Multiplicities for $\pi^{\pm}$ and $K^{\pm}$ Production in Semi-Inclusive DIS on a Proton and Deuteron target

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On behalf of the HERMES collaboration

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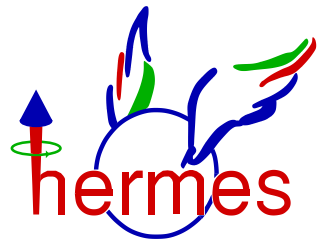
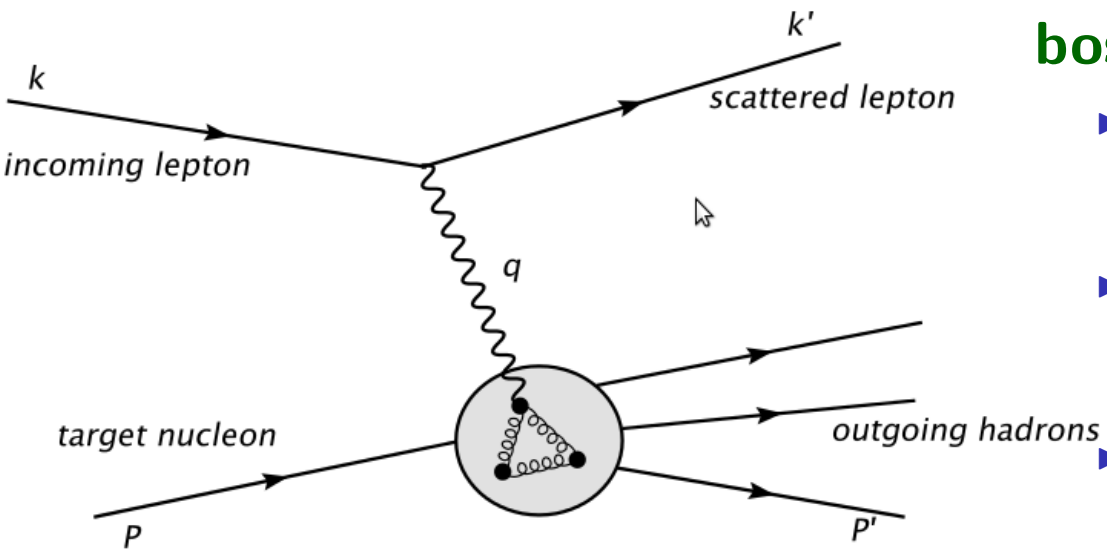


lepton scattering off a proton

- Scattering a high energetic lepton off a nucleon target provides a pathway to the **nucleon substructure**



- Probing happens through neutral electroweak (γ, Z^0) **bosons**
  - **resolution**: $Q^2 \equiv -q^2 \overset{\text{lab}}{=} 4EE' \sin^2 \frac{\theta}{2}$
  - **energy transfer**: $\nu \equiv \frac{Pq}{M} \overset{\text{lab}}{=} E - E'$
  - Final state **invariant mass**: $W^2 \equiv M^2 + 2M\nu - Q^2$

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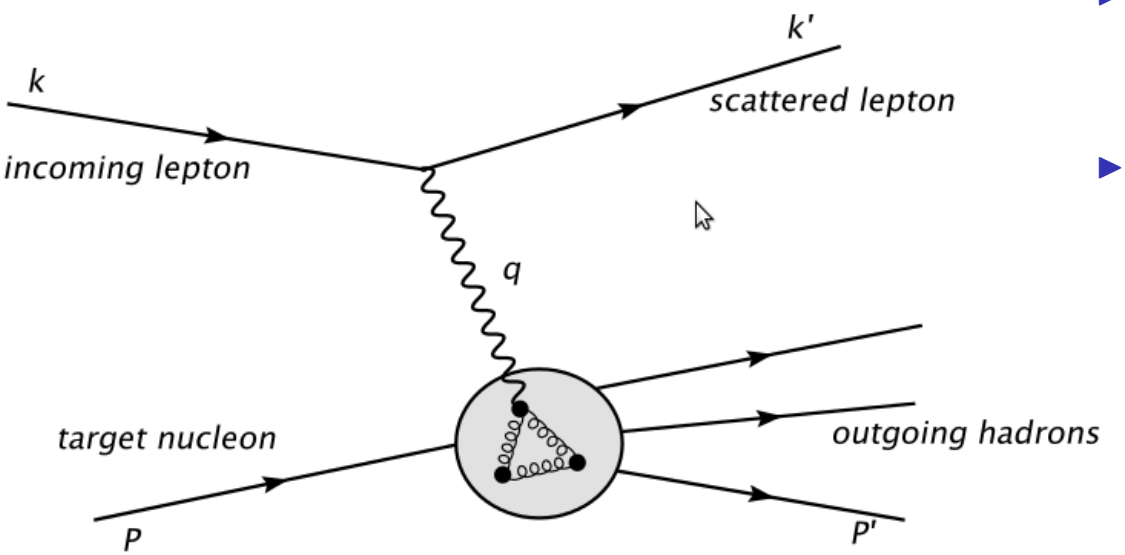
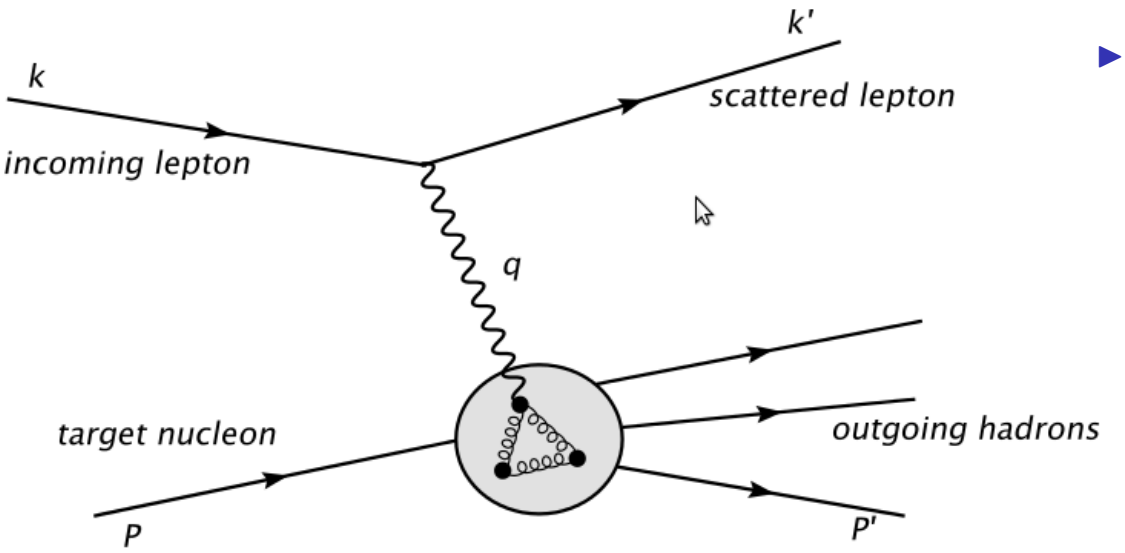


- Additional variables
  - **Fractional energy transfer**:
    $y \equiv \frac{Pq}{Pk} \overset{\text{lab}}{=} \frac{\nu}{E}$
  - **Center of mass energy**:
    $s = (k + P)^2 \overset{\text{lab}}{=} 2ME - M^2$
    - ★ *HERA: 27.6 GeV*
    - ★ $\sqrt{s} \approx 7.1\text{GeV} << M_{Z^0}$
    - ★ *HERMES: Only QED probe*

Semi-inclusive DIS (SIDIS)

- Measure produced hadrons in coincidence with the scattered lepton



- DIS: quark 'kicked out' of nucleon
  - **Longitudinal momentum fraction** carried by struck quark:

$$x \equiv \frac{Q^2}{2M\nu}$$

Semi-inclusive DIS (SIDIS)

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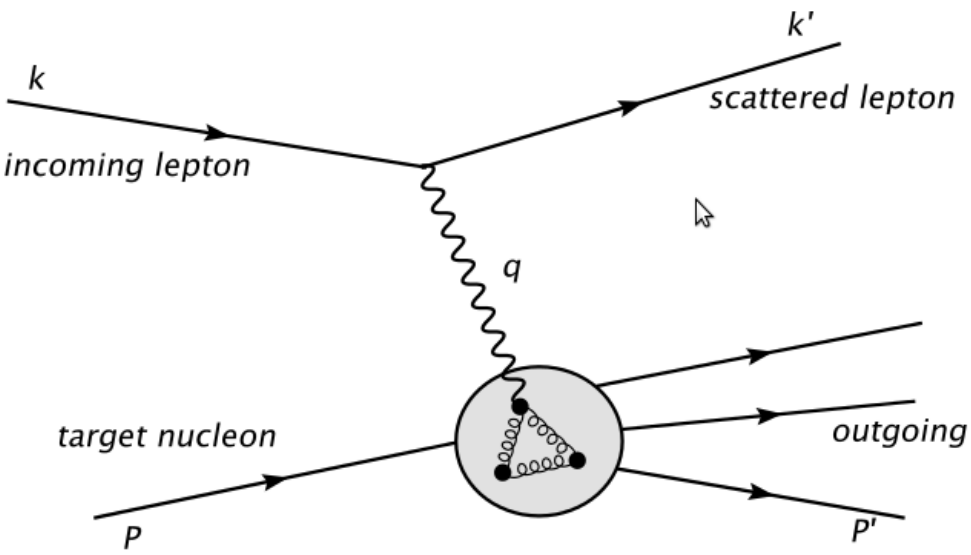


- DIS: quark 'kicked out' of nucleon
- **confinement** prevents free quarks (long distance behavior)
- **fragmentation process** is the evolution into the final state hadrons
- measuring the final state hadrons in SIDIS yields information about this process

- SIDIS is one of the processes that provides access to the hadronization process, complementing the information that can be extracted from Drell-Yan and e^+e^-

Factorization in SIDIS

- Factorization in SIDIS means that we can separate
  - the (**long distance**) **proton structure**
  - the (**short distance**) interaction with the **quasi free** quarks
  - the (**long distance**) hadronization process enforced by **confinement**
- In practice: SIDIS cross section can be written as a convolution of **PDFs** f_1^q and fragmentation functions **(FFs)** D_q^h
- **FF** $D_q^h(z, Q^2)$ depend on the fractional hadron momentum $z \equiv \frac{E_h}{\nu}$, subject to **DGLAP**-like scaling

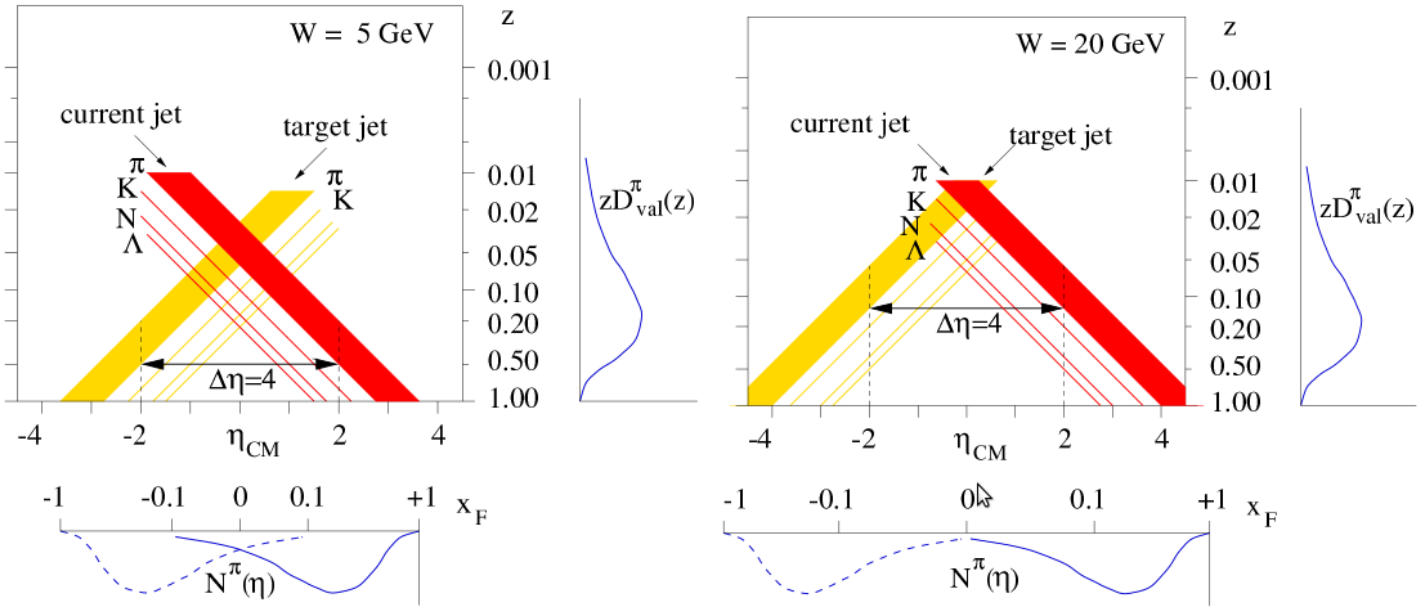
LO SIDIS cross section

$$\frac{d^3\sigma_n^h(Q^2, x, z)}{dx dQ^2 dz} \propto \sum_q e_q^2 f_1^q(Q^2, x) D_q^h(Q^2, z)$$

Assumptions: LO, leading twist factorized QCD

Limits of the Factorization Theorem

- Factorization in x and z dependent parts is not exact, both from theoretical and experimental point-of-view
  - **Theoretical**: Reinteraction of final state quarks with the target remnant (higher-twist effects)
  - **Experimental**: Contamination of the current jet with the target jet



Mulders, AIP Conf.Proc. 588 (2001) 75-88

  - ★ Effect minimized by choosing a lower rapidity limit (described by the Berger Criterion) $\rightarrow$ lower z limit for SIDIS experiments

- Need factorization for **universality**!

Goals of this analysis

- Provide the **most precise multi-dimensional SIDIS dataset** to date
- Enabling:
  - **Evaluation of the quality** of FF (and PDF) **parametrizations**
  - **Input** for the **next generation** of parametrizations
  - Access to the **transverse distributions**

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p_T dependence in the LO TMD formalism

$$\frac{d^5\sigma^h}{dx dQ^2 dz d^2\vec{p}_T} \propto$$

$$\sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta^2(\vec{p}_T - \vec{p}_\perp - z\vec{k}_\perp) f_1^q(x, Q^2, k_\perp) D_q^h(z, Q^2, p_\perp)$$

- ★ **Transverse hadron momentum** p_T
- ★ **intrinsic quark** $k_\perp$
- ★ **fragmentation** $p_\perp$

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  - Access to the **transverse distributions**
- **Tests of the applicability** of the usual LO, leading-twist model **assumptions** at intermediate energies

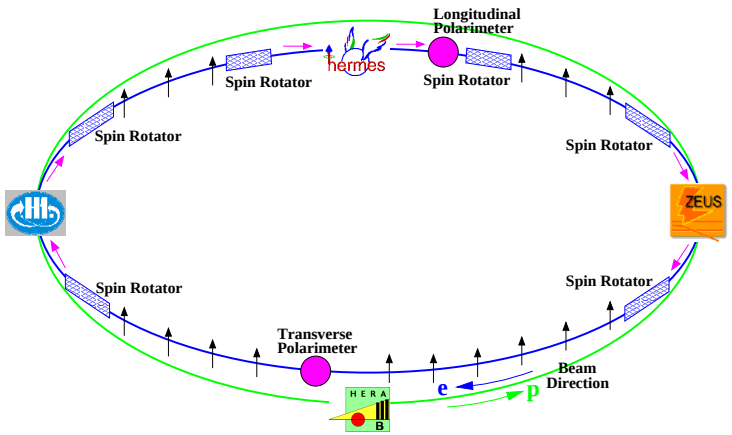
SIDIS Multiplicities

Definition

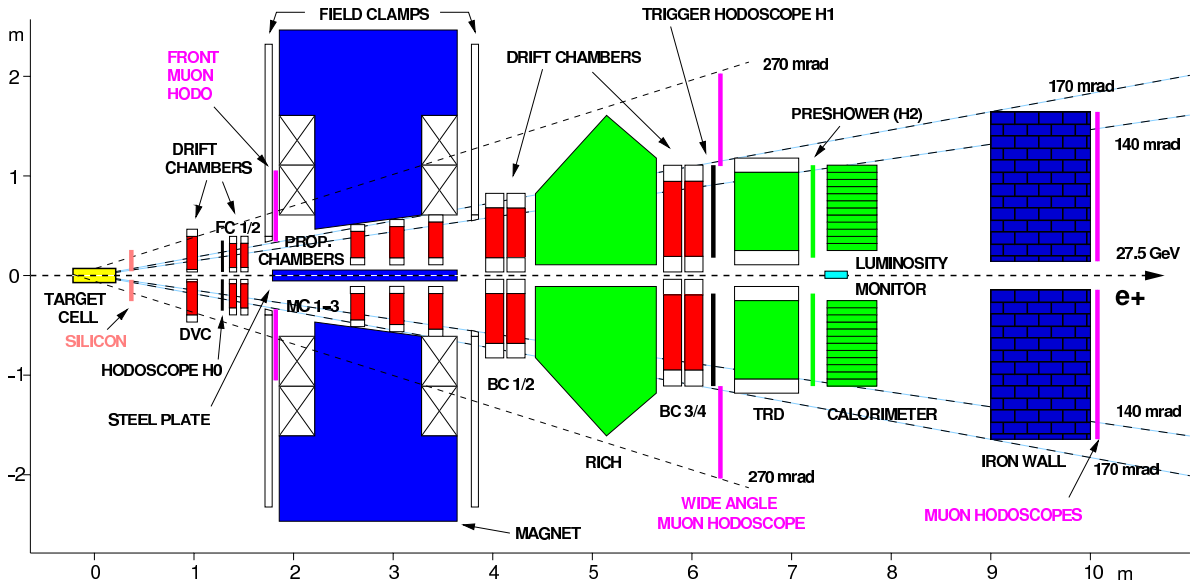
$$M_t^h(Q^2, x, z, p_T) \equiv \frac{d^4 N_t^h(Q^2,x,z,p_T)}{dx dQ^2 dz dp_T} \Big/ \frac{dx dQ^2}{d^2 N_t^{\mathrm{DIS}}(Q^2,x)}$$

- DIS yield $N_t^{\mathrm{DIS}}(Q^2, x)$
- SIDIS yield $N_t^h(Q^2, x, z, p_T)$
- **Multiplicities** instead of cross sections: **no luminosity uncertainty**

The HERMES Experiment



- 27.6 GeV HERA electron/positron beam
- Pure H and D atomic gas target
- Forward spectrometer
- Very clean lepton-hadron separation
- RICH detector enables very good pion-kaon separation



- $Q^2 > 1\text{GeV}^2$
- $W^2 > 10\text{GeV}^2$
- $0.1 < y < 0.85$
- $0.2 < z < 0.8$

SIDIS Multiplicities: New HERMES Results

- **High statistics**
- **3D analysis** (in x, z, p_T and Q^2, z, p_T)
- For identified and charge-separated $\pi^{\pm}$ **and** $K^{\pm}$
- High statistics data require **sophisticated analysis**:

SIDIS Multiplicities: New HERMES Results

- **High statistics**
- **3D analysis** (in x, z, p_T and Q^2, z, p_T)
- For identified and charge-separated $\pi^{\pm}$ **and** $K^{\pm}$
- High statistics data require **sophisticated analysis**:
  - Corrections for trigger inefficiencies
  - Charge-symmetric background correction
  - RICH unfolding
  - Multidimensional smearing-unfolding for radiative effects, limited acceptance and detector smearing
- High precision 3D data **pushes the envelope**

Smearing-unfolding in SIDIS

- A raw measurement does not give experiment-independent information:
  - Usually not known if any **radiative effects** occured (eg. ISR and FSR)
  - Detector has less than full 4π **coverage**
  - Detector has a finite **resolution**

Relation between true and measured quantities

$$\nu_i = \mu_{\text{tot}} \sum_{j=1}^{M} \frac{\int_{\text{bin}\,i} dX \int_{\text{bin}\,j} dY \int d\bar{Y} f(Y) \rho(\bar{Y}|Y) A(\bar{Y}) M(\bar{Y}|X)}{\int_{\text{bin}\,j} dY f(Y)} \mu_j + \beta_i$$

- **Physics distribution** f
- **Background** from outside the acceptance β

Smearing-unfolding in SIDIS

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- Has the shape of a **matrix equation**

$$\nu_i = \sum_{j=1}^{M} S_{ij} \mu_j + \beta_i$$

Smearing-unfolding in SIDIS

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- Has the shape of a **matrix equation**
- **Smearing matrix** S can be calculated in a completely **model-independent** way **if either**:
  - **Acceptance function** A is **flat** within each bin
  - **Distribution** f is **flat** within each bin
- If this is **not the case**, a **reasonable** (better than 10% level) **model for** f is required

Smearing-unfolding in SIDIS

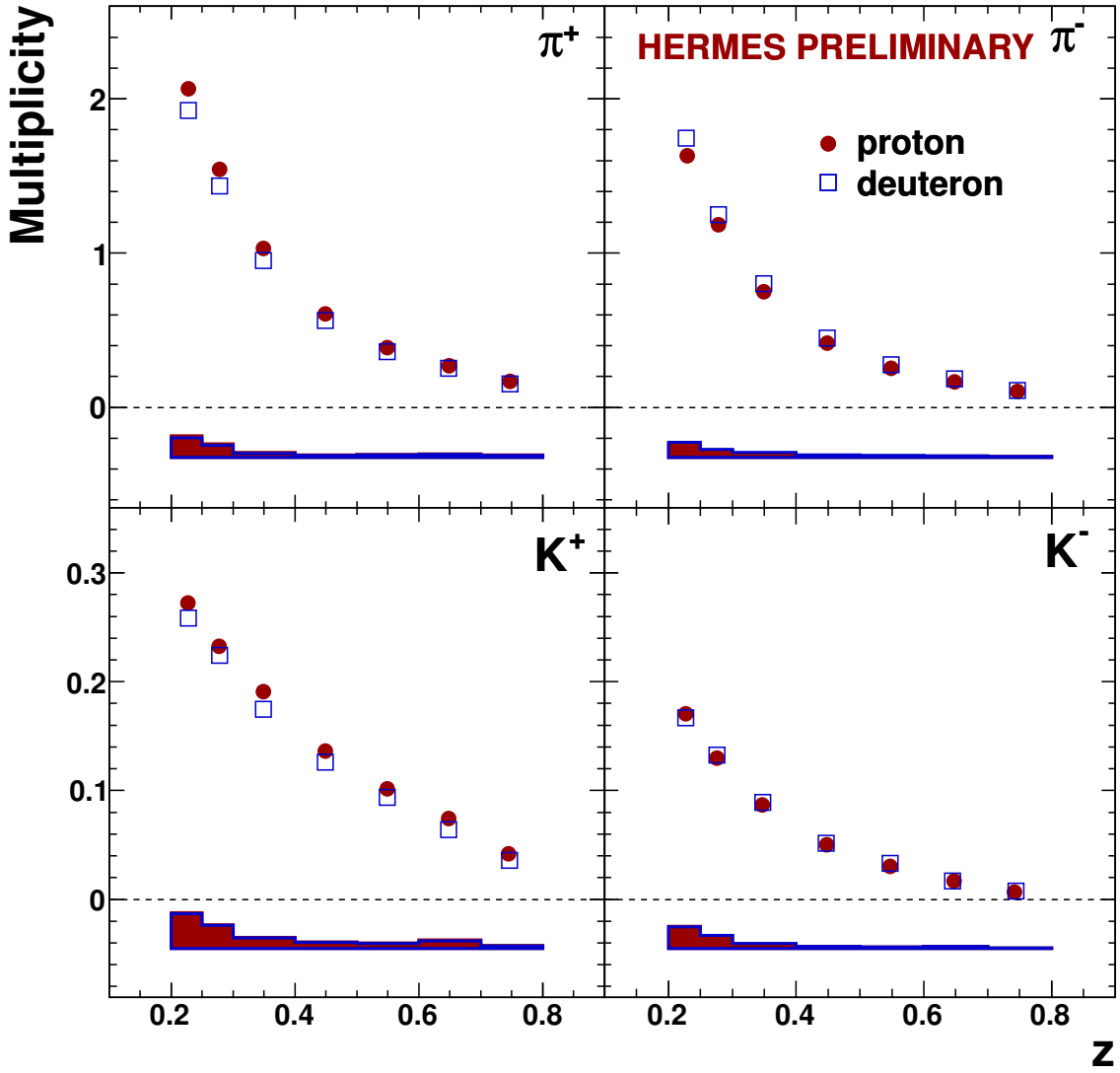
Relation between true and measured quantities

$$\nu_i = \mu_{\text{tot}} \sum_{j=1}^{M} \frac{\int_{\text{bin } i} dX \int_{\text{bin } j} dY \int d\bar{Y} f(Y) \rho(\bar{Y}|Y) A(\bar{Y}) M(\bar{Y}|X)}{\int_{\text{bin } j} dY f(Y)} \mu_j + \beta_i$$

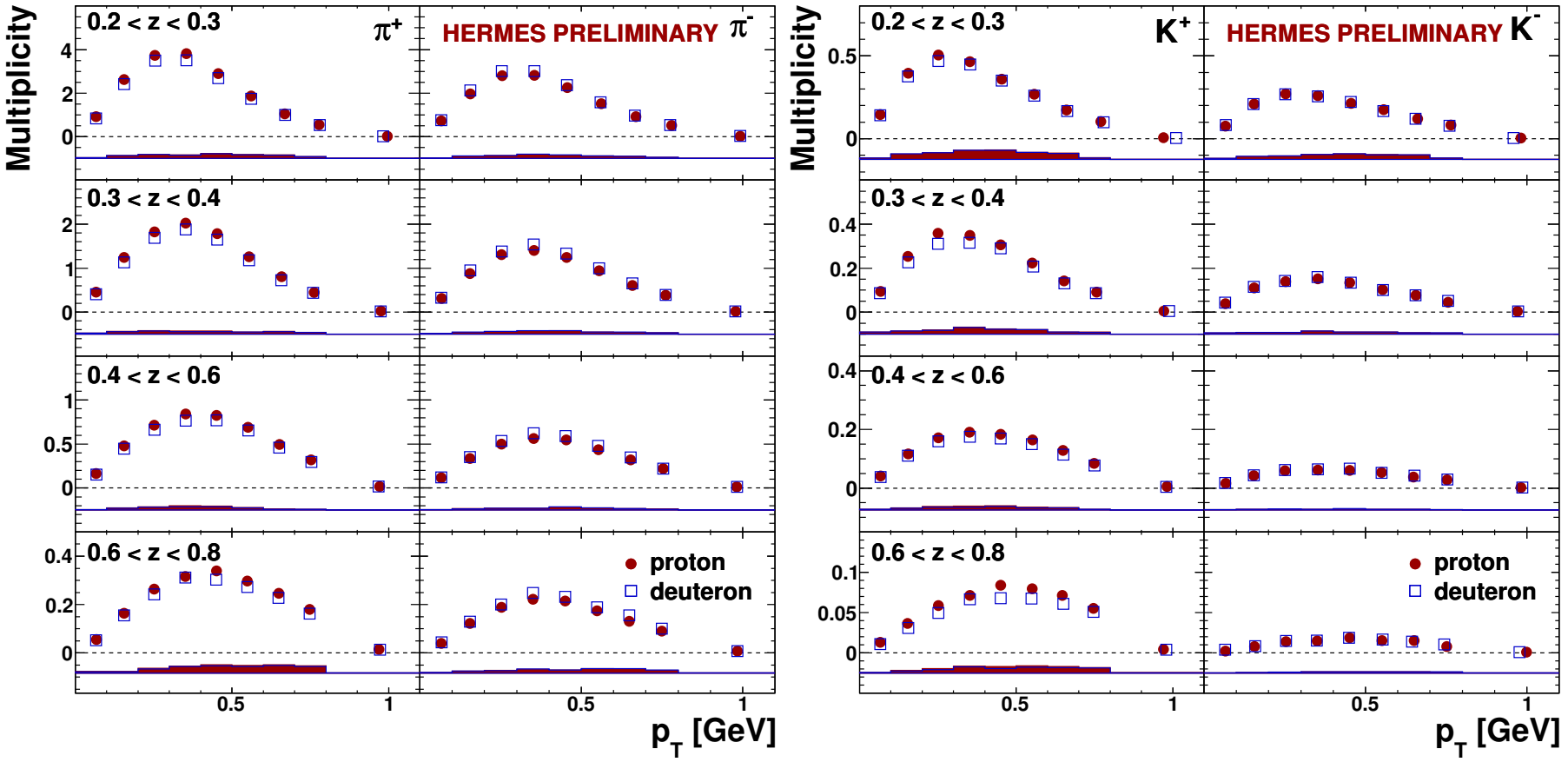
- Has the shape of a **matrix equation**
- **Smearing matrix** S is calculated using **two MC** simulations
- **Solve** for true data by simple **matrix inversion**

$$\mu_j = \sum_{i=1}^{M} S_{ji}^{-1} (\nu_i - \beta_i)$$

Results: Projections vs z



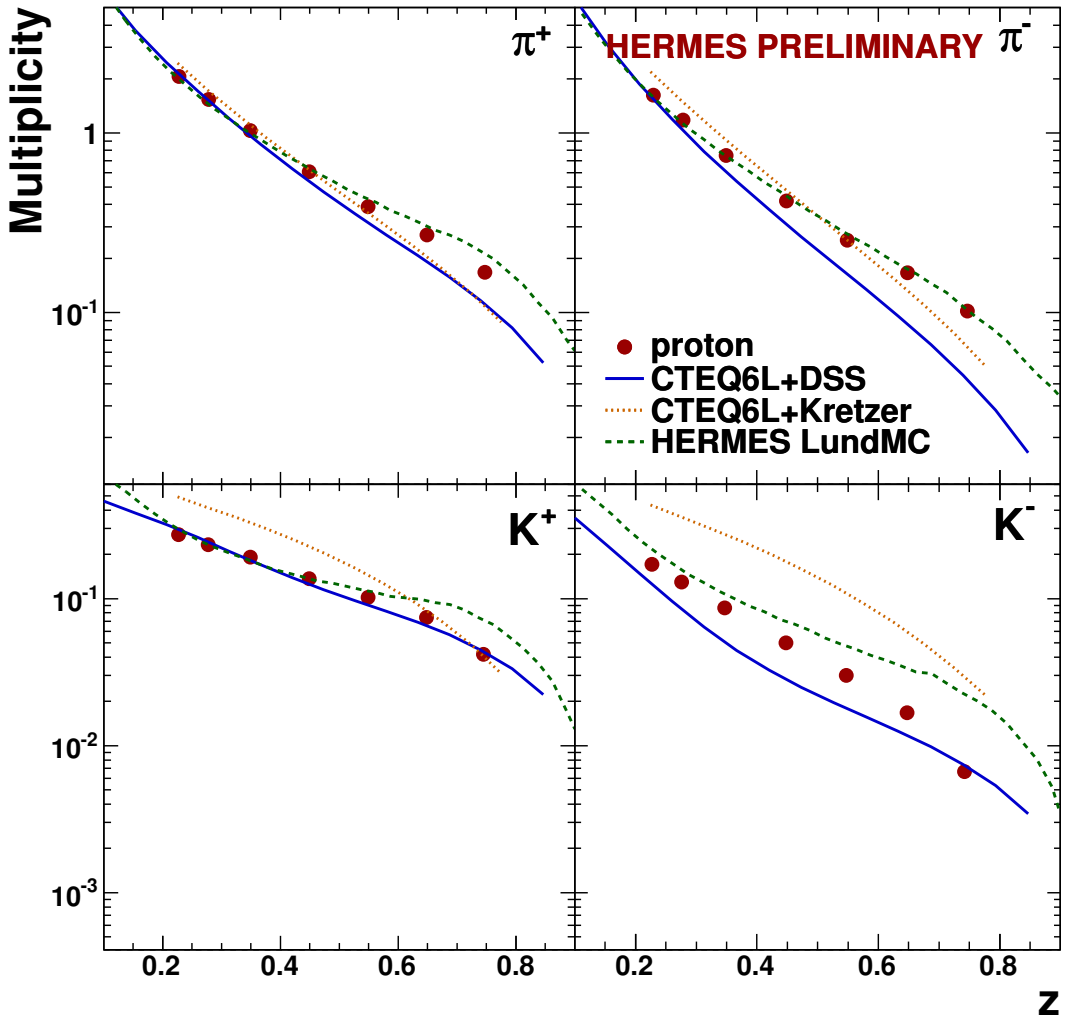
Results: Projections vs zp_T



- p_T dependence in the LO TMD formalism

$$\propto \sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta^2(\vec{p}_T - \vec{p}_\perp - z\vec{k}_\perp) f_1^q(x, Q^2, k_\perp) D_q^h(z, Q^2, p_\perp)$$

Comparison with Predictions: Projections vs z

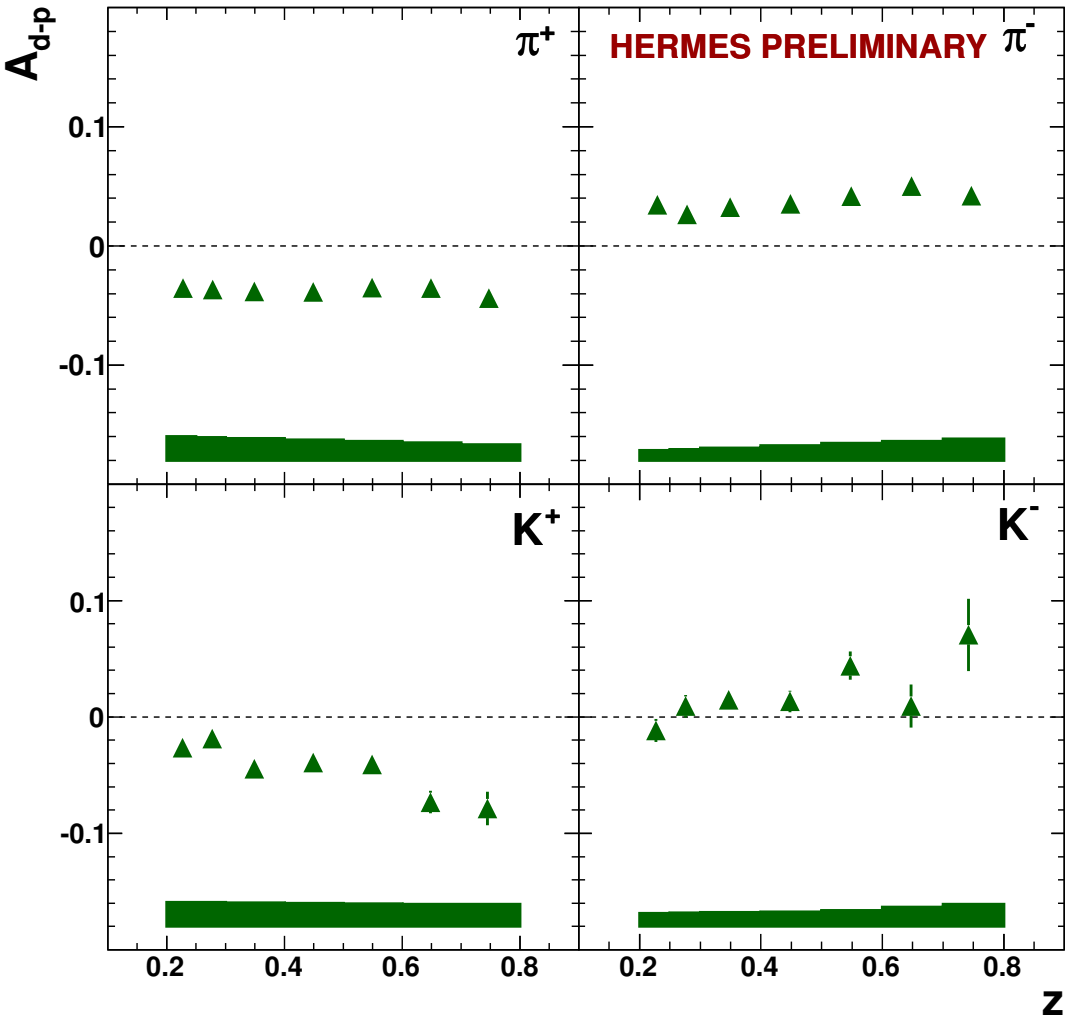


LO Interpretation

- Good agreement with CTEQ6+DSS for π^+ and K^+
- CTEQ6+Kretzer performs well for pions
- Larger deviations for π^-
- Agreement with K^- rather poor

- Model uncertainty not drawn

Proton-deuteron multiplicity asymmetry

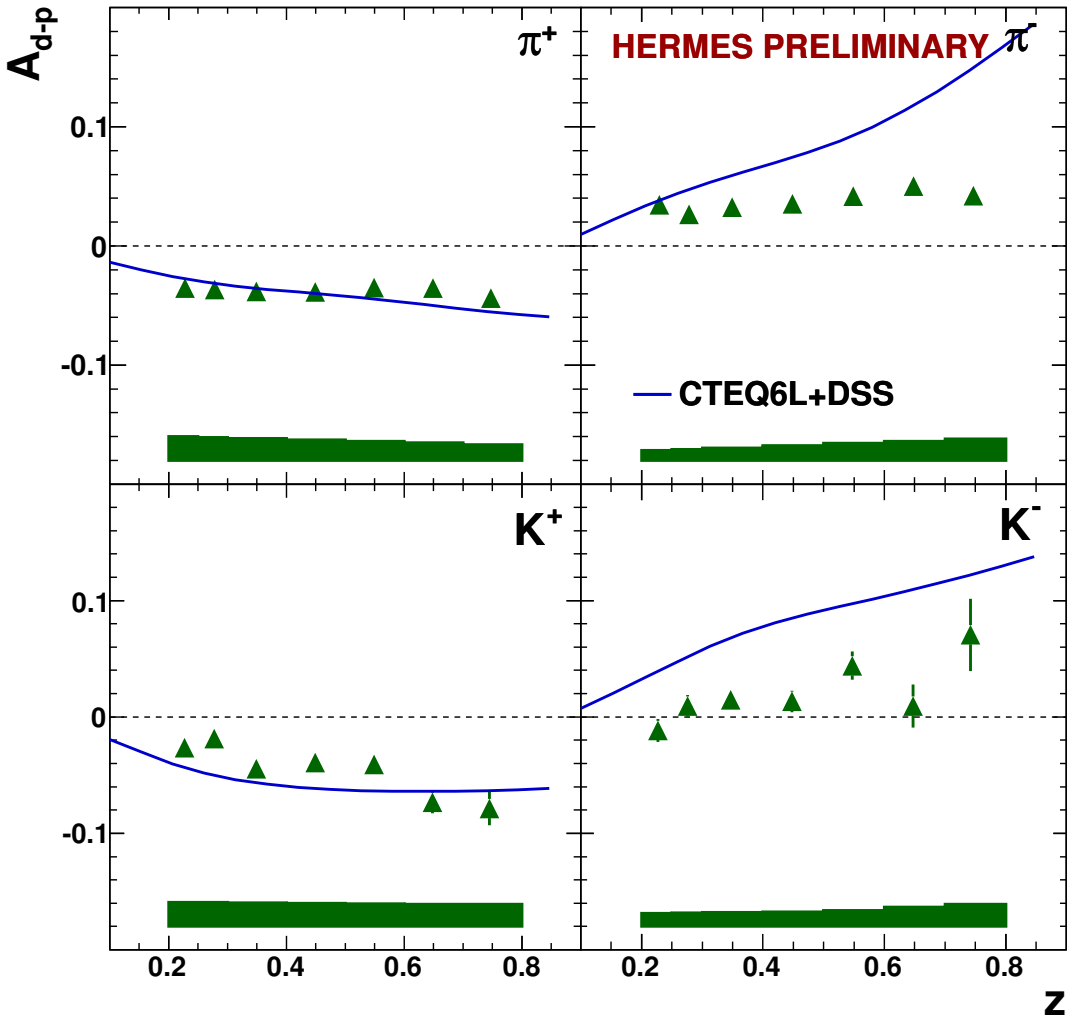


definition:

$$A^h_{d-p} \equiv \frac{M^h_d - M^h_p}{M^h_d + M^h_p}$$

- Reflects different valence quark content
- Improved precision by cancellations in the systematic uncertainty

Proton-deuteron multiplicity asymmetry



definition:

$$A^h_{d-p} \equiv \frac{M^h_d - M^h_p}{M^h_d + M^h_p}$$

LO Interpretation:

- Good agreement with LO model calculations for positive hadrons
- Bigger discrepancy for negative hadrons

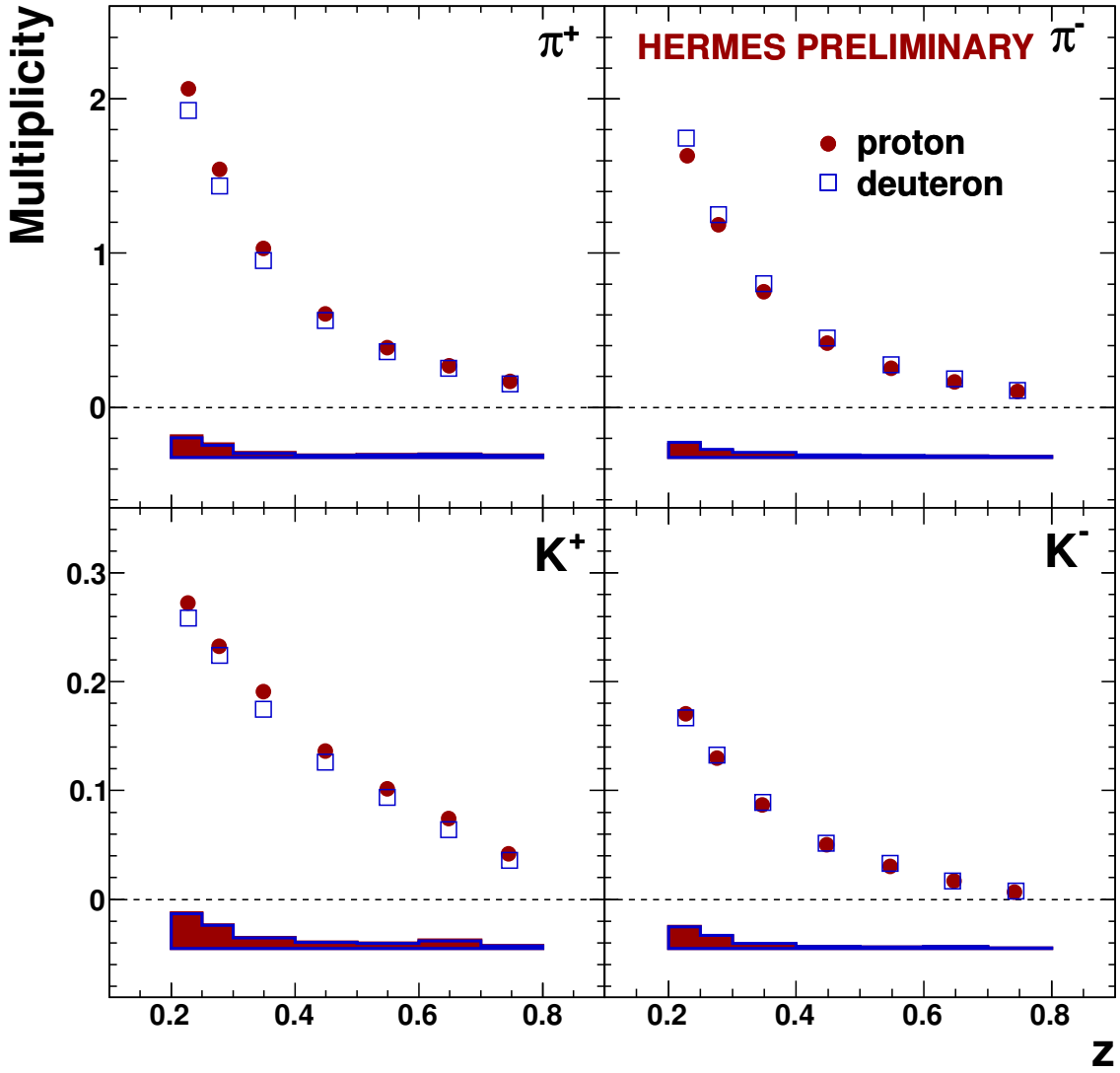
- Model uncertainty not drawn

Conclusions

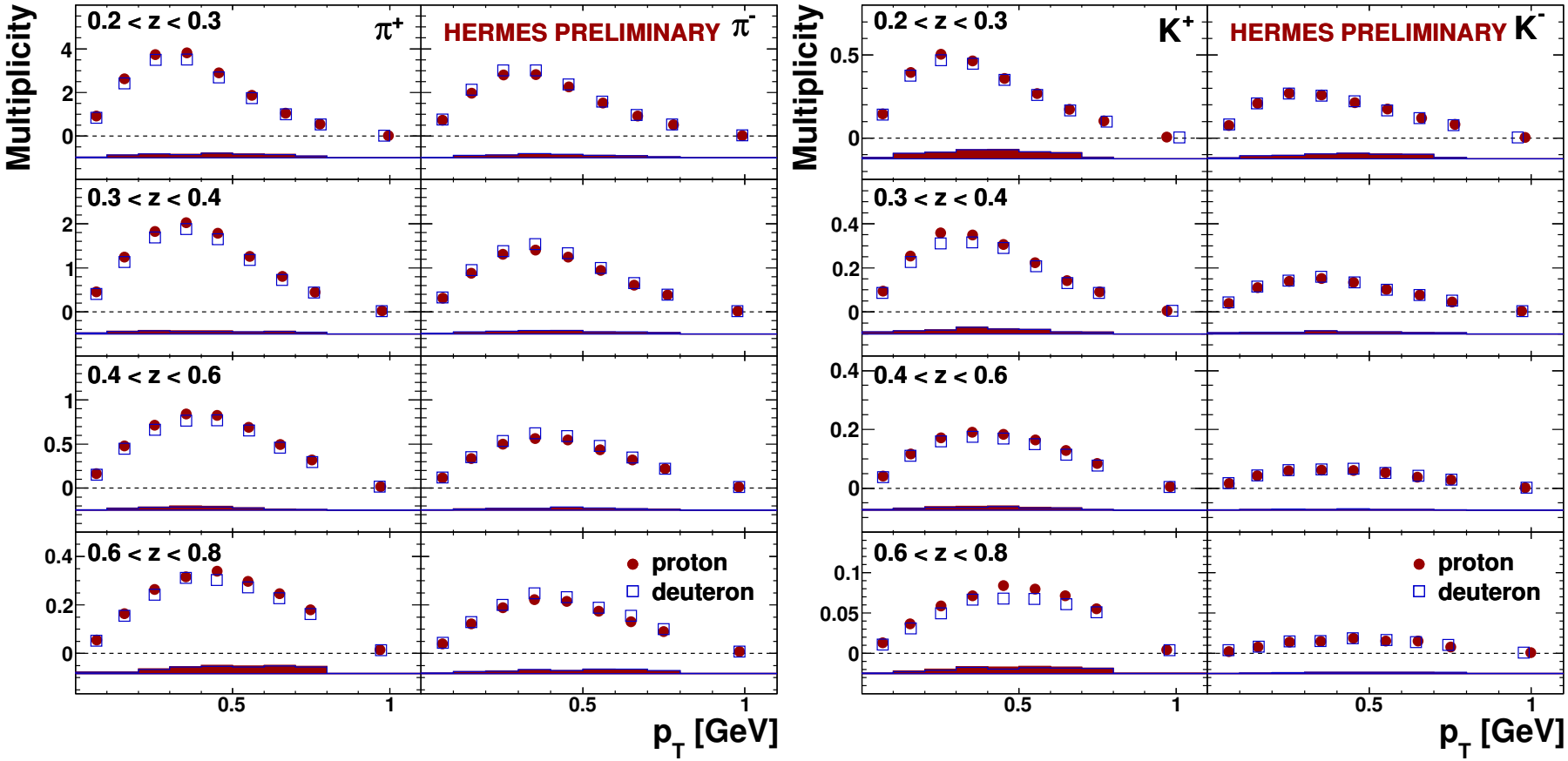
- Unique set of 3D high-precision SIDIS multiplicities for $\pi^{\pm}$ and $K^{\pm}$ on p and d are presented
- By using asymmetries and difference ratios, the precision can be improved even further due to cancellations in the systematic uncertainties
- High value for the next generation of parametrizations
- Data can significantly contribute to knowledge of the quark fragmentation process

BACK-UP SLIDES

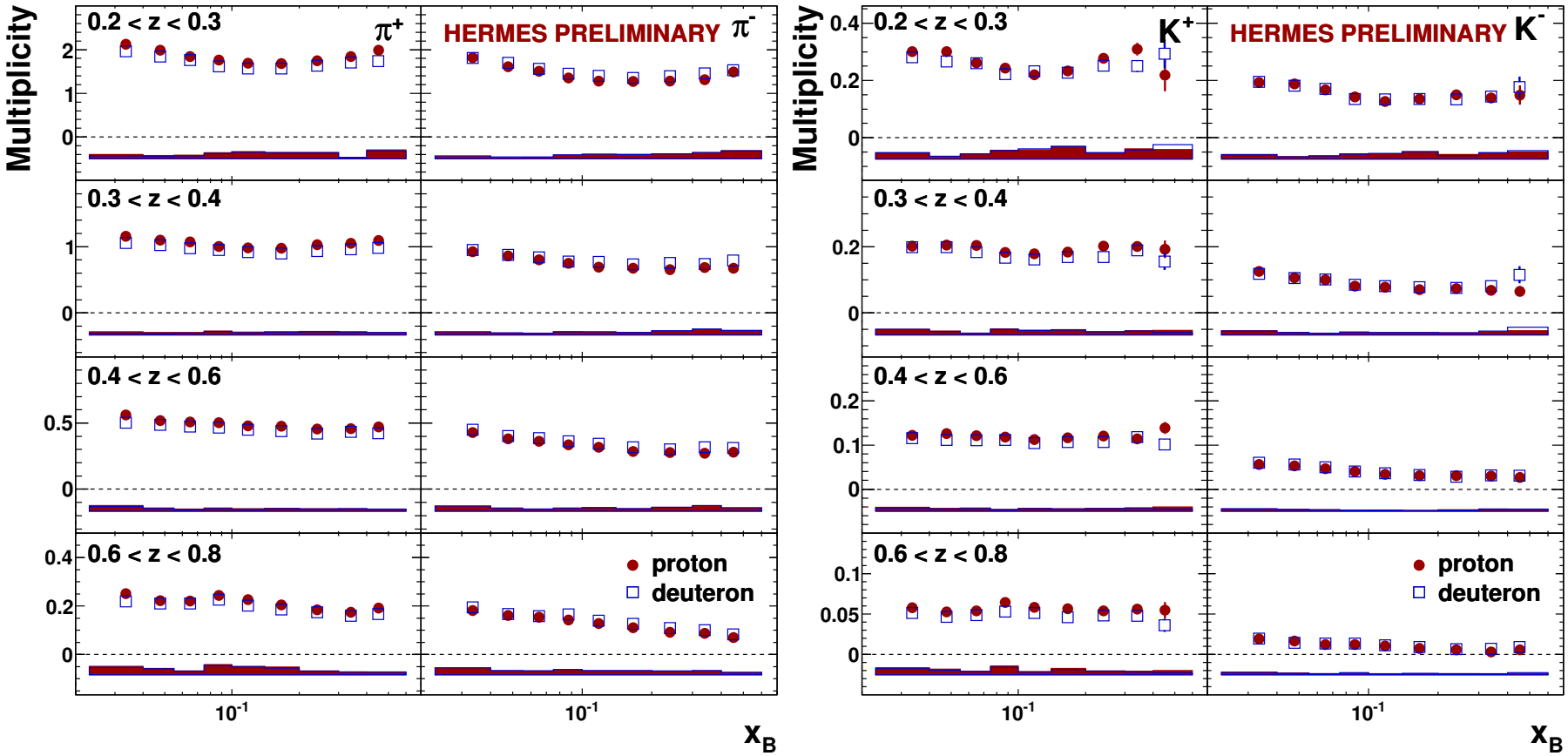
Full Results: Projections vs z



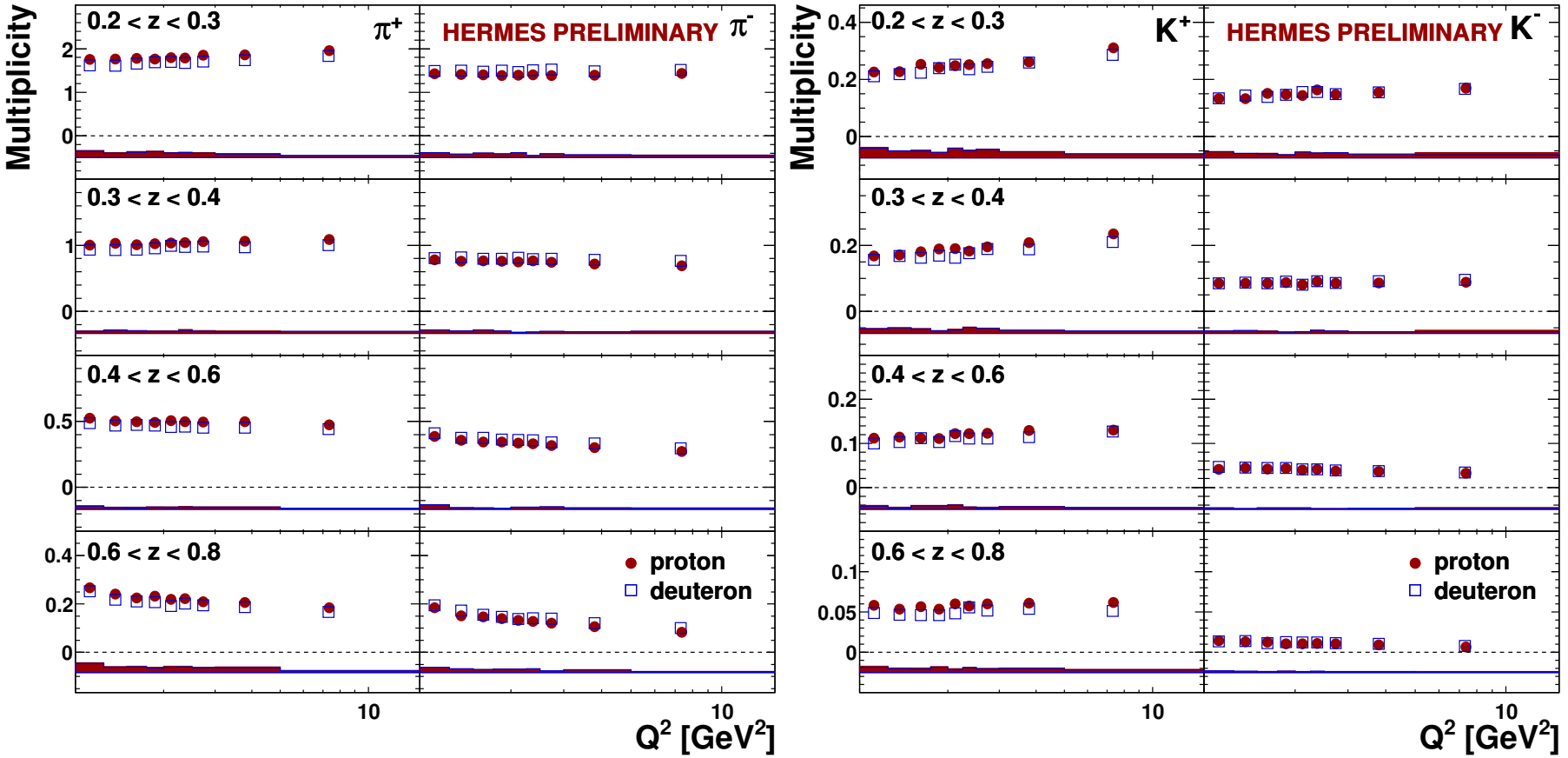
Full Results: Projections vs zp_T



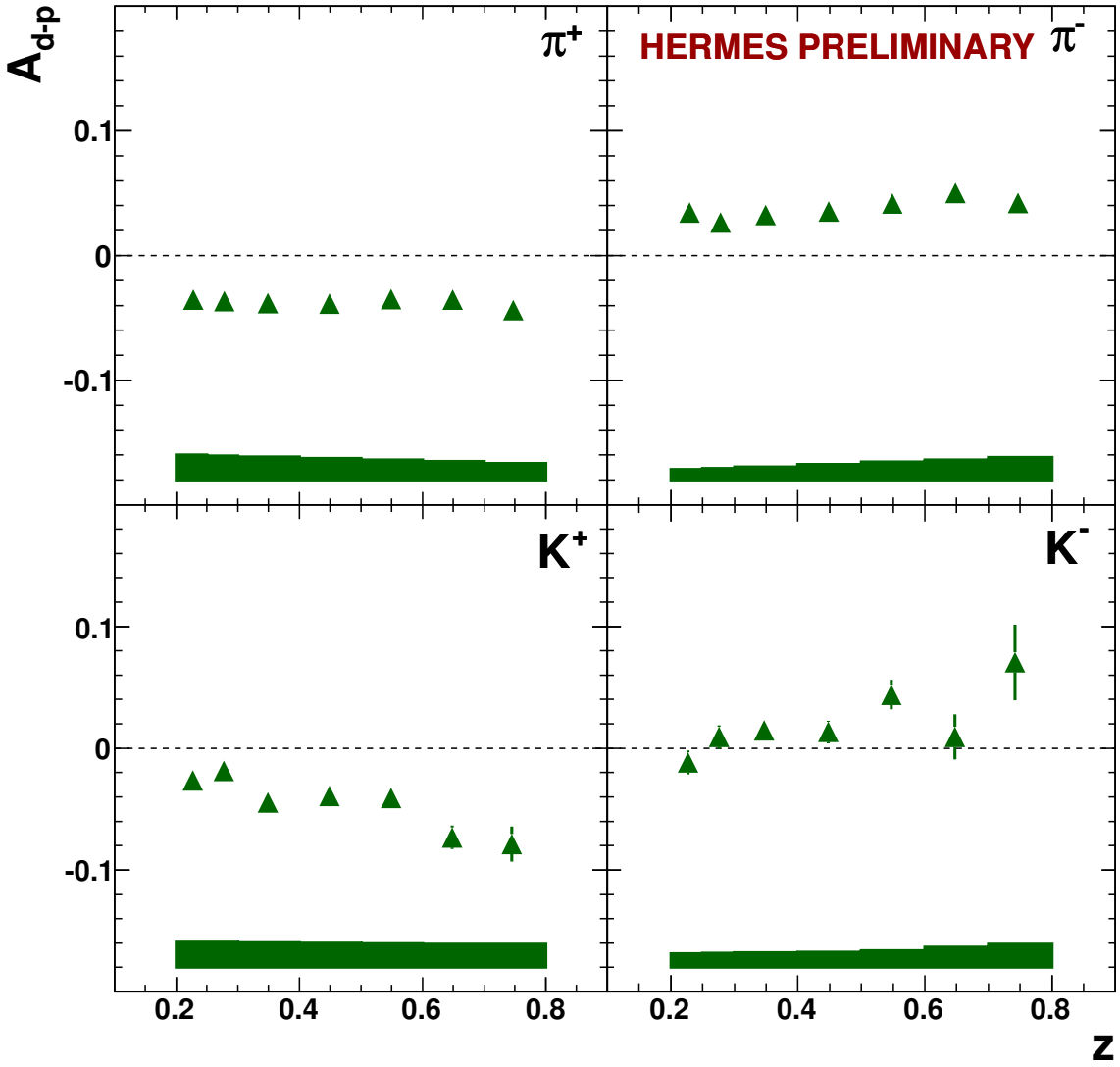
Full Results: Projections vs zx



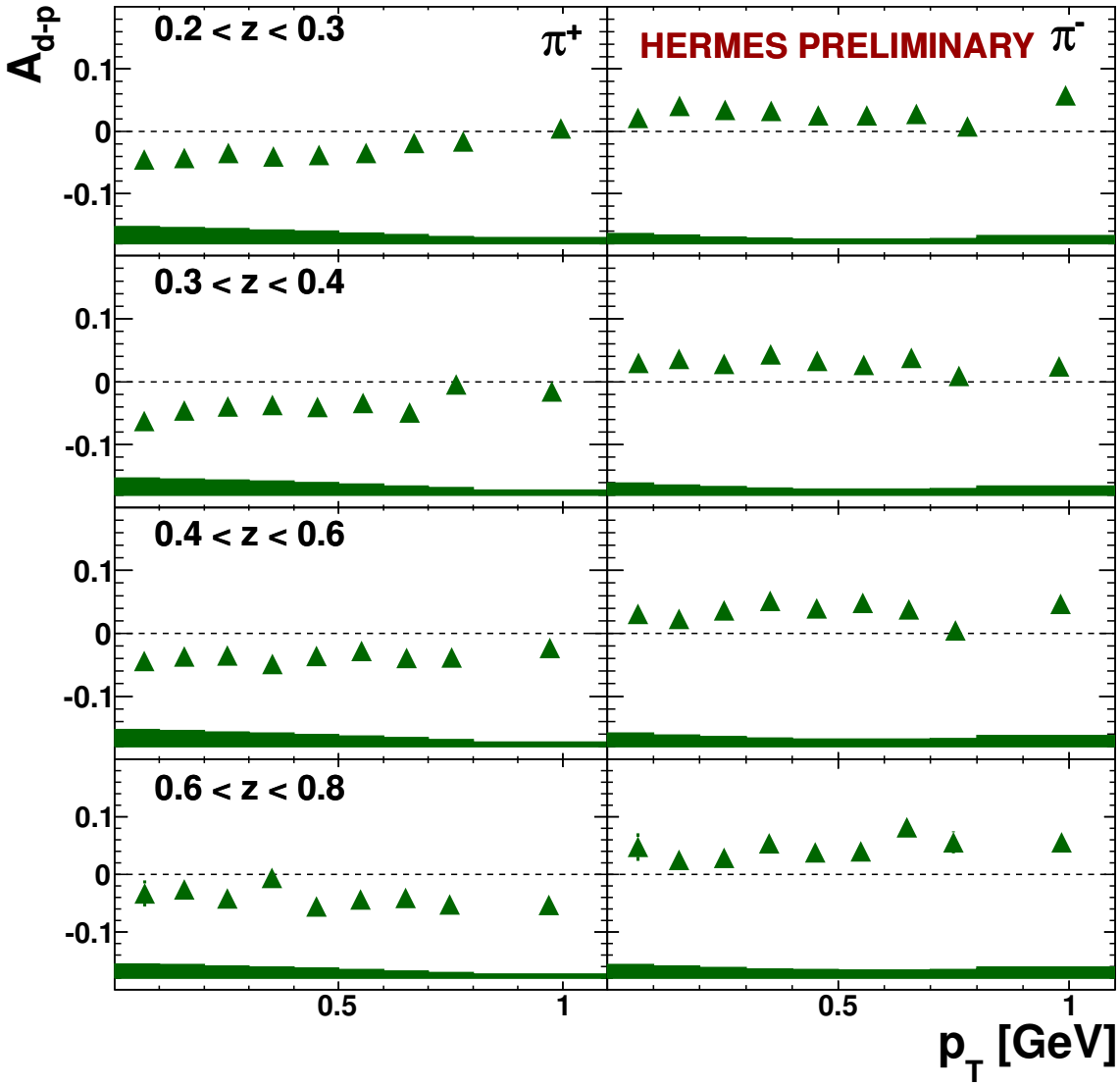
Full Results: Projections vs zQ^2



Full Results: Asymmetries vs z



Full Results: Asymmetries vs zp_T



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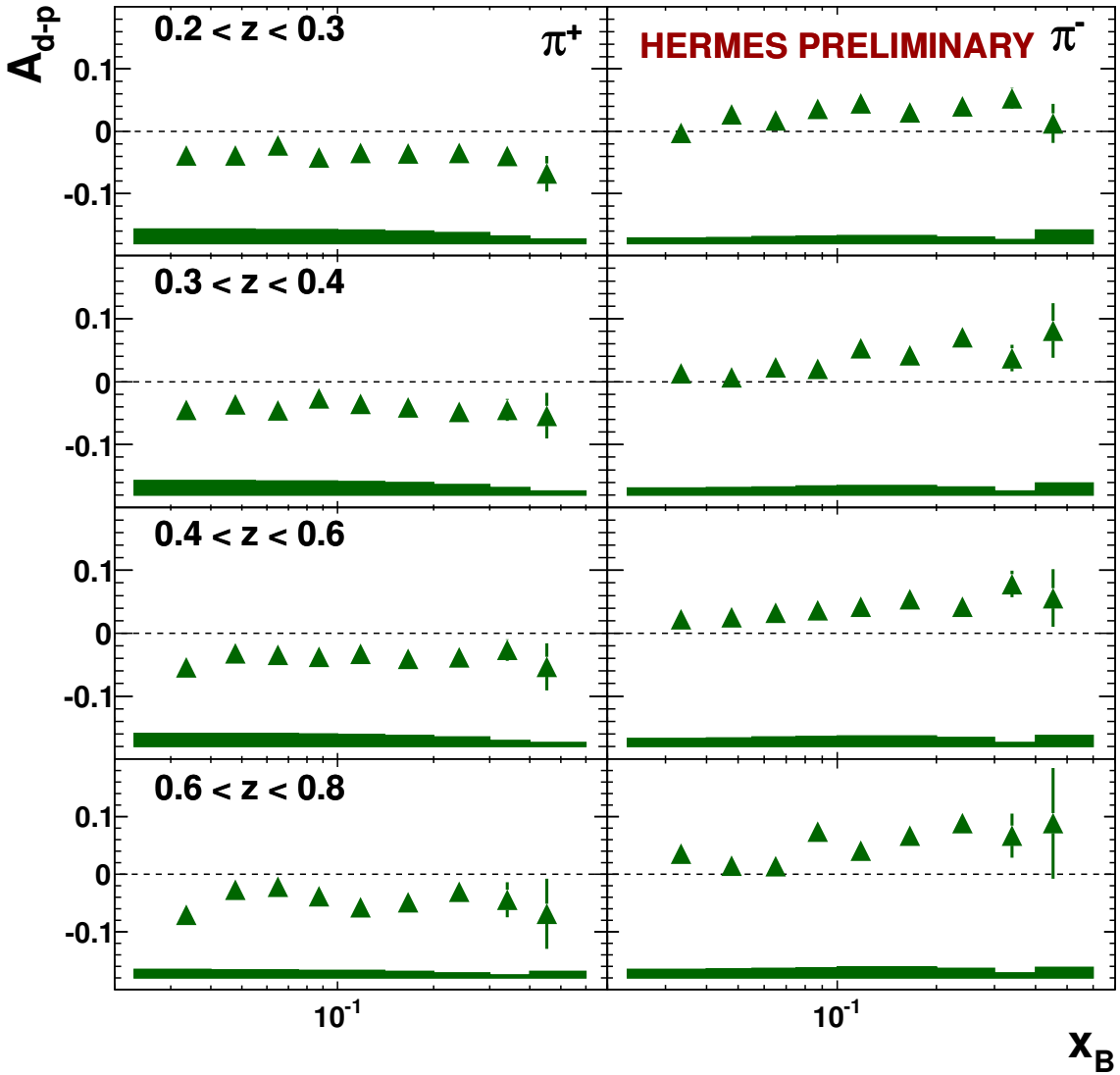

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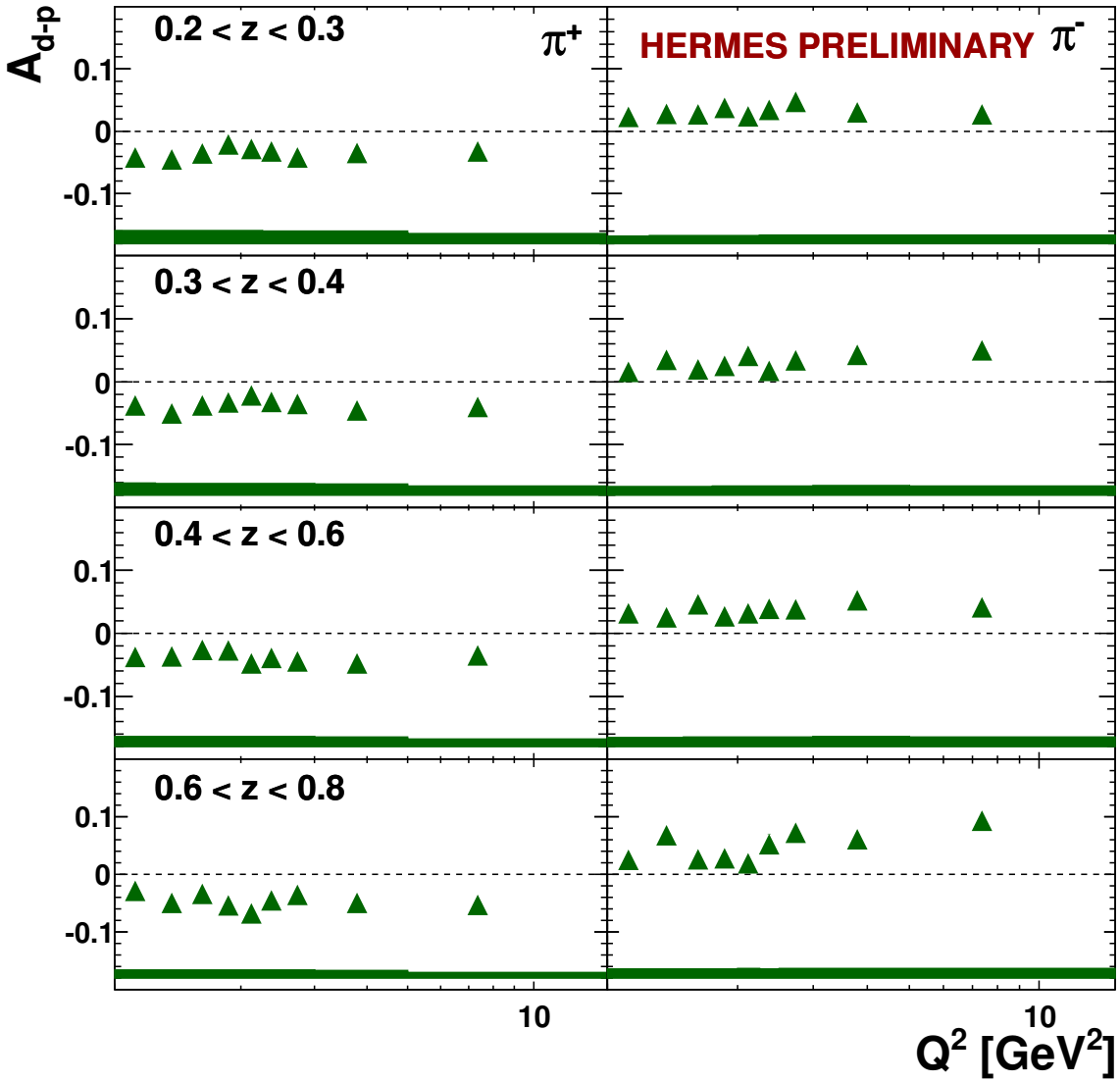
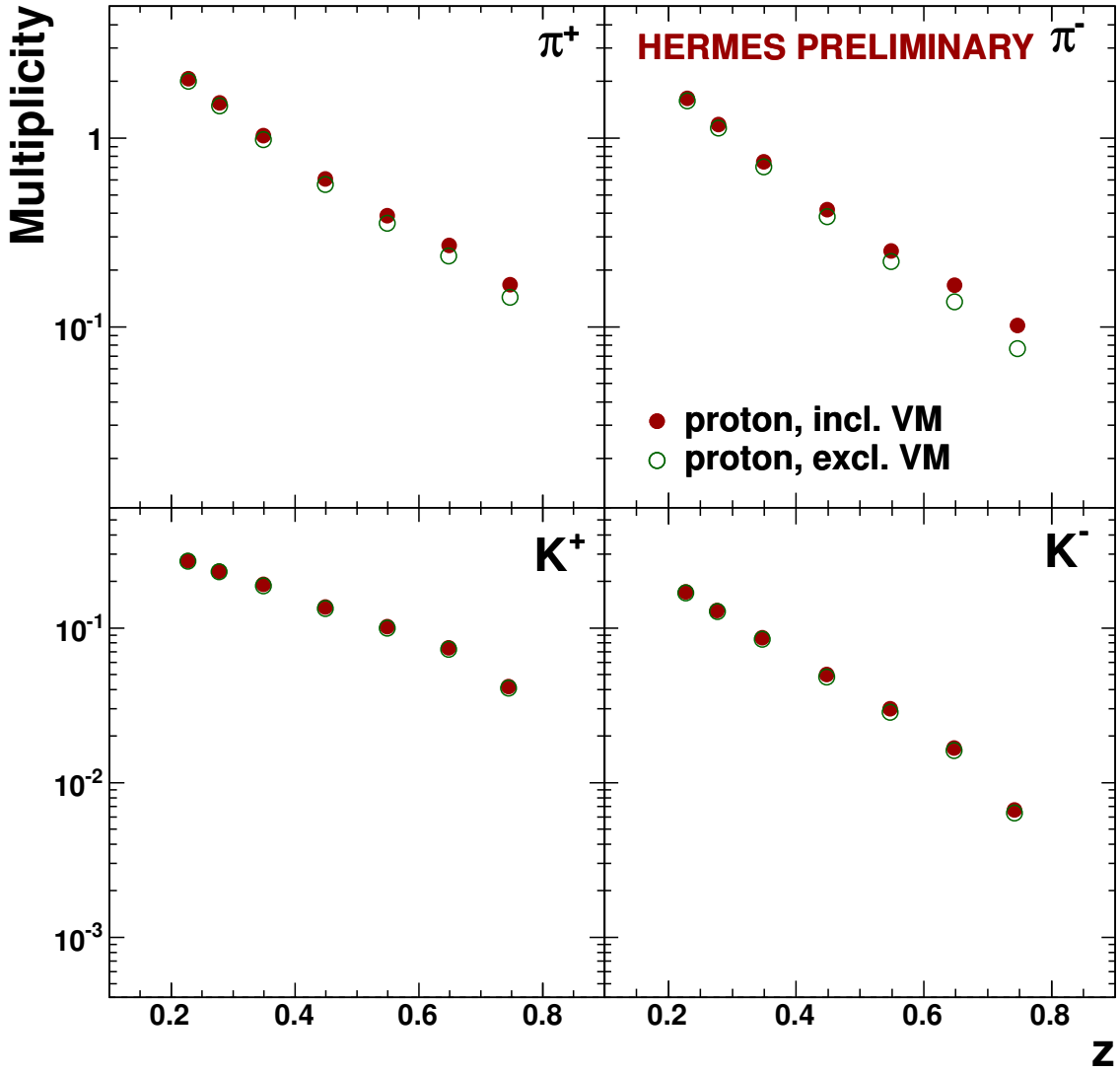


Impact of exclusive VM fractions



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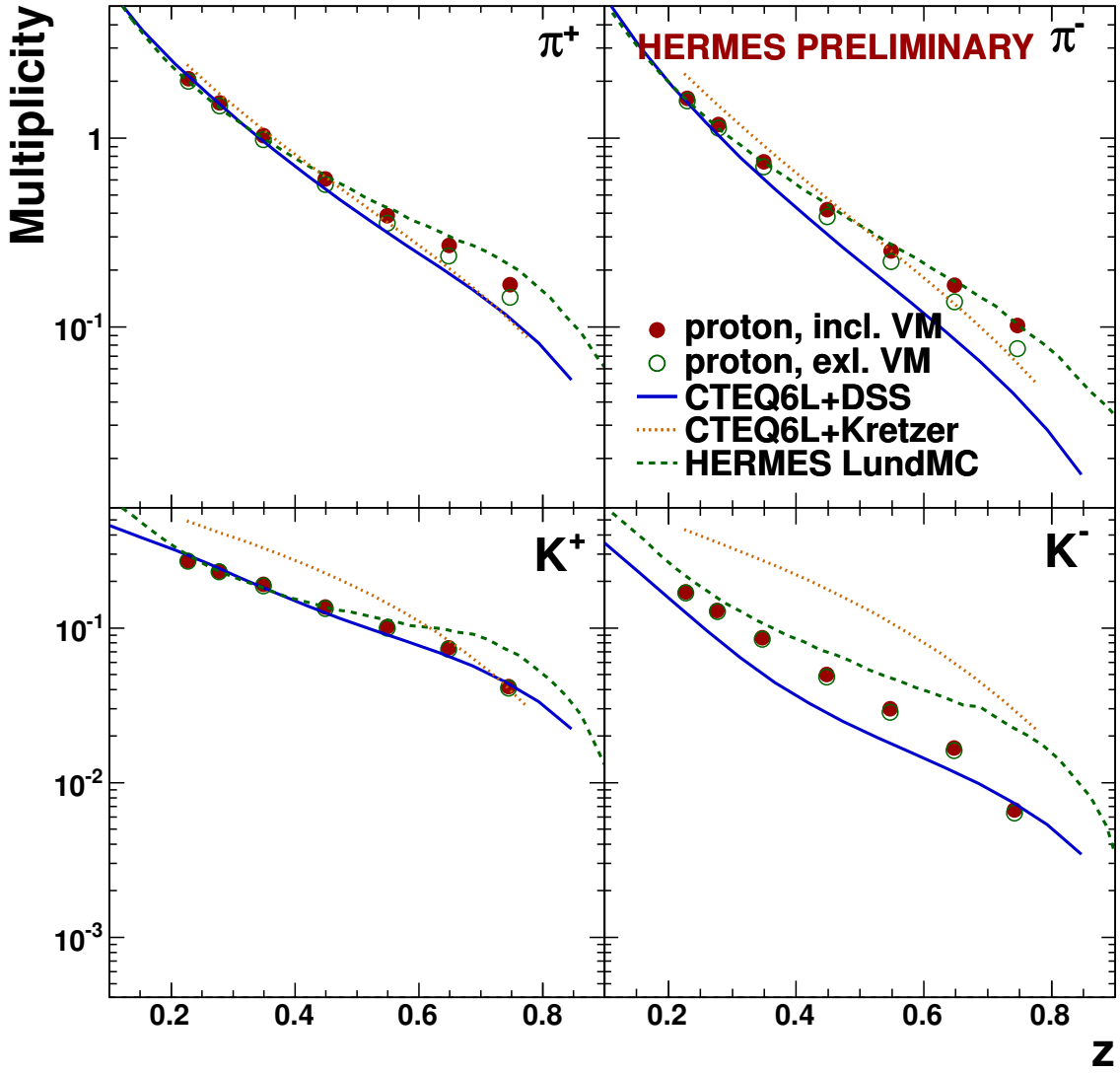
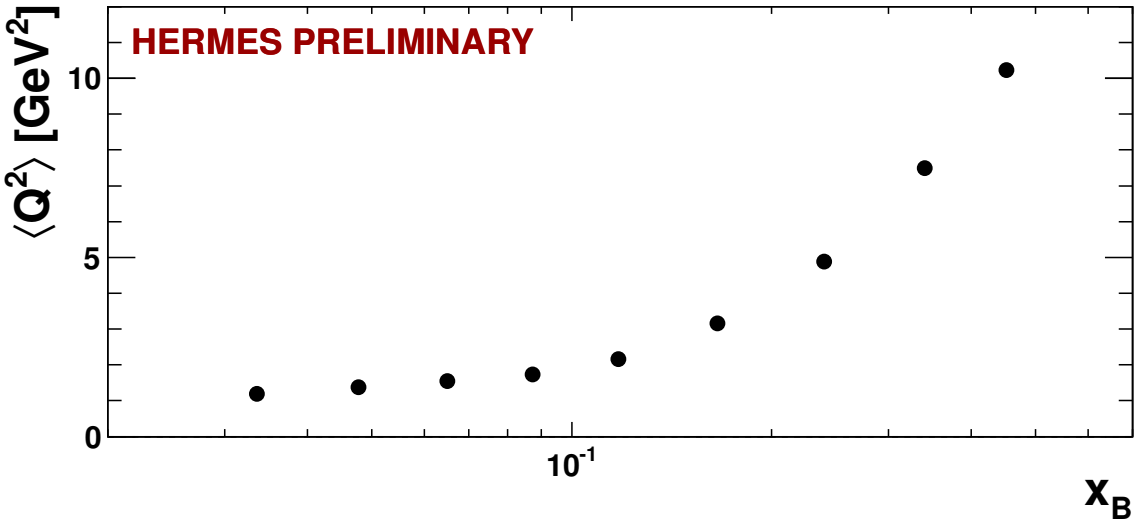
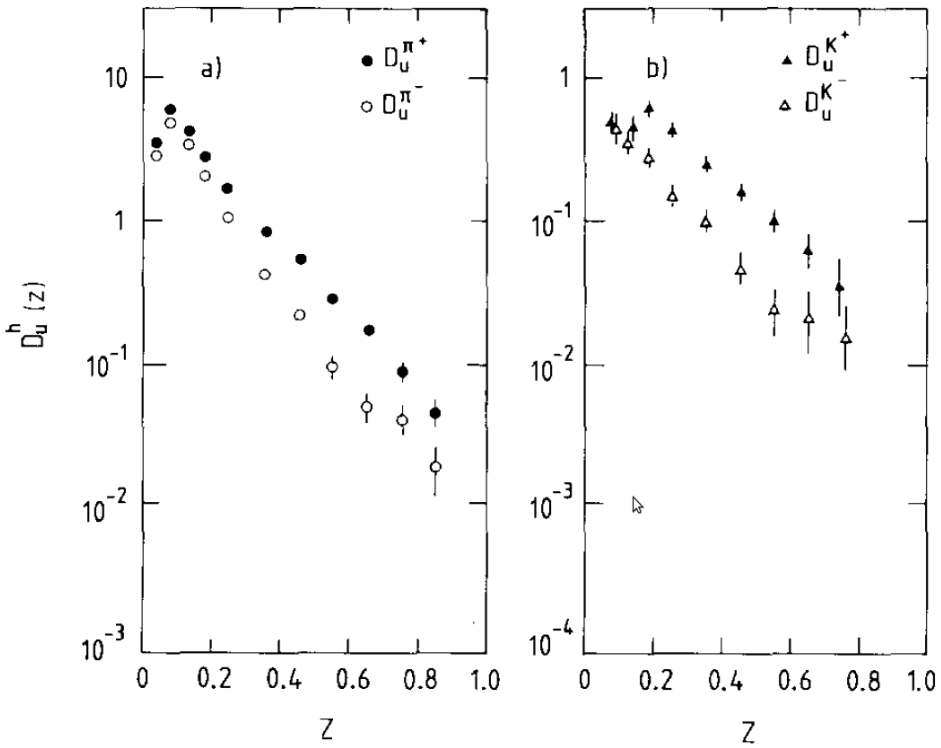


Average Q^2 as a function of x

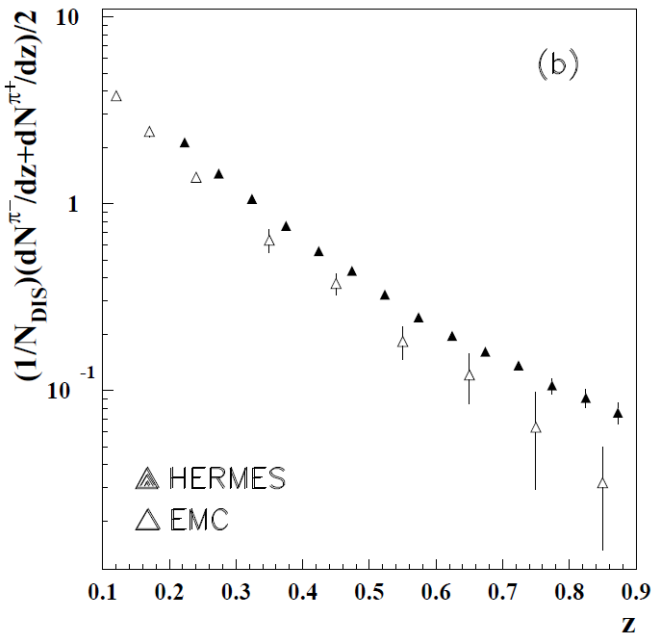


SIDIS Multiplicities: Historical



EMC FFs

Nucl.Phys. B321 (1989) 541



HERMES multiplicities

1996-97 data

Eur.Phys.J. C21 (2001) 599-606