Legacy of HERA: Quarkonium production at ZEUS and H1

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Quarkonia in exclusive & diffractive processes

Quarkonia in inclusive reactions

https://www-h1.desy.de/publications/H1publication.short_list.html

https://www-zeus.desy.de/zeus_papers/zeus_papers.html

Synergies between LHC and EIC for quarkonium physics, 8-12 July 2024

https://indico.ectstar.eu/event/219/overview

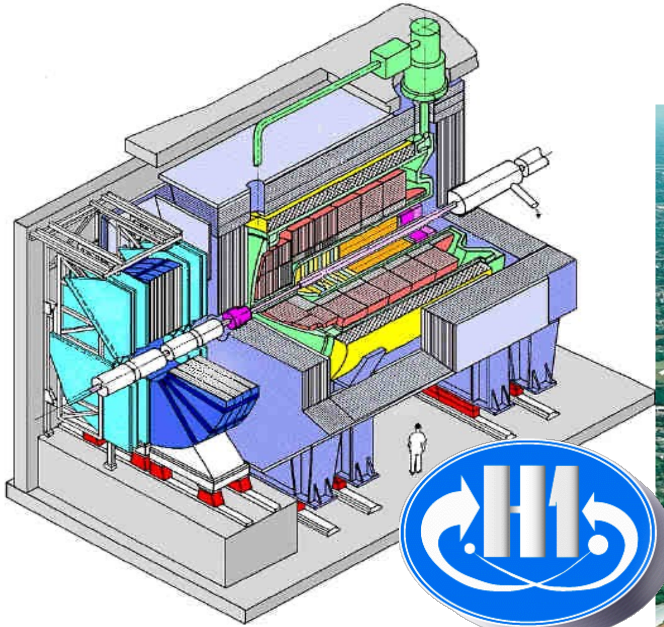
Istituto Nazionale di Fisica Nucleare

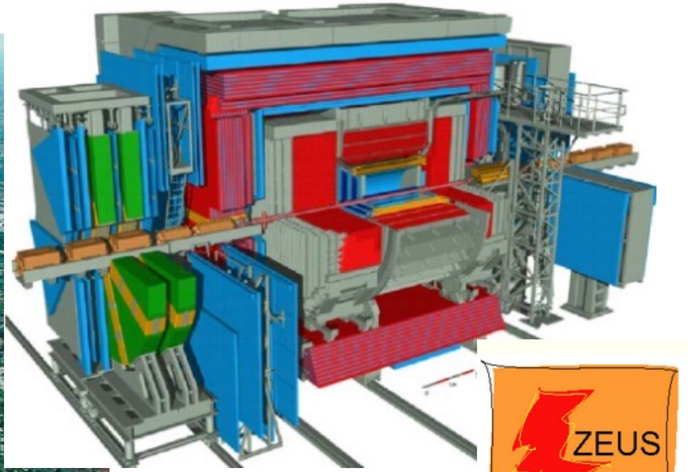
This workshop is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 824093.

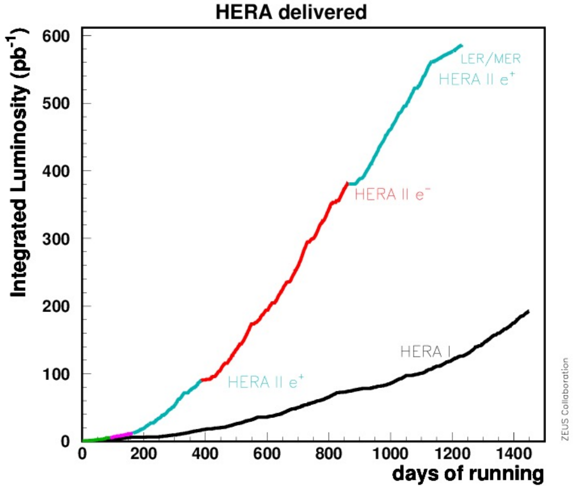
HERA electron/positron-proton collider (1992-2007)

Ee = 27.6 GeV, Ep = 920 GeV (but also 820, 460, 575 GeV)

DESY, Hamburg (DE)





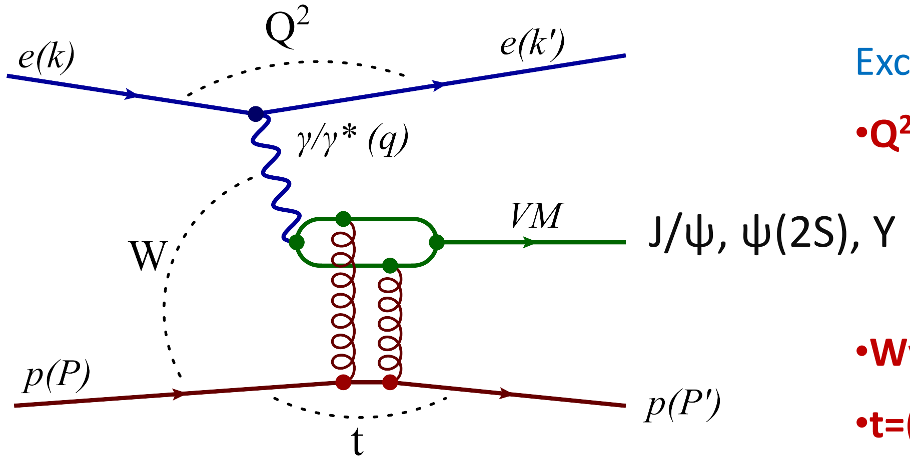


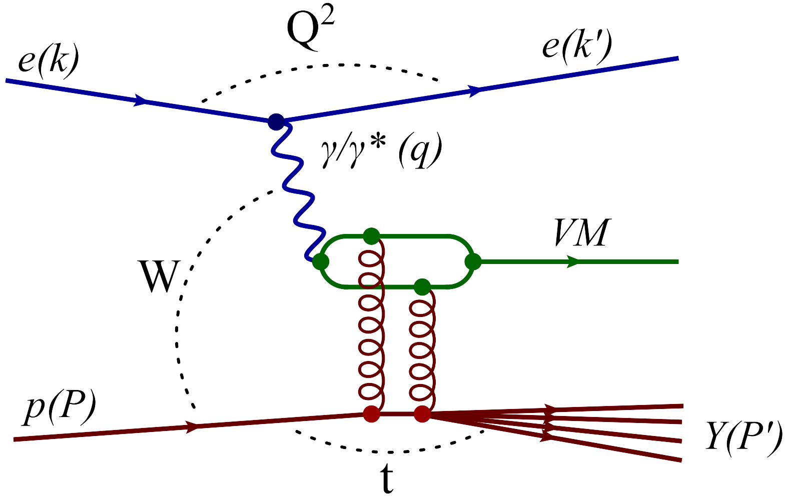
- Total luminosity ~ 0.5 fb^{-1}per experiment
- Center-of-mass energies 318 GeV - 225 GeV

Quarkonia in exclusive & diffractive processes
H1 and ZEUS paper on J/ψ, ψ(2S), Υ production

Photoproduction		H1, Elastic and p-diss J/ψ in PHP Eur.Phys.J.C73 (2013) 2466 H1, Elastic J/ψ in PHP and DIS Eur.Phys.J.C46 (2006) 585 ZEUS, Exclusive PHP of J/ψ mesons Eur. Phys. J. C 24 (2002) 345 H1, Elastic J/ψ and Υ in PHP Phys.Lett.B483 (2000) 23 H1, Elastic and Inelastic J/ψ in PHP Nucl.Phys.B472 (1996) 3
Deep Inelastic Scattering		ZEUS, Exclusive J/ψ in DIS Nucl. Phys. B 695 (2004) 3 H1, Charmonium Production in Deep Inelastic Scattering at HERA, Eur.Phys.J.C10 (1999) 373-393 H1, Elastic ρ0 and J/ψ at large Q2 Nucl.Phys.B468 (1996) 3 ZEUS, Exclusive ρ0 and J/ψ in DIS Eur. Phys. J. C 6 (1999) 603
High-t, Mandelstam variable		ZEUS, p-dissociative J/ψ in PHP at large t JHEP 05 (2010) 085 H1, Diffractive PHP of J/ψ with large t Phys Lett B568 (2003) 205
ψ(2S)		Ψ(2S) / J/ψ ratio in PHP, JHEP 12 (2022) 164 ZEUS, R(σψ(2S)/σJ/ψ(1S) in DIS Nucl. Phys. B 909 (2016) 934 H1, Diffractive PHP of ψ(2S) Phys.Lett.B541 (2002) 251
Υ		ZEUS, Υ in PHP (t-dependence), Phys.Lett. B 708 (2011) 14 ZEUS, Exclusive Υ in PHP, Phys.Lett. B 680 (2009) 4 H1, Elastic J/ψ and Υ in PHP Phys.Lett.B483 (2000) 23 ZEUS, Elastic Υ production, Phys.Lett. B 437 (1998) 432

Kinematics





Exclusive production of Vector Mesons fully described by:

- **Q^2** photon virtuality, kinematic regimes:
  - photoproduction, $Q^2 \approx 0$ GeV^2
  - Deep Inelastic Scattering: $Q^2 > 1$ GeV^2
- **$W\gamma p$** photon-proton centre-of-mass energy
- **$t=(p-p')^2$** – four momentum transfer squared at proton vertex
- **x–Bjorken** x–fraction of proton's momentum carried by struck quark/gluon **$x \sim 1/W^2\gamma p$**

Kinematic variable fully reconstructed usually measuring **scattered electron** (in DIS) and vector meson decay products or final photons or jets. **Scattered p** detected with lower acceptance

Diffractive vector meson production studied at HERA as a function of several scales: Q^2, MV, t over a wide range of $W\gamma p$.

Event topology/selection: exclusive di-muon /di-electron production

Very clean signature: J/ψ mesons identified via the decay channels: μ+μ–, e+e-

Photoproduction: trigger and selection driven by tracking + muon chambers / electrons in CAL

DIS: trigger given by scattered electron in CAL

Selection: 2 tracks matched with calorimeter (MIPs or electron clusters), no additional CAL cluster.

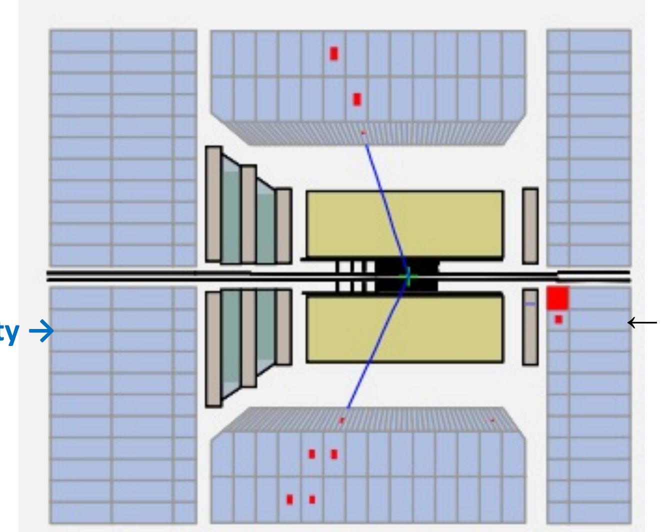
For electron channel, 1 track + 1 CAL electron is also possible

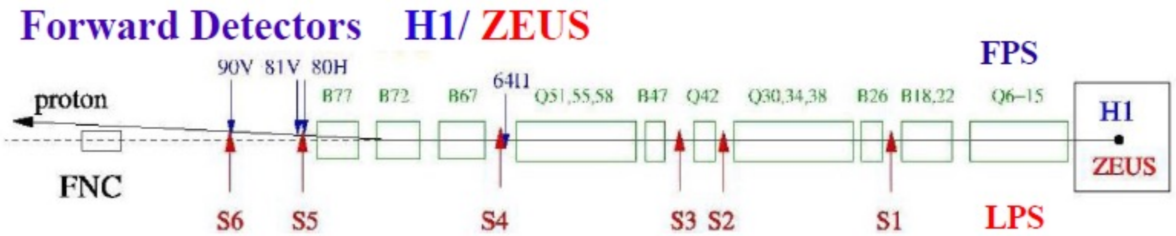
Experimental challenge:

- trigger on exclusive events while rejecting non ep background: halo mu and cosmics

Analysis requires:

- a good understanding of trigger efficiencies
- forward detector to tag/study p-dissociative process

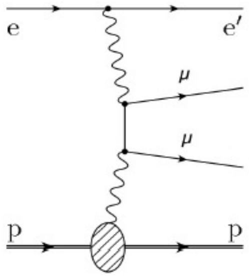


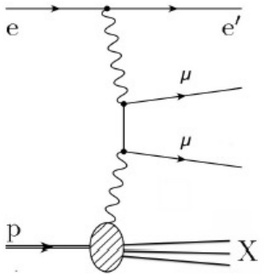


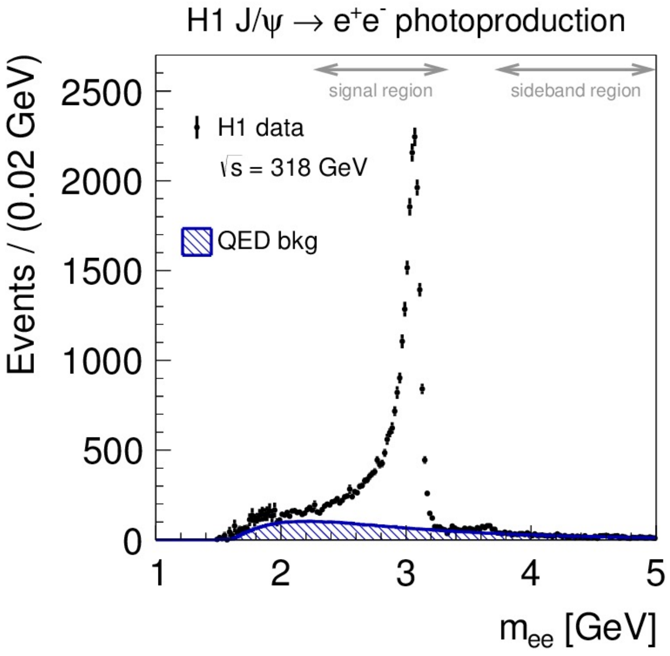
H1: Forward Proton Spectrometer (FPS), Very Forward Proton Spectrometer, Forward Tagging System (HERAII)

ZEUS: Leading Proton Spectrometer; Proton Remnant Tagger (HERAI)

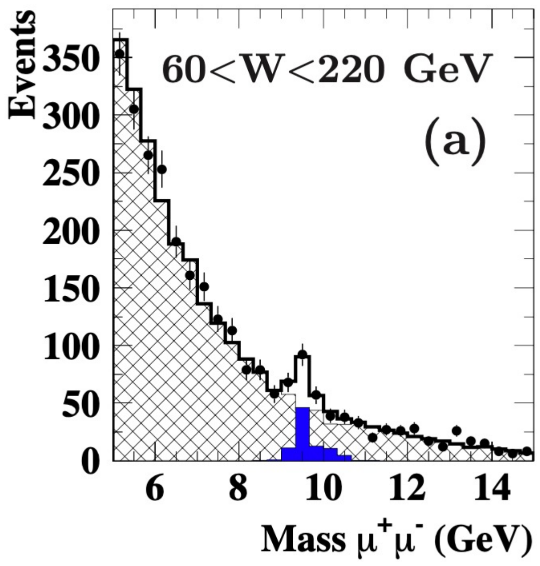
Signal extraction from invariant mass distributions







Υ–> μ+μ– photoproduction



J/ψ, ψ(2S), Υ ->μ+μ–, e+e-

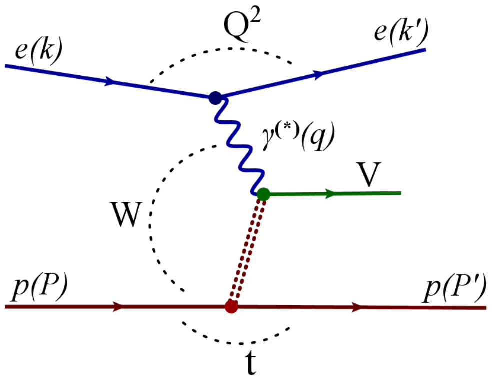
- only background source from QED non-resonant muon/electron pair production γγ->l+l- (Bethe-Heitler process) subtracted by QED simulation, usually normalized in control region, as it contains p-diss contribution, not perfectly simulated

signal events:

- fitted
- or counted in signal region, procedure insensitive to low mass tail due to QED radiation losses and Bremsstrahlung, large for electrons and sizeble for muons; adeguate in regions at low and high W were mass resolution is poor.

Theoretical models

- **Regge phenomenology**: Vector Dominance Model + Soft Pomeron IP exchange



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

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

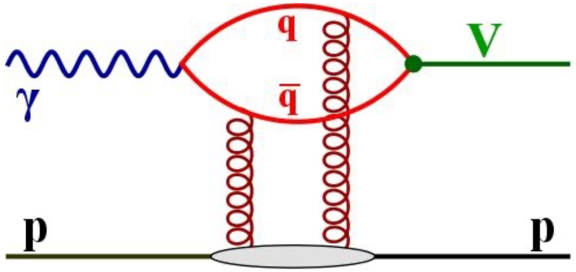
$$\frac{d\sigma}{dt} \propto e^{bt} \left(\frac{W_{\gamma p}}{W_0} \right)^{\delta} \qquad \delta = 4(\alpha_0 - 1)$$

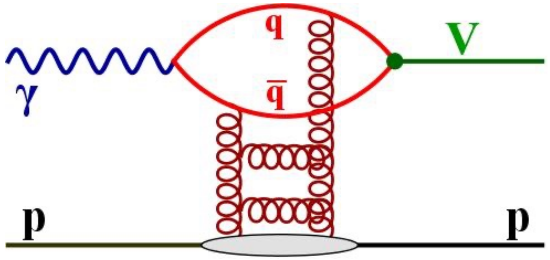
$$b = b_0 + 4\alpha' \ln \left(\frac{W_{\gamma p}}{W_0} \right)$$

Weak energy dependence

$\sigma \propto W^{\delta}_{\gamma p}$

- In the presence of a hard scale (M_{VM}, Q^2, t) calculations in **pQCD** are possible.
- Exchange of a gluon ladder. Fast increase of the cross section with energy



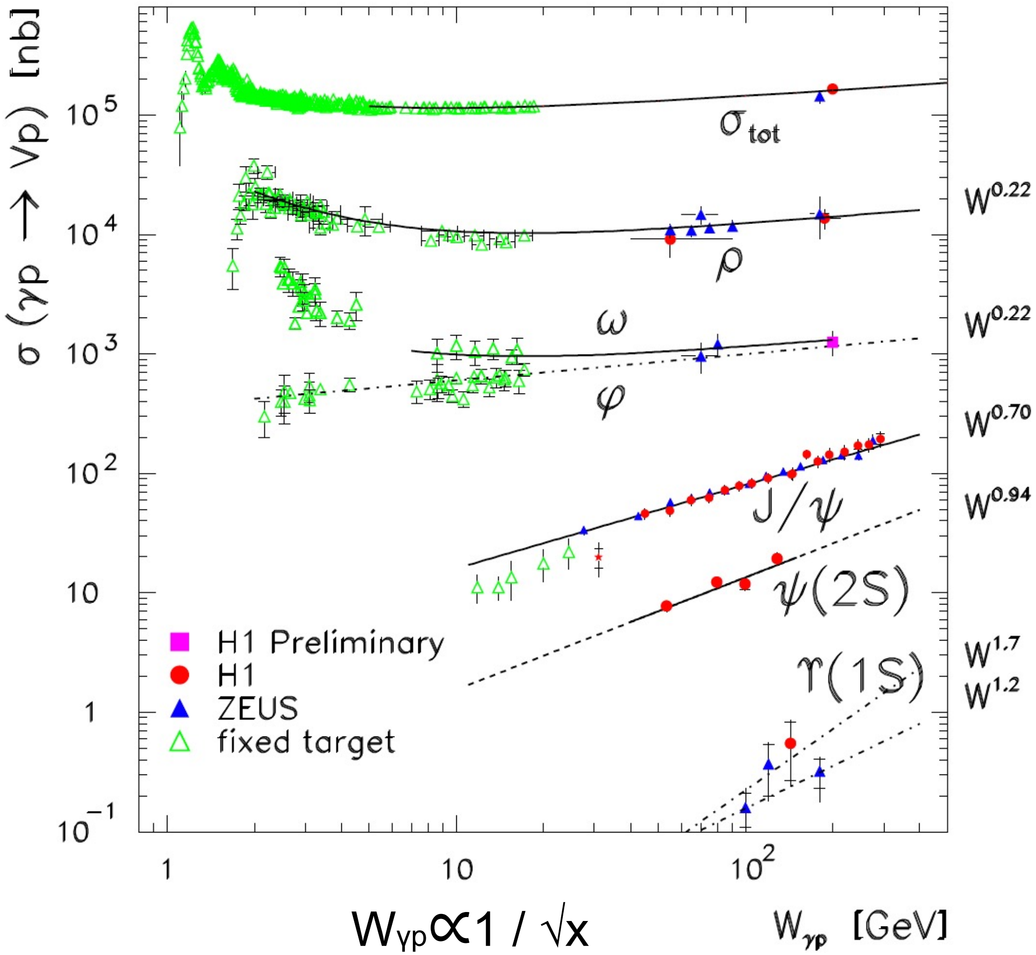


$$\begin{cases} \sigma \propto [x\, g(x, \mu^2)]^2 \\ x = \mu^2 / W^2 \\ \mu^2 \propto (Q^2 + M_V^2) \end{cases}$$

- Generalised Parton Densities relevant here. Calculations performed now at NLO.

Wγp dependence of Elastic Vector Meson Photoproduction

- The cross section dependence on W can be parameterised as $\sigma \sim W^{\delta}{}_{\gamma p}$
- Increasing VM mass, process gets harder



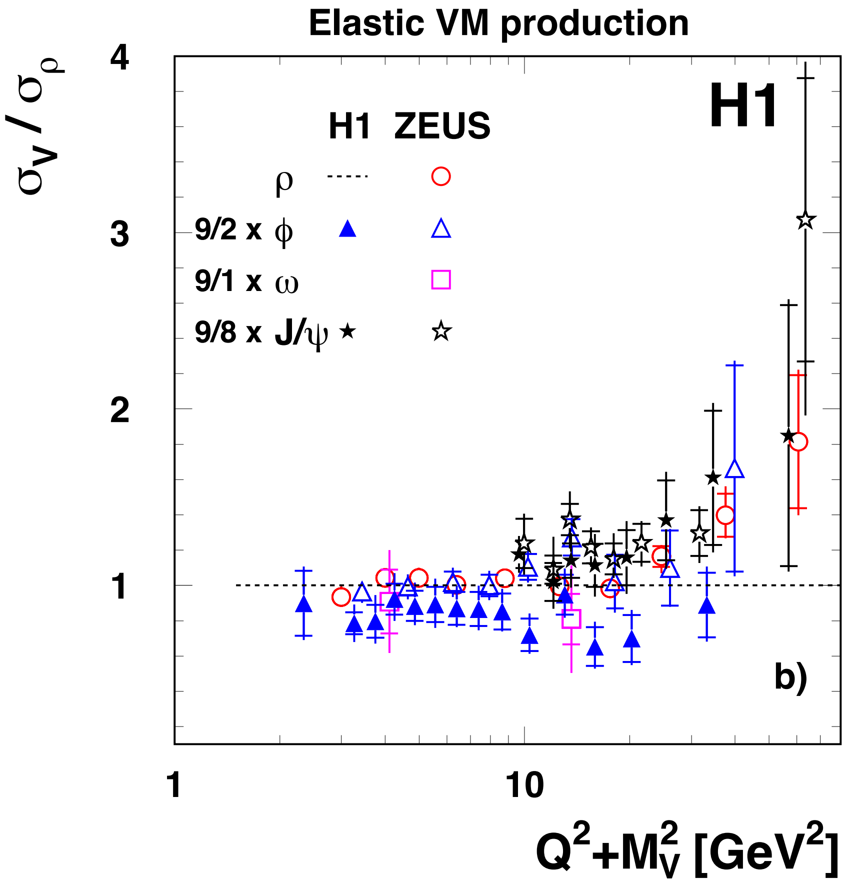
$W_{\gamma p} \propto 1/\sqrt{x}$

Low mass VM consistent with soft model, **δ ~ 0.2**

$\sigma \propto [x\, g(x, \mu)]^2$, with **$x \sim 1/W^2{}_{\gamma p}$**

For high mass VM, rapid rise of cross section with Wγp related to the increasing gluon density with decreasing of fractional momentum

Universality of VM production

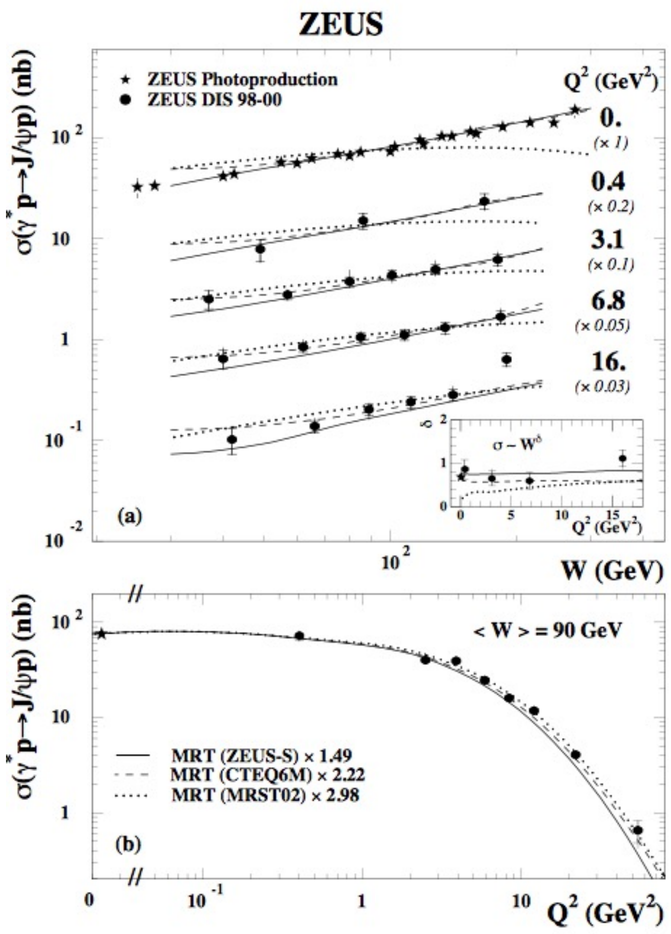


- Despite cross sections of light VM and J/ψ differ by order of magnitude, they are close when corrected for factors accounting VM charge (rho : phi: J/ψ = 9 : 2 : 8) and plotted vs scaling variable $\mu^2 = (Q^2+M^2_V)/4 \simeq 3\text{-}5\ \mathrm{GeV}^2$

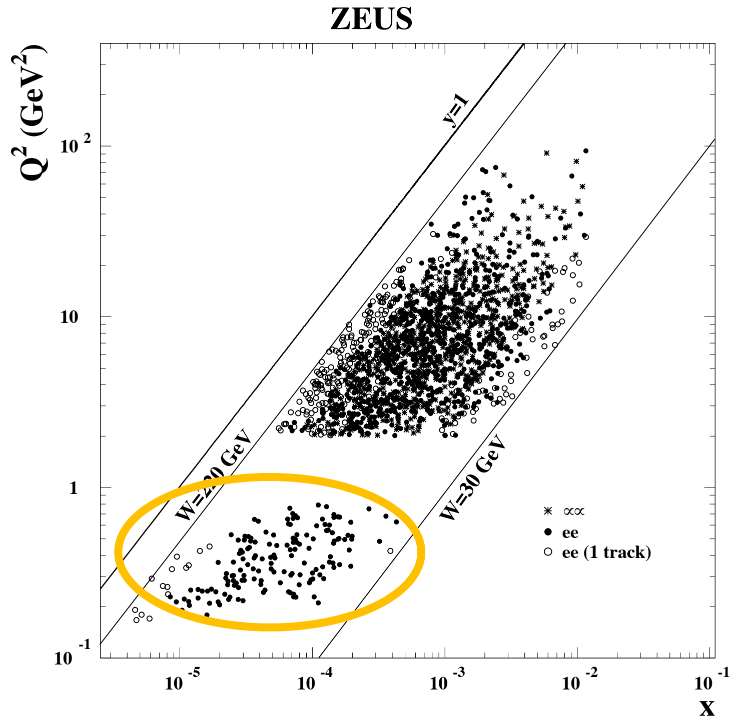
- Ratios, scaled according to quark charge content, close to 1 (up to Wave Function effects) once plotted vs $(Q^2+M^2_V)$

This supports the dipole approach of VM production at high energy: cross sections are essentially determined by the dipole size

Wγp dependence of J/ψ in photoproduction and DIS



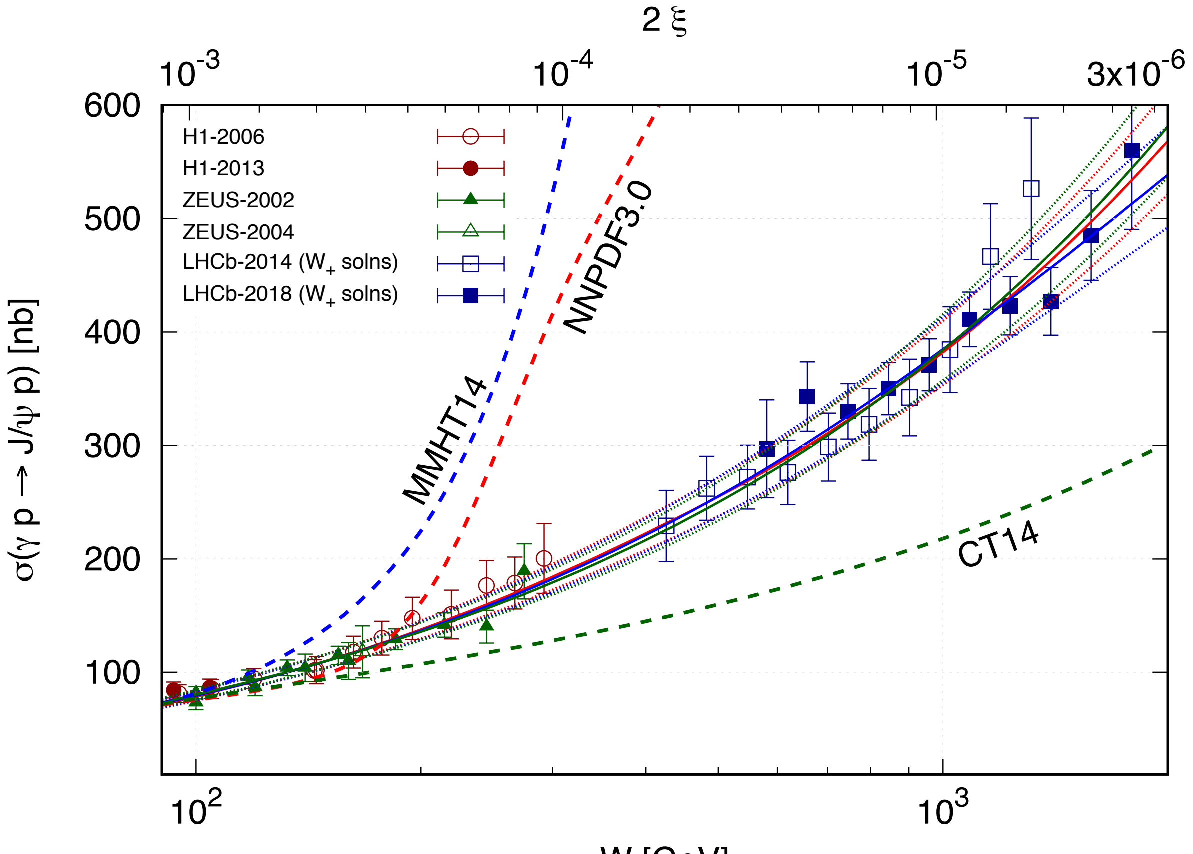
distribution of the J/ψ events in the kinematic plane of Bjorken-x and Q^2

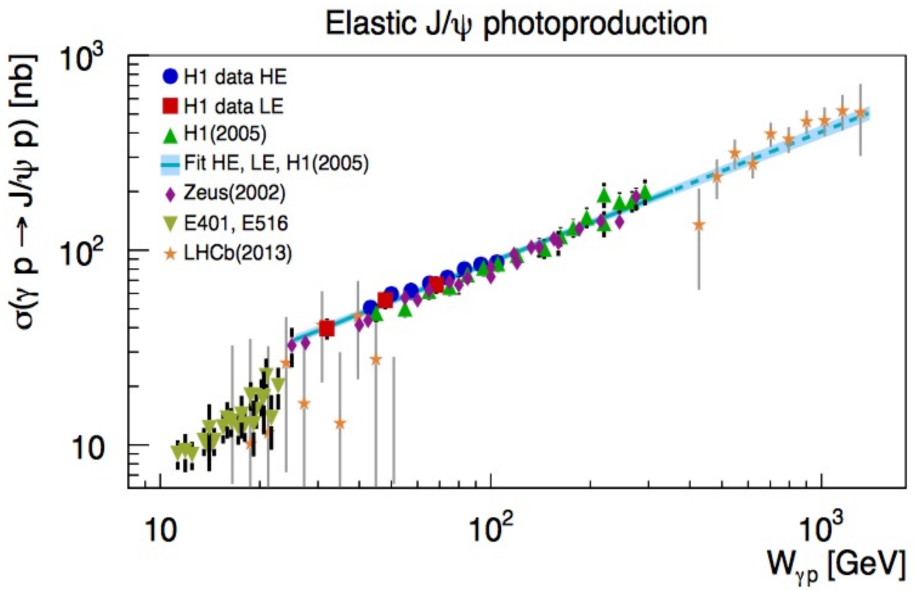


lowest values of Bjorken-x reached in photoproduction

Wγp dependence of J/ψ photoproduction

Since 2015 "data J/ψ p can included in the global PDF fits to determine the gluon in the low x regime" (1507.06942 Jones, Martin, Ryskin, Teubner)

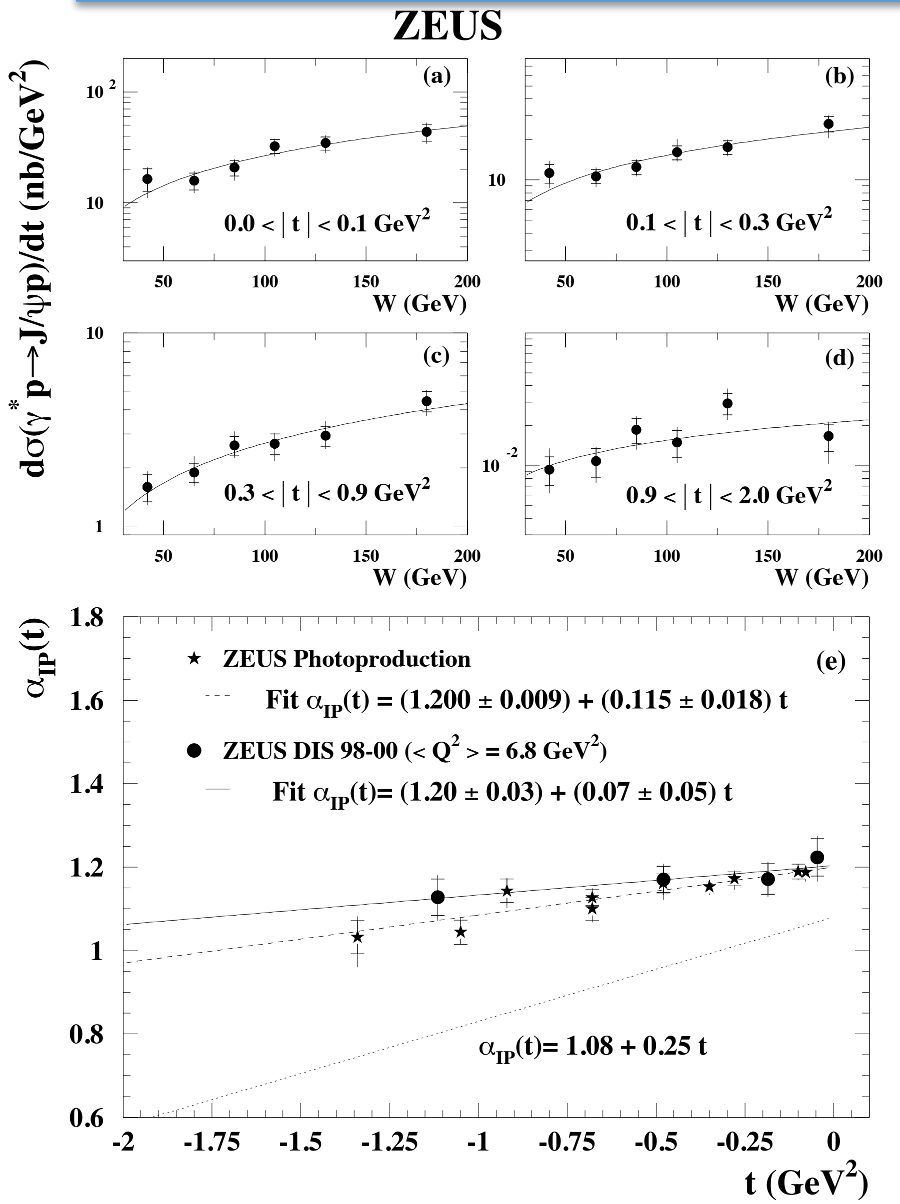




•A. Martin et al Phys. Rev. D 102, 114021 (2020)

No hint of saturation observed in exclusive J/ψ data at the scale μ^2= 2.4 GeV^2 and x down to 10^{-5}.

Regge models - Pomeron trajectory

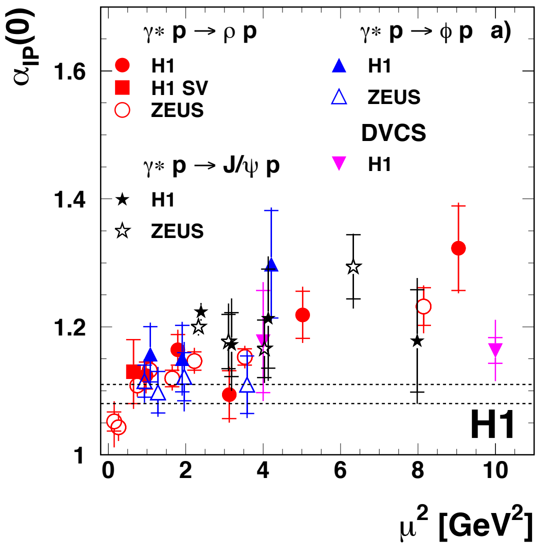


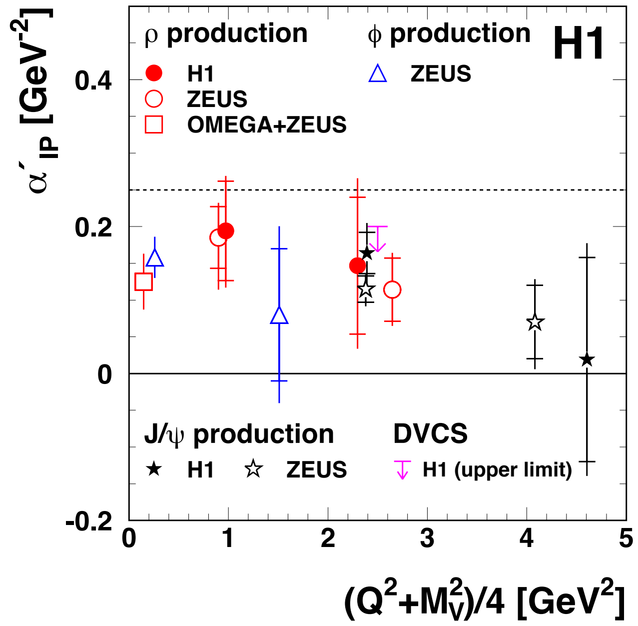
W dependance investigated using parametrisation inspired by Regge theory, interactions mediated by particles

Differential cross sections dσ/dt as a function of W for fixed ranges of t as W^4(α_{IP} (t)−1)

Pomeron trajectory associated to J/ψ is not soft

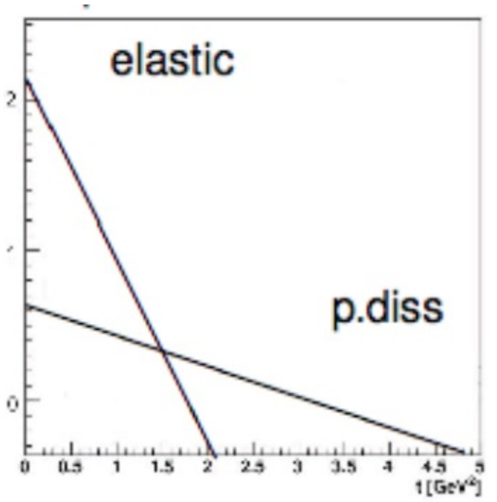
In BFKL approach, α′ is related to the average kt of gluons around the ladder in their random walk, expected to be small

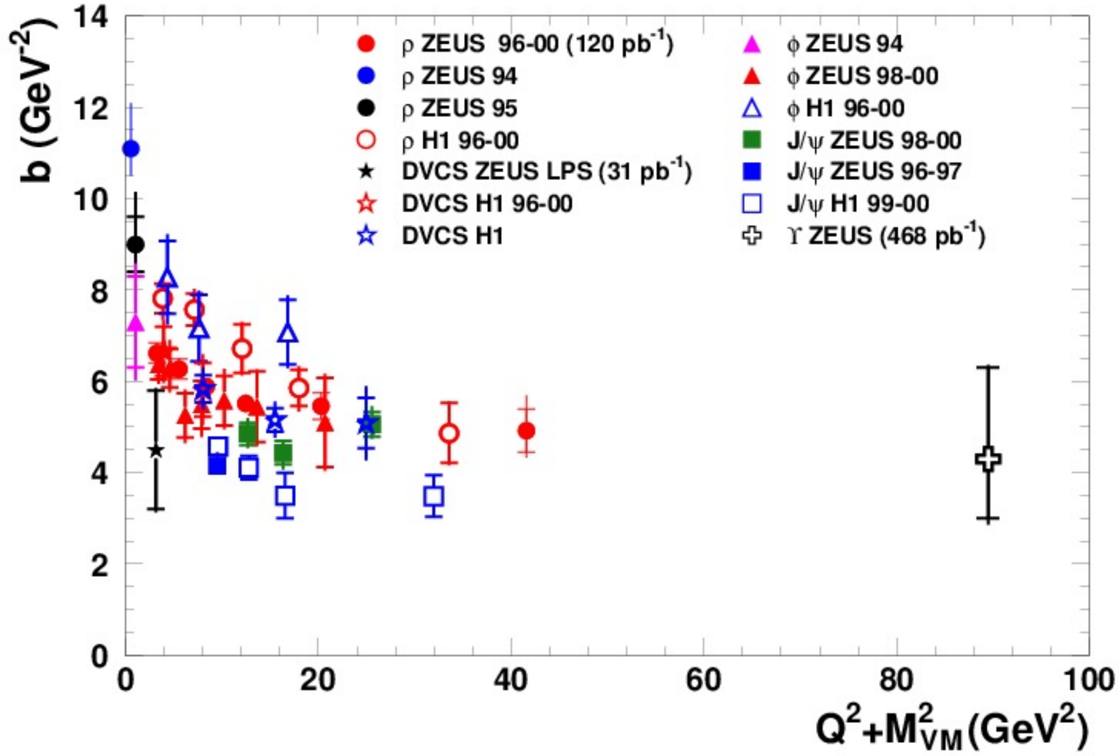




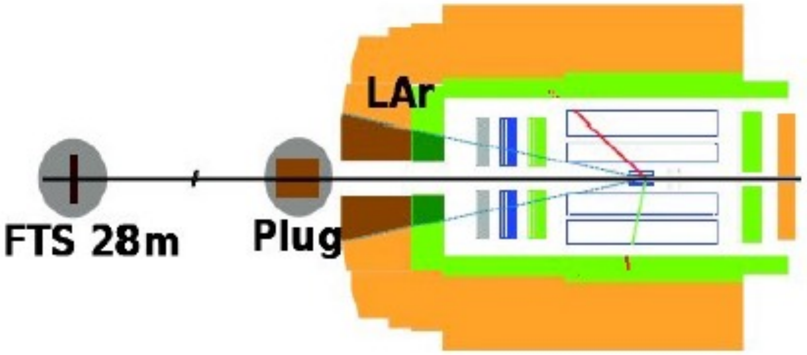
t-dependence of J/ψ photoproduction

- t- dependence of cross section $d\sigma / dt \simeq e^{bt}$
- In optical model approach, b is related to the quadratic size of interacting objects:
- $b \sim (R^2_p + R^2_{VM})/4$
- in p-diss events proton breaks and size is smaller. As σ is similar for exclusive and p-diss. events, p-diss dominates at high-t





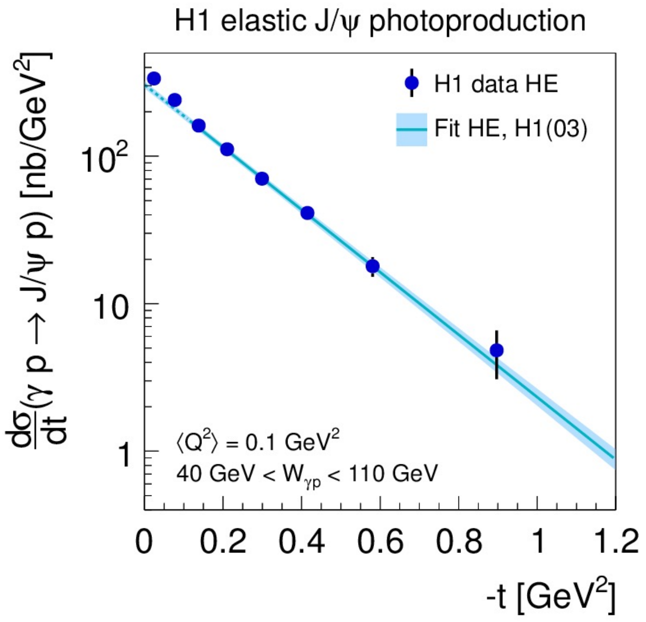
t-dependence of J/ψ photoproduction - low t

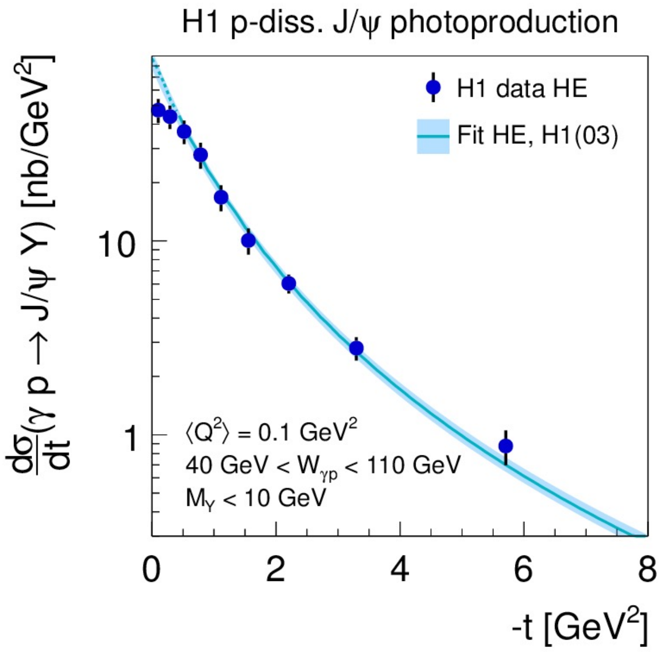


H1:

- Use forward detectors (FTS, Plug, LAr) to tag proton dissociative process at low |t|.
- Use data from HERA low energy run to extends the range to lower Wγp

Simultaneous measurement of elastic and proton-dissociative process.





Phenomenological fits:

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

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

t-dependence of J/ψ photoproduction – b slope

H1 PHP. pdiss $m_p < M_Y < 10$ GeV

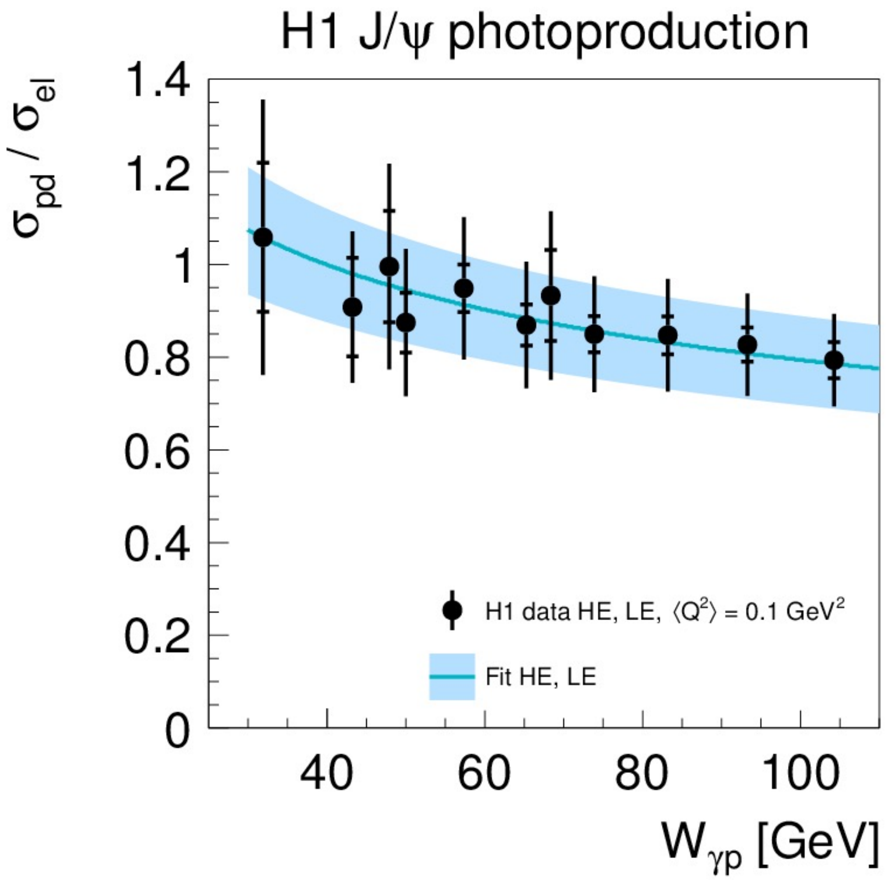
Data period	Process	Parameter	Fit value	Correlation
HE	$\gamma p \to J/\psi\, p$	b_{el}	(4.88 ± 0.15) GeV^{-2}	$\rho(b_{el}, N_{el}) = 0.50$ $\rho(b_{el}, b_{pd}) = 0.49$ $\rho(b_{el}, n) = -0.21$ $\rho(b_{el}, N_{pd}) = 0.68$
		N_{el}	(305 ± 17) nb/GeV^2	$\rho(N_{el}, b_{pd}) = 0.23$ $\rho(N_{el}, n) = -0.07$ $\rho(N_{el}, N_{pd}) = 0.46$
	$\gamma p \to J/\psi\, Y$	b_{pd}	(1.79 ± 0.12) GeV^{-2}	$\rho(b_{pd}, n) = -0.78$ $\rho(b_{pd}, N_{pd}) = 0.76$
		n	3.58 ± 0.15	$\rho(n, N_{pd}) = -0.46$
		N_{pd}	(87 ± 10) nb/GeV^2	
LE	$\gamma p \to J/\psi\, p$	b_{el}	(4.3 ± 0.2) GeV^{-2}	$\rho(b_{el}, N_{el}) = 0.37$ $\rho(b_{el}, b_{pd}) = 0.10$ $\rho(b_{el}, N_{pd}) = 0.41$
		N_{el}	(213 ± 18) nb/GeV^2	$\rho(N_{el}, b_{pd}) = -0.24$ $\rho(N_{el}, N_{pd}) = -0.10$
	$\gamma p \to J/\psi\, Y$	b_{pd}	(1.6 ± 0.2) GeV^{-2}	$\rho(b_{pd}, N_{pd}) = 0.53$
		n	3.58 (fixed value)	
		N_{pd}	(62 ± 12) nb/GeV^2	

- ZEUS Eur. Phys. J. C 24 (2002)
- Finite Mass Sum Rule (from Mueller generalized optical theorem) applied to proton diffraction provide constraints on M_Y spectrum of proton diffractive state, which MC have to respect. It also explain why t-distribution is steeper for resonant part than for the continuum part of proton diffraction
- MC simulation: *In the baryon resonance region, at low M_Y, a resonant component with slope b = 6.5 GeV^{-2} was considered. A second component due to non-resonant proton dissociation with slope b = 0.65 GeV^{-2} was added. The two components were constrained to satisfy the first moment of the finite-mass sum rule*. Ref: G. Alberi and G. Goggi, Phys. Rev. 74, 1 (1980)

ZEUS; proton-diss, continuum region for for $3.5 < M_Y < 30$ GeV and $p^2_T < 10$ GeV^2

- p-diss b = 0.65±0.10 GeV^{-2}
- $\sigma \simeq 1/M_Y$^beta with beta =2.6 +-0.3
- elastic b = 4.15 +0.05 (stat) +0.30 -0.18 (syst) GeV^{-2}

W-dependence of J/psi photoproduction – p. diss.



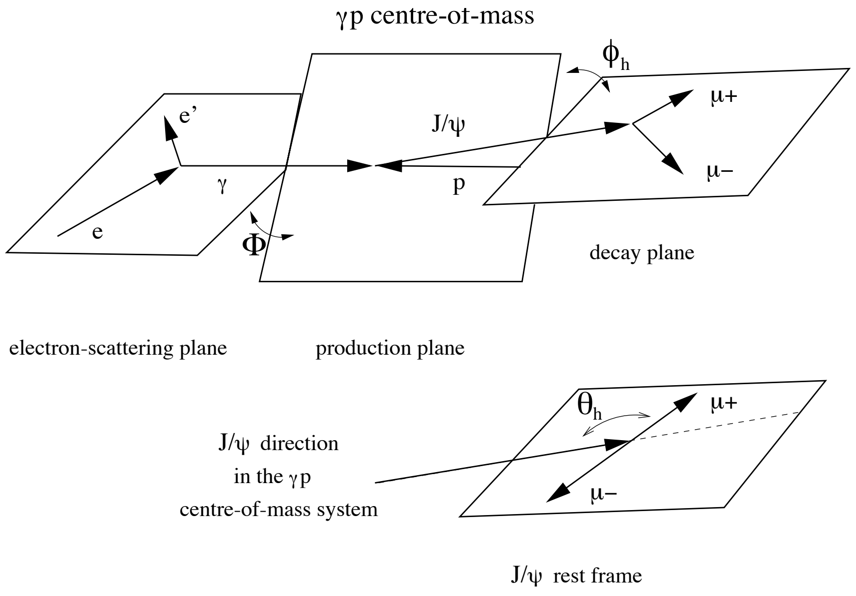
Process	Parameter	Fit value	Correlation
$\gamma p \to J/\psi\, p$	δ_{el}	0.67 ± 0.03	$\rho(\delta_{el}, N_{el})$ =-0.08 $\rho(\delta_{el}, \delta_{pd})$ = 0.01 $\rho(\delta_{el}, N_{pd})$=0.09
	N_{el}	$81 \pm 3\,\mathrm{nb}$	$\rho(N_{el}, \delta_{pd})$ = -0.27 $\rho(N_{el}, N_{pd})$=-0.18
$\gamma p \to J/\psi\, Y$	δ_{pd}	0.42 ± 0.05	$\rho(\delta_{pd}, N_{pd})$=0.09
	N_{pd}	$66 \pm 7\,\mathrm{nb}$	

Ratio of elastic and proton dissociative cross is approximately equal to 1

A slight dependence of this ratio as a function of $W_{\gamma p}$ is observed

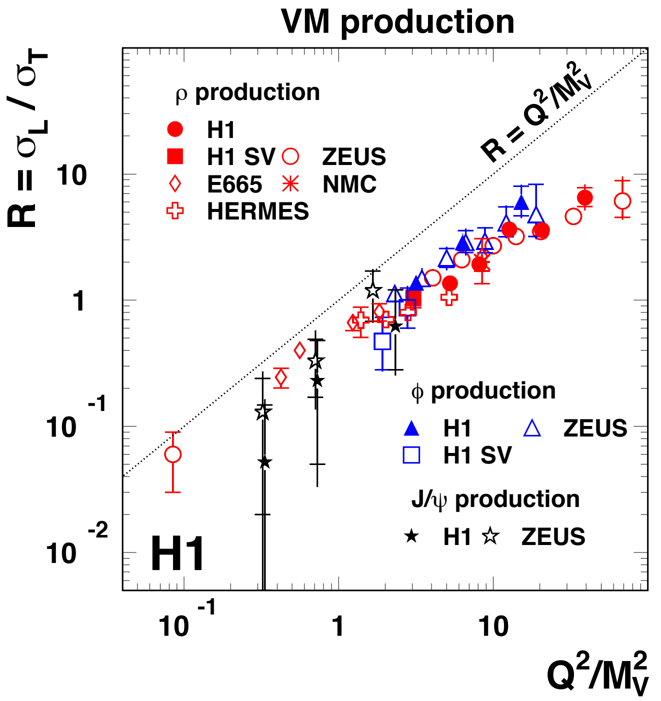
Decay angular distribution, helicity frame

Measurement of VM production and decay angles give access to spin density matrix elements
Angular distr. → spin density matrix elements r_{ji}^{kl} , → helicity amplitudes $T_{\lambda_{VM}\lambda_\gamma}$



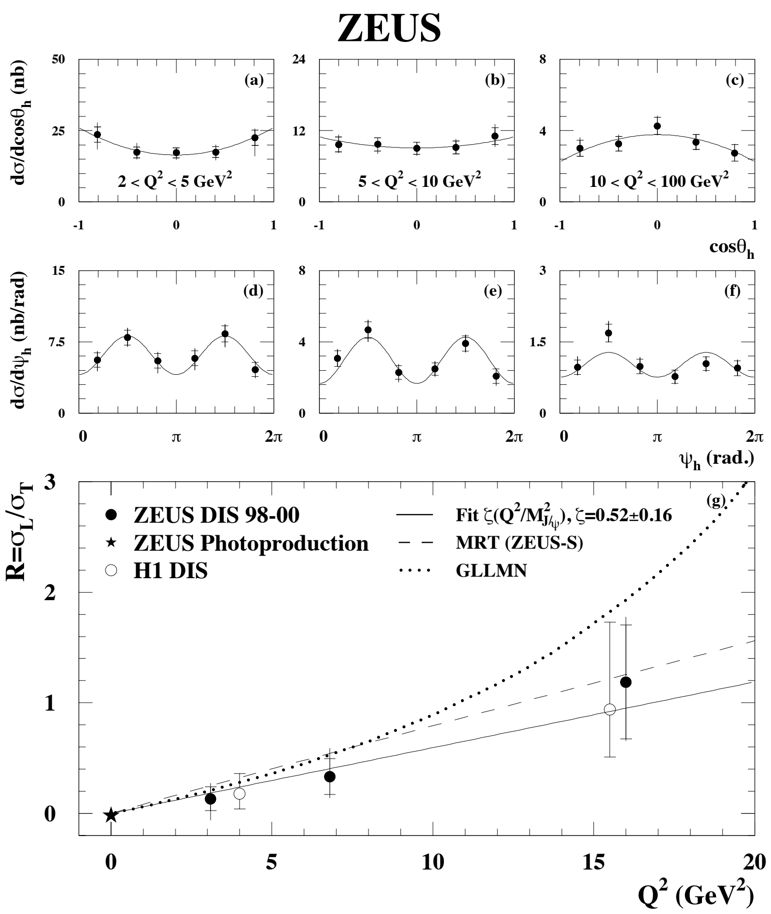
S-channel helicity conservation: the outgoing VM retains the γ helicity

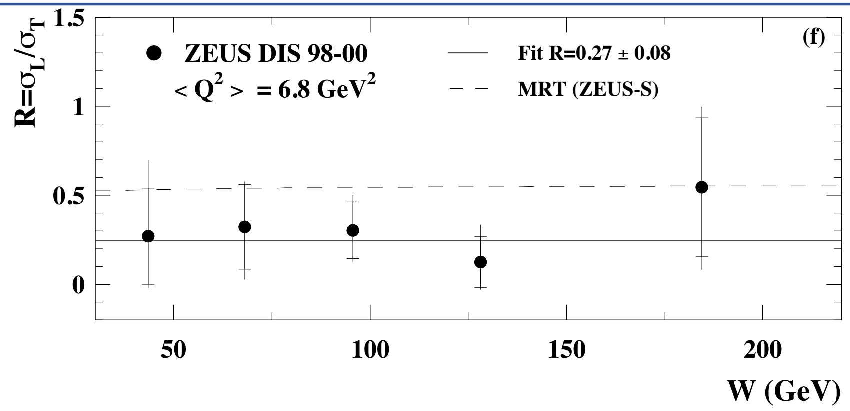
In the accessible Q^2 range, J/ψ production is almost transverse, while for light VM the longitudinal amplitude dominates

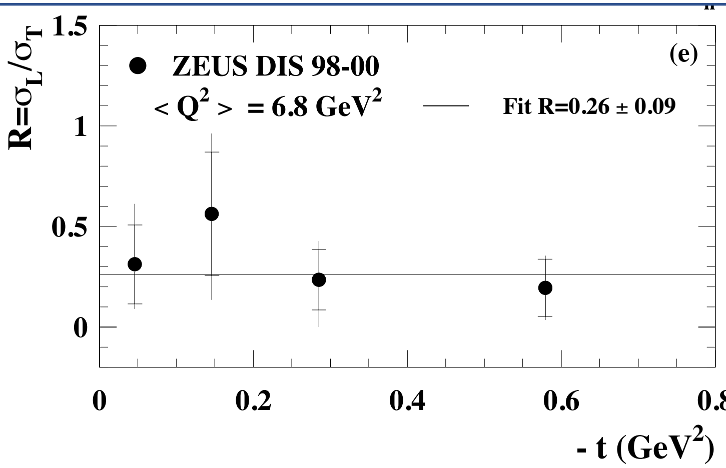


θ_h, ϕ_h angles of decay muons in the meson rest frame
Φ angle between scattering and production plane

Ratio $R = \sigma_L/\sigma_T$ as a function of Q^2 , W and t







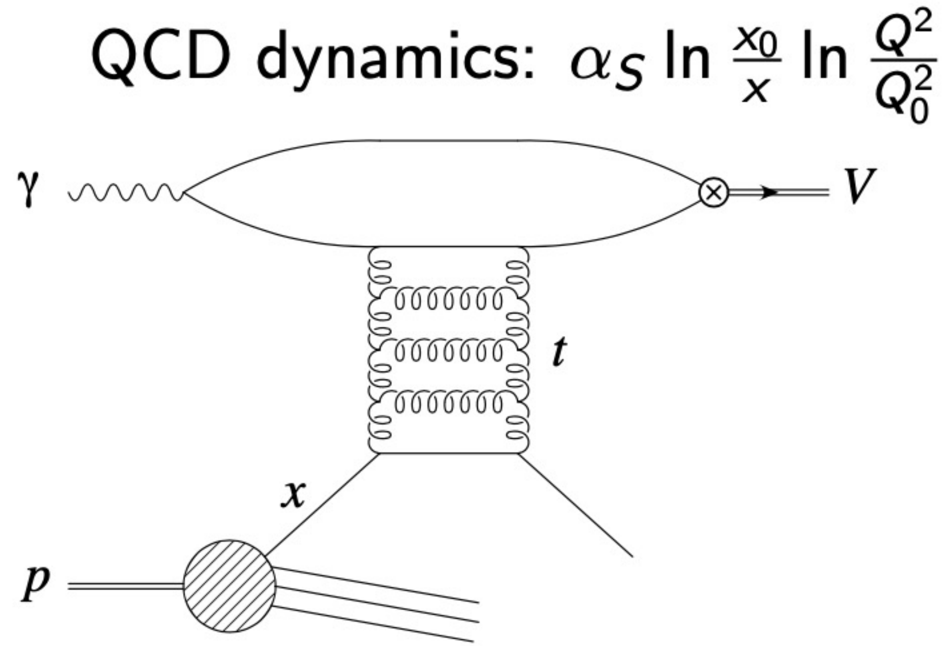
In the accessible Q^2 range, J/ψ production is almost transverse
No dependence from W or t

pQCD: during the interaction, the orbital angular momentum of $q\bar{q}$ can be modified due to the transfer of momentum of the gluons; ⇒ the helicity of the outgoing VM differs from the one of the γ, helicity flip between photon and meson is possible

Photoproduction J/ψ at high t – test BFKL dynamics

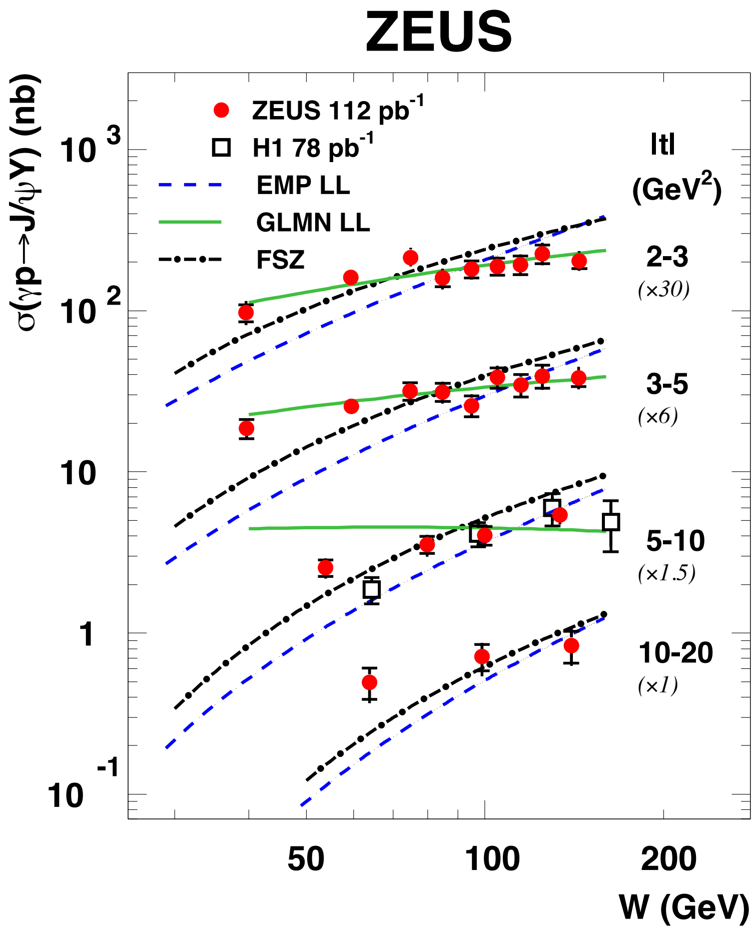
- large values of |t| provide a hard scale
- for |t|>1 GeV^2, process dominated by p-diss production

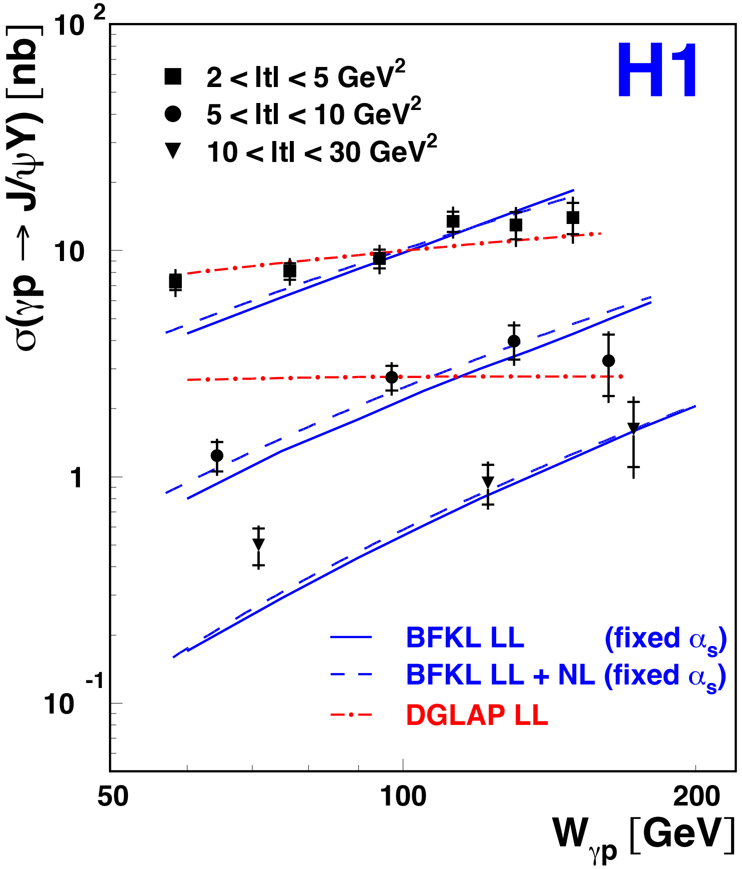
Hard scale at both ends of the exchanged gluon ladder, no strong kt ordering is expected (expected in DGLAP), as in typical BFKL evolution



HERA I data, 1996-2000, 112 pb^{-1} of luminosity
30 < W < 160 GeV, 2 < |t| < 20 GeV^2
z > 0.95, inelasticity cut

J/ψ(1S) at large |t|, W dependence



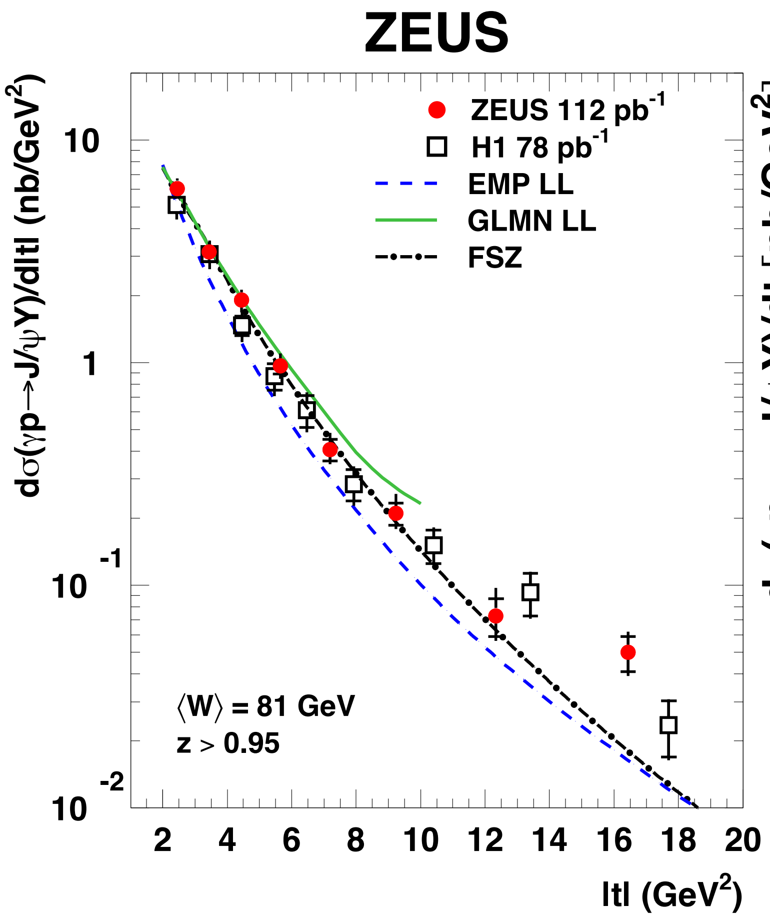


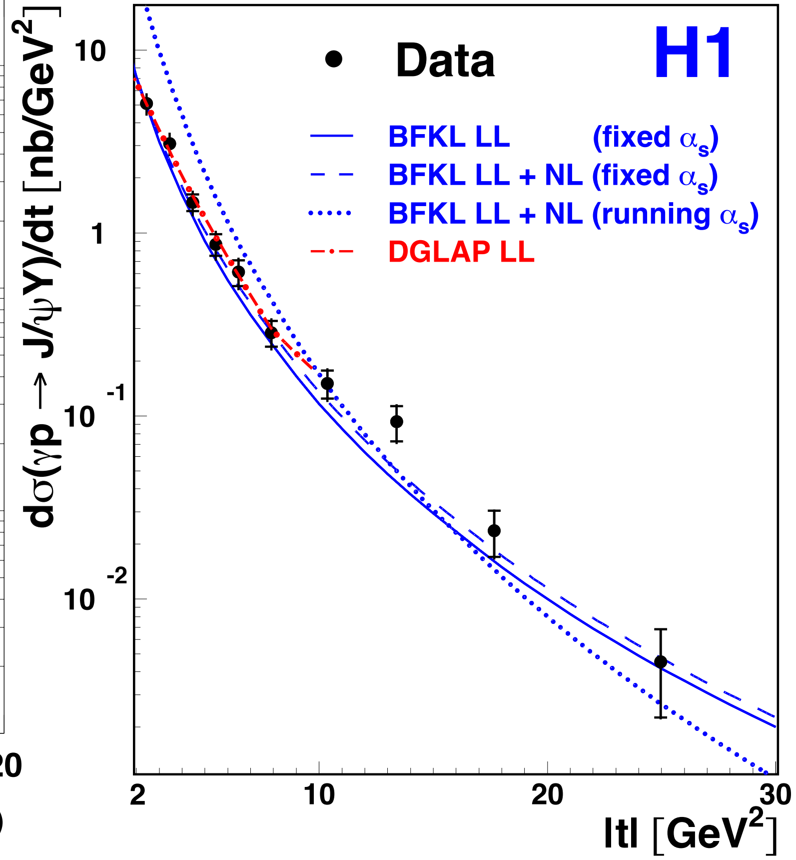
H1 and ZEUS results in good agreement in the common kinematic region

Data rise with W for all t region

BFKL (EMP) predictions too steep
DGLAP (GLMN) approach fails to describe σ rise at low x
FKS: increase of σ due to gluon distribution in the proton

J/ψ(1S) at large |t|; t-dependence





Data cannot be described by a single exponential fit $d\sigma/dt \simeq e^{bt}$ neither by a single power $d\sigma/dt \simeq |t|^n$

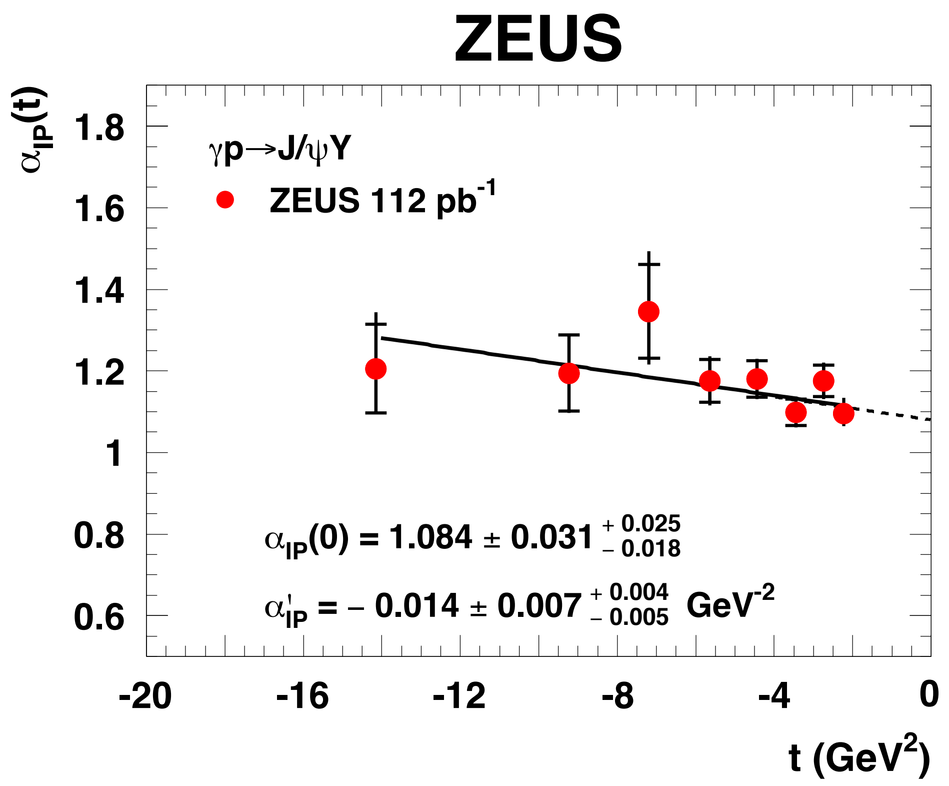
Models predict n dependent on t

Models able to describe data but not for the full t (x) range

EMP (BFKL) below data
GLMN (DGLAP) validity range of $|t| < M_{J/\psi}$
FSZ describe data up to 12 GeV^2

$J/\psi(1S)$ at large $|t|$, W dependence as a function of t

Effective Pomeron trajectory $d\sigma/dt = F(t) \cdot W^{4(\alpha P\,(t)-1)}$



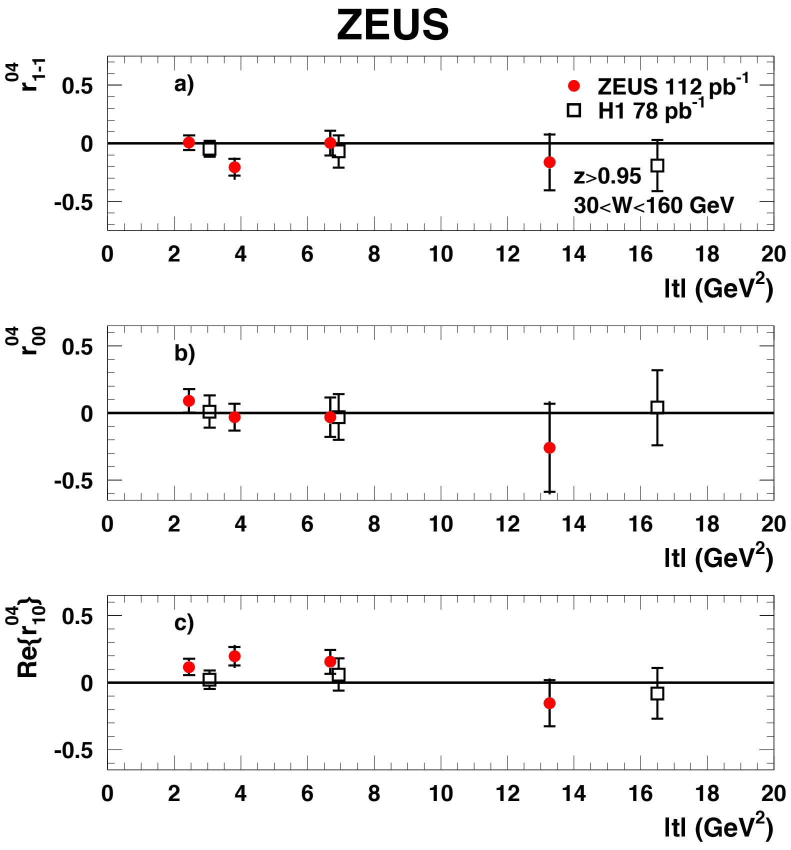
Pomeron intercept consistent with soft $\alpha_{Pl}(0) = 1.0808$ Pomeron

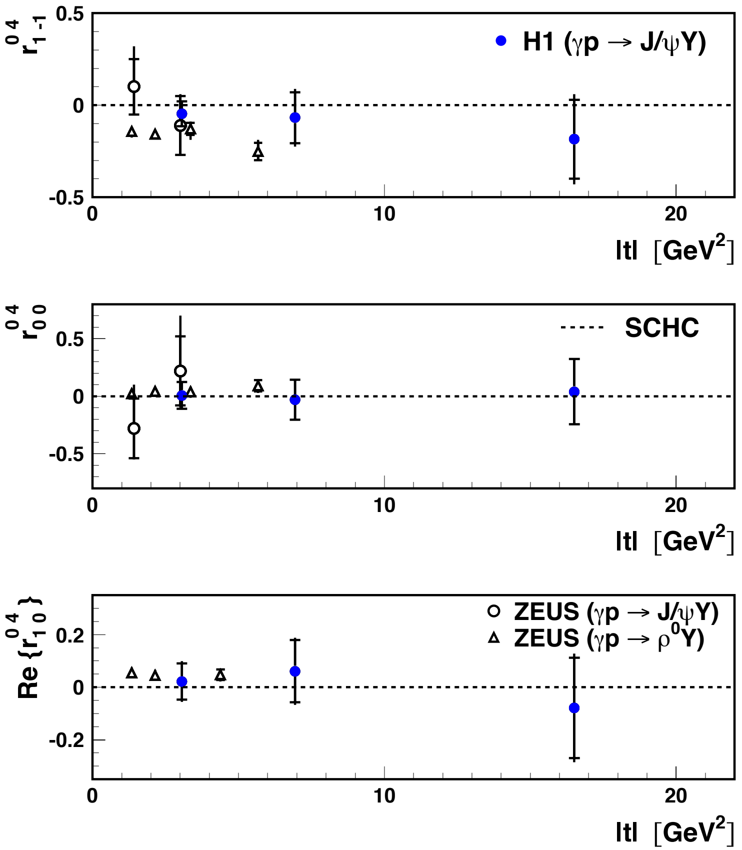
slope consistent with BFKL Pomeron

H1 $\alpha_{Pl}(0) = 1.167 \pm 0.048(\text{stat}) \pm 0.024(\text{syst})$

H1 $\alpha' = -0.0135 \pm 0.0074(\text{stat}) \pm 0.0051(\text{syst})$

Helicity spin density matrix elements as a function of |t|





θ_h, ϕ_h angles
angles of decay muons in the meson rest frame estimated in different t bins
Spin density matrix elements are extracted from fit to the angular distributions

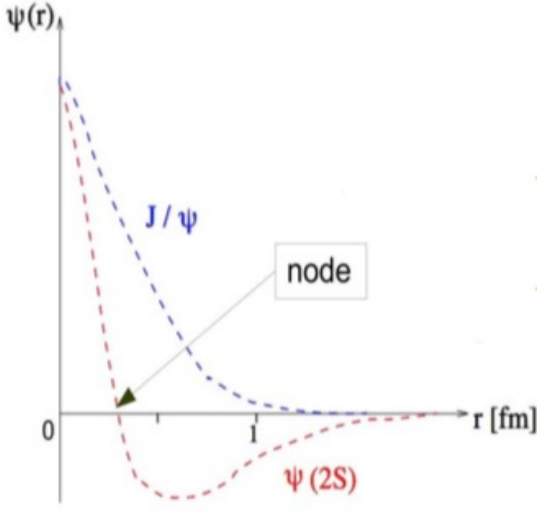
r_{1-1}^{04} is related to interference between non-flip and double flip amplitude

r_{00}^{04} represents the probability that Jψ has 0 helicity
$Re(r_{00}^{04})$ is proportional to the single flip amplitude 10

These spin density elements expected to be 0 in SCHC

ψ(2S) in photoproduction and DIS

ψ(2**S**) **and** J/ψ(1**S**) have same quark content but different wave function



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

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

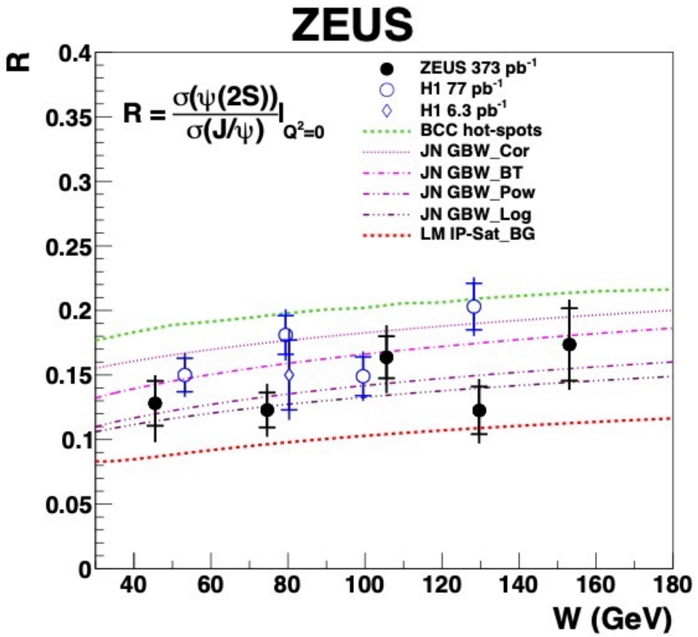
HIKT, Hufner et al.: dipole model, dipole-proton constrained by inclusive DIS data
AR, Armesto and Rezaeian: impact parameter dependent CGC and IP-Sat model KMW,Kowalski Motyka Watt: QCD description and universality of quarkonia production FFJS, Fazio et al.: two component Pomeron model
KNNPZZ, Nemchik et al.: color-dipole cross section derived from BFKL generalised eq. LM, Lappi and Mäntysaari: dipole picture in IP-Sat model

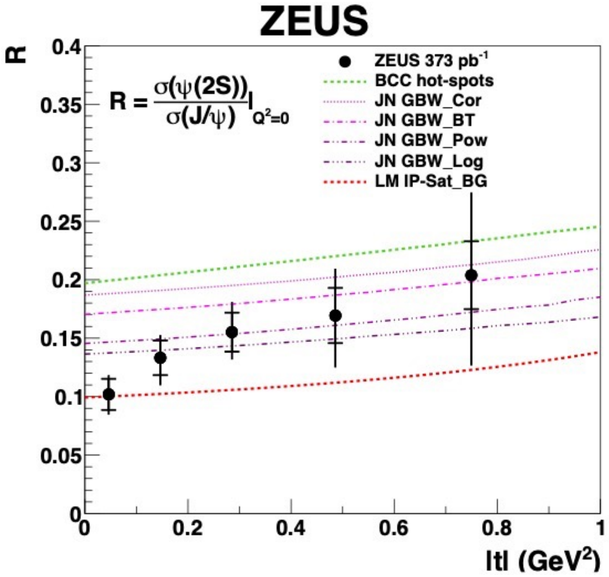
$\langle r^2 \psi(2S)\rangle \sim< 2\, r^2 J/\psi(1S)\rangle$

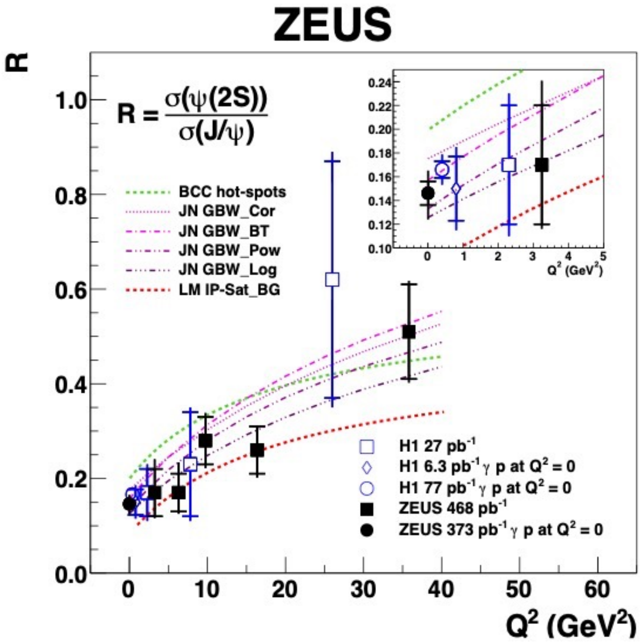
ψ(2S) has a radial node at ~0.4 fm

models predicts $\sigma_{\gamma p\to\psi(2S)p}$ suppressed w.r.t. $\sigma_{\gamma p\to J/\psi(1S)}$

$R = \sigma_{\gamma p \to \psi(2S)p} / \sigma_{\gamma p \to J/\psi(1S)}$ vs Q^2, t, W







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

ZEUS at $Q^2 = 0$ GeV^2 **R =** 0.**146**±0.010(**stat.**)±0.020(**syst.**)

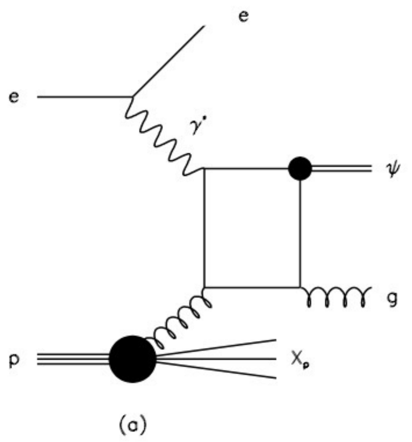
- no or moderate dependence in t
- no or moderated dependence on W
- Increase in Q^2

pQCD model calculations predict R~0.17 in PHP, rising with Q^2 reaching plateau at $Q^2 \gg M^2\psi$

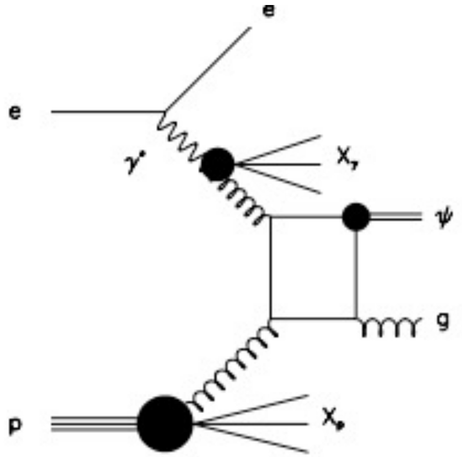
Quarkonia in inclusive reaction
H1 and ZEUS paper on inelastic J/ψ, ψ(2S) production

Photoproduction		ZEUS, inelastic J/ψ and ψ(2S) in PHP *JHEP 02 (2013) 071* H1, inelastic J/ψ and ψ(2S) in PHP, *Eur.Phys.J.C* 68 (2010) 401 ZEUS, inelastic J/ψ and ψ(2S) in PHP *Eur.Phys.J.C* 27 (2003) H1, inelastic J/ψ in PHP, *Eur.Phys.J.C* 25 (2002) 25 ZEUS, inelastic J/ψ in PHP, *Z.Phys.C* 76 (1997) 599 H1, elastic and inelastic J/ψ in PHP, *Nucl.Phys.B* 472 (1996) 3
DIS		ZEUS, inelastic J/ψ in DIS *Eur.Phys.J.C* 44 (2005) H1, inelastic leptoproduction of J/ψ, *Eur.Phys.J.C* 25 (2002) 41 H1, charmonium production in DIS, *Eur.Phys.J.C* 10 (1999) 373

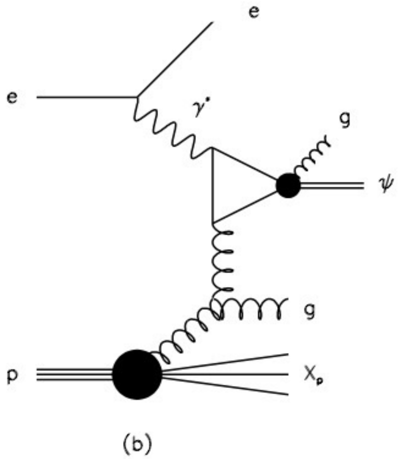
Inelastic J/ψ, ψ(2S) production



Direct photon, color singlet model, medium z



Resolved photon, color singlet model, low z

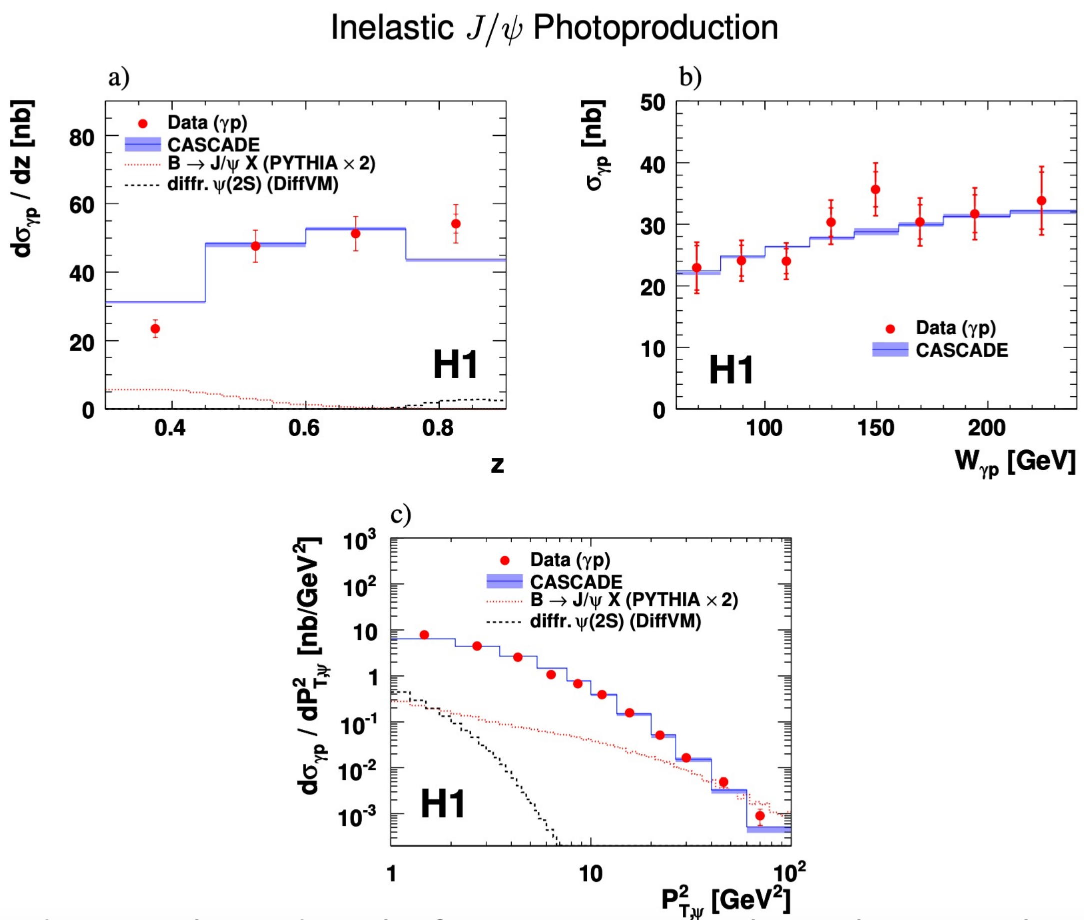


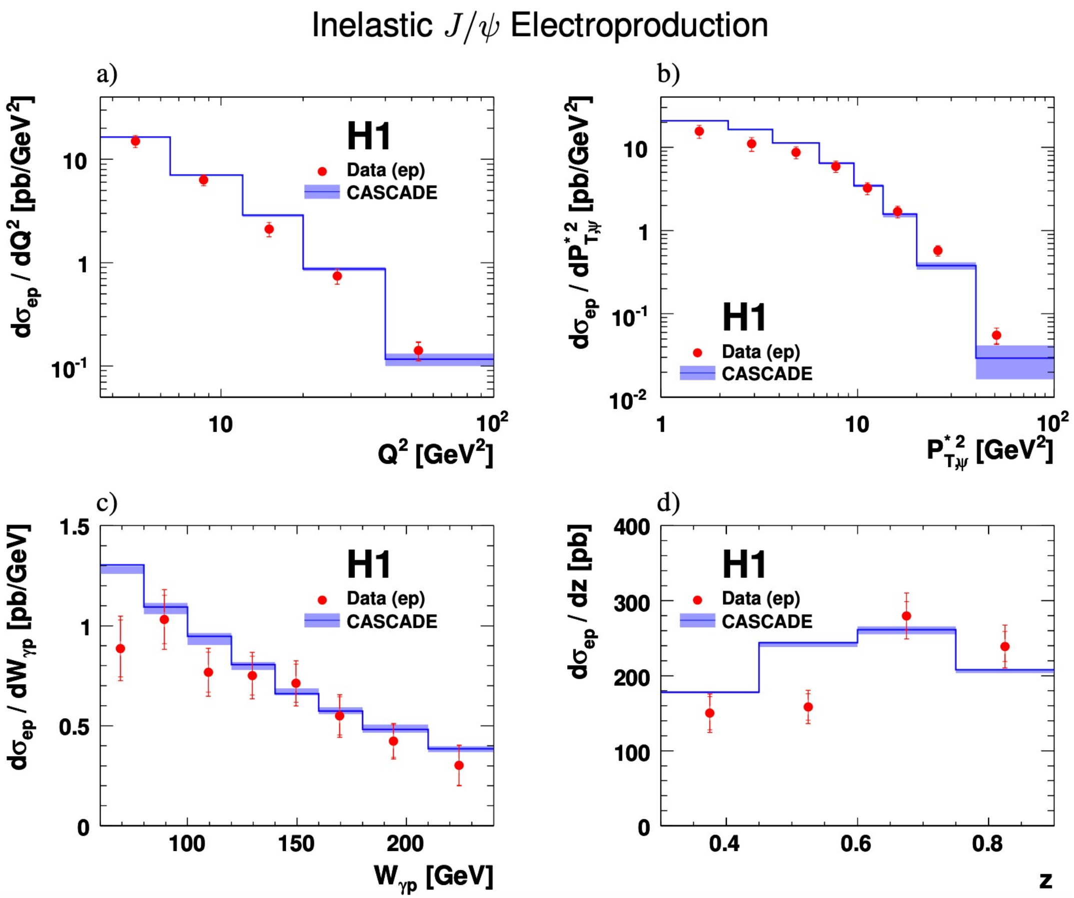
Direct photon, color octet model

z = E_ J/ψ / E_γ (p rest frame)

studied at HERA as a function of several scales: Q^2, z, over a wide range of Wγp (30-270 GeV).

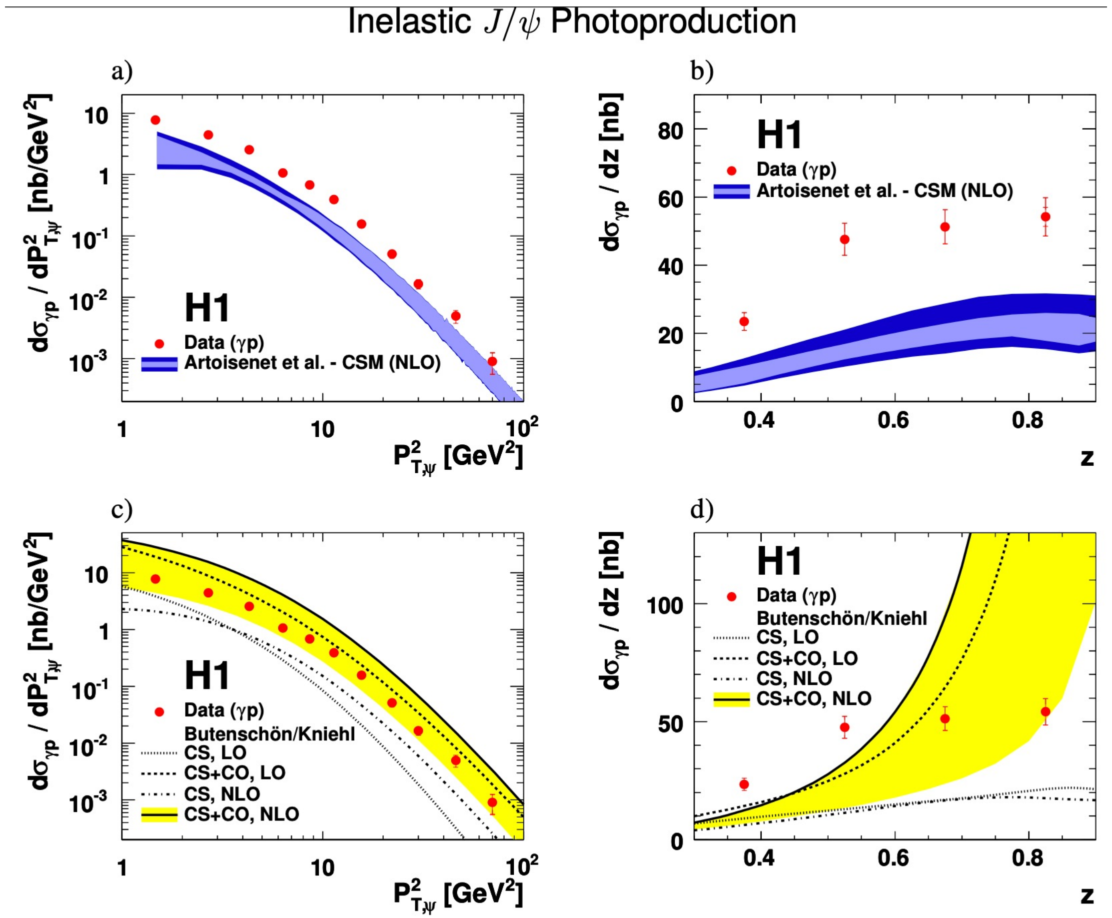
H1 and ZEUS paper on inelastic J/ψ, ψ(2S) production





Predictions based on k_T factorisation in the colour singlet model able to describe cross sections

H1 and ZEUS paper on inelastic J/ψ, ψ(2S) production



- Differential cross sections compared to a number of theory predictions
- Calculations based on collinear factorisation in the colour singlet model at NLO describe the shape but are lower in normalisation
- Calculations beyond NLO are necessary, contributions from colour octet states may be significant

Summary

- Quarkonium is a clean experimental process, but precise measurements require a strategy for trigger and dedicated detectors to tag proton-dissociation

- At HERA, quakonium production was a field of continuos dialogue between data and theory, extremely interesting for pQCD understanding

- This dialogue will continue at EIC