Quark fragmentation in the cold nuclear medium

using kaons and nuclei to discover the mechanisms of hadronization

Will Brooks
U. Santa María, Valparaíso, Chile

Frascati, October 2010

Hadronization in QCD

Hadronization in QCD

- Hadronization is the fundamental process of an energetic quark evolving into one or more hadrons following a hard interaction

Hadronization in QCD

- Hadronization is the fundamental process of an energetic quark evolving into one or more hadrons following a hard interaction
- It is a familiar, but poorly-understood QCD process involving a mixture of perturbative and non-perturbative elements

Hadronization in QCD

- Hadronization is the fundamental process of an energetic quark evolving into one or more hadrons following a hard interaction
- It is a familiar, but poorly-understood QCD process involving a mixture of perturbative and non-perturbative elements
- With SIDIS on nuclei, one can use the interactions of the quarks and hadrons with the nucleus to get *new information* on the hadronization process, allowing more direct access to the *mechanisms of hadronization:*

Hadronization in QCD

- Hadronization is the fundamental process of an energetic quark evolving into one or more hadrons following a hard interaction
- It is a familiar, but poorly-understood QCD process involving a mixture of perturbative and non-perturbative elements
- With SIDIS on nuclei, one can use the interactions of the quarks and hadrons with the nucleus to get *new information* on the hadronization process, allowing more direct access to the *mechanisms of hadronization:*
    - *hadron fragmentation functions are modified*

Hadronization in QCD

- Hadronization is the fundamental process of an energetic quark evolving into one or more hadrons following a hard interaction
- It is a familiar, but poorly-understood QCD process involving a mixture of perturbative and non-perturbative elements
- With SIDIS on nuclei, one can use the interactions of the quarks and hadrons with the nucleus to get *new information* on the hadronization process, allowing more direct access to the *mechanisms of hadronization:*
    - *hadron fragmentation functions are modified*
    - *transverse momentum is broadened*

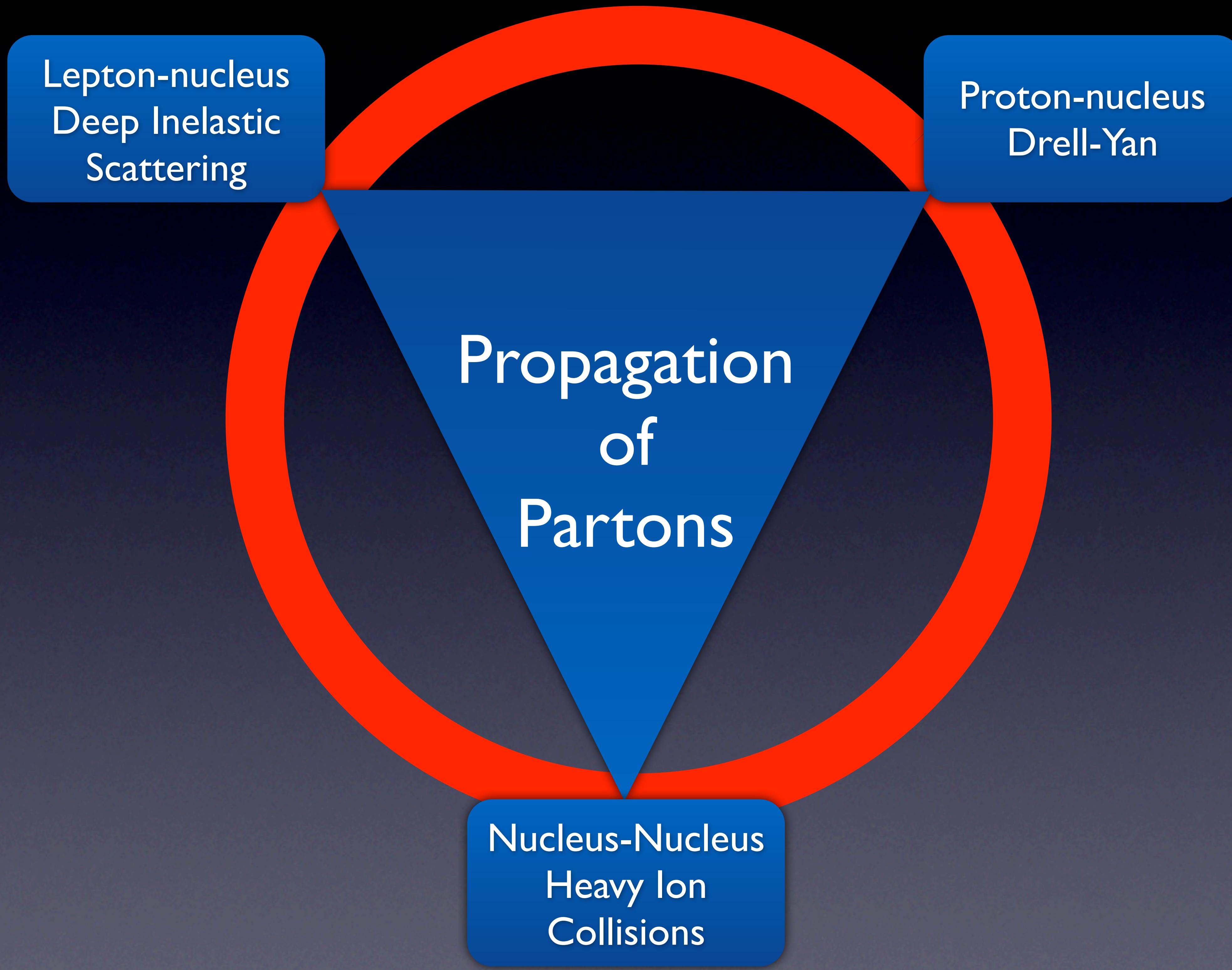
Hadronization in QCD

- Hadronization is the fundamental process of an energetic quark evolving into one or more hadrons following a hard interaction
- It is a familiar, but poorly-understood QCD process involving a mixture of perturbative and non-perturbative elements
- With SIDIS on nuclei, one can use the interactions of the quarks and hadrons with the nucleus to get *new information* on the hadronization process, allowing more direct access to the *<u>mechanisms of hadronization:</u>*
    - *hadron fragmentation functions are modified*
    - *transverse momentum is broadened*
    - *correlations between hadrons are modified*

Hadronization in QCD

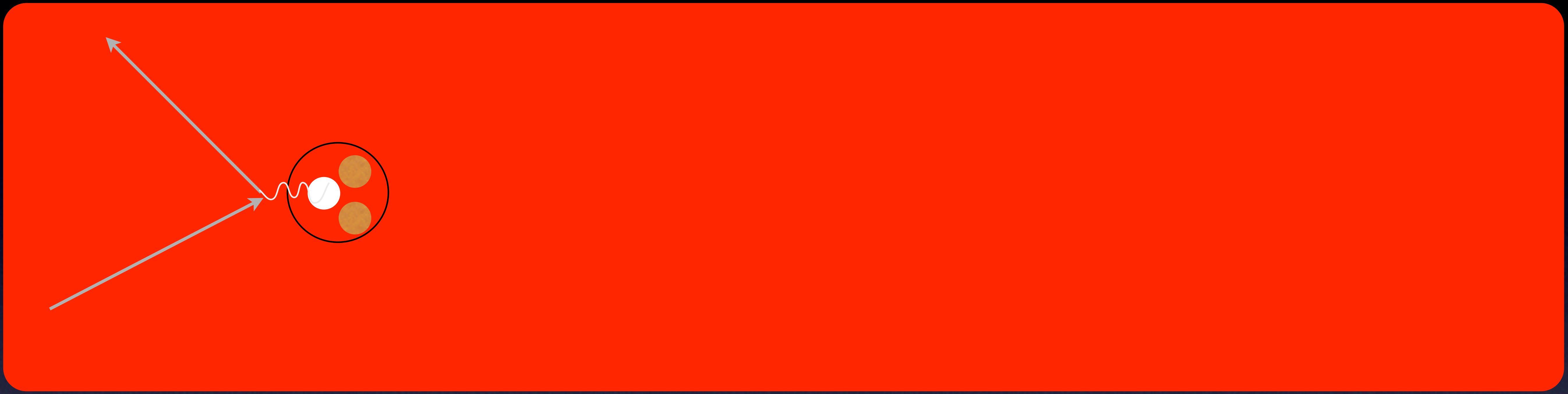
- Hadronization is the fundamental process of an energetic quark evolving into one or more hadrons following a hard interaction
- It is a familiar, but poorly-understood QCD process involving a mixture of perturbative and non-perturbative elements
- With SIDIS on nuclei, one can use the interactions of the quarks and hadrons with the nucleus to get *new information* on the hadronization process, allowing more direct access to the *mechanisms of hadronization:*
    - *hadron fragmentation functions are modified*
    - *transverse momentum is broadened*
    - *correlations between hadrons are modified*
    - *correlated photons, multiplicity correlations, and more*

Connections

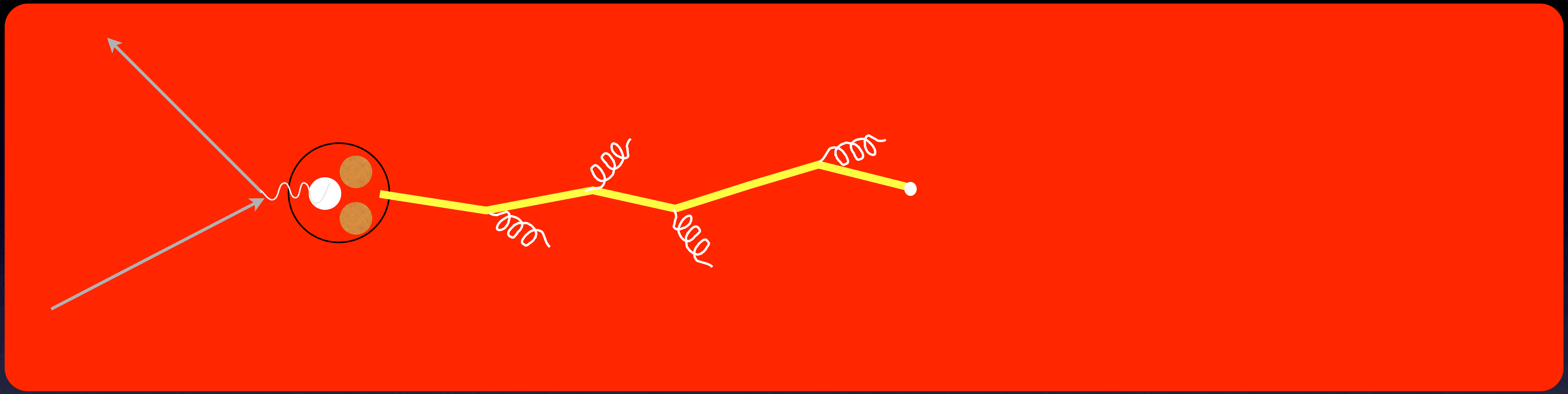


Deep Inelastic Scattering - Vacuum

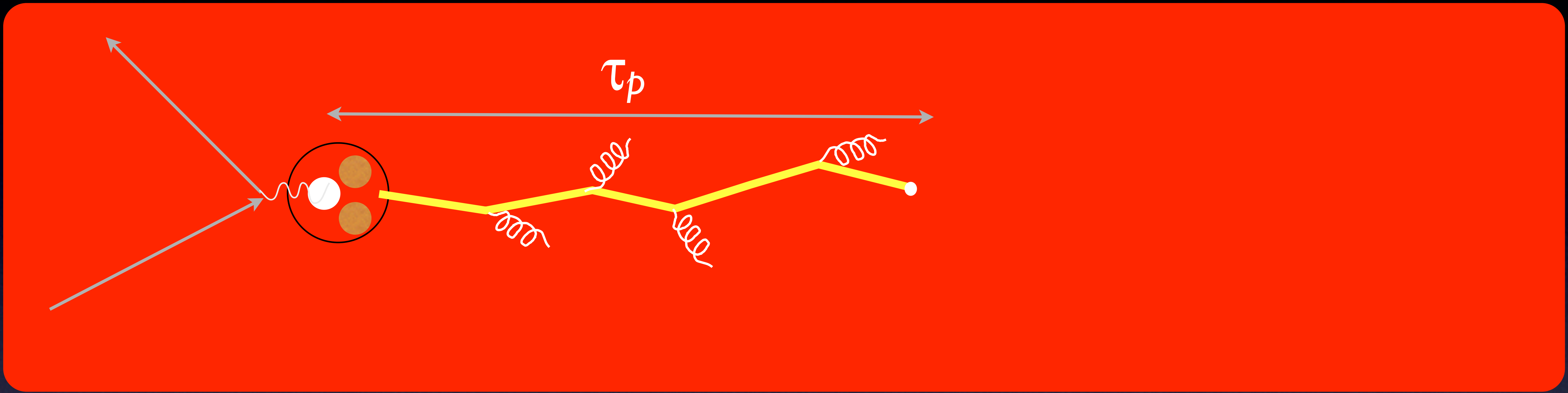
Deep Inelastic Scattering - Vacuum



Deep Inelastic Scattering - Vacuum

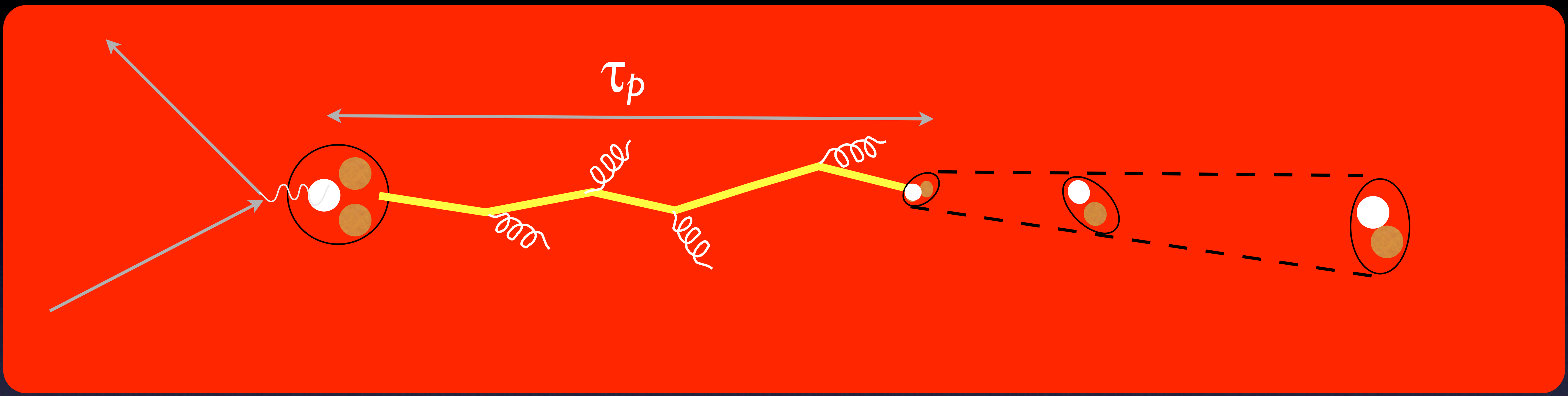


Deep Inelastic Scattering - Vacuum



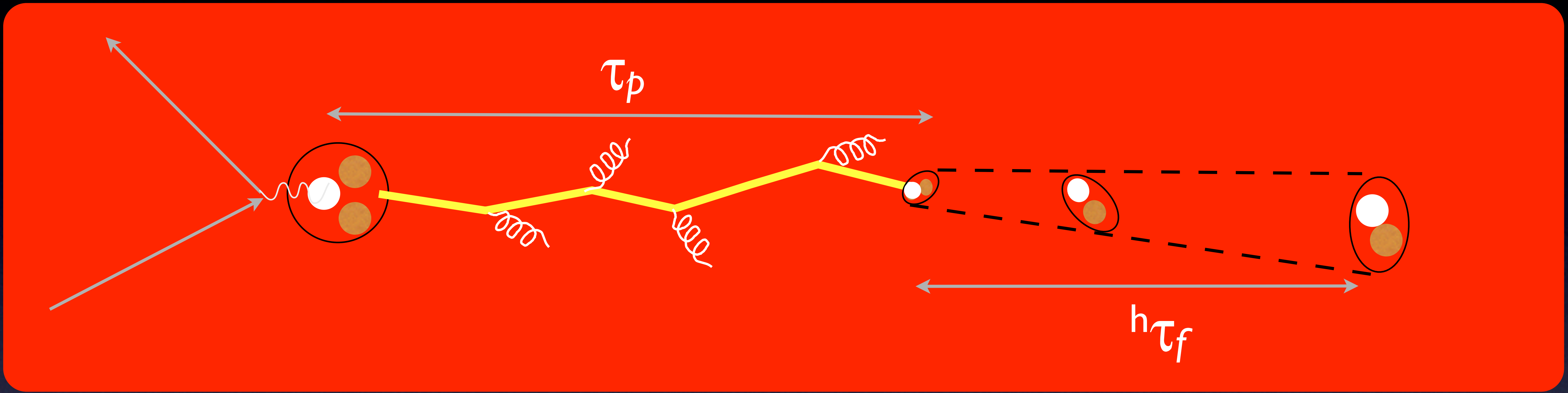
- <u>*production time* τ_p</u> - propagating quark

Deep Inelastic Scattering - Vacuum



- *production time* τ_p - propagating quark

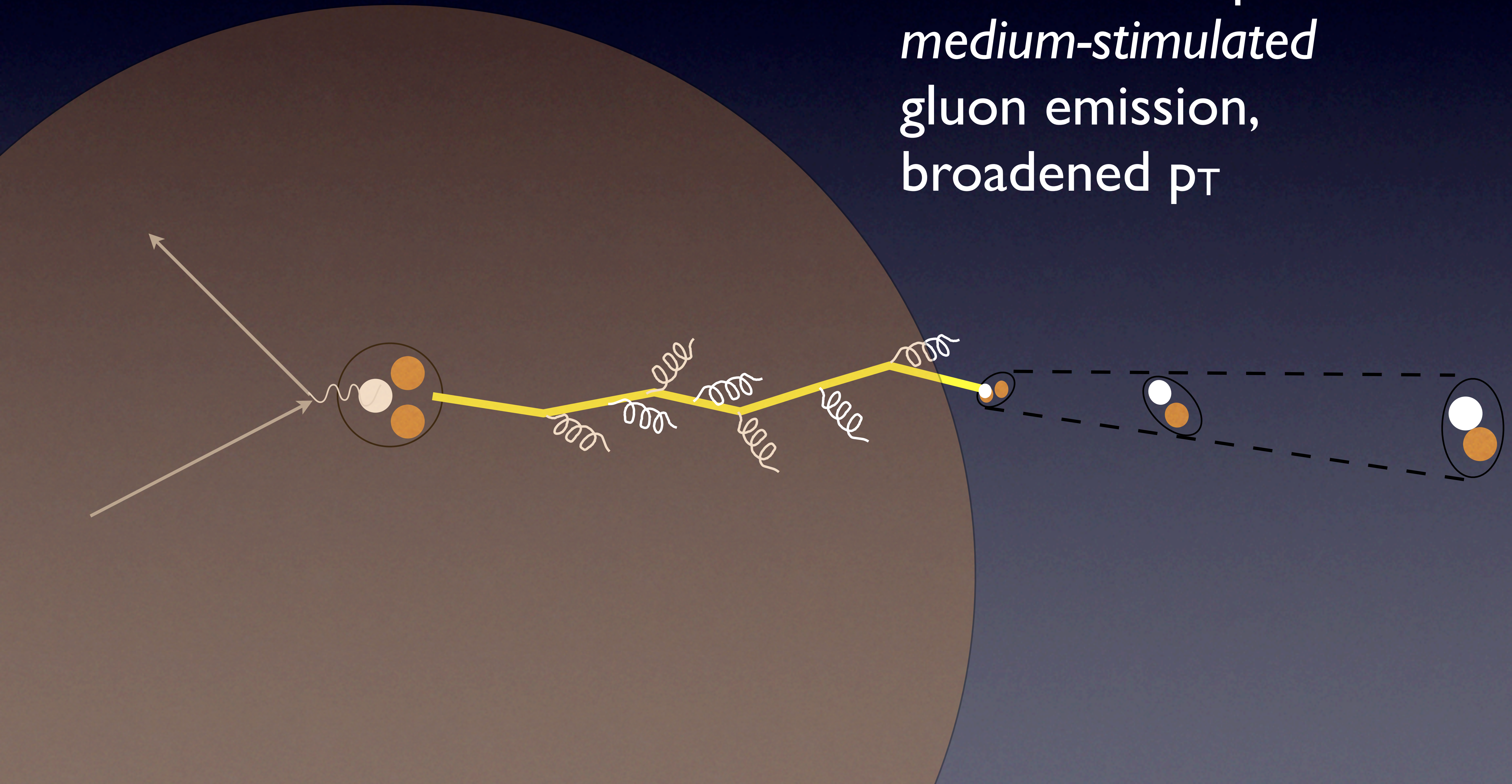
Deep Inelastic Scattering - Vacuum



- *production time* τ_p - propagating quark
- *formation time* ${}^h\tau_f$ - dipole grows to hadron

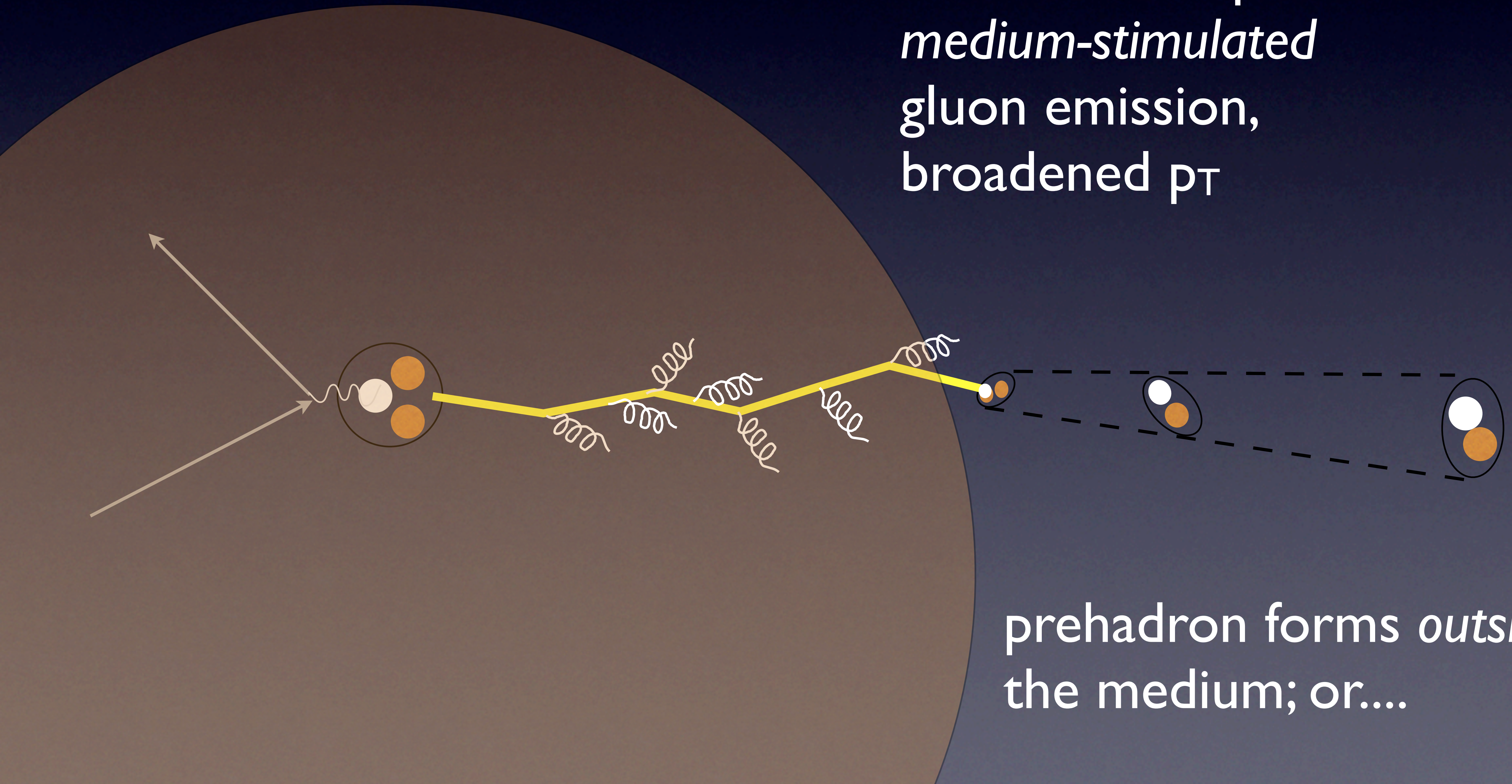
DIS in Cold Nuclear Medium

Partonic multiple scattering:
medium-stimulated
gluon emission,
broadened p_T



DIS in Cold Nuclear Medium

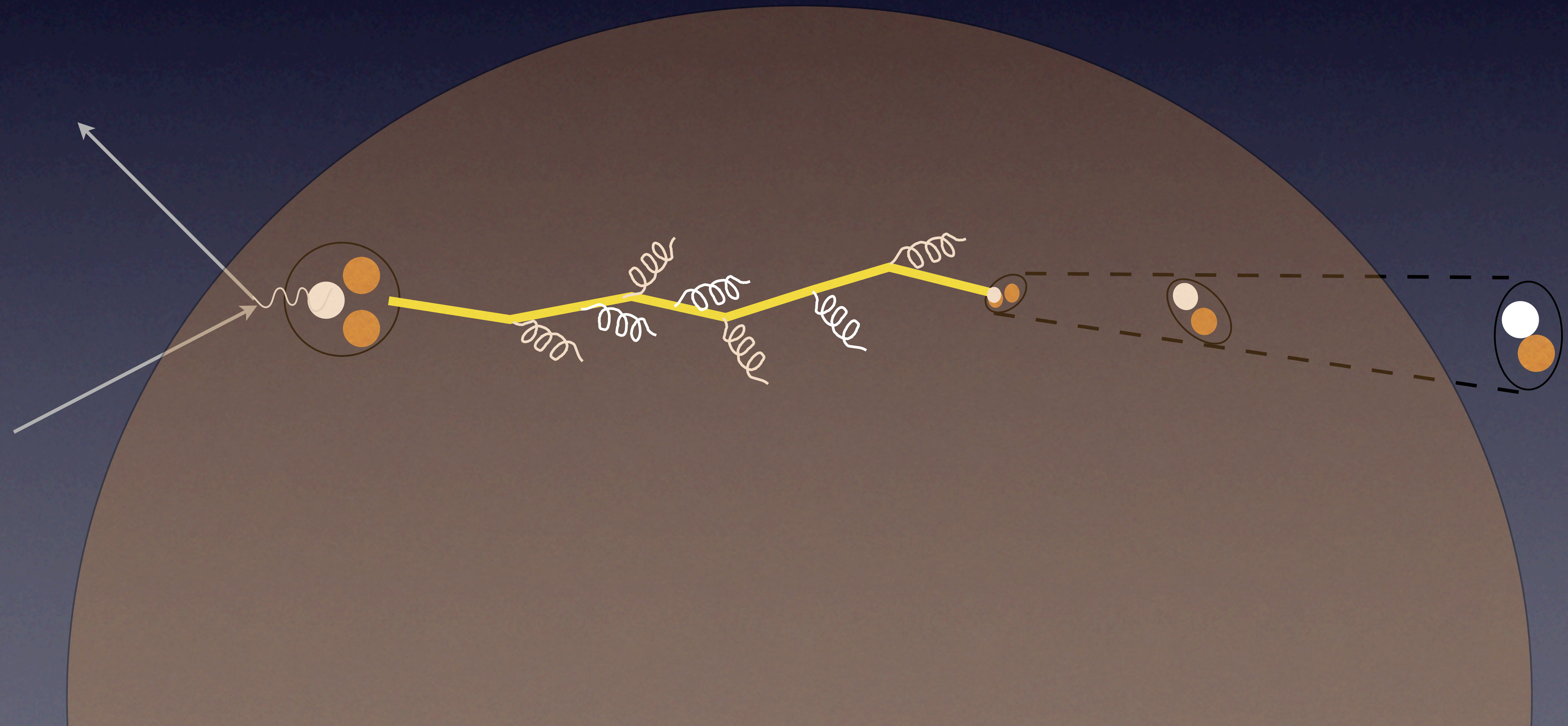
Partonic multiple scattering:
medium-stimulated
gluon emission,
broadened p_T



prehadron forms *outside*
the medium; or....

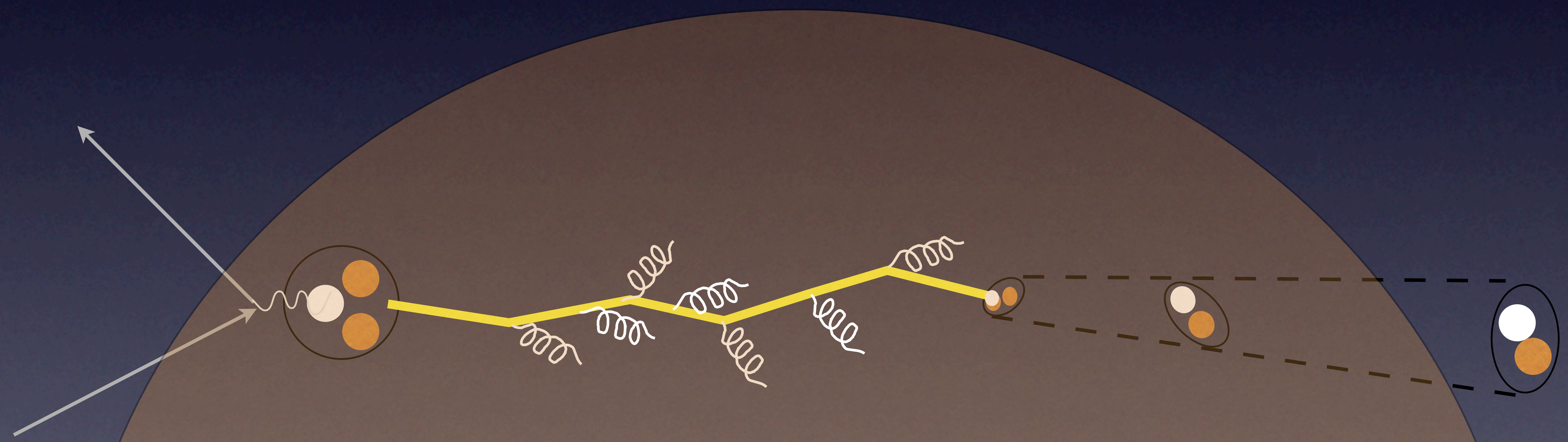
DIS in Cold Nuclear Medium

Hadron forms *inside* the medium; then also have prehadron/hadron interaction



DIS in Cold Nuclear Medium

Hadron forms *inside* the medium; then also have prehadron/hadron interaction



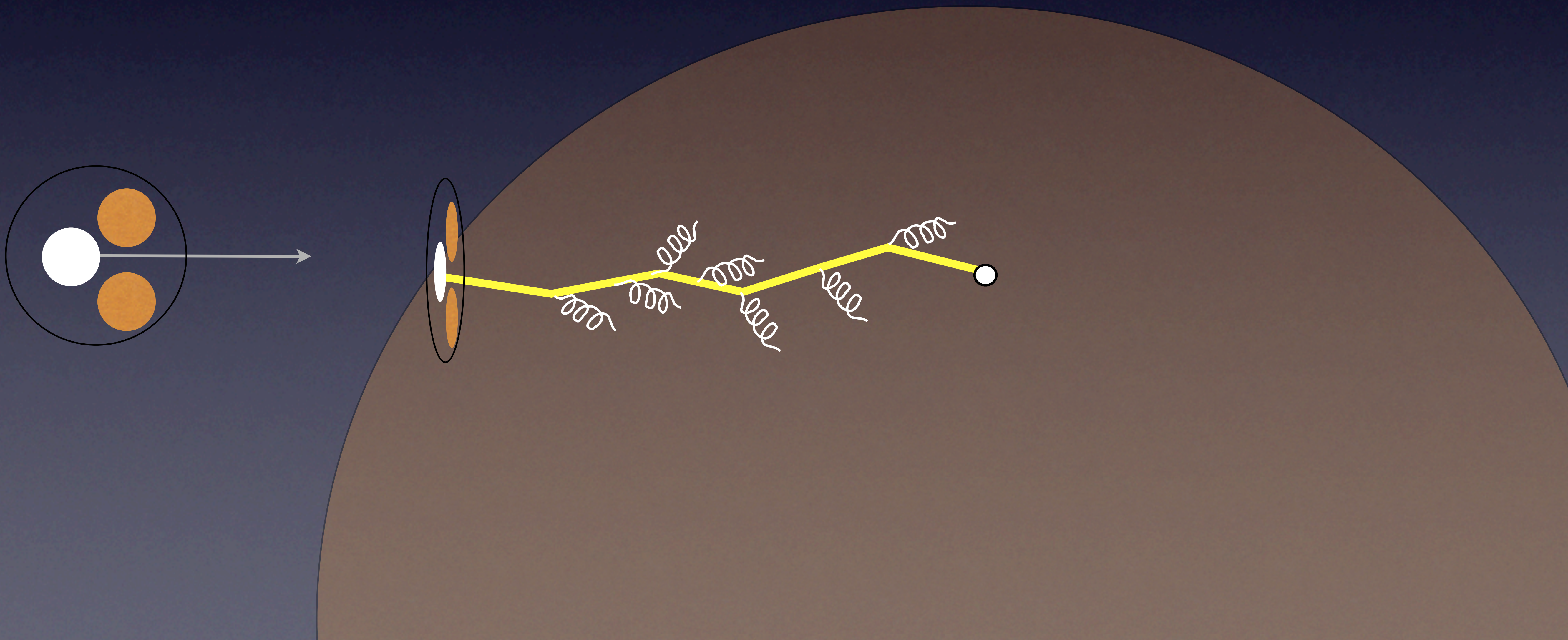
Amplitudes for hadronization *inside* and *outside* the medium can interfere

Drell-Yan in Cold Nuclear Medium

e.g., 800 GeV protons - no in-medium hadronization, but do have p_T broadening

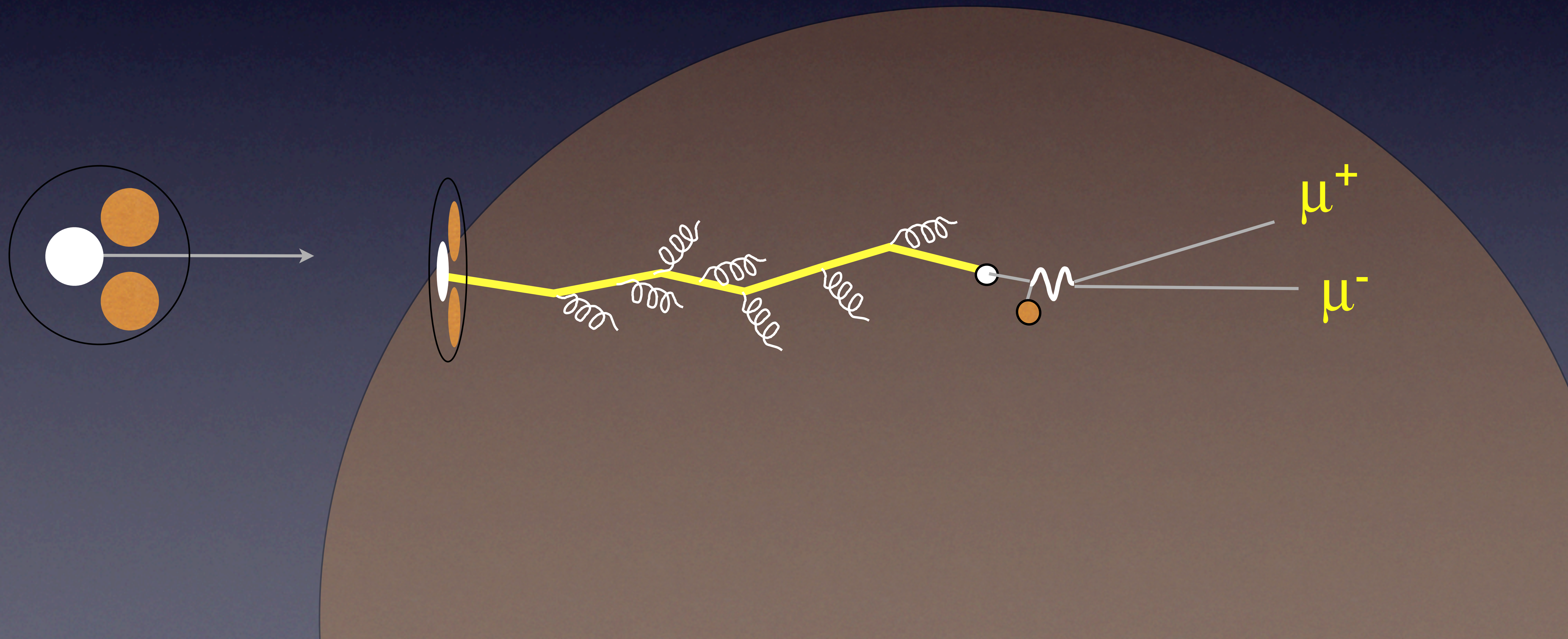
Drell-Yan in Cold Nuclear Medium

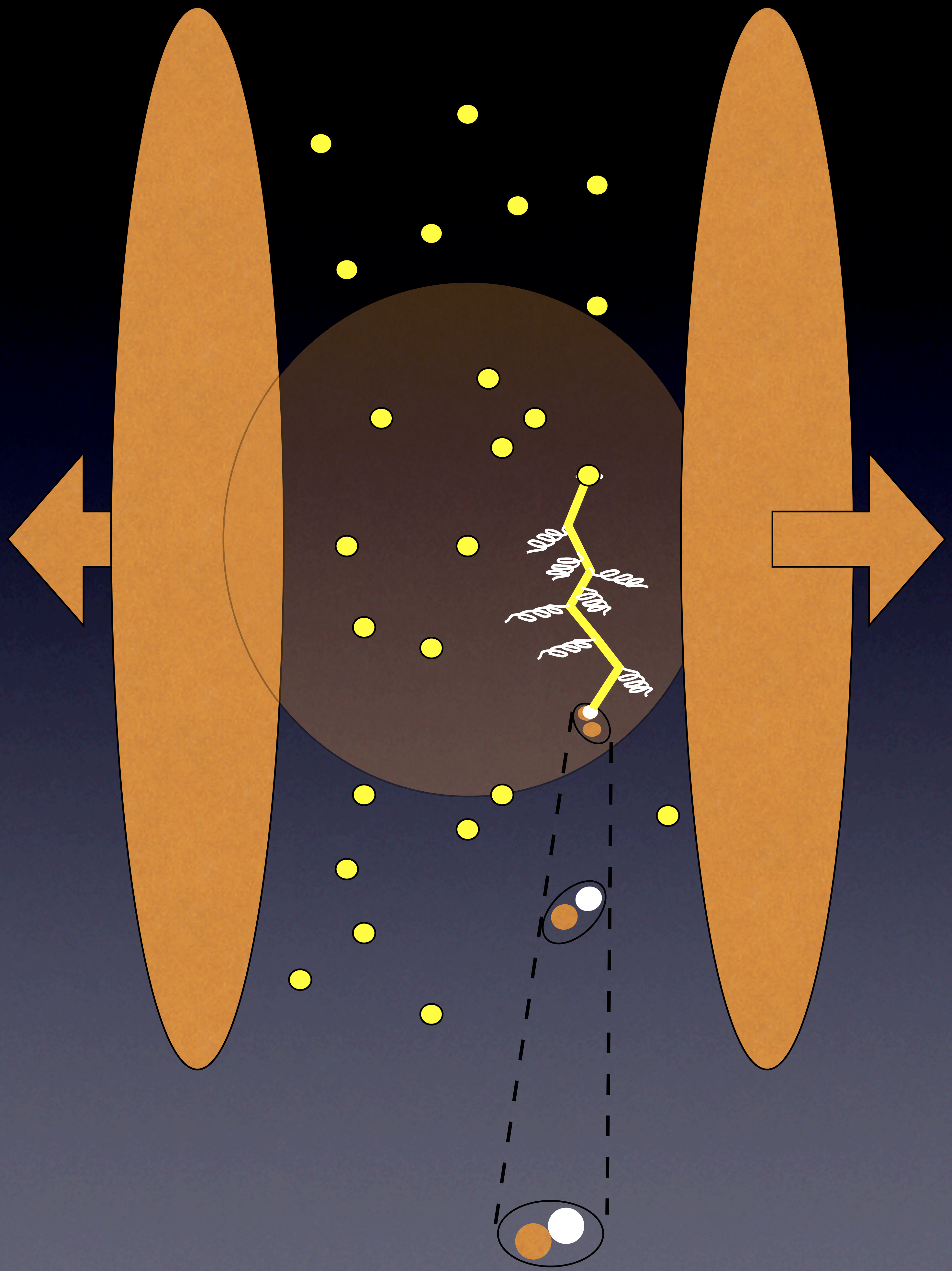
e.g., 800 GeV protons - no in-medium hadronization, but do have p_T broadening



Drell-Yan in Cold Nuclear Medium

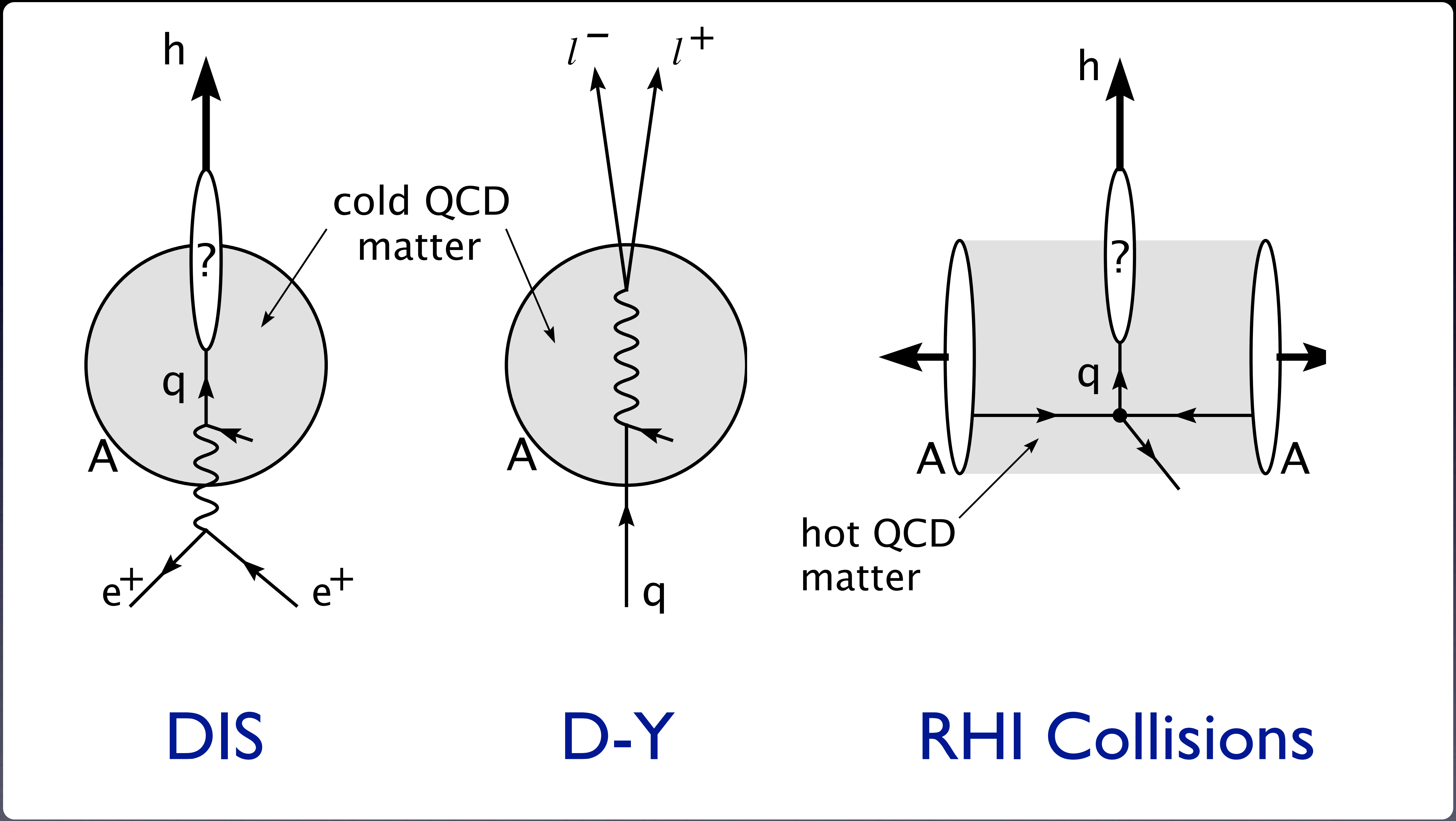
e.g., 800 GeV protons - no in-medium hadronization, but do have p_T broadening





Relativistic Heavy Ion Collisions - parton propagation in a hot dense medium

Comparison of Parton Propagation in Three Processes



Accardi, Arleo, Brooks, d'Enterria, **Muccifora**, Riv.Nuovo Cim.032:439-553,2010 [arXiv:0907.3534]
Majumder, van Leuween, arXiv:1002.2206

BACK-OF-ENVELOPE - τ_p

BACK-OF-ENVELOPE - τ_p

$$\tau_p = \frac{\nu(1 - z_h)}{\frac{dE}{dx}\Big|_{vacuum}}$$

Energy conservation, time dialation

BACK-OF-ENVELOPE - τ_p

$$\tau_p = \frac{\nu(1 - z_h)}{\frac{dE}{dx}\Big|_{vacuum}}$$

Energy conservation, time dialation

String model

$$\frac{dE}{dx}\Big|_{vacuum} \approx \kappa \approx 1 \quad GeV / fm$$

BACK-OF-ENVELOPE - τ_p

$$\tau_p = \frac{\nu(1 - z_h)}{\frac{dE}{dx}\Big|_{vacuum}}$$

Energy conservation, time dialation

String model

$$\frac{dE}{dx}\Big|_{vacuum} \approx \kappa \approx 1 \quad GeV / fm$$

If take, e.g., **z** = $E_{hadron}/\nu = 0.6$, $\nu = 5$ GeV, then ***$t_p \sim 2$ fm/c***

BACK-OF-ENVELOPE - τ_p

$$\tau_p = \frac{\nu(1 - z_h)}{\frac{dE}{dx}\Big|_{vacuum}}$$

Energy conservation, time dialation

String model

$$\frac{dE}{dx}\Big|_{vacuum} \approx \kappa \approx 1 \;\; GeV / fm$$

If take, e.g., $\mathbf{z} = E_{hadron}/\nu = 0.6$, $\nu = 5$ GeV, then ***$t_p \sim 2$ fm/c***

$$\tau_\mathbf{p} = \frac{\nu \mathbf{z}(\mathbf{1} - \mathbf{z})}{\mathbf{Q^2}}$$

BACK-OF-ENVELOPE - ${}^{h}\tau_{f}$

BACK-OF-ENVELOPE - ${}^{h}\tau_f$

Given hadron of size R_h, can build color field of hadron in its rest frame in time no less than $t_0 \sim R_h/c$. In lab frame this is time dialated:

$$t_f \geq \frac{E}{m} R_h$$

BACK-OF-ENVELOPE - ${}^{h}\tau_f$

Given hadron of size R_h, can build color field of hadron in its rest frame in time no less than $t_0 \sim R_h/c$. In lab frame this is time dialated:

$$t_f \geq \frac{E}{m} R_h$$

If take, e.g., the pion mass, radius 0.66 fm, E = 4 GeV, then ***$\tau_f \sim 20$ fm/c***.

BACK OF ENVELOPE, BUT USING QUANTUM MECHANICS - $^{h}\tau_f$

Given propagating pre-hadron with energy E in the lab frame, the time it takes to resolve the final hadron mass is given by the difference between the masses of the nearest two states into which it can evolve (e.g., ground state and first radial excited state), boosted to the lab frame.

$$\tau_f = \frac{2E}{m_1^2 - m_2^2}$$

BACK OF ENVELOPE, BUT USING QUANTUM MECHANICS - $^{h}\tau_f$

Given propagating pre-hadron with energy E in the lab frame, the time it takes to resolve the final hadron mass is given by the difference between the masses of the nearest two states into which it can evolve (e.g., ground state and first radial excited state), boosted to the lab frame.

$$\tau_f = \frac{2E}{m_1^2 - m_2^2}$$

Pion of 4 GeV, m_1=0.14 GeV, m_2 = 1.3 GeV, E = 4 GeV, then *τ_f ~1 fm/c*. (*Much less than previous page! [and Kaons?]*)

BACK OF ENVELOPE, BUT USING QUANTUM MECHANICS - $^{h}\tau_f$

Given propagating pre-hadron with energy E in the lab frame, the time it takes to resolve the final hadron mass is given by the difference between the masses of the nearest two states into which it can evolve (e.g., ground state and first radial excited state), boosted to the lab frame.

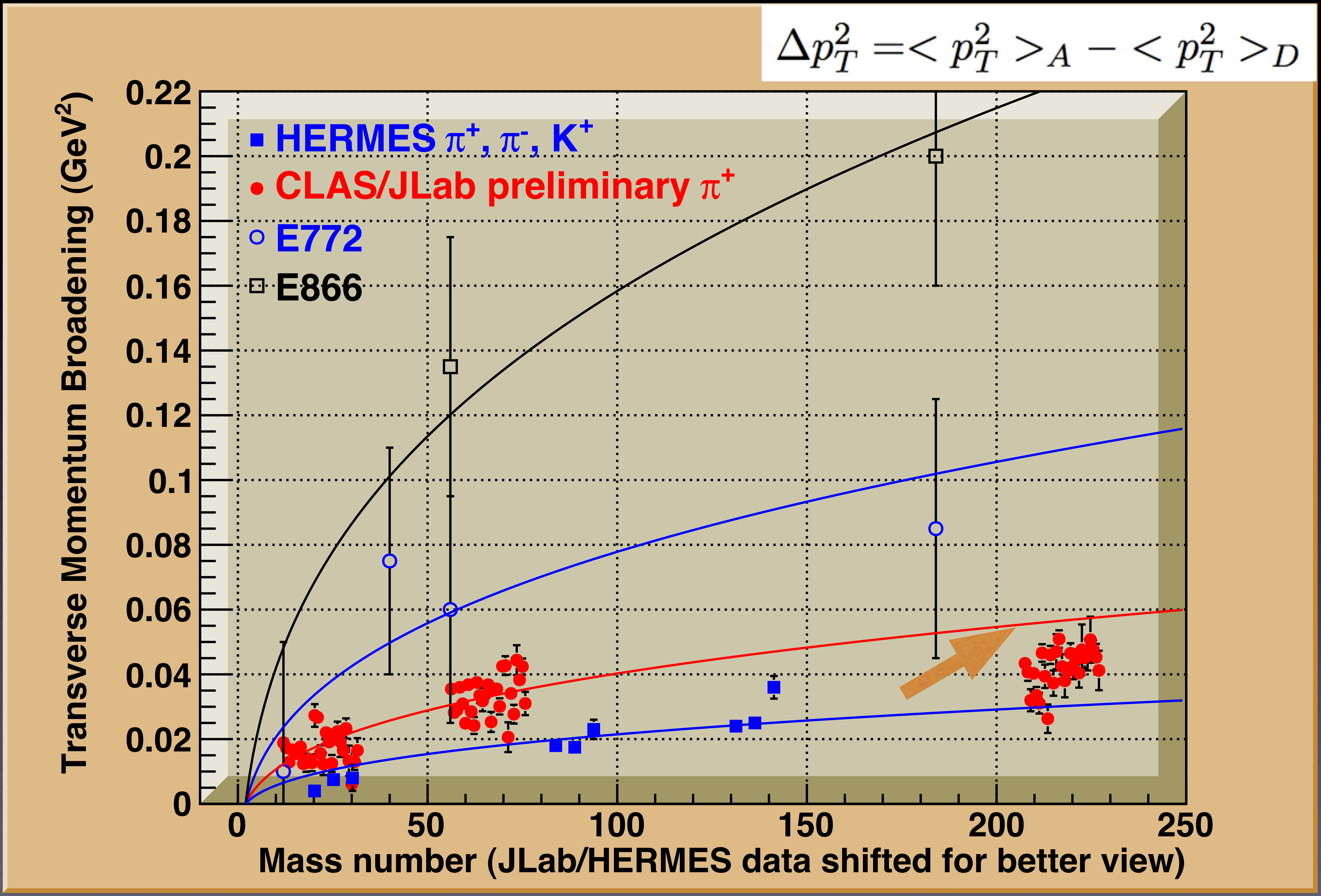
$$\tau_f = \frac{2E}{m_1^2 - m_2^2}$$

Pion of 4 GeV, m_1=0.14 GeV, m_2 = 1.3 GeV, E = 4 GeV, then

τ_f ~1 fm/c. *(Much less than previous page! [and Kaons?])*

p.s., note connection to the quark model and hadron structure!

Comparison of p_T broadening data - Drell-Yan and DIS

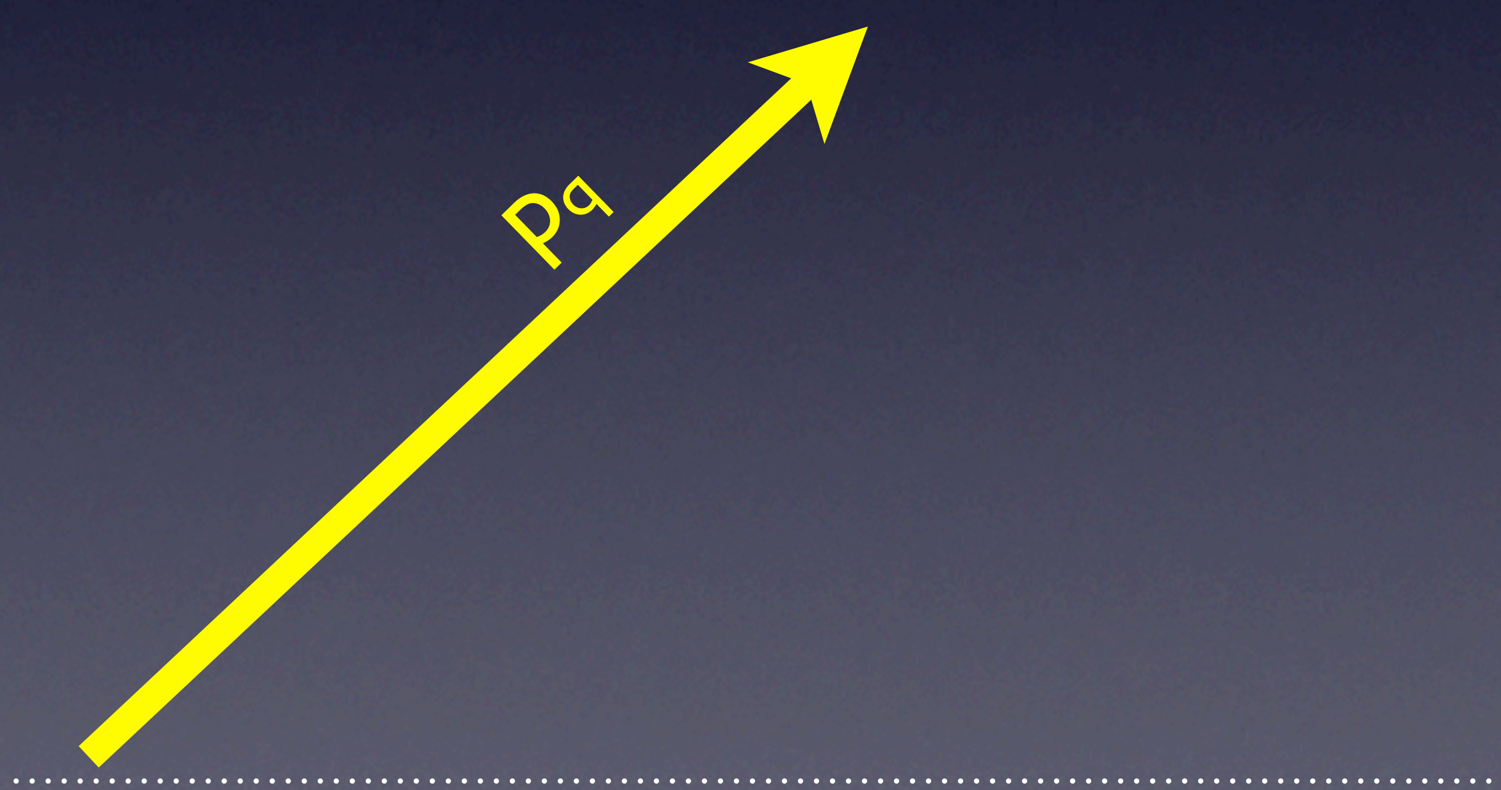


Quark k_T broadening vs. *hadron* p_T broadening

The transverse momentum broadening experienced by a quark is *diluted* by the time it is part of a hadron

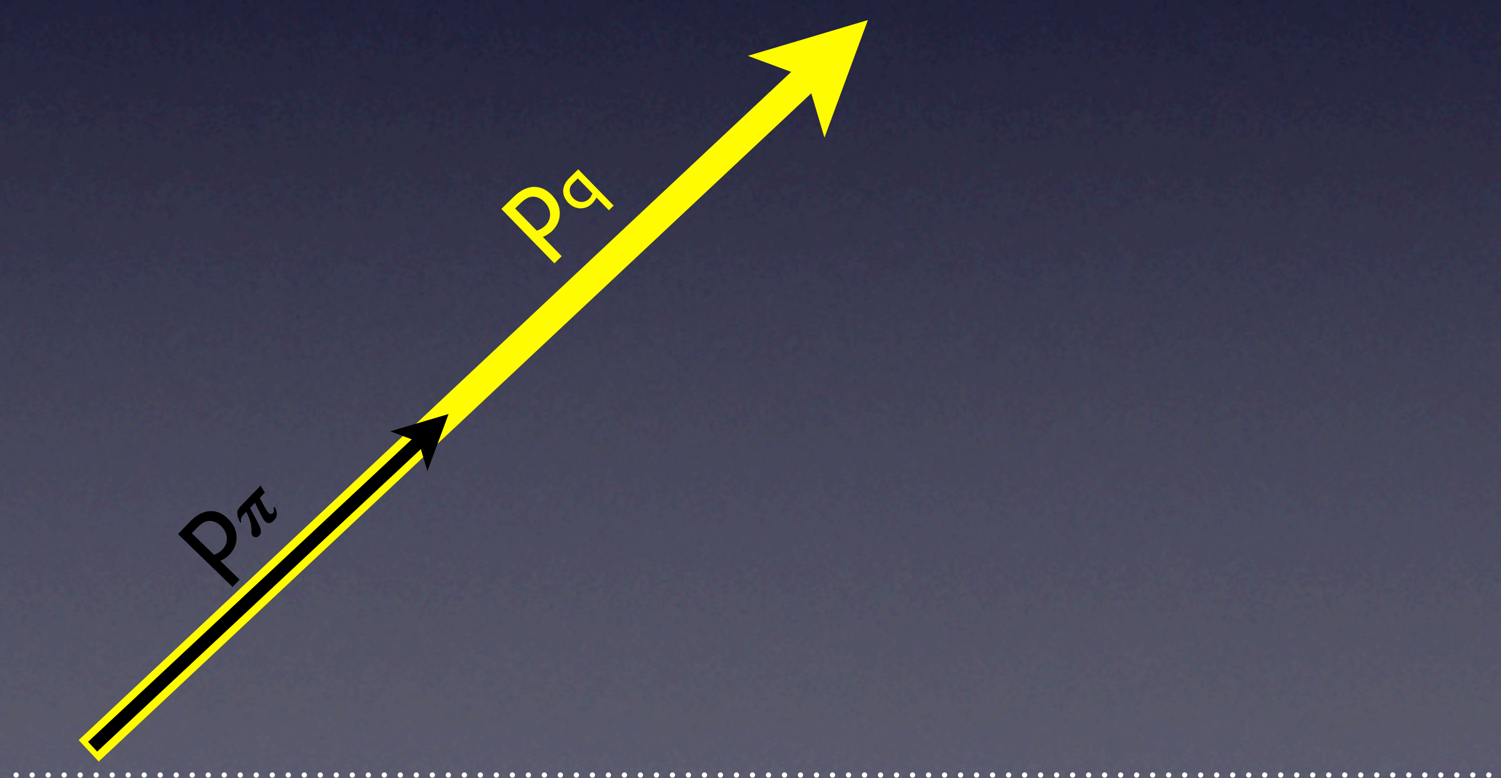
Quark k_T broadening vs. *hadron* p_T broadening

The transverse momentum broadening experienced by a quark is *diluted* by the time it is part of a hadron



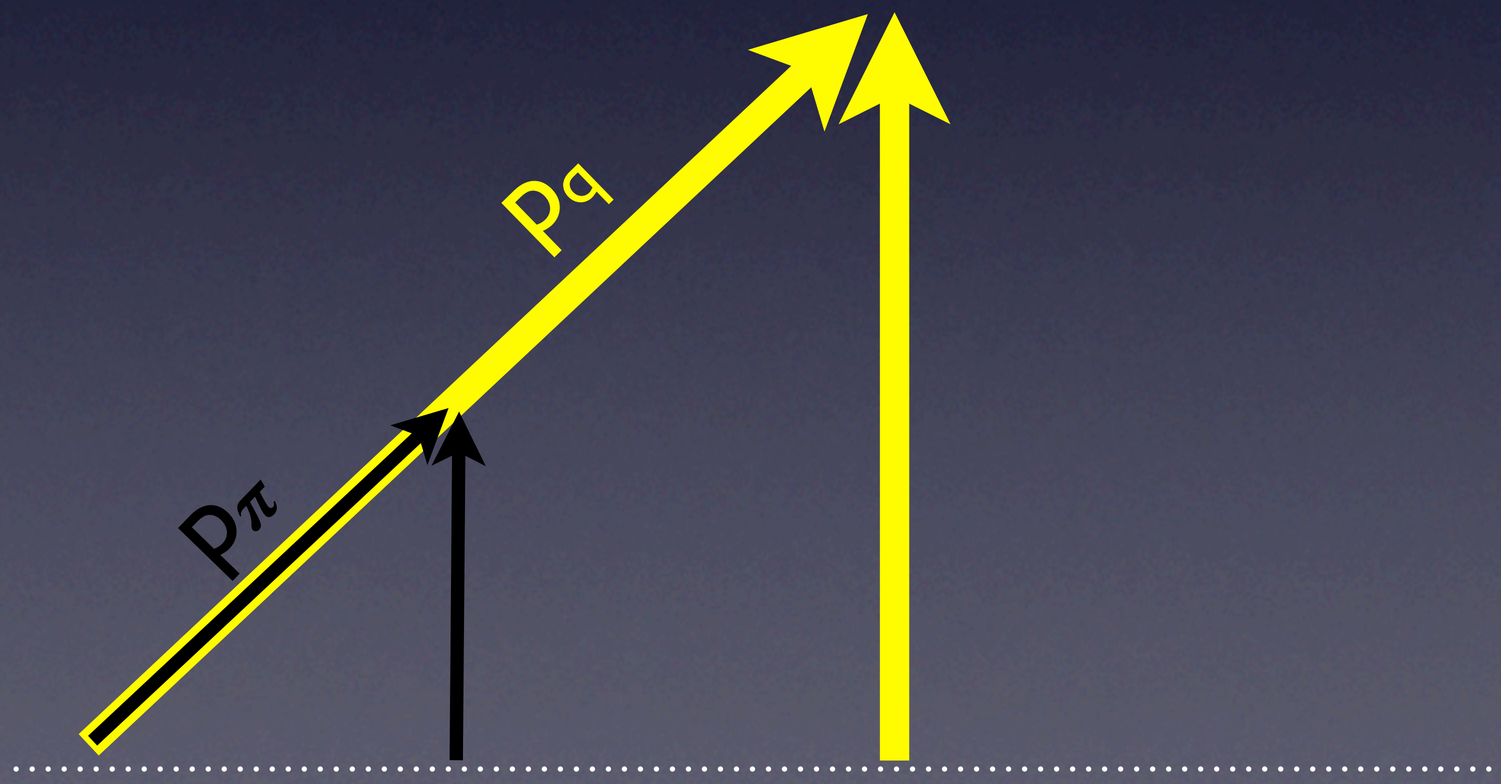
Quark k_T broadening vs. *hadron* p_T broadening

The transverse momentum broadening experienced by a quark is *diluted* by the time it is part of a hadron



Quark k_T broadening vs. *hadron* p_T broadening

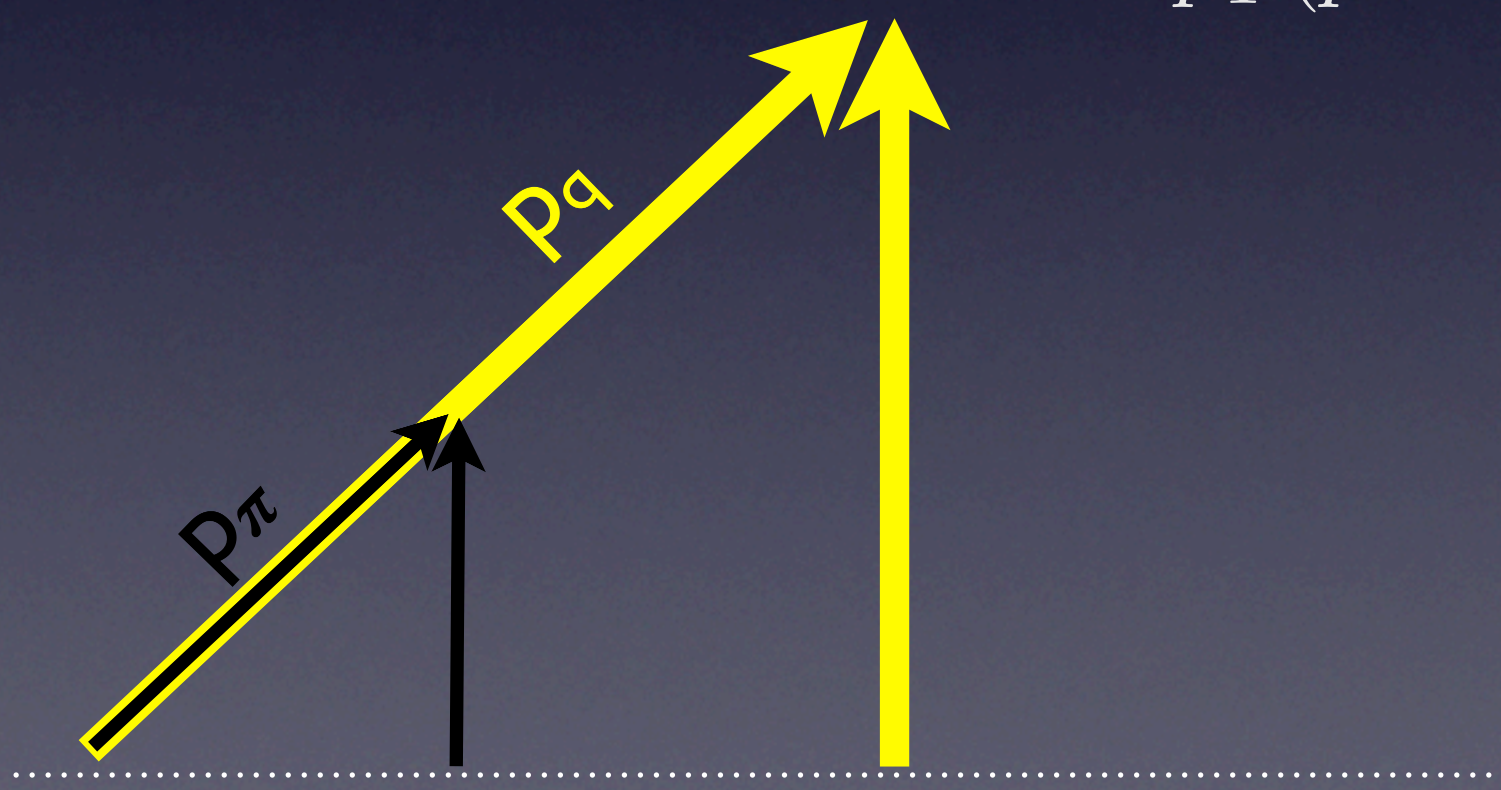
The transverse momentum broadening experienced by a quark is *diluted* by the time it is part of a hadron



Quark k_T broadening vs. *hadron* p_T broadening

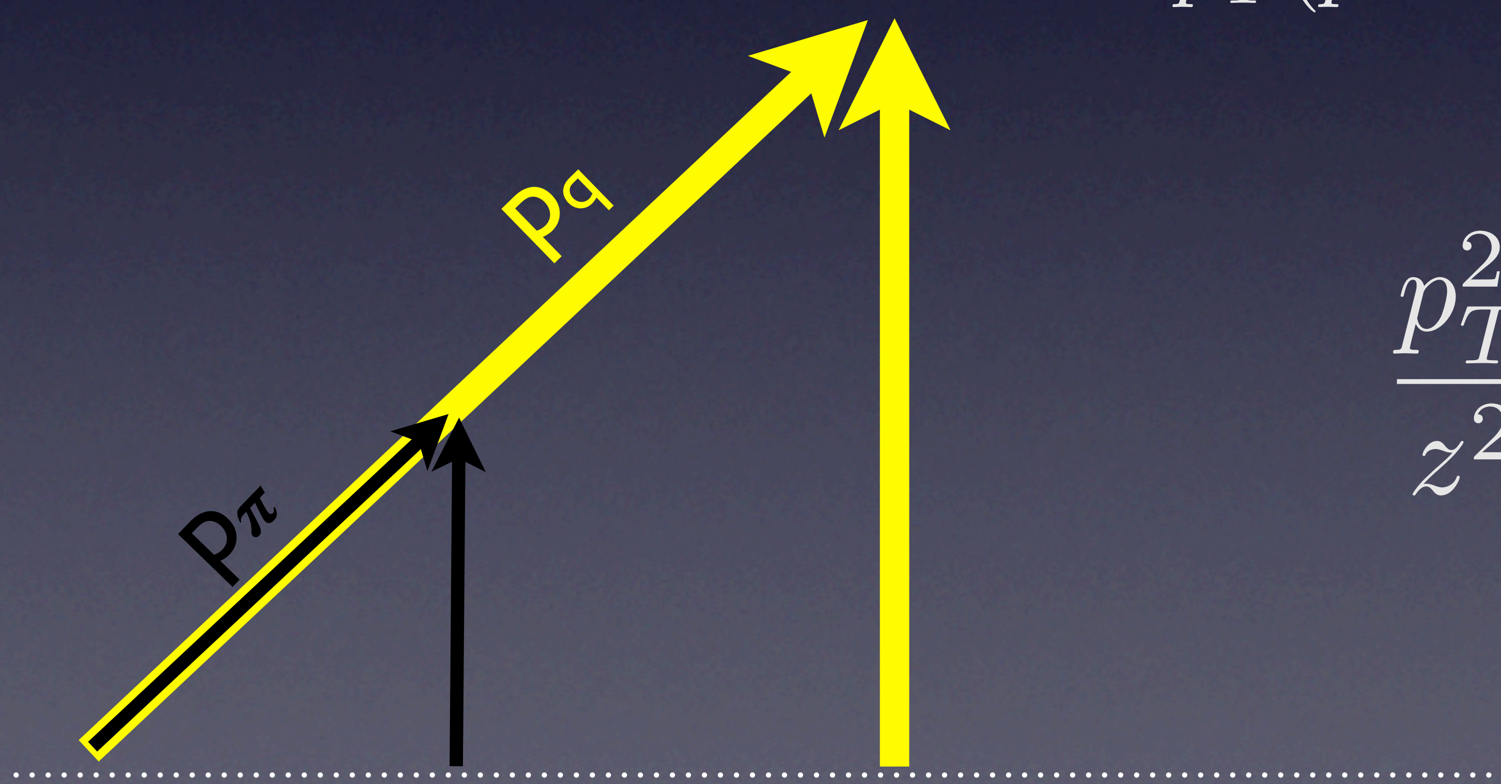
The transverse momentum broadening experienced by a quark is *diluted* by the time it is part of a hadron

$$p_T(pion) \approx z\ k_T(quark)$$



Quark k_T broadening vs. *hadron* p_T broadening

The transverse momentum broadening experienced by a quark is *diluted* by the time it is part of a hadron

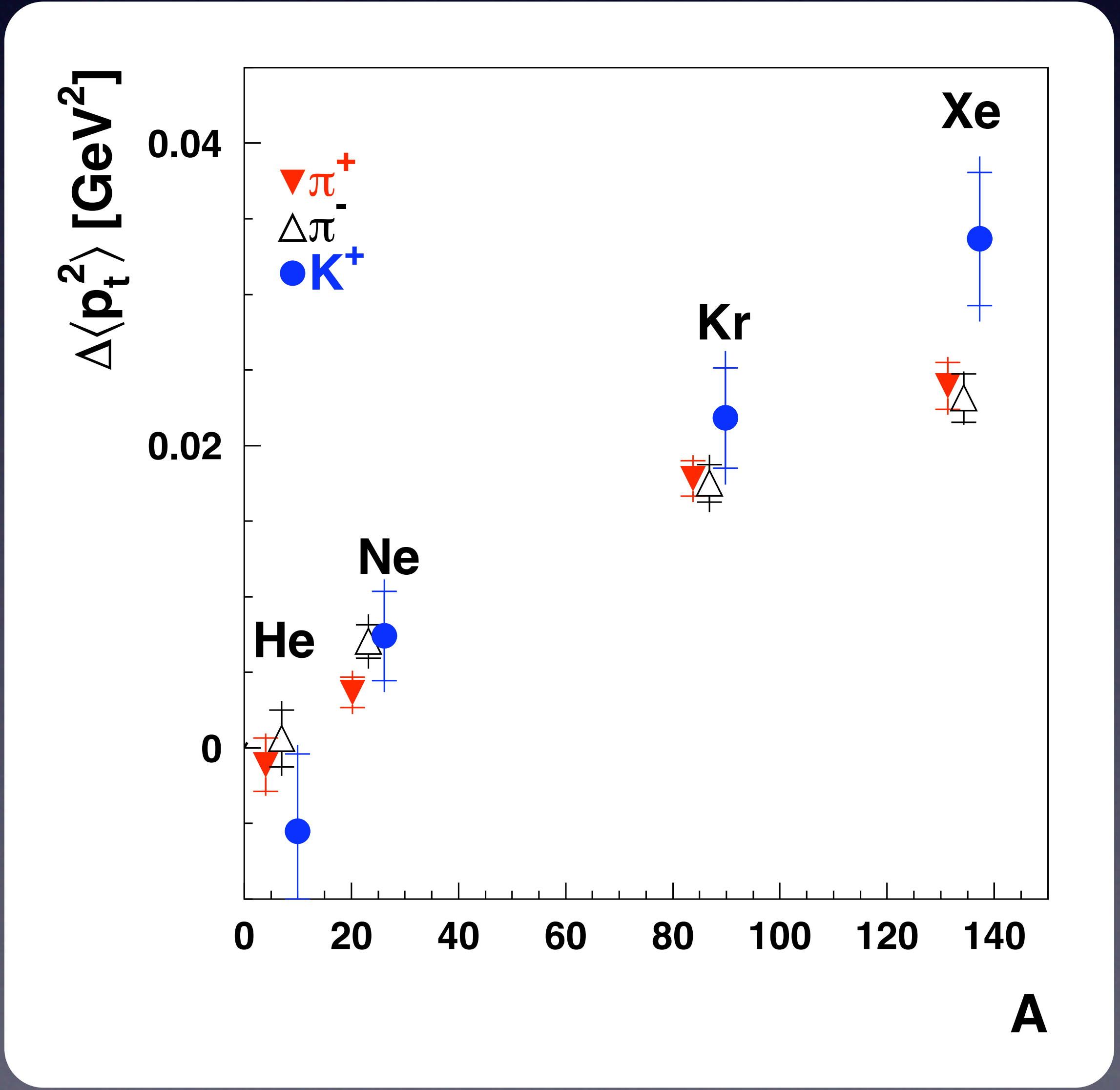


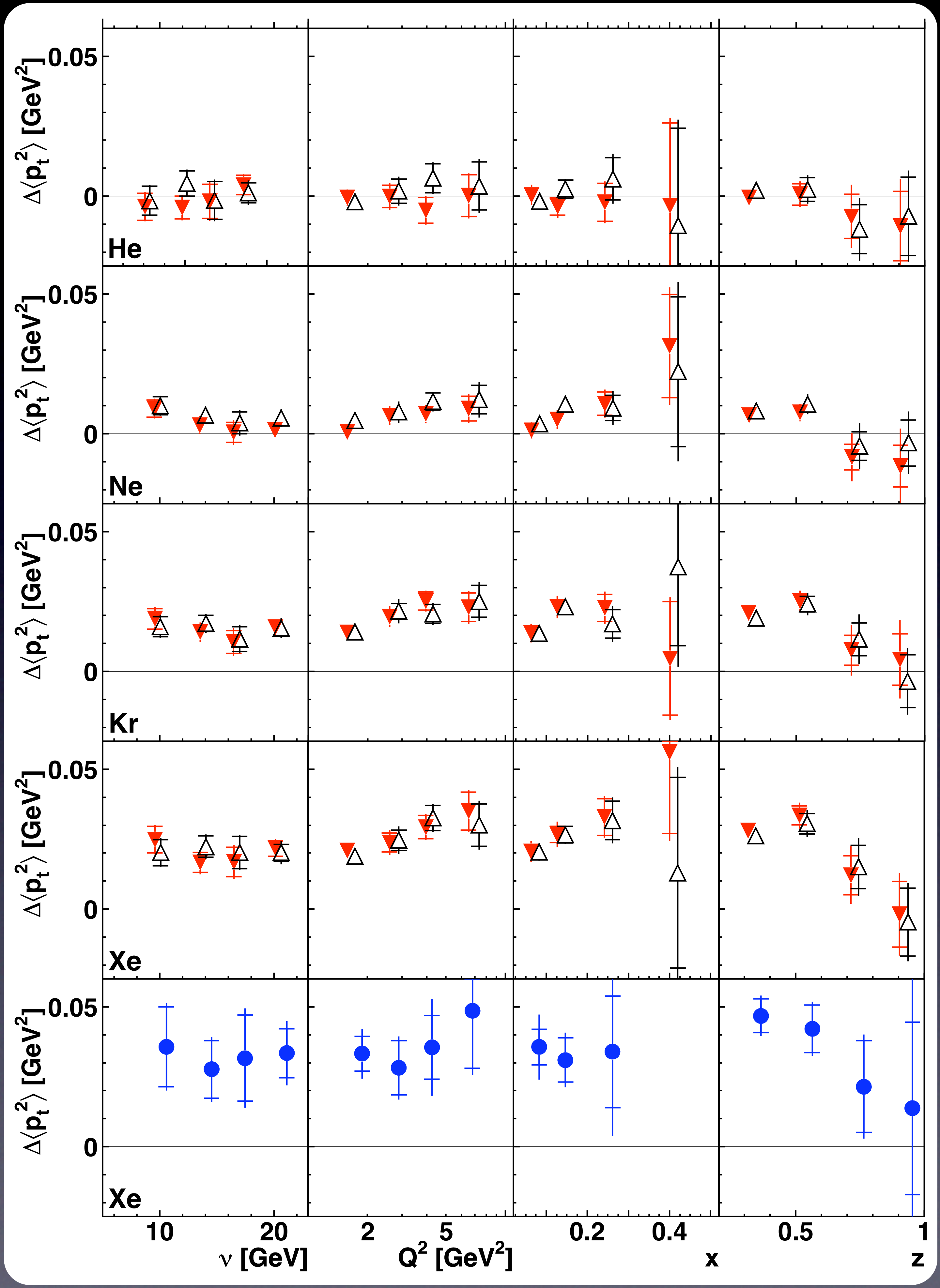
$$p_T(pion) \approx z\ k_T(quark)$$

$$\frac{p_T^2}{z^2} = k_T^2$$

Hermes p_T broadening data

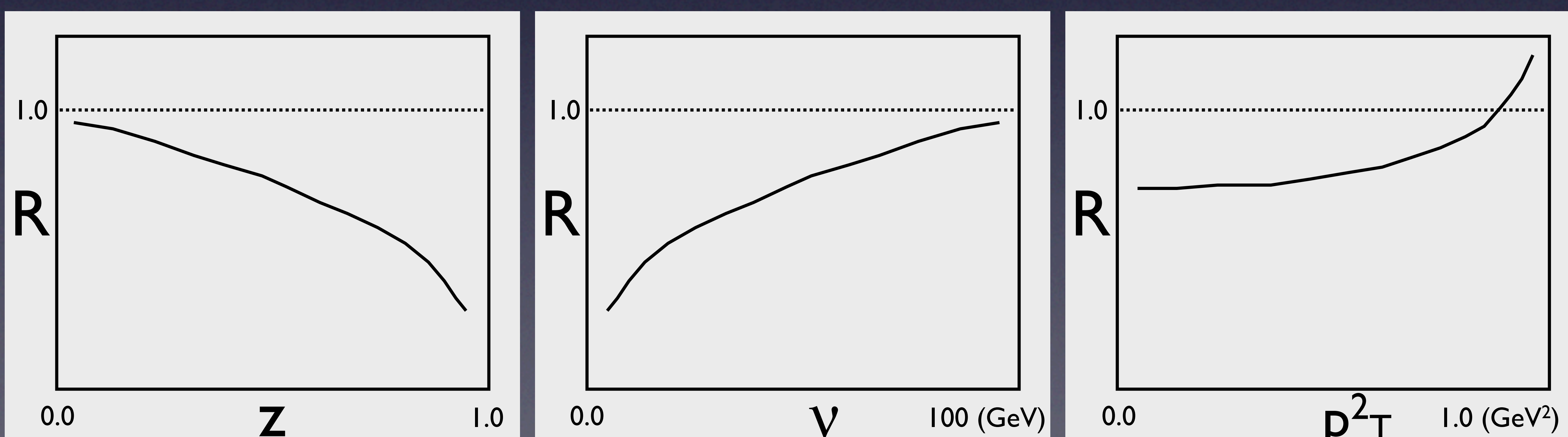
World's first comparison between pion and K^+ p_T broadening





$$R_M^h(z,\nu,p_T^2,Q^2,\phi) = \frac{\left\{ \frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)} \right\}_A}{\left\{ \frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)} \right\}_D}$$

Hadronic multiplicity ratio

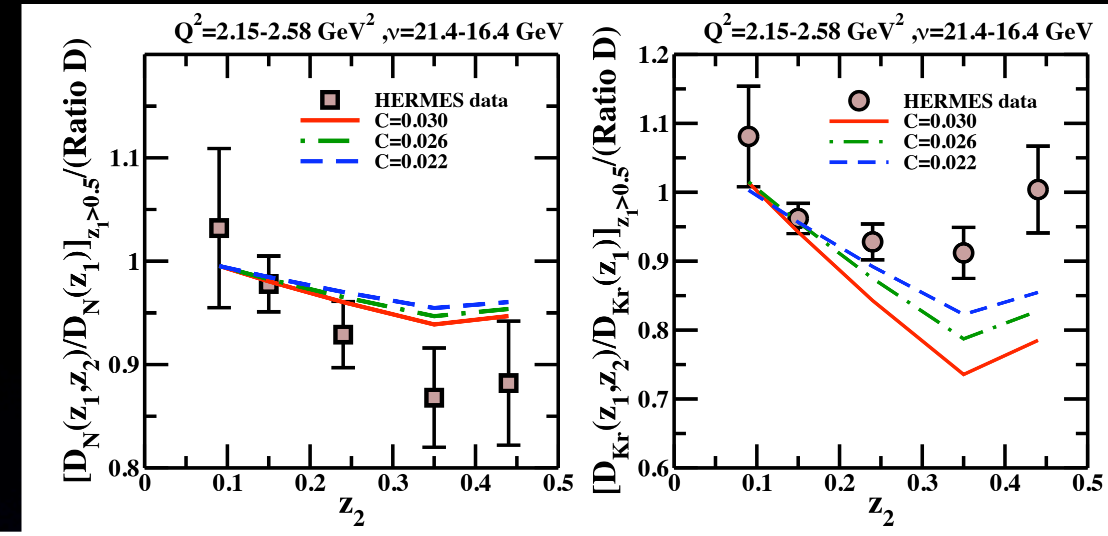


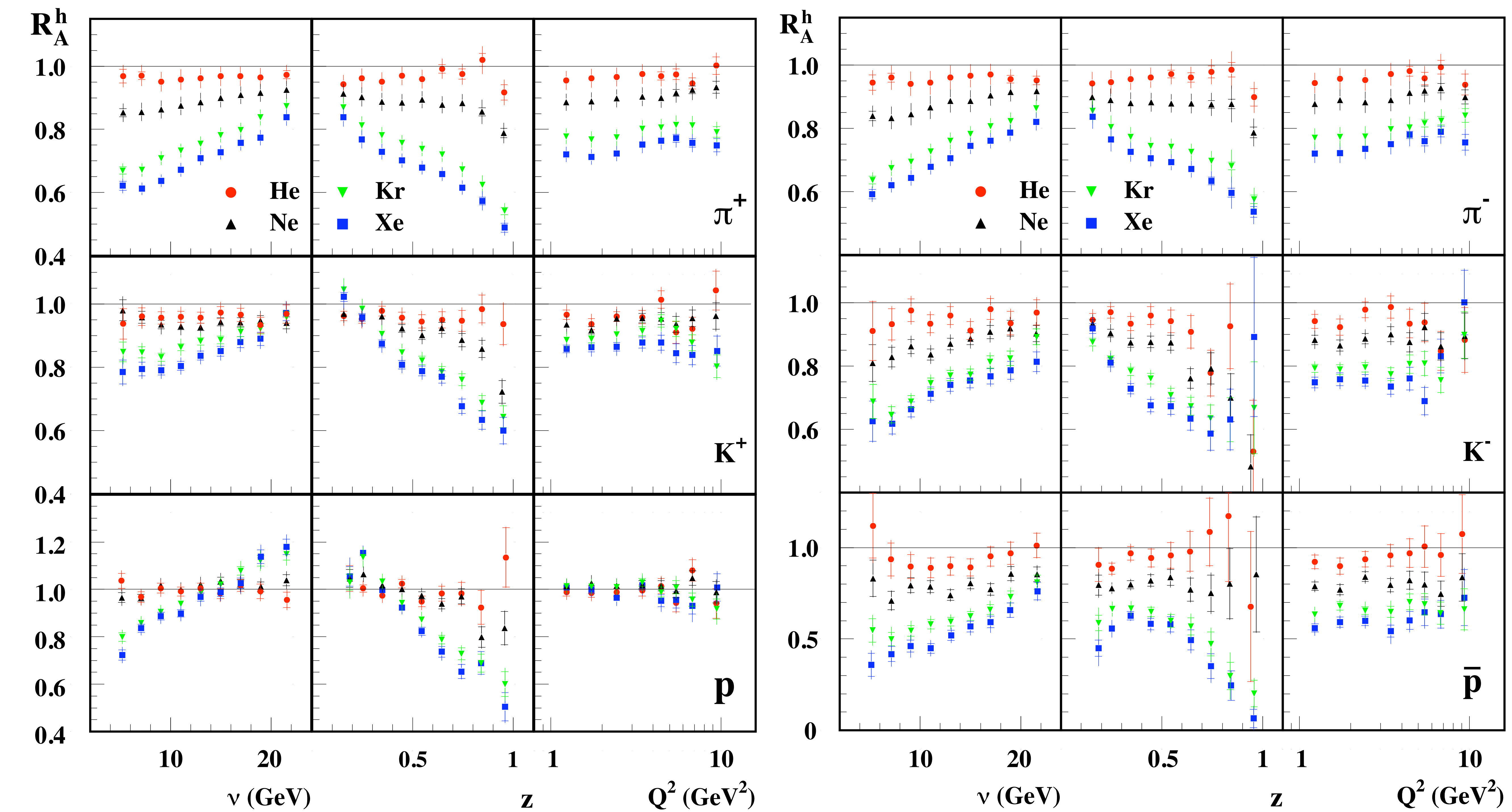
Hermes nuclear target program

Year	E (GeV)	Target	Identified hadrons
1997	27.6	D, N	$h^\pm$, $\pi^\pm$
1999	27.6	D, Kr	$h^\pm$, $\pi^\pm, \pi^0$, $K^\pm$, p, $\overline{p}$
2000	27.6	D, He, Ne	$\pi^\pm, \pi^0$, $K^\pm$, p, $\overline{p}$
2000	12.0	D, N, Kr	$h^\pm$, $\pi^\pm$
2004	27.6	D, Kr, Xe	$\pi^\pm$, $K^\pm, \pi^0$, p, $\overline{p}$
2005	27.6	D, Kr, Xe	$\pi^\pm$, $K^\pm, \pi^0$, p, $\overline{p}$

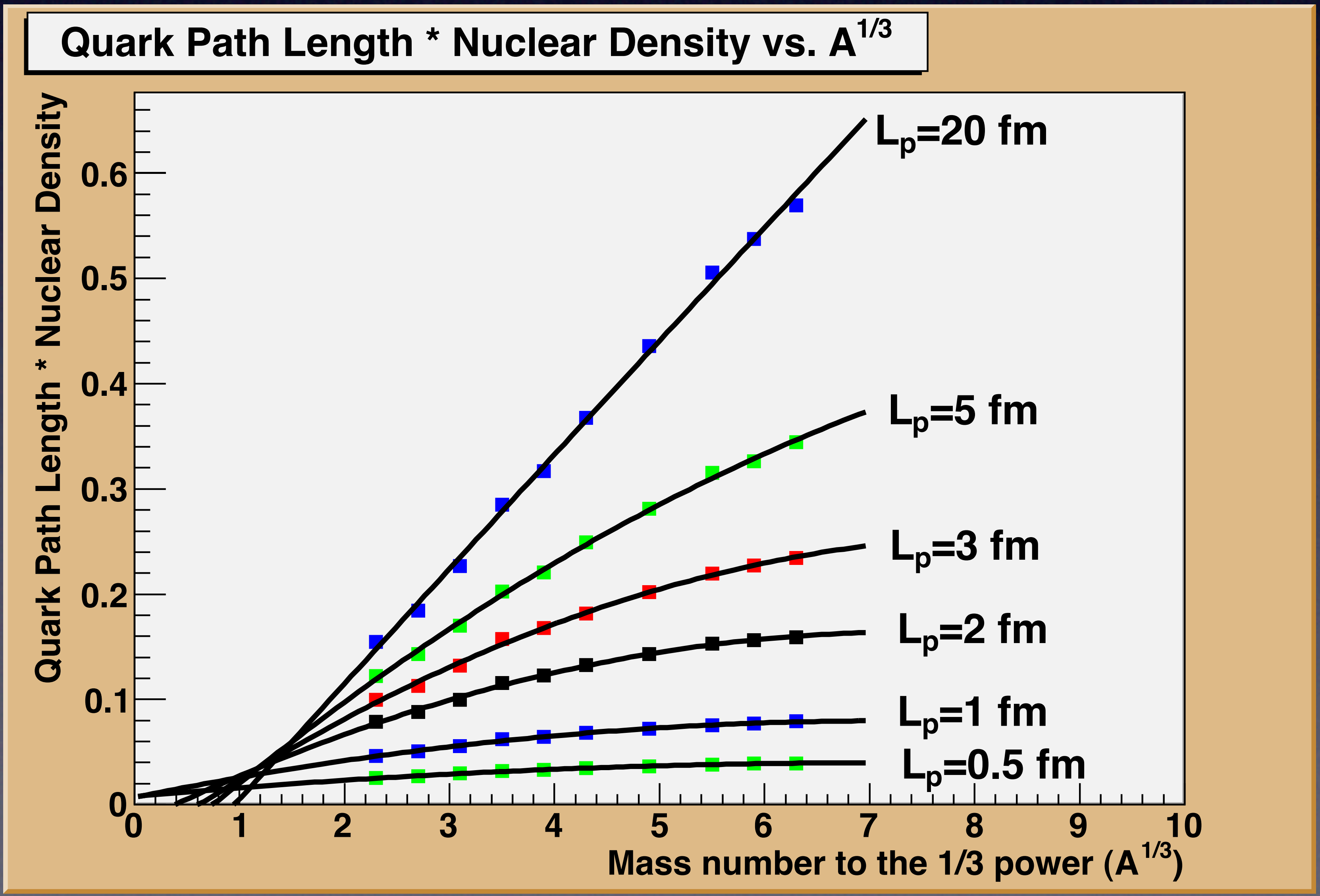
Year	E (GeV)	Target	Identified hadrons
1997	27.6	D, N	$h^\pm$, $\pi^\pm$
1999	27.6	D, Kr	$h^\pm$, $\pi^\pm$, π^0, $K^\pm$, p, $\bar{p}$
2000	27.6	D, He, Ne	$\pi^\pm$, π^0, $K^\pm$, p, $\bar{p}$
2000	12.0	D, N, Kr	$h^\pm$, $\pi^\pm$
2004	27.6	D, Kr, Xe	$\pi^\pm$, $K^\pm$, π^0, p, $\bar{p}$
2005	27.6	D, Kr, Xe	$\pi^\pm$, $K^\pm$, π^0, p, $\bar{p}$

Hermes nuclear target program

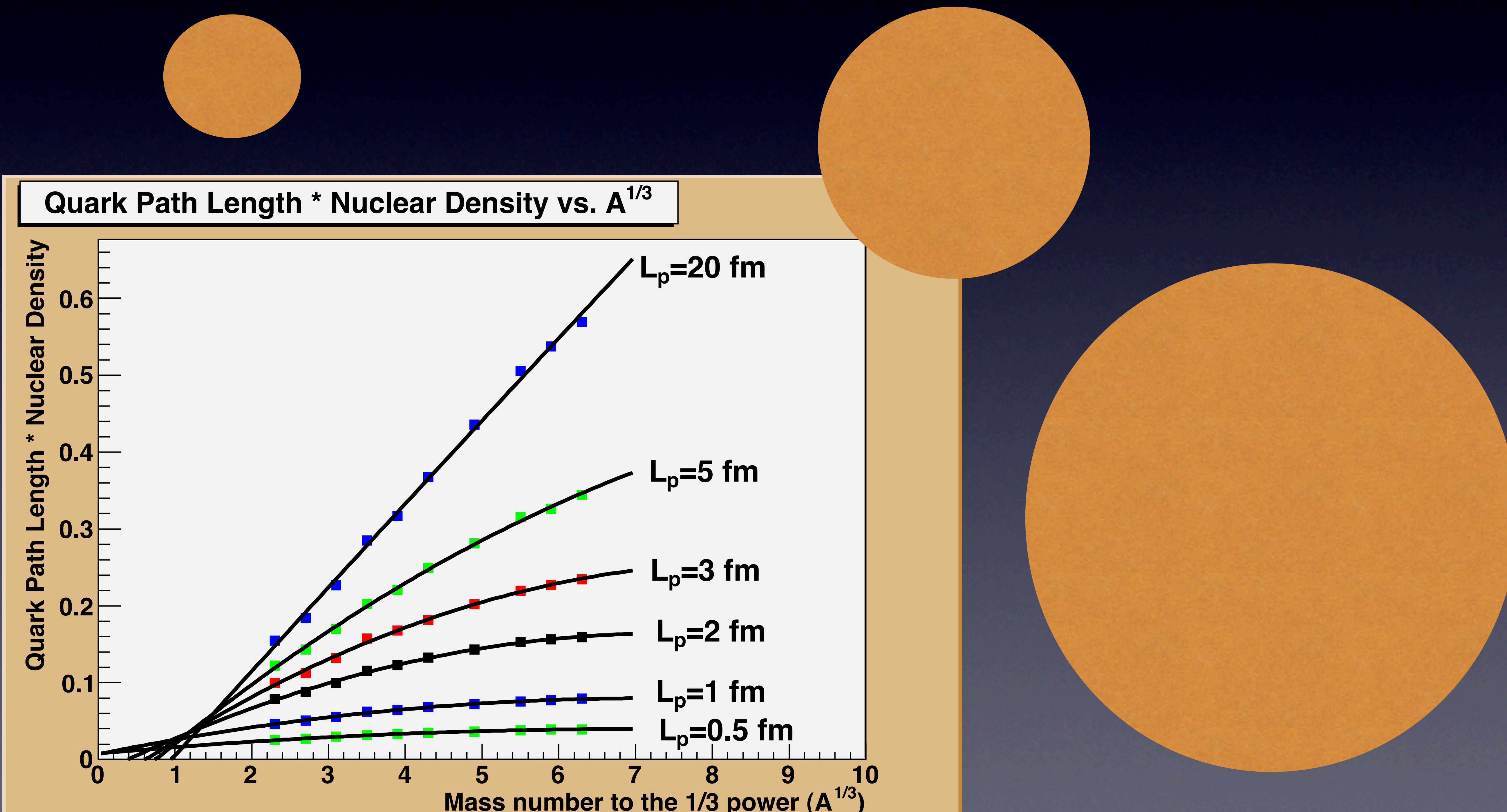




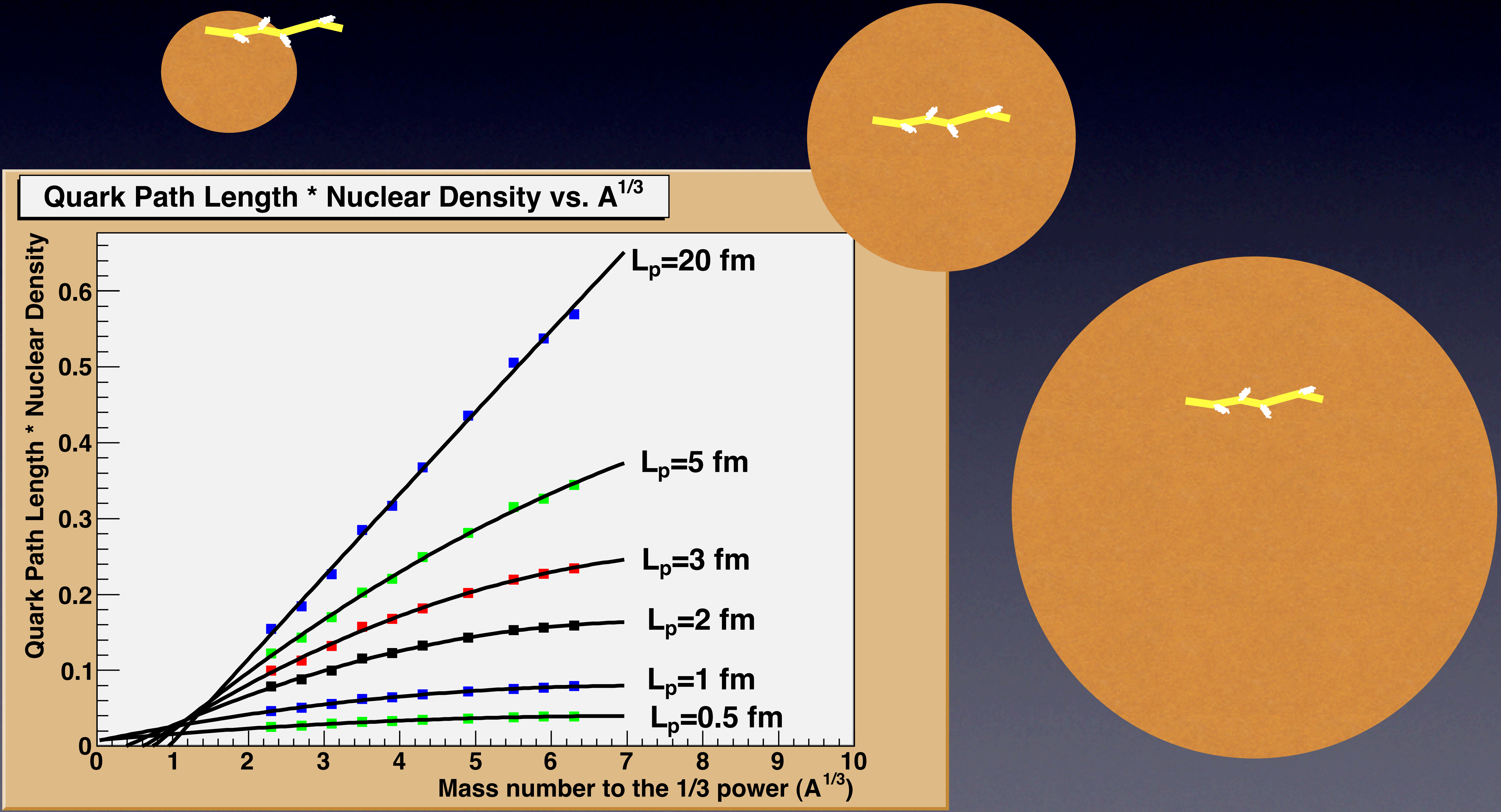
Production Time Extraction - Geometrical Effects



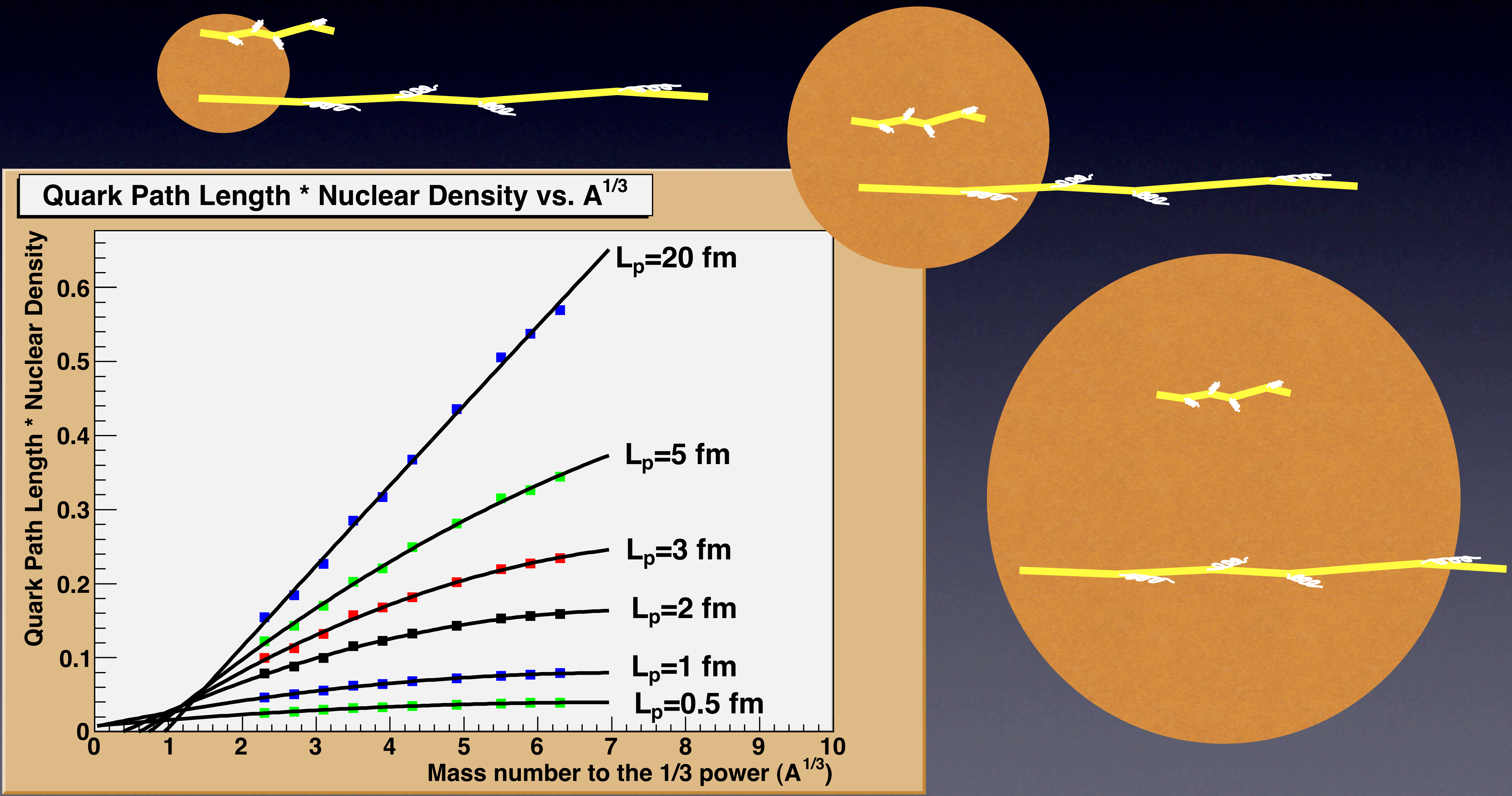
Production Time Extraction - Geometrical Effects



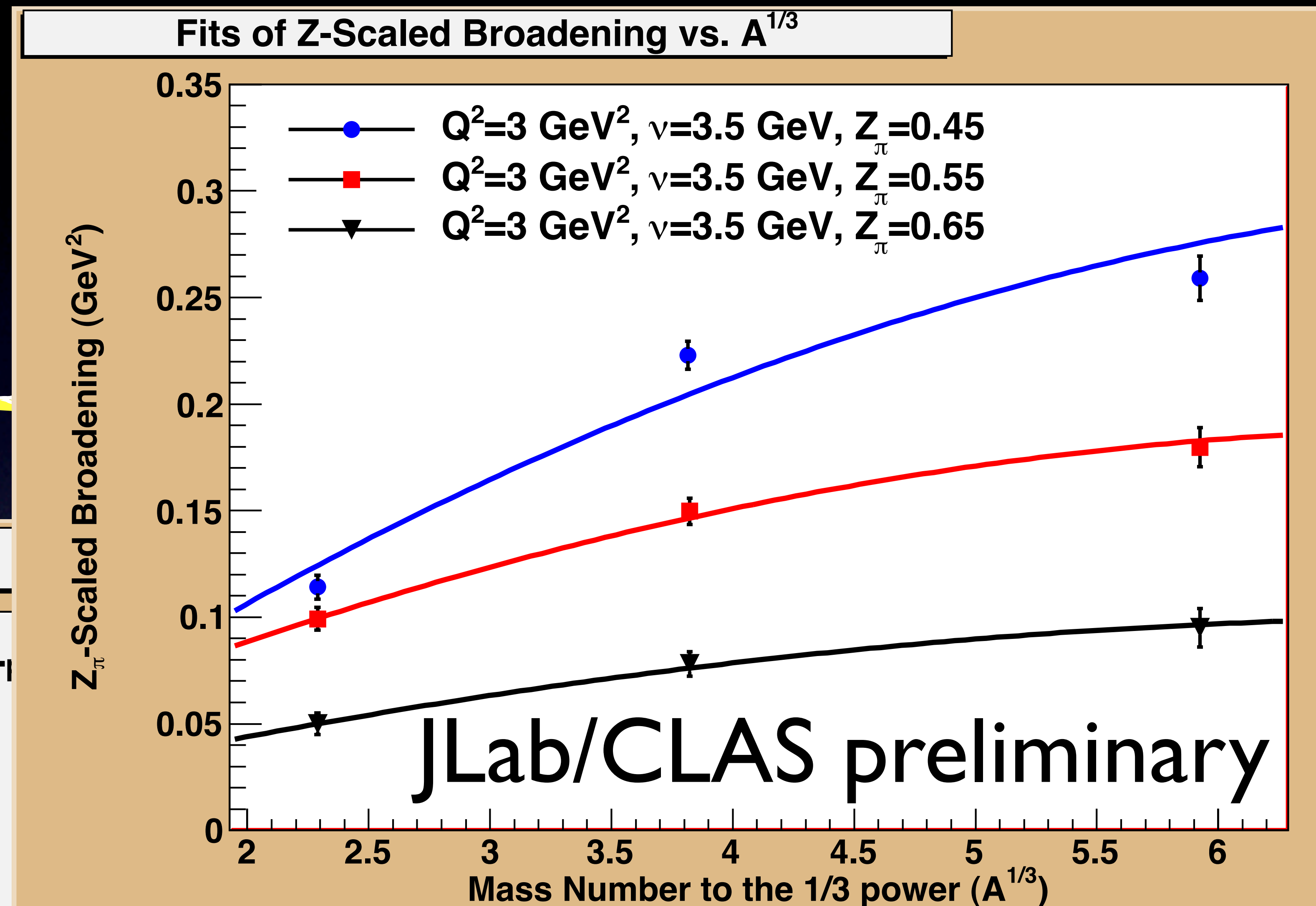
Production Time Extraction - Geometrical Effects

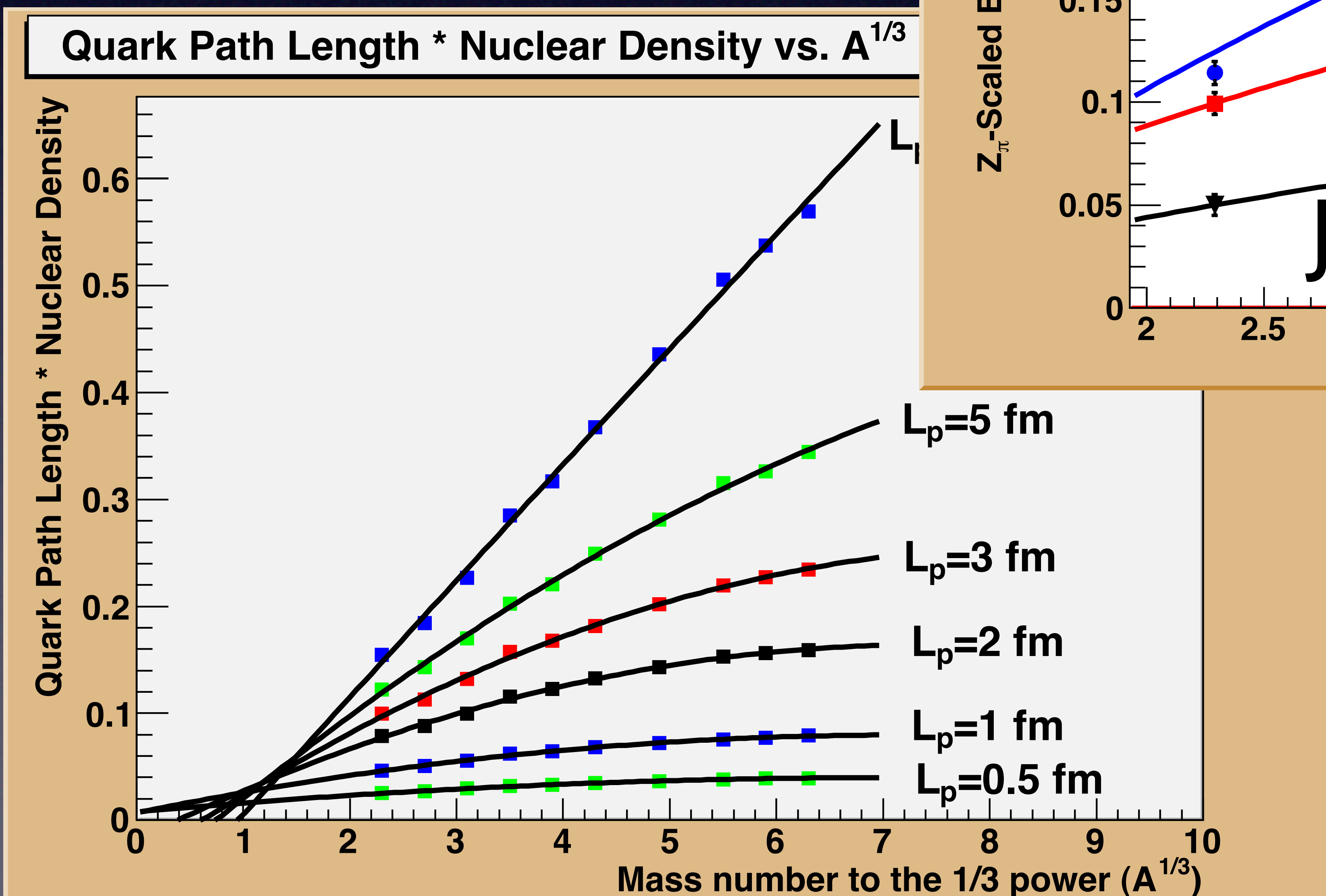


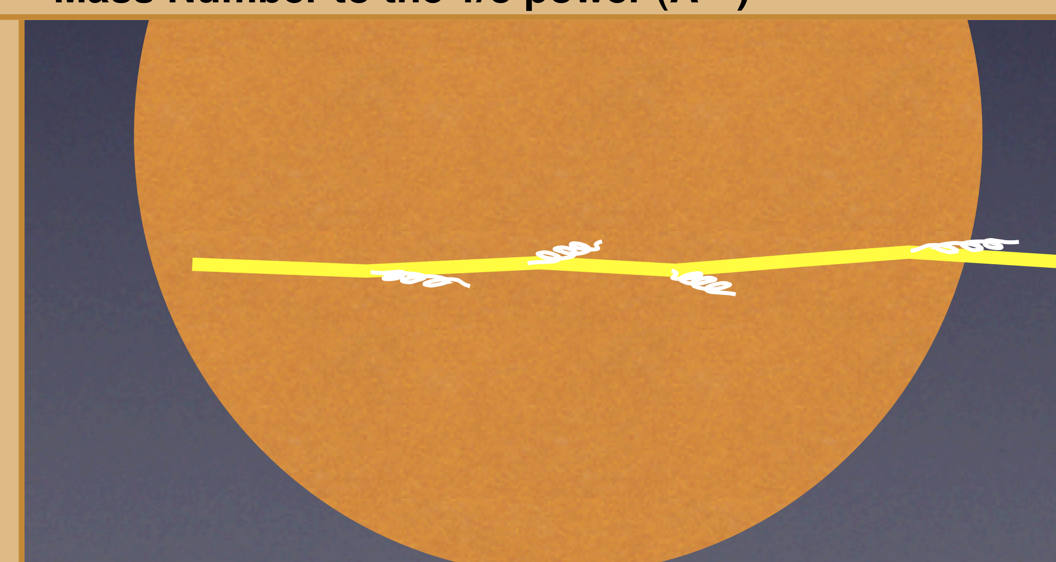
Production Time Extraction - Geometrical Effects



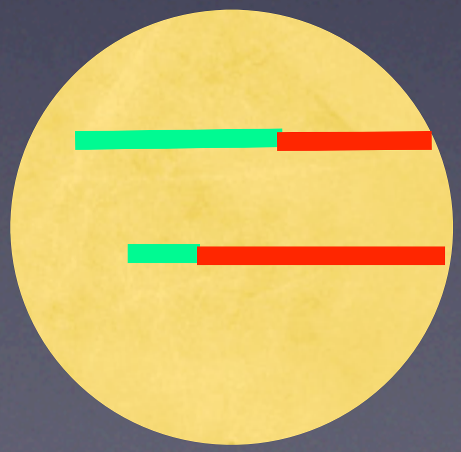
Production Time Extraction - Geometrical Effects





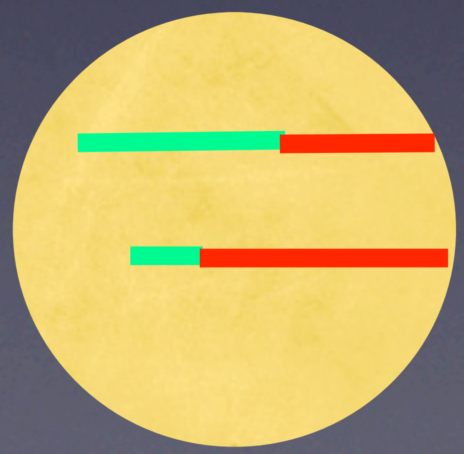


Geometric model



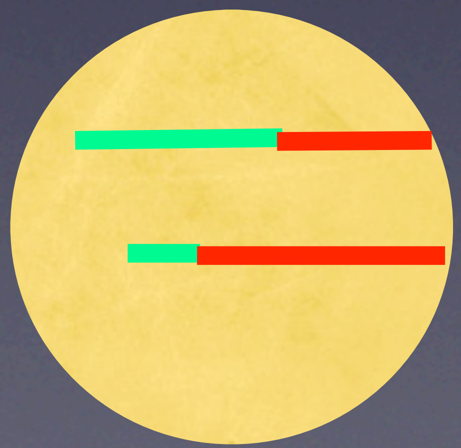
Geometric model

- Three-parameter model:
  - scale factor (proportional to transport coefficient)
  - production time (distributed exponentially)
  - effective absorption cross section



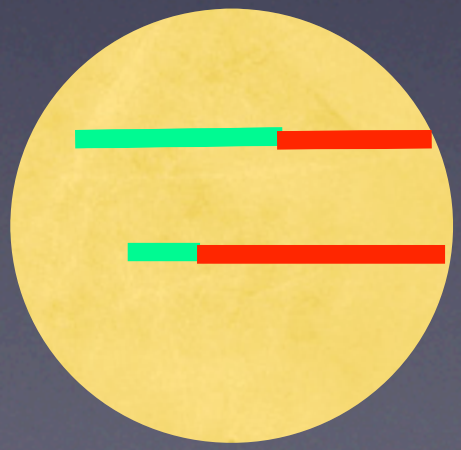
Geometric model

- Three-parameter model:
  - scale factor (proportional to transport coefficient)
  - production time (distributed exponentially)
  - effective absorption cross section
- ***Simultaneous fit*** *of pT broadening and multiplicity ratio in the same 3-fold kinematic bin in* Q^2, ν, *and z*



Geometric model

- Three-parameter model:
  - scale factor (proportional to transport coefficient)
  - production time (distributed exponentially)
  - effective absorption cross section
- ***Simultaneous fit*** *of pT broadening and multiplicity ratio in the same 3-fold kinematic bin in* Q^2*,* ν*, and z*
- Realistic nuclear densities

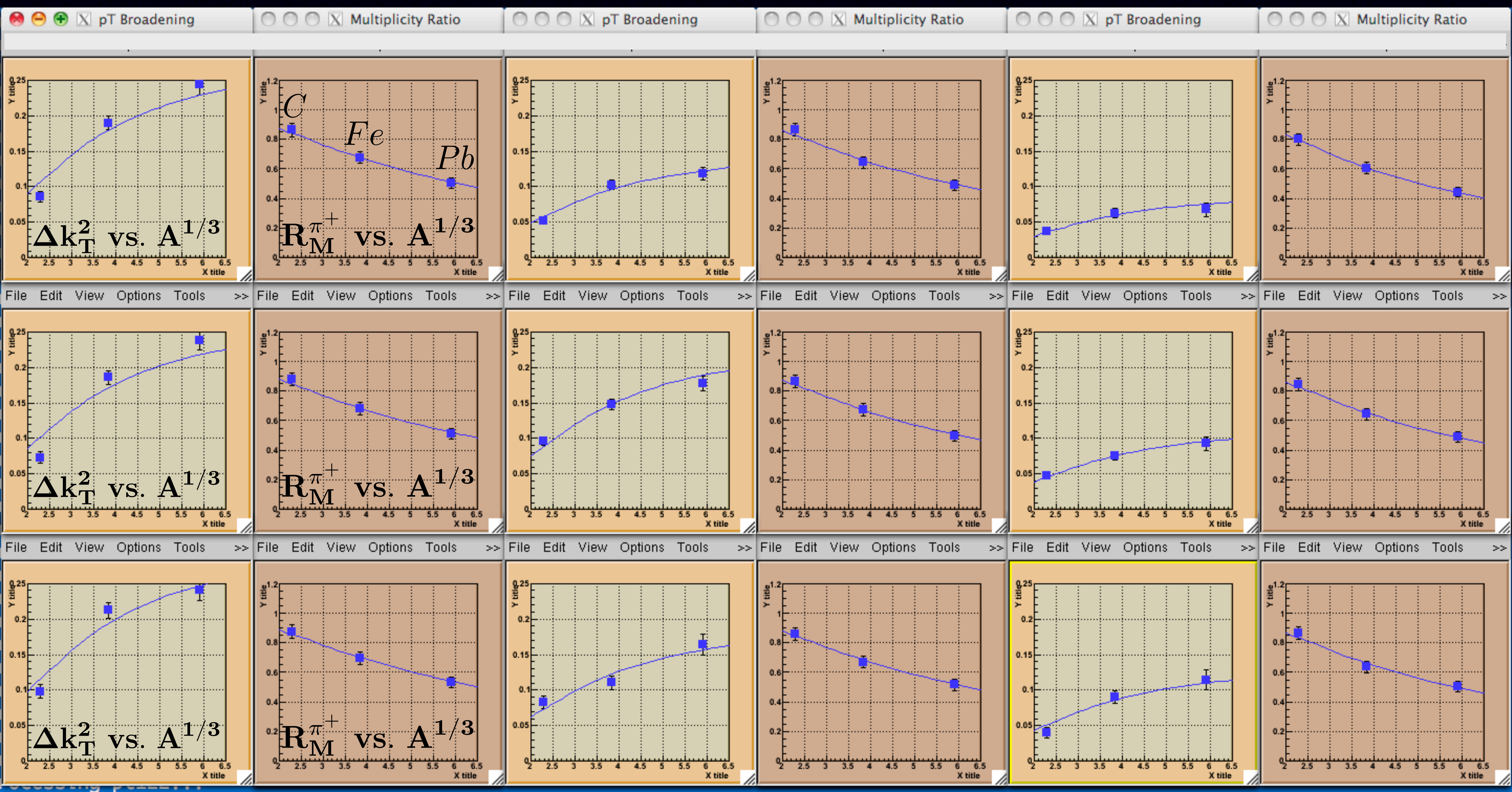


  - Path begins at point with probability proportional to density
  - Part of path is quark, part of path is (pre-)hadron

Results from combined fit

3 parameter geometric model

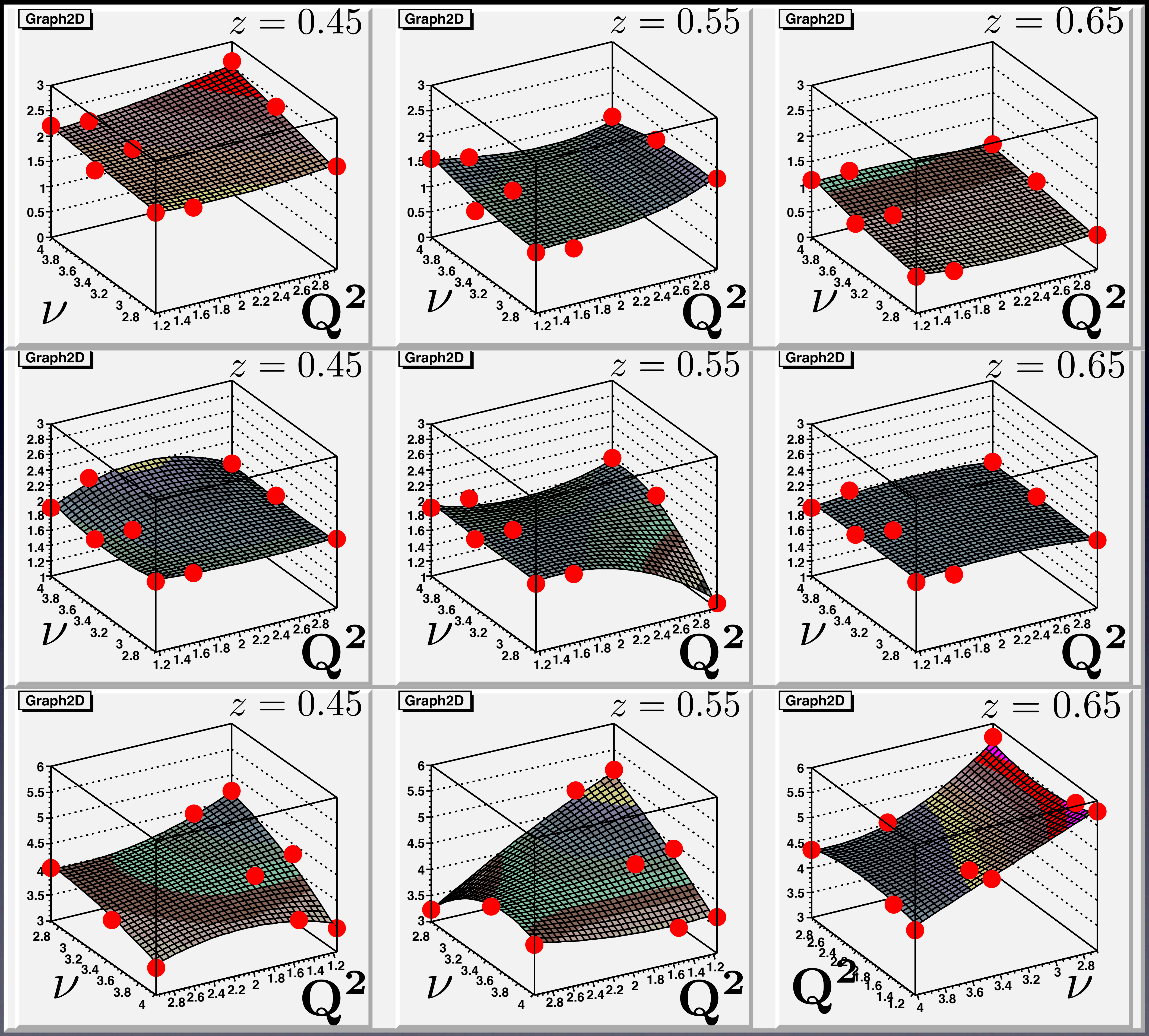
various bins in Q^2, ν, and z



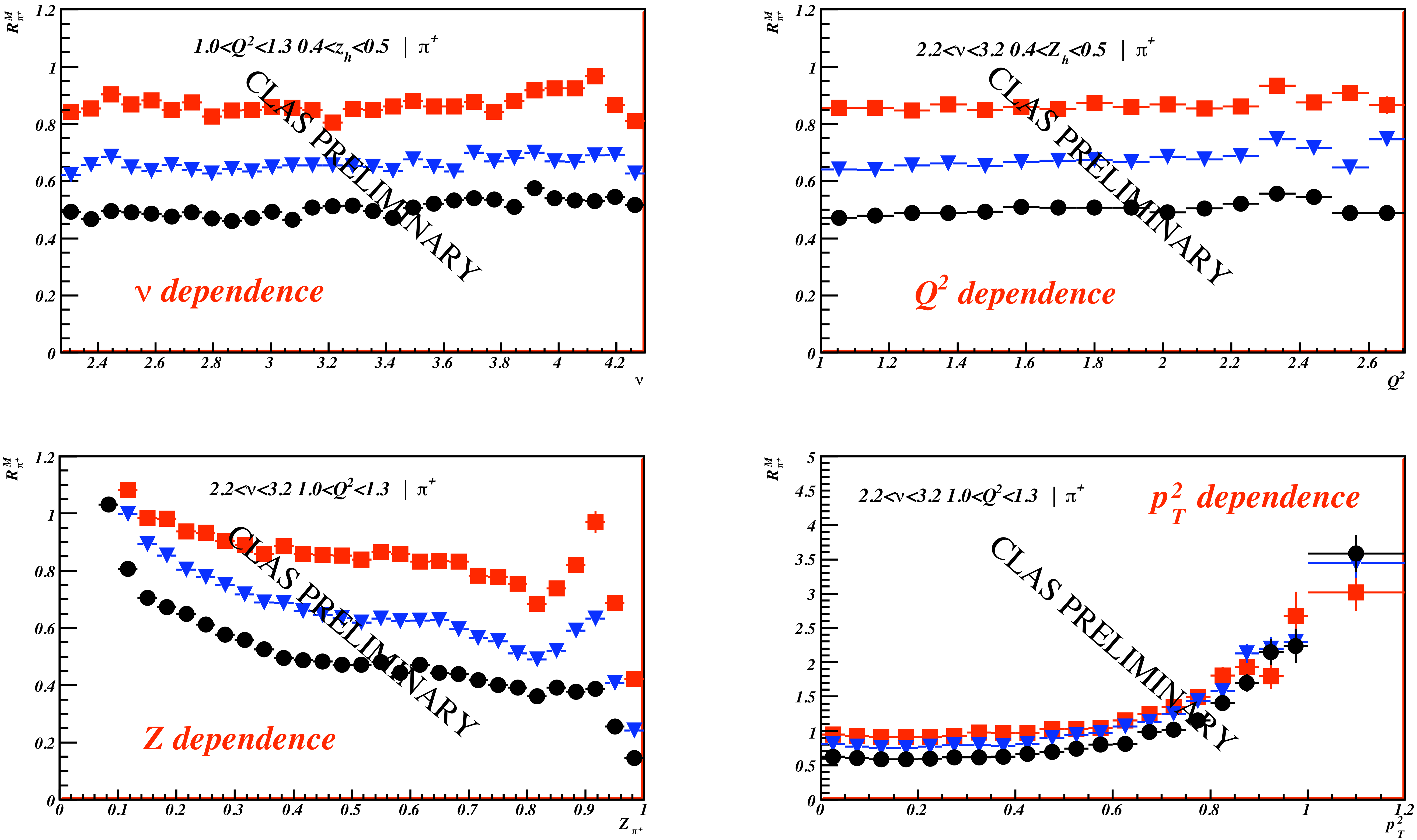
Scale factor $\propto \hat{q}$

Production length l_p

Effective absorption cross section σ



JLab/CLAS 3-D preliminary data



Four out of ~50 plots! K^0, π^-, π^0, η, Λ underway

Conclusions from 3-parameter geometric model (exploratory study)

Conclusions from 3-parameter geometric model (exploratory study)

- Consistent with features of data

Conclusions from 3-parameter geometric model (exploratory study)

- Consistent with features of data
- Dependence of transport coefficient on z

Conclusions from 3-parameter geometric model (exploratory study)

- Consistent with features of data
- Dependence of transport coefficient on z
  - Range: 0.05 - 0.15 GeV^2/fm

Conclusions from 3-parameter geometric model (exploratory study)

- Consistent with features of data
- Dependence of transport coefficient on z
  - Range: 0.05 - 0.15 GeV^2/fm
- Production length ~2 fm

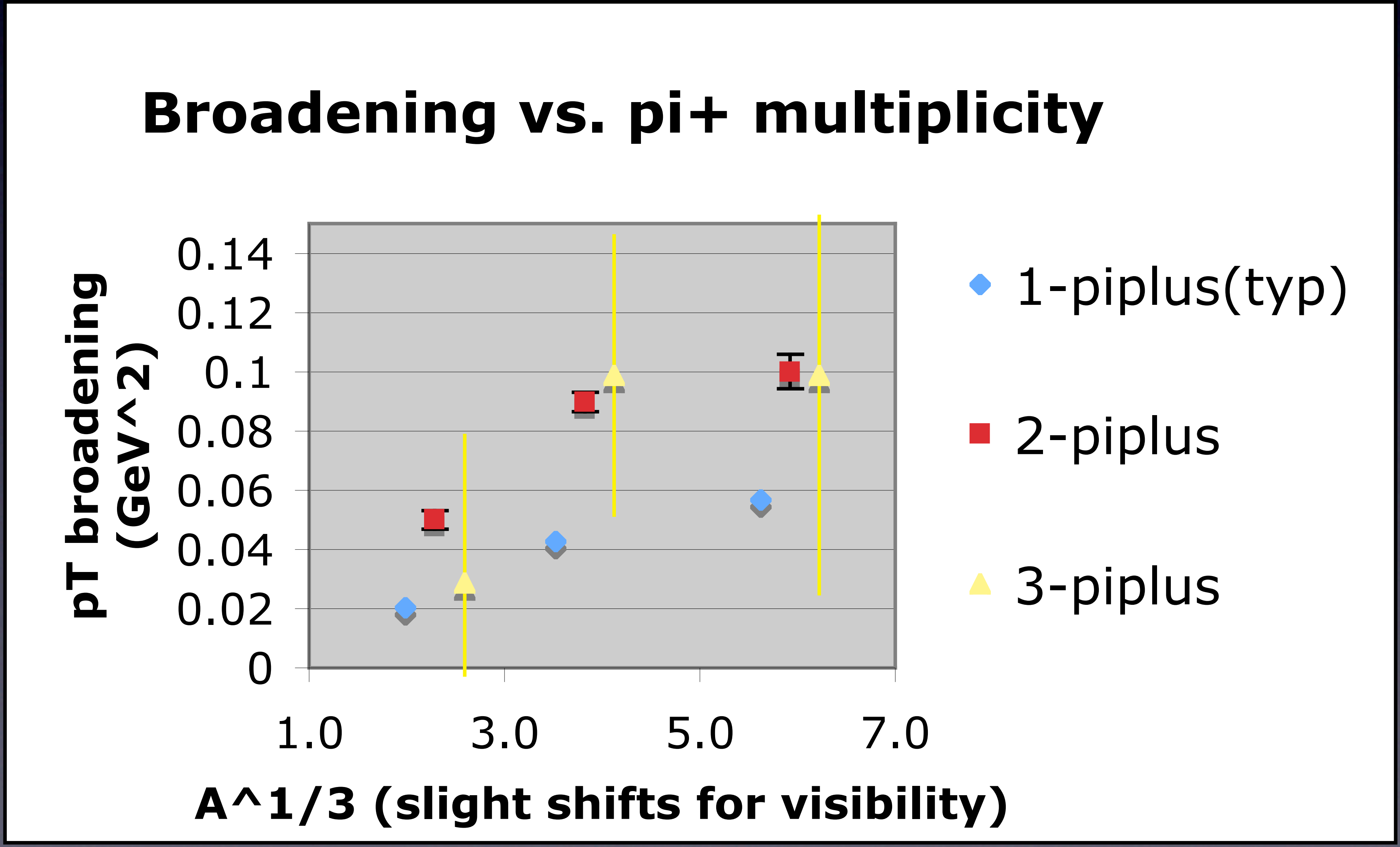
Conclusions from 3-parameter geometric model (exploratory study)

- Consistent with features of data
- Dependence of transport coefficient on z
  - Range: 0.05 - 0.15 GeV^2/fm
- Production length ~2 fm
- Effective cross section moderately larger than hadronic - energy loss mechanism visible (?)

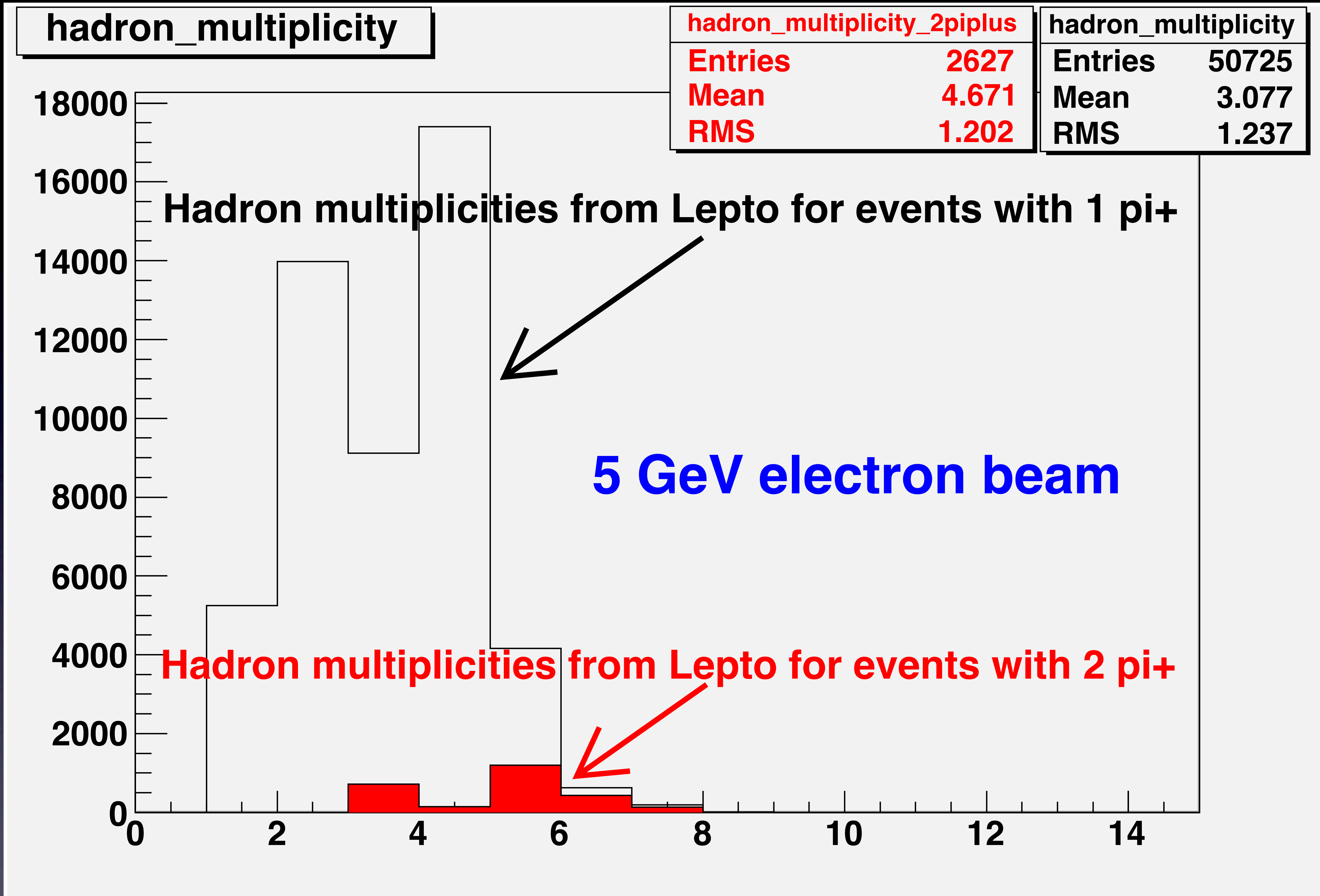
New Multiplicity Studies

Requiring multiple pions allows studies of higher-multiplicity states - feasible because of high luminosities

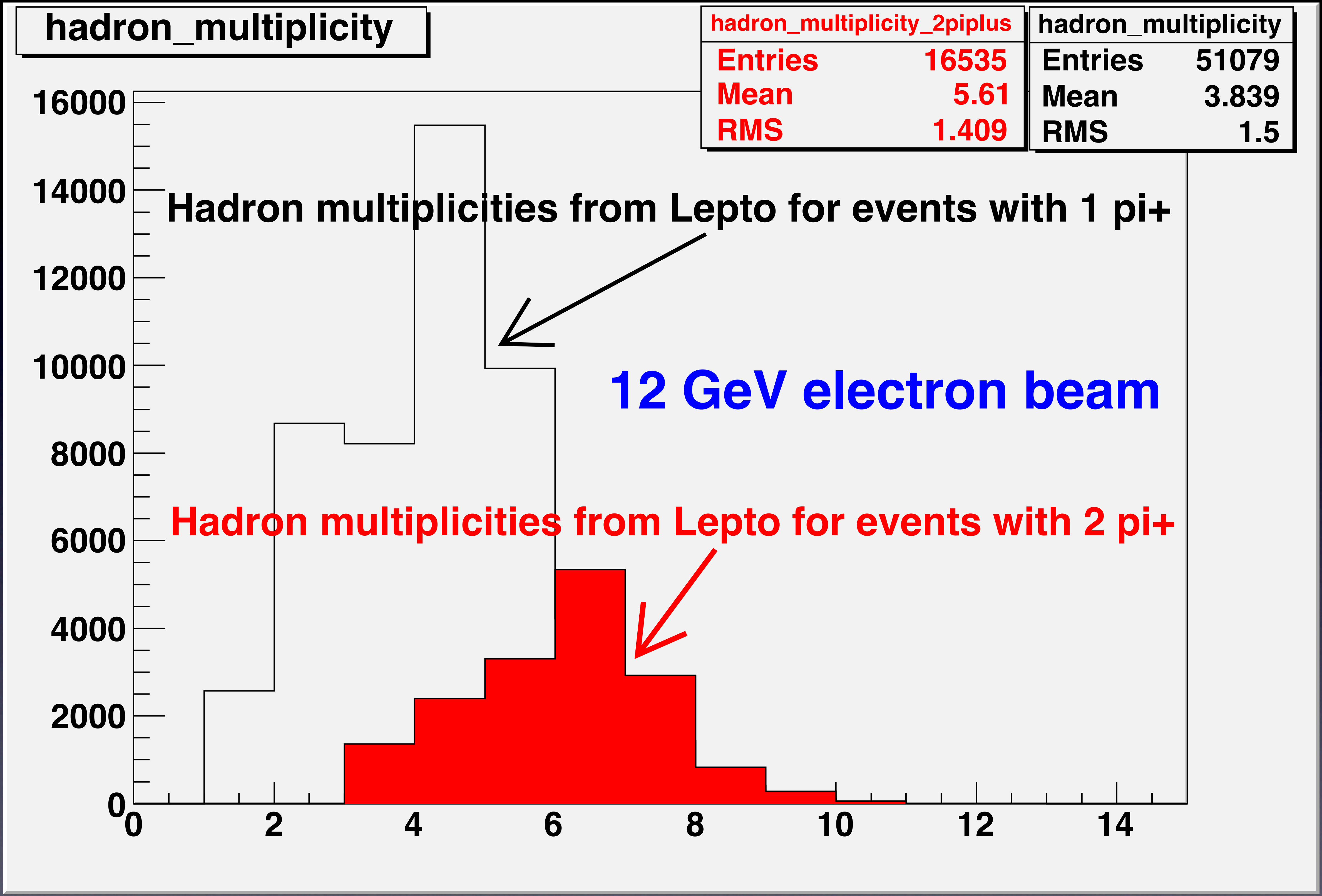
10X higher luminosities for CLAS12!



JLab/CLAS
5 GeV data

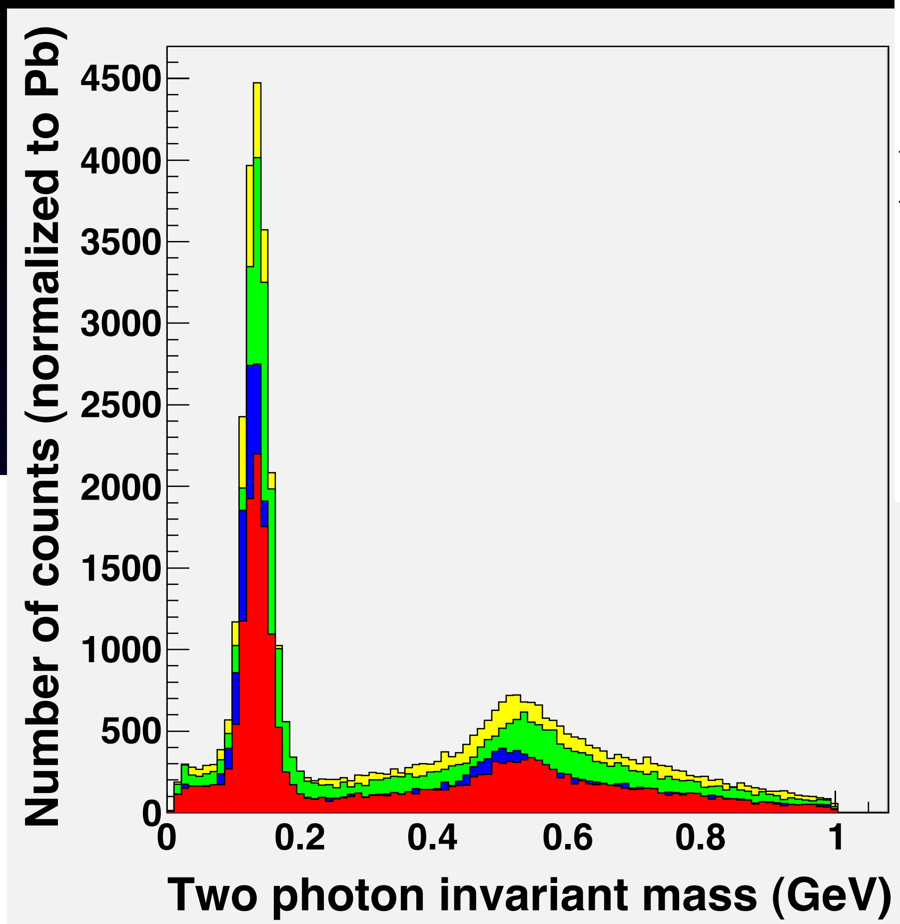


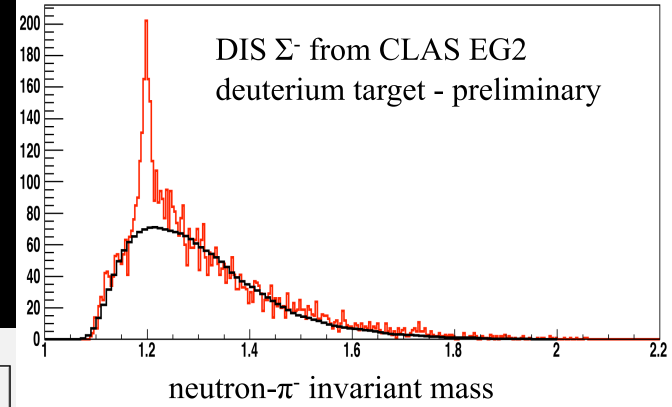
Higher multiplicity may correlate with more in-medium interactions, in analogy with 'centrality' in RHI

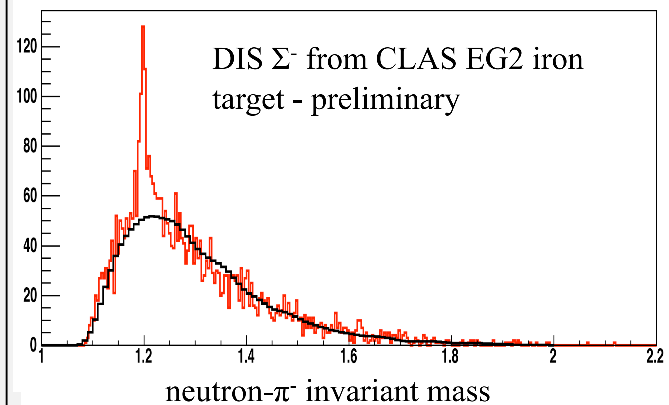


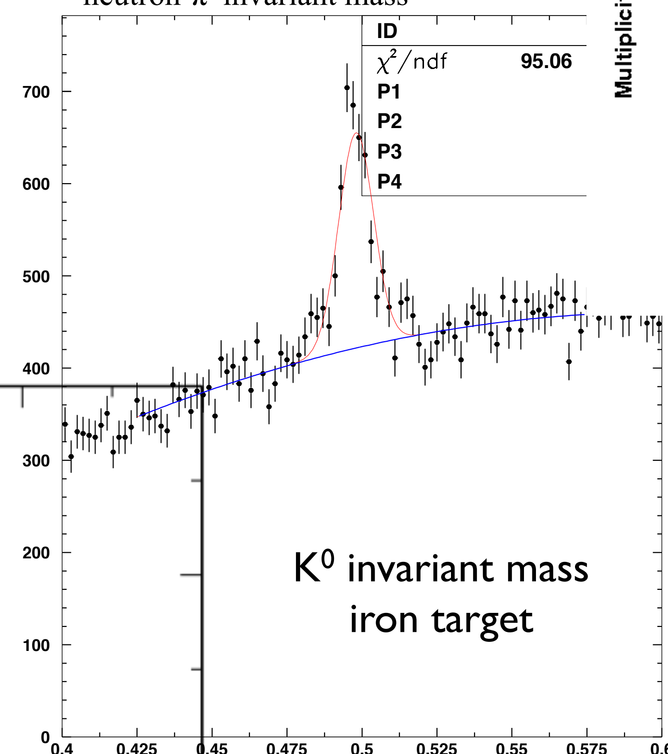
At 12 GeV, more reach to explore multiplicity dependence

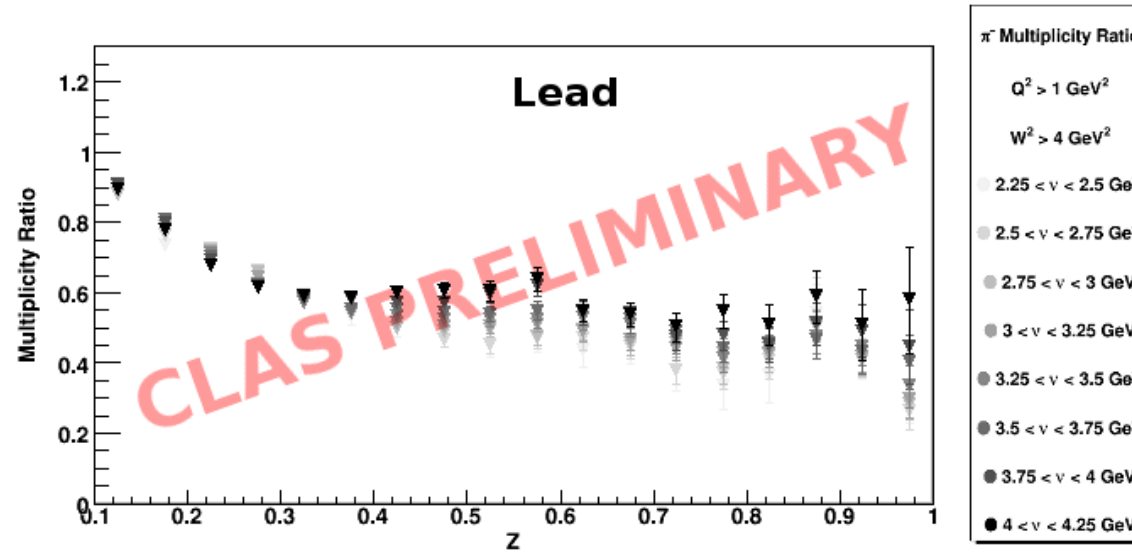
CLAS 5 GeV data under analysis

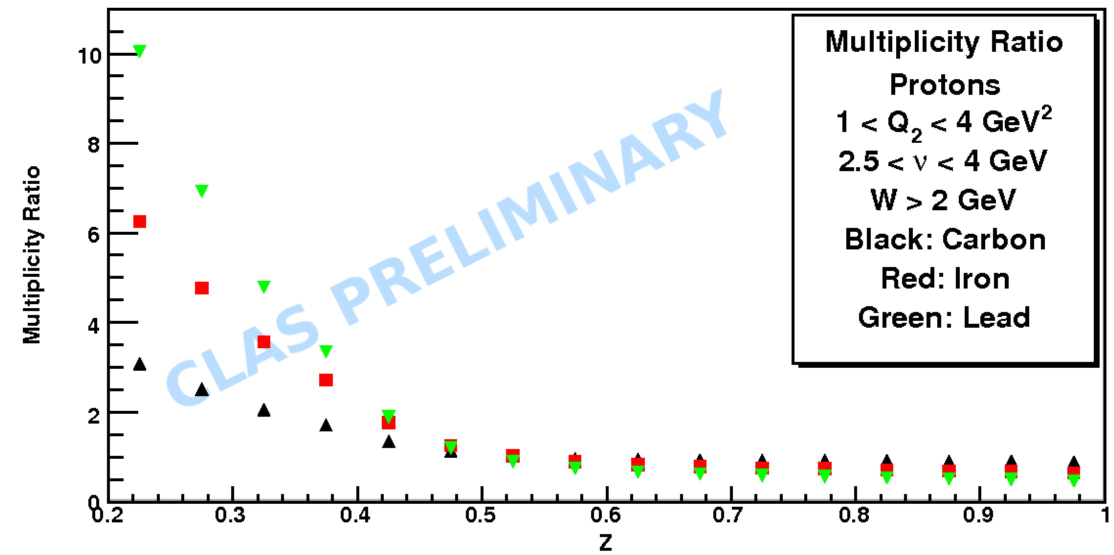


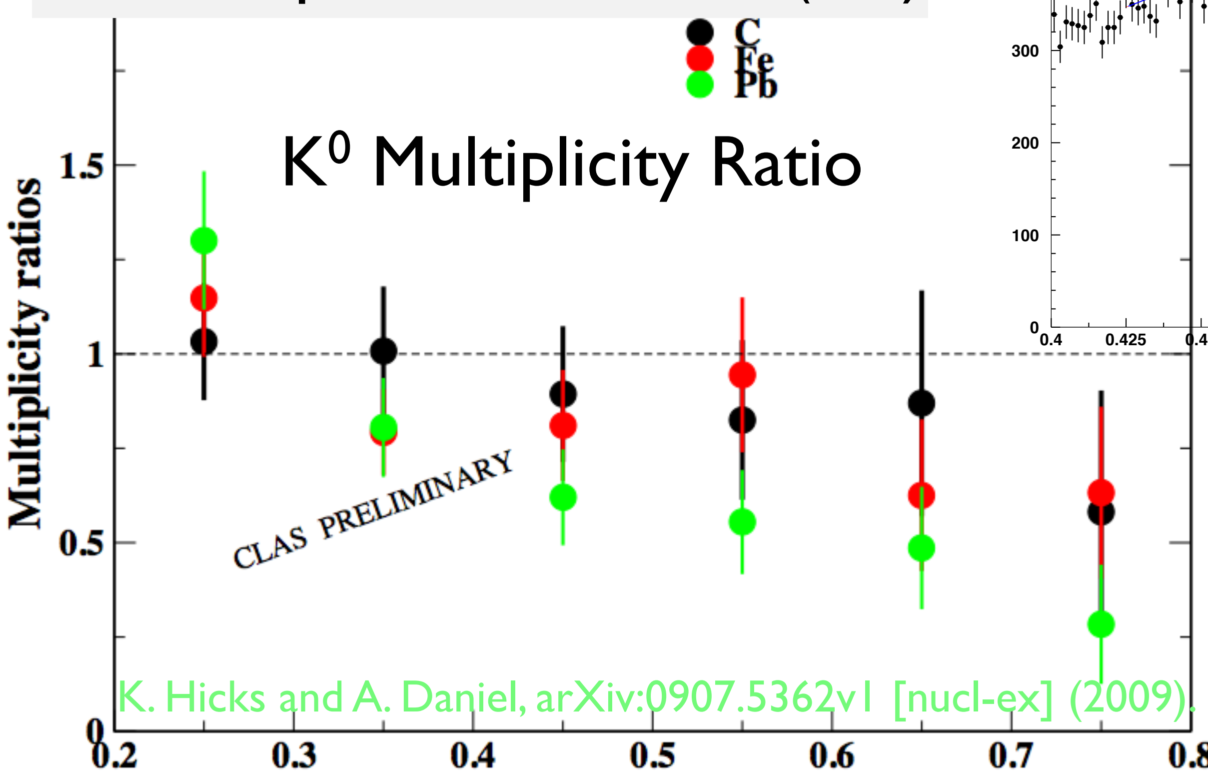












pions, K^0, K^+(lower energy), eta, omega, lambda, sigma

What is the importance of kaons in these studies?

- Provide important continuity between CLAS12 measurements and HERMES measurements
- Can compare K^0 to charged kaons, in pT broadening and multiplicity ratios
- Kaons have smaller cross section than pions - absorption scenario: multiplicity ratio should be larger for kaons - energy loss scenario: opposite trend (based on shapes of fragmentation functions for kaon and pion).
- Will reduce backgrounds on all channels where strangeness is involved, such as lambda baryons or phi mesons.
- ~3 orders of magnitude more integrated luminosity than Hermes, so one can study the details of the K^+ K^- comparison as a function of several kinematic variables simultaneously.

Landscape of kaon hadronization

K^+	$u\bar{s}$
K^-	$\bar{u}s$
K^0	$d\bar{s}$
$\bar{K}^0$	$\bar{d}s$

Landscape of kaon hadronization

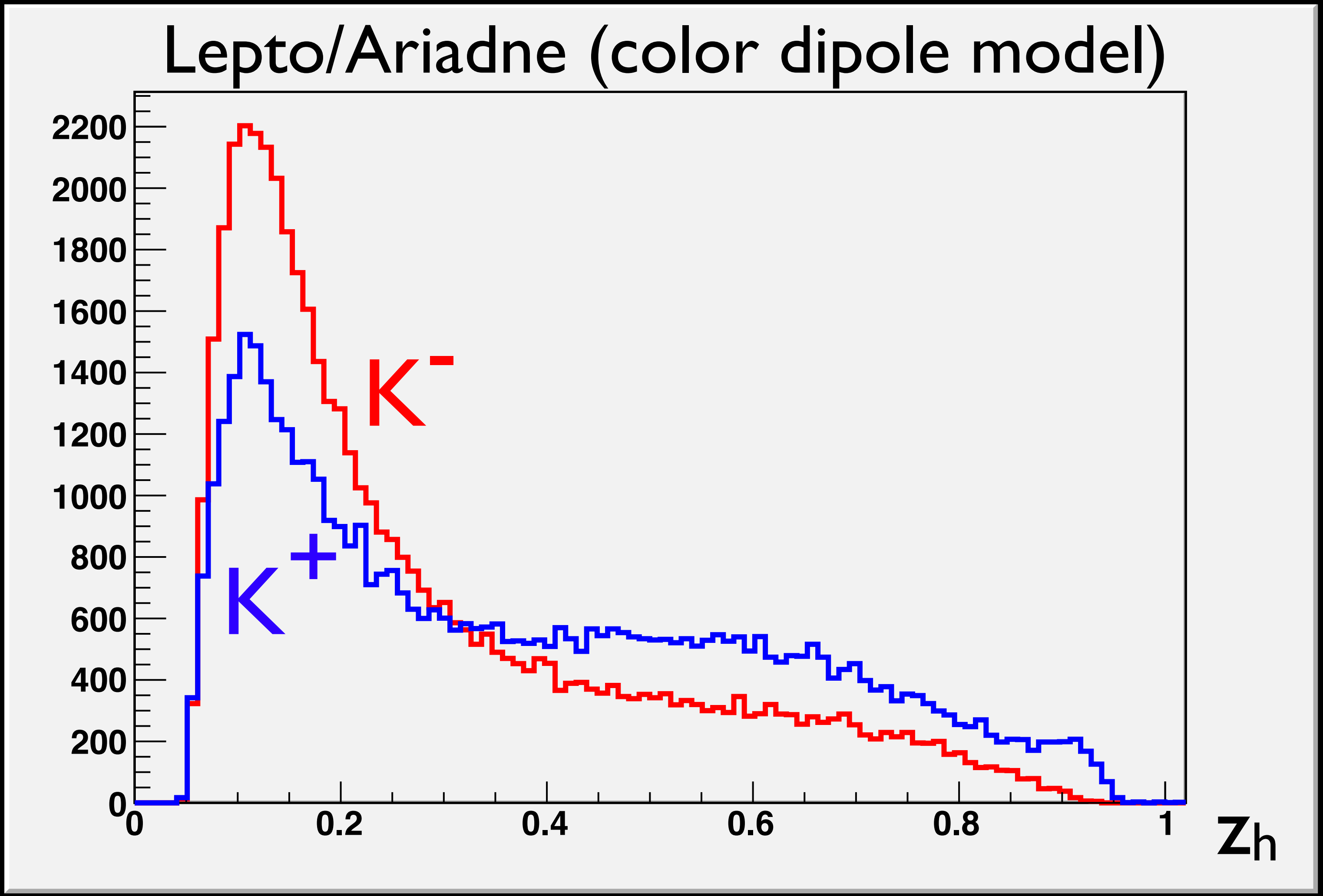
K^+	$u\,\bar{s}$
K^-	$\bar{u}\,s$
K^0	$d\,\bar{s}$
$\bar{K}^0$	$\bar{d}\,s$

- Naively, K^- comes more from mid-string than K^+:

$$\ldots\ldots\underline{\bar{q}\text{--}q}::\underline{\bar{q}\text{--}u}::\underline{\bar{u}\text{--}s}::\underline{\bar{s}\text{--}u} \qquad \text{vs.} \qquad \ldots\ldots\underline{\bar{q}\text{--}u}::\underline{\bar{u}\text{--}s}::\underline{\bar{s}\text{--}q}::\underline{\bar{q}\text{--}u}$$

Landscape of kaon hadronization

K^+	$u\bar{s}$
K^-	$\bar{u}s$
K^0	$d\bar{s}$
$\bar{K}^0$	$\bar{d}s$

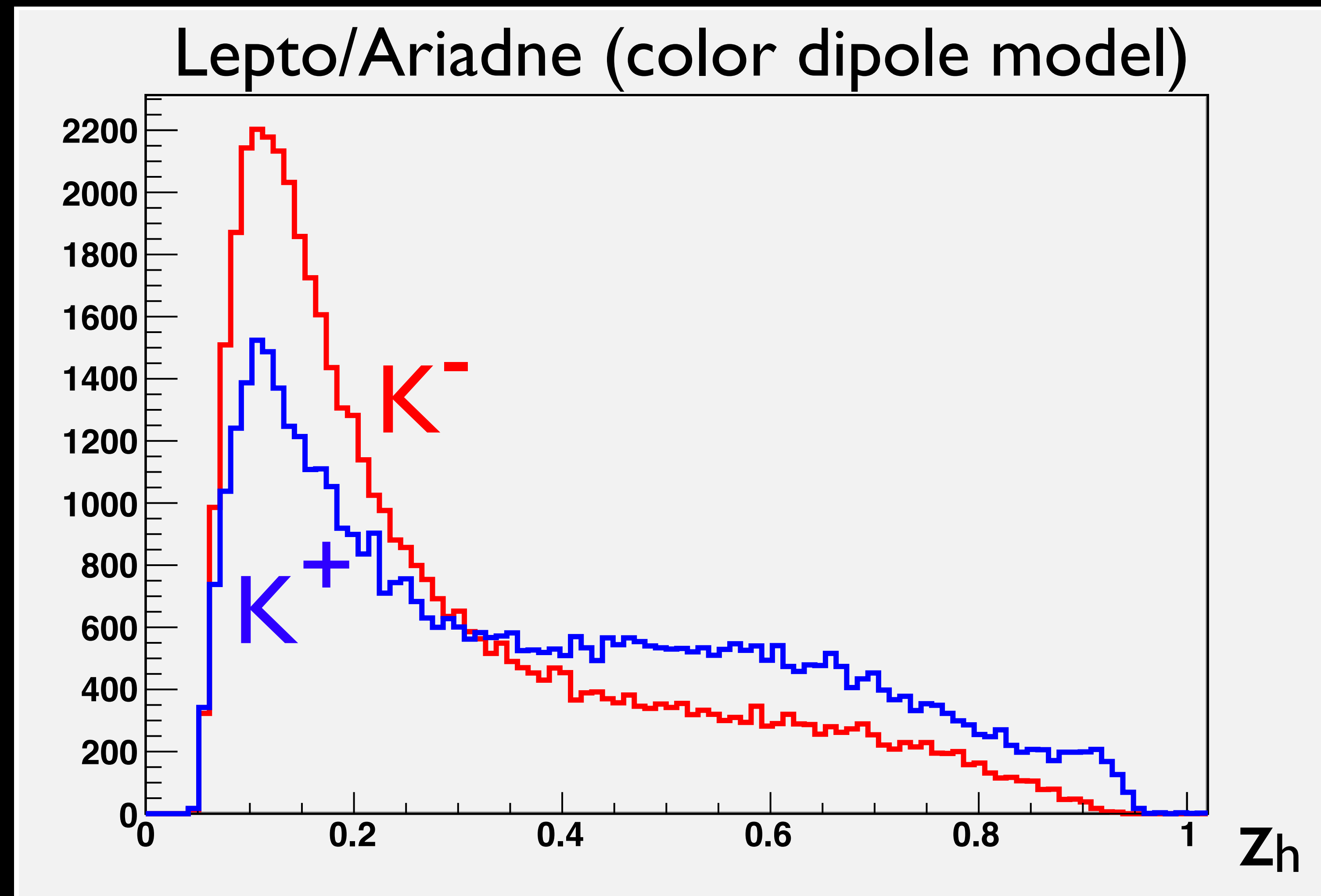


- Naively, K^- comes more from mid-string than K^+:

$......\bar{q}{-}{-}q::\bar{q}{-}{-}u::\bar{u}{-}{-}s::\bar{s}{-}{-}u$ vs. $......\bar{q}{-}{-}u::\bar{u}{-}{-}s::\bar{s}{-}{-}q::\bar{q}{-}{-}u$

Landscape of kaon hadronization

K^+	$u\bar{s}$
K^-	$\bar{u}s$
K^0	$d\bar{s}$
$\bar{K}^0$	$\bar{d}s$



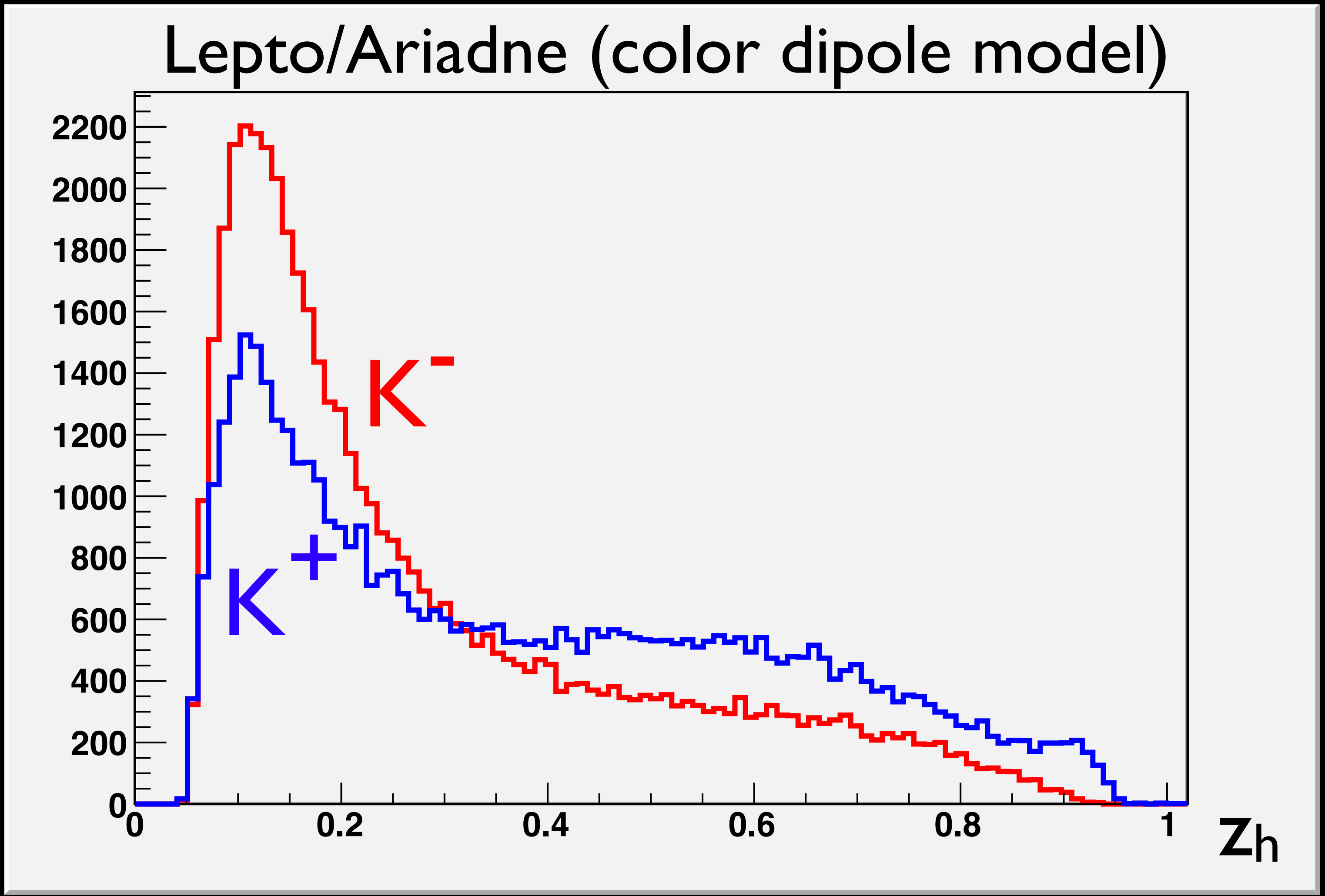
- Naively, K^- comes more from mid-string than K^+:

......$\bar{q}$--q::$\bar{q}$--u::$\bar{u}$--s::$\bar{s}$--u vs. ......$\bar{q}$--u::$\bar{u}$--s::$\bar{s}$--q::$\bar{q}$--u

- Only two of the above kaons can contain a struck valence quark

Landscape of kaon hadronization

K^+	$u\,\bar{s}$
K^-	$\bar{u}\,s$
K^0	$d\,\bar{s}$
$\bar{K}^0$	$\bar{d}\,s$



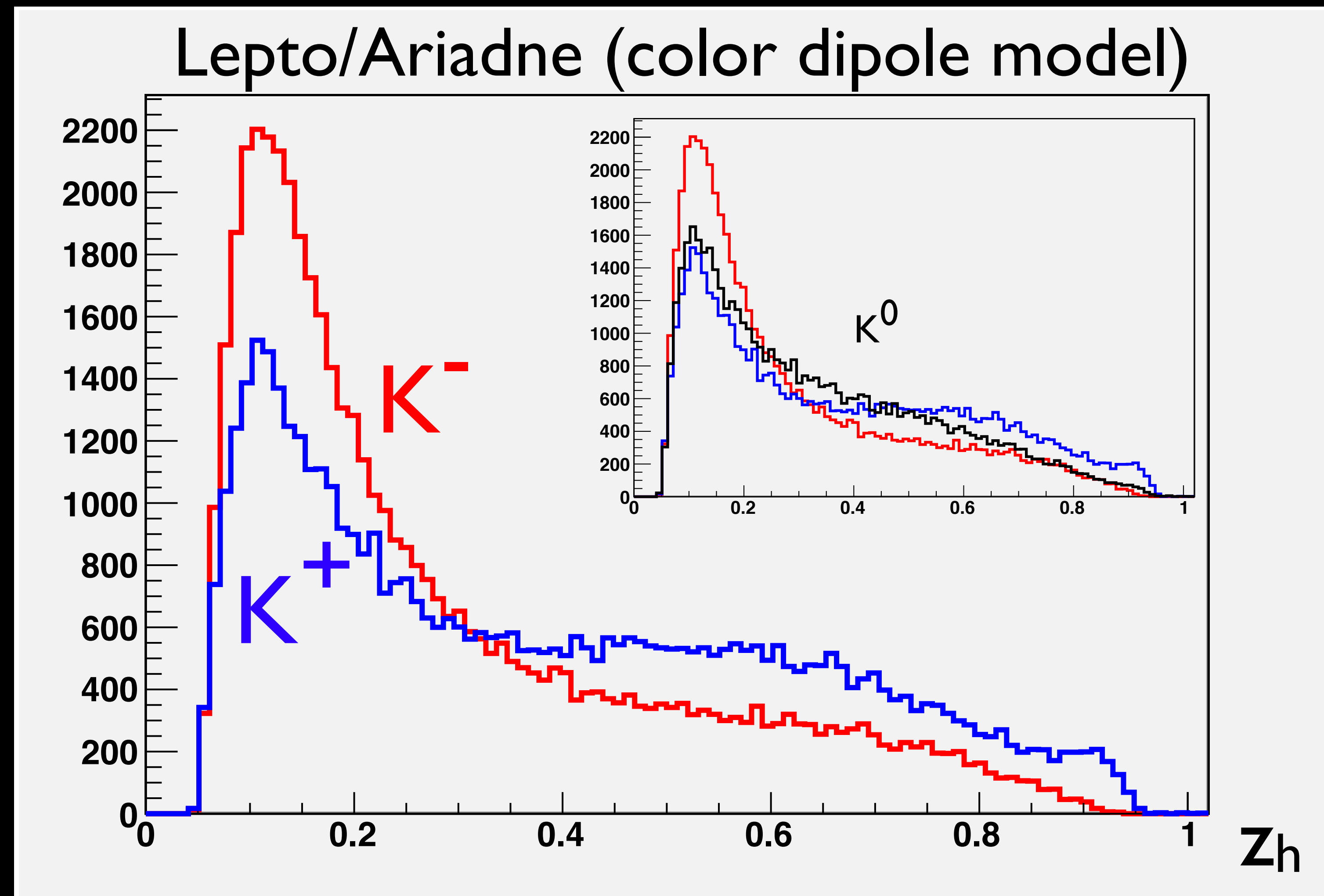
- Naively, K^- comes more from mid-string than K^+:

  ......$\overline{q}$--q::$\overline{q}$--u::$\overline{u}$--s::$\overline{s}$--u vs. ......$\overline{q}$--u::$\overline{u}$--s::$\overline{s}$--q::$\overline{q}$--u

- Only two of the above kaons can contain a struck valence quark
- Cannot distinguish between the two neutral kaons; K^0 thus 'mix' of multiple mechanisms, requires both charged kaons to 'understand' K^0

Landscape of kaon hadronization

K^+	$u\bar{s}$
K^-	$\bar{u}s$
K^0	$d\bar{s}$
$\bar{K}^0$	$\bar{d}s$



- Naively, K^- comes more from mid-string than K^+:

$$......\bar{q}\text{--}q::\bar{q}\text{--}u::\bar{u}\text{--}s::\bar{s}\text{--}u \quad \text{vs.} \quad ......\bar{q}\text{--}u::\bar{u}\text{--}s::\bar{s}\text{--}q::\bar{q}\text{--}u$$

- Only two of the above kaons can contain a struck valence quark
- Cannot distinguish between the two neutral kaons; K^0 thus ‘mix’ of multiple mechanisms, requires both charged kaons to ‘understand’ K^0

Quark Propagation and Hadron Formation

The CLAS12 Experiment in the 12 GeV Era

Dependency of observables (and thus derived quantities, such as production time, formation times, transport coefficient, in-medium cross section, etc.) on mass, flavor, and number of valence quarks

Quark Propagation and Hadron Formation

The CLAS12 Experiment in the 12 GeV Era

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	5.7% (sys)
π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$	3.2% (sys)
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	6.2% (sys)
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	6.7% (sys)
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	8.5% (sys)
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	5.0% (stat)*
$f1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	-
K^0	27 mm	0.50	$d\bar{s}$	4.7% (sys)
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$	4.4% (sys)
p	stable	0.94	ud	3.2% (sys)
$\bar{p}$	stable	0.94	$\overline{ud}$	5.9% (stat)**
Λ	79 mm	1.1	uds	4.1% (sys)
$\Lambda(1520)$	13 fm	1.5	uds	8.8% (sys)
Σ^+	24 mm	1.2	us	6.6% (sys)
Σ^-	44 mm	1.2	ds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	us	16% (stat)*
Ξ^-	49 mm	1.3	ds	7.8% (stat)*

Dependency of observables (and thus derived quantities, such as production time, formation times, transport coefficient, in-medium cross section, etc.) on mass, flavor, and number of valence quarks

Quark Propagation and Hadron Formation

The CLAS12 Experiment in the 12 GeV Era

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	5.7% (sys)
π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$	3.2% (sys)
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	6.2% (sys)
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	6.7% (sys)
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	8.5% (sys)
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	5.0% (stat)*
f1	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	-
K^0	27 mm	0.50	$d\bar{s}$	4.7% (sys)
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$	4.4% (sys)
p	stable	0.94	ud	3.2% (sys)
$\bar{p}$	stable	0.94	$\overline{ud}$	5.9% (stat)**
Λ	79 mm	1.1	uds	4.1% (sys)
$\Lambda(1520)$	13 fm	1.5	uds	8.8% (sys)
Σ^+	24 mm	1.2	us	6.6% (sys)
Σ^-	44 mm	1.2	ds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	us	16% (stat)*
Ξ^-	49 mm	1.3	ds	7.8% (stat)*

*in a bin in z from 0.7-0.8, integrated over all ν, p_T, ϕ_{pq}, and Q^2>5 GeV^2

**in a bin in z from 0.6-0.7, integrated over all ν, p_T, ϕ_{pq}, and Q^2>5 GeV^2

Dependency of observables (and thus derived quantities, such as production time, formation times, transport coefficient, in-medium cross section, etc.) on mass, flavor, and number of valence quarks

Quark Propagation and Hadron Formation

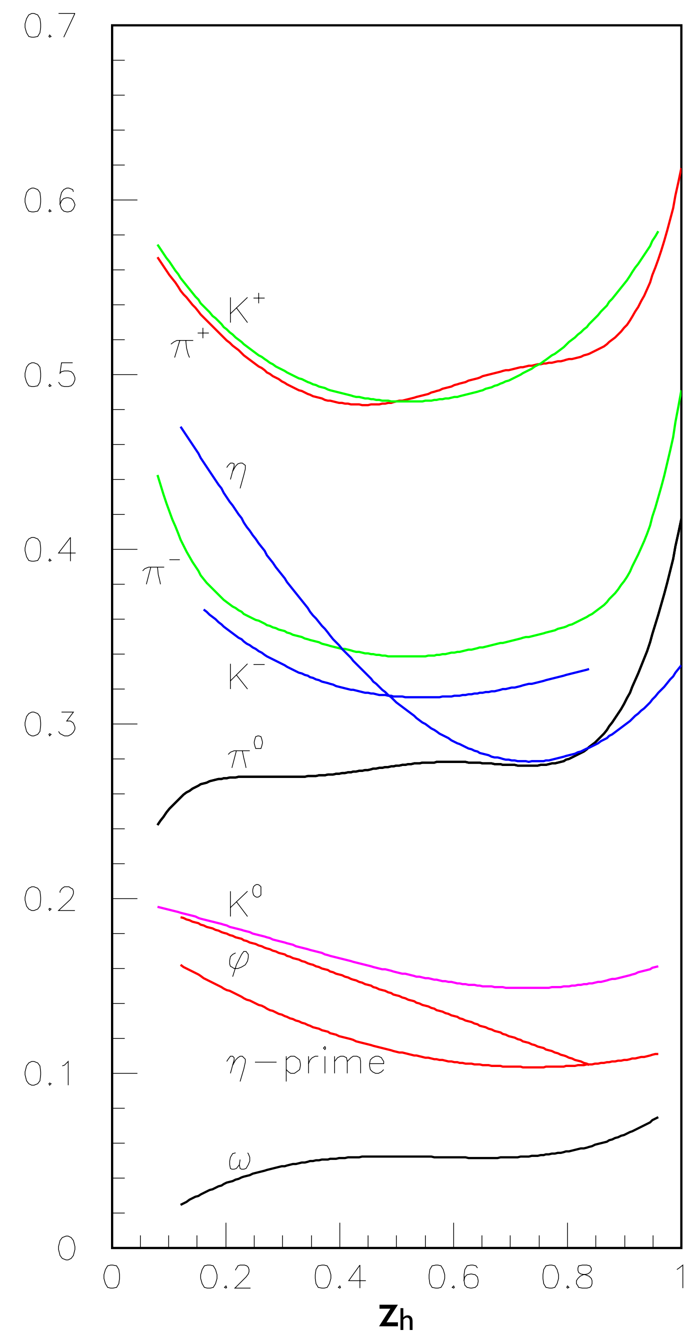
The CLAS12 Experiment in the 12 GeV Era

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	5.7% (sys)
π^+, π^-	7.8 m	0.14	$u\bar{d}, d\bar{u}$	3.2% (sys)
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	6.2% (sys)
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	6.7% (sys)
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	8.5% (sys)
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	5.0% (stat)*
f1	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	-
K^0	27 mm	0.50	$d\bar{s}$	4.7% (sys)
K^+, K^-	3.7 m	0.49	$u\bar{s}, \bar{u}s$	4.4% (sys)
p	stable	0.94	ud	3.2% (sys)
$\bar{p}$	stable	0.94	$\overline{ud}$	5.9% (stat)**
Λ	79 mm	1.1	uds	4.1% (sys)
$\Lambda(1520)$	13 fm	1.5	uds	8.8% (sys)
Σ^+	24 mm	1.2	us	6.6% (sys)
Σ^-	44 mm	1.2	ds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	us	16% (stat)*
Ξ^-	49 mm	1.3	ds	7.8% (stat)*

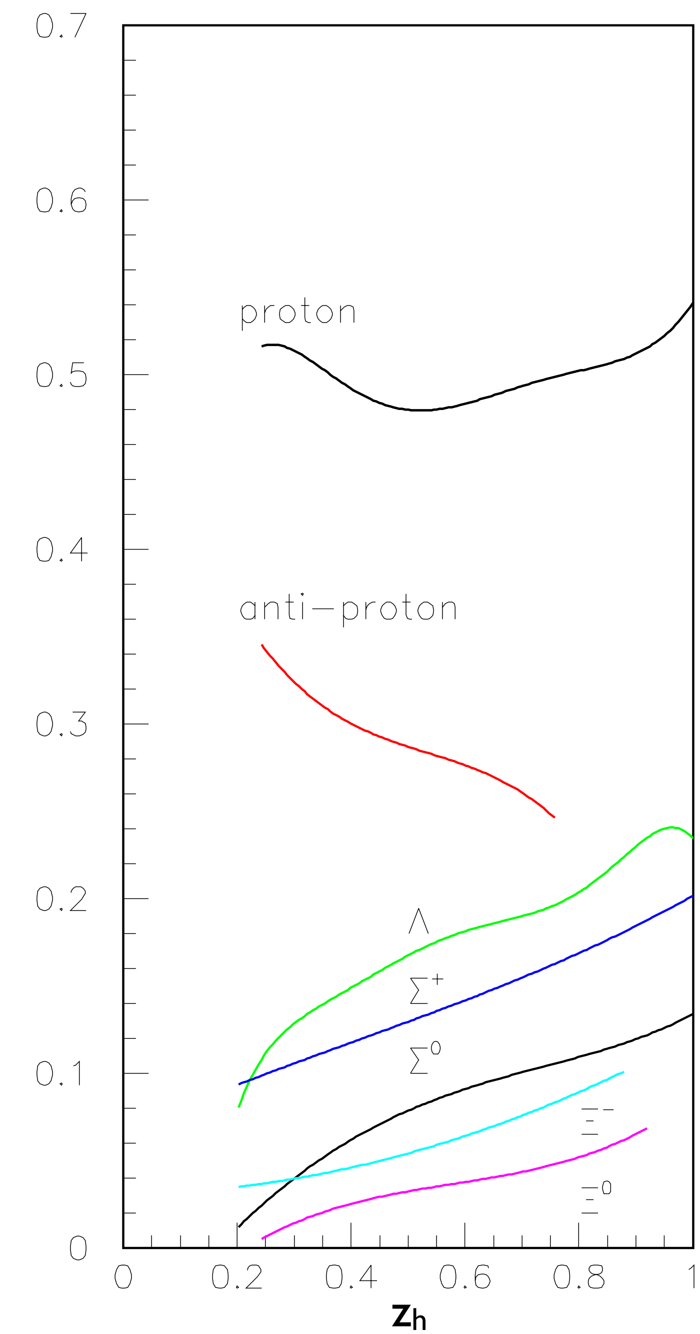
*in a bin in z from 0.7-0.8, integrated over all ν, p_T, ϕ_{pq}, and $Q^2>5$ GeV^2

**in a bin in z from 0.6-0.7, integrated over all ν, p_T, ϕ_{pq}, and $Q^2>5$ GeV^2

Dependency of observables (and thus derived quantities, such as production time, formation times, transport coefficient, in-medium cross section, etc.) on mass, flavor, and number of valence quarks



CLAS12 Acceptance for Mesons



CLAS12 Acceptance for Baryons

Examples of Experimental Data and Theoretical Predictions

Mechanisms of Hadronization

Examples of recent theory progress

- First fully quantum-mechanical calculation of in-medium hadronization
- Perturbative fragmentation via the KPPS-Berger model (KPPS, Phys. Lett. **B**662:117-122, 2008, arXiv:0706.3059v1 [hep-ph]
- Path-integral formulation of quantum mechanics (LCGF)
  - phases and interferences; all relevant timescales
  - includes the probability of prehadron production both inside and outside the medium

Inner/outer interference generates hadron 'attenuation': in-medium interactions affect overlap of dipole to pion wave function

B.Z. **K**opeliovich, H.-J. **P**irner, I.K. **P**otashnikova, Ivan **S**chmidt, A.V. Tarasov, O.O. Voskresenskaya, Phys. Rev. C78:055204,2008 arXiv:0809.4613v2 [hep-ph]

Conclusions

- Rich and exciting program of studies!
  - Hermes data the first with hadron-specific information
  - CLAS at 5 and 11 GeV
- Strangeness production a very important part of these studies of hadronization mechanisms and space-time QCD