Recent Results on J/ψ Photoproduction at HERA

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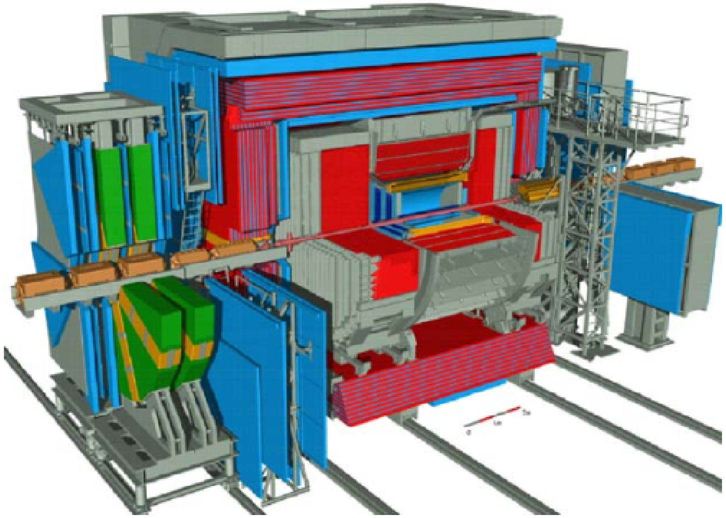
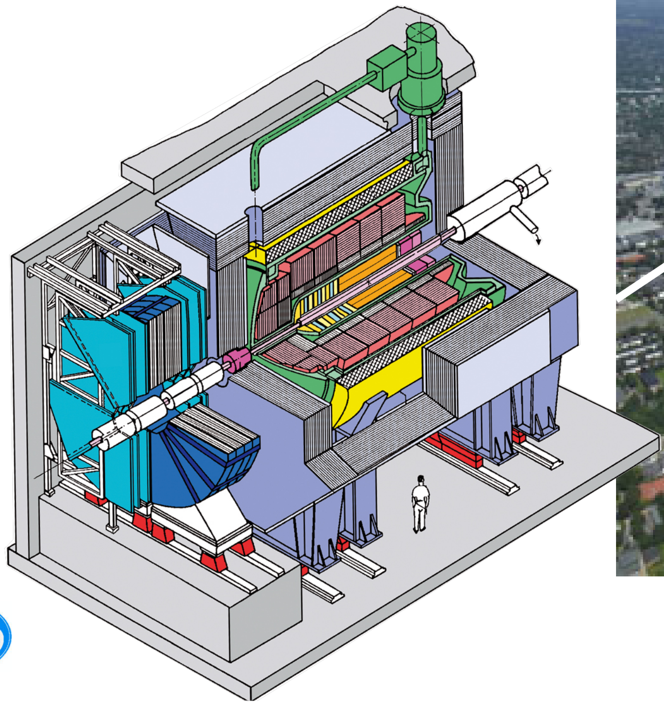
The HERA ep collider (1992 – 2007) at DESY in Hamburg

- ep collider:
- $e^{\pm}$ energy: 27.6 GeV
- p energy: 920 GeV, 460 GeV
- Center of mass energy: 318 GeV, 225 GeV
- 2 collider experiments: H1 and ZEUS

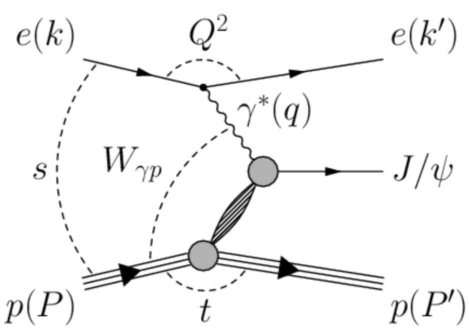




Elastic, proton dissociative and inelastic J/ψ production at HERA

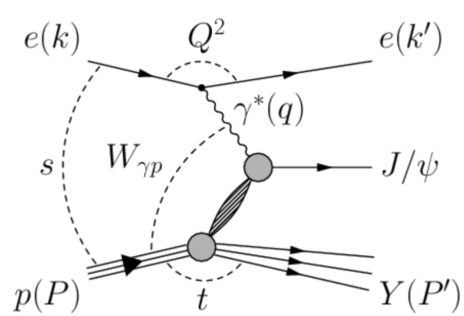
- elastic

$M_Y = m_p$



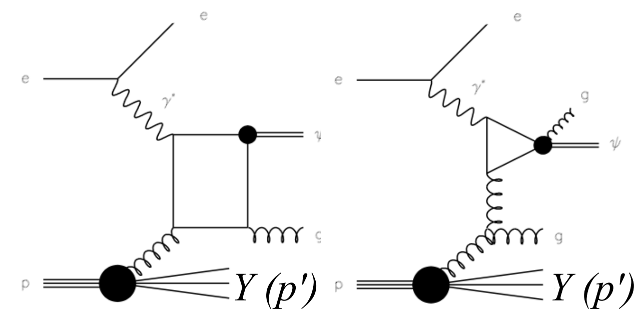
- p-dissociative

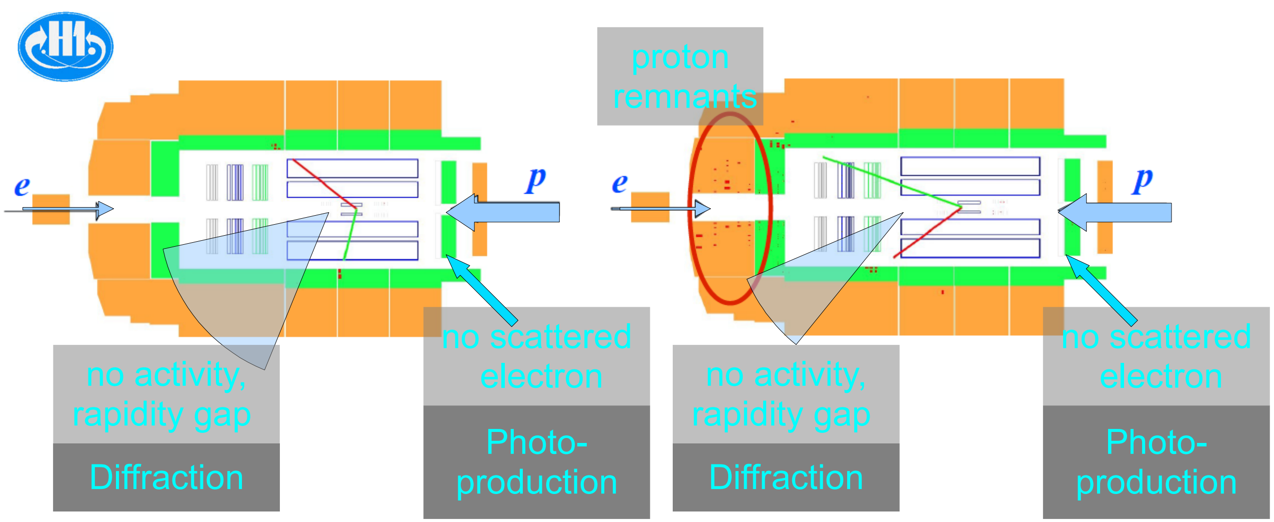
$m_p < M_Y < 10$ GeV

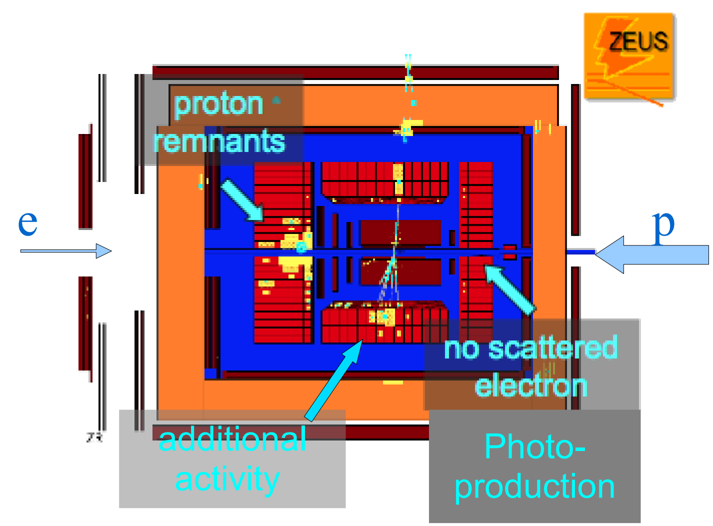


- inelastic

10 GeV $\ll M_Y$





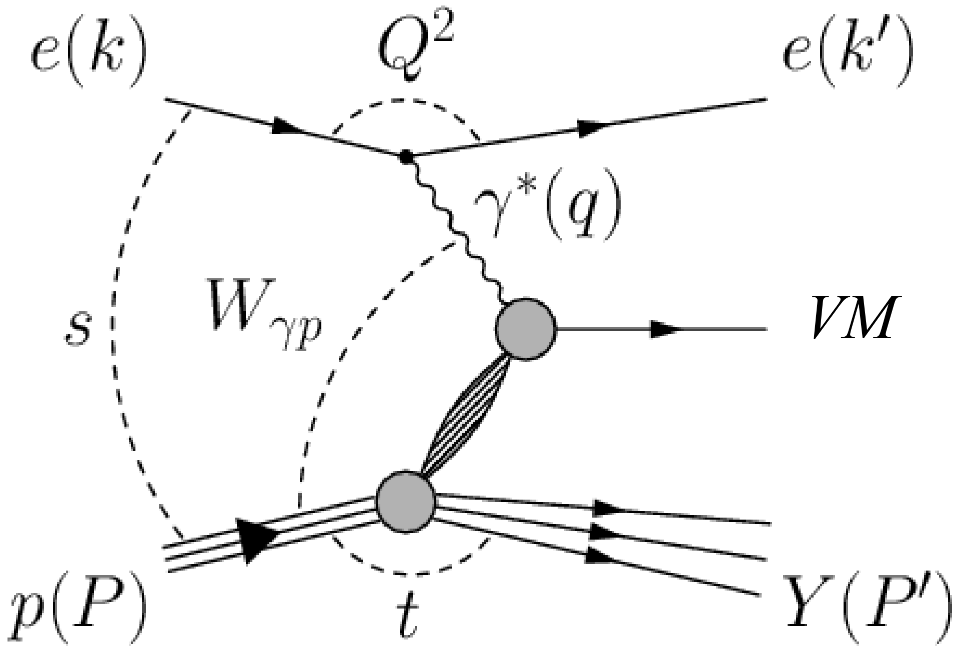


Elastic and Proton-Dissociative Photoproduction of J/ψ Mesons at HERA,
DESY-13-058, Eur. Phys. J. C73 (2013) 2466

Measurement of Inelastic J/ψ and ψ' Photoproduction at HERA, DESY-12-226, JHEP 1302 (2013) 071

HERA as a γ*p collider to study diffractive VM production

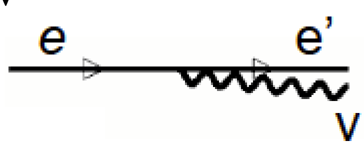
- Kinematics and scales:
  - Photon virtuality: Q^2
  - Squared cm energy of ep system: s
  - CM energy of γp system: $W_{\gamma p}$
  - (4-mom. transfer) at p vertex: t
  - Vector meson mass: M_V



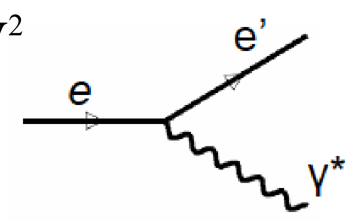
- Diffractive vector meson production can be studied at HERA as a function of several scales Q^2, M_V, t over a wide range of $W_{\gamma p}$.

$VM = (\rho, \omega, \varphi, J/\psi, \psi', \Upsilon)$

- Two kinematic regimes:
  - Photoproduction: $Q^2 \approx 0$ GeV^2



  - Deep Inelastic Scattering: $Q^2 > 1$ GeV^2
    (scattered electron detected)

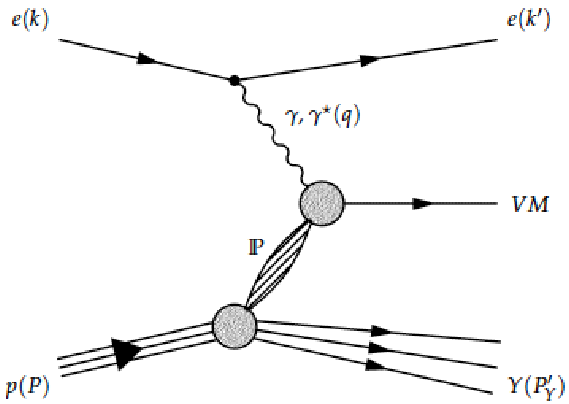


- Two ep cm mass energies:
  - $\sqrt{s}$ = 318 GeV (high energy, HE)
  - $\sqrt{s}$ = 225 GeV (low energy, LE) → also low $W_{\gamma p}$

Theoretical models for diffractive Vector Meson production

Regge Approach

- "soft region"



- Soft Pomeron IP exchange

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

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

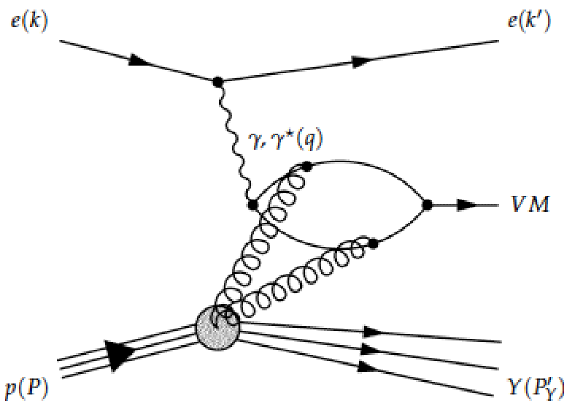
$$\frac{d\sigma}{dt} \propto e^{bt} \left(\frac{W_{\gamma p}}{W_0} \right)^{\delta} \qquad \delta = 4(\alpha_0 - 1)$$

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

- Weak energy dependence of $\sigma \propto W_{\gamma p}^{\delta}$

pQCD Approach

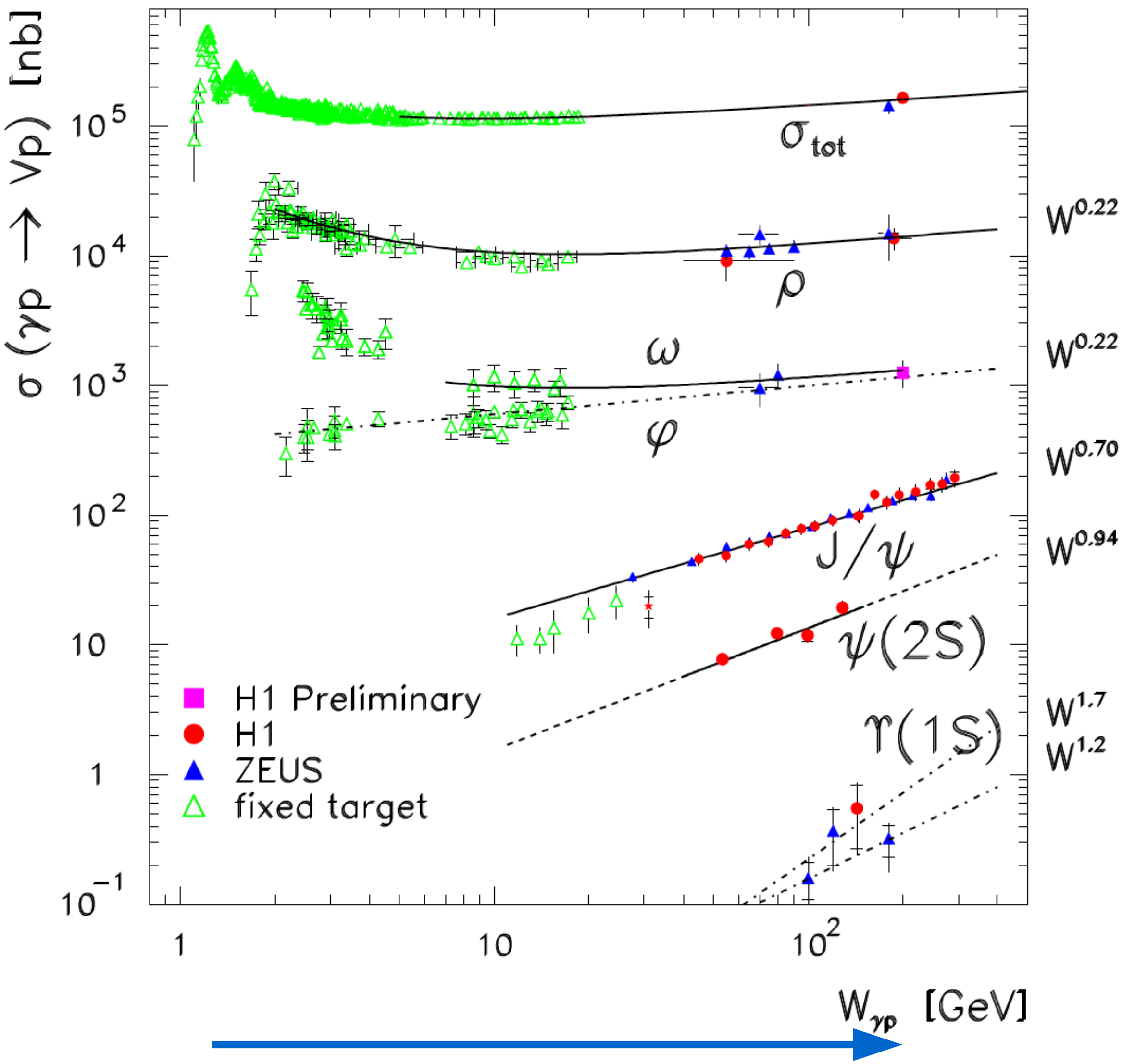
- "hard region", scales for pQCD: Q^2, M_V, t



- Exchange of ≥ 2 gluons:
  1. Virtual photon fluctuates into qq pair
  2. which interacts with the proton trough the exchange of a two gluon-ladder
  3. qq recombines into VM.
- VM cross section has sensitivity to squared gluon density in proton:

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

$W_{\gamma p}$ dependance of Elastic Vector Meson Photoproduction



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

With increase of VM mass (M_V) process gets harder:

- Consistent with soft models, $\delta \sim 0.2$

- Cross section rises faster, $\delta > 0.2$
  → "hard regime"
  → sensitivity to gluon density in proton:
  $\sigma \propto [x\, g(x,M_V)]^2$

t-dependance of Vector Mesons

- Cross section approximately behaves like:

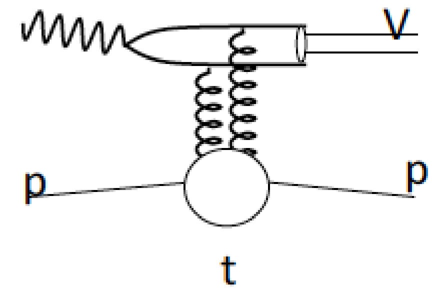
  $$d\sigma / dt \propto e^{-bt}$$

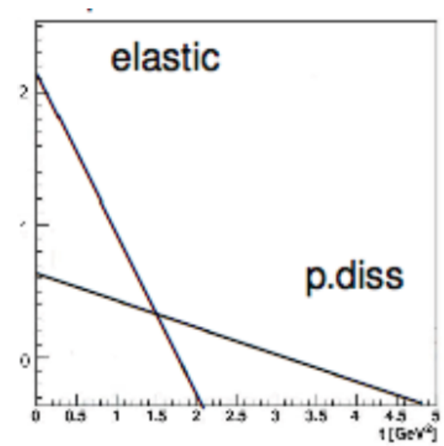
- b is related to the quadratic sum of sizes of the target and projectile:

  $$b = b_V + b_P$$

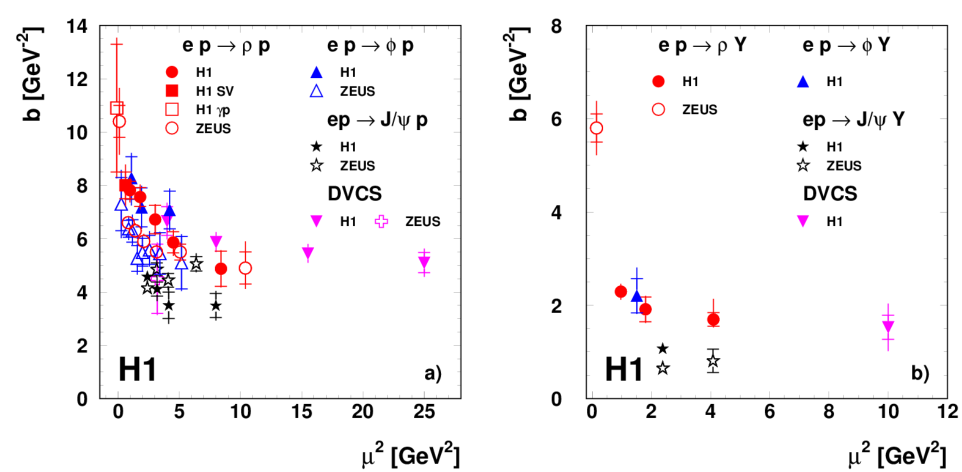
- If the target (i.e. proton) breaks, b_p does not count, i.e. b has to be smaller for p-diss. Since cross section of elas and p-diss is similar, p-diss dominates at large t.

- b decreases with the scale $\mu^2=(Q^2 + M_V^2)/4$ from ~10GeV $^{-2}$ (soft scale) ~5GeV $^{-2}$ (hard scale) for elastic and from ~3GeV $^{-2}$ (soft scale) ~1.5GeV $^{-2}$ (hard scale) for p-dis.

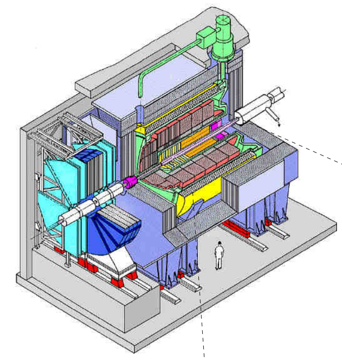




elastic p-diss.

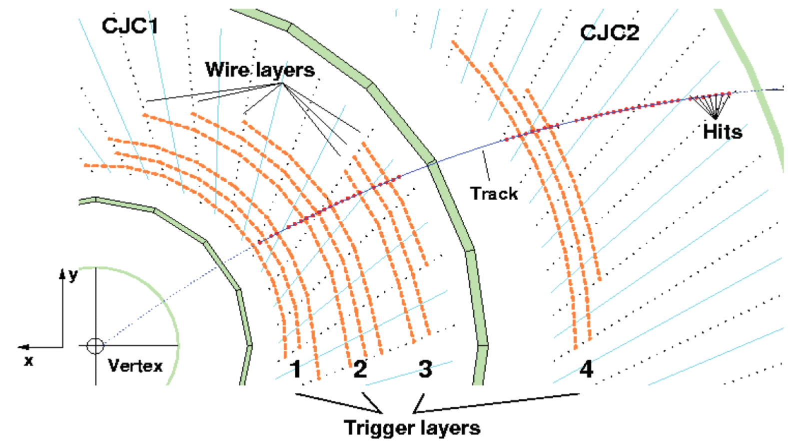


Elastic and Proton dissociative Photoproduction of J/ψ Mesons at HERA

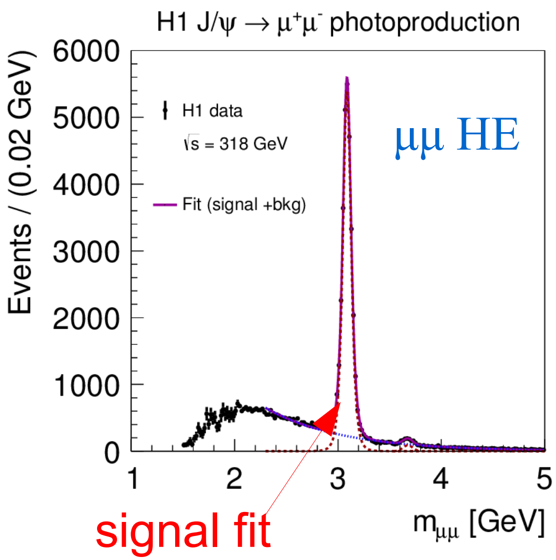


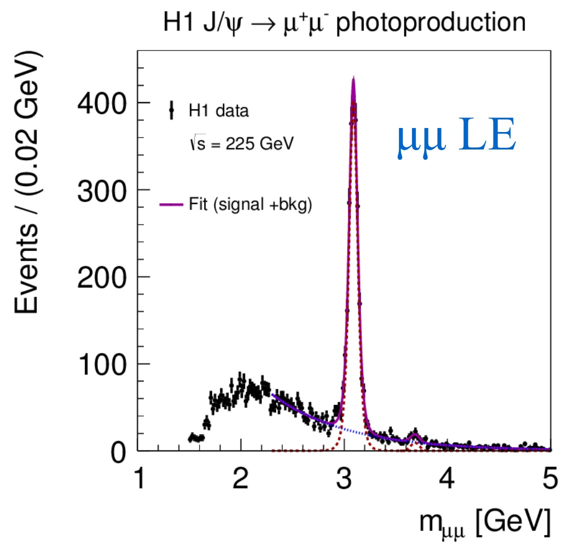
Fast Track Trigger (FTT)
Fits up to 48 **tracks** (within 20μs) **L1-L2**

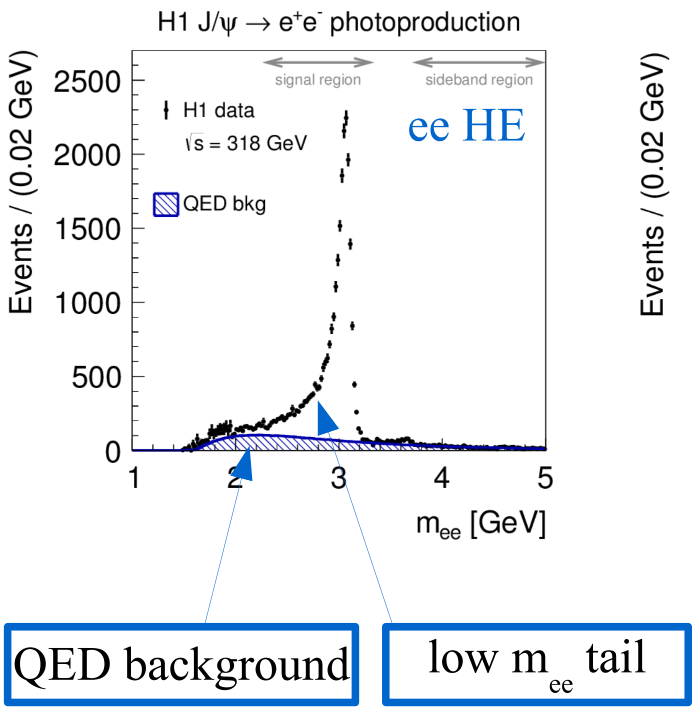
- New H1 analysis, DESY-13-058, Eur. Phys. J. C73 (2013) 2466, arXiv:1304.5162
- Extends the range to lower $W_{\gamma p}$
  - Use data from HERA low energy run
- Use Fast Track Trigger (FTT)
  - Purely track based information
  - Triggers on electron and muon decay channels: $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$
- Simultaneous measurement of elastic and proton-dissociative process.
- Use forward detectors (FTS, Plug, LAr) to tag proton dissociative process at low |t|.
- Measure proton dissociative process to low |t| values.

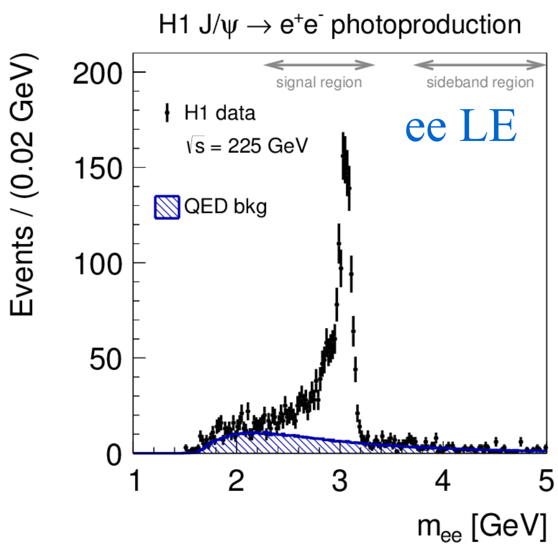


Signal extraction from invariant mass distributions









$J/\psi \rightarrow \mu^{\pm}\mu^{\mp}$

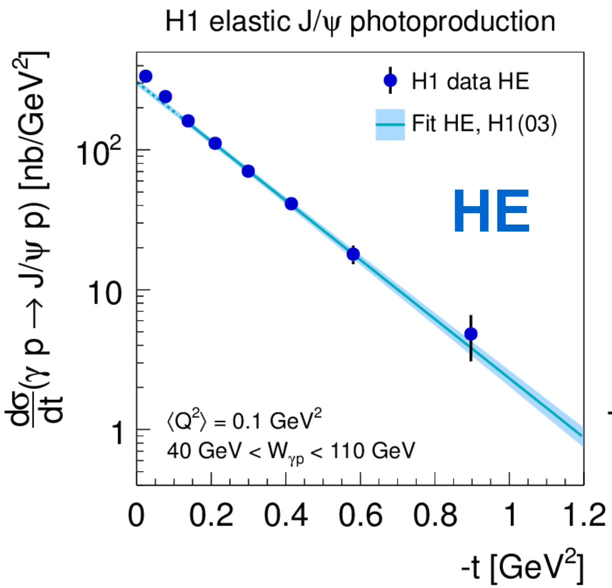
- Fits to signal and non-resonant background distributions
- Functions: Student't for signal, exponential for background.
- ~30000 events for HE and ~2300 events for LE

$J/\psi \rightarrow e^{\pm}e^{\mp}$

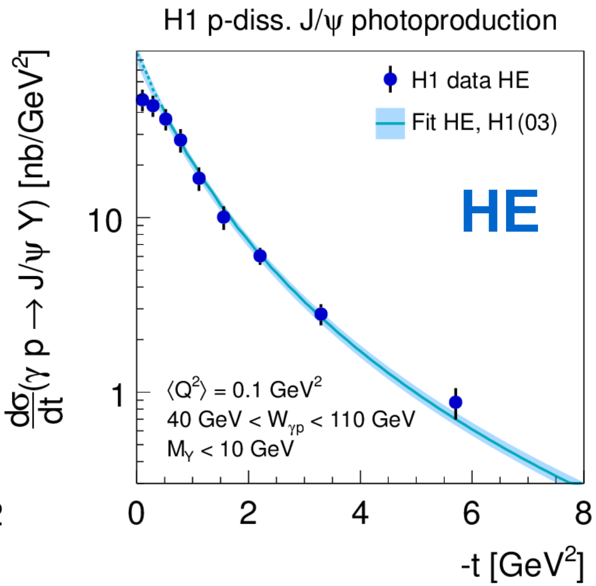
- Non-resonant background subtracted by QED simulation and counting of events in signal region.
- Procedure insensitive to low m_{ee} tail due to QED radiation losses and Bremsstrahlung.
- Possible, since no other background other than QED in selection.
- ~24000 events for HE and ~1800 for LE.

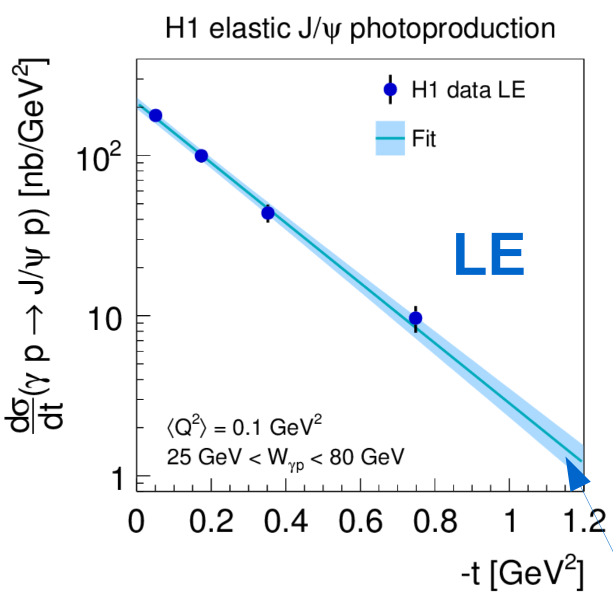
Elastic and proton dissociative cross sections as a function of t

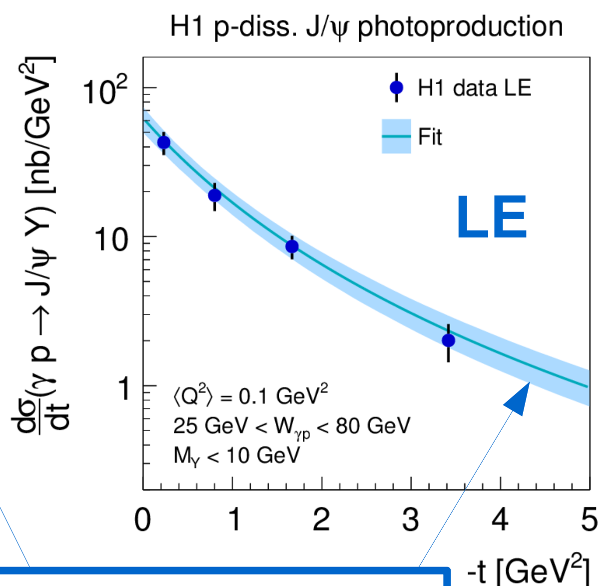
elastic



p-diss.







Phenomenological fits

Phenomenological fit model:

- Elastic:

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

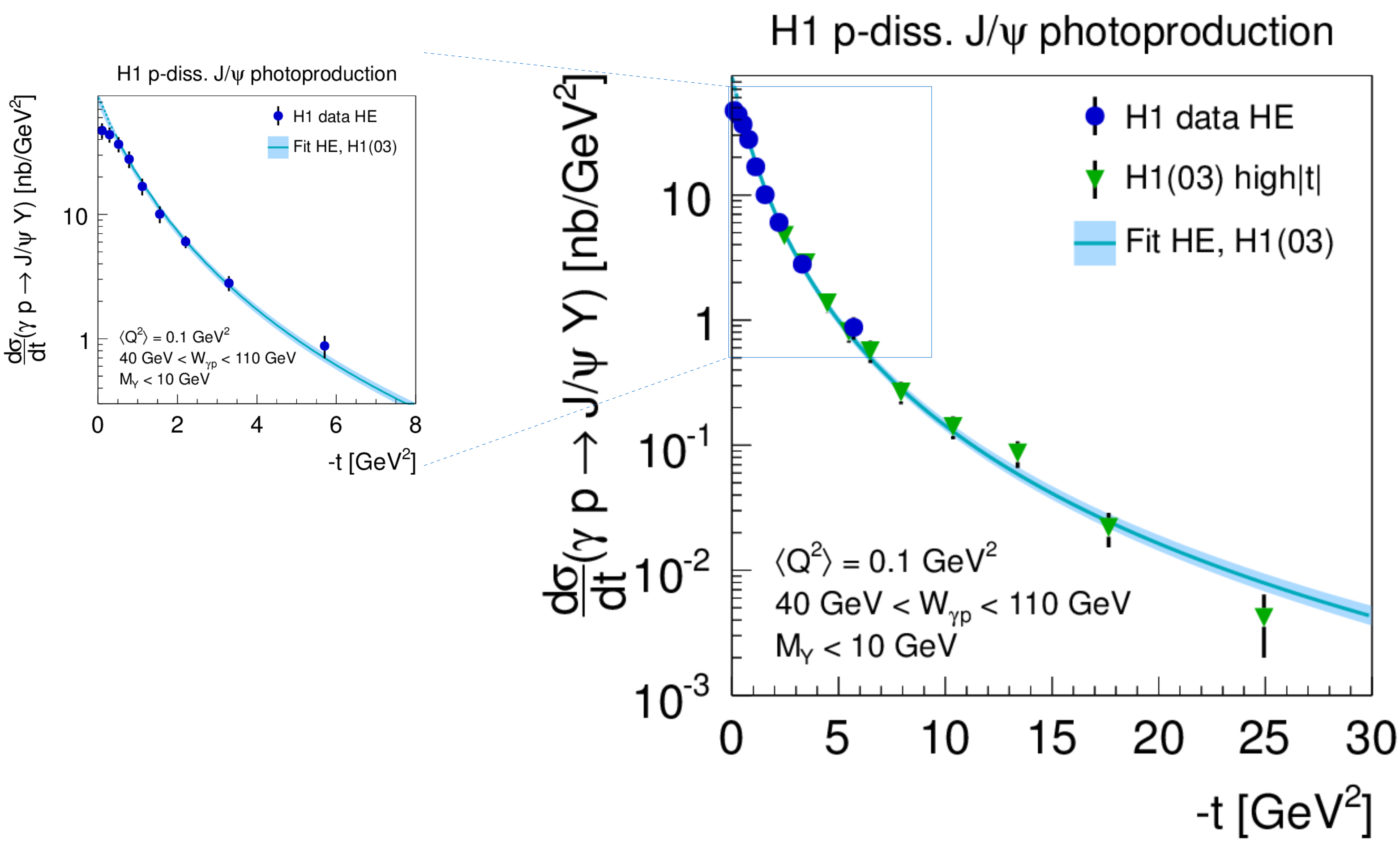
- Proton dissociative:

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

- Simultaneous χ^2 fit of elastic and p.-diss. cross sections:
  - including all correlations.
    - including previous H1 high t-data (DESY-03-061, hep-ex/0306013)
  - excluding 2 lowest |t|-points.

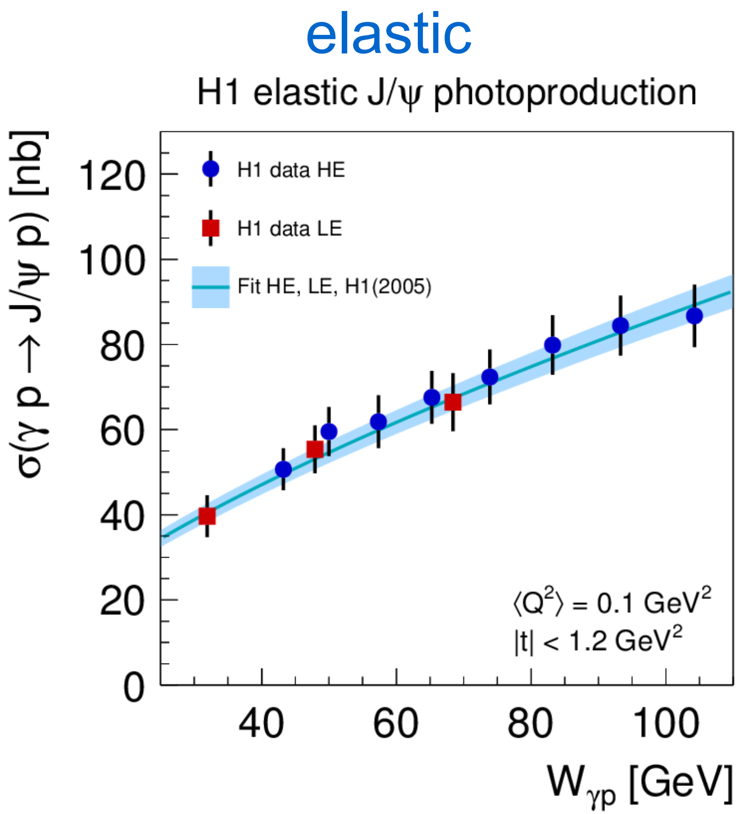
Data period	Process	Parameter	Fit value	Correlation
HE	$\gamma p \to J/\psi\, p$	b_{el}	(4.88 ± 0.15) GeV^{-2}	$\rho(b_{el}, N_{el}) = 0.50$; $\rho(b_{el}, b_{pd}) = 0.49$; $\rho(b_{el}, n) = -0.21$; $\rho(b_{el}, N_{pd}) = 0.68$
		N_{el}	(305 ± 17) nb/GeV^2	$\rho(N_{el}, b_{pd}) = 0.23$; $\rho(N_{el},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

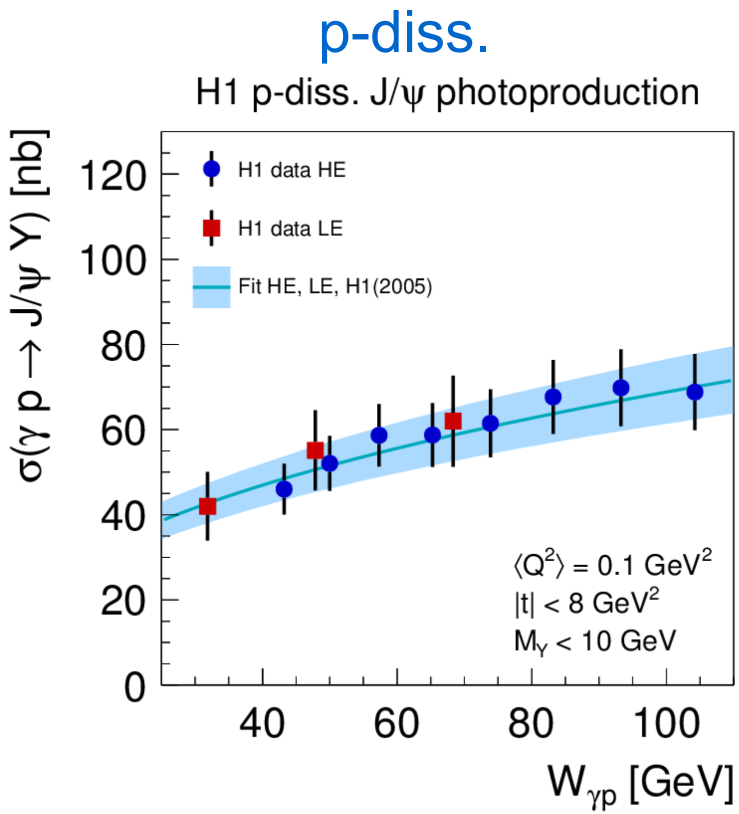
Proton dissociative cross sections as a function of t



- Comparison with the previous high-|t| measurement (H1 03)
- Good agreement in overlap region.
- New proton dissociative measurement extends the reach to very low |t| values.

Elastic and proton dissociative cross sections as a function of $W_{\gamma p}$



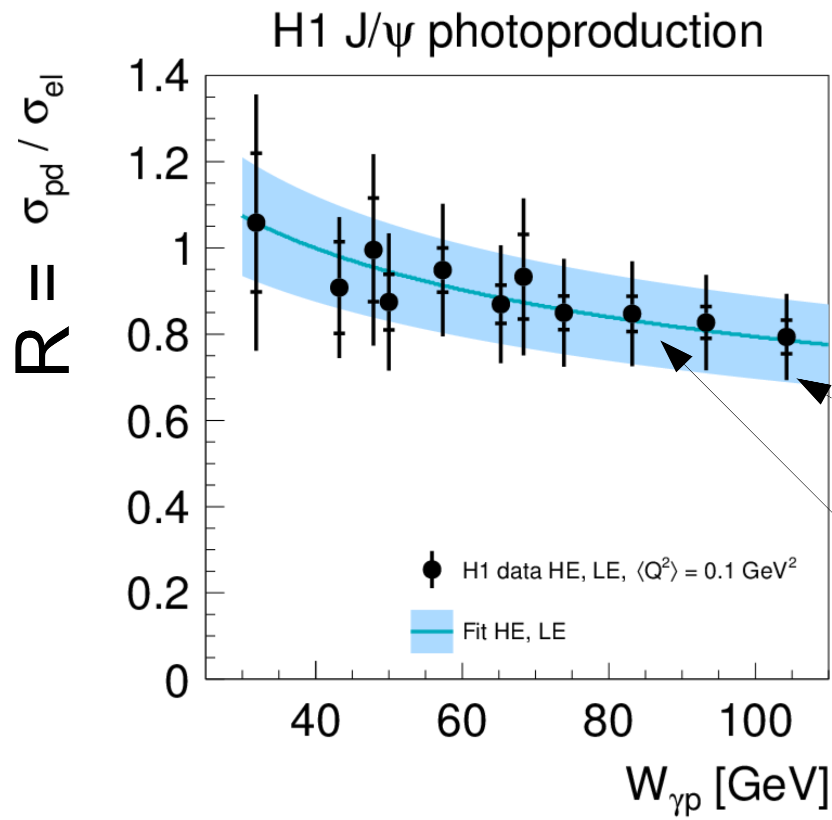


Phenomenological fit model:

- Parametrisation (for elastic and p-diss.)
  $\sigma = N\,(W_{\gamma p} / W_0)^{\delta}$ with $W_0 = 90\text{GeV}$
- Simultaneous χ^2 fit of elastic and p.-diss. cross sections:
  - including all correlations.
    - including previous H1 data (DESY-05-161, hep-ex/0510016)

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}	$81 \pm 3\,\text{nb}$	$\rho(N_{el}, \delta_{pd})$ = -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}	$66 \pm 7\,\text{nb}$	

Ratio of elastic and proton dissociative versus $W_{\gamma p}$



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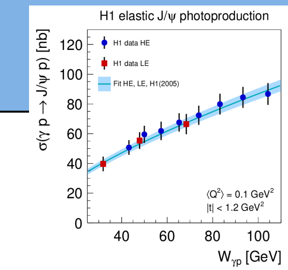
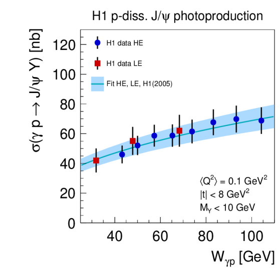


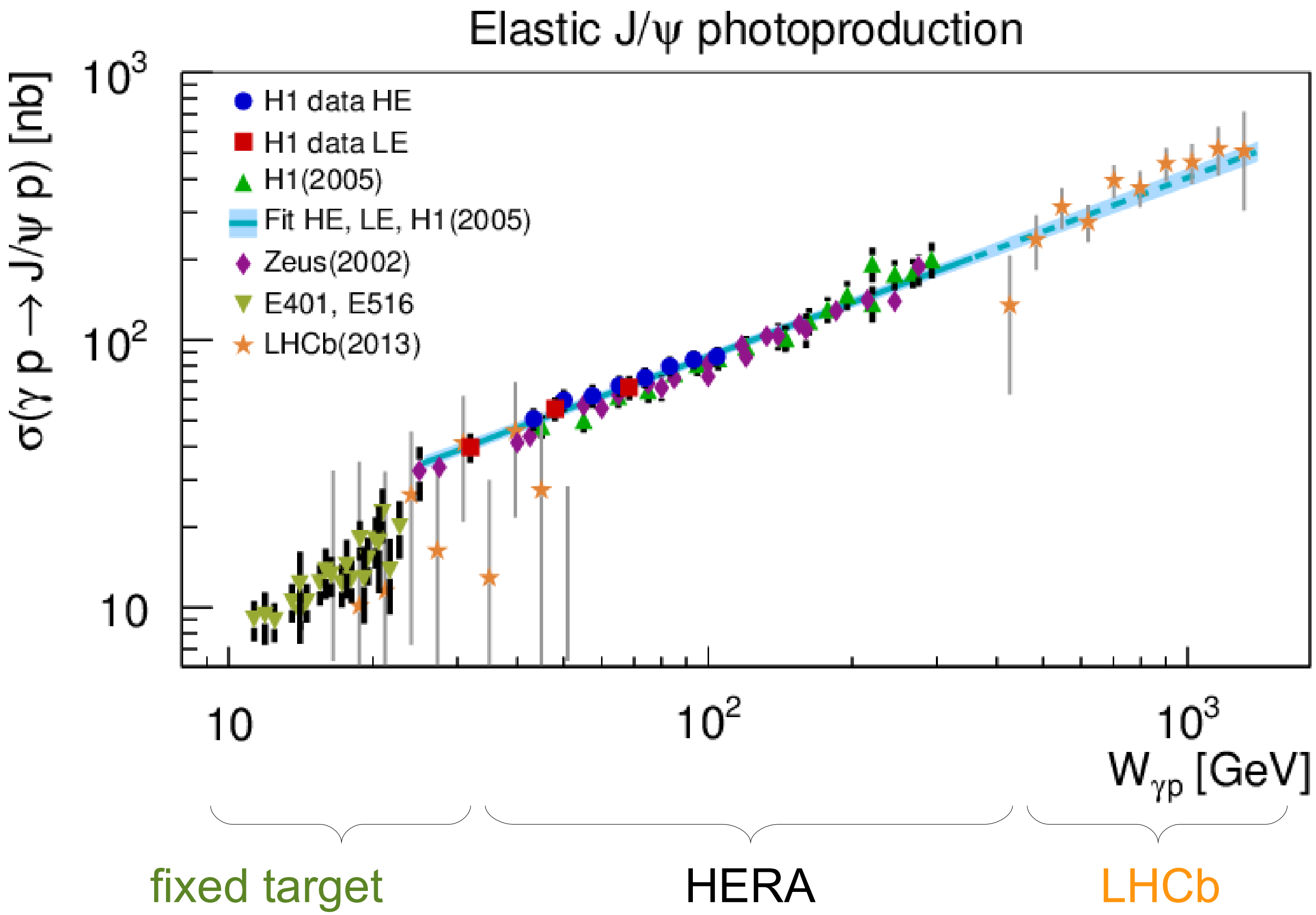


Total and uncorrelated errors (inner error bars)

Band: Ratio of fitted functions to elas and p-diss. cross sections (see slide 14).

- 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, which can be parametrized as $N_R\,(W_{\gamma p} / W_0)^{\delta R}$ with $N_R = 0.81 \pm 0.11$, $\delta R = -0.25 \pm 0.0.06$

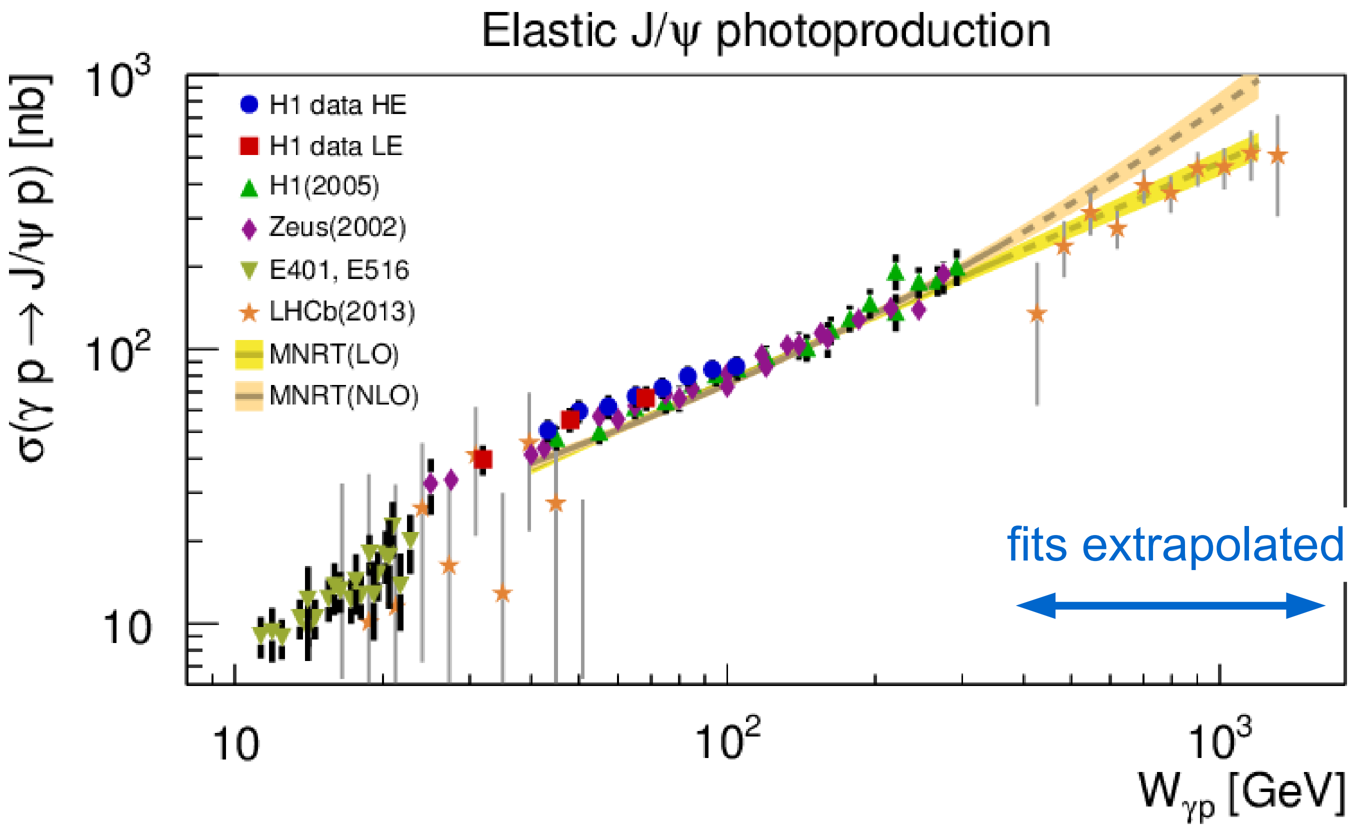
Comparison to fixed target and LHCb data

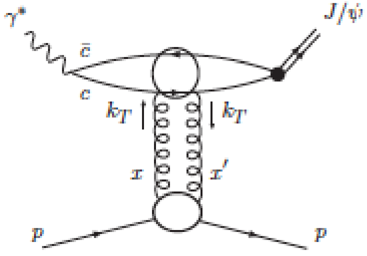


PRL 48 (1982) 73
PRL 52 (1984) 795
arXiv: 1301.7084

- New measurement in the transition region of the fixed target and the previous HERA data.
- Fixed target data: seem to have a steeper slope and lower normalization.
- Fit to H1 data extrapolated to higher $W_{\gamma p}$ values: describes the LHCb data.

Comparison to previous fits based on QCD calculations





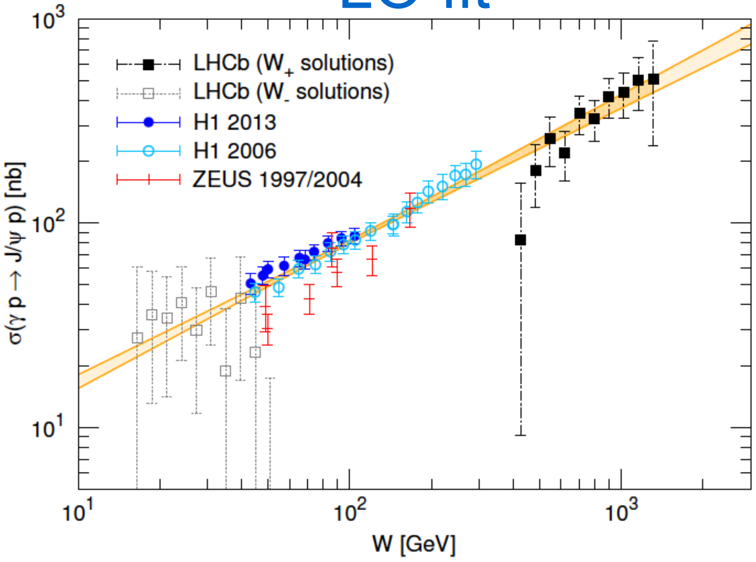
A.Martin et al., arXiv:0709.4406:

$\sigma \propto \quad [x^*g(x,\mu^2)]^2$

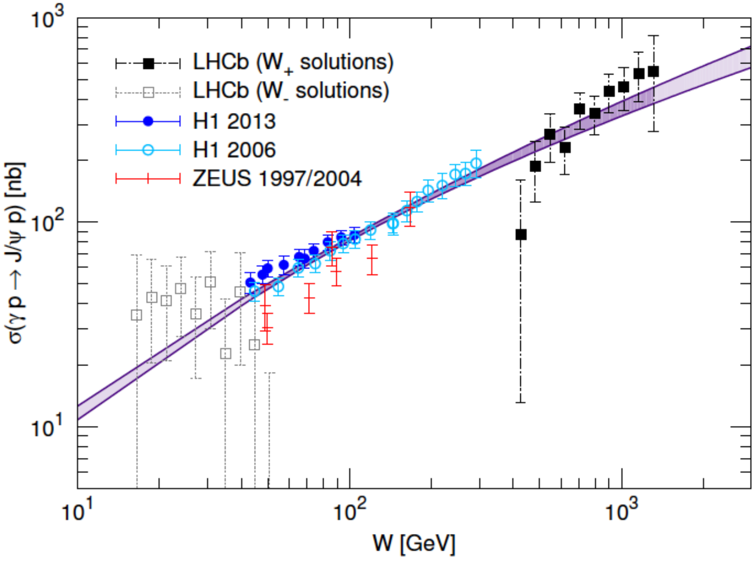
- LO and NLO fit to previous J/ψ data and extrapolated to higher $W_{\gamma p}$.
- LO fit describes the LHCb data.
- High precision J/ψ data give important input to gluon density at low x:
  → with the HERA J/ψ data one could reach $x \approx 10^{-5}$, with the LHCb data $x \approx 10^{-6}$.

Comparison to new fits based on QCD calculations

LO fit

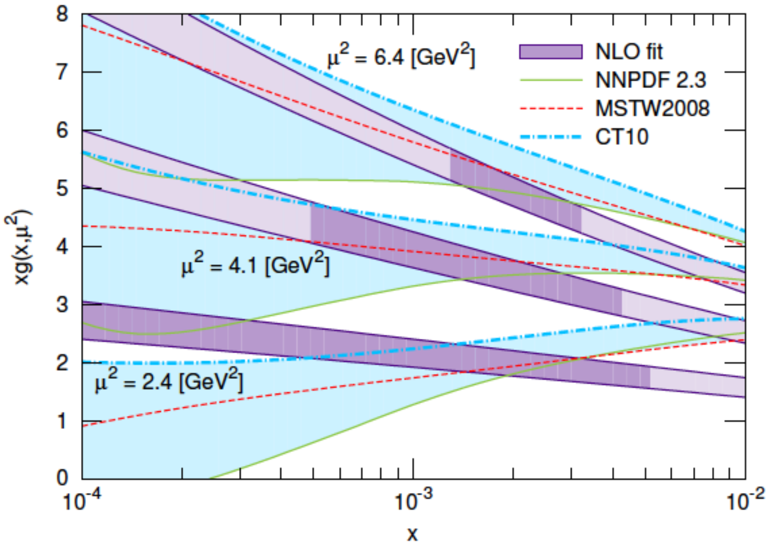


NLO fit



- New LO and NLO describe the data well.

- NLO gluon pdf compared to recent gluon pdfs from global analyses:
  → below $x \approx 10^{-3}$ the uncertainties on the pdfs from the global analyses are large, and could be reduced using J/ψ data .



S.P. Jones, A.D. Martin, M. Ryskin and T. Teubner, arXiv:1307.7099

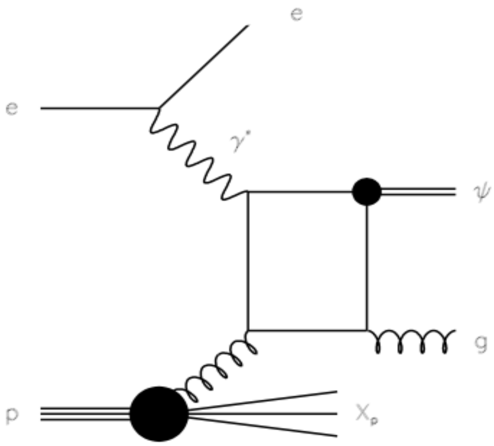
Inelastic J/ψ and ψ' production at HERA

- Different pQCD models:
  - Color singlet model (CS): cc pair emerges from the hard process with the quantum numbers of the meson.
  - Color octet model (CO): cc pair has different quantuum numbers → soft gluons are radiated.
- Key question:
  - Test QCD and interplay of CS and CO model.
- Quantity to measure "inelasticity":
  - Fraction of incident photon energy carried by the meson:

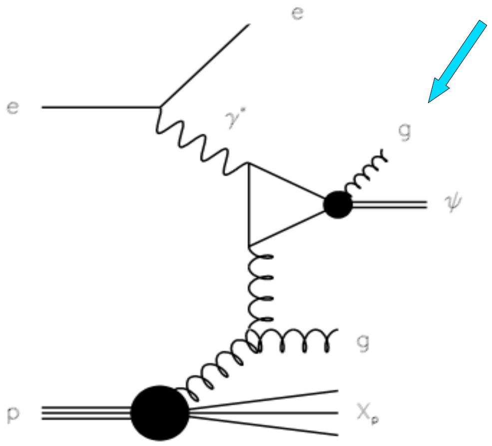
$$z = \frac{(E - p_Z)_\psi}{(E - p_Z)}$$

  - z = 1 for elastic events → main background source to this analysis

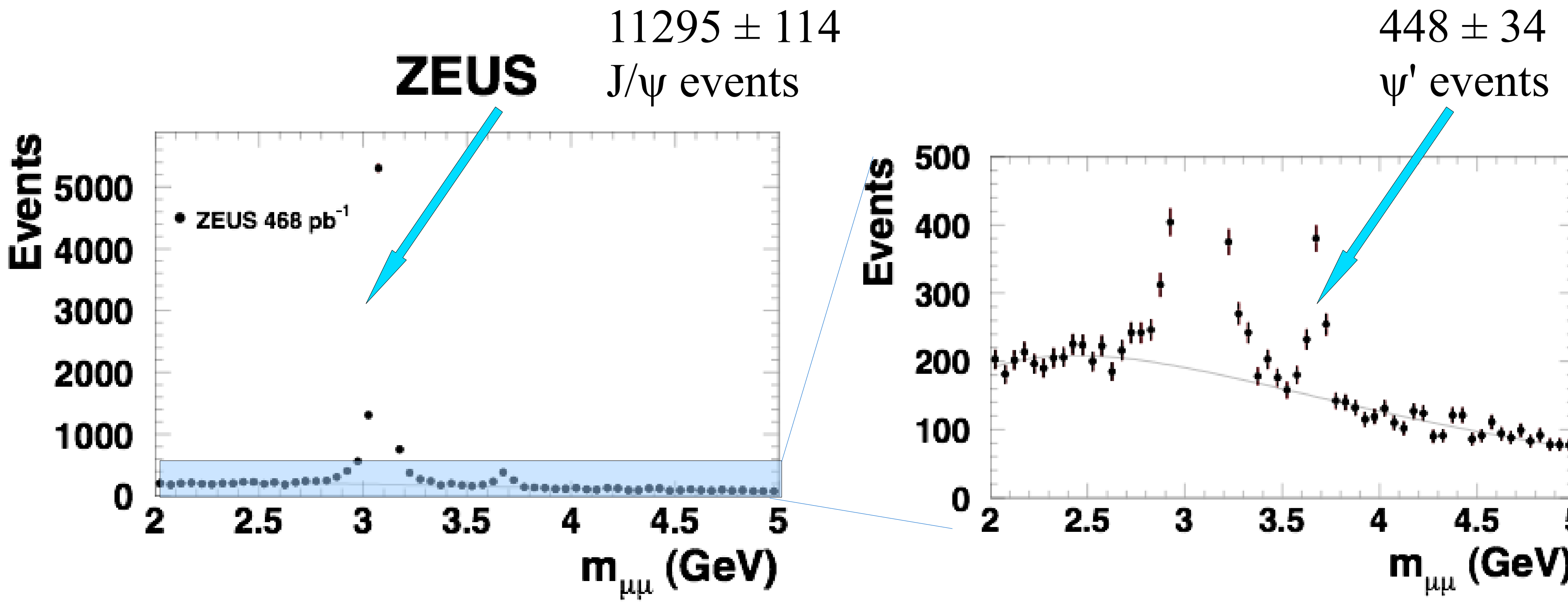
CS model



CO model

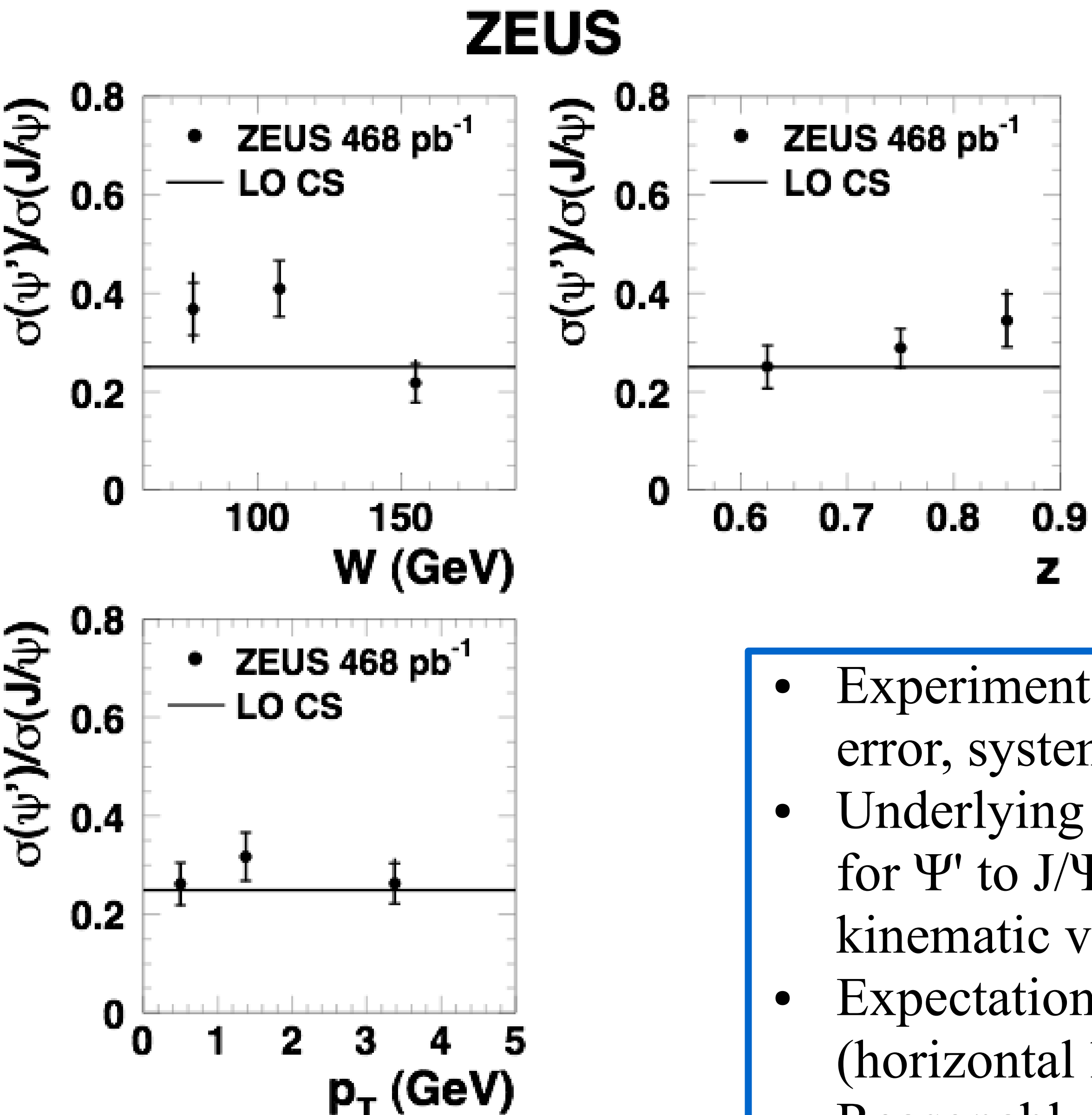


Signal peaks of J/ψ and ψ'



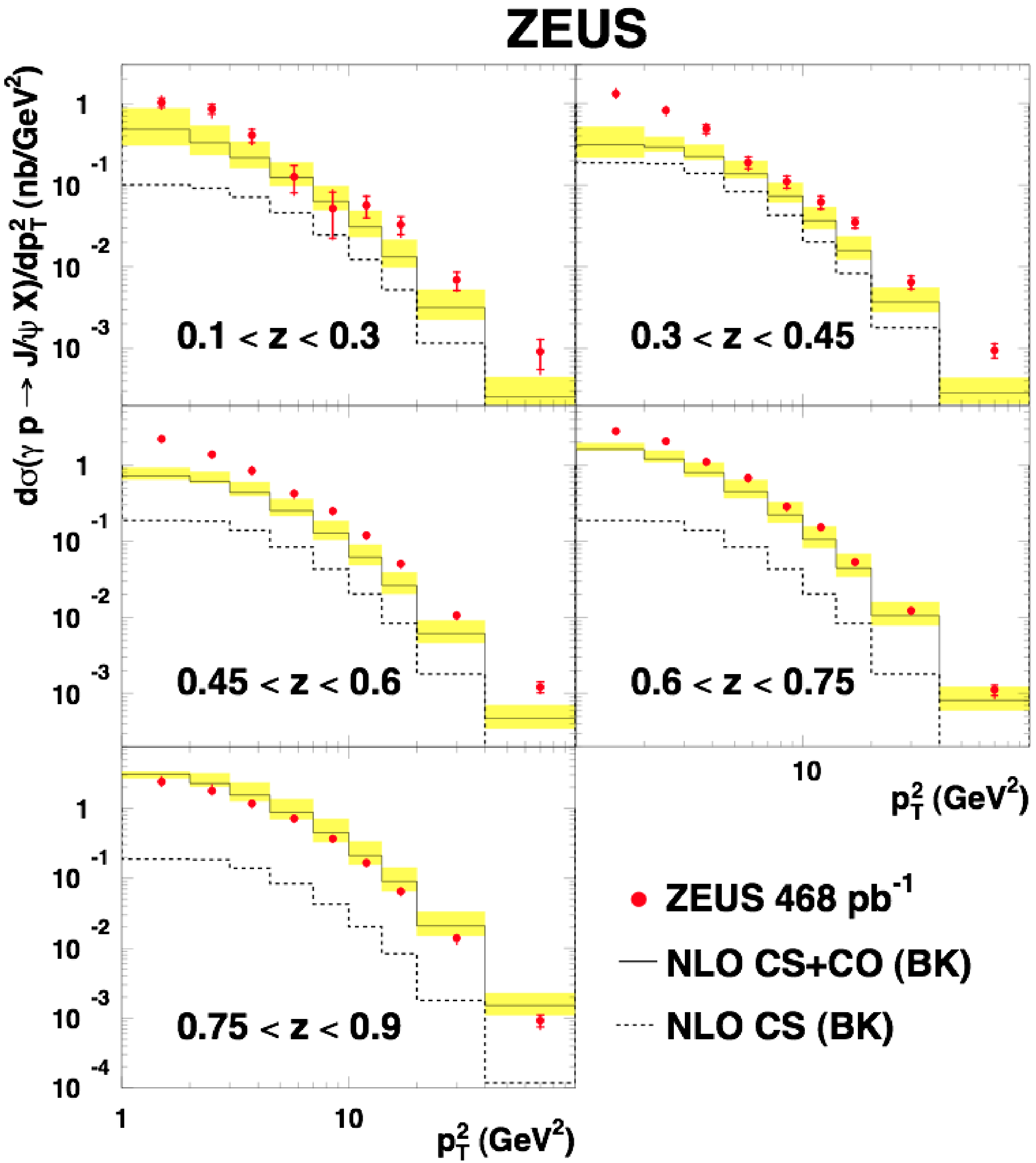
- The J/ψ signal here, include
  - the inelastic ψ' feed-down via the decay ψ' → J/ψ X. Contribution to cross sections ~15%.
  - the contribution from beauty decays, ~1.6%.

ψ' to J/ψ photoproduction cross section ratio



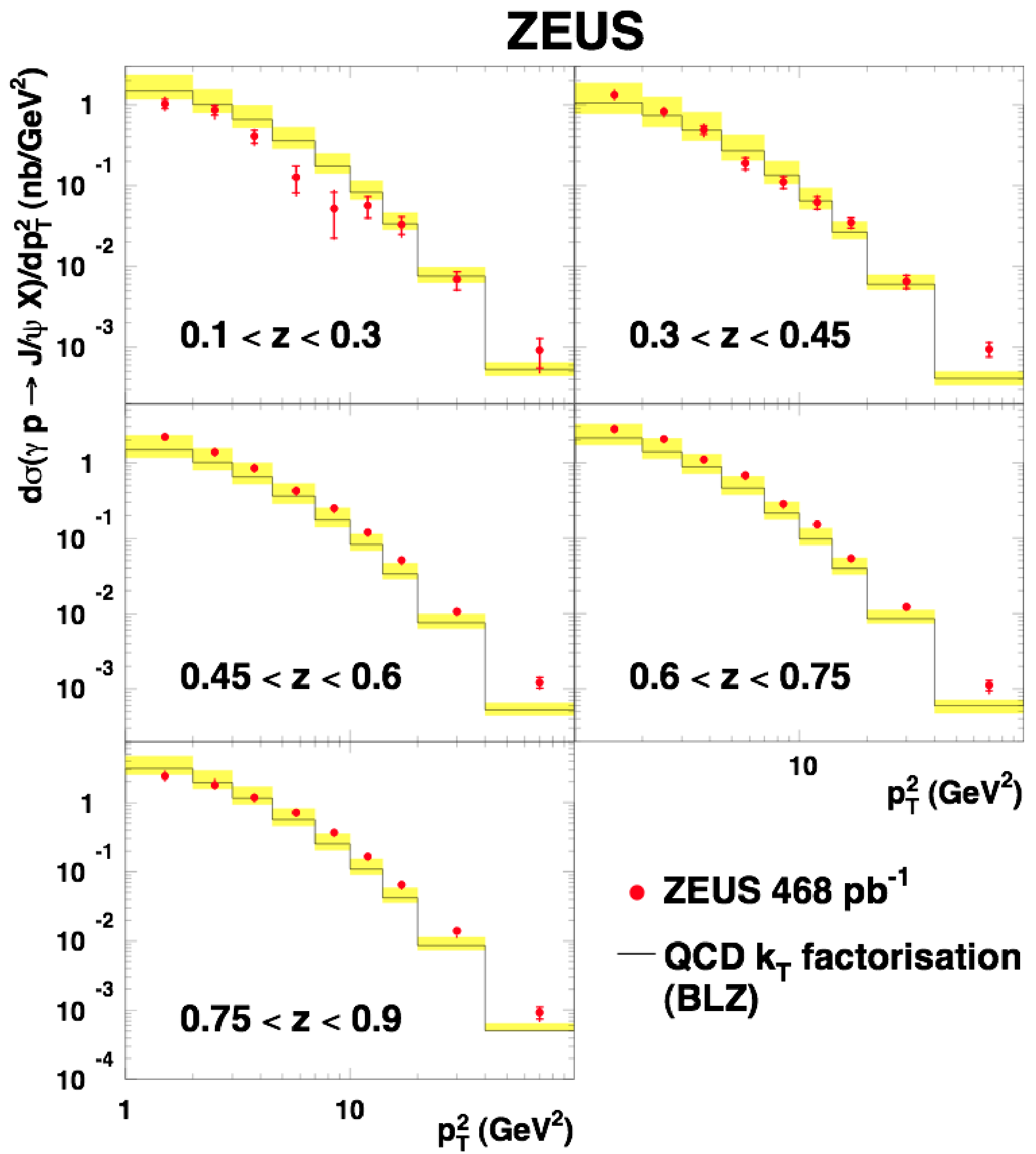
- Experimental error dominated by statistical error, systematic errors mainly cancel.
- Underlying production mechanism identical for Ψ' to J/Ψ → expect no dependencies on kinematic variables.
- Expectation for in CS model: 0.25 (horizontal line)
- Reasonably well agreement is observed.

Double differential cross sections compared to NRQCD prediction



- High precision of the data.
- NRQCD-NLO calculation within the large errors roughly describes the data.
- CO contribution is essential.

Comparison to k_T-factorization prediction



- LO k_T-factorization prediction based on:
  - CCFM evolution → gluons with non-zero p_T.
  - CS matrix elements.
- Good description of the data within large normalization uncertainties

Summary and Conclusions

- Differential cross sections have been measured for elastic and proton dissociative J/ψ photoproduction:
  - as a functions of t and $W_{\gamma p}$ and analyzed in phenomenological fits.
  - The proton dissociative cross section is measured precisely at small |t| for the first time at HERA.
  - The ratio of the elastic to proton dissociative cross section is approximately unity, but slightly falls with $W_{\gamma p}$.
  - The elastic J/ψ data has sensitivity to the gluon density at low x.

- Differential cross sections have been measured for inelastic J/ψ photoproduction:
  - as functions of p_T^2 and z.
  - Ratios of ψ' to J/ψ are measured.
  - The results are compared to NLO CS+CO calculations and to a LO CS model in the k_T factorization framework.

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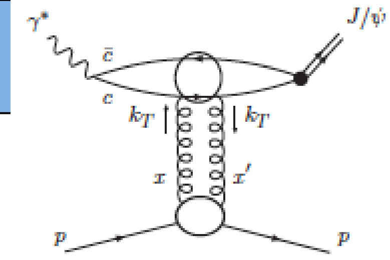
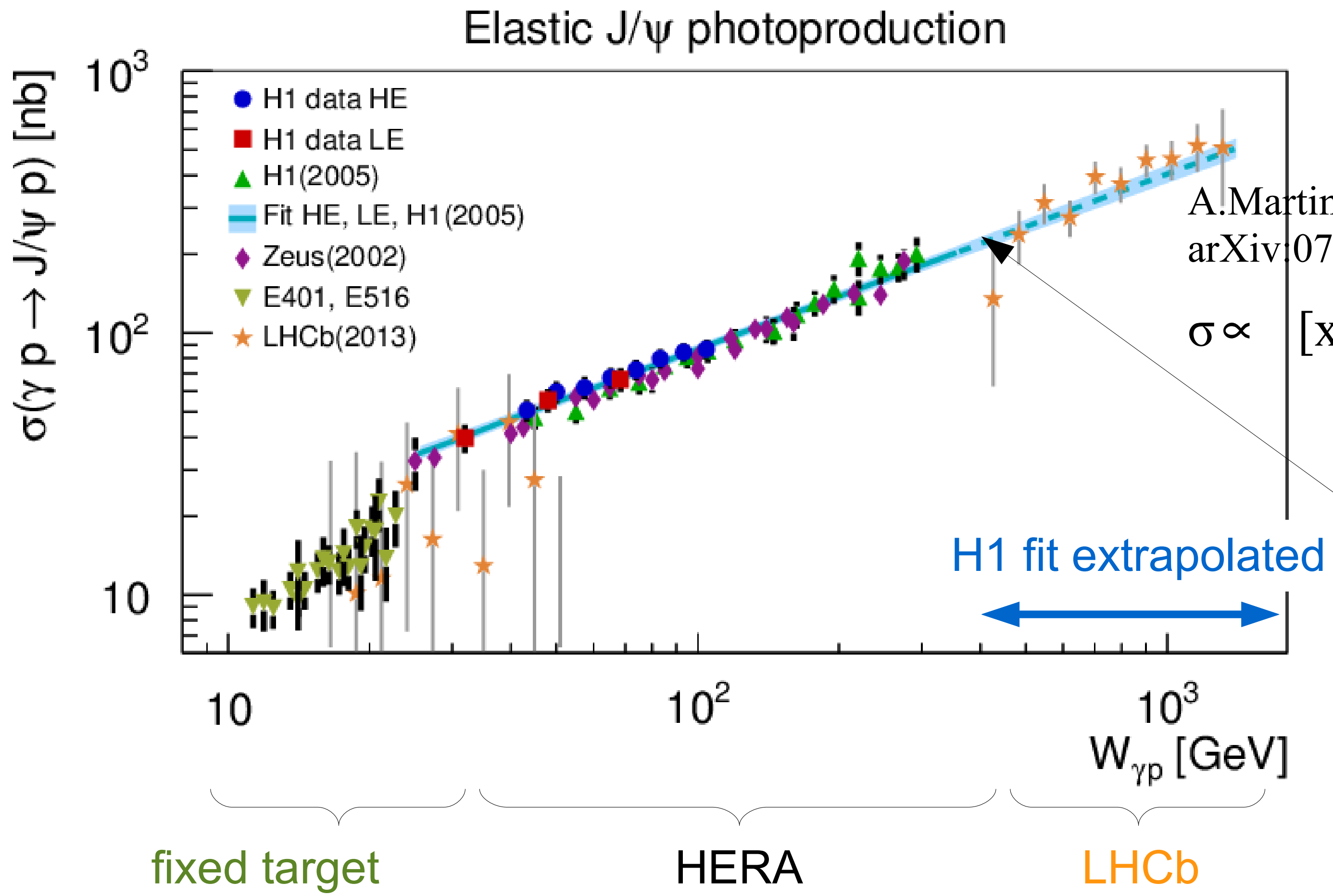
Sensitivity to the gluon density





A.Martin et al., arXiv:0709.4406:

$\sigma \propto \; [x^*g(x,\mu^2)]^2$

H1 fit:

$\sigma = N\,(W_{\gamma p} / W_0)^\delta$

with W_0 = 90GeV

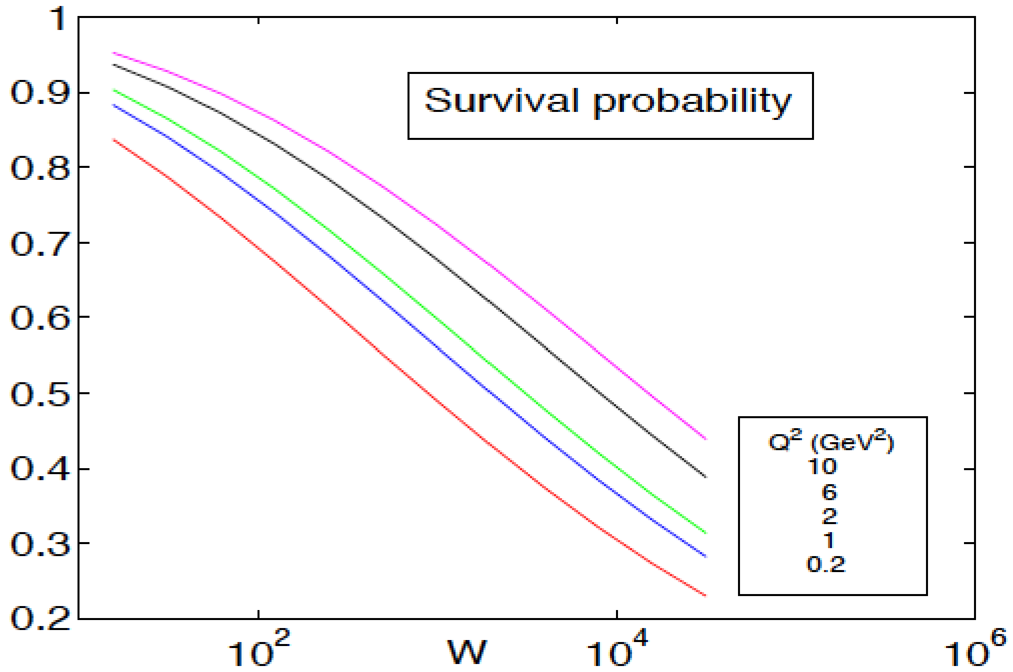
- Following A. Martin et al., δ can be related to a LO gluon density as $x^*g(x,\mu^2)=N^*x^{-\lambda}$ via $\delta \approx 4^*\lambda$, $\mu^2=(Q^2+M_{J/\psi}{}^2)/4$, $W_{\gamma p} \propto \; 1/\sqrt{x}$.
- λ from this fit $\lambda_{J/\psi}(\mu^2=2.4\text{GeV}^2)=0.168\pm0.008$ agrees to previous fits to inclusive DIS data $\lambda_{J/\psi}(Q^2=2.5\text{GeV}^2)=0.166\pm0.006$.

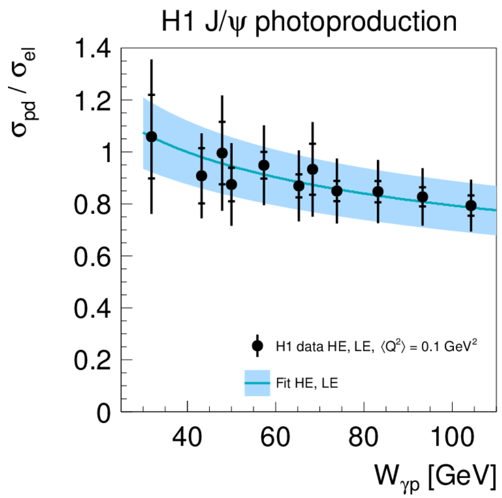
DESY-08-171, arXiv:0904.0929

Falling ratio of p-diss. over elas cross section predicted?

E. Gotsman, A. Kormilitzin, E. Levin, U. Maor (Tel Aviv Un.), "Survival probability for high mass diffraction", arXiv:hep-ph/0702053

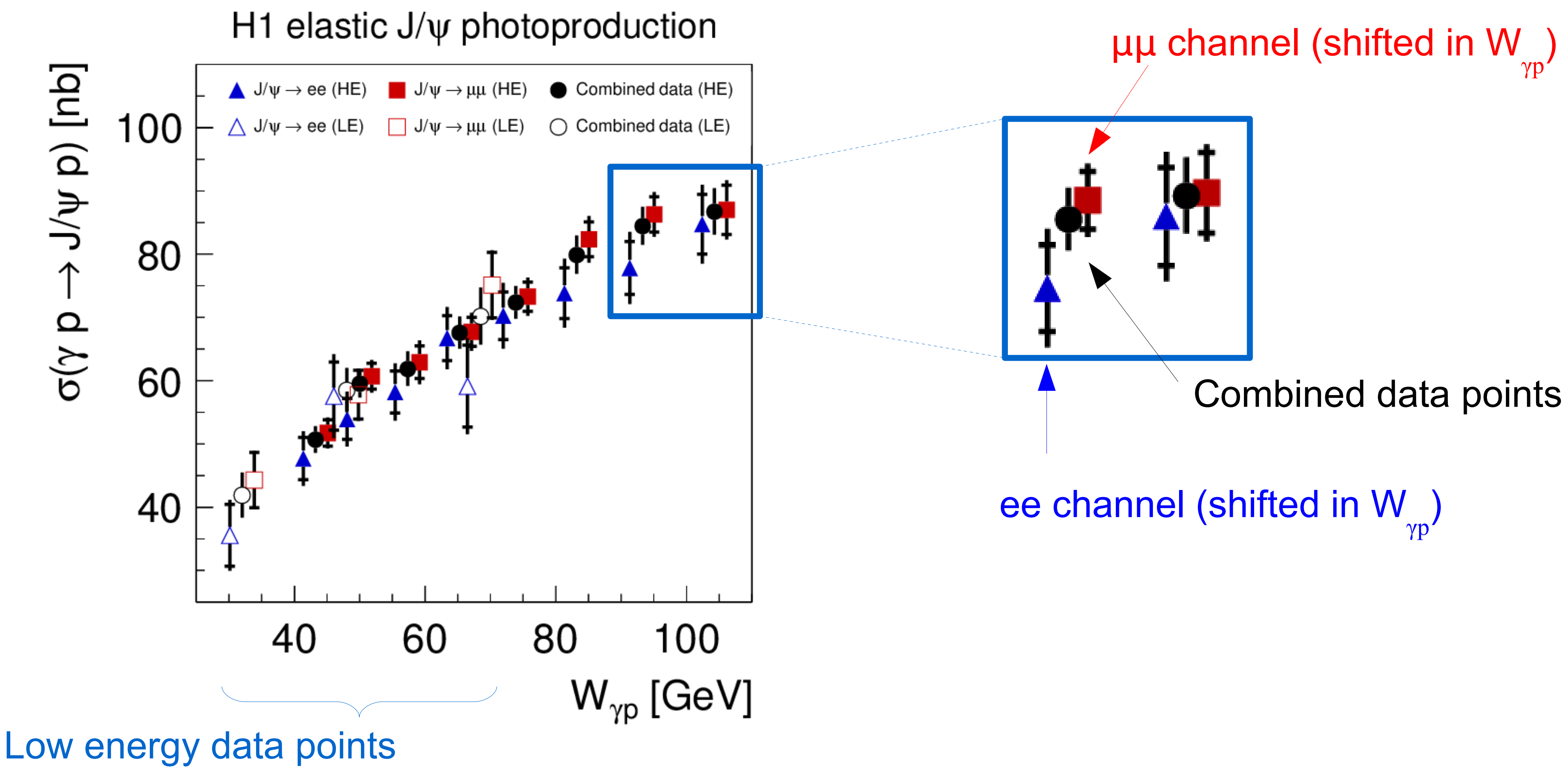
A large rapidity gap (LRG) process is defined as one where no hadrons are produced in a sufficiently large rapidity interval. Diffractive LRG are assumed to be produced by the exchange of a color singlet object with quantum numbers of the vacuum, which we will refer to as the Pomeron. We wish to estimate the probability that a LRG, which occurs in diffractive events, survives rescattering effects which populate the gap with secondary particles coming from the underlying event.



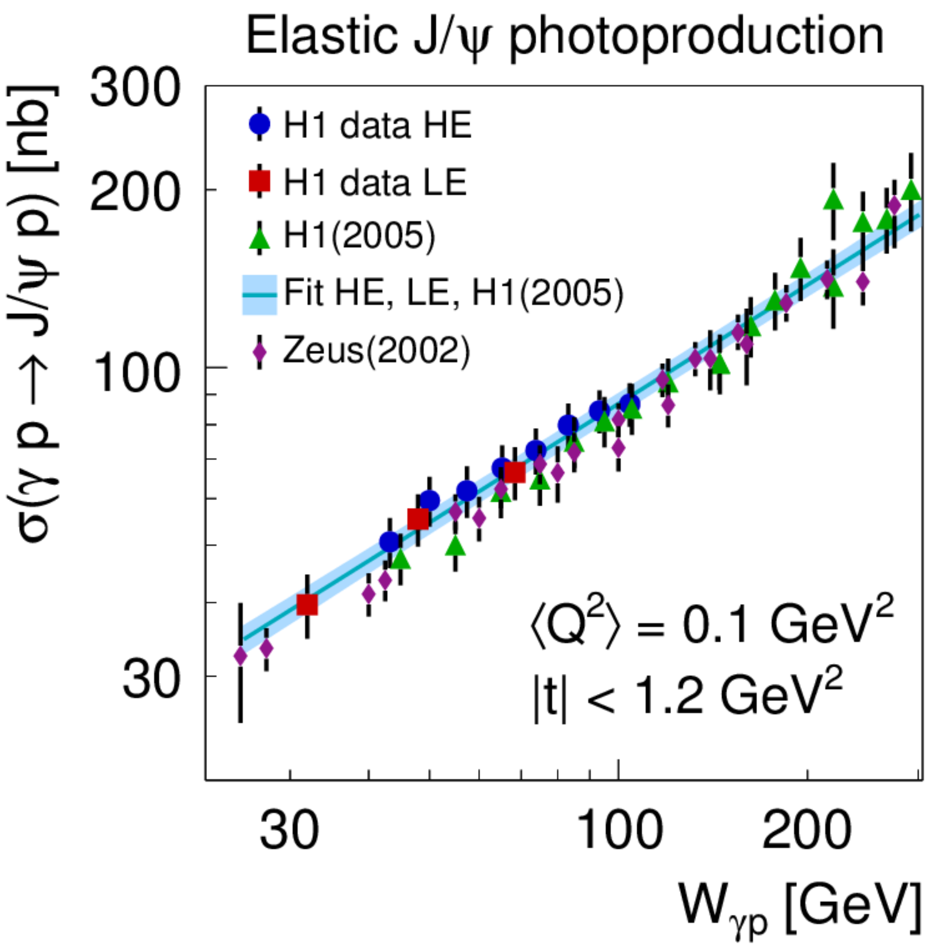


Combination of e^+e^- and $\mu^+\mu^-$ decay channels

- Done by minimizing a χ^2 function taking into account:
  - Full statistical error matrix from unfolding procedure
  - Common systematic errors
- Leads to reduced errors.
- Separately done for cross sections as a functions of t and $W_{\gamma p}$.



Comparison to previous H1 and ZEUS data

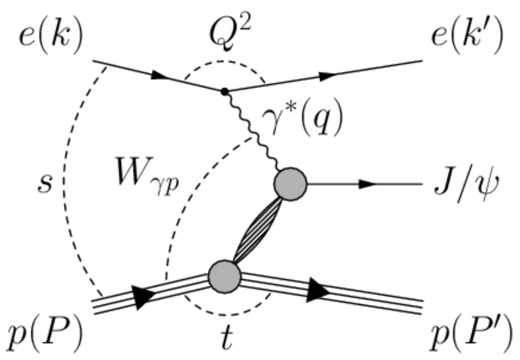


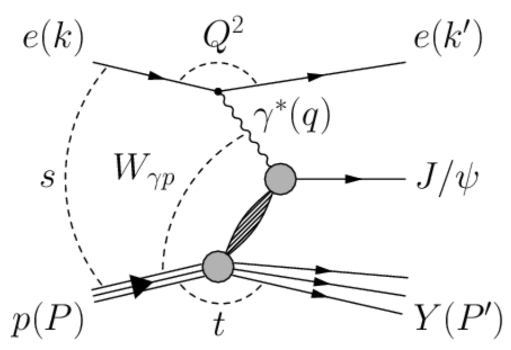
- Large overlap with previous H1 and ZEUS measurements.
- Similar precision in the range $30 < W_{\gamma p} < 110$ GeV. (Normalization uncertainties of ~5% are not shown).
- Good agreement of HERA measurements.

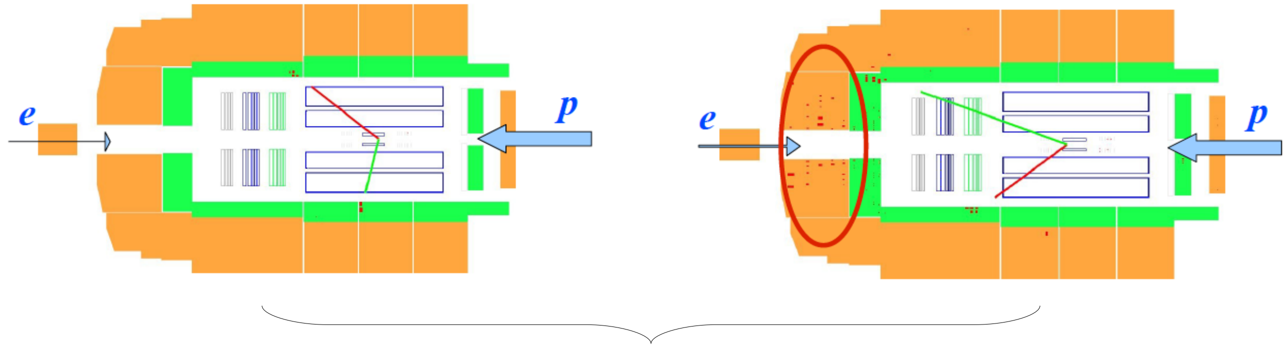
Elastic and proton dissociative J/ψ production

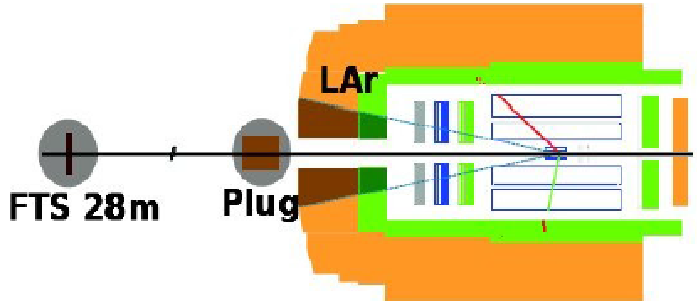
- Elastic
  $M_Y = m_p$

- p-diss.
  $m_p < M_Y < 10$ GeV









Experimental tagging of p-diss.:

- High |t| → tag
- Use forward detectors (FTS, Plug, LAr) for low |t| values.

Regularised unfolding of elastic and proton dissociative cross sections

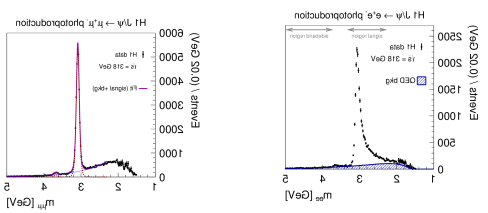
- Event-by-event distinction of the elastic and proton dissociative process is not possible, unfolded on statistical basis.
- Done by solving the matrix equation **y = A x** with a smoothness constraint.

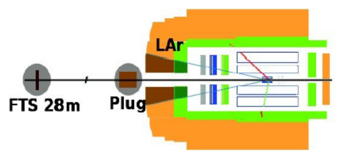
$$y = A\,x$$

Input:

Measured number of events in bins of:

- $t_{rec} = -p_{T,J/\psi}^{2}$, $W_{\gamma p\ rec} = s\,(E_{J/\psi} - p_{z,J/\psi}) / 2E_e$
- tagged and non-tagged

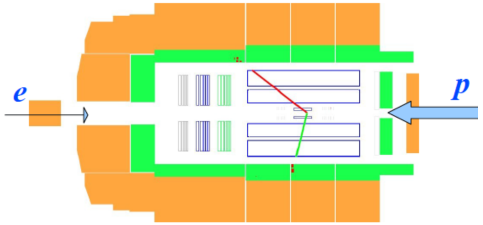




Response matrix:

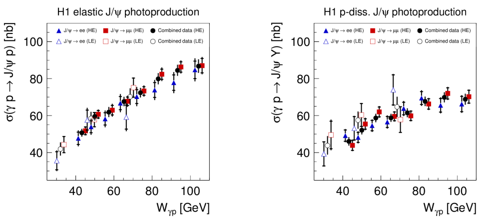
Calculated from simulation:

- physics model ⊗ detector simulation (based on GEANT)

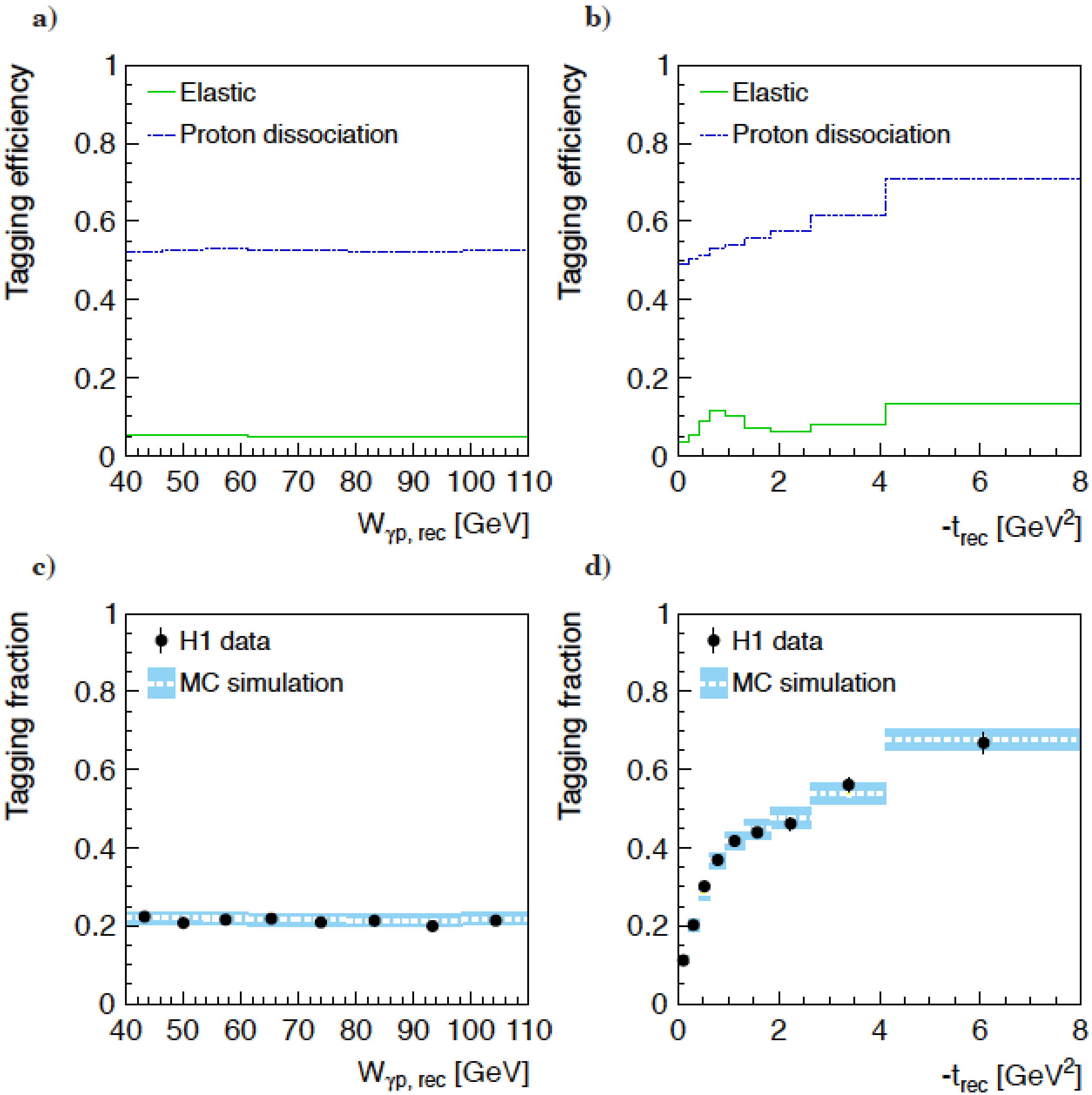


Output:

Elastic and proton dissociative cross sections



Tagging efficiency and fractions



Control distributions.