



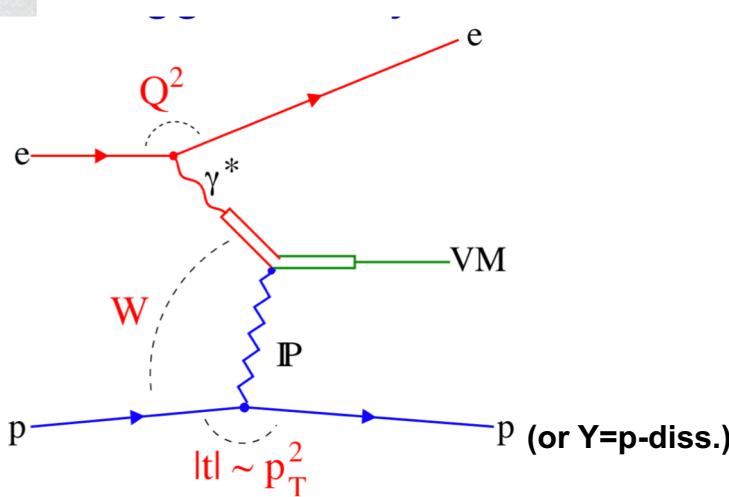
Exclusive $\pi^+\pi^-$ and $\rho(770)$ Meson Photoproduction at HERA

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(On Behalf of the H1 Collaboration)

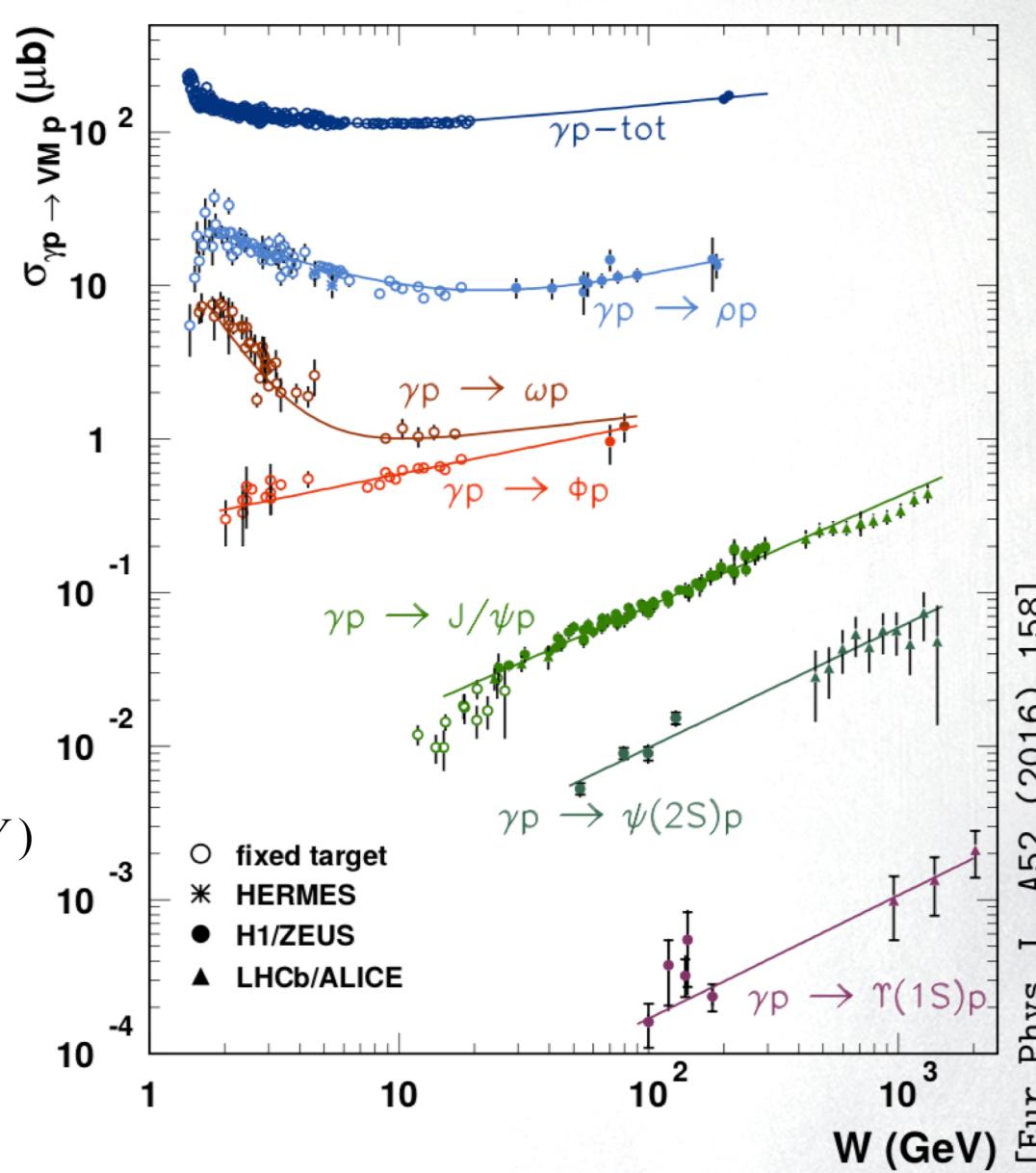
ISMD 2021

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Vector Meson Photoproduction



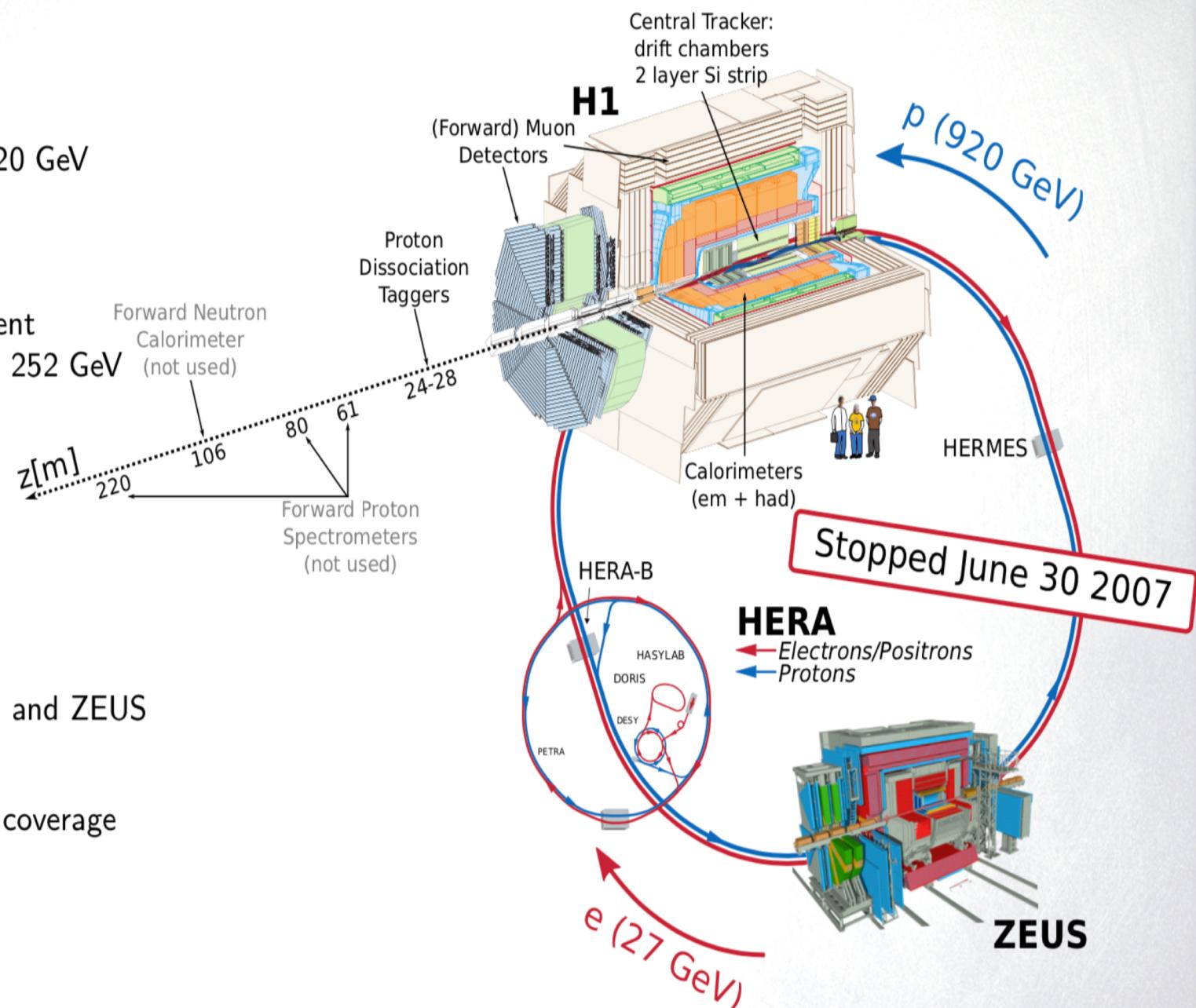
- $J^{PC}(\gamma) = 1^{--}$
→ vector mesons ($\rho_0, \omega, \phi, \dots$) fluctuation
- **color singlet exchange:**
→ Regge picture: low-erg. IReggeons,
high-erg. IPomeron
→ experimental:
large rapidity gaps (e.g. between VM and p/Y)
- cross section cms energy dependence:
 $\sigma(W_{\gamma p}) \sim W_{\gamma p}^{-\delta}$
→ related to Regge trajectories:
 $\delta(t) = 4(\alpha_{IP}(t) - 1)$
- momentum transfer at p -vertex t :
 $d\sigma/dt(t) \sim e^{-b|t|}$



HERA ep Collider and H1 experiment

— HERA: —

- world's only ep collider
- $E_e = 27.6 \text{ GeV}$, max $E_p = 920 \text{ GeV}$
- max $\sqrt{s} = 319 \text{ GeV}$
- 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



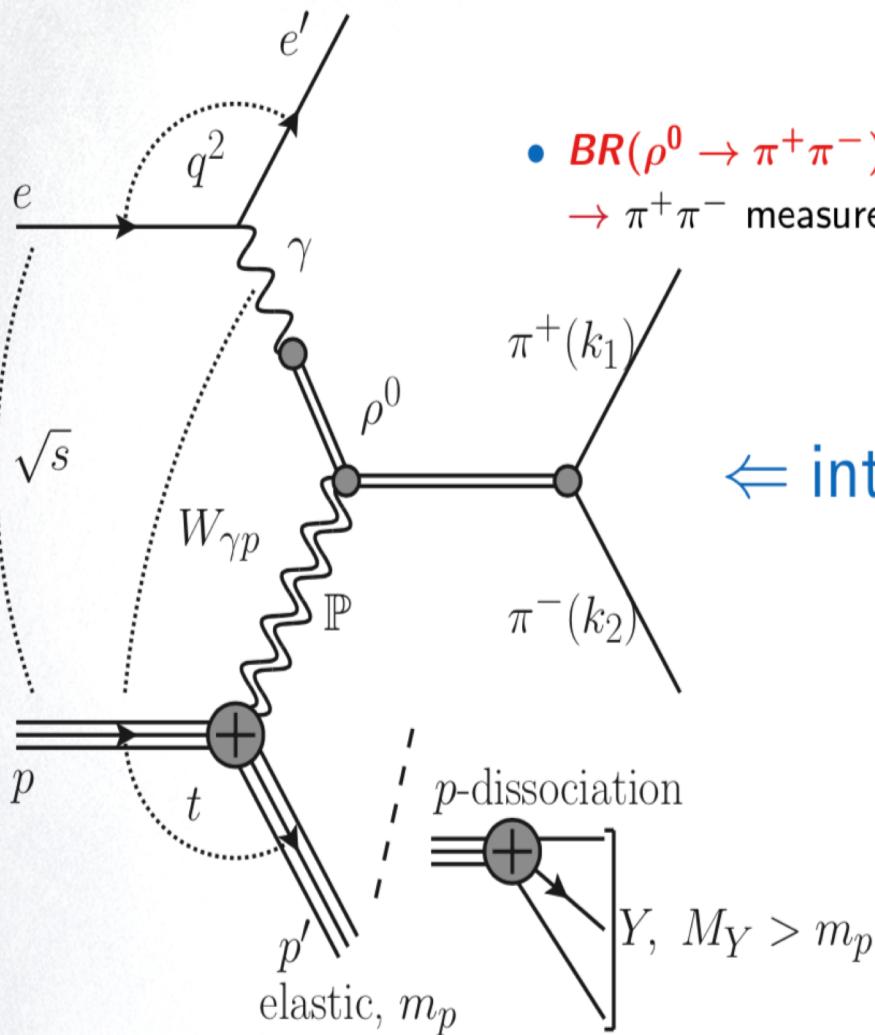
— Detectors —

- 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- → photoproduction

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

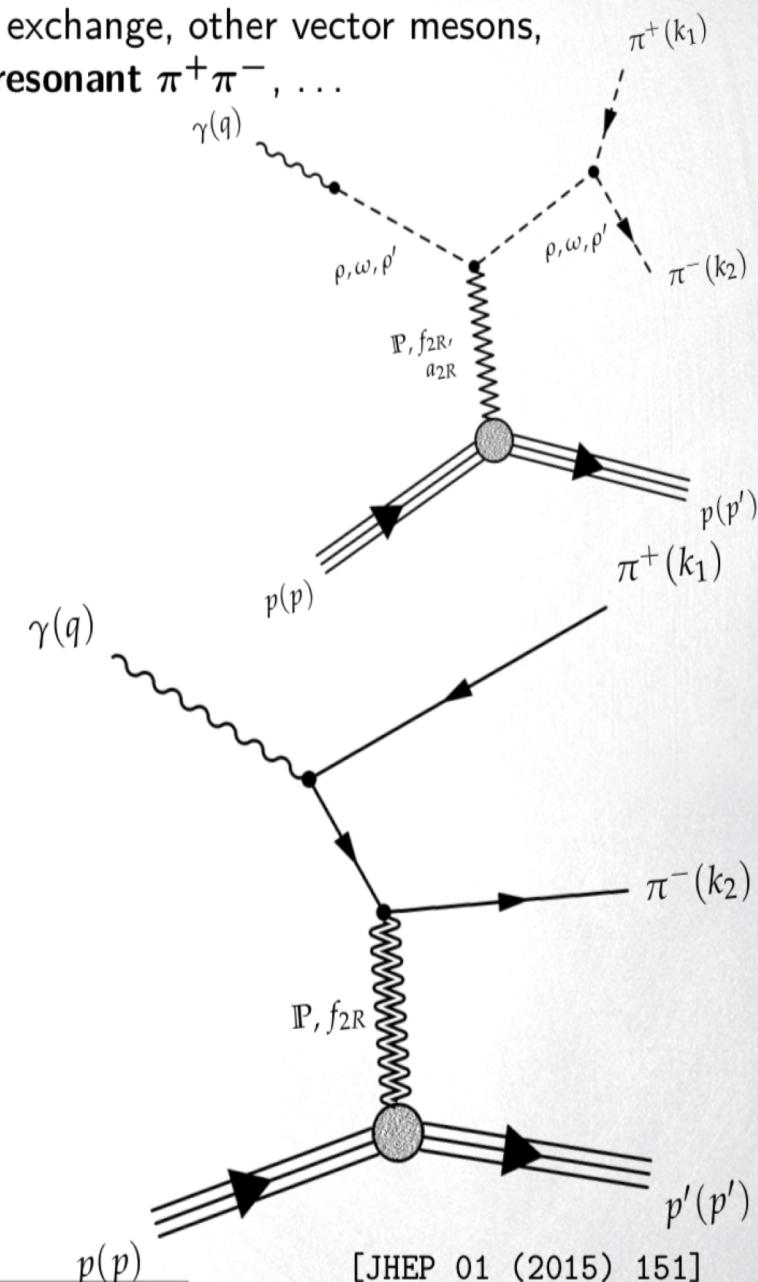


- $BR(\rho^0 \rightarrow \pi^+\pi^-) \sim 100\%$
→ $\pi^+\pi^-$ measurement

← interference ⇒

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

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



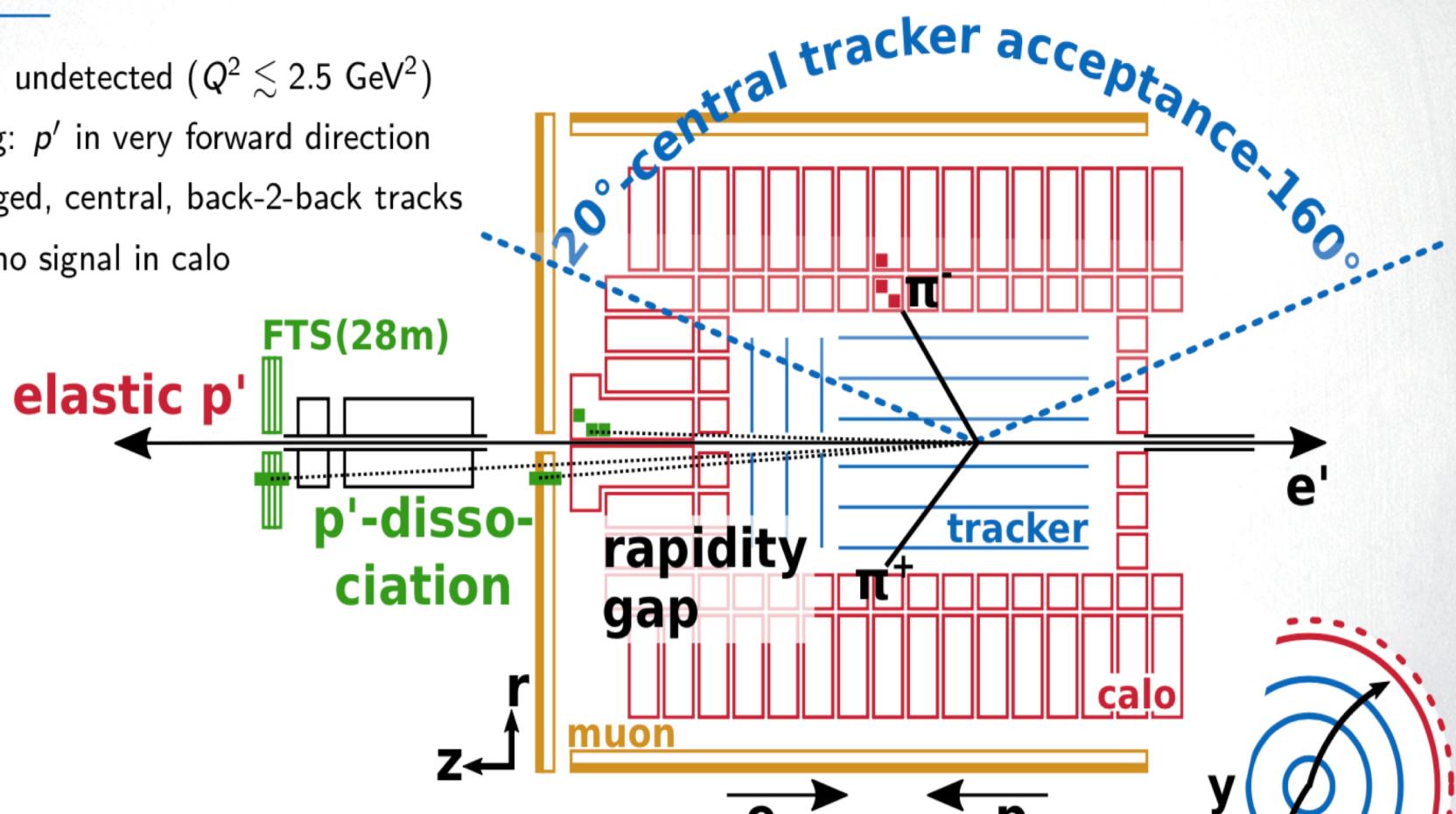
- elastic scattering vs proton dissociating

dissociation: $p'^2 = M_Y^2 > m_p^2 \rightarrow$ dominates at large $|t|$

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

— Event topology —

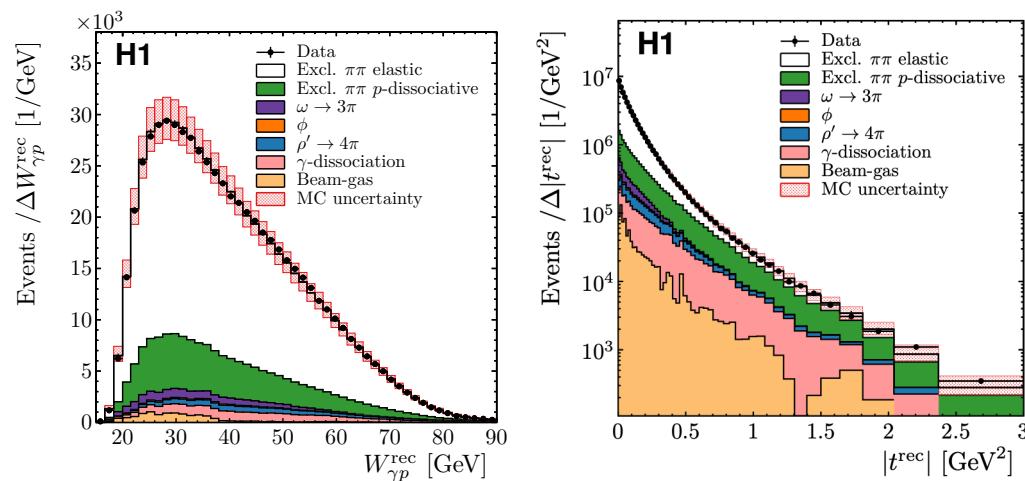
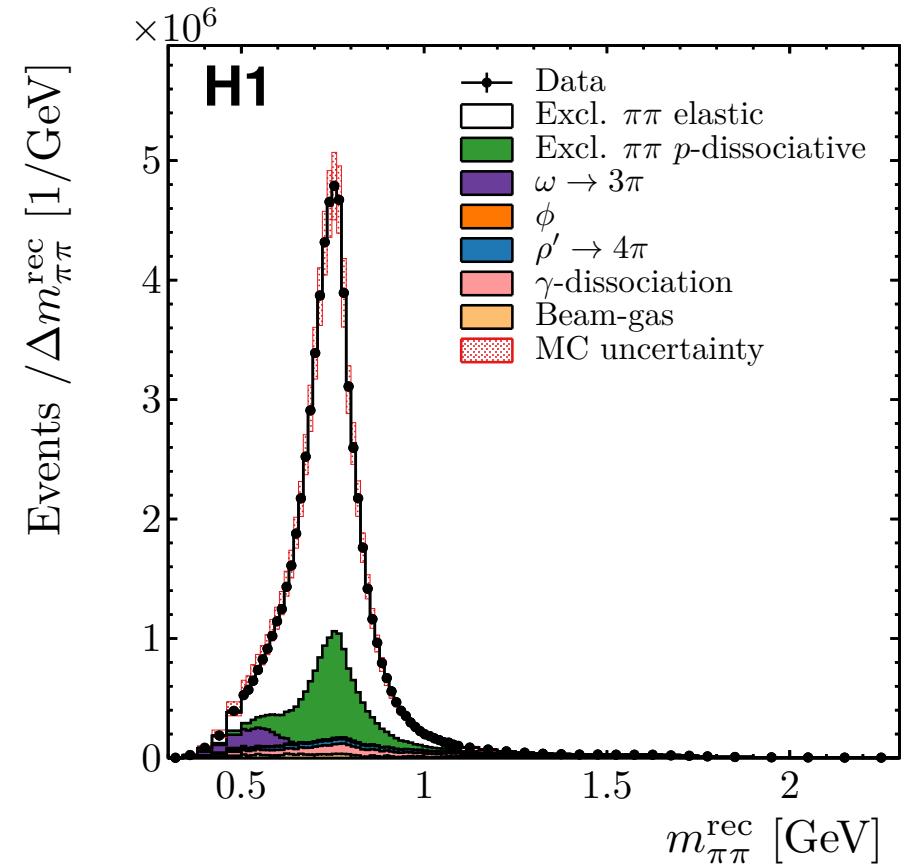
- photoproduction: e' undetected ($Q^2 \lesssim 2.5$ GeV 2)
- diffractive scattering: p' in very forward direction
- two oppositely charged, central, back-to-back tracks
- $p_T \lesssim 1$ GeV: often no signal in calo



— Challenges —

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

Data Set and Monte-Carlo Modelling



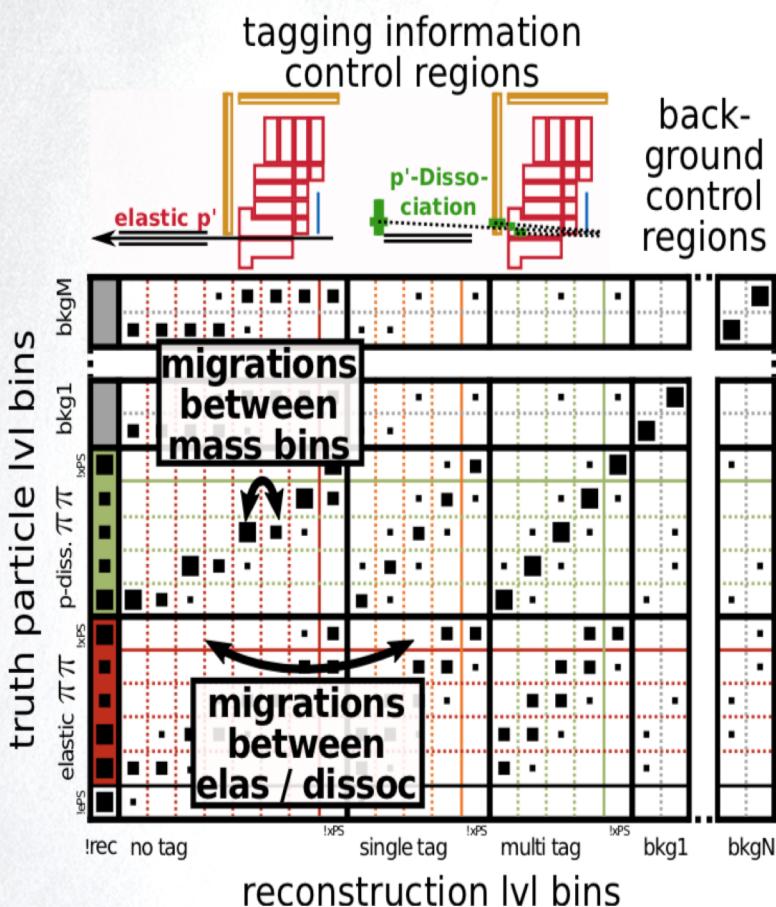
- $\sqrt{s} = 319 \text{ GeV } 2006/2007$ positron data set
- $L \simeq 1.3 \text{ pb}^{-1}$ (downscaled trigger)
- $\sim 9 \cdot 10^5$ selected $\pi^+\pi^-$ events

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

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

— 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 —

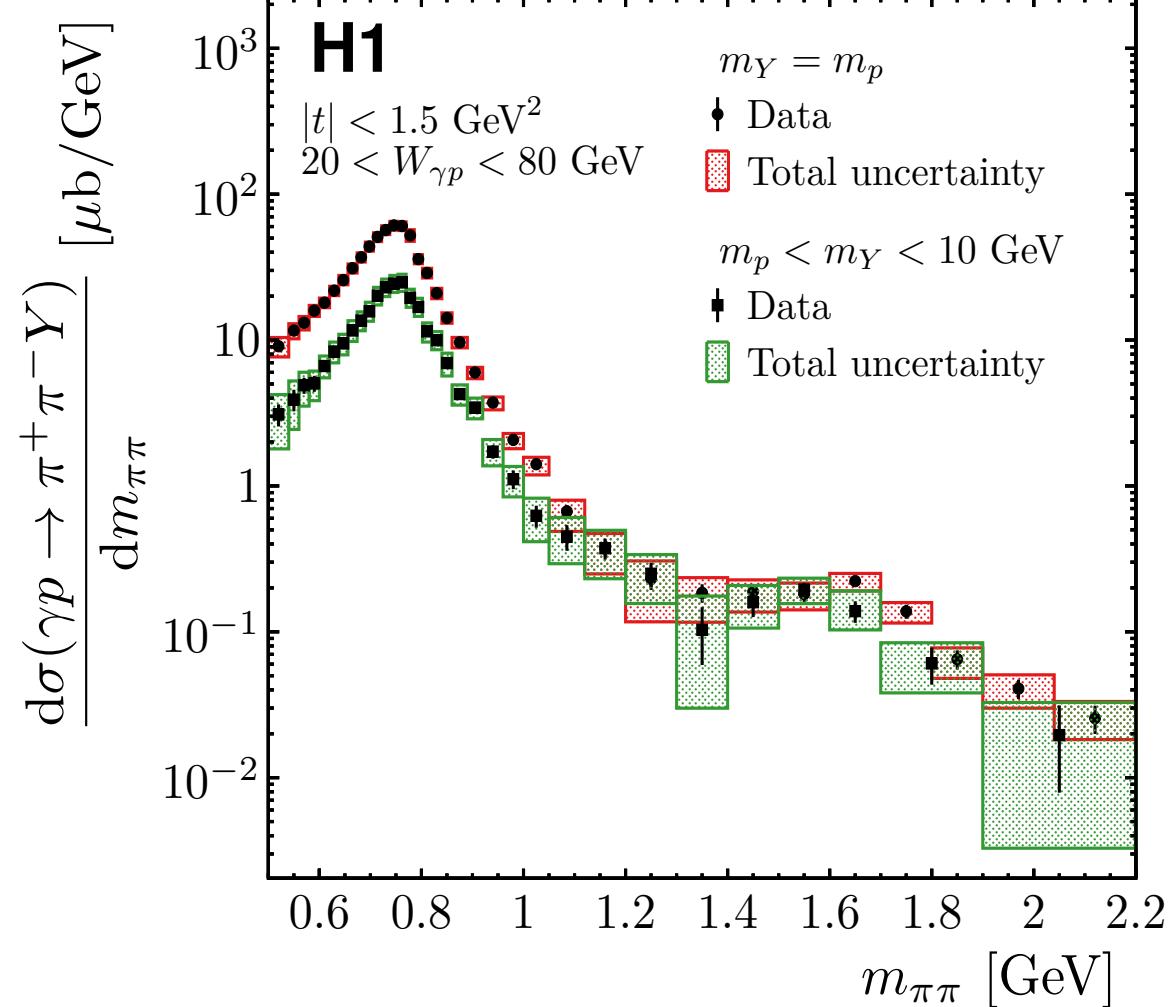
0.5 GeV	<	$m_{\pi\pi}$	< 2.2	GeV
20 GeV	<	$W_{\gamma p}$	< 80	GeV
		$ t $	< 1.5	GeV^2
		Q^2	< 2.5	GeV^2
elastic:				
		M_Y	= m_p	GeV
p-dissociative:				
		m_p	< M_Y	< 10 GeV

— Photoproduction cross section —

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

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



— Fiducial cross section: —

	$\sigma [\mu\text{b}]$	stat. [μb]	syst. [μb]
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$m_Y = m_p$ 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

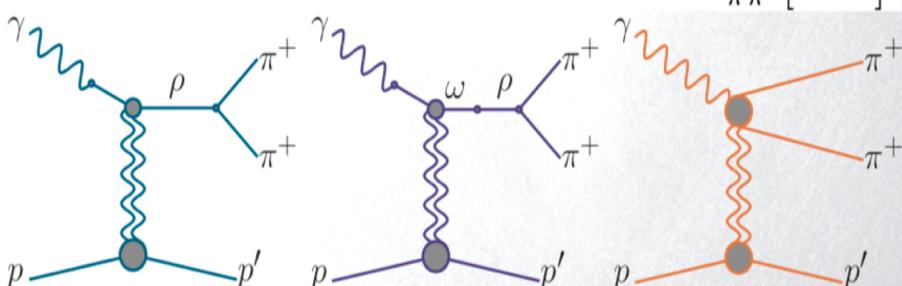
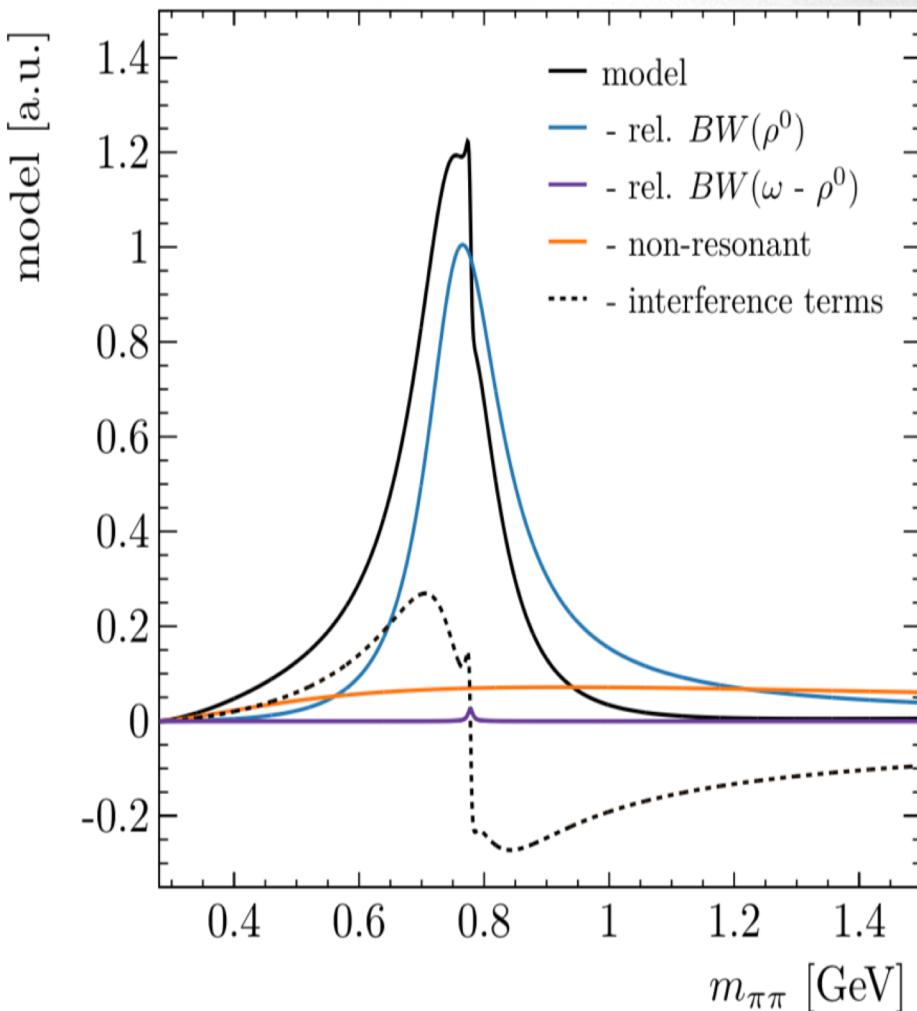
Extraction of $\sigma(\gamma p \rightarrow \rho^0 Y)$ contribution

— Söding-inspired 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 interference model
- $0.6 \leq m_{\pi\pi} \leq 1$ GeV

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

- 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)



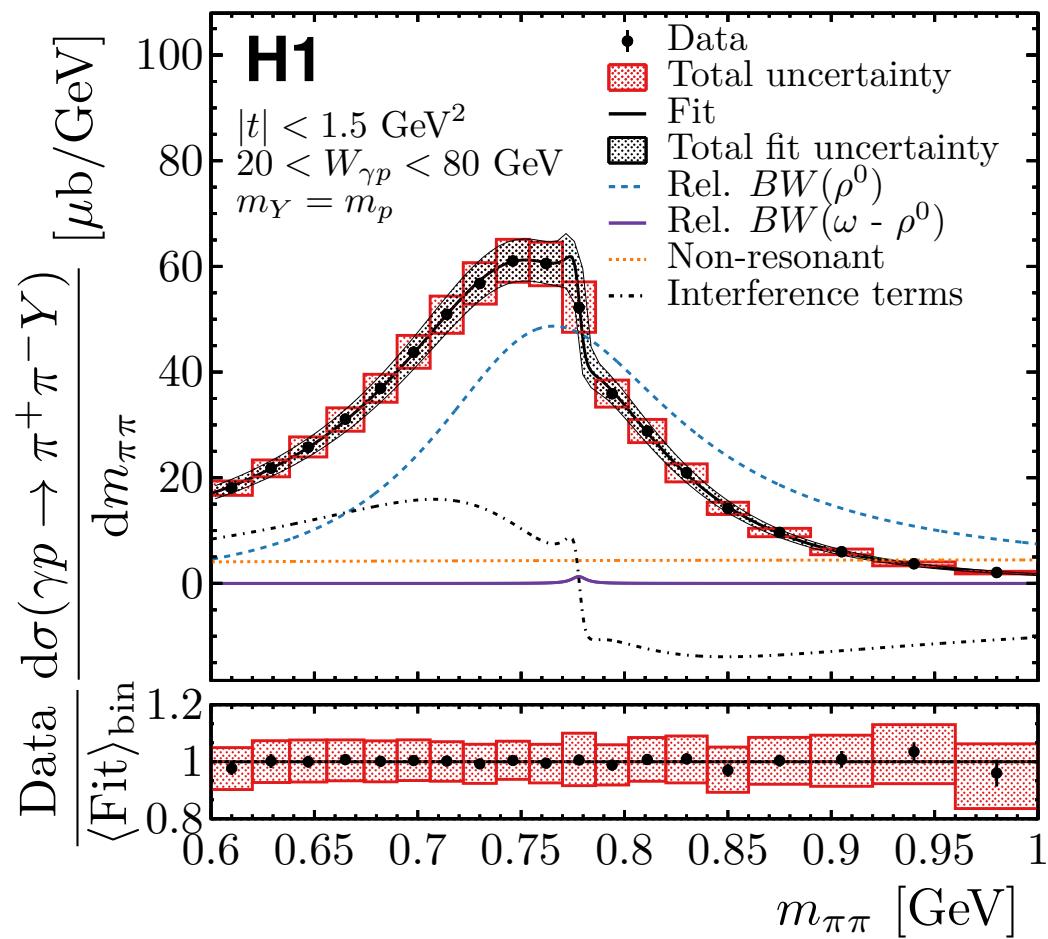
$$\sigma(\gamma p \rightarrow \rho^0 p) : \sim \int_{2m_\pi}^{m_\rho + 5\Gamma_\rho} \left| A_\rho(m_{\pi\pi}) \right|^2 dm_{\pi\pi}$$

1D Fit Results: $d\sigma(\gamma p \rightarrow \rho^0 Y)/dm_{\pi\pi}$

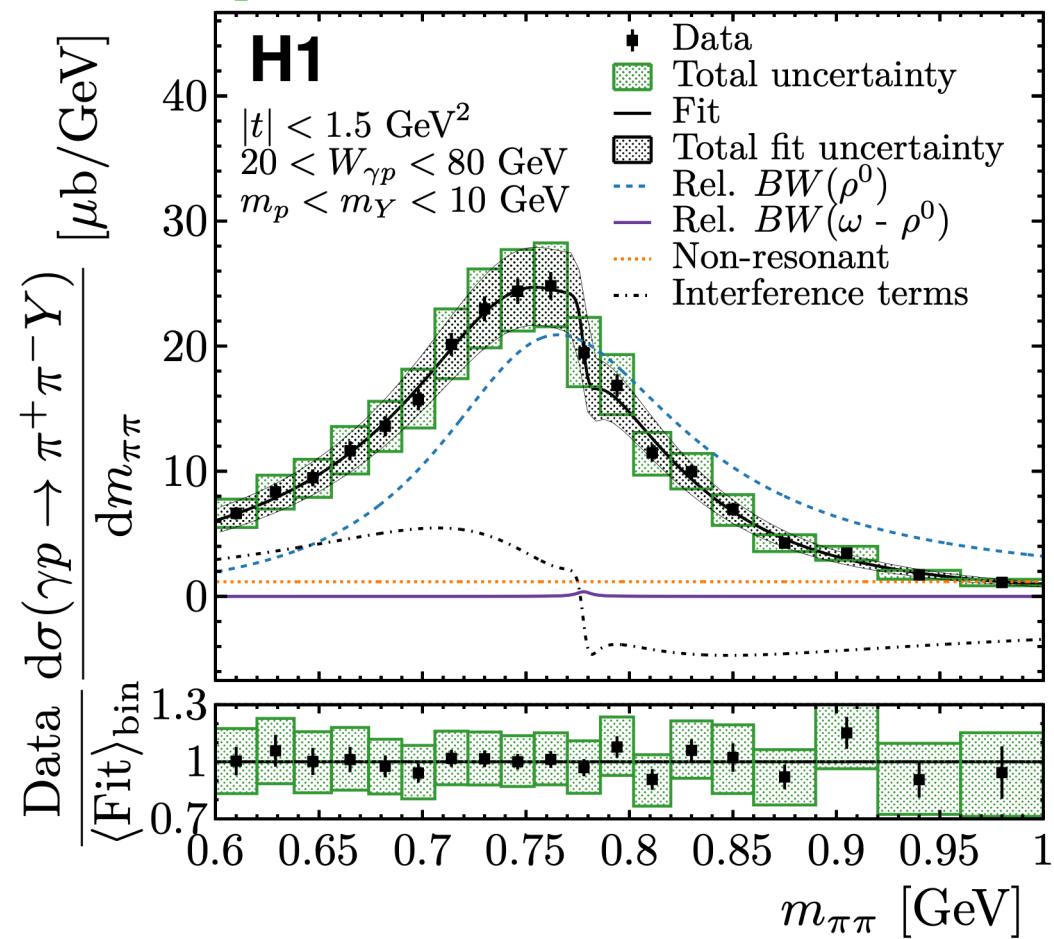
- fit **elastic** and ***p*-dissociative** together
- different non-resonant contributions
→ shape differences
- Mass and width parameters compatible with PDG

	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 ($e^+ e^-$)

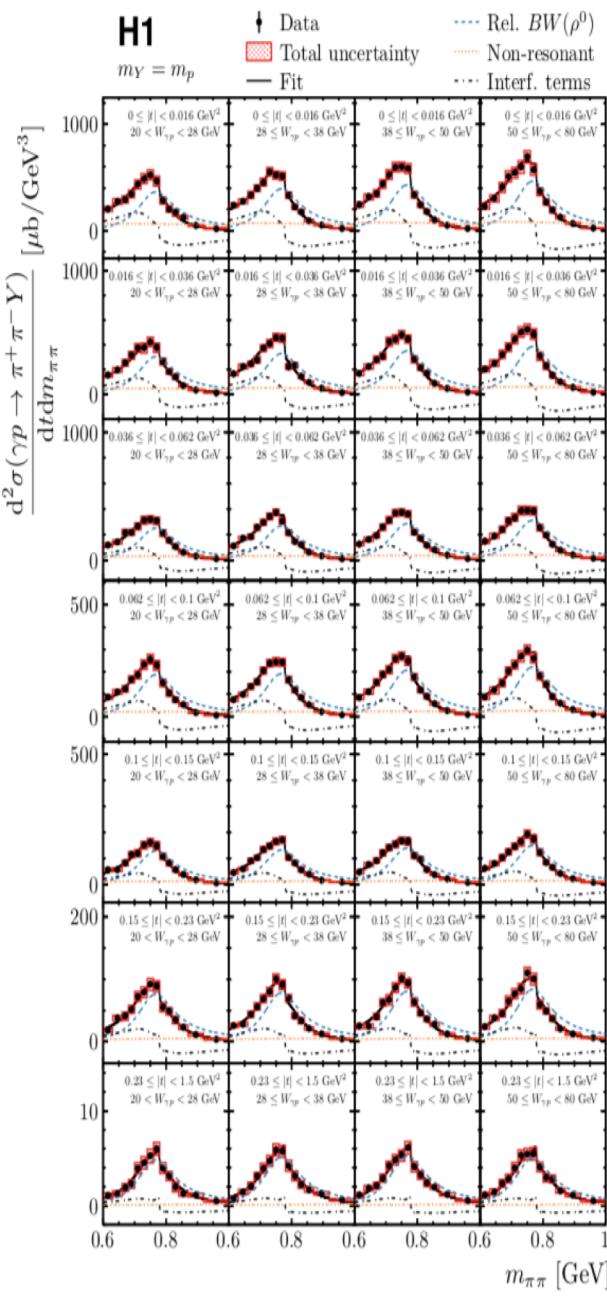
Elastic:



p-dissociative:

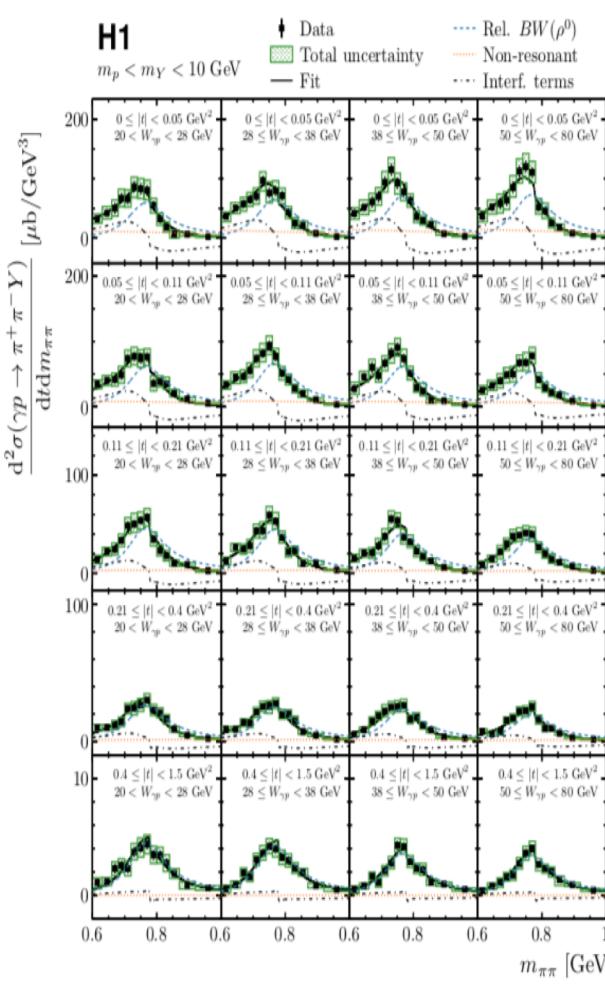


Kinematic ρ^0 Cross Section Dependences



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)



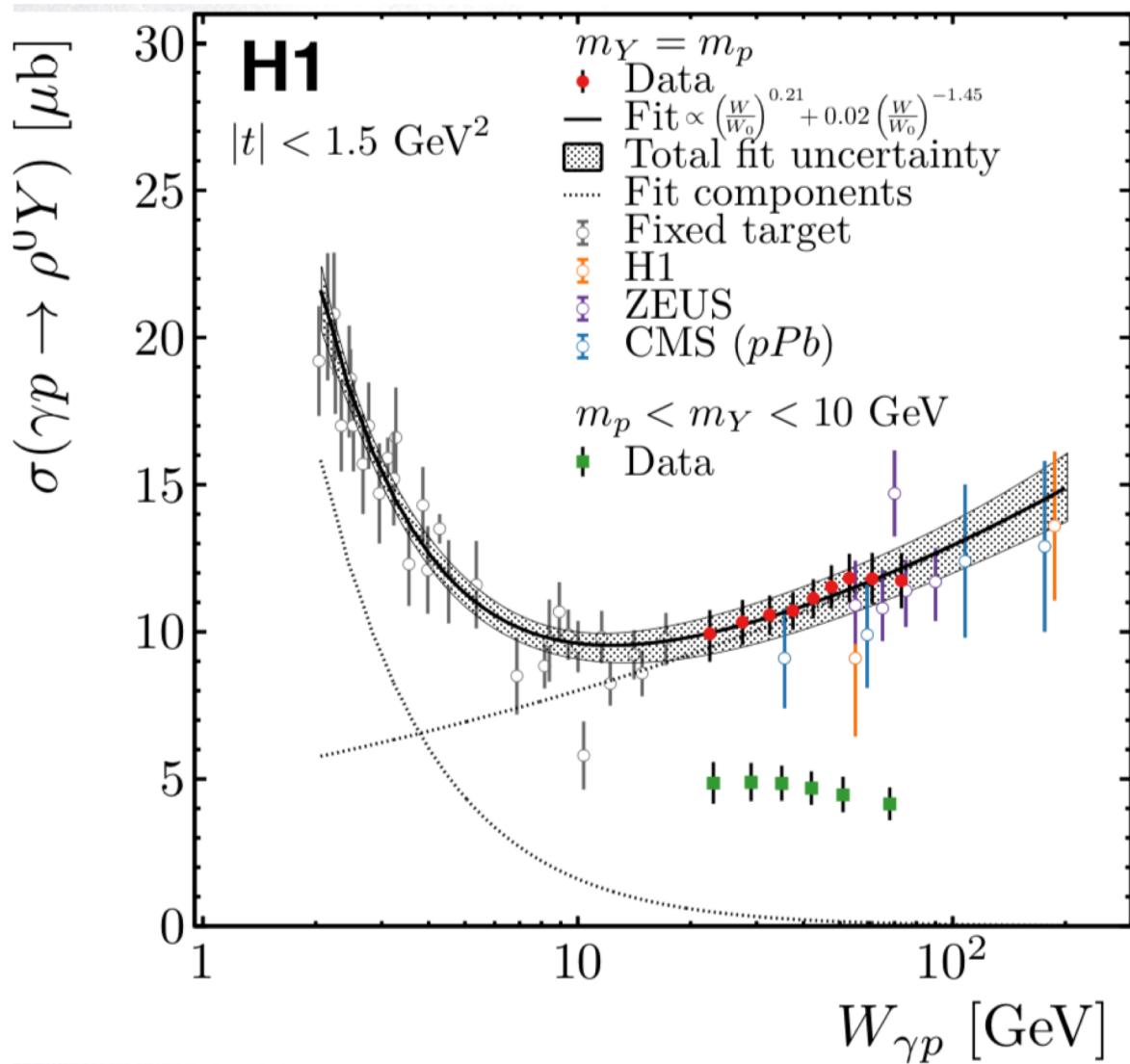
ii) fit $m_{\pi\pi}$ lineshape model

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



Parametrization and fit

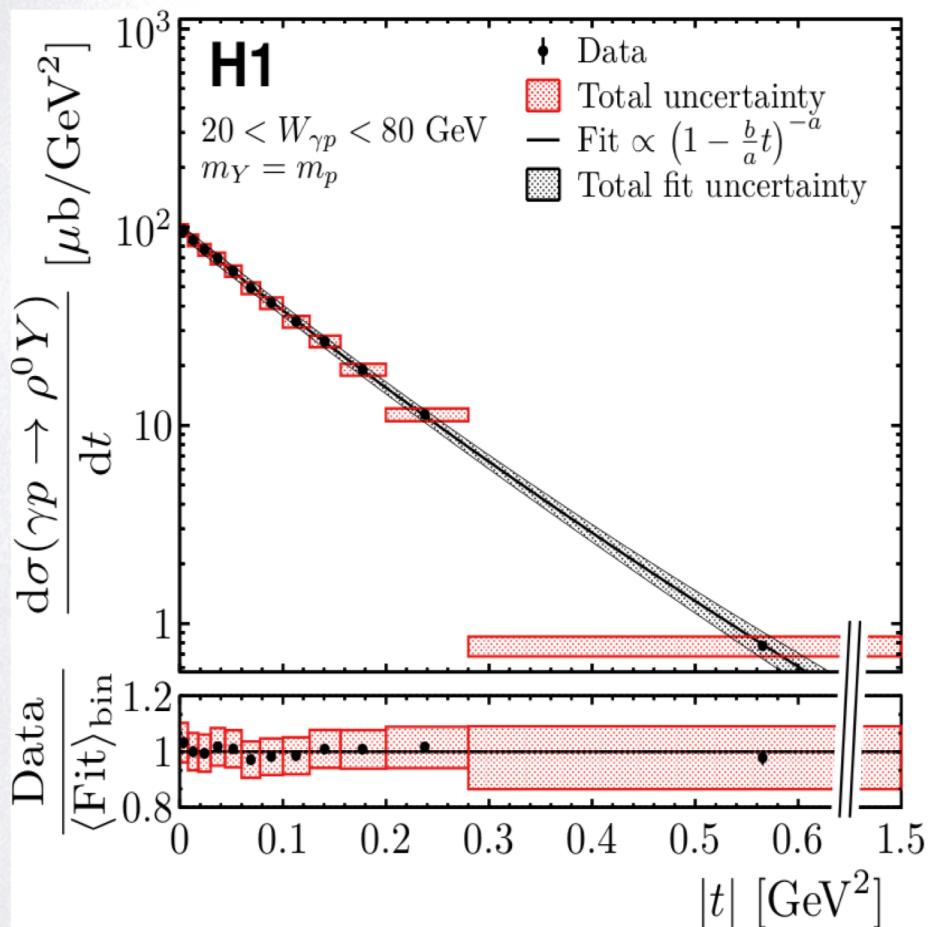
- **this measurement:** $\sigma \propto W^\delta$: ($20 < W_{\gamma p} < 80 \text{ GeV}$)
 - fit **elastic** & **dissociative** together
- $\delta_{\text{el}} = +0.171 \pm 0.009^{+0.039}_{-0.026}$
- $\delta_{\text{pd}} = -0.156 \pm 0.026^{+0.081}_{-0.079}$
- $\delta_{\text{pd}} \neq \delta_{\text{el}}$:
 - phasespace shaping by $m_Y < 10 \text{ GeV}$ 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)
 - $\delta_{\text{IP,el}} = +0.207 \pm 0.015^{+0.053}_{-0.033}$
 - $\delta_{\text{IR,el}} = -1.45 \pm 0.12^{+0.35}_{-0.21}$
- $\delta_{\text{IP,el}} > \delta_{\text{el}}$:
 - 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
- both components deviate from exponential in considered range
- stronger deviation* (smaller a) for *harder dissociative* spectrum

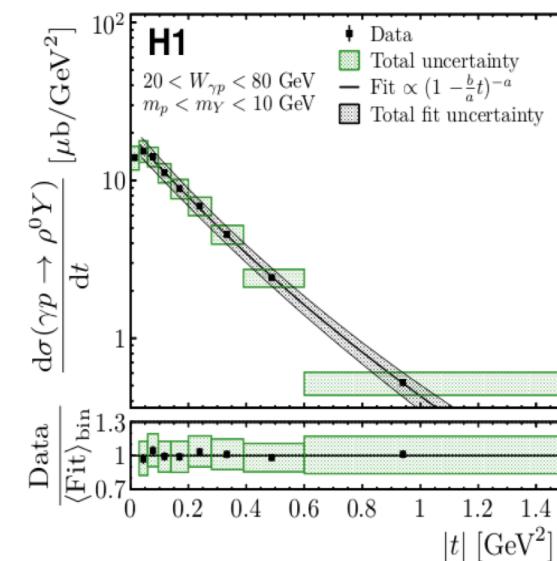


$$b_{\text{el}} = 9.59 \pm 0.10 \begin{array}{l} +0.17 \\ -0.12 \end{array} \text{ GeV}^{-2}$$

$$a_{\text{el}} = 19.8 \pm 2.7 \begin{array}{l} +4.9 \\ -4.7 \end{array}$$

$$b_{\text{pd}} = 4.79 \pm 0.19 \begin{array}{l} +0.37 \\ -0.39 \end{array} \text{ GeV}^{-2}$$

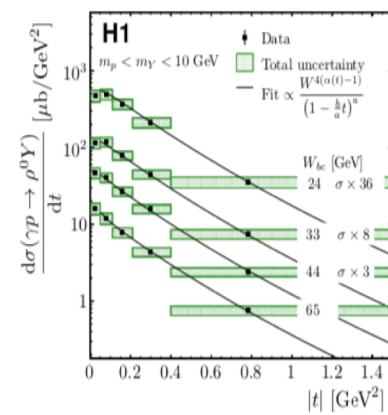
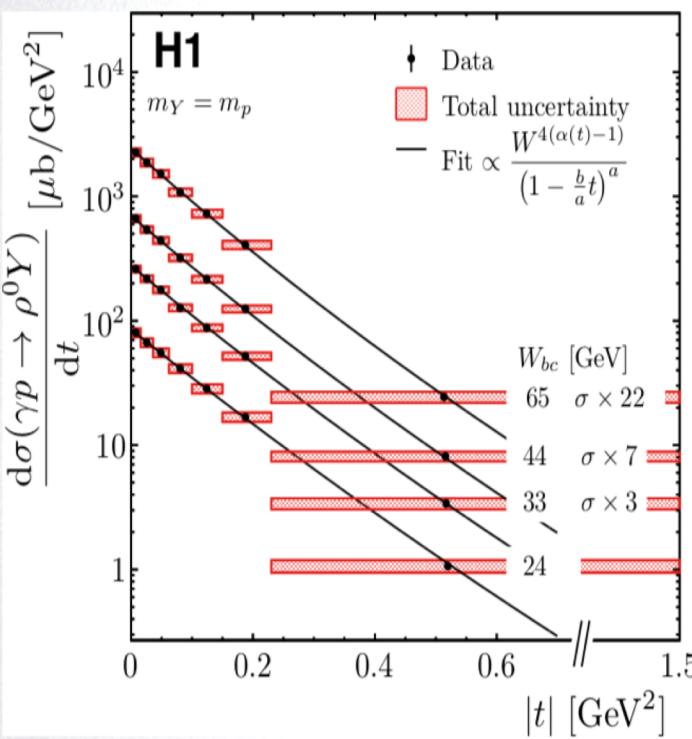
$$a_{\text{pd}} = 9.1 \pm 1.5 \begin{array}{l} +3.1 \\ -2.4 \end{array}$$



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 $t \rightarrow \pm\infty$
 - curves in right plots



(shaped by fiducial phase space cuts)

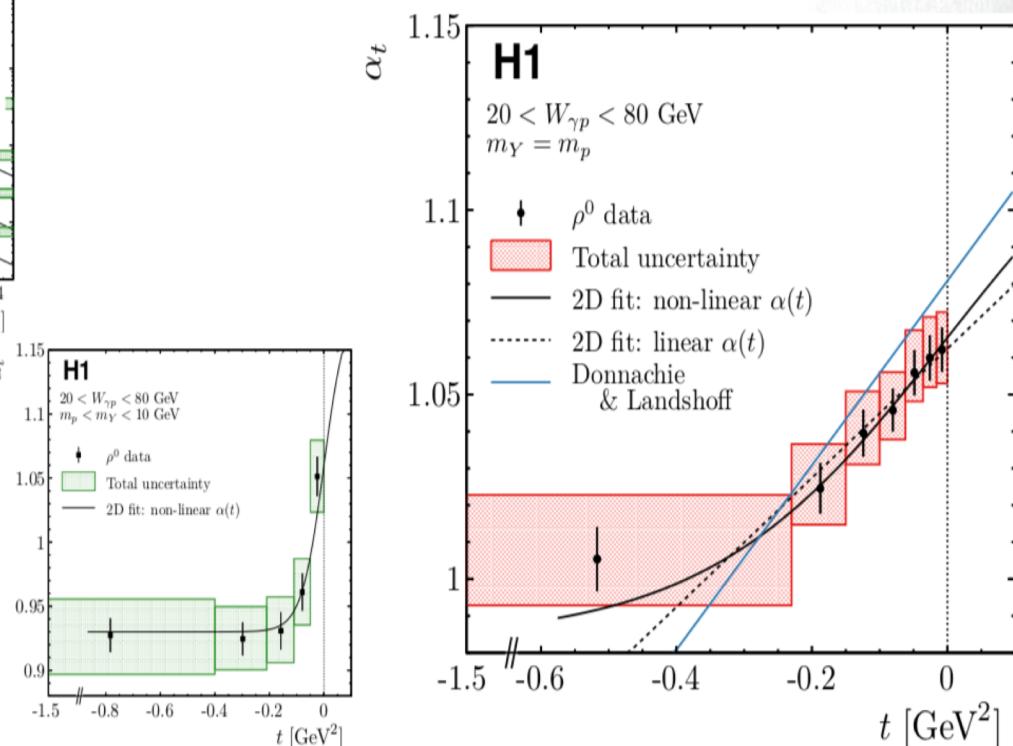
elastic ⇒ leading trajectory parameters:

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

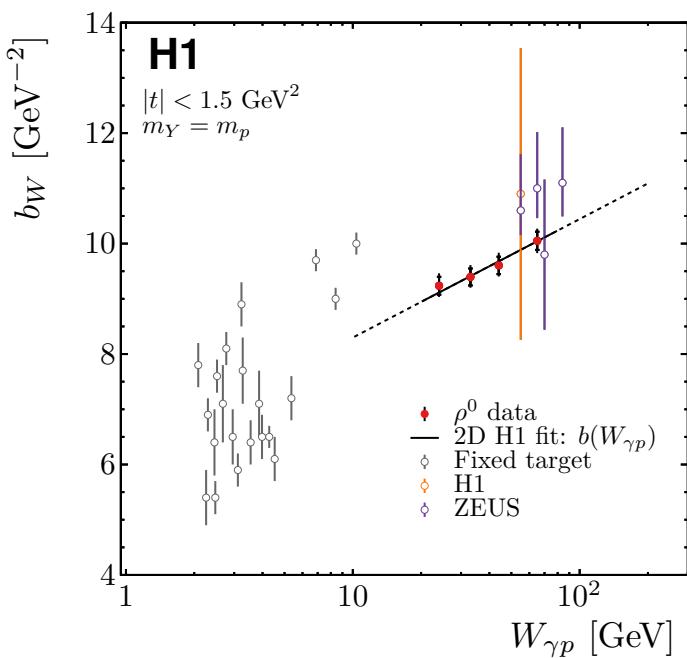
GeV $^{-2}$

— 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



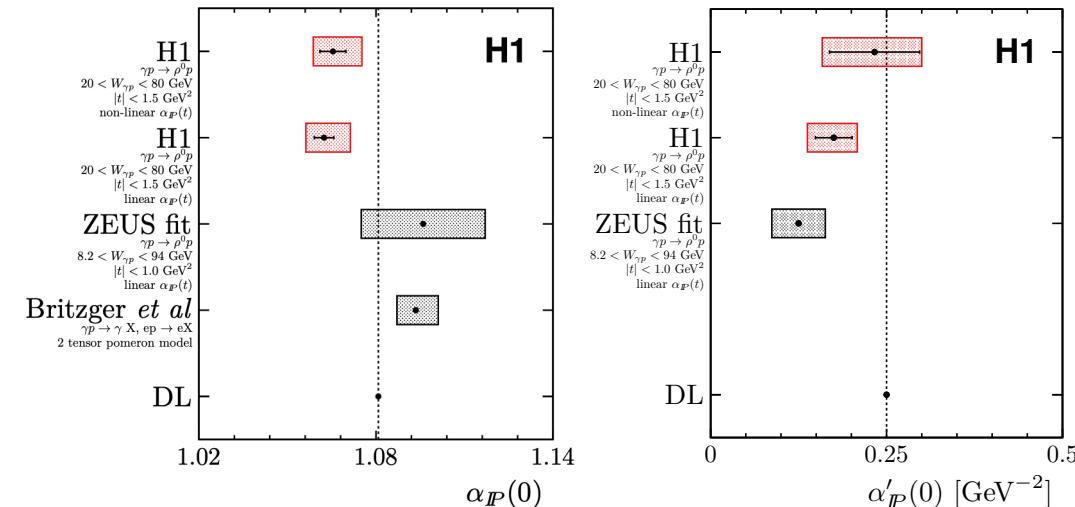
Summary



- **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

— Leading Regge trajectory —

- determine precise leading trajectory from single experiment
- alternative interpretation: shrinkage of forward peak (displayed)
- potential reggeon contribution $\Rightarrow \alpha_{IP}(t)$ or $\alpha_{IP+IR}(t)$?
- 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 \[hep-ex\]](https://arxiv.org/abs/2005.14471)



BACKUP SLIDES

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 $0 \leq n_{\text{tags}} \leq 3$
- 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

