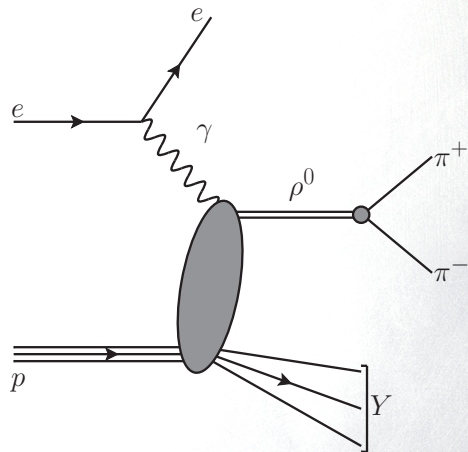


Overview

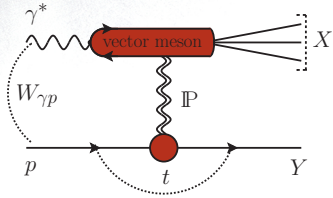
- measurement of $\pi^+\pi^-$ photoproduction at HERA
 - modelling of the $m_{\pi\pi}$ spectrum
 - extraction of $\rho(770)$ cross sections w/ kinematic dependences
 - extraction of the leading Regge trajectory
-
- submitted to EPJ C [[arxiv:2005.14471](https://arxiv.org/abs/2005.14471)]

Arthur Bolz (DESY)
for the H1 Collaboration

ICHEP 2020 | Prague
July 28 - August 6 2020



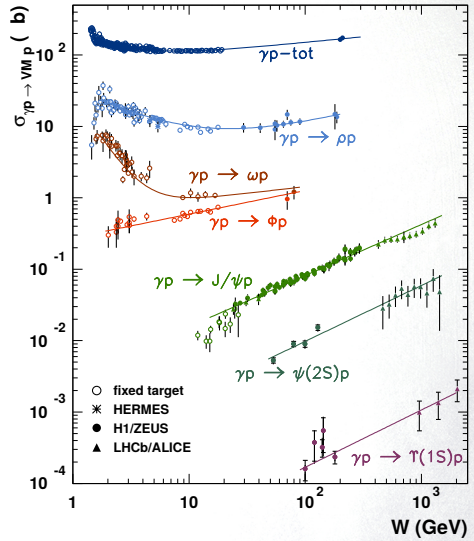
Vector Meson Photoproduction



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

Soft diffraction

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



- HERA: $20 \lesssim W_{\gamma p} \lesssim 300 \text{ GeV}$

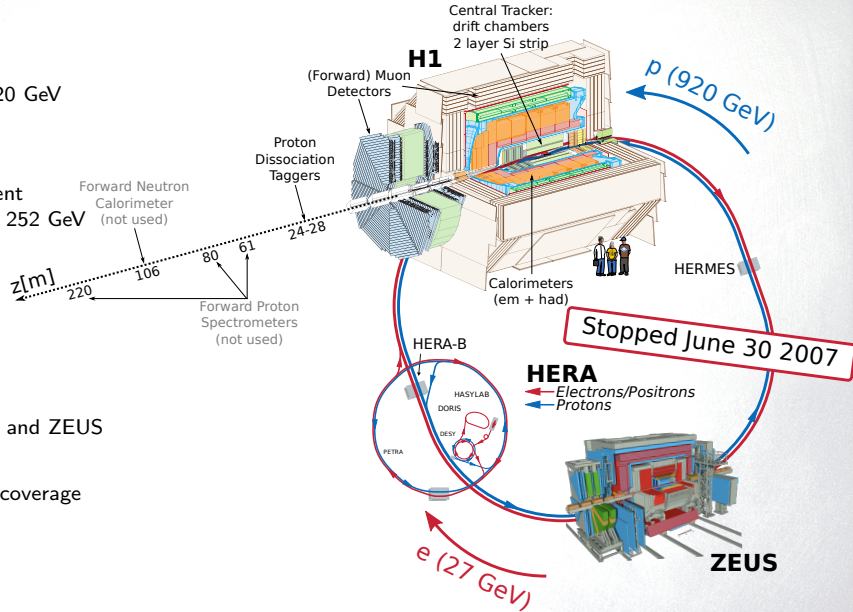
[Eur. Phys. J. A52 (2016) 158]



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
- $\mathcal{L}_{int} \sim 0.5 \text{ fb}^{-1}$ per experiment
+ datasets at $\sqrt{s} = 225$ and 252 GeV



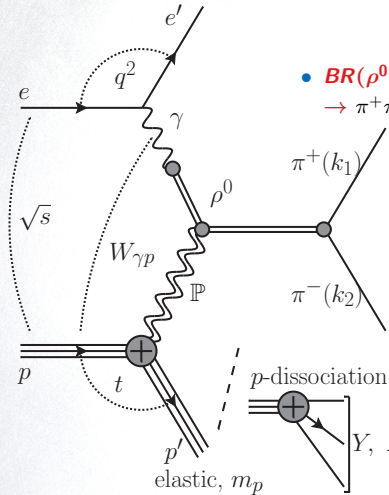
Detectors

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

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

- electro- \rightarrow photoproduction**

$Q^2 = -q^2 \rightarrow 0 \text{ GeV}^2$ with quasi-real γ



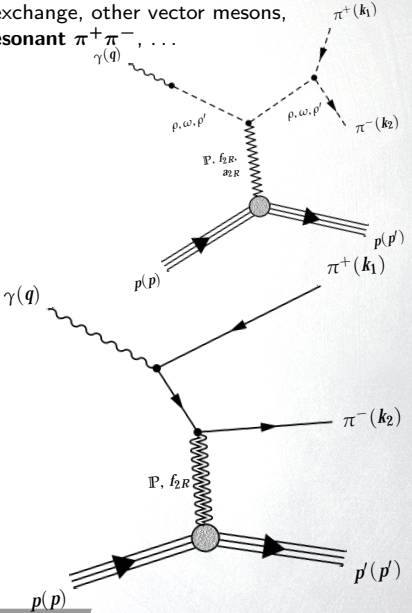
- $BR(\rho^0 \rightarrow \pi^+\pi^-) \sim 100\%$**
 $\rightarrow \pi^+\pi^-$ measurement

\Leftarrow interference \Rightarrow

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

- other contributions to $\pi^+\pi^-$**

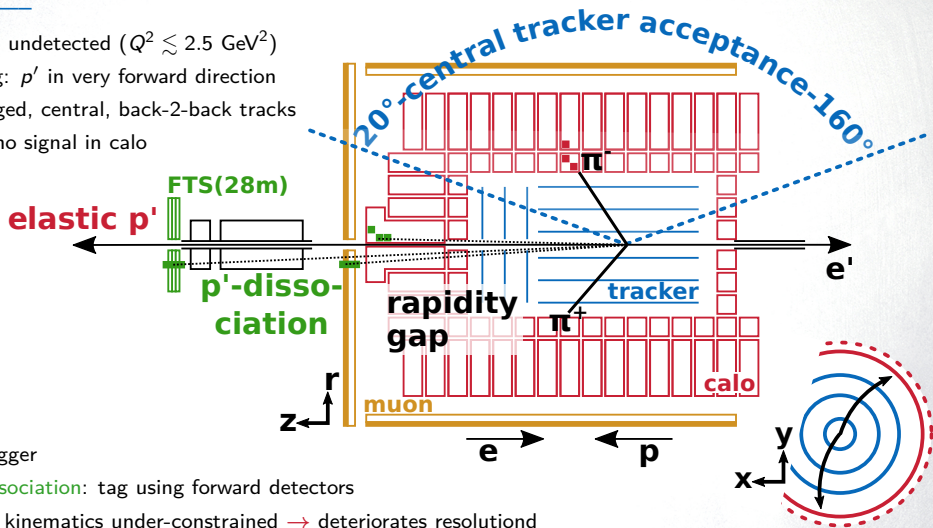
γ, \mathbb{R} exchange, other vector mesons, non-resonant $\pi^+\pi^-, \dots$



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

Event topology

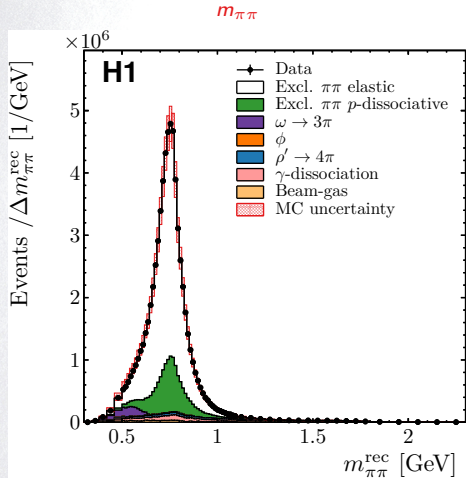
- photoproduction: e' undetected ($Q^2 \lesssim 2.5 \text{ GeV}^2$)
- diffractive scattering: p' in very forward direction
- two oppositely charged, central, back-2-back tracks
- $p_T \lesssim 1 \text{ GeV}$: often no signal in calo



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

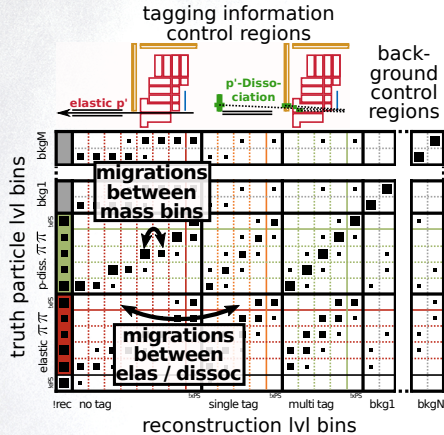
- $\sqrt{s} = 319$ GeV 2006/2007 positron data set
- $\mathcal{L} \simeq 1.3 \text{ pb}^{-1}$ (downscaled trigger)
- $\sim 9 \cdot 10^5$ selected $\pi^+\pi^-$ events



— 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:**
 - $\omega \rightarrow \pi^+\pi^-\pi^0$
 - $\phi \rightarrow K^+K^-, K_S K_L, \pi^+\pi^-\pi^0, \rho\pi, \eta\gamma$
 - $\rho' \rightarrow \rho\pi\pi, \pi\pi\pi\pi$
 - γ -dissociation → hadrons via JETSET
- **proton-dissociation:**
 - $d\sigma^{\gamma p}/dM_Y^2 \propto (1/M_Y^2)^\delta \otimes$ measured resonance structure
 - $M_Y < 1.9$ GeV : N^* resonance with measured decay channels
 - $M_Y > 1.9$ GeV : p' → 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

$$\begin{aligned}
 0.5 \text{ GeV} &< m_{\pi\pi} < 2.2 \text{ GeV} \\
 20 \text{ GeV} &< W_{\gamma p} < 80 \text{ GeV} \\
 |t| &< 1.5 \text{ GeV}^2 \\
 Q^2 &< 2.5 \text{ GeV}^2
 \end{aligned}$$

elastic:

$$M_Y = m_p \text{ GeV}$$

p-dissociative:

$$m_p < M_Y < 10 \text{ GeV}$$

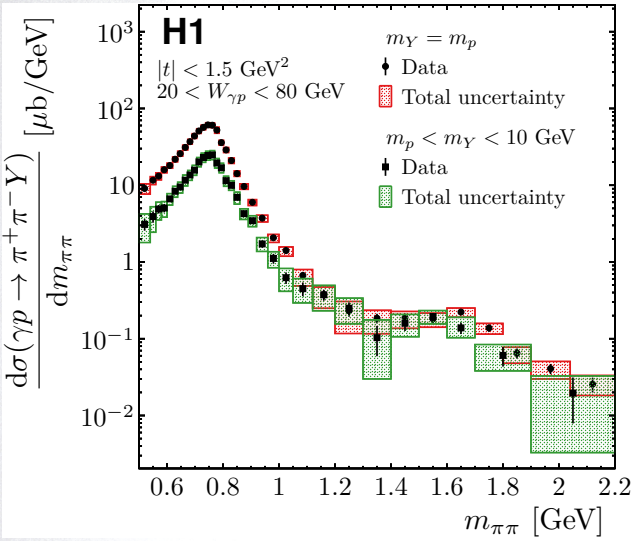
Photoproduction cross section

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

- effective flux $\Phi_{\gamma/e}^{\text{eff}}$ correction: $Q^2 < 2.5 \text{ GeV}^2 \rightarrow Q^2 = 0$
- Weizsäcker-Williams and VDM approach



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



— Fiducial cross section: —

	$\sigma [\mu\text{b}]$	stat. $[\mu\text{b}]$	syst. $[\mu\text{b}]$
$m_Y = m_p$	11.52	± 0.06	+0.76 -0.78
$m_p < m_Y < 10 \text{ GeV}$	4.68	± 0.06	+0.62 -0.64

systematic uncertainties:

Source of uncertainty	Rel. σ uncertainty [%]	
	$m_Y = m_p$	$m_p < m_Y < 10 \text{ GeV}$
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 ($m_Y, Q^2, \text{bgr.}$)	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 $\sigma(\gamma p \rightarrow \rho^0 Y)$

— Söding model —

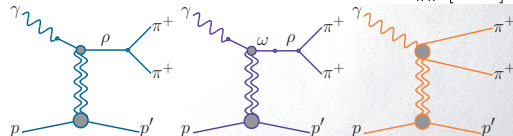
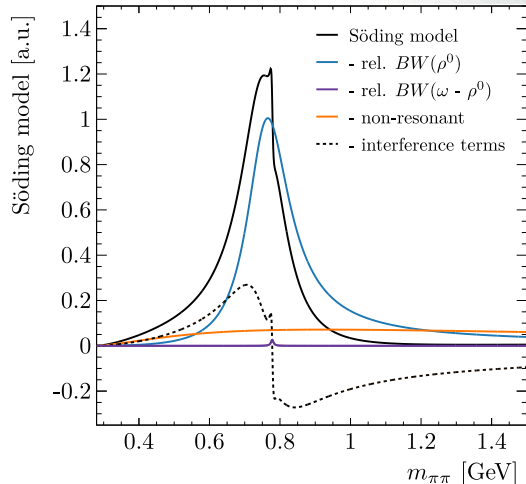
- $\sigma(\pi^+\pi^-)$: ρ^0 , $\omega(782)$, and non-resonant contributions (...)
- fit $d\sigma(\gamma p \rightarrow \pi^+\pi^- Y)/dm_{\pi\pi}$ ($m_{\pi\pi}$) with Söding model
- $0.6 \leq m_{\pi\pi} \leq 1$ GeV

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

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

— ρ^0 cross section —

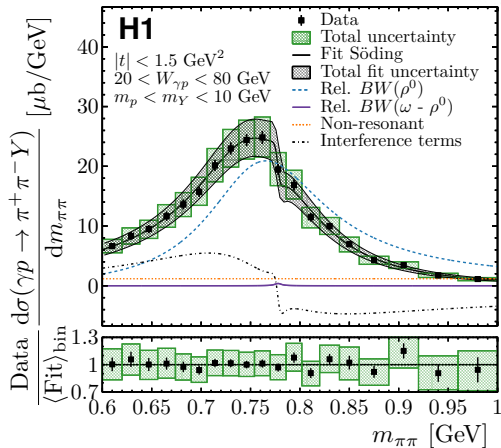
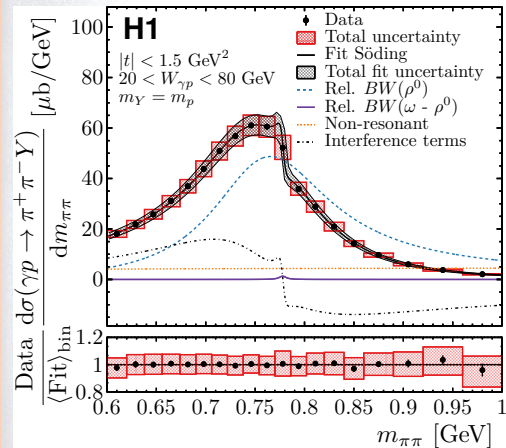
$$\sigma(\gamma p \rightarrow \rho^0 p) := \int_{2m_\pi}^{m_\rho + 5\Gamma_\rho} \left| \underline{A_\rho}(m_{\pi\pi}) \right|^2 dm_{\pi\pi}$$



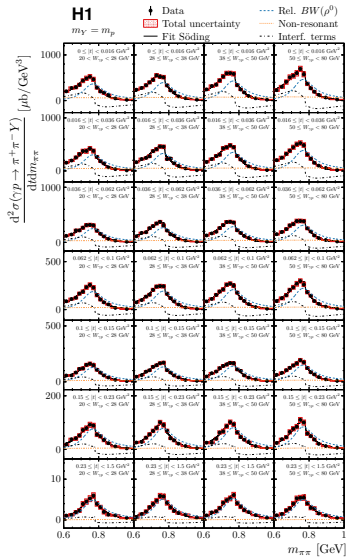
Söding Fit Results

- fit **elastic** and **ρ -dissociative** together
- different non-resonant contributions \rightarrow shape differences

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

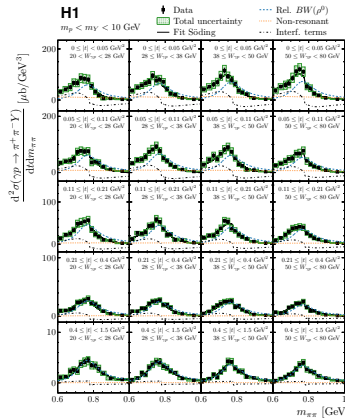


Extraction of Kinematic ρ^0 Cross Section Dependences



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)



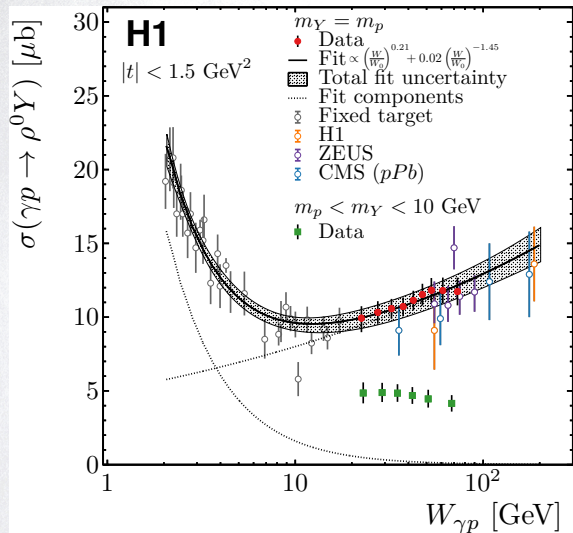
ii) fit Söding model

- 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 $\sigma(\gamma p \rightarrow \rho^0 Y)$



— Parametrization and fit —

- **this measurement:** $\sigma \propto W^{\delta}$: ($20 < W_{\gamma p} < 80 \text{ GeV}$)
 → fit **elastic** & **dissociative** together
 - $\delta_{\text{el}} = +0.171 \pm 0.009 \begin{matrix} +0.039 \\ -0.026 \end{matrix}$
 - $\delta_{\text{pd}} = -0.156 \pm 0.026 \begin{matrix} +0.081 \\ -0.079 \end{matrix}$
- $\delta_{\text{pd}} \neq \delta_{\text{el}}$:
 → phasespace shaping by $m_Y < 10 \text{ GeV}$ cut!
 → suppresses high $W_{\gamma p}$ stronger than low $W_{\gamma p}$
- **all elastic data:** $\sigma \propto W^{\delta_{\text{IP}}} + f W^{\delta_{\text{IR}}}$: (displayed)
 - $\delta_{\text{IP,el}} = +0.207 \pm 0.015 \begin{matrix} +0.053 \\ -0.033 \end{matrix}$
 - $\delta_{\text{IR,el}} = -1.45 \pm 0.12 \begin{matrix} +0.35 \\ -0.21 \end{matrix}$
- $\delta_{\text{IP,el}} > \delta_{\text{el}}$:
 → Reggeon contribution in present analysis range?
 → $O(2\%)$ at $W_0 = 40 \text{ GeV}$

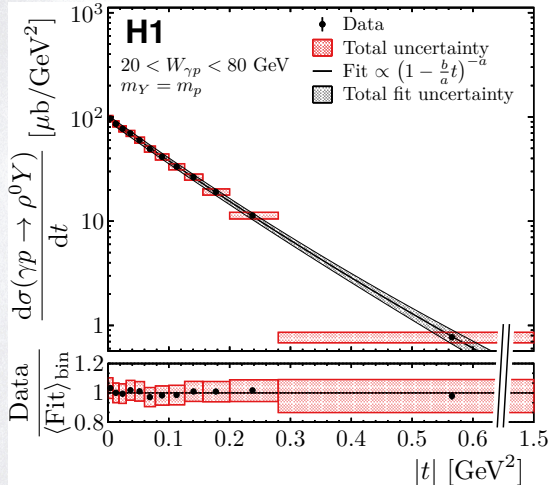


t Dependence of ρ^0 Cross Section $d\sigma(\gamma p \rightarrow \rho^0 Y)/dt$

Parametrization and fit

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

- fit **elastic** & **dissociative** in simultaneously
 - independent parameters
 - bin-centre correction via function bin-averaging

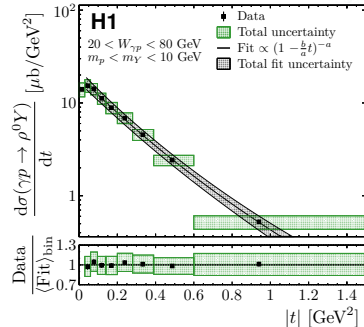


$$b_{el} = 9.59 \pm 0.10^{+0.17}_{-0.12} \text{ GeV}^{-2}$$

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

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

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



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

— 2D Regge fit —

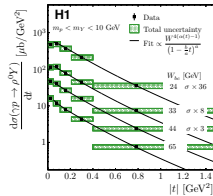
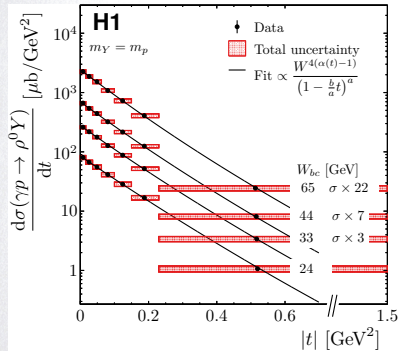
- parametrization $\propto (1 - bt/a)^{-a} W_{\gamma p}^{4(\alpha(t)-1)}$
- $\alpha(t) = \alpha_0 + \beta ((\exp(-4\alpha_1/\beta) + 1)^{-1} - 1/2)$
 - is linear $\alpha_0 + \alpha_1 t$ at small $|t|$
 - becomes constant $\alpha_0 \pm \beta/2$ for $t \rightarrow \pm\infty$
 - curves in right plots

elastic \Rightarrow leading trajectory parameters:

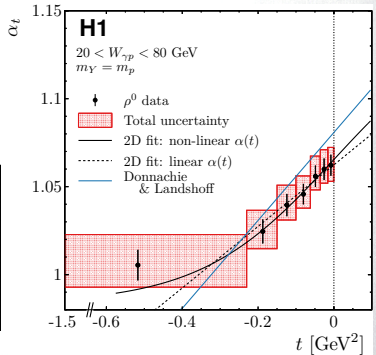
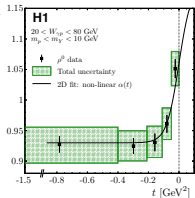
α_0	$= 1.0654 \pm 0.0044$	$+0.0088$ -0.0050	GeV^{-2}
α_1	$= 0.233 \pm 0.064$	$+0.020$ -0.038	
β	$= 0.164 \pm 0.068$	$+0.051$ -0.045	

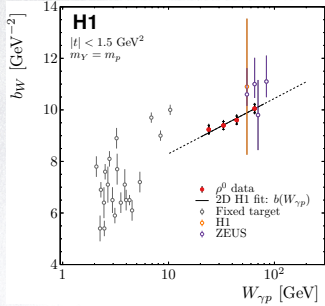
— For visualization —

- 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)



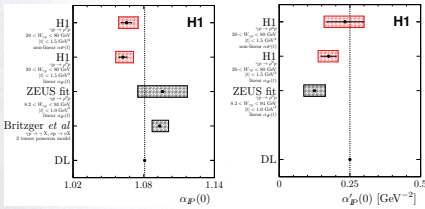


— ρ^0 photoproduction at H1/HERA —

- measured up to three-dimensional $\pi^+\pi^-$ cross sections at high precision
- **elastic** and **proton-dissociative** component
- extracted 1D & 2D ρ^0 distributions via Söding 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 $\Rightarrow \alpha_{\text{IP}}(t)$ or $\alpha_{\text{IP}+\text{IR}}(t)$?
- indication for non-linear effects at large $|t|$ but not significant



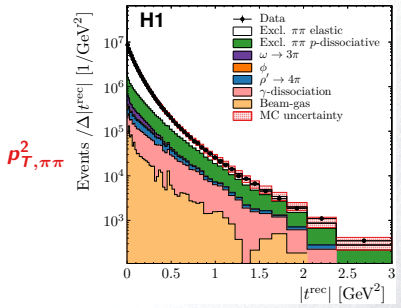
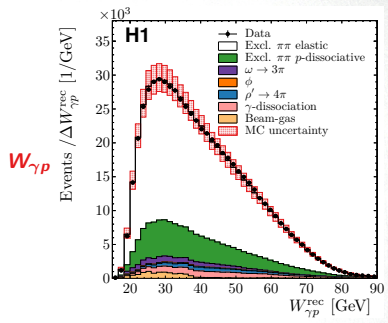
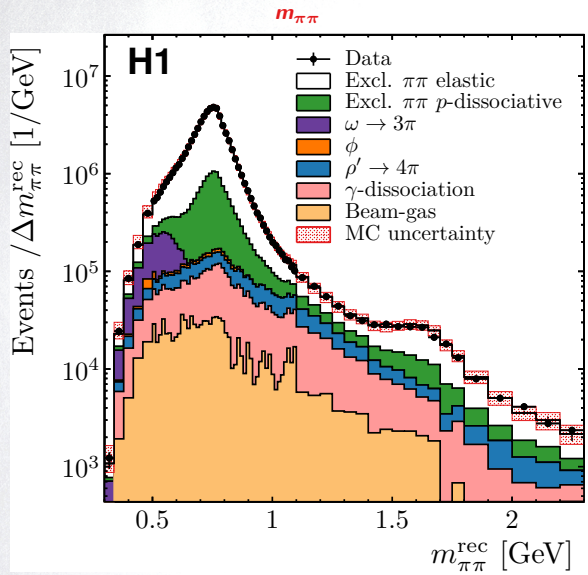
— Publication: —

- submitted to EPJ C
- preprint arxiv:2005.14471 [hep-ex]

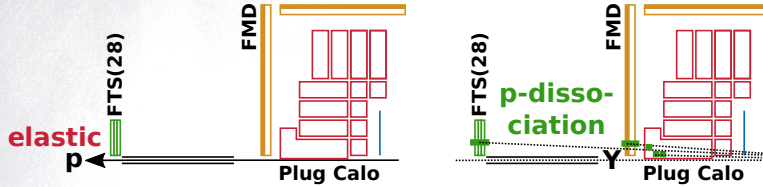




BACKUP



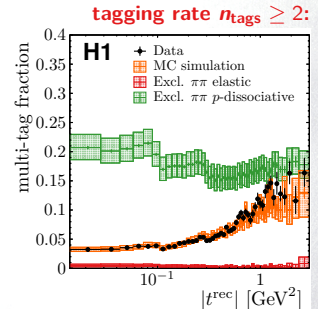
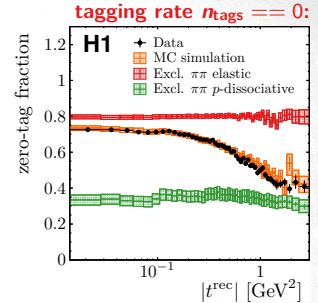
Proton Dissociation Tagging



- 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:

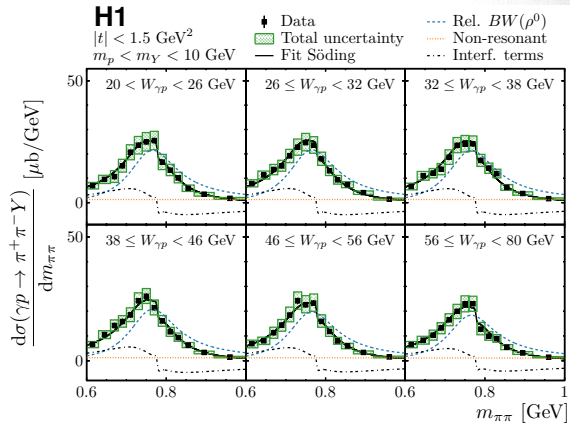
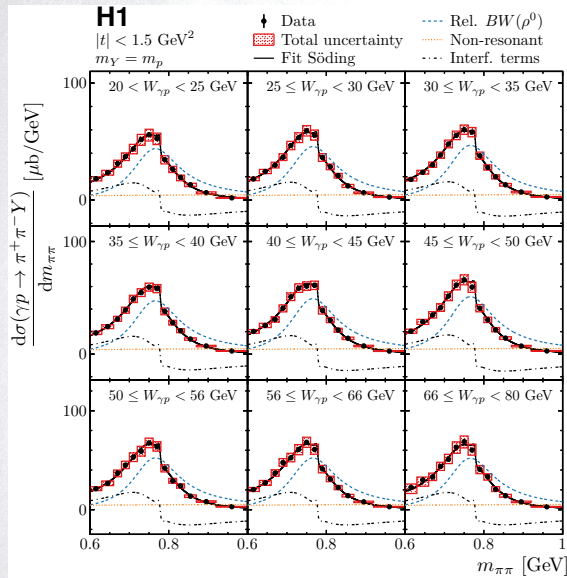
N_{pd}/N	$n_{tags} == 0$	$n_{tags} == 1$	$n_{tags} \geq 2$
	10%	36%	91%

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





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



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

