Diffractive J/psi production at HERA

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Istituto Nazionale di Fisica Nucleare

Center For Frontiers In Nuclear Science ad-hoc Workshop:

Target fragmentation and diffraction physics with novel processes: ultraperipheral, electron-ion, and hadron collisions

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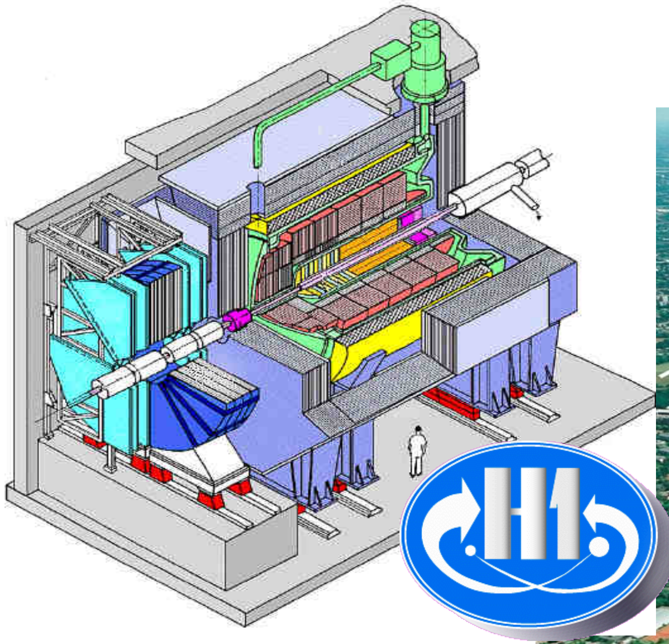
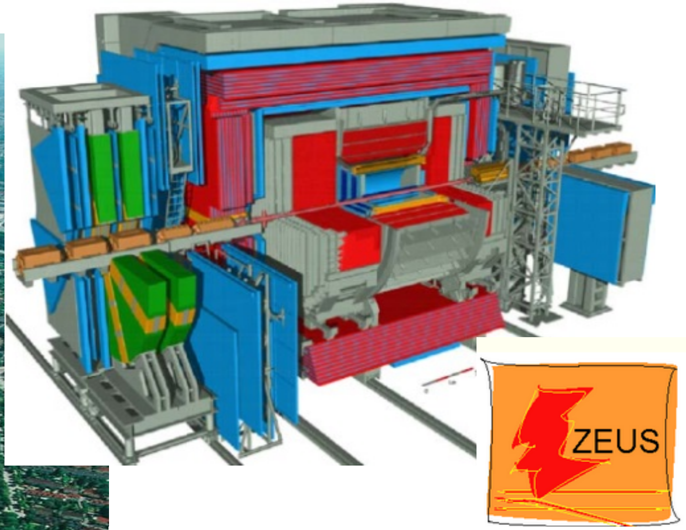
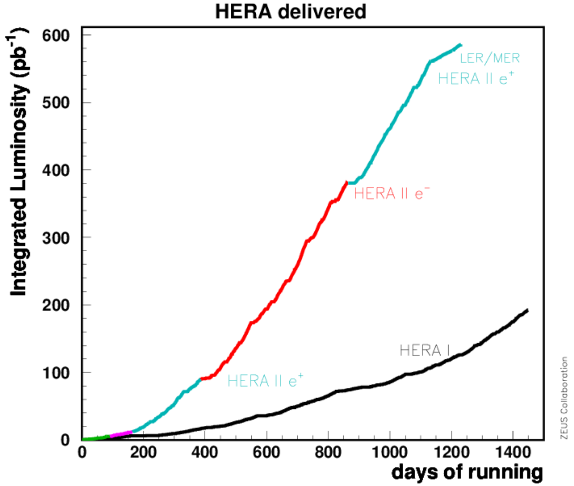
https://indico.bnl.gov/event/14009/

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

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





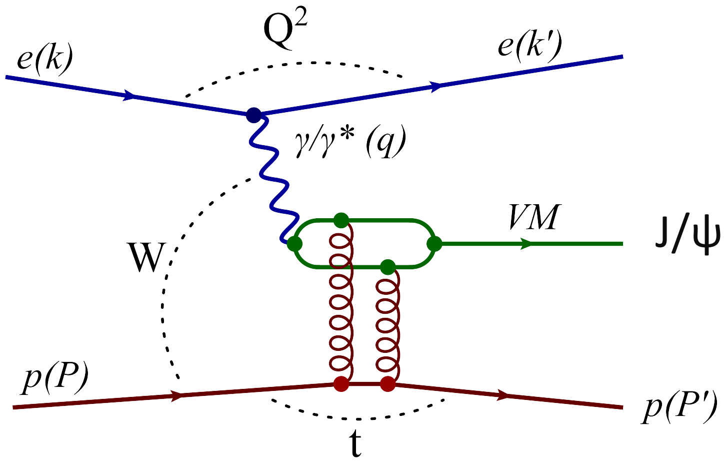


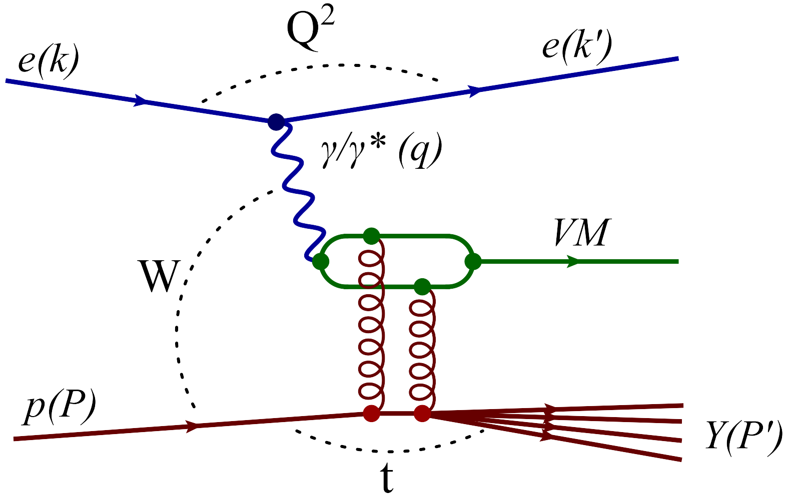
- total luminosity ~ 0.5 fb^{-1}per experiment
- Center-of-mass energies 318 GeV - 225 GeV

H1 and ZEUS paper on J/ψ, ψ(2S) 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 in PHP Phys.Lett.B483 (2000) 23 H1, Elastic and Inelastic J/ψ in PHP Nucl.Phys.B472 (1996) 3
DIS		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		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' / J/ψ ratio [ZEUS prel-15-003] 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

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** 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 **$x \sim 1/W^2_{\gamma p}$**

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.

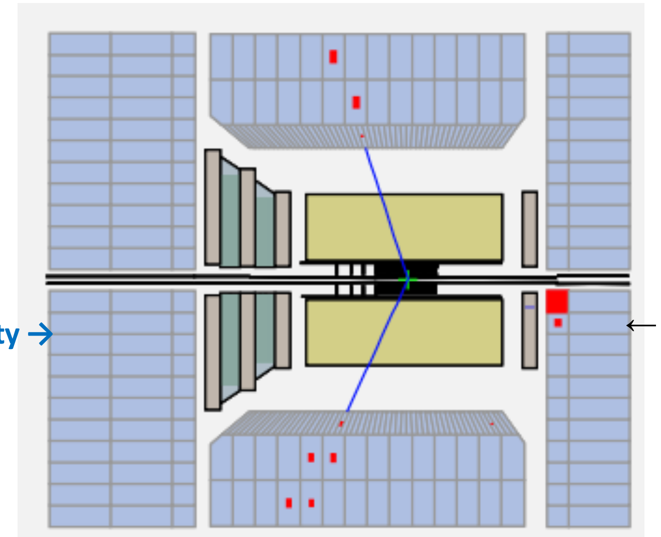
For electron channel, 1 track + 1 CAL electron is also possible

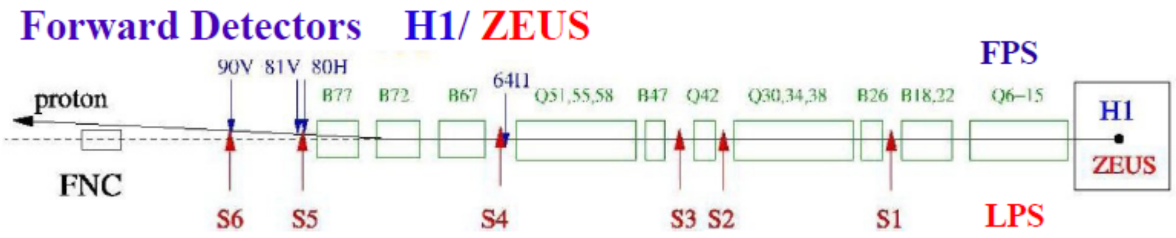
Experimental challenge:

- 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

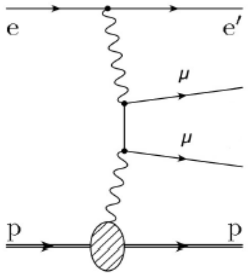


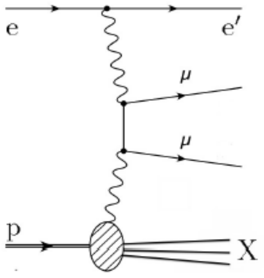


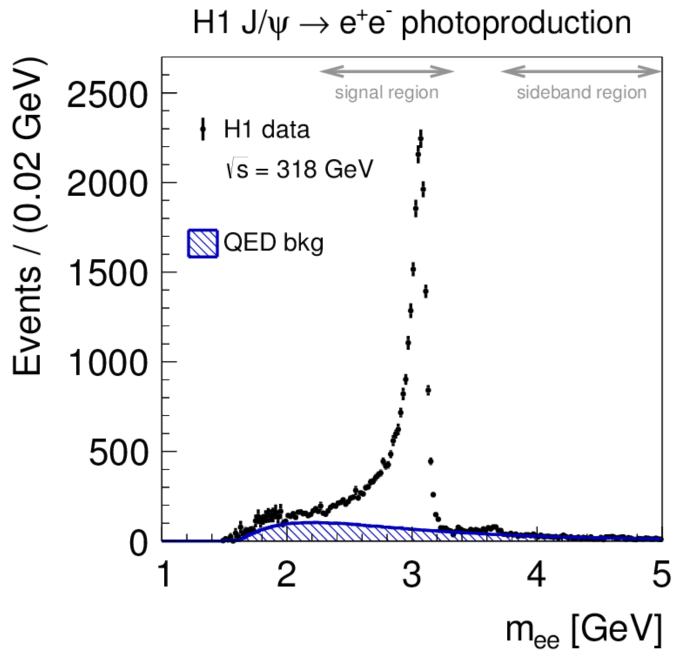
H1: FPS, Very Forward Proton Spectrometer, Forward Tagging System

ZEUS: LPS; Proton Remnant Tagger

Signal extraction from invariant mass distributions







J/ψ ->μ+μ−, e+e-

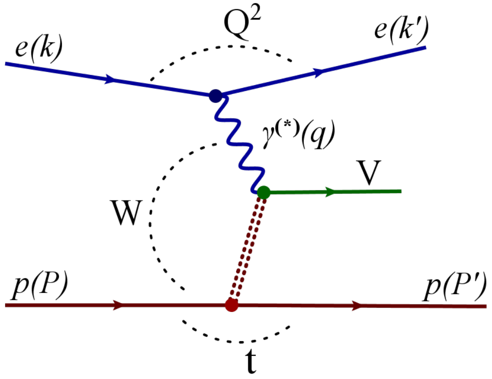
- only background source from QED non-resonant muon/electron pair production γγ->l+l- (Bethe-Heitler process) subtracted by QED simulation, usually normalized in control region, as it contains p-diss contribution, not perfectly simulated

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



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

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

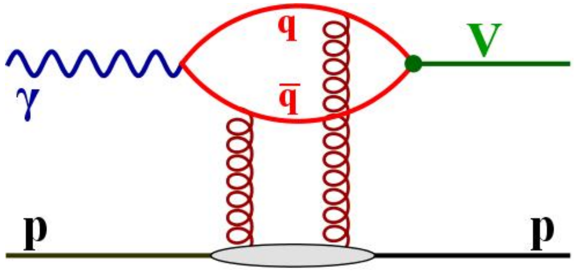
$$\frac{d\sigma}{dt} \propto e^{bt} \left(\frac{W_{\gamma p}}{W_0} \right)^{\delta} \qquad \delta = 4(\alpha_0 - 1)$$

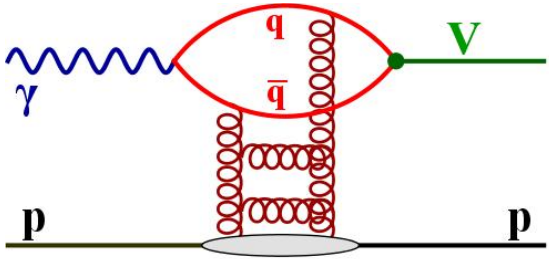
$$b = b_0 + 4\alpha' \ln \left(\frac{W_{\gamma p}}{W_0} \right)$$

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



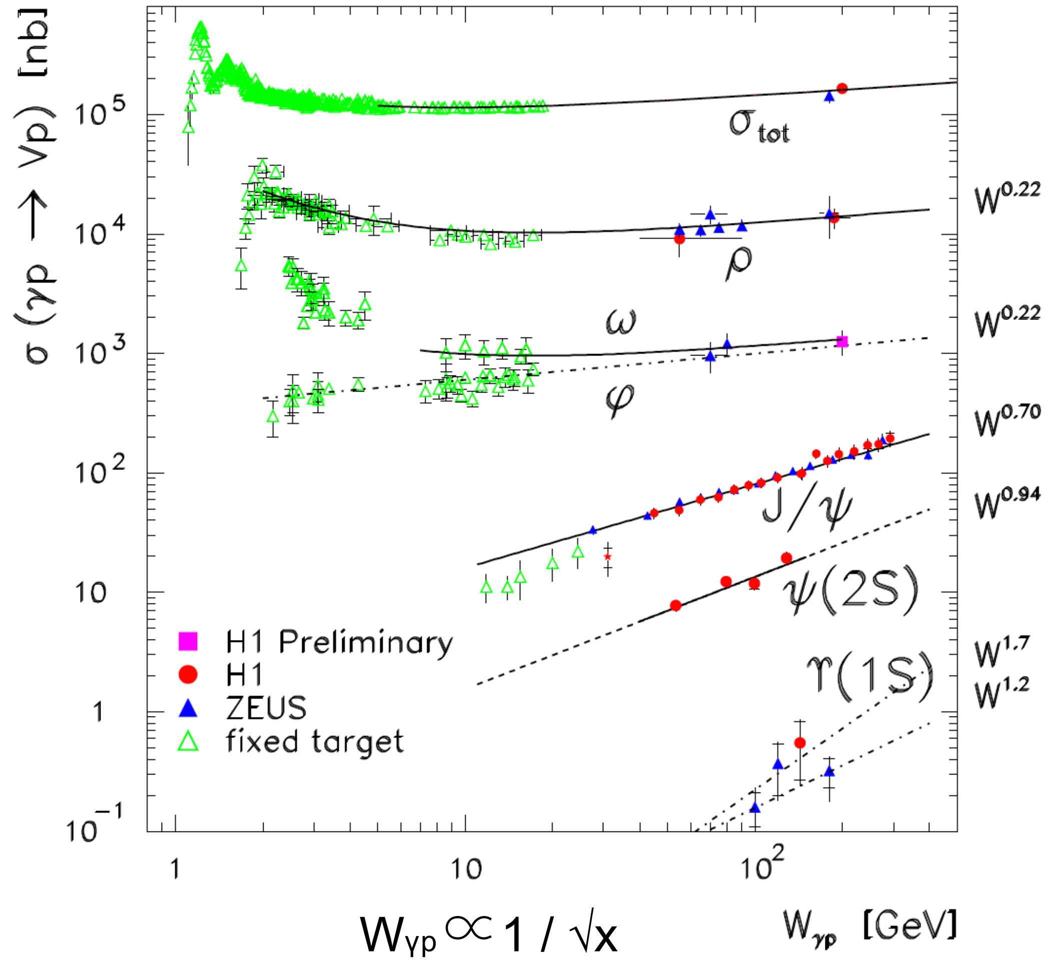


$$\begin{cases} \sigma \propto [x\, g(x, \mu^2)]^2 \\ x = \mu^2 / W^2 \\ \mu^2 \propto (Q^2 + M_V^2) \end{cases}$$

- GPDs 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

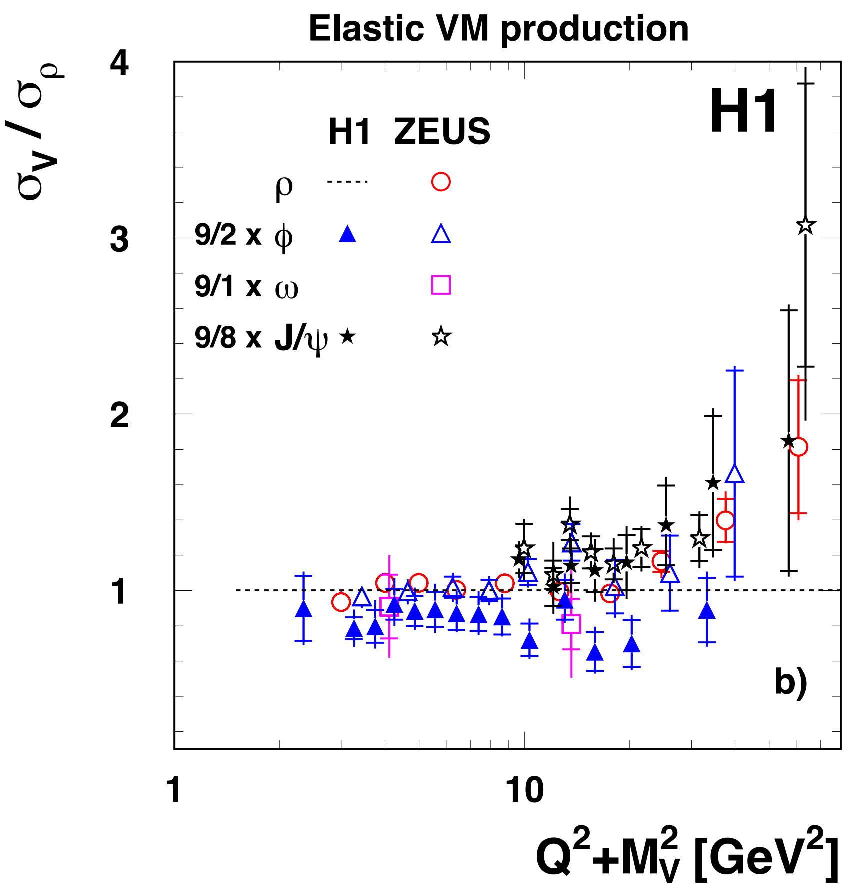


$W_{\gamma p} \propto 1/\sqrt{x}$

Low mass VM consistent with soft model, **$\delta \sim 0.2$**

Rapid rise of cross section with Wγp related to the increasing gluon density with decreasing of fractional momentum **$\sigma \propto [x\, g(x, \mu)]^2$**, with **$x \sim 1/W^2_{\gamma p}$**

Universality of VM production

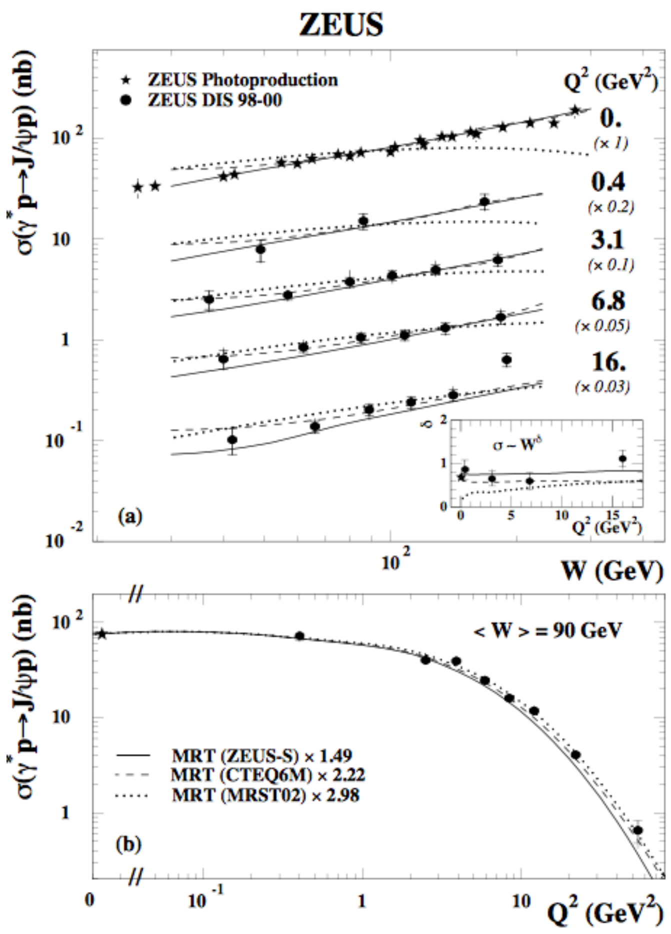


- Despite cross sections of light VM and J/psi differ by order of magnitude, they are close when corrected for factors accounting VM charge (rho : phi: J/psi = 9 : 2 : 8) and plotted vs scaling variable $\mu^2 = (Q^2+M^2_V)/4 \simeq 3\text{-}5\ GeV^2$

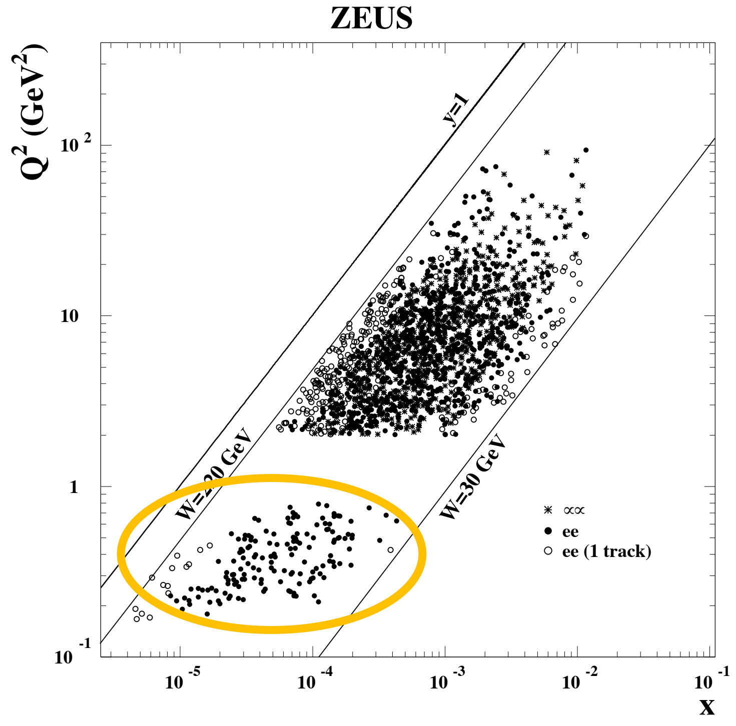
- Ratios, scaled according to quark charge content, close to 1 (up to WF effects) once plotted vs $(Q^2+M^2_V)$

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

Wγp dependence of J/psi in photoproduction and DIS



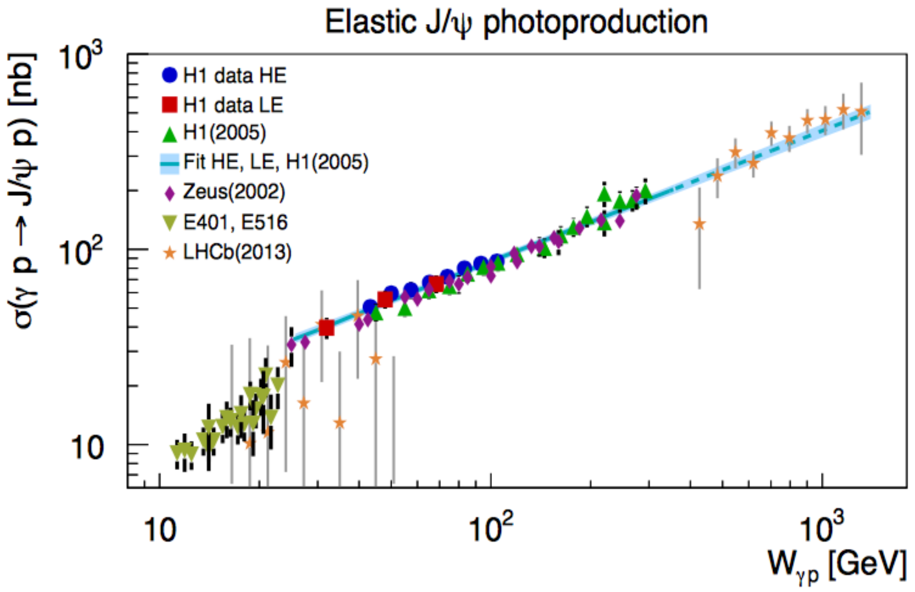
distribution of the J/psi events in the kinematic plane of Bjorken-x and Q^2

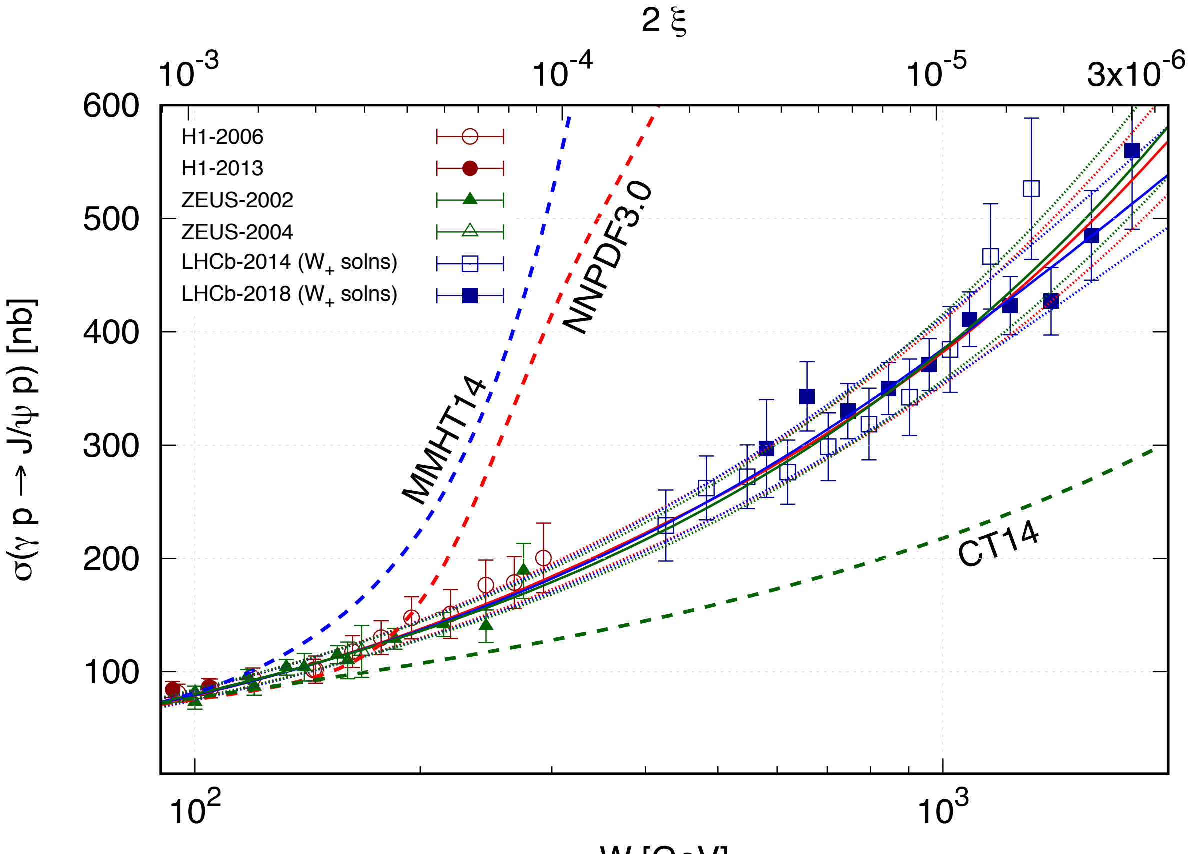


lowest values of Bjorken-x reached in photoproduction

Wγp dependence of J/psi photoproduction

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

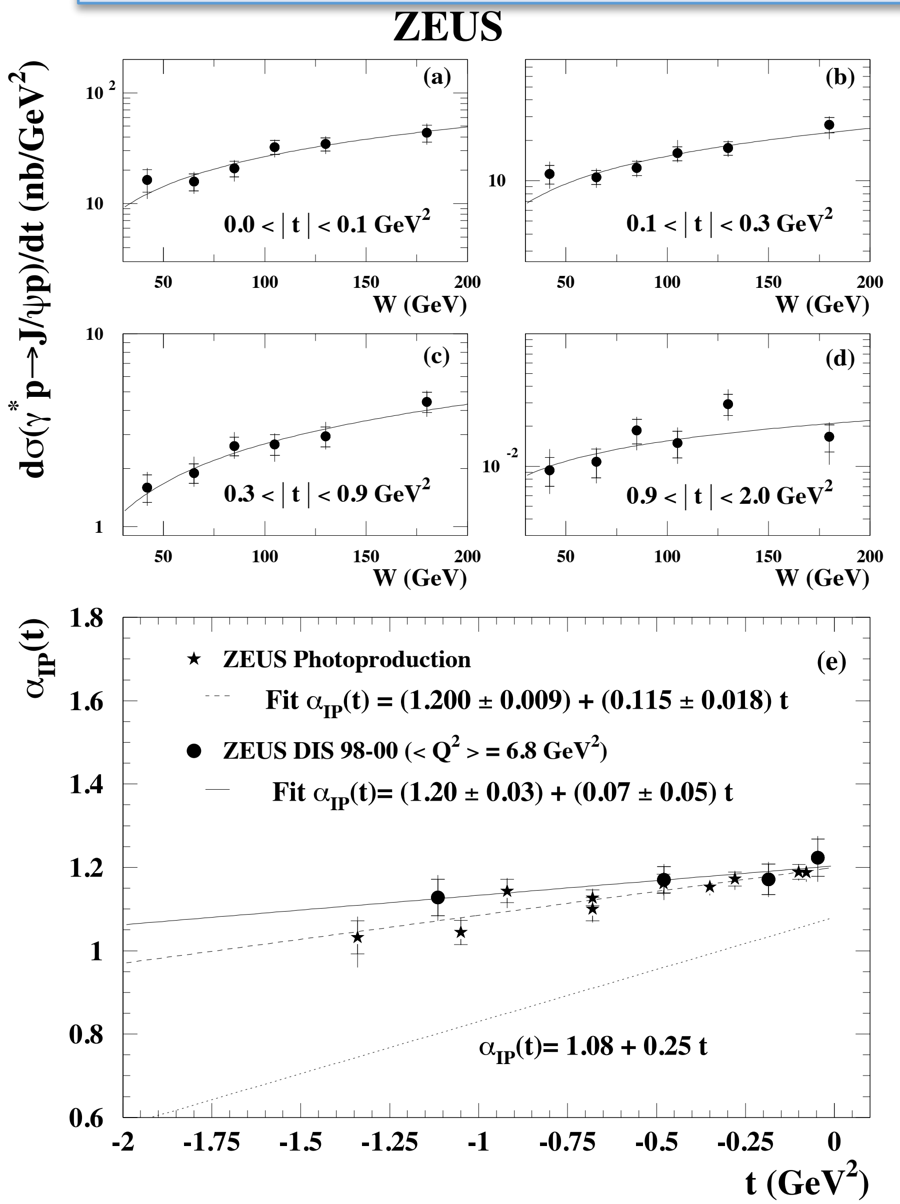




•A. Martin et al Phys. Rev. D 102, 114021 (2020)

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

Regge models - Pomeron trajectory

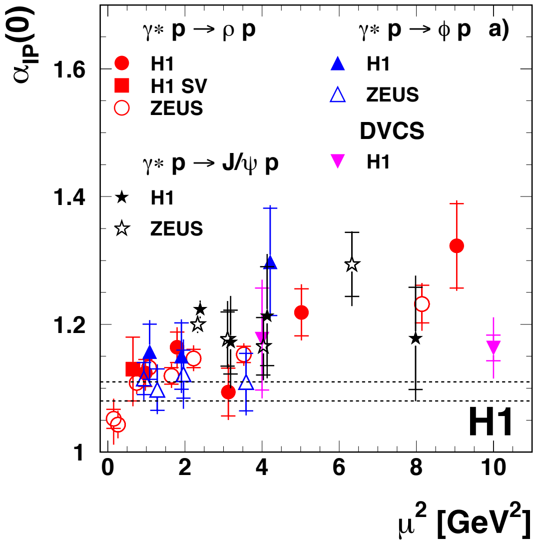


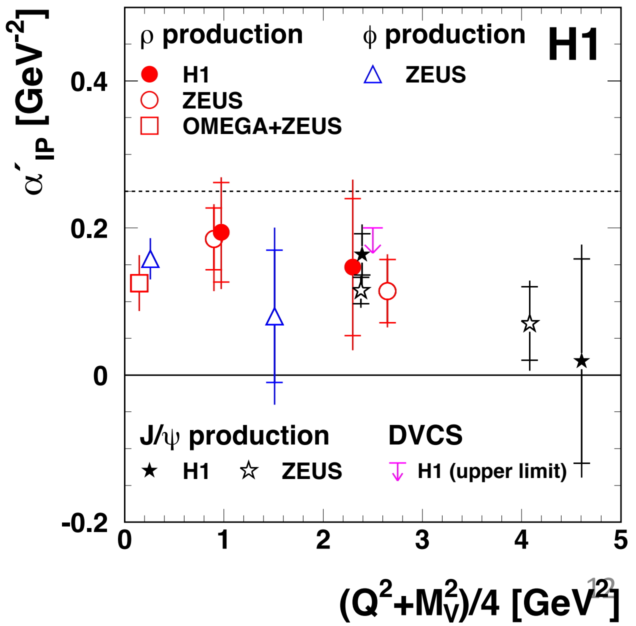
W dependance investigated using parametrisation inspired by Regge theory

Differential cross sections dσ/dt as a function of W for fixed ranges of t as $W^{4(\alpha_{IP}(t)-1)}$

Pomeron trajectory associated to J/psi is not soft

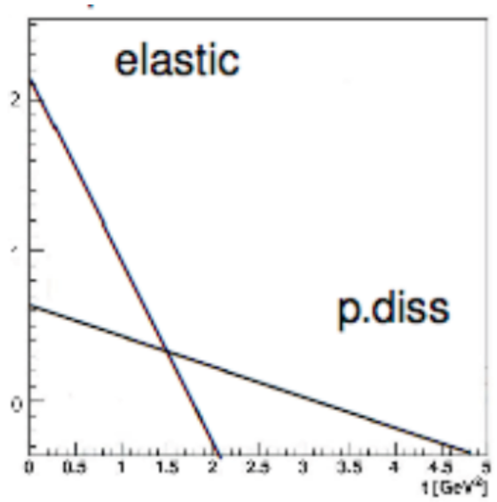
In BFKL approach, α′ is related to the average kt of gluons around the ladder in their random walk, expected to be small

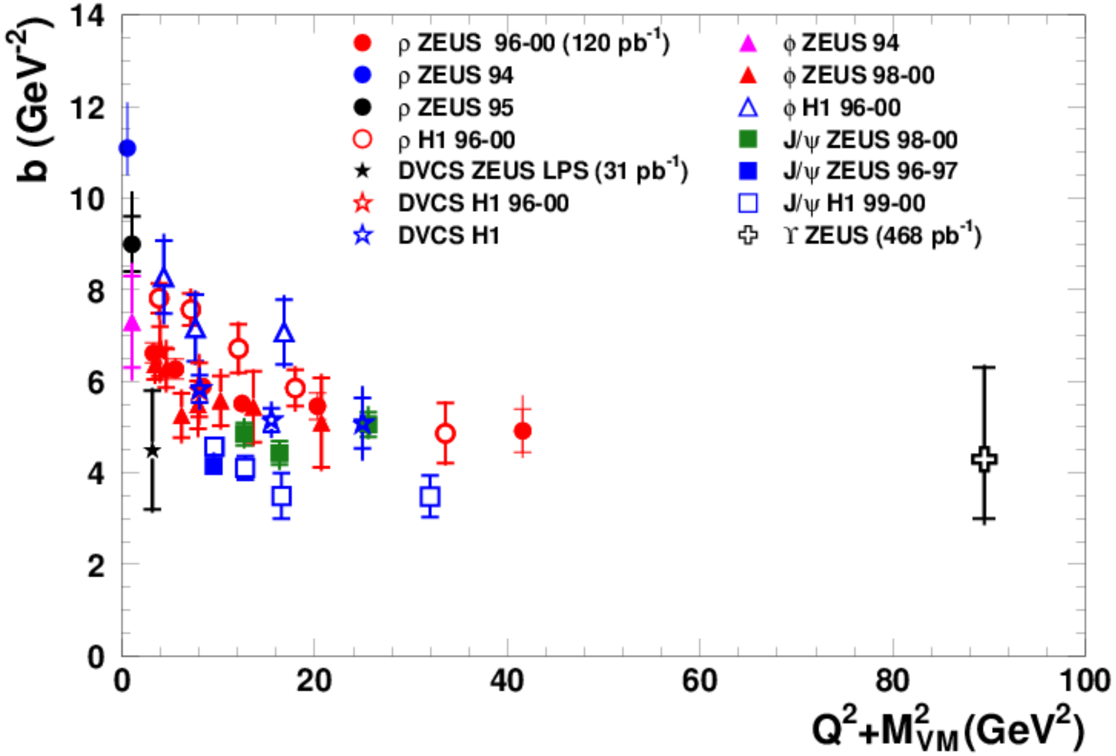




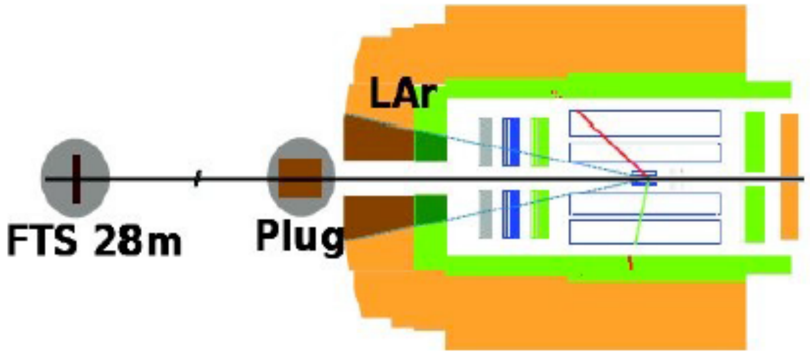
t-dependence of J/psi photoproduction

- t- dependence of cross section $d\sigma / dt \simeq e^{bt}$
- In optical model approach b is related to the quadratic size of inteacting 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





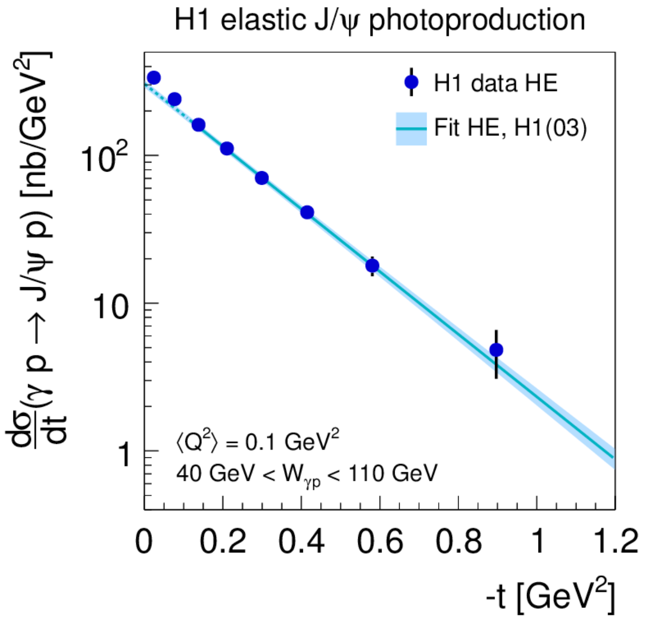
t-dependence of J/psi photoproduction - low t

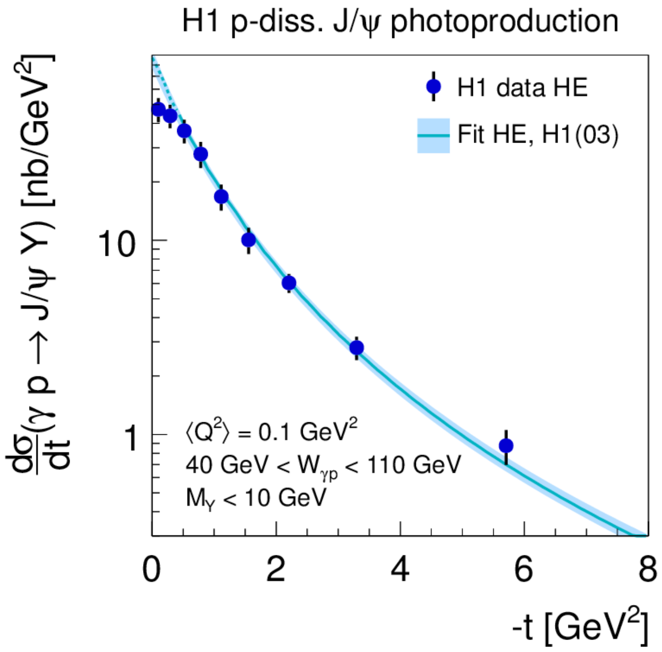


H1:

- 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/psi photoproduction – b slope

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

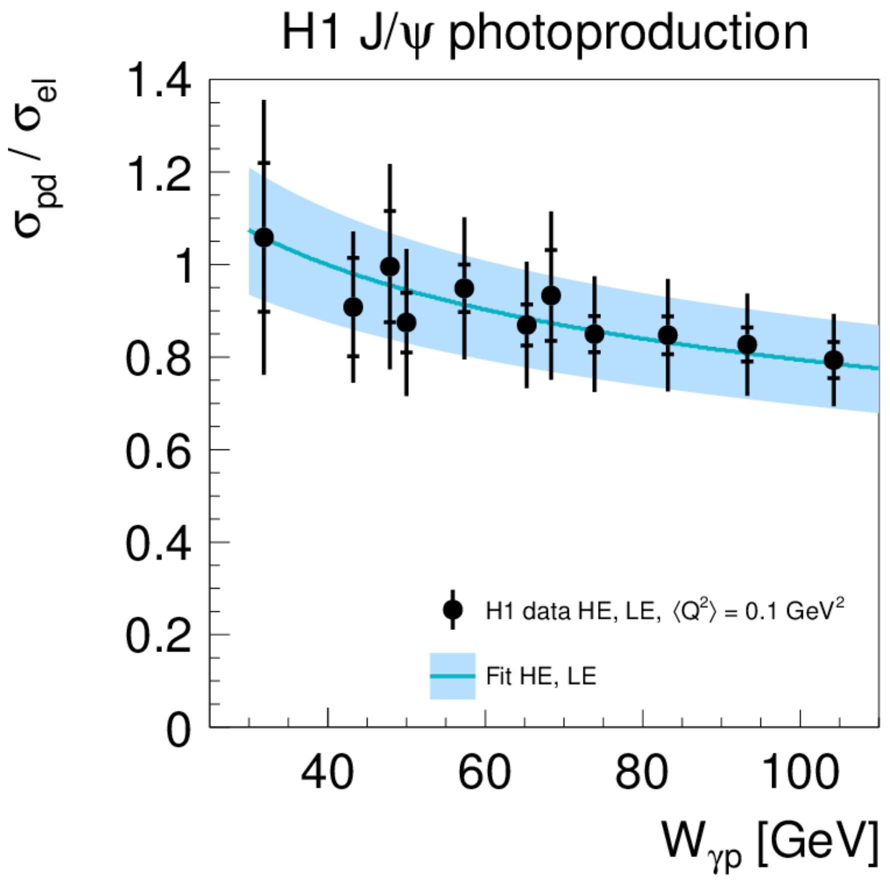
Data period	Process	Parameter	Fit value	Correlation
HE	$\gamma p \to J/\psi\, p$	b_{el}	(4.88 ± 0.15) GeV^{-2}	$\rho(b_{el}, N_{el}) = 0.50$ $\rho(b_{el}, b_{pd}) = 0.49$ $\rho(b_{el}, n) = -0.21$ $\rho(b_{el}, N_{pd}) = 0.68$
		N_{el}	(305 ± 17) nb/GeV^2	$\rho(N_{el}, b_{pd}) = 0.23$ $\rho(N_{el}, n) = -0.07$ $\rho(N_{el}, N_{pd}) = 0.46$
	$\gamma p \to J/\psi\, Y$	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.



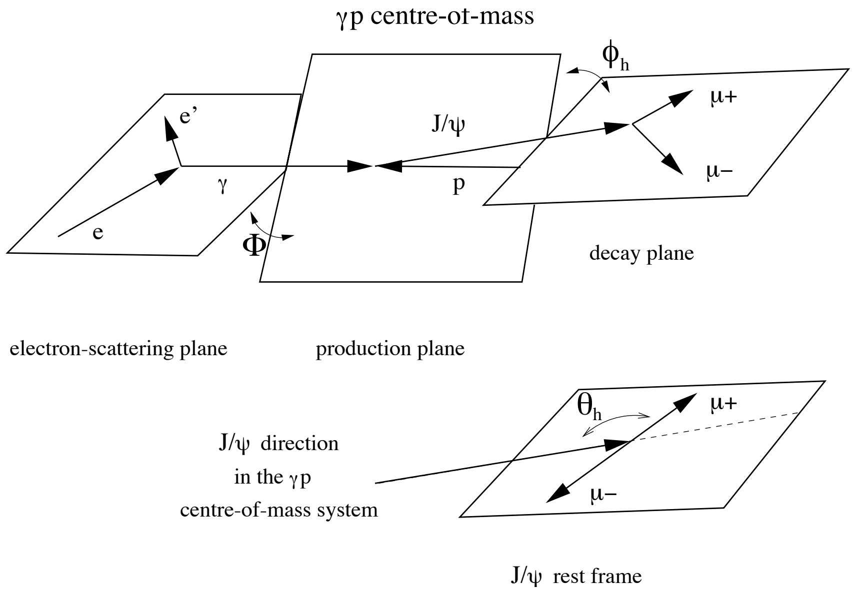
Process	Parameter	Fit value	Correlation
$\gamma p \to J/\psi\, p$	δ_{el}	0.67 ± 0.03	$\rho(\delta_{el}, N_{el})$ =-0.08 $\rho(\delta_{el}, \delta_{pd})$ = 0.01 $\rho(\delta_{el}, N_{pd})$=0.09
	N_{el}	81 ± 3 nb	$\rho(N_{el}, \delta_{pd})$ = -0.27 $\rho(N_{el}, N_{pd})$=-0.18
$\gamma p \to J/\psi\, Y$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

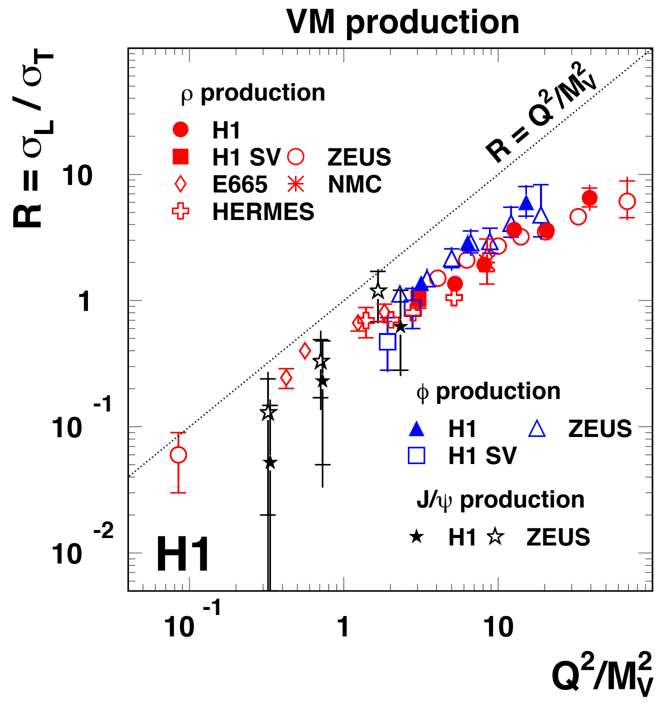
Decay angular distribution, helicity frame

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 $T_{\lambda_{VM}\lambda_\gamma}$



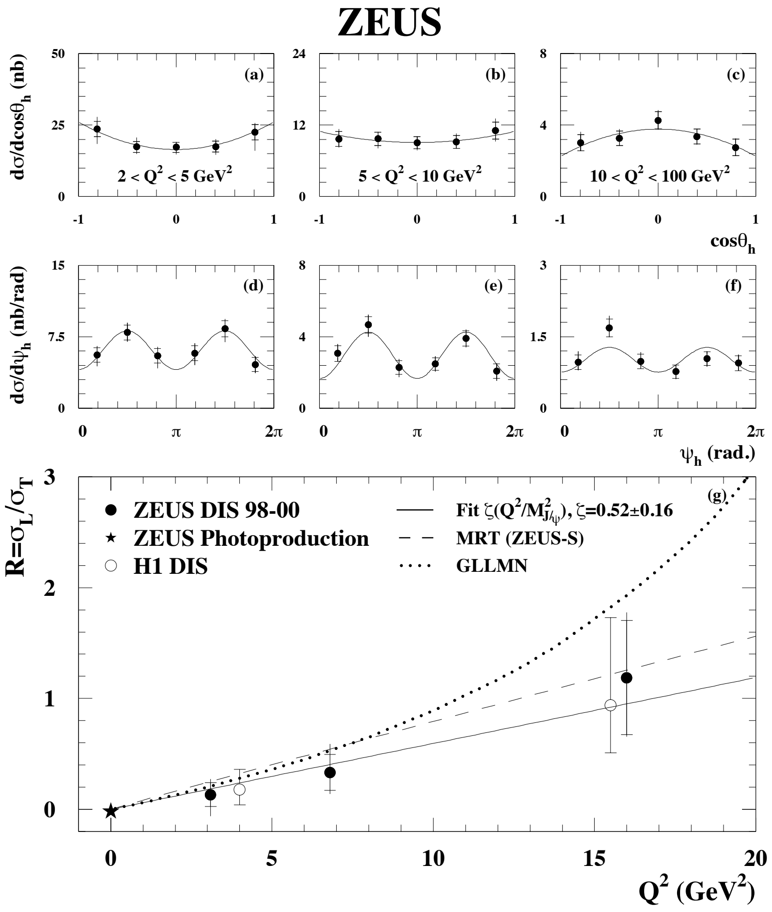
S-channel helicity conservation: the outgoing VM retains the γ helicity

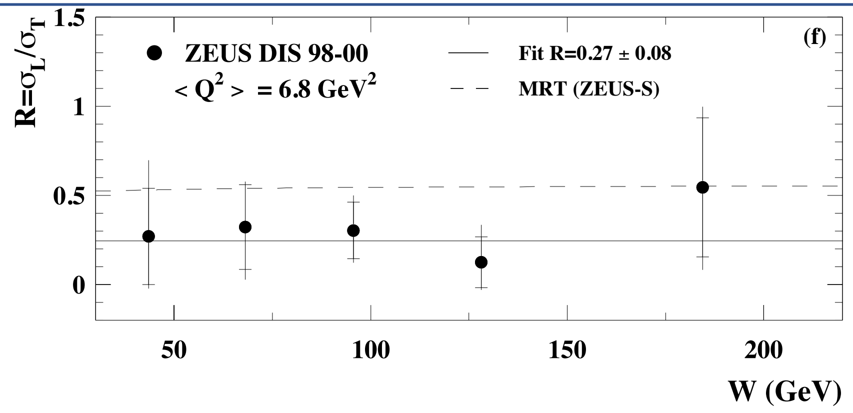
In the accessible Q² range, J/psi production is almost transverse, while for light VM the longitudinal amplitude dominates

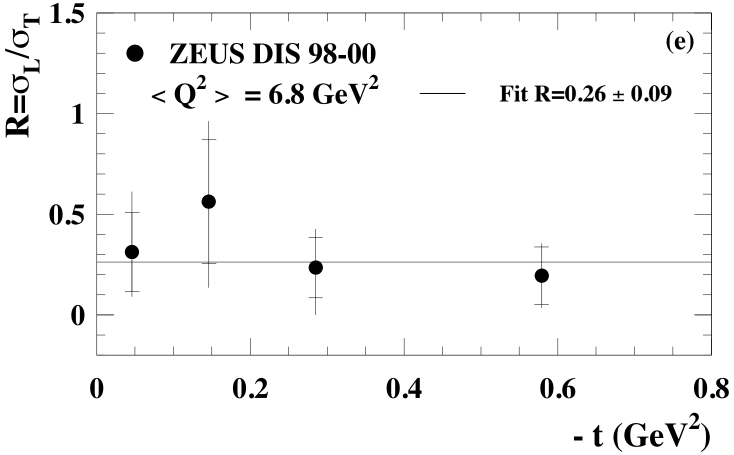


θ_h, ϕ_h angles of decay muons in the meson rest frame
Φ angle between scattering and production plane

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







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

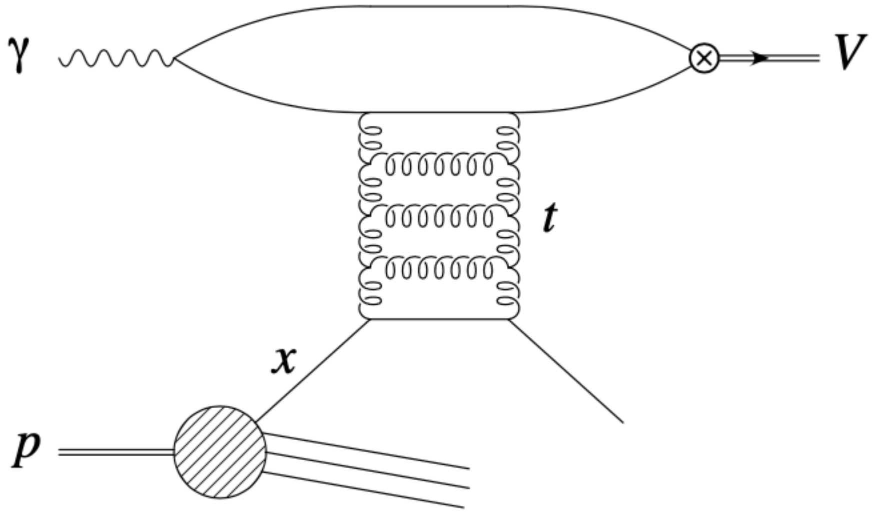
pQCD: during the interaction, the orbital angular momentum of $q\bar{q}$ can be modified due to the transfer of momentum of the gluons; ⇒ the helicity of the outgoing VM differs from the one of the γ, helicity flip between photon and meson is possible

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

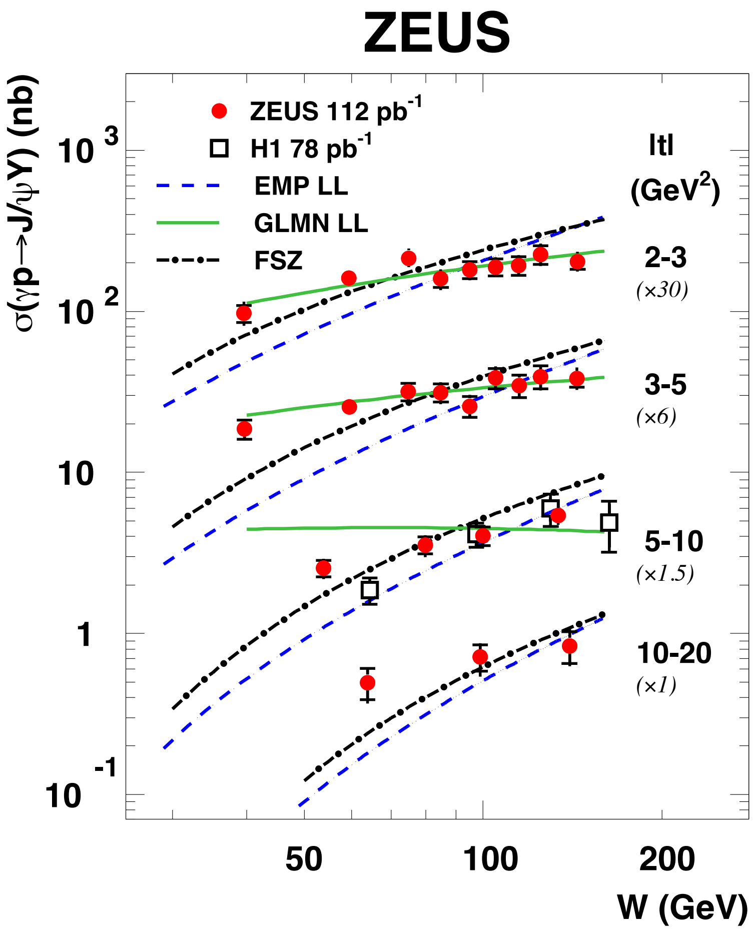
Hard scale at both end of the exchanged gluon ladder, no strong kt ordering is expected (expected in DGLAP), as in typical BFKL evolution

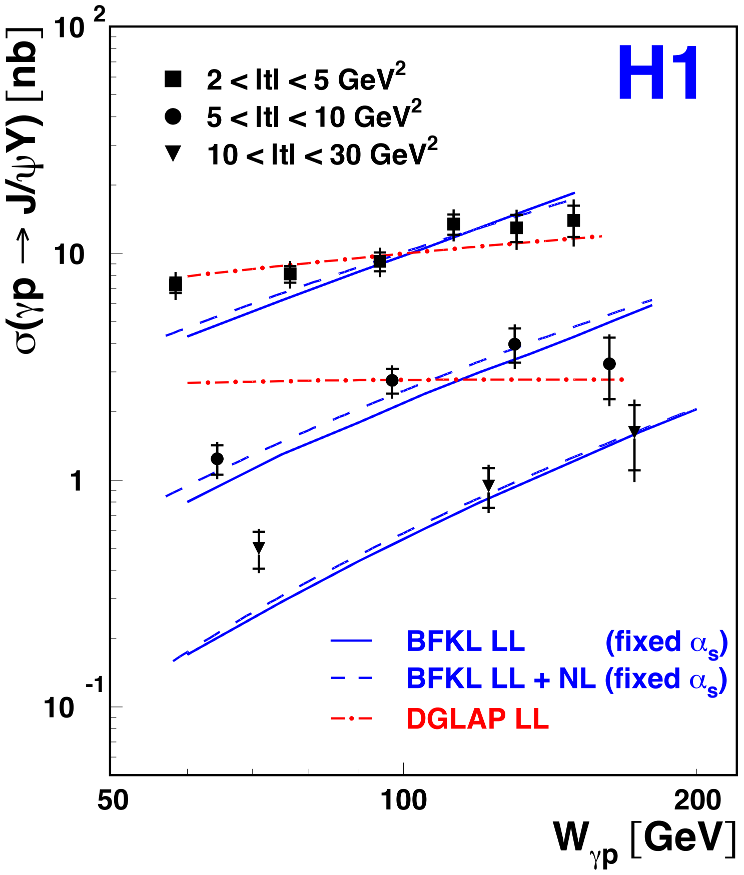
QCD dynamics: $\alpha_S \ln \frac{x_0}{x} \ln \frac{Q^2}{Q_0^2}$



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

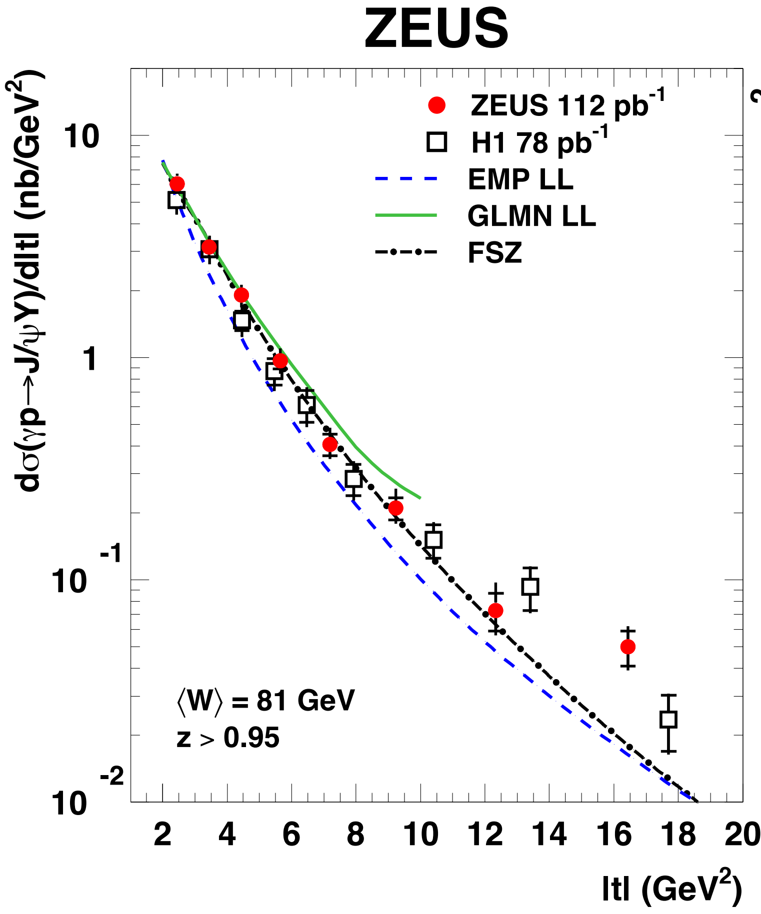
Data rise with W for all t region

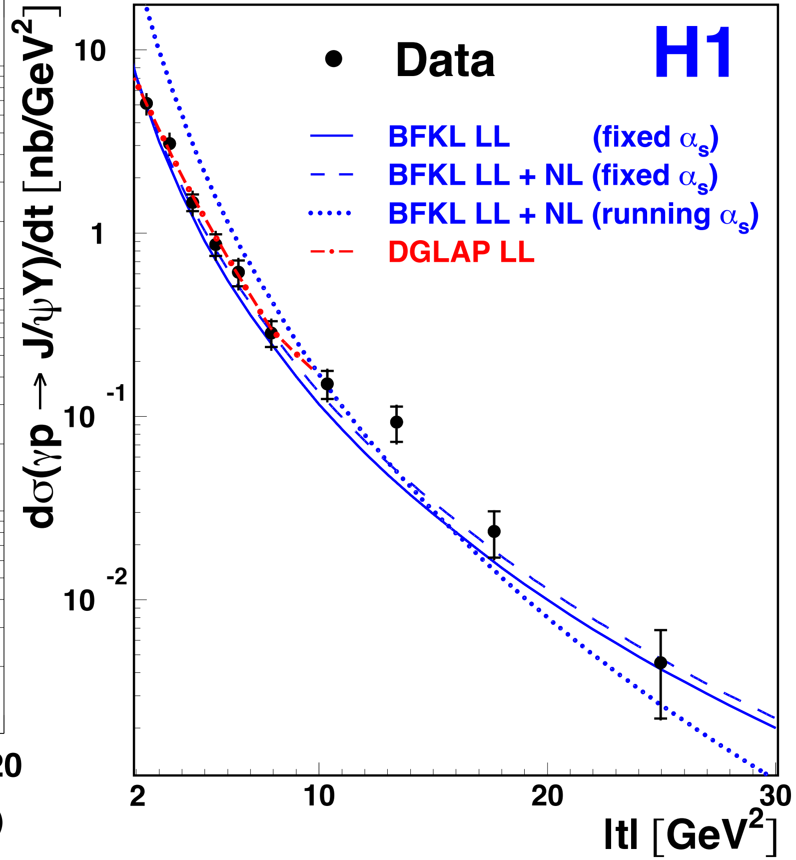
BFKL (EMP) predictions too steep

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 $d\sigma/dt \simeq |t|^n$

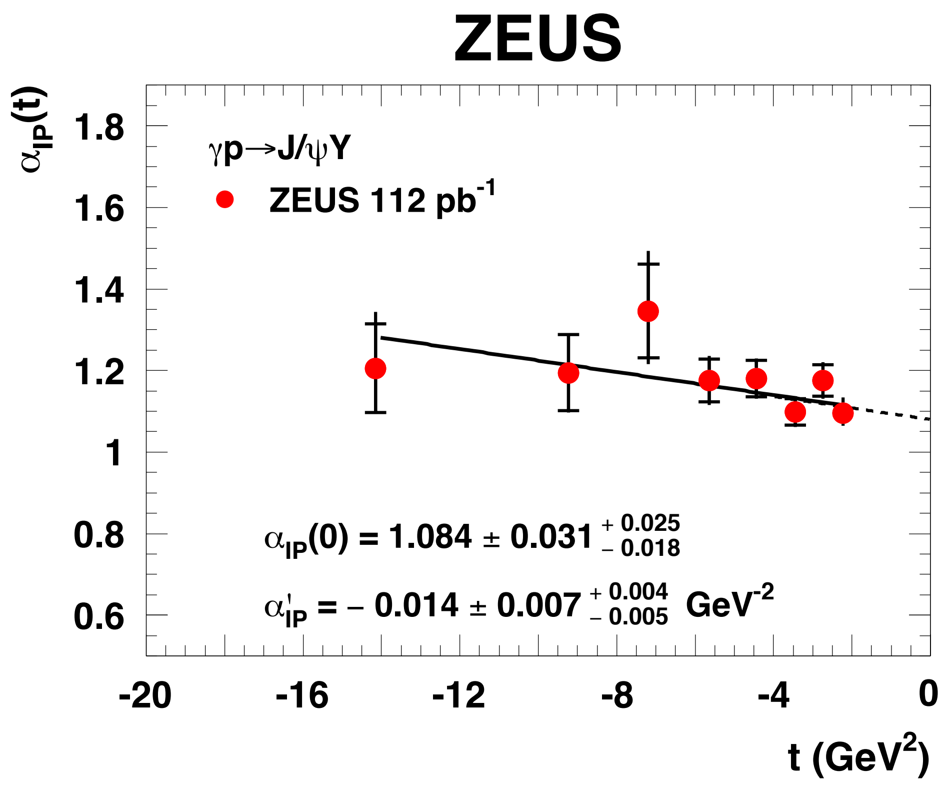
Models predict n dependent on t

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

EMP (BFKL) below data
GLMN (DGLAP) validity range of $|t| < M_{J2/\psi}$
FSZ describe data up to 12 GeV^2

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

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



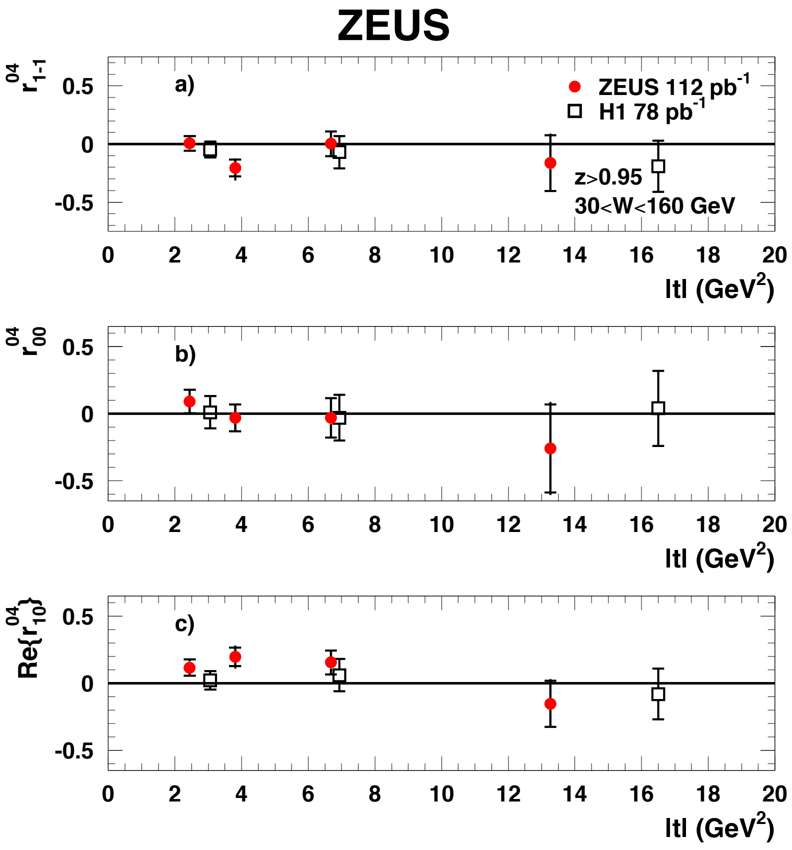
Pomeron intercept consistent with soft $\alpha_{Pl}(0) = 1.0808$

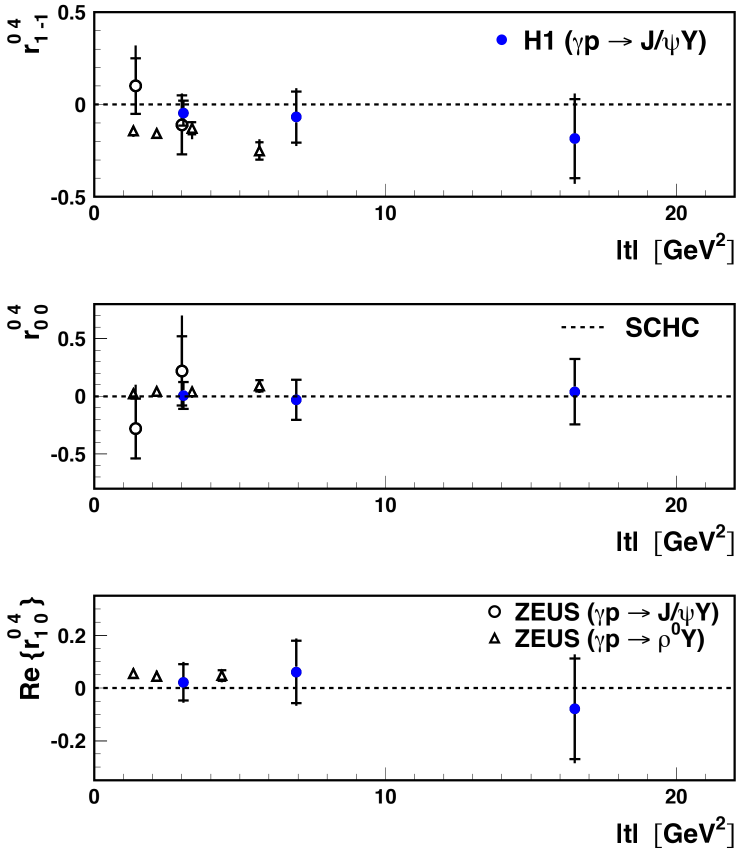
Pomeron slope consistent with BFKL Pomeron

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

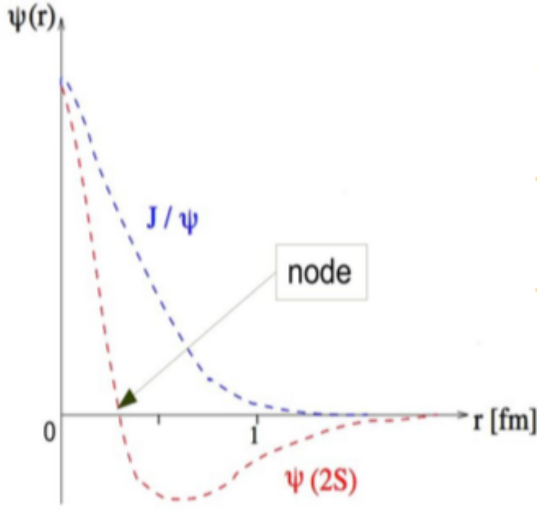
r_{1-1}^{04} is related to interference between non-flip and double flip amplitude

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

$\psi(2S)$ in photoproduction and DIS

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

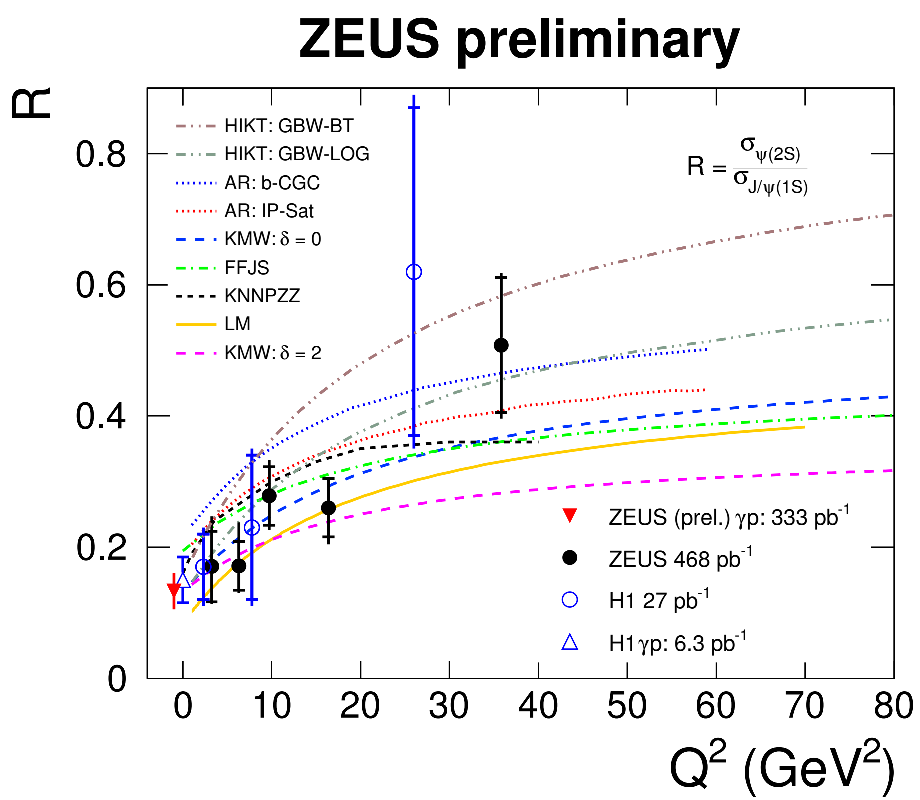
HIKT, Hufner et al.: dipole model, dipole-proton constrained by inclusive DIS data
AR, Armesto and Rezaeian: impact parameter dependent CGC and IP-Sat model KMW,Kowalski Motyka Watt: QCD description and universality of quarkonia production FFJS, Fazio et al.: two component Pomeron model
KNNPZZ, Nemchik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

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

$\psi(2S)$ has a radial node at ~0.4 fm

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

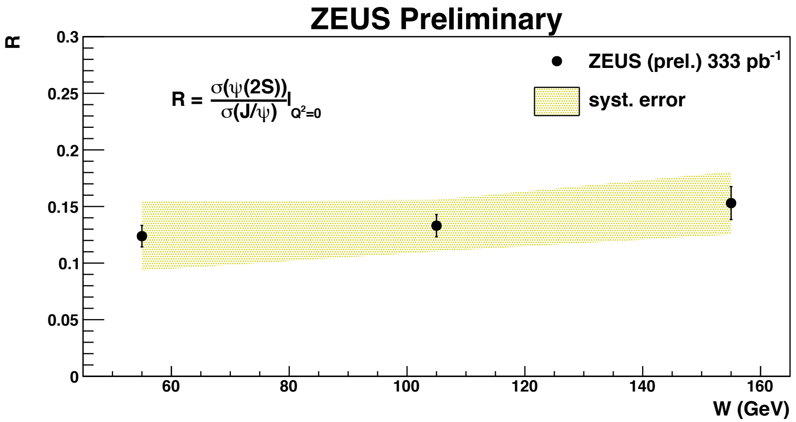
$R = \sigma_{\gamma p \to \psi(2S)p} / \sigma_{\gamma p \to J/\psi(1S)}$ vs Q^2, t, W



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

ZEUS prel: highest precision at $Q^2 = 0$ GeV^2
R = 0.1332±0.0065(**stat.**)±0.0270(**syst.**)

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



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

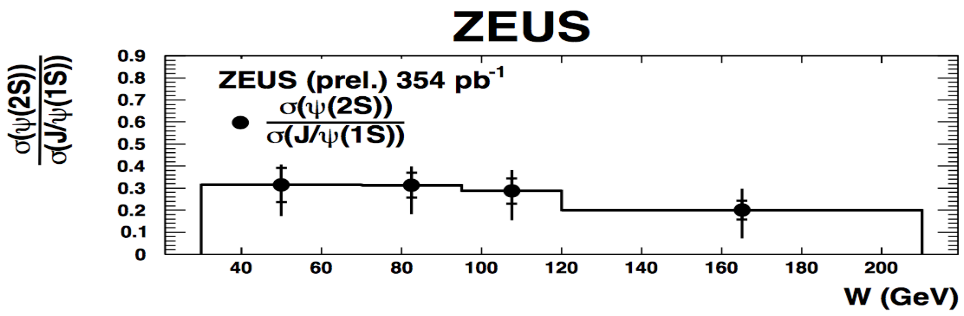
Summary

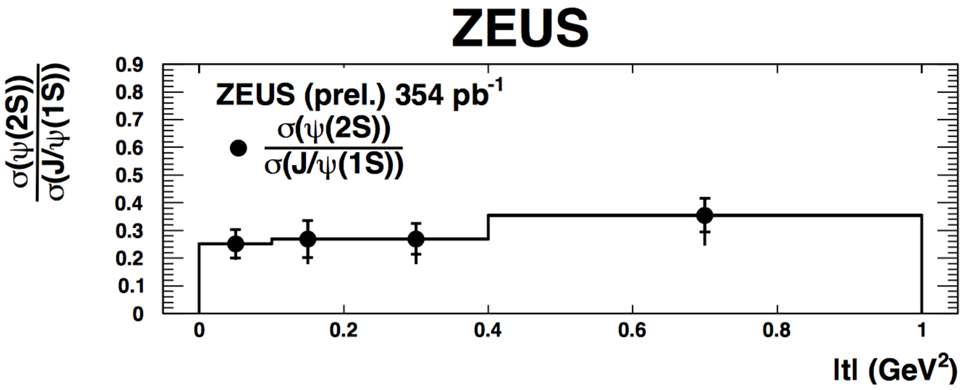
- Exclusive J/ψ(1S) production extremely interesting for theory, specially pQCD
- It is a clean experimental process, but precise measument requires a strategy for trigger and dedicated detectors to tag proton-dissociation

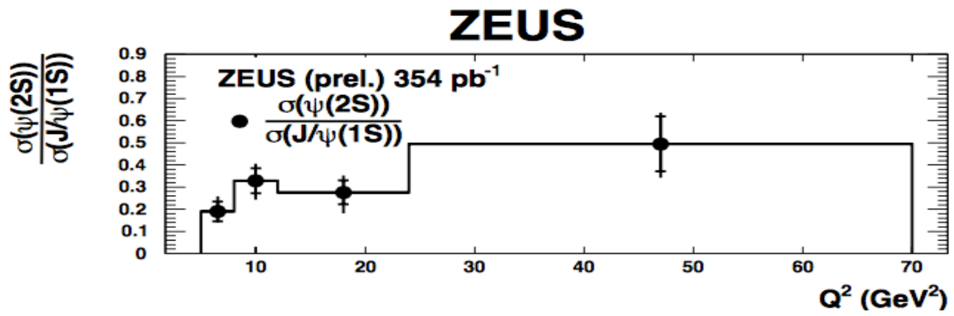
Waiting for the discussion!

H1 and ZEUS paper on VM production

H1 Topic	Journal	ZEUS Topic	Journal
Exclusive $\pi^+\pi^-$ and ρ^0 in PHP	Eur.Phys.J.C80 (2020), 1189	$R(\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)})$ in DIS	Nucl. Phys. B 909 (2016) 934
Exclusive ρ^0 with Leading n in PHP	Eur.Phys.J.C76 (2016) 1, 41	Exclusive Electroproduction of 2π	Eur.Phys.J. C 72 (2012) 1869
Elastic and p-diss J/ψ in PHP	Eur.Phys.J.C73 (2013) 2466	$\Upsilon(1S)$ in PHP (t-dependence)	Phys.Lett. B 708 (2012) 14
Diffractive ρ^0 and ϕ in DIS	JHEP05 (2010) 032	P-dissociative J/ψ in PHP at large t	JHEP 05 (2010) 085
Diffractive PHP of ρ^0 with large t	Phys.Lett.B 638 (2006) 422	Exclusive PHP of Υ Mesons	Phys. Lett. B 680 (2009) 4
Elastic J/ψ in PHP and DIS	Eur.Phys.J.C46 (2006) 585	Exclusive ρ^0 in DIS	PMC Physics A 1, 6
Diffractive PHP of J/ψ with large t	Phys Lett B568 (2003) 205	Exclusive ϕ in DIS	Nucl. Phys. B 718 (2005) 3
Diffractive PHP of $\psi(2S)$	Phys.Lett.B541 (2002) 251	Exclusive J/ψ in DIS	Nucl. Phys. B 695 (2004) 3
Helicity structure of ρ^0 in DIS	Phys.Lett.B539 (2002) 25	P-dissociative VM in PHP at large t	Eur. Phys. J. C 26 (2003) 389
Elastic ϕ in DIS	Phys.Lett.B483 (2000) 360	Exclusive PHP of J/ψ mesons	Eur. Phys. J. C 24 (2002) 345
Elastic J/ψ and Υ in PHP	Phys.Lett.B483 (2000) 23	Exclusive ω in DIS	Phys. Lett. B 487 (2000) 273
Elastic ρ^0 in DIS	Eur.Phys.J.C13 (2000) 371	Diffractive PHP of VM at large t	Eur. Phys. J. C 14 (2000) 213
Quasi-elastic ($z > 0.95$) $\psi(2S)$ in PHP	Phys.Lett.B421 (1998) 385	Spin-Density ME of Exclusive ρ^0 in DIS	Eur. Phys. J. C 12 (2000) 393
P-diss. ρ^0 and Elastic ϕ in DIS	Z.Phys.C75 (1997) 607	Exclusive ρ^0 and J/ψ in DIS	Eur. Phys. J. C 6 (1999) 603
Elastic and Inelastic J/ψ in PHP	Nucl.Phys.B472 (1996) 3	Elastic Υ Photoproduction	Phys. Lett. B 437 (1998) 432
Elastic ρ^0 and J/ψ at large Q^2	Nucl.Phys.B468 (1996) 3	Elastic and p-Dissociative ρ^0 in PHP	Eur. Phys. J. C 2 (1998) 247
Elastic Rho0 in PHP	Nucl.Phys.B463 (1996) 3	Elastic J/ψ in PHP	Z. Phys. C 75 (1997) 215
		Elastic ω in PHP	Z. Phys. C 73 (1996) 73
		$\gamma^* p \to \phi p$ in DIS	Phys. Lett. B 380 (1996) 220
		Elastic ϕ in PHP	Phys. Lett. B 377 (1996) 259
		Elastic ρ^0 in PHP	Z. Phys. C 69 (1995) 39
		Exclusive ρ^0 in DIS	Phys. Lett. B 356 (1995) 601







- Ratio:
  - Independent of W
  - Independent of t
  - Increase with Q^2