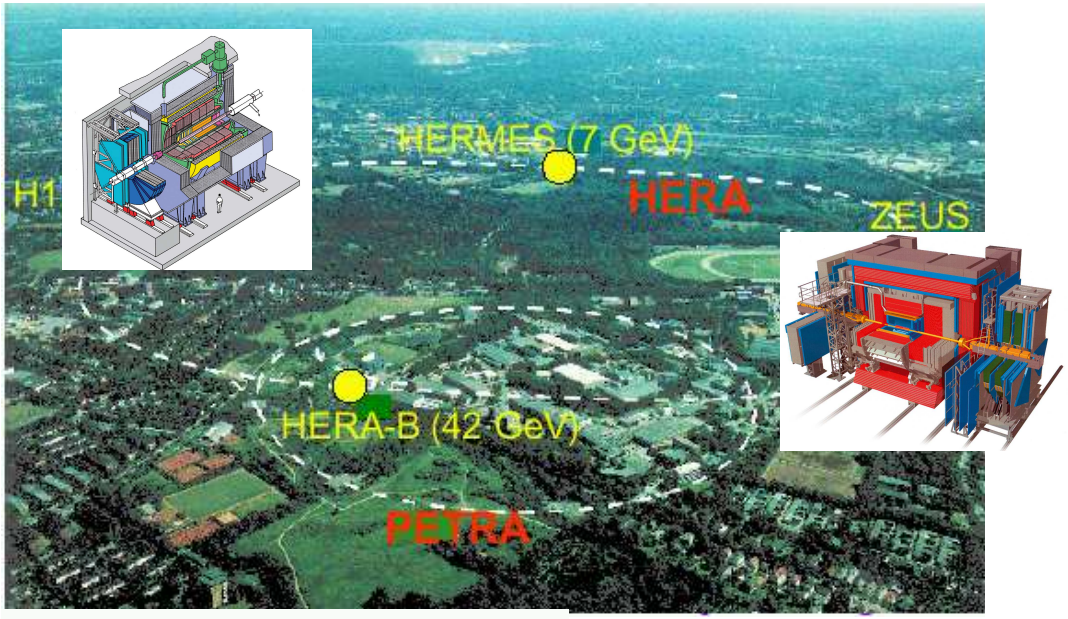
11-15 October 2021, LIP Lisbon

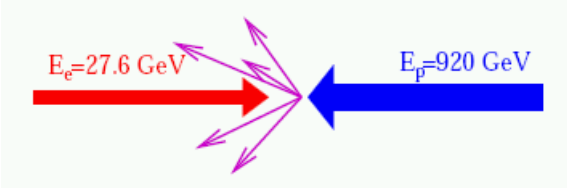
Exclusive $\pi^+\pi^-$ and ρ^0 Photoproduction at HERA

Sergey Levonian, DESY

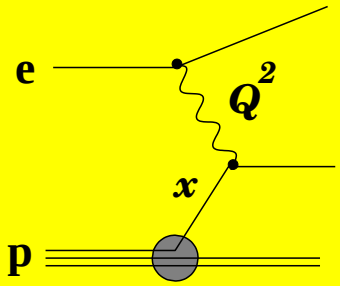
for the H1 Collaboration

HERA: The World's Only ep Collider





$(\sqrt{s} = 319\ \text{GeV})$



$Q^2 > 1\ \text{GeV}^2$

Deep Inelastic Scattering (DIS)

$Q^2 \approx 0\ \text{GeV}^2$

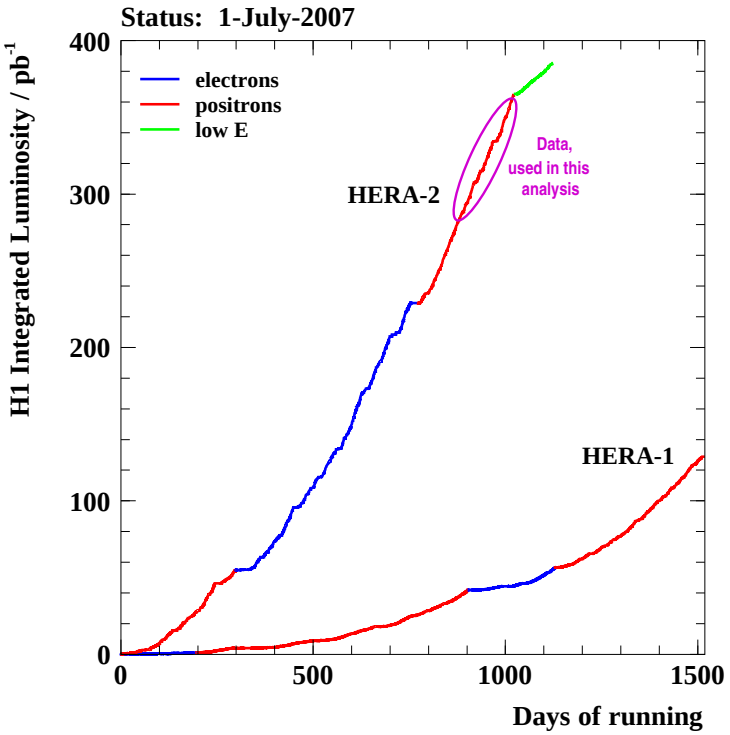
Photoproduction (PHP)

HERA-1 (1993-2000) $\simeq 120\ \text{pb}^{-1}$

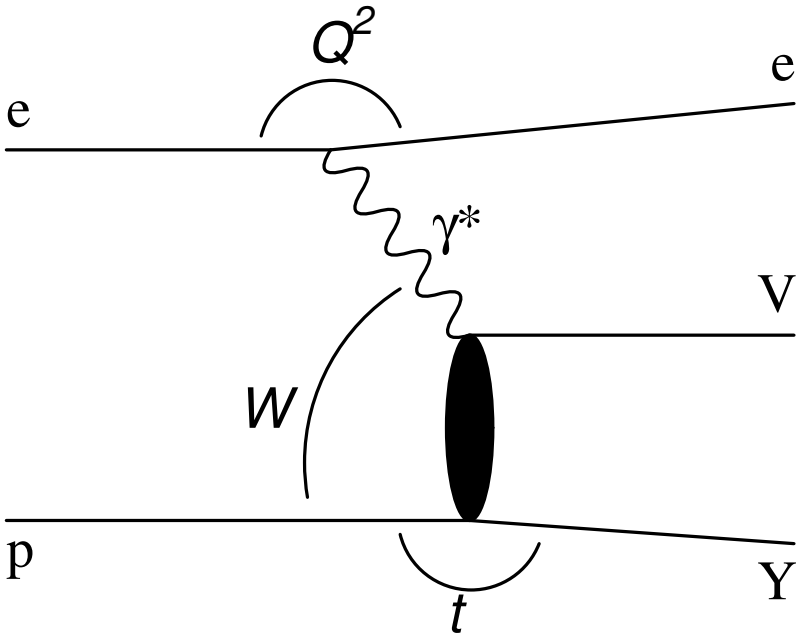
HERA-2 (2003-2007) $\simeq 380\ \text{pb}^{-1}$

Final Data samples

H1+ZEUS: $2 \times 0.5\ \text{fb}^{-1}$



VM Measurements Landscape at HERA



$= \rho, \omega, \phi, J/\psi, \Upsilon, ...$

Covered PS at HERA

$0 < Q^2 < 100\ \mathrm{GeV}^2$

$20 < W < 305\ \mathrm{GeV}$

$0 < |t| < 30\ \mathrm{GeV}^2$

Hard scale can be provided by Q^2 and M_V^2 (at γ^* vertex) or/and by $|t|$ (at p vertex)

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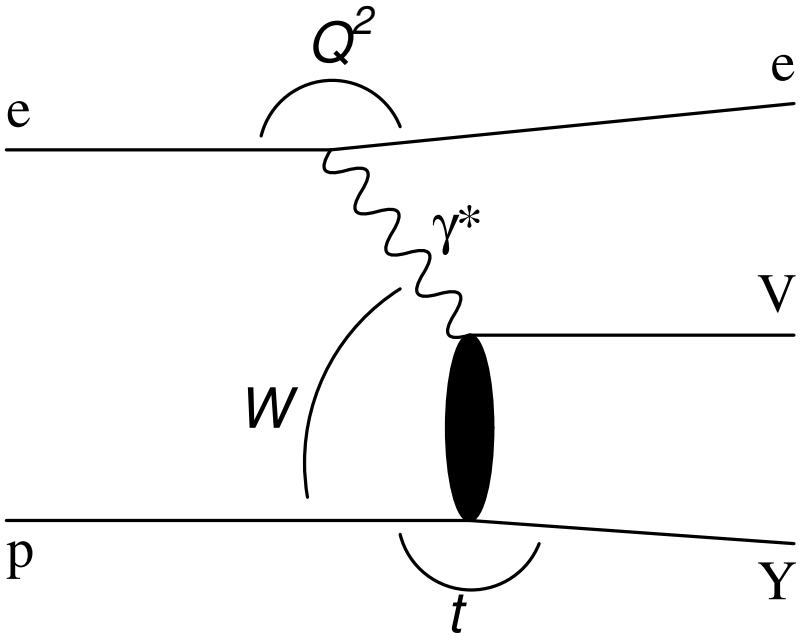

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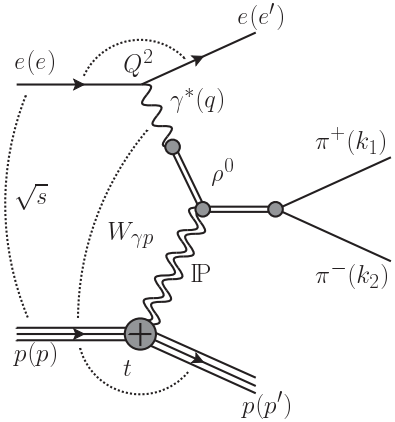
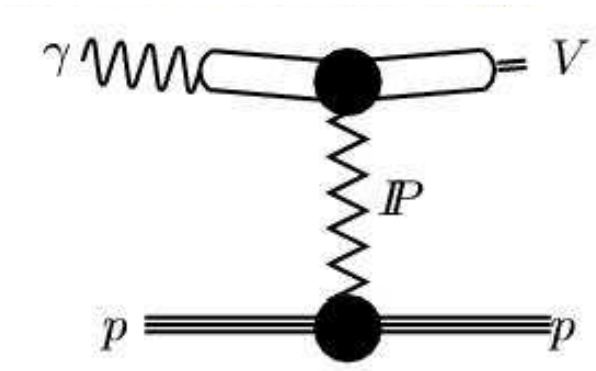
- H1 and ZEUS published in total ~ 40 papers on VM topics.
- In this talk most recent publication of H1 collaboration is presented: *Eur.Phys.J.C80 (2020), 1189* ([arXiv:2005.14471]).

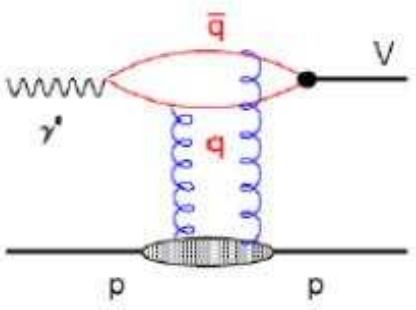


Modelling VM Production at HERA

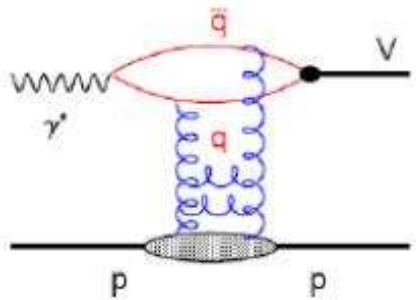
No hard scale present



Hard scale(s) present



LO 2 gluons



LL1/x ladder

VDM ⊕ Regge

CD picture ($\sigma \propto \Psi_{\gamma^* \to q\bar{q}} \cdot \sigma_{(q\bar{q})p} \cdot \Psi_{q\bar{q} \to V}$)

soft $I\!P$omeron exchange

$\alpha_{I\!P}(0)=1.08;\ \alpha'_{I\!P}=0.25$

$\sigma \propto W^{4(\alpha_{I\!P}-1)}$

$(\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} t)$

hard $I\!P$omeron diagrams

$\alpha_{I\!P}(0) \simeq 1.20;\ \alpha'_{I\!P} \simeq 0$

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

Questions of interest

- γp vs hh - is $I\!P$ trajectory universal?
- Is $I\!P$ trajectory indeed linear?
- Transition to hard regime: when and how?
- Direct access to (low x) gluons
- DGLAP vs BFKL evolution
- Confront $\sigma_{(q\bar{q})p}$ models with data

$\Rightarrow$ Pomeron and QCD vacuum structure

H1 Detector

- Central Tracker: drift chambers and two-layer silicon strip detector

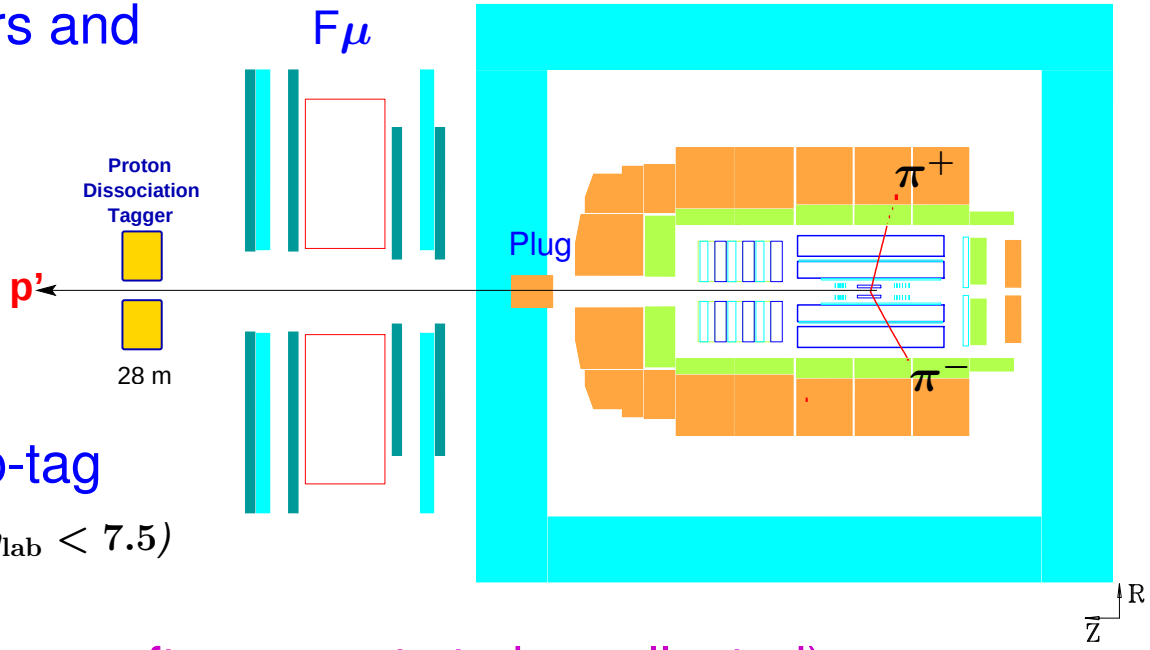
  ($20^\circ < \theta < 160^\circ$ used in VM analyses)

- EM+Had Calorimeters

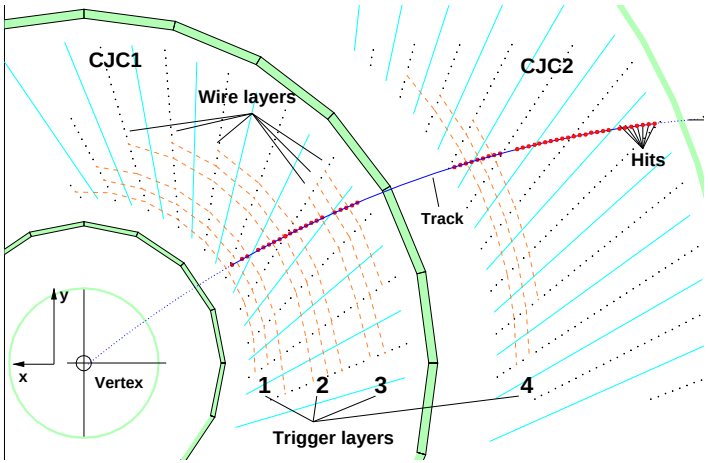
  ($4^\circ < \theta < 178^\circ$)

- Forward Detectors: Fμ,Plug,p-tag

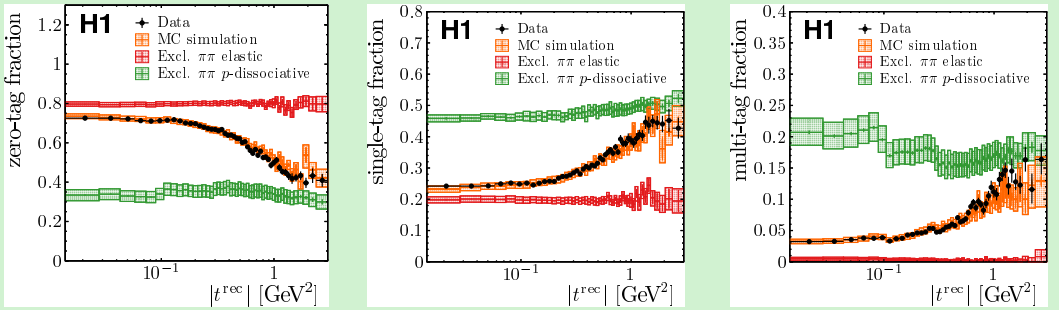
  (effective pseudorapidity coverage $3.5 < \eta_{\rm lab} < 7.5$)



Powerful fast track trigger (allows soft γp events to be collected)



Separation of EL and PD events using Fwd tagging



Data Sample and MC modelling

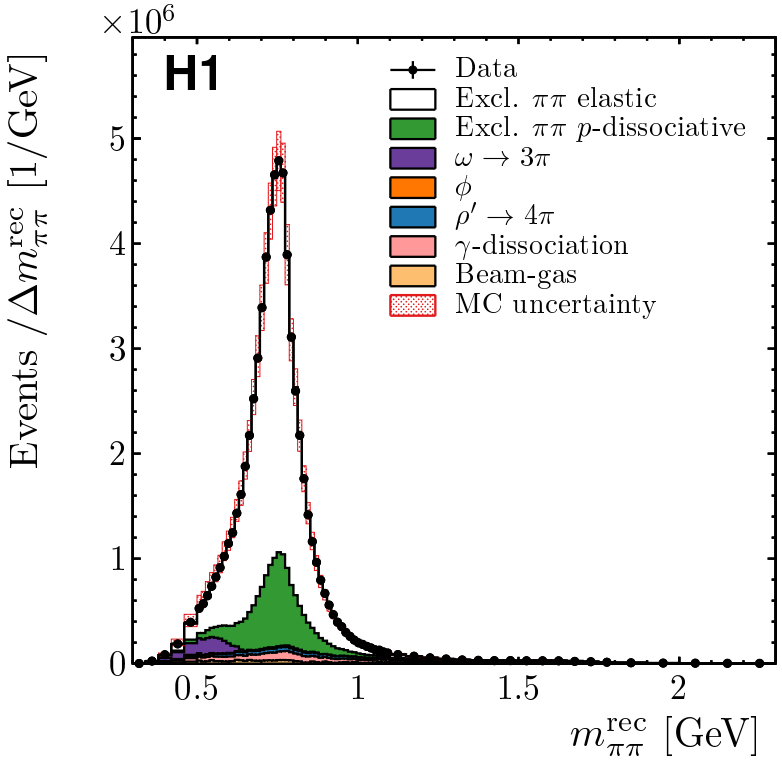
$15\ \text{GeV} < W_{\gamma p} < 90\ \text{GeV}$

$0.3\ \text{GeV} < m_{\pi\pi} < 2.3\ \text{GeV}$

$p^2_{t,\pi\pi} \simeq |t| < 3\ \text{GeV}^2$

$Q^2 < 2.5\ \text{GeV}^2; \quad M_Y < 10\ \text{GeV}$

$\mathcal{L} = 1.3\ \text{pb}^{-1} \quad \sim 944,000$ events



DiffVM MC (Regge + VDM)

- **$\pi^+\pi^-$ signal:** elastic and p-dissociative

  tuned to data in $W_{\gamma p}$, $m_{\pi\pi}$, t

  includes also $\omega \to \pi^+\pi^-$ and non-resonant $\pi^+\pi^-$ contributions

- **backgrounds:**

  $\omega \to \pi^+\pi^-\pi^0$

  $\phi \to K^+K^-,\ K_SK_L,\ \pi^+\pi^-\pi^0,\ \rho\pi,\ \eta\gamma$

  $\rho' \to \rho\pi\pi,\ 4\pi$

  γ-dissociation: $M_X \to$hadrons via Jetset

- **proton dissociation:**

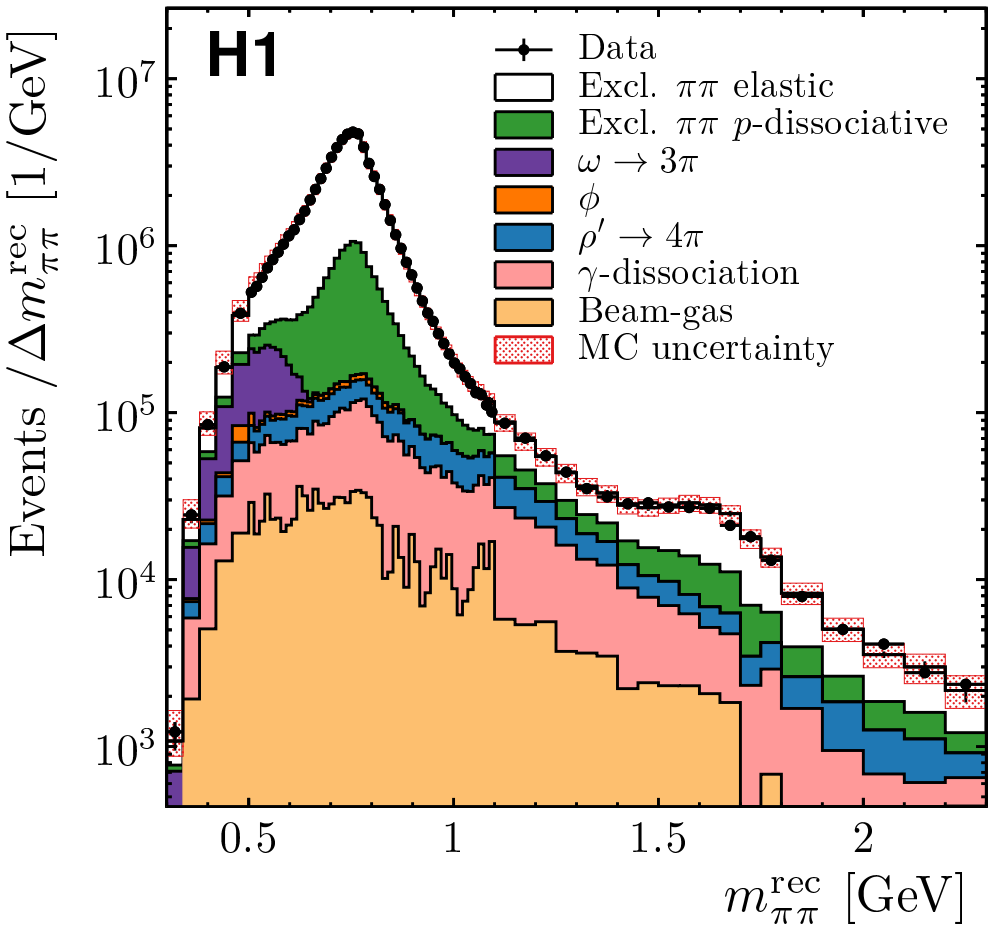
  continuum & resonances; $\mathrm{d}\sigma_{\gamma p}/\mathrm{d}M_Y^2 \propto (1/M_Y^2)^\delta$

  $M_Y < 1.9$ GeV: $N^\star$ with measured decay channels

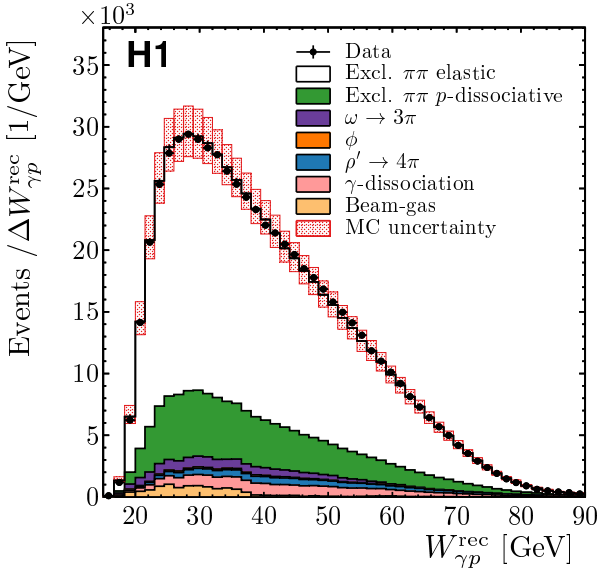
  $M_Y > 1.9$ GeV: $p' \to$hadrons via Jetset

Control Plots

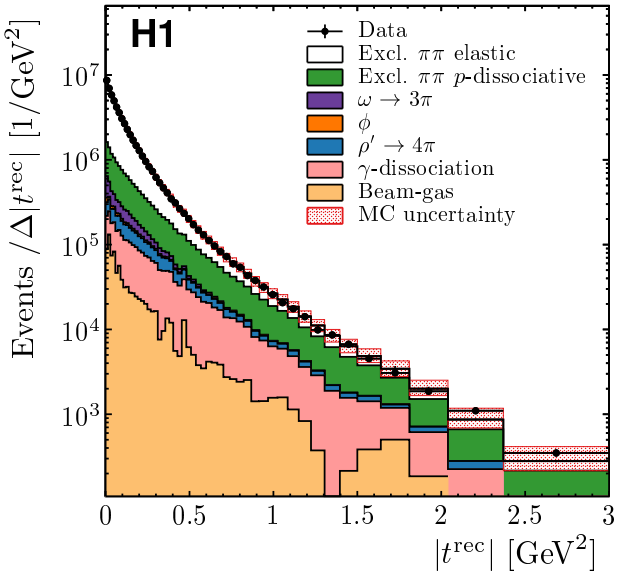
$m_{\pi\pi}$



$W_{\gamma p}$



t



Good description in all variables

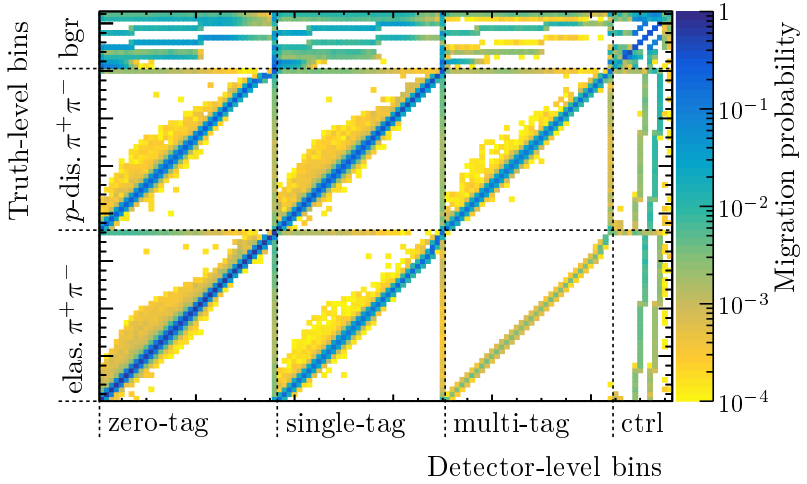
$\pi^+\pi^-$ Cross Section Determination

Analysis phase space	Fiducial measurement phase space
$15.0 < W_{\gamma p} < 90.0$ GeV	$20.0 < W_{\gamma p} < 80.0$ GeV
$\lvert t\rvert < 3.0$ GeV^2	$\lvert t\rvert < 1.5$ GeV^2
$0.3 < m_{\pi\pi} < 2.3$ GeV	$0.5 < m_{\pi\pi} < 2.2$ GeV
$Q^2 < 2.5$ GeV^2	$Q^2 < 2.5$ GeV^2
$m_Y < 10.0$ GeV	elastic: $m_Y = m_p$
	p-dissociative: $m_p < m_Y < 10.0$ GeV

Unfolding particle level cross sections:

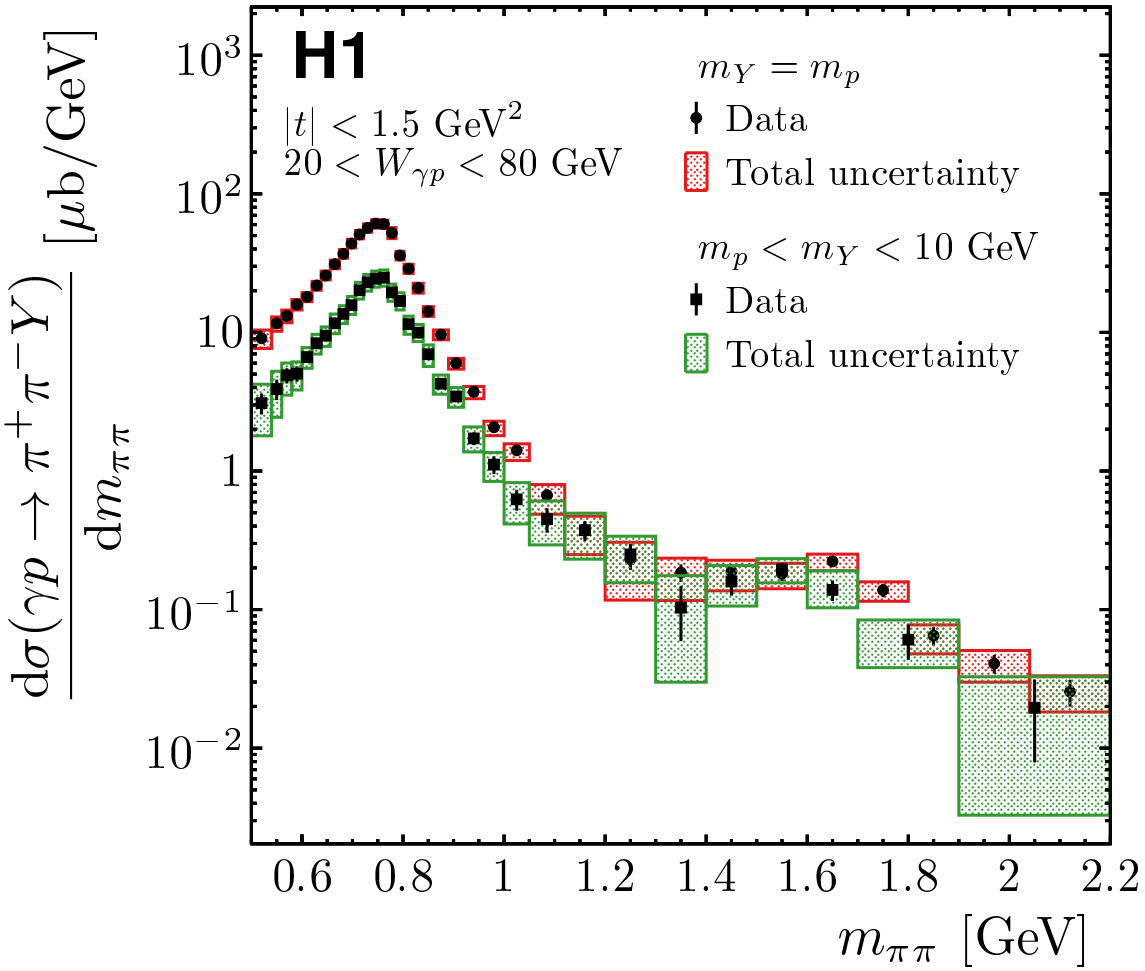
- subtract backgrounds
- correct signal for detector efficiency and resolution
- separate elastic from p-dissociative contributions

Regularised template fit using *TUnfold* package



$$\frac{\mathrm{d}^2\sigma(\gamma p\to\pi^+\pi^- Y)}{\mathrm{d}m_{\pi\pi}\mathrm{d}t}(m_{\pi\pi}, t; W_{\gamma p}) = \frac{N^Y_{\text{unfolded}}}{\Delta t \Delta m_{\pi\pi}\cdot\mathcal{L}\cdot\Phi_{\gamma/e}(W_{\gamma p})}$$

$\mathrm{d}\sigma(\gamma p \to \pi^+\pi^- Y)/\mathrm{d}m_{\pi\pi}$



Unfolded 1-D $m_{\pi\pi}$ distribution

Fiducial Cross sections

$$\sigma(\gamma p \to \pi^+\pi^- p) =$$
$$11.52 \pm 0.06(\text{stat.})^{+0.76}_{-0.78}(\text{syst.})\,\mu\text{b}$$

$$\sigma(\gamma p \to \pi^+\pi^- Y) =$$
$$4.68 \pm 0.06(\text{stat.})^{+0.62}_{-0.64}(\text{syst.})\,\mu\text{b}$$

Main sources of syst. uncertainty:

- trigger
- forward tagging
- calorimeter

$\Rightarrow$ Fit mass distribution around ρ^0 with Söding-like model

Extracting ρ^0 Cross Section

$$\frac{d\sigma_{\pi^+\pi^-}}{dm_{\pi\pi}}(m_{\pi\pi}) = \frac{N}{(1+f_\omega+f_{nr})^2}\cdot\left|\mathcal{RBW}_\rho(m_{\pi\pi}) + f_\omega e^{i\phi_\omega}\mathcal{RBW}_\omega(m_{\pi\pi}) + f_{nr}e^{i\phi_{nr}}\frac{B_{nr}(m_{\pi\pi})}{B_{nr}(m_\rho)}\right|^2$$

Fitted parameters:

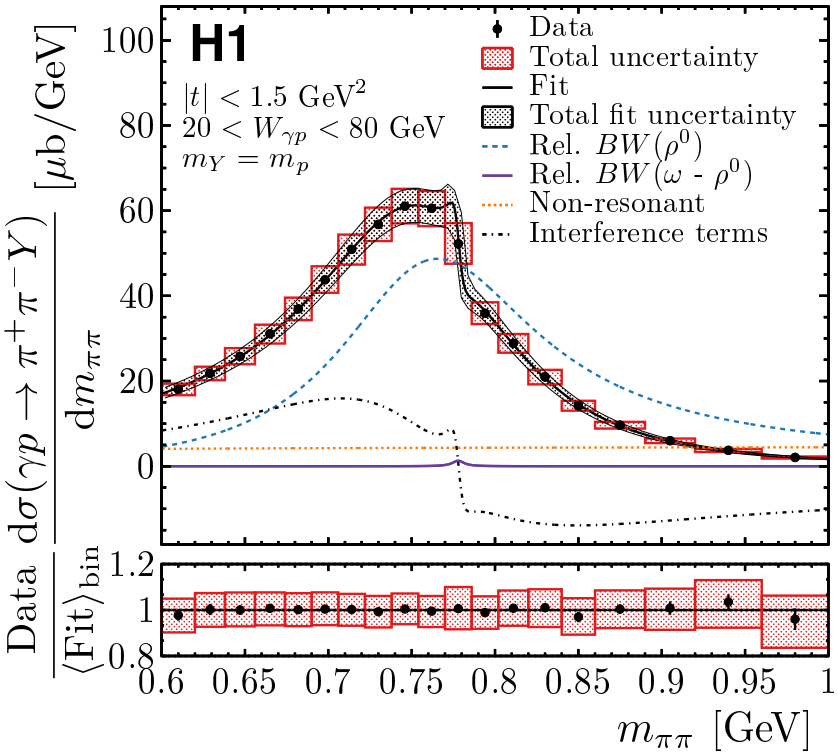
$m_{\rho^0} = 770.8 \pm 2.6$ MeV

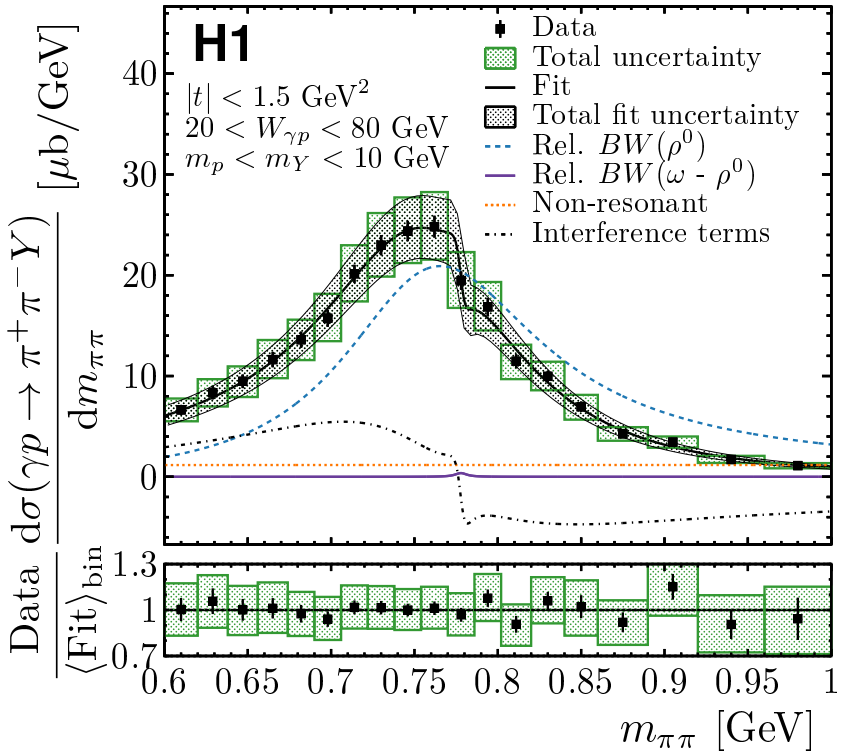
$\Gamma_{\rho^0} = 151.3 \pm 3.2$ MeV

$m_\omega = 777.9 \pm 4.0$ MeV

non-res term: $B_{nr} = \left(\frac{m_{\pi\pi}-2m_\pi}{(m_{\pi\pi}-2m_\pi)^2+\Lambda_{nr}^2}\right)^{\delta_{nr}}$

$\chi^2/\mathrm{n_{dof}} = 24.6/24$

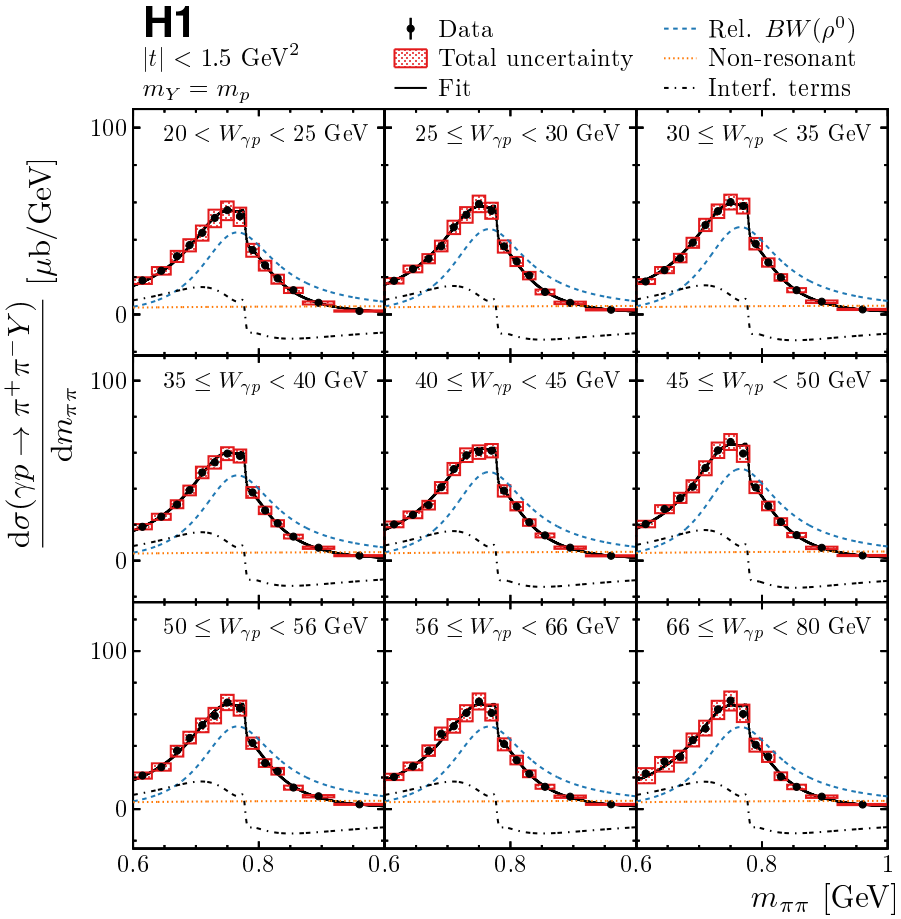


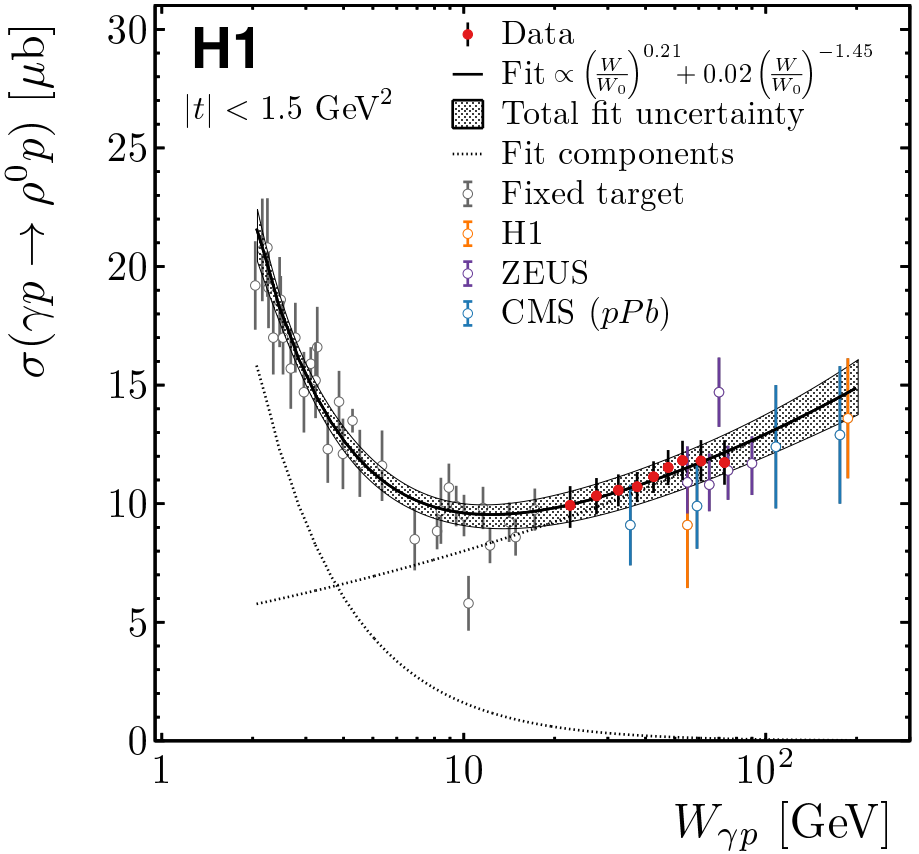


W dependence of elastic ρ^0 cross section

Unfolding 2-D distributions $W_{\gamma p}^{rec} \otimes m_{\pi\pi}^{rec}$

and fitting simultaneously in all $W_{\gamma p}$ bins

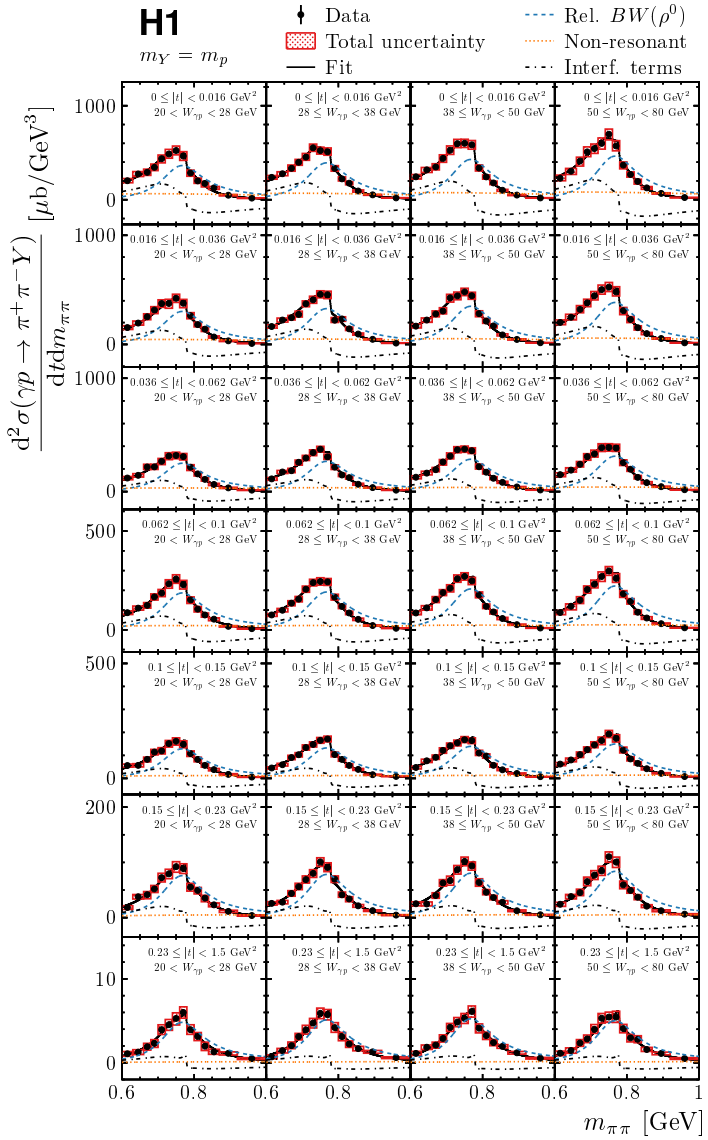




Regge-like fit yielding $\chi^2/n_{dof} = 84.3/43$

$\Rightarrow$ ‘Soft’ Pomeron at work

t dependence of elastic ρ^0 cross section

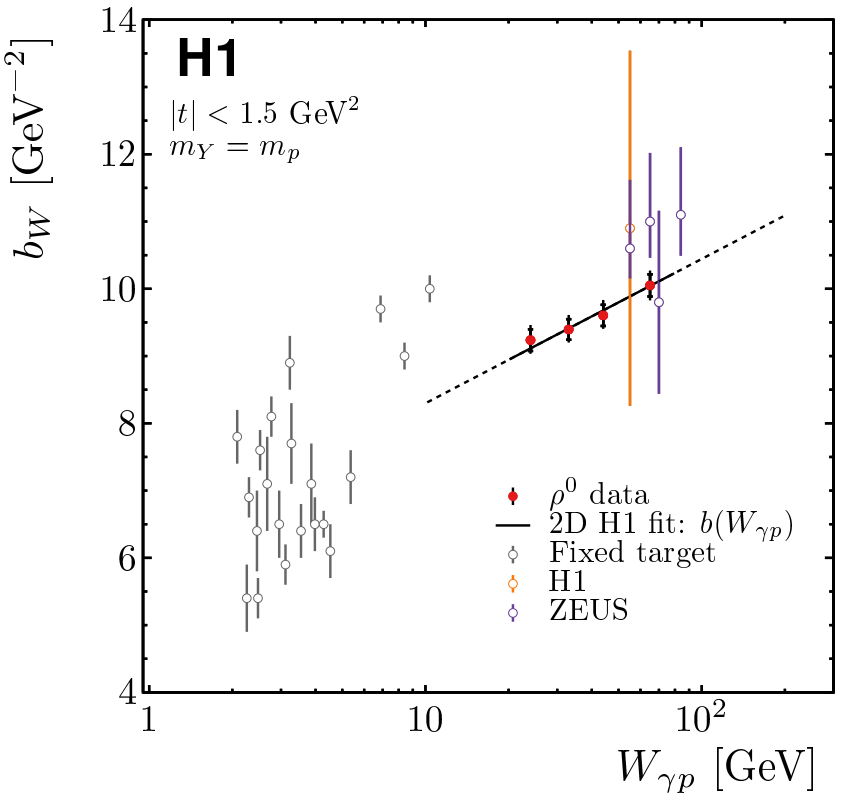


Unfolding 3-D distributions $t^{rec} \otimes W_{\gamma p}^{rec} \otimes m_{\pi\pi}^{rec}$

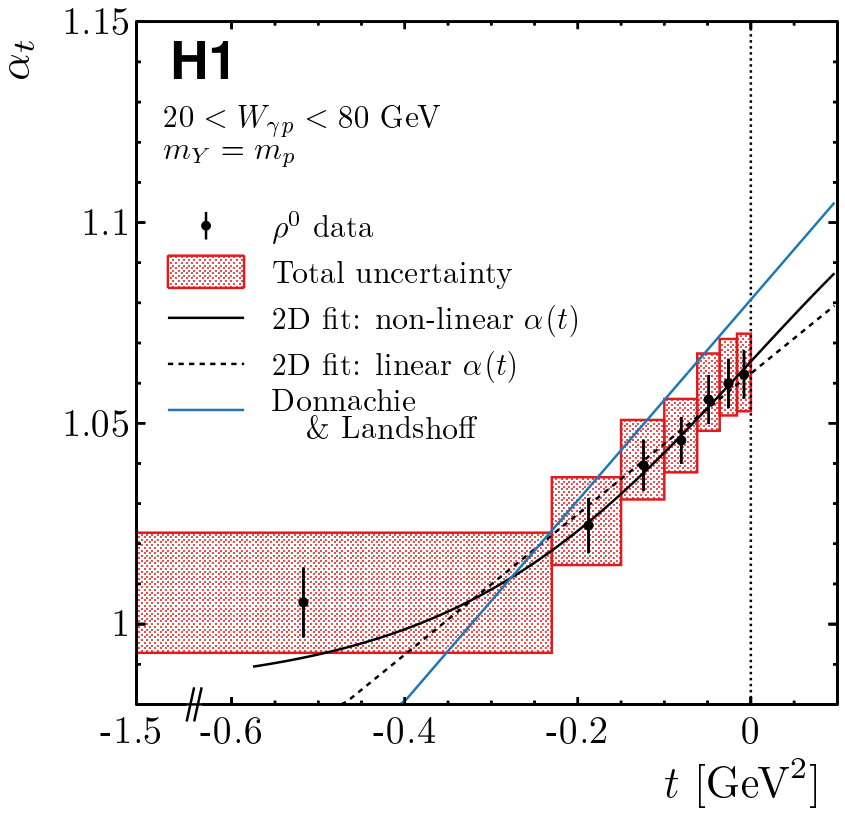
(the underlying response matrix has $1243_{\text{detector}} \times 882_{\text{truth}}$ bins)

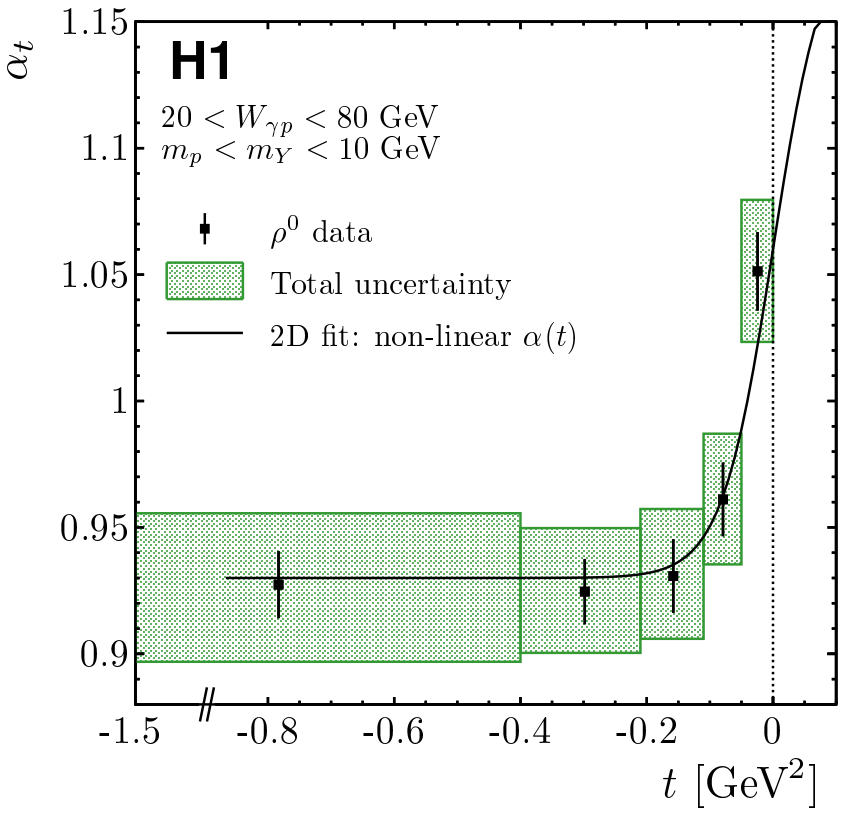
Simultaneous fit yields $\chi^2/n_{\text{dof}} = 804.0/607$

Shrinkage: $b_{el}(W_{\gamma p}) = b_{el}(W_0) + 4\alpha'_{I\!P} \log(W_{\gamma p}/W_0)$



Effective Pomeron trajectory





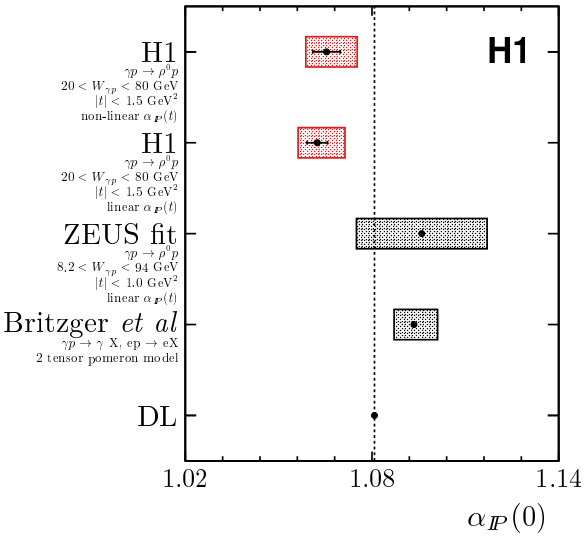
Points: $\alpha(t)$ as measured separately in each t bin by fitting a simple power law $\propto W_{\gamma p}^{4(\alpha_t-1)}$ with free fit parameters α_t

Curves: The trajectories extracted from a simultaneous 2D-fit to the $W_{\gamma p}$ and t dependencies (*see in the Appendix*).

$\Rightarrow$ Clear non-linearity at large $|t|$

Summary

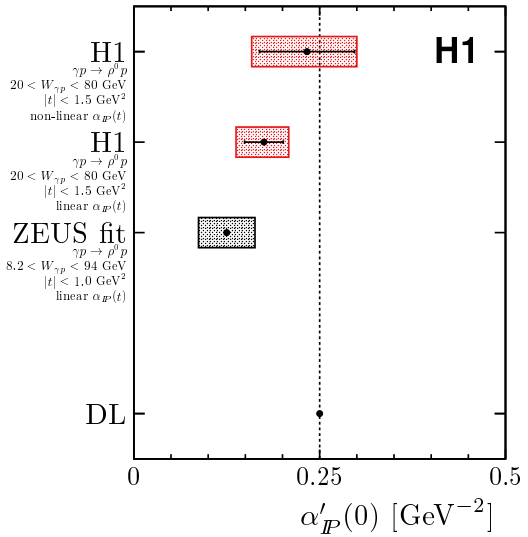
- Final and most precise measurement is presented of exclusive $\pi^+\pi^-$ photoproduction at HERA.
- ρ^0 cross sections and resonance parameters are determined both in elastic and proton-dissociative channels.
- In the context of Regge theory the effective Pomeron trajectory is extracted using linear and non-linear ansätze.



non-linear $\alpha_{I\!P}(t)$

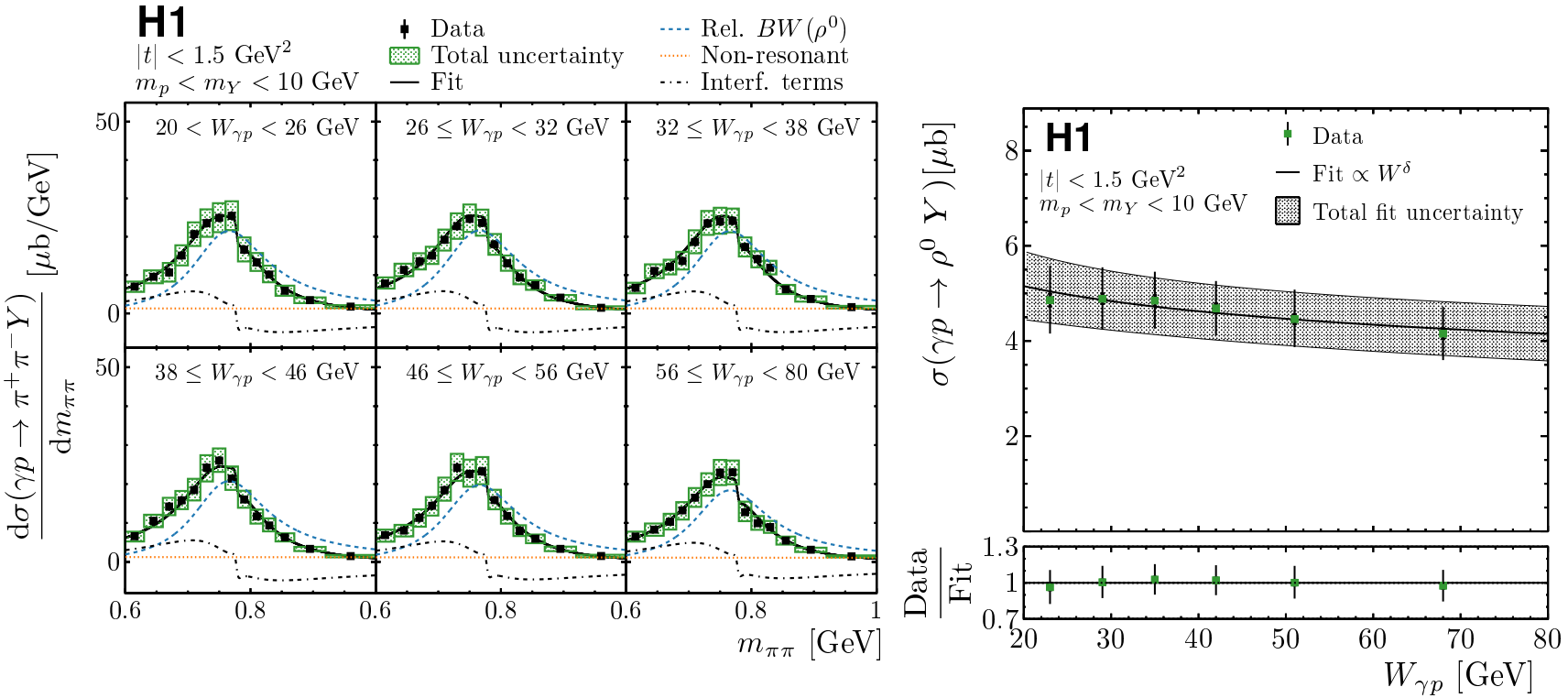
linear $\alpha_{I\!P}(t)$

$\sigma^{\mathrm{tot}}_{\gamma^* p}(W)$



Extra slides

W dependence of p-diss. ρ^0 cross section

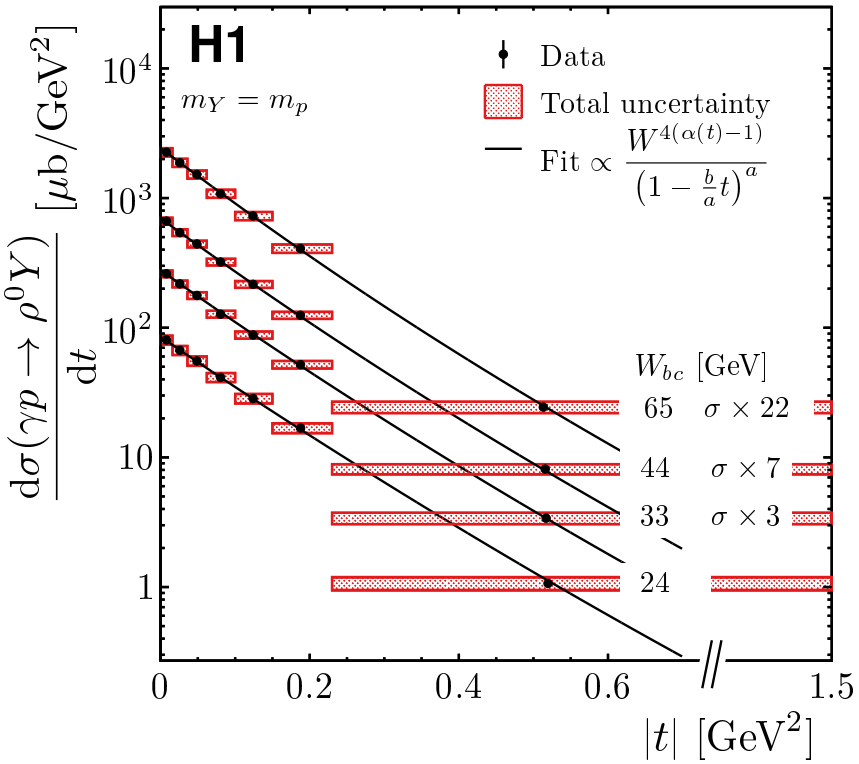


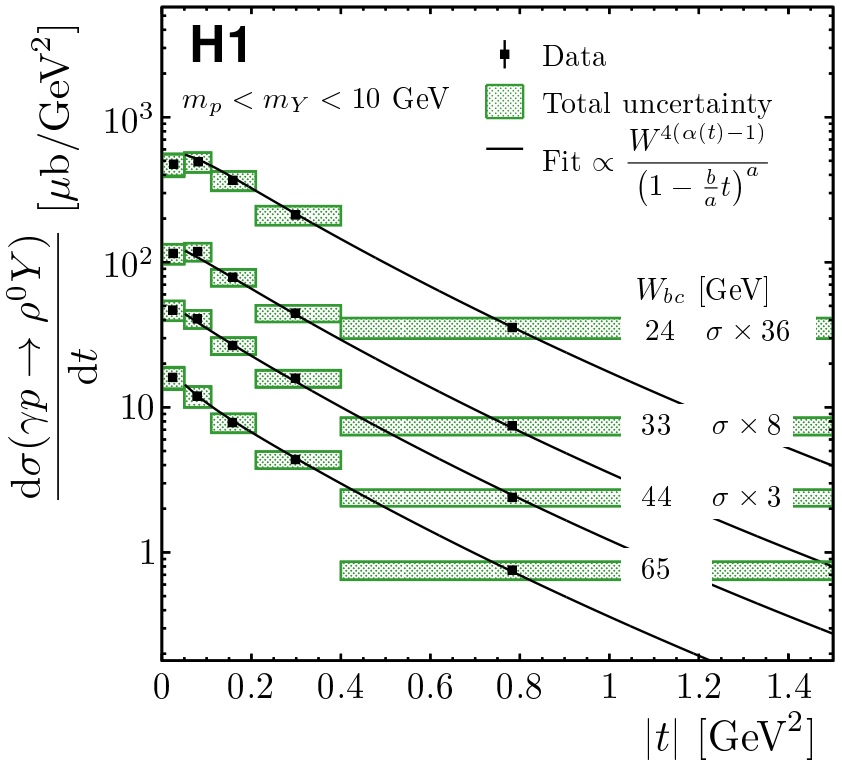
Extracted $W_{\gamma p}$ dependence is affected by Phase space cut $M_Y < 10$ GeV

Regge fit of the t and W dependence

$$\frac{\mathrm{d}\sigma_\rho}{\mathrm{d}t}(t; W_{\gamma p}) = \frac{\mathrm{d}\sigma_\rho}{\mathrm{d}t}(t; W_0)\left(\frac{W_{\gamma p}}{W_0}\right)^{4(\alpha(t)-1)} \qquad \frac{\mathrm{d}\sigma_\rho}{\mathrm{d}t}(t) = \frac{\mathrm{d}\sigma_\rho}{\mathrm{d}t}(0)\left(1-\frac{bt}{a}\right)^{-a} \quad \text{(at } W_0 = 40\text{GeV)}$$

$$\alpha(t) = \alpha_0 + \beta\left(\left(\exp -\frac{4\alpha_1 t}{\beta} + 1\right)^{-1} - \frac{1}{2}\right)$$





$$\chi^2_{\text{stat.}}/\text{n}_{\text{dof}} = 31.7/32$$