Overview of Fragmentation Function Measurements at HERMES

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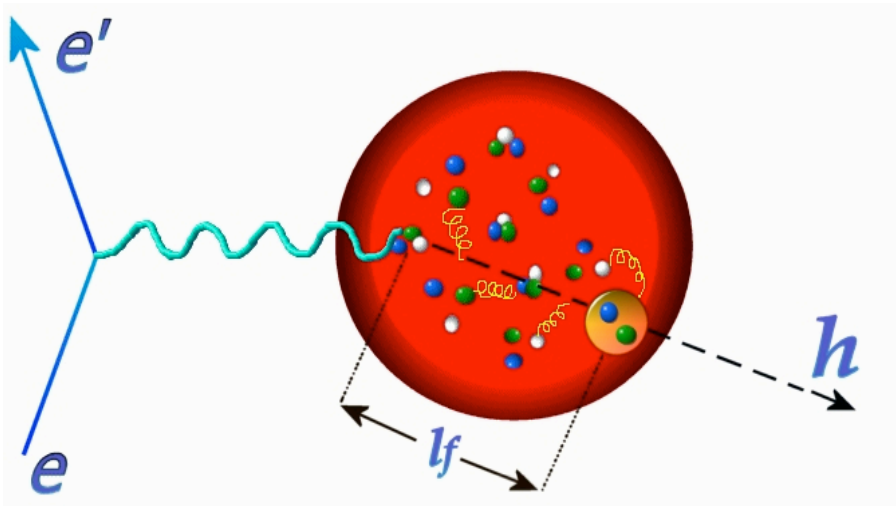
University of Illinois at Urbana-Champaign
Workshop on High-pT and Jet Physics, BNL, Jun 20, 2005

Outline

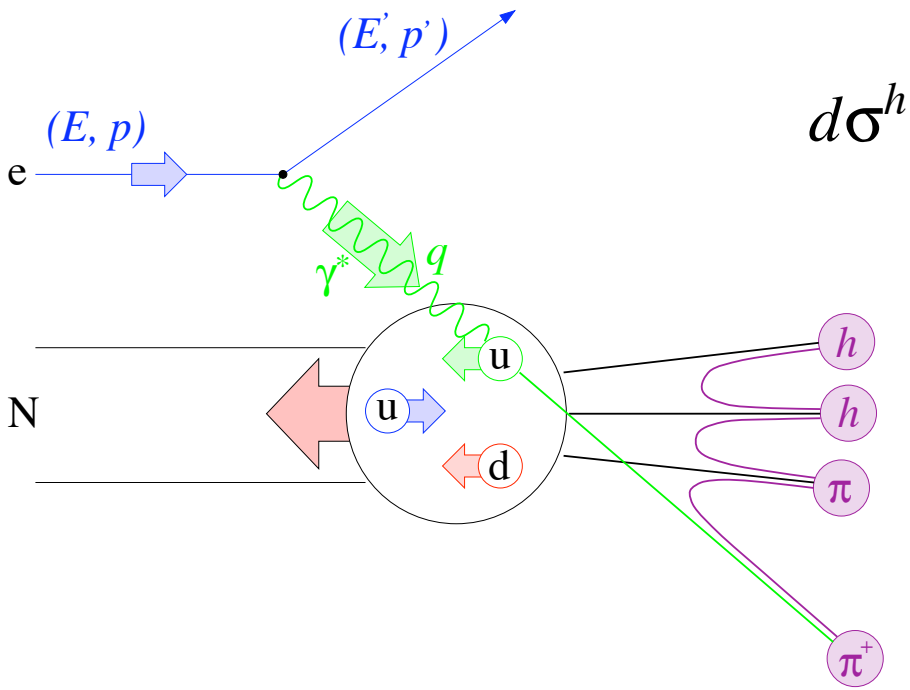
- *Intro: Fragmentation Functions*
- *The HERMES Experiment*
- *Latest multiplicities from HERMES Run 1 (hydrogen target)*
- *Fragmentation in heavy nuclear targets: a quick overview*



Thanks to Bino Maiheu, Pasquale diNezza & Andy Miller for slides!

Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

*In SIDIS, a **hadron h** is detected in **coincidence** with the scattered lepton:*



Factorization of the cross-section:

$$d\sigma^h \sim \sum_q e_q^2\, q(x) \cdot \hat{\sigma} \cdot D^{q\to h}(z)$$

The perturbative part

Cross-section for elementary photon-quark ***subprocess***

Large energies ➡ asymptotic freedom
➡ can calculate!

The Distribution Function

momentum ***distribution of quarks q*** within their proton bound state

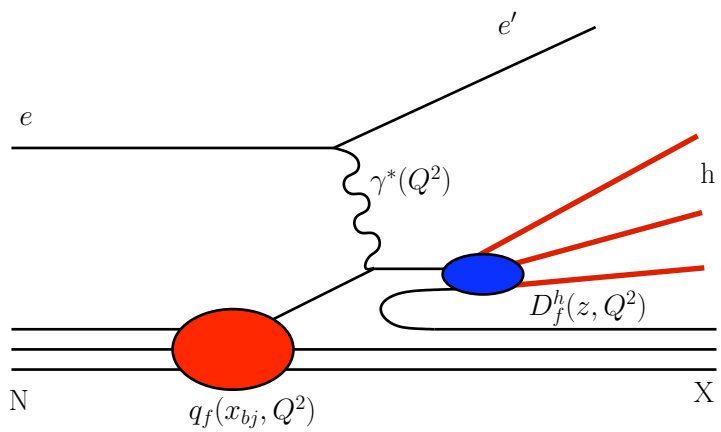
➡ **lattice QCD** progressing steadily

The Fragmentation Function

momentum ***distribution of hadrons h*** formed from quark *q*

➡ not even lattice can help ...

Mission statement



- SIDIS : $e + N \rightarrow e' + h + X$
- how do partons inside the nucleon break free to form hadrons ?
- described by $D_f^h(z, Q^2)$
- scale Q^2, momentum fraction x_{bj}
- $z = E_h/\nu$, where $\nu = E - E'$

flavor/charge separated hadron multiplicities

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

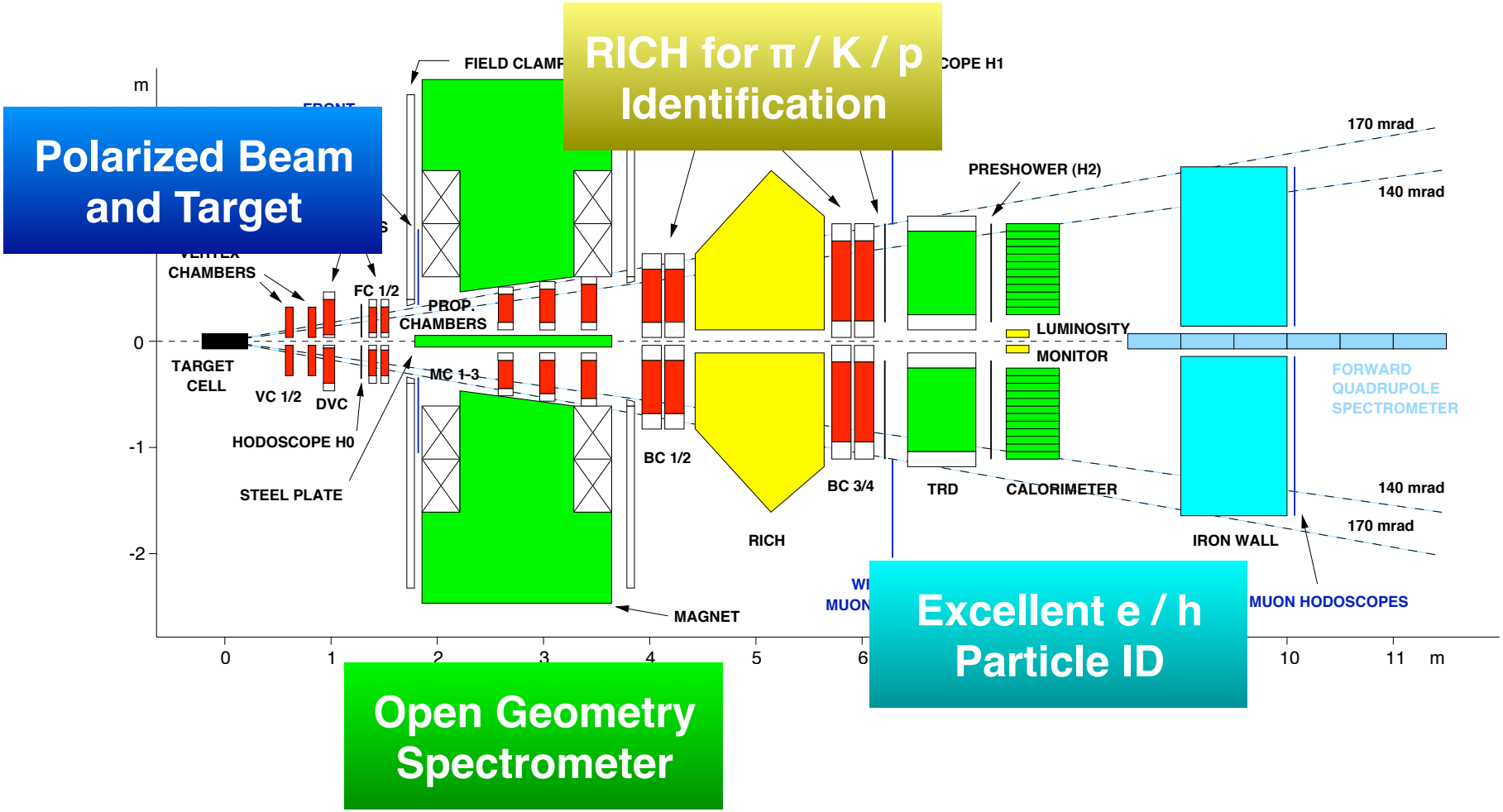
Motivation

- flavor separation of multiplicities : HERMES allows us to do this (RICH)
- Importance of this study at HERMES ?
  - test factorization at HERMES energies $\sqrt{s} \approx 7$ GeV
  - study fragmentation functions that were developed for e^+e^- at high energies
    $\rightsquigarrow$ still valid at $\langle Q^2 \rangle$ of 2.5 GeV^2 ?

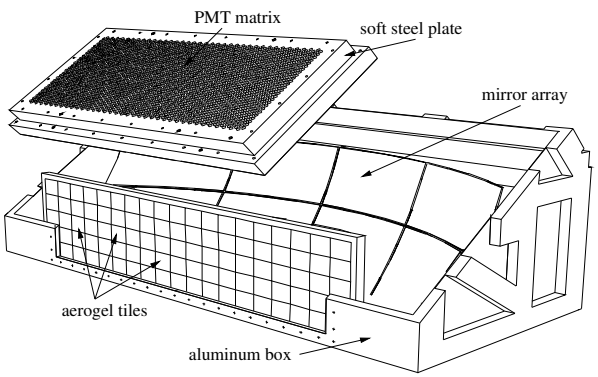
Challenges

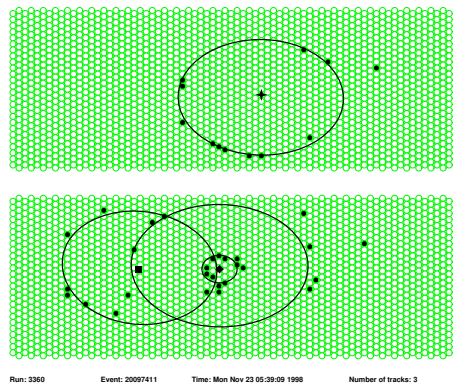
- note : exclusive VM production $\rightsquigarrow$ contribution of hadrons in SIDIS sample. Totally different process ! $\leftarrow$ correct for this.
- aim is to extract absolute numbers : difficult with HERMES acceptance !

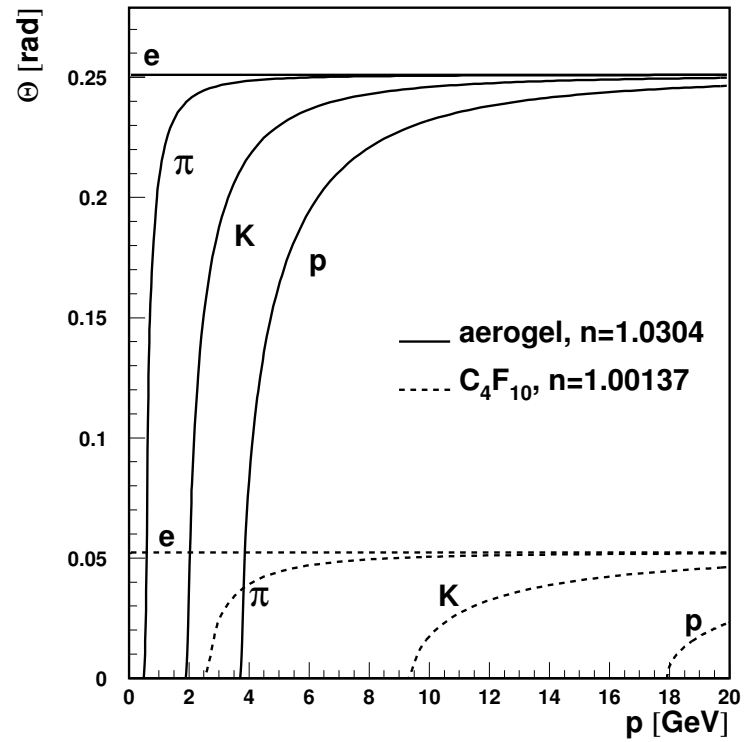
The HERMES Experiment



RICH particle identification







- $\cos\theta_c = \frac{c}{nv} = \frac{1}{\beta n}$
- two radiators: aerogel and C_4F_{10}
- cone projections and reconstruct Čerenkov angles (Ray Tracing)
- first dual radiator RICH

HERMES Run I: Data Taking

Longitudinally Polarized Target

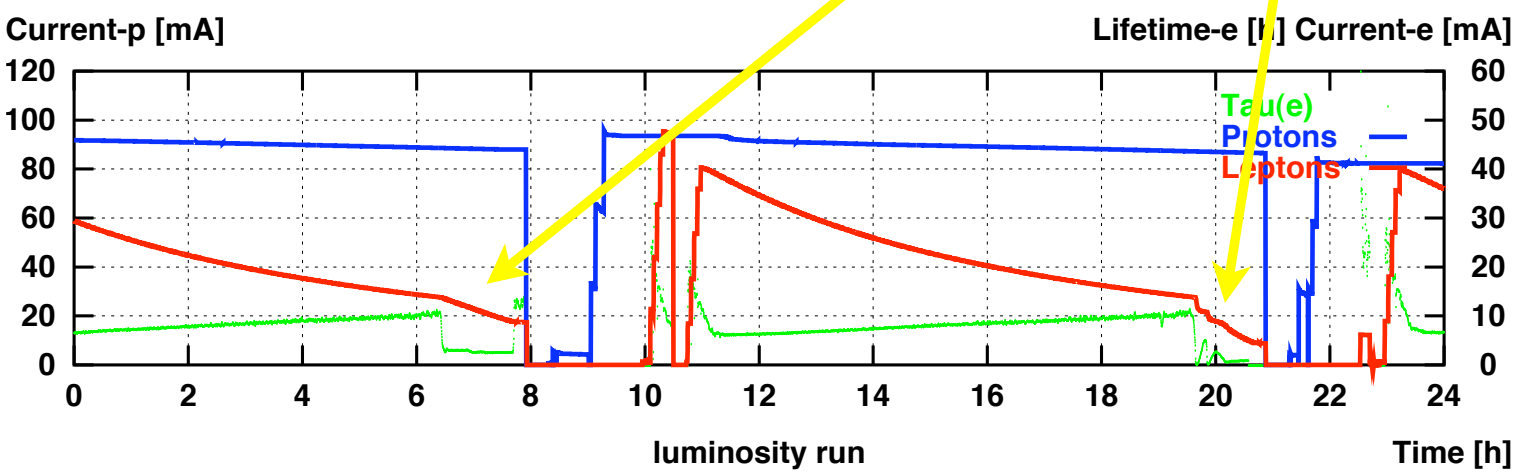
- 1995: ^{3}He target → 3 M DIS
- 1996-97: H target → 2.5 M DIS
- 1998-2000: D target & ***RICH detector***

  → $\pi/K/p$ separation ... and ***8 M DIS!***

Unpolarized Data Taking

- 1996-97: H, D, ^{3}He → 10 M DIS
- 1997: ^{14}N → 2.2 M DIS
- 1998-2000: H, D, ^{4}He, ^{14}N, ^{20}Ne, ^{84}Kr → ***18 M DIS!***

Last part of each fill is now dedicated to **high-density unpolarized** runs

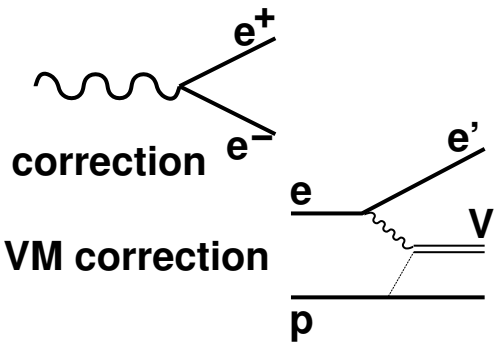


Analysis Overview

Enormous analysis effort by
Elke Aschenauer, Achim Hillenbrand, Bino Maiheu

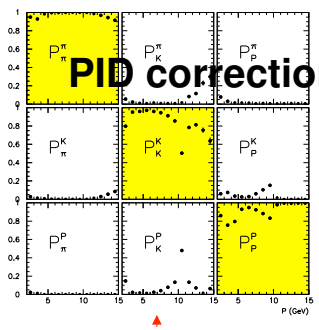
HERMES data production

background correction



2

excl. VM correction

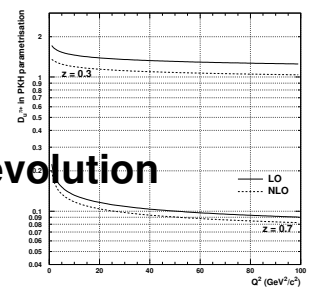


PID correction

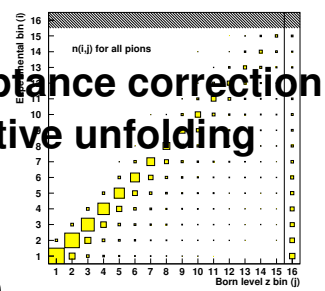
1

experimental multiplicities

Q^2 evolution



acceptance correction
radiative unfolding



3

monte carlo

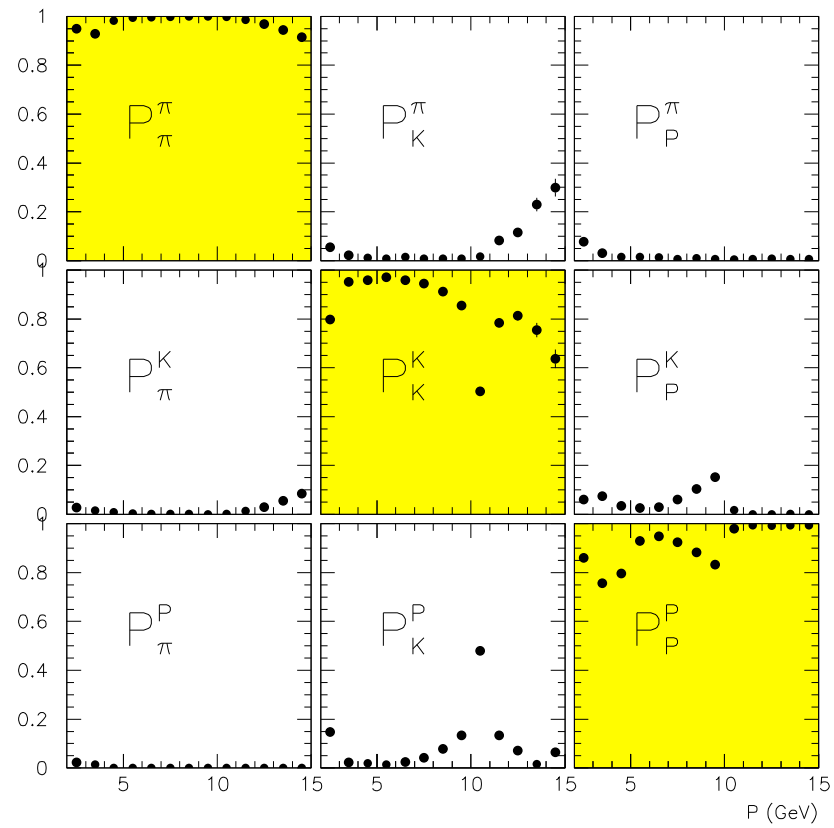
born level multiplicities

Hadron PID correction 1

- important : extracting absolute numbers
- correct for misidentification
- $\mathcal{P}_t^i$: *probability that a particle of type t was identified as type i.*

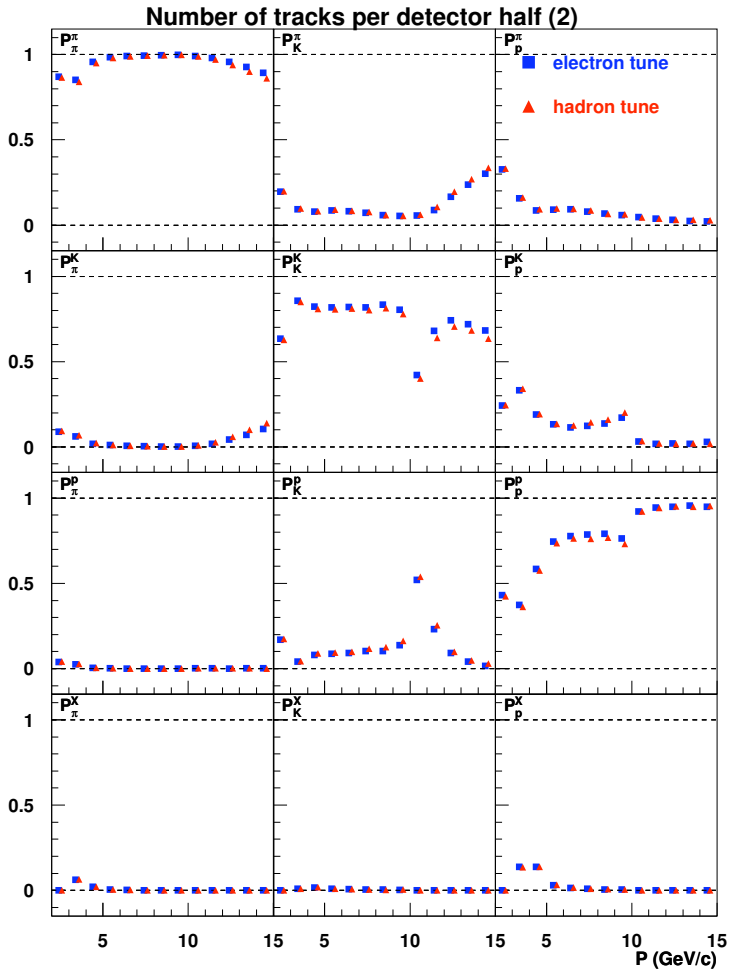
$$\begin{pmatrix} I_\pi \\ I_K \\ I_P \end{pmatrix} = \begin{pmatrix} \mathcal{P}_\pi^\pi & \mathcal{P}_K^\pi & \mathcal{P}_P^\pi \\ \mathcal{P}_\pi^K & \mathcal{P}_K^K & \mathcal{P}_P^K \\ \mathcal{P}_\pi^P & \mathcal{P}_K^P & \mathcal{P}_P^P \end{pmatrix} \cdot \begin{pmatrix} N_\pi \\ N_K \\ N_P \end{pmatrix}$$

- $\mathcal{P}$ obtained from GEANT3 description of RICH
- $\vec{N} = \mathcal{P}_{trunc}^{-1} \cdot \vec{I}$
- $\rightsquigarrow$ weight for hadron tracks



P matrices binned in momentum & track multiplicity / detector half

Performance modeling of the RICH



non-perfect knowledge of the response of the RICH ⇝ systematic uncertainty

only one RICH :-) ⇝ no independent check for hadron efficiency over full momentum range and for different event topologies

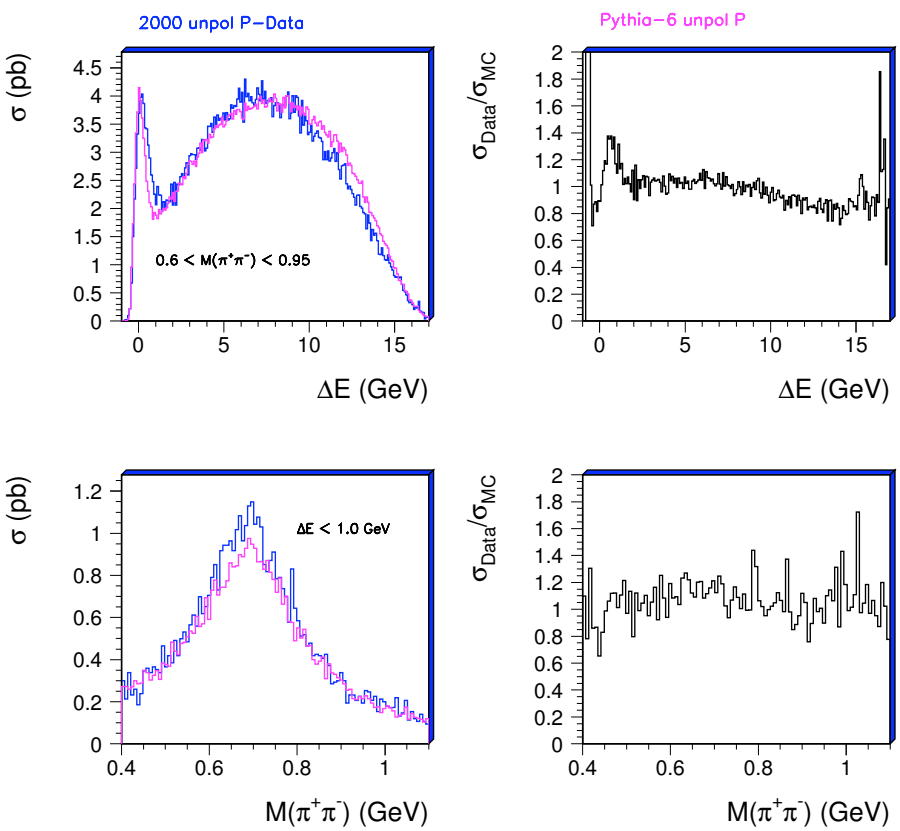
2 tunes in RICH MC description :

- $\beta = 1$ particles : tune Čerenkov angle and photon yield distributions with electrons
- hadrons : tune using decaying particles (ϕ, K_S, Λ) from PYTHIA and data

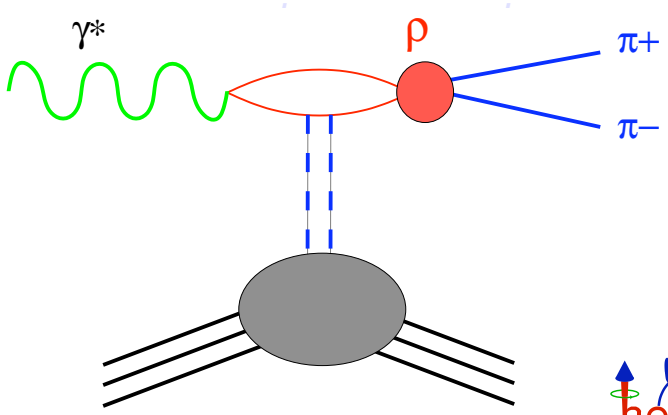
⇒ systematic uncertainty on the $\mathcal{P}$ matrix

Contamination from exclusive VM processes

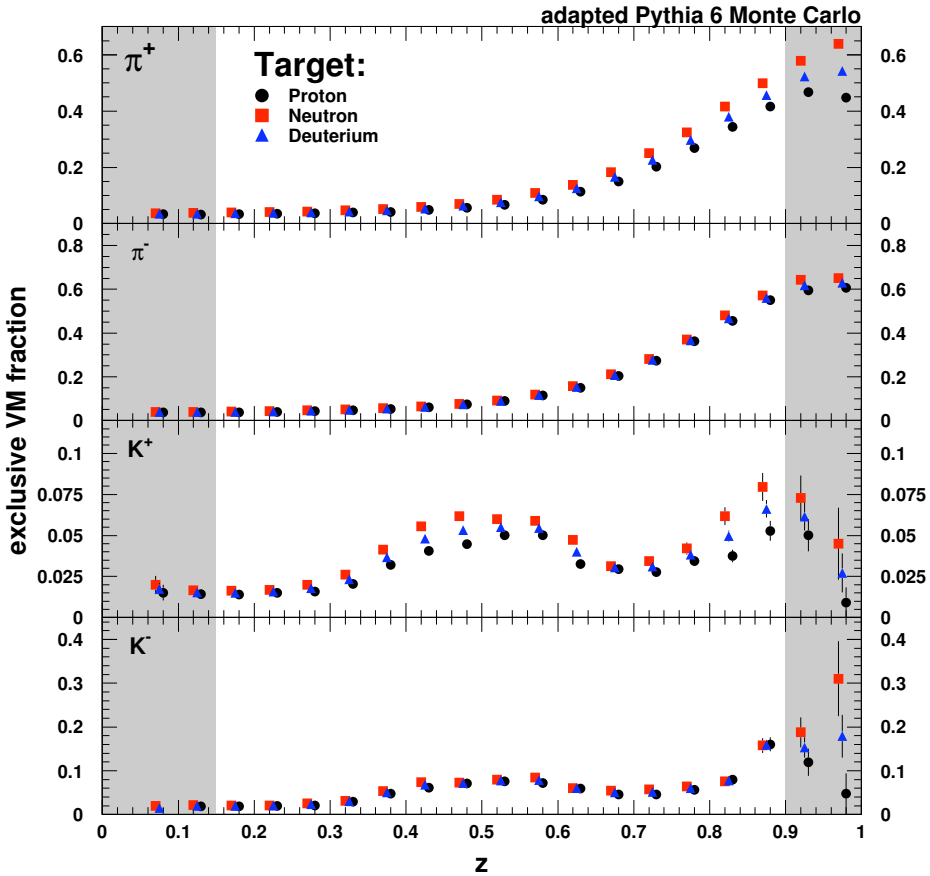
2



- exclusive VM production : totally different process than SIDIS.
- estimate contribution from MC (VMD+SIDIS): PYTHIA 6 (adapted e.g. RADGEN)



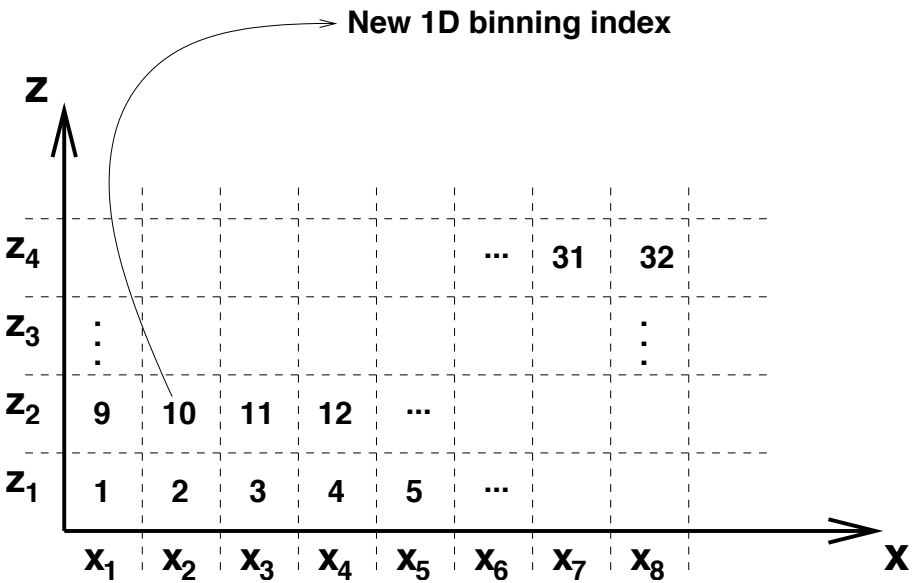
Contamination from exclusive VM processes



- exclusive VM production : totally different process than SIDIS.
- estimate contribution from MC (VMD+SIDIS): PYTHIA 6 (adapted e.g. RADGEN)
- ratio : $N^h_{diffr}(z)/N^h_{SIDIS}(z)$
- large contribution at high z ($\sim$ 40 - 50 %) for π
- kaons only contribution of about 10 %

Smearing/Acceptance correction 3

Smearing moves events from one kinematic bin into another. The flow is represented by $S(i,j)$ $\longrightarrow$ aim is to move the events back !



2D-binning of smeared SIDIS events in both x and z

- smearing involves both detector effects (track reconstruction) as well as QED radiative corrections
- treat all of the smearing with acceptance correction in one go
- reduce model dependency $S(i,j) = n(i,j)/n^B(j)$
- clear treatment of the uncertainties involved

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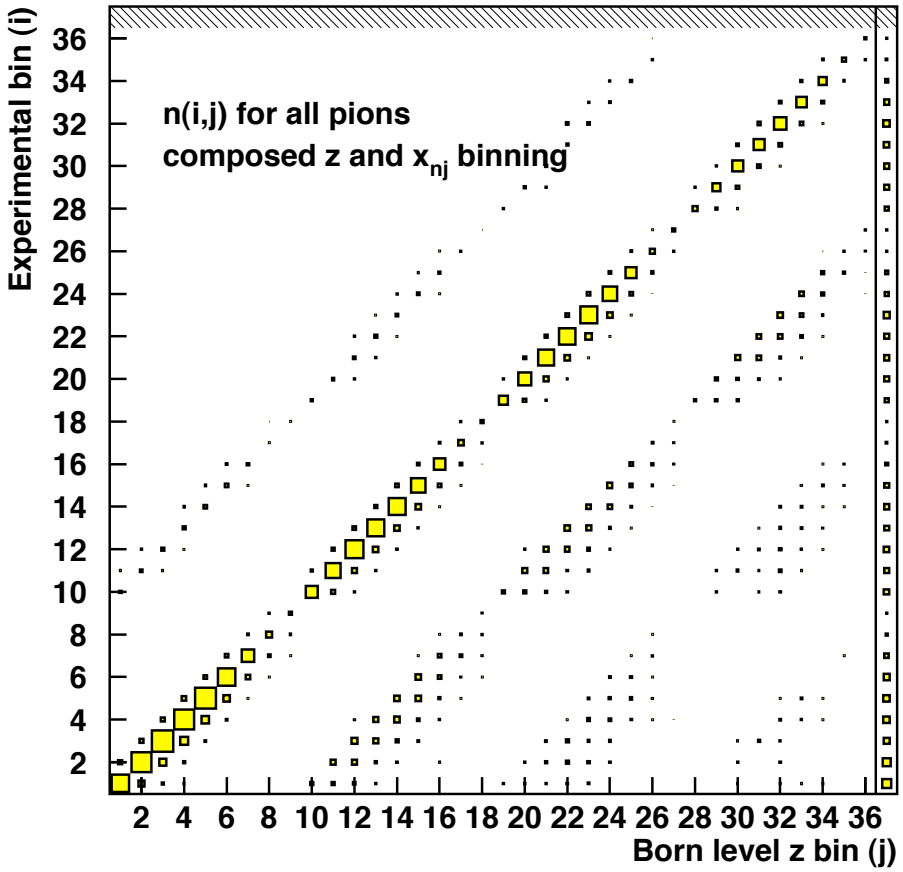

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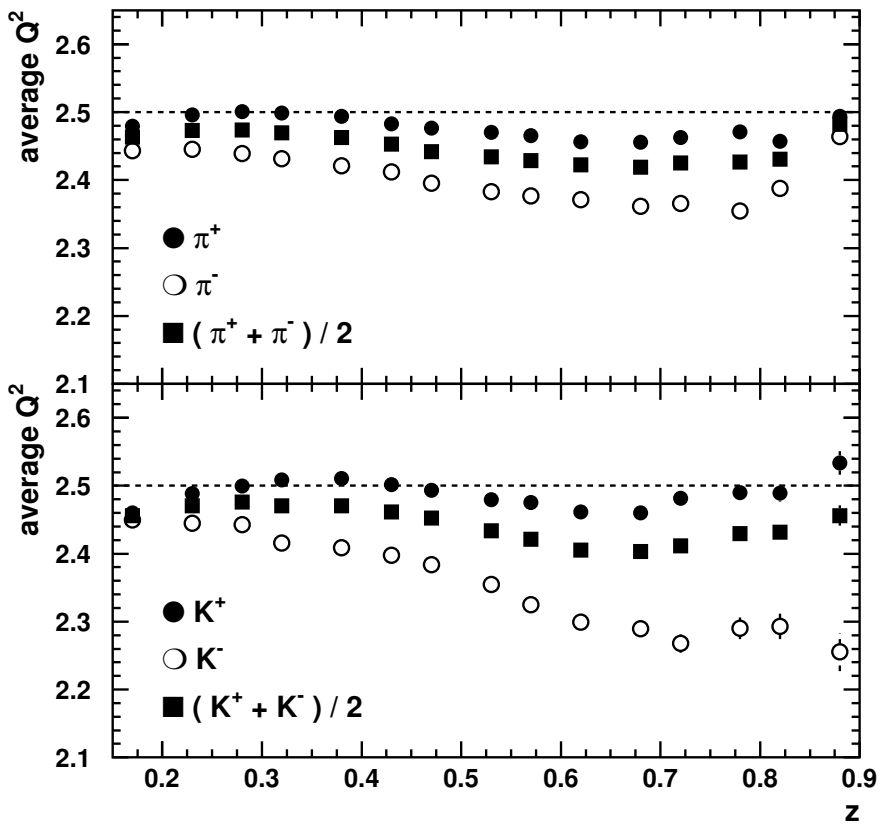
Another small word about the MC sample

- Use LEPTO generator together with the JETSET model
- * JETSET tune :
- parton distribution parametrization in MC : CTEQ6
- QED radiative corrections : RADGEN
- Detector was described by either
  - Full GEANT3 description + tracking code
  - Smearing generator (track lookup + kinematical smearing p, θ_x, θ_y, ...)

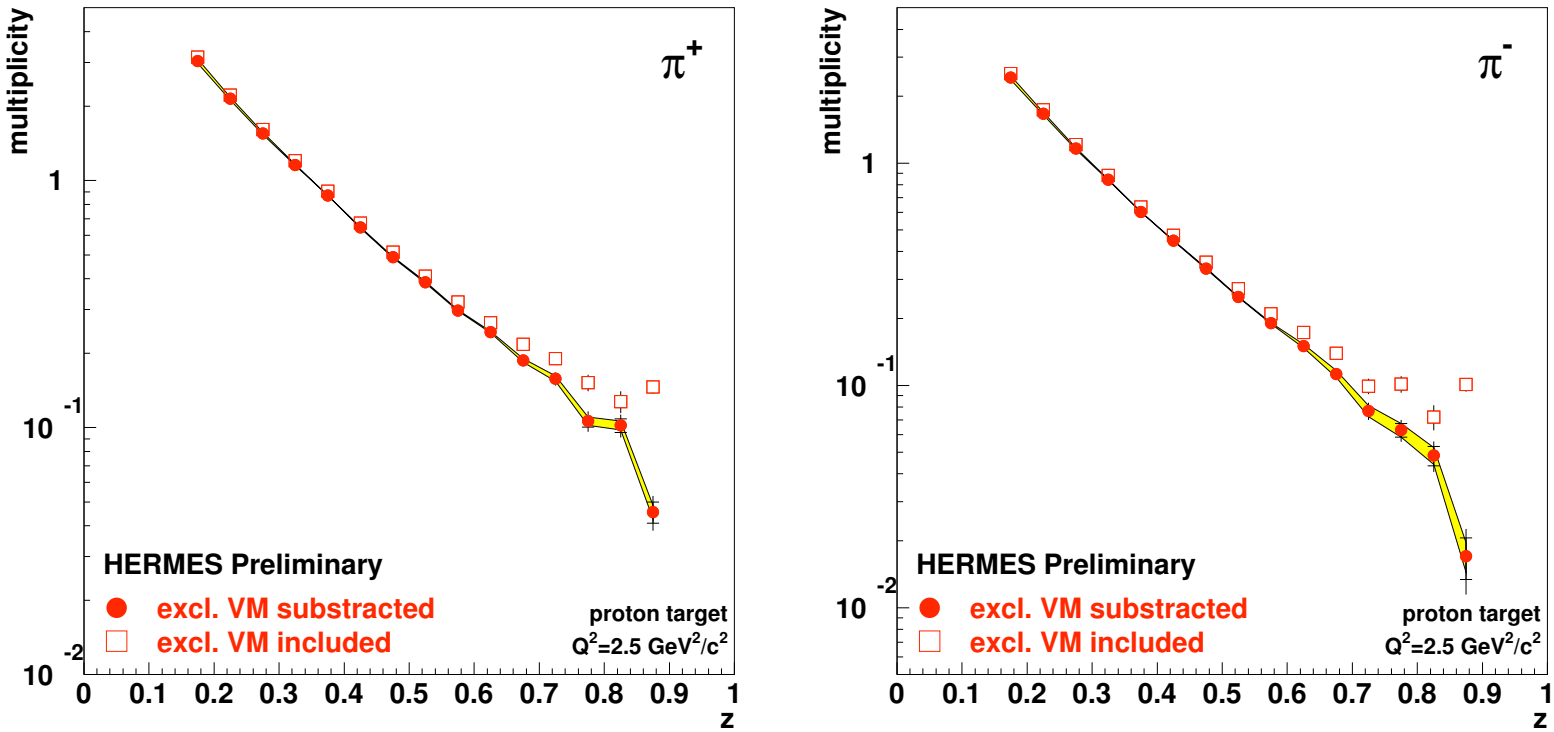
* Jetset carefully **tuned** to yields within HERMES acceptance ... various tunes used to estimate **systematic error** on acceptance correction (**small**)

Q^2 evolution



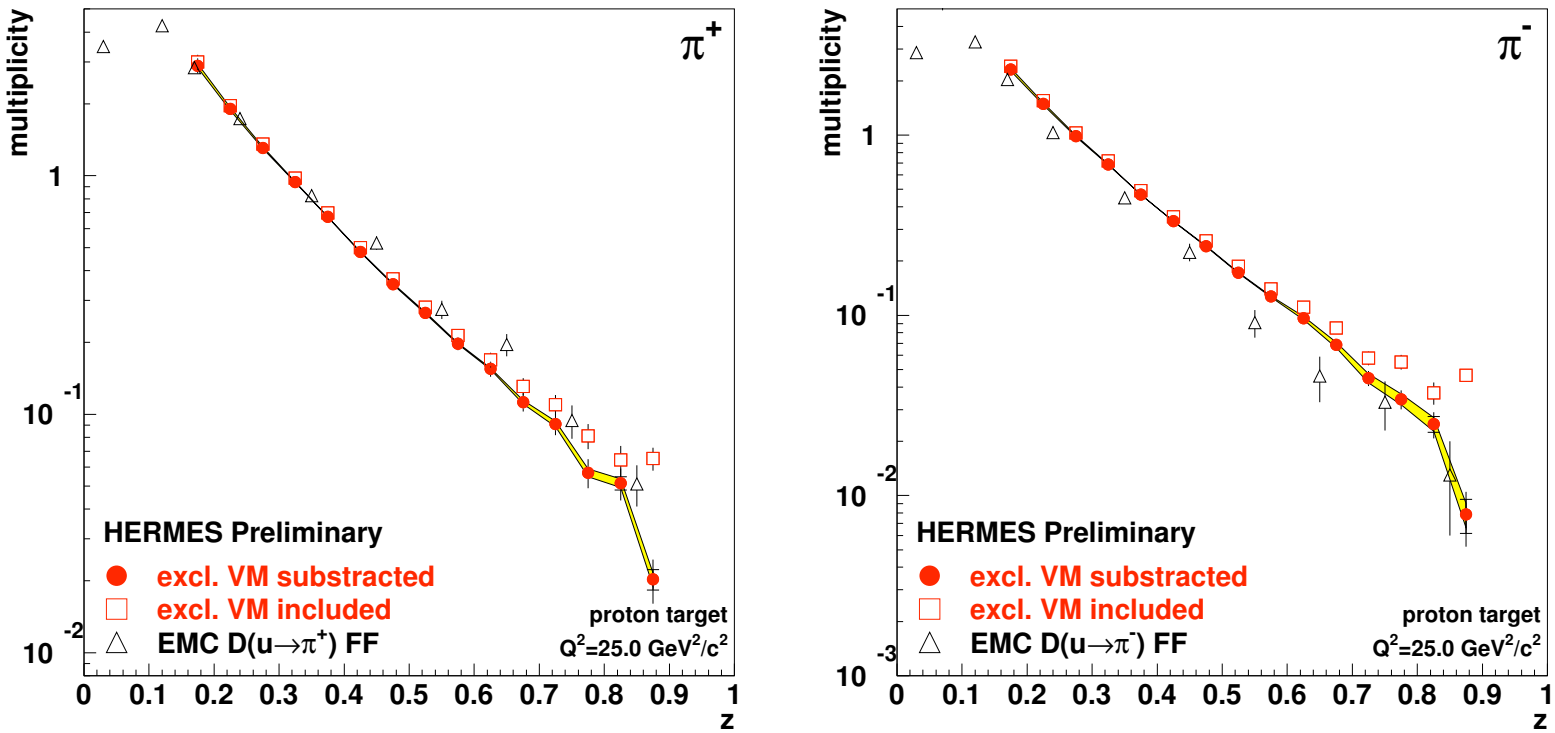
- $$\frac{\sum_f e_f^2 \int_0^1 dx\, q_f(x,Q^2) D_f^h(z,Q^2)}{\int_0^1 \frac{dx}{x} F_2(x,Q^2)}$$
- Q^2 variation small in z, but... e.g. vs. x_{bj}
- want to compare to EMC ($Q^2 \approx 25$)
- use PKH (Kretzer) parametrization + CTEQ6 $\overline{\text{MS}}$
- systematic error on the correction factor (ALLM, integration, PDF set, NLO FF)
- vs z : $\sim 1-2\%$ ($Q_0^2 \sim 2.5$), up to 50 % ($Q_0^2 \sim 25$)
- vs x_{bj} : up to 50 %

Results for pions :: multiplicity versus z



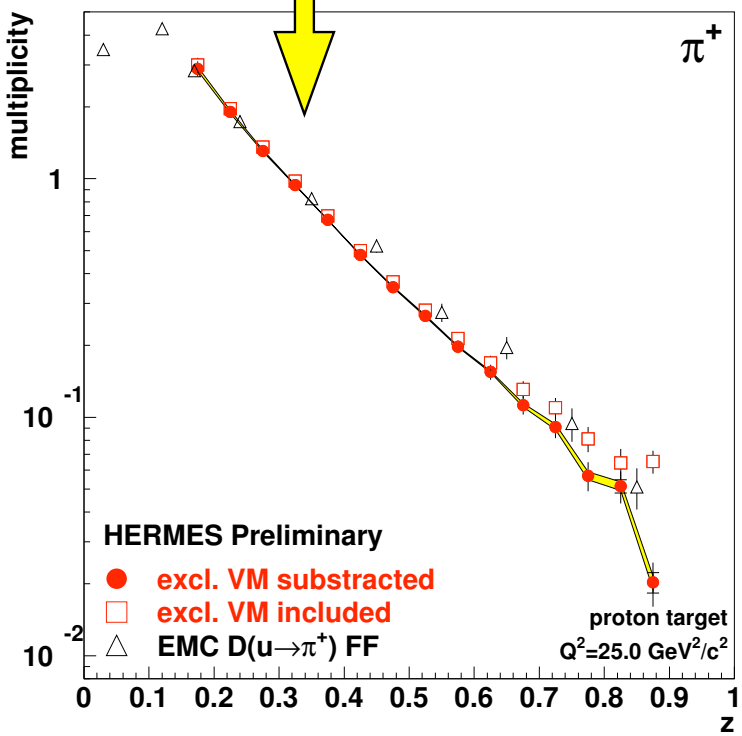
- Systematic uncertainty mainly from hadron PID correction
- $Q^2 > 1$ GeV^2, $W^2 > 10$ GeV^2

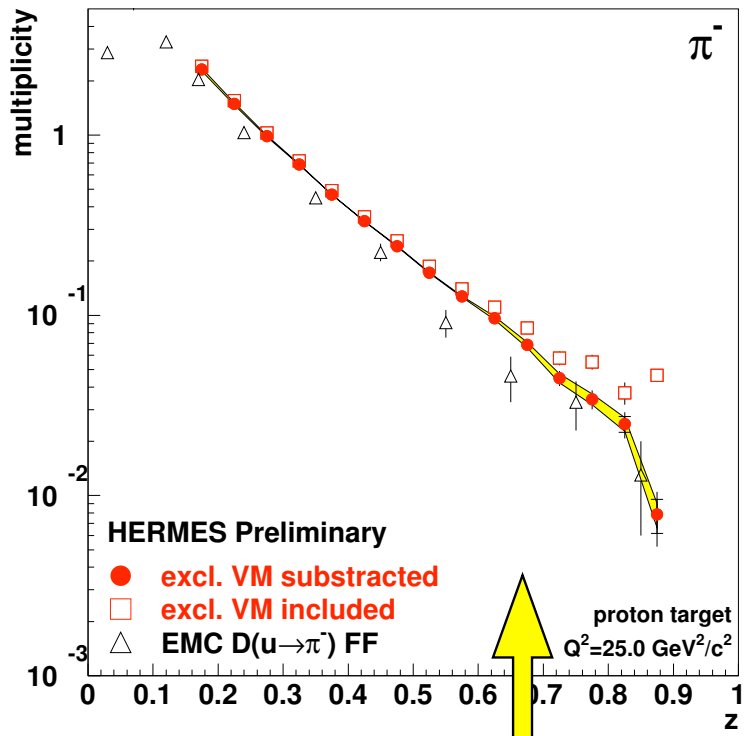
Results for pions :: multiplicity versus z ($Q_0^2 = 25$ GeV^2)



- Comparison with EMC, Nucl. Phys. **B321** (1989) 541-560
- EMC: $D_u^{\pi^\pm}$

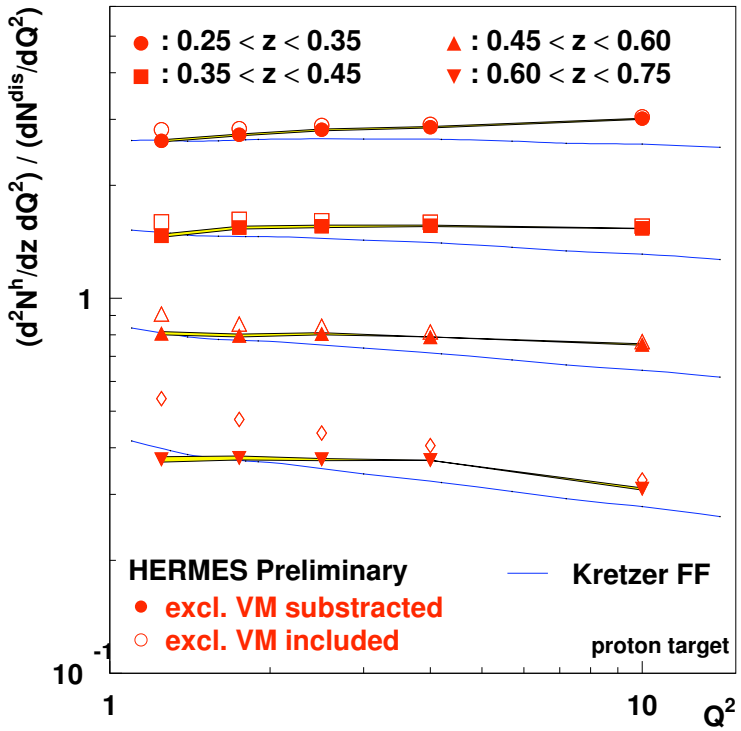
$$\frac{1}{N_{\mathrm{DIS}}}\frac{dN^{\pi^+}}{dz} = \frac{(4u+\bar{d})D_1 + (d+4\bar{u})D_2 + (s+\bar{s})D_s}{4u+d+4\bar{u}+\bar{d}+s+\bar{s}} \approx D_1 \quad (Q_0^2 = 25\ \mathrm{GeV}^2)$$

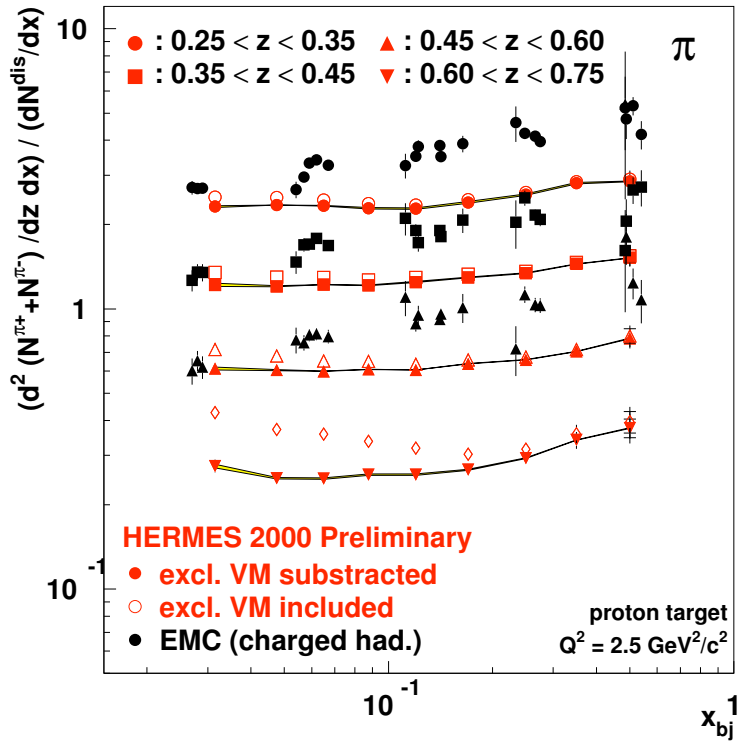




$$\frac{1}{N_{\mathrm{DIS}}}\frac{dN^{\pi^-}}{dz} = \frac{(4u+\bar{d})D_2 + (d+4\bar{u})D_1 + (s+\bar{s})D_s}{4u+d+4\bar{u}+\bar{d}+s+\bar{s}} \approx \frac{4u\,D_2 + d\,D_1}{4u} > D_2$$

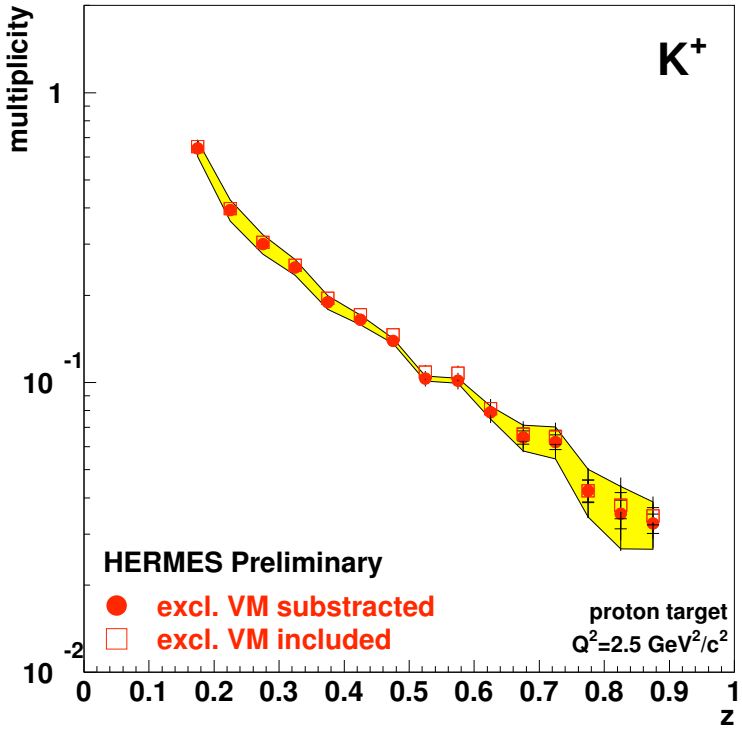
$$\frac{1}{N_{\mathrm{DIS}}}\frac{dN^{(\pi^+ + \pi^-)}}{dz} = \frac{(4u+d+4\bar{u}+\bar{d})(D_1+D_2)+2(s+\bar{s})D_s}{(4u+d+4\bar{u}+\bar{d})+(s+\bar{s})} \approx D_1(z)+D_2(z)$$

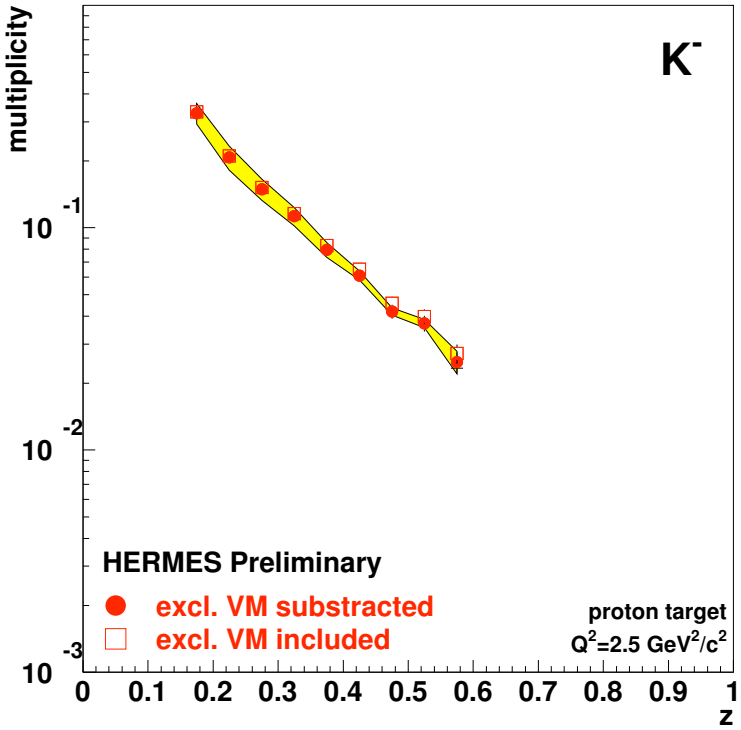




Very weak x-dependence: s-quark effects < 10% ...
NLO mixing of x,z dependences? *Slight* factorization breaking?

Results for kaons :: multiplicity versus z

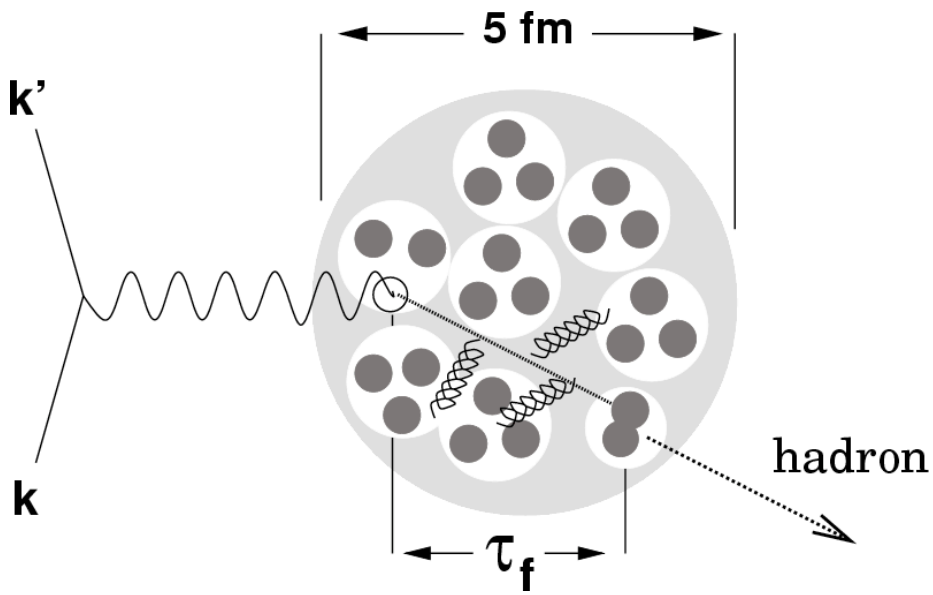




- charge separated kaon multiplicities
- systematic uncertainty (RICH)
- low K^- statistics, and note different scale !

The Space-Time Structure of Fragmentation

By embedding the fragmentation process within a nucleus, one can use the nuclear radius as a yardstick against which to measure the **time scale of hadron formation** .



Single Time Scale Model

Postulate: hadron formation time is a constant (τ_h), apply Lorentz boost

$$\tau_f = \tau_h \frac{E_h}{m_h} = \tau_h \frac{z\nu}{m_h}$$

$\rightarrow \tau_f$ depends on ν, and z, m_h

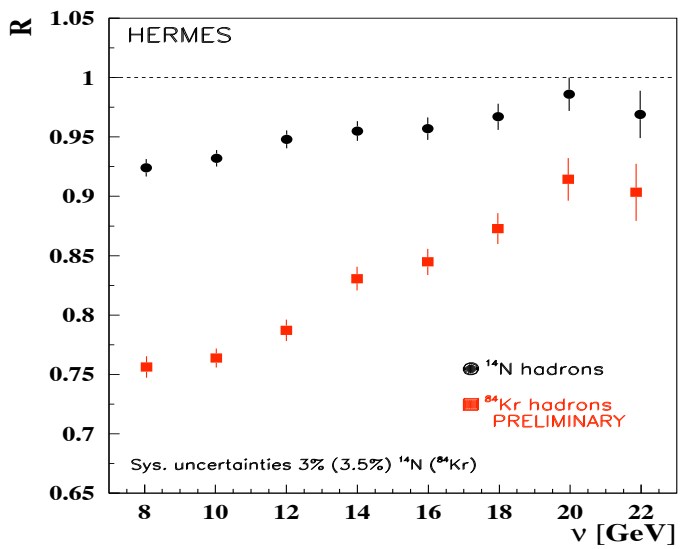
Once hadron is formed, will be suppressed by final state interactions with nuclear medium
$\Rightarrow$ study hadron multiplicity ratio

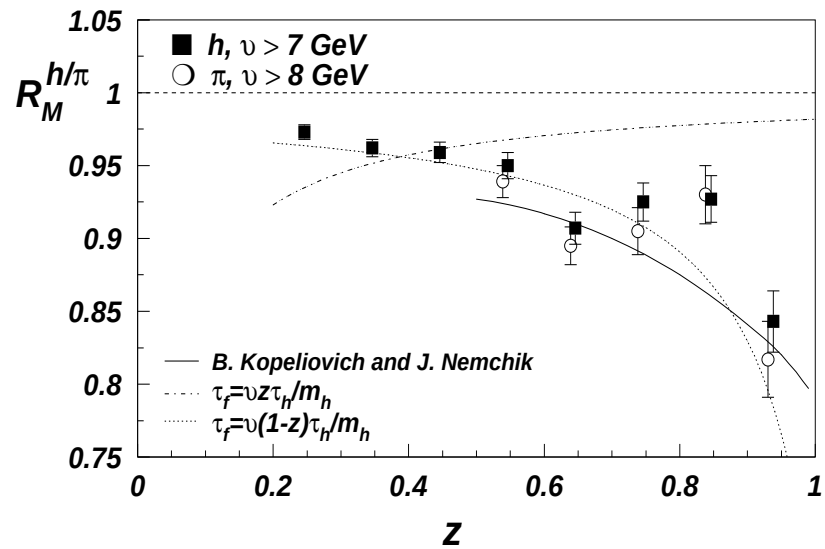
$$R_A^h(z,\nu) = \left(\frac{1}{N_e}\frac{d^2N_h}{dz\,d\nu}\right)_A \Big/ \left(\frac{1}{N_e}\frac{d^2N_h}{dz\,d\nu}\right)_D$$

Hadron Attenuation at HERMES

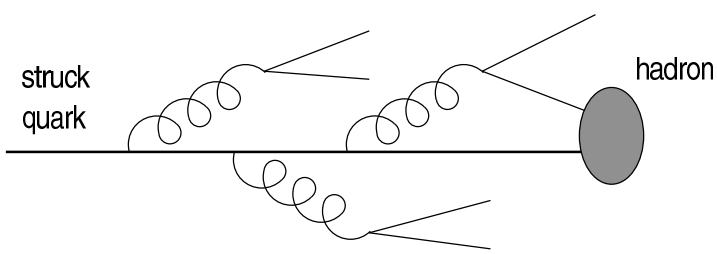
ν **dependence** shows the expected Lorentz behavior ...

However z **dependence** does ***not***





Gluon Bremsstrahlung Model



At high z:

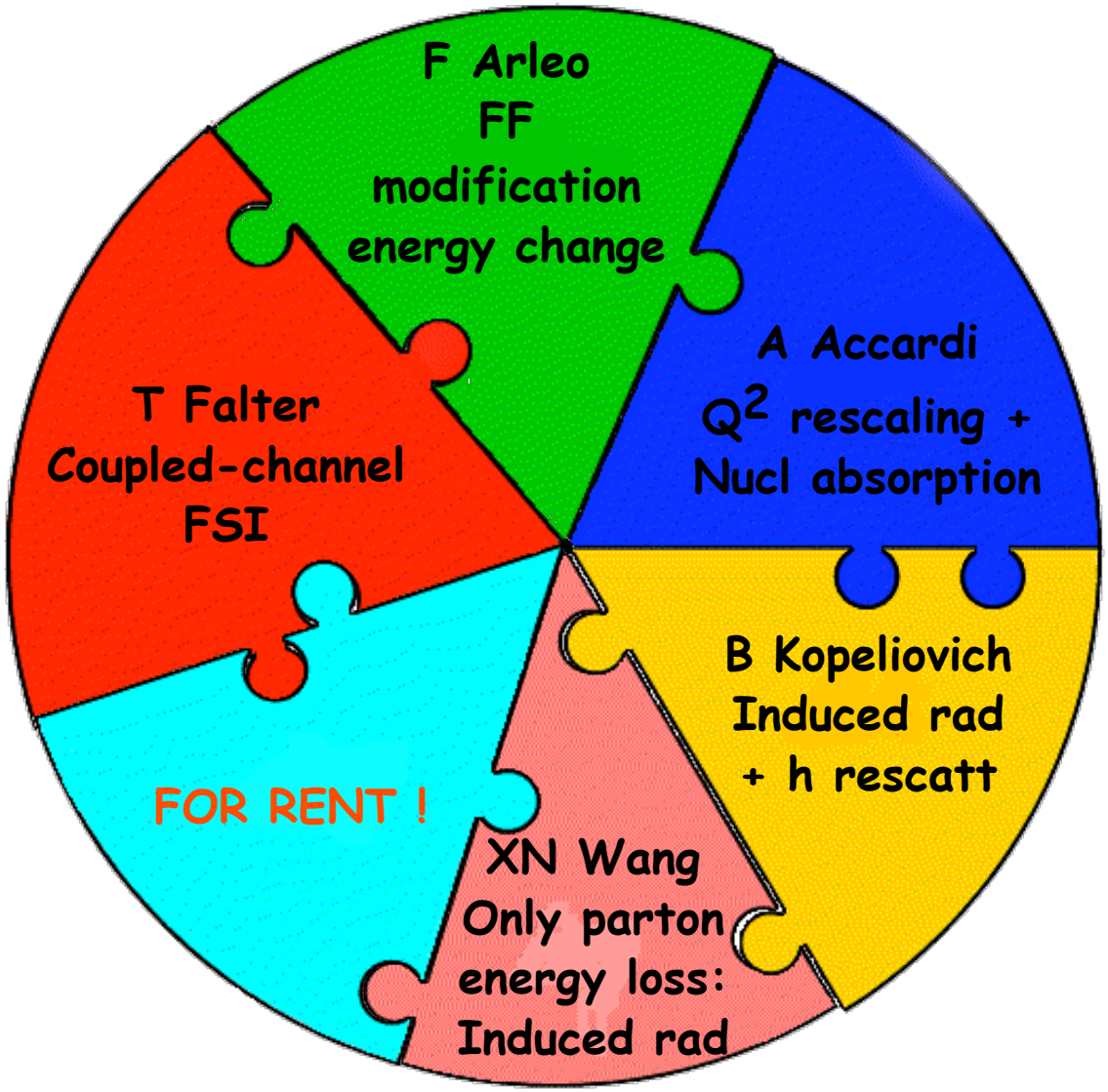
$\rightarrow$ few gluons radiated

$\rightarrow$ ***short*** formation time $\tau_f = \nu(1-z)c_h$

$\rightarrow$ larger attenuation by nuclear rescattering

N.C.R. Makins, ICHEP 2002, Amsterdam

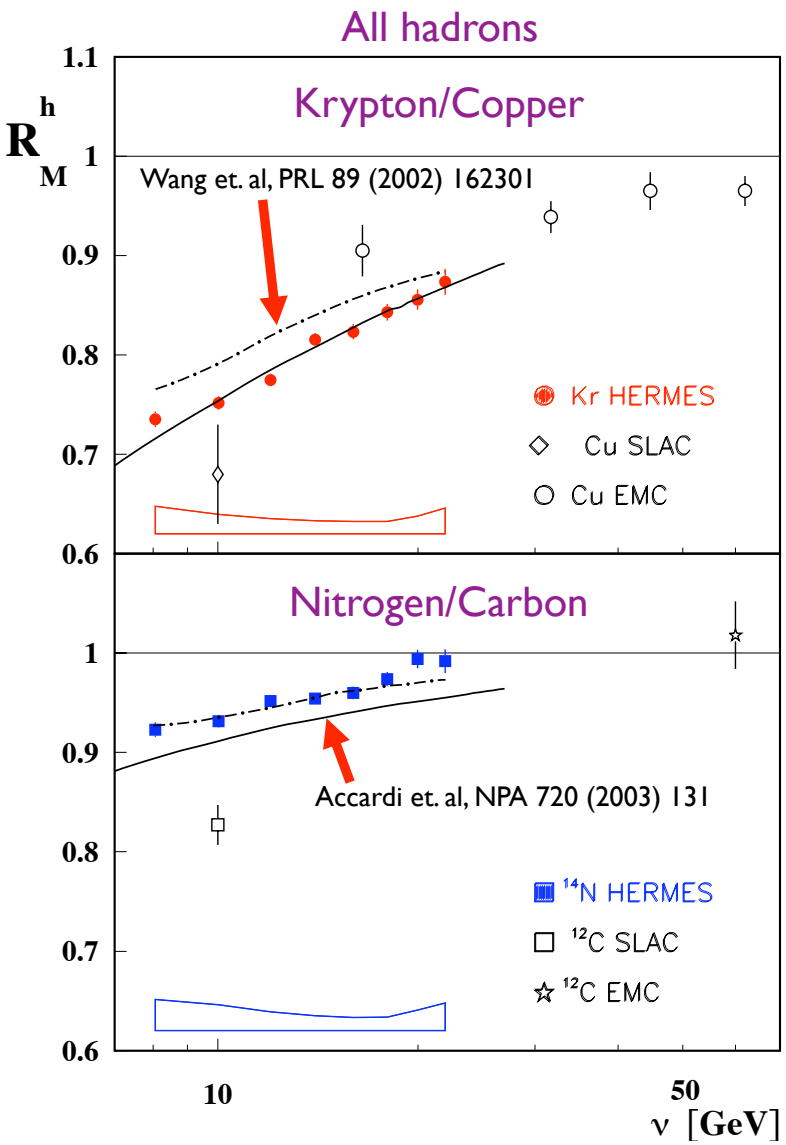
Theoretical Interpretations



They really don't fit together so nicely!

Nuclear Attenuation of Hadrons in DIS

The old and the new...



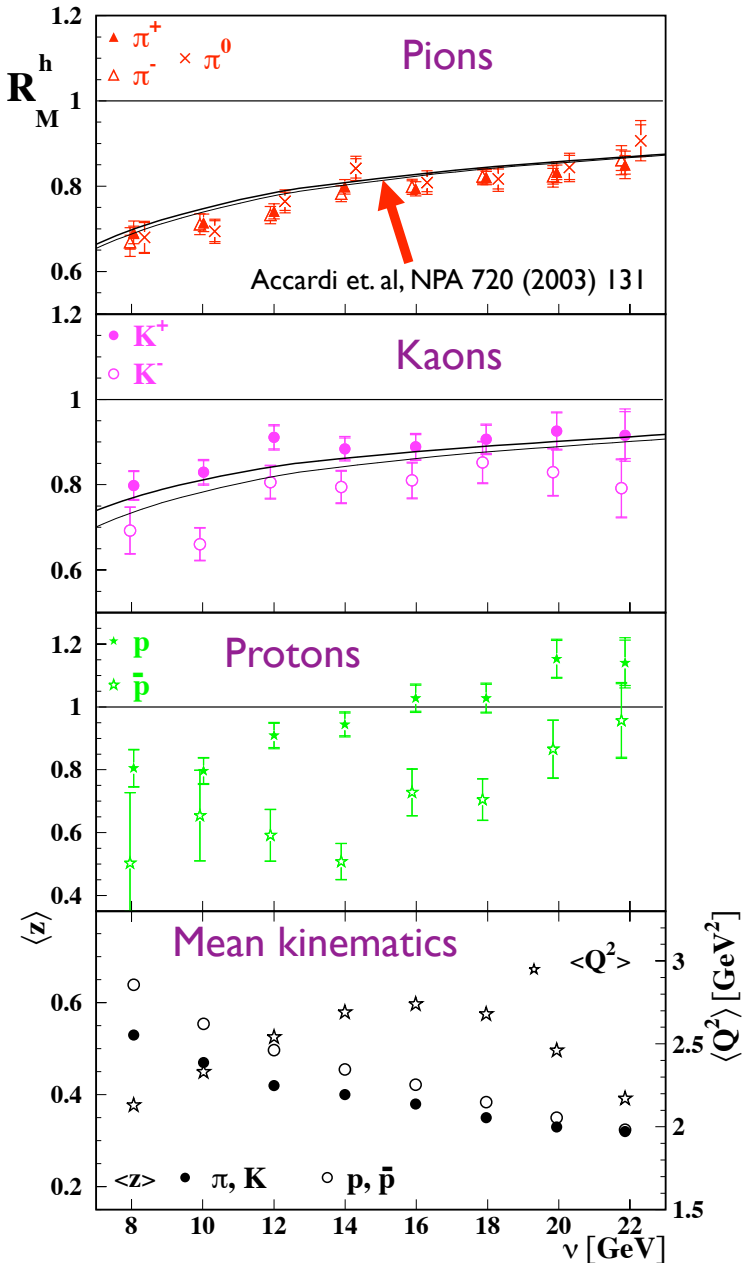
$$R_M^h(z,\nu,p_t^2,Q^2) \equiv \frac{\left.\dfrac{N_h(z,\nu,p_t^2,Q^2)}{N_e(\nu,Q^2)}\right|_A}{\left.\dfrac{N_h(z,\nu,p_t^2,Q^2)}{N_e(\nu,Q^2)}\right|_D}$$

- HERMES energy **ideal**: hadron formation lengths comparable to nuclear sizes
- Some basic model features:

(1) **before hadron formation**: parton energy loss / gluon bremsstrahlung / 'rescaling' of FF's

(2) **after hadron formation**: rescattering / absorption by nuclear medium

Identified hadrons: ν dependence on Krypton



Experimental findings:

- $\pi^+ = \pi^- = \pi^0 \sim K^-$

  $\sigma_{\pi+} = \sigma_{\pi-} = 25$ mb

- K^+ less attenuated than K^-

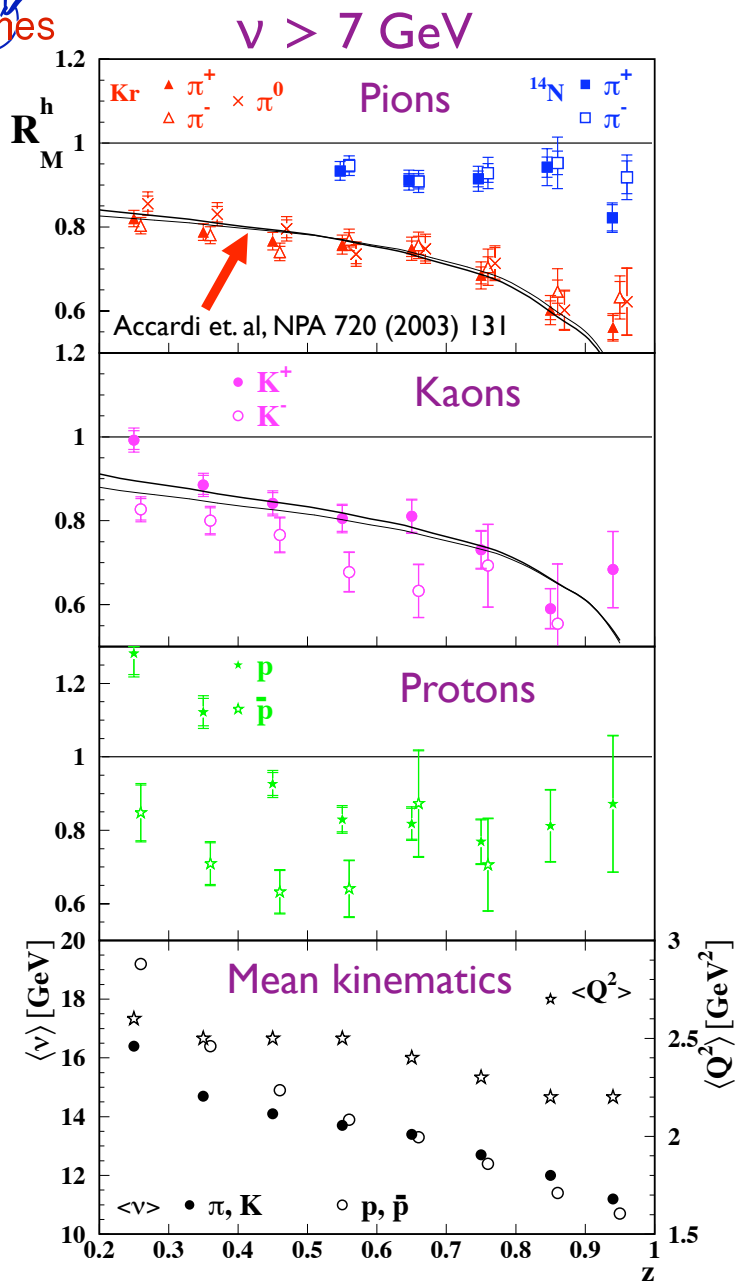
  $\sigma_{K+} = 17$ mb, $\sigma_{K-} = 23$ mb

- p less attenuated than $\bar{p}$, π, K

  $\sigma_p = 40$ mb, $\sigma_{p-} = 60$ mb

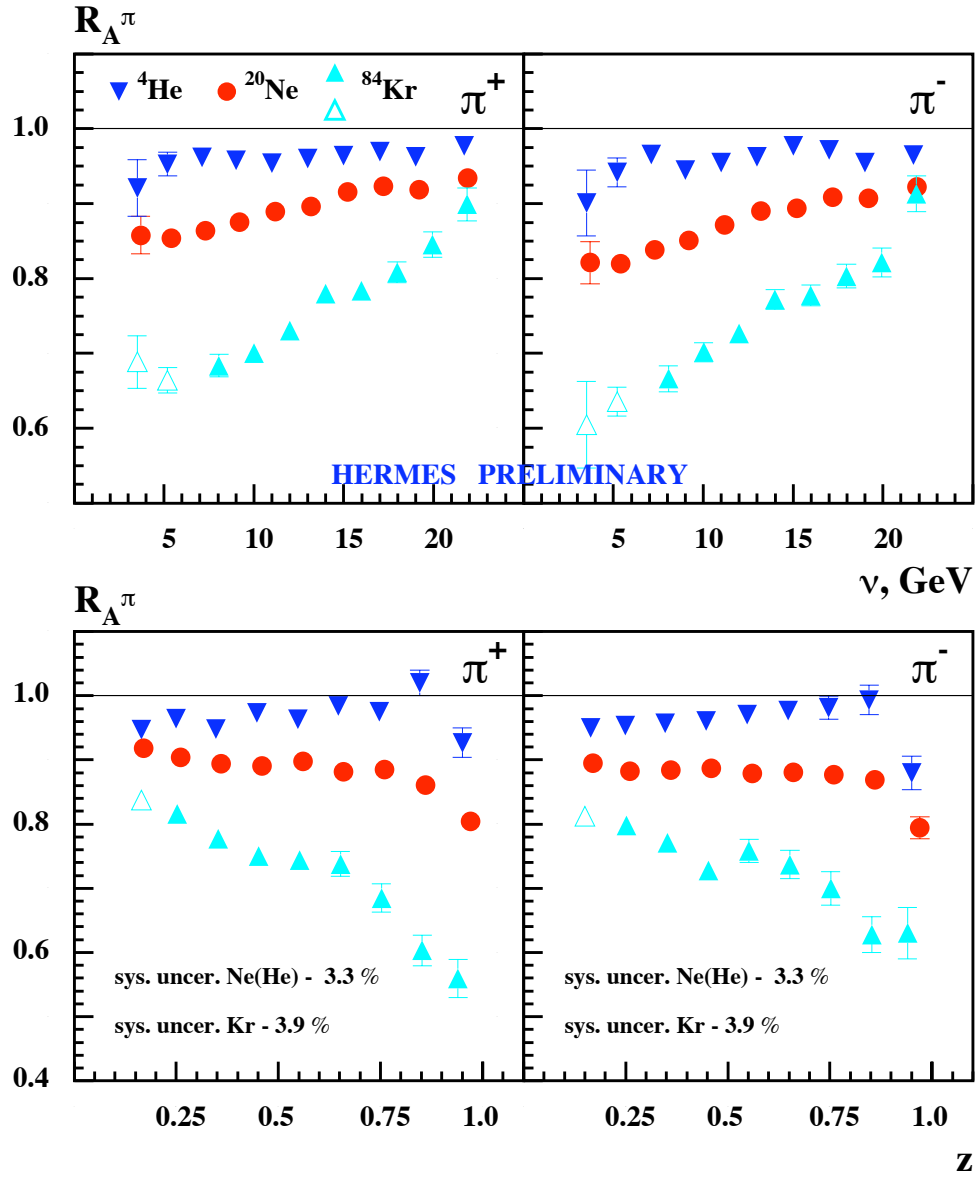
  But nuclear protons can be knocked out as secondaries

Identified hadrons: z dependence on Krypton



- Attenuation increases at large z on Krypton for all hadrons (except p?)
- Larger attenuation at large z may be understood as being due to early production times of colour-neutral prehadron before the primary quark had time to lose much energy
- Strong dependence on nuclear mass

Nuclear Mass Dependence



Clear effect as a function of the atomic mass number

Assuming the dependence:

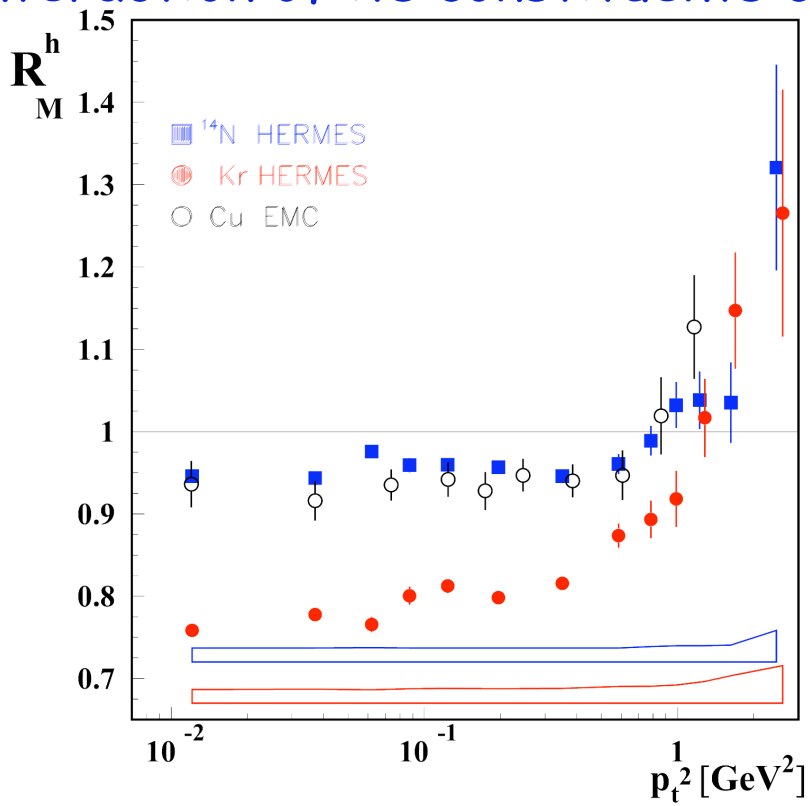
$$A^{\alpha} = 1 - R^{h}_{att}$$

Data suggest $\alpha \sim 2/3$

Xenon data is immanent!

P_t dependence

In DIS neither multiple scattering of the incident particle nor interaction of its constituents complicate the interpretation



Data show a p_t enhancement similar to that observed in pA scattering (Cronin effect)

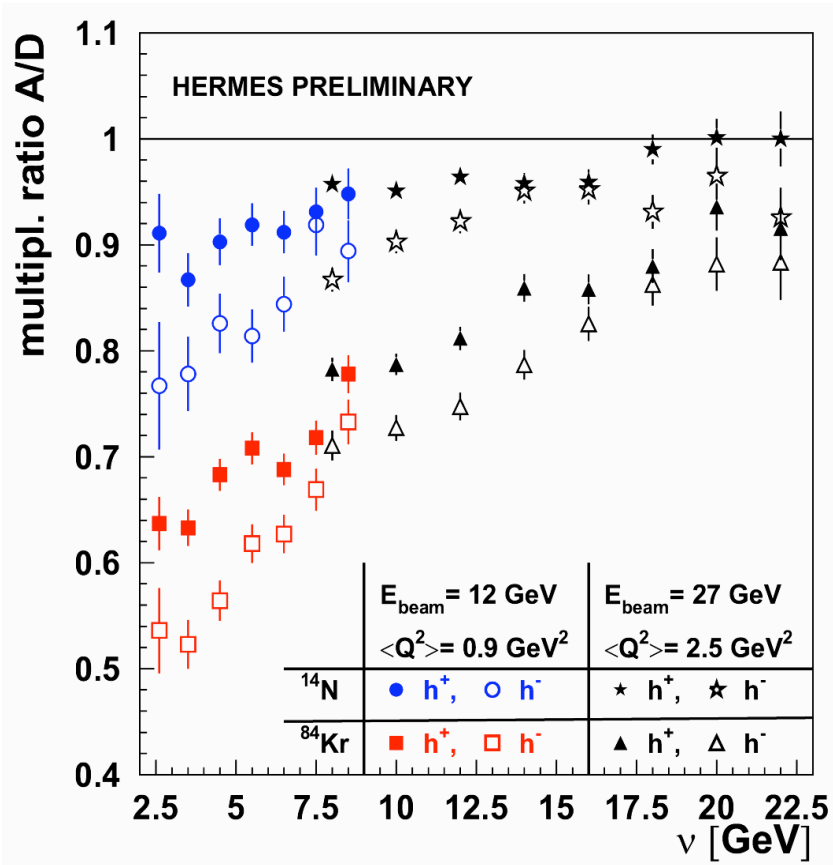
The hard component of incoherent parton scattering becomes dominant at p_t~1-2 GeV

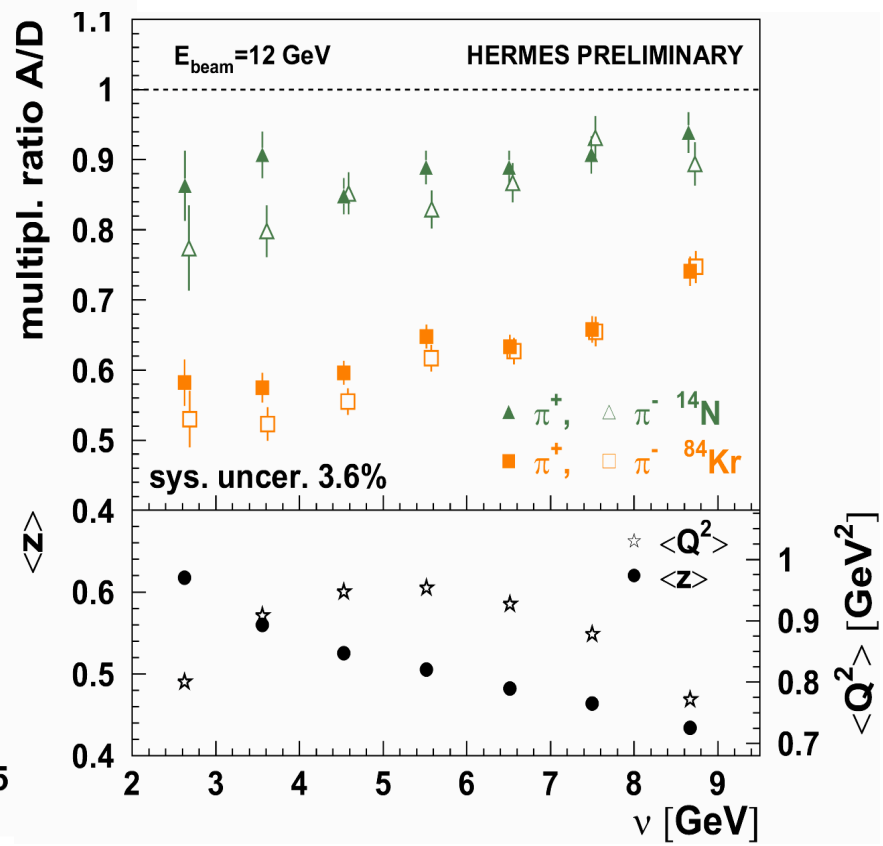
DIS provides clean & reliable information on quark transport in **cold nuclear matter**

HERA Injection Energy: Dedicated Running Periods

Hadrons and Pions @ E_{beam}=12 & 27 GeV

Extension of the ν range down to 2 GeV





Conclusions and Outlook

- **Charge- & flavour-separated multiplicities** extracted from DIS with unprecedented statistical precision (including first **kaon** multiplicities)
- Long & careful analysis, to treat data in **model-indepent way** with careful analysis of uncertainties
- Results compare well with **e+e- fragmentation functions** obtained at much higher scales (& look forward to new BELLE data!)
- **No signs** of strong factorization breaking at HERMES scales
- Wealth of data on **nuclear modifications** of fragmentation process, helpful for RHIC data analysis
- Plenty more **more data** on its way from Run 2! :-)