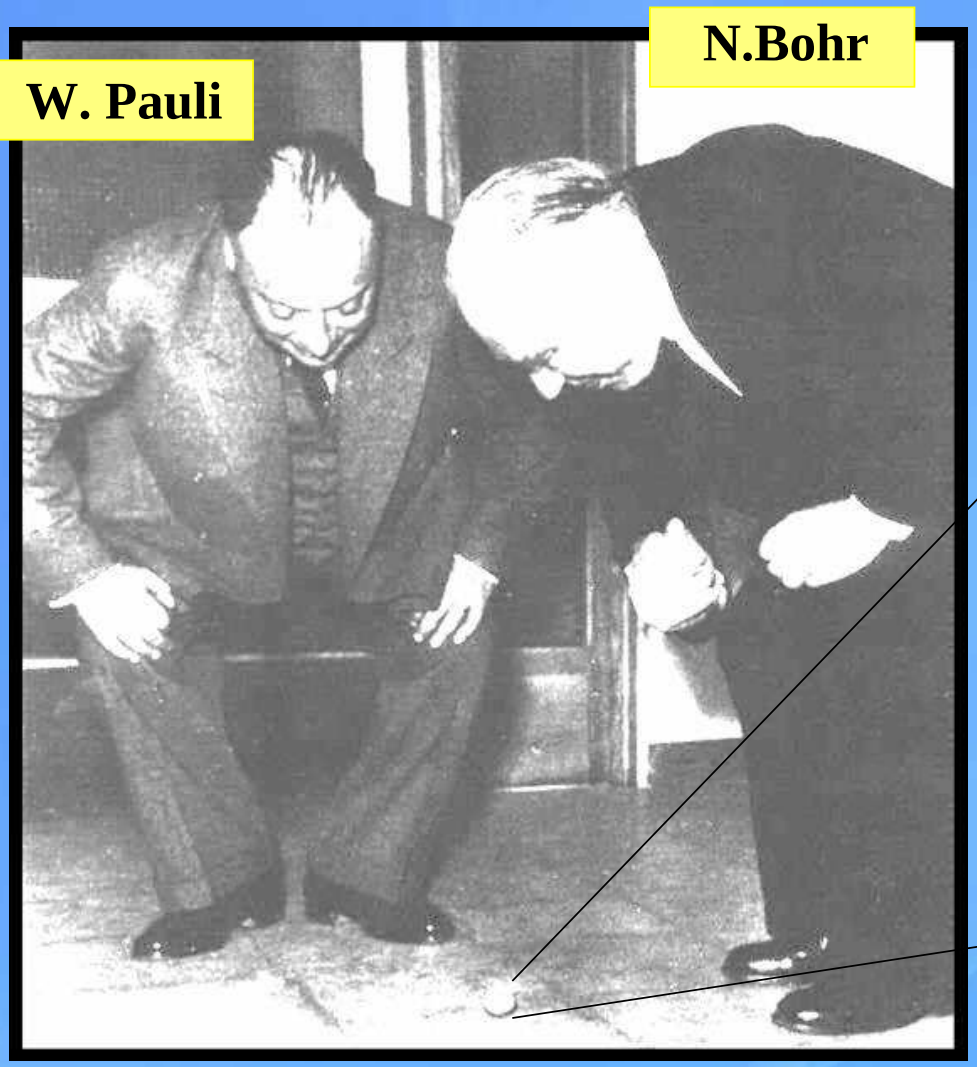
The Spin of the Nucleon

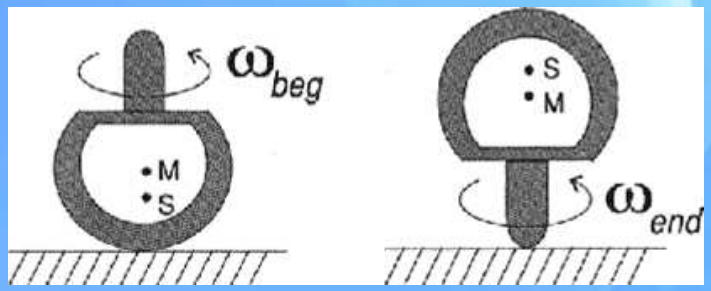
— The View from HERMES —

E.C. Aschenauer

DESY

Fascinated by Spin ?





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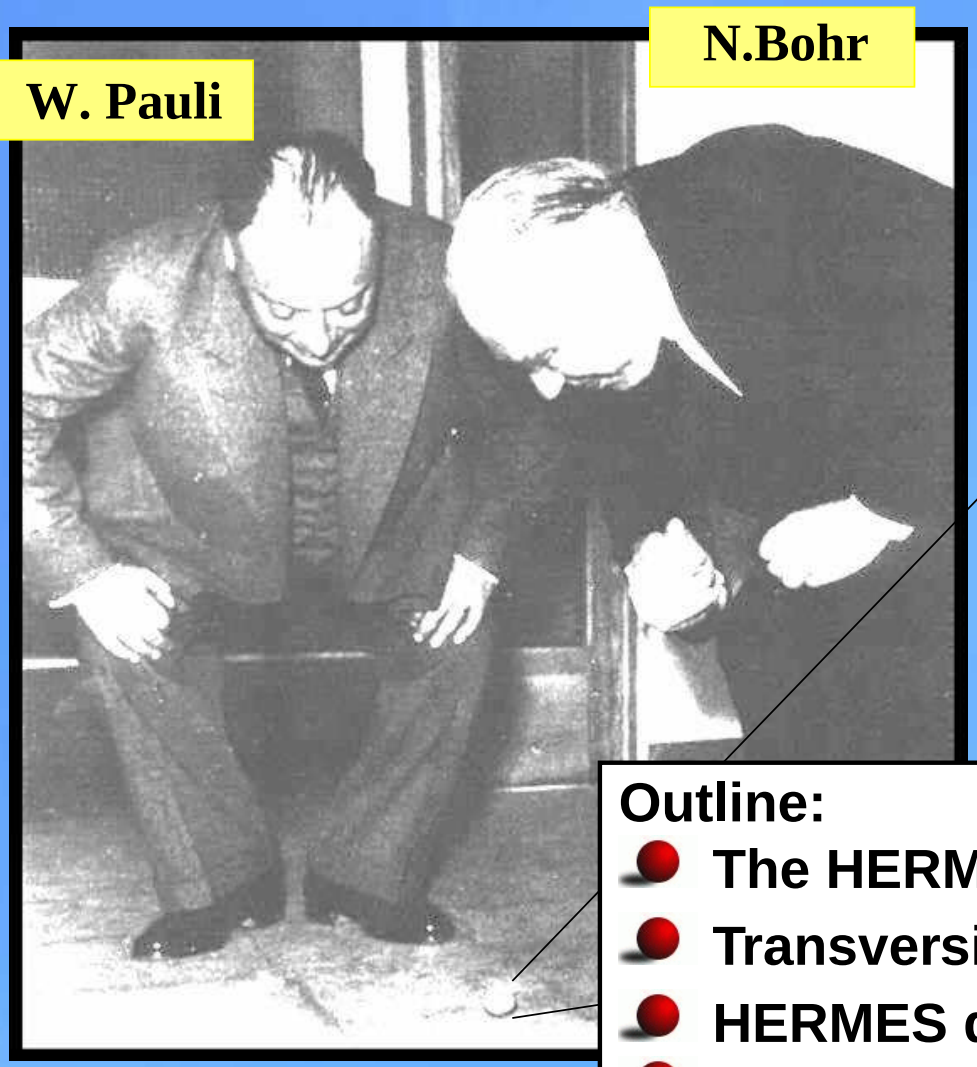
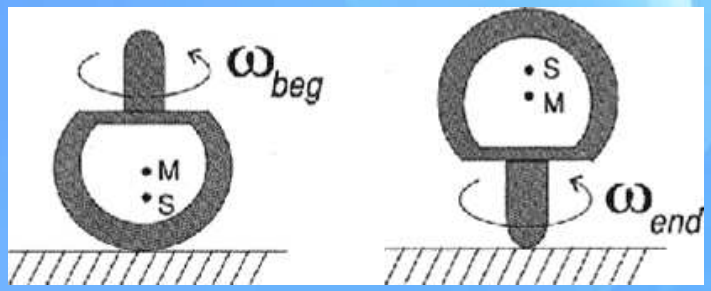
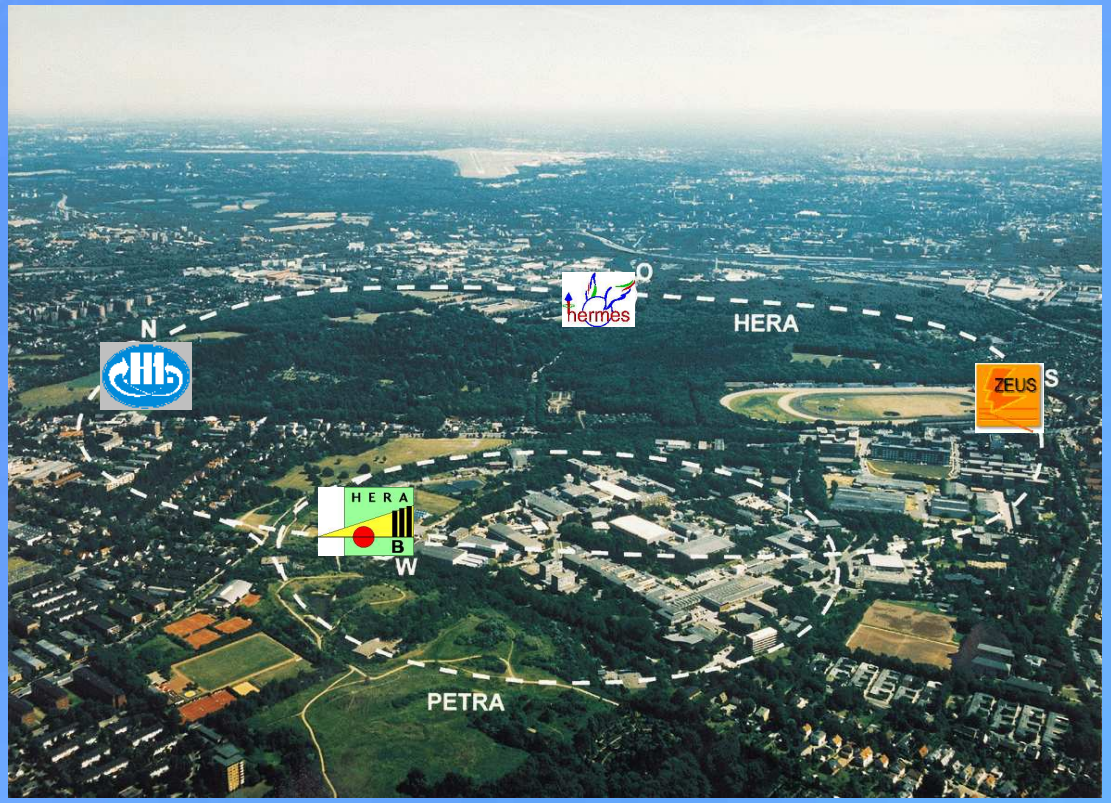


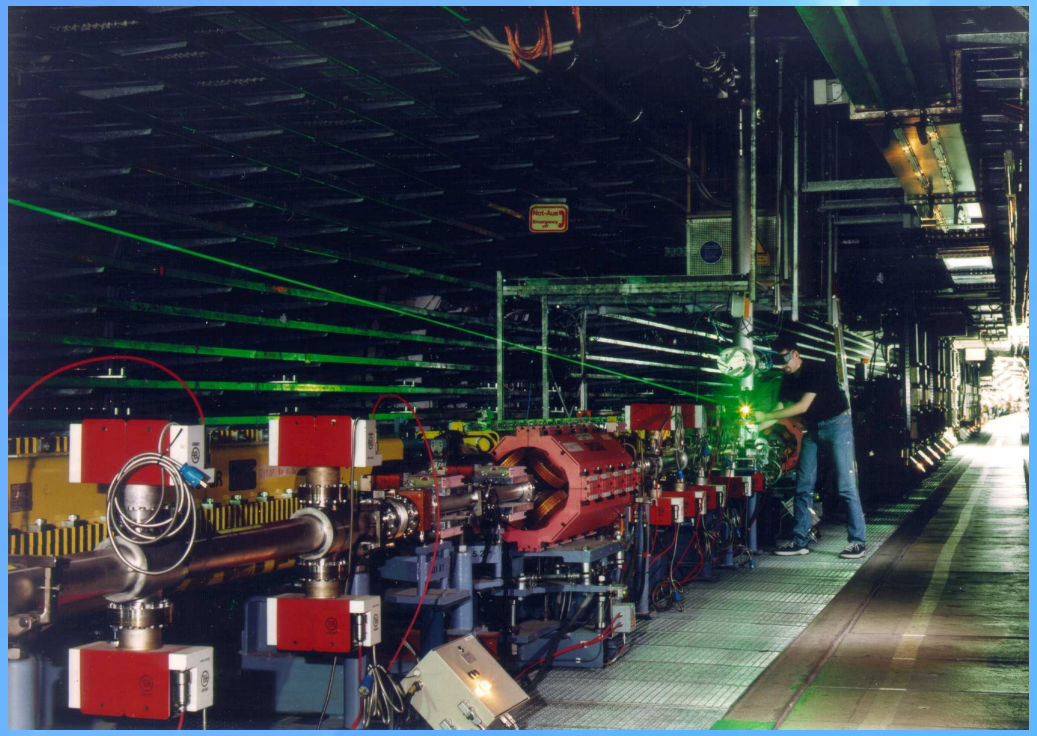


Outline:

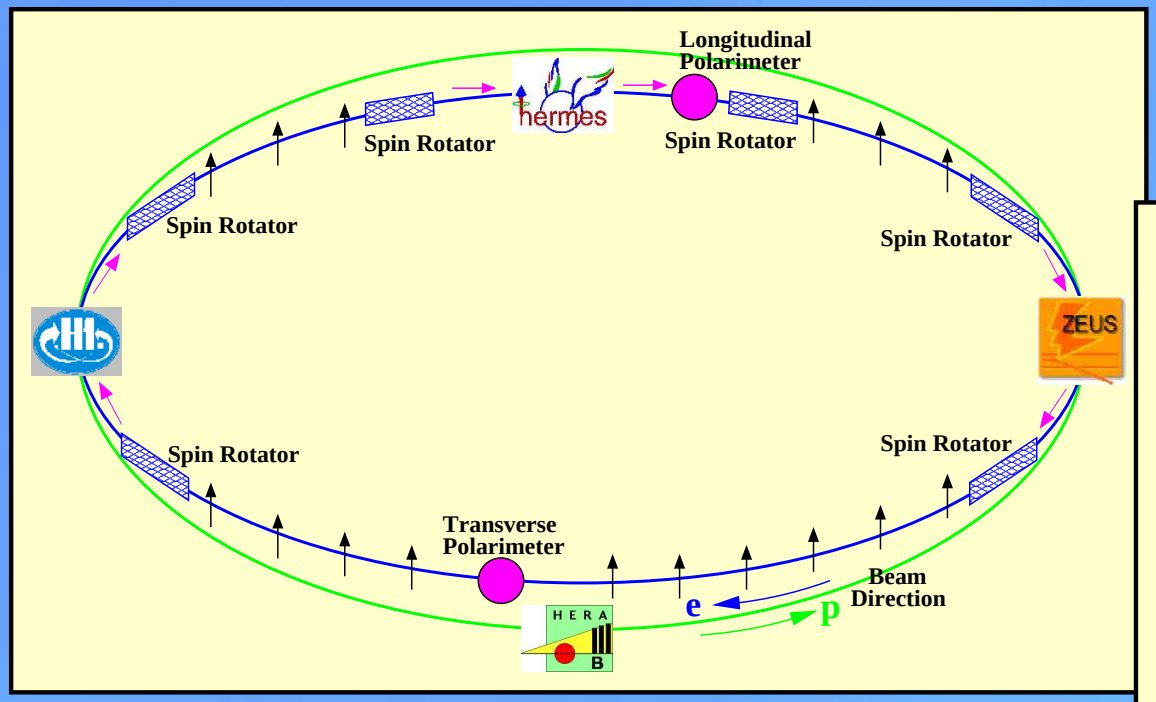
- **The HERMES Experiment**
- **Transversity, Sivers and friends**
- **HERMES data to constrain GPDS**
- **Hadron Multiplicities**

HERA at DESY

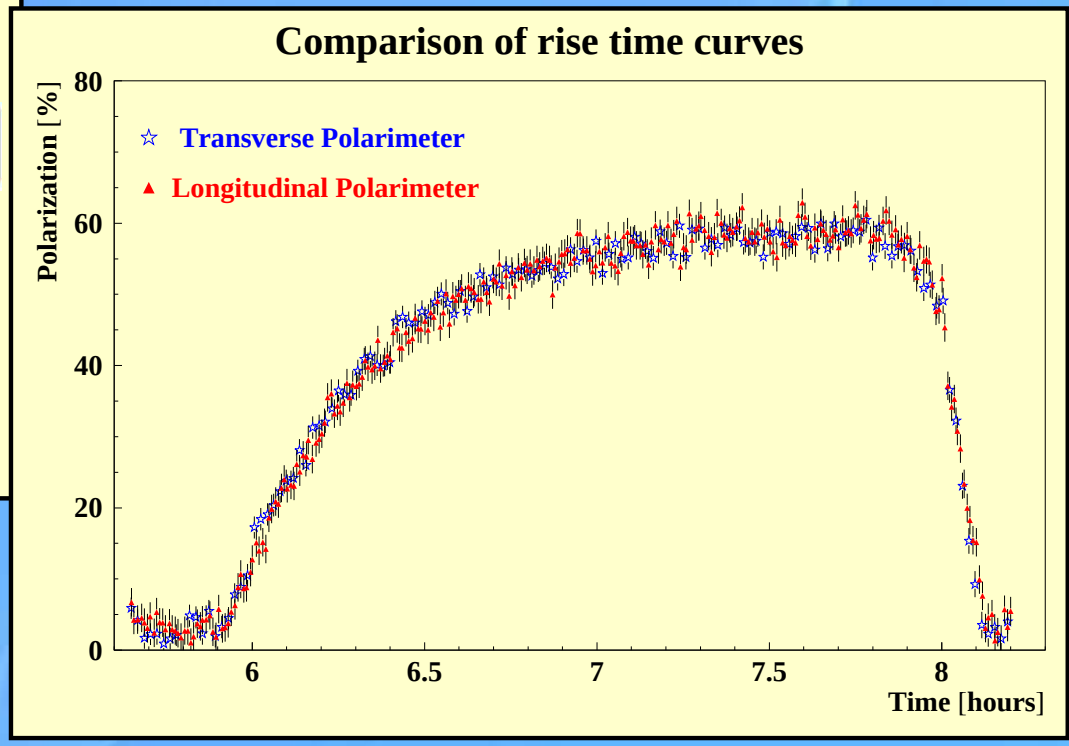




HERA at DESY



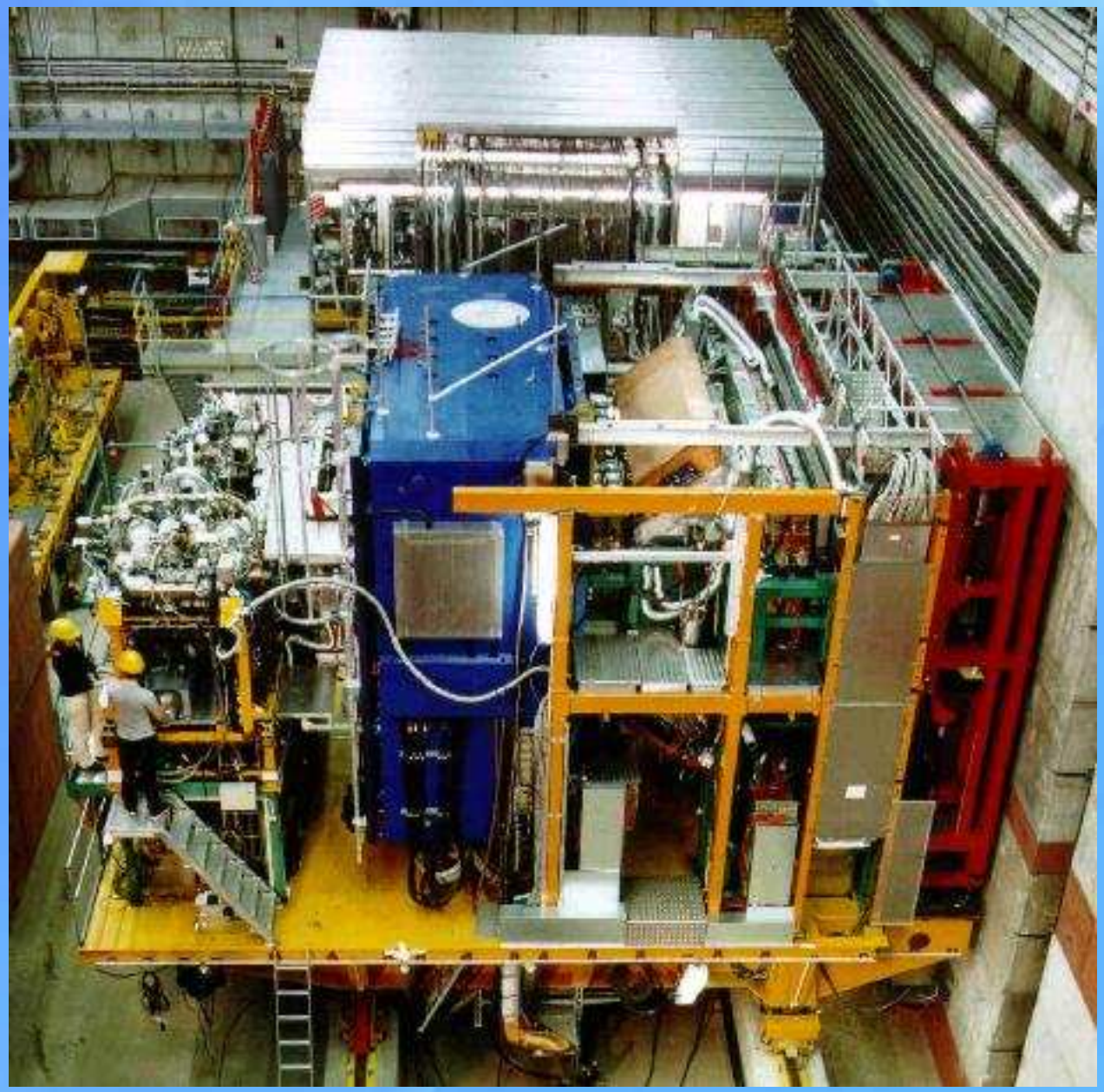
- **Online measurement of beam polarization with two Compton back scattering polarimeters**



- **HERA-e self-polarizing by emission of synchrotron radiation**
  $\longrightarrow$ **Transverse Polarization**
- **Longitudinal polarization at HERMES via spin-rotators**

Beam Polariasation $< \mathrm{P_B} > \sim 55\%$
$\Delta \mathrm{P_B}/\mathrm{P_B} = 1.8 - 3.4\%$

The HERMES Detector



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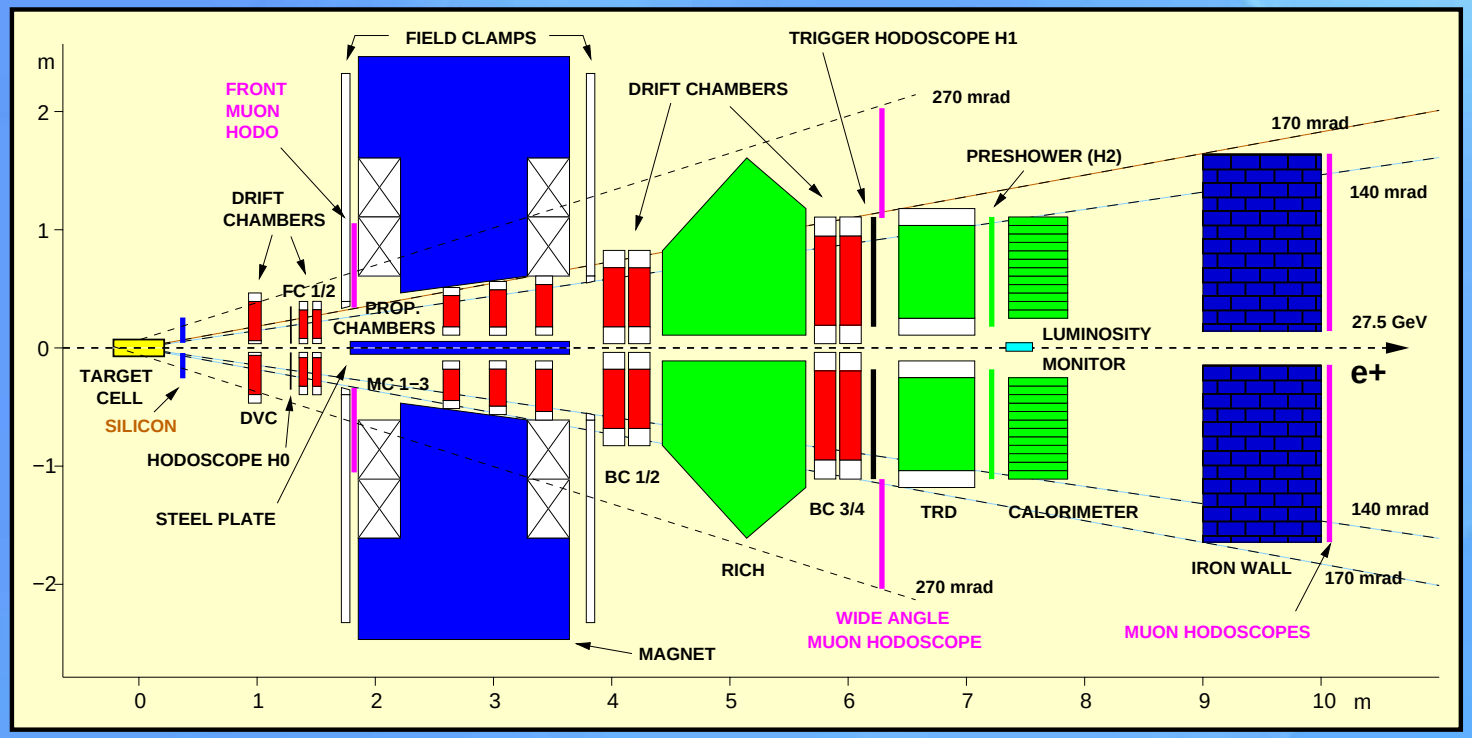
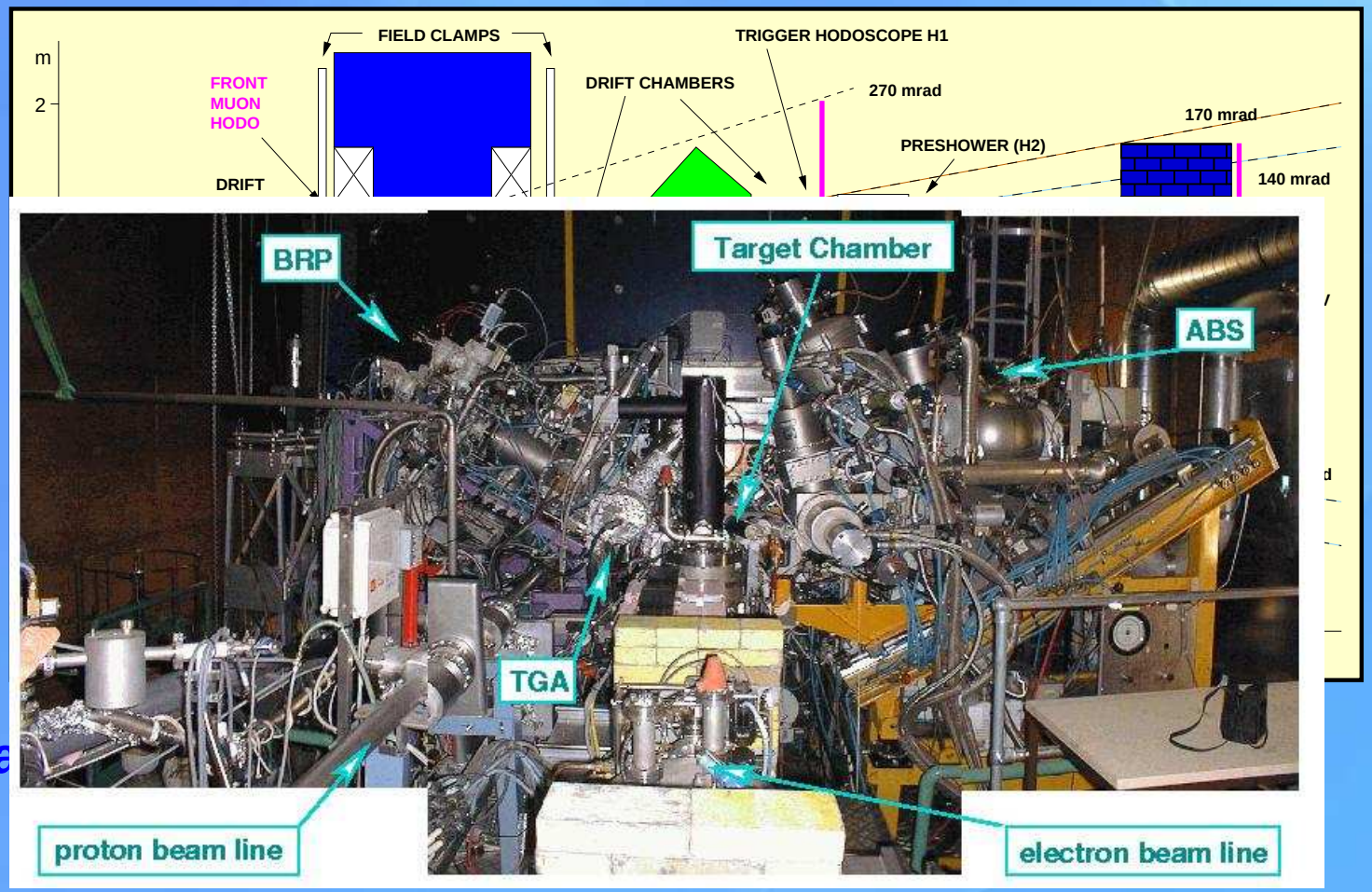


Kinematic Range: **0.02 $\leq$ x $\leq$ 0.8 at $Q^2 \geq$ 1GeV^2 and W $\geq$ 2GeV**

$\Theta_x \leq$ 175 mrad, 40 mrad $\leq \Theta_y \leq$ 140 mrad

Reconstruction: **δp/p 1.0 - 2.0%, $\delta\Theta \leq$ 1.0mrad**

The HERMES Detector

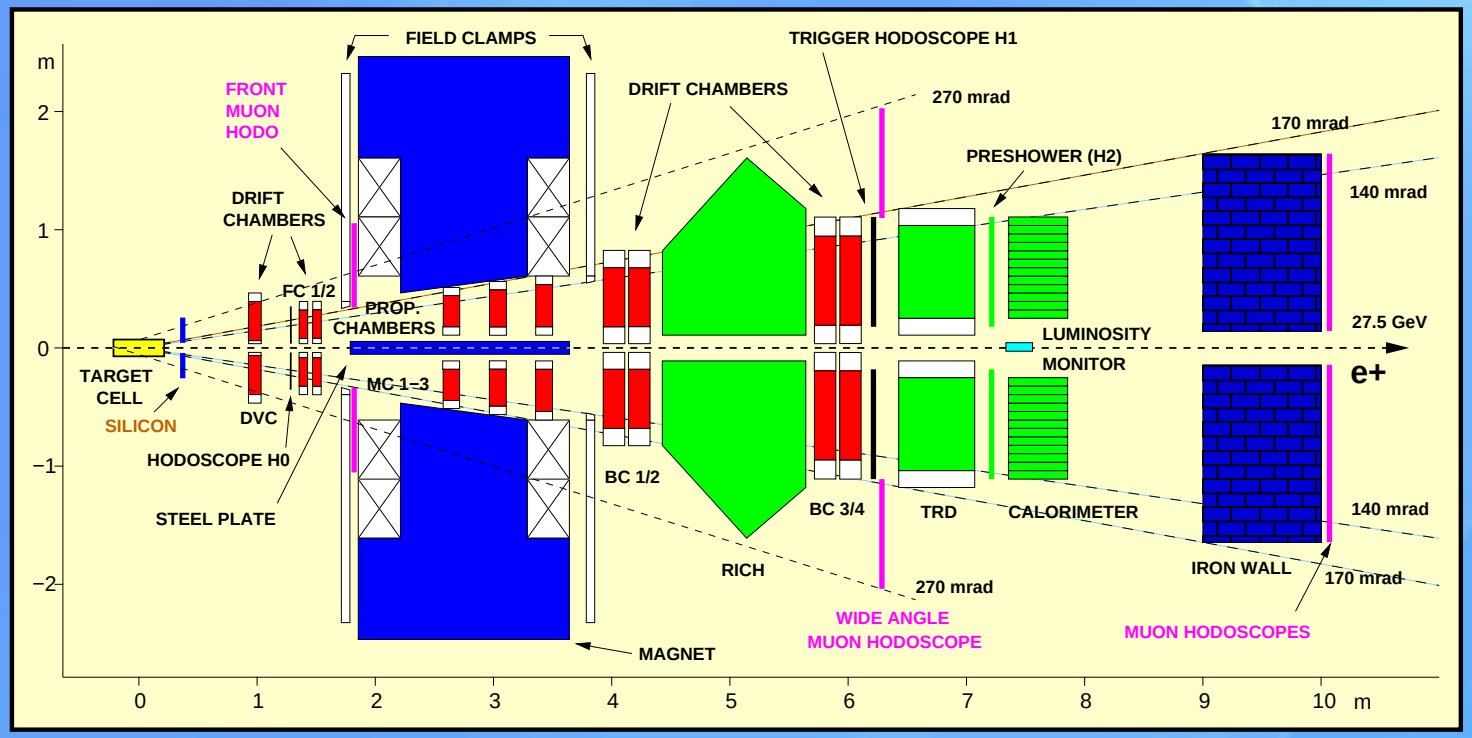


Kinematic Ra

Reconstruction: δ**p/p 1.0 - 2.0%,** $\delta\Theta \leq$ **1.0mrad**

Internal Gas Target (no dilution): $\overrightarrow{\mathrm{He}}$, $\overrightarrow{\mathrm{D}}$, $\overrightarrow{\mathrm{H}}$, **H**$^{\uparrow}$ **unpol: H**$_2$**, D**$_2$**, He, N**$_2$**, Ne, Ar, Kr, Xe**

The HERMES Detector



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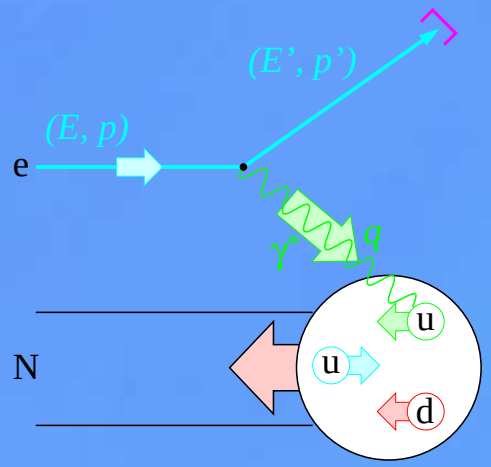
Particle ID: TRD, Preshower, Calorimeter
$\Rightarrow$ 1997: $\check{C}$erenkov 1998 $\Rightarrow$: RICH + Muon-ID

DIS Kinematics

Inclusive Scattering:



detect scattered lepton

$$Q^2 \overset{lab}{=} 4EE'\sin^2(\tfrac{\theta}{2}) \qquad \nu \overset{lab}{=} E - E'$$

$$W^2 \overset{lab}{=} M^2 + 2M\nu - Q^2$$

$$x \overset{lab}{=} \frac{Q^2}{2M\nu} \qquad y \overset{lab}{=} \frac{\nu}{E} = \frac{p\cdot q}{p\cdot k}$$

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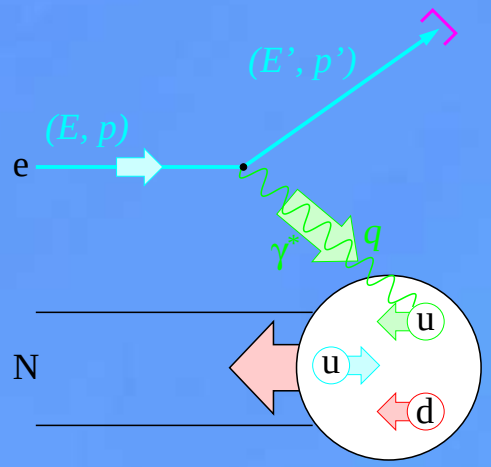

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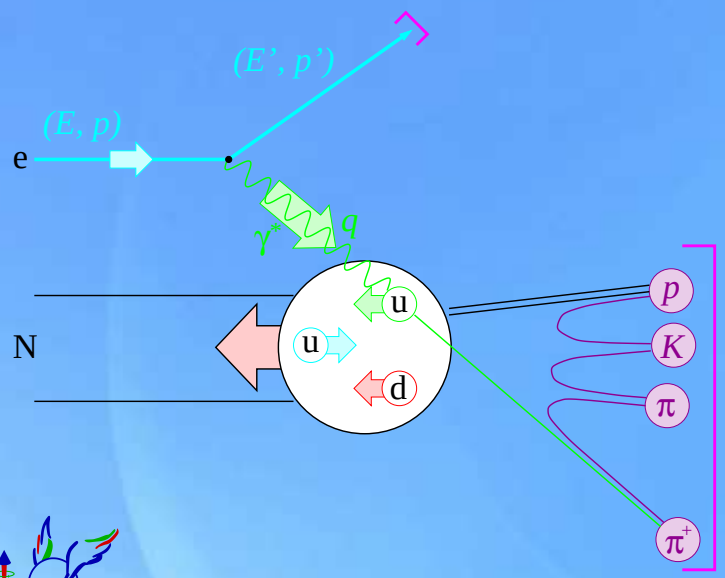
Semi-Inclusive Scattering:

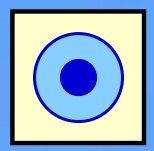
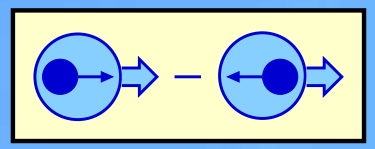
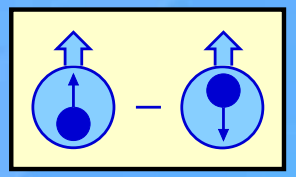
detect scattered lepton and produced hadrons



$$\eta = \frac{log(E^h_{cm} - p^h_{||})}{2*(E^h_{cm} + p^h_{||})}$$

$$z \overset{lab}{=} \frac{E_h}{\nu}$$

Leading Twist Quark Distributions

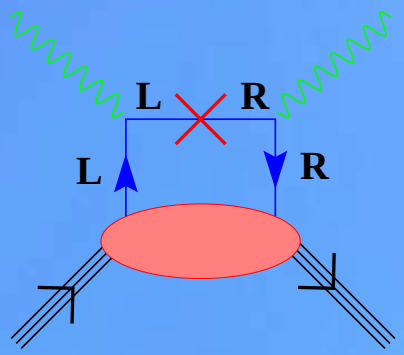
momentum distribution	helicity distribution	transversity distribution
$q(x, Q^2)$	$\Delta q(x, Q^2)$	$\delta q(x, Q^2)$
forward quark-nucleon amplitudes: (in helicity basis)		
$\sim \mathrm{Im}\,(A_{++,++} + A_{+-,+-})$	$\sim \mathrm{Im}\,(A_{++,++} - A_{+-,+-})$	$\sim \mathrm{Im}\,(A_{+-,-+})$
measures spin average	**measures helicity difference**	**measures helicity flip**
probabilistic interpretation:		
		
(in helicity basis)	**(in helicity basis)**	**(in basis of transverse spin eigen states)**

$\Rightarrow$ **complete description of quark momentum** (P) **and spin** (S) **at leading twist:**

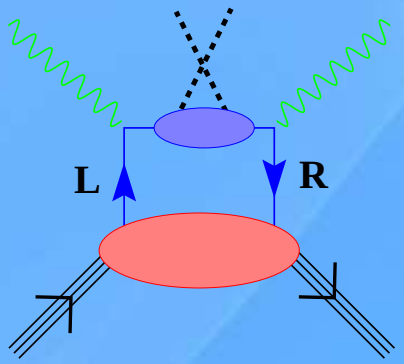
$$\Phi(x) = \frac{1}{2}\left\{q(x, Q^2)\not{P} + \lambda_N \Delta q(x, Q^2)\gamma_5\not{P} + \delta q(x, Q^2)\not{P}\gamma_5\not{S}_\perp\right\}$$

Properties of transversity

- The Difference between distributions $\Delta q(x, Q^2)$ and $\delta q(x, Q^2)$ provides measurement of the relativistic nature of the quarks inside the nucleon.
- The transversity distribution is chiral-odd,



cannot be determined in inclusive DIS

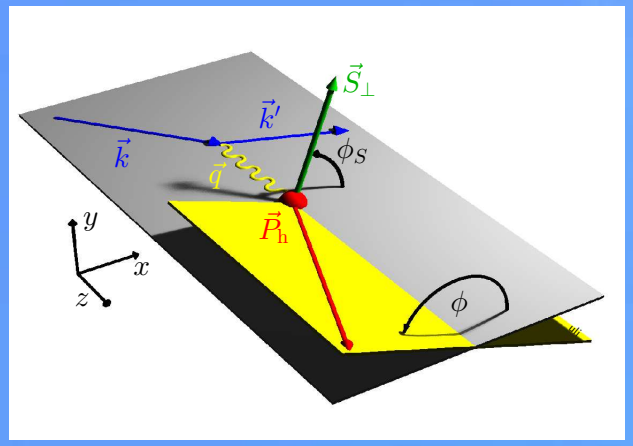


another chiral-odd fragmentation (or distribution) function is needed

- The transversity distribution can be measured:
  with two hadrons in the initial state or one hadron both in initial and final state
  One hadron has to be transversely polarized
- At HERMES $\delta q(x, Q^2) \times H_1^{\perp}\left(z, (-zk_T)^2\right)$ is accessible in azimuthal single-spin asymmetries in semi-inclusive DIS.

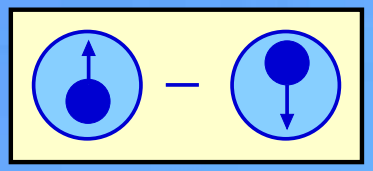
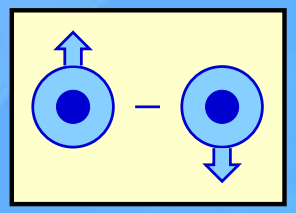
Azimuthal Single-Spin Asymmetries

- **Semi-inclusive DIS on a transversely polarized target:**



In addition to the azimuthal angle ϕ the azimuthal angle ϕ_s is observable. Non-vanishing $P_{h\perp}$ is caused by intrinsic transverse momenta p_T and k_T

- **Generalized distribution and fragmentation functions:**

Collins function $H_1^\perp\left(z,(-zk_T)^2\right)$	Sivers function $f_{1T}^\perp\left(x,p_T^2\right)$
fragmentation function	distribution function
	
chiral-odd	chiral-even
	implies non-vanishing L_z^q
naive time reversal odd $\Rightarrow$	naive time reversal odd $\Rightarrow$
azimuthal single-spin asymmetries	azimuthal single-spin asymmetries

Collins and Sivers Moments

- The transverse target cross section contains a convolution integral over intrinsic transverse momenta $\mathbf{p_T}$ and $\mathbf{k_T}$
- Assuming a Gaussian dependence one can disentangle the convolution integral.
- The unweighted (i.e. no weighting by $\frac{|\mathbf{P_{h\perp}}|}{\mathbf{z}}$) asymmetry $\mathbf{A^h_{UT}}$ (for each hadron type $\mathbf{h}$) becomes:

$$\mathbf{A^h_{UT}} \approx \mathbf{2}\,|\mathbf{S_T}|\,\underbrace{\sin(\mathbf{\Phi}+\mathbf{\Phi_S})}_{\text{distinctive}}\,\frac{\overbrace{\mathbf{B}(\mathbf{y})\sum_{\mathbf{q}}\left(\mathbf{e_q^2}\,\delta\mathbf{q}(\mathbf{x},\mathbf{Q^2})\,\mathbf{H_1^{\perp(1/2)q}}(\mathbf{z})\right)\Big/\sqrt{\langle\mathbf{p_T^2}\rangle+\langle\mathbf{k_T^2}\rangle}}^{\text{Collins moment}}}{\mathbf{A}(\mathbf{x},\mathbf{y})\sum_{\mathbf{q}}\mathbf{q}(\mathbf{x},\mathbf{Q^2})\,\mathbf{D_1^q}(\mathbf{z})}$$

$$-\ \mathbf{2}\,|\mathbf{S_T}|\,\underbrace{\sin(\mathbf{\Phi}-\mathbf{\Phi_S})}_{\text{signature}}\,\frac{\overbrace{\mathbf{A}(\mathbf{x},\mathbf{y})\sum_{\mathbf{q}}\left(\mathbf{e_q^2}\,\mathbf{f_{1T}^{\perp(1/2)q}}\,\mathbf{D_1^{\perp q}}(\mathbf{z})\right)\Big/\sqrt{\langle\mathbf{p_T^2}\rangle+\langle\mathbf{k_T^2}\rangle}}^{\text{Sivers moment}}}{\mathbf{A}(\mathbf{y})\sum_{\mathbf{q}}\mathbf{q}(\mathbf{x},\mathbf{Q^2})\,\mathbf{D_1^q}(\mathbf{z})}$$

UT means unpolarized beam (U) and transversely polarized target (T).
$\mathbf{S_T}$ states target polarization vector.

Extraction of Collins and Sivers Moments

- **Determination of unweighted asymmetries for charged pions:**

$$\mathbf{A_{UT}^{\pi^\pm}(\Phi,\Phi_S)} = \frac{\mathbf{1}}{\langle \mathbf{P_z} \rangle} \cdot \frac{\mathbf{N_h^{\Uparrow}(\Phi,\Phi_S) - N_h^{\Downarrow}(\Phi,\Phi_S)}}{\mathbf{N_h^{\Uparrow}(\Phi,\Phi_S) + N_h^{\Downarrow}(\Phi,\Phi_S)}}$$

$\langle \mathbf{P_z} \rangle = \mathbf{0.754 \pm 0.050}$ **(average target polarization value)**

- **Moments are extracted in the two-dimensional fit:**

Sivers moment

$$\mathbf{A_{UT}^{\pi^\pm}(\Phi,\Phi_S)} = \mathbf{2} \cdot \langle \sin(\mathbf{\Phi - \Phi_S}) \rangle_{\mathbf{UT}}^{\pi^\pm} \cdot \sin(\mathbf{\Phi - \Phi_S}) +$$

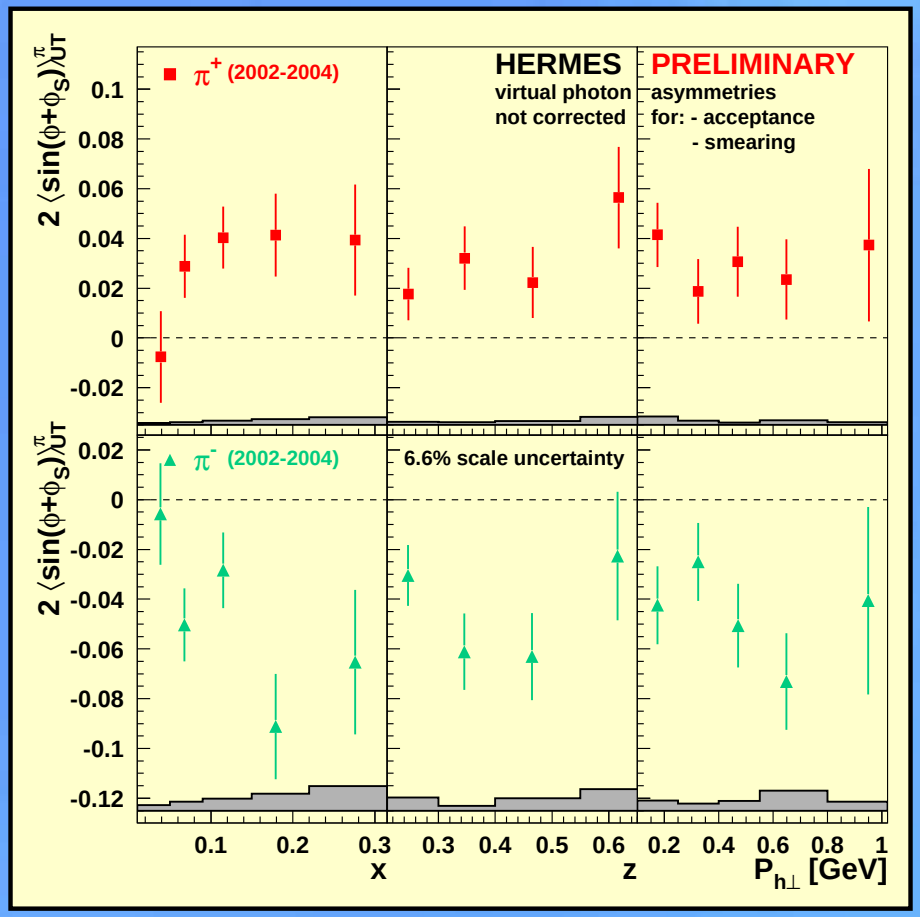
Collins moment

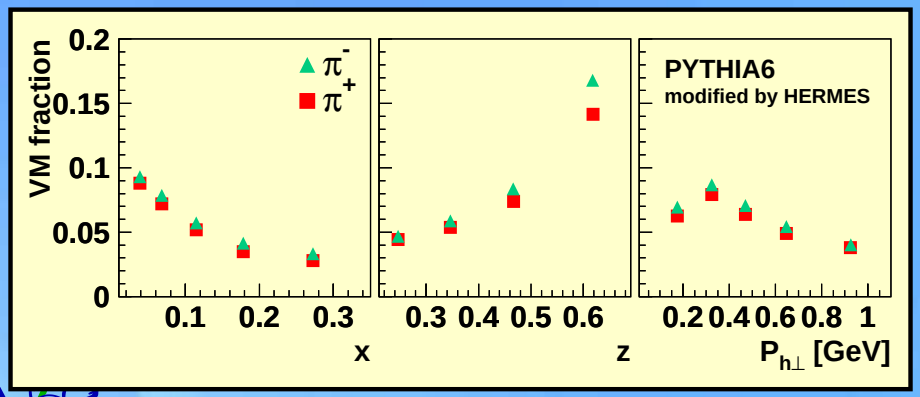
$$\mathbf{2} \cdot \langle \sin(\mathbf{\Phi + \Phi_S}) \rangle_{\mathbf{UT}}^{\pi^\pm} \cdot \frac{\mathbf{B}(\langle \mathbf{y} \rangle)}{\mathbf{A}(\langle \mathbf{x} \rangle, \langle \mathbf{y} \rangle)} \sin(\mathbf{\Phi + \Phi_S}) +$$

$$\mathbf{c_3} \cdot \sin(\mathbf{2}\phi - \phi_\mathbf{S}) + \mathbf{c_4} \cdot \sin \phi_\mathbf{S} + \mathbf{c_5}$$

$\mathbf{A}(\langle \mathbf{x} \rangle, \langle \mathbf{y} \rangle)$, $\mathbf{B}(\langle \mathbf{y} \rangle)$: **kinematic factors;** c_3, $\mathbf{c_4}$, c_5: **fit parameters**

Unweighted Collins Moment





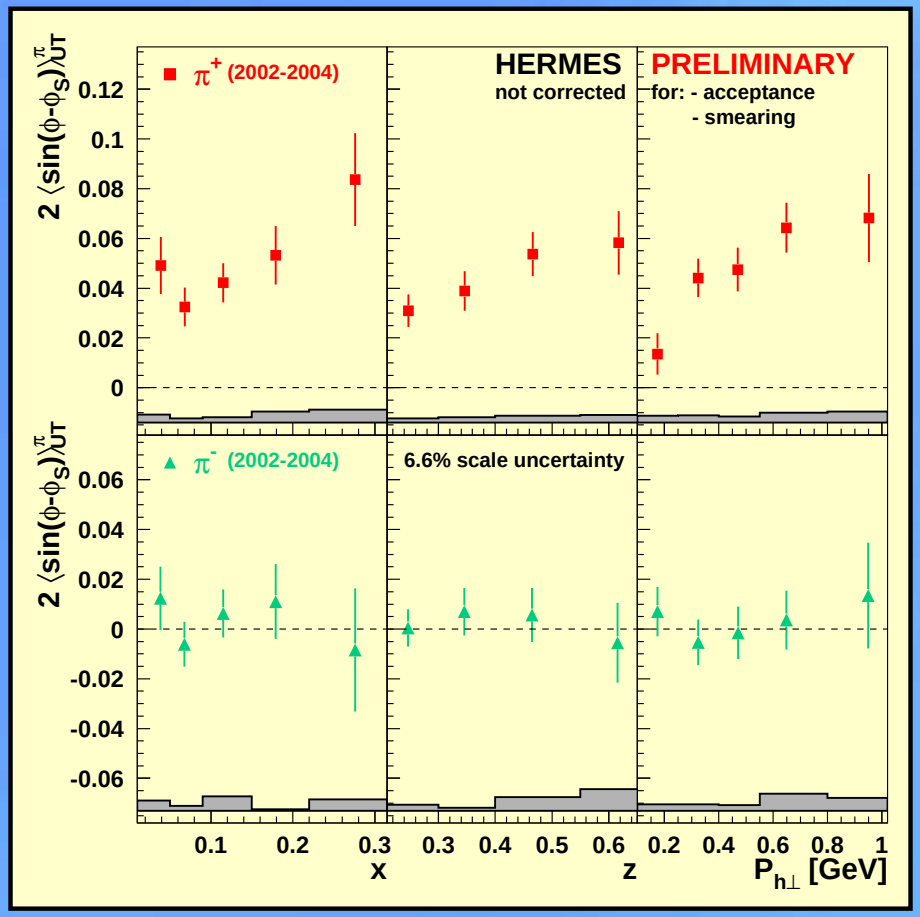
Results of 2002–2004 data:

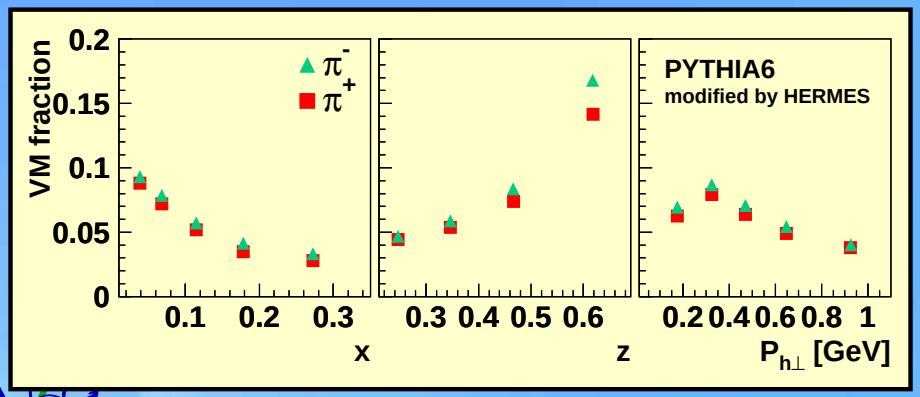
- **Result is consistent with published Collins moments.**
- **Collins moment is positive for π^+ and negative for π^-.**
- **The large negative π^- moment is unexpected.**
- **Additional information on the Collins fragmentation function (from BELLE) is needed in order to extract the transversity distribution.**

Systematic uncertainties:

- **Common scale uncertainty of 6.6% in the moments.**
- **Background asymmetry of diffractive vector mesons.**

Unweighted Sivers Moment





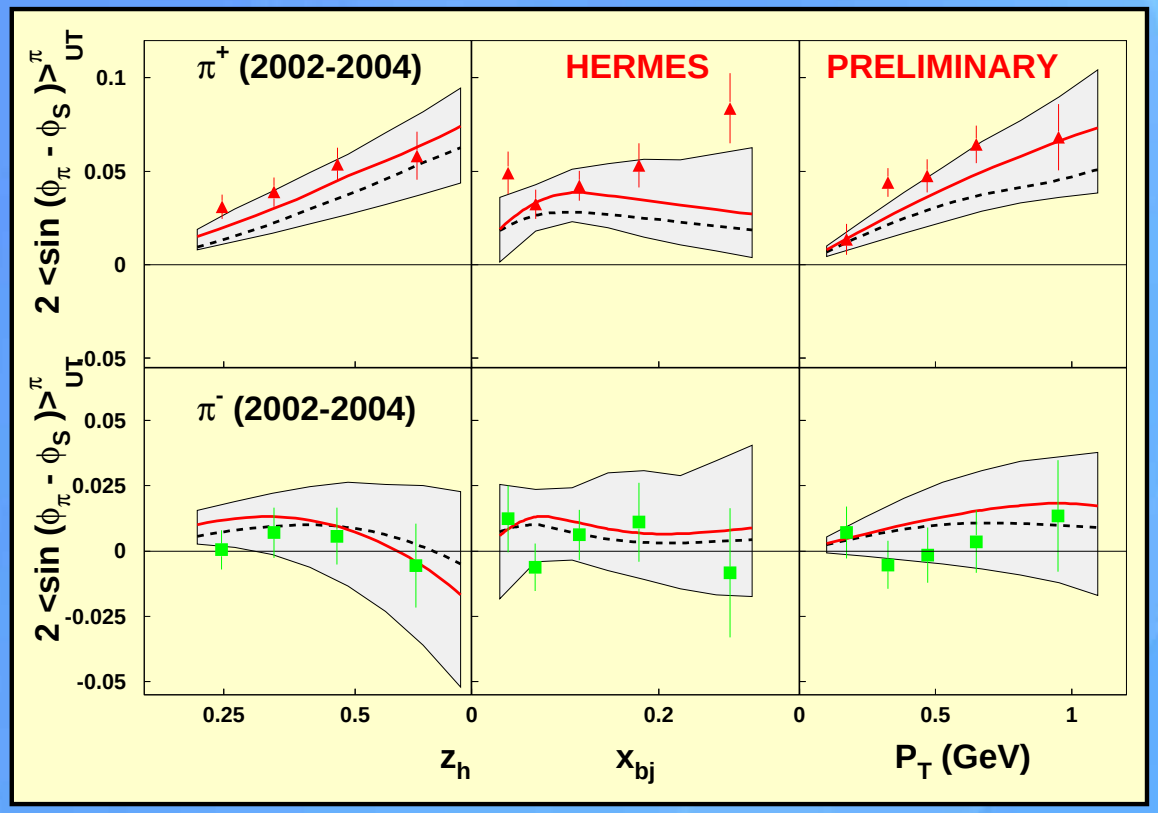
Results of 2002–2004 data:

- **Result is consistent with published Sivers moments.**
- **Sivers moment is significantly positive for π^+ and implies a non-vanishing orbital angular momentum L_z^q.**
- **Sivers moment for π^- is consistent with zero.**
- **Since spin independent fragmentation function is known, extraction of Sivers function is possible.**

Systematic uncertainties:

- **Common scale uncertainty of 6.6% in the moments.**
- **Background asymmetry of diffractive vector mesons.**

Unweighted Sivers Moment: Exp. vs. Theory



- **Nice agreement between data and theoretical prediction**
- **Theory: M. Anselmino et al. hep-ph/0501196**
  Intrinsic $k_\perp$ determined from unpolarized $\cos(\Phi)$ data

Subleading-Twist Effects

Transverse polarized target:

- **in theory:** polarization w.r.t. the virtual photon $\rightarrow \mathbf{A}_{\mathbf{UT,q}}^{\sin(\phi \pm \phi_{\mathbf{S}})}$
- **in experiment:** polarization w.r.t. the lepton beam $\rightarrow \mathbf{A}_{\mathbf{UT,l}}^{\sin(\phi \pm \phi_{\mathbf{S}})}$

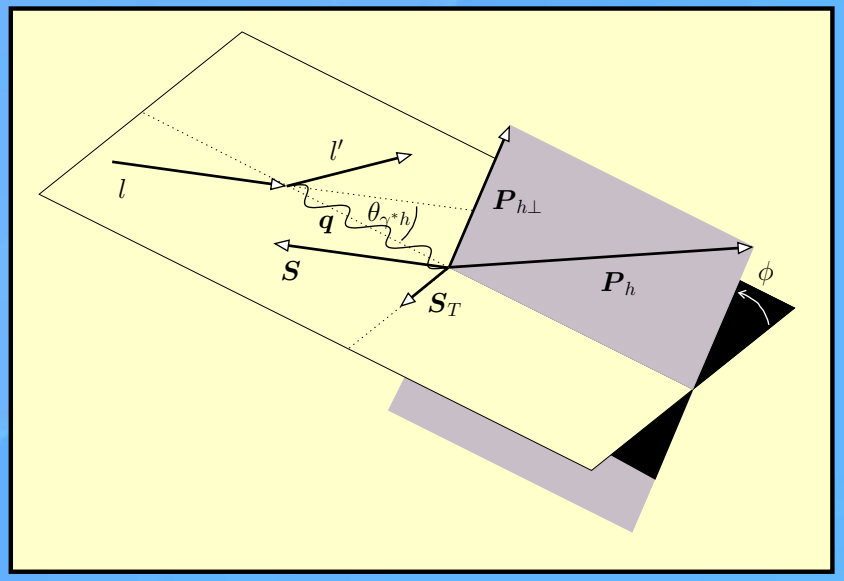
- **Conversion with subleading-twist term:**

$$\mathbf{A}_{\mathbf{UT,q}}^{\sin(\phi \pm \phi_{\mathbf{S}})} \approx \mathbf{A}_{\mathbf{UT,l}}^{\sin(\phi \pm \phi_{\mathbf{S}})} - \frac{\mathbf{1}}{\mathbf{2}} \sin\theta_{\gamma^*} \mathbf{A}_{\mathbf{UL,l}}^{\sin\phi}$$

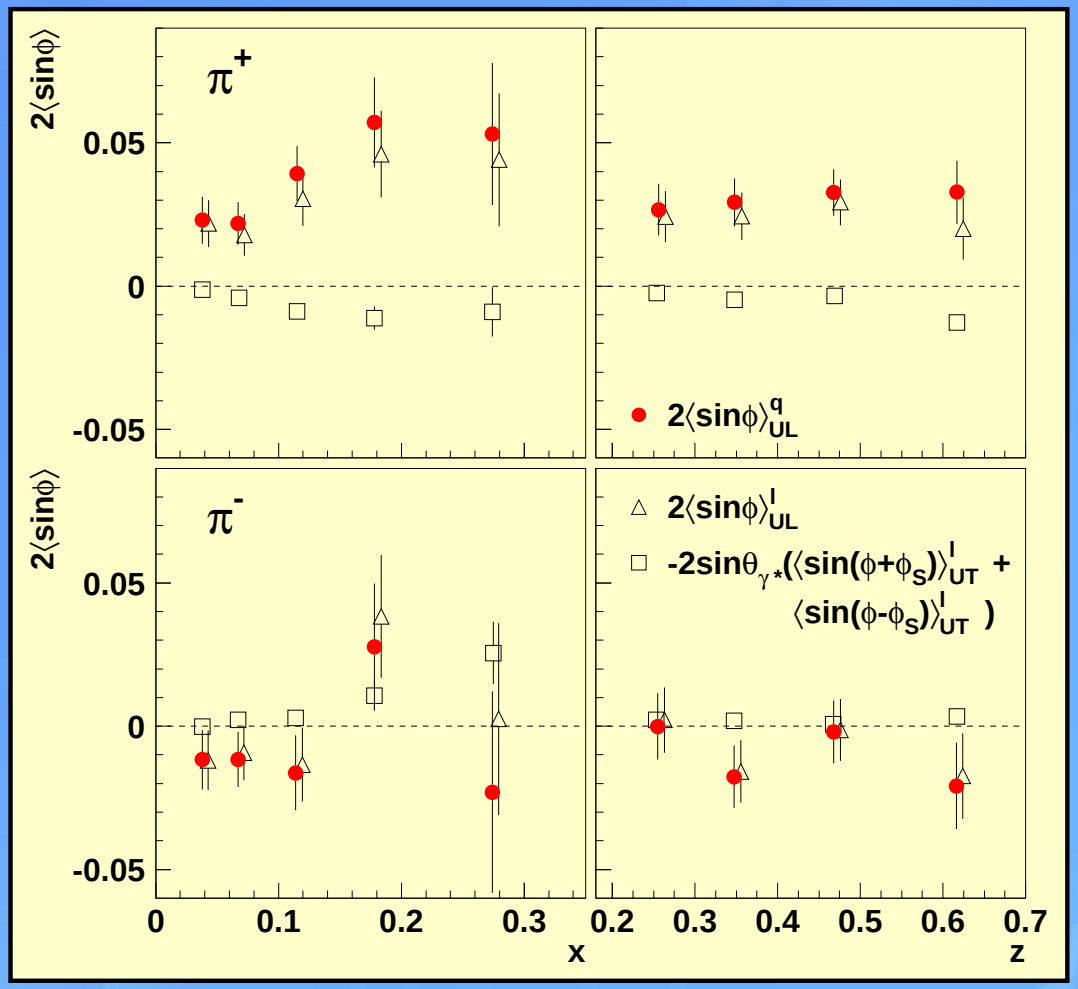
θ_{γ^*} **polar angle between the incoming beam direction and the virtual photon direction**

- **Longitudinal lepton moments** $\langle \sin\phi \rangle_{\mathbf{UL}}^{\mathbf{l}}$ **(subleading-twist) are extracted.**

Semi-inclusive DIS on a longitudinally polarized target:



Results of $A_{UL,q}^{\sin\Phi}$



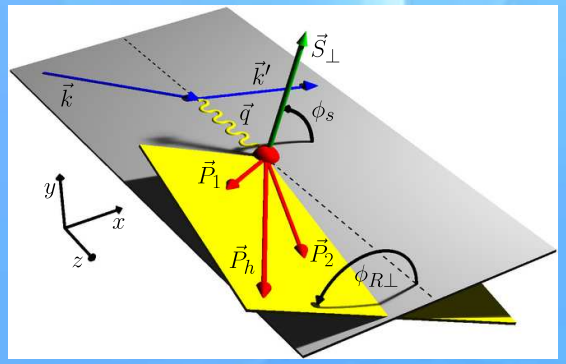
Results:

- $A_{UL,q}^{\sin\phi}$ **is about 2-5% for** π^+
- **and approximately zero for** π^-
- **Systematic uncertainty is less than** 0.003**.**
- **Maximum difference** $|A_{UT,q} - A_{UT,l}| < 0.004$

Interference FF

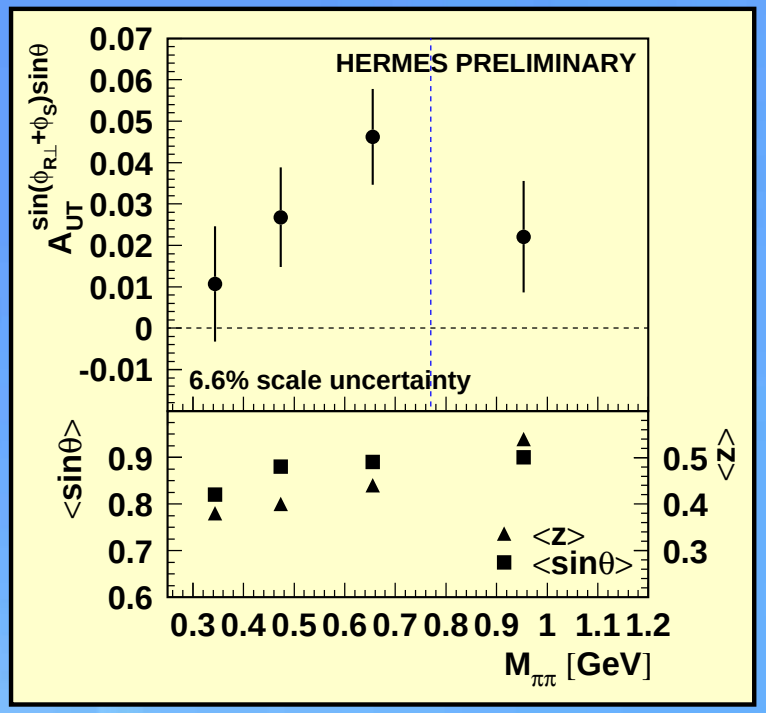
An independent way to attack transversity $\delta q(x, Q^2)$

$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S)\sin(\theta)\delta q(x, Q^2) H_1^{\sphericalangle}$$



Expansion of $H_1^{\sphericalangle}$ in Legendre moments:

$$H_1^{\sphericalangle}(z, \cos(\theta), M_{\pi\pi}^2) = H_1^{\sphericalangle,sp}(z, M_{\pi\pi}^2) + \cos(\theta) H_1^{\sphericalangle,pp}(z, M_{\pi\pi}^2)$$



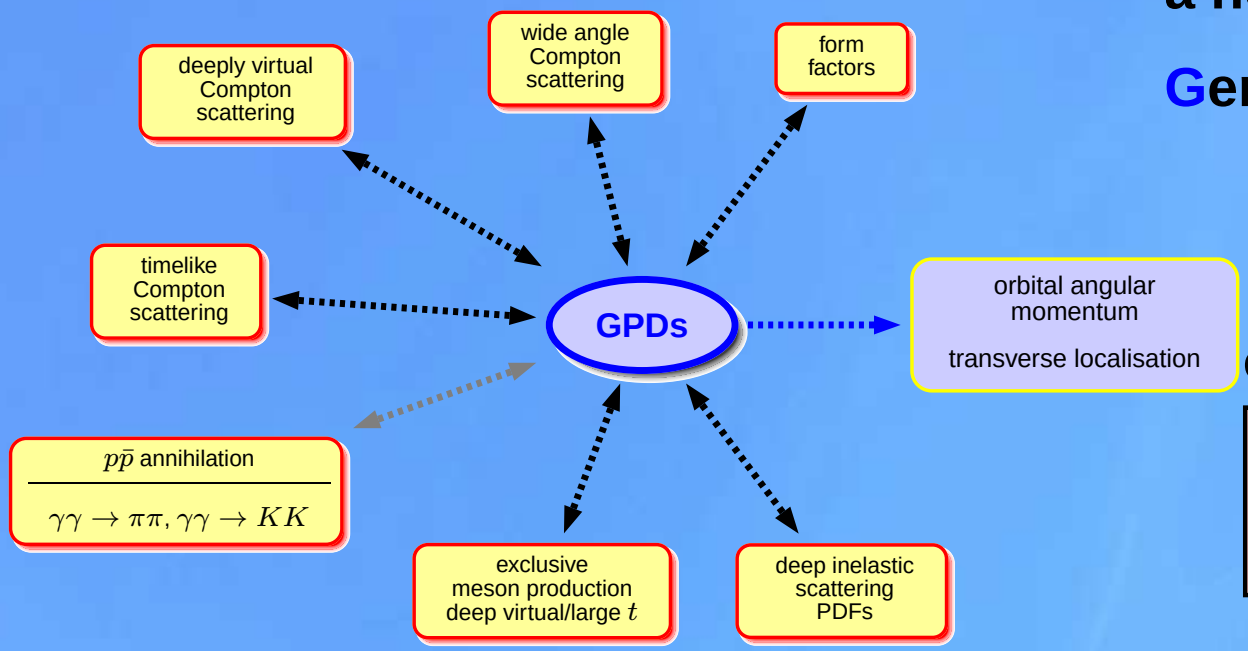
- **positive asymmetry moment for all invariant mass bins**
- **result does not support predicted sign change at the ρ^0 mass (Jaffe et al.)**

The Hunt for L_q

Study of hard exclusive processes leads to a new class of PDFs

Generalised Parton Distribut ions

$H^q, E^q, \tilde{H}^q, \tilde{E}^q$



$\Rightarrow$ **possible access to orbital angular momentum**

$$J_q = \frac{1}{2}\left(\int_{-1}^{1} x\mathrm{d}x(H^q + E^q)\right)_{t\to 0}$$
$$J_q = \frac{1}{2}\Delta\Sigma + L_q$$

exclusive: all products of a reaction are detected

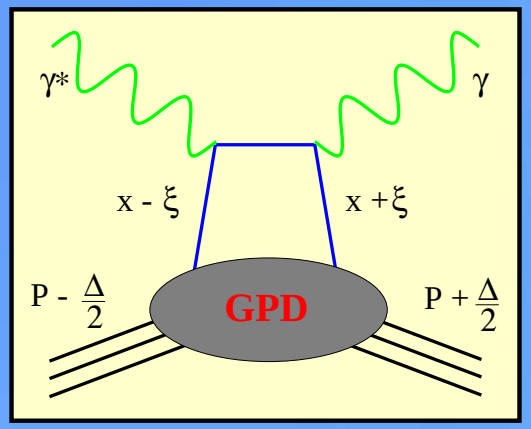
$\Longrightarrow$ **missing energy (ΔE) and missing Mass (M_x) = 0**

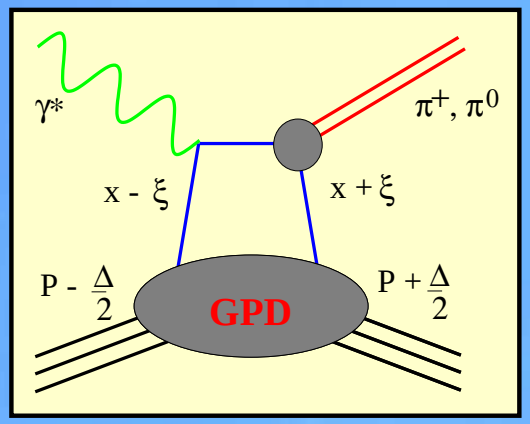
GPDs Introduction I

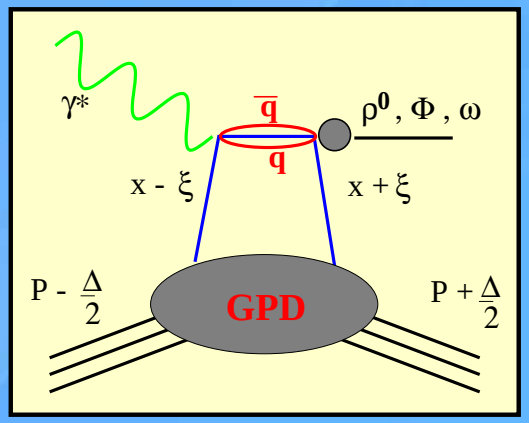
What does GPDs characterize?

unpolarized	polarized	
$\mathbf{H^q(x,\xi,t)}$	$\mathbf{\tilde{H}^q(x,\xi,t)}$	**conserve nucleon helicity**
		$H^q(x,0,0) = q$ **,** $\tilde{H}^q(x,0,0) = \Delta q$
$\mathbf{E^q(x,\xi,t)}$	$\mathbf{\tilde{E}^q(x,\xi,t)}$	**flip nucleon helicity**
		not accessible in DIS

quantum numbers of final state $\Rightarrow$ select different GPDs







DVCS:
$\mathbf{H^q, E^q, \tilde{H}^q, \tilde{E}^q}$
$\mathbf{A_C, A_{LU}, A_{UL}, A_{UT}}$

pseudo-scalar mesons
$\mathbf{\tilde{H}^q, \tilde{E}^q}$
$\mathbf{A_{UL}, A_{UT}}, \sigma_{\pi^+}$

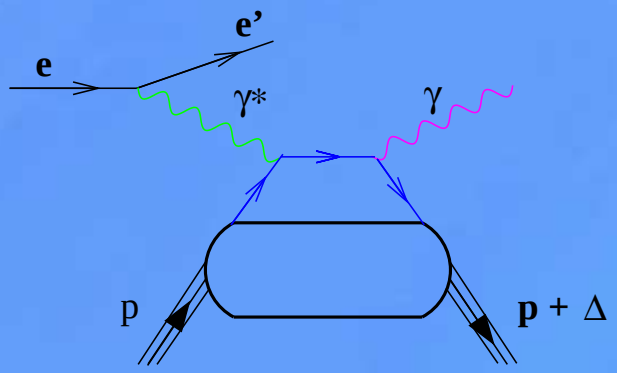
vector mesons
$\mathbf{H^q, E^q}$
$\mathbf{A_{UL}}, \sigma_{\rho,\phi,\omega}, \mathbf{A_{UT}}$

x, t, ξ **defined on the light cone**

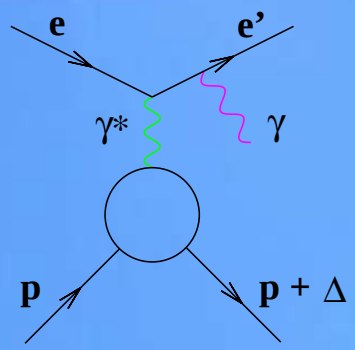
x**: unobservable internal variable in DVCS** t**: momentum transfer (**$t = \Delta^2$**)**

ξ**: longitudinal momentum transfer between 2 partons (**$\xi = \frac{x_{Bj}}{2-x_{Bj}}$**)**

DVCS $ep \to e'\gamma p$



DVCS



Bethe-Heitler (BH)

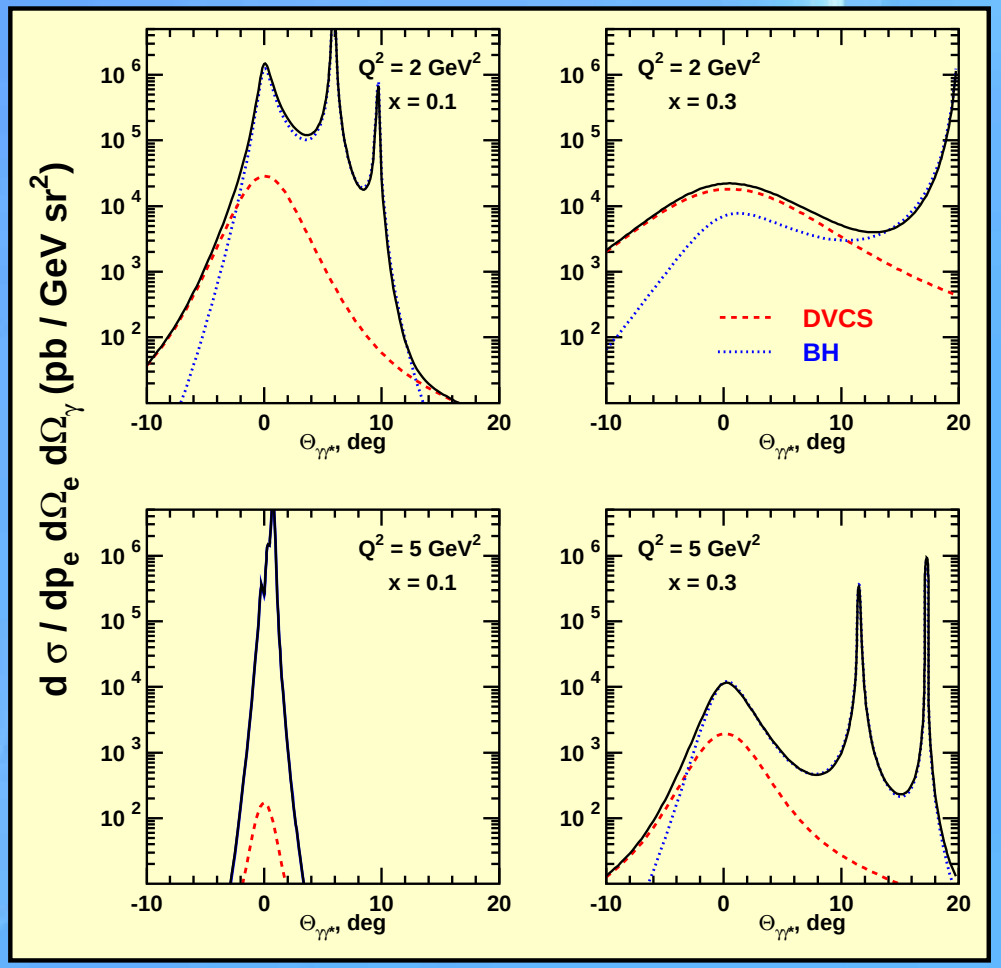
$$d\sigma \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + (\mathcal{T}^*_{BH}\mathcal{T}_{DVCS} + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH})$$

HERMES, JLAB:
DVCS-BH interference:

$\Longrightarrow$ **use BH as a vehicle to study DVCS**

H1, ZEUS:
measure DVCS cross section directly

HERMES / JLAB kinematics:
BH cross section larger than DVCS

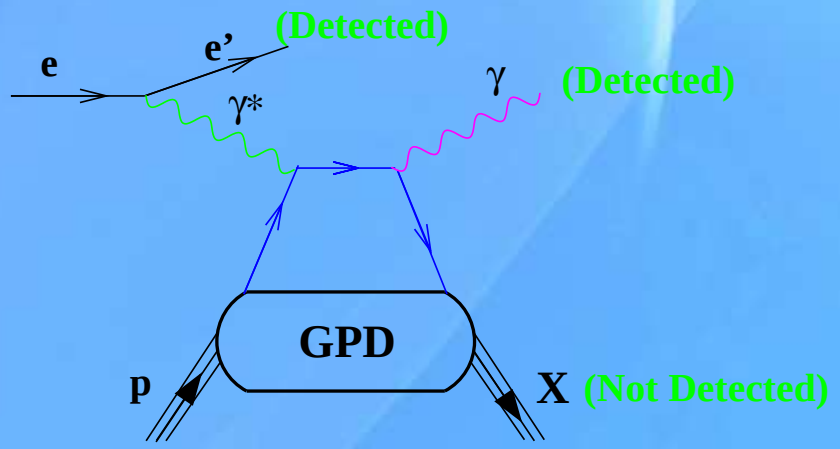


[Korotkov, Nowak, hep-ph/0108077]

DVCS azimuthal asymmetries

$$\mathbf{d}\sigma \propto (\mathcal{T}^*_{BH}\mathcal{T}_{DVCS} + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH}) + |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2$$

isolate BH-DVCS interference term $\Longrightarrow$ non-zero azimuthal asymmetries



$\Rightarrow$ **unpolarized target**

- **beam helicity asymmetry:**

$$\mathbf{d}\sigma_{\overleftarrow{\mathbf{e}^+}} - \mathbf{d}\sigma_{\overrightarrow{\mathbf{e}^+}} \propto \mathrm{Im}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS}) \propto \sin\phi \Longrightarrow \mathbf{H^u(x,\xi,t)}$$

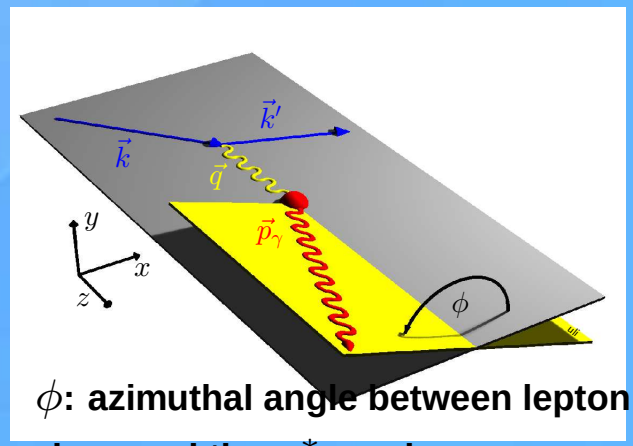
- **beam charge asymmetry:**

$$\mathbf{d}\sigma_{\mathbf{e}^+} - \mathbf{d}\sigma_{\mathbf{e}^-} \propto \mathrm{Re}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS}) \propto \cos\phi \Longrightarrow \mathbf{H^u(x,\xi,t)}$$

$\Rightarrow$ **unpolarized beam**

- **longitudinal target spin asymmetry:**

$$\mathbf{d}\sigma_{\overleftarrow{\mathbf{p}}} - \mathbf{d}\sigma_{\overrightarrow{\mathbf{p}}} \propto \mathrm{Im}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS}) \propto \sin\phi \Longrightarrow \mathbf{\tilde{H}^u(x,\xi,t)}$$

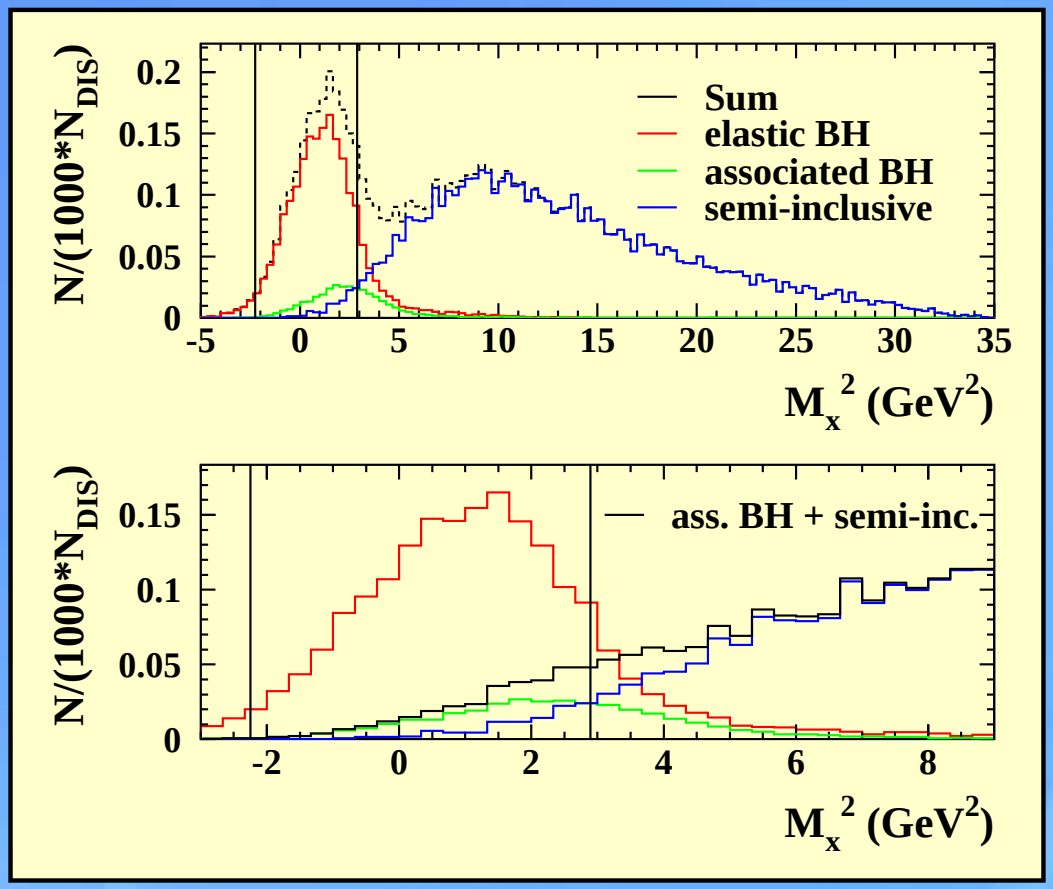


ϕ: azimuthal angle between lepton scattering plane and the $\gamma^*\gamma$ - plane

DVCS at HERMES

$\Longrightarrow$ **Exclusivity has to be ensured by missing mass:** $\mathrm{M_x^2} = (q + p - p_\gamma)^2 = M_p^2$

$\Longrightarrow$ **Energy resolution in exclusive region:** $\sigma(\mathrm{M_x}) \approx$ **0.8 GeV**



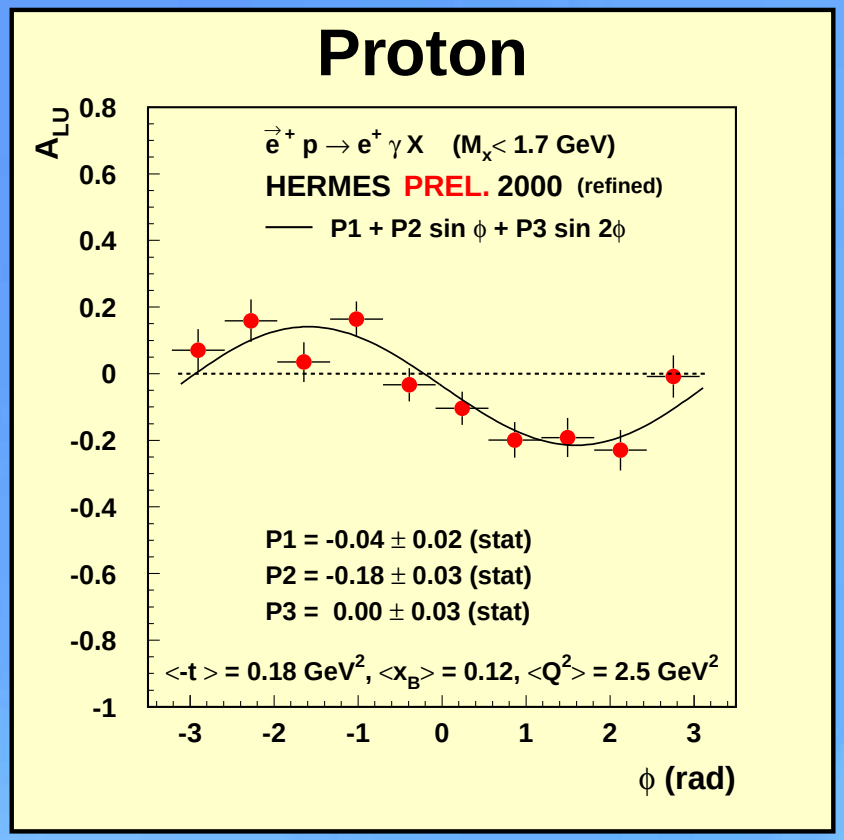
MC (M_x < 1.7 GeV):

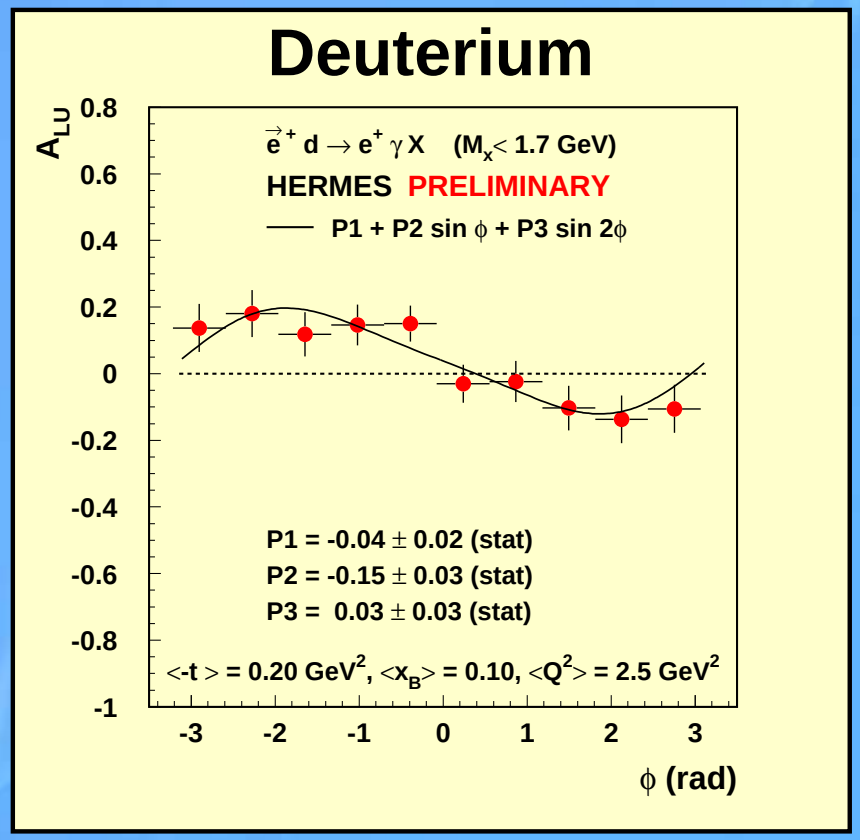
- **Elastic contribution 85%**
- **Associated (with excitation of the nucleon into resonance, e.g. Δ) 10%**
- **Semi-inclusive background (mostly from π^0) 5%**

Beam Spin Asymmetry

$$\mathbf{d}\sigma_{\overrightarrow{\mathbf{e}^+}} - \mathbf{d}\sigma_{\overleftarrow{\mathbf{e}^+}} \Longrightarrow \mathbf{A}_{\mathbf{LU}}^{\sin\phi} \propto \mathrm{Im}\mathbf{H}^{\mathbf{u}}(\mathbf{x}, \xi, \mathbf{t})$$

$$\mathbf{A}_{\mathbf{LU}}(\phi) = \frac{\mathbf{1}}{\langle \mathbf{P}_{\mathbf{B}} \rangle} \frac{\overrightarrow{\mathbf{N}}(\phi) - \overleftarrow{\mathbf{N}}(\phi)}{\overrightarrow{\mathbf{N}}(\phi) + \overleftarrow{\mathbf{N}}(\phi)}$$

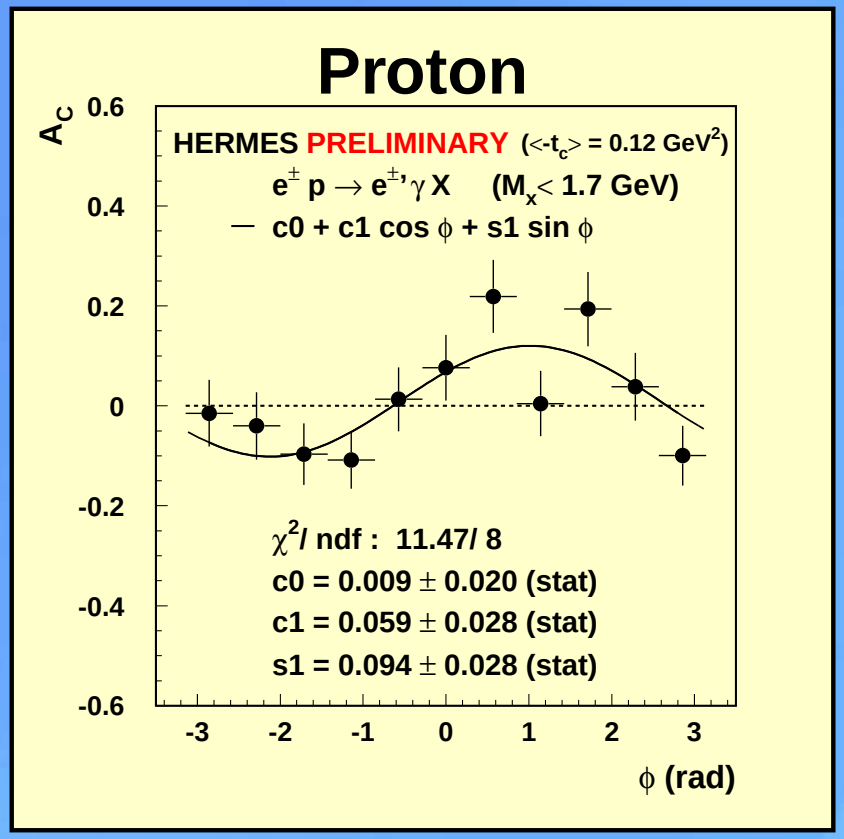


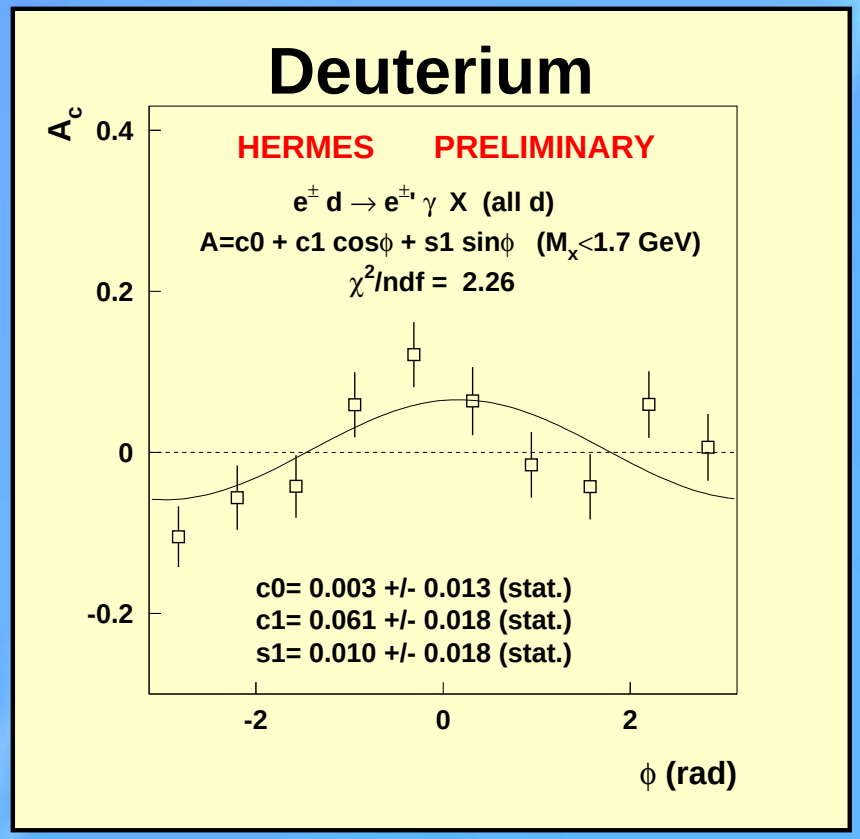


Beam Charge Asymmetry

$$d\sigma_{e^+} - d\sigma_{e^-} \Longrightarrow A_C^{\cos\phi} \propto \mathrm{Re}H^u(x,\xi,t)$$

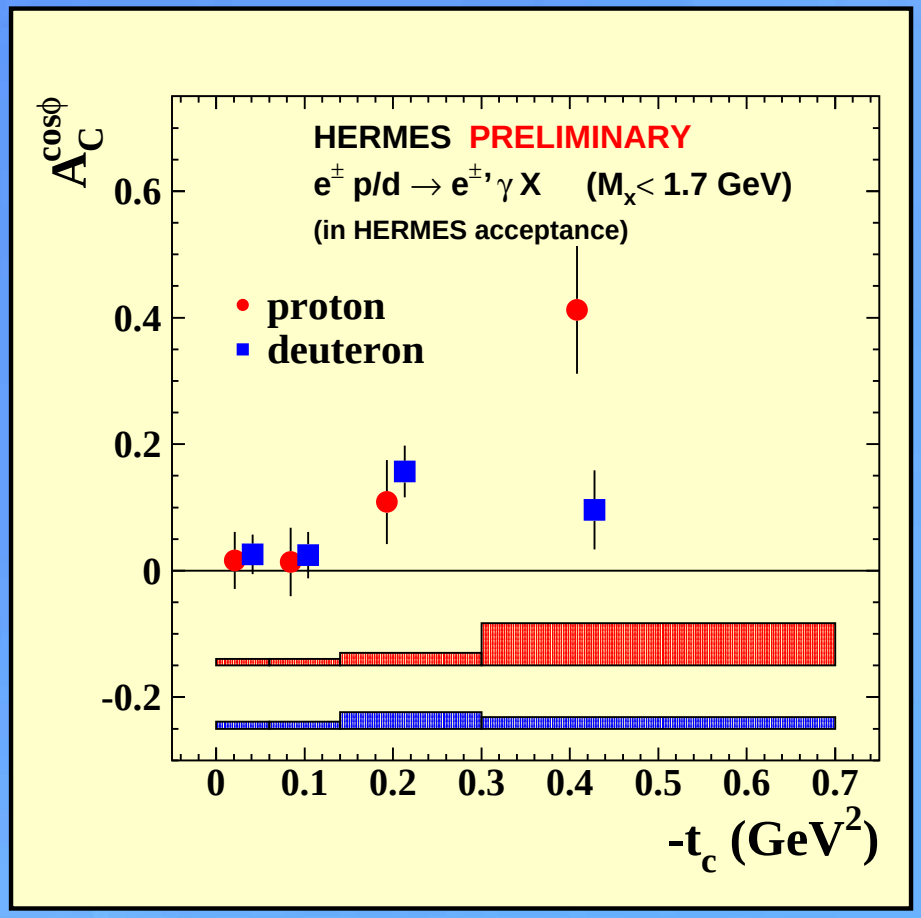
$$A_C(\phi) = \frac{N_{e^+}(\phi) - N_{e^-}(\phi)}{N_{e^+}(\phi) + N_{e^-}(\phi)}$$





$A_C^{\sin\phi} \neq 0 \Longrightarrow$ **Non zero P_B**

Beam Charge Asymmetry vs. t



GPD model: M. Vanderhaeghen et al.

Proton vs. Deuterium

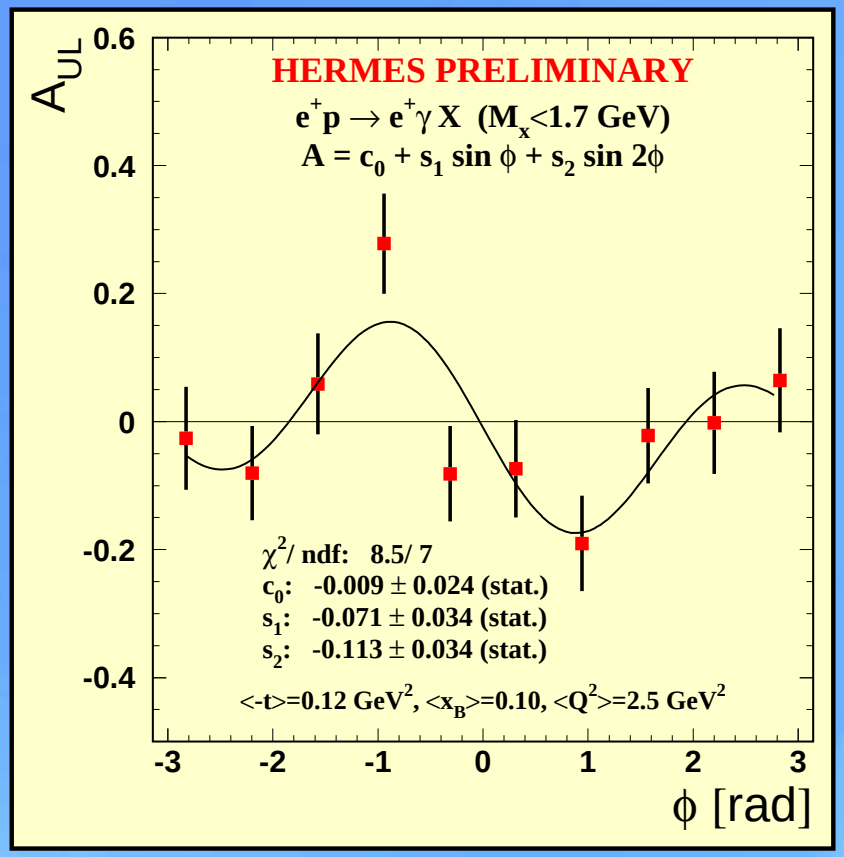
- 1st Deuterium bin has 40% coherent contribution
  $\Longrightarrow$ No difference between eP and eD
- Difference in the the last bin due to increasing neutron form factors
- BCA may constrain GPD models

Longitudinal Target Spin Asymmetry

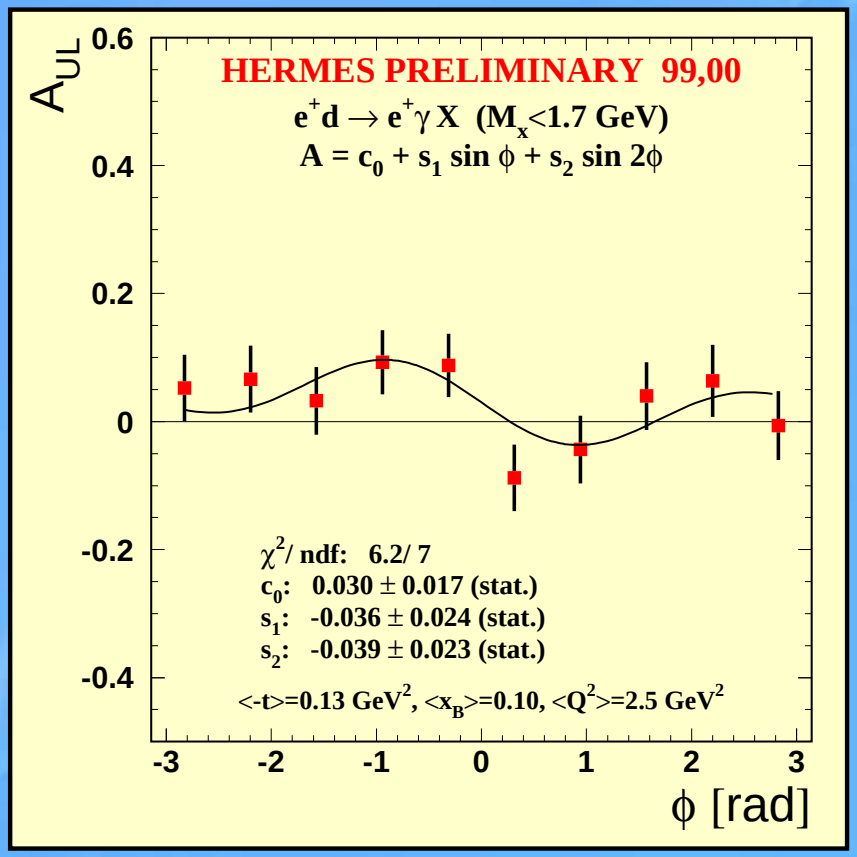
$$d\sigma_{\vec{p}} - d\sigma_{\overleftarrow{p}} \Longrightarrow A_{UL}^{\sin\phi} \propto \mathrm{Im}\tilde{H}^{u}(x,\xi,t)$$

$$A_{LU}(\phi) = \frac{1}{\langle P_T \rangle} \frac{\vec{N}(\phi) - \overleftarrow{N}(\phi)}{\vec{N}(\phi) + \overleftarrow{N}(\phi)}$$

Proton

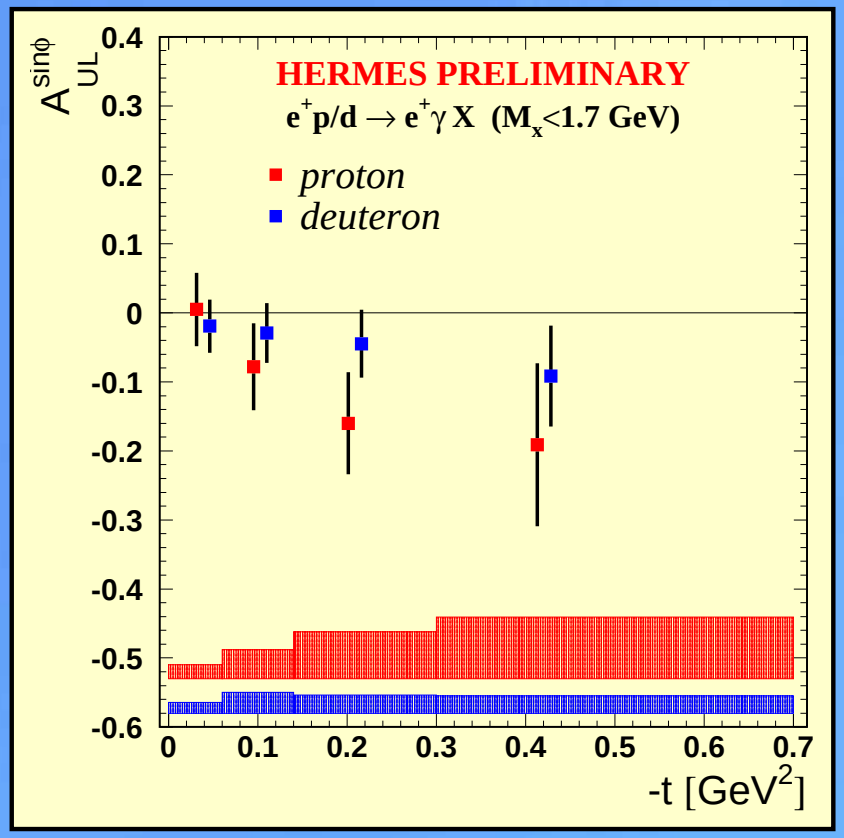


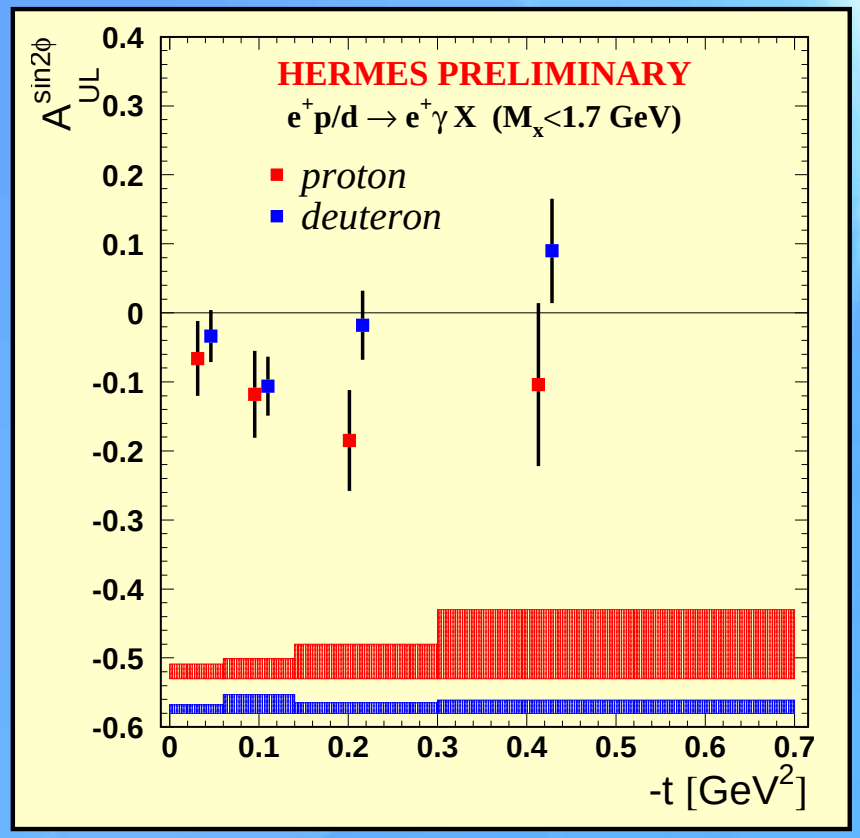
Deuterium



Sizeable unexpected $A_{UL}^{\sin 2\phi} \Longrightarrow$ sensitive to e.g. twist-3 Im $(H^3\tilde{H}^3)$

Longitudinal Target Spin Asymmetry vs. t





- eD coherent production 40% in 1st bin
  $\Longrightarrow$ No difference between eP and eD
- $\mathbf{A_{UL}^{\sin 2\phi}}$ is bigger than predicted by GPD-model
  $\Longrightarrow$ interaction dependent (qGq) twist-3 missing
  only WW twist-3 part taken into account

Exclusive π^+ production / How to extract

- **Production mechanismen:** $e\vec{p} \rightarrow e' \underbrace{n}_{\text{not detected}} \pi^+$

Exclusive π^+ production / How to extract

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- **no exclusive π^- production at a proton target**

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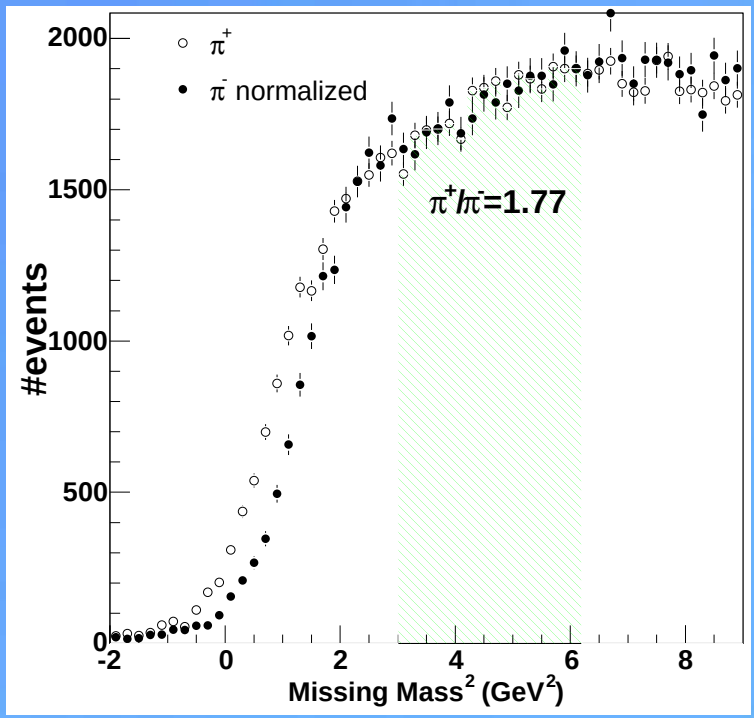
$\Longrightarrow$ **Trick: exclusive** $\pi^+ \sim M_x(\pi^+) - M_x(\pi^-)$



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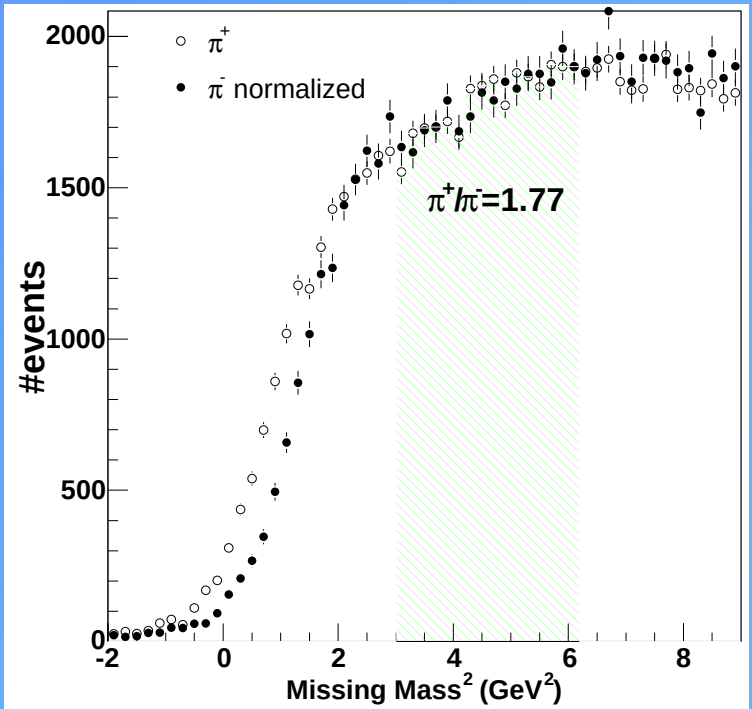

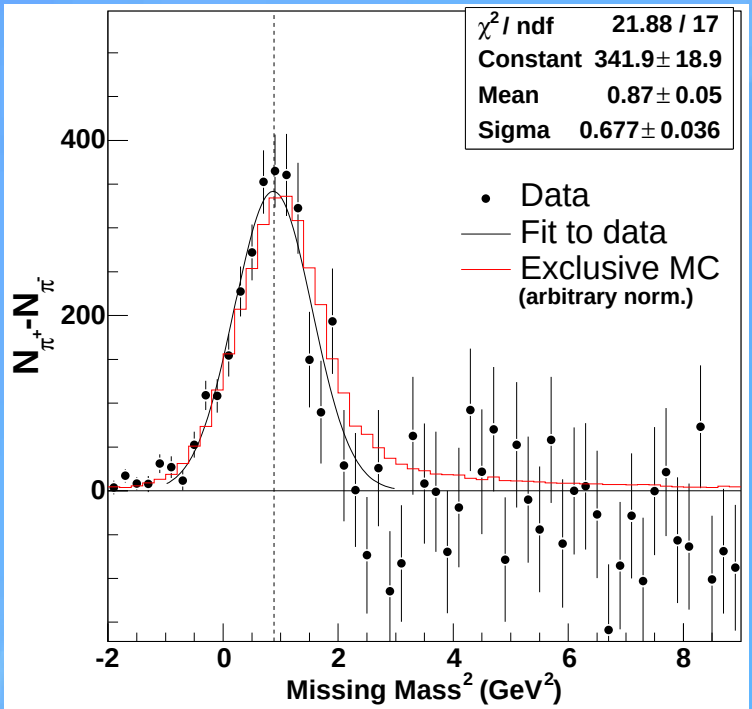

clear peak at missing mass $\sim \mathrm{M_n}$

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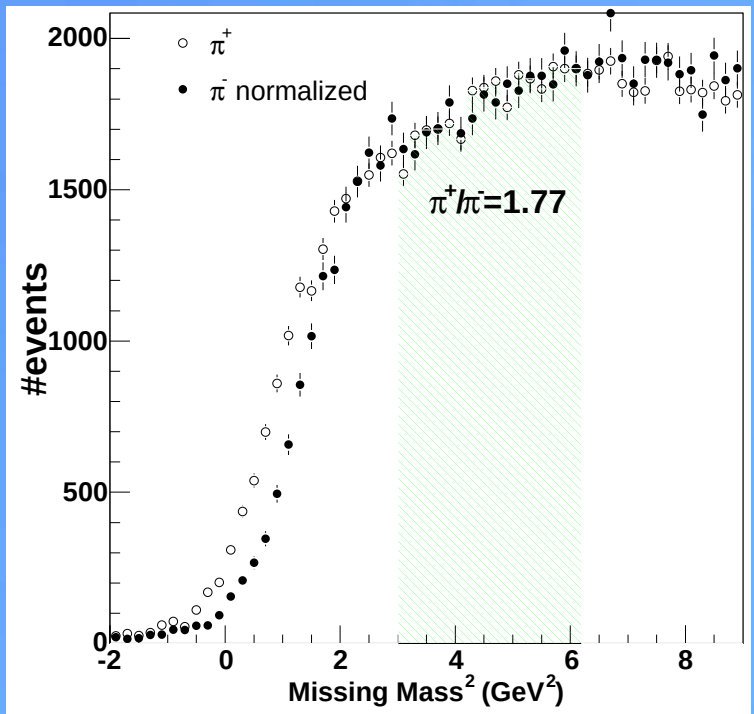
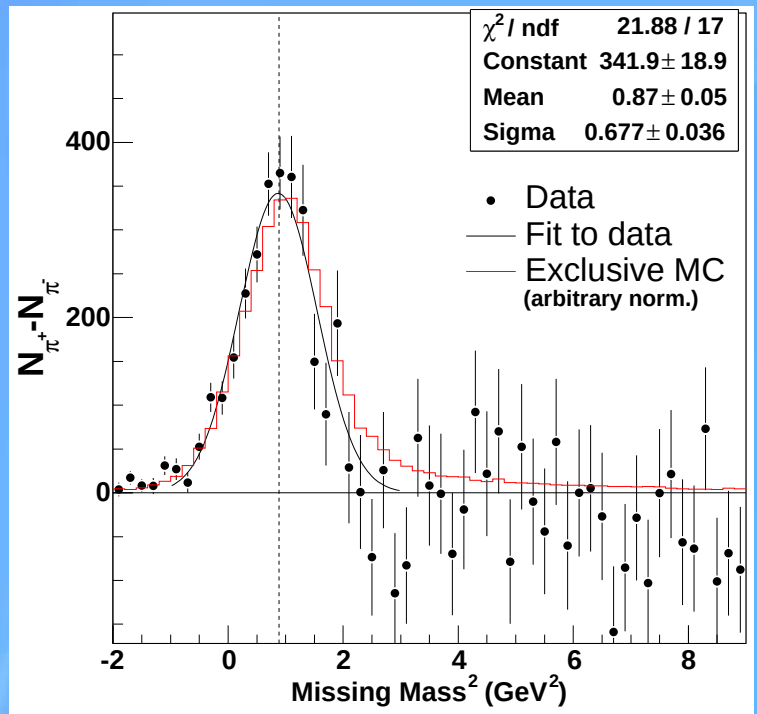




clear peak at missing mass $\sim \mathrm{M_n}$

$\Rightarrow$ **Problematic: difference in relative contribution of resonant and non-resonant channels to π^+, π^- yield**

First Hint on $\tilde{\mathrm{H}}, \tilde{\mathrm{E}}$

Cross section for exclusive π^+ production $\mathbf{ep} \Longrightarrow \mathbf{e}\pi^+(\mathbf{n})$

$\sigma_{\mathbf{tot}} = \sigma_{\mathbf{T}} + \epsilon\sigma_{\mathbf{L}} \Longrightarrow \sigma_{\mathbf{L}} \sim (\tilde{\mathbf{H}} + \tilde{\mathbf{E}})^{\mathbf{2}}$

L/T separation not possible:

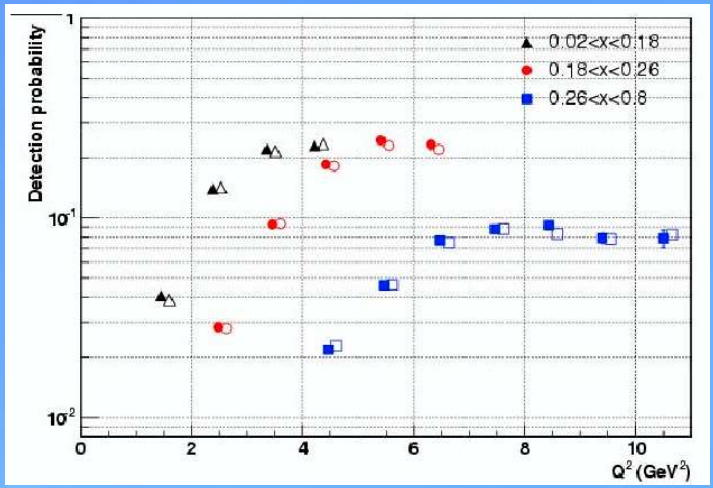
BUT:

Hermes kinematics: $\epsilon > 0.8$

$\sigma_{\mathbf{T}}$ **suppressed by** $1/\mathbf{Q}^{\mathbf{2}}$

●: Vanderhaeghen, Guichon & Guidal (1999)

○: Mankiewicz, Piller & Radyushkin (1999)



$\Longrightarrow$ **Systematic error** $\sim$ **5%**

First Hint on $\tilde{H}, \tilde{E}$

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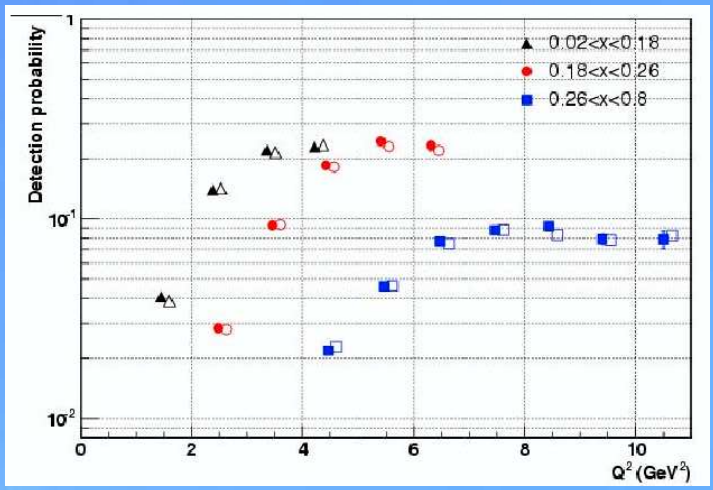
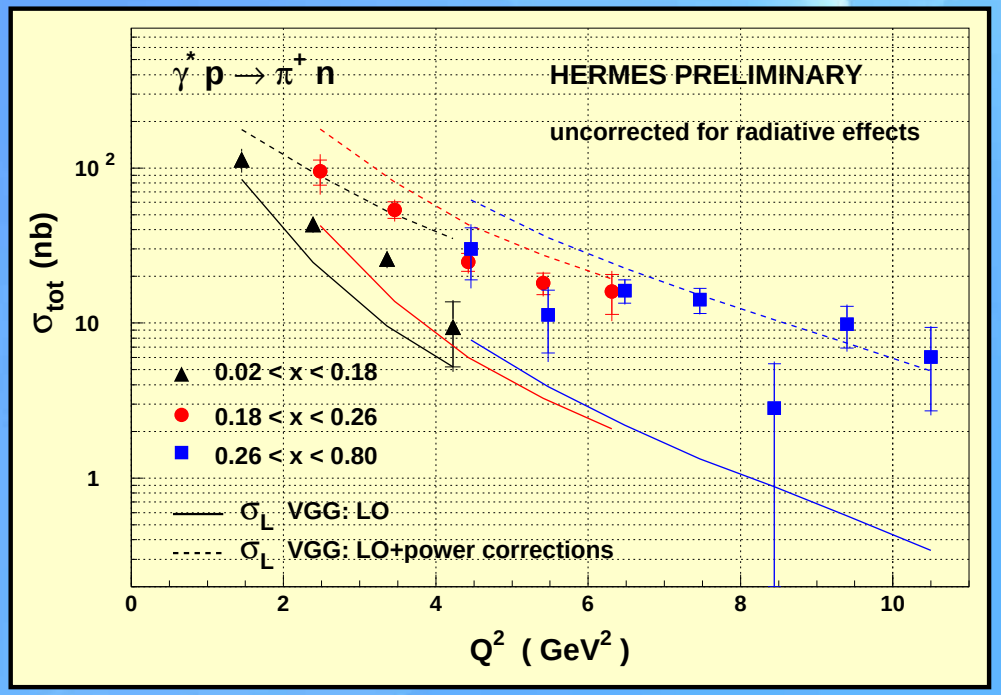


$\Longrightarrow$ **Systematic error $\sim$ 5%**



$\Longrightarrow$ **Q^2 dependence is in general agreement with the theoretical expectation**

$\Longrightarrow$ **Power correction calculations overestimate the data**

Reduced cross section

- Factorization theorem predicts a $1/Q^6$ dependence for σ_L at fixed x and t
- Cross section can be written as

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}\frac{x^2}{1-x}\frac{1}{Q^4}\frac{1}{\sqrt{1+\frac{4m^2x^2}{Q^2}}}\sum_{spin}|\mathcal{A}(\gamma^\star p \to pM)|^2$$

Reduced cross section

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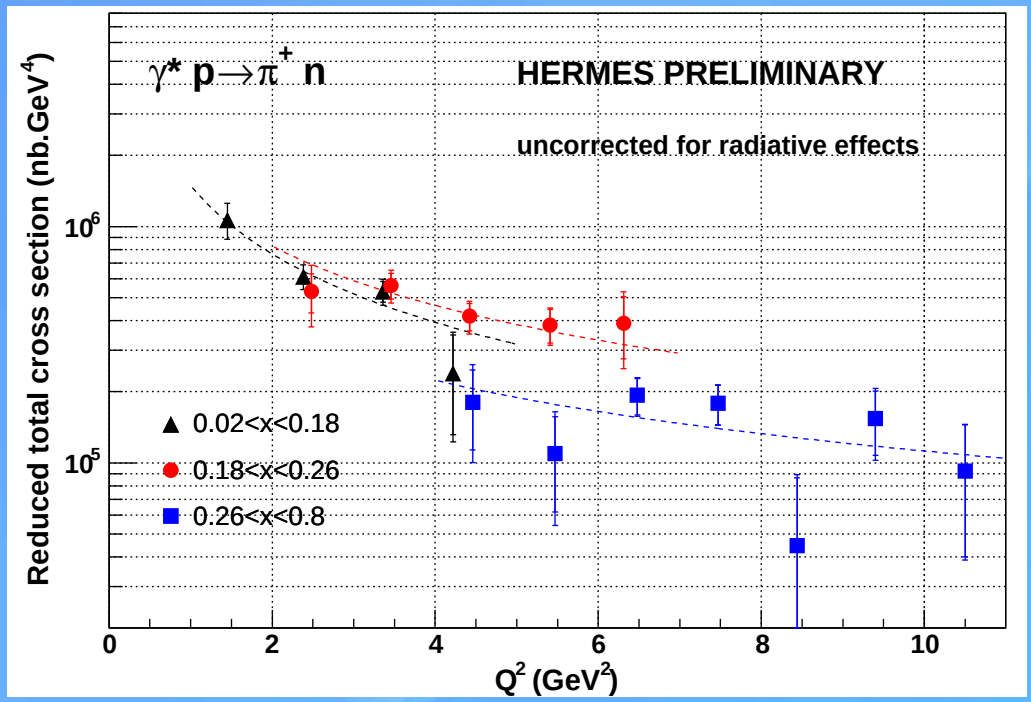


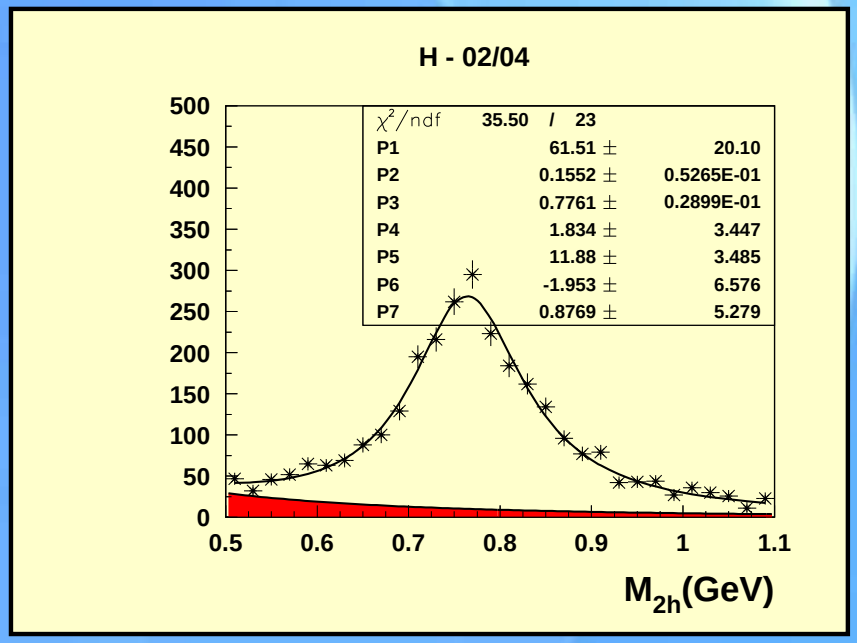
Fit to data of a $\frac{1}{Q^p}$ function:

p = 1.9 $\pm$ 0.5 1.7 $\pm$ 0.6 1.5 $\pm$ 1.0

Exclusive VM production

$$\mathbf{e + p \longrightarrow e + p + \rho^0}$$

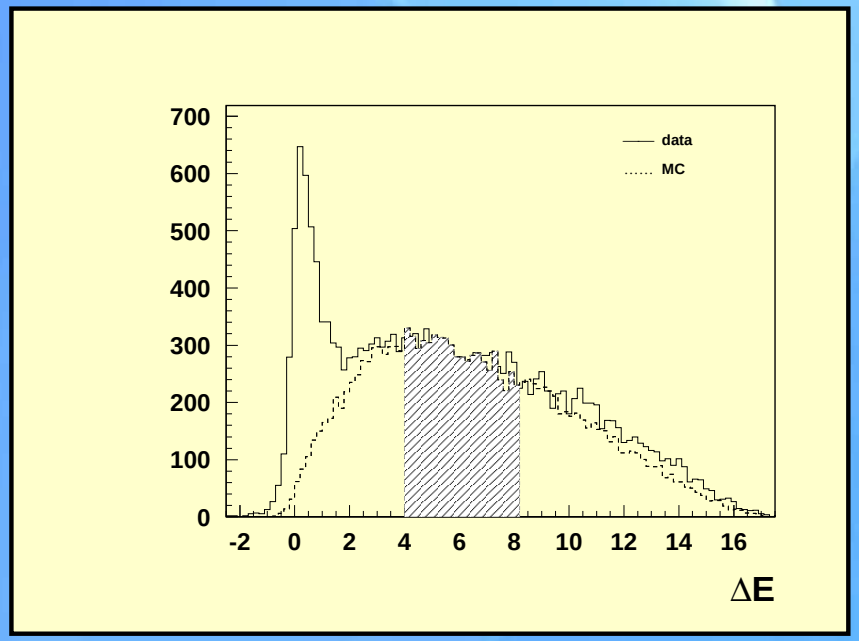
- **reconstruct ρ^0 from $\mathbf{h^+h^-}$pairs**



Exclusive VM production

$$\mathbf{e + p \longrightarrow e + p + \rho^0}$$

- reconstruct ρ^0 from $\mathrm{h^+h^-pairs}$
- Exclusivity ensured by missing energy $\Delta\mathrm{E}$
  $\Longrightarrow$ background estimated using MC



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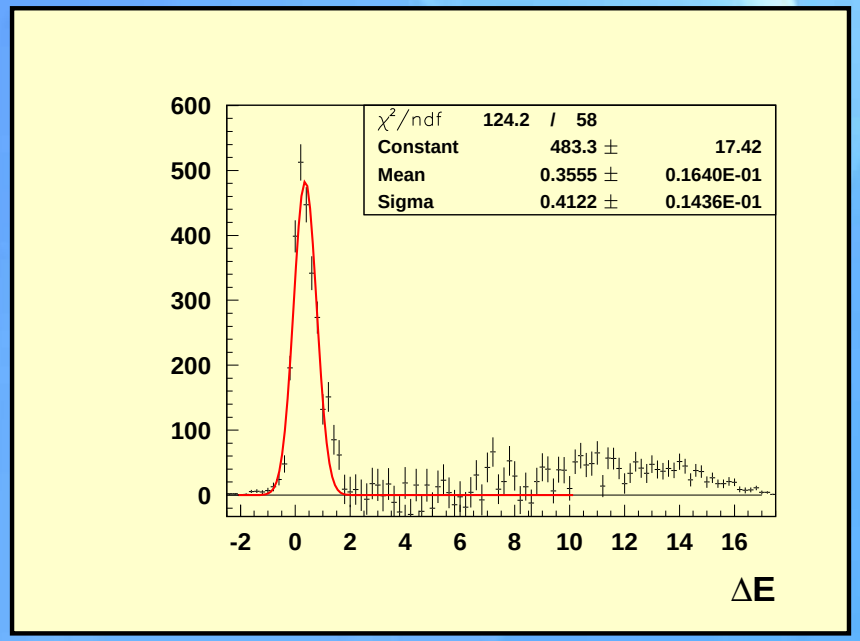

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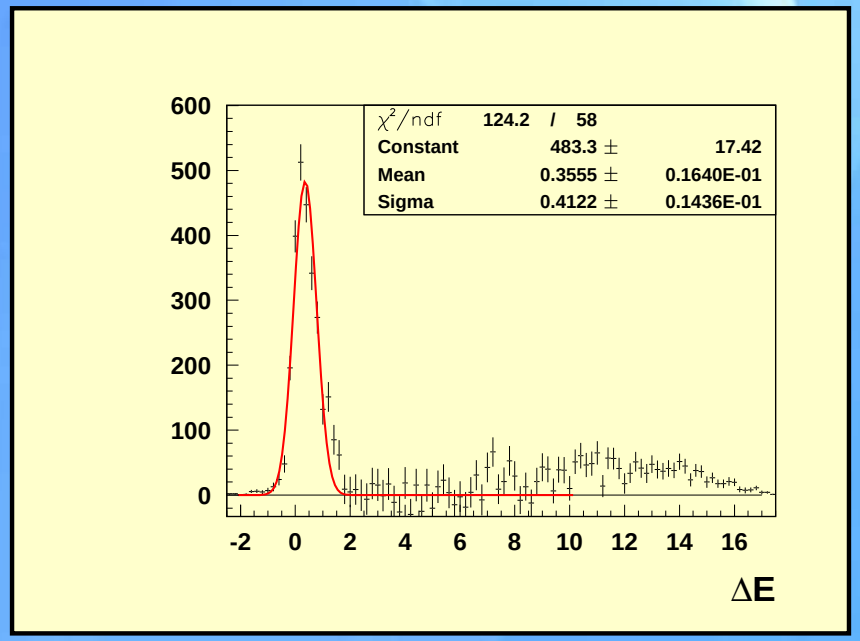
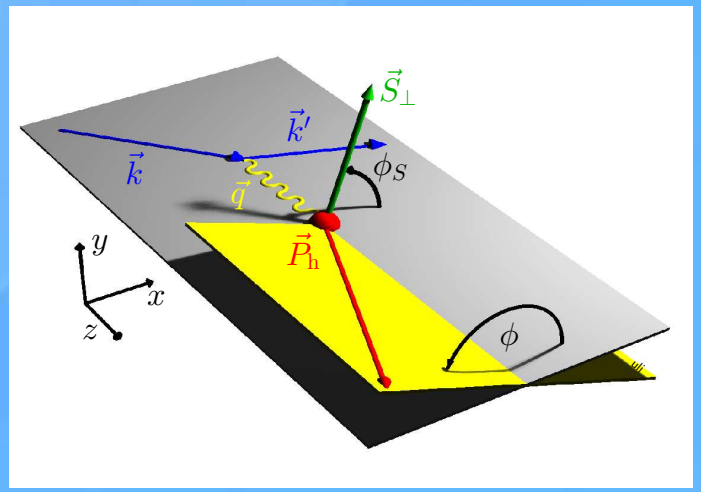
- **Transverse Target Spin Asymmetry**

$$\mathbf{A_{UT}(\phi - \phi_s) = \frac{1}{|P_T|}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}}$$

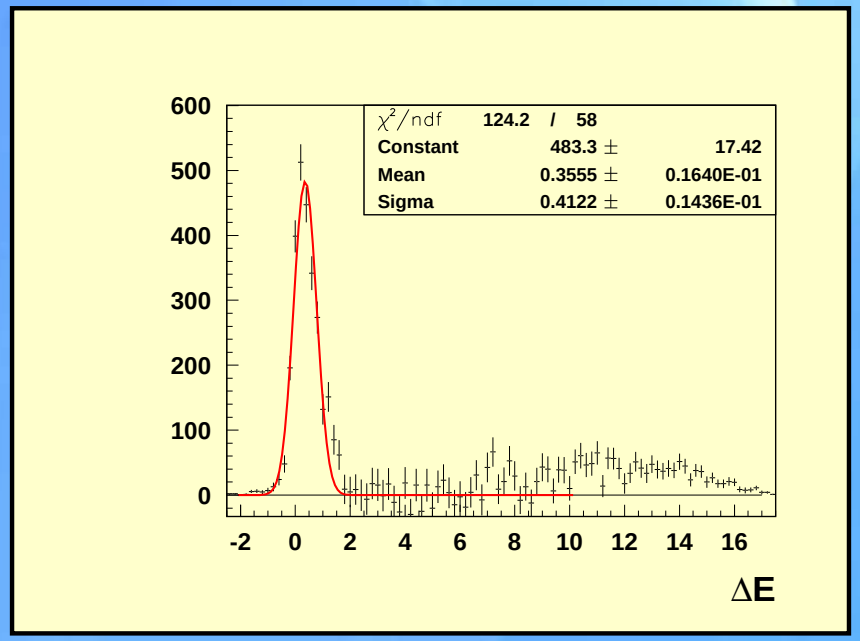


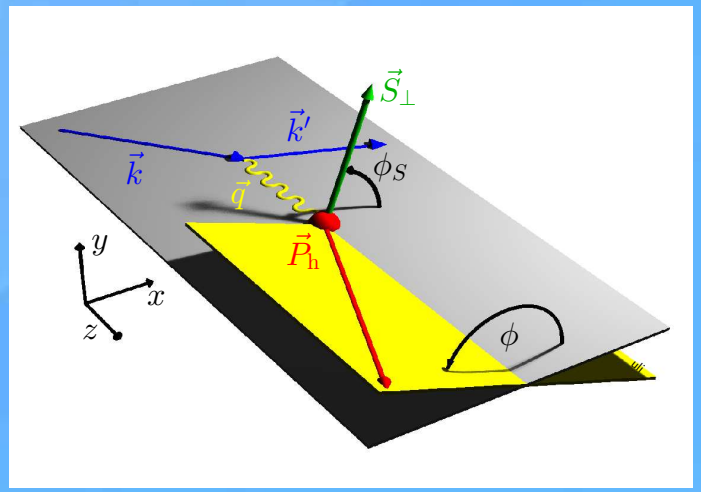


Exclusive VM production

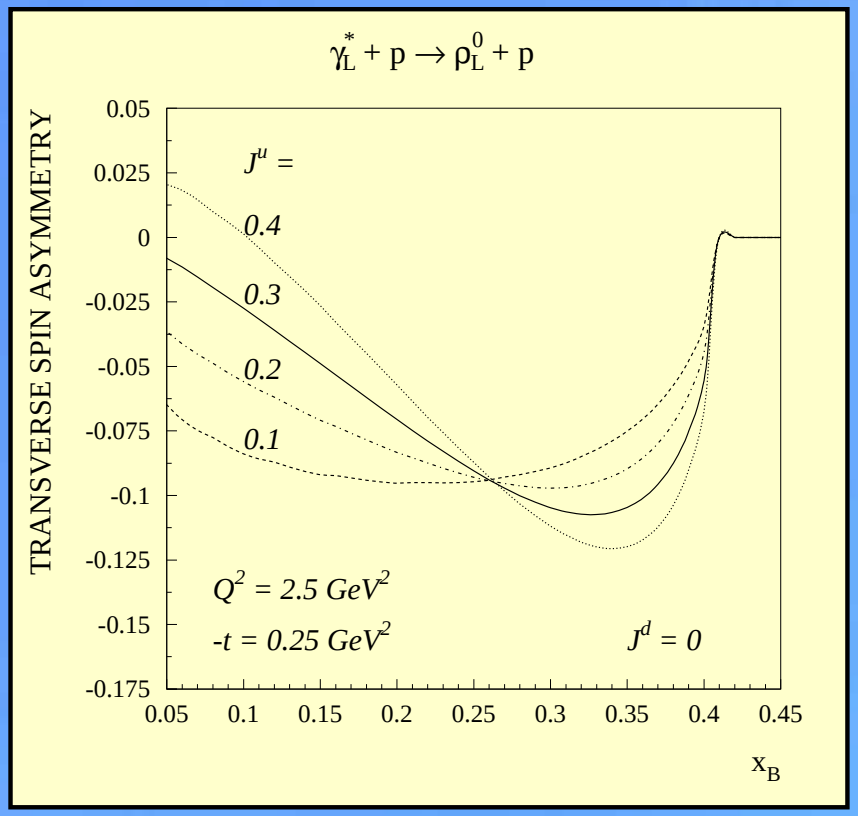
$$\mathbf{e + p \longrightarrow e + p + \rho^0}$$

- **reconstruct ρ^0 from $\mathrm{h^+h^-}$pairs**
- **Exclusivity ensured by missing energy $\Delta\mathrm{E}$**
  $\Longrightarrow$ background estimated using MC
- **Transverse Target Spin Asymmetry**
  $$\mathbf{A_{UT}(\phi - \phi_s) = \frac{1}{|P_T|}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}}$$
- $\mathbf{A_{UT}(\phi - \phi_s)}$ **sensitive to GPD $\mathbf{E}$**





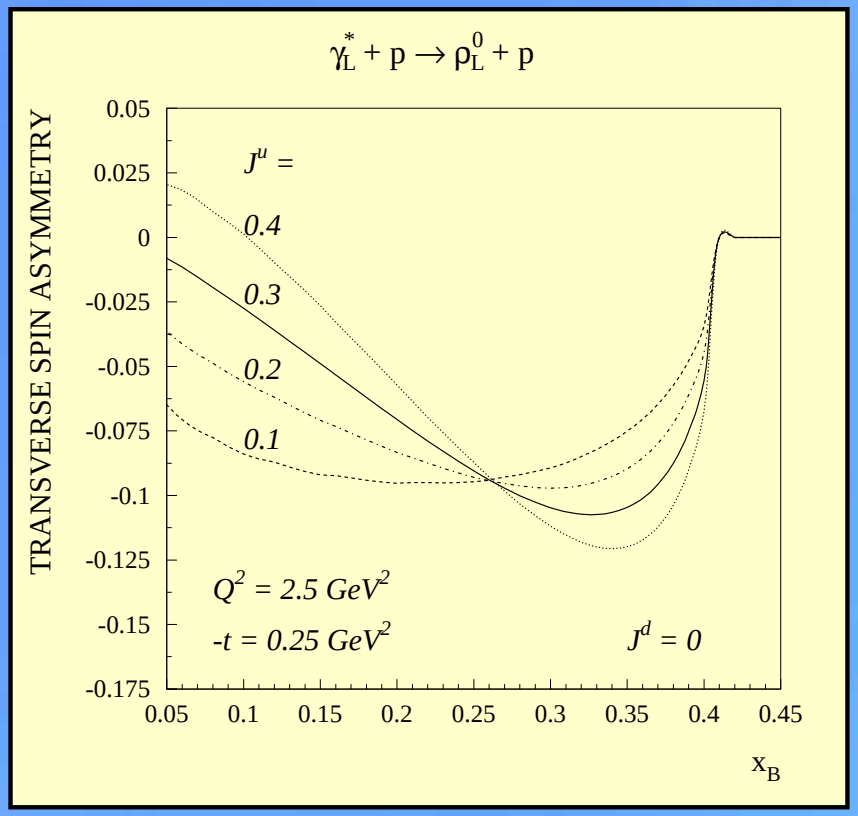
A_{UT} *for exclusive* ρ^0 *production*



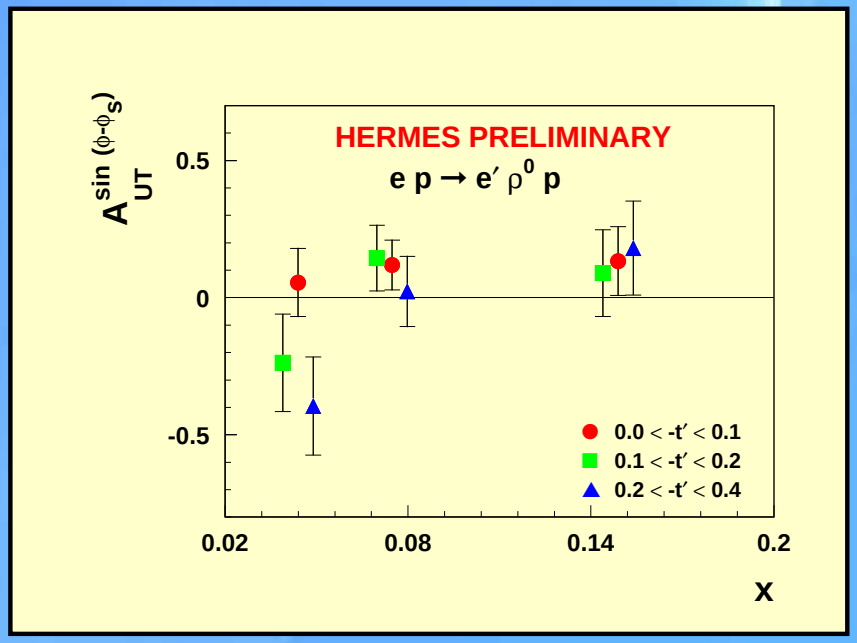
Goeke et al. hep-ph/0106012

- **Sensitivity to** $\mathbf{J^u}$
- $\mathbf{A_{UT}^{\sin(\phi-\phi_s)}} \sim -\mathcal{A}$
  $\Longrightarrow$ **Hermes asymmetry slope positive**

A_{UT} *for exclusive* ρ^0 *production*



Goeke et al. hep-ph/0106012

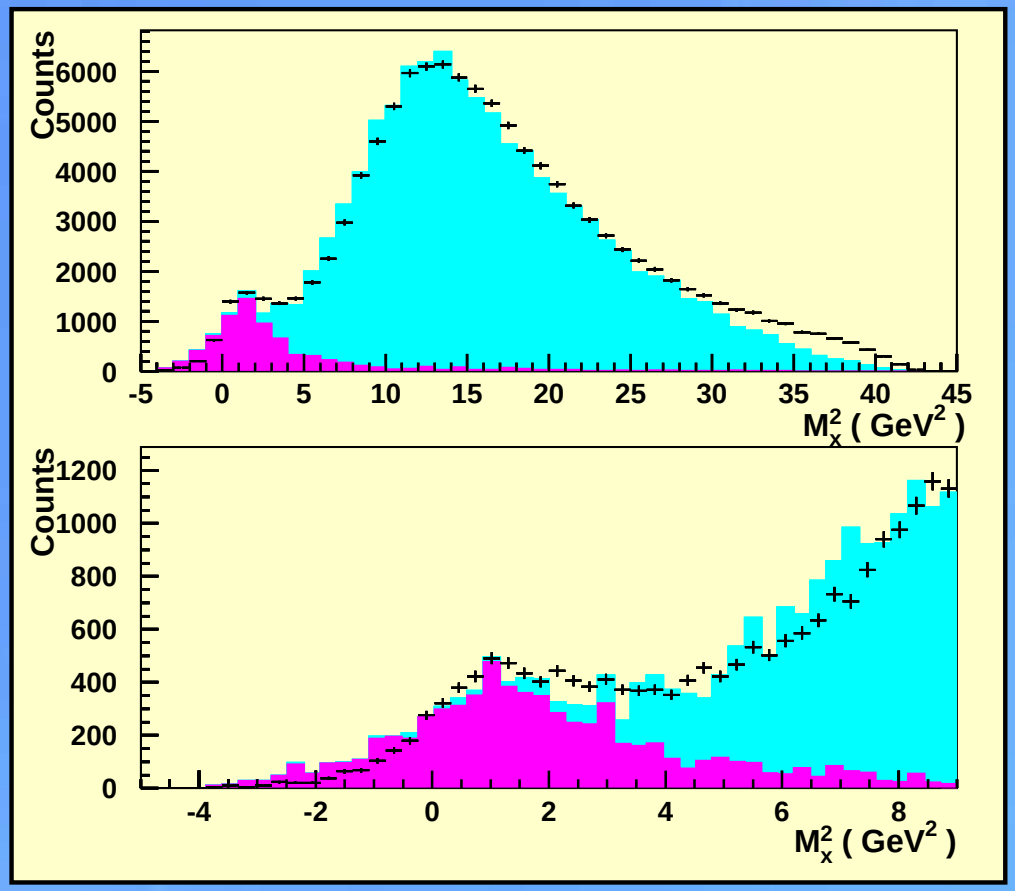


- **Sensitivity to J^u**
- $A_{UT}^{\sin(\phi-\phi_s)} \sim -\mathcal{A}$
  $\Longrightarrow$ **Hermes asymmetry slope positive**

- **Indication of positive slope**
- **Increasing statistics: separation of $\sigma_L - \sigma_T$**

Improve Exclusivity

$$\mathbf{M_x(ep \longrightarrow e'\gamma + X)}$$

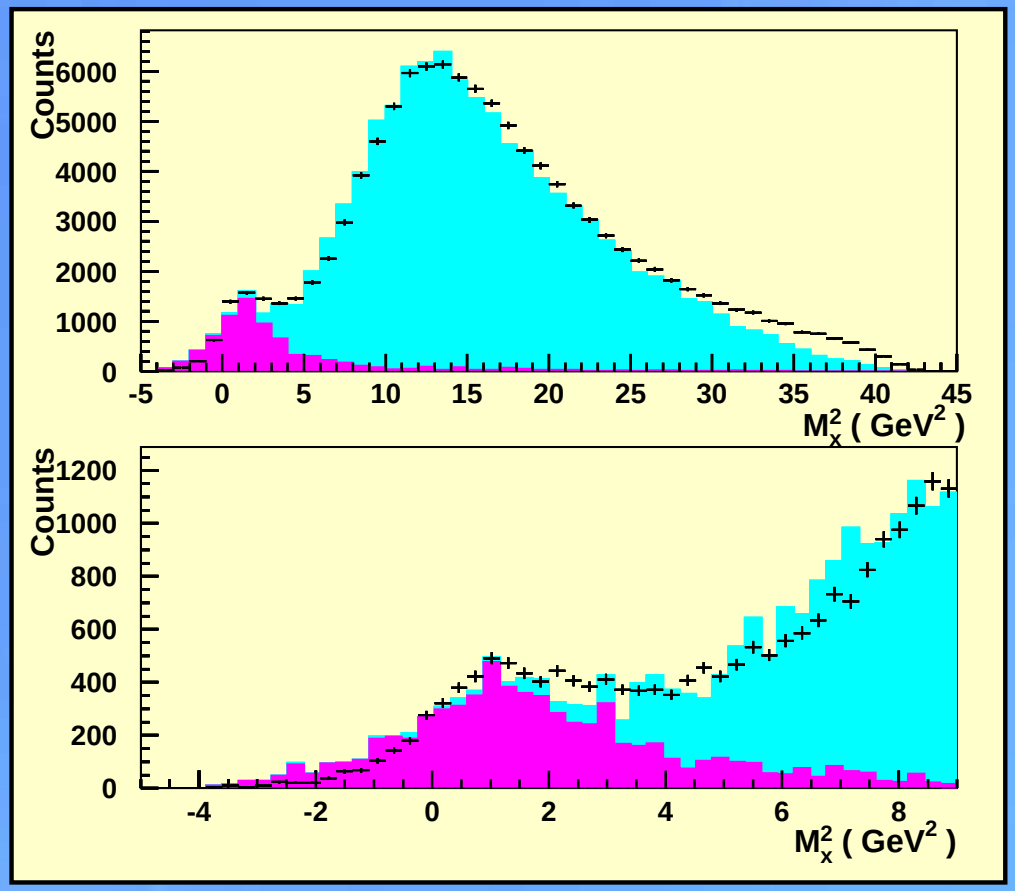


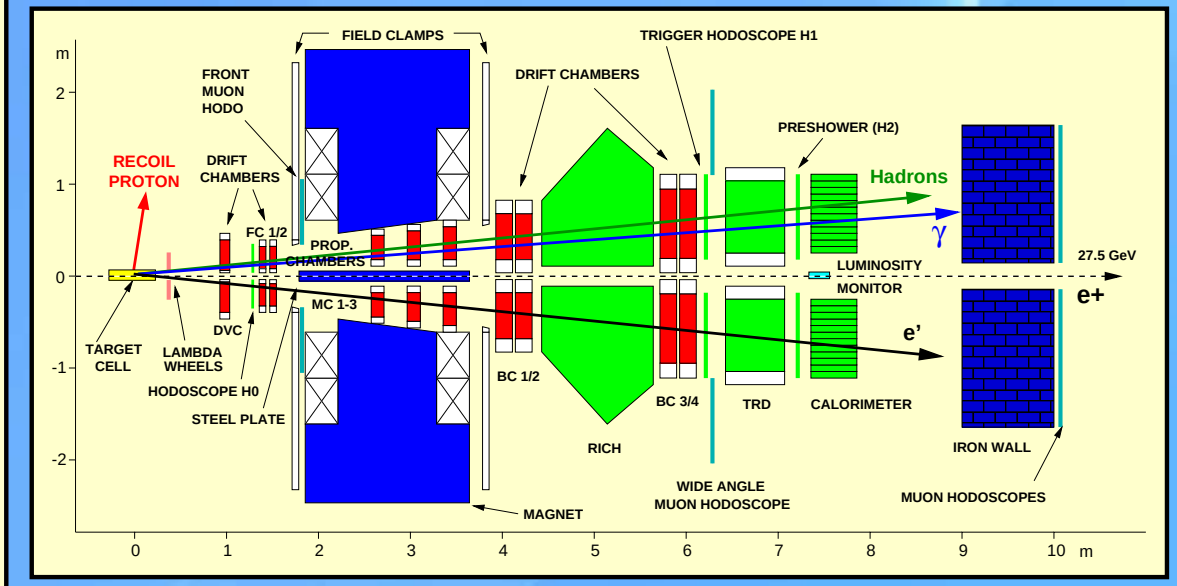
$\Longrightarrow$ **Exclusivity is ensured by missing mass $\mathrm{M_x}$**

$\mathrm{M_x}$-resolution in exclusive region: $\sigma \approx$ 0.8 GeV

Improve Exclusivity

$$\mathbf{M_x(ep \longrightarrow e'\gamma + X)}$$





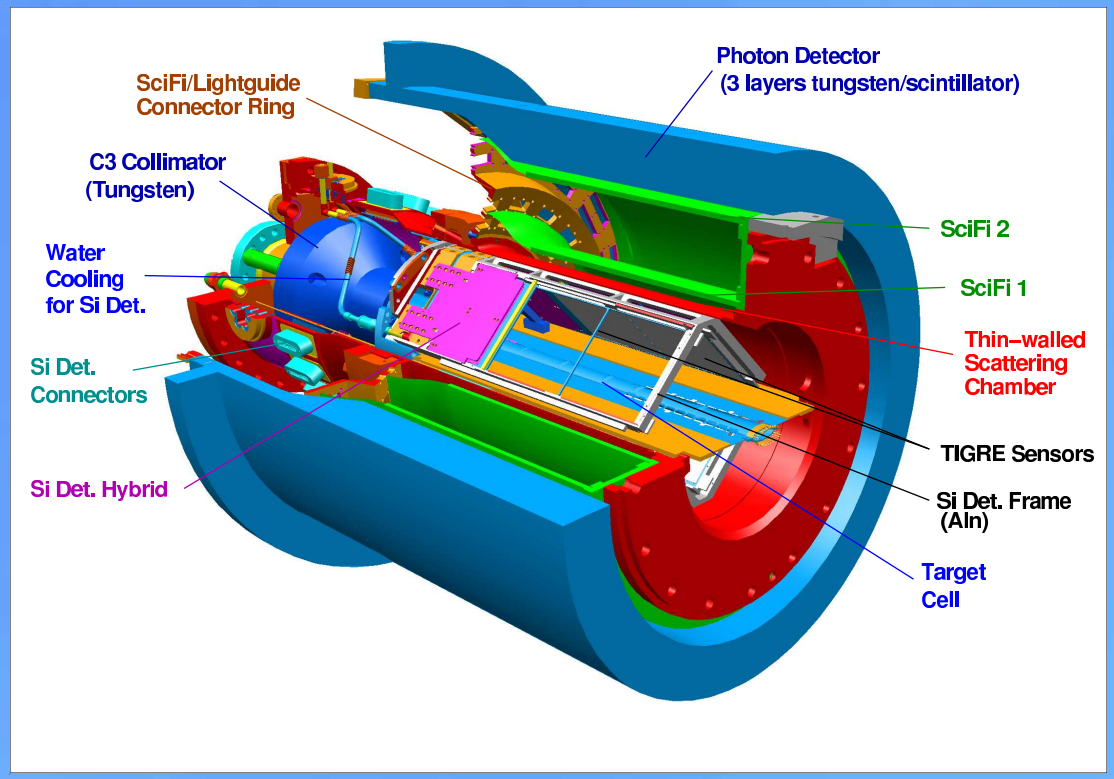
$\Longrightarrow$ **Modify target region**

$\Longrightarrow$ **Exclusivity is ensured by missing mass $\mathbf{M_x}$**

$\mathbf{M_x}$-resolution in exclusive region: $\sigma \approx$ 0.8 GeV

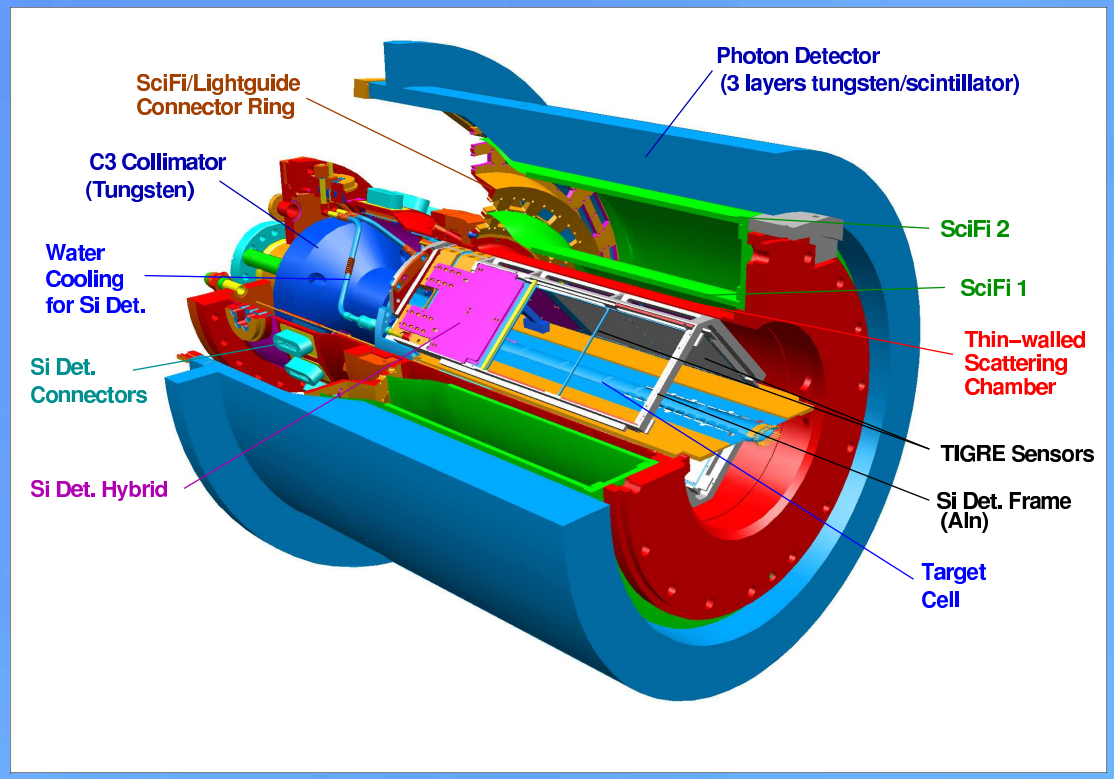
Need to improve exclusivity $\Rightarrow$ detect recoil proton

The HERMES Recoil Detector



build by DESY, Erlangen, Ferrara, Frascati, Gent, Giessen, Glasgow and PNPI

The HERMES Recoil Detector

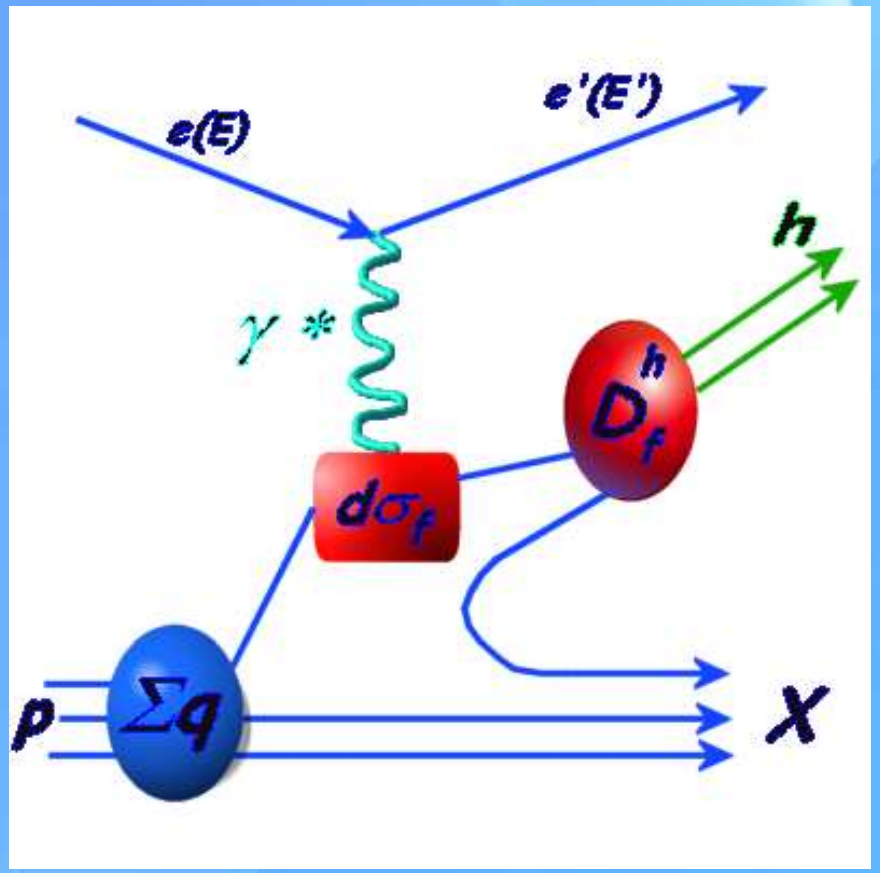


build by DESY, Erlangen, Ferrara, Frascati, Gent, Giessen, Glasgow and PNPI

- **detection of the recoiling proton**
  - $\Rightarrow$ **p: 135 - 1200 MeV /c**
  - $\Rightarrow$ **76 % ϕ acceptance**
  - $\Rightarrow$ **π/p-PID via dE/dx**
- **Background Suppression**
  - $\Rightarrow$ **semi-incl.: 5% $\rightarrow$ $<<$1%**
  - $\Rightarrow$ **associated: 11% $\rightarrow$ $\sim$1%**
- **improve t-resolution by factor 10**
  - $\Rightarrow$ **study kinematical dependences**
- **data taking in 2006/2007**

Why is a FF extraction important for HERMES

- enter in Δq, δq and $f_{1T}^{\perp}$ extraction
- test factorization at HERMES energies $\sqrt{s} \sim 7\mathrm{GeV}$
- are the FF from e^+e^- applicable at ep and/or $\langle Q^2 \rangle = 2.5\mathrm{GeV}$



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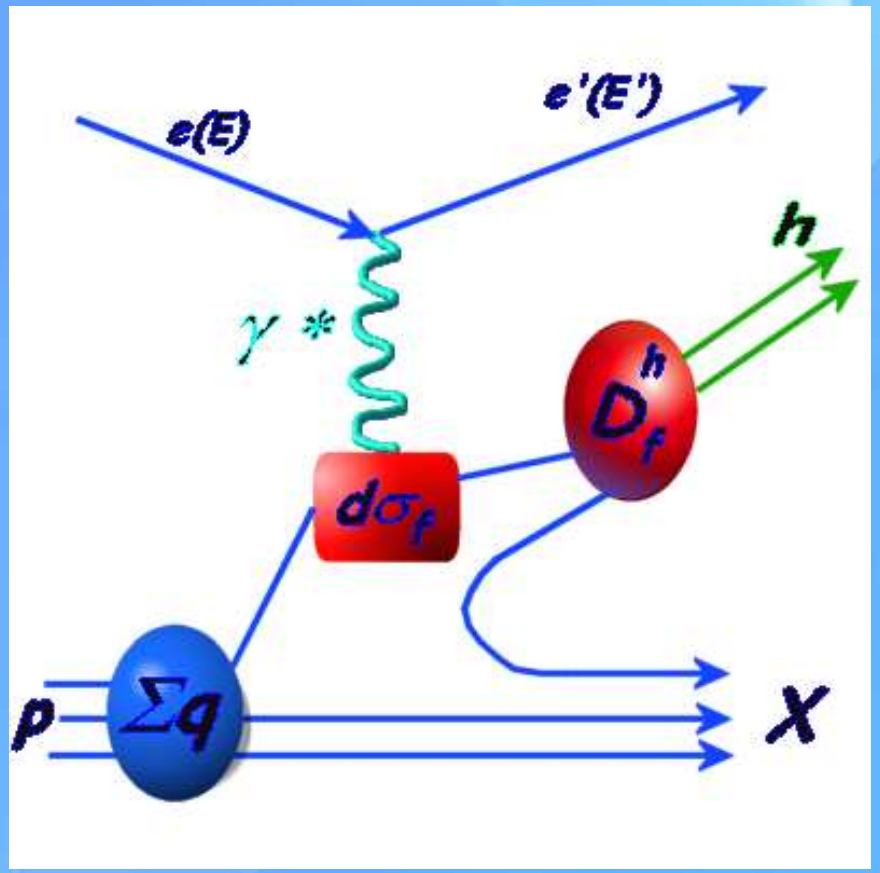


Extract π, K, p multiplicities:

$$\frac{1}{N^{DIS}} \cdot \frac{dN^h(z,Q^2)}{dz} = \frac{\sum_f e_f^2 \int_0^1 dx q_f(x,Q^2) D_f^h(z,Q^2)}{\sum_f e_f^2 \int_0^1 dx q_f(x,Q^2)}$$

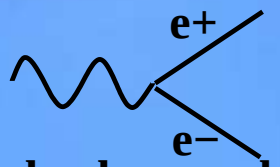
How to extract FF/Multiplicities at HERMES

unpolarised H & D data

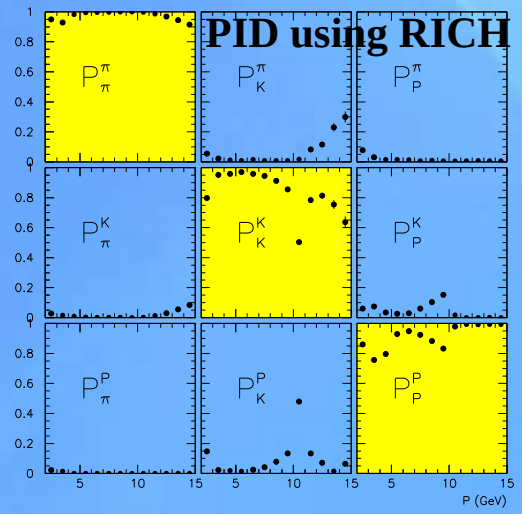
experimental multiplicities in acceptance

How to extract FF/Multiplicities at HERMES

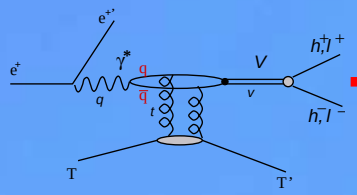
unpolarised H & D data



c.s. background correction



excl. VM correction

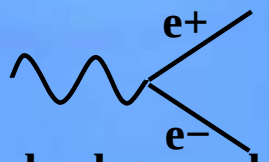


experimental multiplicities in acceptance

MC

How to extract FF/Multiplicities at HERMES

unpolarised H & D data



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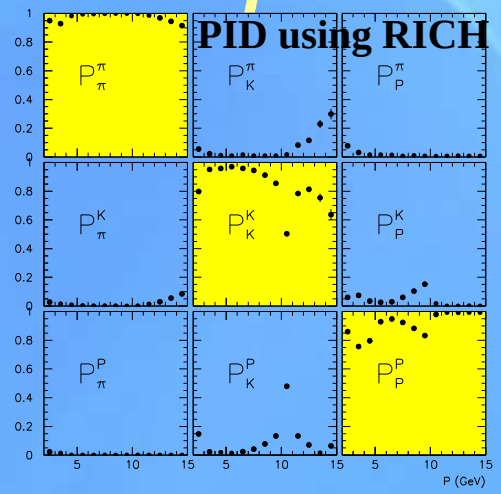

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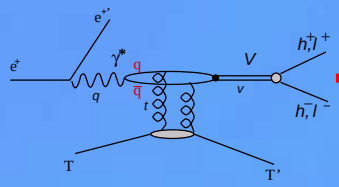


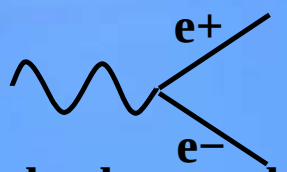
experimental multiplicities in acceptance

MC

born level multiplicities

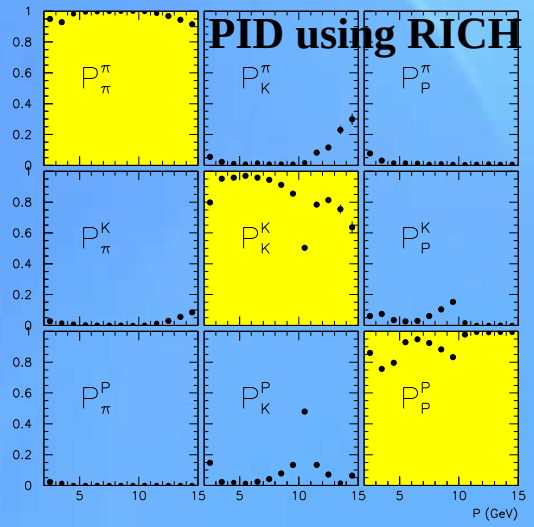
How to extract FF/Multiplicities at HERMES

unpolarised H & D data

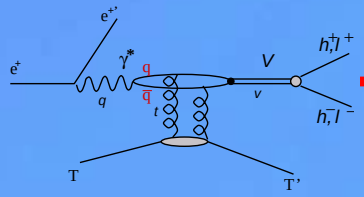


c.s. background correction

PID using RICH

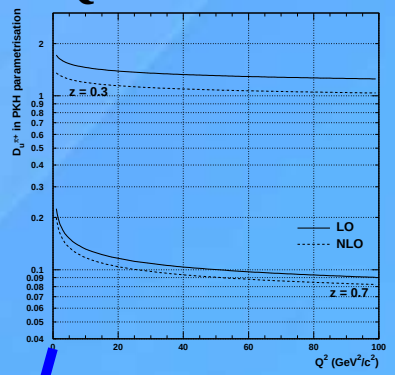


excl. VM correction

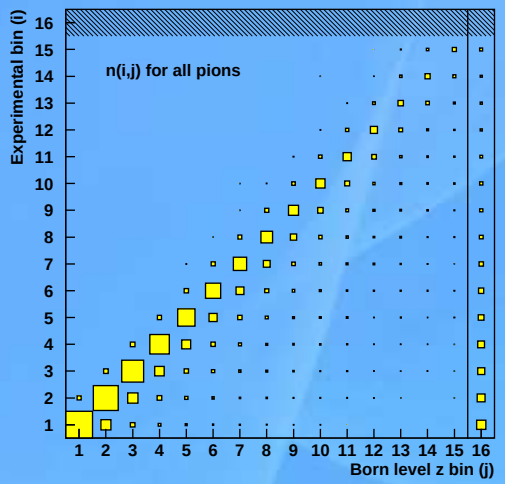


experimental multiplicities in acceptance

Q^2 – Evolution



acceptance correction radiative unfolding

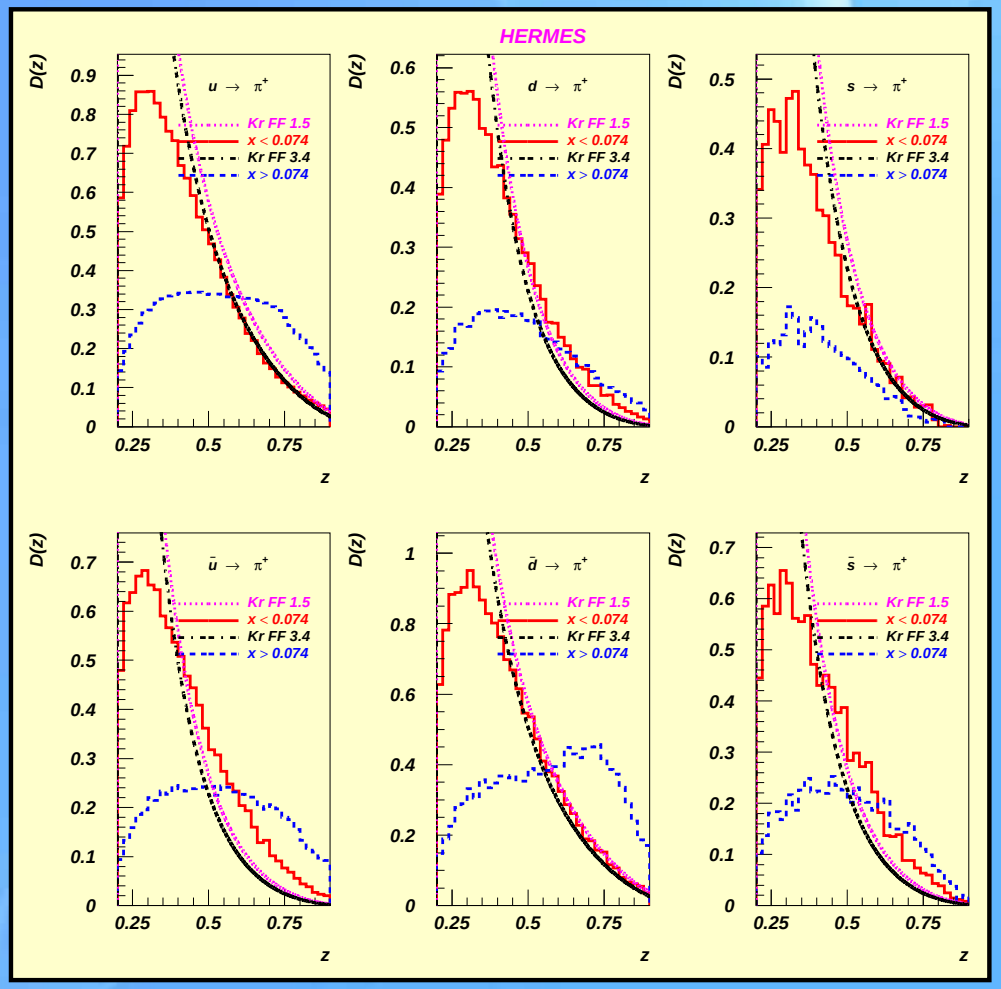


MC

born level multiplicities

How bad is the MC/Purity Method

- **Strong criticism by A. Kotzinian (hep-ph/0410093)**
  $\Longrightarrow$ strong x dependence in MC-FF
  $\Longrightarrow$ need to use fracture functions instead of FF or purity method to extract Δq



How bad is the MC/Purity Method

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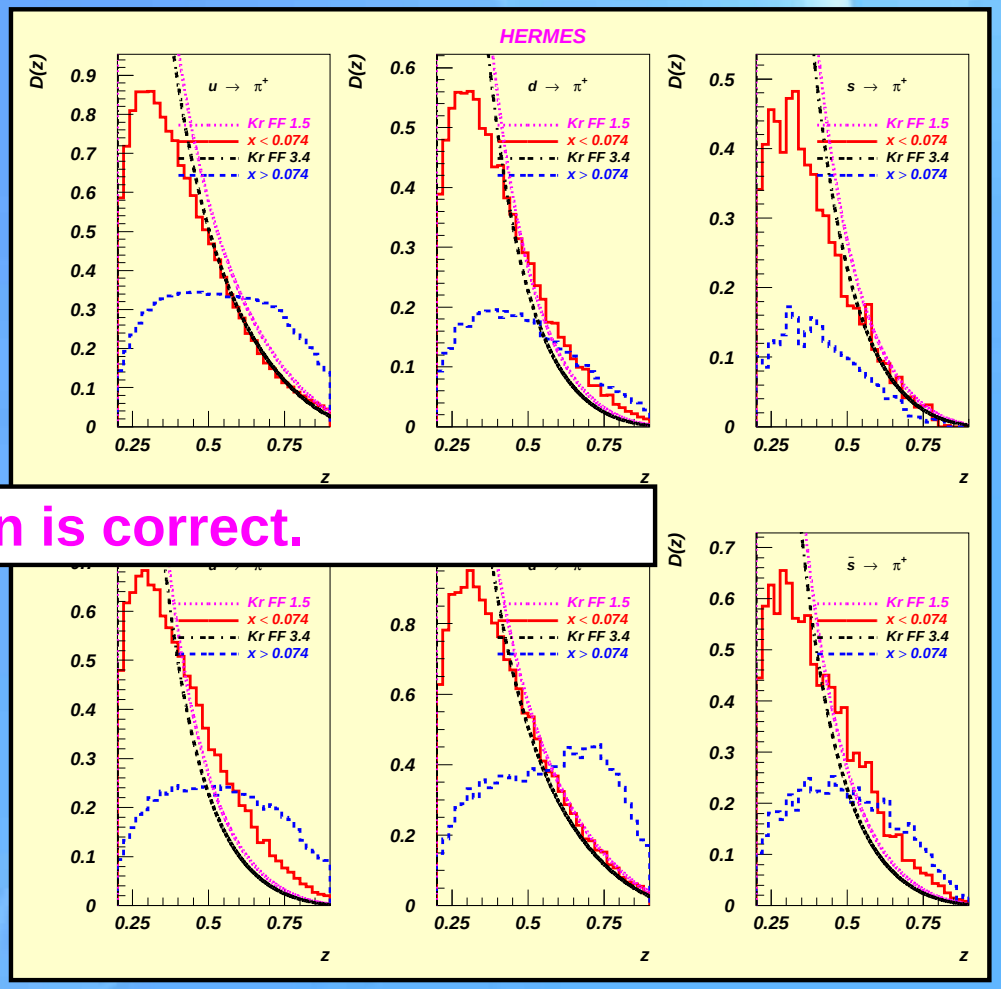
  - ⟹ strong x dependence in MC FF
  - ⟹ [illegible]
  - **instead of FF or purity method to extract Δq**



Let's see if Mr Kotzinian is correct.

Data - MC Agreement

- **MC: Lepto in combination with JETSET; PDF: CTEQ-6L**
  Fragmentation parameters tuned to HERMES multiplicities in acceptance
- **Data:** $\mathbf{Q^2 > 1GeV^2, W^2 > 10GeV^2, z > 0.2, 2GeV < p_{(\pi,K,p)^\pm} < 15GeV}$
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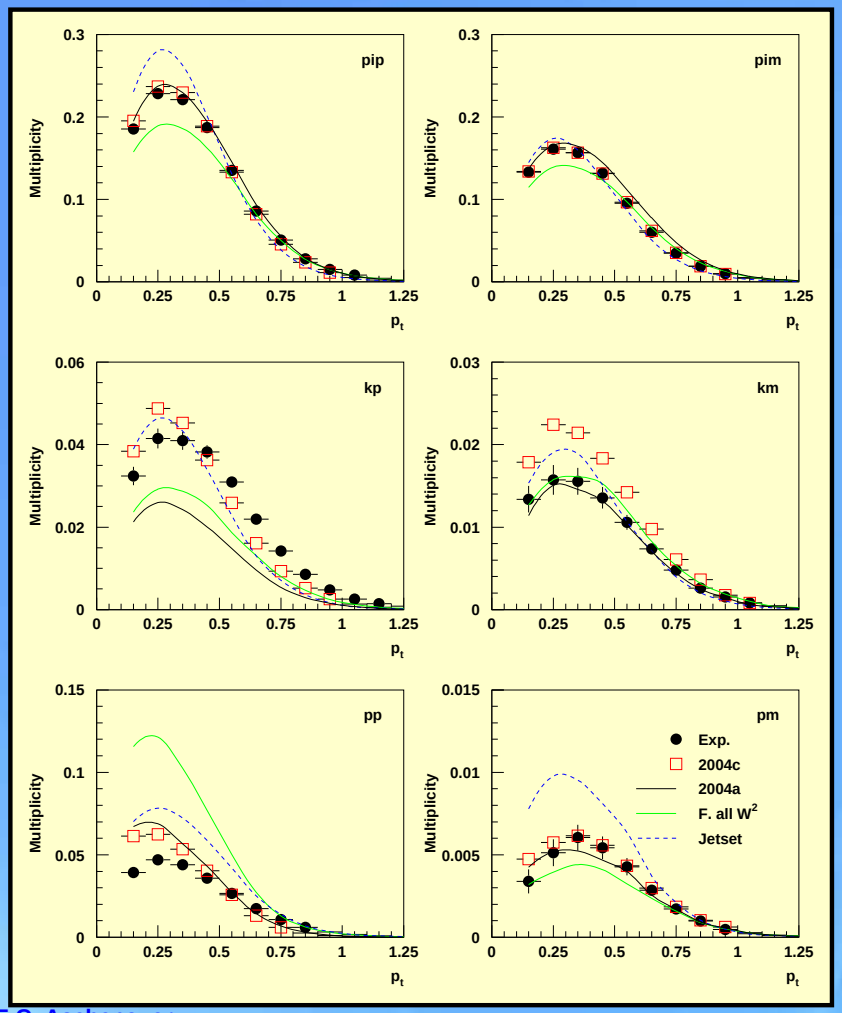

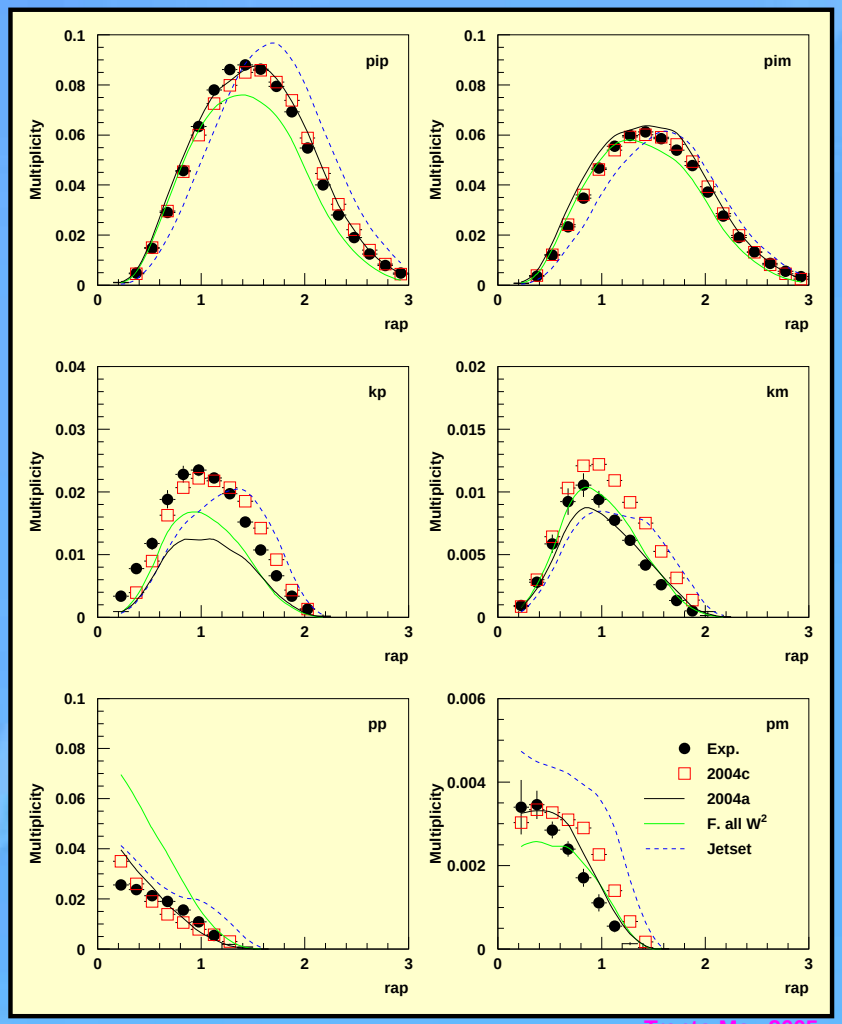

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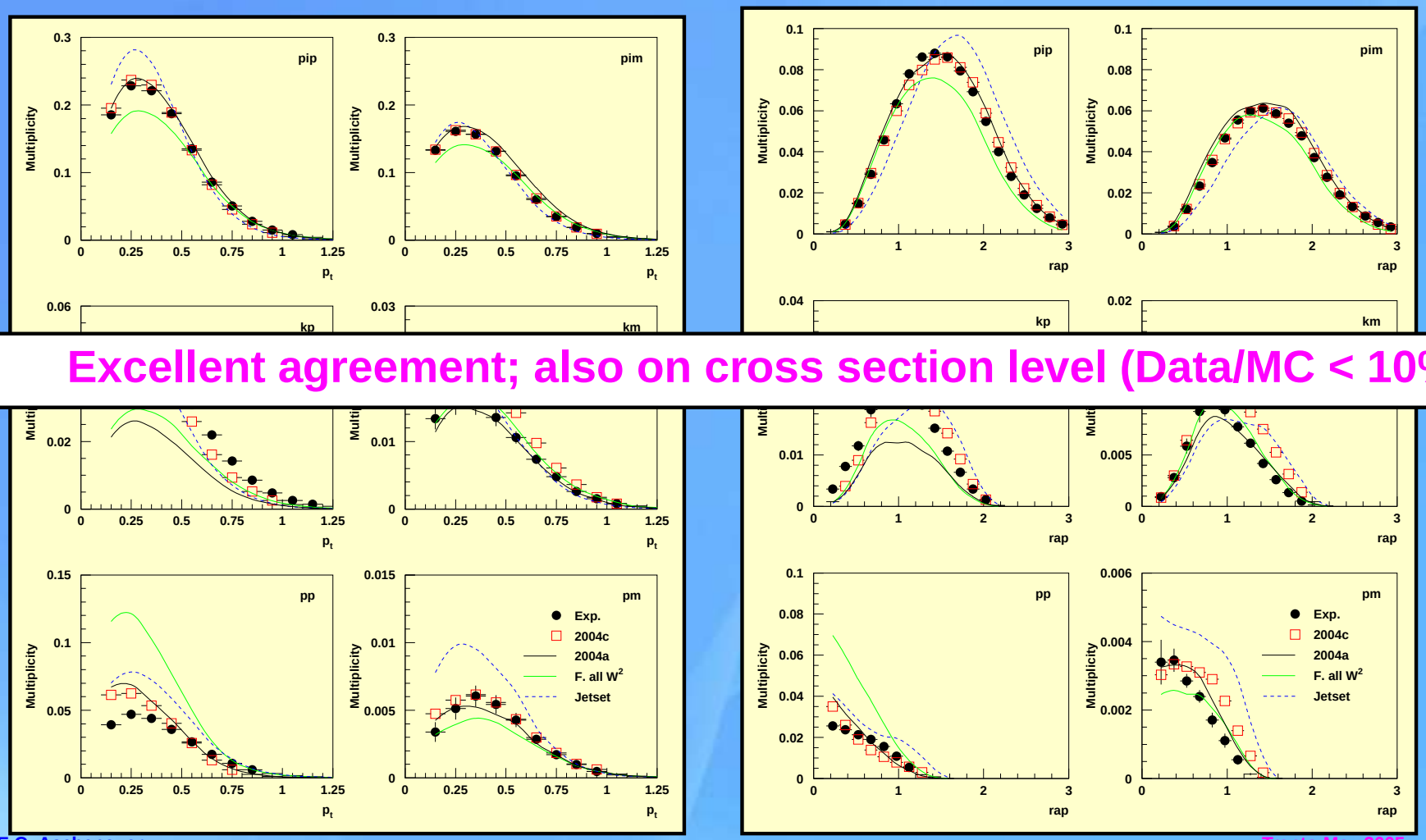
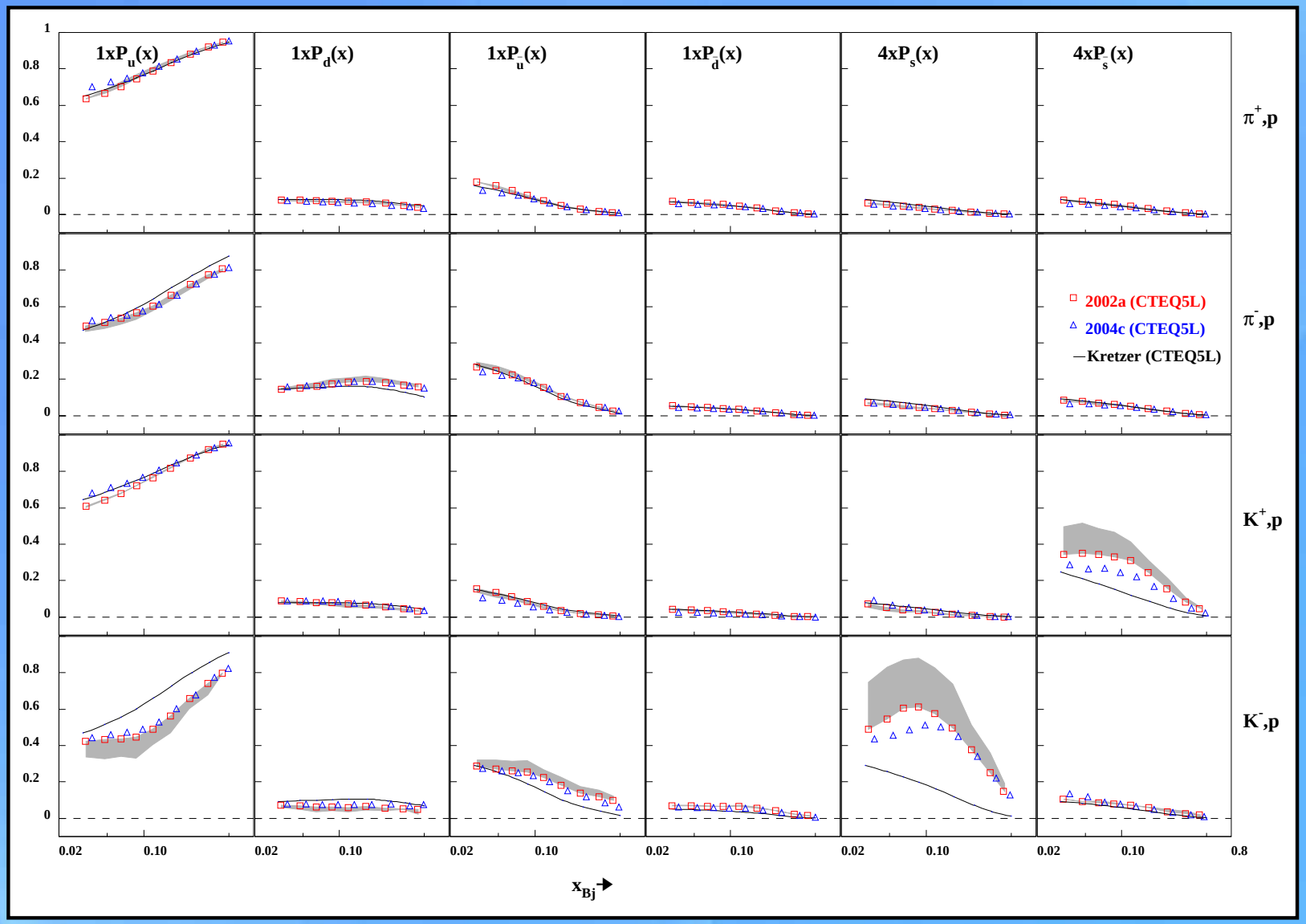


Excellent agreement; also on cross section level (Data/MC < 10%)

MC Sanity Checks

- **Compare Purities extracted from 'HERMES-Lepto' and S. Kretzer FF**



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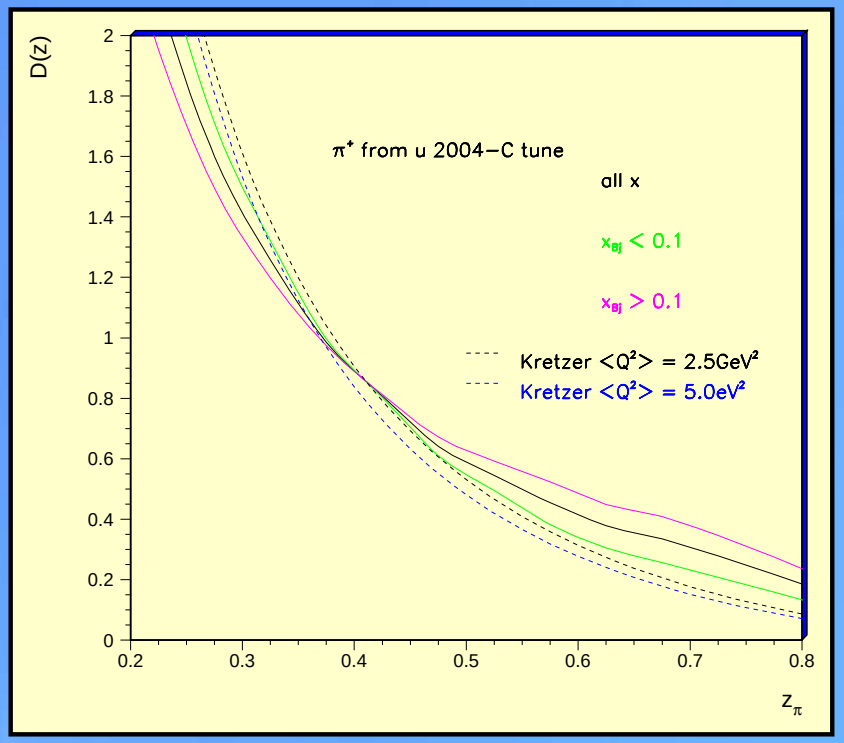
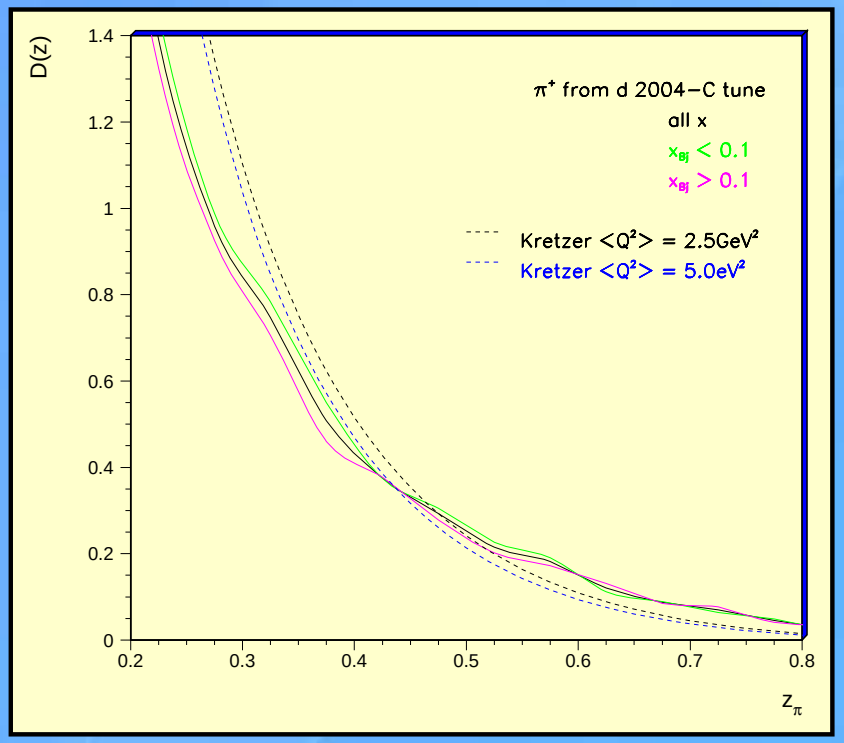
  $\Longrightarrow$ Good agreement
- **Check Dr. Kotzinians findings**





- **no strong $\mathbf{x_{bj}}$ dependence seen ! Why?**
  Dr. Kotzinian placed a momentum cut of $\mathbf{4.5GeV < p_{(\pi,K,p)^\pm} < 13GeV}$
  Remember: $\mathbf{z = E_{(\pi,K,p)^\pm}/\nu}$
  If $\mathbf{x_{bj}}$ is high $\longrightarrow$ ν is low $\longrightarrow$ if hadron momentum is required high
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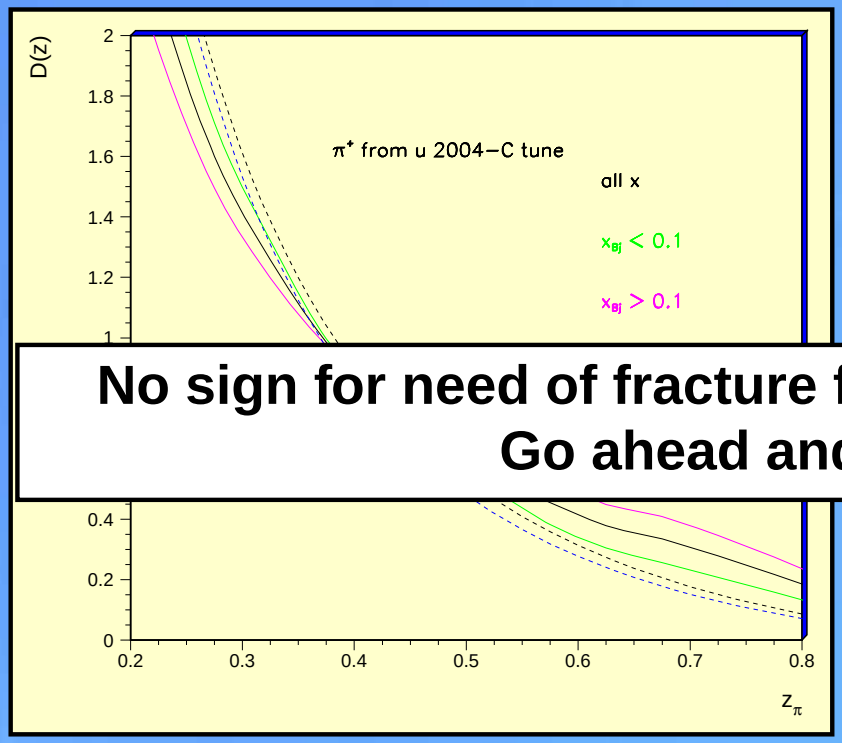

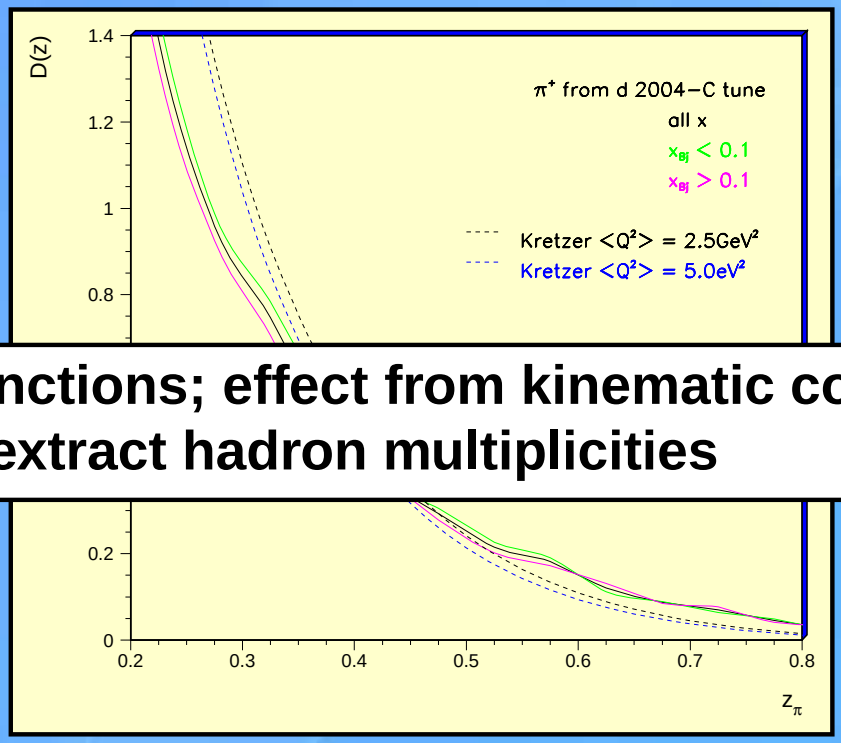

No sign for need of fracture functions; effect from kinematic correlations.
Go ahead and extract hadron multiplicities

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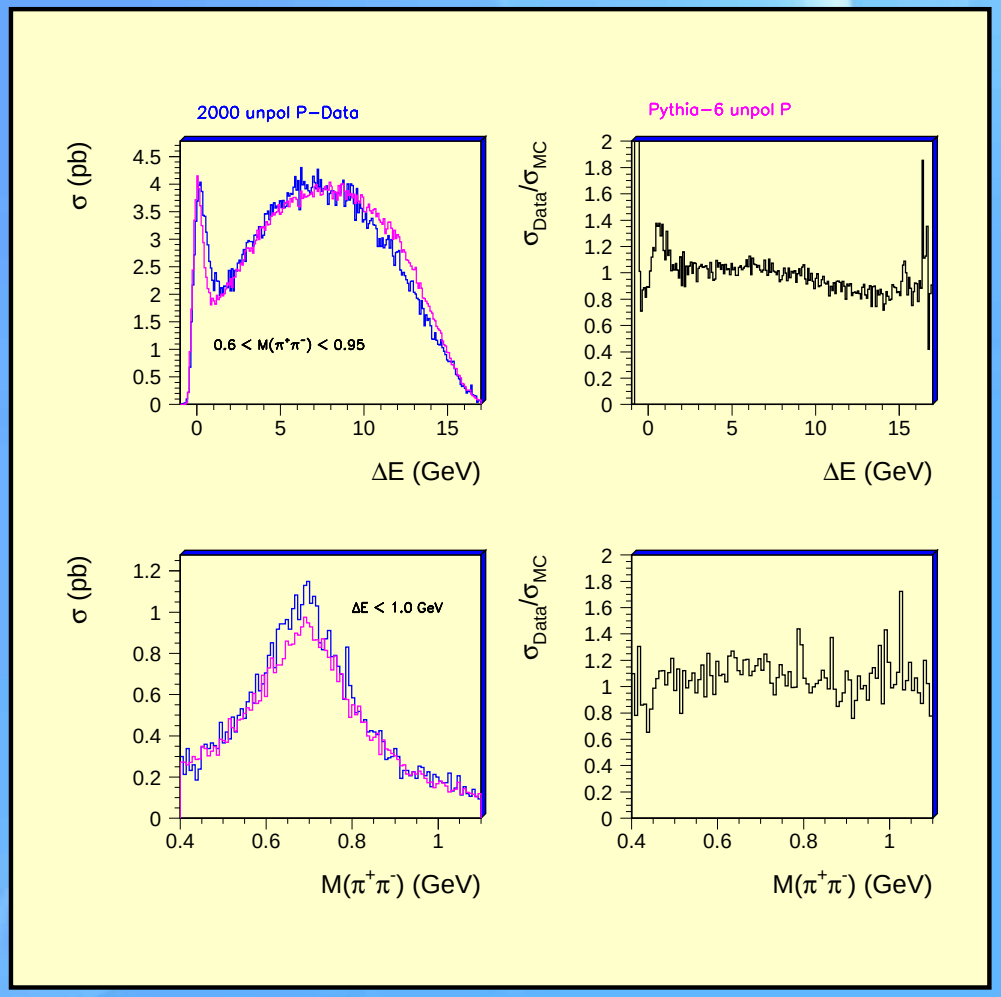
Exclusive VM Contamination

- **exclusive VM production: totally different process than SIDIS**
- **estimate contribution from PYTHIA-6: changes: QED-radiation, VMD-model, ...**



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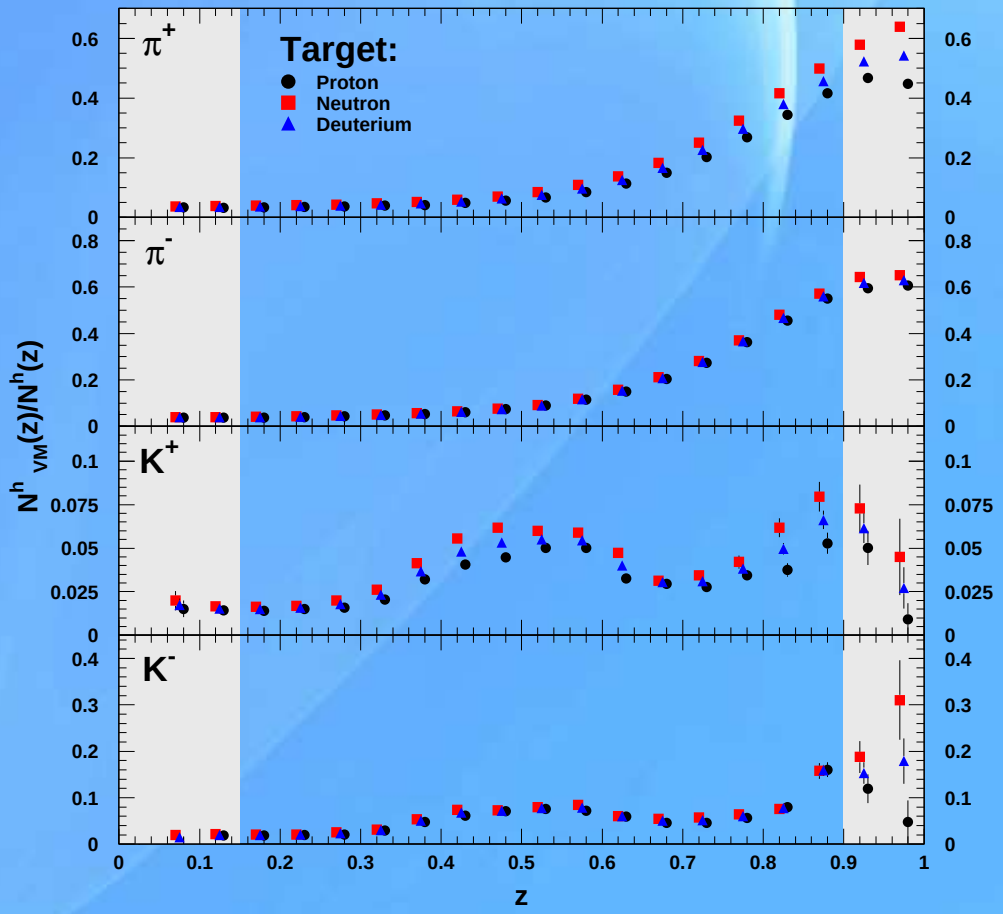
  contribution for K moderate vs z



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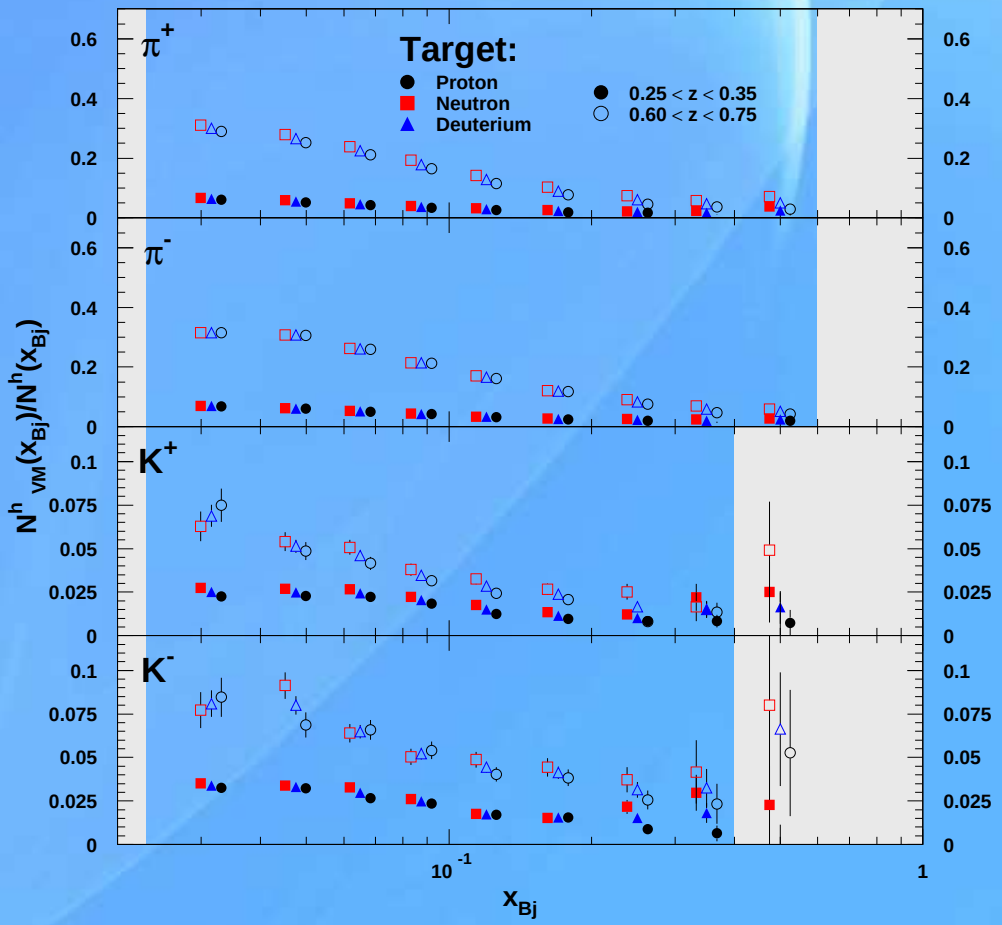
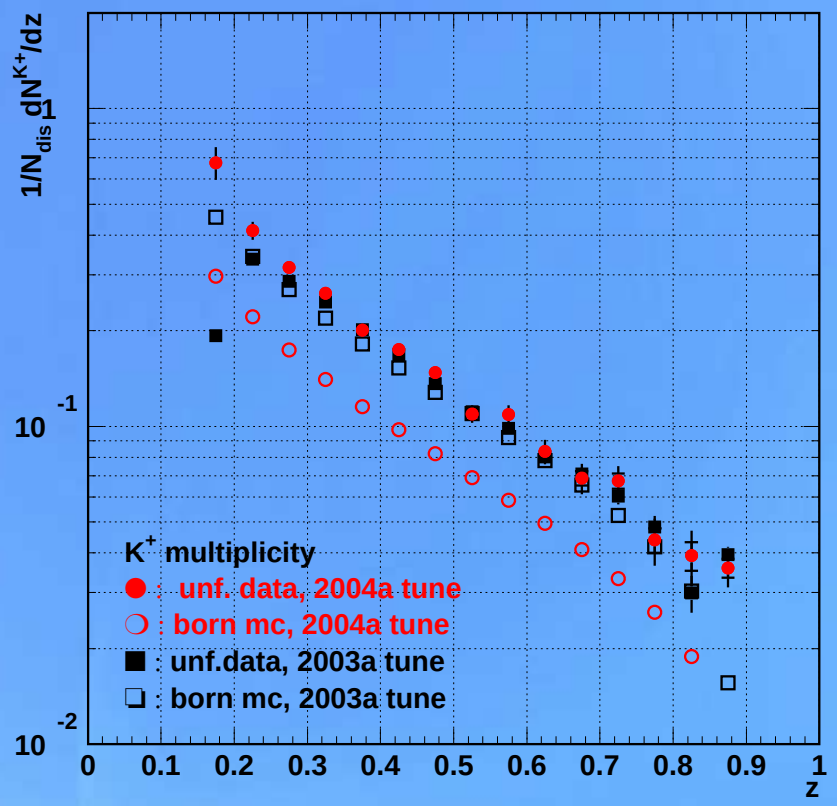
- contribution growing for small x_{bj} for both π and K

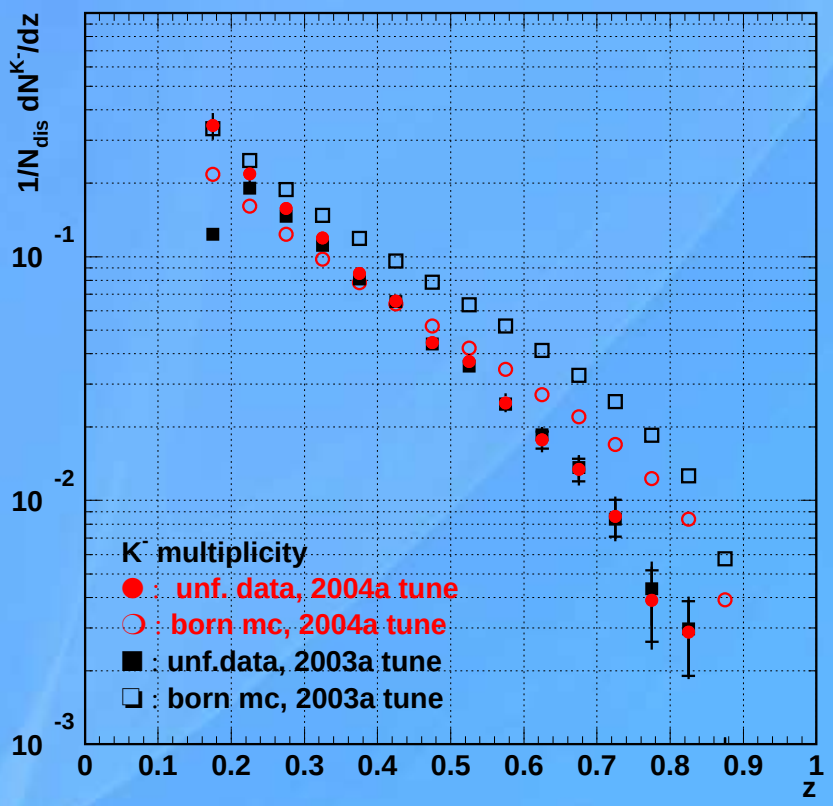


The HERMES acceptance

Acceptance small at low z, up to 35% at high z

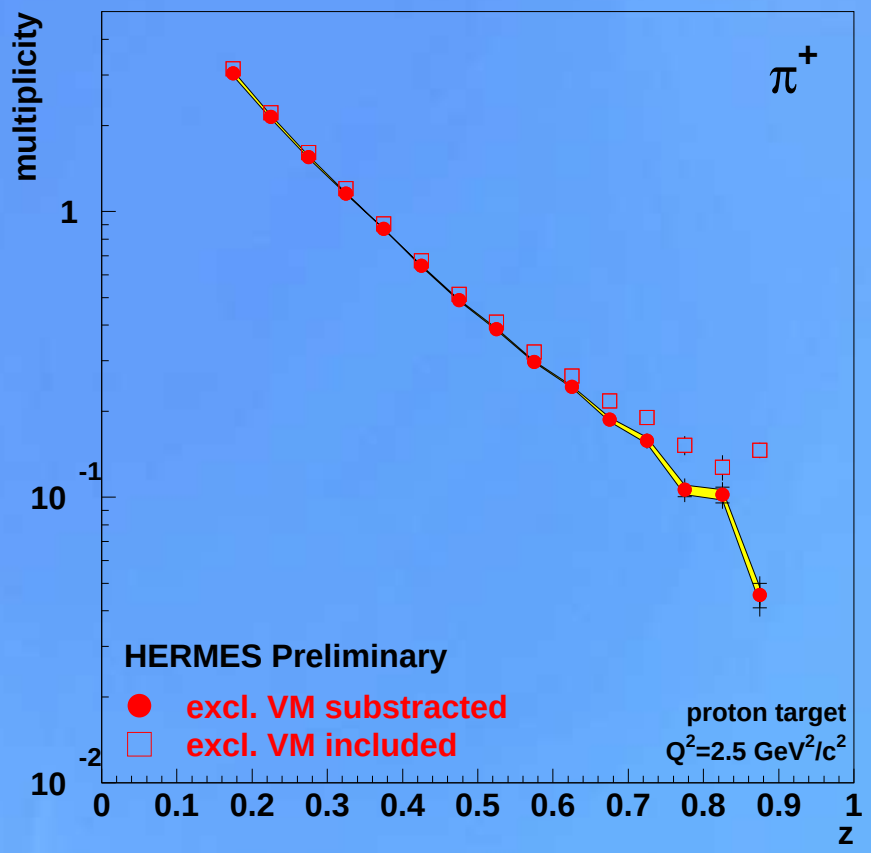
However the acceptance samples the phase space enough to fix the dynamics

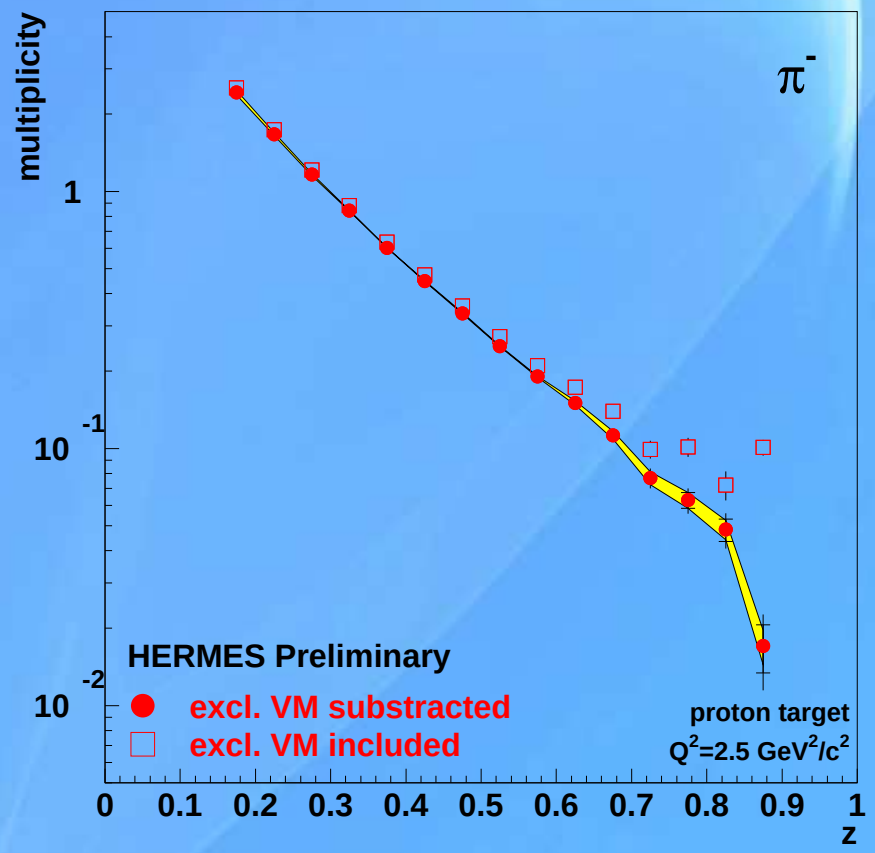




figures systematic study only; not a HERMES result

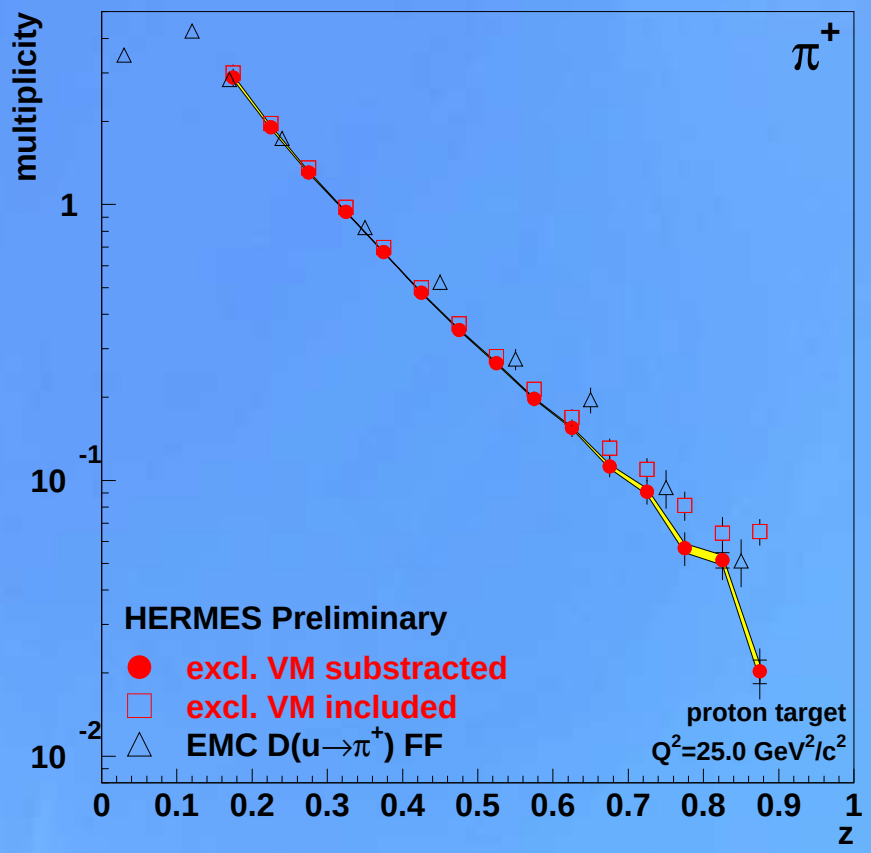
$\pi^{\pm}$ - Multiplicity vs. z

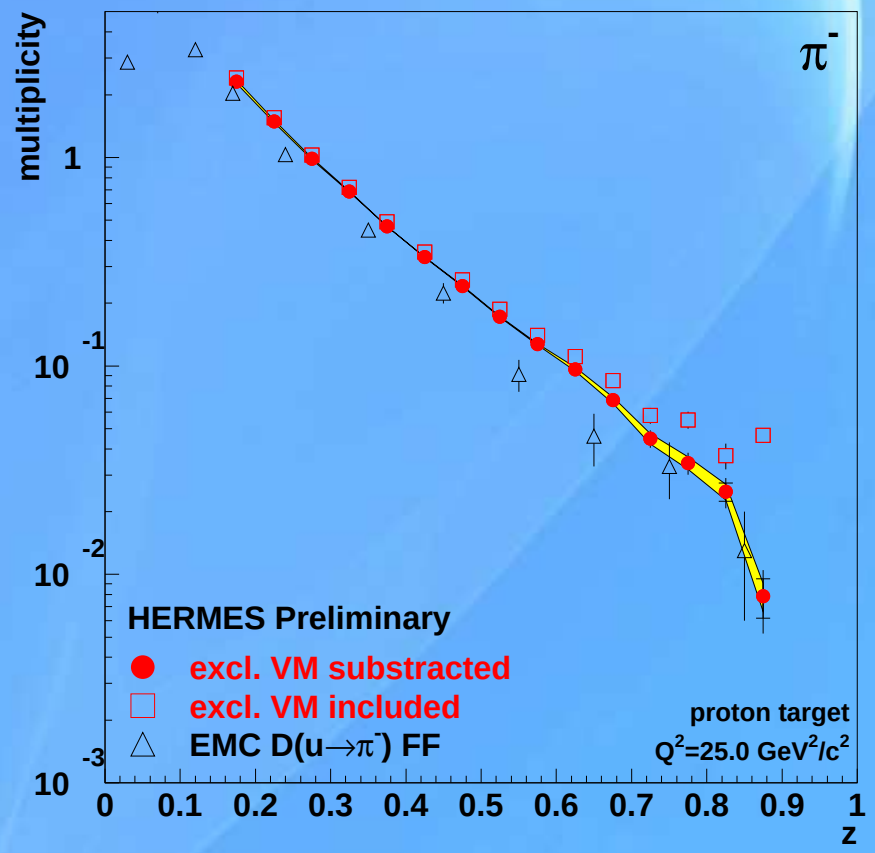




- **Systematic uncertainty mainly from hadron PID correction**
- $\mathbf{Q^2 > 1GeV^2, W^2 > 10GeV^2}$

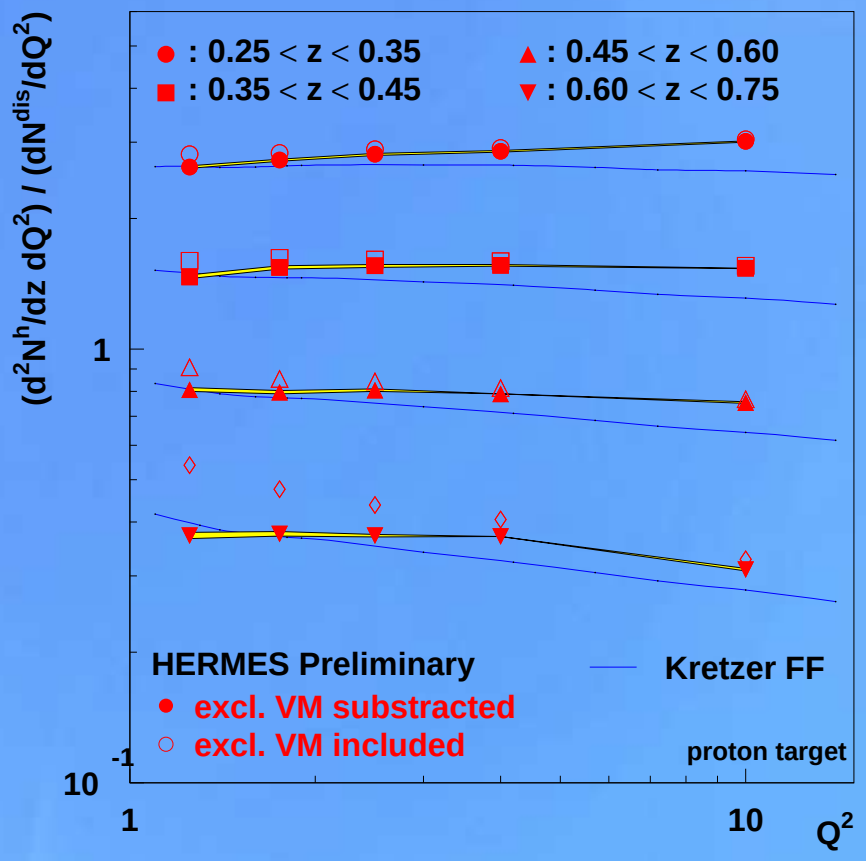
$\pi^{\pm}$ - Multiplicity vs. z

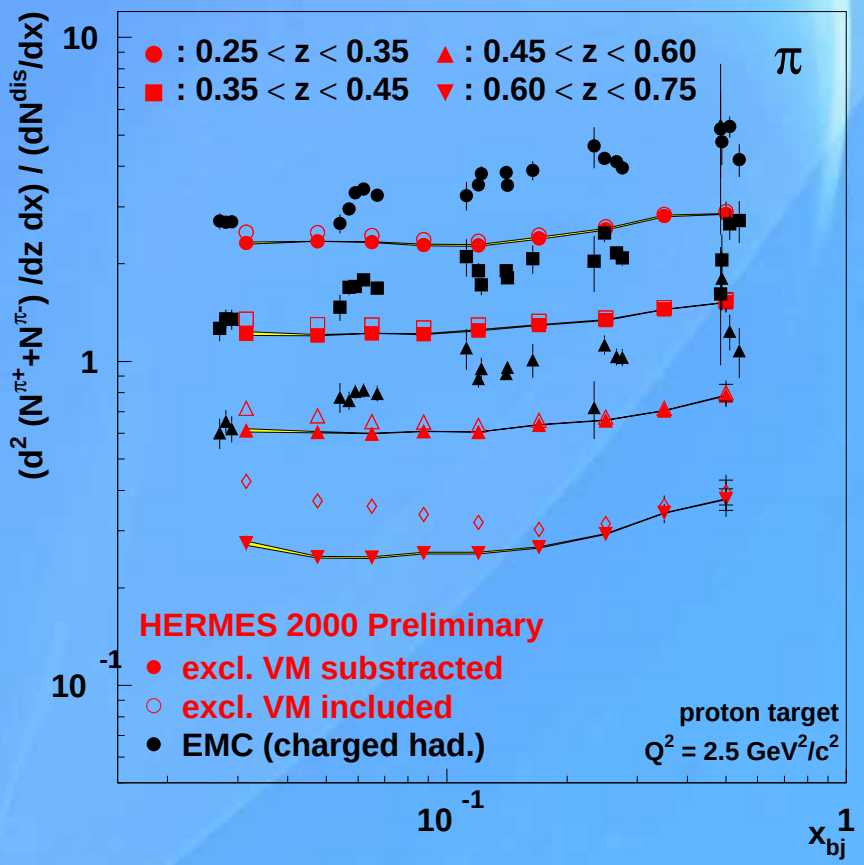




- **Comparison with EMC, Nucl. Phys. B321 (1989) 541**
- **EMC: Fragmentation Function $D_u^{\pi^{\pm}}$**

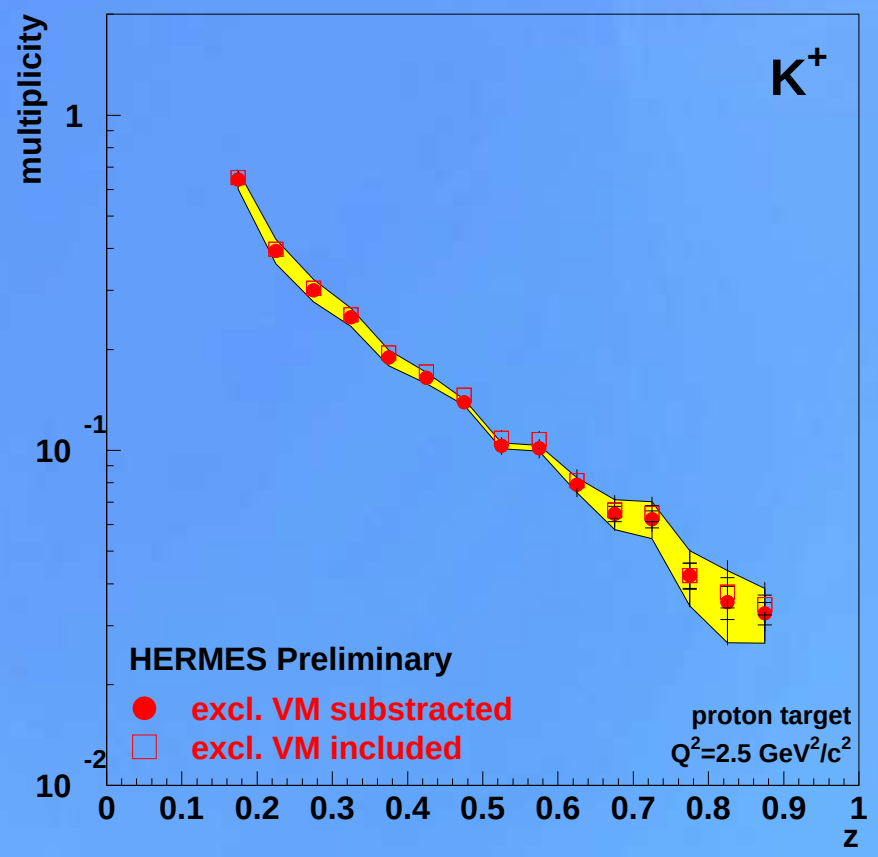
$\pi^{\pm}$ - Multiplicity vs. Q^2 and x_{bj}

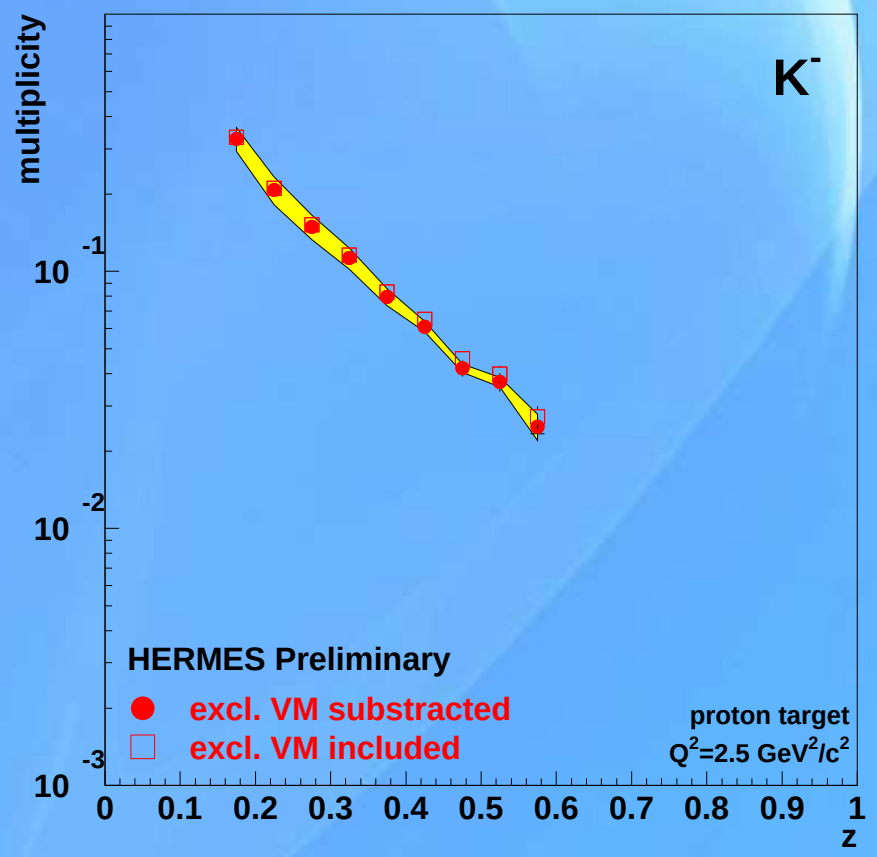




- **Reasonable agreement with results using S. Kretzter FF**
- **very weak x_{bj} dependence**

$K^{\pm}$ - *Multiplicity vs. z*





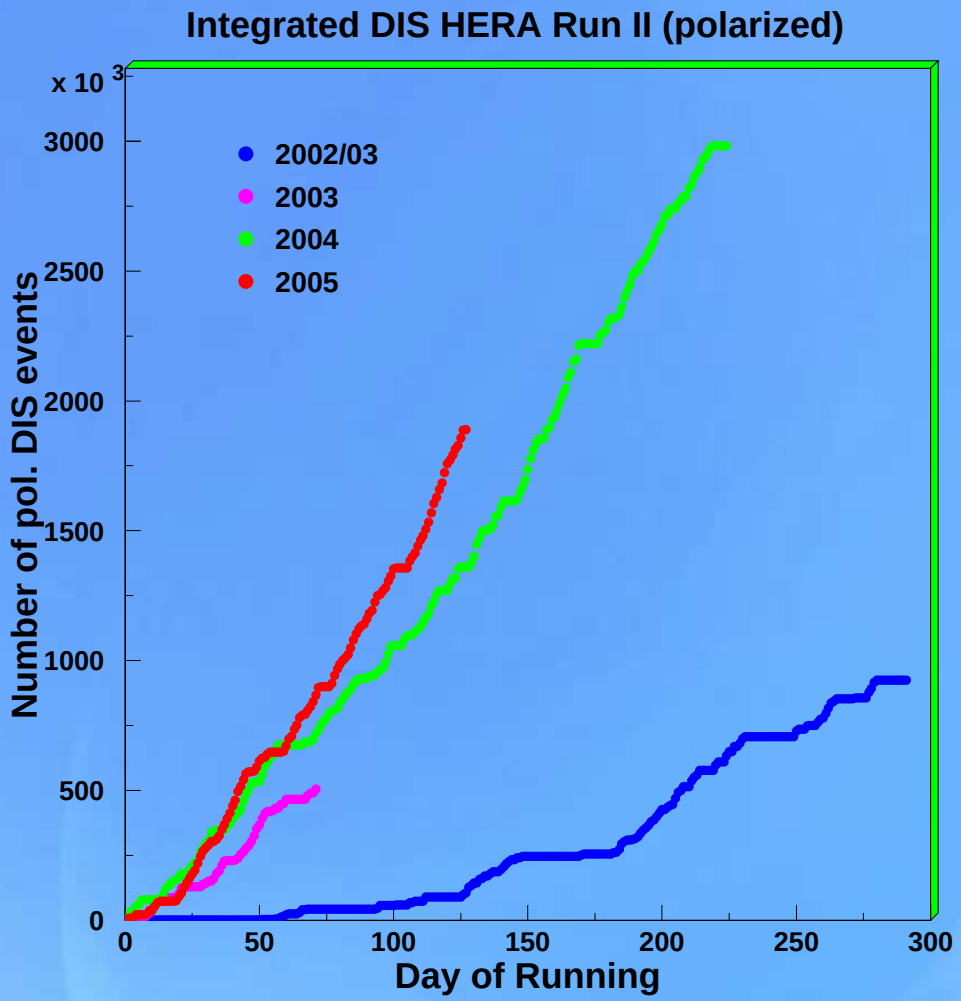
- charge separated Kaon multiplicities
- Systematic uncertainty mainly from hadron PID correction
- low K^{-} statistics $\Longrightarrow$ more statistics under way

and Summary

- **HERMES continues happily taking data with a transverse polarised p-target**

Outlook and Summary

- **HERMES continues happily taking data with a transverse polarised p-target**
  ⟹ Will have much more data till end of 2005



and Summary

- **HERMES continues happily taking data with a transverse polarised p-target $\Longrightarrow$ Will have much more data till end of 2005**
  - **together with Collins FF from Bell will allow us hopefully to extract $\mathbf{f_{1T}^{\perp}}$ and $\delta\mathbf{q}$**
  - **DVCS and exclusive ρ^0: $\mathbf{A_{UT}} \Longrightarrow$ sensitive to GPD E**
  - **exclusive π^+: $\mathbf{A_{UT}} \Longrightarrow$ sensitive to GPD $\tilde{\mathbf{H}}$, $\tilde{\mathbf{E}}$**

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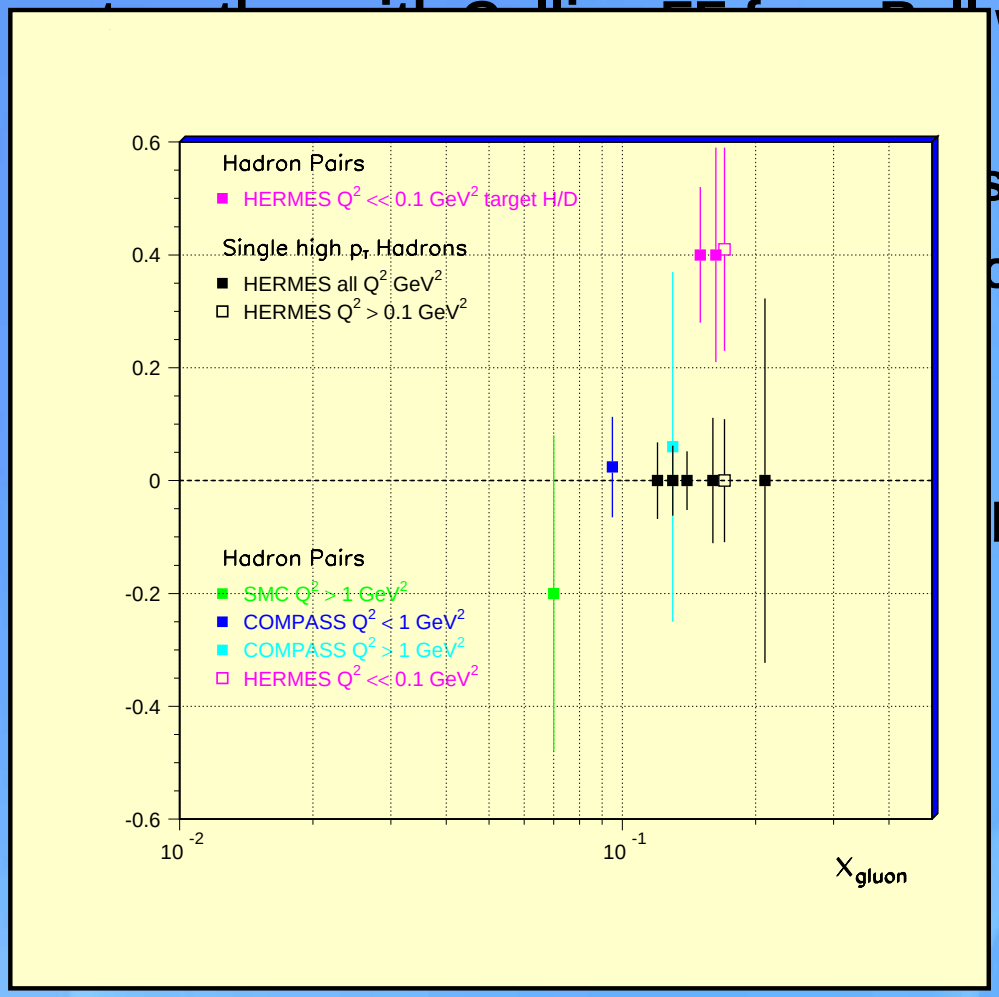

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