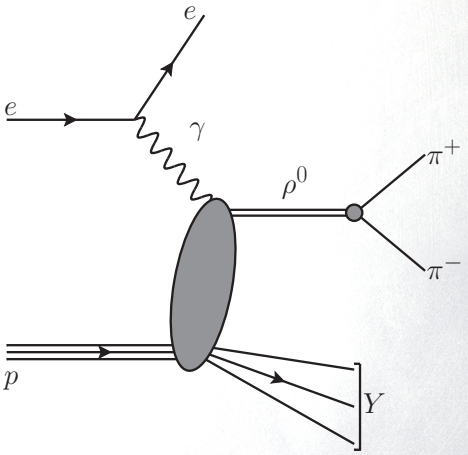
Exclusive $\pi^+\pi^-$ and $\rho(770)$ Meson Photoproduction at HERA

Overview

- measurement of $\pi^+\pi^-$ photoproduction at HERA
- modelling of the $m_{\pi\pi}$ spectrum
- extraction of $\rho(770)$ cross sections w/ kinematic dependences
- extraction of the leading Regge trajectory
- outlook: ρ' meson photoproduction

- Eur.Phys.J.C 80 (2020) 12, 1189



Arthur Bolz (DESY)
for the H1 Collaboration

MESON 2021 | Virtual
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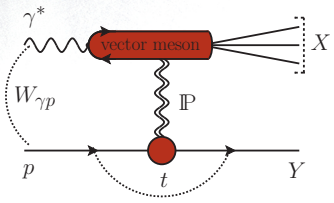
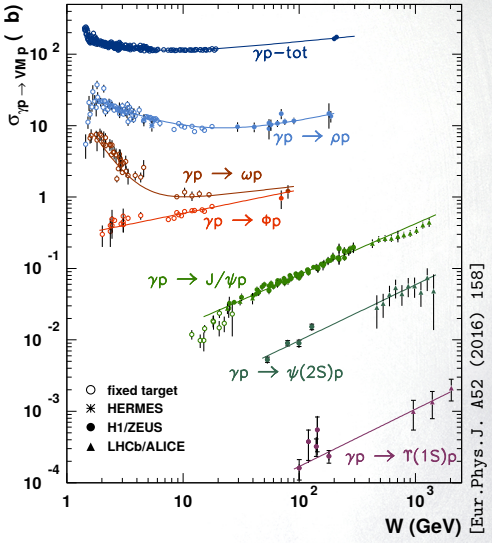
Vector Meson Photoproduction



- $\gamma \to q\bar{q}$ fluctuations $\to$ bound states
- $J^{PC}(\gamma) = 1^{--} \to$ vector mesons $(\rho^0, \omega, \phi, \dots)$
- long lifetime $\to$ strong interaction: $\sigma(\gamma \text{ had}) \sim \sigma(\text{had had})$

Soft diffraction

- color singlet exchange:
  - $\to$ Regge picture: low-erg. $\mathbb{R}$egeons, high-erg. $\mathbb{P}$omeron
  - $\to$ experimental: large rapidity gaps (e.g. between X and Y)
- cross section cms energy dependence: $\boldsymbol{\sigma(W_{\gamma p}) \sim W_{\gamma p}{}^{\delta}}$
  - $\to$ related to Regge trajectories: $\boldsymbol{\delta(t) = 4(\alpha_{\mathbb{P}}(t) - 1)}$
- momentum transfer at p-vertex t: $\boldsymbol{d\sigma/dt(t) \sim e^{-b|t|}}$



$\to$ HERA: $20 \lesssim W_{\gamma p} \lesssim 300$ GeV $\leftarrow$

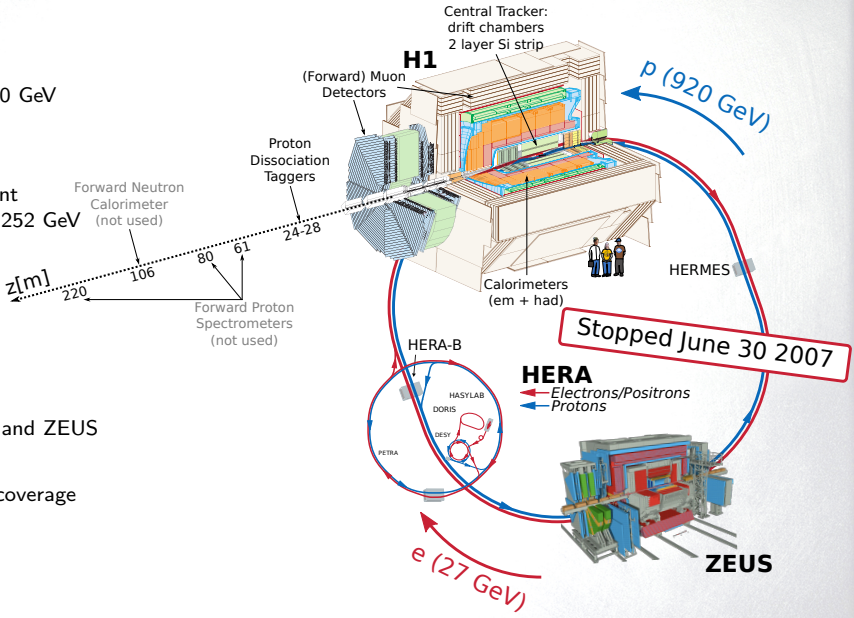
HERA $e^{\pm}p$ Collider at DESY

HERA:

- world's only ep collider
- $E_e = 27.6$ GeV, max $E_p = 920$ GeV
- max $\sqrt{s} = 319$ GeV
- e^+p and e^-p data
- $\mathcal{L}_{int} \sim 0.5$ fb^{-1} per experiment
  + datasets at $\sqrt{s} = 225$ and 252 GeV

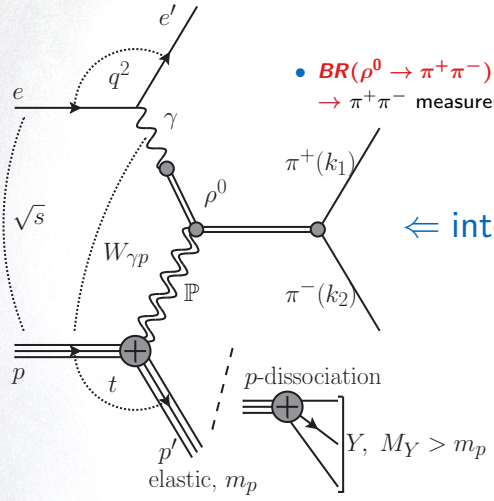
Detectors

- two collider experiments: H1 and ZEUS
- multi-purpose detectors
- $\sim 4\pi$ calorimeter (em&had) coverage
- tracking in central region
- forward detectors



Diffractive $\rho^0 \to \pi^+\pi^-$ Photoproduction at HERA

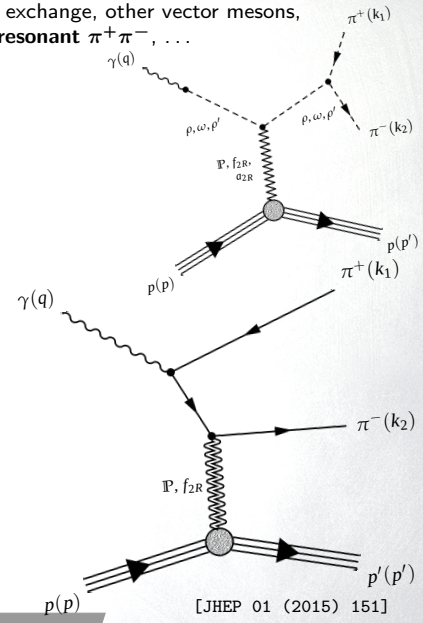
- **electro- → photoproduction**
  $Q^2 = -q^2 \to 0$ GeV^2 with quasi-real γ



- ***BR*($\rho^0 \to \pi^+\pi^-$) ∼ 100%**
  → $\pi^+\pi^-$ measurement

⇐ interference ⇒

- **other contributions to $\pi^+\pi^-$**
  $\gamma, \mathbb{R}$ exchange, other vector mesons,
  non-resonant $\pi^+\pi^-$, . . .



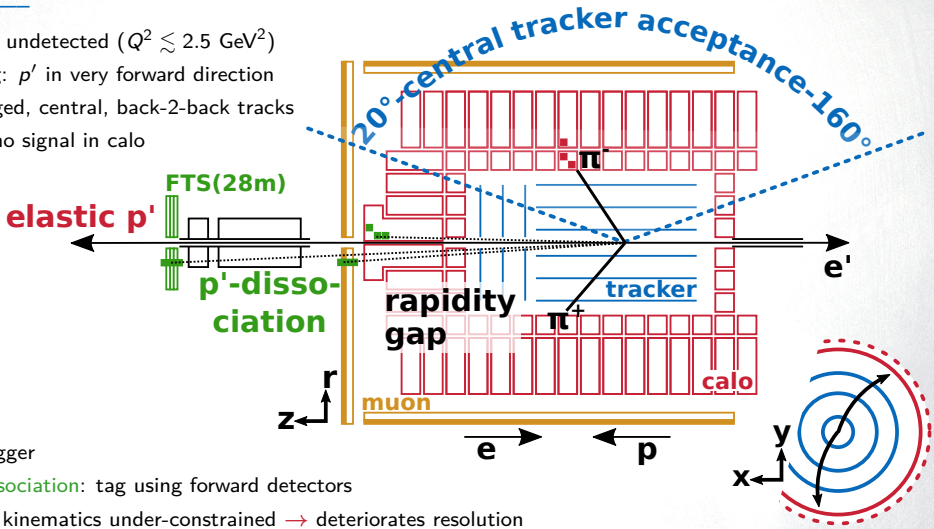
[JHEP 01 (2015) 151]

- **elastic scattering** vs **proton dissociating**
  dissociation: $p'^2 = M_Y^2 > m_p^2$ → dominates at large $|t|$

$\pi^+\pi^-$ Photoproduction in H1

Event topology

- photoproduction: e' undetected ($Q^2 \lesssim 2.5$ GeV^2)
- diffractive scattering: p' in very forward direction
- two oppositely charged, central, back-2-back tracks
- $p_T \lesssim 1$ GeV: often no signal in calo



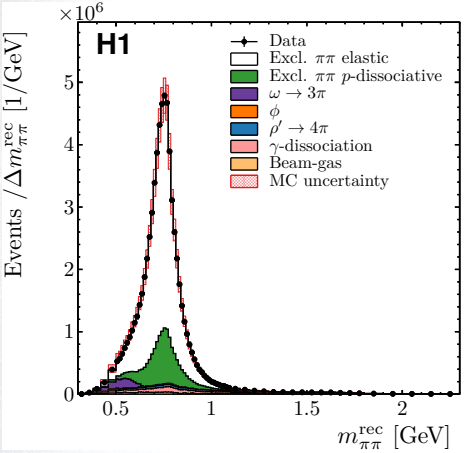
Challenges

- trigger: L1 track trigger
- elastic vs proton-dissociation: tag using forward detectors
- $Q^2 > 0$, $M_Y \neq m_p$: kinematics under-constrained $\rightarrow$ deteriorates resolution
- tracker acceptance: many (small) backgrounds

Data Set - MC Modelling

- $\sqrt{s} = 319$ GeV 2006/2007 positron data set
- $\mathcal{L} \simeq 1.3$ pb^{-1} (downscaled trigger)
- $\sim 9 \cdot 10^5$ selected $\pi^+\pi^-$ events

$m_{\pi\pi}$



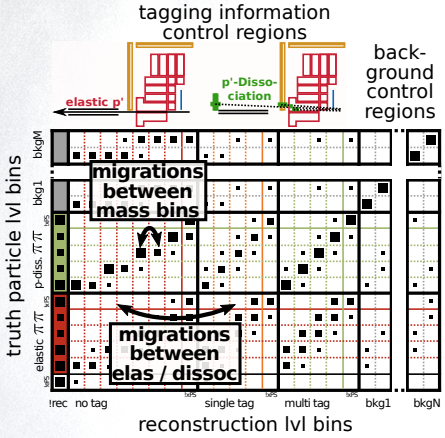
Modelling by DIFFVM MC

- $\pi^+\pi^-$ **signal:** elastic & proton-dissociative
  → tuned to data in $W_{\gamma p}$, $m_{\pi\pi}$, t
  → models also ω, ρ', non-resonant → $\pi^+\pi^-$ contributions

- **backgrounds:**
  → $\omega \to \pi^+\pi^-\pi^0$
  → $\phi \to K^+K^-$, $K_S K_L$, $\pi^+\pi^-\pi^0$, $\rho\pi$, $\eta\gamma$
  → $\rho' \to \rho\pi\pi$, $\pi\pi\pi\pi$
  → γ-dissociation → hadrons via JETSET

- **proton-dissociation:**
  → $\mathrm{d}\sigma^{\gamma p}/\mathrm{d}M_Y^2 \propto (1/M_Y^2)^\delta \otimes$ measured resonance structure
  → $M_Y < 1.9$ GeV : N^* resonance with measured decay channels
  $M_Y > 1.9$ GeV : $p' \to$ hadrons via JETSET

Unfolding particle-level cross sections:



- subtract backgrounds
- correct signal for detector efficiency and resolution
- **separate elastic from dissociative contributions**
- regularized template fit using TUnfold

Reduced fiducial phasespace

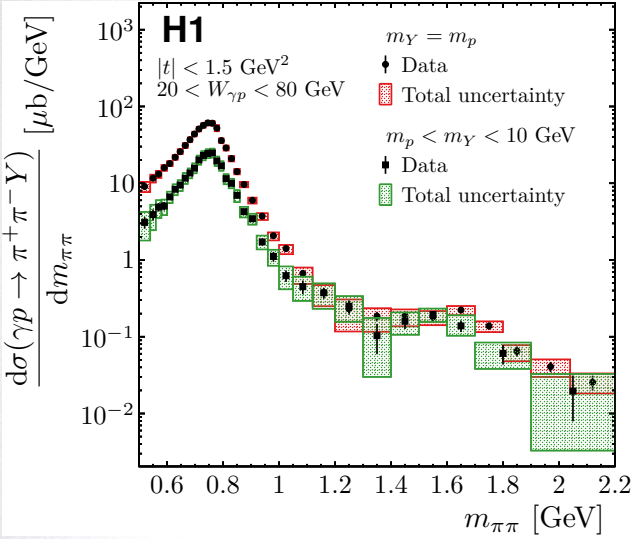
0.5 GeV	$<$	$m_{\pi\pi}$	< 2.2	GeV
20 GeV	$<$	$W_{\gamma p}$	< 80	GeV
		$\lvert t\rvert$	< 1.5	GeV^2
		Q^2	< 2.5	GeV^2
elastic:				
		M_Y	$= m_p$	GeV
p-dissociative:				
m_p	$<$	M_Y	< 10	GeV

Photoproduction cross section

$$\frac{\mathrm{d}^2\sigma(\gamma p \to \pi^+\pi^- Y)}{\mathrm{d}m_{\pi\pi}\mathrm{d}t}(m_{\pi\pi}, t;\, W_{\gamma p}) = \frac{N_{\mathrm{unf}}(\gamma^* p \to \pi^+\pi^- Y)}{\Delta m_{\pi\pi}\, \Delta t\, \mathcal{L}_{\mathrm{int}}\, \Phi^{\mathrm{eff}}_{\gamma/e}}$$

- effective flux $\Phi^{\mathrm{eff}}_{\gamma/e}$ correction: $\boldsymbol{Q^2 < 2.5\ \mathrm{GeV}^2 \to Q^2 = 0}$
- Weizsäcker-Williams and VDM approach

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



Fiducial cross section:

	σ[μb]	stat.[μb]	syst. [μb]
$m_Y = m_p$	11.52	± 0.06	$^{+0.76}_{-0.78}$
$m_p < m_Y < 10$ GeV	4.68	± 0.06	$^{+0.62}_{-0.64}$

systematic uncertainties:

	Rel. σ uncertainty [%]	
Source of uncertainty	$m_Y = m_p$	$m_p < m_Y < 10$ GeV
Statistical	0.5	1.2
Trigger	4.1	5.3
Tracking	1.4	1.3
Momentum scale	0.1	0.1
Calorimeter	1.5	7.3
Tagging	2.0	8.4
Normalisation	3.9	3.9
MC model (m_Y, Q^2, bgr.)	2.0	2.7
MC model ($m_{\pi\pi}$, $W_{\gamma p}$, t)	0.1	0.4
Total	6.6	13.3

Extraction of ρ^0 Contribution $\sigma(\gamma p \to \boldsymbol{\rho^0} Y)$

Söding-inspired model

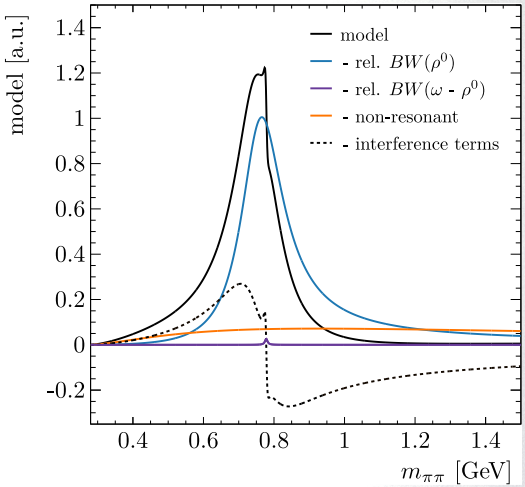
- $\sigma(\pi^+\pi^-)$: ρ^0, $\omega(782)$, and non-resonant contributions (...)
- fit $\mathrm{d}\sigma(\gamma p \to \pi^+\pi^- Y)/\mathrm{d}m_{\pi\pi}$ ($m_{\pi\pi}$) with interference model
- $0.6 \leq m_{\pi\pi} \leq 1$ GeV

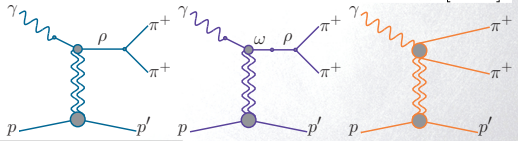
$$\frac{\mathrm{d}\sigma(\gamma p \to \pi^+\pi^- p)}{\mathrm{d}m_{\pi\pi}} \propto \left| A_{\rho,\omega}(m_{\pi\pi}) + A_{non-res}(m_{\pi\pi}) \right|^2$$

- ρ^0 und ω: relativistic Breit-Wigners
- $\omega \to \pi^+\pi^-$ only via ω-ρ mixing (G-parity: $\omega \to \pi^+\pi^-\pi^0$)
- phenomenological non-resonant background (not pQCD)

ρ^0 cross section

$$\sigma(\gamma p \to \rho^0 p) :\sim \int_{2m_\pi}^{m_\rho + 5\Gamma_\rho} \left| A_\rho(m_{\pi\pi}) \right|^2 \mathrm{d}m_{\pi\pi}$$

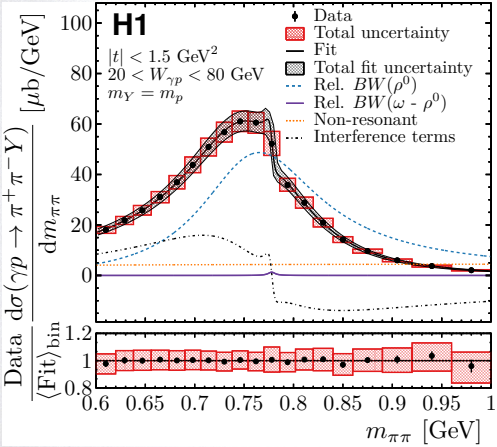


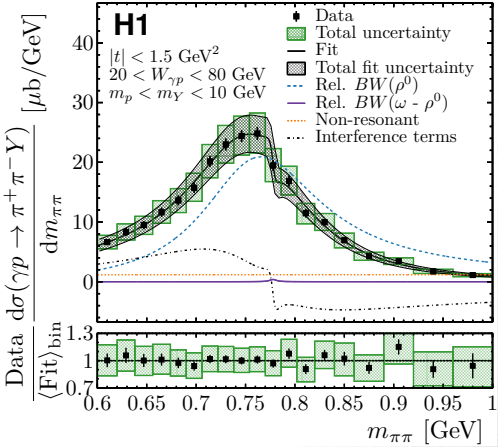


1D $m_{\pi\pi}$ Distributions Fit Results

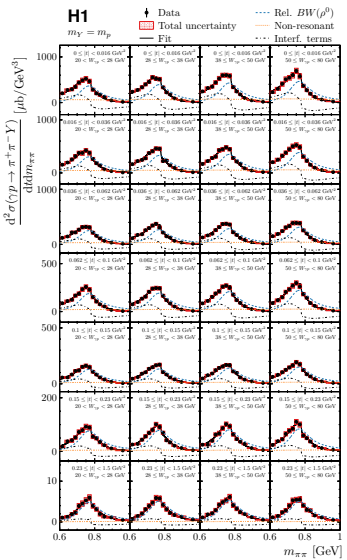
- fit elastic and p-dissociative together
- different non-resonant contributions → shape differences

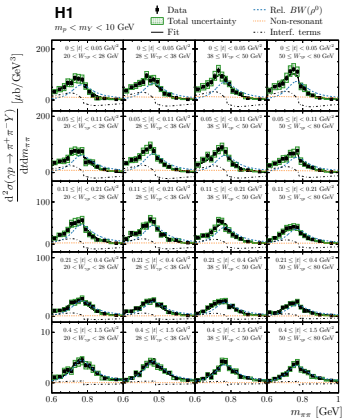
	measured	PDG	
m_ρ[MeV]	$770.8 \pm 1.3^{+2.3}_{-2.4}$	769.0 ± 1.0	(γp)
Γ_ρ [MeV]	$151.3 \pm 2.2^{+1.6}_{-2.8}$	151.7 ± 2.6	(γp)
m_ω [MeV]	$777.9 \pm 2.2^{+4.3}_{-2.2}$	782.7 ± 0.1	(e^+e^-)





Extraction of Kinematic ρ^0 Cross Section Dependences



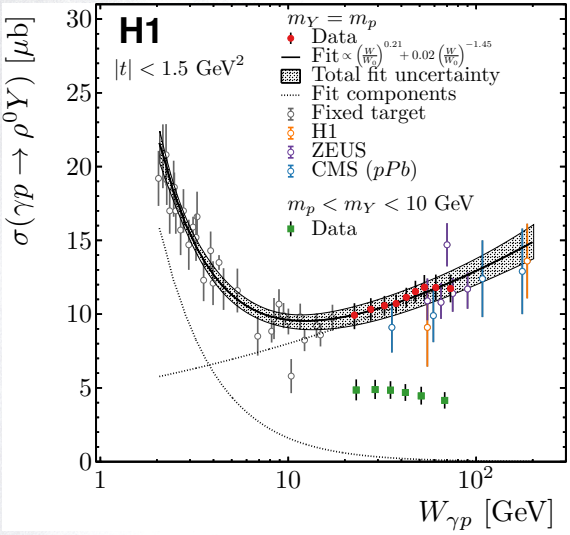


i) unfold elastic (p-dissociative) $m_{\pi\pi}$ distributions in
- → 9 (6) $W_{\gamma p}$,
- → 12 (9) t, and
- → 4×7 (4×5) $W_{\gamma p} \times t$ bins (displayed)

ii) fit $m_{\pi\pi}$ lineshape model
- → to all $m_{\pi\pi}$ distributions simultaneously
- → assumptions on parameter dependences
- → displayed fit: 65 parameters

iii) integrate ρ^0 component
- → propagate uncertainty correlations

Energy Dependence of ρ^0 Cross Section $\sigma(\gamma p \to \rho^0 Y)$



Parametrization and fit

- **this measurement: $\sigma \propto W^{\delta}$:** ($20 < W_{\gamma p} < 80$ GeV)
  → fit elastic & dissociative together

  $\delta_{\text{el}} = +0.171 \pm 0.009\ ^{+0.039}_{-0.026}$

  $\delta_{\text{pd}} = -0.156 \pm 0.026\ ^{+0.081}_{-0.079}$

- $\delta_{\text{pd}} \neq \delta_{\text{el}}$:
  → phasespace shaping by $m_Y < 10$ GeV cut!
  → suppresses high $W_{\gamma p}$ stronger than low $W_{\gamma p}$

- **all elastic data: $\sigma \propto W^{\delta_{\mathbb{P}}} + f\, W^{\delta_{\mathbb{R}}}$:** (displayed)

  $\delta_{\mathbb{P},\text{el}} = +0.207 \pm 0.015\ ^{+0.053}_{-0.033}$

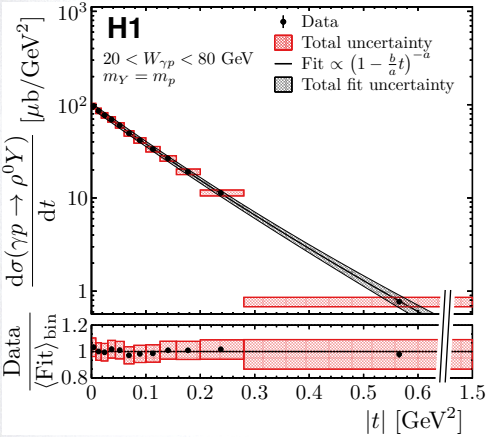
  $\delta_{\mathbb{R},\text{el}} = -1.45 \pm 0.12\ ^{+0.35}_{-0.21}$

- $\delta_{\mathbb{P},\text{el}} > \delta_{\text{el}}$:
  → Reggeon contribution in present analysis range?
  → $O(2\%)$ at $W_0 = 40$ GeV

Parametrization and fit

- $\mathrm{d}\sigma/\mathrm{d}t \propto \left(1 - \frac{bt}{a}\right)^{-a}$
  - → small $|t|$: $\sim \exp(b\,t)$
  - → large $|t|$: $\sim |t|^{-a}$

- fit elastic & dissociative in simultaneously
  - → independent parameters
  - → bin-centre correction via function bin-averaging
- both components deviate from exponential in considered range
- *stronger deviation* (smaller a) for *harder* dissociative spectrum

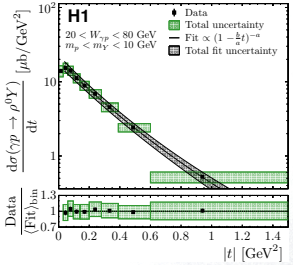


$b_{\mathrm{el}} = 9.59 \pm 0.10\,^{+0.17}_{-0.12}$ GeV^{-2}

$a_{\mathrm{el}} = 19.8 \pm 2.7\,^{+4.9}_{-4.7}$

$b_{\mathrm{pd}} = 4.79 \pm 0.19\,^{+0.37}_{-0.39}$ GeV^{-2}

$a_{\mathrm{pd}} = 9.1 \pm 1.5\,^{+3.1}_{-2.4}$



Regge fit ρ^0 Cross Section as Function of $W_{\gamma p}$ and t

2D Regge fit

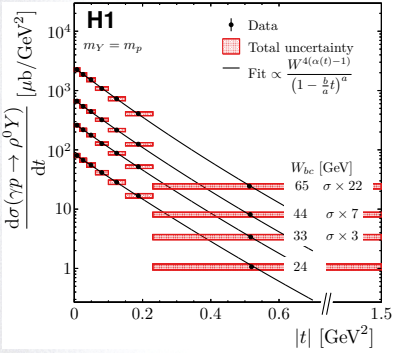
- parametrization $\propto (1 - bt/a)^{-a}\, W_{\gamma p}^{4(\alpha(t)-1)}$
- $\alpha(t) = \alpha_0 + \beta\left((\exp(-4\alpha_1/\beta) + 1)^{-1} - 1/2\right)$
  - → is linear $\alpha_0 + \alpha_1 t$ at small $|t|$
  - → becomes constant $\alpha_0 \pm \beta/2$ for $t \to \pm\infty$
  - → curves in right plots

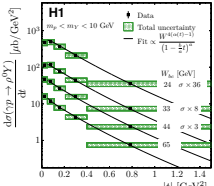
elastic ⇒ leading trajectory parameters:

α_0	= 1.0654	± 0.0044	$^{+0.0088}_{-0.0050}$	
α_1	= 0.233	± 0.064	$^{+0.020}_{-0.038}$	GeV^{-2}
β	= 0.164	± 0.068	$^{+0.051}_{-0.045}$	

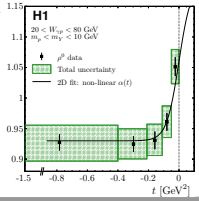
For visualization

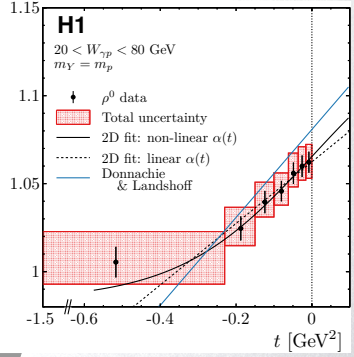
- 1D fit $\propto W_{\gamma p}^{4(\alpha_t - 1)}$ with free α_t in all t bins
  - → data points in right plots



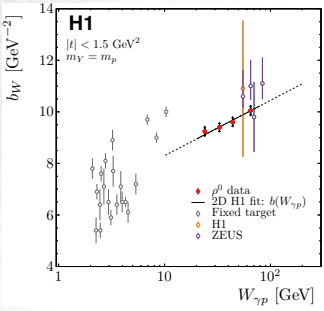


(shaped by fiducial phase space cuts)





Summary

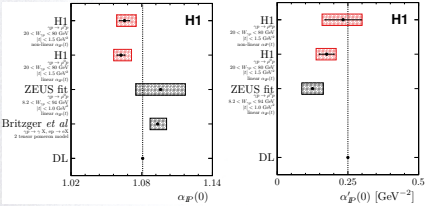


ρ^0 photoproduction at H1/HERA

- measured up to three-dimensional $\pi^+\pi^-$ cross sections at high precision
- elastic and proton-dissociative component
- extracted 1D & 2D ρ^0 distributions via fit model
- interpreted ρ^0 cross sections with fits

Leading Regge trajectory

- determine precise leading trajectory from single experiment
- alternative interpretation: shrinkage of forward peak (displayed)
- potential reggeon contribution $\Rightarrow$ $\alpha_{I\!P}(t)$ or $\alpha_{I\!P+I\!R}(t)$?
- indication for non-linear effects at large $|t|$ but not significant



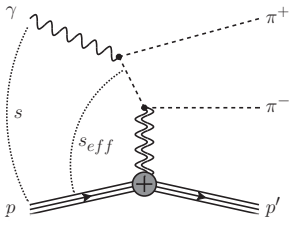
Publication:

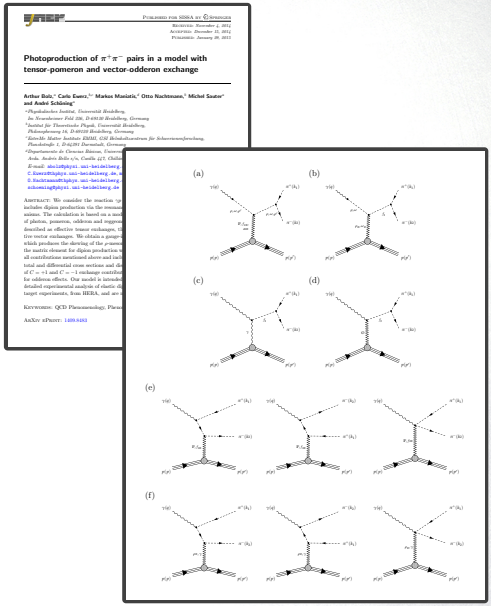
- Eur.Phys.J.C 80 (2020) 12, 1189
- e-print: arxiv:2005.14471 [hep-ex]
- data: H1 webpage or via HEPData (soon)

Excursion I: Towards Better Modeling

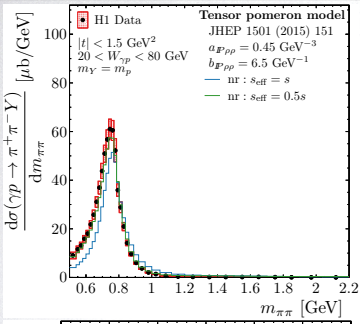
Tensor pomeron + vector odderon model

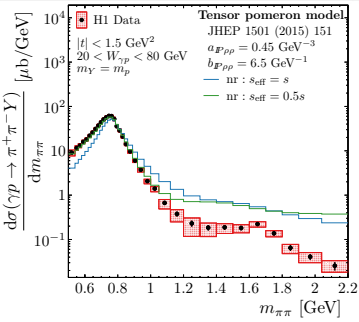
- by C. Ewerz, M. Maniatis and O. Nachtmann
  [Annals Phys. 342 (2014) 31]
- applied to $\pi^+\pi^-$ photoproduction already in 2014
  [JHEP 01 (2015) 151]
- here: (private) comparison to H1 data
- modification of non-resonant amplitudes to describe ρ^0 peak:
  $\rightarrow$ "effective" average $\pi - p$ scattering energy $s_{\text{eff}} \simeq \frac{s}{2}$

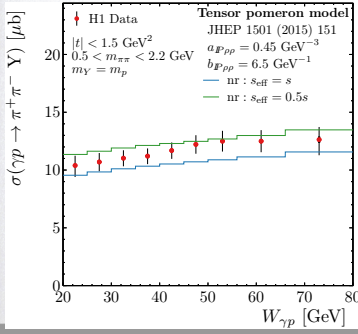


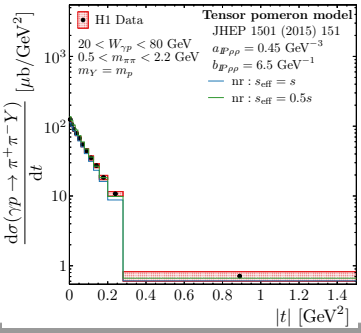


Excursion I: Towards Better Modeling









- "out-of-the-box" good description of ρ^0 peak
- including features such as ω edge
- gauge-invariant skewing mechanism
- reasonable description of $W_{\gamma p}$ and t shapes

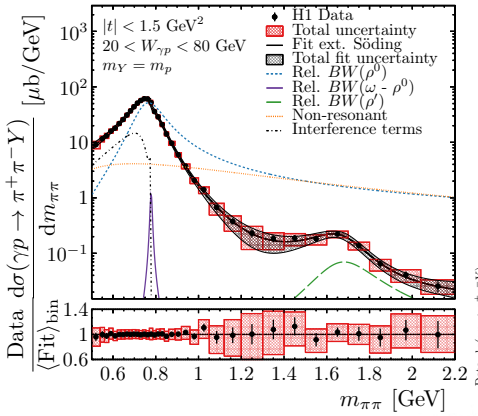
- modeling break-down at higher $\pi^+\pi^-$ masses
- tuning of model parameters needed
- model also predicts $\pi^+\pi^-$ decay angles
- dedicated data analysis needed to get further insight

Excursion II: A Rho Prime Primer $\rho' \to \pi^+\pi^-$

Fit of full mass range
(private fit)

$$\frac{\mathrm{d}\sigma(\gamma p \to \pi^+\pi^- p)}{\mathrm{d}m_{\pi\pi}} \propto \left| A_{\rho,\omega}(m_{\pi\pi}) + \mathrm{e}^{i\phi_{nr}} A_{non-res}(m_{\pi\pi}) + A_{\rho'}(m_{\pi\pi}) \right|^2$$

- above model extended by:
  - → non-zero non-resonant phase
  - → single Breit-Wigner ρ' contribution
- $m_{\rho'} \sim 1.69$ GeV
- $\Gamma_{\rho'} \sim 0.29$ GeV
- $\sigma_{\gamma p \to \rho'(\to \pi^+\pi^-)p} \sim 0.03\ \mu$b
  - → $\sim 0.3\ \% \cdot \sigma_\rho$
  - → $\sim 25\ \% \cdot \sigma_{\pi^+\pi^-|m_{\pi\pi} \geq 1.2\ \mathrm{GeV}} \sim 0.13\ \mu$b
- no model systematics evaluated!



- $m_{\pi\pi}$ lineshape fit with two ρ' resonances, $\rho(1450)$ and $\rho(1700)$, does not give stable results

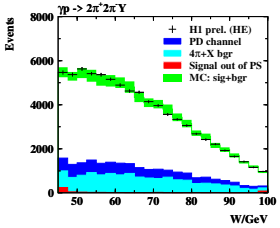
Excursion II: Independent $\rho' \to 2\pi^+2\pi^-$ Analysis

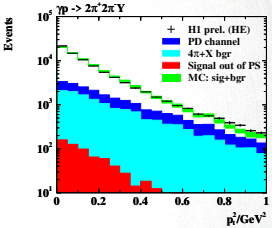
—— Preliminary 2018 results ——

[H1prelim-18-011]

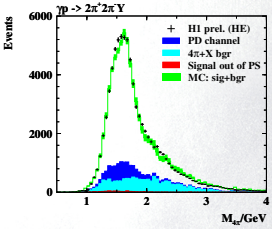
- two data samples:
  → high energy $\sqrt{s} = 319$ GeV: $L_{\text{int}} = 7.6\text{pb}^{-1}$
  → high energy $\sqrt{s} = 225$ GeV: $L_{\text{int}} = 1.7\text{pb}^{-1}$
- events with four tracks (net charge zero)
- veto electrons and other energy deposits not associated with tracks
- veto on signals in the forward muon and proton dissociation tagger

		$\lvert t\rvert$	< 1	GeV^2
		Q^2	< 2	GeV^2
		M_Y	< 1.6	GeV
LE data				
35 GeV	$<$	$W_{\gamma p}$	< 75	GeV
HE data				
45 GeV	$<$	$W_{\gamma p}$	< 100	GeV





- control plots (high-E) $W_{\gamma p}$, p_T^2, $M_{4\pi}$
- $\sim 15\%$ backgrounds
- $\sim 10\%$ p-dissoc. events w/ $M_Y < 1.6$ GeV



Excursion II: $2\pi^+2\pi^-$ Cross Section

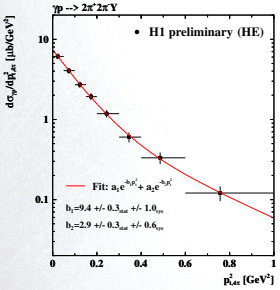
Fiducial inclusive cross section

- correct data for acceptance
- correct to $Q^2 = 0$
- at average $W_{\gamma p} = 75$ GeV:

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

- $2\pi^+2\pi^-$ production rate is about 1/10 of $\pi^+\pi^-$

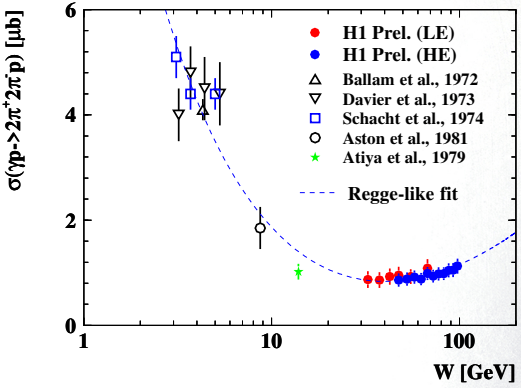
inclusive cross section vs t



- VM production typical exponential drop-off
- sum of 2 exponential
- elastic & p-dissoc. contribute with different slopes
- $b_{2\pi^+2\pi^-} \sim b_{\rho(770)}$

Elastic cross section vs $W_{\gamma p}$

- subtract p-dissoc. contribution $\rightarrow$ can compare to low-$W_{\gamma p}$ data

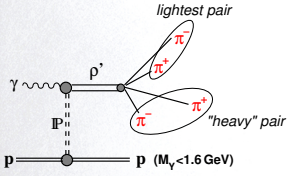


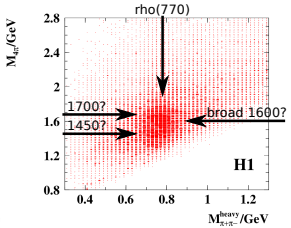
- H1 data explore higher energy & are more precise than previous measurements
- world data well described by Regge-like fit (similar to $\rho(770)$)

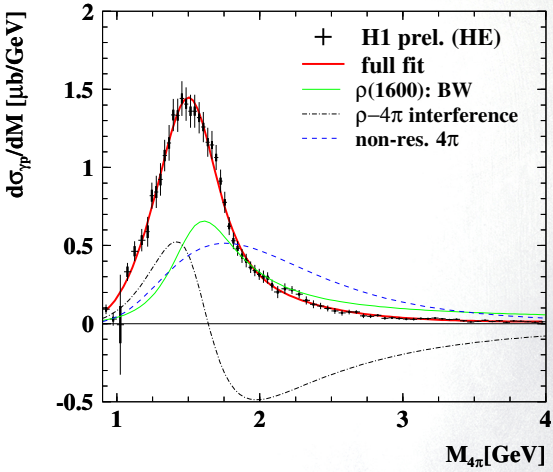
Excursion II: $\rho' \to 2\pi^+2\pi^-$ Extraction

parametrize and fit $M_{4\pi}$ distribution

- including one Breit-Wigner ρ', and non-resonant background with complex phase
- model describes data reasonably well
- data would be consistent with pre-1988 PDG knowing single $\rho(1600)$ resonance
- constraining two ρ' resonances, $\rho(1450)$ and $\rho(1700)$, more challenging and work-in-progress
- considering cascade decay $\rho' \to \rho(770)\pi^+\pi^- \to \pi^+\pi^-\pi^+\pi^-$ challenging and work-in-progress



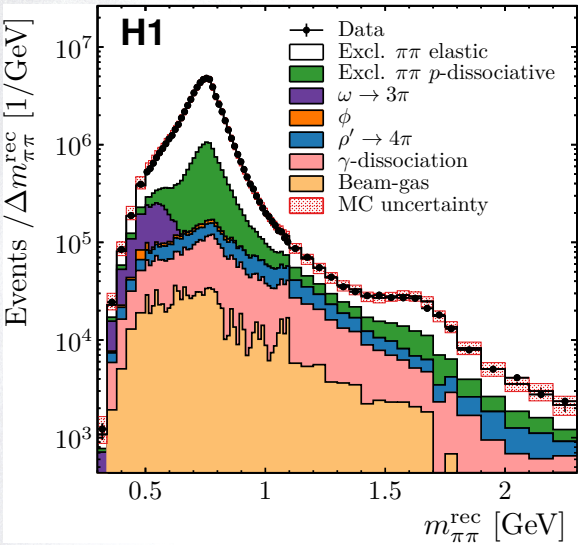




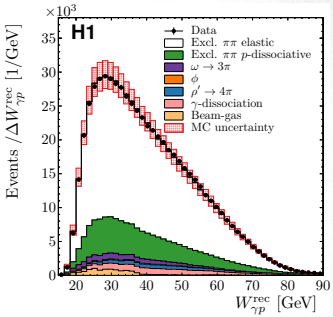
BACKUP

Data Set - Control Plots

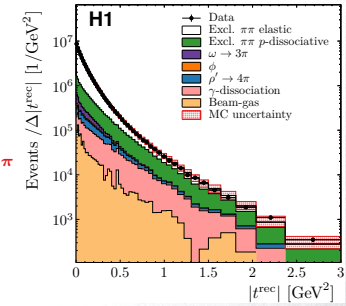
$m_{\pi\pi}$



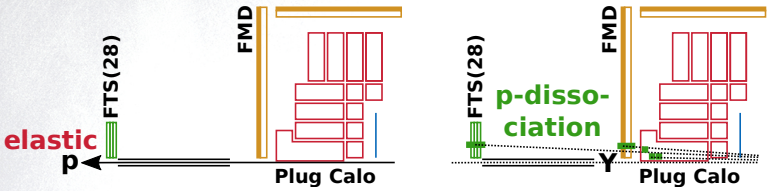
$W_{\gamma p}$



$p^2_{T,\pi\pi}$



Proton Dissociation Tagging

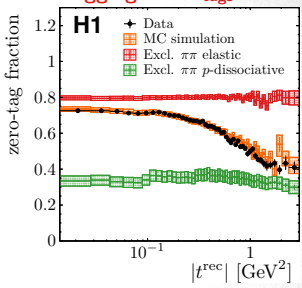


- forward detectors FTS(28m) ($\eta \lesssim 7.5$), FMD, Plug calo
- proton remnants $\Rightarrow$ induce signals $\Rightarrow$ define **"tags"**
- poor detector modeling $\Rightarrow$ "tag" = binary hit/no-hit info
- acceptance & efficiency $\Rightarrow$ limited p-dissoc. tagging rate
- noise & secondary particles $\Rightarrow$ finite elastic mistag rate
- sum possible tags $0 \leq n_{tags} \leq 3$
- 3 control regions:

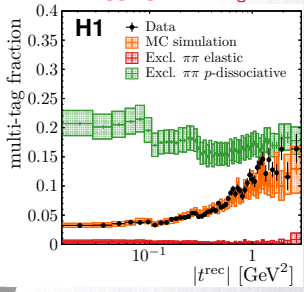
	$n_{\text{tags}} == 0$	$n_{\text{tags}} == 1$	$n_{\text{tags}} \geq 2$
N_{pd}/N	10%	36%	91%

$\Rightarrow$ normalize elas./p-dissoc. (MC) components

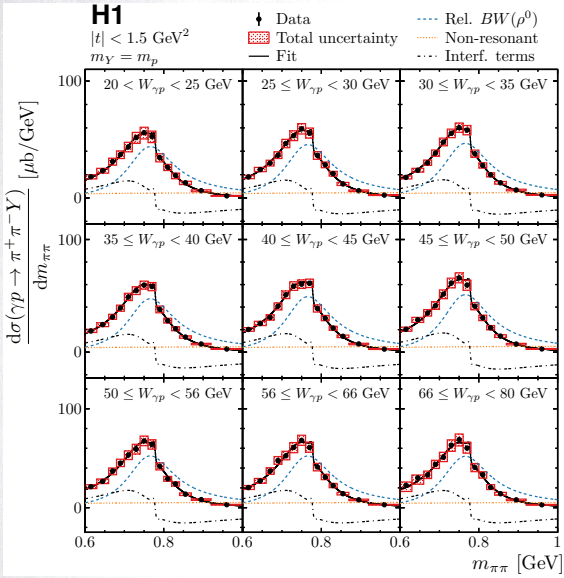
tagging rate $n_{\text{tags}} == 0$:

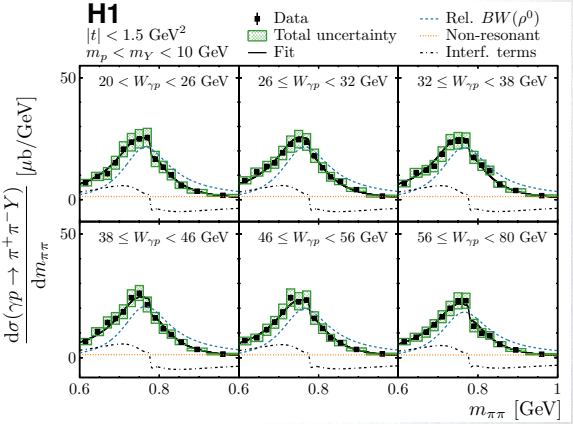


tagging rate $n_{\text{tags}} \geq 2$:



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





$d^2\sigma(\gamma p \to \pi^+\pi^- Y)/dm_{\pi\pi}dt$ ($m_{\pi\pi}$) in t Bins