High-precision SIDIS at intermediate energies: Exploring the limits of precocious scaling at HERMES and beyond.

http://www-hermes.desy.de/multiplicities

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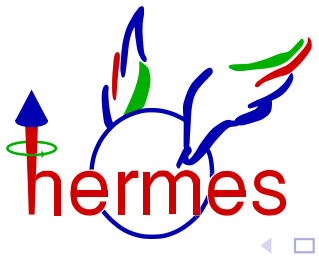
University of Illinois at Urbana-Champaign

April 23, 2013
Temple University, Department of Physics



Section 1

About factorization and precocious scaling

What happens in a High Energy Collision?

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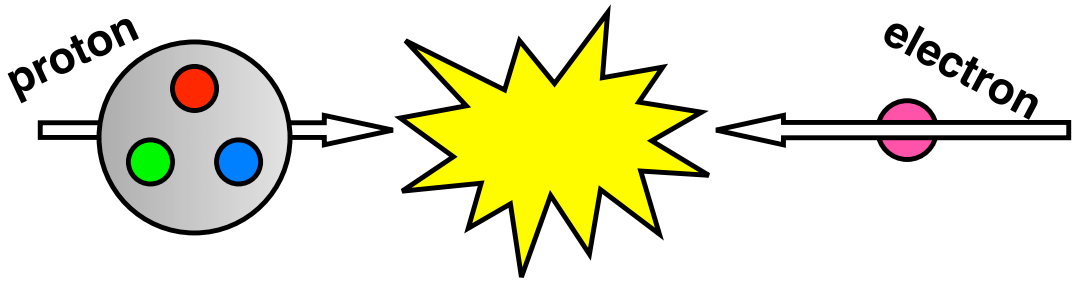

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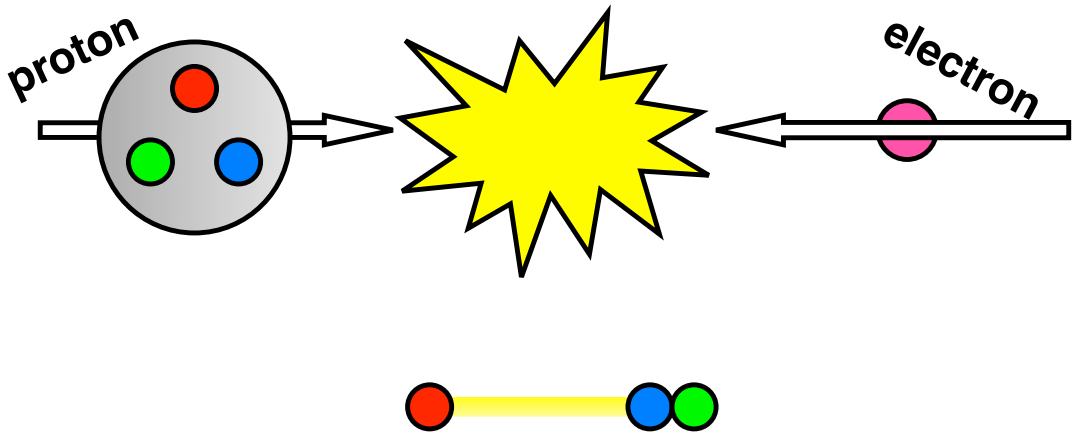

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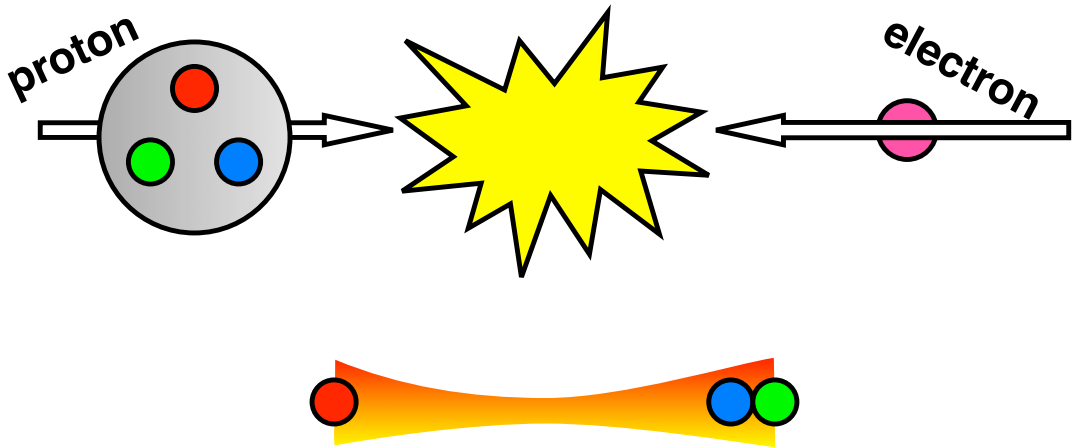

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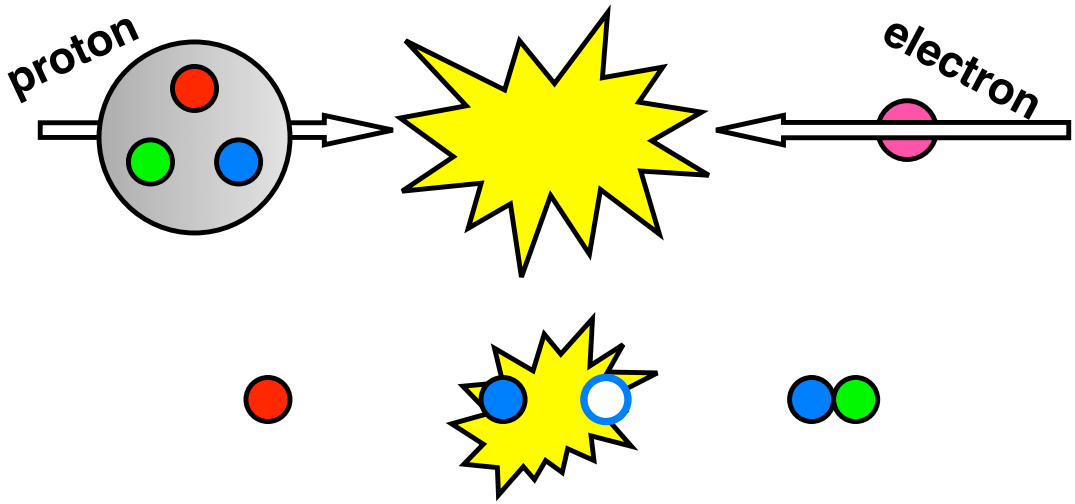

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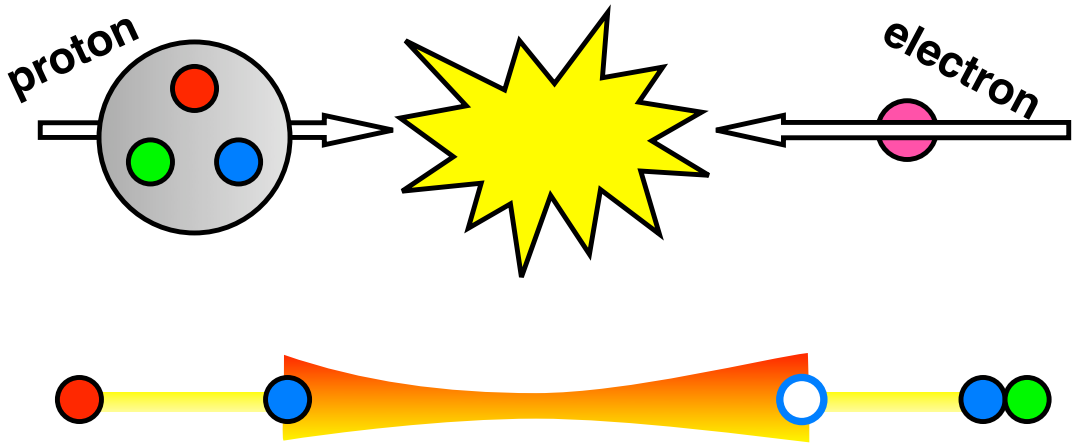

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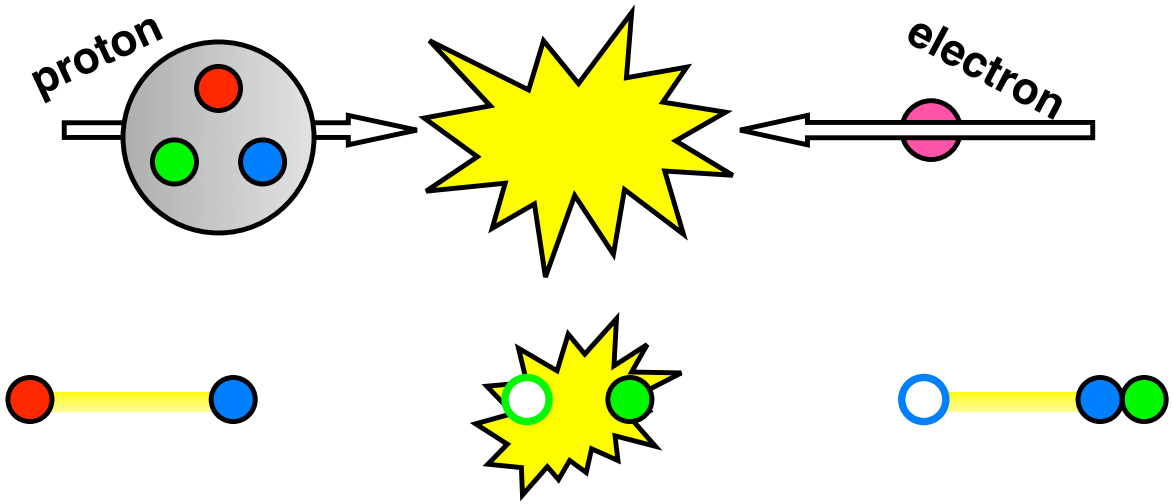

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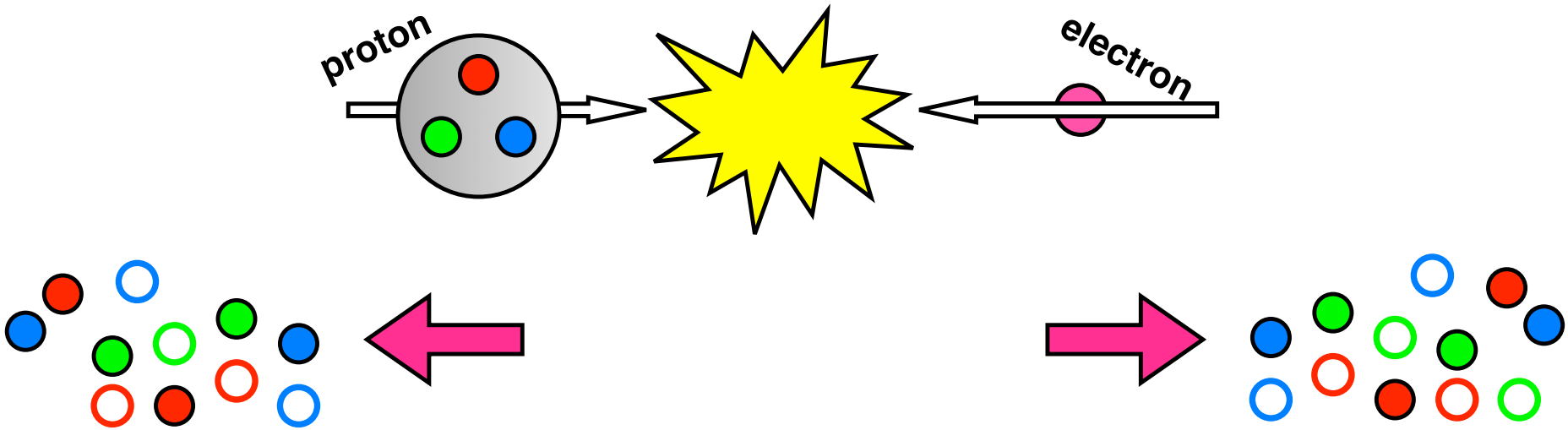

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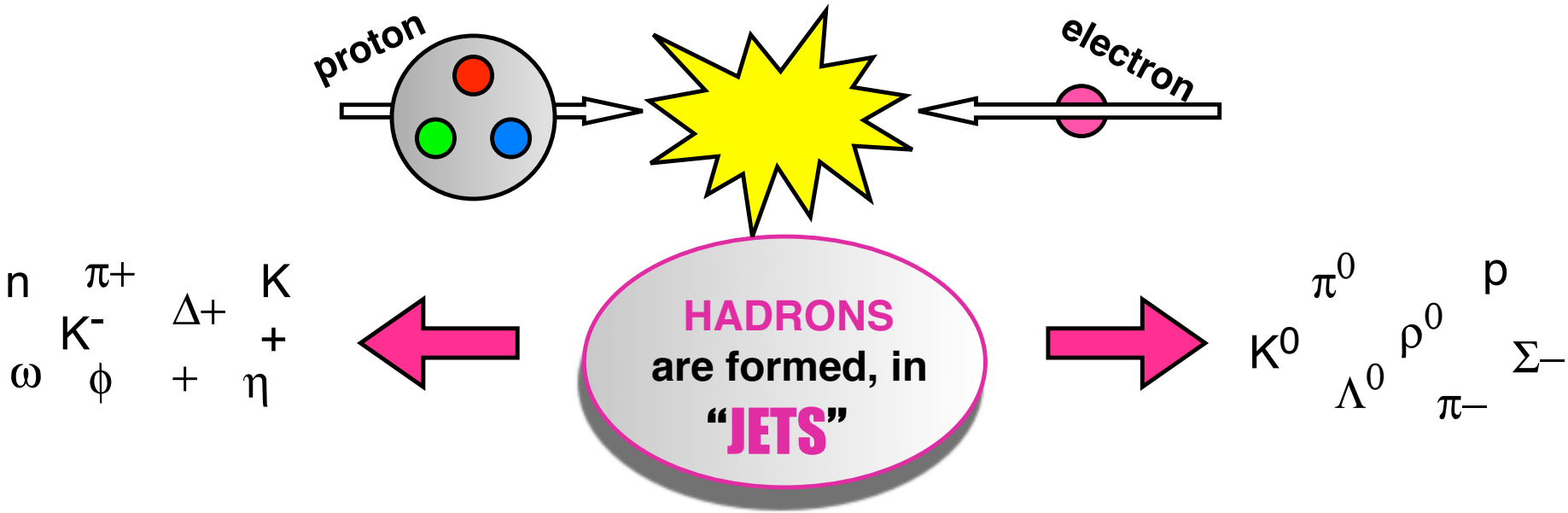

Confinement at Work!

Creation of hadrons from the struck quark: **the fragmentation process**

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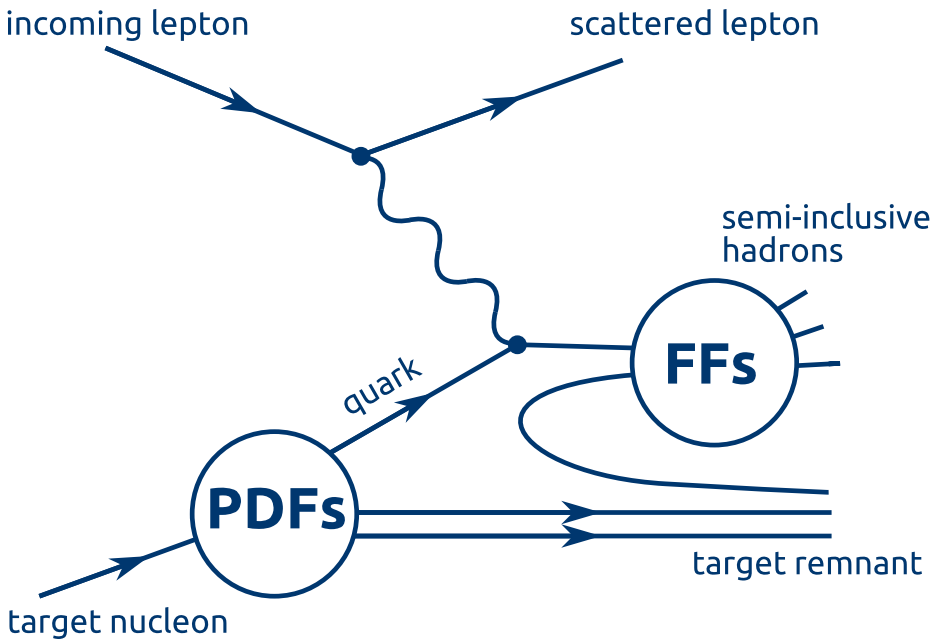
- A **hadron** h is detected **in coincidence** with the **scattered lepton**:



Factorization of the cross section

$$d\sigma^h \propto \Sigma_q e_q^2 \, \mathbf{f_1^q(x)} \otimes \hat{\sigma} \otimes \mathbf{D_q^h(z)}$$

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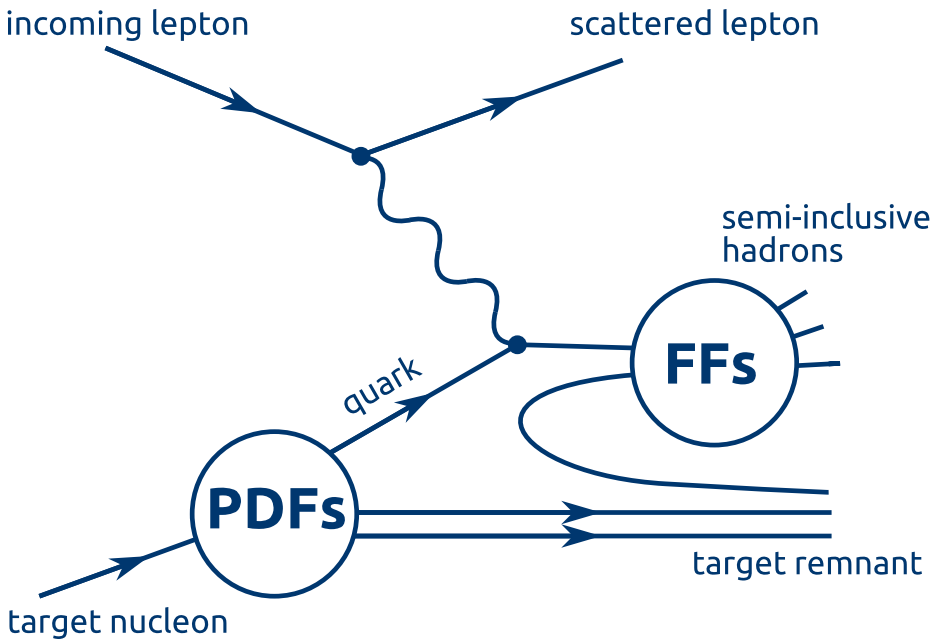

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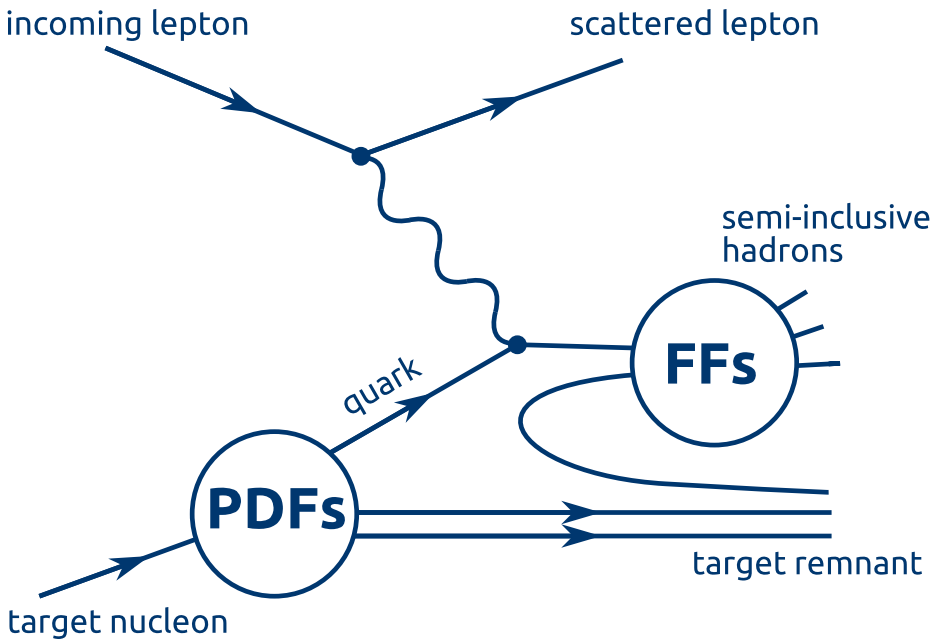

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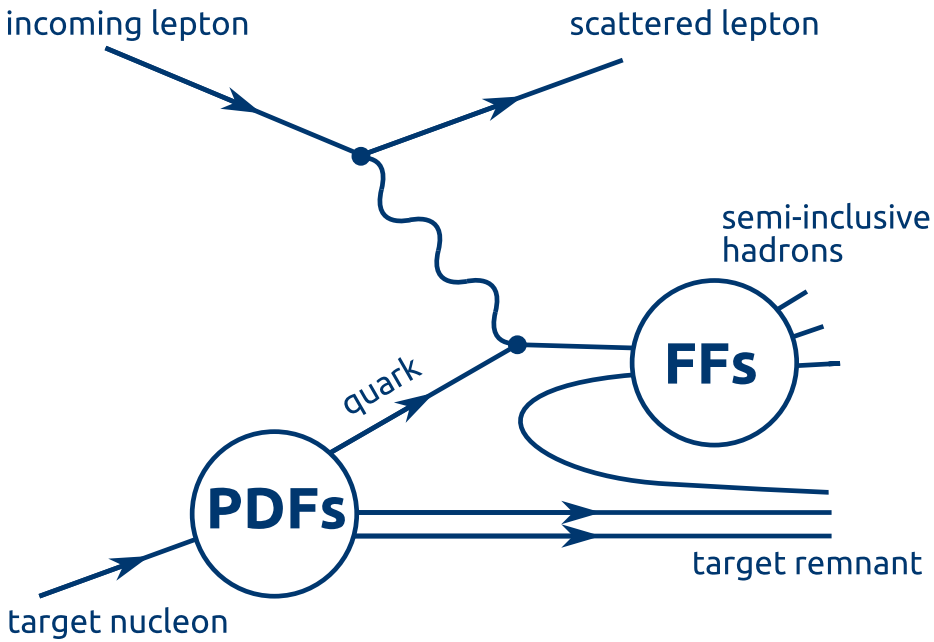

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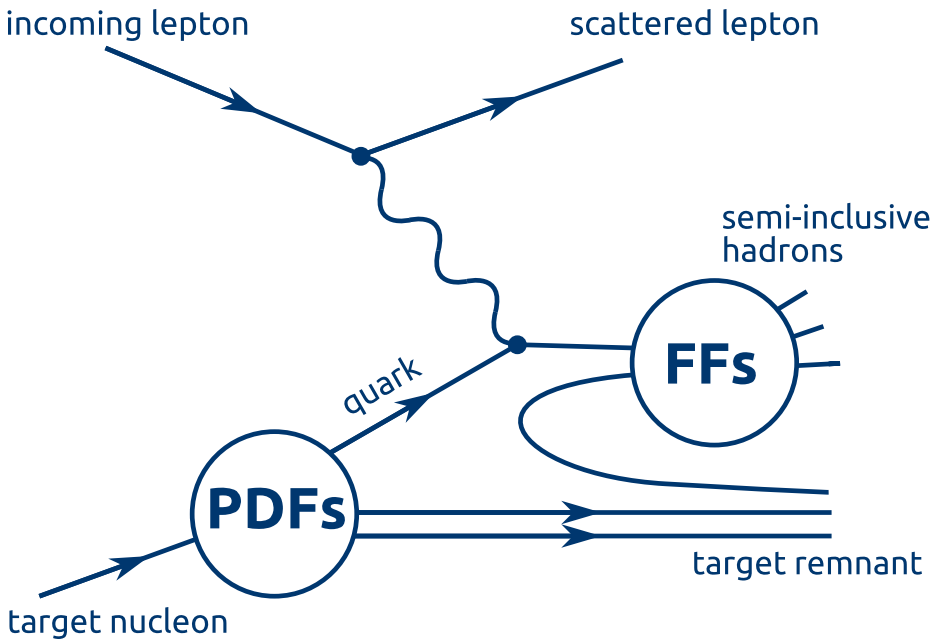

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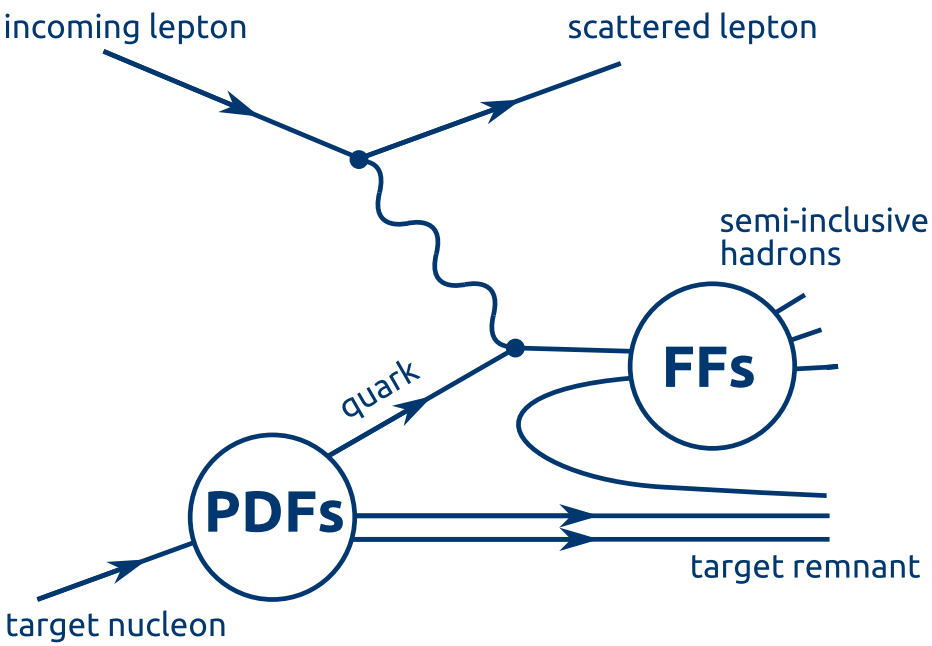
← **Universal!** →

Scaling, evolution and factorization scale



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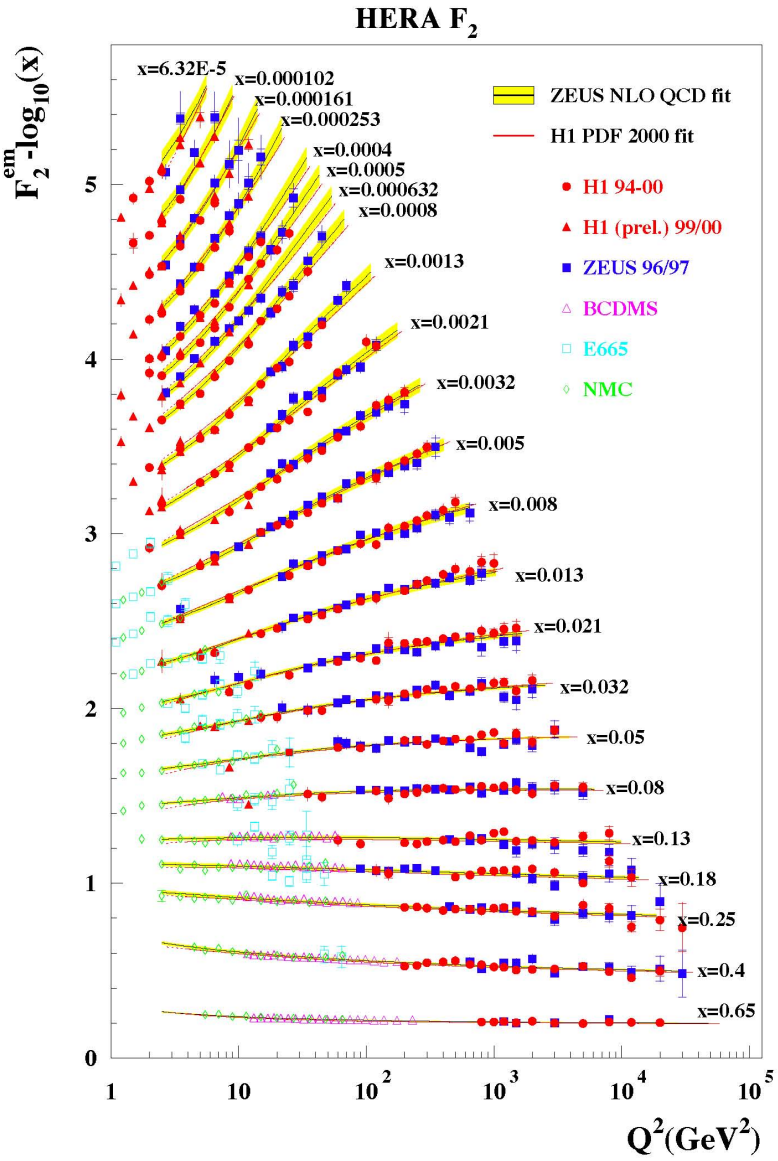

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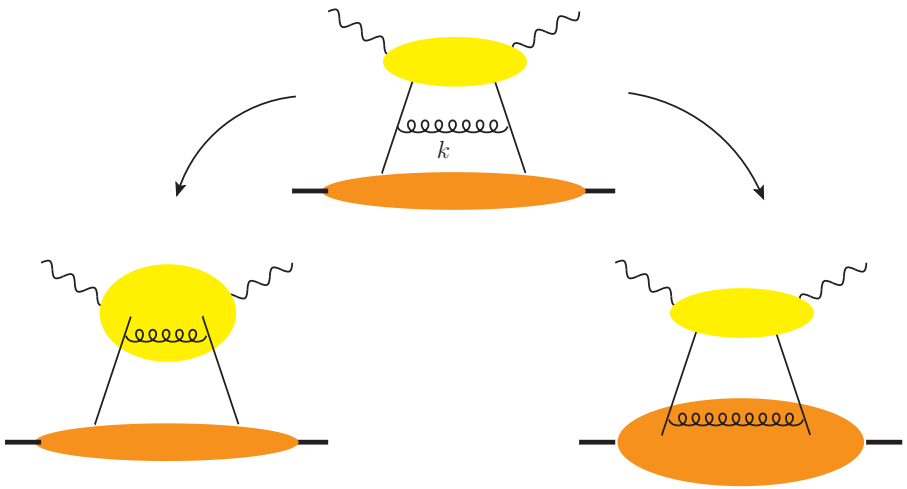

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- **BUT: Scaling violation!**
- **QCD evolution:**
  - PDFs depend on **factorization scale** $\mu \sim Q$
  - μ separates structure from dynamics
  - **Observables independent of** $\mu \rightarrow$ evolution equations for PDFs (DGLAP)

Limits of factorization: QCD

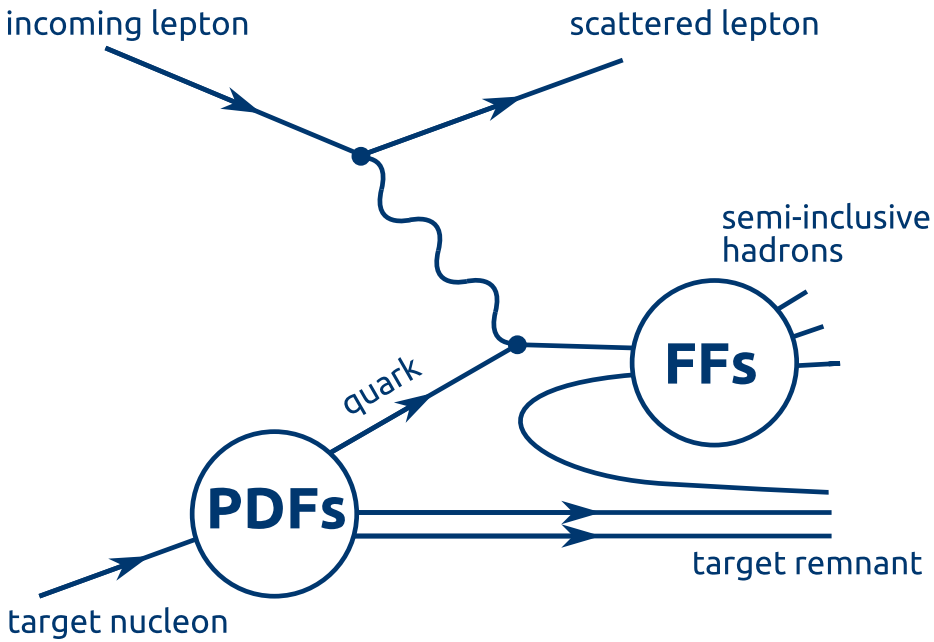
Complications arise when the hard scale Q is not really hard (towards $Q \sim M$)

- Mass effects
- Higher order terms in α_s become larger
- Initial- and final-state interactions start to play a larger role
- Higher twist terms in become larger
- ...

- Only **break factorization if not properly taken into account**
- **Simple interpretation** through intuitive QPM-like LO factoriziation **not possible anymore**

Limits of factorization: SIDIS

- **Clear separation of current and target** "jet" seems to be needed...



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- $\mathbf{D_q^h}$ **only depends on the struck quark.**
  - Independent of target and process
  - Only depends on fractional hadron momentum $z = P_h/\nu$.

Limits of factorization: SIDIS

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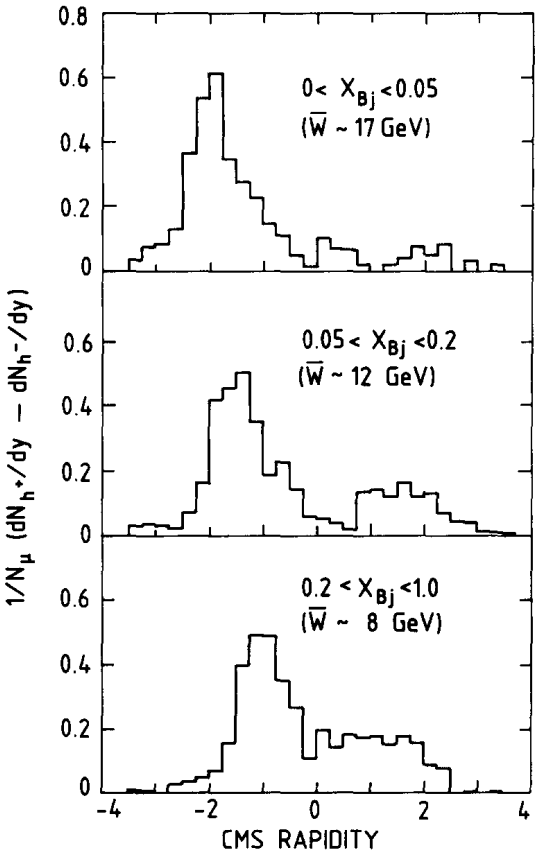
EMC, PR162 (1988)



- Jet **FWHM: 2 units of rapidity** y.

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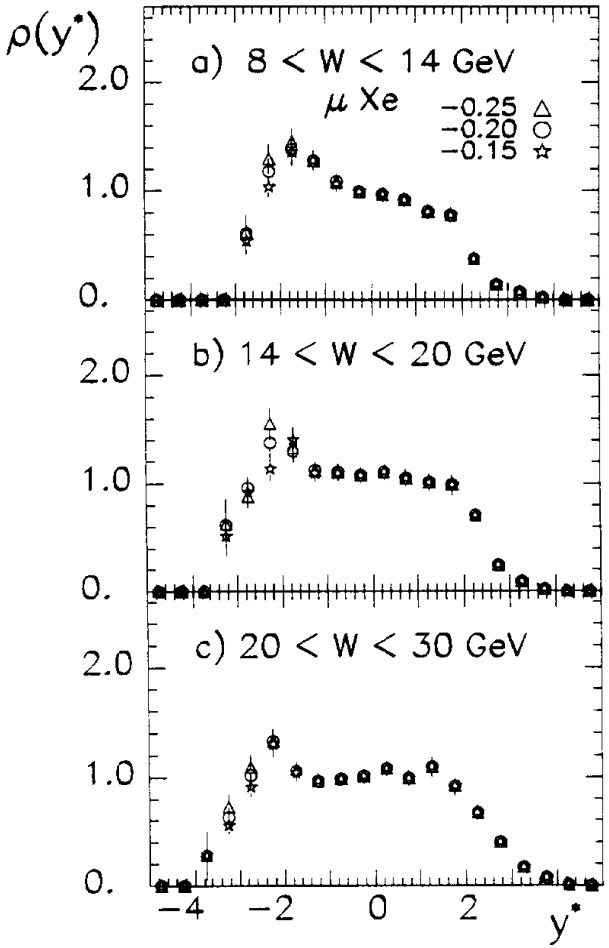
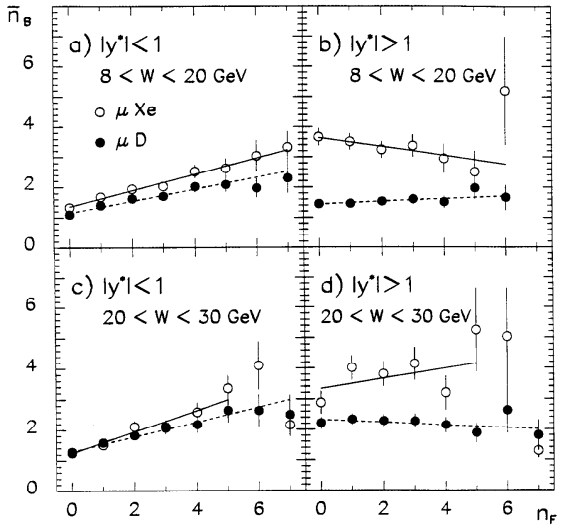
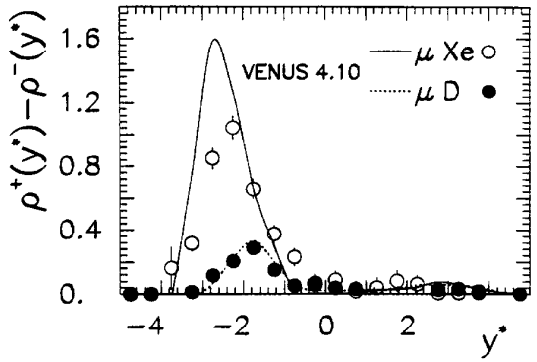
E665, ZPC (1993)



- Jet **FWHM: 2 units of rapidity** y.
- **Lower rapidity limit** required to fully disentangle the forward and backward hemisphere.





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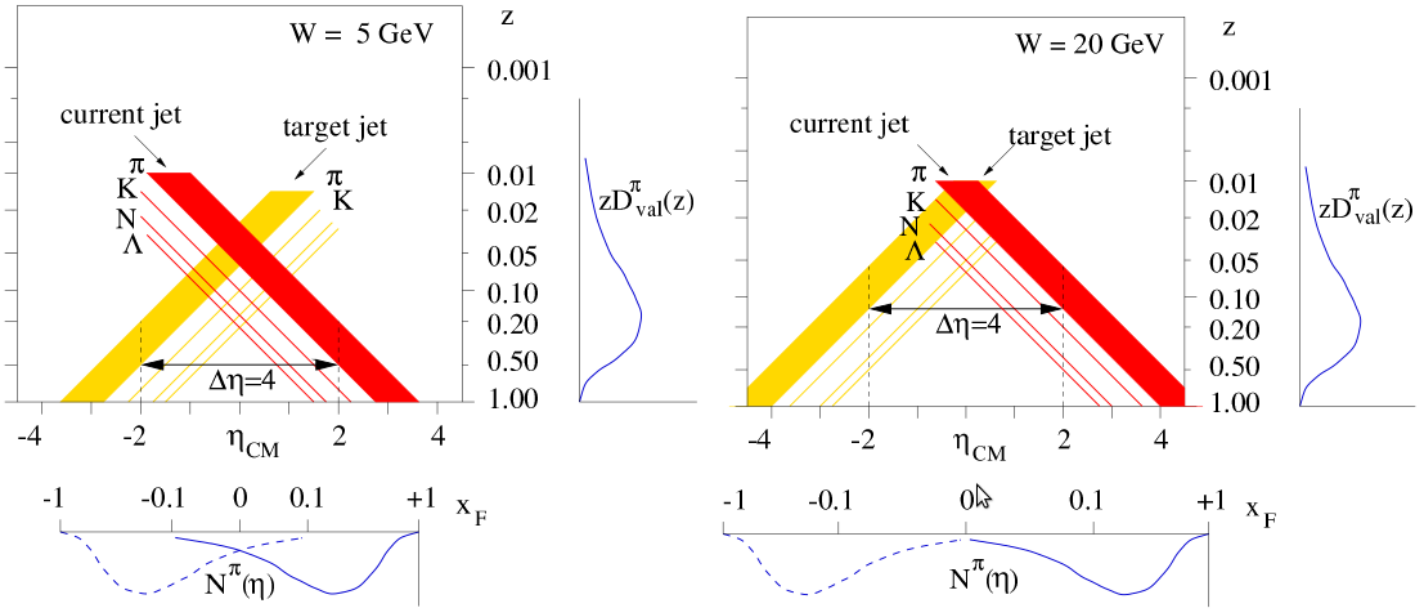
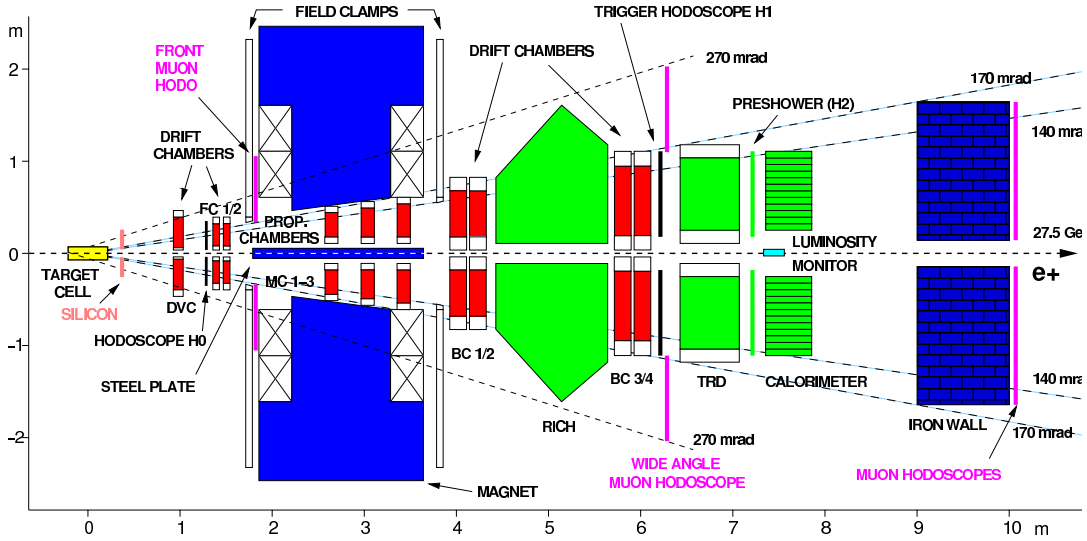
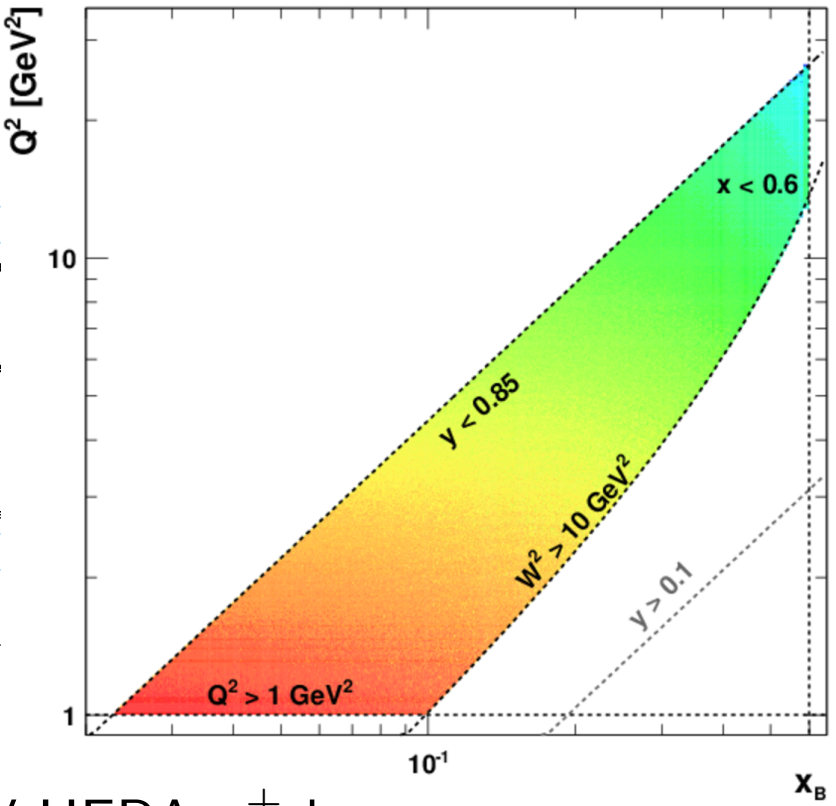


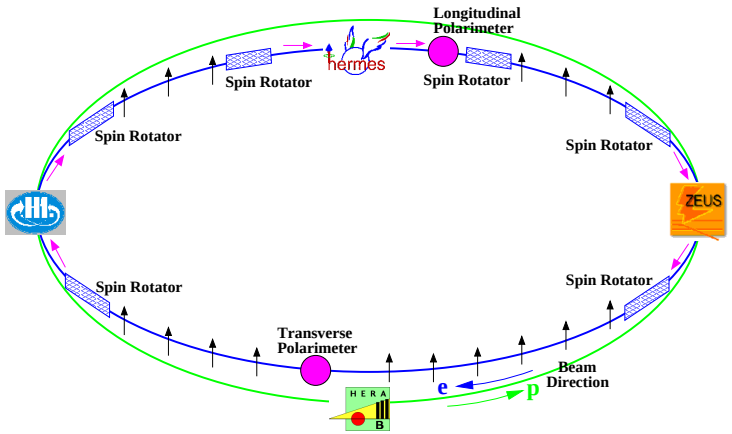
Mulders, AIP Conf.Proc. 588 (2001) 75-88

- **Full separation: need 4 units of rapidity** between jets
- **This requires:**
  - **Lower limit in** W (invariant mass of the $\gamma^* p$ system)
  - $y^h = \ln(2P^h/M^h) \rightarrow$ also **lower limit in** z

The HERMES Experiment



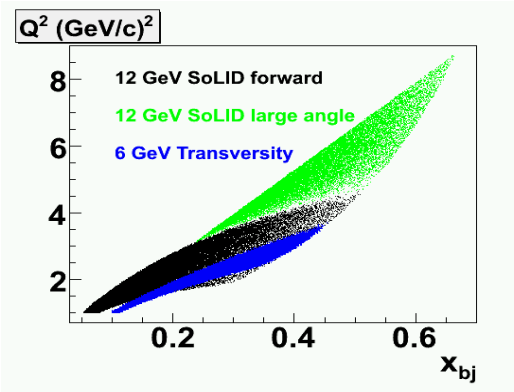




- 27.6 GeV HERA $e^{\pm}$ beam
- Forward spectrometer
  - Pure H and D atomic gas target
  - Clean lepton-hadron identification
  - Very good $\pi - K$ separation with RICH

HERMES as a measure of future challenges

SOLID

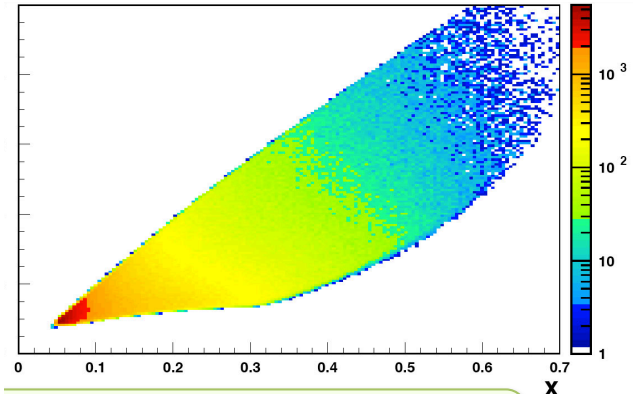


$E_{beam} = 12$ GeV

$\sqrt{s} = 4.9$ GeV

2 GeV $< W <$ 4.8 GeV

CLAS12



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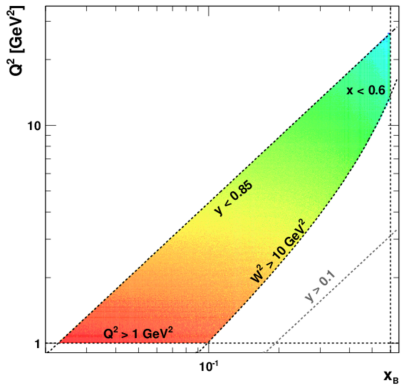

$E_{beam} = 27.6$ GeV

$\sqrt{s} = 7.43$ GeV

3.2 GeV $< W <$ 7.43 GeV

- $W_{MAX} = \sqrt{s}$

HERMES as a measure of future challenges

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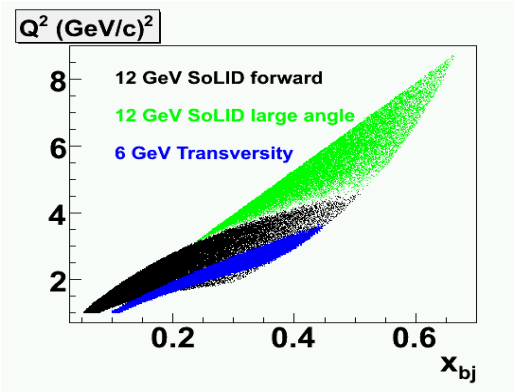

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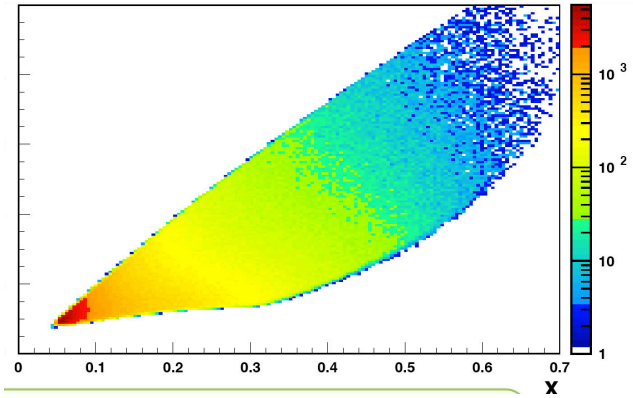

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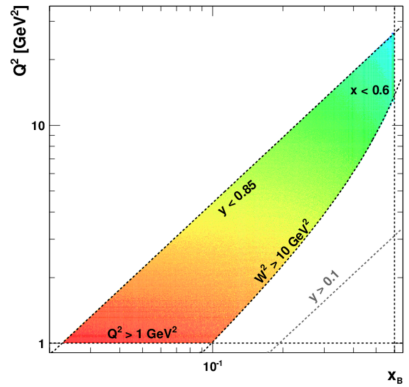

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3.2 GeV $< W <$ 7.43 GeV

- $W_{MAX} = \sqrt{s}$
- **Berger criterion:**
  - Full separation for $y^h_{\max} = 4$
  - $y^h_{\max} \approx \ln(W/M_h) = 4$
  - for π : $W > 7.6$ GeV
  - for K: $W > 27$ GeV

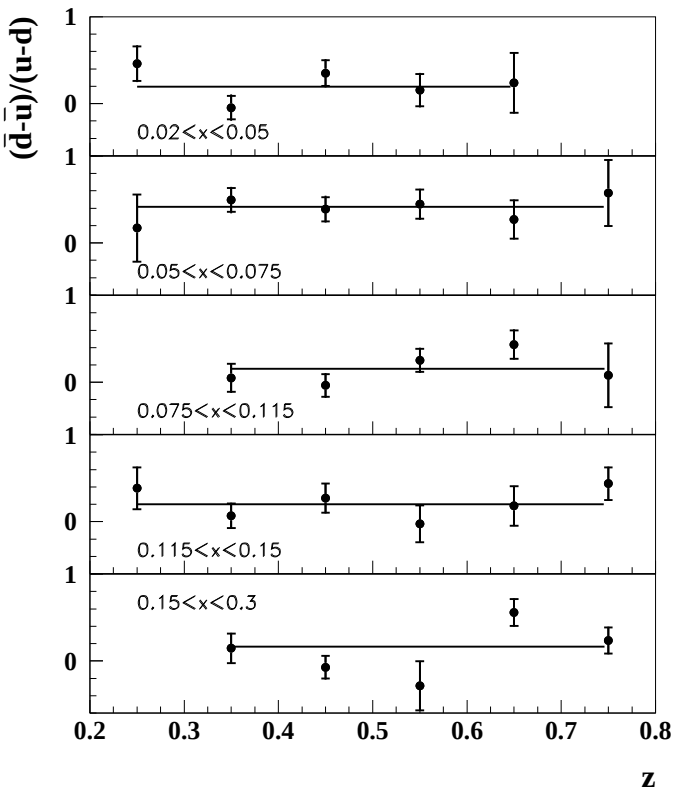
- **Problematic!?!**
  - **But... Factorization seems to work for HERMES?**

Factorization and precocious scaling

Precocious scaling

Factorized QCD appears to be working in energy regimes down to $Q \sim M$... and for SIDIS far below the Berger treshold...

HERMES, PRL81 (1998)



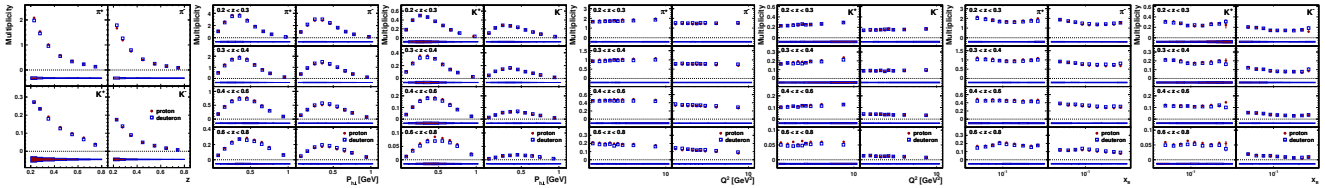
- Independent of z
- **Simple QPM-like factorization holds at HERMES**
- Caveat:
  - Model dependent extraction, depends on FFs, isospin symmetry, ...
  - Low statistics
  - Can we do better?

Section 2

Multiplicity analysis: Experimental

SIDIS Multiplicities: New HERMES Results

- **FINAL** JUST RELEASED! *A. Airapetian et al, Phys. Rev. D (2013) (in press)*
- **High statistics**
- **3D analysis** $(x(Q^2), z, P_{h\perp})$



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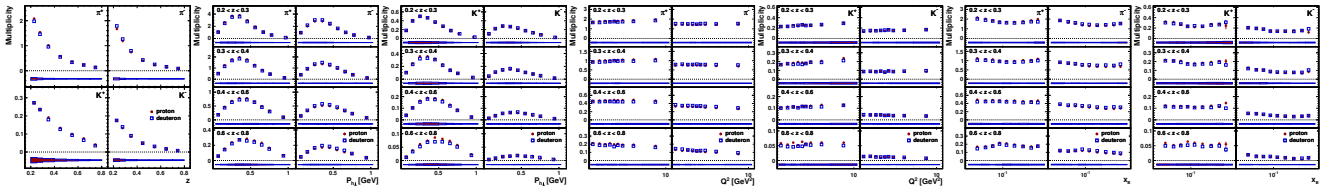
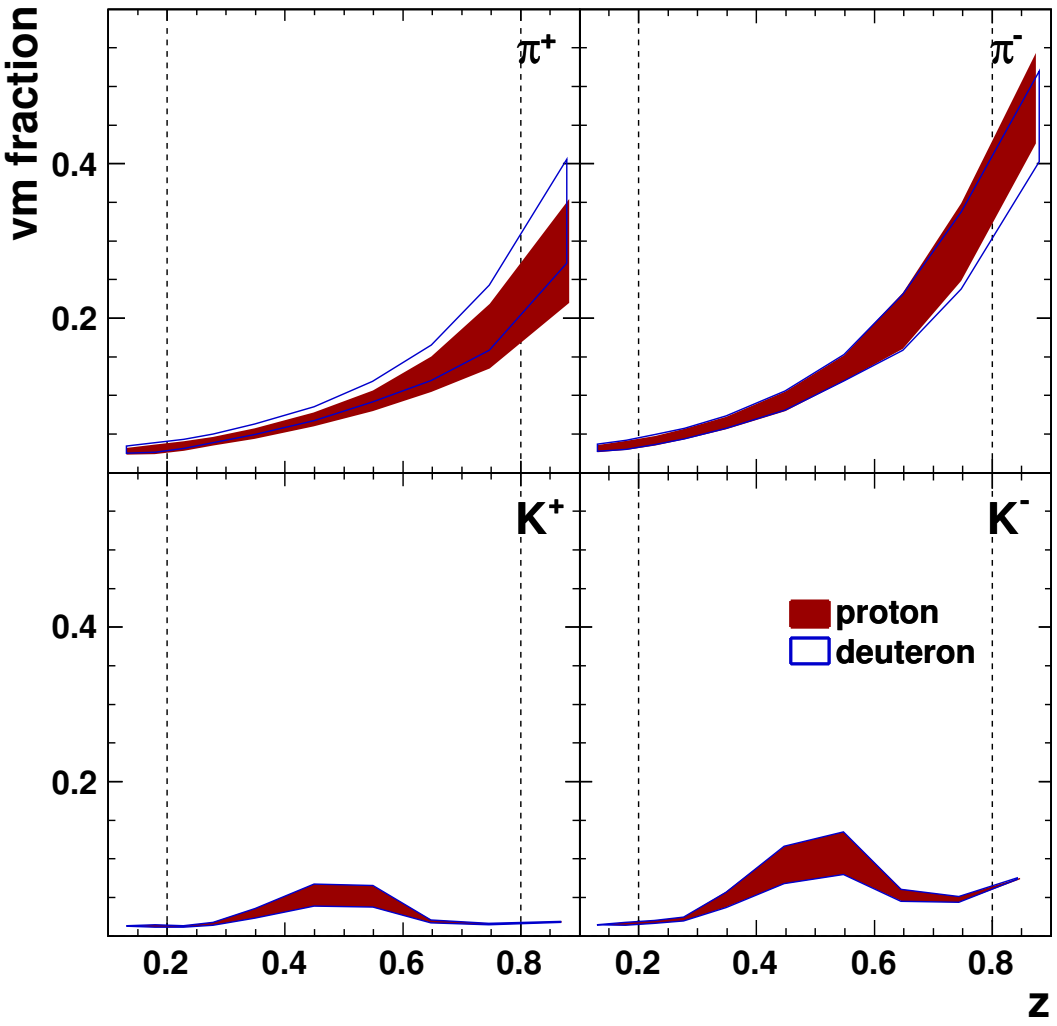


- **sophisticated analysis** required:
  - Corrections for trigger inefficiencies
  - Charge-symmetric background correction
  - **RICH unfolding**
  - Correction for **exclusive vector mesons** (optional)
  - Multidimensional **smearing-unfolding** for radiative effects, limited acceptance and detector smearing
  - Final results corrected to 4π Born (single-photon exchange).
- **Systematics dominated**
  - Highly correlated, challenge to properly estimate and understand

Exclusive vector meson contamination



- **Diffractive ρ^0 and ϕ** contaminate the SIDIS π and K sample
- Correction obtained from tuned PYTHIA
  - Applied at the fully differential level
  - Most of the correction canceled by the corresponding inclusive correction
  - **systematic** $< 1\%$
- **results** available both **with and without** this correction
- This presentation: **with** VM correction

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

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

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

Smearing-unfolding in SIDIS

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

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

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

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

Smearing-unfolding in SIDIS

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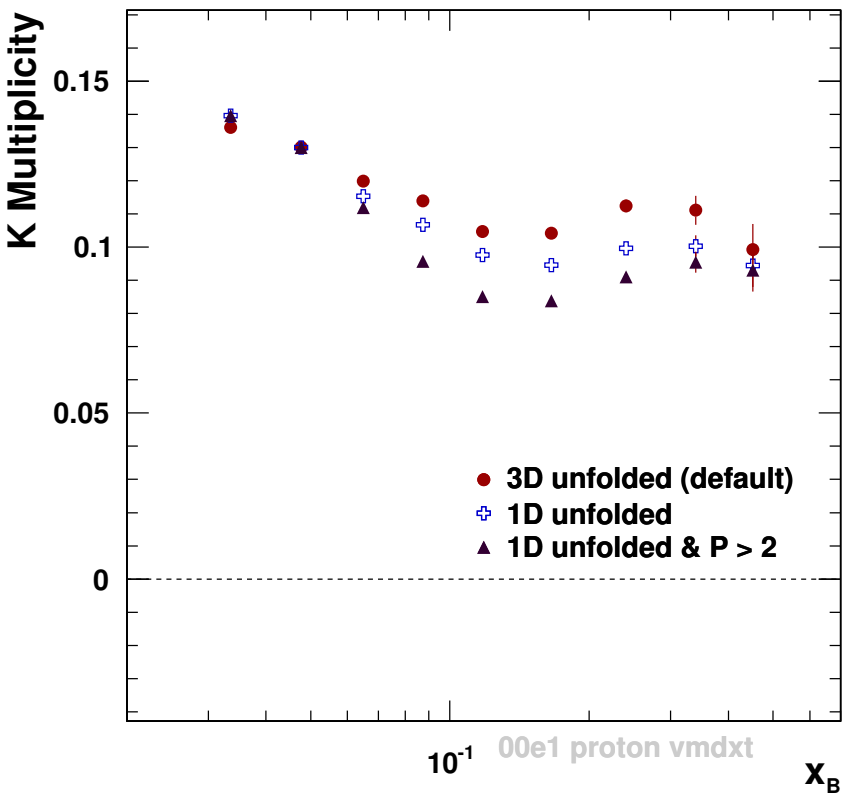
- **Smearing matrix** S is calculated using **two MC** simulations
- Completely **model-independent if either**:
  - **Acceptance function** A is **flat** within each bin
  - **Distribution** f is **flat** within each bin
- If this is **not the case**, a **reasonable** (better than 10% level) **model for f** is required
- This analysis: systematic uncertainty from the 1σ contour in MC parameter space

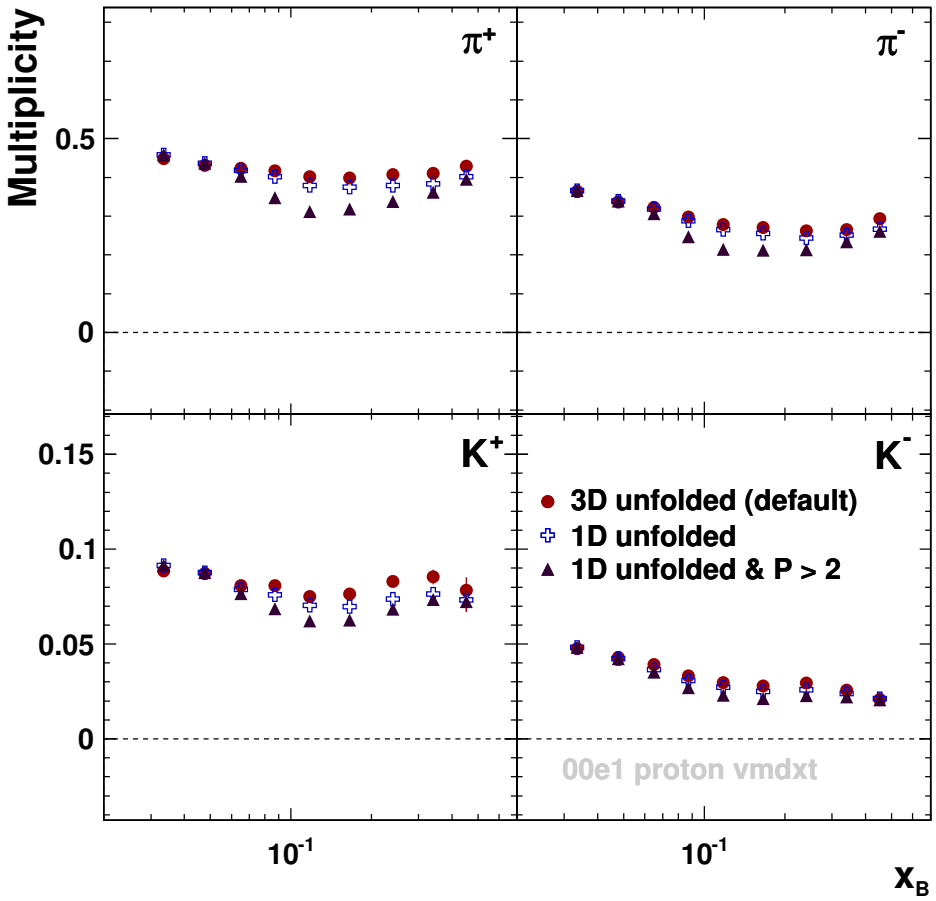
Importance of a multidimensional approach



3D vs 1D (and P cut)

- Neglecting to unfold in z **changes the x dependence dramatically**.
- The **momentum cut** has a **similar effect**.

Importance of a multidimensional approach



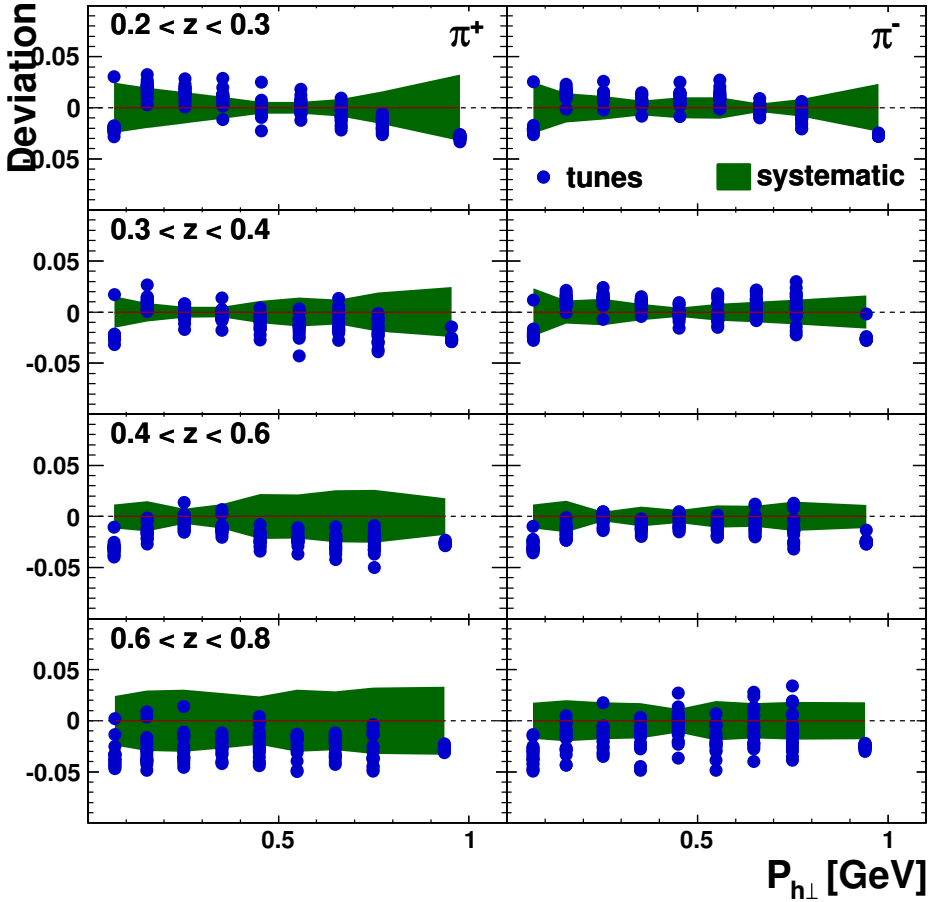
3D vs 1D (and P cut)

- Neglecting to unfold in z **changes the x dependence dramatically**.
- The **momentum cut** has a **similar effect**.

Unfolding and MC Model Systematic

- Caused by **finite bin width**.
- **Estimate:**
  - **Vary the LUND MC tune** over its 1σ contour.
  - Unfold with each of the 1σ tunes.
  - Compare final multiplicities.

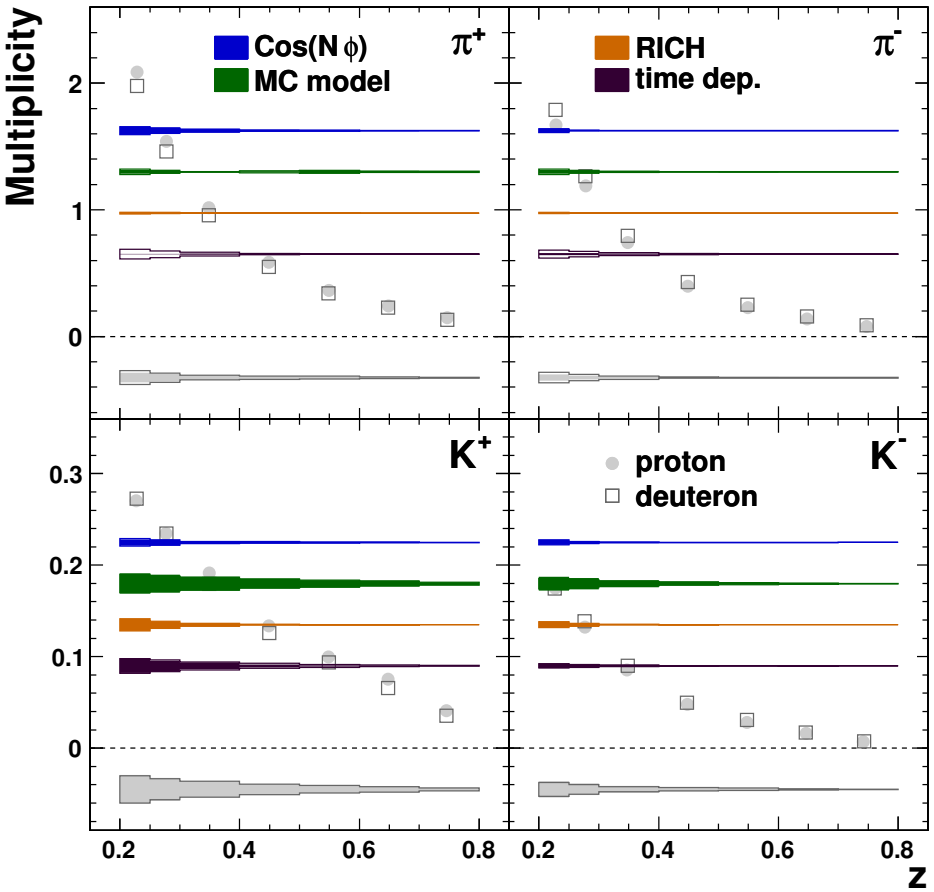
Unfolding and MC Model Systematic



- Caused by **finite bin width**.
- **Estimate:**
  - **Vary the LUND MC tune** over its 1σ contour.
  - Unfold with each of the 1σ tunes.
  - Compare final multiplicities.
  - **Generally** $\sim 2-3\%$.

Systematics breakdown

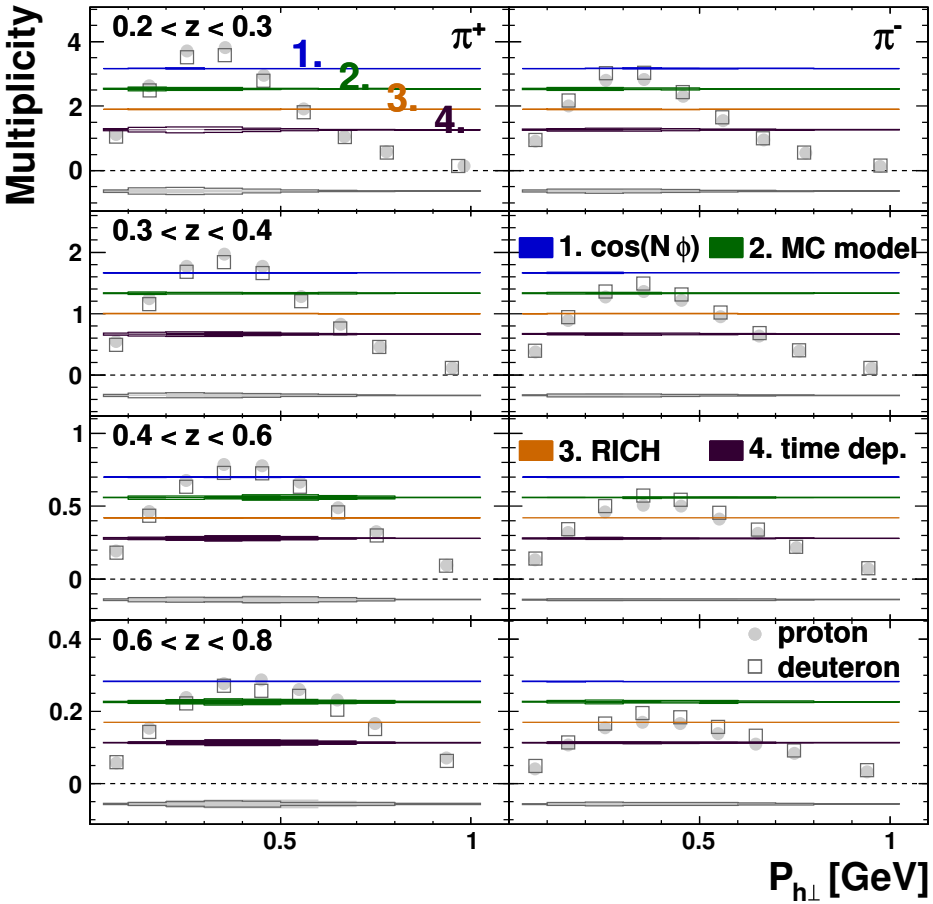
- **Dominant** contributions to the systematic:



- $\cos N\phi$ **modulations**
- **MC Model**
- **RICH**
- **time dependence**

Systematics breakdown

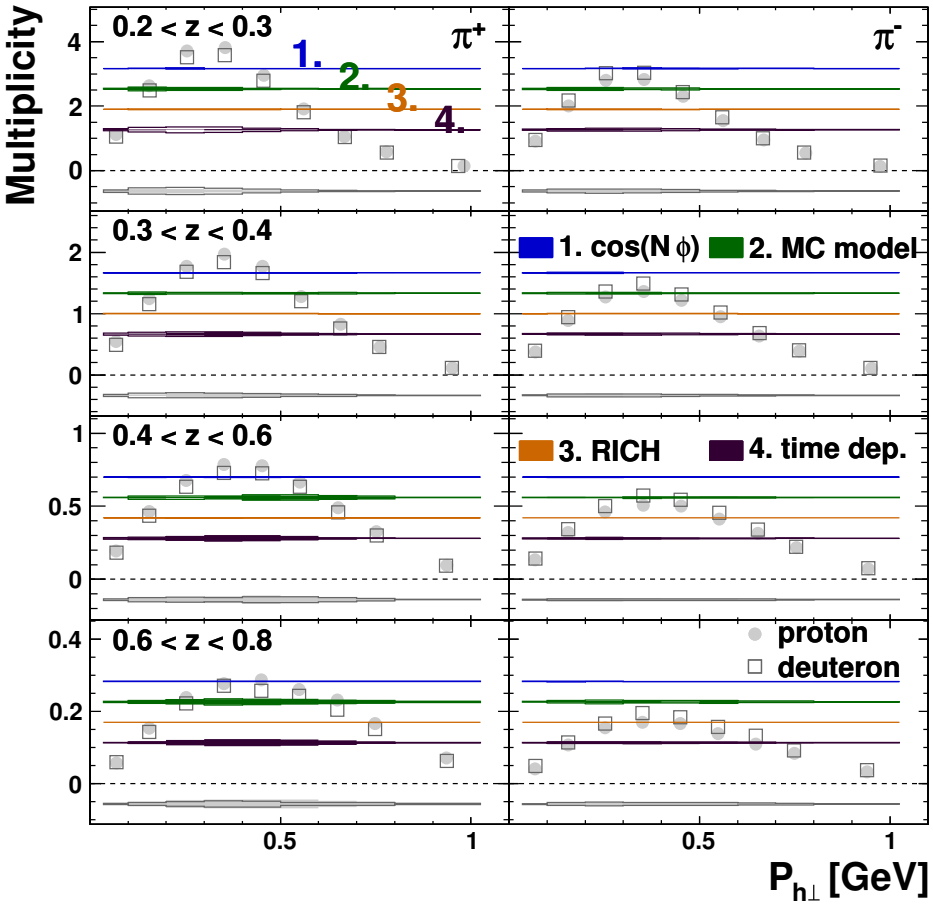
- **Dominant** contributions to the systematic:

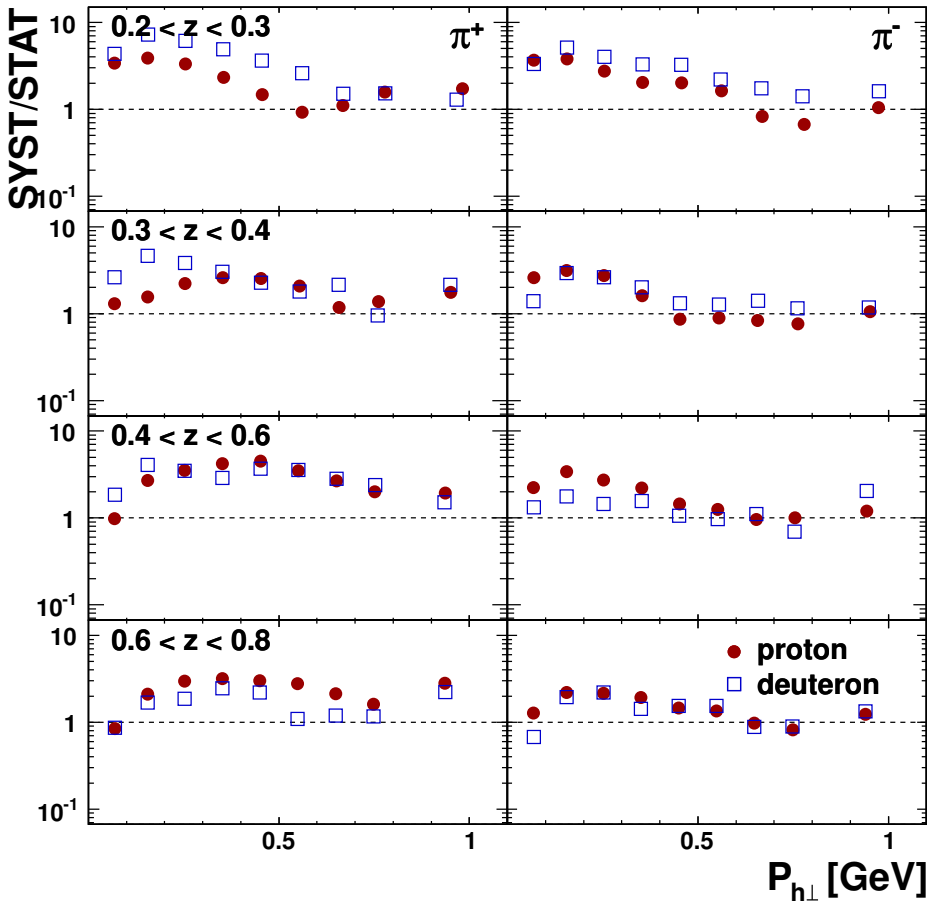


- $\cos N\phi$ **modulations**
- **MC Model**
- **RICH**
- **time dependence**

Systematics breakdown

- **Systematics dominated!** Even without the 2006-2007 data!



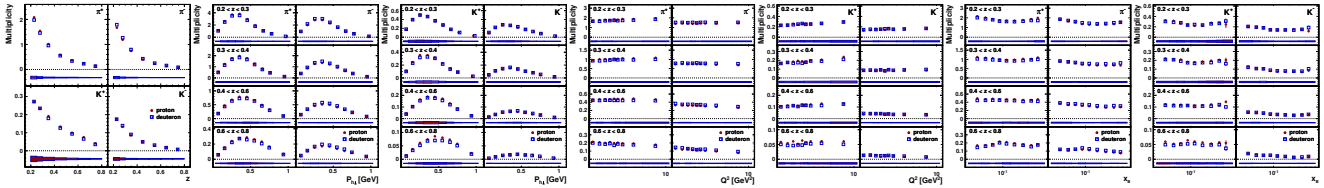


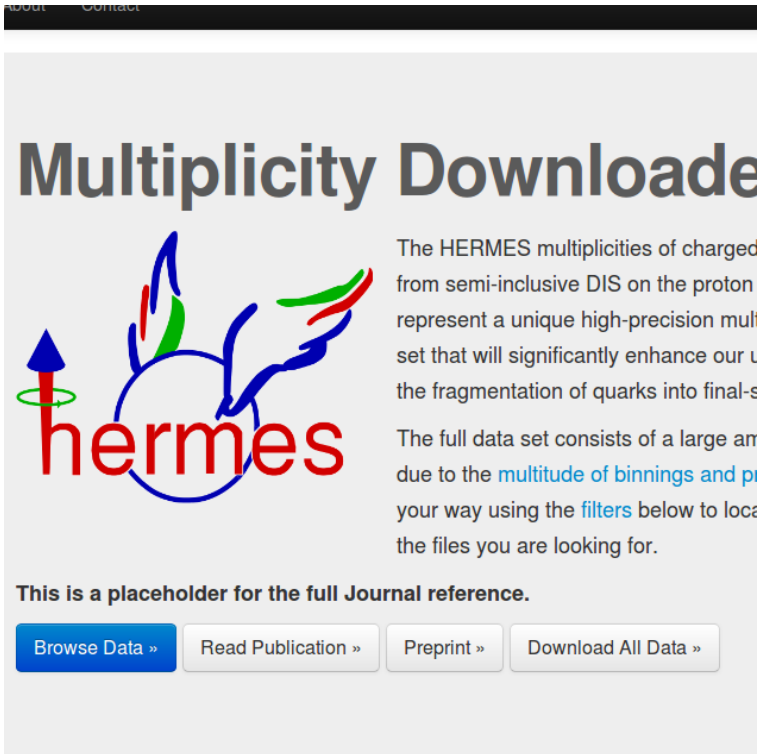
Providing the data

A. Airapetian et al, Phys. Rev. D (2013) (in press) arXiv:1212.5407v1 [hep-ex]

`http://www-hermes.desy.de/multiplicities`

Providing the data: the multiplicity website

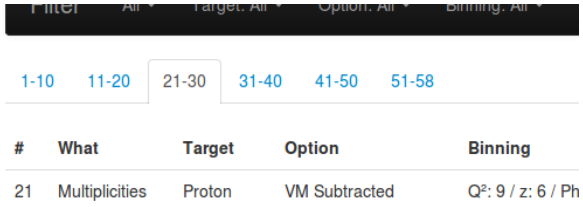




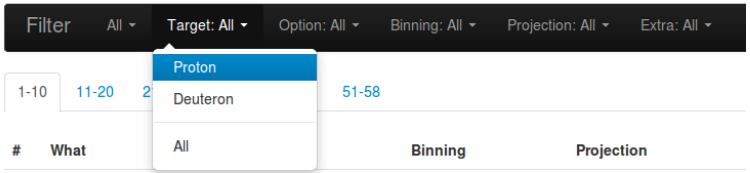
- Provides all **datafiles and available figures**.
- **Multiplicities** (differential and in various projections) **Asymmetries and ratios**
- Both **with and without** the correction for **exclusive vector mesons**
- Proper handling of the **correlated systematics**

http://www-hermes.desy.de/multiplicities

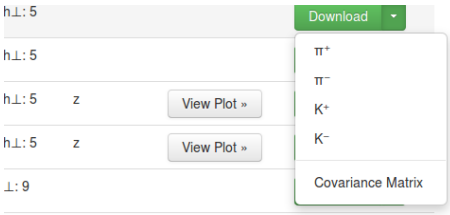
- **Browse** the data files



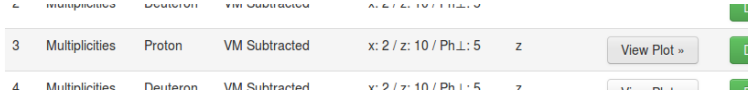
- Use **filters** for intuitive file selection

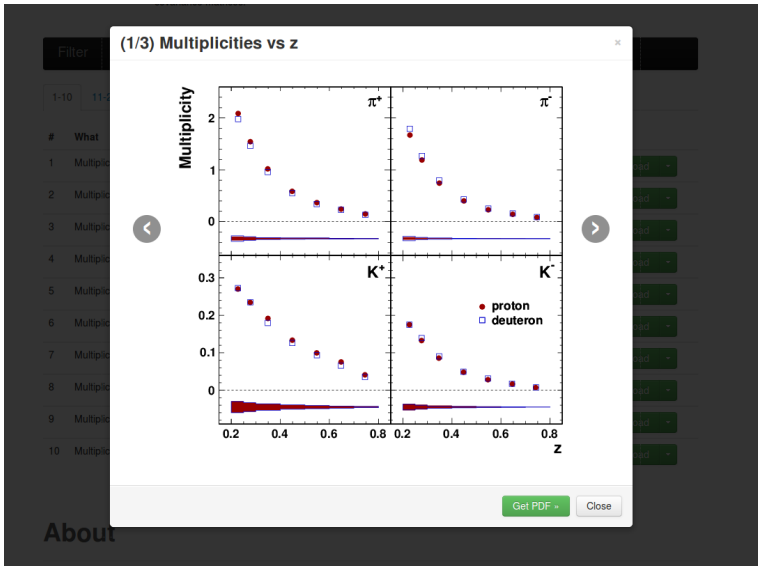


- **Download** the final results



- **View and download** available figures





http://www-hermes.desy.de/multiplicities

- **Understand** what version of the data you have.

File name structure

```
hermes.(TARGET.)BINNING.(PROJECTION.)OPTION.WHAT.list.gz
```

- `TARGET` : Either `proton` or `deuteron` . Blank in case of the target asymmetries.
- `BINNING` : Can be `z-3D` , `zpt-3D` , `zQ2-3D` `zx-3D` or `zxpt-3D` . The binning codes are defined below in
- `PROJECTION` : Blank in case of the 3D data without projection, or `VARIABLE-proj` for projected data. For exa projection versus z, or `zx-proj` for a 2D projection versus x in z slices.
- `OPTION` : Results with the vector meson contribution subtracted are labelled `vmsub` , results without this correc
- `WHAT` :
  - Multiplicity files are labelled `mults_PARTICLE` (for example: `mults_piplus`).
  - The covariance matrices for the multiplicities are labelled `covmat_mults` .
  - Target asymmetry files are labelled `asymm_PARTICLE` (for example: `asymm_piplus`).
  - The covariance matrices for the target asymmetries are labelled `covmat_asymm` .

- Get an **overview** of what is available.

Binning

The smearing-unfolding method to correct for QED radiative effects, limited geometric acc minimum granularity in all variables, allowing us to pursuit five different specialized binning be accomodated.

1. High resolution in z.
2. High resolution in $P_{h\perp}$ with z slices.
3. High resolution in x with z and $P_{h\perp}$ slices.
4. High resolution Q^2 with z and $P_{h\perp}$ slices.

- Detailed **description** of the different binnings.

High resolution in z

- **Name:** `z-3D`
- **Profile:** x: 2 / z: 10 / $P_{h\perp}$: 5
- **Use for:** The projection versus z, and for analyses that benefit from the full binning
- **Edges:**

Variable	Edges
Q^2 [GeV^2]	> 1
x	0.023 - 0.085 - 0.6
z	0.1 - 0.15 - 0.2 - 0.25 - 0.3 - 0.4 - 0.5 - 0.6 - 0.7 - 0.8 - 1.1
$P_{h\perp}$ [GeV]	0.0 - 0.1 - 0.3 - 0.45 - 0.6 - 1.2

High resolution in $P_{h\perp}$ with z slices

- **Name:** `zpt-3D`
- **Profile:** x: 2 / z: 6 / $P_{h\perp}$: 9
- **Use for:** The projection versus $P_{h\perp}$, The projection versus z and $P_{h\perp}$, and for analys
- **Edges:**

Variable	Edges
Q^2 [GeV^2]	> 1
x	0.023 - 0.085 - 0.6
z	0.1 - 0.2 - 0.3 - 0.4 - 0.6 - 0.8 - 1.1
$P_{h\perp}$ [GeV]	0.0 - 0.1 - 0.2 - 0.3 - 0.4 - 0.5 - 0.6 - 0.7 - 0.8 - 1.2

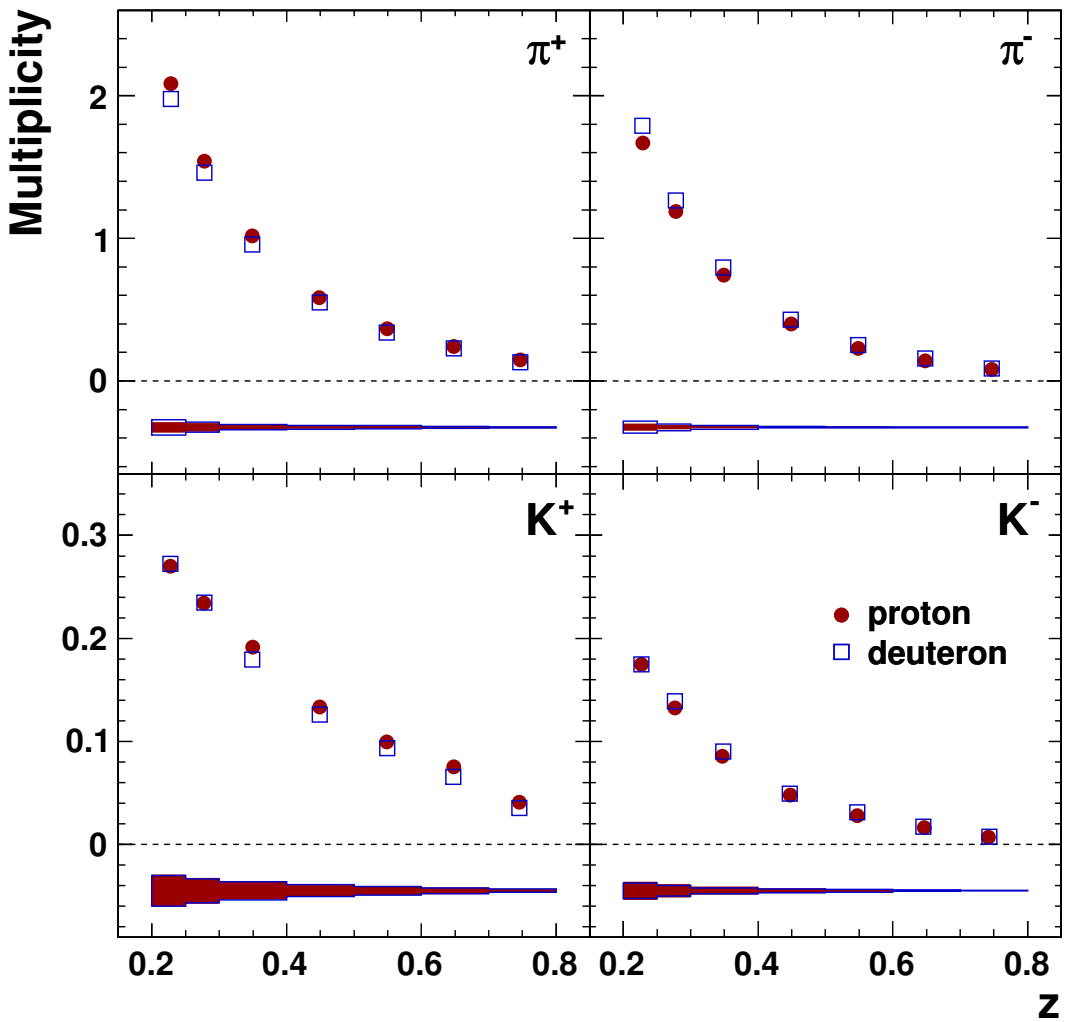
High resolution in x with z slices

Section 4

The final HERMES multiplicities

A little sampler.

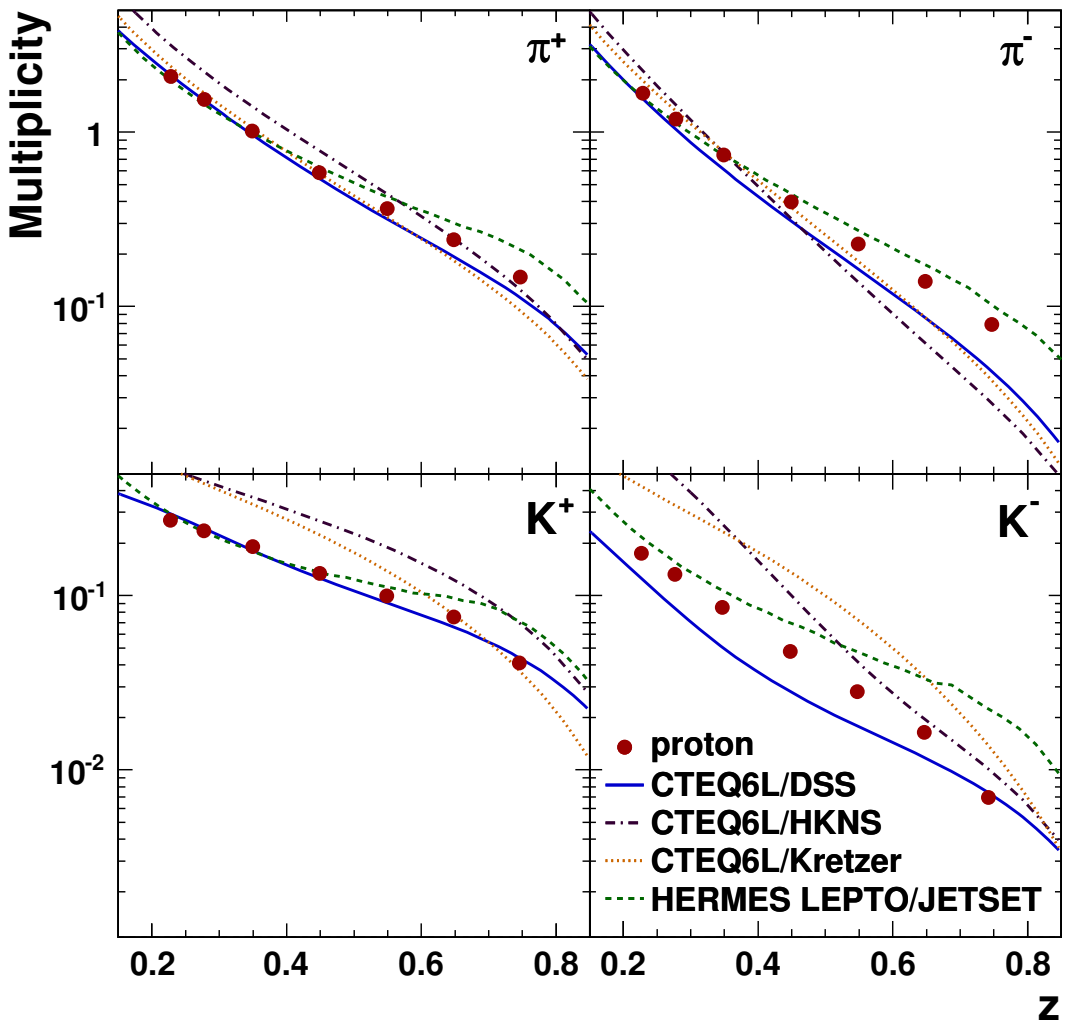
Multiplicities: Projected vs z



- u-**quark dominance**.
- deuteron has less u-quarks.
- K^- **pure sea** object $(s\bar{u})$.

- **systematic uncertainties** between particles/targets **correlated**.
- **Asymmetries and ratios increase precision** even further.

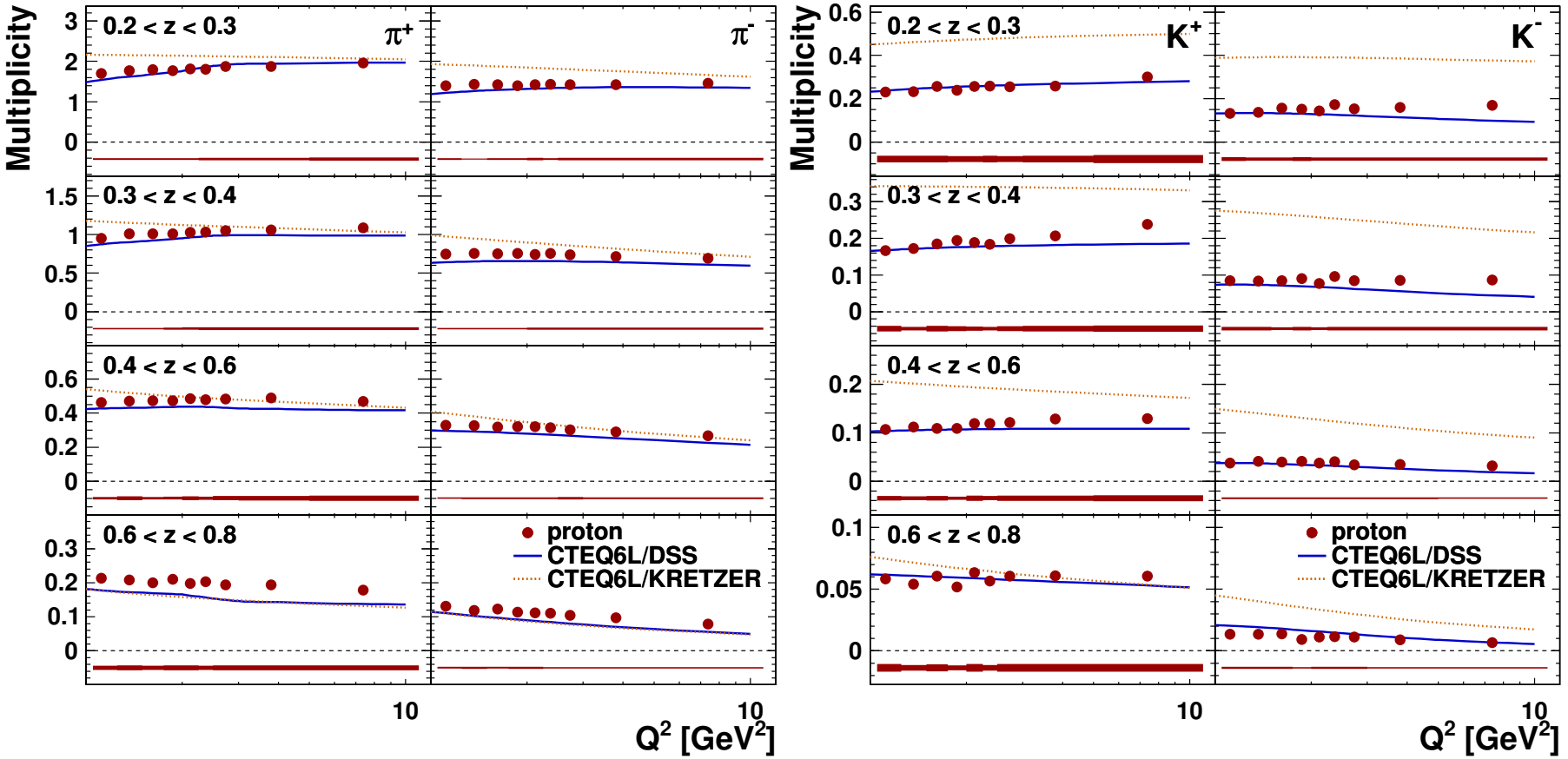
One dimensional comparison with LO predictions



- **Good agreement CTEQ6+DSS for π^+ and K^+** up to medium z.
- CTEQ6+Kretzer performs well for pions.
- Larger deviations for π^- and K^-.
- Room for **improvement at high z, and in the disfavored sector**.

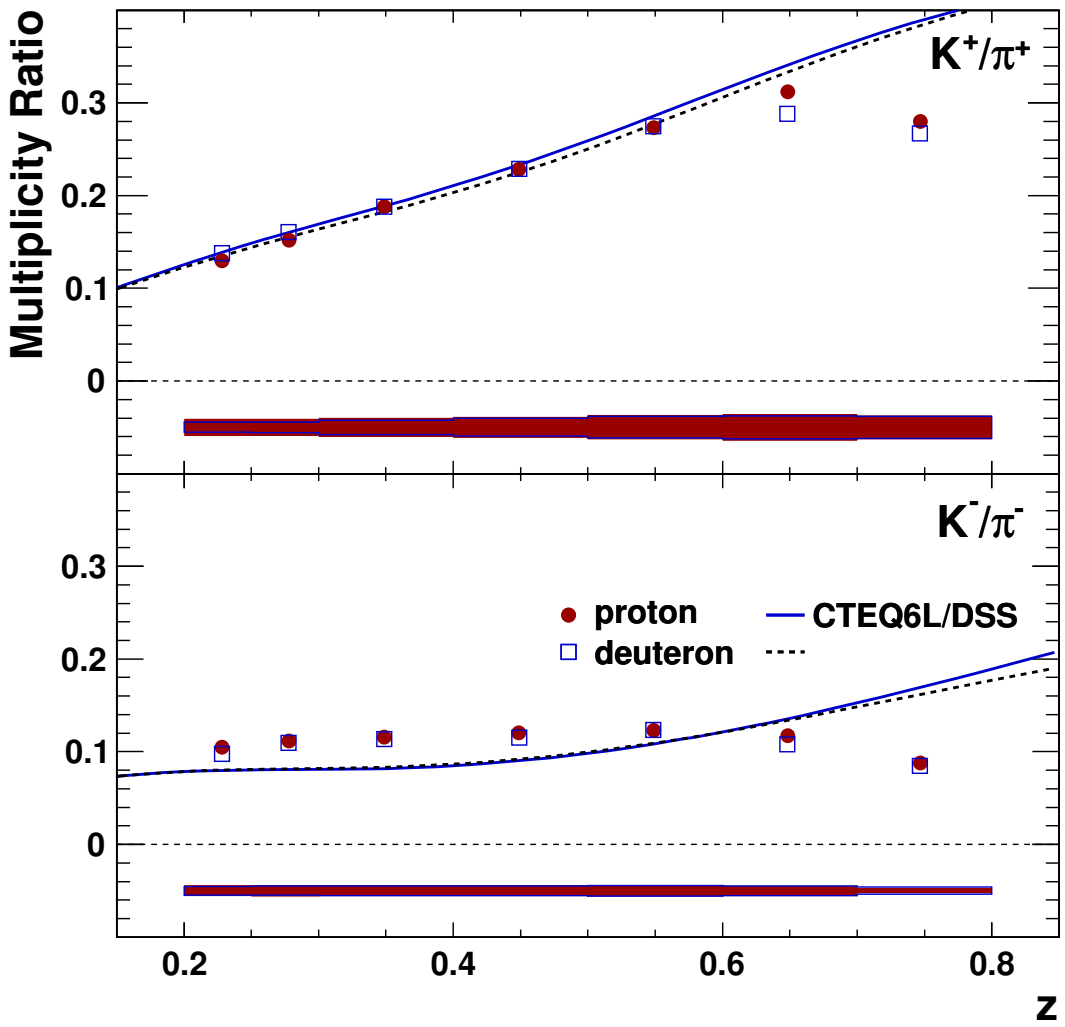
DSS, de Florian et al, PRD 75 (2007)

Input for the next generation of FFs



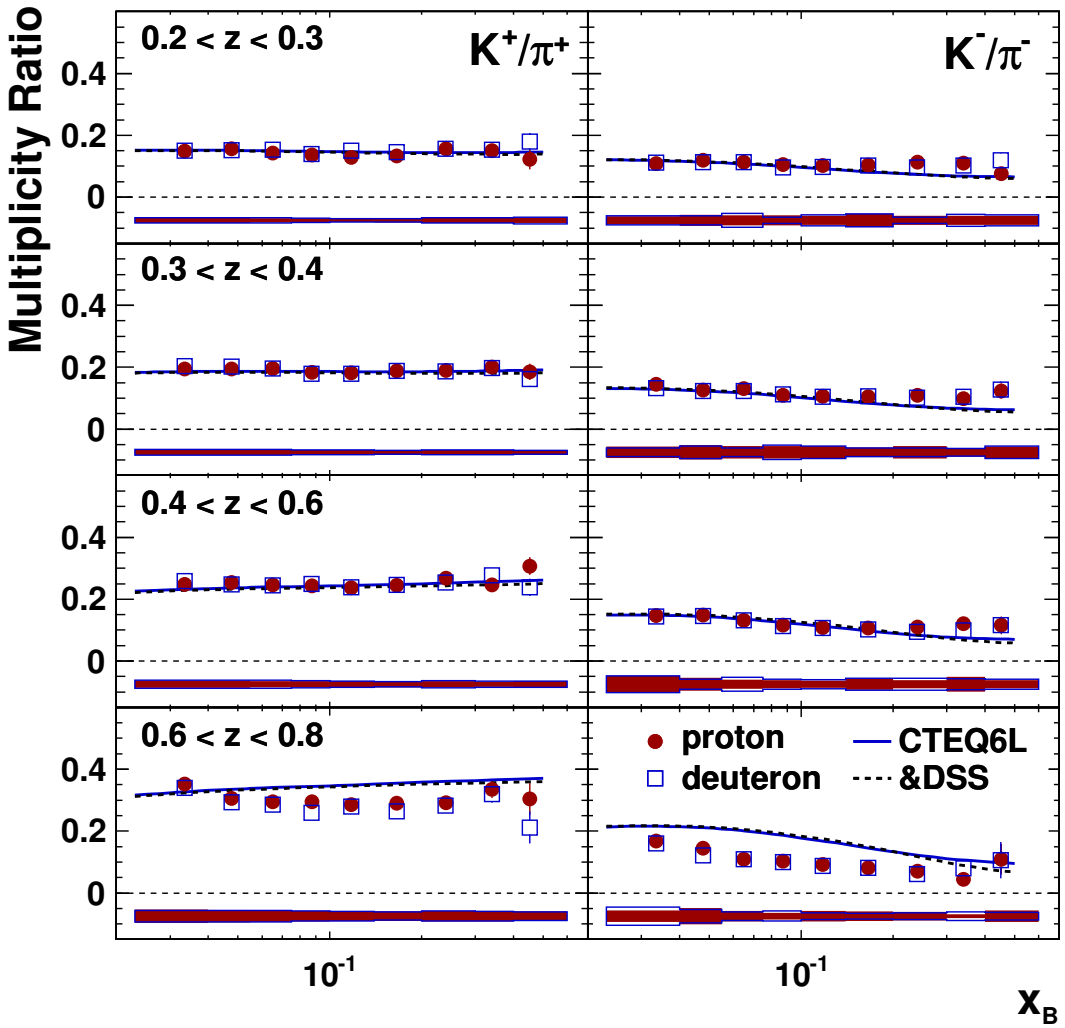
- CTEQ6L+DSS perform **very well up to medium** z.
- **Larger discrepancies at high** z.

K/π and strangeness suppression



- **Very good agreement** with the LO prediction.
- u dominance: K^+/π^+ at high z shows the **extra cost of producing an** $s\bar{s}$ compared to a $d\bar{d}$.
- **Strangeness suppresion larger** than previous fits.
- Also observed during the HERMES LUND MC tuning.

K/π in 2 dimensions



- **LO parametrizations** predict the π/K ratio **very well up to medium** z
- **At high** z**, LO calculations overshoot** the measurement for the entire valence region

Section 5

Pushing the envelope

Applicability QPM-like factorization and the limits of precocious scaling.

QPM-like factorization is intuitive

Valence ratio d_v/u_v

$$\frac{d_v}{u_v} \approx \frac{4R^\pi + 1}{4 + R^\pi}$$

$$R^\pi = 2\frac{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} - 1$$

Light sea asymmetry $(\bar{d} - \bar{u})/(u - d)$

$$\frac{\bar{d} - \bar{u}}{u - d} \approx \frac{4k^{\text{sea}} - \rho^\pi}{1 - k^{\text{sea}}\rho^\pi}$$

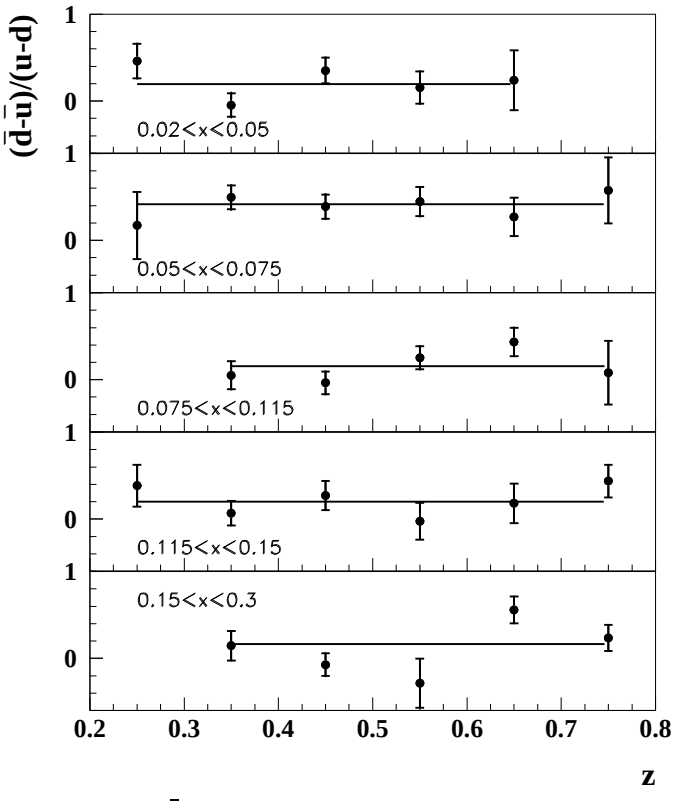
$$\rho^\pi = \frac{\sigma_p^{\pi^-} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_d^{\pi^+}}$$

$$k^{\text{sea}} = \frac{4 - \eta}{4\eta - 1} \quad \text{where} \quad \eta = \frac{D_{\text{unf}}}{D_{\text{fav}}}$$

- Both should **depend on x, not z:**
  - **Signature of factorization.**
- Light sea asymmetry requires $D_{\text{unf}}/D_{\text{fav}}$ as input.

Where are the limits of QPM-like factorization?

HERMES, PRL81 (1998)



- Important result but **not ideal test** due to higher model dependence
- $\int d_v / \int u_v$ **finally possible!**
  - **RICH** and RICH unfolding.
  - **Multi-dimensional smearing-unfolding**.
  - Near-perfect grasp of interplay between the different **systematics**.
- **High z exclusive, low z backward hemisphere.**

Where are the limits of QPM-like factorization?

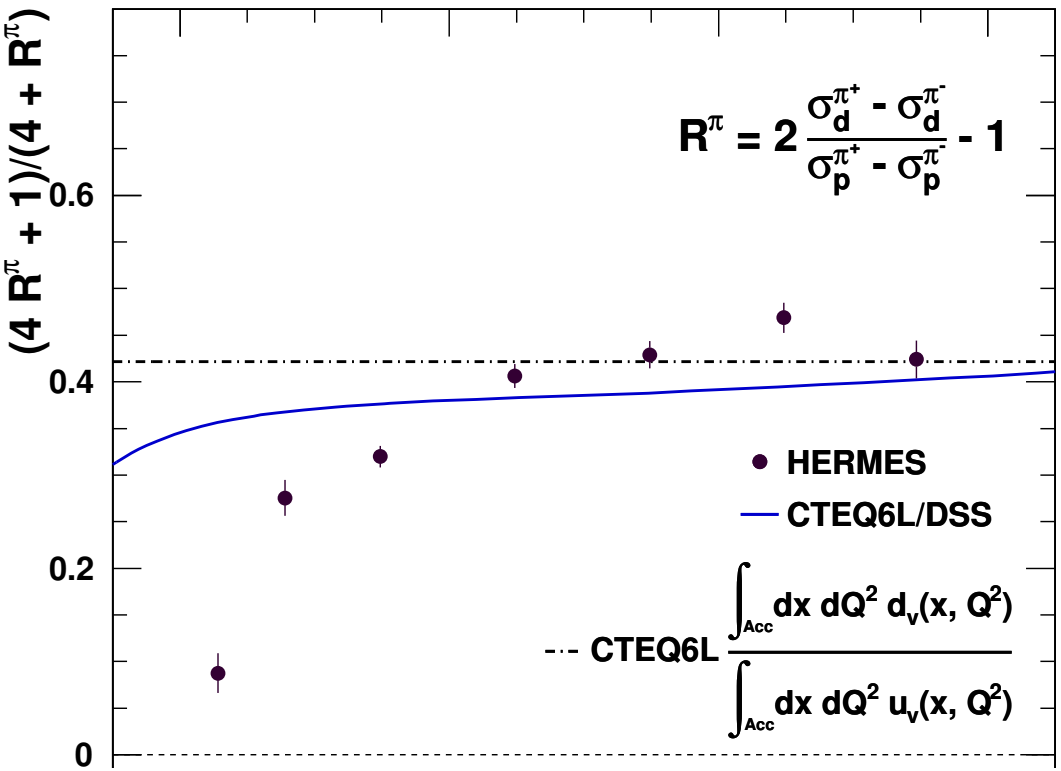
LO access

$$R^{\pi}(z) \equiv 2\frac{\int_{Acc.} dxdQ^2(\sigma_d^{\pi^+} - \sigma_d^{\pi^-})}{\int_{Acc.} dxdQ^2(\sigma_p^{\pi^+} - \sigma_p^{\pi^-})} - 1 \approx \frac{\int_{Acc.} dxdQ^2(u_v - 4k^{\mathrm{val}} d_v)}{\int_{Acc.} dxdQ^2(d_v - 4k^{\mathrm{val}} u_v)}$$

$$\rightarrow \frac{\int_{Acc.} dxdQ^2 d_v}{\int_{Acc.} dxdQ^2 u_v} \approx \frac{4k^{\mathrm{val}} R^{\pi} + 1}{4k^{\mathrm{val}} + R^{\pi}}$$

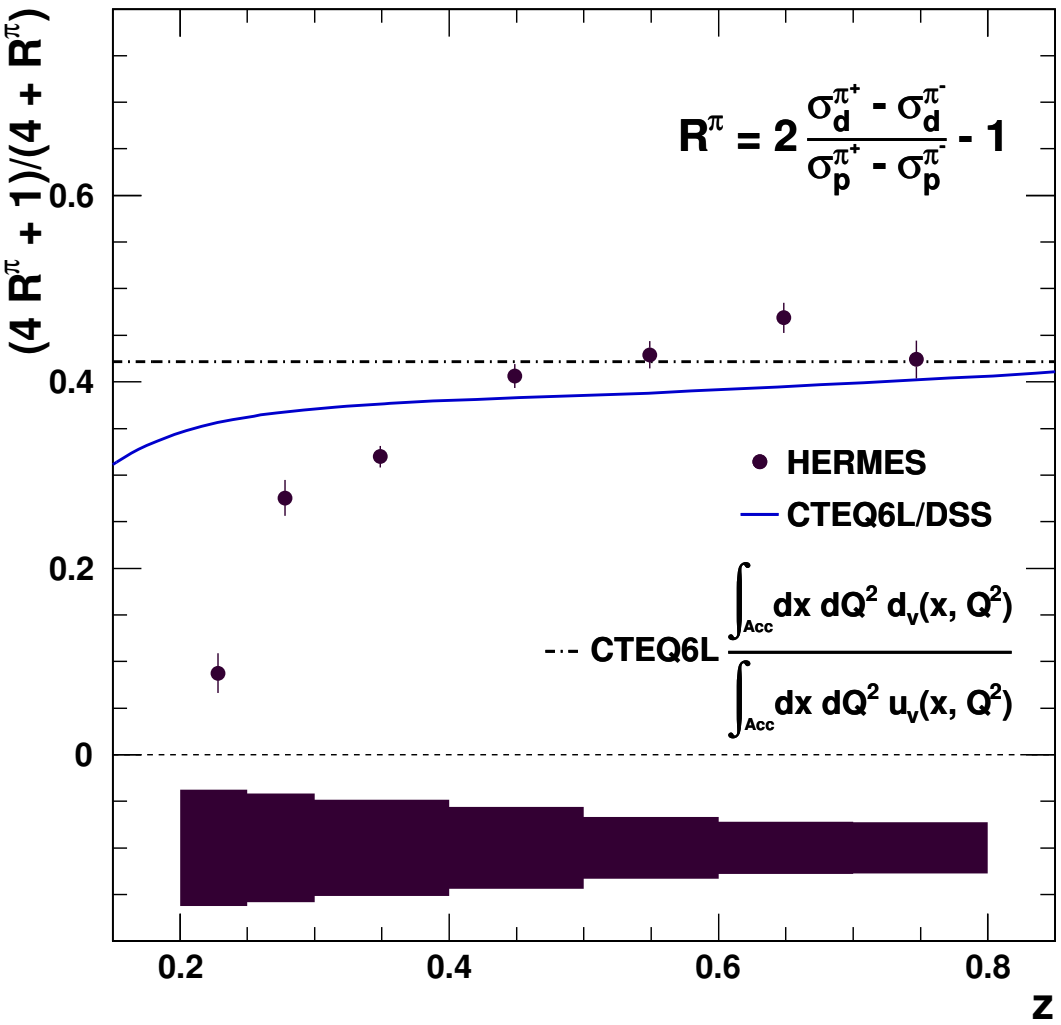
- $k^{\mathrm{val}} \equiv \frac{D_u^{\pi^+} - D_{\bar{u}}^{\pi^+}}{D_d^{\pi^+} - D_{\bar{d}}^{\pi^+}} \rightarrow 1$ (isospin symmetry).
- Pushes the experimental precision to a limit:
  - A proper treatment of the **correlated systematics** is crucial.
- Very **sensitive to theoretical assumptions**:
  - Applicability of the LO, leading twist framework.
  - Additional assumptions (eg. isospin symmetry, cf. DSS).

Where are the limits of QPM-like factorization?



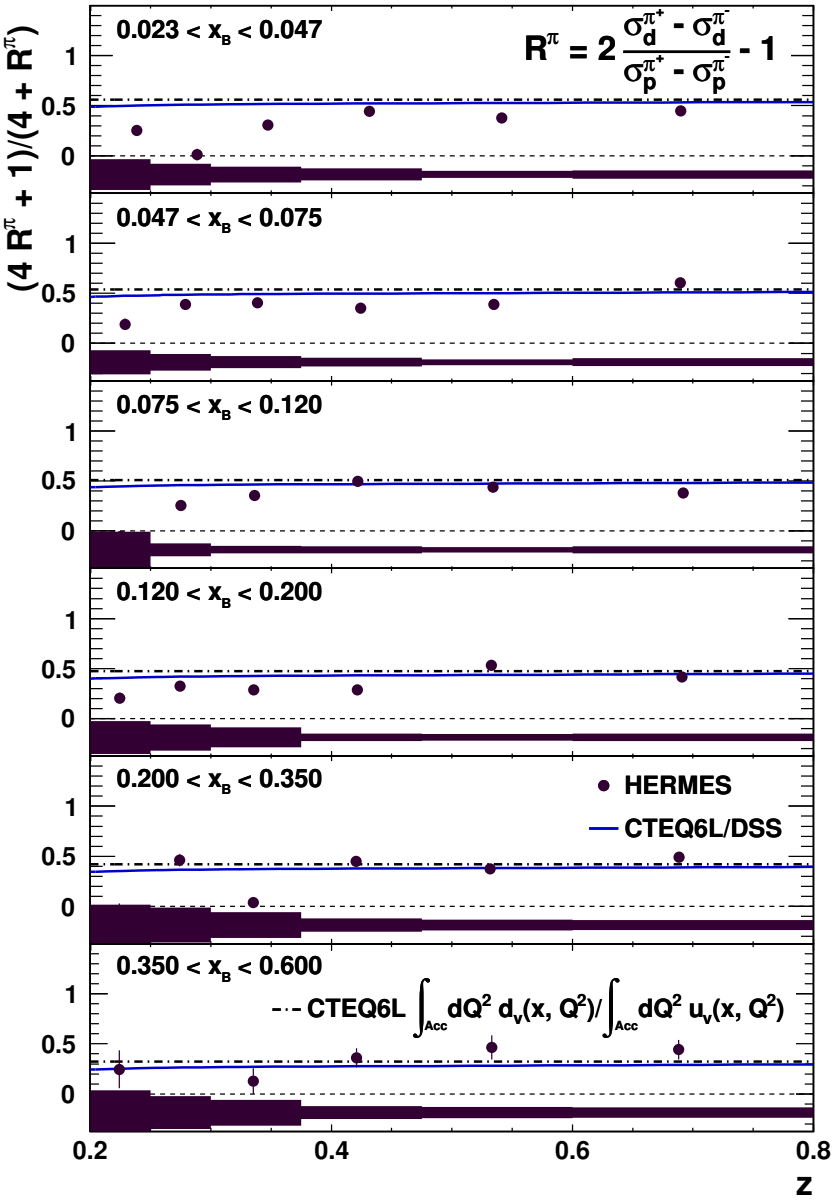
Cropped for dramatic effect

Where are the limits of QPM-like factorization?



- Very good **agreement for mid-to-high** z.
- **Lowest point** $> 3\sigma$ from the prediction:
  - Target remnant or theory?
  - Realistic FF assumption (DSS) lessens the discrepancy,
  - $\rightarrow$Probably mix.
- Results generally **systematics dominated**.
- **CTEQ curve below 0.5 due to the integral over the HERMES acceptance (see page 9).**

Where are the limits of QPM-like factorization?



- **Lessons:**
  - **Discrepancy HAS to occur at low z.** This should be carefully considered when moving towards that limit.
  - **Precocious scaling** holds very well **mid-to-high z.**
  - More **precise knowledge of FF symmetries** required.
- **SYSTEMATICS!**
  - Going higher in statistics doesn't make sense anymore.
  - **On to CEBAF!**
  - **Multi-D binning key** for unfolding and interpretation.

Section 6

Bonus: Transverse momentum dependence of the multiplicities

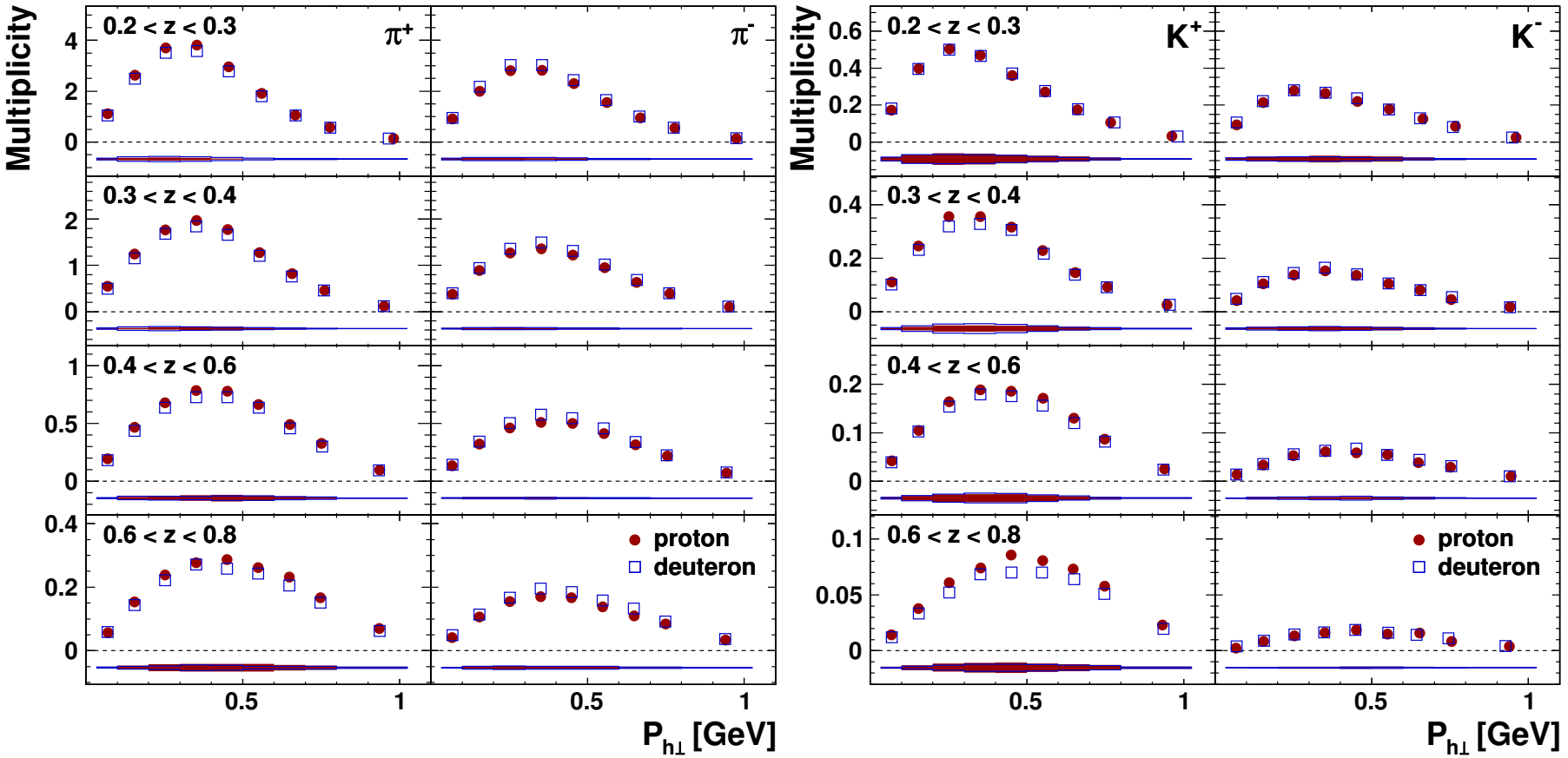
Transverse momentum dependence

- The multidimensional results provide leverage in the **quest to unfold intrinsic quark p_T** and **fragmentation k_T** from the **transverse hadron momentum $P_{h\perp}$**
  - Leverage the simultaneous binning in $P_{h\perp}$, z and x (or Q^2)
  - Access the shape of the unpolarized TMD
  - Provide a handle on flavor separation
  - Constrain TMD models and calculations

$P_{h\perp}$ dependence in the LO TMD formalism

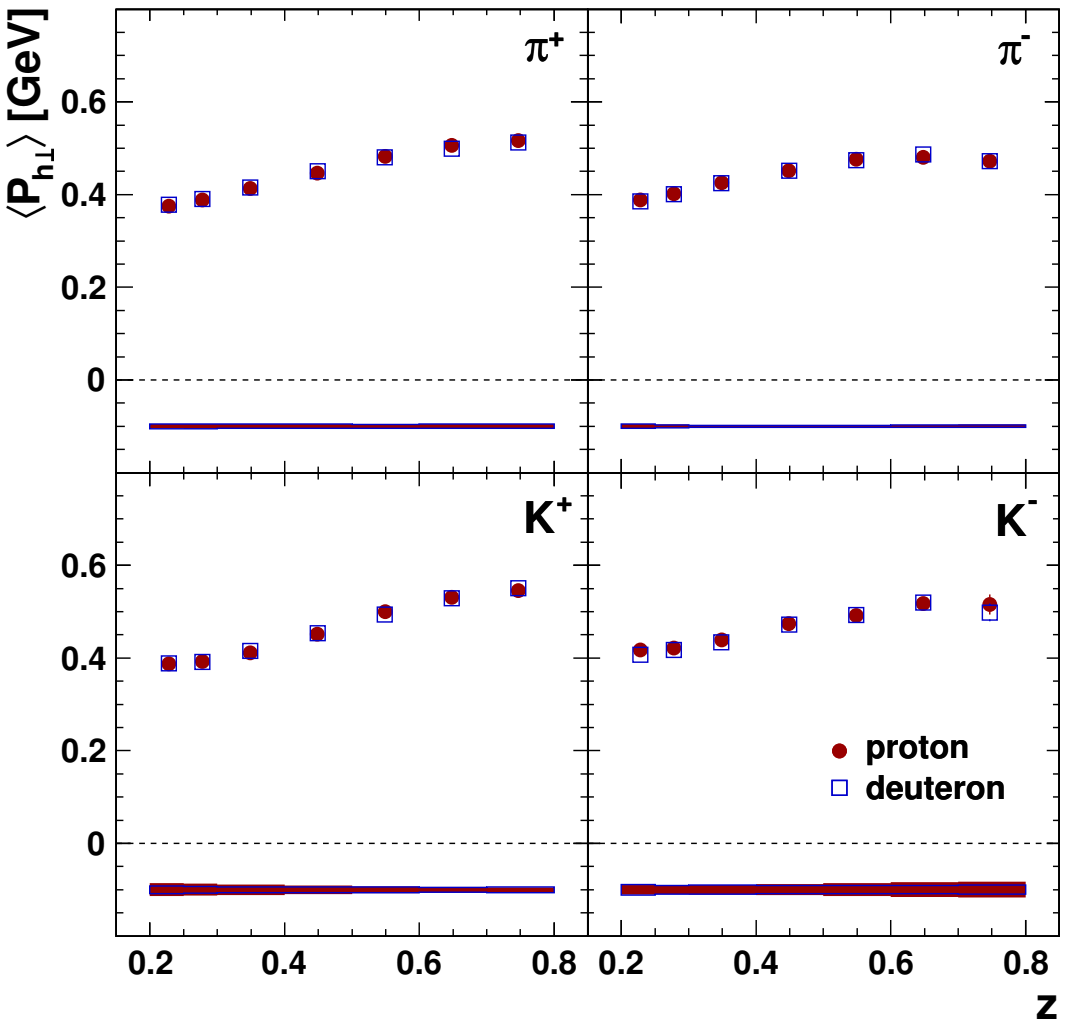
$$\frac{d^5\sigma^h}{dx dQ^2 dz \mathbf{d^2\vec{P}_{h\perp}}} \propto \sum_q e_q^2 \int \mathbf{d^2\vec{p}_T d^2\vec{k}_T} \delta^2(\mathbf{\vec{P}_{h\perp}} - \mathbf{\vec{k}_T} - z\mathbf{\vec{p}_T}) \mathbf{f_1^q(x, Q^2, p_T) D_q^h(z, Q^2, k_T)}$$

The shape of $P_{h\perp}$ in z slices



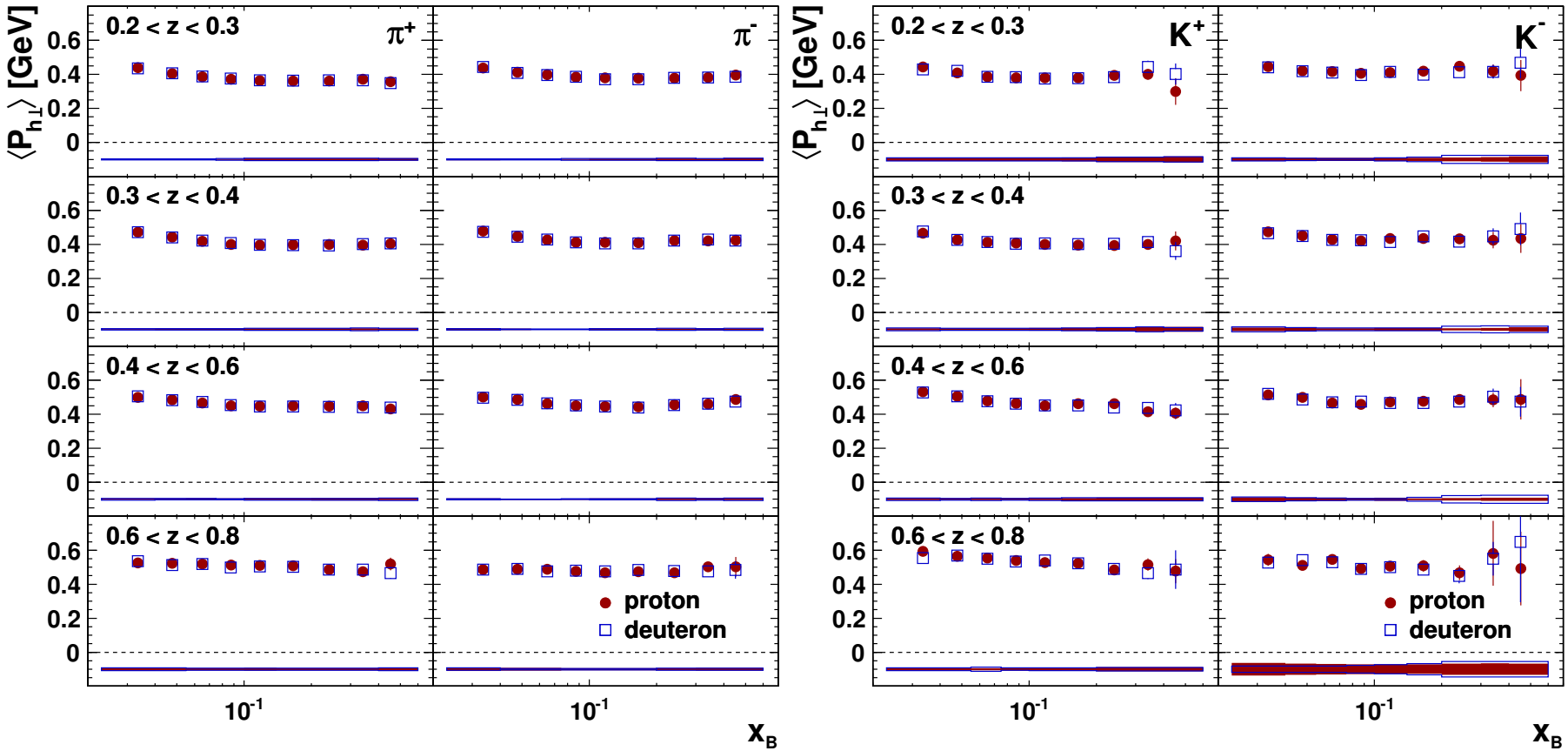
- Superficially consistent with the **Gaussian ansatz**
- **Average and width** function of kinematics and hadron type.

$\langle P_{h\perp} \rangle$ as a function of z



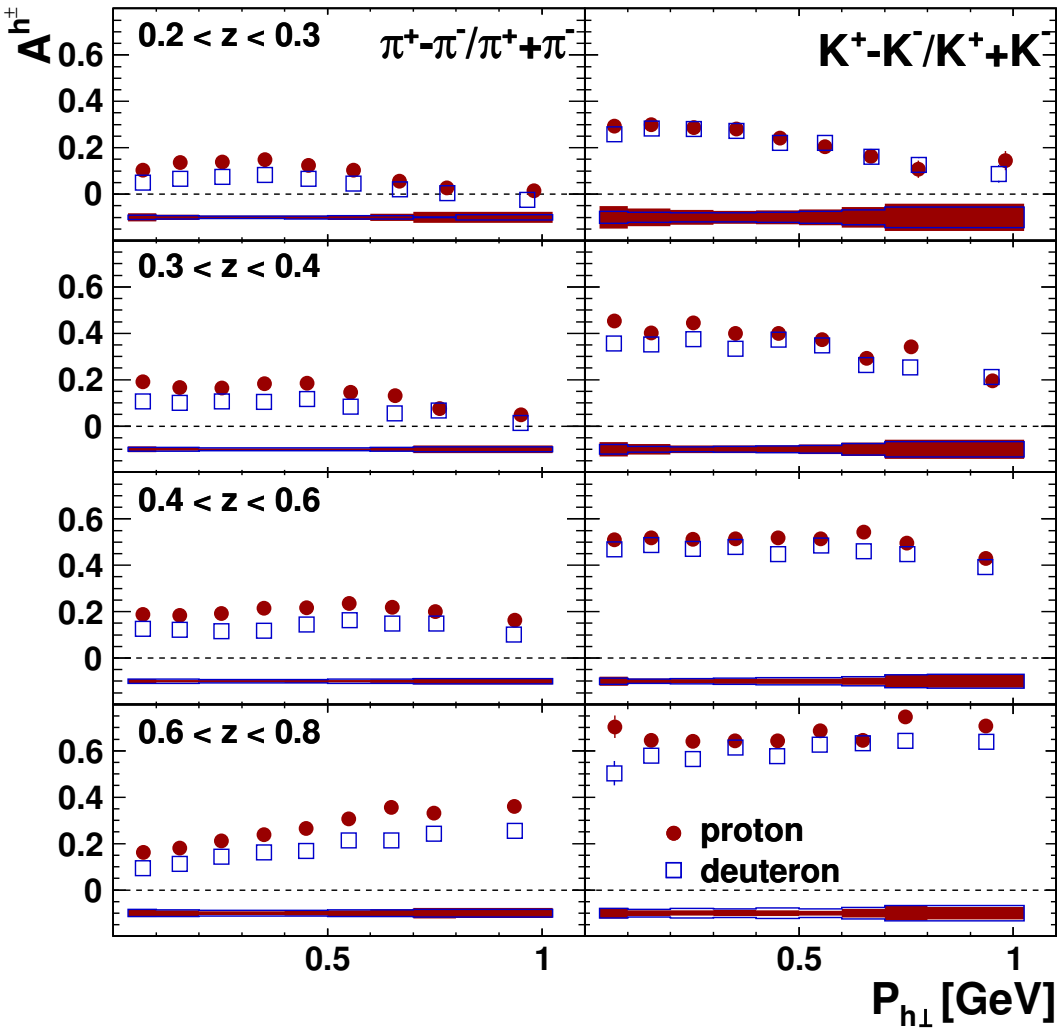
- Rising function of z
- $\langle P_{h\perp} \rangle$ for K **higher than** π at larger z
  - Point-to-point significance of 2σ
  - **Strangeness suppression**: at high z, K sample contains (relatively) more sea events than π
  - Could *hint* at **higher intrinsic** $\langle p_T \rangle$ for the sea?

$\langle P_{h\perp} \rangle$ in 2 dimensions



- Slightly falling function of x
  - Also hints at **higher intrinsic** $\langle p_T \rangle$ for the sea

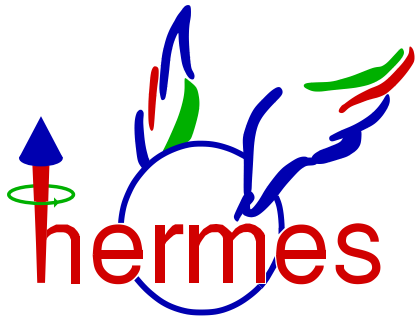
Hadron charge asymmetry



- Numerator contains proportionally more valance than the denominator
- Especially at higher z
- Ratio encodes information about the **shape of the intrinsic p_T distribution**

Summary

- Unique set of 3D high-precision SIDIS multiplicities for $\pi^{\pm}$ and $K^{\pm}$ on p and d are presented
- Enabling:
  - **Evaluation of the quality** of FF (and PDF) **parametrizations**
  - **Input** for the **next generation** of parametrizations
  - Access to the **transverse distributions**
- What do these high-precision results teach us?
  - Crucial to consider the **fully differential case**
  - Systematics have to be carefully considered
  - If possible, take into account the correlations in the systematic uncertainties when calculating derived quantities
- Precocious scaling continues down to HERMES energy!
- Get the data at `http://www-hermes.desy.de/multiplicities`



arXiv:1212.5407v1 [hep-ex]

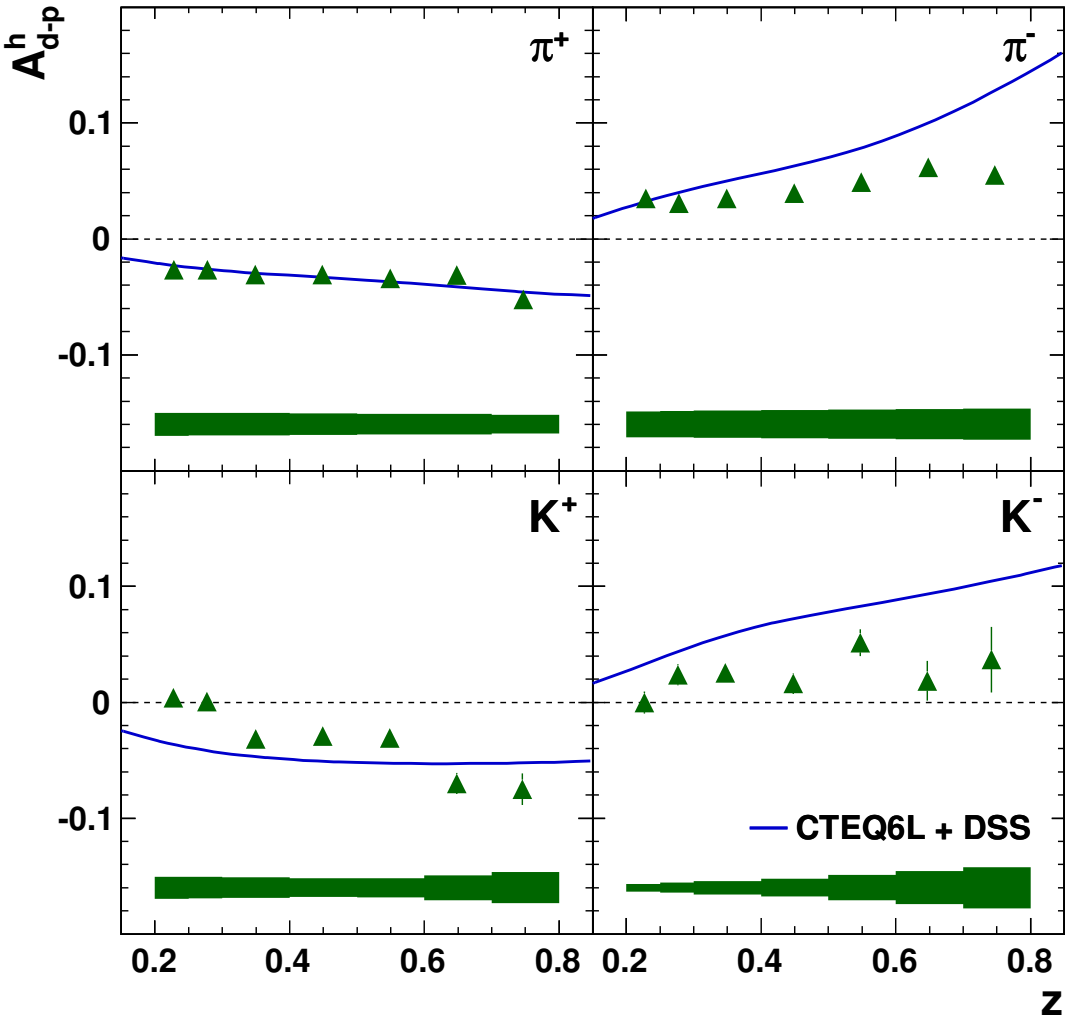
A. Airapetian et al, Phys. Rev. D (2013) (in press)

http://www-hermes.desy.de/multiplicities

https://www.npl.illinois.edu

http://nsf.gov

BACKUP: Proton-deuteron multiplicity asymmetry

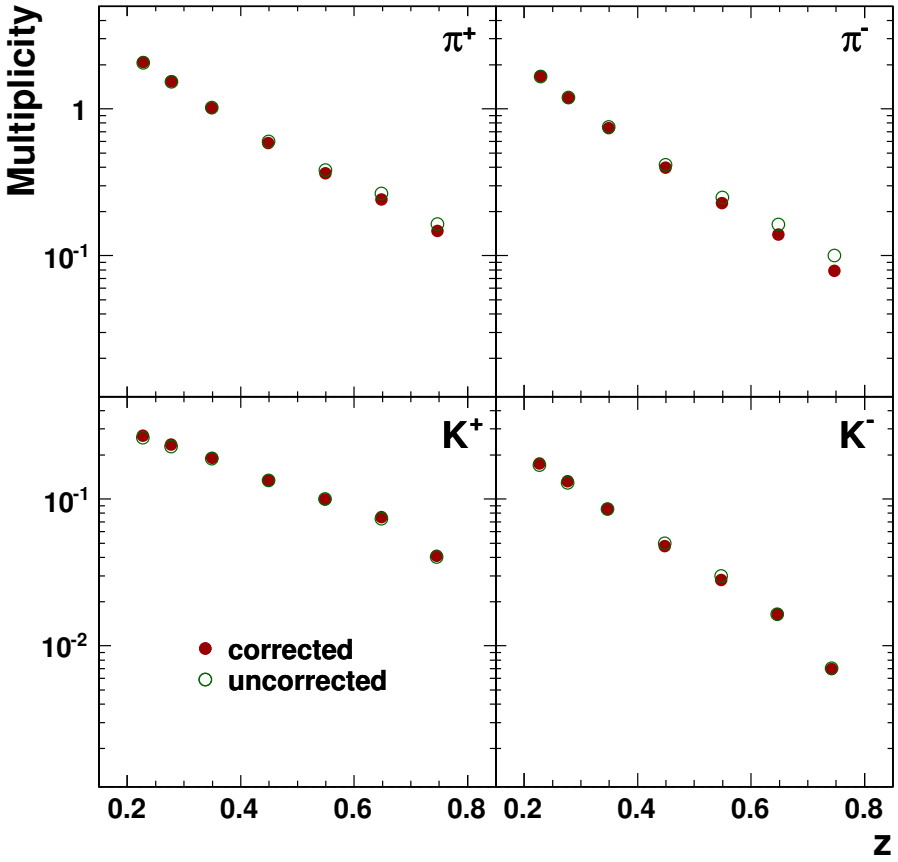


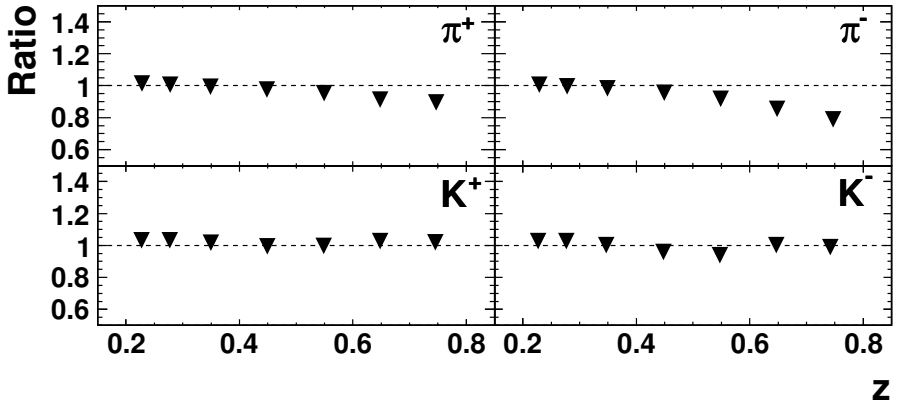
definition:

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

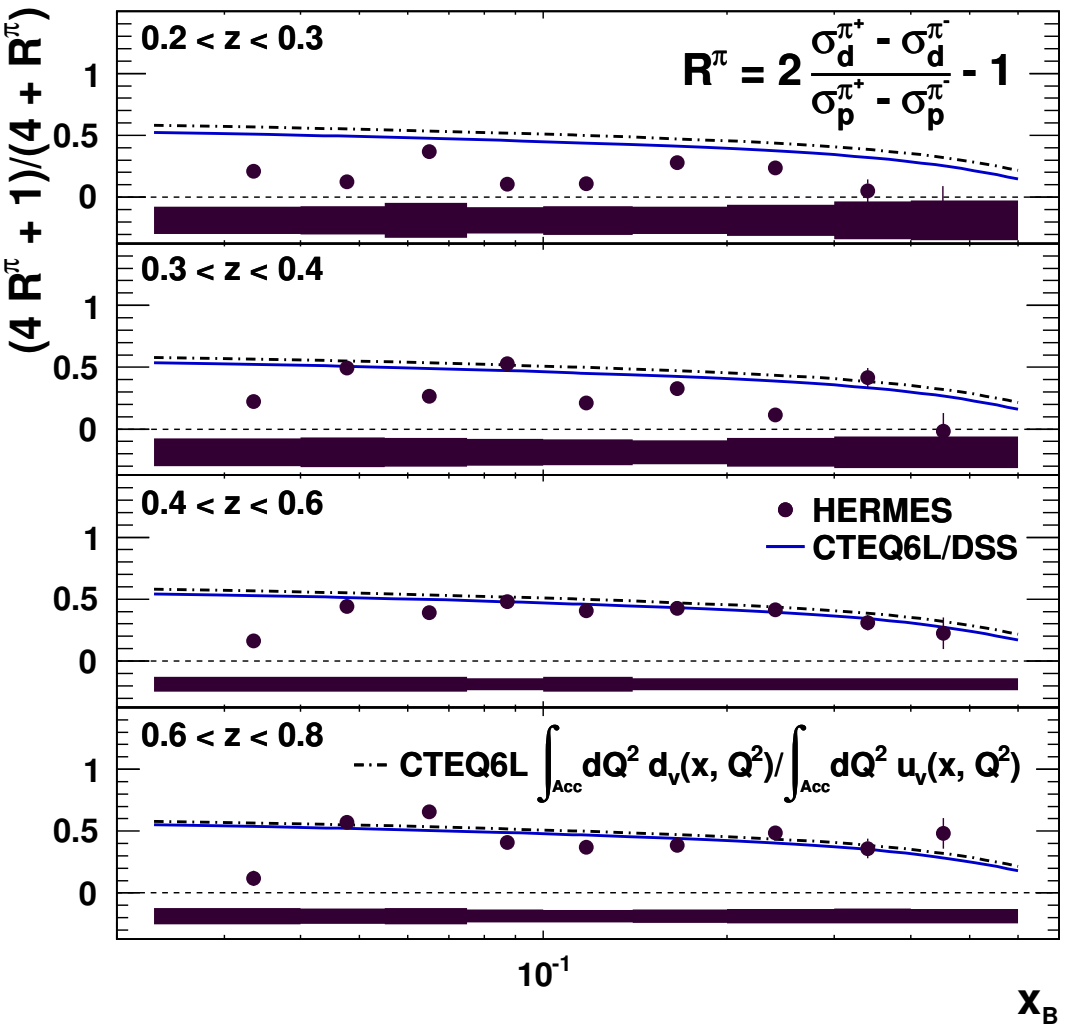
- Reflects different valence quark content
- **Improved precision by cancellations** in the systematic uncertainty

BACKUP: Effect of the correction for exclusive VM



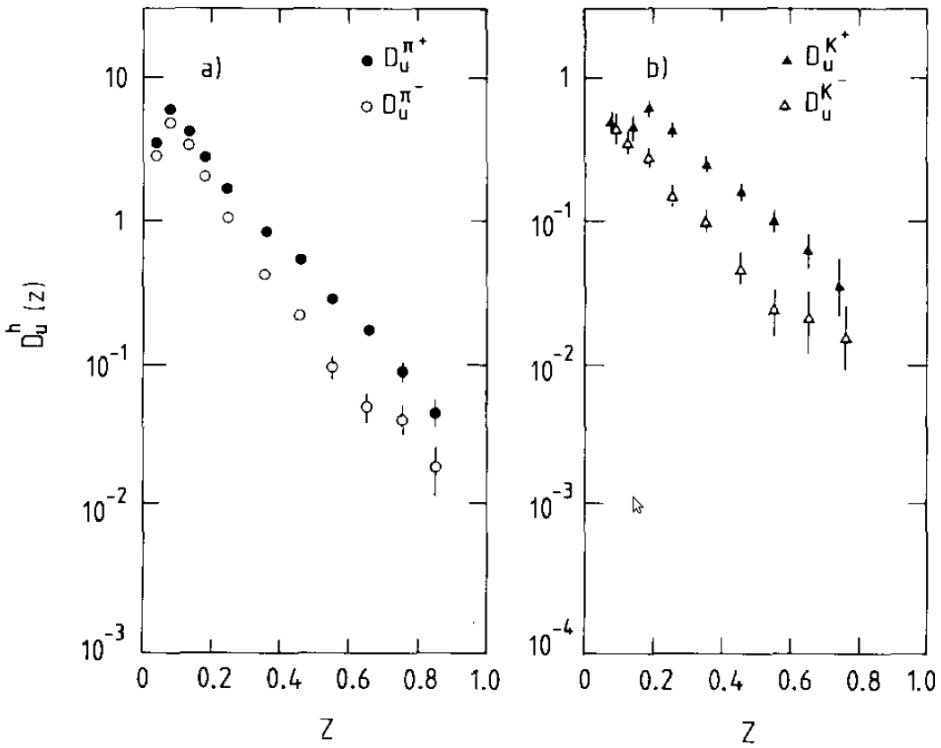


BACKUP: Pushing the envelope



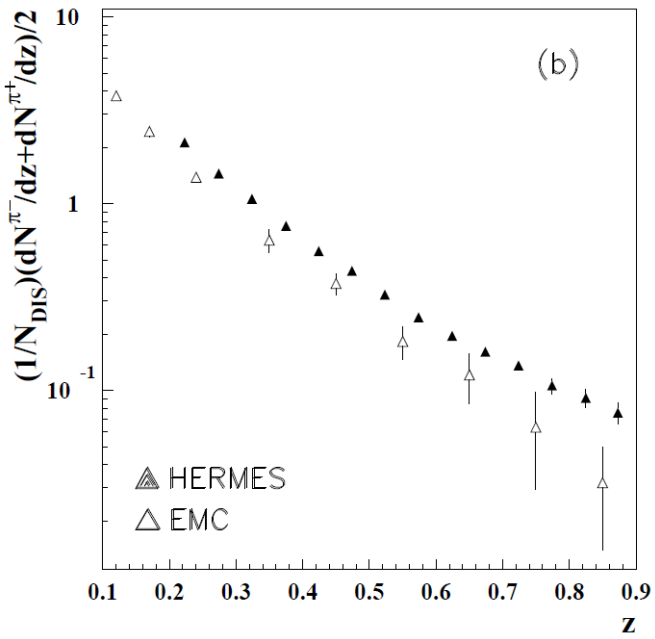
- Discrepancy is a function of z
- Lessons
  - More **precise knowledge of FF symmetries** required
  - Possible **target remnant** influence should be carefully **considered** when analyzing data near the **low-z** limit
  - The framework holds surprizingly well mid-to-high z at intermiate energies

BACKUP: SIDIS Multiplicities: Historical



EMC FFs

Nucl.Phys. B321 (1989) 541



HERMES multiplicities

1996-97 data

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