Nuclear p_t-broadening at HERMES

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for the HERMES collaboration

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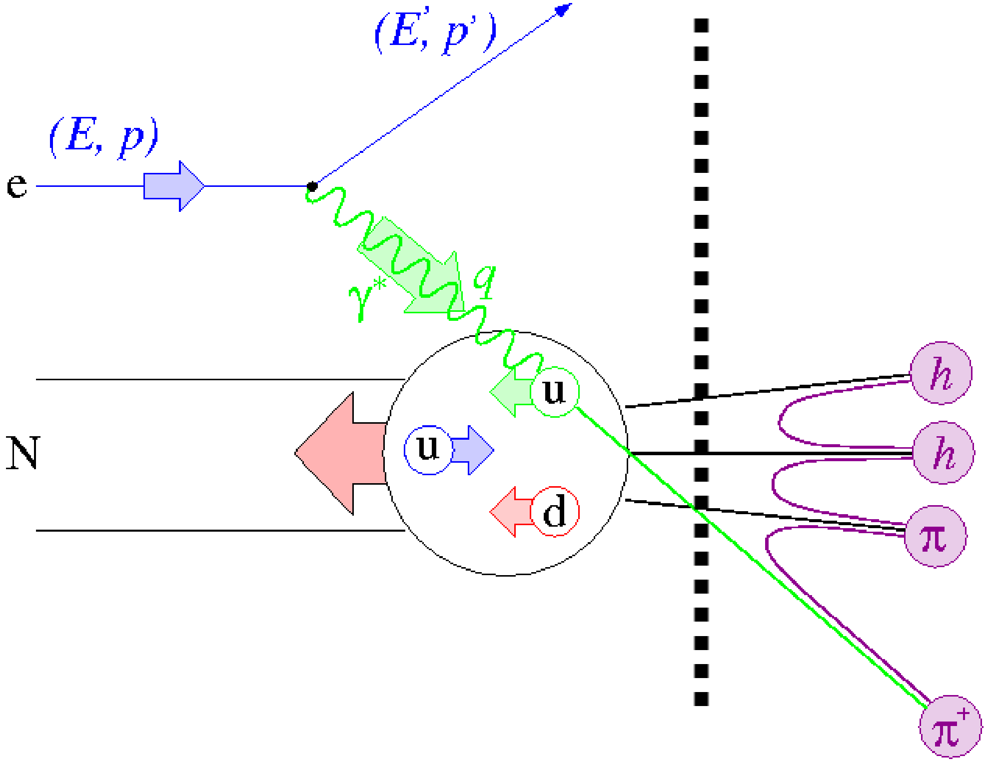
Outline

- Nuclear p_t-broadening

  ⇒ (nuclear) SIDIS
  ⇒ Nuclear p_t-broadening
  ⇒ HERMES spectrometer
  ⇒ Results

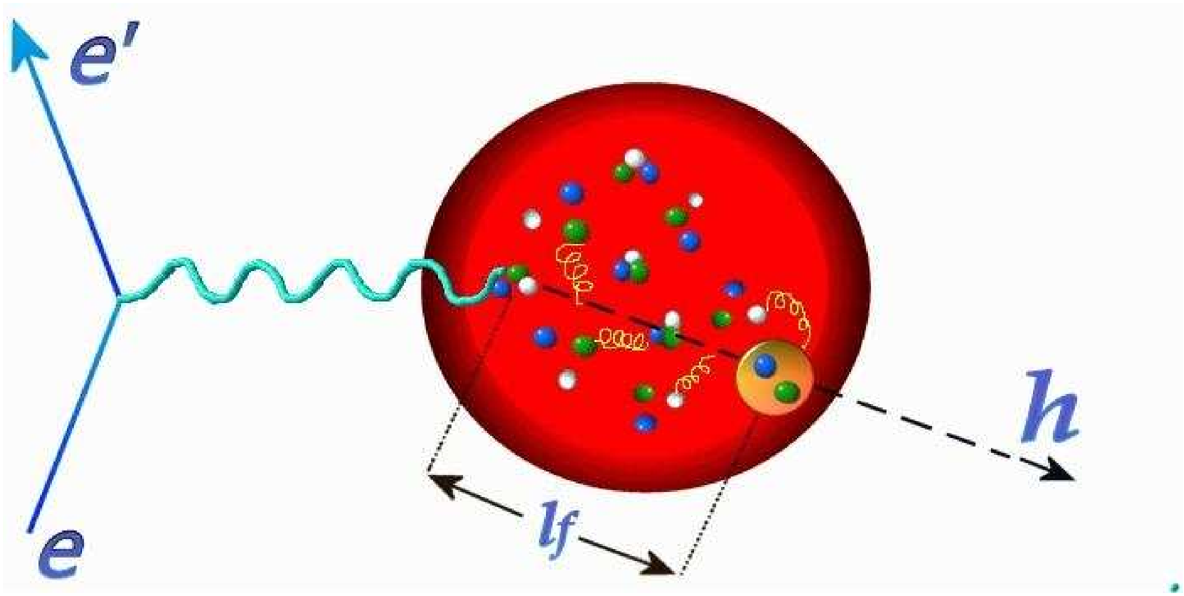
Semi Inclusive Deep Inelastic Scattering (SIDIS)



$$d\sigma \propto \sum_f e_f^2 \cdot q_f(x_{bj}, Q^2) \cdot \sigma \cdot D_f^h(z, Q^2)$$

- $e^{\pm}$ + N $\rightarrow$ $e^{\pm}$ + h + X
- $q^2 = -Q^2$: squared 4-momentum transfer
- ν = $E_{\gamma*}$ = $E - E'$ (target rest frame)
- W^2 = $(\mathbf{N} + \mathbf{q})^2$: squared invariant mass $\gamma^* N$
- $x_{bj} = \frac{Q^2}{2M\nu}$
- $z = \frac{E_h}{\nu}$
- p_t: transverse p of hadron to γ^*

Nuclear SIDIS as hadronization laboratory



- Hadronization likely inside nucleus
- Nano lab to study hadronization

  ⇒ Multiple scattering centers (1-2 fm)

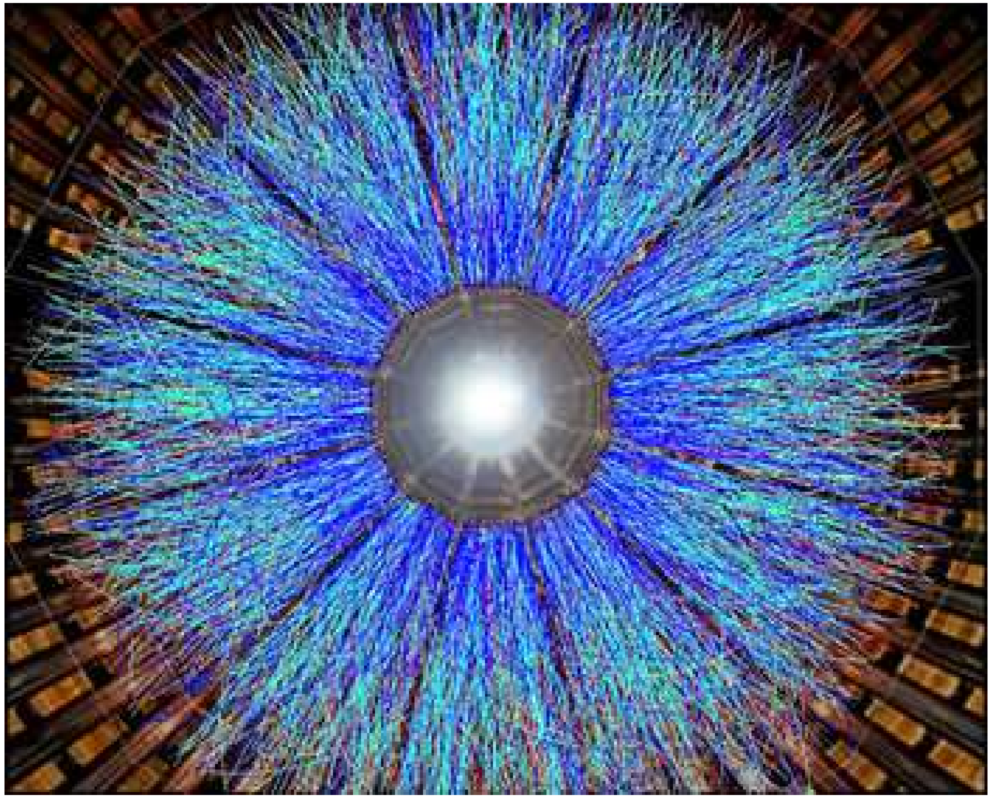
- Nuclear effects like:

  ⇒ EMC effect: $\frac{\sigma_A}{\sigma_N}(x_{bj}) \neq 1$

  ⇒ Nuclear attenuation: $\frac{\frac{\#had}{\#DIS}_A}{\frac{\#had}{\#DIS}_D} \neq 1$

  ⇒ p_t-broadening

Why nuclear SIDIS?



Gold-gold collision at RHIC
$\sim$ 6000 tracks

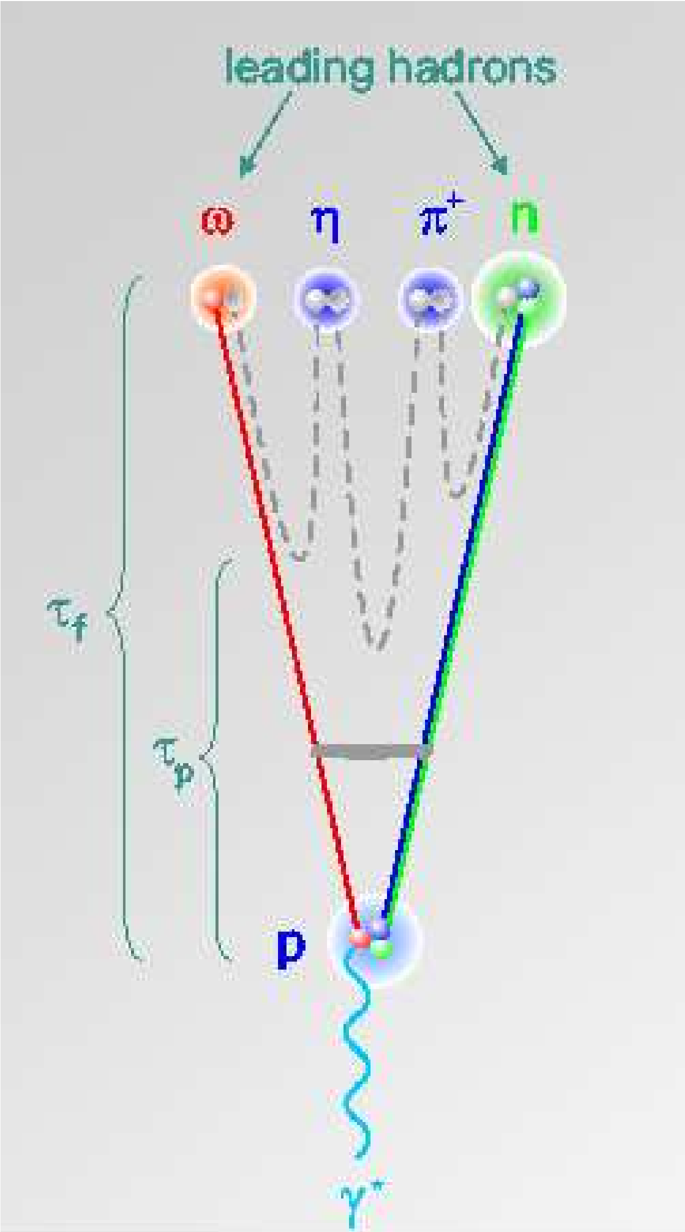
- No Initial State Interactions

  $\Rightarrow$ Relatively clean

- At HERMES no jets
  $\rightarrow$ $\langle$1 event$\rangle$: 3.5 tracks

- Helps understanding ion-ion collisions

$\Delta\langle p_t^2\rangle^h$ and production time/length



- $\Delta\langle p_t^2\rangle^h = \langle p_t^2\rangle_A^h - \langle p_t^2\rangle_D^h$

  $\Rightarrow$ Called p_t-broadening

  $\Rightarrow$ Measure production time (t_p)

  $*$ Space-time evolution of hadronization

- $\Delta\langle p_t^2\rangle \sim t_p$ *Nucl. Phys. A740, 211*

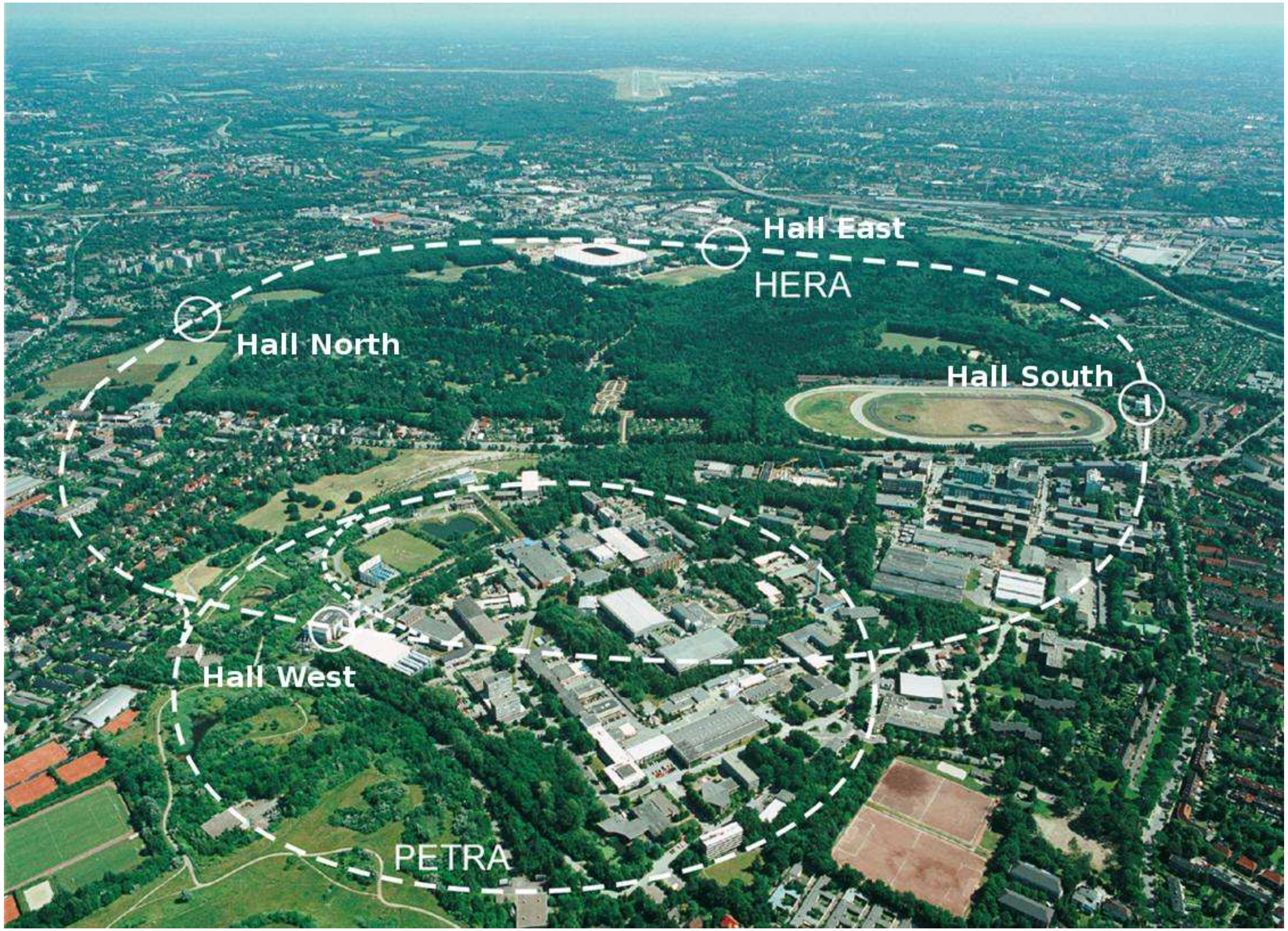
  $\Rightarrow$ $t > t_p$ no broadening occurs

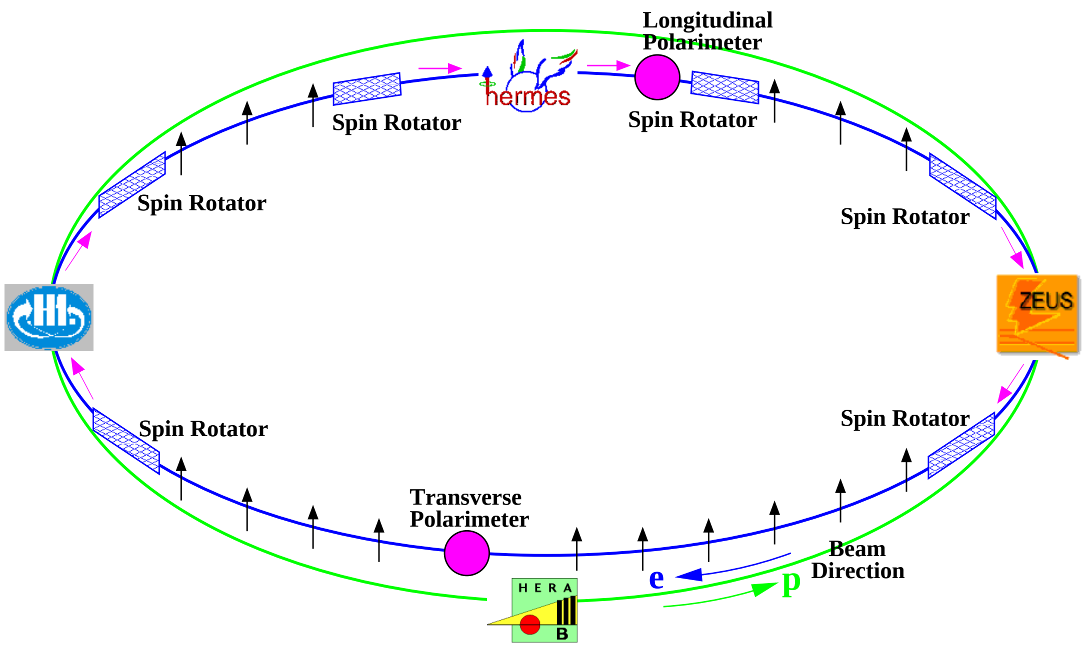
  $*$ Inelastic scattering suppressed (fast hadrons)

  $*$ $\sigma_{elastic}$ very small

  · Pions mfp $>$ 20 fm

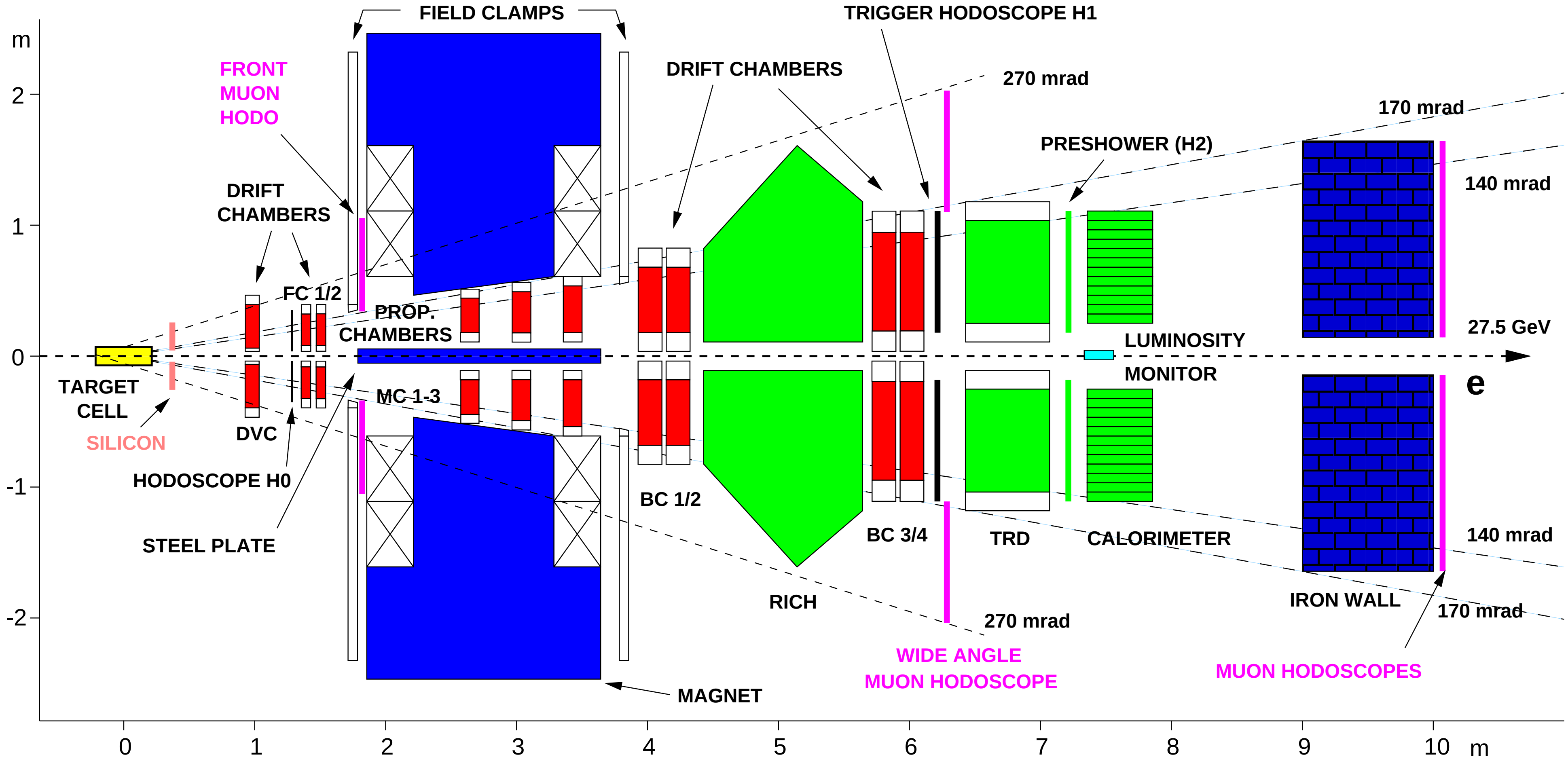
HERMES spectrometer to measure p_t-broadening





- HERA storage ring:
  - ⇒ 27.6 GeV/c $e^{\pm}$ beam (polarized)
    - ∗ (Sokolov-Ternov effect)
  - ⇒ 920 GeV/c proton beam
- HERMES: $e^{\pm}$ on “fixed” gas target
  - ⇒ H , D, ^{3}He, ^{4}He, N, Ne, Kr, Xe
- Operational till July 2, 2007, 10:00 am

Side view of the HERMES spectrometer



Tracking Momentum measurement Particle identification (l/h $>$ 98%)

32.8 ft. long / 13.1 ft. wide

Extract $\Delta\langle p_t^2\rangle^h$

- $\langle p_t^2\rangle_{\mathrm{D,\ Ne,\ Kr,\ Xe}} = \frac{1}{n}\sum_{i=1}^{n}(p_t^2)_i$
- $\Delta\langle p_t^2\rangle_{\mathrm{Ne,\ Kr,\ Xe}} = \langle p_t^2\rangle_{\mathrm{Ne,\ Kr,\ Xe}} - \langle p_t^2\rangle_{\mathrm{D}}$

  $\Rightarrow$ Corrections:
  - ∗ Acceptance/smearing
  - ∗ Radiative effects
  - ∗ Exclusive ρ^0 decay $\pi^{\pm}$
- As function of ν, Q^2, z, and A
- For π^+, π^-, K^+
- Apply kinematic cuts

Kinematic cuts

- Inclusive

  $\Rightarrow\ 1 < Q^2 < 10$ GeV^2
  - spatial scale $\sim \frac{1}{\sqrt{Q^2}}$
  - $Q^2 > 1 \rightarrow$ partons

  $\Rightarrow\ W > 2$ GeV
  - No resonances

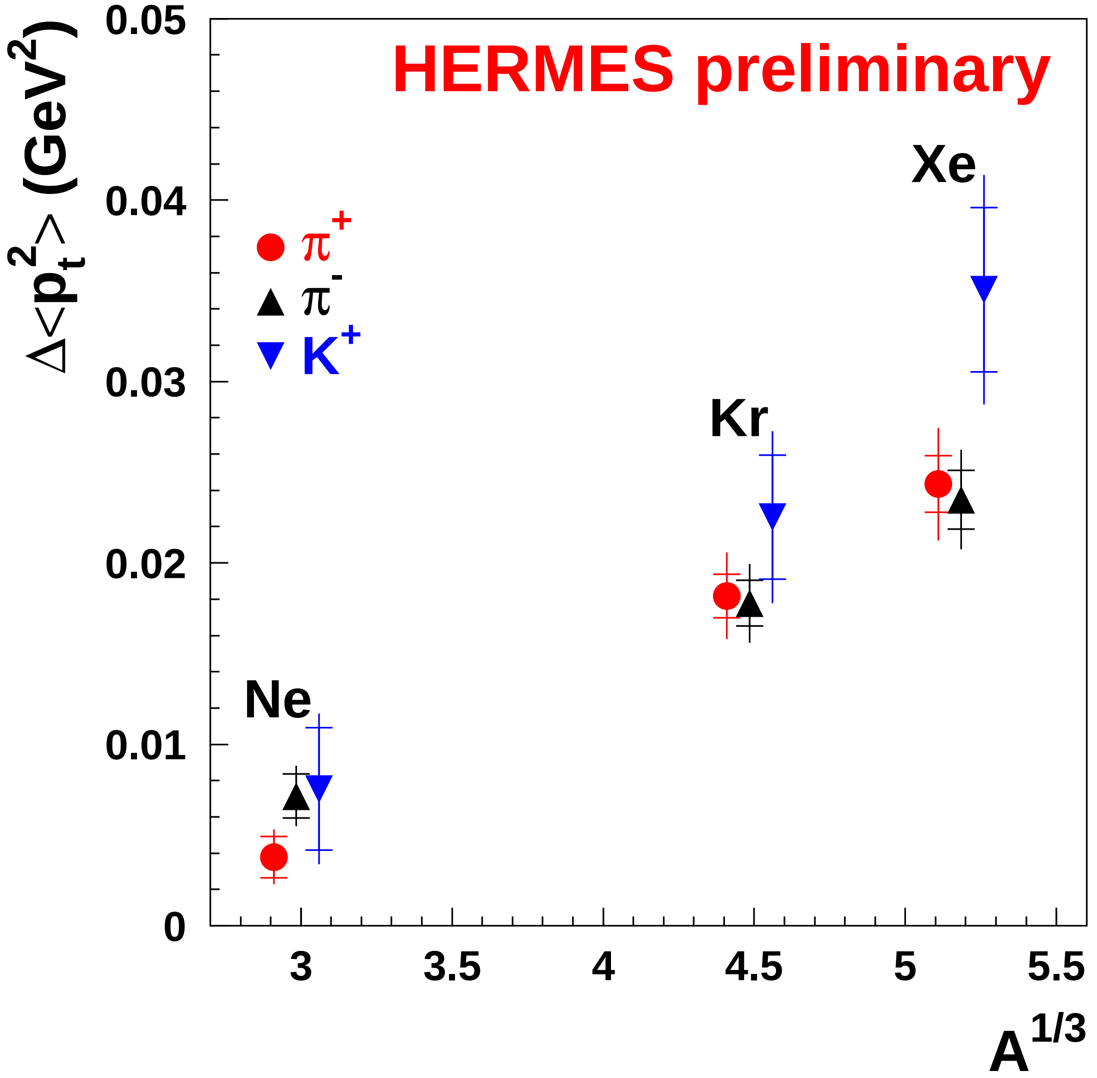
  $\Rightarrow\ \nu < 23$ GeV
  - Radiative effects

- Semi Inclusive

  $\Rightarrow\ 0.2 < z < 1.0$

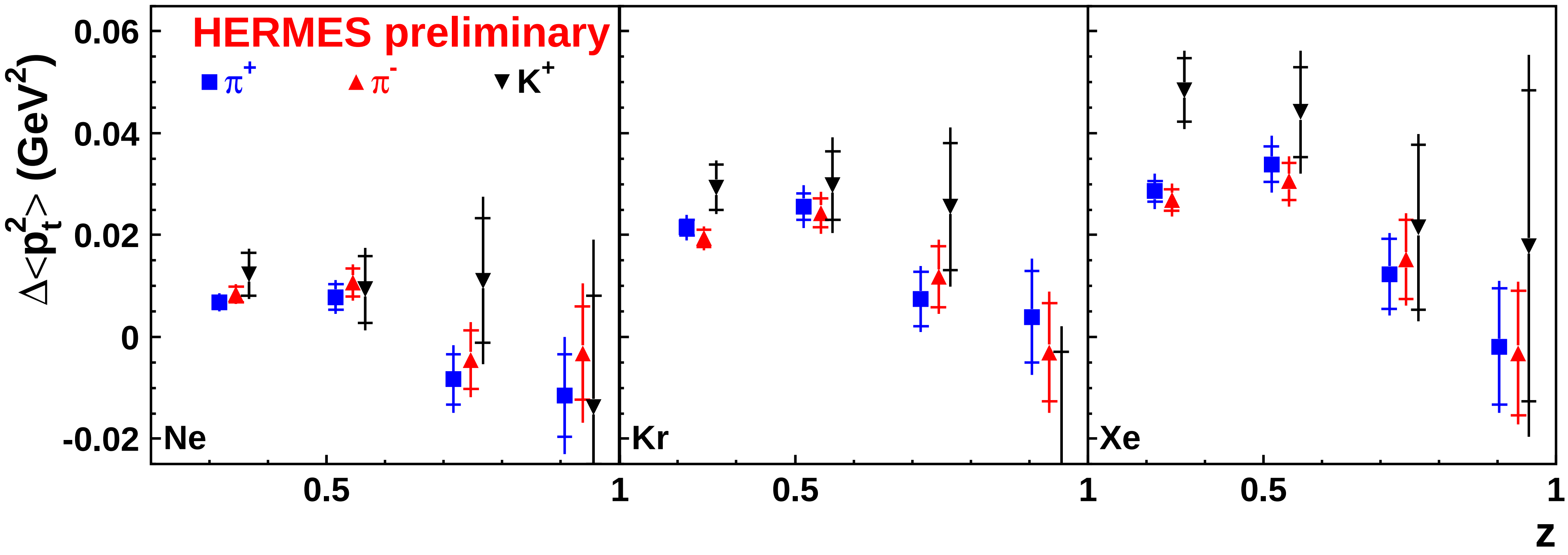
  $\Rightarrow\ 2 < p^{\pi,K} < 15$ GeV

Results: A-dependence



- Linear vs $A^{1/3}$
- $\langle p_t^2 \rangle$ around 0.25 GeV^2 large effect
- Direct evidence of p_t-broadening in leptoproduction

Results: z-dependence

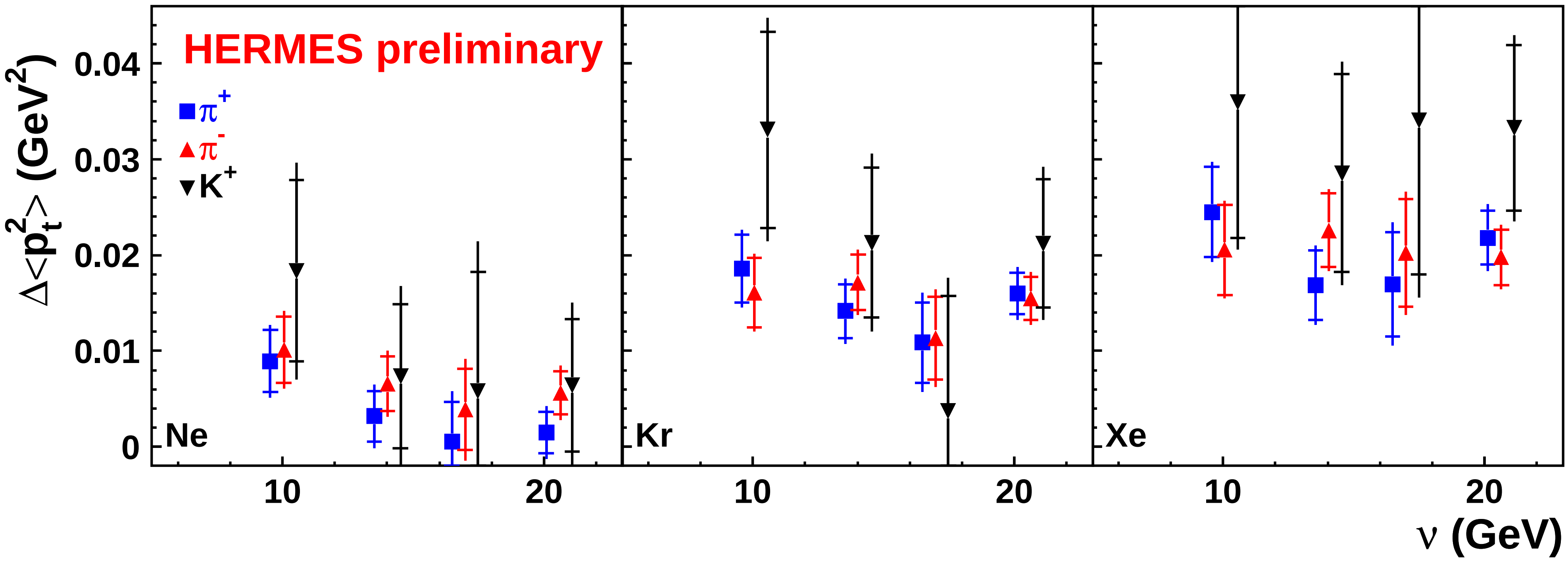


- Clear A-dependence

$\Rightarrow\ z = \frac{E_h}{\nu}$

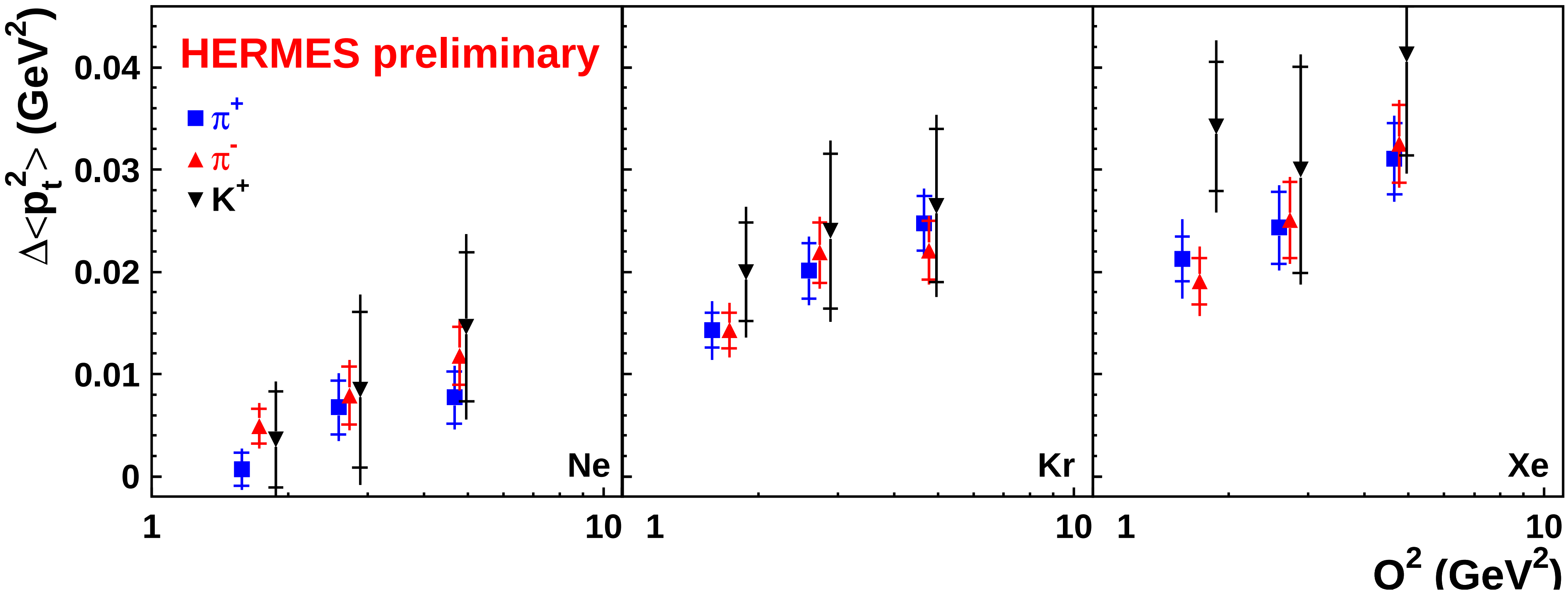
$\Rightarrow$ pre-hadron $t_p \rightarrow 0$

Results: ν-dependence



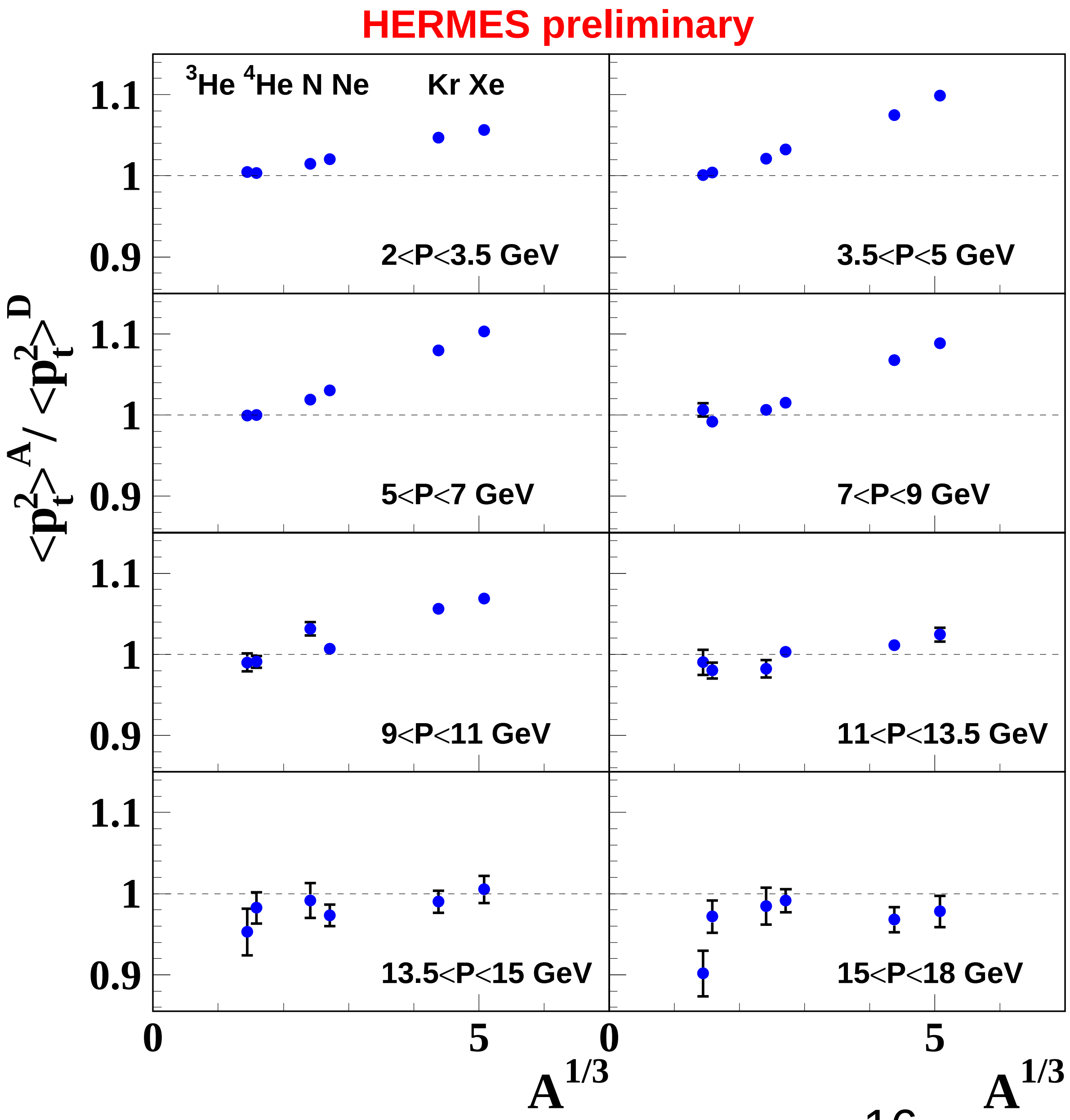
- Clear A-dependence
- Broadening goes (slightly) down with increasing ν

Results: Q^2-dependence



- Clear A-dependence
- Broadening goes up with Q^2 - hint of saturation

Results: p_t-ratio vs A$^{1/3}$

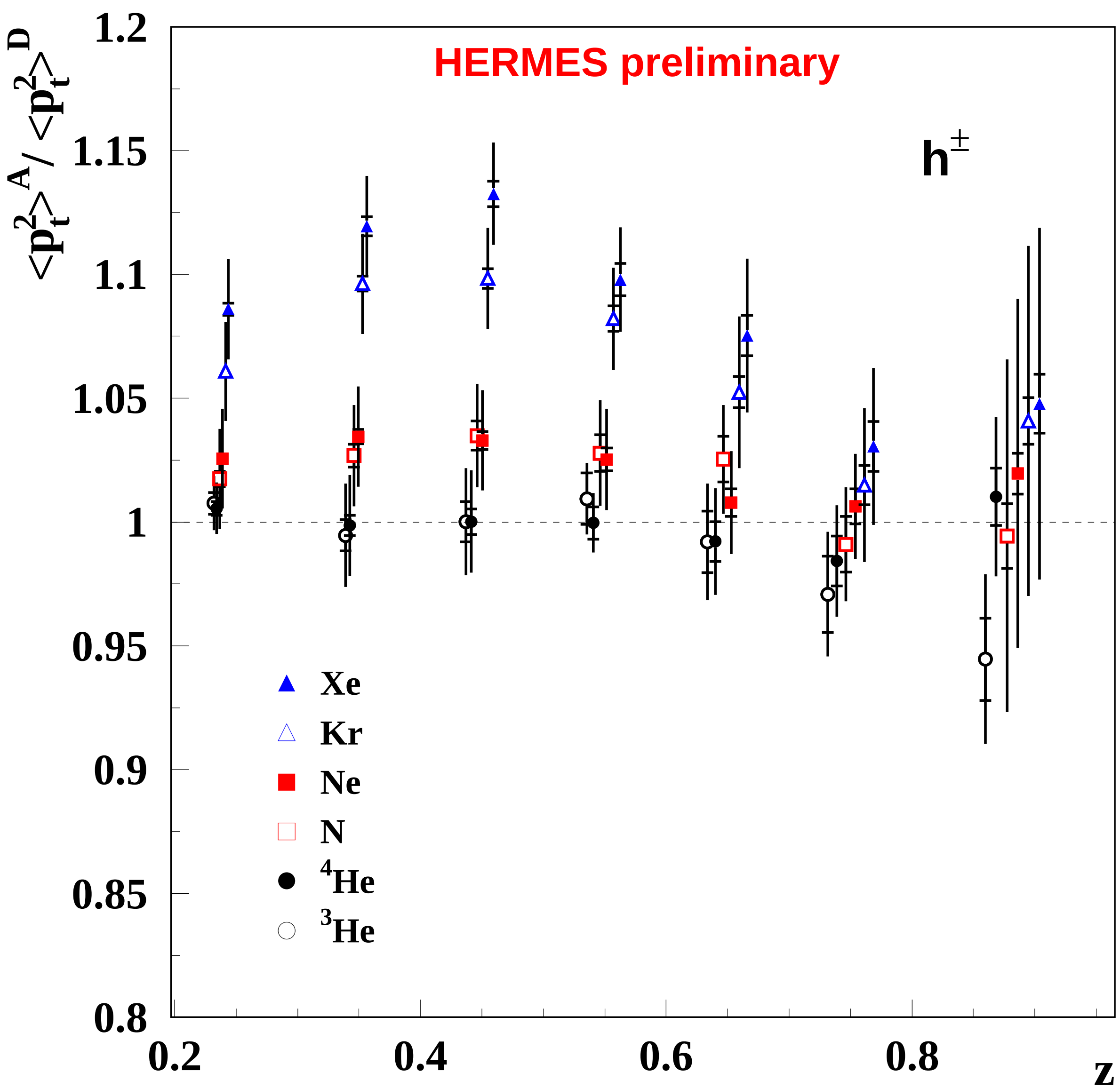


- Small nuclei:

  $\Rightarrow$ size $< l_p$

- High P $=$ high z

Results: p_t-ratio versus z



- Clear A-dependence
- High z $\rightarrow$ 1
- All available targets

Conclusions

- New HERMES results on nuclear effects in hadronization:

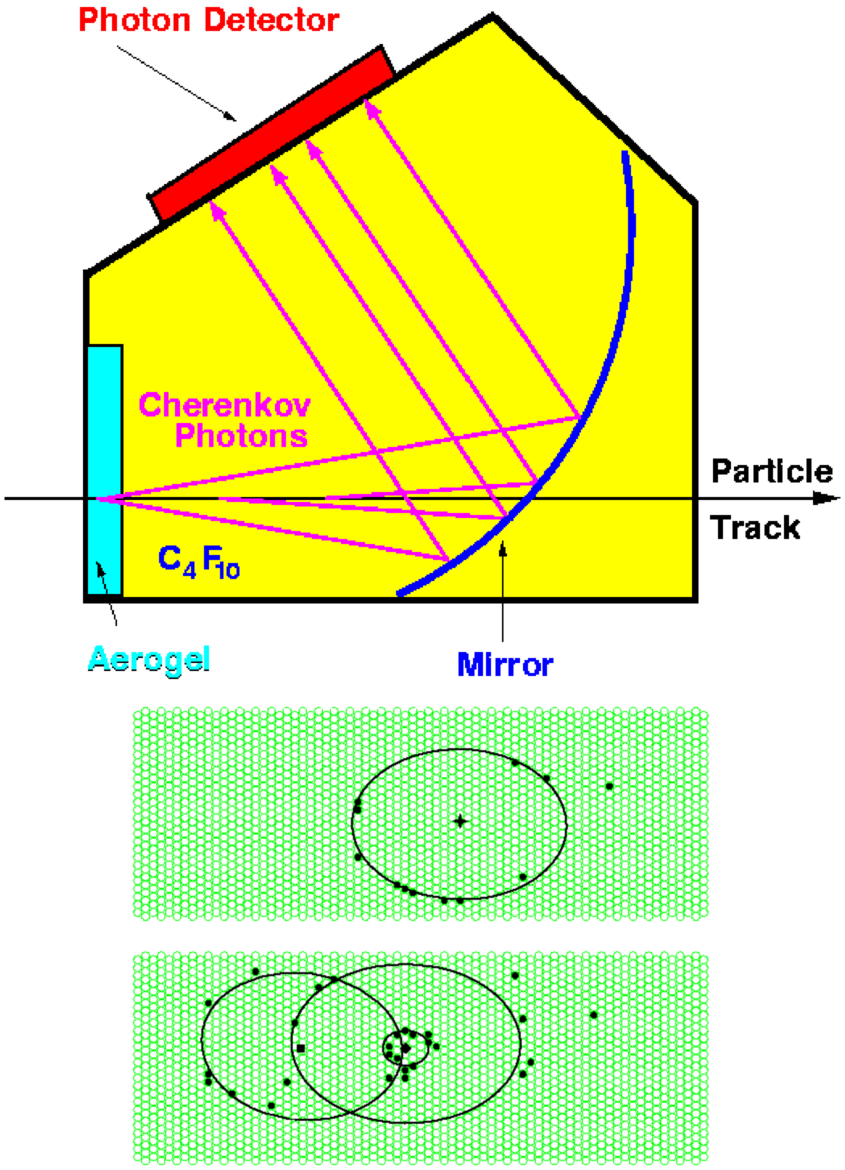
  ⇒ p_t-ratios:
  - ∗ For all available targets
  - ∗ All charged hadrons

  ⇒ First absolute measurement of p_t-broadening in lepto-production:
  - ∗ On Ne, Kr, and Xe
  - ∗ Different hadron types
  - ∗ Versus several kinematic variables
  - ∗ A clear signal of broadening is observed
    - · Constraint on pre-hadron mechanism

- Together with nuclear attenuation:
  Most extended data set on space-time evolution of hadronization!

Additional slides

RICH unfolding = correction for hadron misidentification



- P-matrices (Mont Carlo produced)

$$\begin{pmatrix} I_\pi \\ I_K \\ I_P \\ I_X \end{pmatrix} = \begin{pmatrix} P_\pi^\pi & P_\pi^K & P_\pi^P \\ P_K^\pi & P_K^K & P_K^P \\ P_P^\pi & P_P^K & P_P^P \\ P_X^\pi & P_X^K & P_X^P \end{pmatrix} \cdot \begin{pmatrix} N_\pi \\ N_K \\ N_P \end{pmatrix}$$

$$\vec{N} = P_{trunc}^{-1} \cdot \vec{I}_{trunc}$$

- Impact on statistics:

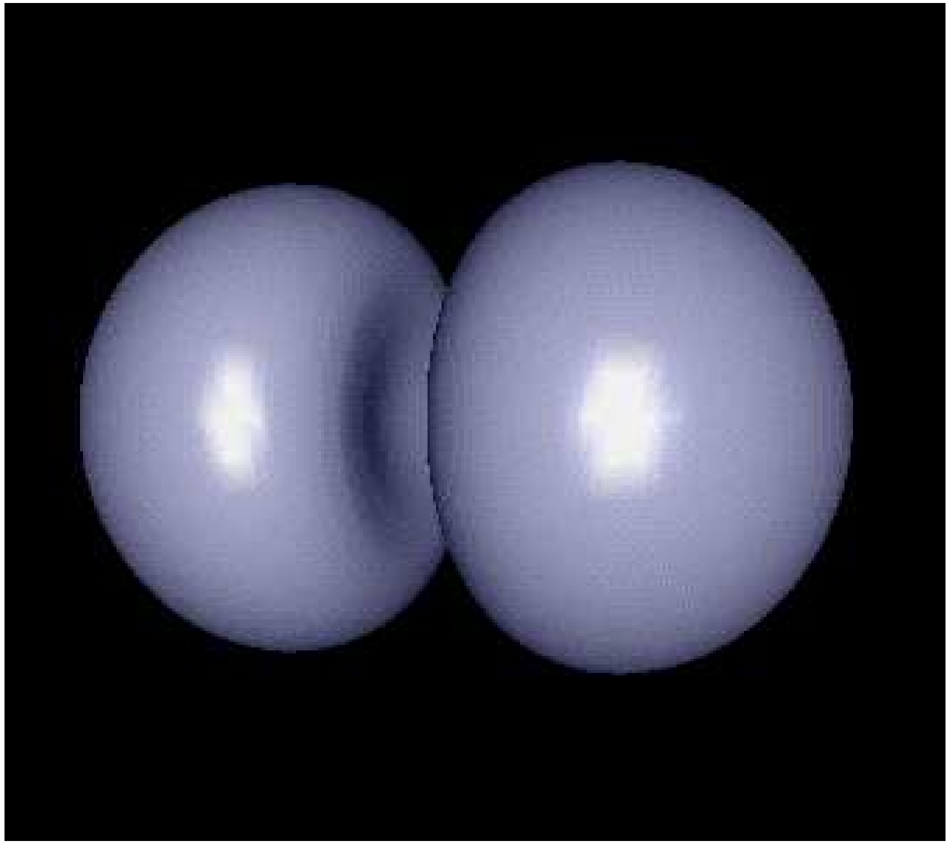
$\Rightarrow$ π^+: -0.4 %
$\Rightarrow$ π^-: +1.3 %
$\Rightarrow$ K^+: -4.4 %

- No impact on $\Delta\langle p_t^2\rangle$ behavior

- RICH efficiencies:

$\Rightarrow$ π: 98%
$\Rightarrow$ K: 88%

Exclusive ρ^0 correction



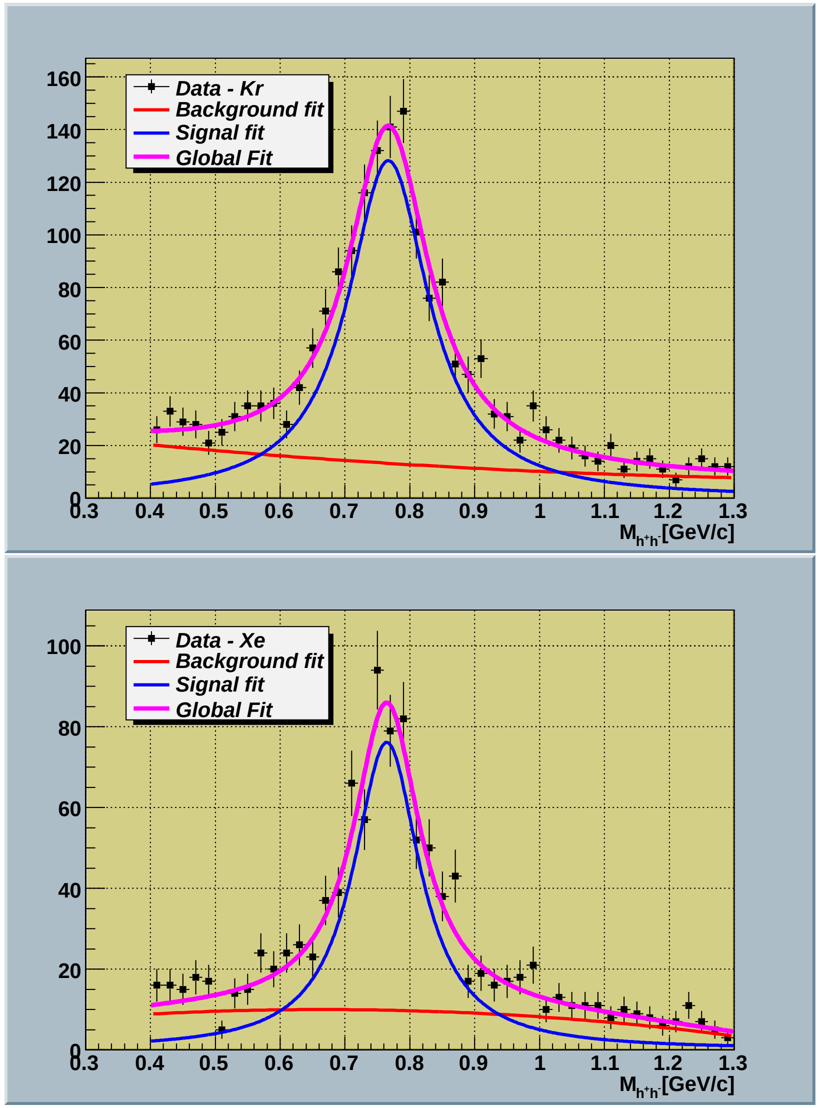
↑ Depiction of a ρ^0 decay ↑

- Vector Meson Dominance model:

  $\Rightarrow$ γ^* fluctuates in ρ^0
  $\Rightarrow$ scatters off nucleon (incoherent)
  $\Rightarrow$ scatters off nucleus (coherent)

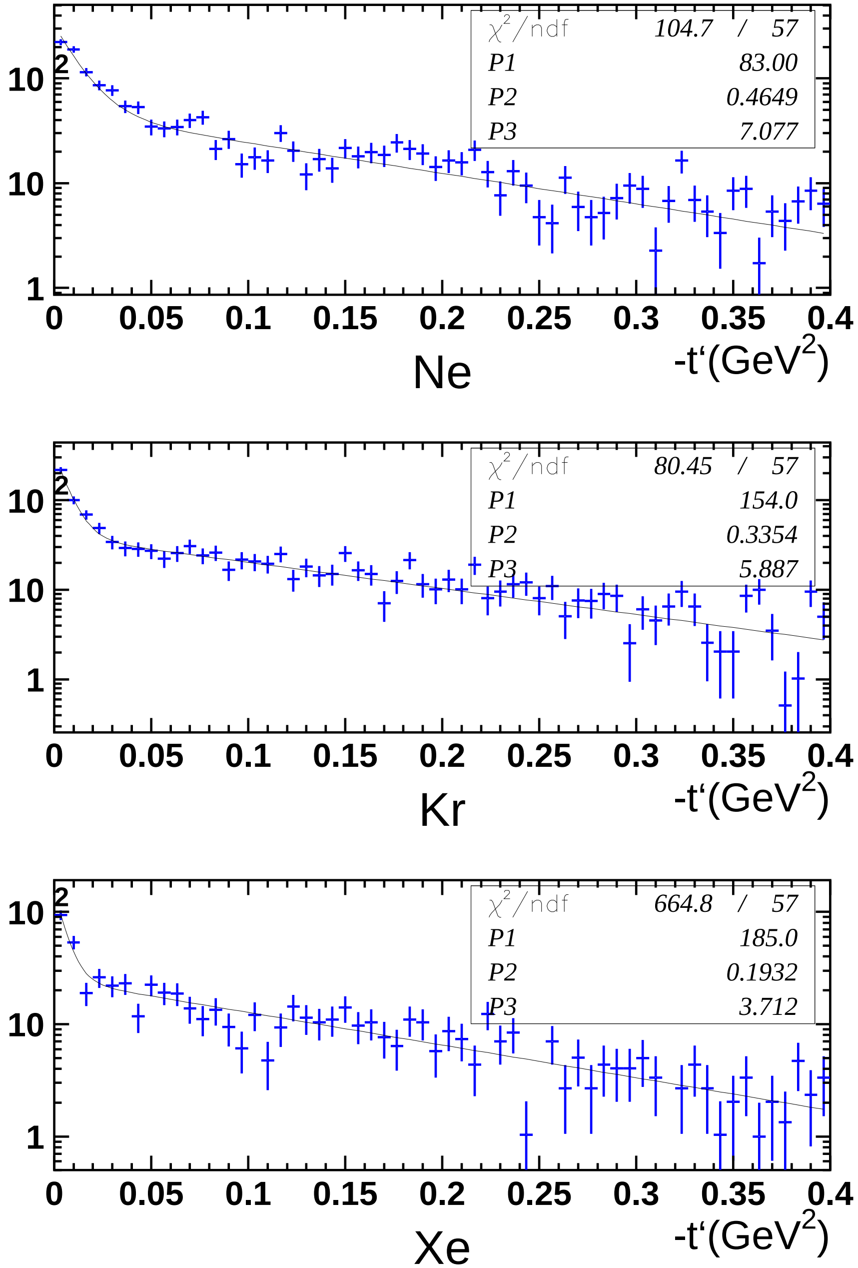
- Not hadronization

Exclusive ρ^0s from data



- Cuts used:
  - ⇒ SIDIS cuts
  - ⇒ $0.6 < M_{h^+h^-} < 1.0$ GeV
  - ⇒ Hadron multiplicity = 2
  - ⇒ -t' $<$ 0.4 GeV^2
    - $*$ (4-mom.)^2 transfer to target
  - ⇒ $\Delta E <$ 0.6 GeV
    - $*$ $\Delta E = \frac{M_x^2 - M_{targ}^2}{2M_{targ}}$
- Fit:
  - ⇒ Breit Wigner + Background
  - ⇒ Background correction

Exclusive ρ^0: $-t'$ spectrum



- -t' Background corrected

  $\Rightarrow$ (4-mom.)^2 transfer to target

- $f(-t') = a_n(b_{inc}e^{b_{inc}.t'} + a_0.b_{coh}.e^{b_{coh}.t'})$

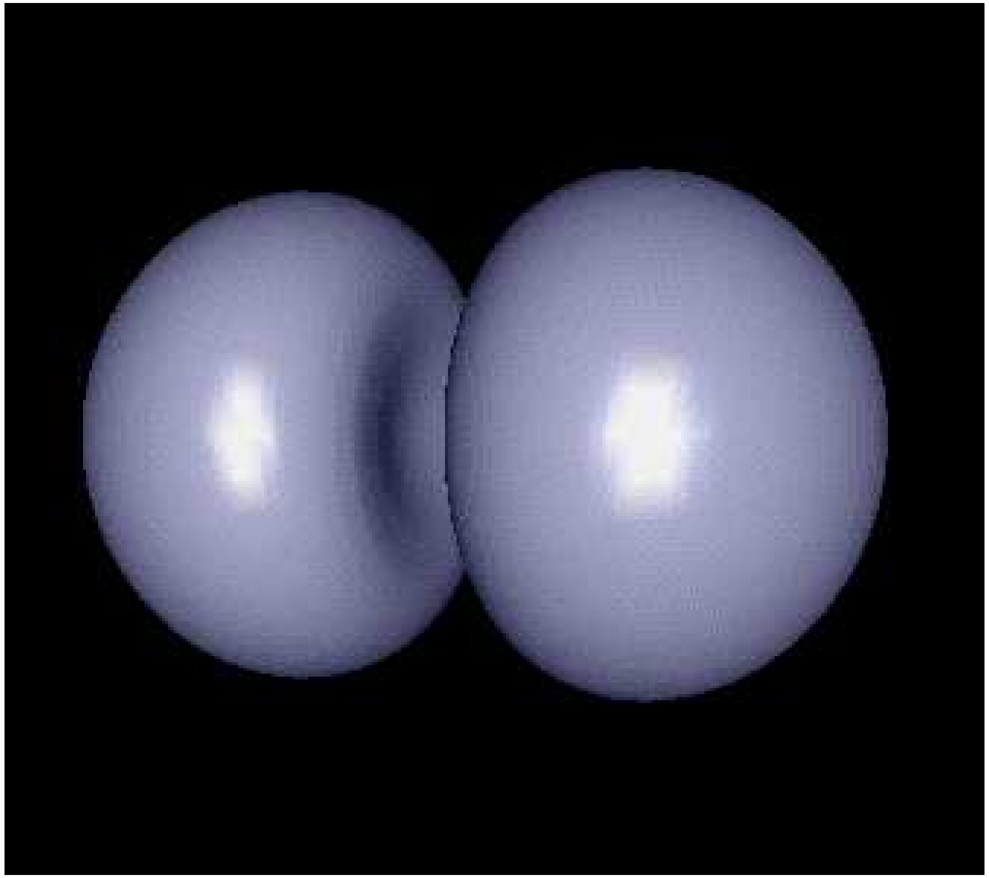
  PRL 82 (1999) 3025

  $\Rightarrow$ b_{inc} incoherent slope

  $\Rightarrow$ b_{coh} coherent slope

  $\Rightarrow$ a_0 relative weight: coherent to incoherent

Exclusive ρ^0: MC

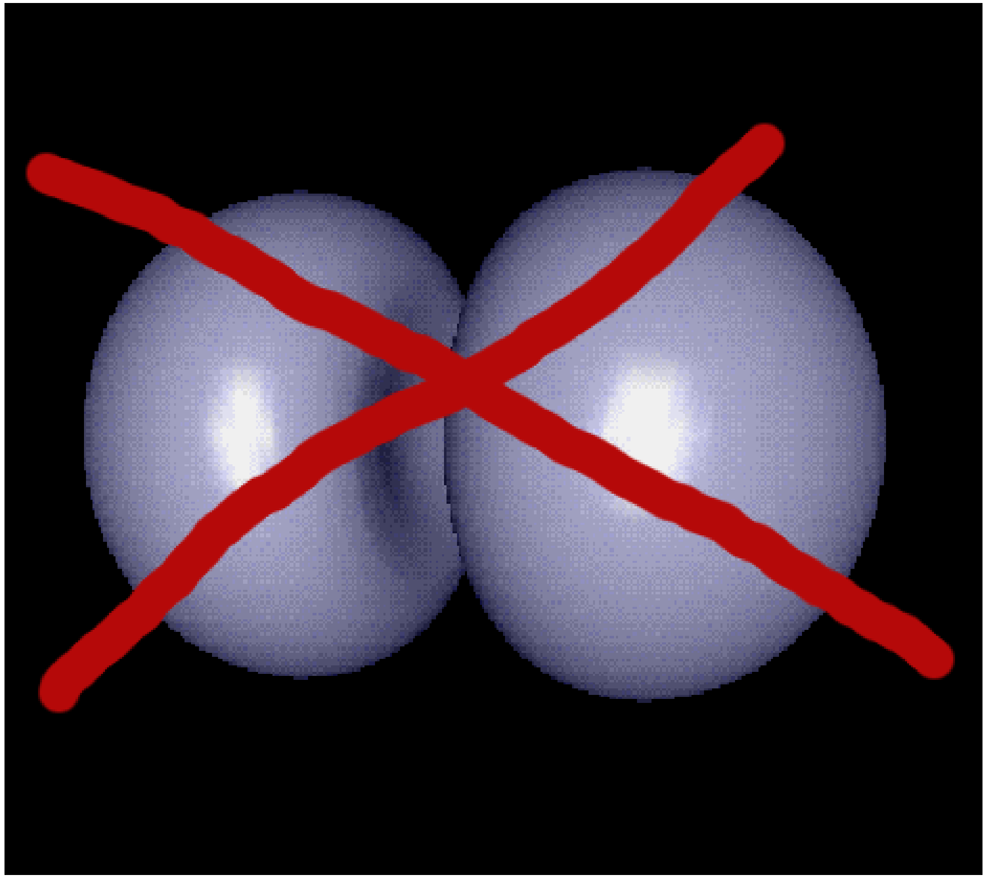


- Tunable ρ-Monte Carlo (MC)

  $\Rightarrow$ Use b_{inc}, b_{coh}, and a_0
  $\Rightarrow$ Nuclear ρ-MC

- Normalize nuclear ρ-MC to $\#\rho^0$ in data

Exclusive ρ^0: MC



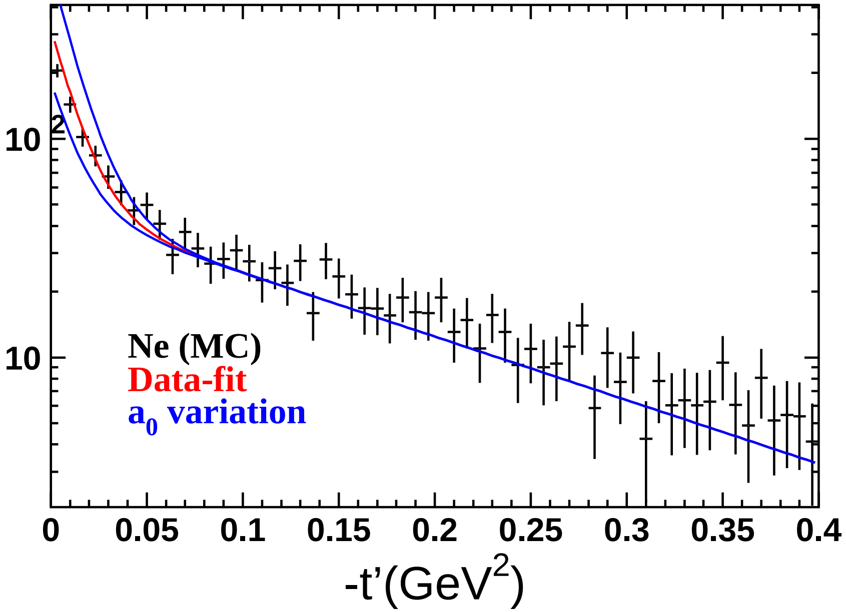
- Tunable ρ-Monte Carlo (MC)

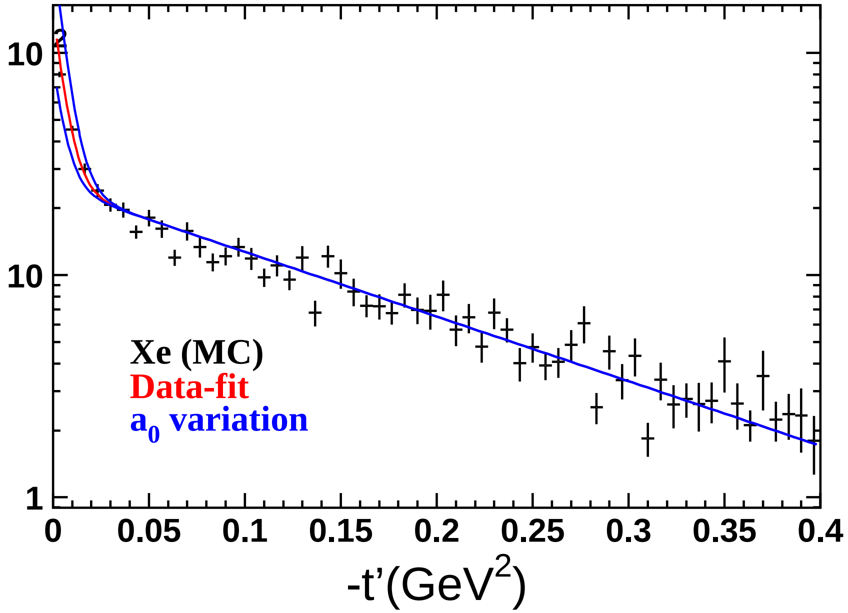
  $\Rightarrow$ Use b_{inc}, b_{coh}, and a_0
  $\Rightarrow$ Nuclear ρ-MC

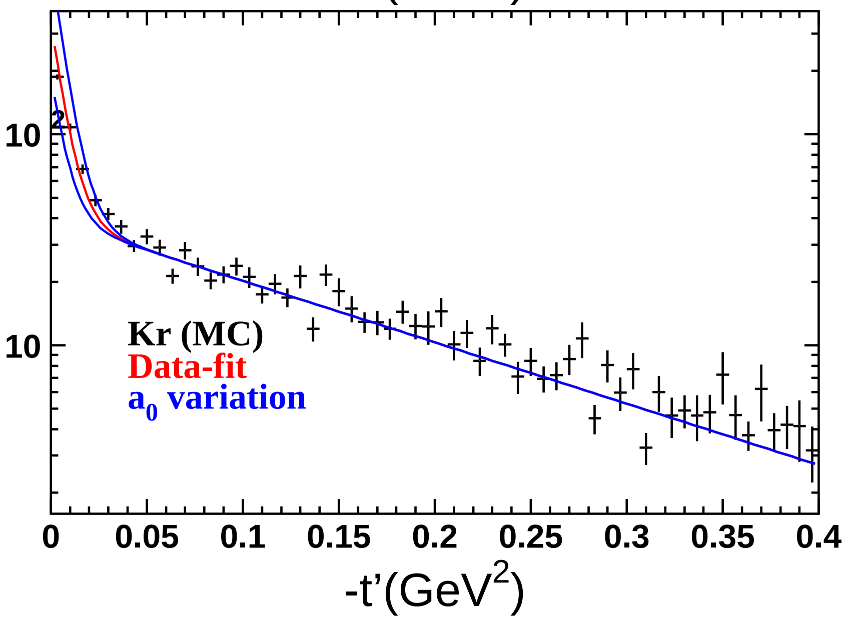
- Normalize nuclear ρ-MC to $\#\rho^0$ in data

- Subtract ρ^0-pions (MC) from data
  $\rightarrow$ bin per bin

Exclusive ρ^0: MC - data



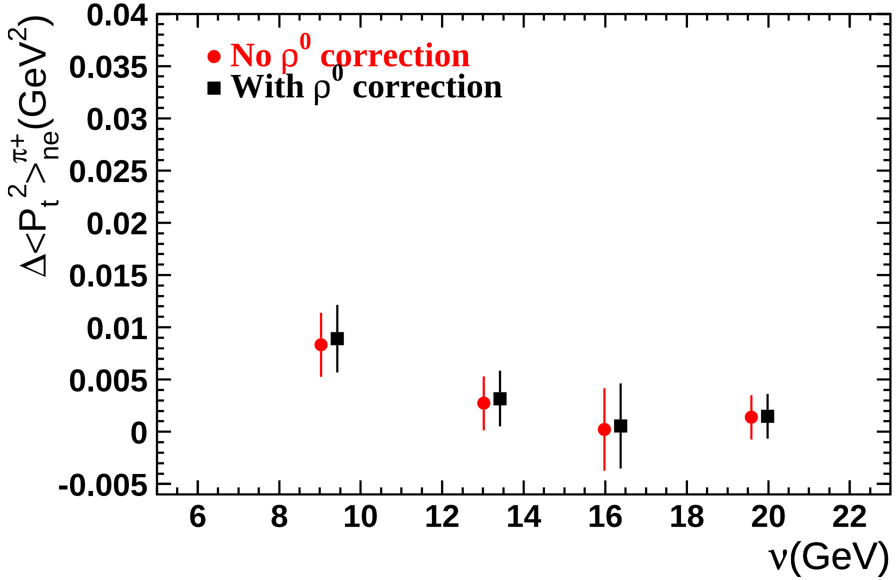


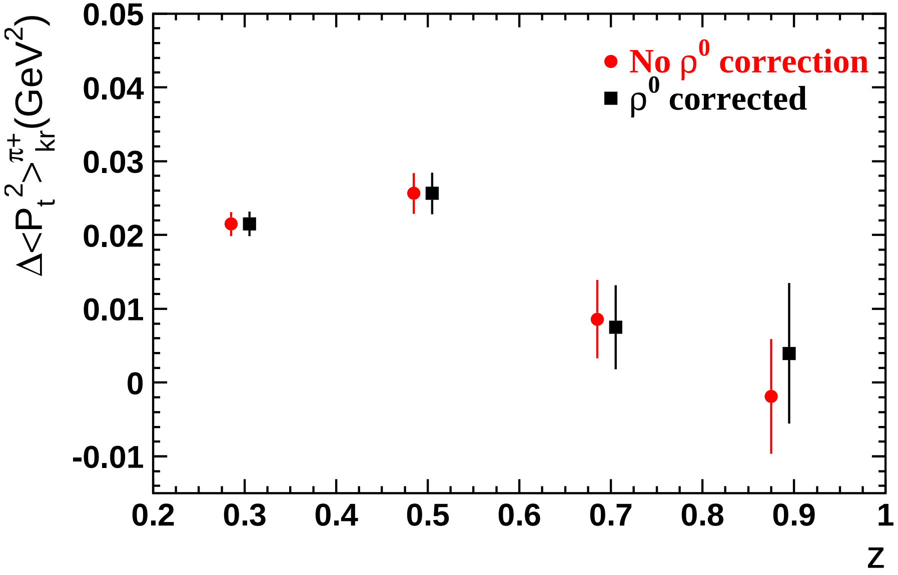


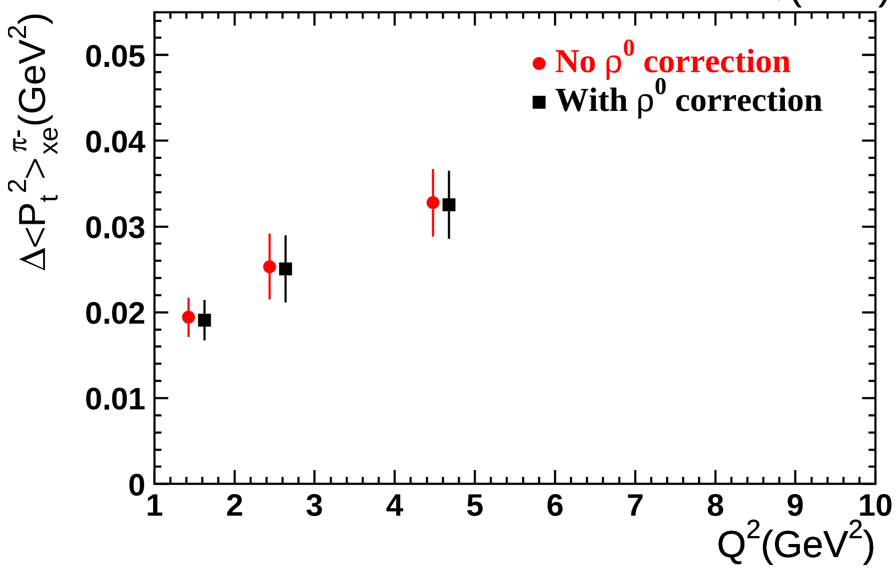
- χ^2 = 0.98(Ne) - 2.58(Kr) - 2.73(Xe)
- a_0 variation

$\Rightarrow$ Systematic error

Impact ρ^0 correction on p_t- broadening



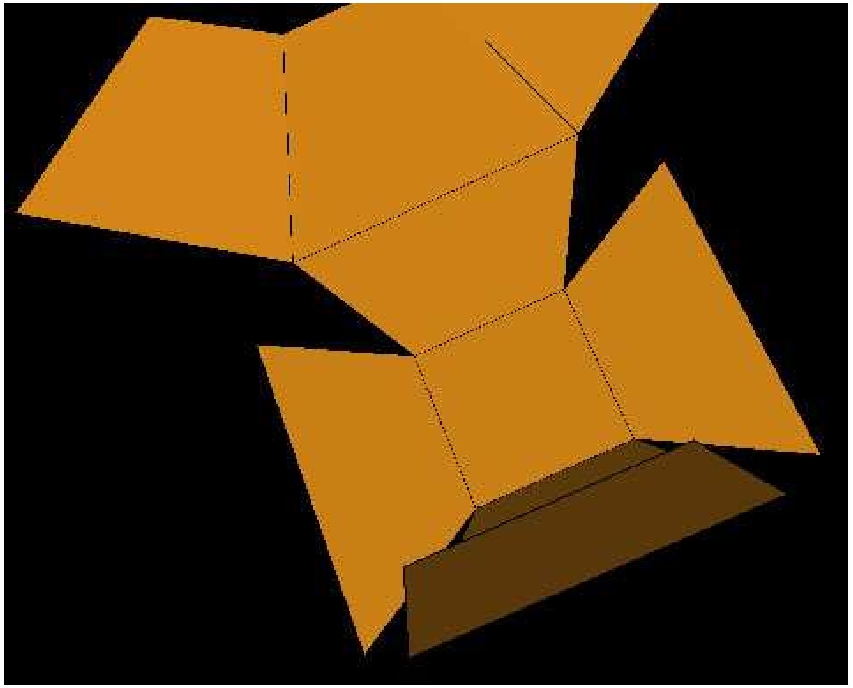




- Only effect in highest z-bin

$\Rightarrow\ >$ 50 % contribution

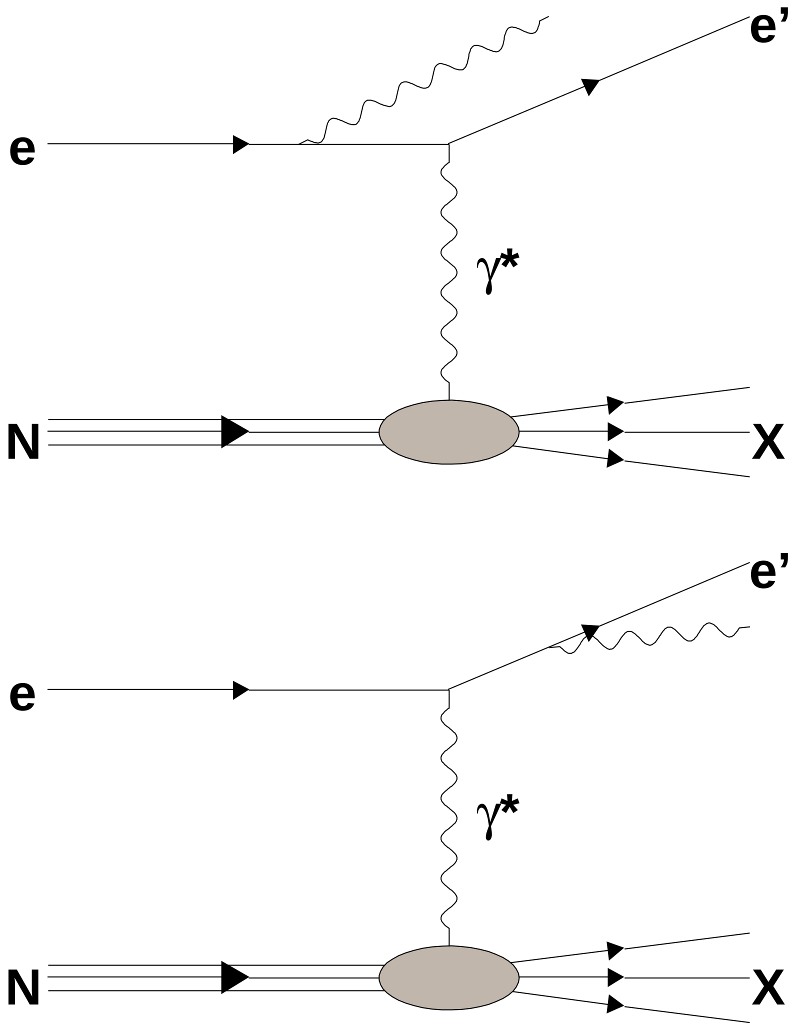
Unfolding



- Correct for acceptance/smearing:

  ⇒ HMC spectrometer simulation (GEANT3)

Unfolding



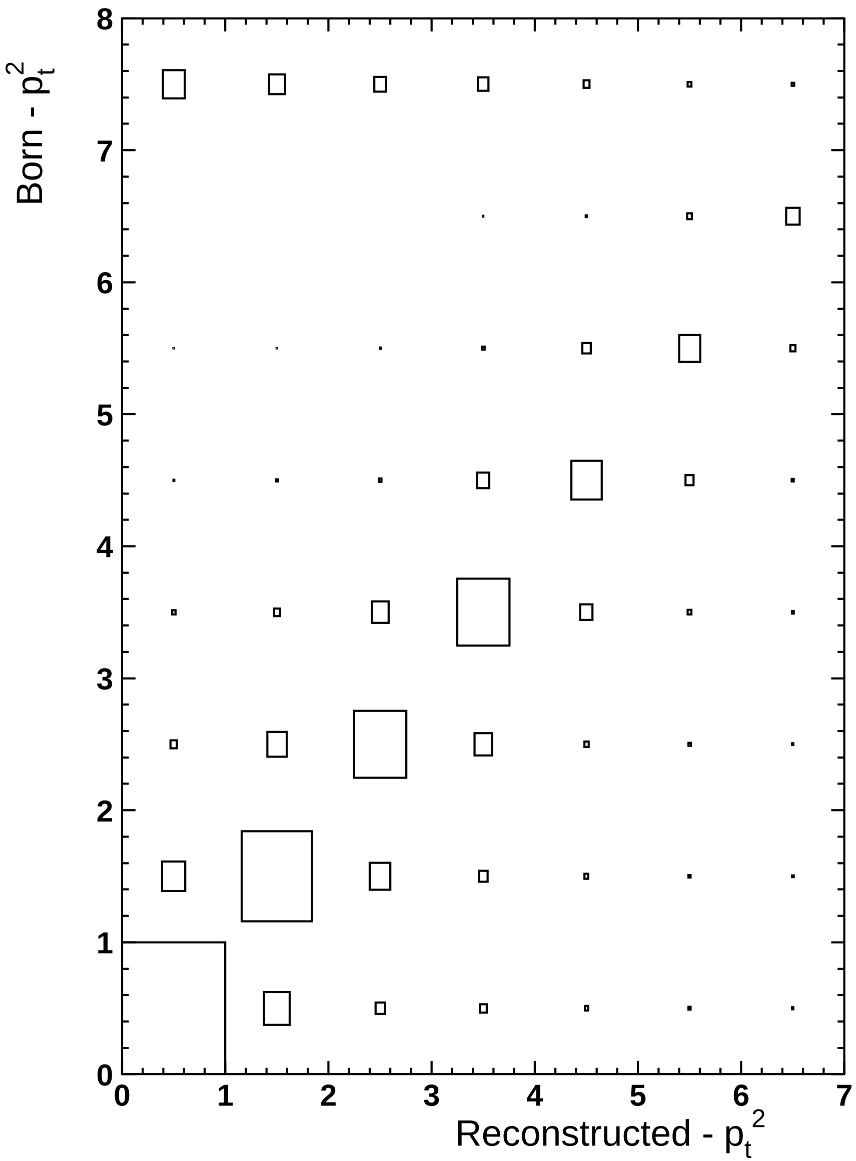
- Correct for acceptance/smearing:

  ⇒ HMC spectrometer simulation (GEANT3)

- Correct for QED radiation.

  ⇒ RADGEN

Unfolding



- Correct for acceptance/smearing:

  ⇒ HMC spectrometer simulation (GEANT3)

- Correct for 1^{st} order QED radiation.

  ⇒ RADGEN

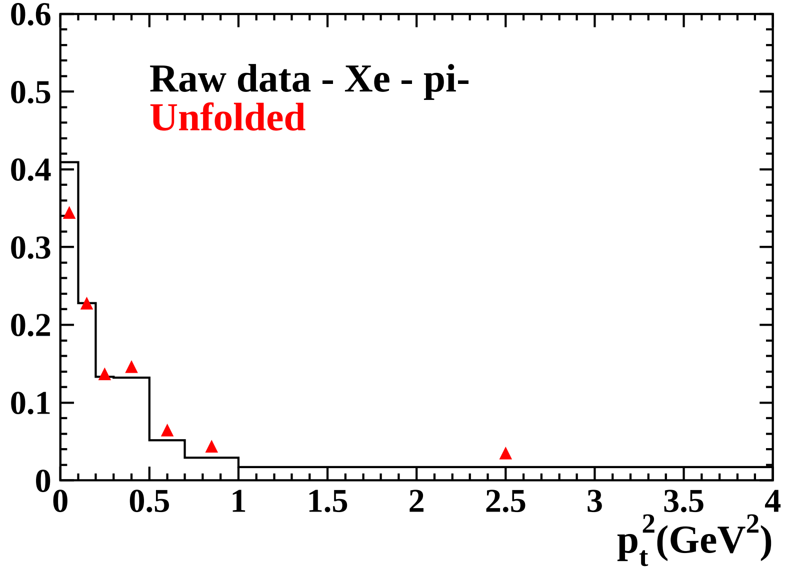
- Tuned PYTHIA + RADGEN + HMC

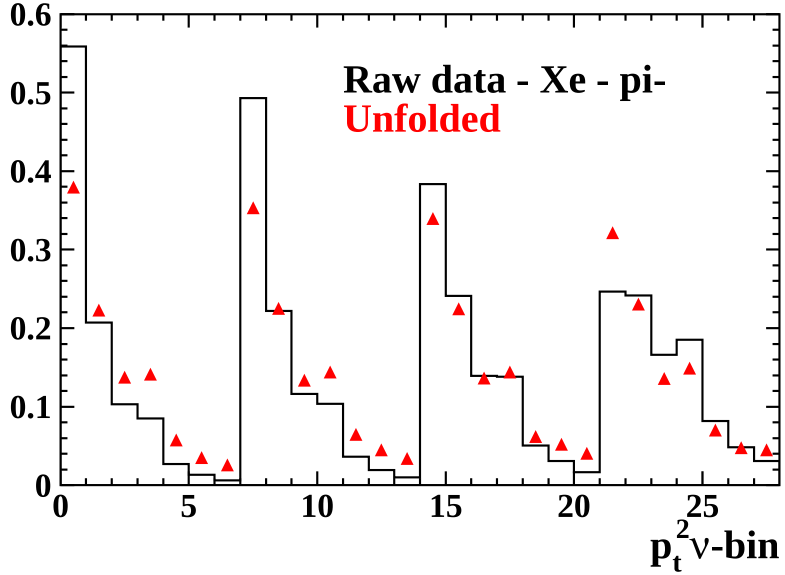
  ⇒ Unfold data: smearing matrices

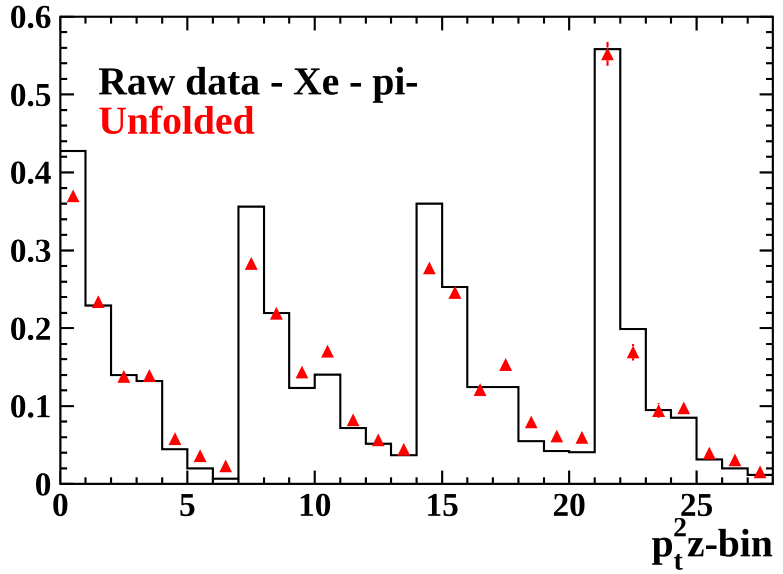
  ⇒ Not so model dependent

    * In systematic error

Impact unfolding on p_t^2 spectra

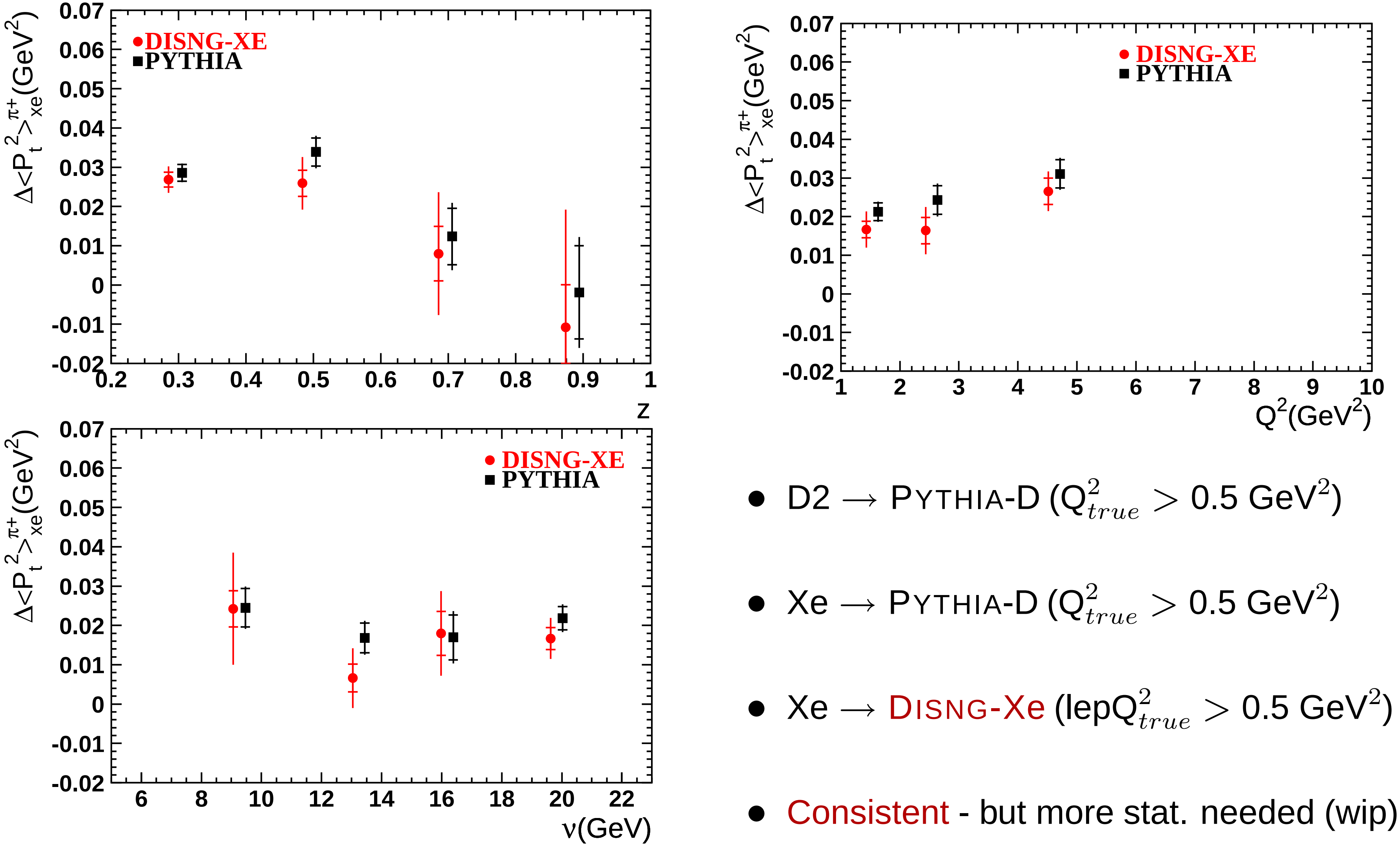






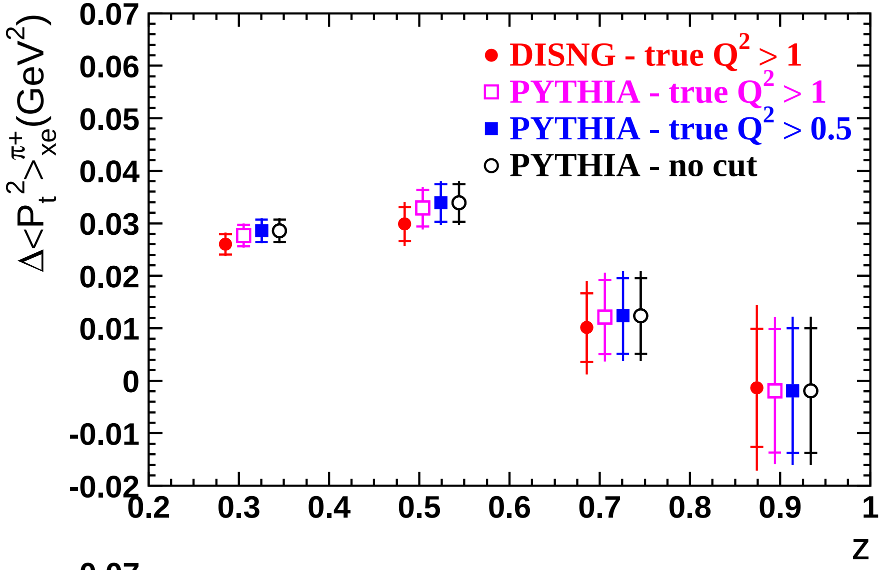
- p_t^2-binning (GeV^2): 0 - 0.1 - 0.2 - 0.3 - 0.5 - 0.7 - 1.0 - 4.0
- **Normalized values!** (to total #events in z, ν, or Q^2 bin)
- Decrease in lowest p_t^2 bins
- Slight increase in highest p_t^2 bins

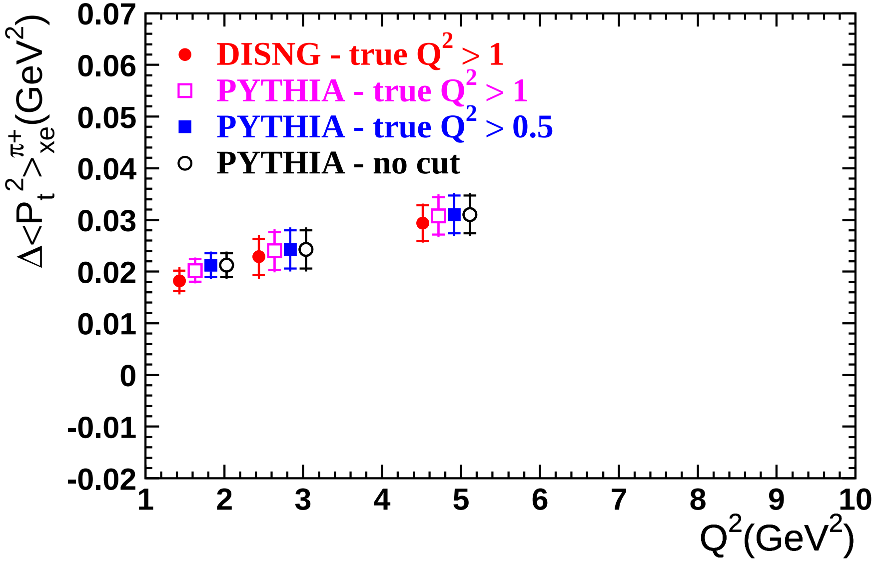
Nuclear dependence of radiative effects

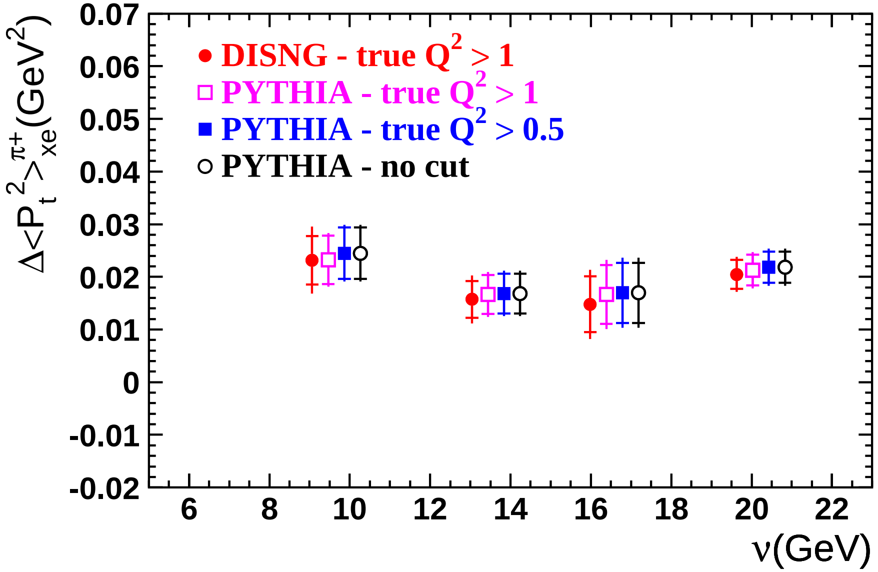


- D2 → PYTHIA-D ($Q^2_{true} > 0.5$ GeV^2)
- Xe → PYTHIA-D ($Q^2_{true} > 0.5$ GeV^2)
- Xe → DISNG-Xe (lep$Q^2_{true} > 0.5$ GeV^2)
- Consistent - but more stat. needed (wip)

Monte Carlo dependence of the unfolding







- Difference due to diff. generator and background (Q^2_{true}, W^2_{true} cut)
- Added to systematic error