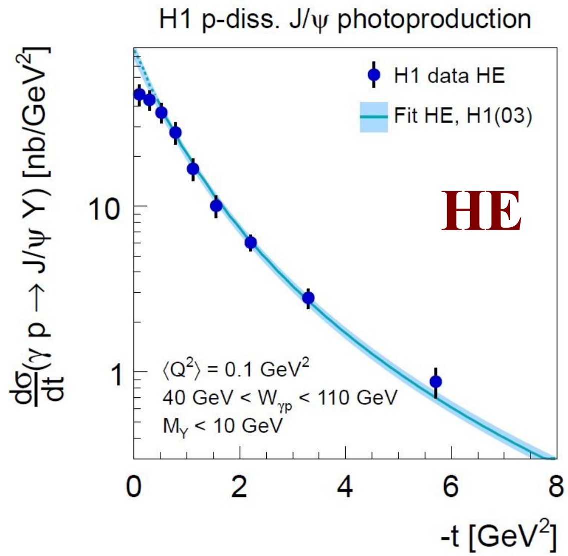


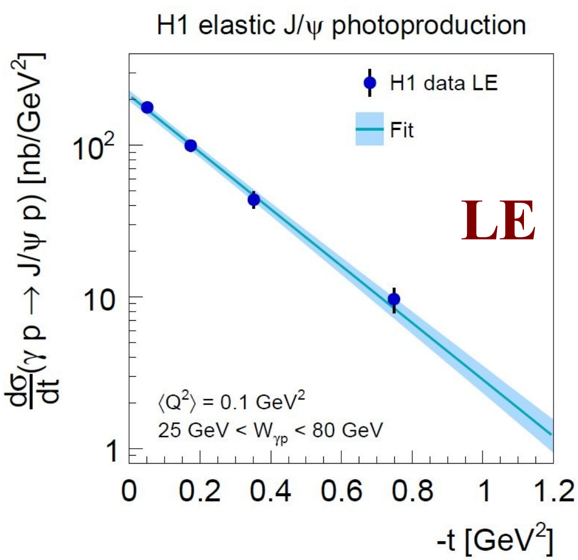
- Combination of decay channels separately for elastic and p-diss. processes by χ^2 minimisation with
  - full statistical error matrix
  - correlated systematic errors
  - applying common uncertainties after the combination

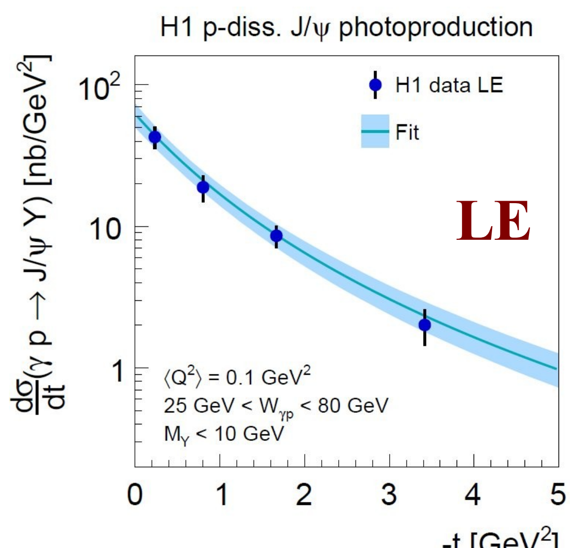
Elastic and P-diss. cross sections vs. |t|

Elastic **P-diss.**









Parameterisation:

- Elastic

  $$d\sigma/dt = N_{el}\, e^{-b_{el}|t|}$$

- P-diss.

  $$d\sigma/dt = N_{pd}(1+(b_{pd}/n)|t|)^{-n}$$

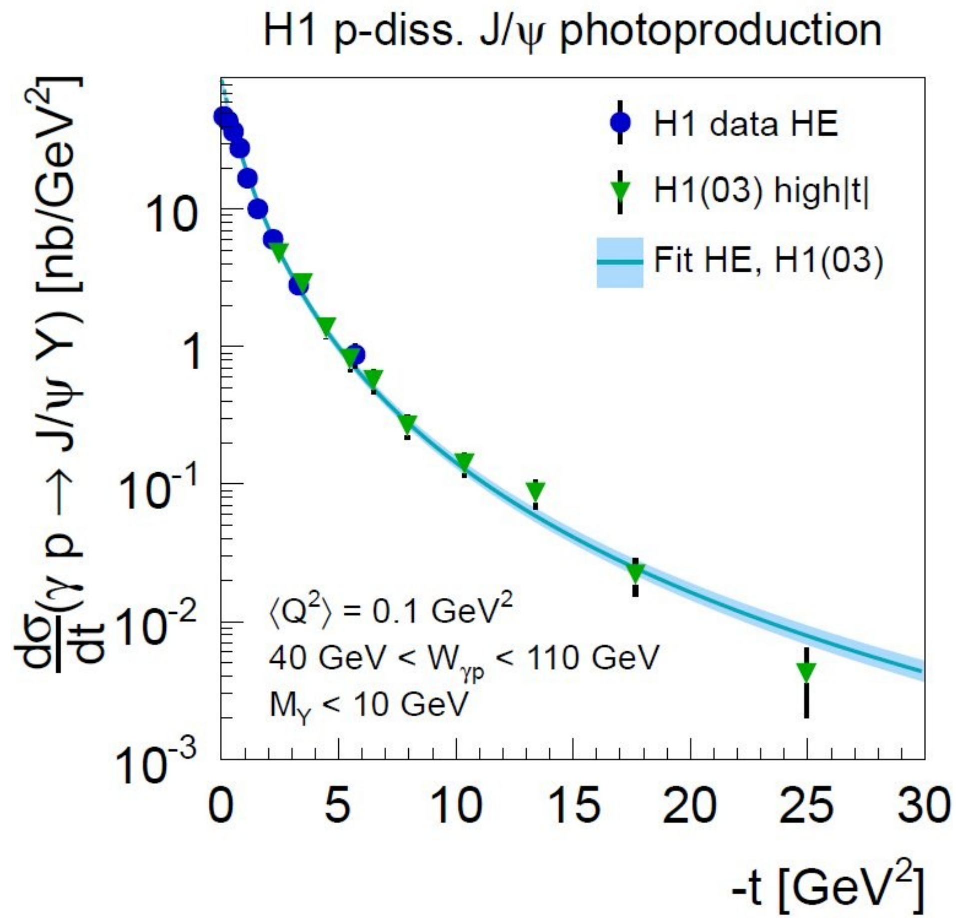
- Simultaneous fit of elastic and p-diss. cross sections

HE: fit includes previous high |t| data H1(03) [PL B568(2003) 205]

HE
$$b_{el} = 4.88 \pm 0.15\, GeV^2$$
$$b_{pd} = 1.79 \pm 0.12\, GeV^2$$
$$n = 3.58 \pm 0.15$$

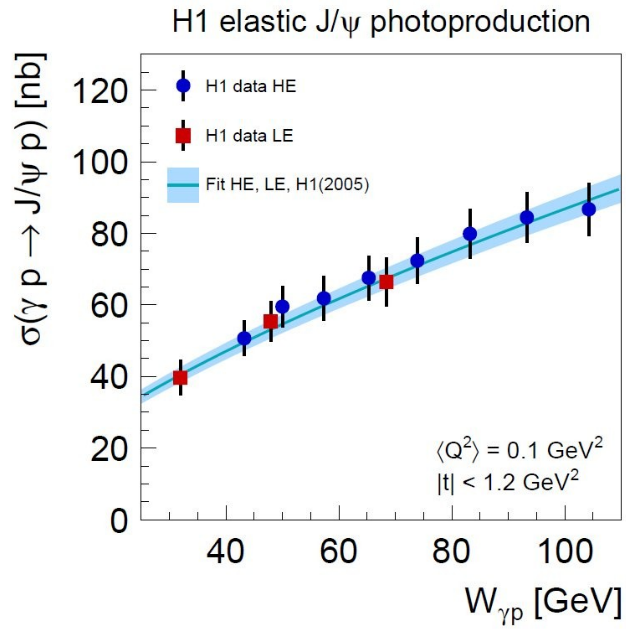
LE
$$b_{el} = 4.3 \pm 0.2\, GeV^2$$
$$b_{pd} = 1.6 \pm 0.2\, GeV^2$$
$$n = 3.58 (\text{fixed})$$

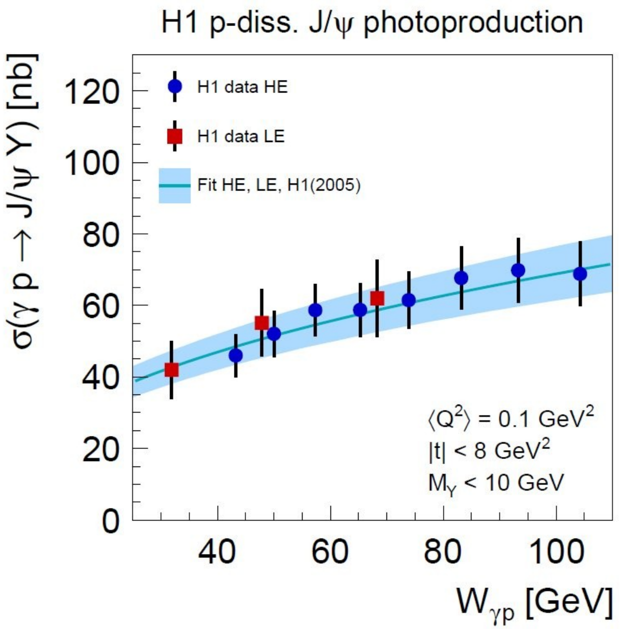
P-diss. cross section vs. t



- Comparison with the previous high |t| measurement [H1(03)]
- High $|t|$ data extrapolated to match $W_{\gamma p}$, Q^2 and M_Y range of present data
- The new p-diss. measurement extends the reach to small values of |t|.
- Good agreement in the overlap region

Elastic and P-diss. cross sections vs. $W_{\gamma p}$





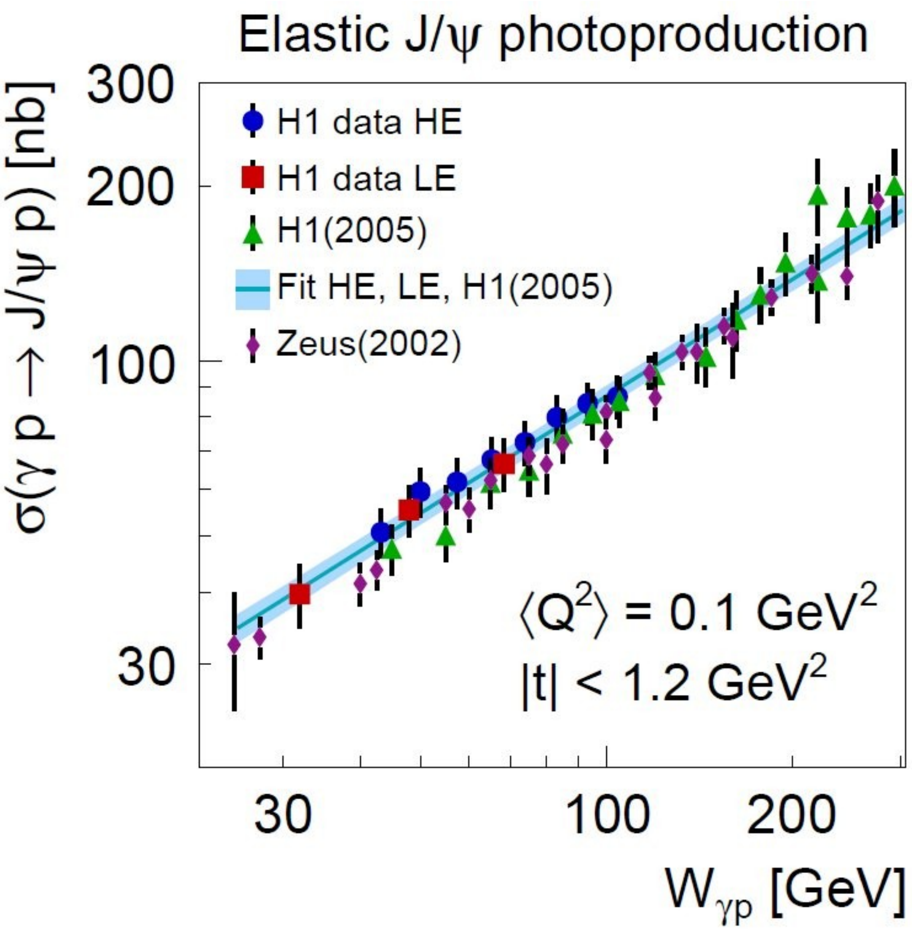
Fit includes H1(2005) [hep-ex/0510016]

- Simultaneous fit, taking into account correlations between elastic and p-diss. cross sections
- Fit function parameterised as: $\sigma = N(W_{\gamma p}/W_0)^{\delta}$

  with $W_0 = 90\,GeV$ $\quad \delta(t) = 4(\alpha(t) - 1)$

- Results: $\delta_{el} = 0.67 \pm 0.03 \qquad \delta_{pd} = 0.42 \pm 0.05$
- These values are in agreement with previous H1 measurements

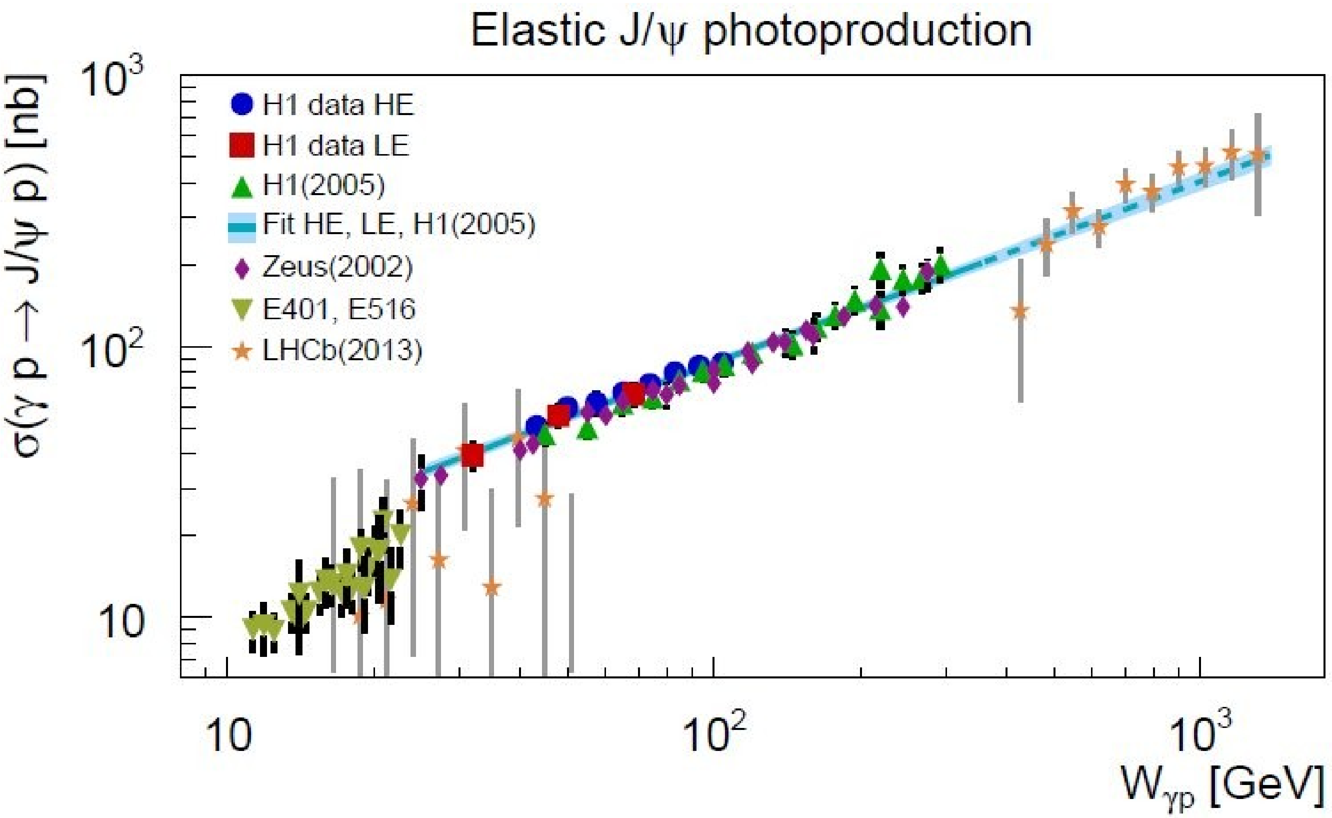
Comparison to other HERA measurements



- Large overlap with previous H1 and ZEUS [hep-ex/0201043] measurements
- Similar precision in range $30\,GeV < W_{\gamma p} < 110\,GeV$

Good agreement of HERA experiments

HERA data in comparison with fixed target and LHCb data

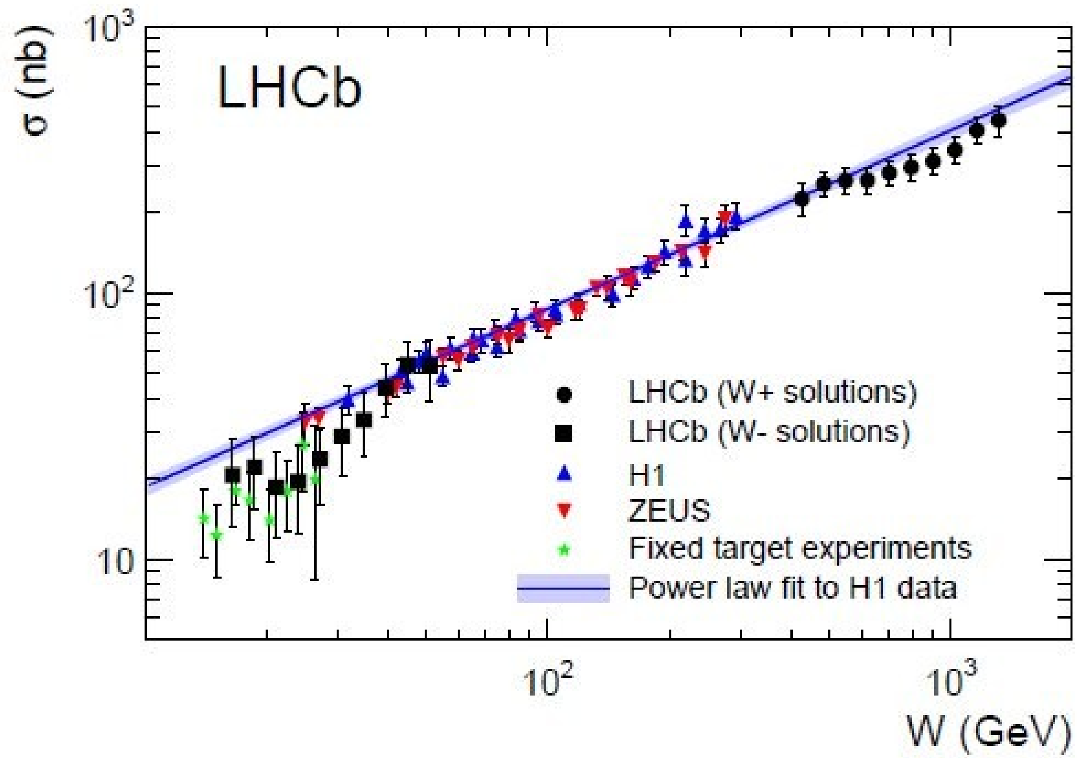


- Fixed target and LHCb data

[PRL 48(1982) 73]
[PRL 52(1984) 795]
[arXiv:1301.7084]

- New measurements in the transition region from fixed target to HERA data
- Fixed target data: steeper slope, lower normalisation ?
- H1 power-law fit , extrapolated to higher $W_{\gamma p}$, describes LHCb data well

HERA data in comparison with fixed target and LHCb data

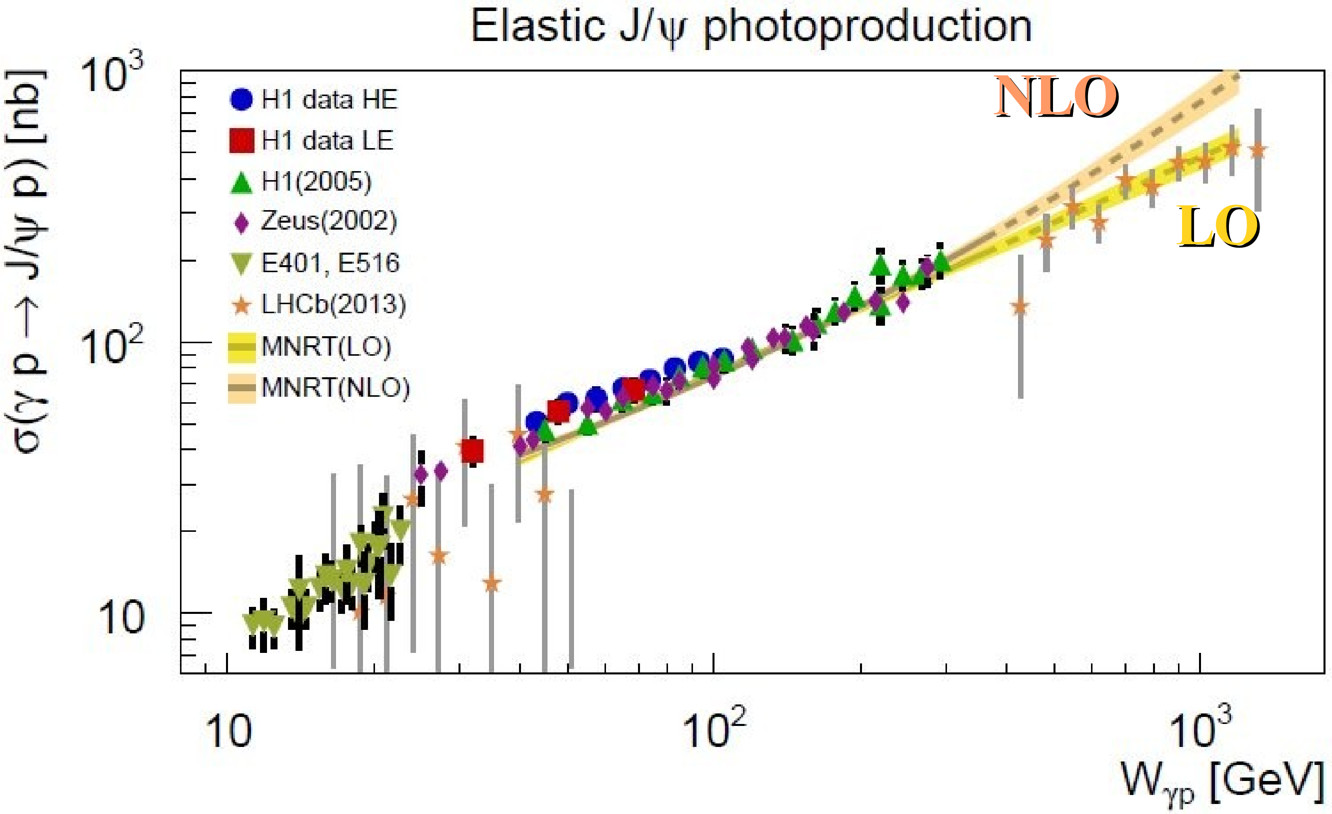


- Fixed target and LHCb data

[PRL 48 (1982) 73]
[PRL 52 (1984) 795]
[PL B316 (1993) 197]
[arXiv:1401.3288v2]

- New measurements in the transition region from fixed target to HERA data
- Fixed target data: steeper slope, lower normalisation ?
- An extrapolation of power-law obtained by H1 , describes LHCb data **marginally**

Comparison to QCD calculations

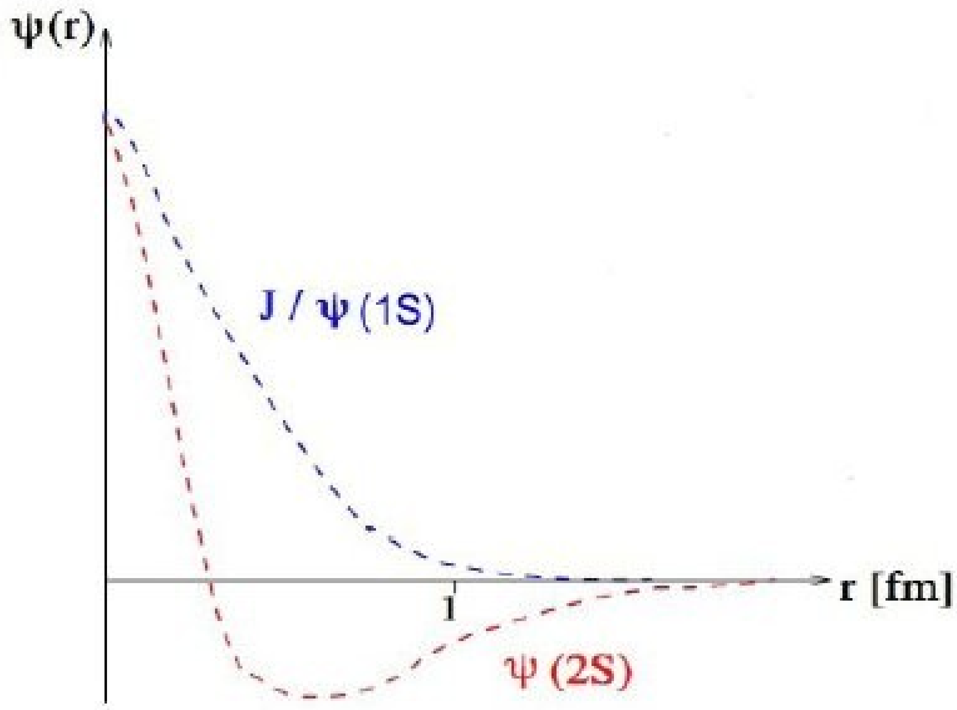


- LO and NLO fits to previous J/ψ measurements at HERA
  (A.Martin et al. [arXiv:0709.4406])
- Note: NLO gluon density determined from fits to J/ψ data of H1 (2005) and ZEUS (2002) (thus, agreement with HERA data is expected)
- Both fits extrapolated to higher $W_{\gamma p}$
- LO fit describes LHCb data
- High precision J/ψ data give important input to gluon at small x

Measurement of the Cross Section Ratio $\sigma(\psi(2S))/\sigma(J/\psi(1S))$ in Deep Inelastic exclusive ep scattering at HERA

(ZEUS-prel-14-003)

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



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

- Tests the dynamics of the hard process
- Sensitive to radial charmonium wave function

$\psi(2S)$ wave function is different from $J/\psi(1S)$ wave function:

- has node at ~ 0.35 fm
- $<r^2(\psi(2S))> \approx 2 <r^2(J/\psi(1S))>$

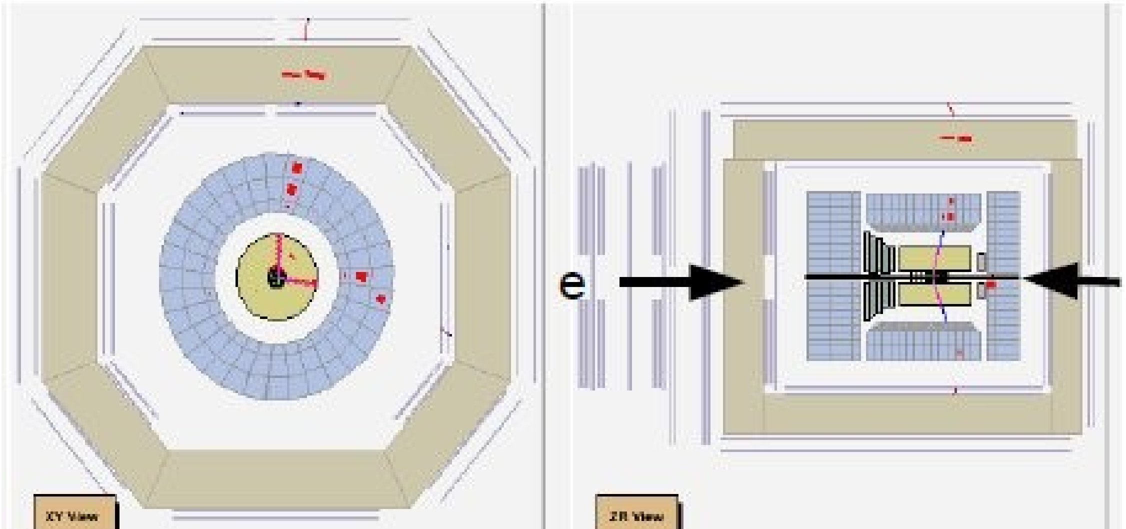
PQCD model prediction: [J.Nemchik et al., 1994, 1998]

* R ≈ 0.17 (photoproduction)

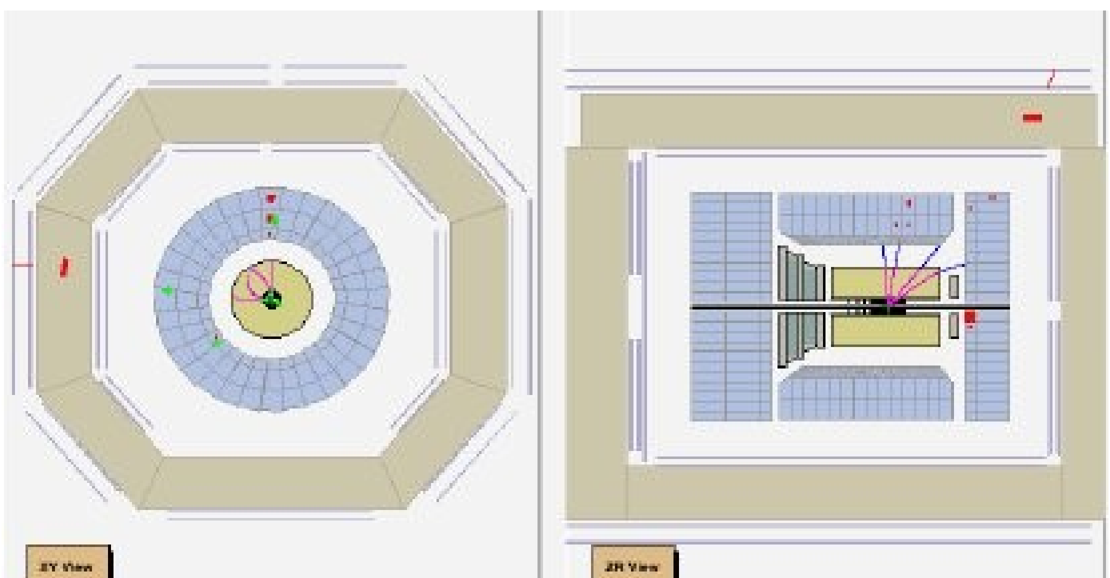
* R rises with Q^2 (DIS)

Data samples: 2-prong and 4-prong events

HERA II data (2003-2007): *Int.Lumi= 354 pb*$^{-1}$



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



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

$J/\psi(1S)\rightarrow\mu^+\mu^-$
1738 *ev.*

$\psi(2S)\rightarrow\mu^+\mu^-$
66 *ev.*

$\psi(2S)\rightarrow J/\psi\,\pi^+\pi^-;\ J/\psi\rightarrow\mu^+\mu^-$
82 *ev.*

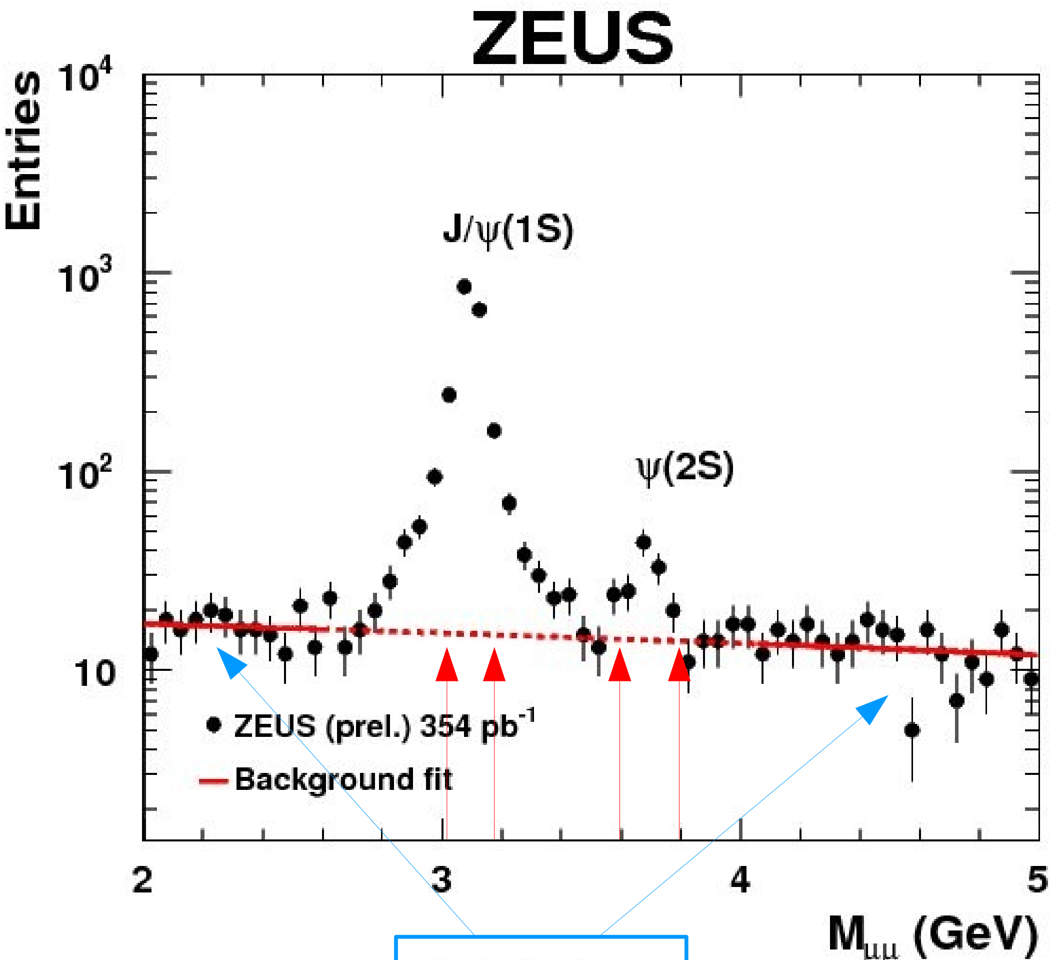
$30\leq W\leq 210\ GeV$

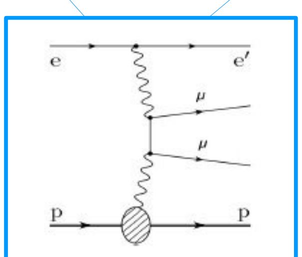
$5\leq Q^2\leq 70\ Gev^2$

$|t|\leq 1\ Gev^2$

- Scattered *e* with E >10 GeV reconstructed in RCAL
- Two reconstructed tracks identified as $\mu^+\mu^-$
  For $\psi(2S)\rightarrow J/\psi\,\pi^+\pi^-$ in addition two pion tracks from common vertex
- Detector otherwise empty (disregarding noise)
- Scattered *p* undetected

2-prong signal: $J/\psi(1S) \to \mu^+\mu^-$, $\psi(2S) \to \mu^+\mu^-$

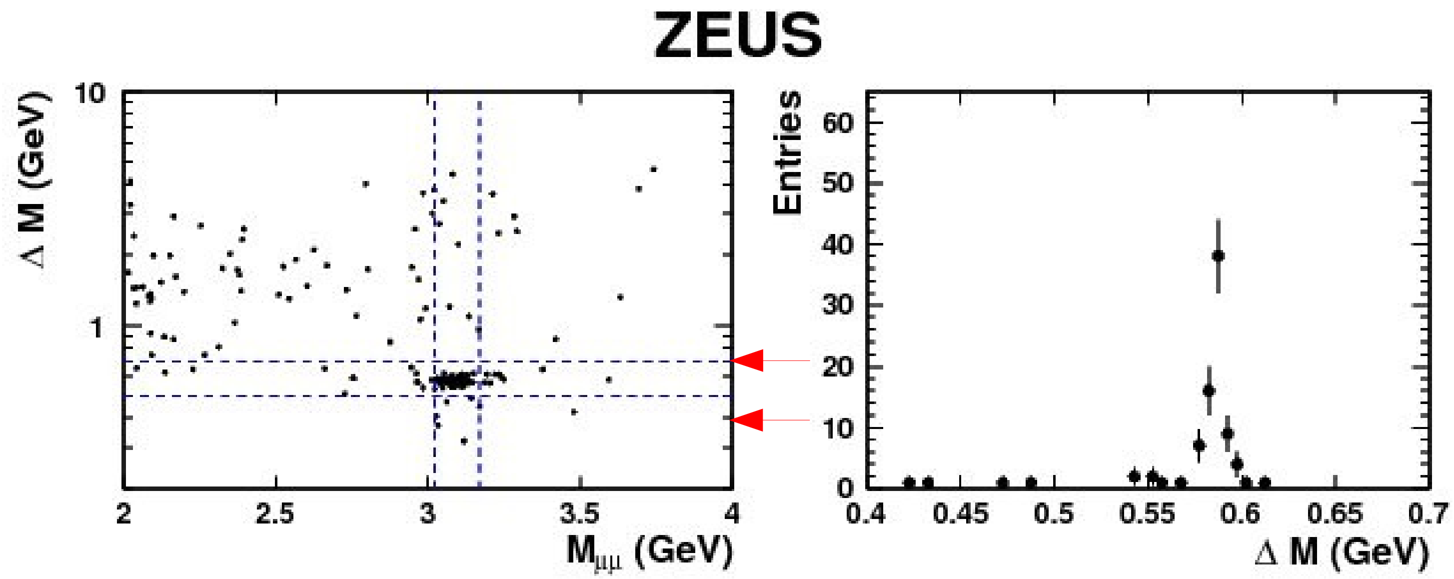




Background

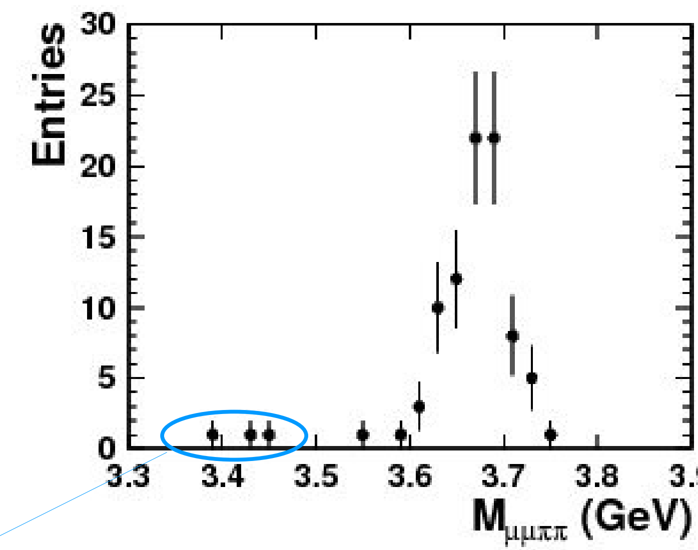
- Straight line background fit using the sidebands $2 < M_{\mu\mu} < 2.62\, GeV$ and $4.05 < M_{\mu\mu} < 5\, GeV$
- J/ψ and ψ′ mass windows for the ratio $3.02 < M_{\mu\mu} < 3.17\, GeV$ and $3.59 < M_{\mu\mu} < 3.79\, GeV$
  Window widths different due to changing mass resolution
- All events above background in these windows used for the ratio $\sigma_{\psi(2S)} / \sigma_{J/\psi}$
- MC study: this choice minimizes systematic uncertainty

4-prong signal: $\psi(2S) \rightarrow J/\psi(1S)\pi^+\pi^-$



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

• ZEUS (prel.) 354 pb^{-1}



Windows:

J/ψ: $3.02 < M_{\mu\mu} < 3.17\ GeV$

"ψ´": $0.5 < \Delta M < 0.7\ GeV$

$M_{\mu\mu}$ in J/ψ window

background: ≤ 3 events

Ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$: measurement results

$Int.\ Lumi = 354\ pb^{-1}$

$30 \leq W \leq 210\ GeV$

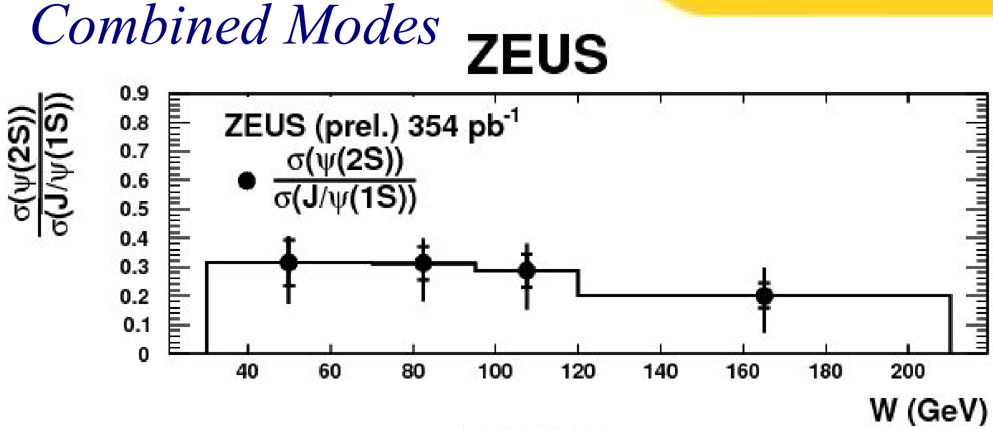
$5 \leq Q^2 \leq 70\ GeV^2$

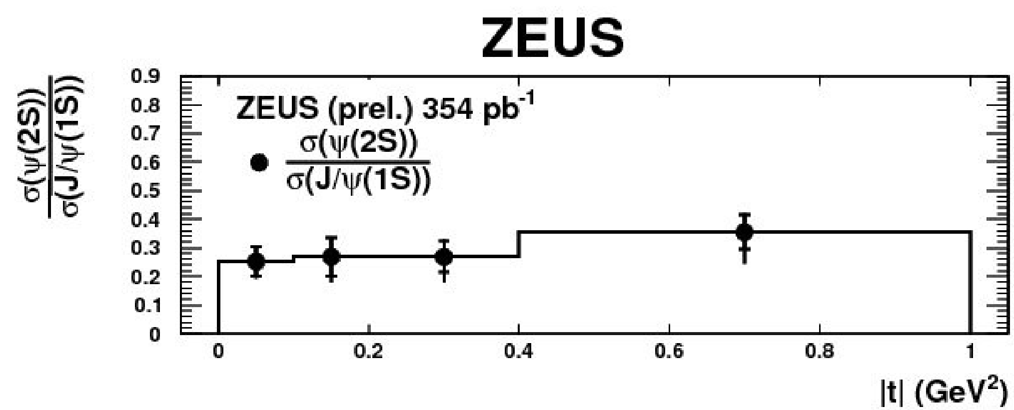
$|t| \leq 1\ GeV^2$

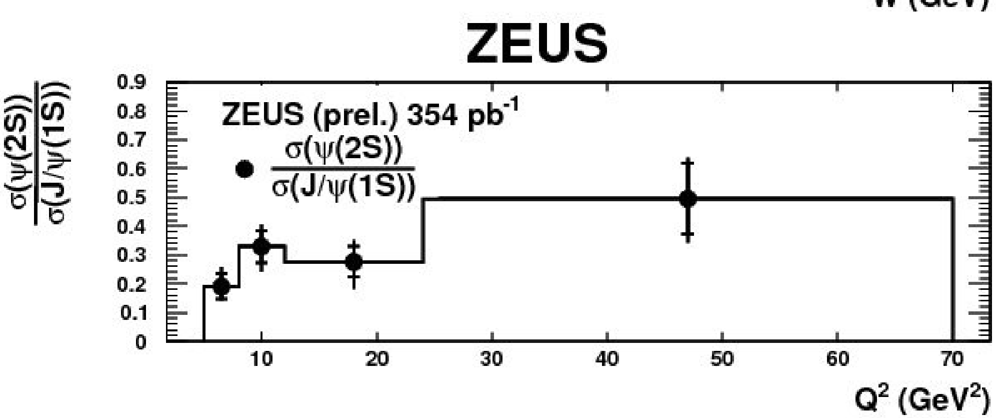
3 Measurements

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

Combined Modes





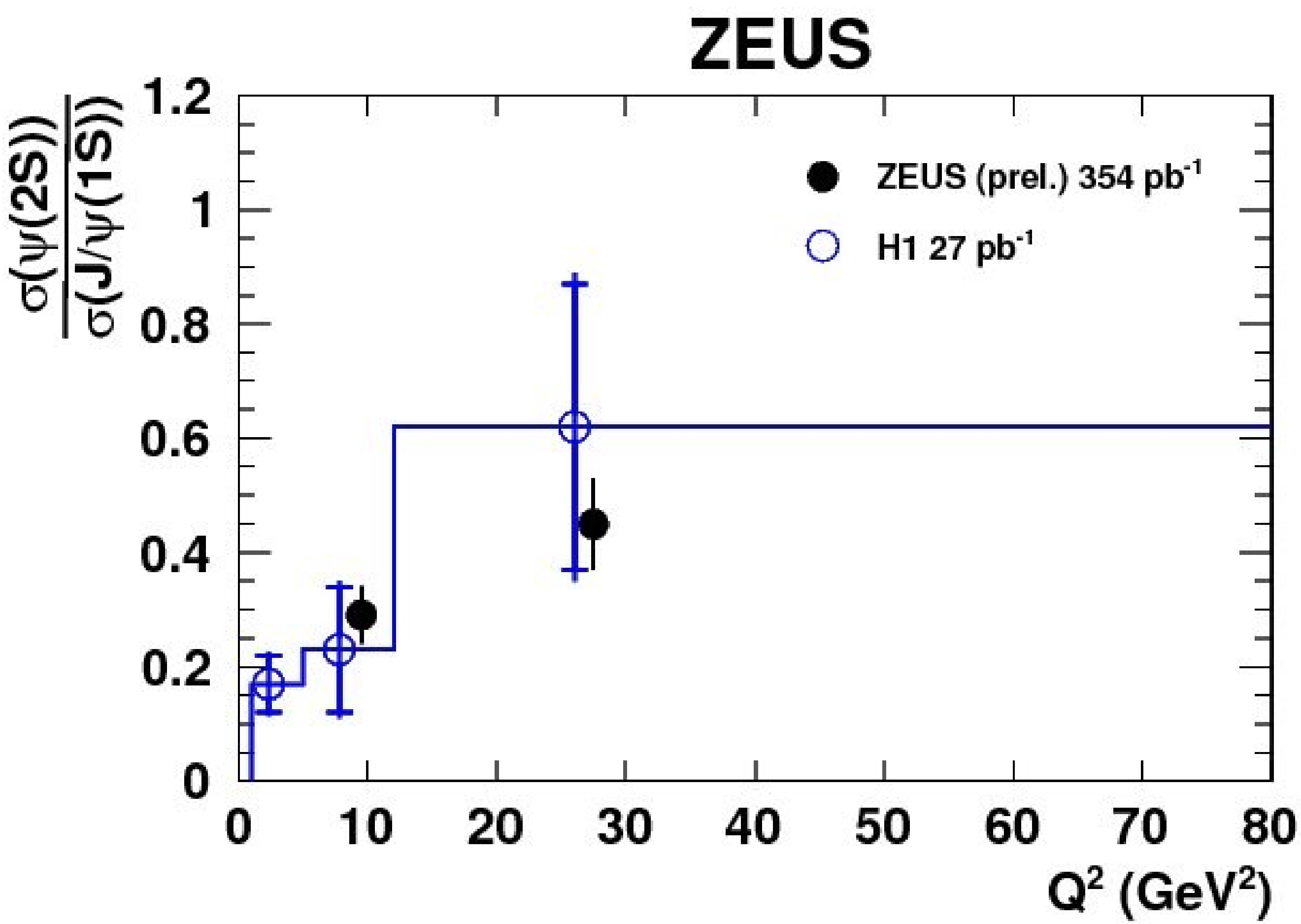


Cross section ratio:

- Increases with Q^2
- Independent of W and t

Ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$: H1 - ZEUS comparison

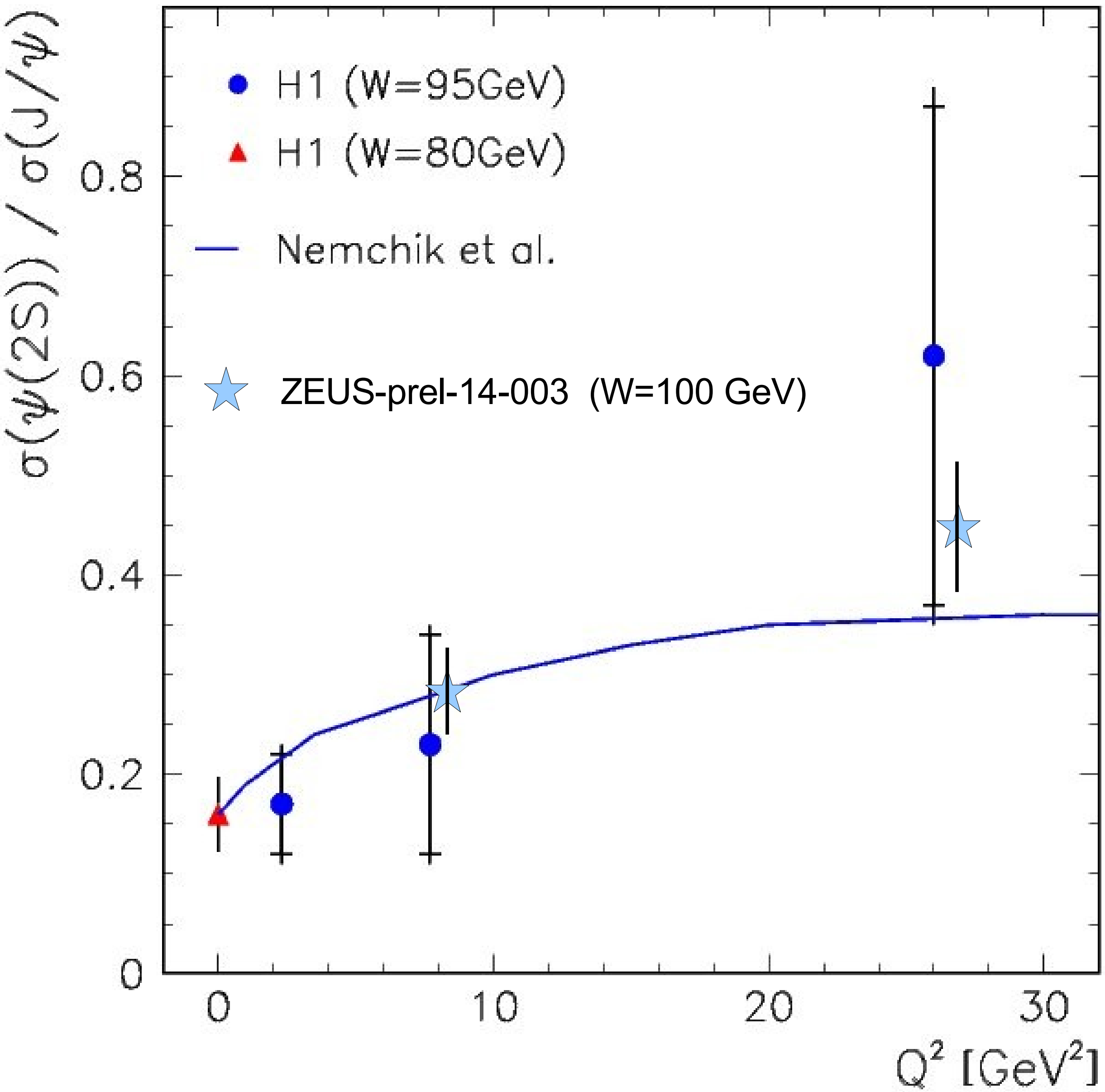
ZEUS data: Q^2 bins 5–12 , 12–80 GeV² (as used by H1 [Eur. Phys. J. **C10** (1999) 373])



$$40 < W < 180\, GeV$$
$$1 < Q^2 < 80\, GeV^2$$

- Good agreement between H1 and ZEUS data
- Ratio $\dfrac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ increases with Q^2
- Significantly improved precision with ZEUS HERA II data

Comparison to theory



H1: Eur. Phys. J C10 (199) 373

- Predictions of Nemchik et al. agree well with the new ZEUS HERA II results.
  J. Exp.Theor. Phys.86 (1998) 21, [arXiv:hep-ph/9712469v1]

Conclusions

- Elastic and proton dissociative diffractive J/ψ photoproduction
  differential cross section as function of $|t|$ and $W_{\gamma p}$
  Kinematic range: $|t| < 8\,GeV^2,\ 25 < W_{\gamma p} < 110\,GeV$
- $J/\psi \rightarrow \mu^+\mu^-,\ e^+e^-$ decay channels combined and interpreted using fits.
- Elastic and p-diss. cross sections extracted simultaneously using unfolding.
- For the first time at HERA:
  p-diss. diffractive J/ψ production measured precisely at small $|t|$.
- HERA proton low energy run: adds information at lower $W_{\gamma p}$ values.
- Good agreement with previous HERA measurements.
- QCD inspired model is able to describe HERA and LHC data.
- Fixed target data differ in slope and possibly in normalisation.

ZEUS

- New measurement of cross section ratio $\sigma(\psi(2S))/\sigma(J/\psi(1S))$
  in exclusive DIS using the high statistics HERA II data
  Kinematic range: $5 \leq Q^2 \leq 70\,GeV^2,\ |t| \leq 1\,GeV^2,\ 30 \leq W \leq 210\,GeV$
- Precision significantly improved compared to previous H1 result (HERA I).
- Ratio increases with Q^2 and is independent of W and $|t|$.
- Good agreement with previous H1 HERA I results and with theory.

Backup

Comparison to new QCD Calculations

S.P. Jones, A.D. Martin, M.G. Ryskin and T. Teubner **[arXiv:1307.7099v1]**

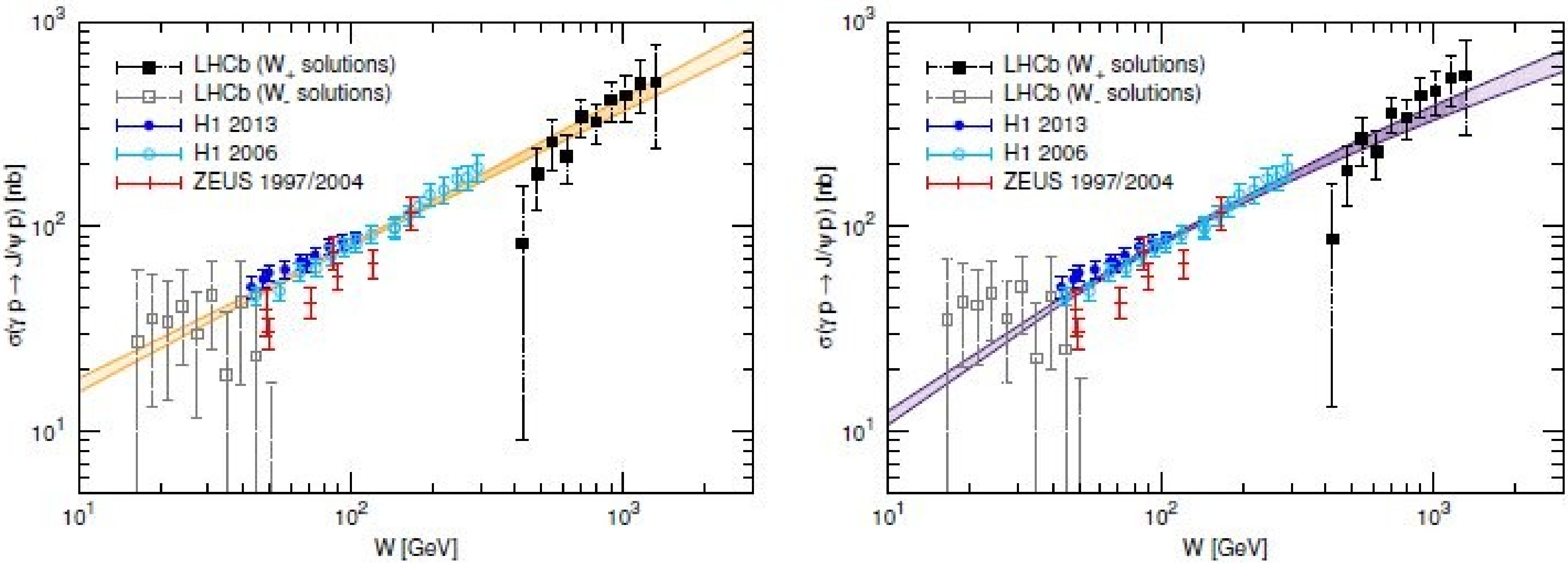


Figure 3: LO (left panel) and NLO (right panel) fits to exclusive J/ψ data. Photoproduction data from H1 [7, 4] and ZEUS [21, 22] are displayed along with the LHCb [5] W_+ and W_- solutions as described in the text. The darker shaded areas indicate the region of the available data. Included in the fit but not displayed are the H1 [7] and ZEUS [22] electroproduction data. The widths of the bands indicate the uncertainties of the fitted cross section resulting from the 1σ experimental error.

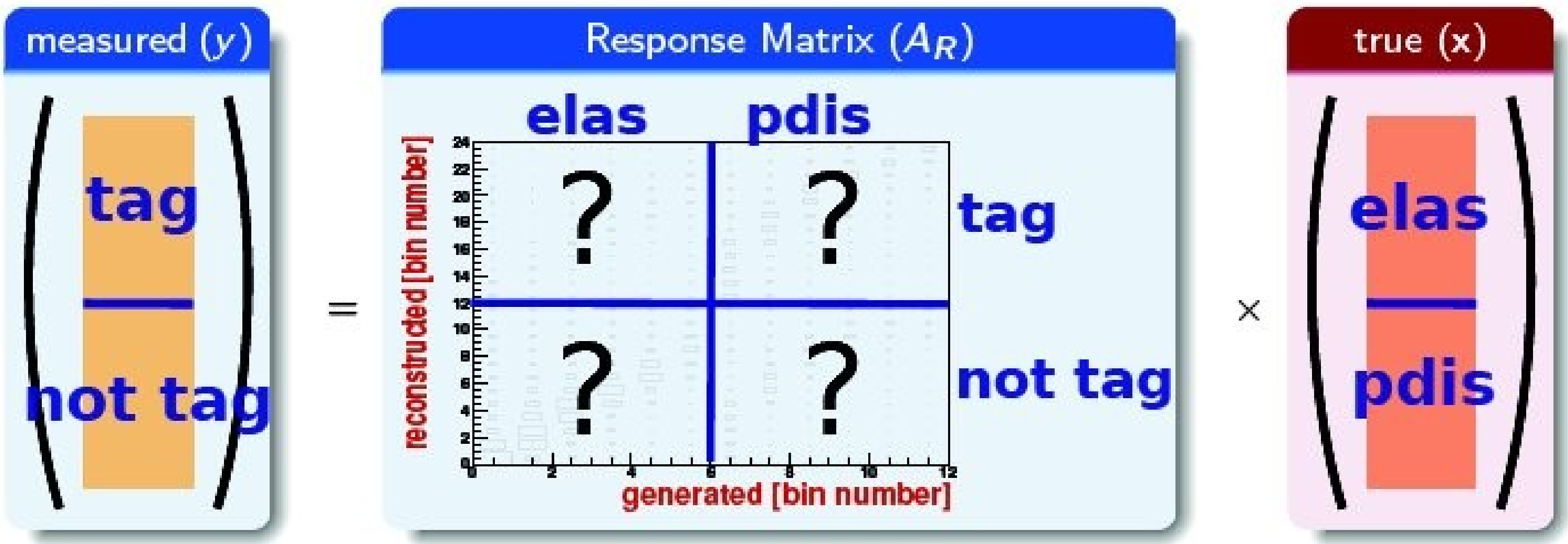
Regularised Unfolding of the Cross Sections

(F. Huber)

- Use regularised unfolding for disentangling of elastic and proton dissociative process and for taking correctly into account the migrations.
- Unfolding is done to true variables.

$$y = A_R \cdot x$$

A_R	Response matrix
x	true number of events
y	reconstructed number of events
L	regularisation matrix



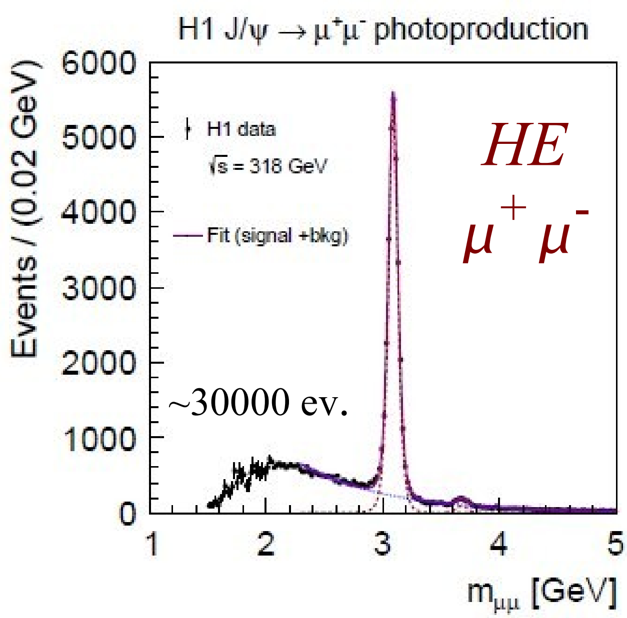
Vector filled with number of signal events from mass distribution fits.

Matrix filled with MC.

Output of unfolding

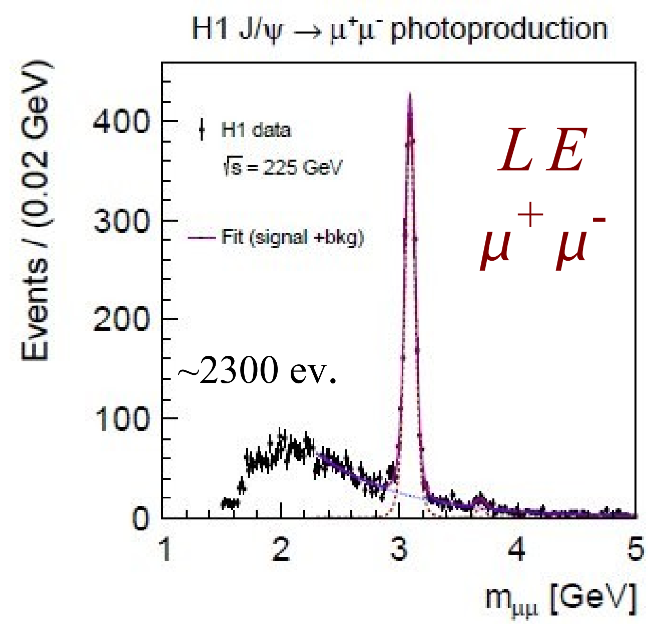
Result:
- Separate measurements of σ_{el}, σ_{pd}
- First σ_{pd} measurement at low |t|

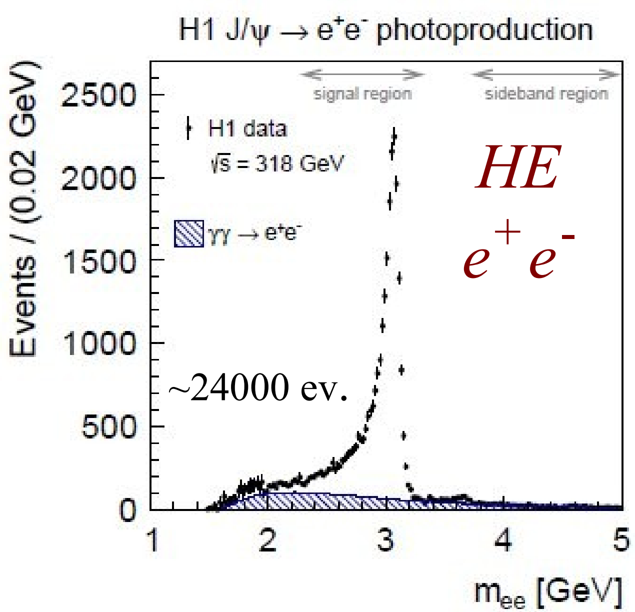
Invariant Mass Distributions



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

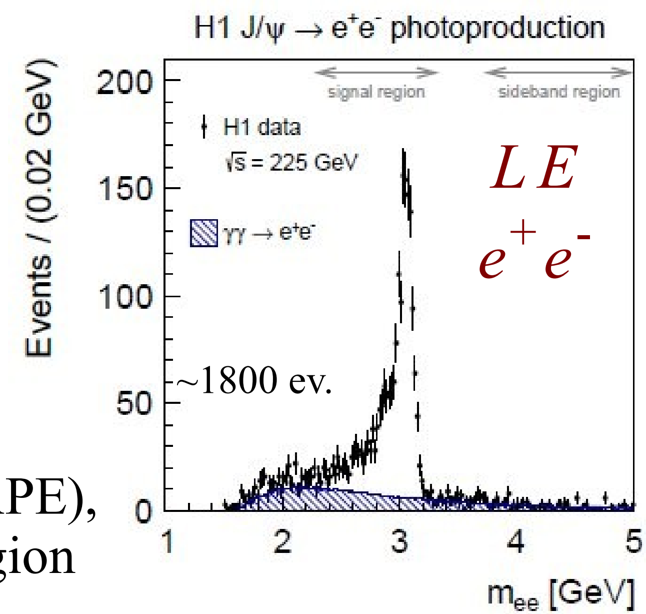
- Student's t-function for signal description
- exponential distribution for non-resonant background



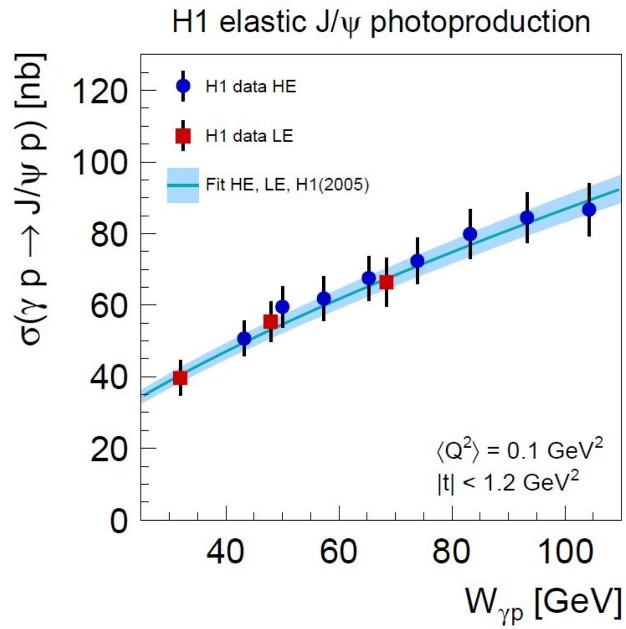


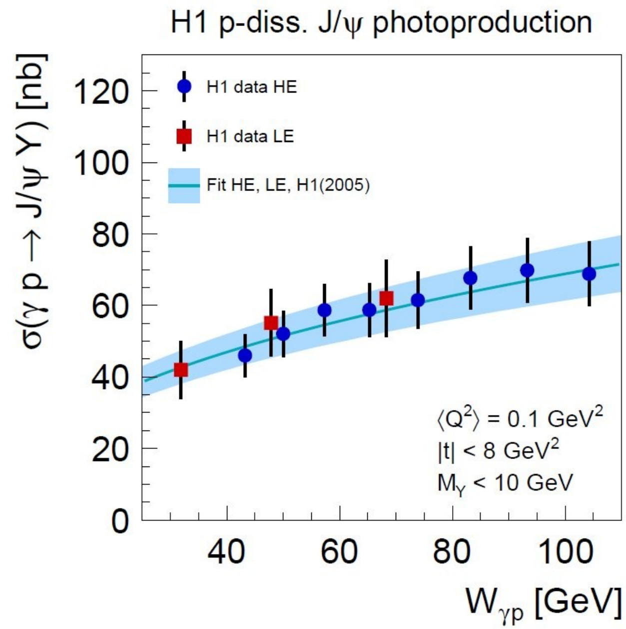
$$J/\psi \rightarrow e^+e^-$$

- m_{ee} low mass tail:
  - * QED radiation losses
  - * Bremsstrahlung from *e*
- Non-resonant background subtracted by simulation (GRAPE), counting of events in signal region



Elastic and P-diss. Cross Sections vs. $W_{\gamma p}$





Fit includes H1(2005) [hep-ex/0510016]

- Fit function parametrised as: $\sigma = N(W_{\gamma p}/W_0)^{\delta}$

  with $W_0 = 90\,GeV$ $\quad \delta(t) = 4(\alpha(t) - 1)$

- Results: $\delta_{el} = 0.67 \pm 0.03$ $\quad \delta_{pd} = 0.42 \pm 0.05$

  $\alpha(0)_{el} = 1.20 \pm 0.01$ $\quad \alpha(0)_{pd} = 1.09 \pm 0.02$

$$\alpha(t) = \alpha(0) + \alpha' \cdot t$$

Note:

$\alpha'_{el} = 0.164 \pm 0.028 \pm 0.030\,GeV^{-2}$

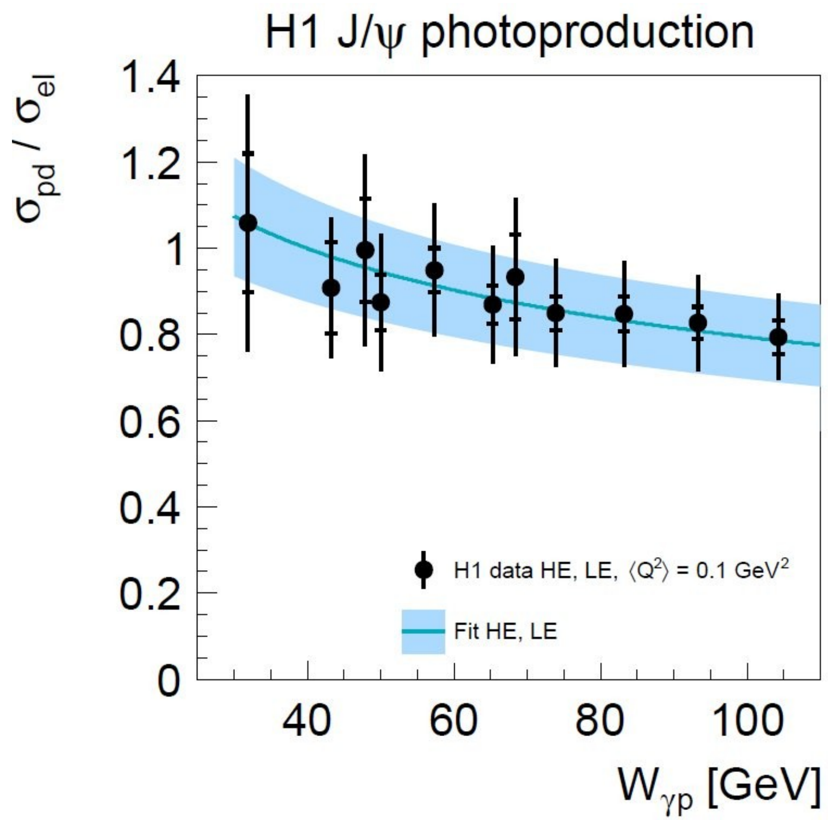
$\alpha'_{pd} = -0.0135 \pm 0.0074 \pm 0.0051\,GeV^{-2}$

$\langle t \rangle_{el} = -0.2\,GeV^2$

$\langle t \rangle_{pd} = -1.2\,GeV^2$

- These values are in agreement with previous H1 measurements

Ratio $\sigma_{pd} / \sigma_{el}$ vs. $W_{\gamma p}$



Fit function: $N_R (W_{\gamma p} / W_0)^{\delta_R}$

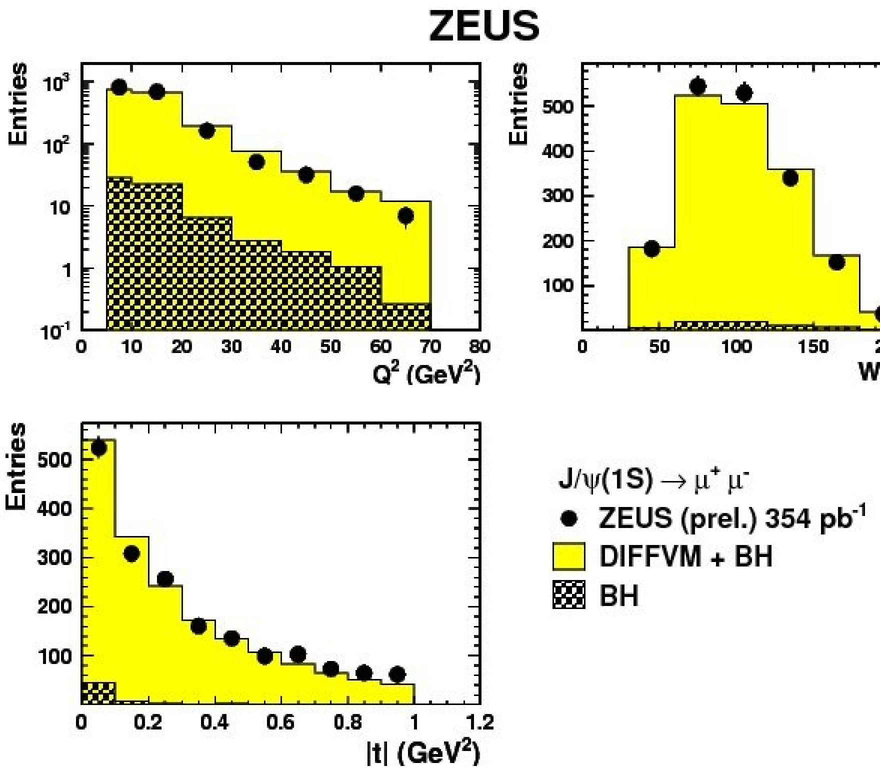
with $W_0 = 90\,GeV$

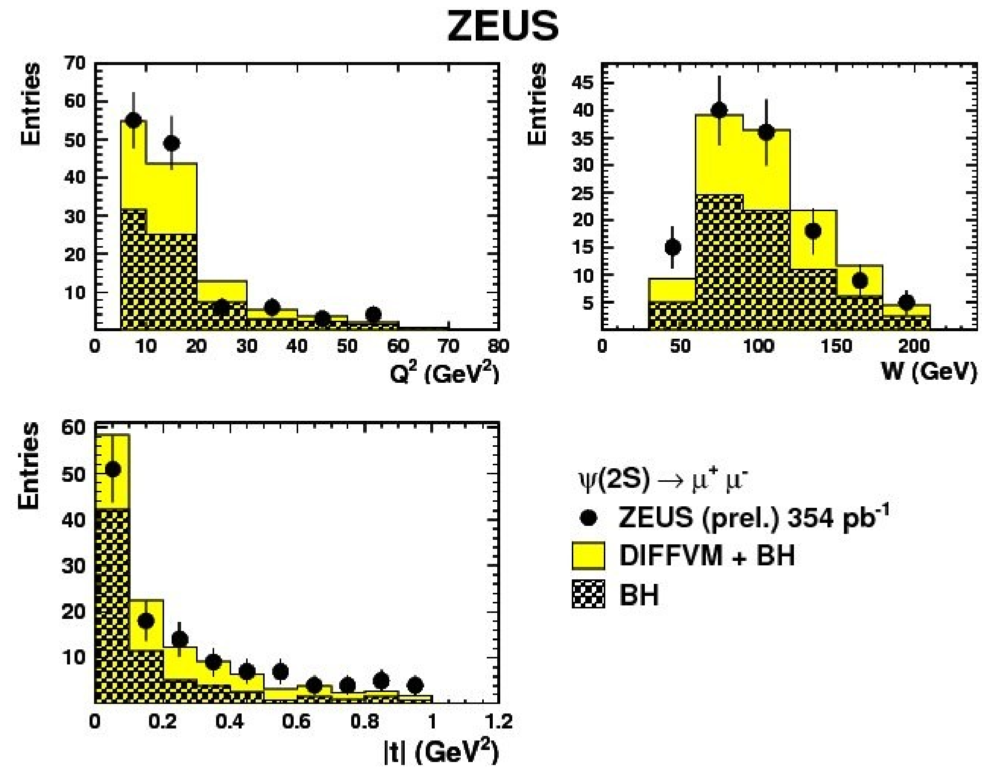
$$N_R = N_{pd} / N_{el} = 0.81 \pm 0.10$$

$$\delta_R = \delta_{pd} - \delta_{el} = -0.25 \pm 0.06$$

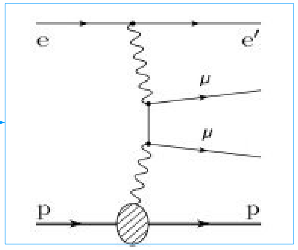
Ratio $\sigma_{pd} / \sigma_{el}$ only slowly decreasing with increasing $W_{\gamma p}$

Control Distributions: $J/\psi(1S) \rightarrow \mu^+\mu^-, \psi(2S) \rightarrow \mu^+\mu^-$





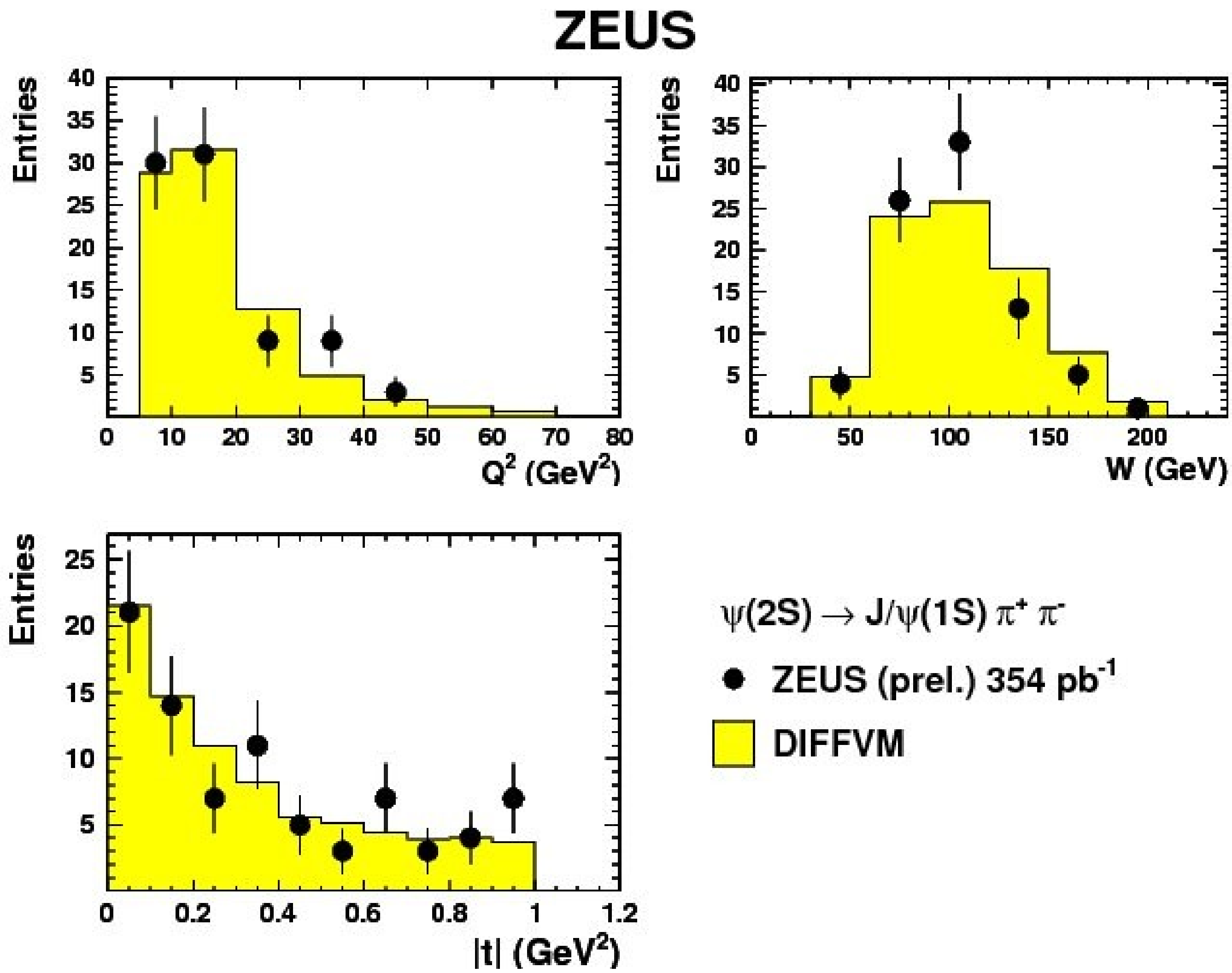
- MC: DIFFVM for exclusive vector meson production
  GRAPE for background



- MC reweighted in Q², |t| and decay angles, and normalised to data

- Good description of data by MC

Control Distributions for $\psi(2S) \to J/\psi\,\pi^+\pi^-$



- MC reweighted in Q^2 and $|t|$, and normalised to data
- Good description of data by MC