

# Final results on exclusive $\pi^+$ cross sections

Cynthia Hadjidakis, Delia Hasch, Ivana Hristova  
on behalf of the HERMES Collaboration



DESY



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- ▶ Generalised Parton Distributions
- ▶ Exclusive  $\pi^+$  production at HERMES
  - ▶ Cross section measurements and results
  - ▶ Preliminary study of transverse spin asymmetry

# Generalised Parton Distributions

- in the limit of  $Q^2 \gg$  at  $x_B$ ,  $t$  fixed,  $\gamma^* p$  amplitude factorises

- contributions to the cross section

$\gamma_L^*$	leading-twist, QCD factorisation theorem
$\gamma_L^* - \gamma_T^*$	$\frac{1}{Q}$ suppressed
$\gamma_T^*$	$\frac{1}{Q^2}$ suppressed

- for exclusive  $\pi^+$  production  $\gamma^* p \rightarrow \pi^+ n$

$$\sigma_L \propto (1 - \xi^2) |\tilde{H}|^2 - \xi^2 t |\tilde{E}|^2 - \xi^2 \text{Re}(\tilde{E}^* \tilde{H})$$

$\xi$ : skewness

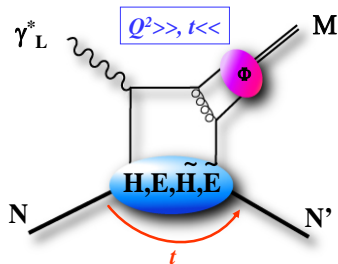
- relation to PDFs and FFs

$$\tilde{H}(x, 0, 0) = \Delta q(x) \text{ for } t \rightarrow 0$$

$$\int_{-1}^1 dx \tilde{H}(x, \xi, t) = g_A(t)$$

$$\int_{-1}^1 dx \tilde{E}(x, \xi, t) = g_P(t)$$

- how to access GPDs?



- exclusive production of
 

$\gamma$	$\rightarrow$	$H, E, \tilde{H}, \tilde{E}$
$\rho, \omega, \phi$	$\rightarrow$	$H, E$
$\pi, \eta$	$\rightarrow$	$\tilde{H}, \tilde{E}$

- !** no precocious scaling at  $Q^2 \geq 1 \text{ GeV}^2$  for hard exclusive meson production

# Exclusivity for $ep \rightarrow e'\pi^+n$ at HERMES

- no recoil detection

⇒ missing mass technique:

$$M_X^2 = (q_e + q_p - q_{e'} - q_{\pi^+})^2$$

for  $(N_{\pi^+} - N_{\pi^-})^{\text{data}}$

for  $(N_{\pi^+} - N_{\pi^-})^{\text{PYTHIA}}$

⇒  $N_{\pi^+}^{\text{excl}}$  obtained as a  
double difference

PYTHIA Monte Carlo generator:

-no nucl.res. and excl. $\pi^+$  processes

-tuned to HERMES SIDIS and VM prod.

- kinematic requirements

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

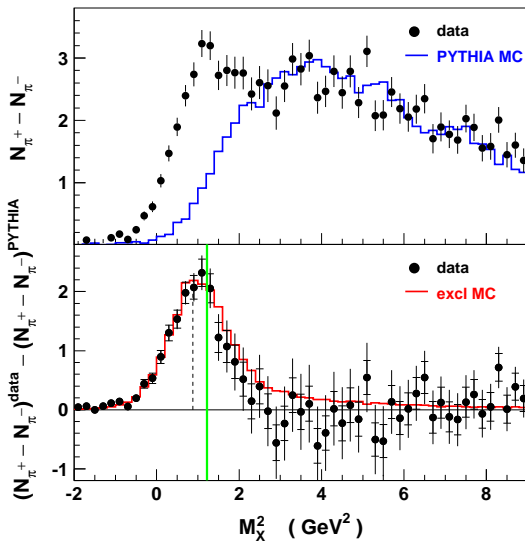
$$W^2 > 10 \text{ GeV}^2$$

$$y < 0.85$$

$$p_\pi > 7 \text{ GeV}$$

- $M_X^2 < 1.2 \text{ GeV}^2$

- $t' = t - t_0$



Exclusive peak clearly centred at the neutron mass  
Mean and width in agreement with exclusive MC

## Cross section determination

- $ep \leftrightarrow \gamma^* p$ :  $\frac{d\sigma^{\gamma^* p \rightarrow \pi^+ n}(x_B, Q^2, t', \phi)}{dt' d\phi} = \frac{1}{\Gamma_V(x_B, Q^2)} \frac{d\sigma^{ep \rightarrow e' \pi^+ n}(x_B, Q^2, t', \phi)}{dx_B dQ^2 dt' d\phi}$
- Hand convention:  $\Gamma_V(x_B, Q^2) = \frac{\alpha}{8\pi} \frac{1}{M_p^2 E^2} \frac{Q^2}{x_B^3} \frac{1-x_B}{1-\epsilon}$ ,  $\epsilon$ :  $\gamma^*$  polarisation parameter

$$\frac{d\sigma^{\gamma^* p \rightarrow \pi^+ n}(x_B, Q^2, t')}{dt'} = \frac{1}{\Gamma_V(\langle x_B \rangle, \langle Q^2 \rangle)} \frac{N_{\pi^+}^{excl}}{\mathcal{L} \Delta x_B \Delta Q^2 \Delta t' \kappa(x_B, Q^2) \eta}$$

$N_{\pi^+}^{excl}$   $\pi^+$  events after background subtr.

$\Gamma_V$  virtual-photon flux factor

$\mathcal{L}$  integrated luminosity

$\kappa$  detection probability

$\eta$  radiative correction factor

$\Delta$  bin size

For the data sample 1996-2005:

•  $N_{\pi^+}^{excl} = 4510$  events,  $[2 - 20\%]_{\text{sys}}$   $\mathcal{L} = 0.4 \text{ fb}^{-1}$   $[5\%]_{\text{sys}}$

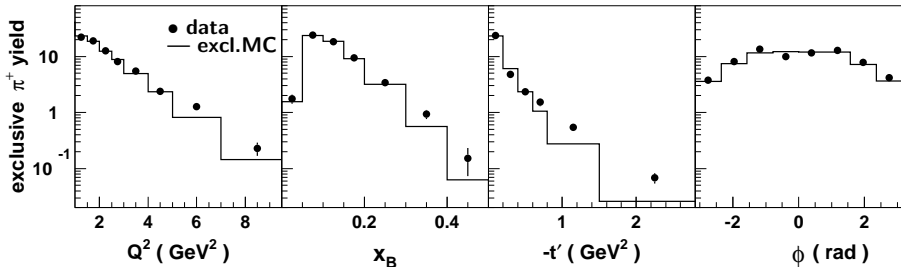
• kinematic range

$1 < Q^2 < 11 \text{ GeV}^2 \rightarrow$  four  $Q^2$  bins

$0.02 < x_B < 0.55 \rightarrow$  three  $x_B$  bins

$0 < -t' < 3 \text{ GeV}^2 \rightarrow$  six  $-t'$  bins

# Exclusive distributions: Monte Carlo comparison



## exclusive MC (GPD models):

• Vanderhaeghen, Guichon, Guidal [PRD60\(1999\)094017](#)

or

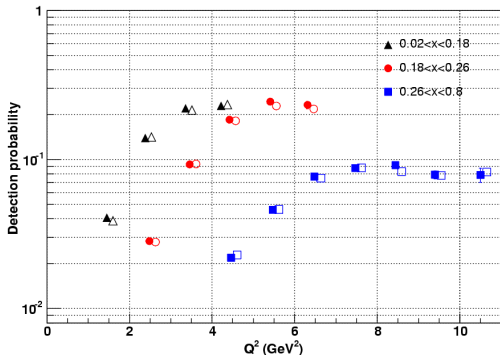
○ Mankiewicz, Piller, Radyushkin [EPJC10\(1999\)307](#)

$$\kappa = \frac{N_{\pi^+}^{rec}}{N_{\pi^+}^{gen}} = [0.04 - 0.28] \quad \text{acc. } [0.1-0.7] \quad \text{cuts } [0.4-0.5]$$

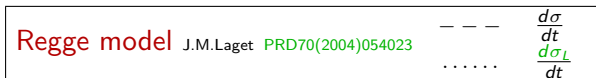
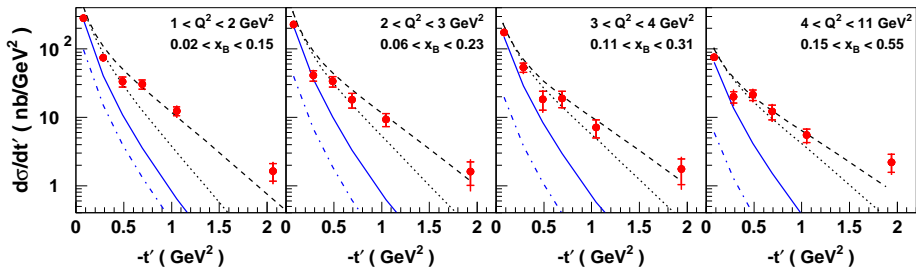
$\kappa$ : probability to detect  $e'$  and  $\pi^+$  (generated in  $4\pi$ ) in the HERMES spectrometer; [ $\sim 15\%$ ]<sub>sys</sub>

$$\eta = \frac{\sigma^{obs}}{\sigma^{Born}} = 0.77, \text{ at } M_X^2 < 1.2 \text{ GeV}^2$$

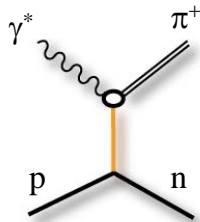
-dominated by vertex&loop corrections  
-independent of kinematics



# Results: the differential cross sections PLB659(2008)486

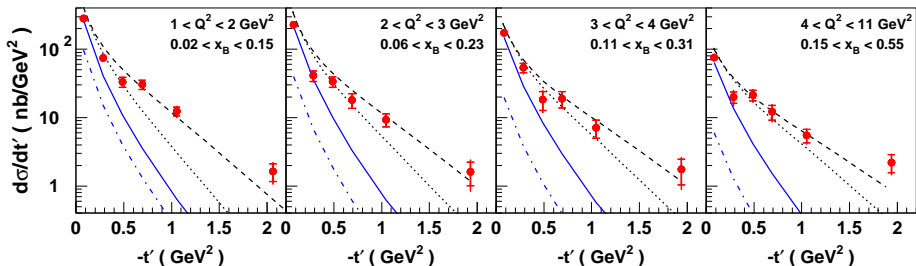


- ▶  $\pi^+$  production described by exchange of  $\pi$  and  $\rho$  Regge trajectories
- ▶  $Q^2$ - and  $-t'$ -dependent FFs for  $\pi\pi\gamma$  and  $\pi\rho\gamma$
- ▶  $\sigma_T$  predicted to be 15-25% of  $\sigma$  (about 6% at low  $-t'$ )



good description of the magnitude, and  $-t'$ ,  $Q^2$  dependences of the data

# Comparison with theory PLB659(2008)486

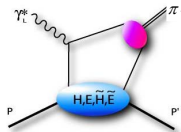
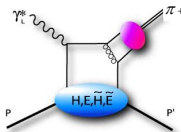


**GPD model** for  $\frac{d\sigma_L}{dt'}$

- · - leading-order calculations
- with power corrections

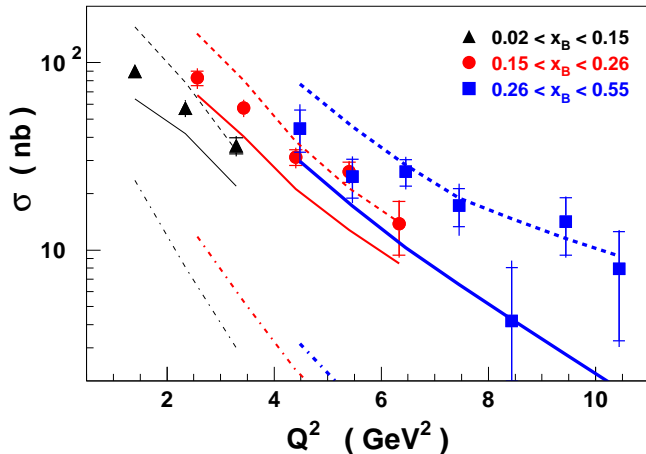
Vanderhaeghen, Guichon, Guidal PRD60(1999)094017

- ▶  $\tilde{E}$  dominated by pion-pole,  $F_\pi$
- ▶  $\tilde{H}$  neglected
- ▶ Regge-inspired  $t$  dependence for  $\tilde{E}$
- ▶ power corrections due to intrinsic  $k_T$  and **soft-overlap** contribution



fair agreement with data at lower  $-t'$  if power corrections are included

# Results: the total cross section PLB659(2008)486

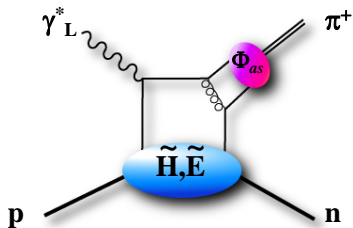


GPD model	- - -	leading-order calculations
	—	with power corrections
Regge model	- - -	Regge model for $\sigma$

GPD model: fair agreement, Regge model: good description of data



# Transverse spin asymmetry

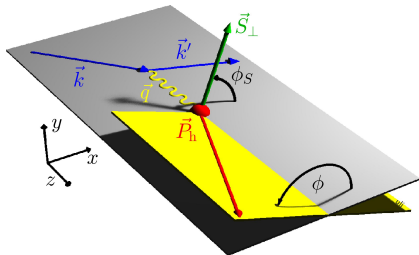


unp. cross section  
spin asymmetry

$$\sigma_{UU} \propto |\tilde{H}|^2 - t|\tilde{E}|^2 - \text{Re}(\tilde{E}^*\tilde{H})$$

$$\propto \text{Im}(\tilde{E}^*\tilde{H})/\sigma_{UU}$$

higher order corrections cancel  
scaling reached at lower  $Q^2$



For transversely polarised target:

$$\sigma_{UT} \propto |\vec{S}_T| \sin(\phi - \phi_S) \text{Im}(\tilde{E}^*\tilde{H}) + \dots$$

$\Rightarrow$  extract  $A_{UT}^{\sin(\phi - \phi_S)}$  plus additional  
five sine amplitudes

M. Diehl, S. Sapeta EPJC41(2005)515

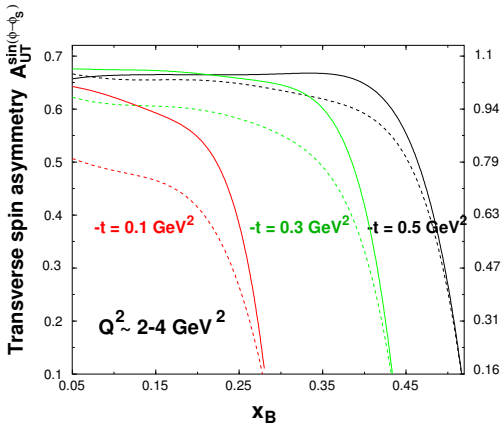
# Theoretical prediction for $A_{UT}^{\sin(\phi-\phi_S)}$

$$A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{\text{Im}(\tilde{\mathcal{E}}^* \tilde{\mathcal{H}})}{|\tilde{\mathcal{H}}|^2 - t|\tilde{\mathcal{E}}|^2 - \text{Re}(\tilde{\mathcal{E}}^* \tilde{\mathcal{H}})}$$

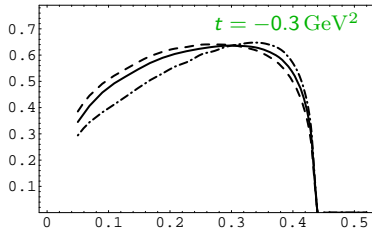
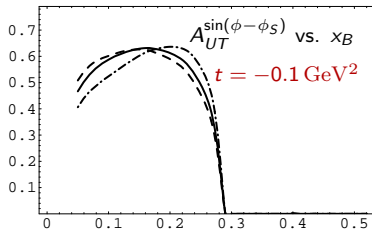
$\tilde{H}, \tilde{E}$ : chiral quark-soliton model of GPDs  
asymptotic and Chernyak-Zhitnitsky DA

$\tilde{H}$ : double distribution ansatz  
 $\tilde{E}$ : pion pole-dominated ansatz  
small LO and NLO corrections

[Frankfurt et al.; PRD60(1999)014010]

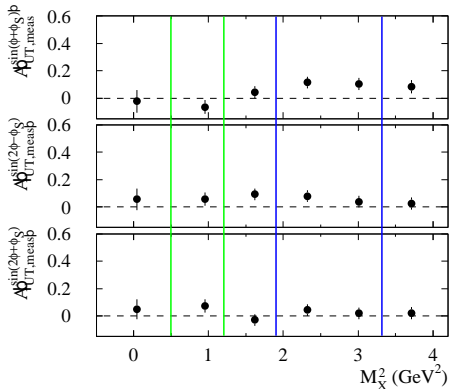
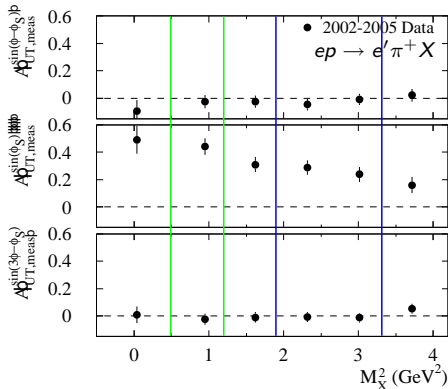


[Belitsky, Müller; PLB513(2001)349]



# Measured asymmetry $A_{UT}$ vs. squared missing mass

measured = exclusive signal  $f_{\pi^+}^{excl} = \frac{N_{\pi^+}^{excl}}{N_{\pi^+}^{data}} \approx \frac{1}{2}$   $A_{UT}$  in  $M_X^2 = [0.5 - 1.2] \text{ GeV}^2$   
 plus background  $1 - f_{\pi^+}^{excl}$   $A_{UT,bg}$  in  $M_X^2 = [1.9 - 3.3] \text{ GeV}^2$



► background correction → extract exclusive asymmetry

$$A_{UT,\pi^+}^{excl} \equiv A_{UT,bg.corr} = \frac{1}{f_{\pi^+}^{excl}} A_{UT} - \frac{1 - f_{\pi^+}^{excl}}{f_{\pi^+}^{excl}} A_{UT,bg}$$

# Kinematic dependences of $A_{UT,\pi^+}^{excl}$

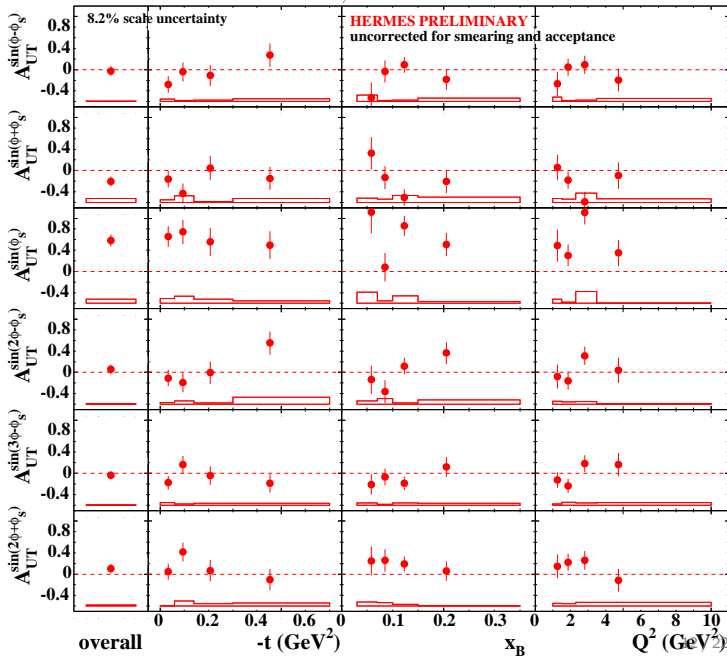
$$ep \rightarrow e'\pi^+n$$

$$-t \equiv -t'$$

$$\langle -t \rangle = 0.182 \text{ GeV}^2$$

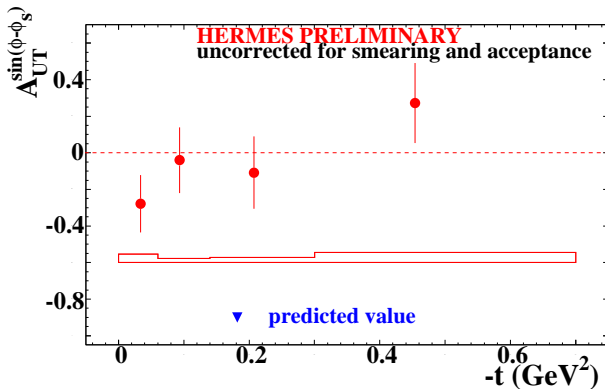
$$\langle x \rangle = 0.126$$

$$\langle Q^2 \rangle = 2.38 \text{ GeV}^2$$



# Leading asymmetry amplitude $A_{UT}^{\sin(\phi-\phi_s)}$ vs. $-t$

- ▶ measurement indicates a sign change over  $-t$  or consistency with zero
- ▶ cross section results indicate power corrections to  $\tilde{E}$  are important
  - ▶ therefore  $\tilde{E}$  increases substantially
  - ▶ but  $\tilde{H}$  remains small



$\Rightarrow A_{UT}^{\sin(\phi-\phi_s)}$  measurement consistent with cross section result

# Summary and conclusions

## Exclusive $\pi^+$ cross section

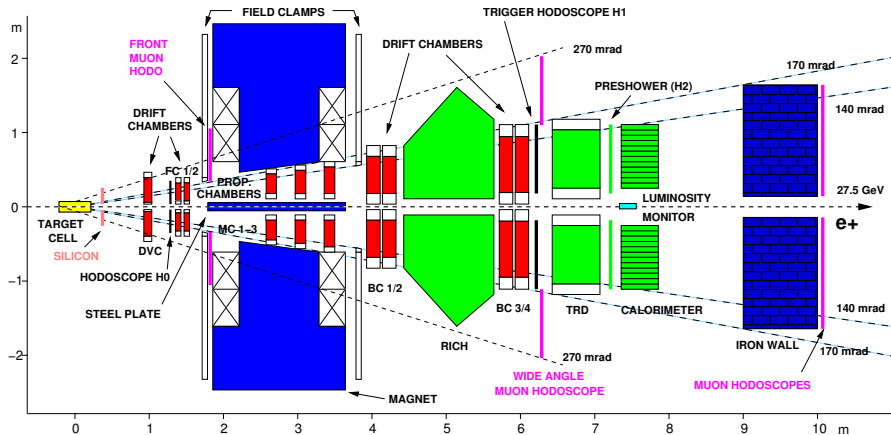
- ▶ results from recent paper [PLB 659 \(2008\) 486](#)
- ▶ GPD model in fair agreement with data at low values of  $-t$ ; data support the order of magnitude of power corrections
- ▶ Regge model provides good description of the kinematic dependences

## Transverse spin asymmetry

- ▶ **preliminary results**
- ▶ first experimental attempt to study this observable
- ▶ larger statistics required for more detailed studies of the kinematic dependences, for example @ JLab

# Backup slides

# The HERMES experiment at DESY

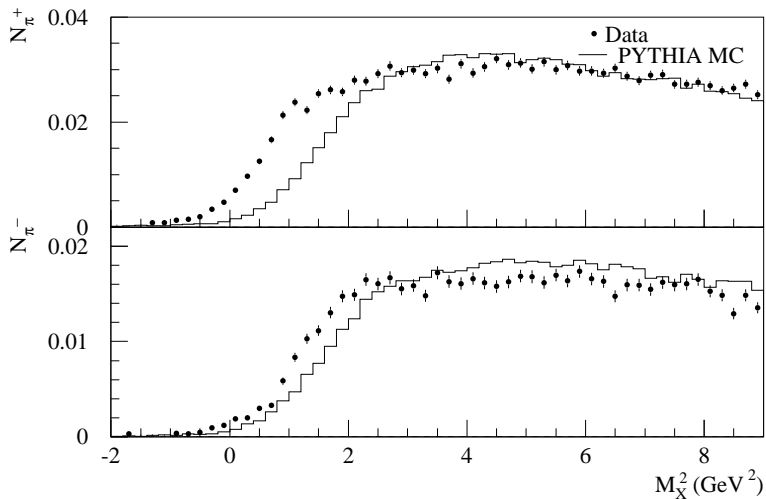


- internal (polarised) hydrogen fixed target, 27.6 GeV (polarised)  $e^\pm$  beam  
1.5 T m,
- tracking system: drift chambers  $\Delta\theta = 0.6$  mrad, vertical dipole magnet  $\frac{\Delta p}{p} = 0.5\%$
- lepton-hadron separation: > 99% efficiency; particle identification:  $\pi, p_\pi = 1-15$  GeV

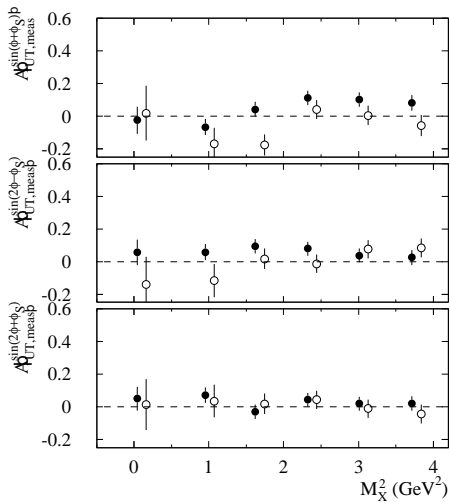
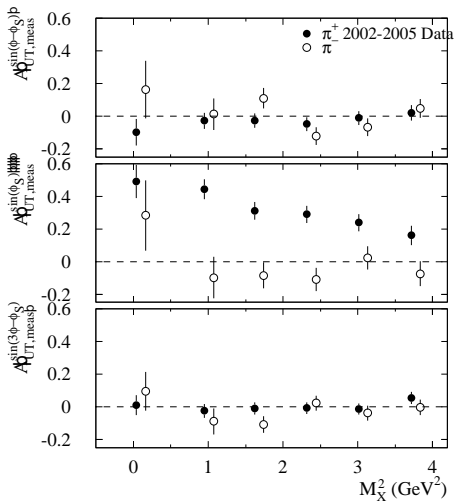


# Data-to-PYTHIA comparison of yields

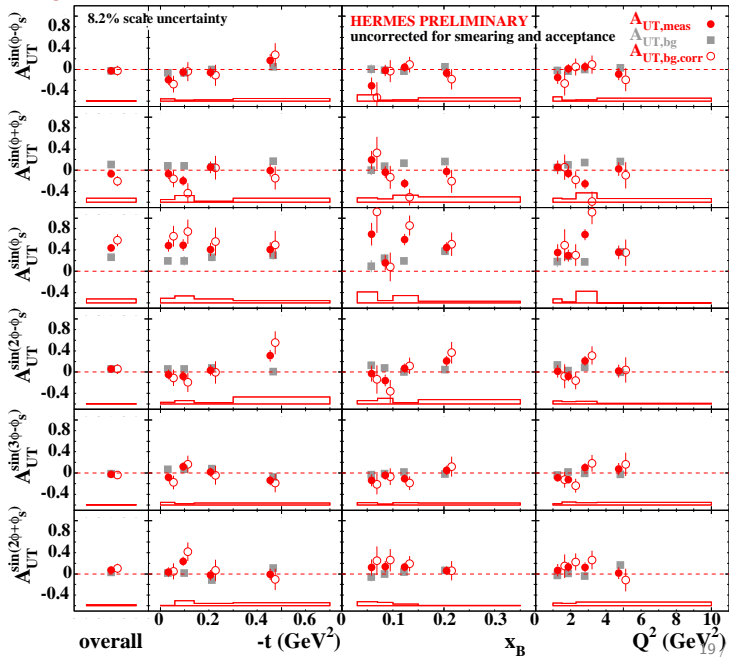
- ▶ PYTHIA processes: 95,99 (DIS); 91,92,94 (VMD)
- ▶ worse agreement between  $\pi^-$  data and PYTHIA



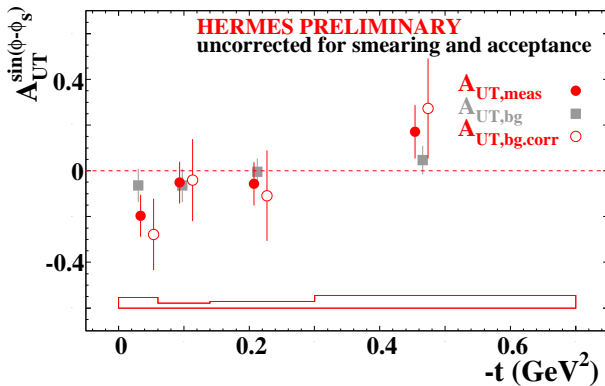
# Raw amplitudes vs. $M_X^2$ for $\pi^+$ and $\pi^-$



# Kinematic dependences of $A_{UT}$

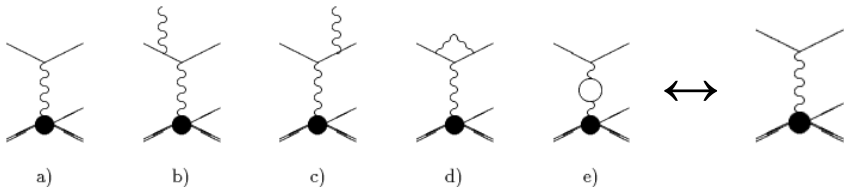


$A_{UT}^{\sin(\phi-\phi_s)}$  vs.  $-t$



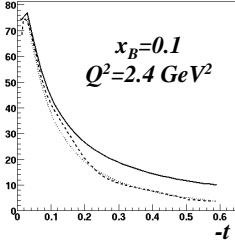
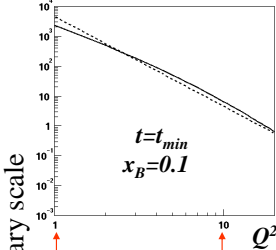
# Radiative effects for exclusive $\pi^+$ production

$$\sigma^{obs}(x_B, Q^2) \longleftrightarrow \sigma^{Born}(x_B, Q^2)$$



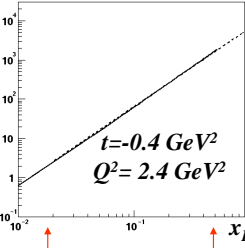
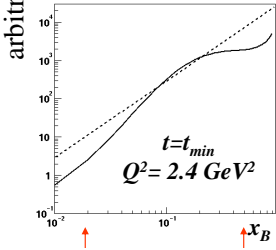
- correct the measured cross section by  $\eta = \frac{\sigma^{obs}}{\sigma^{Born}} = 0.77$
- RADGEN adapted to exclusive processes with VGG GPD model as input  
Akushevich, Böttcher, Ryckbosch [hep-ph/9906408](https://arxiv.org/abs/hep-ph/9906408), A. Ilyichev
- little variation of  $\eta$  ( $< 3\%$ ) as a function of  $x_B$ ,  $Q^2$ , or  $t'$  for  $M_X^2 < 1.2 \text{ GeV}^2$
- compute at Born level  $\langle x_B \rangle$ ,  $\langle Q^2 \rangle$ ,  $\langle t' \rangle$ ,  $\Gamma_V(\langle x_B \rangle, \langle Q^2 \rangle)$
- corrections applied for smearing 12/15% ( $< 25/35\%$ ), bin size  $\delta = 1.08 (< 1.2)$

# GPD models



— VGG model  
 ..... Tuned VGG ( $\tilde{E}^* e t$ )  
 - - Piller model

↑↑ Hermes kinematics



→ different dependence for VGG and Piller

▶ VGG model: Vanderhaeghen, Guichon, Guidal [PRD 60 \(1999\) 094017](#)

▶ Piller model: Mankiewicz, Piller, Radyushkin [EPJC 10 \(1999\) 307](#)