

NEW TRENDS in HIGH-ENERGY PHYSICS

(experiment, phenomenology, theory)

Odessa (Ukraine)

May 12–18, 2019



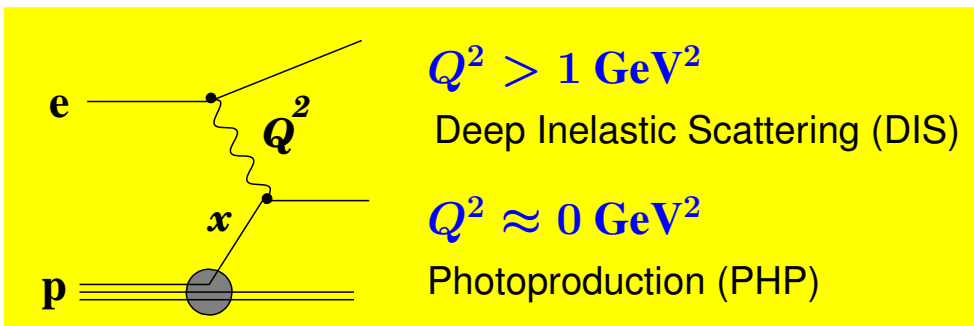
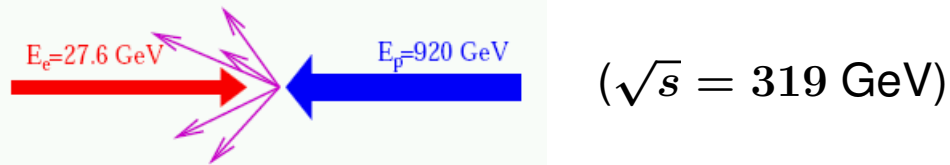
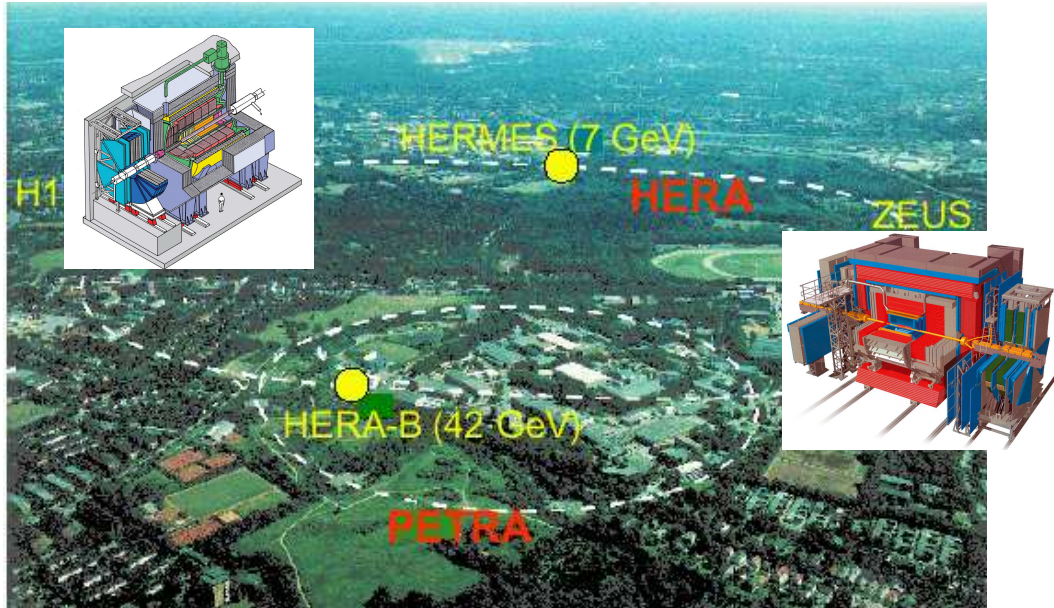
Exclusive ρ^0 and ρ'
Photoproduction at HERA



Sergey Levonian, DESY
for the H1 Collaboration



HERA: The World's Only ep Collider

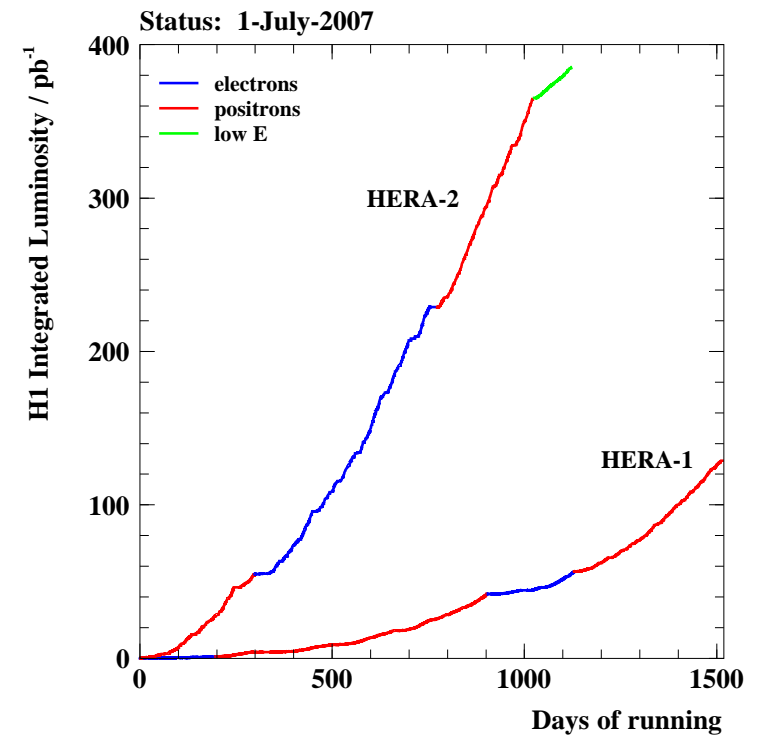


HERA-1 (1993-2000) $\simeq 120 \text{ pb}^{-1}$

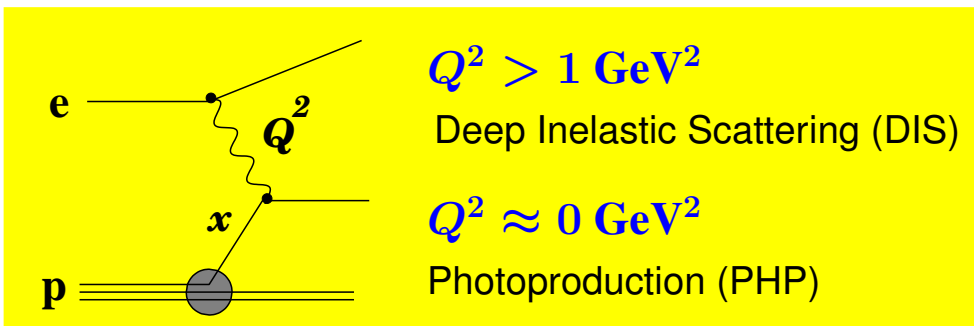
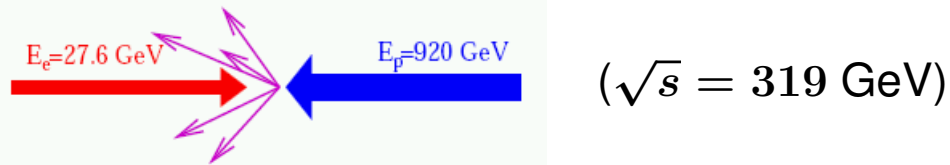
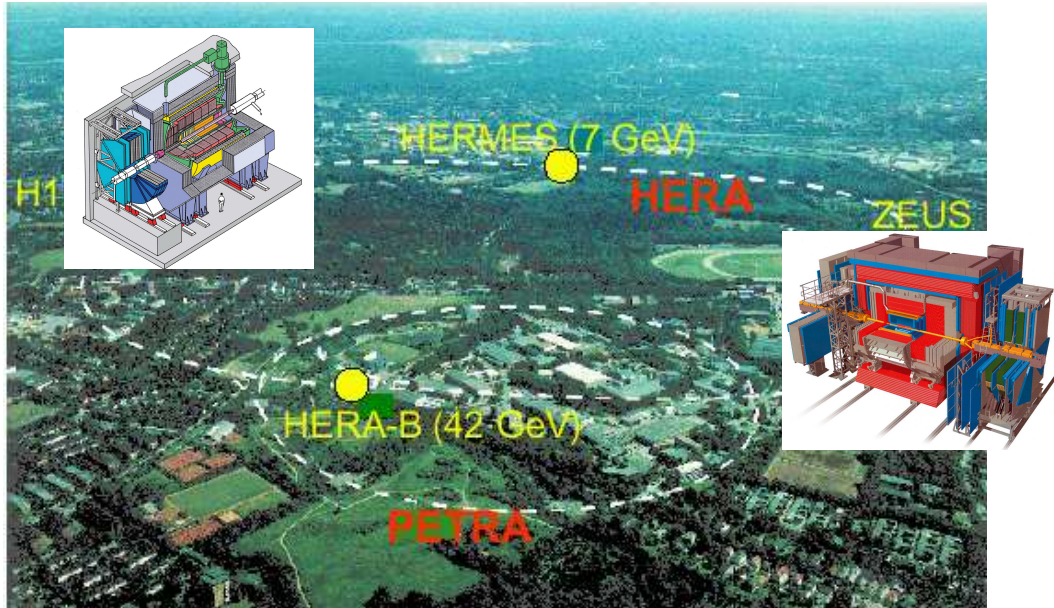
HERA-2 (2003-2007) $\simeq 380 \text{ pb}^{-1}$

Final Data samples

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



HERA: The World's Only ep Collider

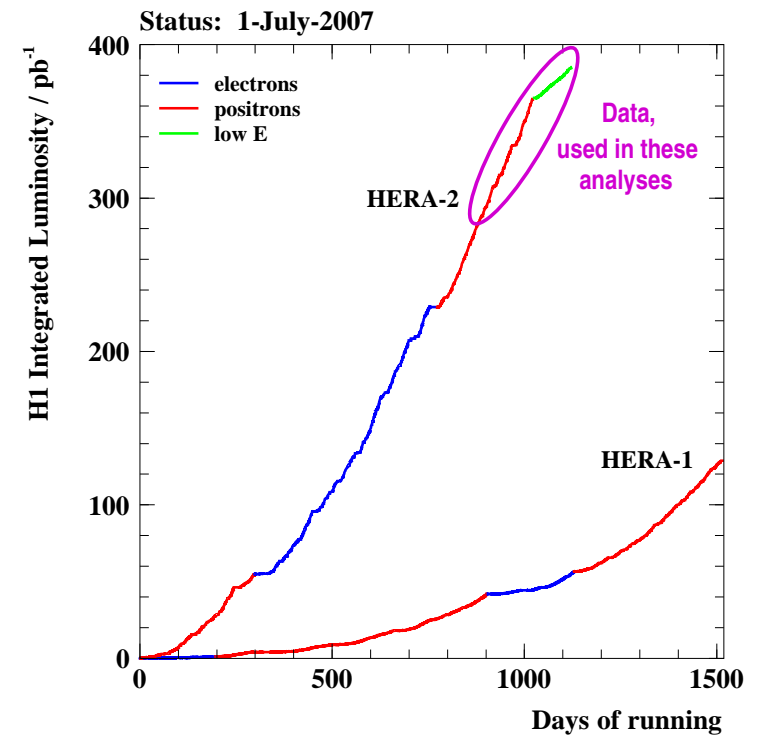


HERA-1 (1993-2000) $\simeq 120 \text{ pb}^{-1}$

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

Final Data samples

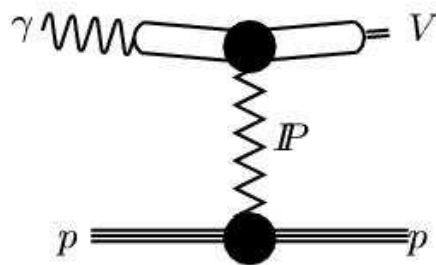
H1+ZEUS: $2 \times 0.5 \text{ fb}^{-1}$



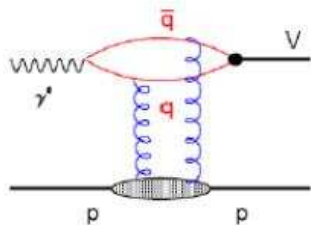
Vector Mesons at HERA

- Data at $W > 20$ GeV are all from HERA
- HERA VM Photoproduction data are well described by Regge-type power law $\sigma \propto W^\delta$
- Transition from soft to hard regime at universal scale $\mu^2 = (Q^2 + M_V^2)/4 \approx 4 \div 5 \text{ GeV}^2$
- Low-mass VM: only few points are measured and only for ground states ρ, ω, ϕ

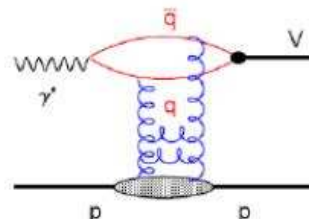
VM: soft vs hard \mathbb{P}



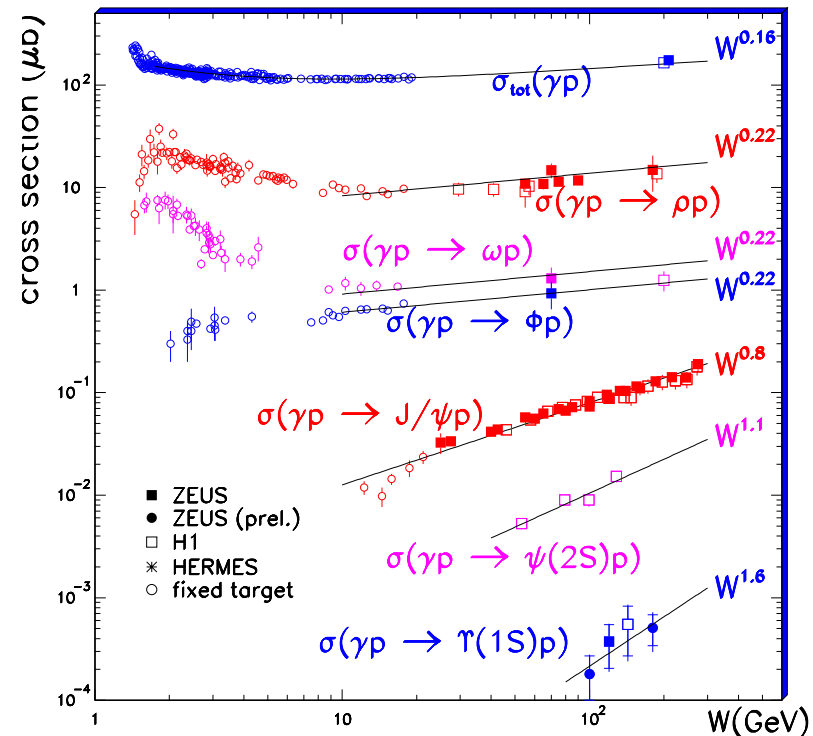
$$\alpha_{\mathbb{P}}(t) = \alpha(0) + \alpha' t; \quad \delta = 4(\alpha_{\mathbb{P}} - 1)$$



LO 2 gluons



LL1/x ladder



H1 Detector

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

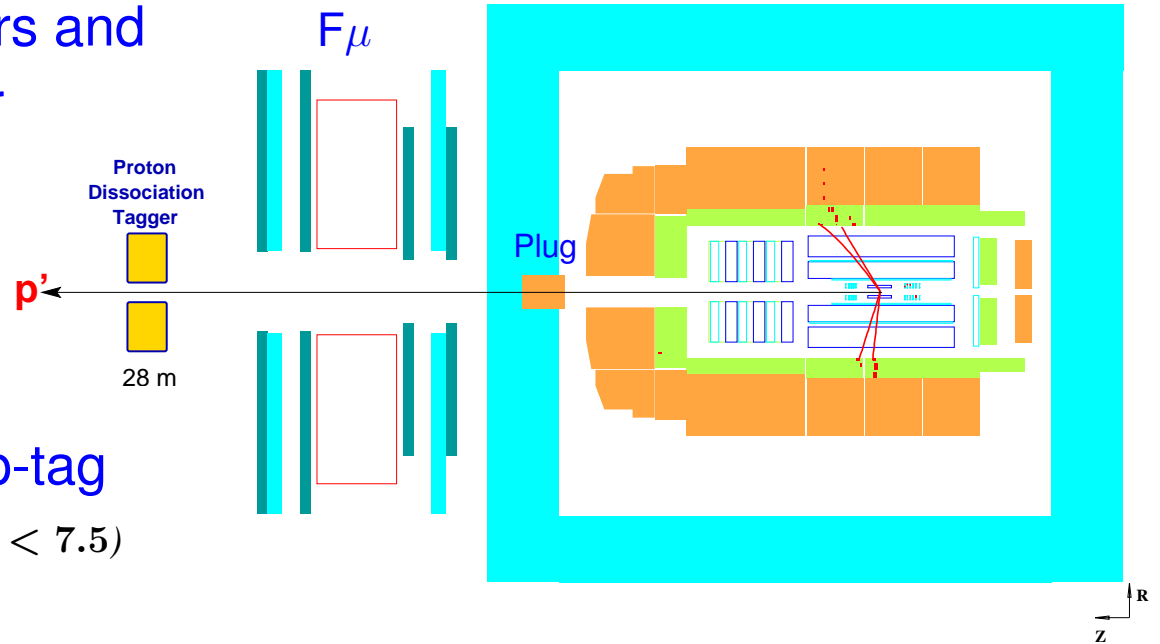
($20^\circ < \theta < 160^\circ$ used in VM analyses)

- EM+Had Calorimeters

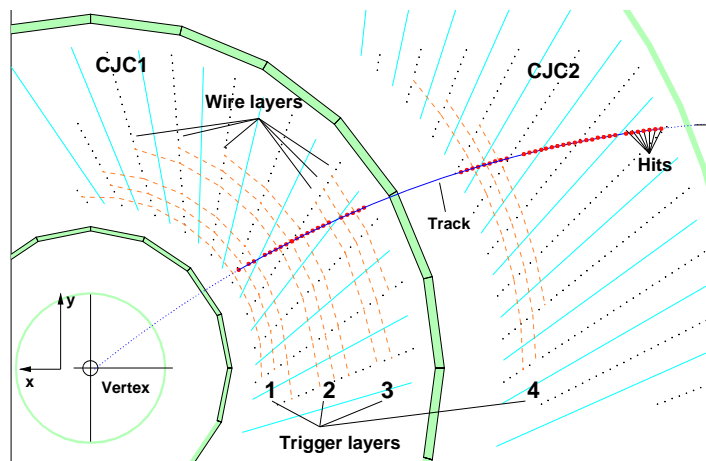
($4^\circ < \theta < 178^\circ$)

- Forward Detectors: F_μ , Plug, p-tag

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



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



$$\gamma p \rightarrow \pi^+ \pi^- Y$$

HE $\mathcal{L} = 1.3 \text{ pb}^{-1} \sim 700,000 \text{ events}$

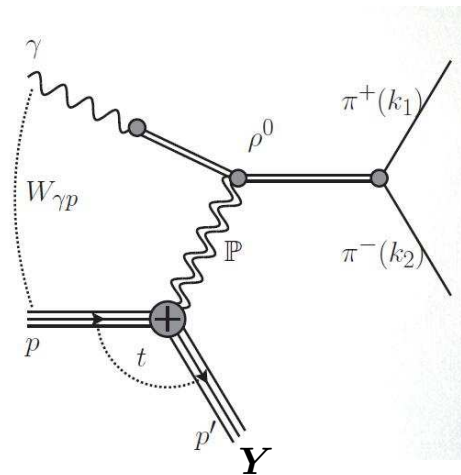
$$\gamma p \rightarrow 2\pi^+ 2\pi^- Y$$

HE $\mathcal{L} = 7.6 \text{ pb}^{-1} \sim 80,000 \text{ events}$

LE $\mathcal{L} = 1.7 \text{ pb}^{-1} \sim 14,400 \text{ events}$

ρ^0 Analysis

$$\gamma p \rightarrow \pi^+ \pi^- Y$$



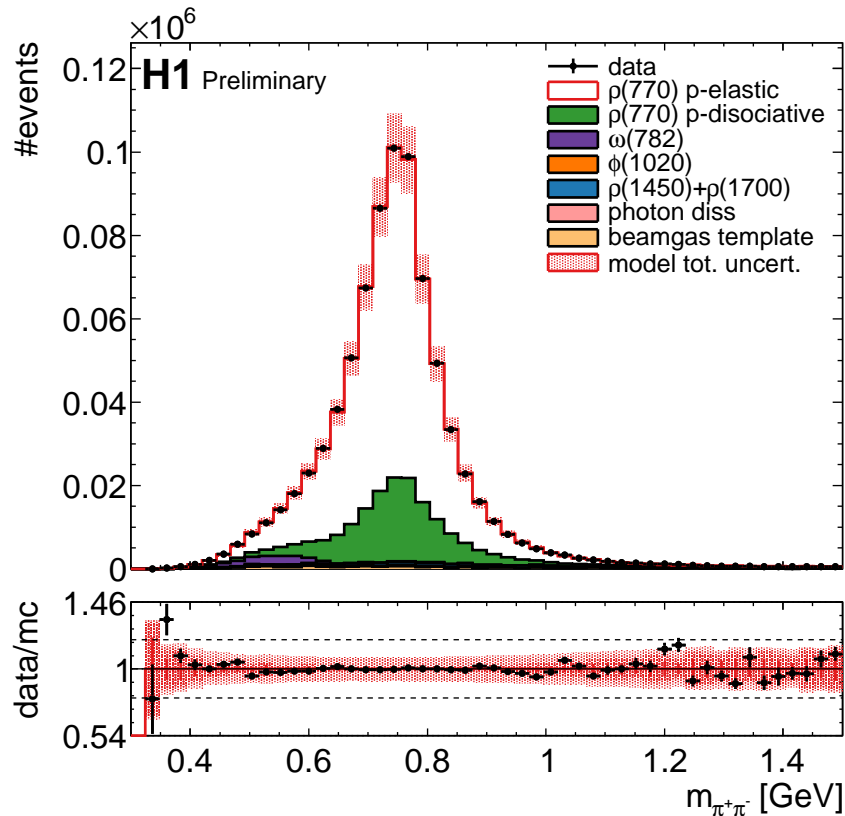
Data Sample and MC modelling

$$15 \text{ GeV} < W_{\gamma p} < 100 \text{ GeV}$$

$$0.3 \text{ GeV} < m_{\pi\pi} < 1.5 \text{ GeV}$$

$$p_{t,\pi\pi}^2 \simeq |t| < 2 \text{ GeV}^2$$

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



DiffVM MC (Regge + VDM)

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

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

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

- backgrounds:**

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

$$\phi \rightarrow K^+K^-, K_S K_L, \pi^+\pi^-\pi^0, \rho\pi, \eta\gamma$$

$$\rho' \rightarrow \rho\pi\pi, 4\pi$$

$$\gamma\text{-dissociation: } M_X \rightarrow \text{hadrons via Jetset}$$

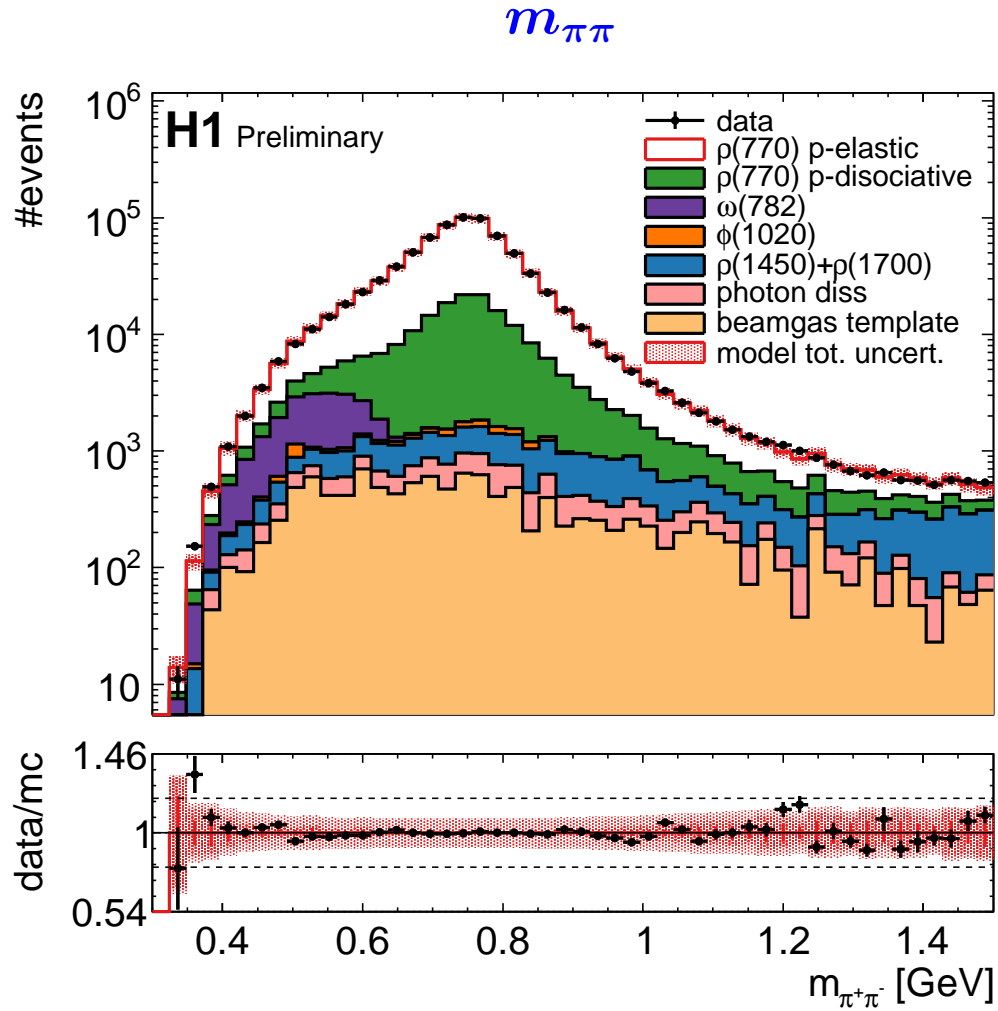
- proton dissociation:**

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

$M_Y < 1.9 \text{ GeV}$: N^* with measured decay channels

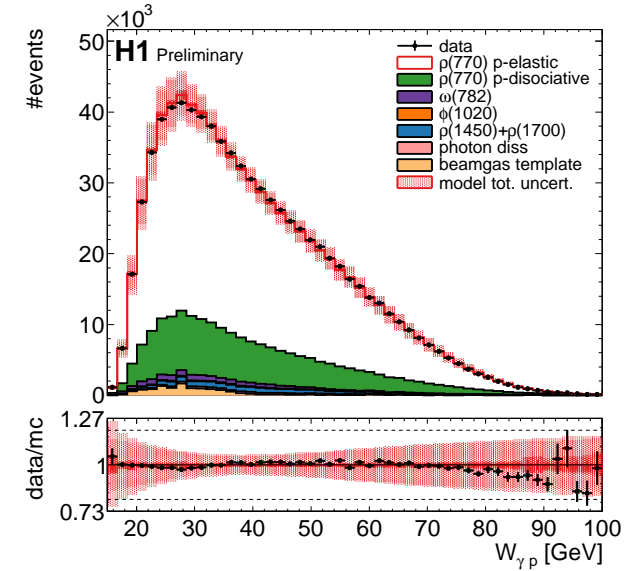
$M_Y > 1.9 \text{ GeV}$: $p' \rightarrow \text{hadrons via Jetset}$

Control Plots

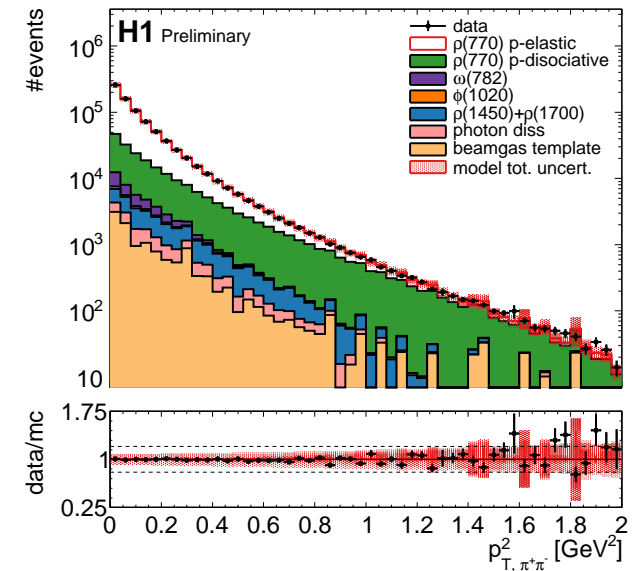


Good description in all variables

$W_{\gamma p}$



$p_{T,\pi\pi}^2$



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

Differential cross section definition

$$\frac{d\sigma(\gamma p \rightarrow \pi^+\pi^- Y)}{dm_{\pi\pi}}(W_{\gamma p}, m_{\pi\pi}) = \frac{N_{\text{unfolded}}^Y(W_{\gamma p}, m_{\pi\pi})}{\mathcal{L} \cdot \Delta m_{\pi\pi} \cdot \Phi_{\gamma/e}(W_{\gamma p})}$$

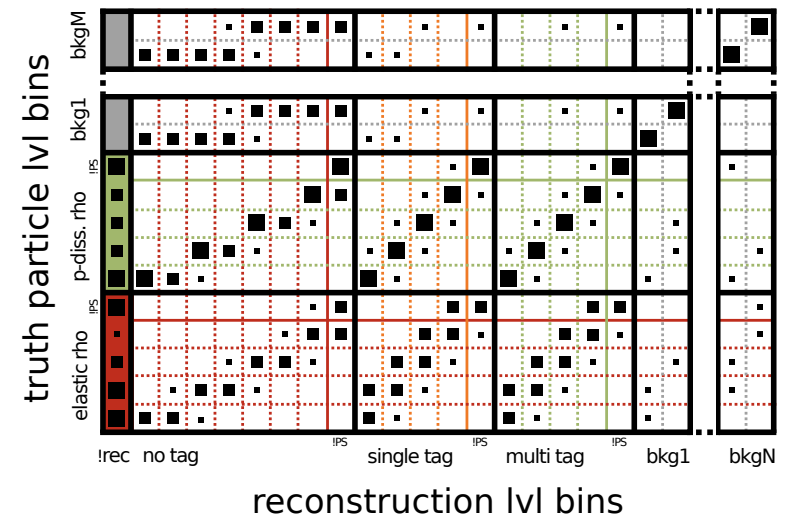
Reduced measurement Phase Space

20 GeV	\leq	$W_{\gamma p}$	\leq 80	GeV
0.4 GeV	\leq	$m_{\pi\pi}$	\leq 1.2	GeV
		$-t$	\leq 1.5	GeV ²
		Q^2	\leq 0.1	GeV ²
elastic:				
		M_Y	$= m_p$	GeV
p-dissociative:				
m_p	$<$	M_Y	\leq 10	GeV

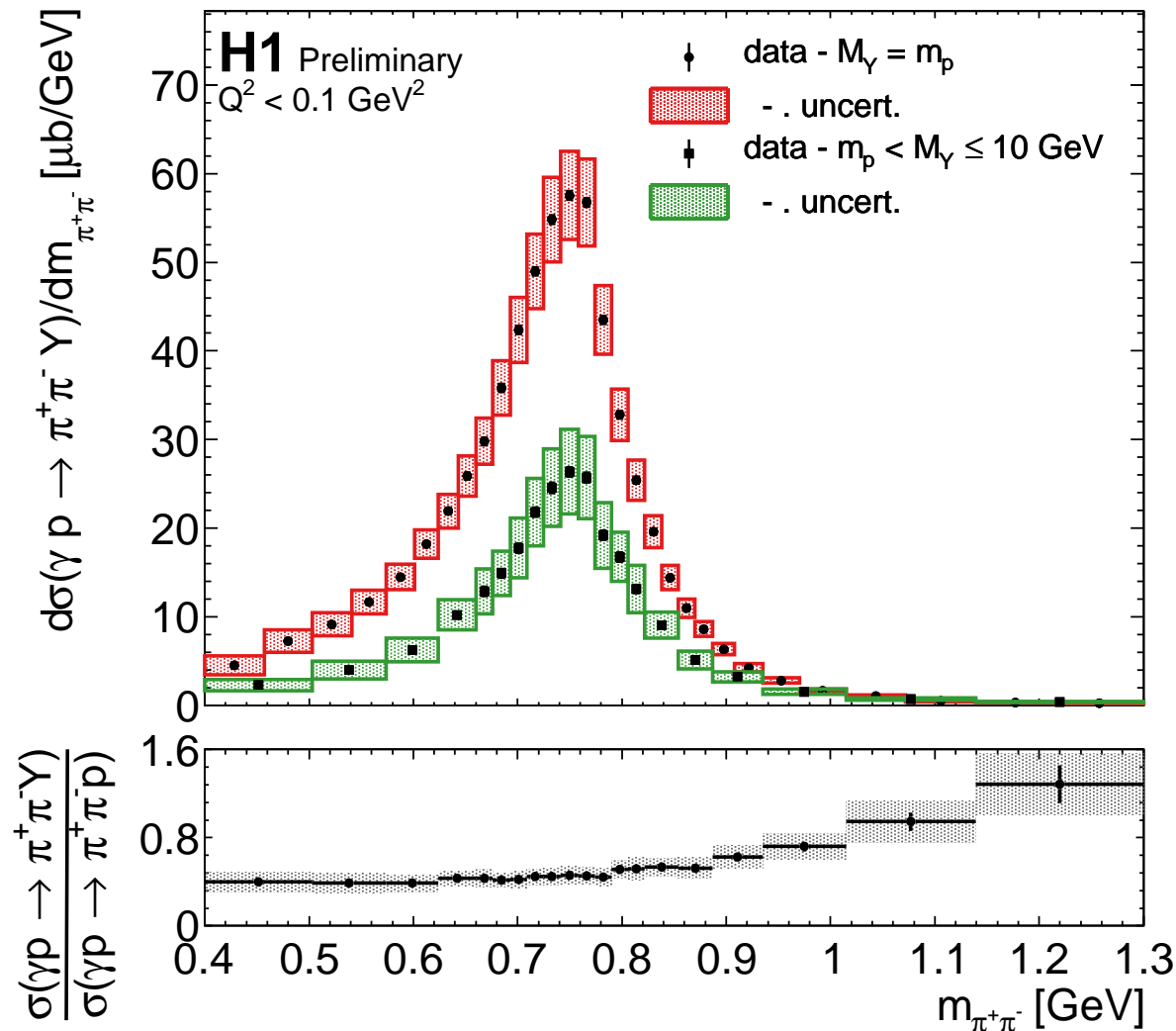
Unfolding particle level cross sections:

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

Regularised template fit using *TUnfold* package



- p-dissociation separated using 3 tagging control regions
- backgrounds normalised in 4 control regions

$$d\sigma(\gamma p \rightarrow \pi^+ \pi^- Y)/dm_{\pi\pi}$$


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

Fiducial Cross sections

	$\sigma [\mu\text{b}]$	stat. [μb]	syst. [μb]
$\gamma p \rightarrow \pi^+ \pi^- p$	11.36	± 0.04	$\pm 1.17^*$
$\gamma p \rightarrow \pi^+ \pi^- Y$	5.17	± 0.04	$\pm 0.94^*$

*not fully evaluated

Main sources of syst. uncertainty:

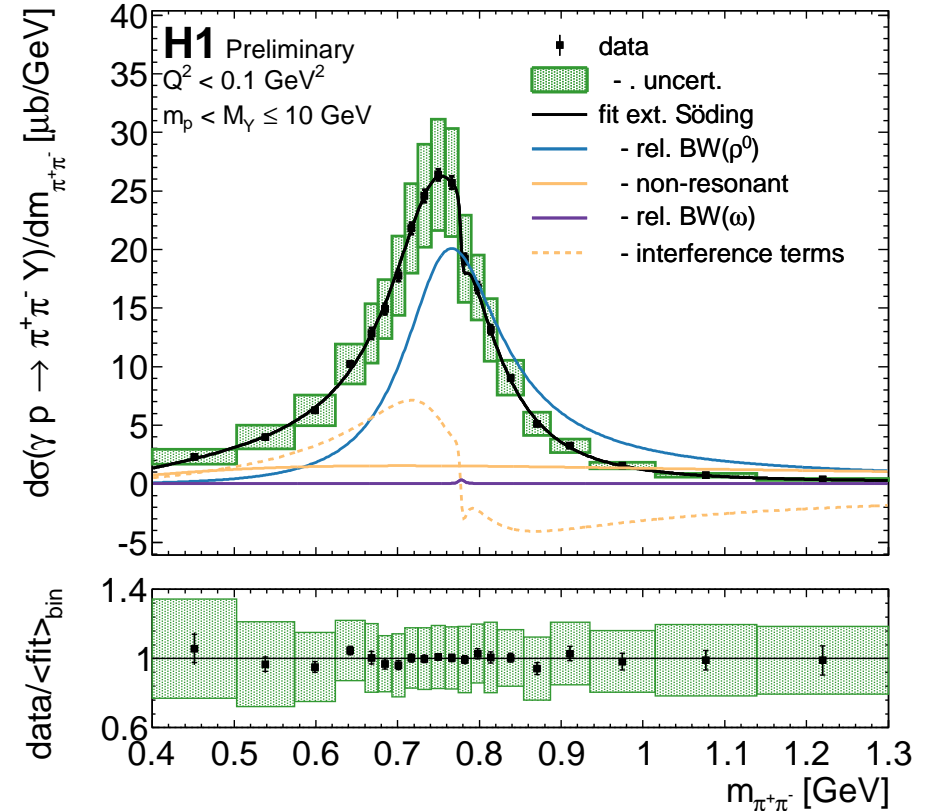
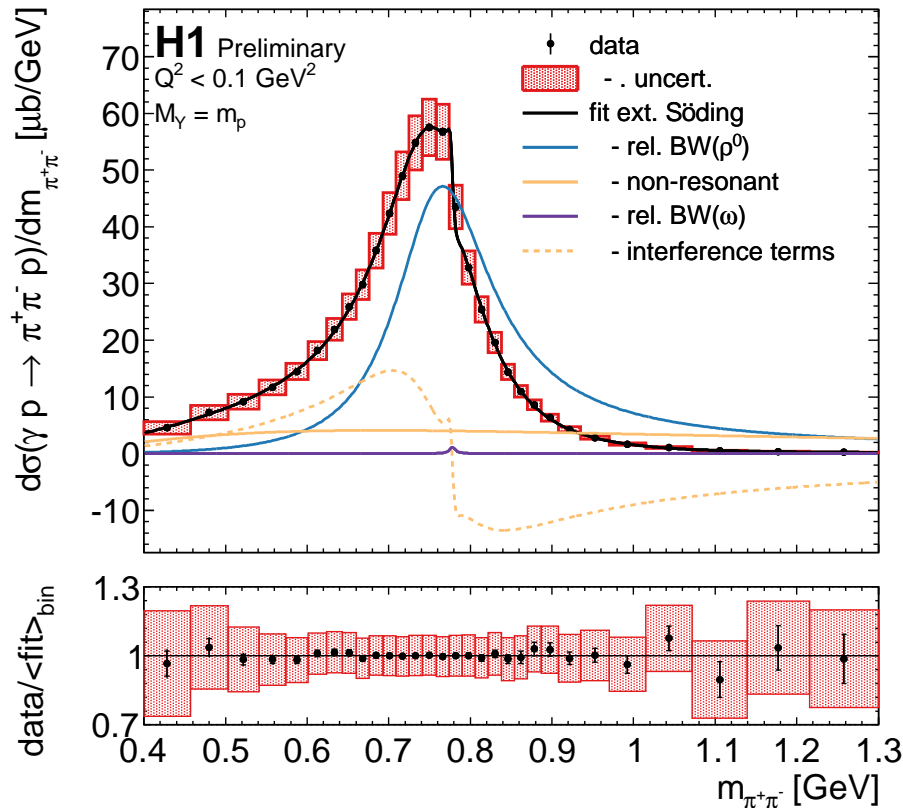
- trigger
- forward tagging
- calorimeter

Extracting ρ^0 Cross Section

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

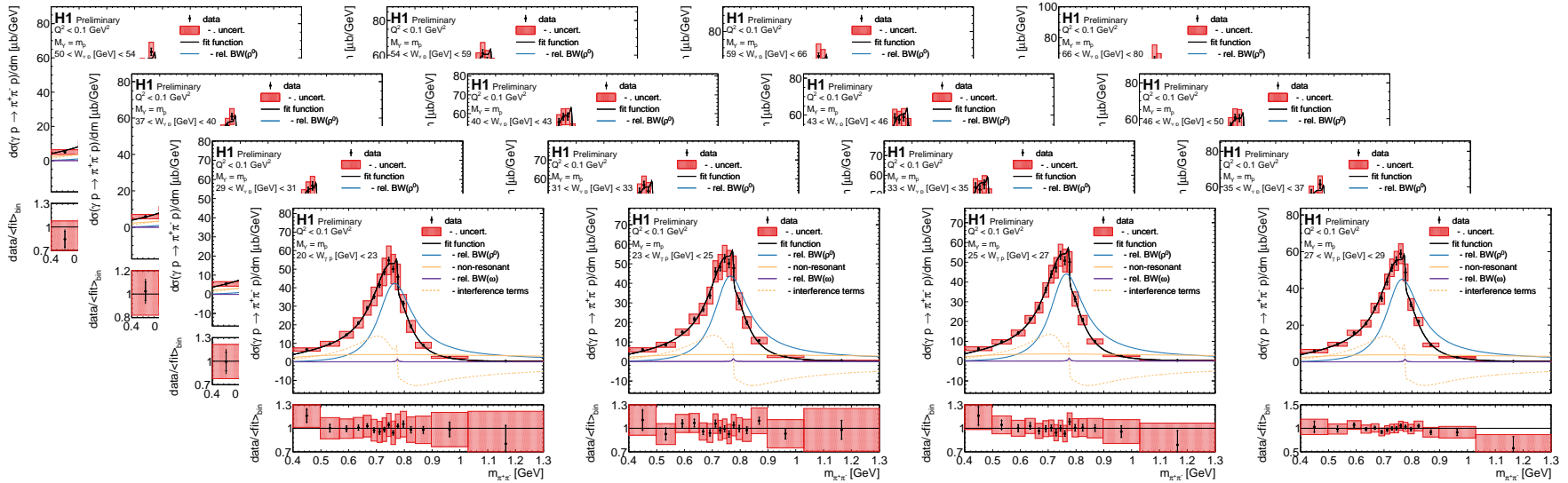
non-res term: $B_{nr} = \left(\frac{m_{\pi\pi} - 2m_\pi}{(m_{\pi\pi} - 2m_\pi)^2 + \Lambda_{nr}^2} \right)^{\delta_{nr}}$

Fitted parameters: $m_{\rho^0} = 771 \pm 1(\text{stat.}) \text{ MeV}$
 $\Gamma_{\rho^0} = 150 \pm 1(\text{stat.}) \text{ MeV}$

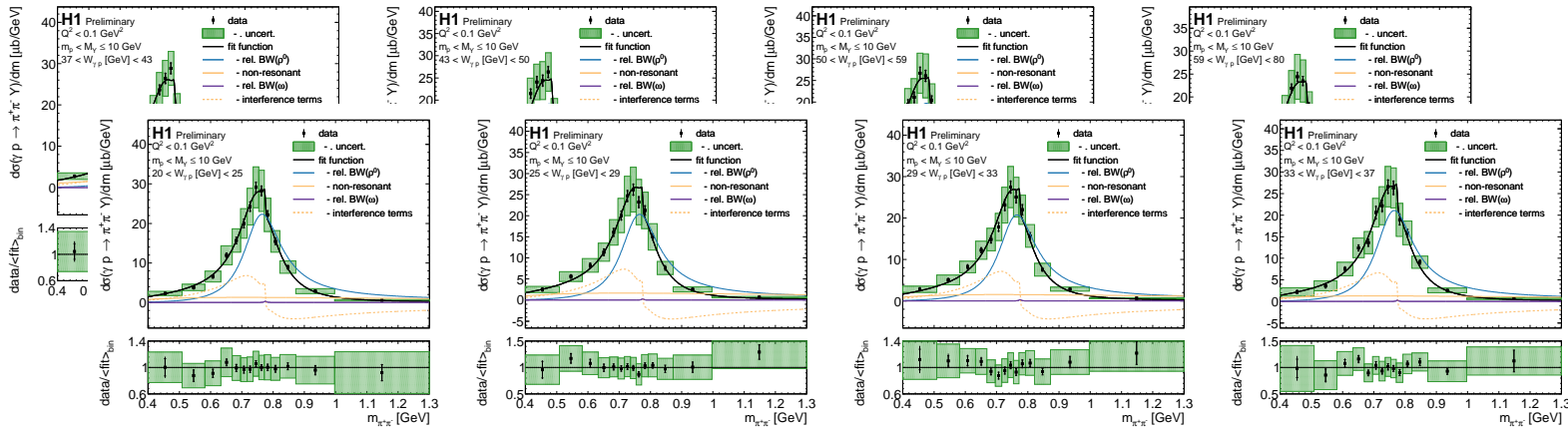


Extracting ρ^0 Cross Section in bins of $W_{\gamma p}$

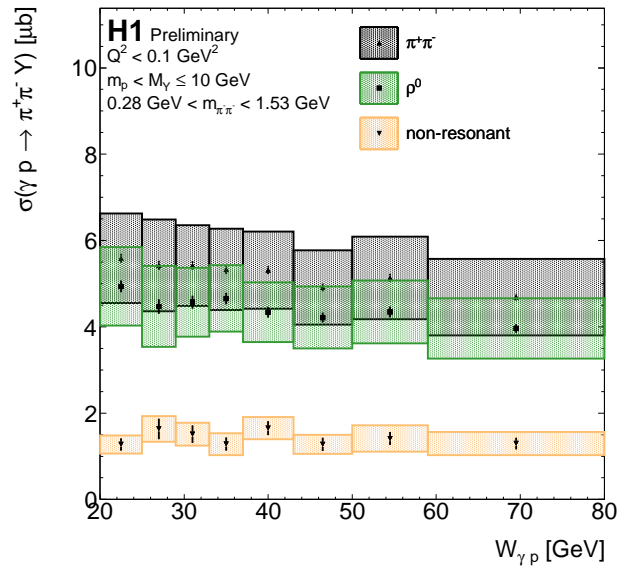
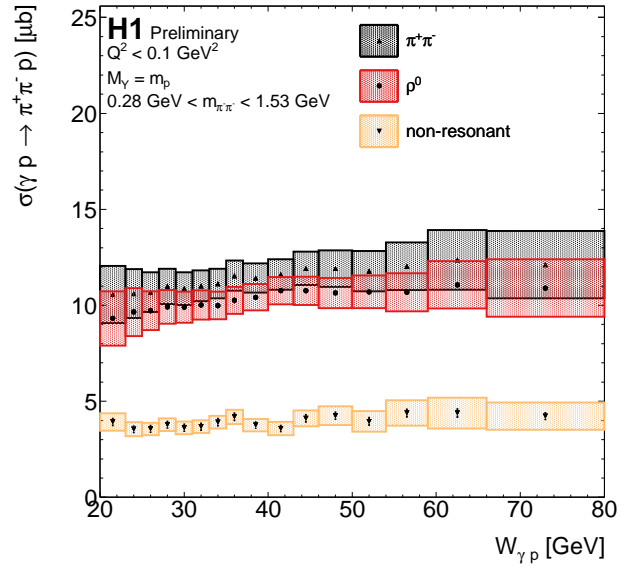
2D unfolding ($m_{\pi\pi} \otimes W_{\gamma p}$) \Rightarrow $d\sigma(\gamma p \rightarrow \pi^+\pi^-Y)/dm_{\pi\pi}$ in 16 elastic $W_{\gamma p}$ bins



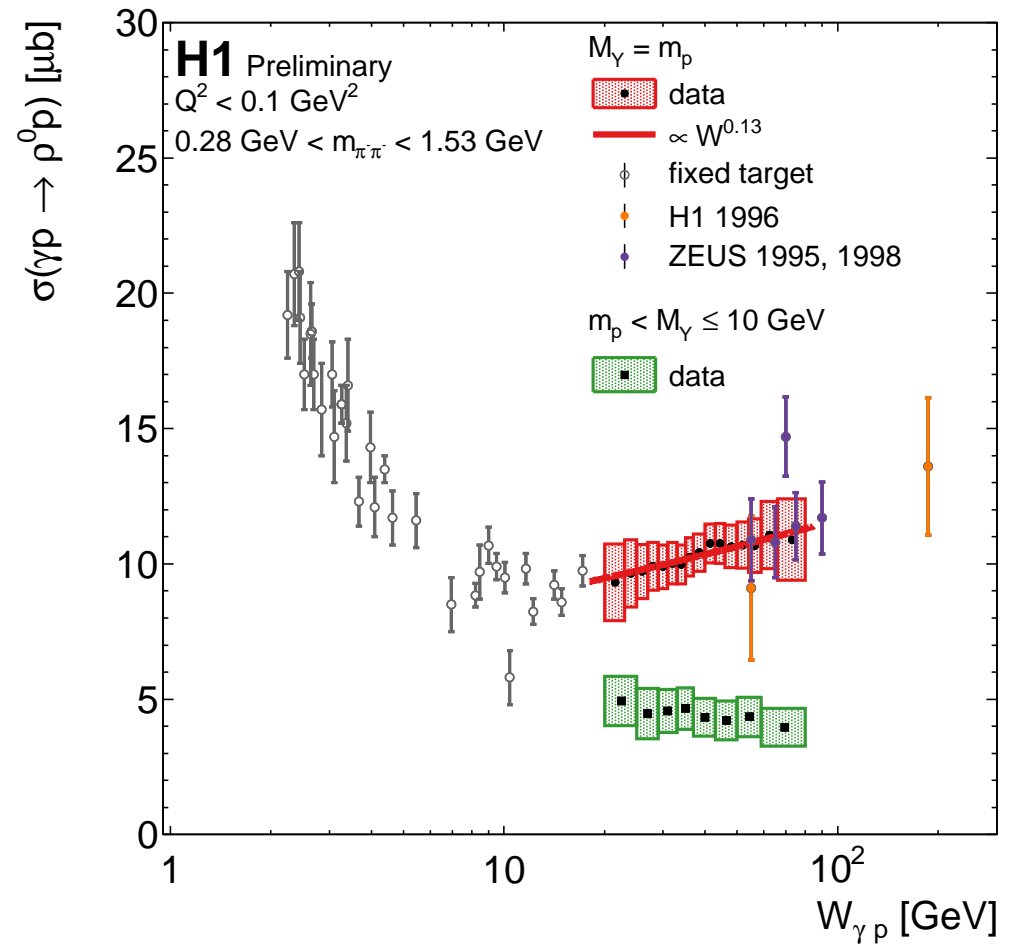
2D unfolding ($m_{\pi\pi} \otimes W_{\gamma p}$) \Rightarrow $d\sigma(\gamma p \rightarrow \pi^+\pi^-Y)/dm_{\pi\pi}$ in 8 proton-dissociative $W_{\gamma p}$ bins



Energy Dependence of ρ^0 Cross Sections



- Cross sections - from fit function integral
- P-diss. cross section affected by PS restrictions

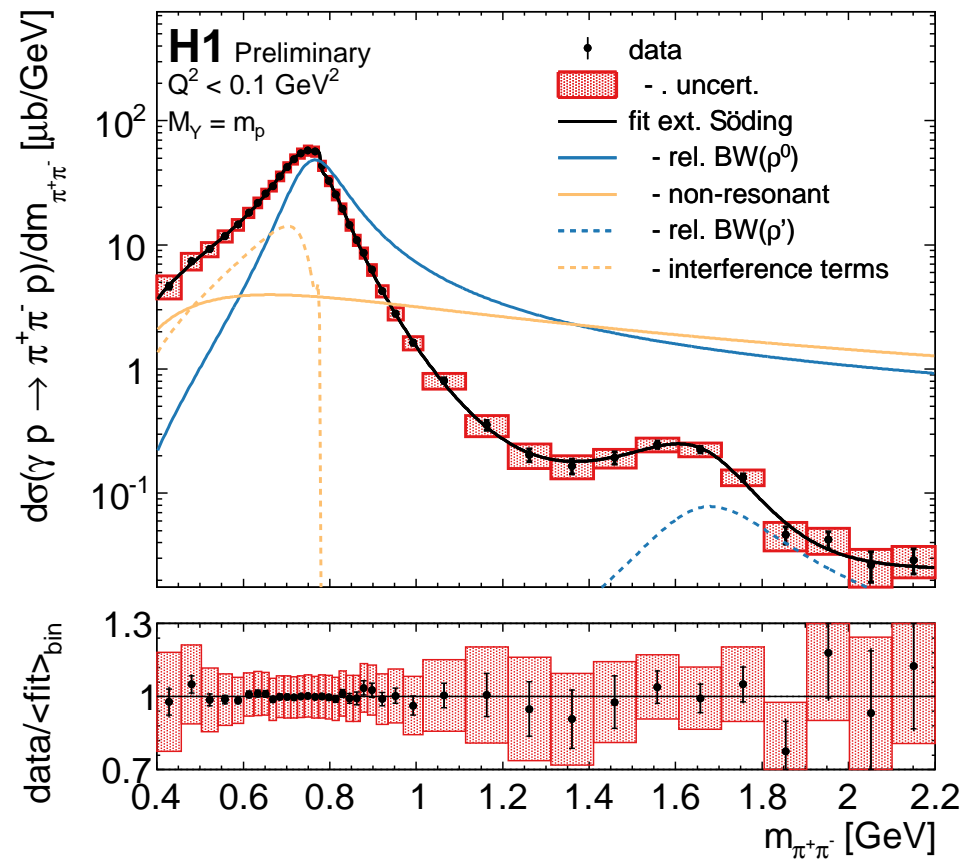


$\pi^+\pi^-$ Mass Spectra in Extended Mass Range

- look at extended range $m_{\pi\pi} < 2.2$ GeV
- good fit with one extra $BW_{\rho'}$

$$m_{\rho'} \simeq 1700 \text{ MeV}$$

$$\Gamma_{\rho'} \simeq 300 \text{ MeV}$$

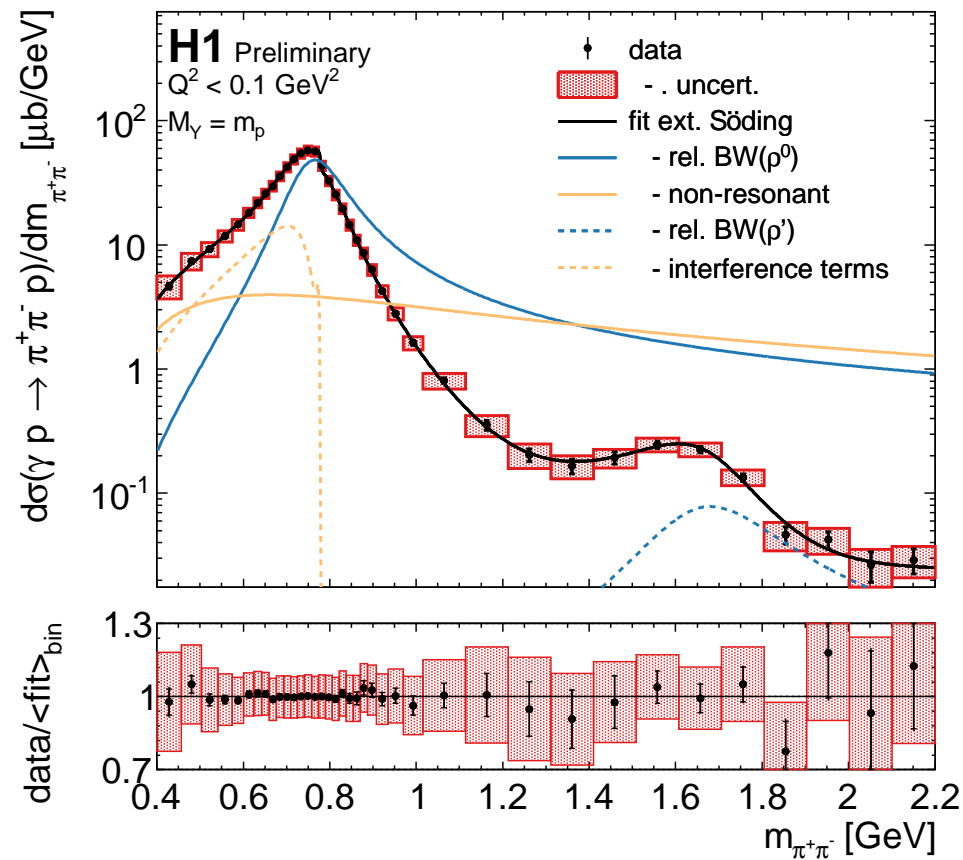


$\pi^+\pi^-$ Mass Spectra in Extended Mass Range

- look at extended range $m_{\pi\pi} < 2.2$ GeV
- good fit with one extra $BW_{\rho'}$

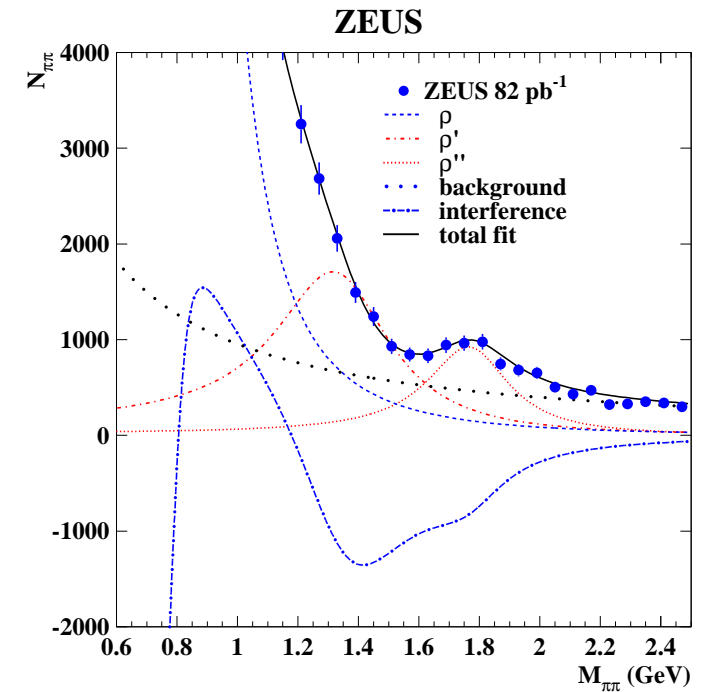
$$m_{\rho'} \simeq 1700 \text{ MeV}$$

$$\Gamma_{\rho'} \simeq 300 \text{ MeV}$$



Similar measurement by ZEUS [2012]
 but in DIS regime ($Q^2 > 2 \text{ GeV}^2$)

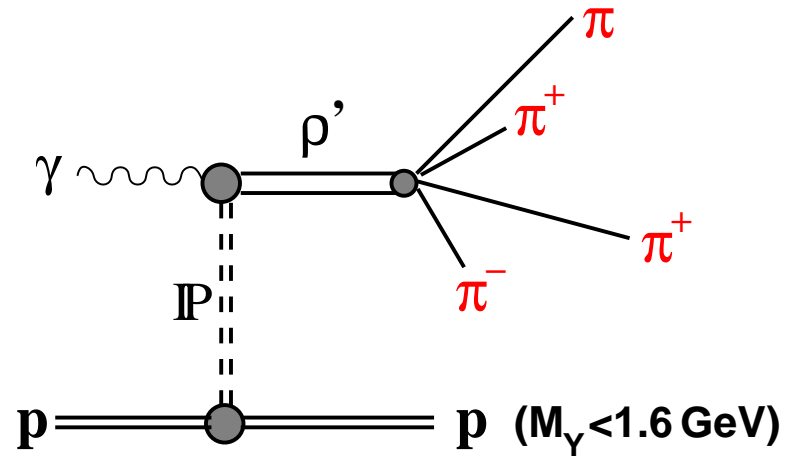
Complicated fit, large $\rho(770)$ 'bgr'
 both $\rho(1450)$ and $\rho(1700)$ observed



➡ Try 4π final state

ρ' Analysis

$$\gamma p \rightarrow 2\pi^+ 2\pi^- Y$$



Analysis sketch

Experimental information is sparse

Dominant decay channel: $\rho\pi\pi$

$\rho(1450)$ [1]

$$I^G(J^{PC}) = 1^+(1^{--})$$

Mass $m = 1465 \pm 25$ MeV [1]

Full width $\Gamma = 400 \pm 60$ MeV [1]

$\rho(1450)$ DECAY MODES	Fraction (Γ_i/Γ)	ρ (MeV/c)
$\pi\pi$	seen	720
4π	seen	669
e^+e^-	seen	732
$\eta\rho$	seen	311
$a_2(1320)\pi$	not seen	54
$K\bar{K}$	not seen	541
$K\bar{K}^*(892)+$ c.c.	possibly seen	229
$\eta\gamma$	seen	630

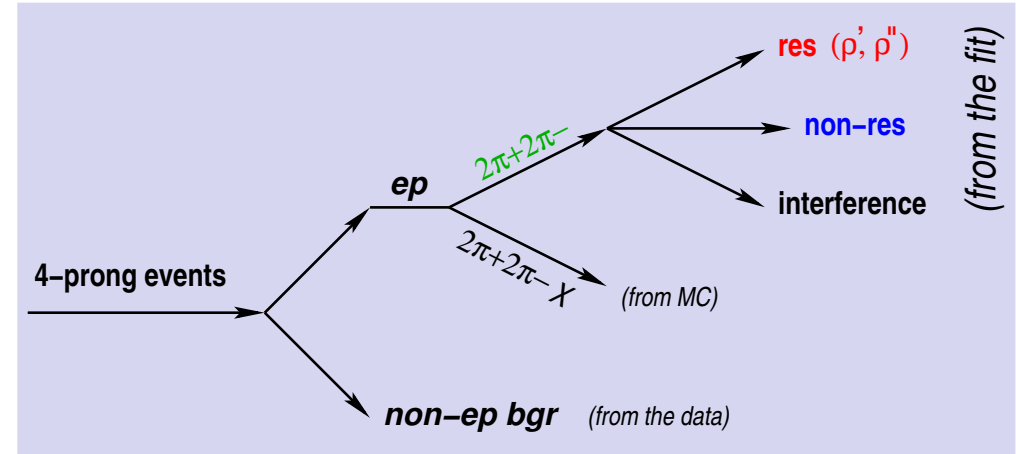
$\rho(1700)$ [1]

$$I^G(J^{PC}) = 1^+(1^{--})$$

Mass $m = 1720 \pm 20$ MeV [1] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)

Full width $\Gamma = 250 \pm 100$ MeV [1] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)

$\rho(1700)$ DECAY MODES	Fraction (Γ_i/Γ)	ρ (MeV/c)
$2(\pi^+\pi^-)$	large	803
$\rho\pi\pi$	dominant	653
$\rho^0\pi^+\pi^-$	large	651
$\rho^\pm\pi^\mp\pi^0$	large	652
$a_1(1260)\pi$	seen	404
$h_1(1170)\pi$	seen	447
$\pi(1300)\pi$	seen	349
$\rho\rho$	seen	372
$\pi^+\pi^-$	seen	849



- 4 tracks with zero net charge, from nominal vertex
veto e' and other energies not associated with tracks
veto on forward activity (LRG)
- non- ep background at low $W_{\gamma p} \Rightarrow$ defines $W_{\gamma p}^{\min}$ cut
- $2\pi^+2\pi^-X$ background: take from MC (DiffVM/PYTHIA)
cross-check MC vs data using wrong charge background
- fit 4π mass spectra to extract ρ' cross sections

Control Plots

Two data samples: **HE** ($\sqrt{s} = 319$ GeV, $\mathcal{L} = 7.6$ pb $^{-1}$), **LE** ($\sqrt{s} = 225$ GeV, $\mathcal{L} = 1.7$ pb $^{-1}$)

Phase Space:

$$Q^2 < 2 \text{ GeV}^2 \text{ (PHP)}$$

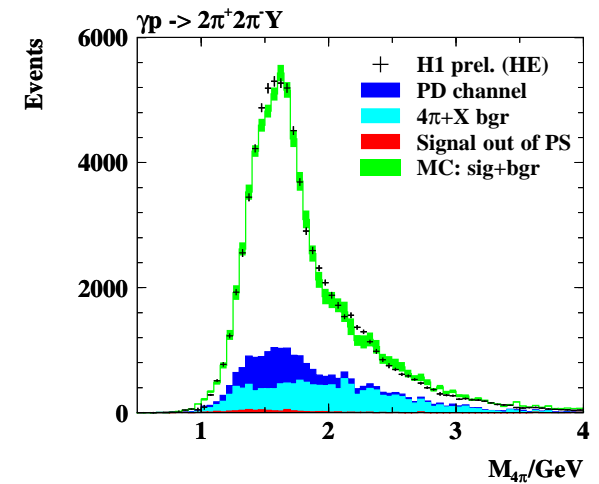
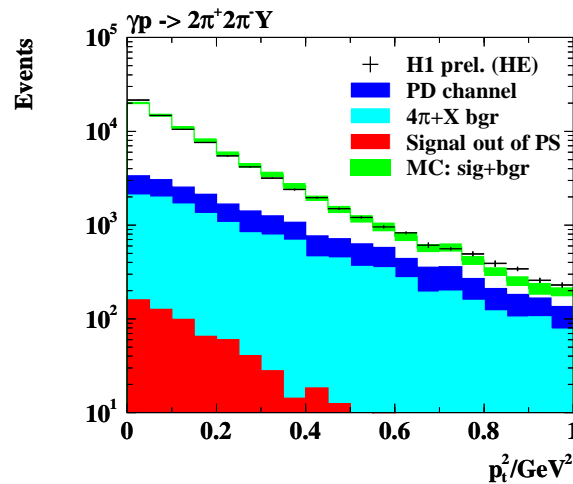
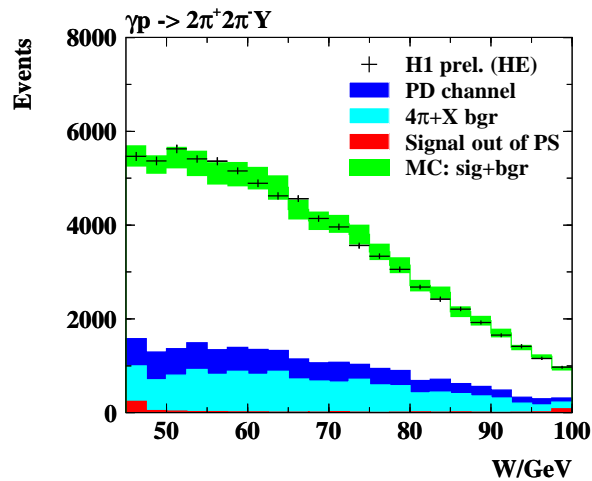
$$45 < W/\text{GeV} < 100 \text{ (at } \sqrt{s} = 319 \text{ GeV)}$$

$$35 < W/\text{GeV} < 75 \text{ (at } \sqrt{s} = 225 \text{ GeV)}$$

$$M_Y < 1.6 \text{ GeV}, \quad |t| < 1 \text{ GeV}^2$$

- Remaining background $\sim 15\%$
- Contamination from p -diss. events with $M_Y < 1.6$ GeV: $\sim 10\%$

Control plots for **HE** sample (*more in backup*)



Green band represents ($4\pi + X$) background subtraction systematics only

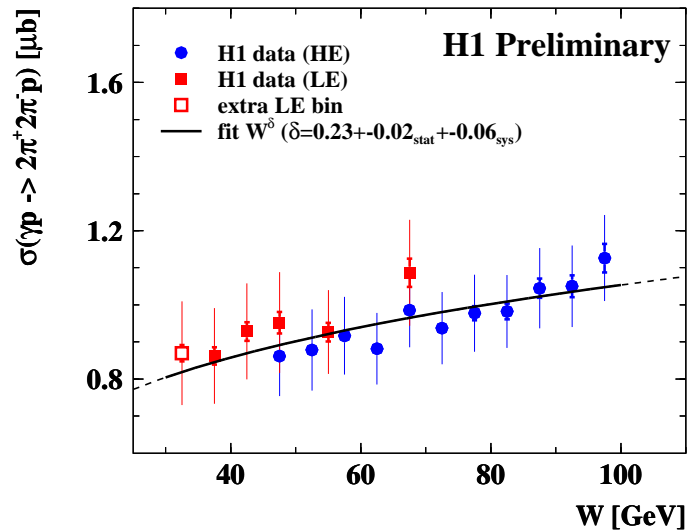
Cross Section vs $W_{\gamma p}$

Total cross section at the reference point $W = 75$ GeV:

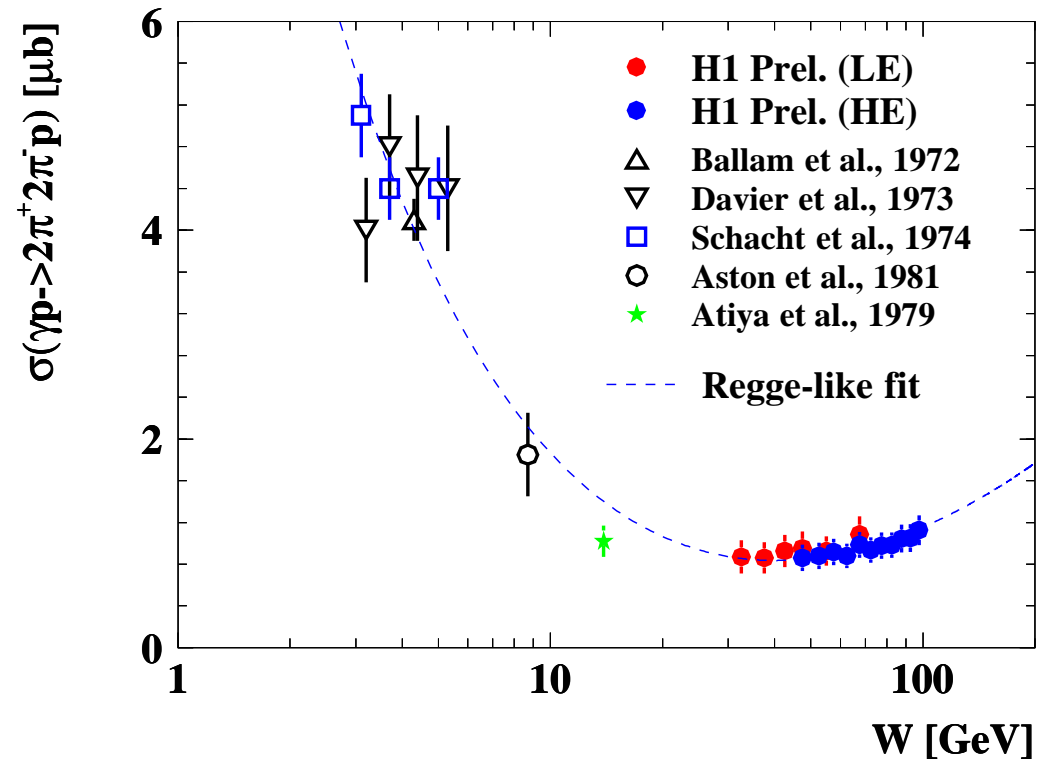
$$\sigma_{\gamma p \rightarrow 2\pi^+ 2\pi^- Y} = (1.07 \pm 0.01_{\text{stat}} \pm 0.14_{\text{sys}}) \mu\text{b}$$

$$R = \frac{\sigma(\gamma p \rightarrow 2\pi^+ 2\pi^- p)}{\sigma(\gamma p \rightarrow \pi^+ \pi^- p)} \approx 9\%$$

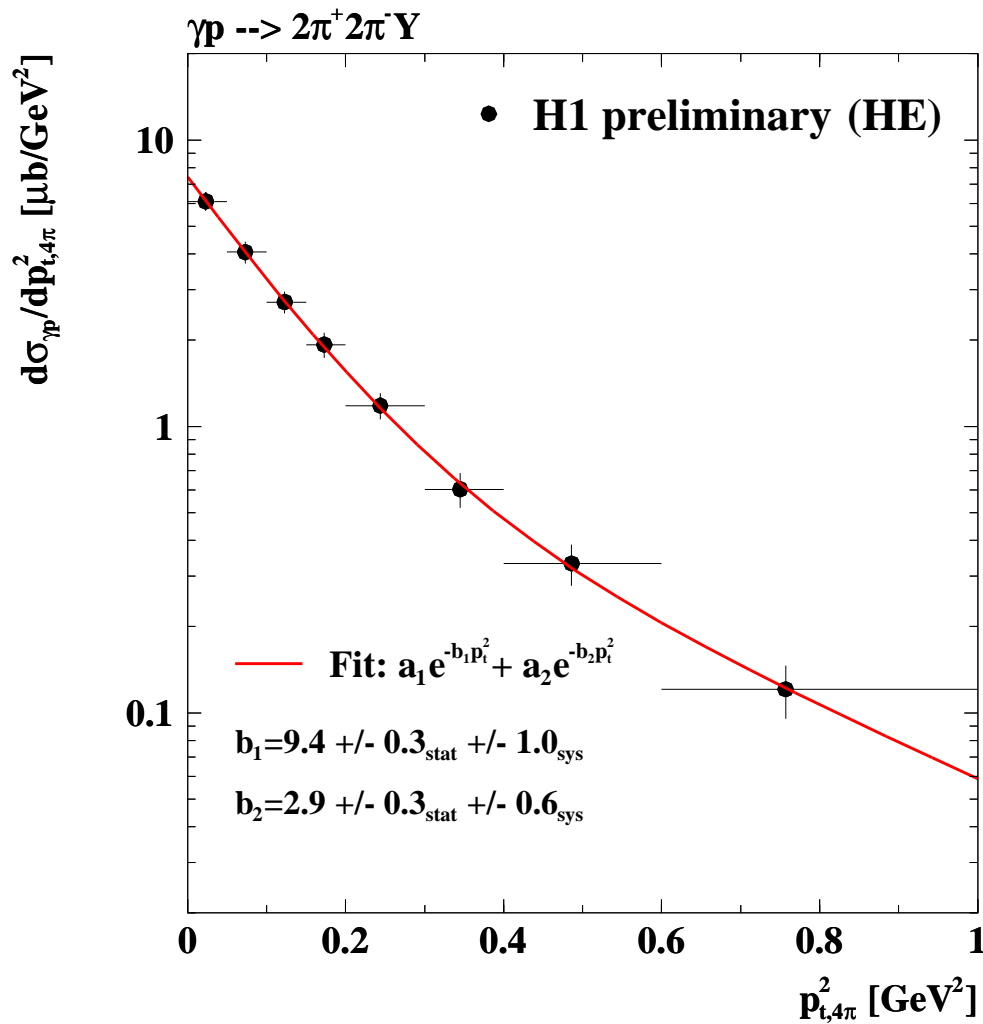
Subtract remaining p-dissociative contribution
to compare to fixed target photoproduction data



World data are well described by Regge-like fit
(Reggeon and soft Pomeron contributions)

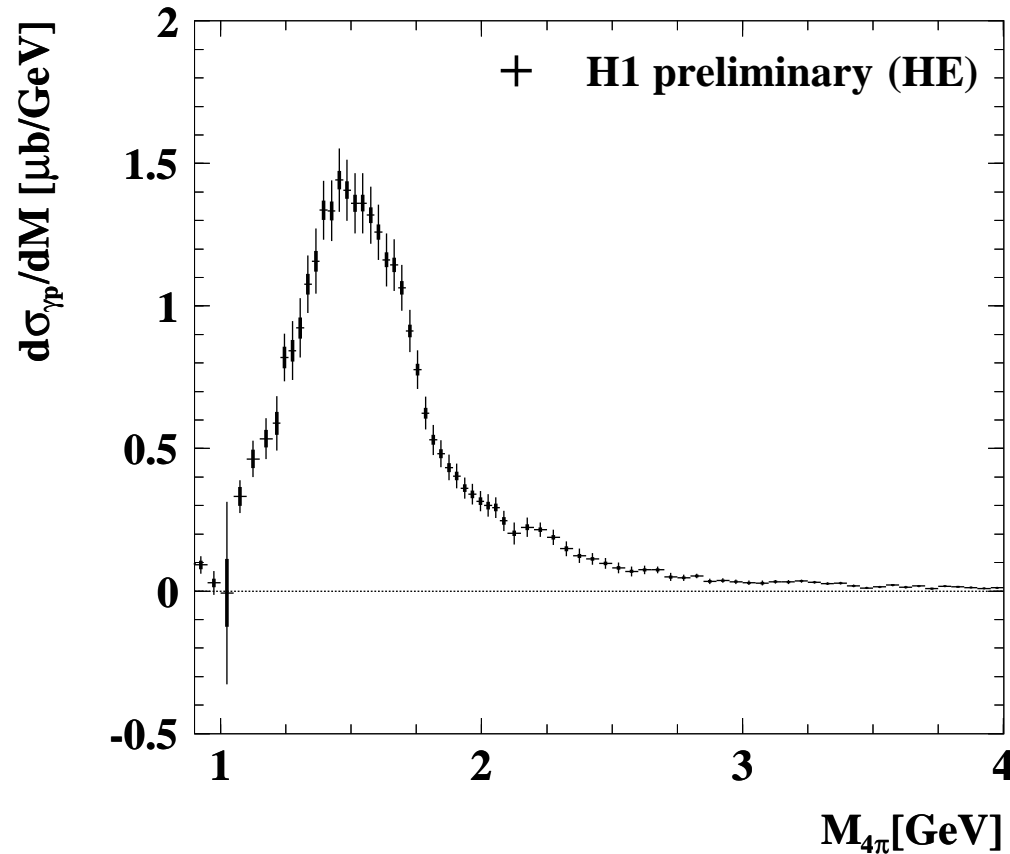


Cross Section as a function of t



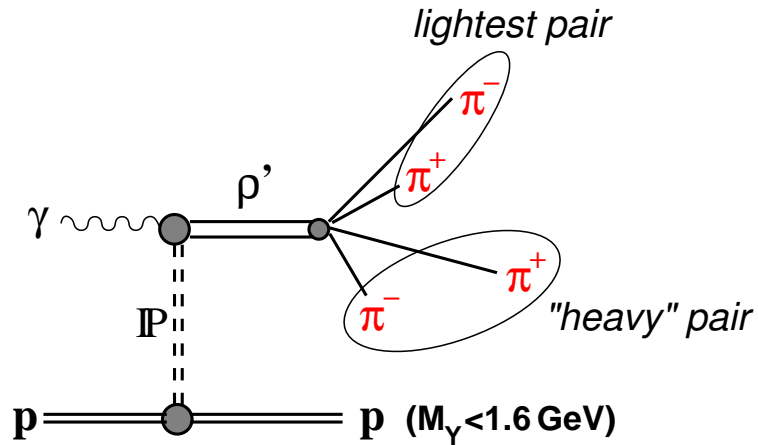
- Exponential fall-off in t , typical for diffractive VM production
- Slope b_1 is similar to that of $\rho(770)$ in photoproduction
- Second exponent possibly due to: proton-dissociative processes, non-resonant production amplitude

Cross Section as a function of Mass



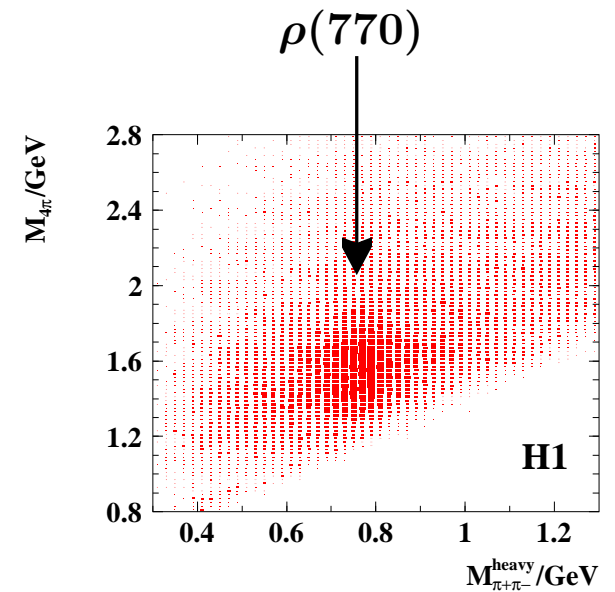
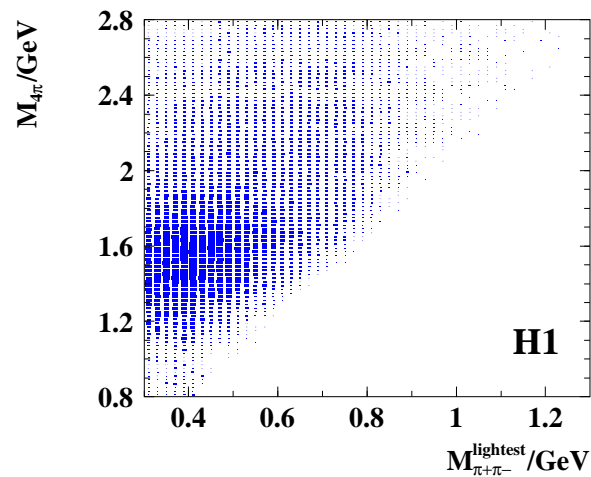
- Vast majority of events populate mass range around 1.6 GeV with the width of ~ 600 MeV
- This supports the expectation of predominantly resonant production of the final state
- No clear indication of 2 resonances; distribution shape similar to that in earlier fixed target γp experiments

Decay modes



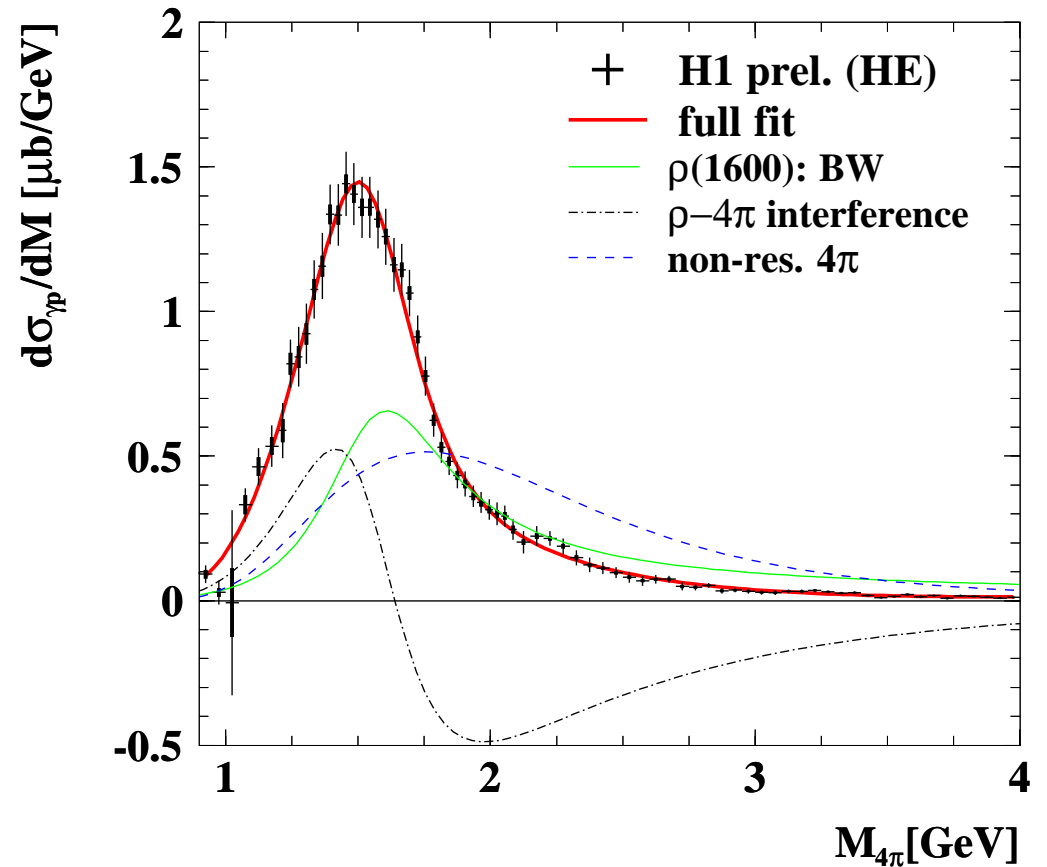
- Study correlations of $M_{4\pi}$ with invariant mass of oppositely charged pion pairs
- Caveat: these distributions are not corrected for acceptance effects

- Prominent structure at m_{ρ^0} is observed
- One broad resonance at $M_{4\pi} = 1600$ or two at $M_{4\pi} = 1450$ and 1700 ?



A simple resonance fit

- Simple fit including one Breit-Wigner, non-resonant term and complex phase describes data fairly well
- Fit with two resonances gives similar quality
- More sophisticated fits in progress taking into account intermediate ρ^0 in cascade decay $\rho' \rightarrow \rho\pi\pi \rightarrow 4\pi$

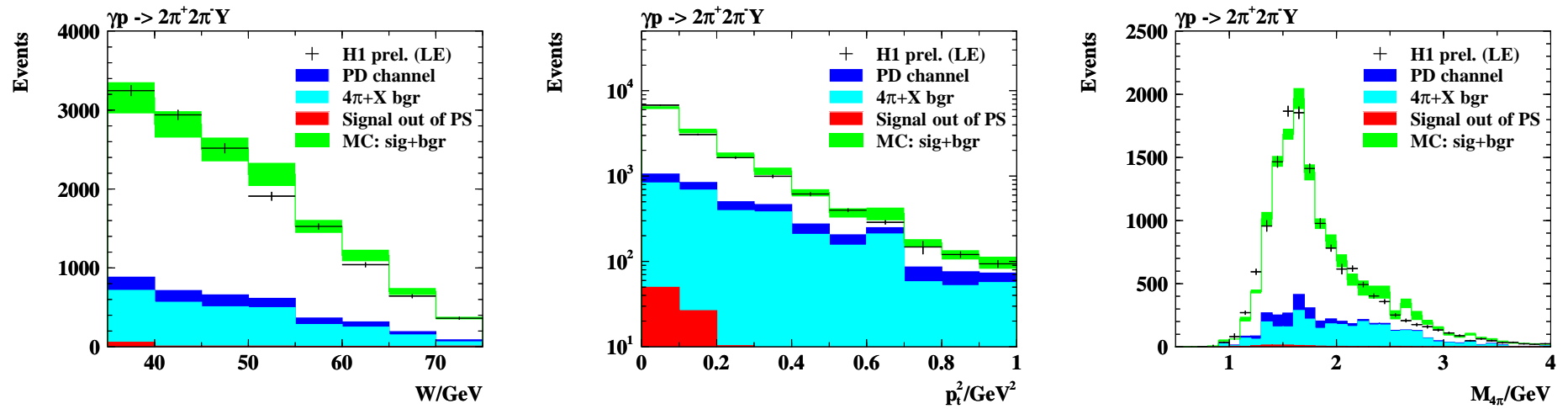


Summary and Outlook

- Large statistics $\pi^+\pi^-$ sample collected and analysed thanks to the upgraded H1 detector capabilities.
- Sophisticated unfolding procedure allowed to measure differential $\pi^+\pi^-$ photoproduction cross sections and separate elastic from proton-dissociative components.
- ρ^0 cross sections are extracted using extended Söding model and taking into account interfering ρ^0, ω and non-resonant $\pi^+\pi^-$ terms.
- 3D unfolding in progress, with the aim to measure double-differential cross section in W and t and to extract Pomeron trajectory.
- Photoproduction of exclusive $2\pi^+2\pi^-$ final states is measured for the first time at HERA.
- The W and t dependencies are similar to previous $\rho(770)$ measurement.
- Mass distribution indicates, that the reaction proceeds predominantly via ρ' production and decay. More sophisticated mass fits are being worked on to distinguish one- from two-resonance hypotheses.
- An extension to DIS regime is in progress, with the aim to investigate Q^2 dependence for the ratio $R(\rho'/\rho)$.

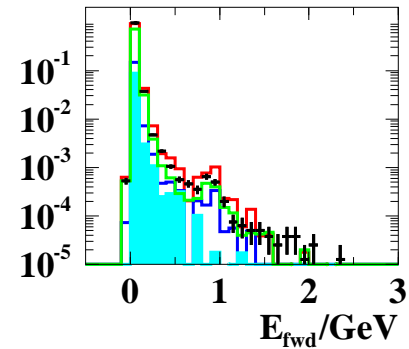
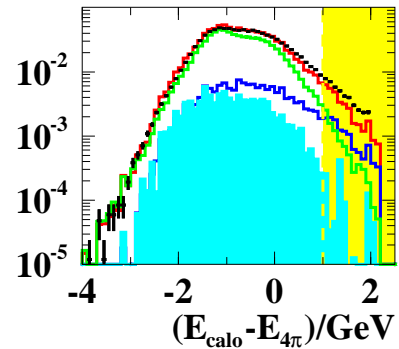
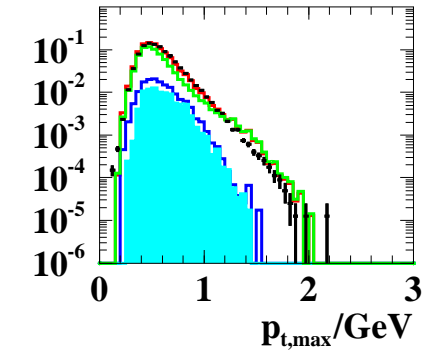
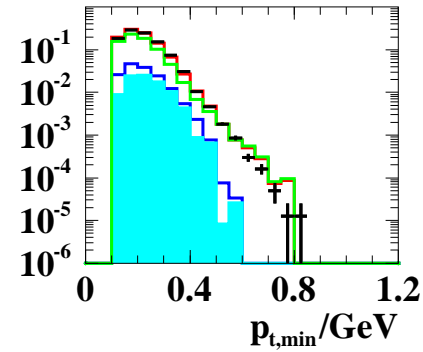
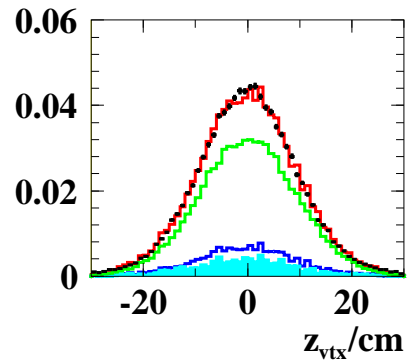
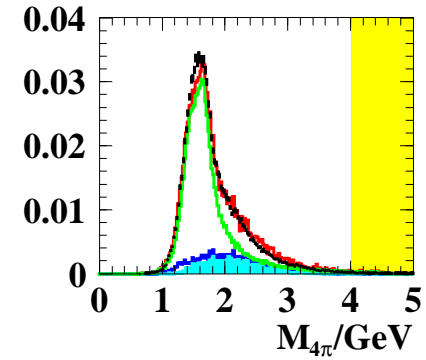
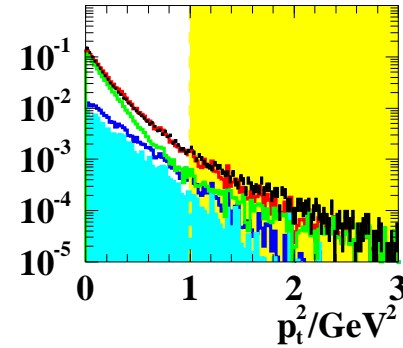
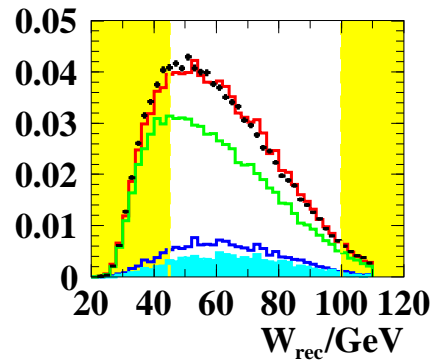
Backup Slides

Basic Control Plots (LE)



Green band represents ($4\pi + X$) background subtraction systematics only

Control Plots (HE)



Normalised plots: $1/N \frac{dN}{dx}$

- + H1 preliminary (HE)
- MC: $\rho(1450)+\rho(1700)+4\pi$
- MC: $(4\pi+X)$ background
- MC: non-resonant 4π
- MC: $\rho(1450)+\rho(1700)$

Acceptances in HE PHP regime

