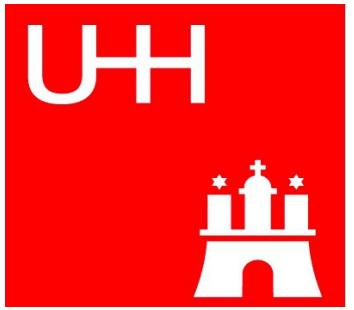
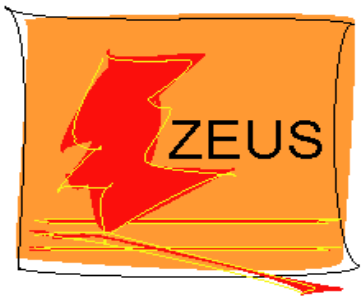
Quarkonium Production at HERA



Nataliia Kovalchuk
(Hamburg University)
on behalf of the **H1 & ZEUS Collaborations**



Quarkonium 2014
CERN, 10-14 November 2014

Charmonium production at HERA Overview

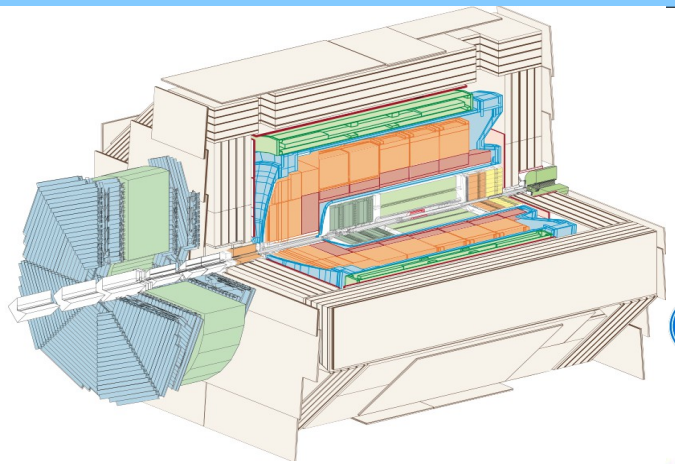
Recent results from HERA

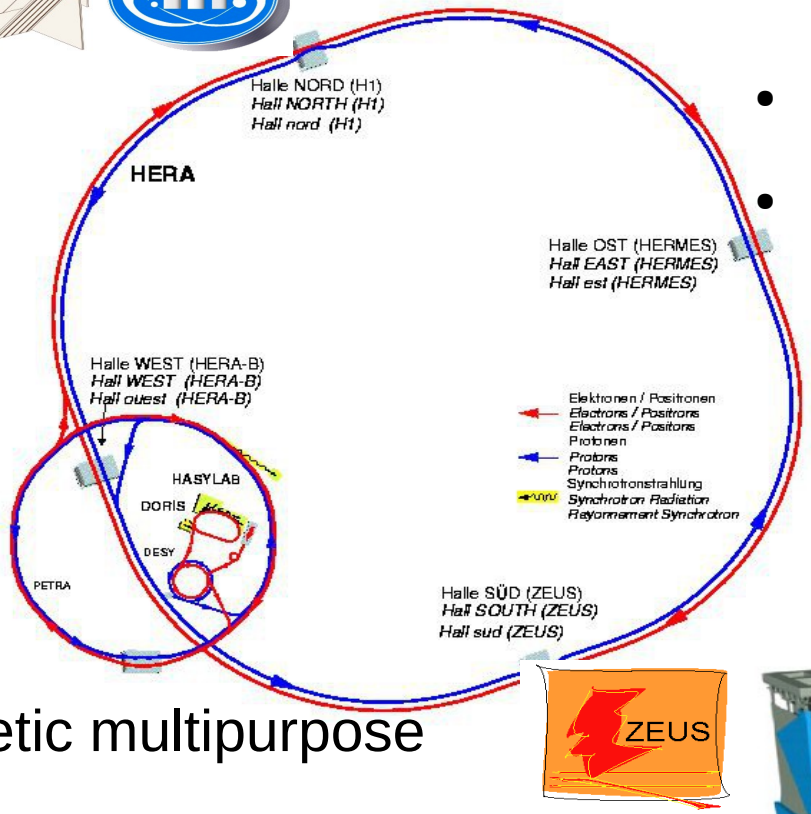
1) H1: Elastic and Proton-Dissociative Photoproduction of J/ψ Mesons at HERA [arXiv:1304.5162]

2) ZEUS: Measurement of the cross-section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in DIS [ZEUS-prel-14-003]

3) ZEUS: Measurement of Inelastic J/psi and psi' Photoproduction at HERA [arXiv:1211.6946]

H1 and ZEUS experiments at HERA





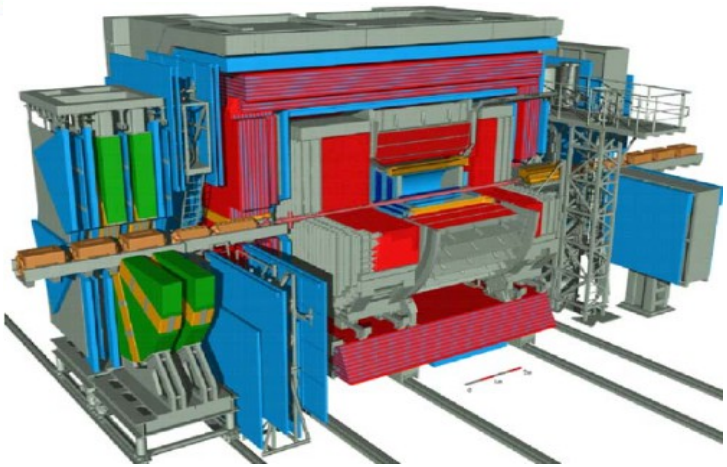
HERA: ep collider

- Colliding beams:

  920(820) GeV **p**

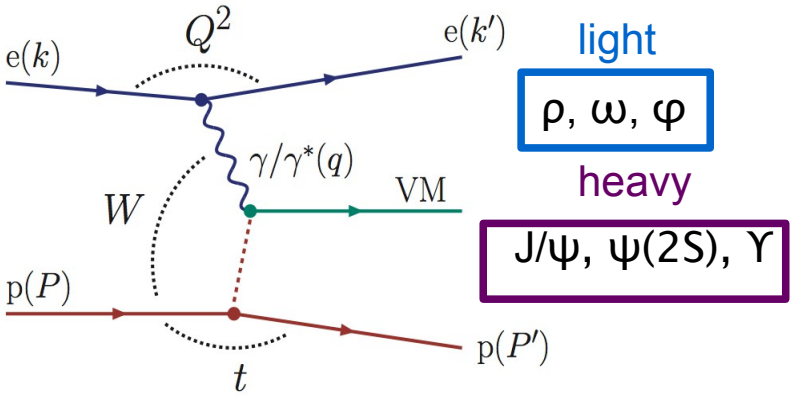
  27.5 GeV $\mathbf{e^{\pm}}$
- $\sqrt{s} \approx 320\ (300)\ GeV$
- Data taking: 1992 - 2007

- **H1 & ZEUS** – hermetic multipurpose detectors
- Total collected luminosity:
  ~0.5 fb^{-1} per experiment



Diffractive vector meson (VM) production at HERA

elastic (exclusive)



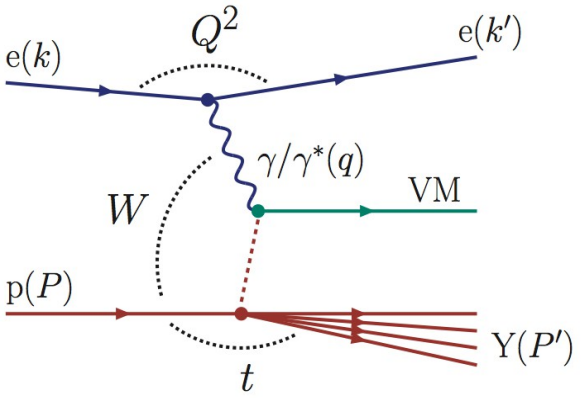
light

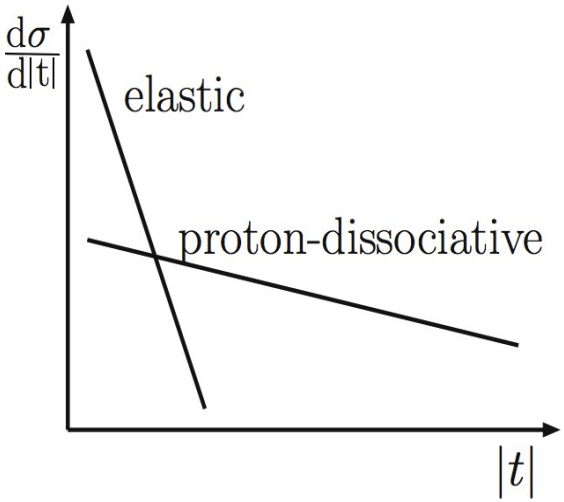
ρ, ω, φ

heavy

J/ψ, ψ(2S), ϒ

proton-dissociative





Q^2 < 1 GeV^2 — γp

Q^2 > 1 GeV^2 — DIS

Q^2 — photon virtuality $Q^2 = - q^2 = - (k - k')^2$

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

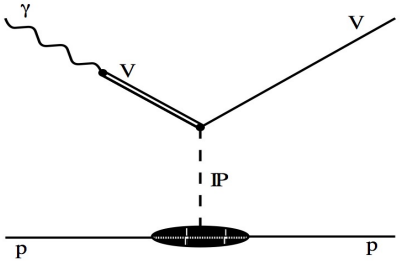
t — 4-mom. transfer squared at proton vertex $t = (P - P')^2$

Experimentally very clean process in wide kinematic range

Why do we measure? test models

Vector Dominance Model (VDM) + Regge:

$\gamma^* p \rightarrow Vp = (\gamma^* \rightarrow V) \times (Vp \rightarrow Vp)$



soft interaction

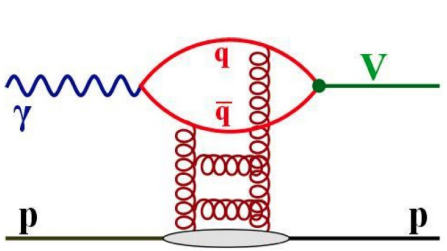
↓

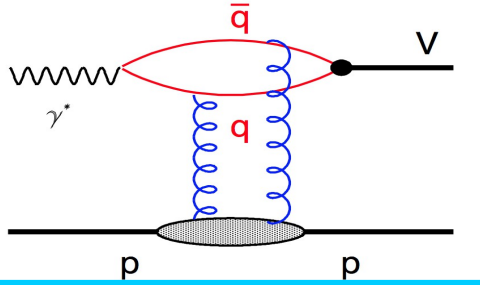
Pomeron exchange

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

pQCD models

VM = qqbar dipol, exchange of ≥ 2 gluons
(Color Singlet — QCD Pomeron)





Expected to work if hard scale present

$$\sigma \propto W^{\delta} \qquad \delta \approx 4[\alpha(0) - \frac{\alpha'}{b_0} - 1] \qquad \alpha_{IP}(t) = \alpha(0) + \alpha' \cdot t$$

(DL - Donnachie — Landshoff)

Weak energy dependence of cross-section:

$\delta \approx 0.22$

Steep rise of σ_L with W:

$\delta \approx 0.8(J/\psi), 1.1(\psi(2S))$

$$\frac{d\sigma}{d|t|} = e^{-b|t|} \qquad b(W) = b_0 + 4\alpha' ln(W)$$

Very small scattering angles =>

$b \approx 10\ GeV^{-2} \qquad \alpha' \approx 0.25\ GeV^{-2}$

b slope increases with W => shrinkage

Universal exponential *t* dependence:

$b \approx 4 - 5\ GeV^{-2} \qquad \alpha' \approx 0$

No shrinkage

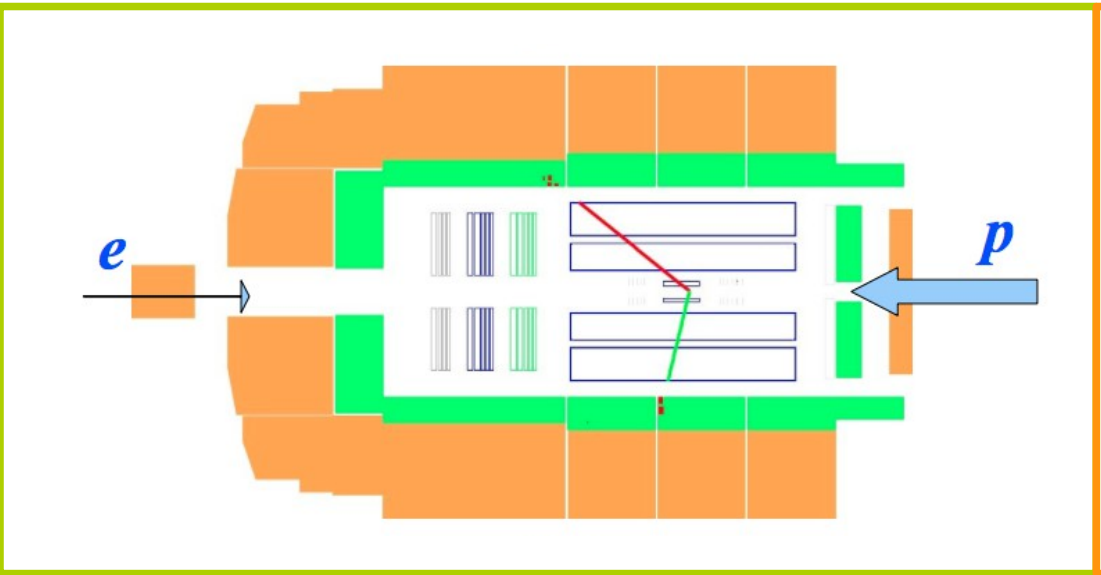
1) Elastic and Proton-Dissociative Photoproduction of J/ψ Mesons

- NO scattered *e* reconstructed in CAL
- Scattered *p* undetected

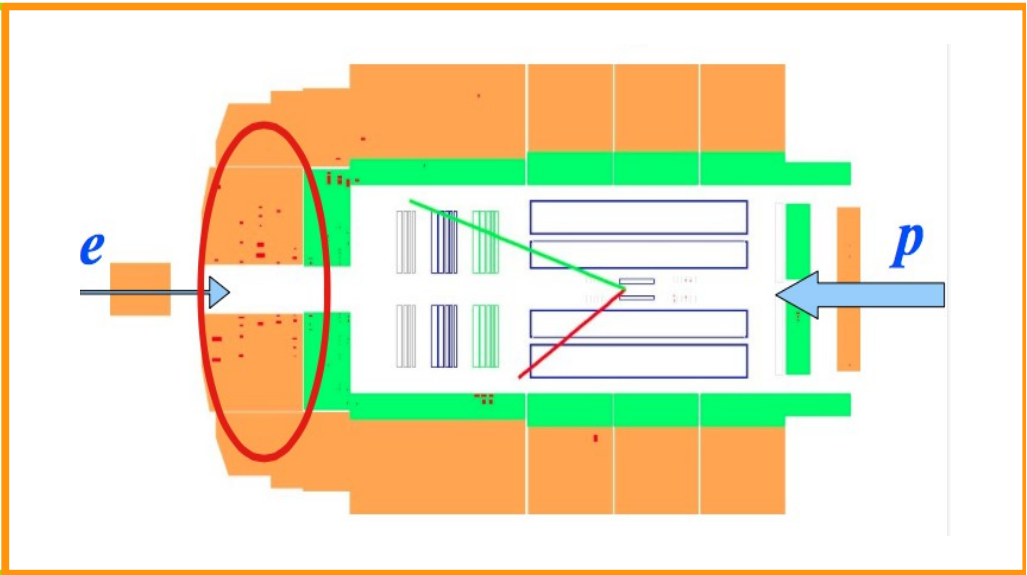
$J/\psi \rightarrow \mu^+ \mu^-$, $e^+ e^-$

- **Elastic:** Exactly two oppositely charged tracks identified $|t_{rec}| < 1.2$ GeV^2
- **Proton-Dissociative:** Large value of $|t_{rec}| \geq 1.5$ GeV^2

or energy deposits in forward detectors

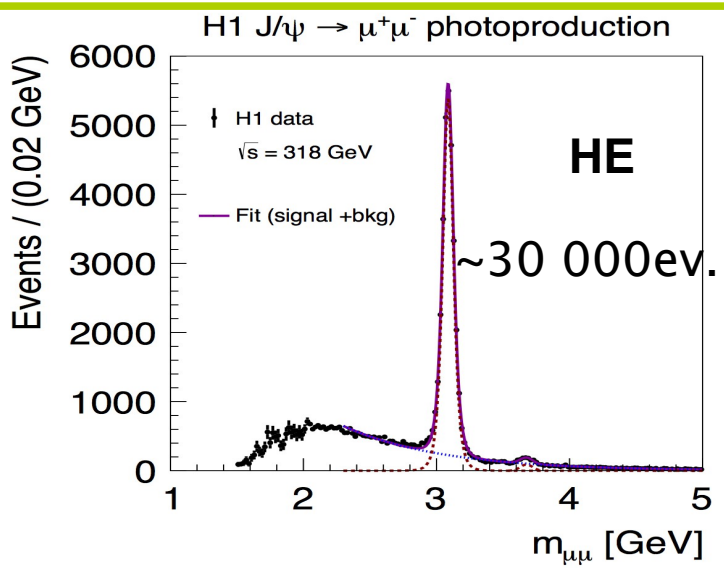


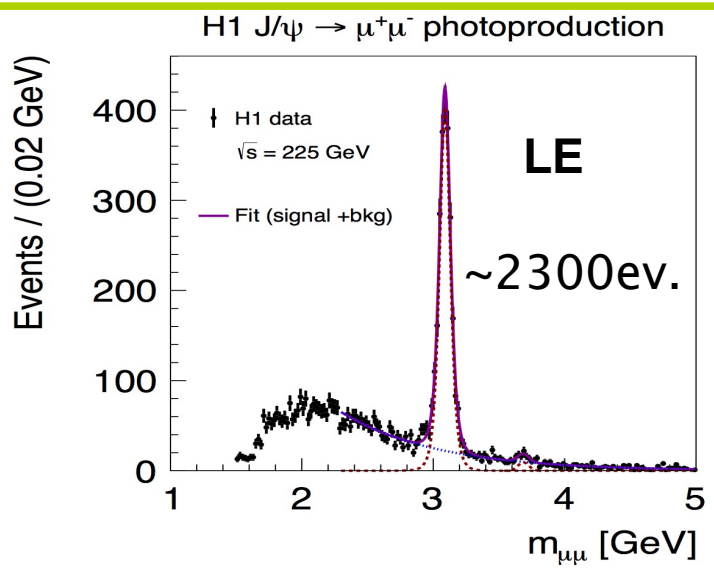
Elastic



Proton-Dissociative

Background subtraction



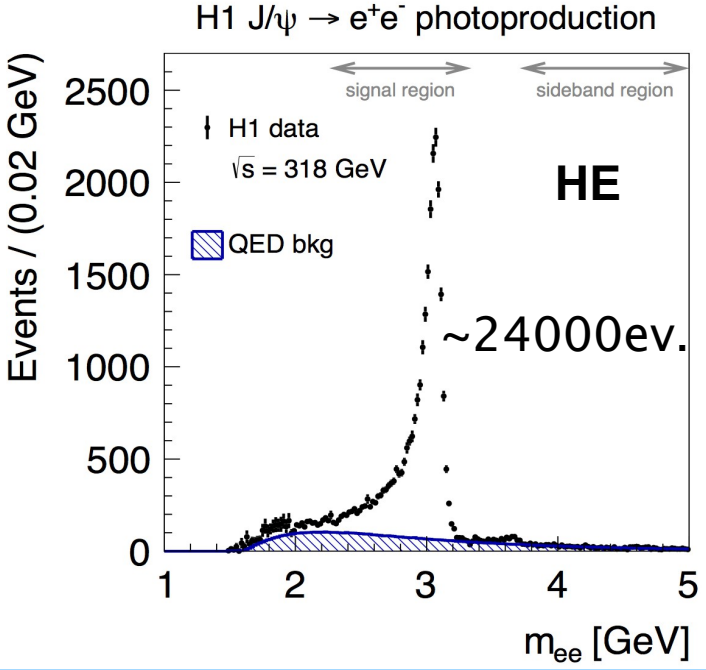


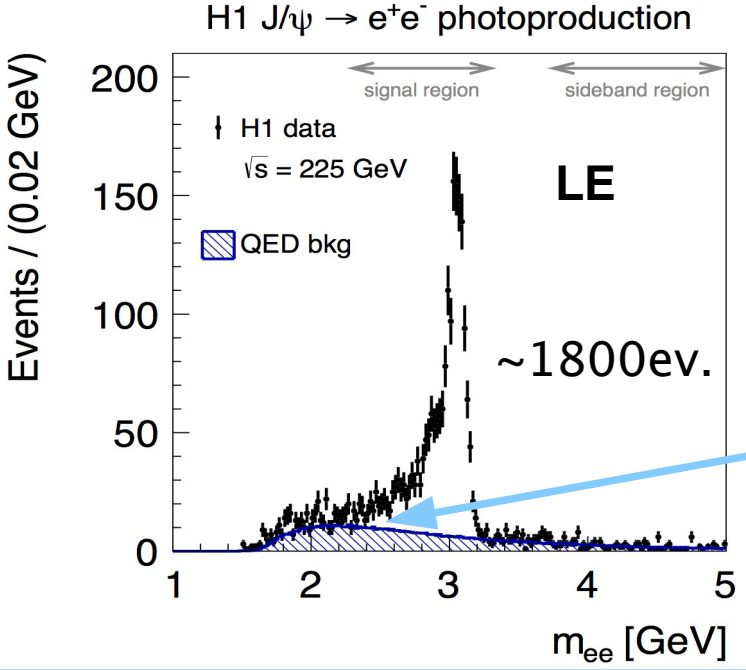
$J/\psi \rightarrow \mu^+\mu^-$

HE = high energy run
E_p = 920 GeV

LE = low energy run
E_p = 460 GeV

exponential distribution for the non-resonant background

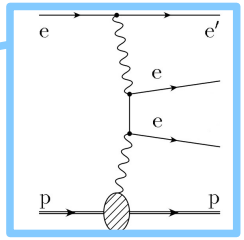




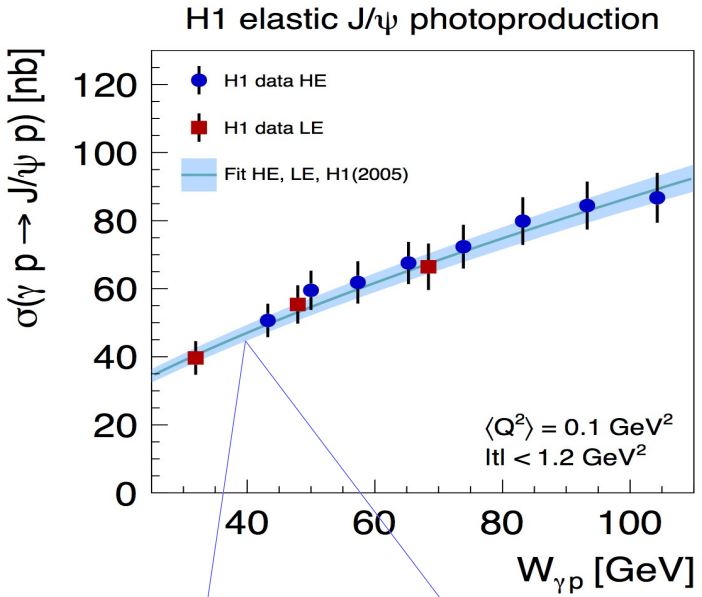
$J/\psi \rightarrow e^+e^-$

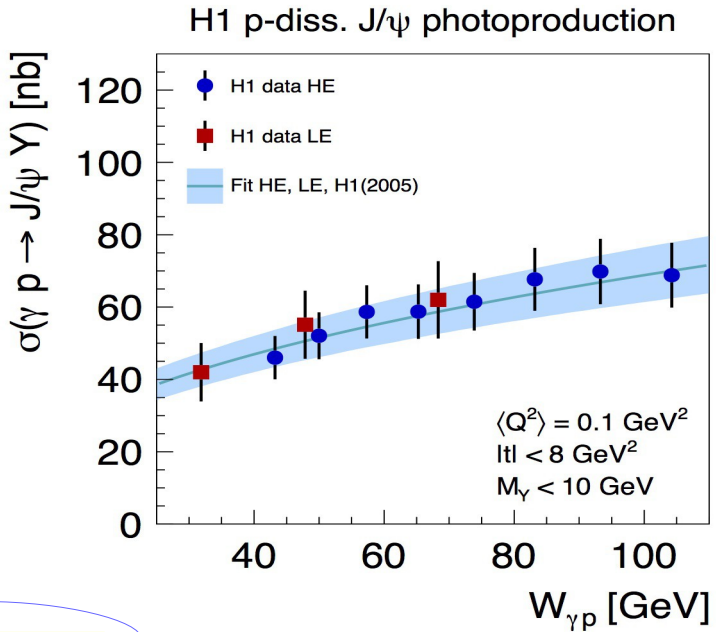
$25 < W < 110$ GeV

$|t| \leq 8$ GeV^2



Combined elastic and proton-dissociative cross section as a function of W





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

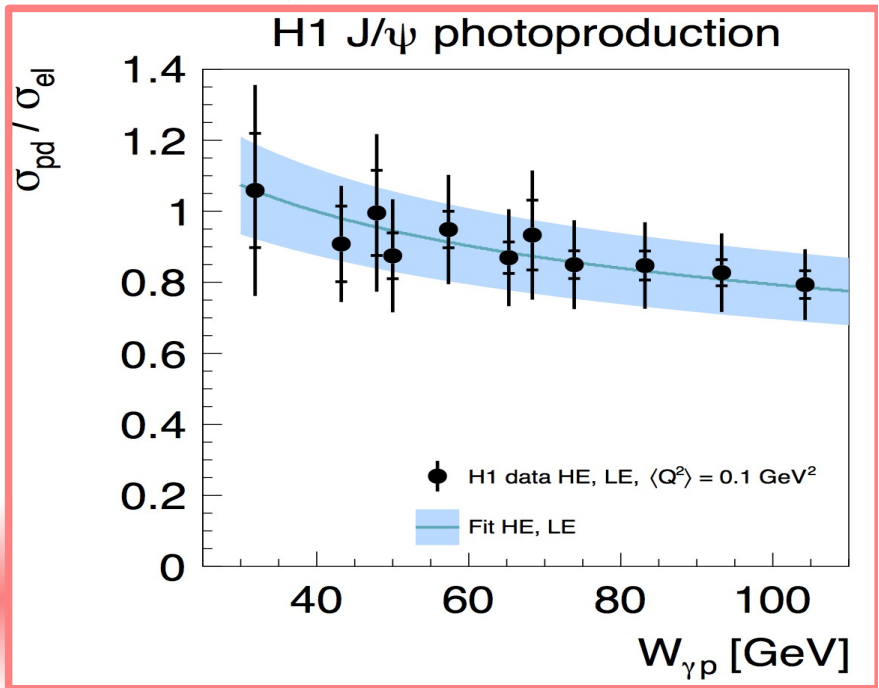
Fit function parametrised as: $\sigma = N(W_{\gamma p}/W_0)^{\delta}$

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

Results:

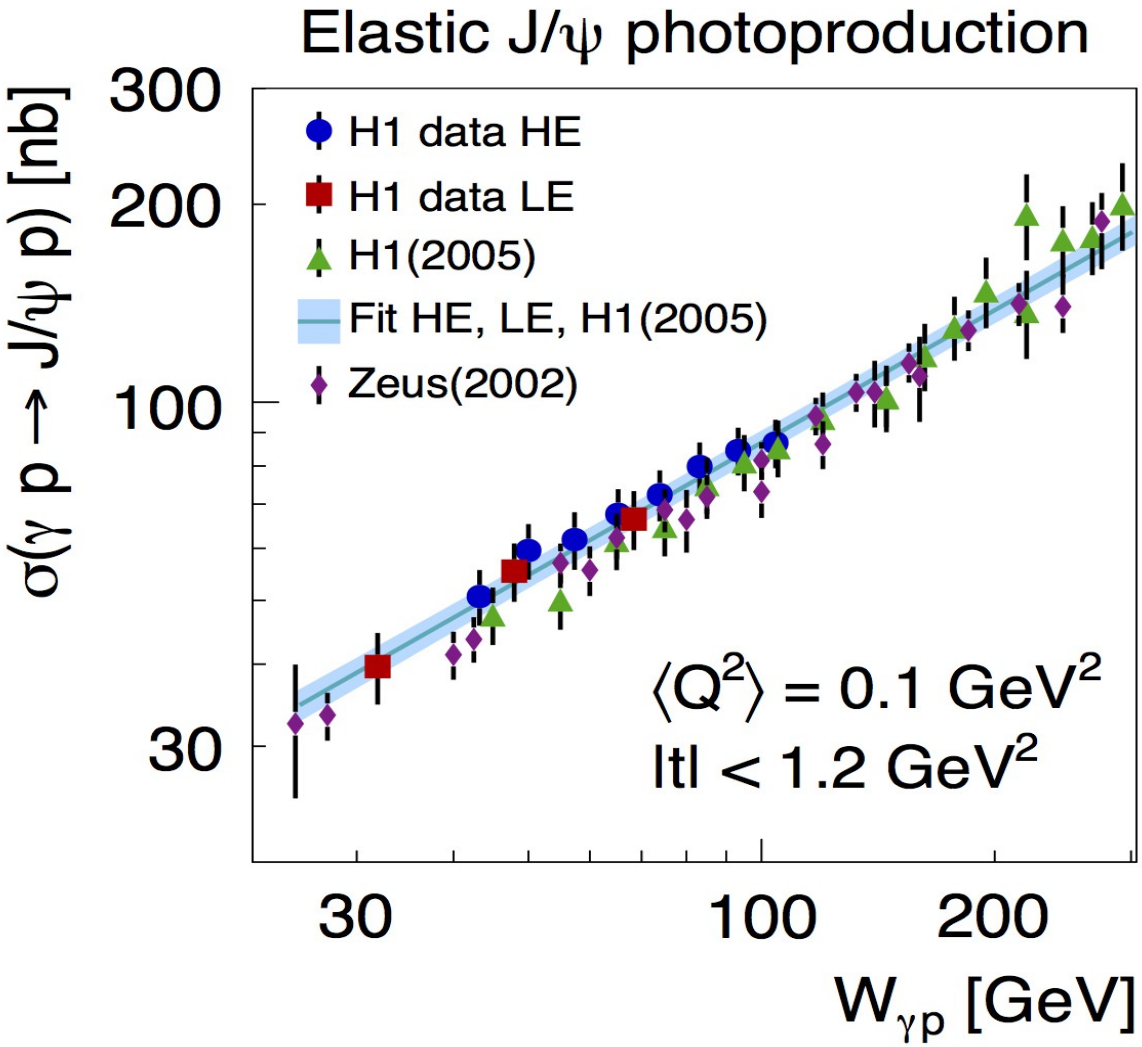
$$\delta_{el} = 0.67 \pm 0.03$$

$$\delta_{pd} = 0.42 \pm 0.05$$



W-dependence of the proton-dissociative channel is significantly weaker than that of the elastic channel

Comparison with previous measurements

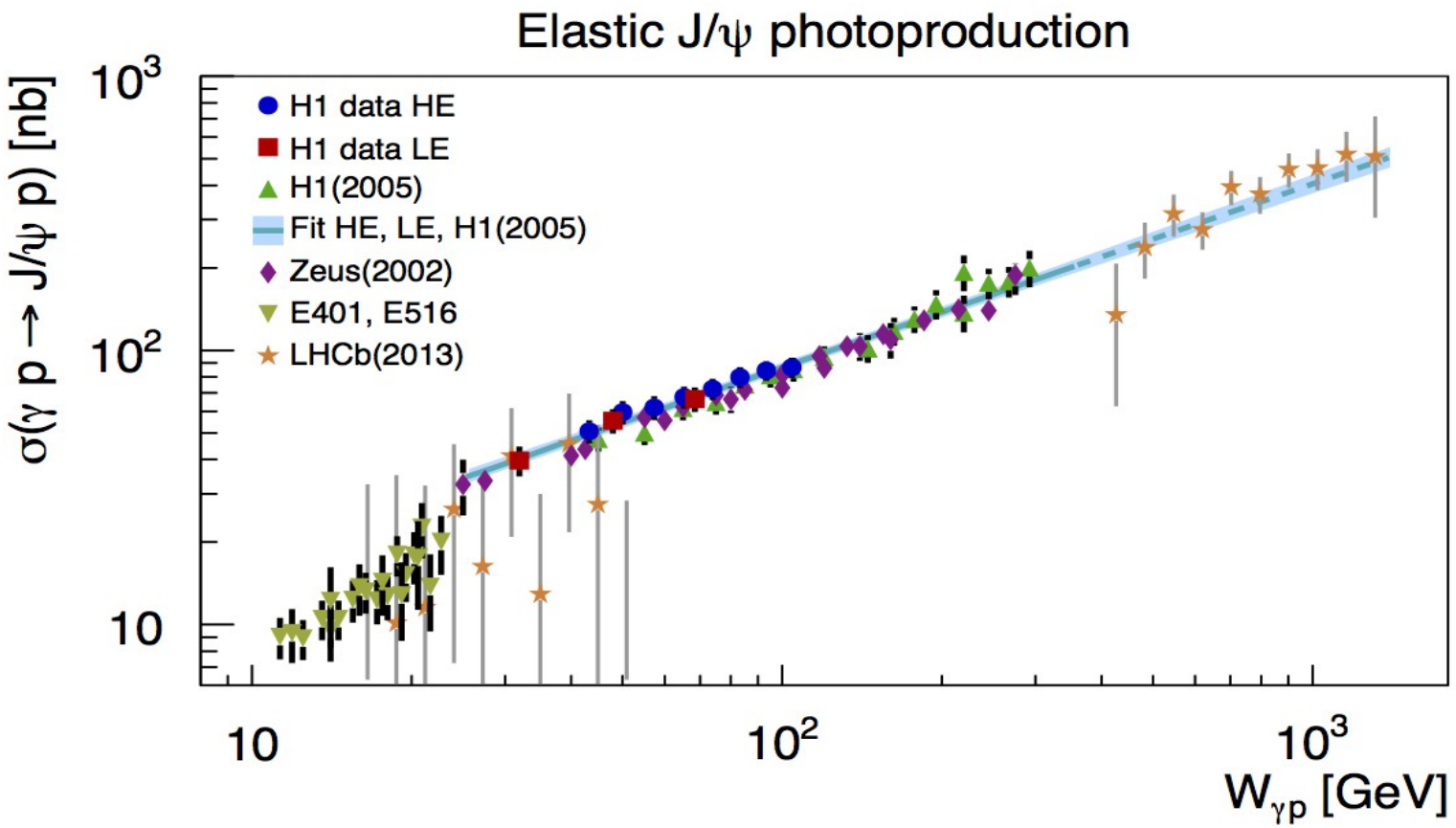


• Similar precision in range 30 < W< 110 GeV

Results are in a good agreement with previous H1 and ZEUS [hep-ex/0201043] measurements

Comparison with fixed target and LHCb data

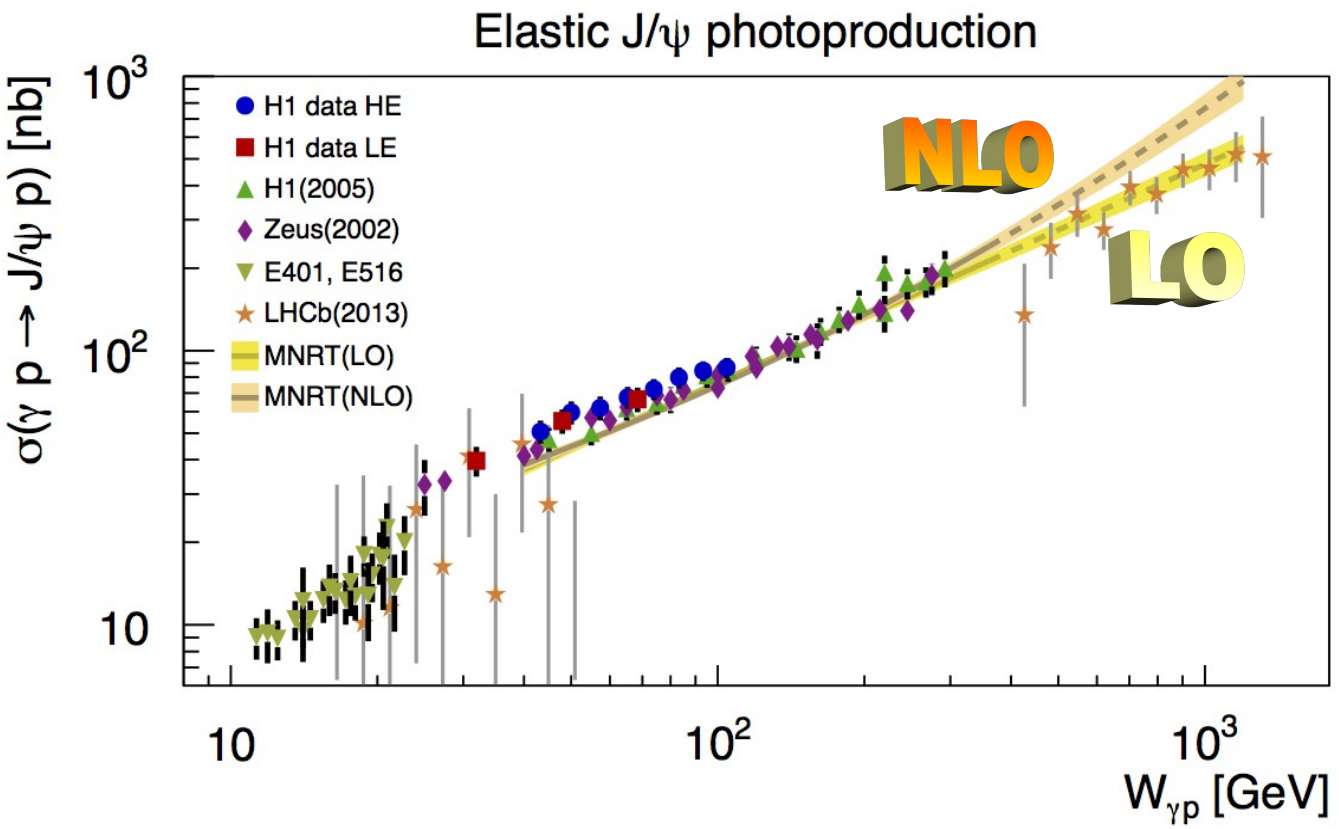
[PRL48(1982) 73] [PRL52(1984)795] [arXiv:1301.7084]



Results are in a good agreement with LHCb data

Fixed target data has steeper slope

Comparison to QCD calculations

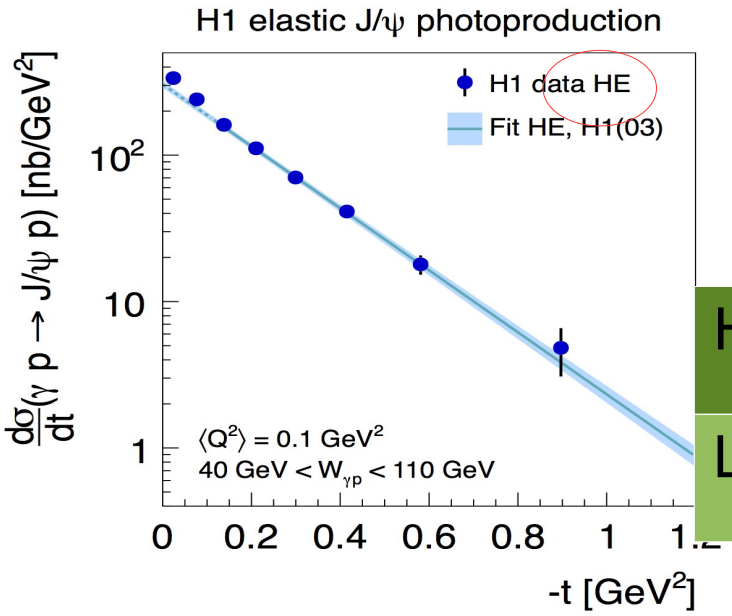


LO and NLO fits to previous J/ψ measurements at HERA [arXiv:0709.4406]

LO fits describe LHCb data
Both fits extrapolated to higher W

Elastic and proton-dissociative cross section as a function of |t|

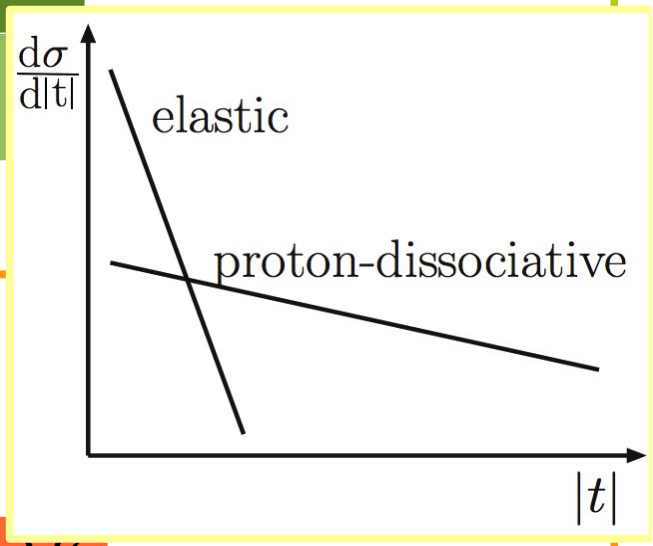
Elastic



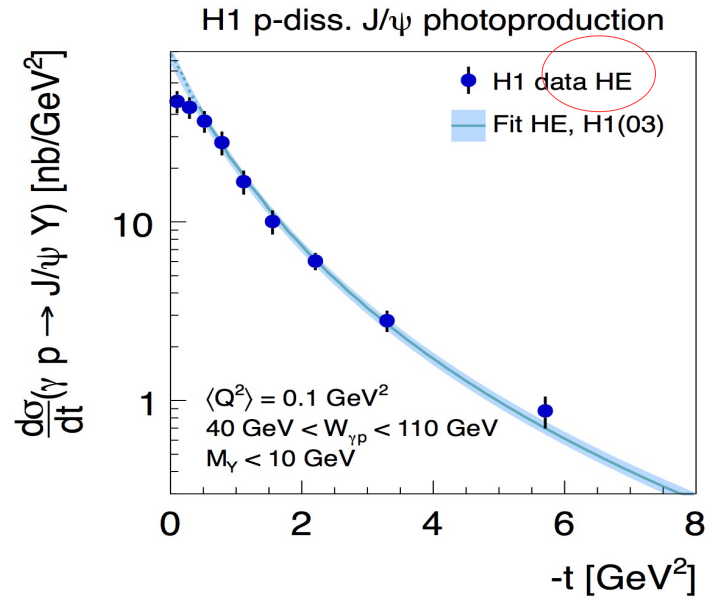
Parameterization:

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

HE	$b_{el} = 4.88 \pm 0.15$ GeV^2
LE	$b_{el} = 4.3 \pm 0.2$ GeV^2



Proton-dissociative

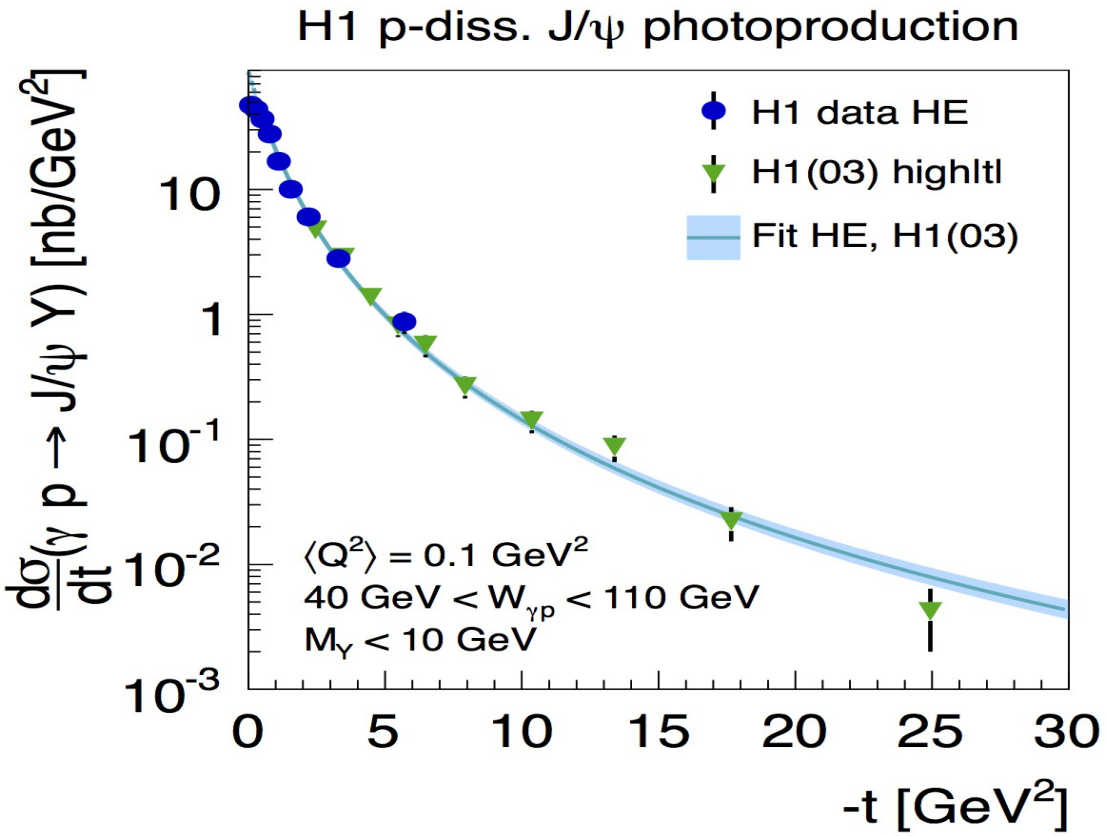


Parameterization:

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

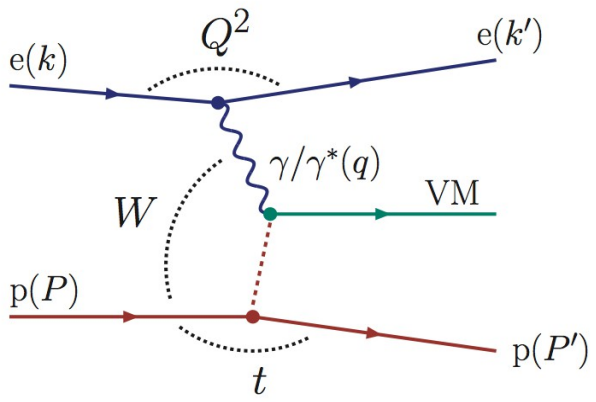
HE	$b_{pd} = 1.79 \pm 0.12$ GeV^2 $n = 3.58 \pm 0.15$
LE	$b_{pd} = 1.6 \pm 0.2$ GeV^2 $n = 3.58$(fixed)

Elastic and proton-dissociative cross section as a function of |t|



Comparison with previous high |t| measurement [H1(03)] result in a good agreement in the overlap region

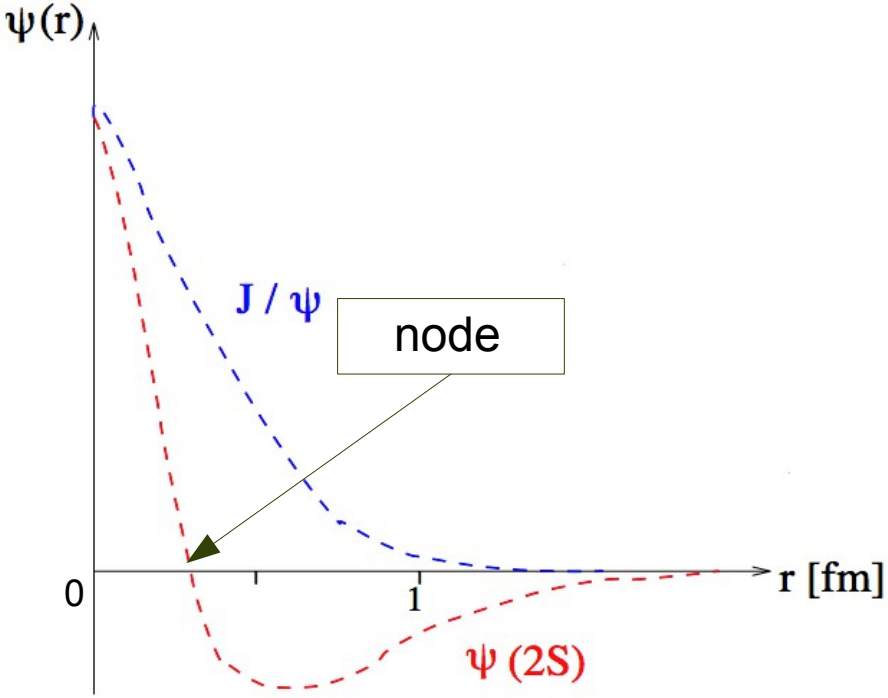
2. Cross-section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in DIS



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

gives information about the dynamics of hard process

sensitive to radial wave function of charmonium



ψ(2S) wave function different from J/ψ(1S) 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)

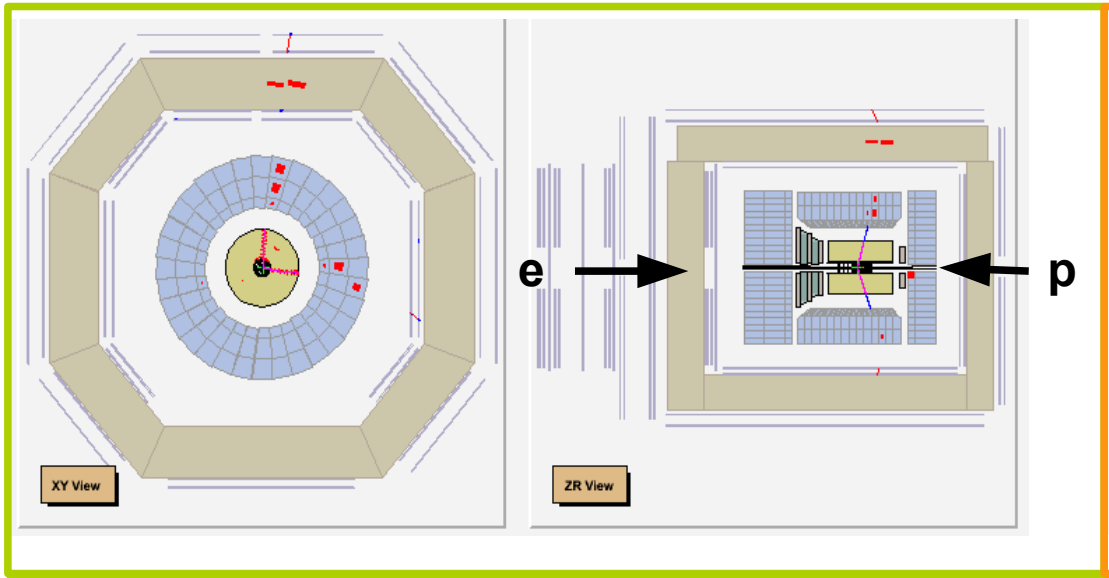
[ZEUS-prel-14-003]

Elastic ψ(2S) -> $\mu^+\mu^-$ & J/ψ(1S) -> $\mu^+\mu^-$

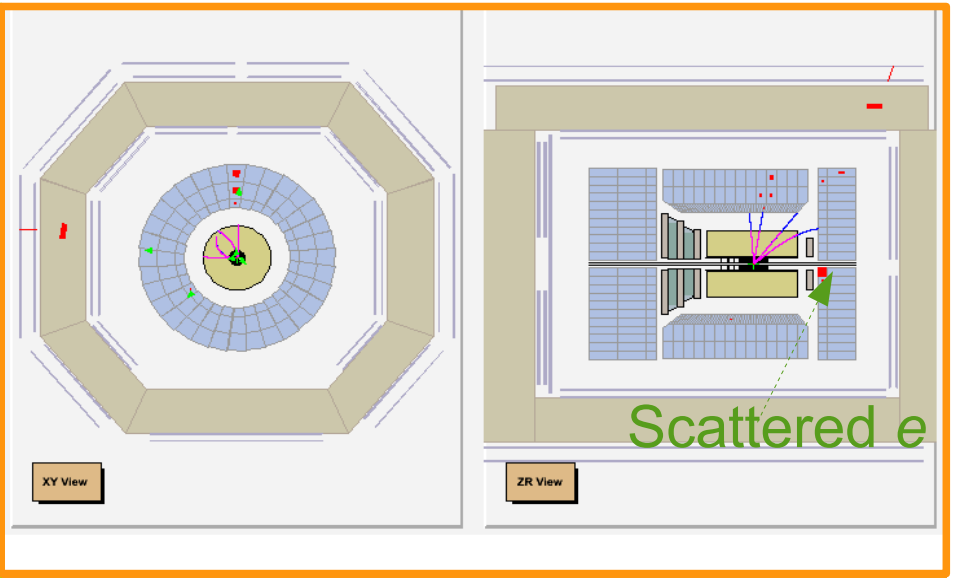
$\psi(2S) \rightarrow J/\psi\ \pi^+\ \pi^-;\ J/\psi \rightarrow \mu^+\ \mu^-$
$\psi(2S) \rightarrow \mu^+\ \mu^-$
$J/\psi(1S) \rightarrow \mu^+\ \mu^-$

- Scattered *e* reconstructed in CAL
- Scattered *p* undetected
- Two reconstructed tracks identified as muons

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

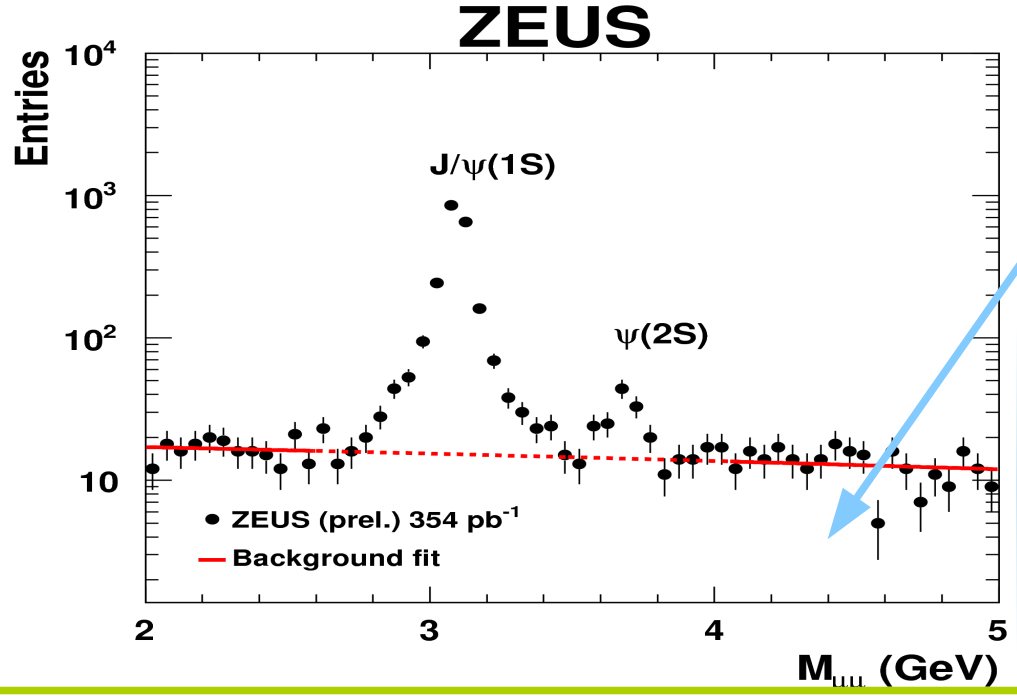


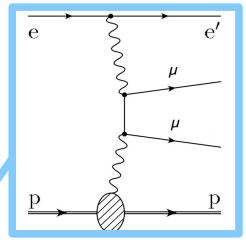
$J/\psi(1S) \rightarrow \mu^+\mu^-$



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

Background subtraction



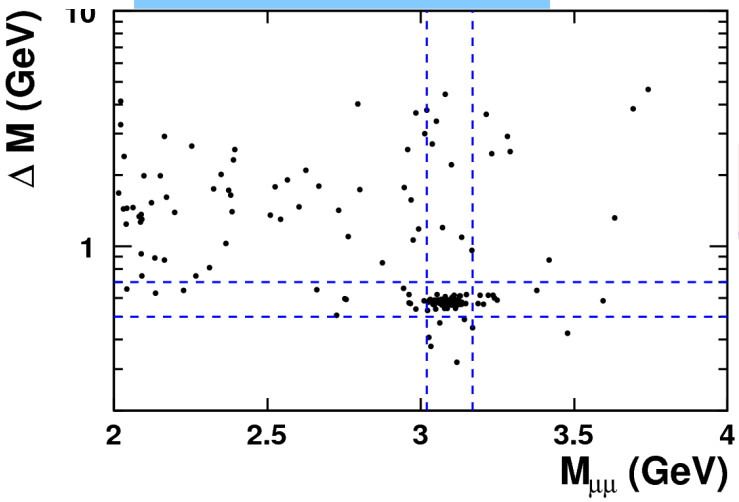


$J/\psi(1S) \rightarrow \mu^+\mu^-$

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

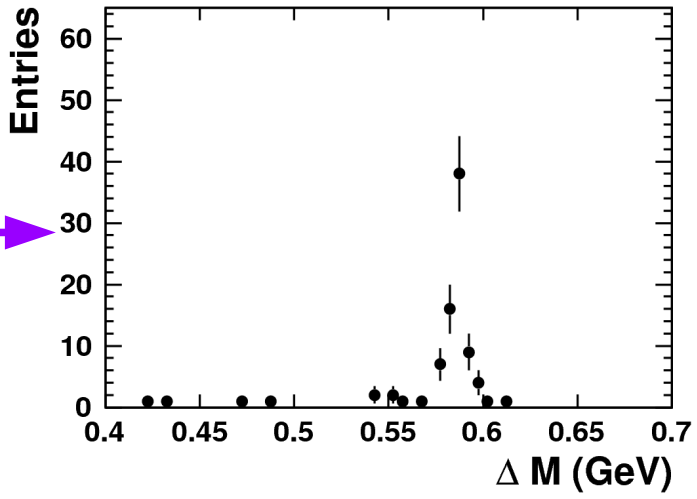
Sideband of the signal:
$2 < M_{\mu\mu} < 2.62$ GeV and
$4.05 < M_{\mu\mu} < 5$ GeV
fitted by straight line

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



$M_{\mu\mu}$ C[3.02–3.17]GeV

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



σ(ψ(2S))/σ(J/ψ(1S)) in full kinematic range

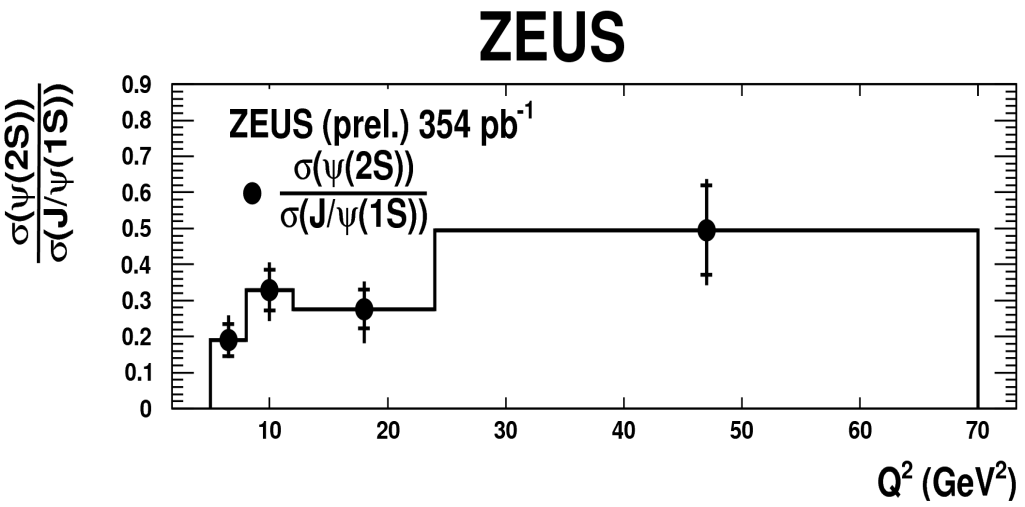
J/ψ → μ⁺ μ⁻ : 1738 ev.
ψ' → μ⁺ μ⁻ : 66 ev.
ψ(2S) → J/ψ π⁺π⁻ : 82 ev.

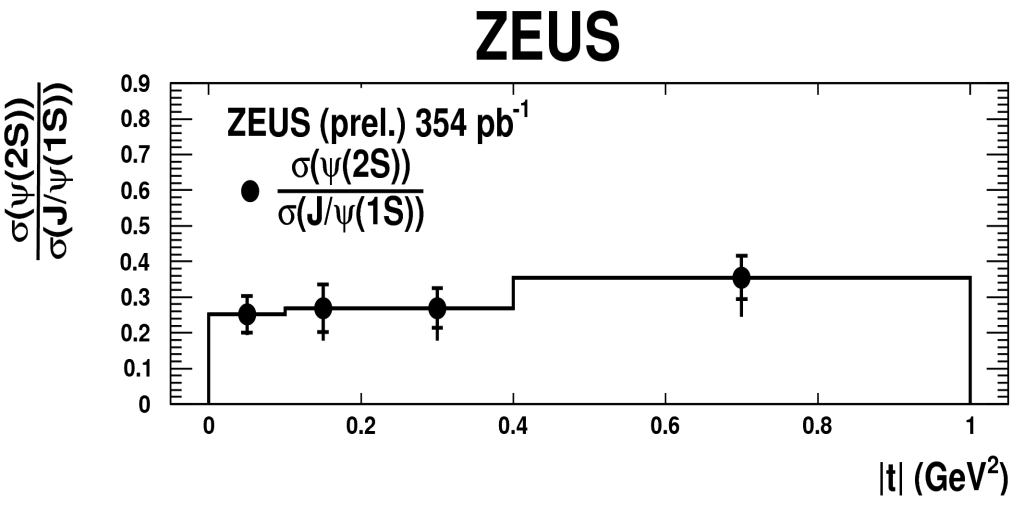
$30 \leq W \leq 210$ GeV
$5 \leq Q^2 \leq 70$ GeV^2
$|t| \leq 1$ GeV^2

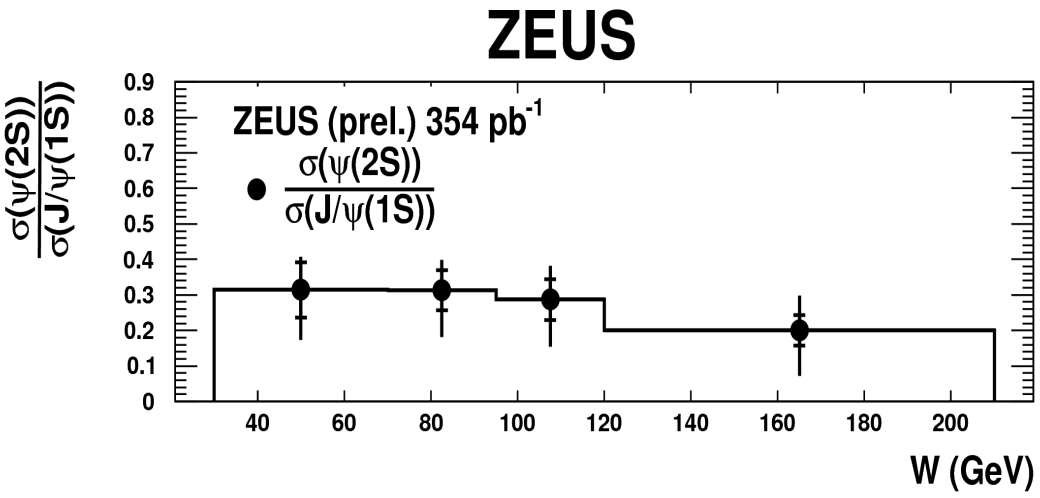
$\psi(2S)$ decay mode	$\sigma(\psi(2S))/\sigma(J/\psi(1S))$
$\rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$	$0.29 \pm 0.04^{+0.02}_{-0.01}$
$\rightarrow \mu^+\mu^-$	$0.25 \pm 0.05^{+0.04}_{-0.02}$
combined	$0.28 \pm 0.03^{+0.02}_{-0.01}$

Both ratio measurements agree

$\sigma(\psi(2S))/\sigma(J/\psi(1S))$ vs Q^2, W and $|t|$







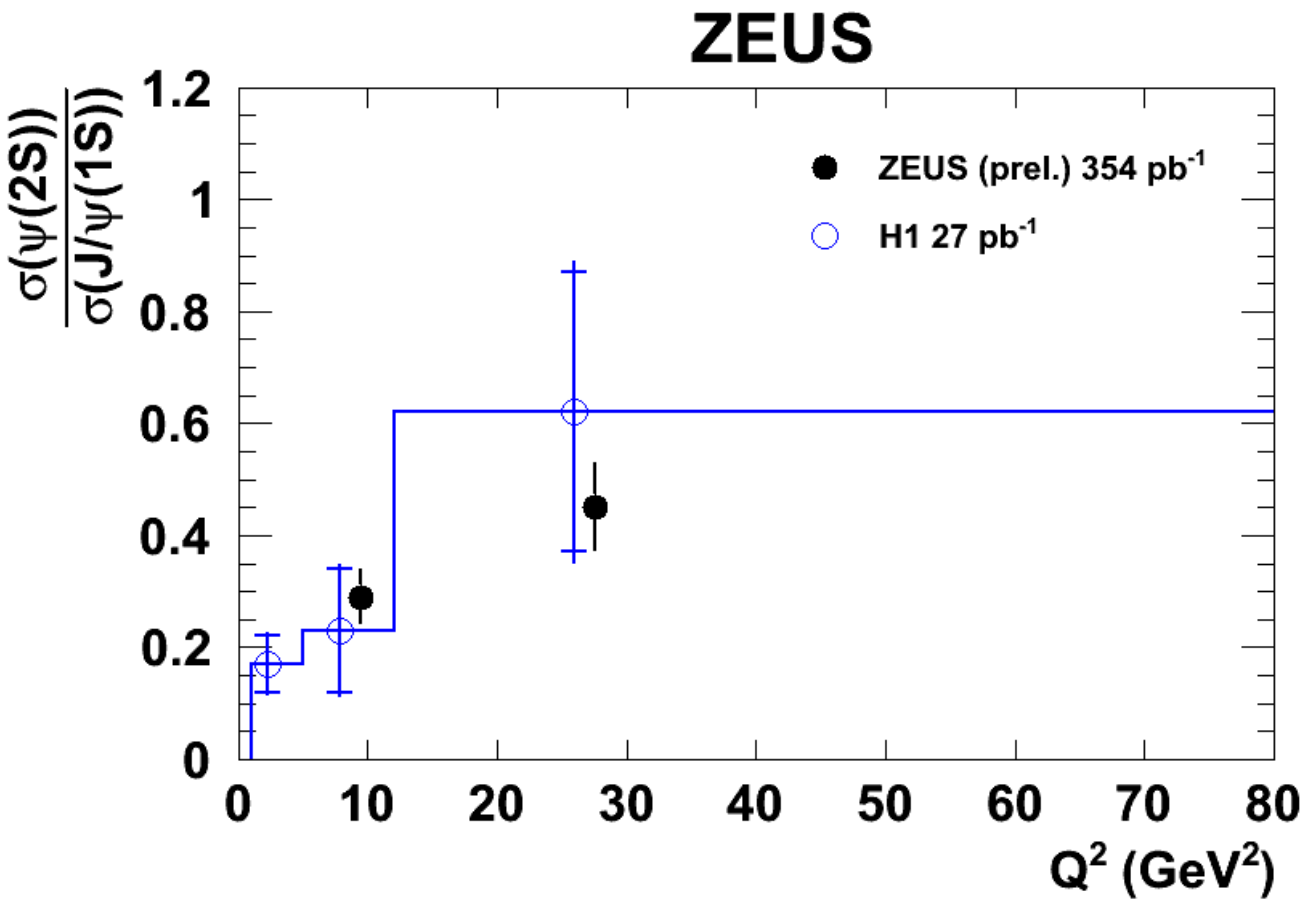
$\sigma(\psi(2S))/\sigma(J/\psi(1S))$

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

ZEUS — H1 comparison

- ZEUS data analysed in Q^2 bins used by H1 (Q^2: 5 — 12 and 12 — 80 GeV^2)

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



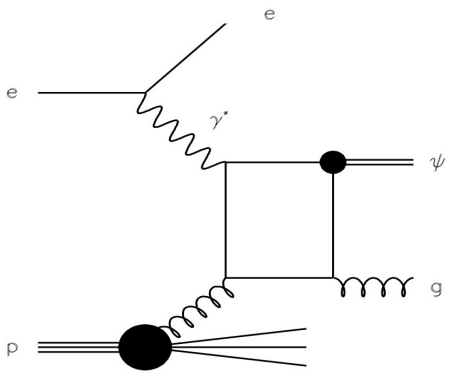
H1 collaboration:
Eur.Phys.J.C10:373-393,

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

3. Measurement of Inelastic J/ψ and ψ' Photoproduction at HERA [arXiv:1211.6946]

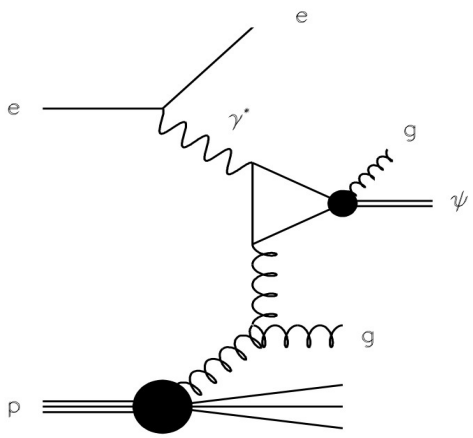
Charmonium production (J/ψ and ψ')

Colour Singlet model

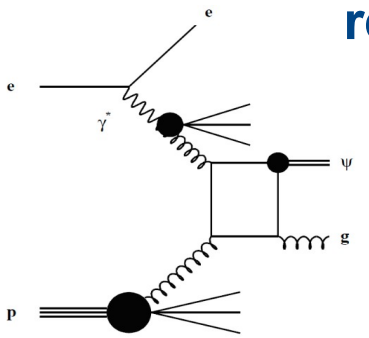


direct γ
0.2 < z < 0.9
p-rest frame: z = E(ψ)/E(γ*)

Color Octet model



Colour Singlet model



resolved γ
z < 0.2

Other contributions to the signal

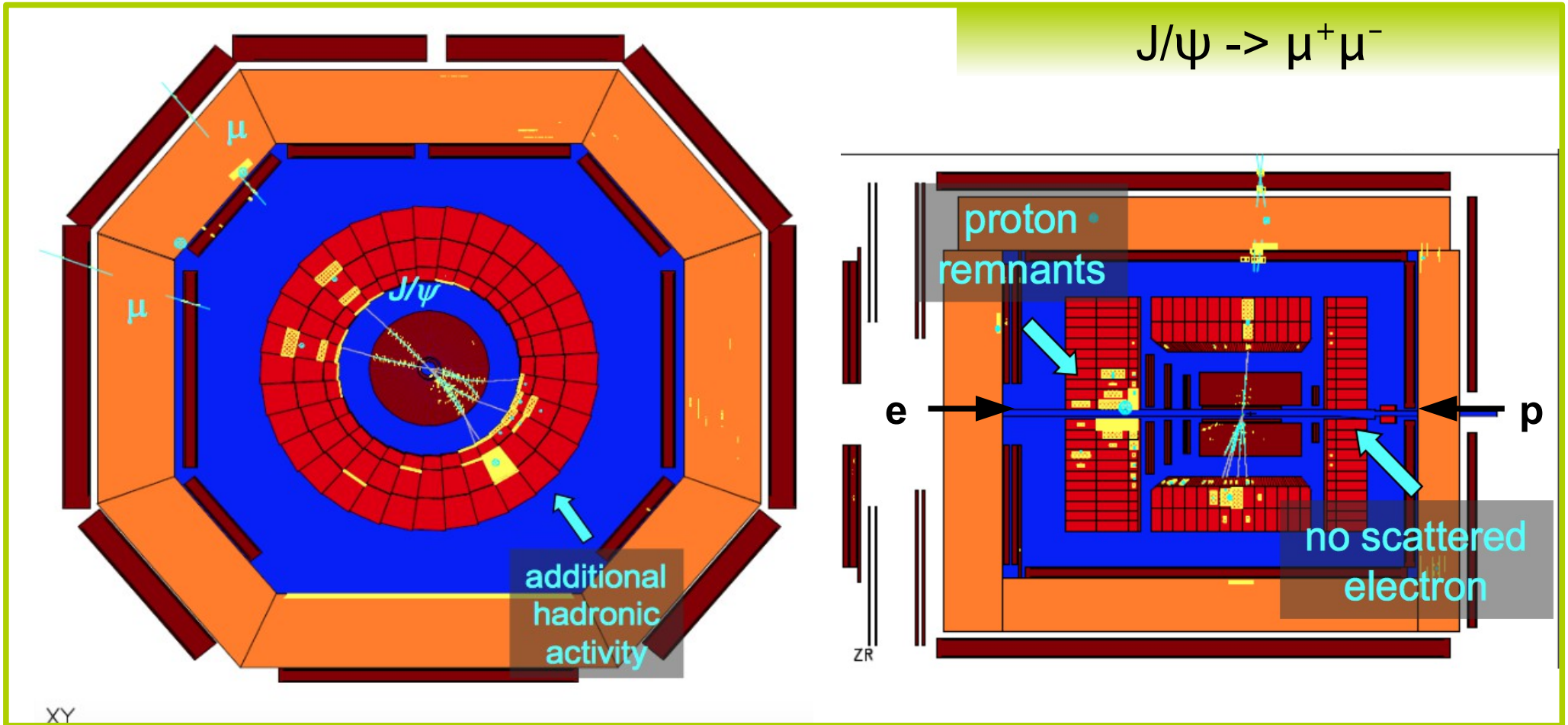
- ψ → J/ψ(→μμ)X decay
- J/ψ from B meson decay
- J/ψ from proton diffractive dissociation

Inelastic J/ψ -> $\mu^+\mu^-$

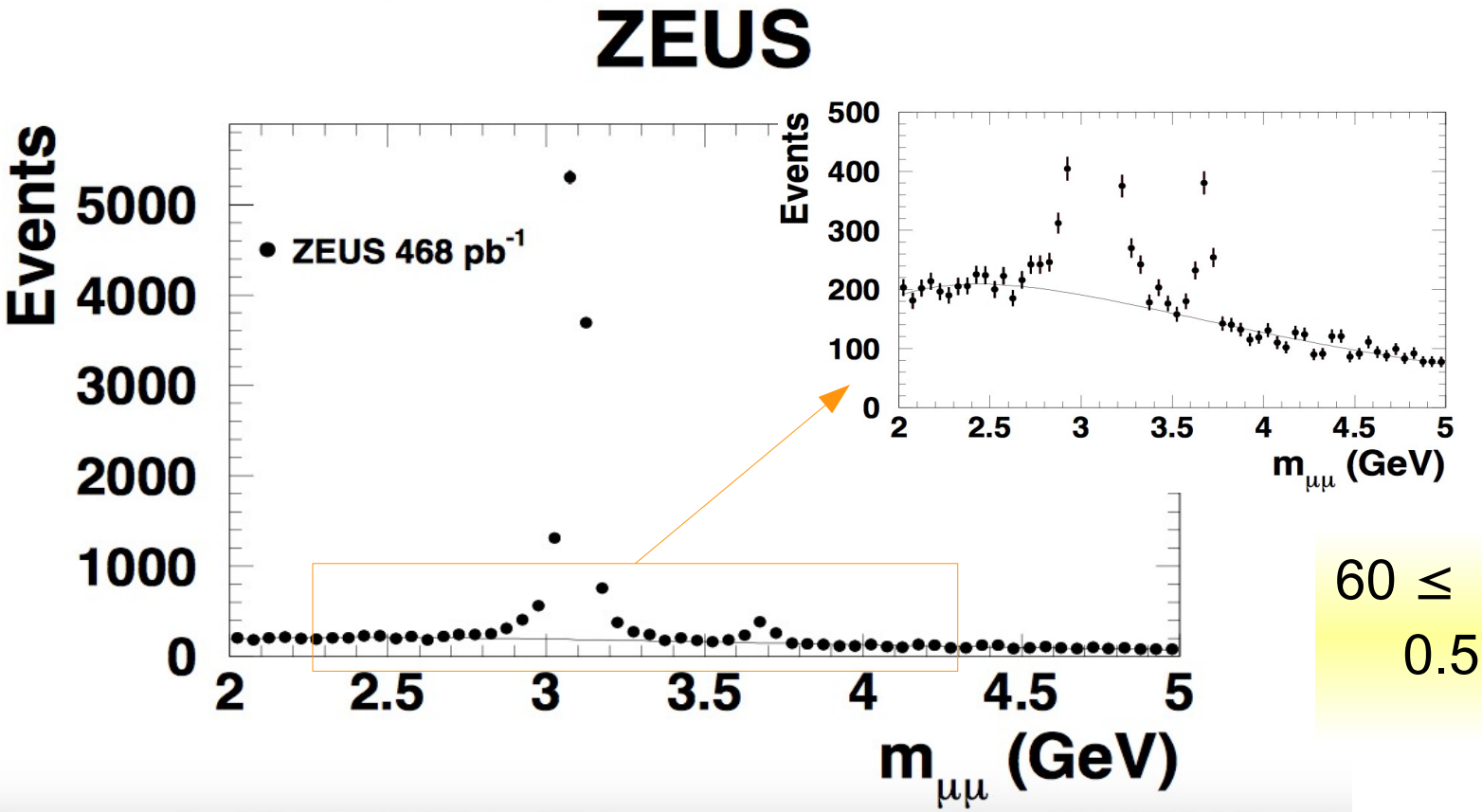
- NO scattered *e* reconstructed in CAL
- Proton remnant
- Two primary-vertex tracks with invariant mass between 2 — 5 GeV

  & restricted to the pseudorapidity region $|\eta| < 1.75$
- Additional hadronic activity

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



Event number determination



$60 \leq W \leq 190$ GeV

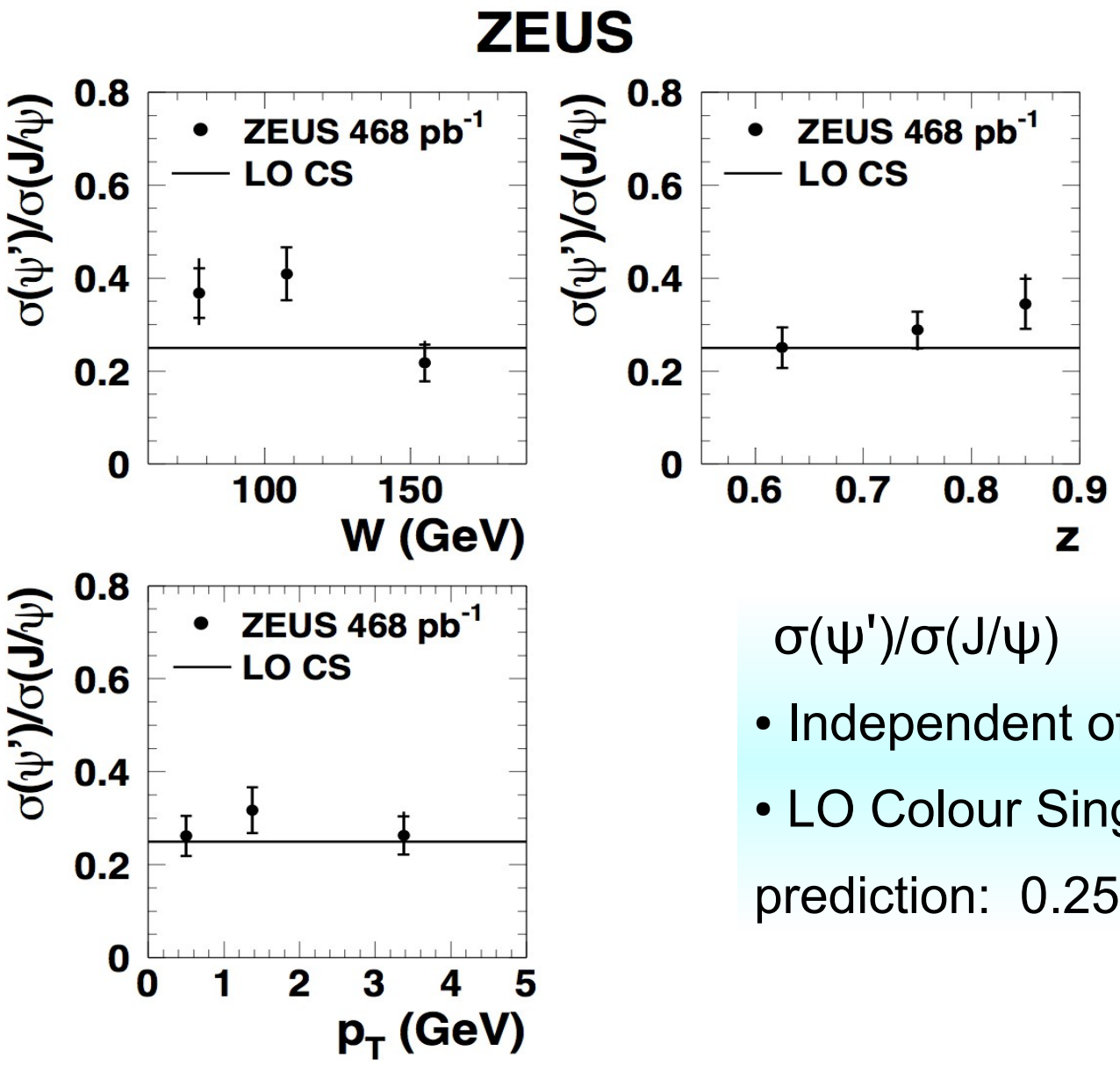
$0.55 \leq z \leq 0.9$

Sideband of the signal: $2 < M_{\mu\mu} < 2.75$ GeV and $3.8 < M_{\mu\mu} < 5$ GeV
fitted by product of a *second-order polynomial* and an *exponential* function

$J/\psi \rightarrow \mu^+ \mu^-$: 11295 ev.
$\psi' \rightarrow \mu^+ \mu^-$: 448 ev.

Charmonium from proton diffractive dissociation: subtracted

ψ' and J/ψ cross section ratio



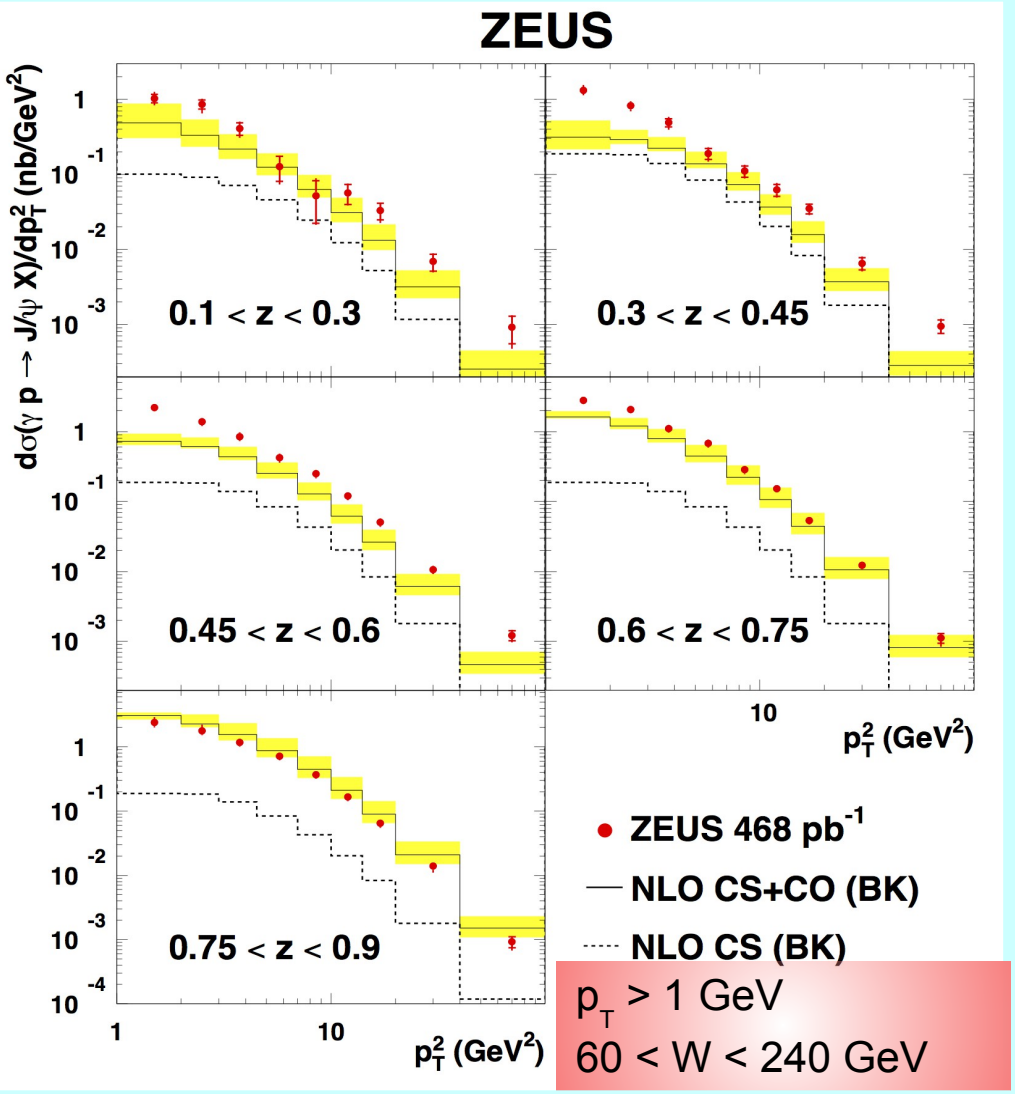
0.55 < z < 0.9
60 < W <190 GeV

σ(ψ')/σ(J/ψ)

- Independent of W, z pT
- LO Colour Singlet model

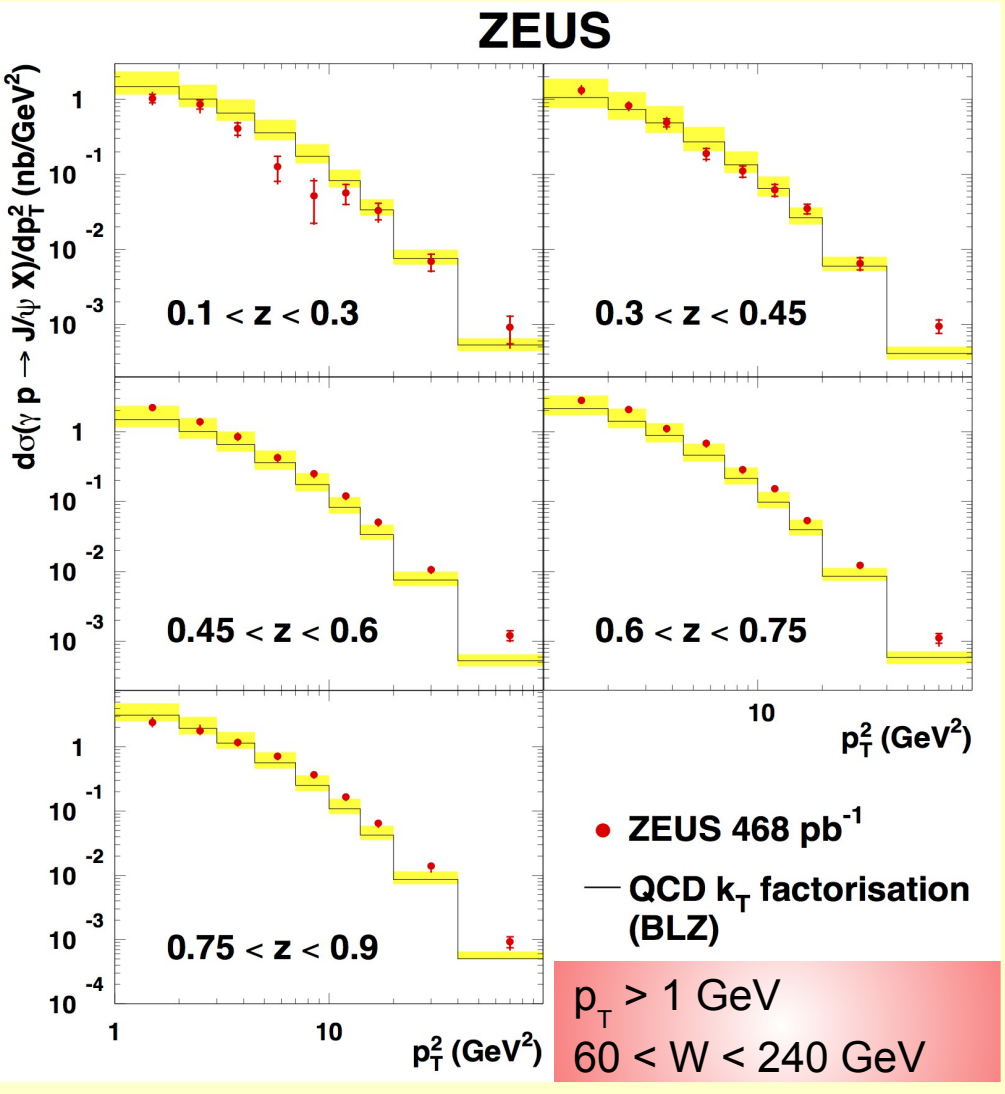
prediction: 0.25 (hor. line)

J/ψ p_T^2 differential cross section



p_T > 1 GeV
60 < W < 240 GeV

Theory: full NLO computation including Colour Singlet & Color Octet terms

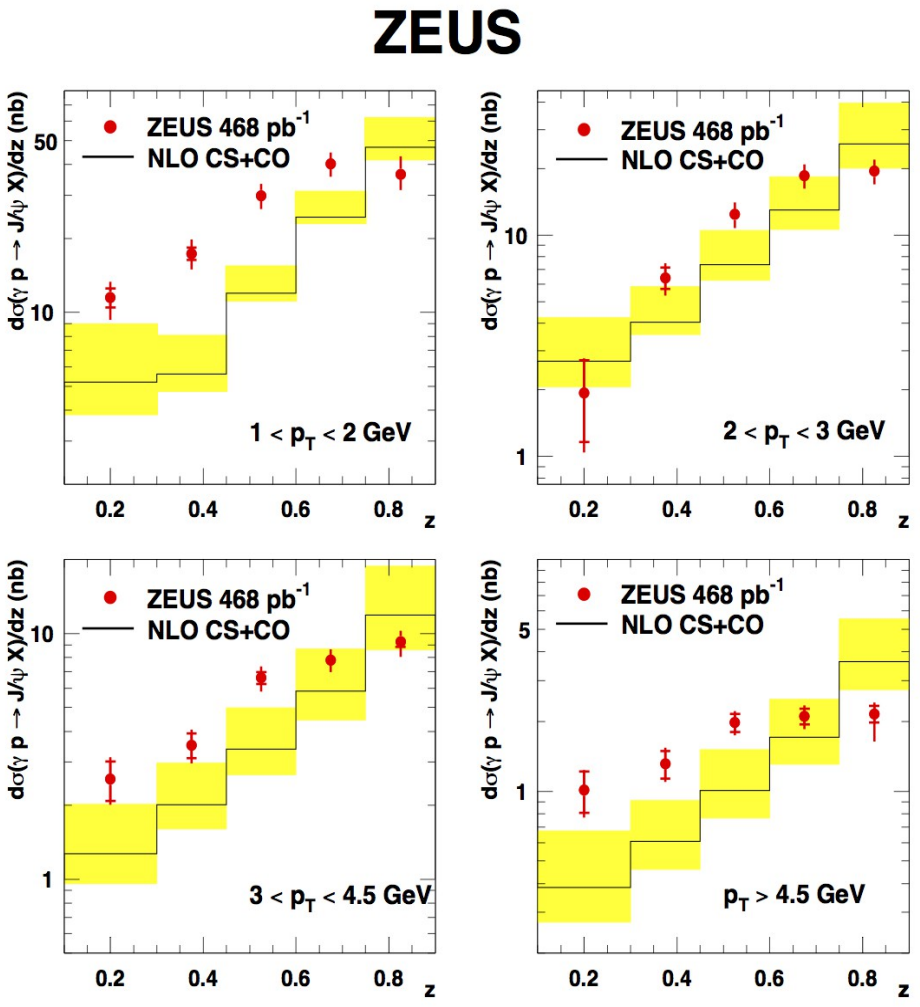


p_T > 1 GeV
60 < W < 240 GeV

Theory: LO CS model framework amended with non zero initial state gluons k_T

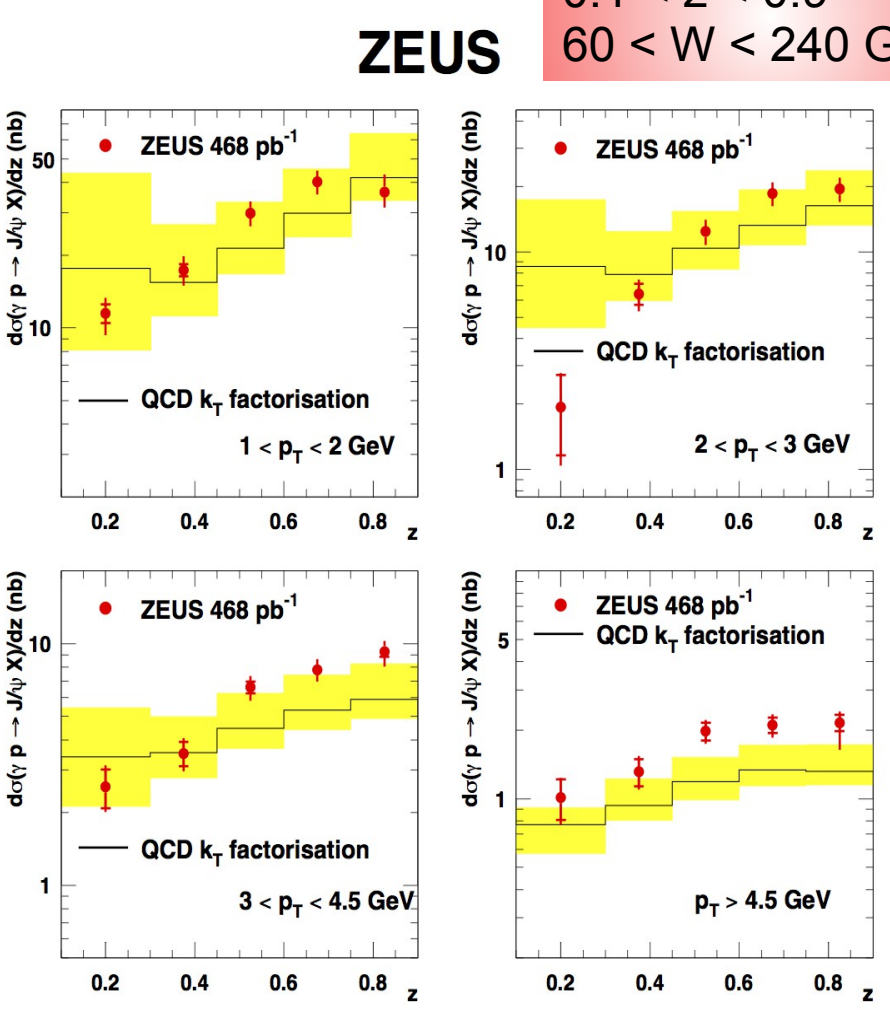
Theory describes data within theoretical uncertainties

J/ψ z differential cross section



Theory: full NLO computation including Colour Singlet & Color Octet terms

$0.1 < z < 0.9$
$60 < W < 240$ GeV



Theory: LO CS model framework amended with non zero initial state gluons k_T

Theory describes data within theoretical uncertainties

Summary of recent HERA quarkonium results

- **Elastic and proton-dissociative photoproduction of J/ψ**
  - new H1 data agree well with previous HERA measurements and with a model based on two gluon exchange
  - W-dependence of the proton-dissociative channel is found to be significantly weaker than that of the elastic channel

- **Cross section ratio R = σ(ψ(2S))/σ(J/ψ) in DIS**
  - first ZEUS measurement
  - improved accuracy compared to older H1 result
  - R increases with Q2

- **Inelastic J/ψ and ψ(2S) photoproduction**
  - ψ(2S) / J/ψ ratio ~ 0.25, as predicted by LO CS modeal

  - double differential J/psi cross sections vs z and p_T^2:

    LO k_T calculation using CS terms alone ~ good description

    but large uncertainties

    recent NLO calculation in collinear approximation ~ rough description, CO terms are absolutely essential

Backup slides

1) Elastic and Proton-Dissociative Photoproduction of J/ψ Mesons

[arXiv:1304.5162]

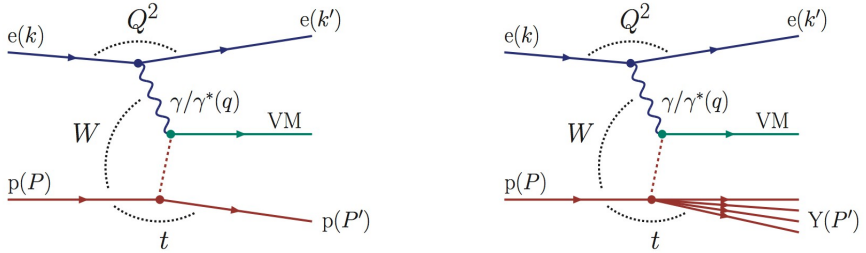
Analysed channels $J/\psi \rightarrow \mu^+ \mu^-$, $e^+ e^-$

Data samples

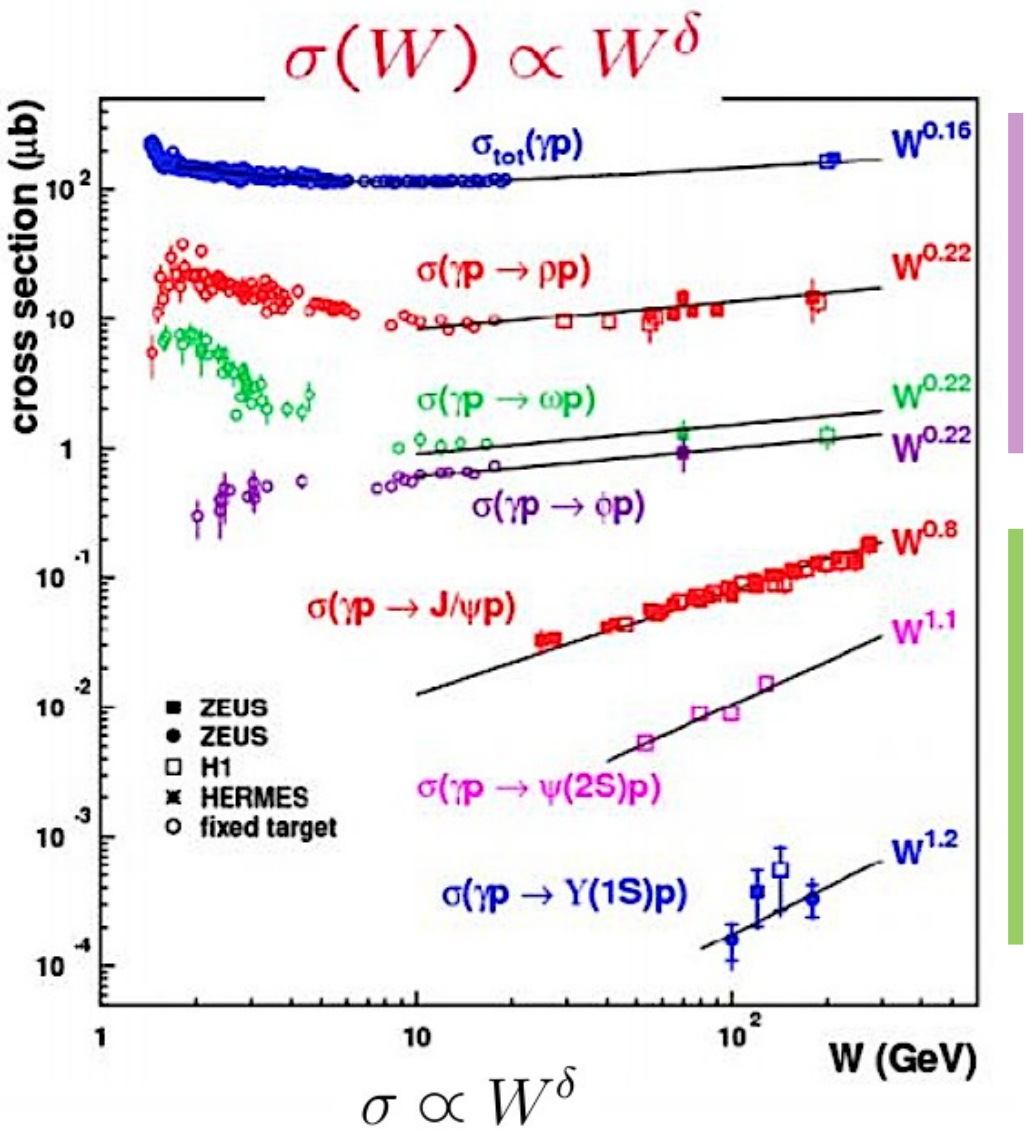
high energy run	E_p = 920 GeV	E_e = 27.5 GeV	$\sqrt{s}$ = 318GeV	L = 130 pb^{-1}
low energy run	E_p = 460 GeV	E_e = 27.5 GeV	$\sqrt{s}$ = 225 GeV	L = 10.8 pb^{-1}

MC-data samples

DIFFVM for exclusive and proton-dissociative VM production



Energy dependence in photoproduction



Low mass: ρ, ω, φ

$M^2_{VM} \approx 1\ GeV^2$

No perturbative scale => weak energy dependence

Soft regime

High mass: J/ψ, ψ(2S), ϒ

Hard scale => strong energy dependence

Hard regime

VM production at HERA: transition between soft and hard regimes