Study of Few-Nucleon Systems with the CLAS

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Quark Confinement and the Hadron Spectrum IX
2 September 2010, Madrid, Spain

Outline

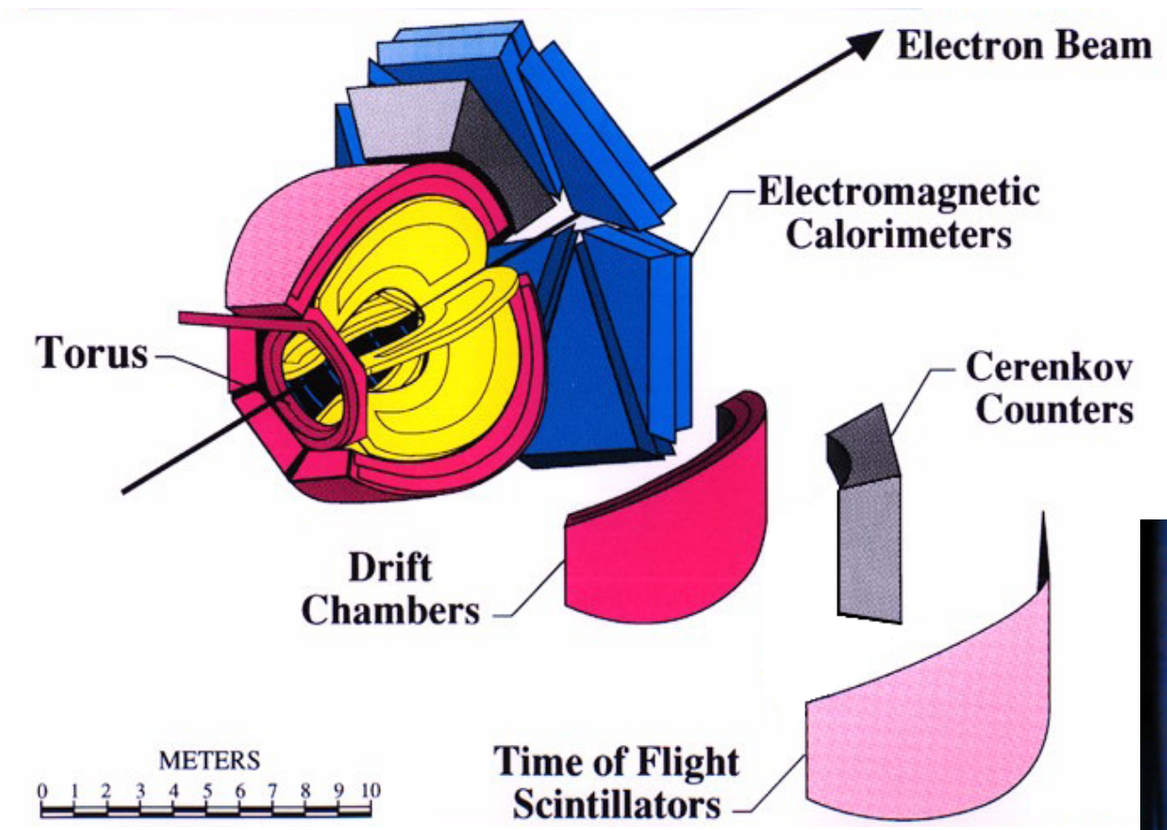
- Introduction.
- Studies of Short-Range Correlations in Nuclei.
- Studies of Three-Body Mechanisms in Photodisintegration.
- Studies of Onset of Scaling of Invariant Cross Sections of Exclusive Processes.
- Summary.

Thomas Jefferson National Accelerator Facility

JLab in Newport News, VA

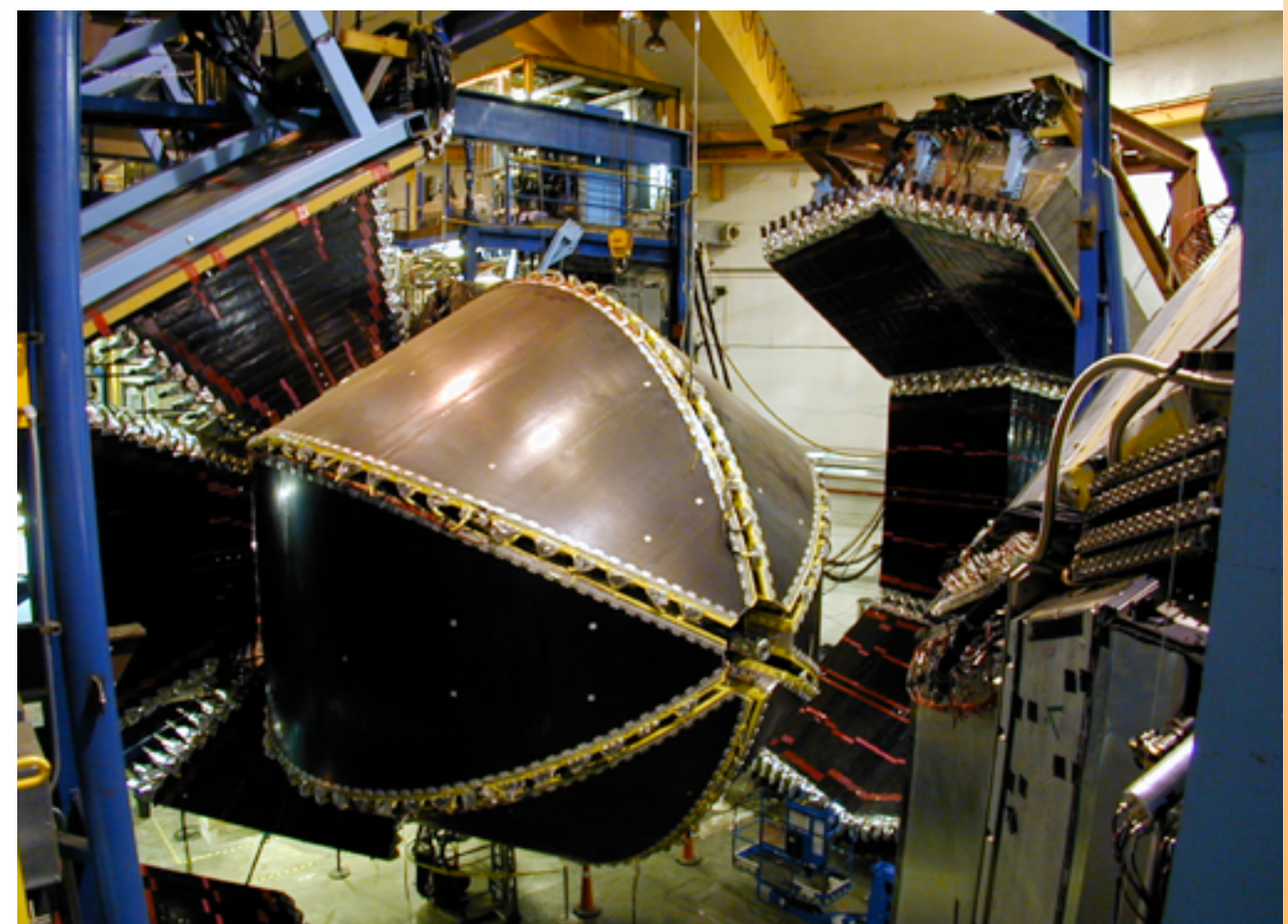
- Electron-beam accelerator
- Polarized c.w. electron beam
- Beam energies up to E_0 = 6 GeV
- Three experimental Halls A, B, and C

The CEBAF Large Acceptance Spectrometer CLAS

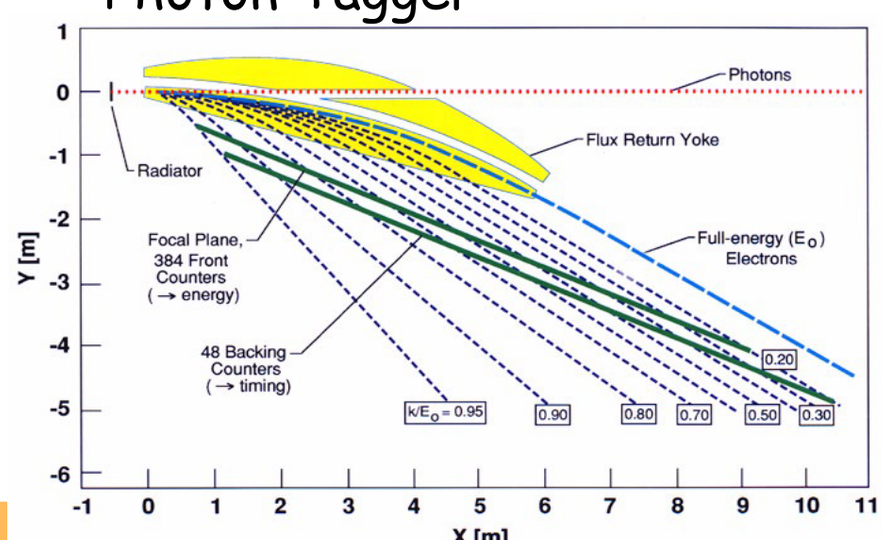


Performance

- $L = 10^{34}\ cm^{-2}\ s^{-1}$
- $\Delta p/p \sim 0.5-1\ \%$
- $\sim 4\pi$ acceptance
- Best suited for multiparticle final states
- Bremsstrahlung Photon Tagger ($\Delta E_\gamma/E_\gamma \sim 10^{-3}$)



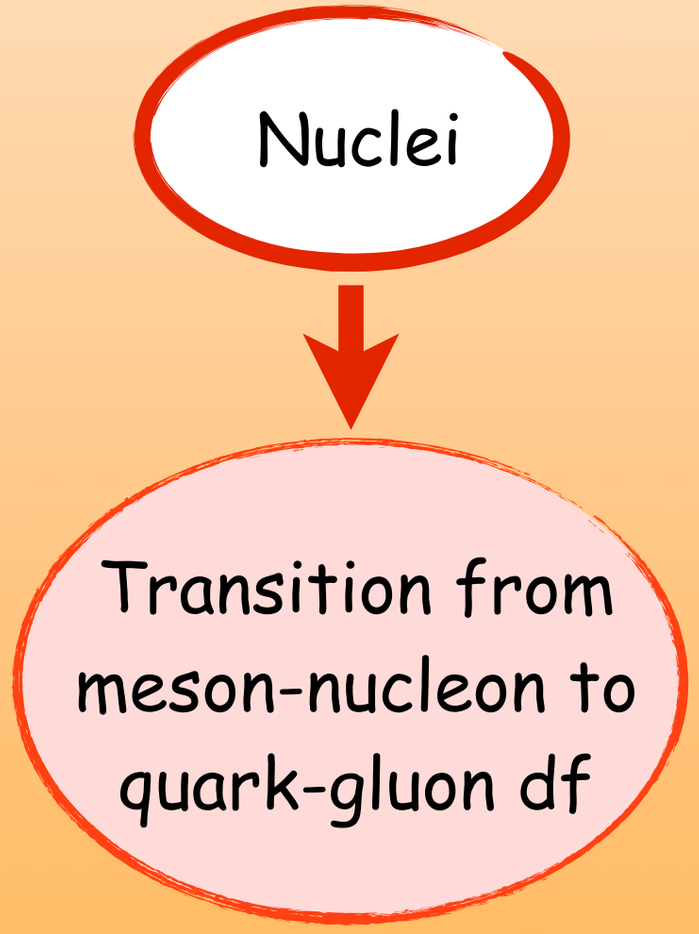
Photon Tagger



Physics with the CLAS

Nuclei

Physics with the CLAS



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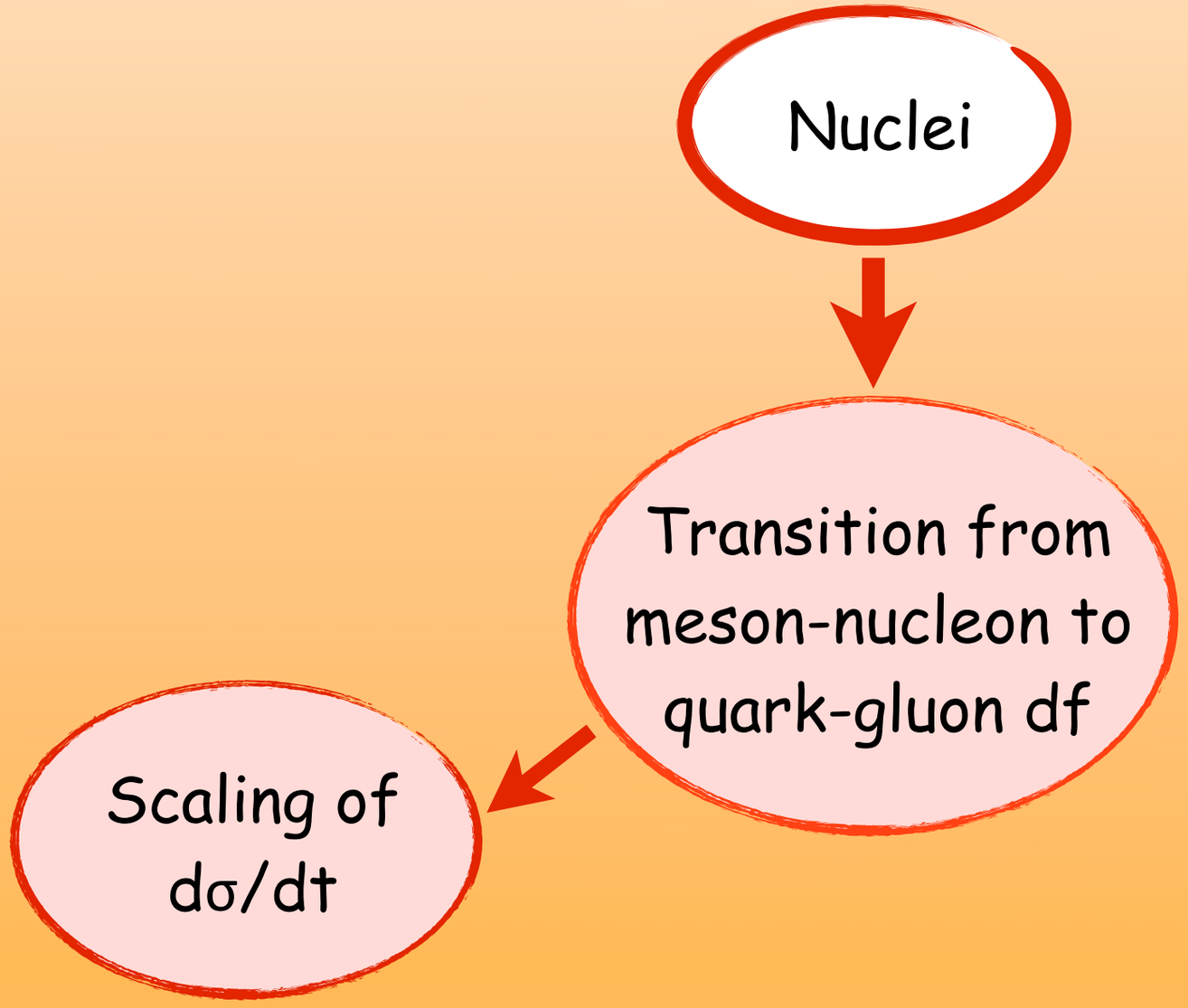

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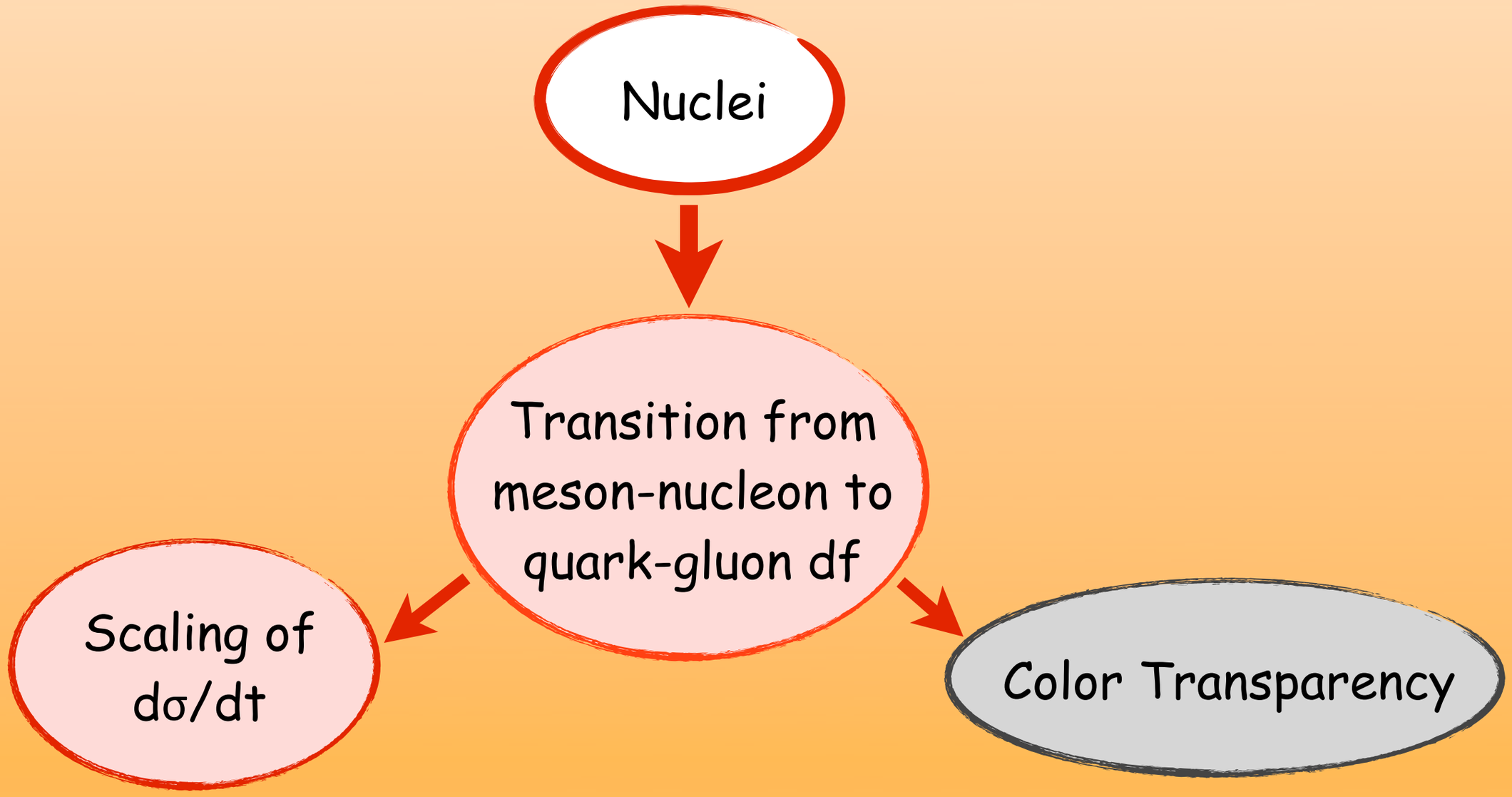

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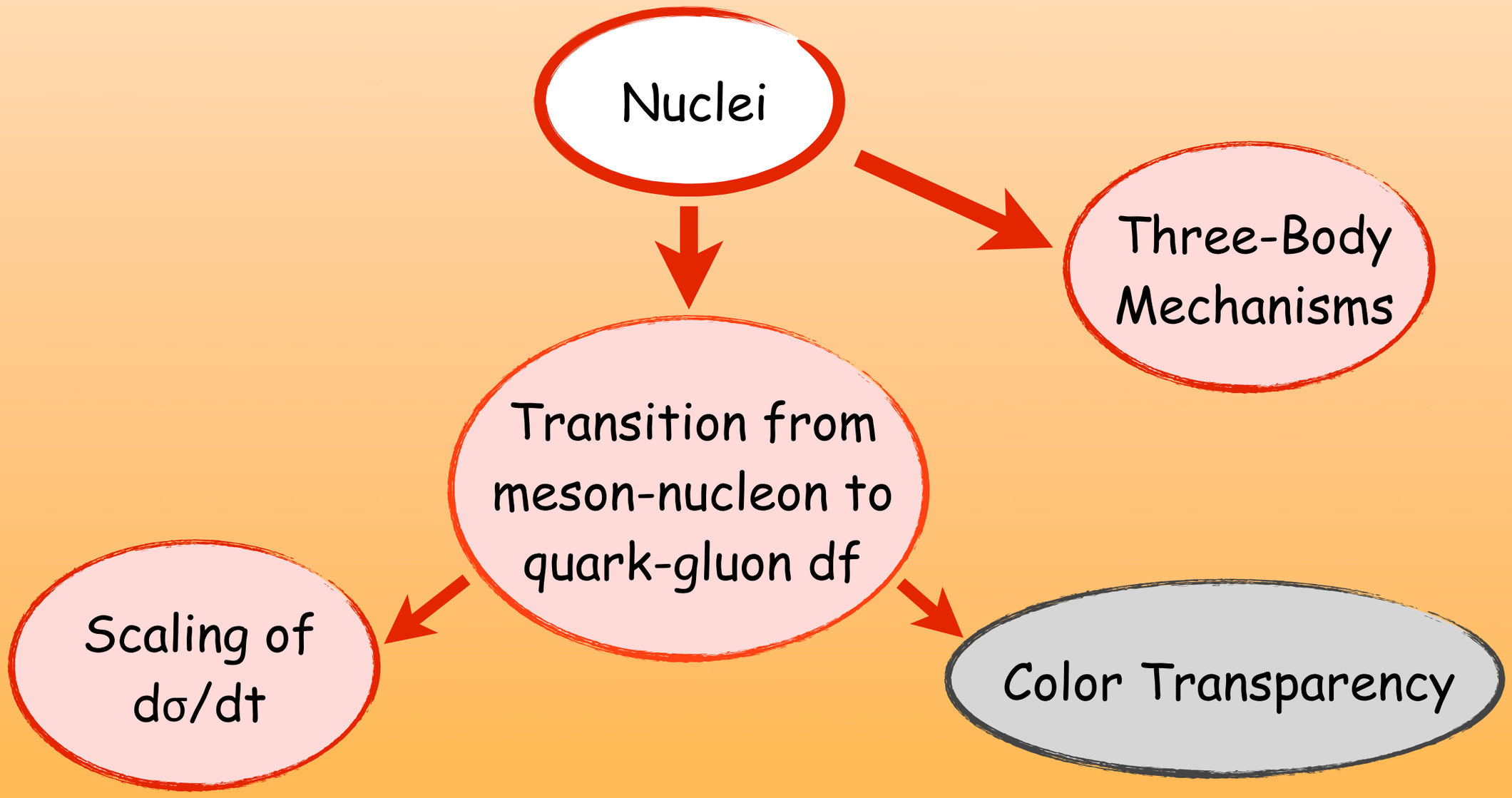

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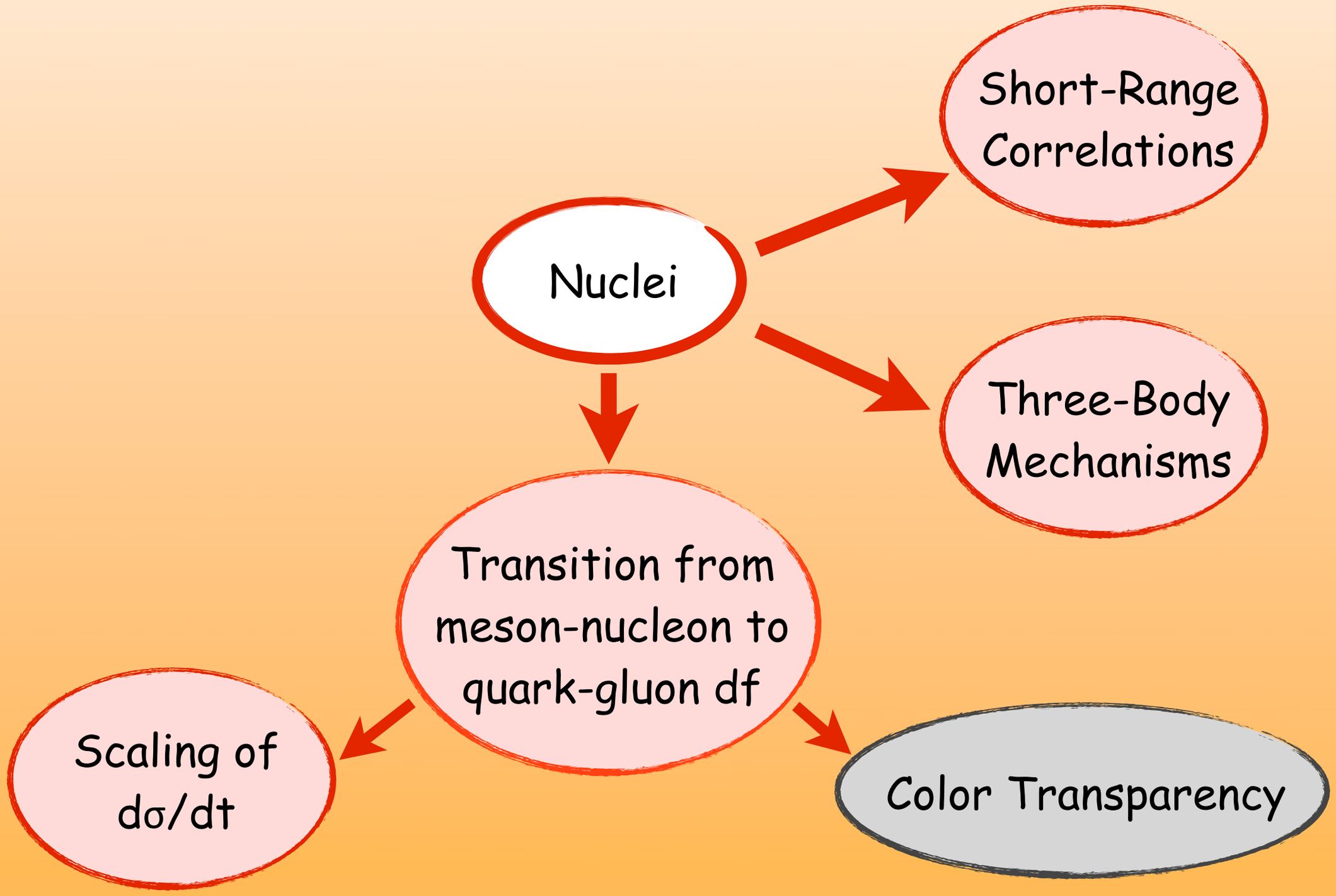

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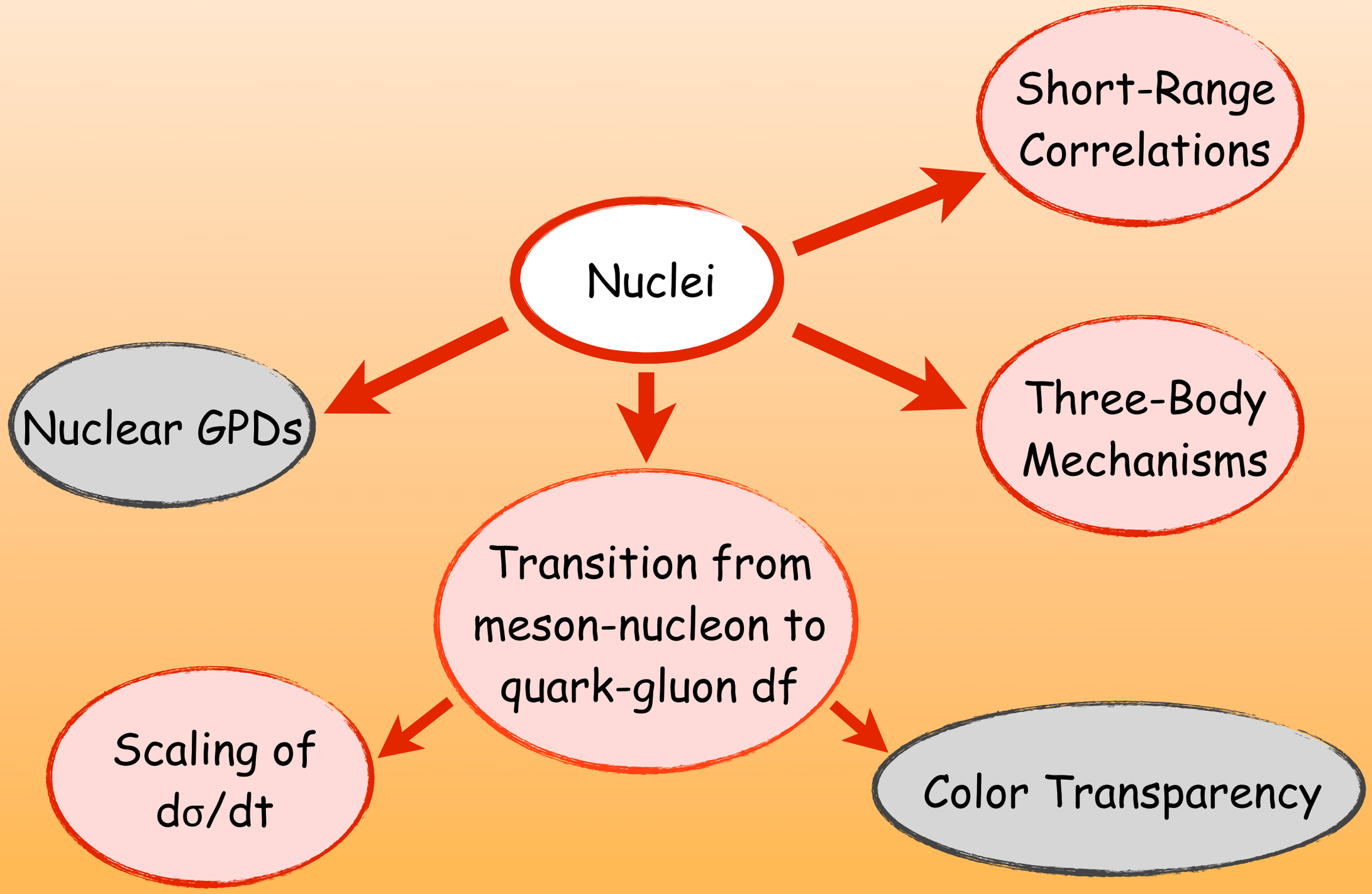

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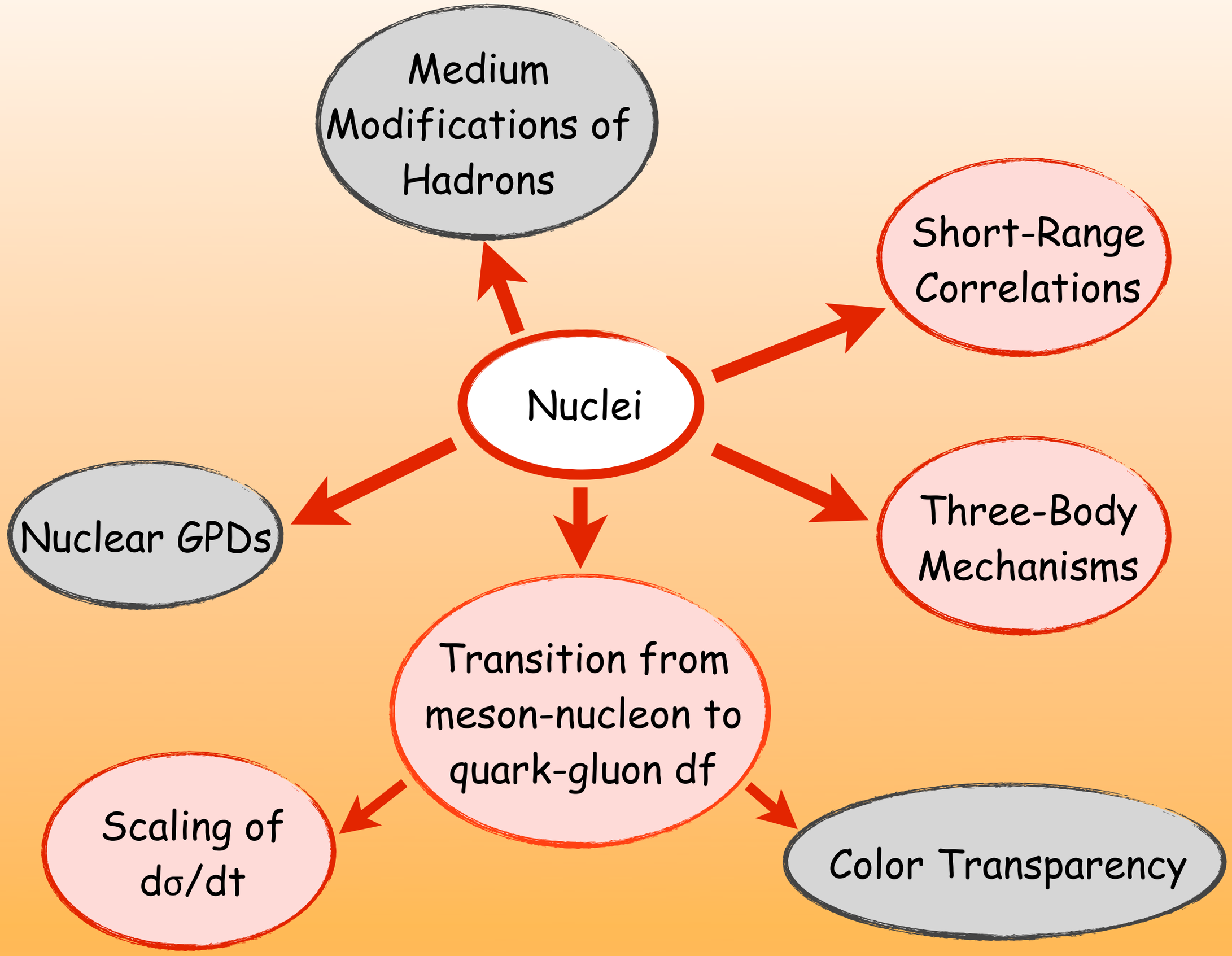
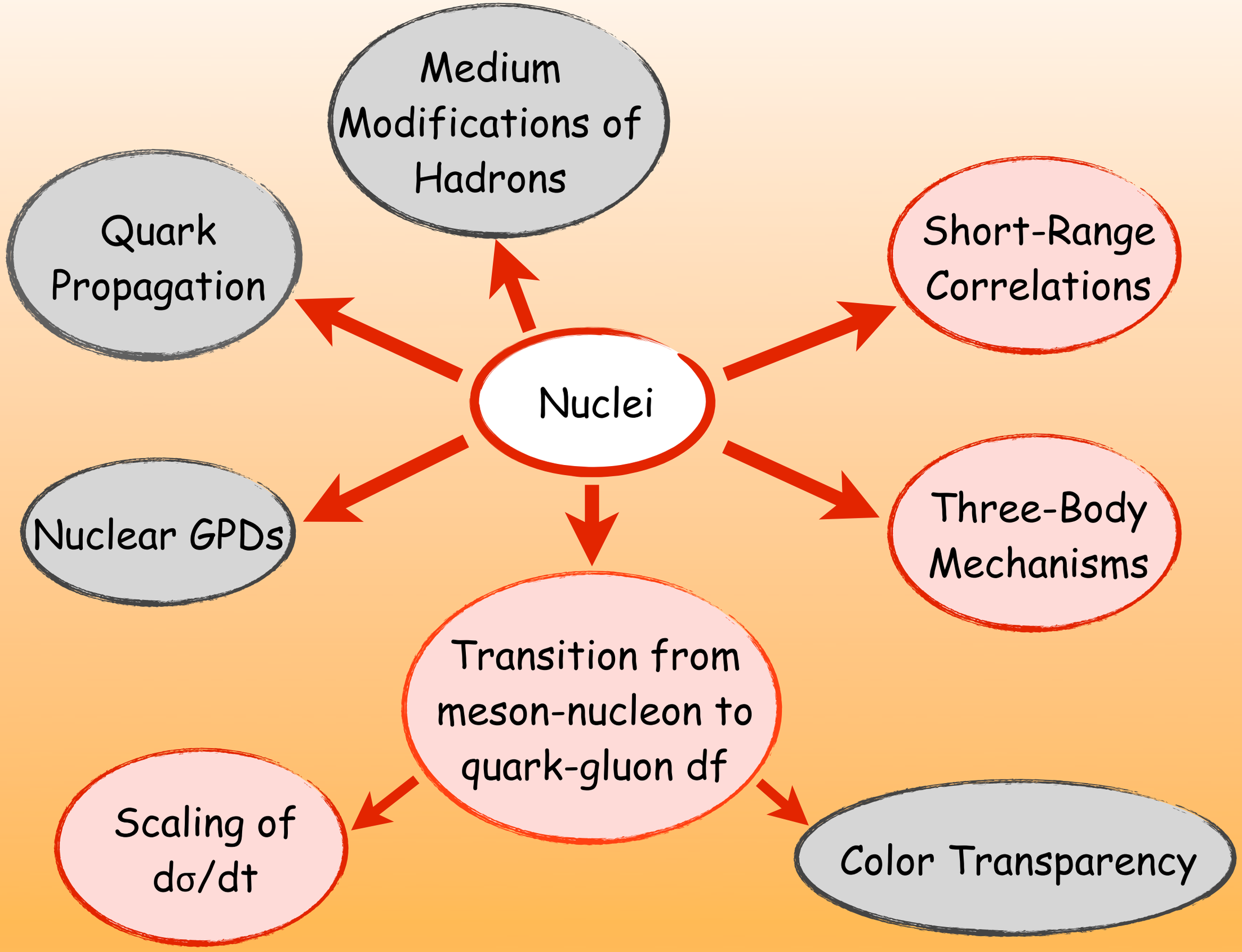
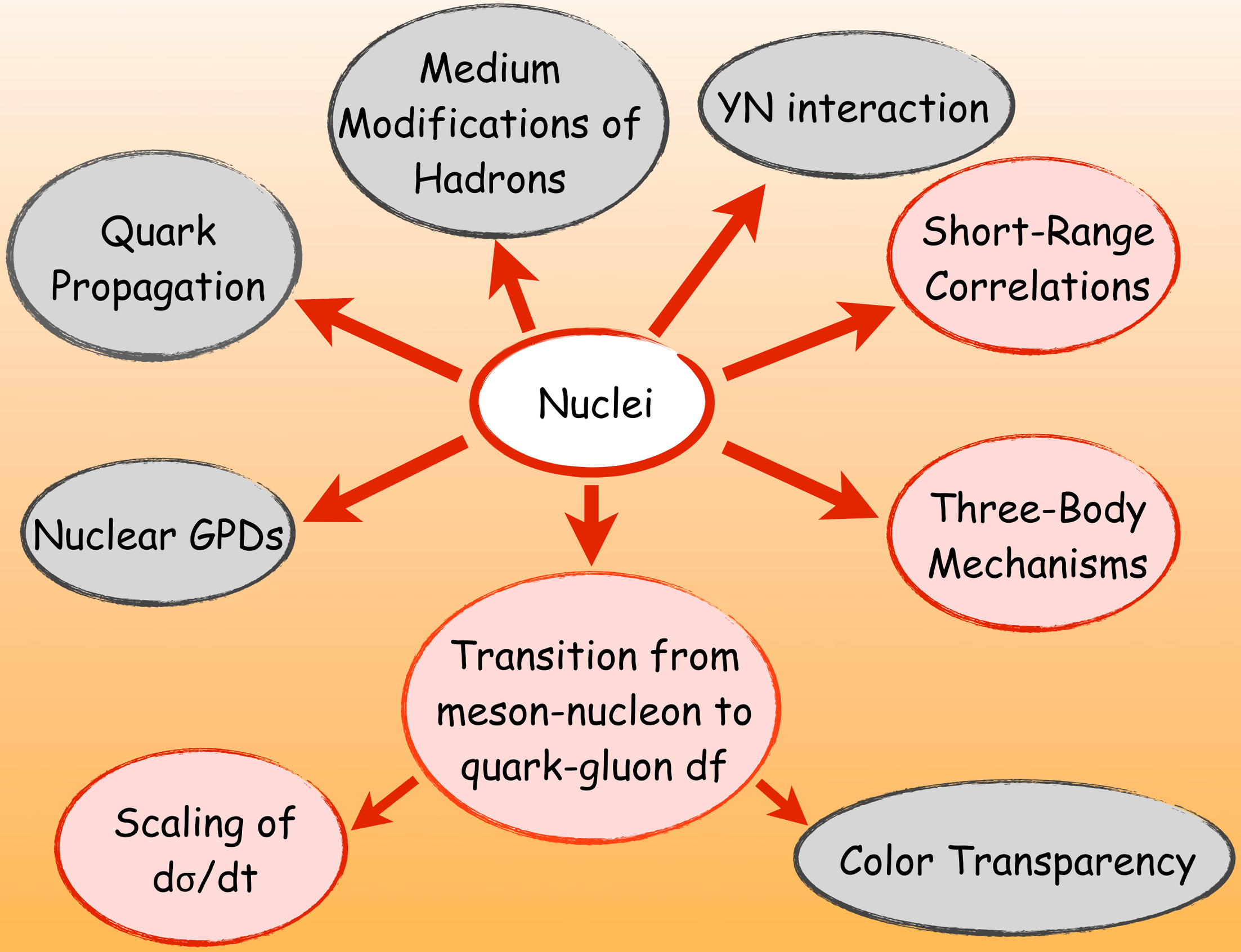


Physics with the CLAS



Physics with the CLAS



The Dual Universe of Nuclear Physics

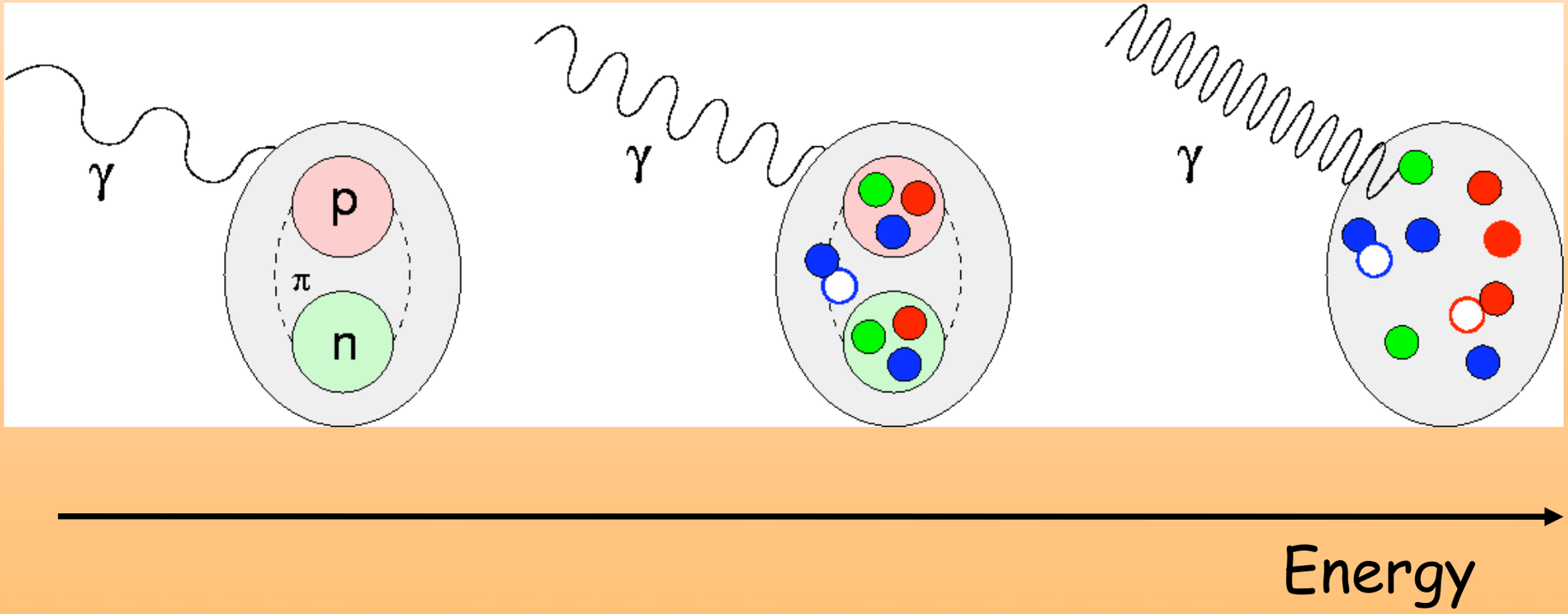
Our understanding of the strong interaction depends on the scale…

$$\lambda = \frac{h}{p}$$

p = 1 GeV/c
probes 1.2 fm

meson-nucleon picture

quark-gluon

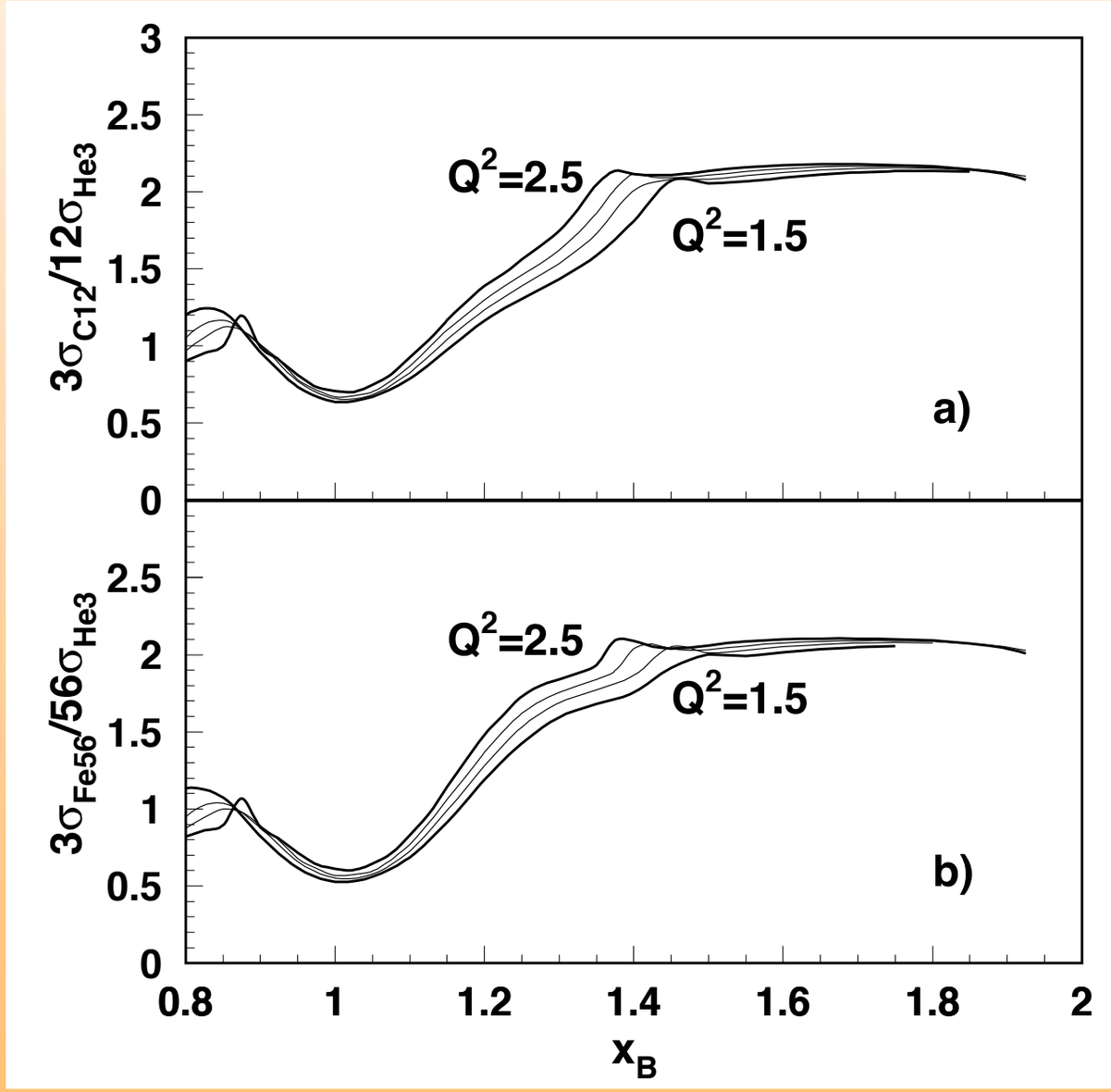


When does the transition between the two descriptions happen? How to describe it?

Theoretical Description of Nuclear Dynamics

- Low Energies: Effective Field Theory (nucleons or nucleons and pions)
- High Energies: pQCD
- Medium Energies: traditional nuclear models, quark models, pQCD extensions through factorization (relevant degrees of freedom?).
  - Some Open Questions
    - short-range correlations (SRC)
    - three-body mechanisms
    - color transparency
    - hidden color

Nuclear Structure at Short Distances
Short-Range Correlations



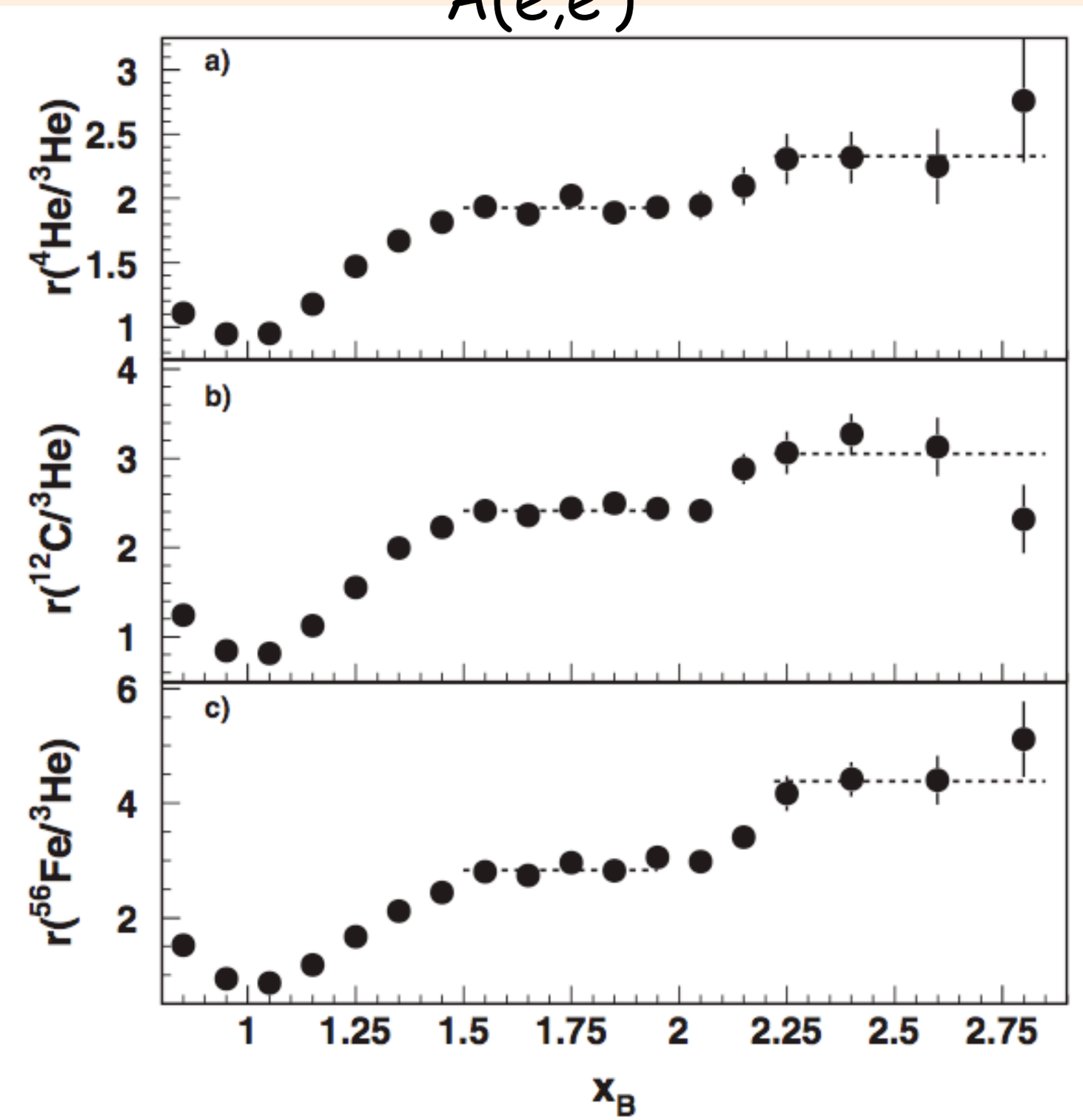
$$R(Q^2, x_B) = \frac{\sigma_{A1}(Q^2, x_B)/A_1}{\sigma_{A2}(Q^2, x_B)/A_2}$$

- high nucleon momentum ($p>p_f$) balanced by only one other nucleon
- give rise to high-momentum part of nuclear wf
- nucleon momentum distributions similar for light and heavy nuclei
- scaling of A(e,e') cross section at high momenta

K. S. Egiyan et al, Phys. Rev. C **68**, 014313 (2003)

Nuclear Structure at Short Distances: SRC

A(e,e')



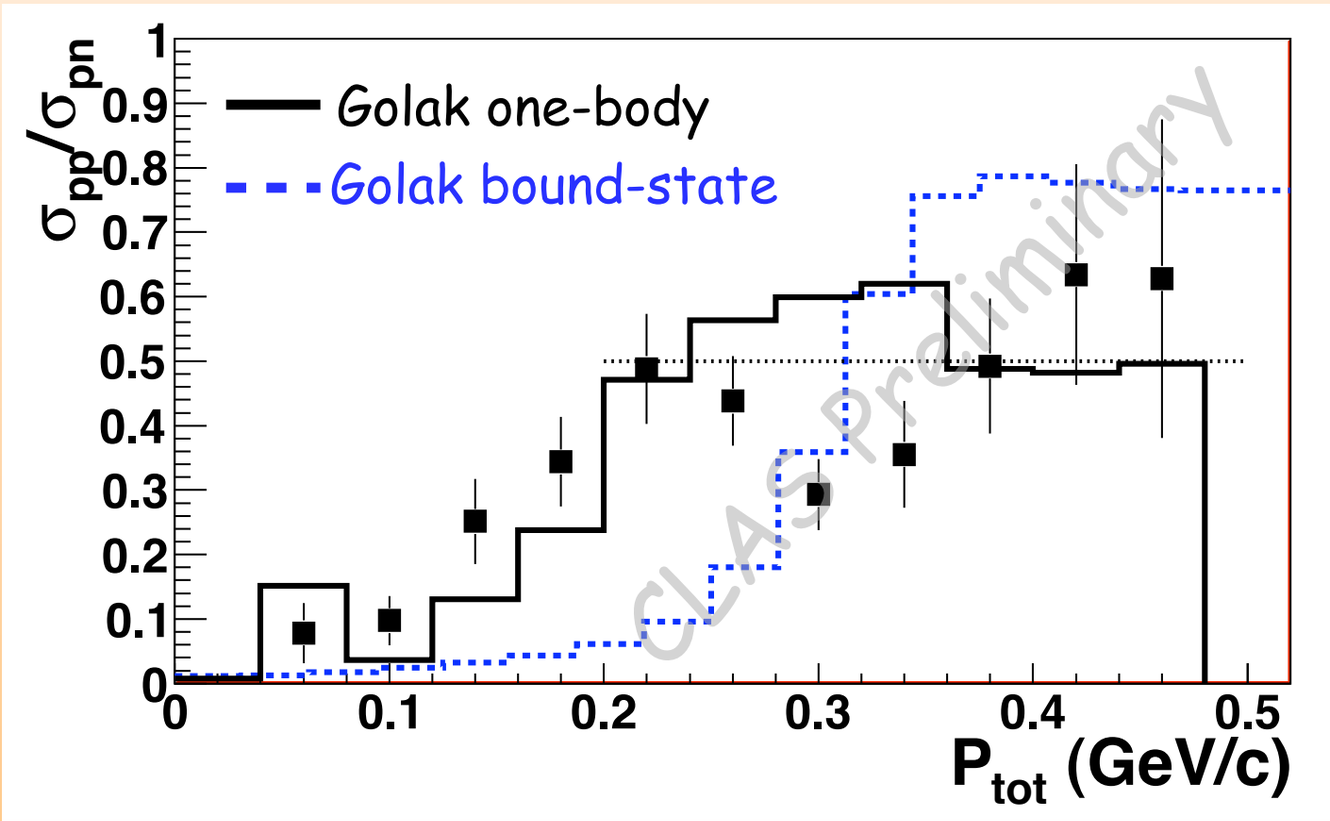
- quantified NN and NNN SRC probabilities
- more than 90% of all nucleons with k≥300 MeV/c belong to NN SRC
- NN SRC build of 6q, ΔN, ΔΔ < 10 - 20% of the NN SRC
- NNN SRC present in nuclei with significant probability

K. S. Egiyan et al, Phys. Rev. Lett. **96**, 082501 (2006)

M. Strikman, Nucl. Phys. A **827**, 240c (2009)

Nuclear Structure at Short Distances: SRC

$^3He(e,e'pp)n$



- pp to pn cross section ratio increases quickly to 0.4 - 0.5
- indicative of tensor correlations in pn pairs

H. Baghdasaryan et al, arXiv:1008.3100v1 [nucl-ex], (2010)

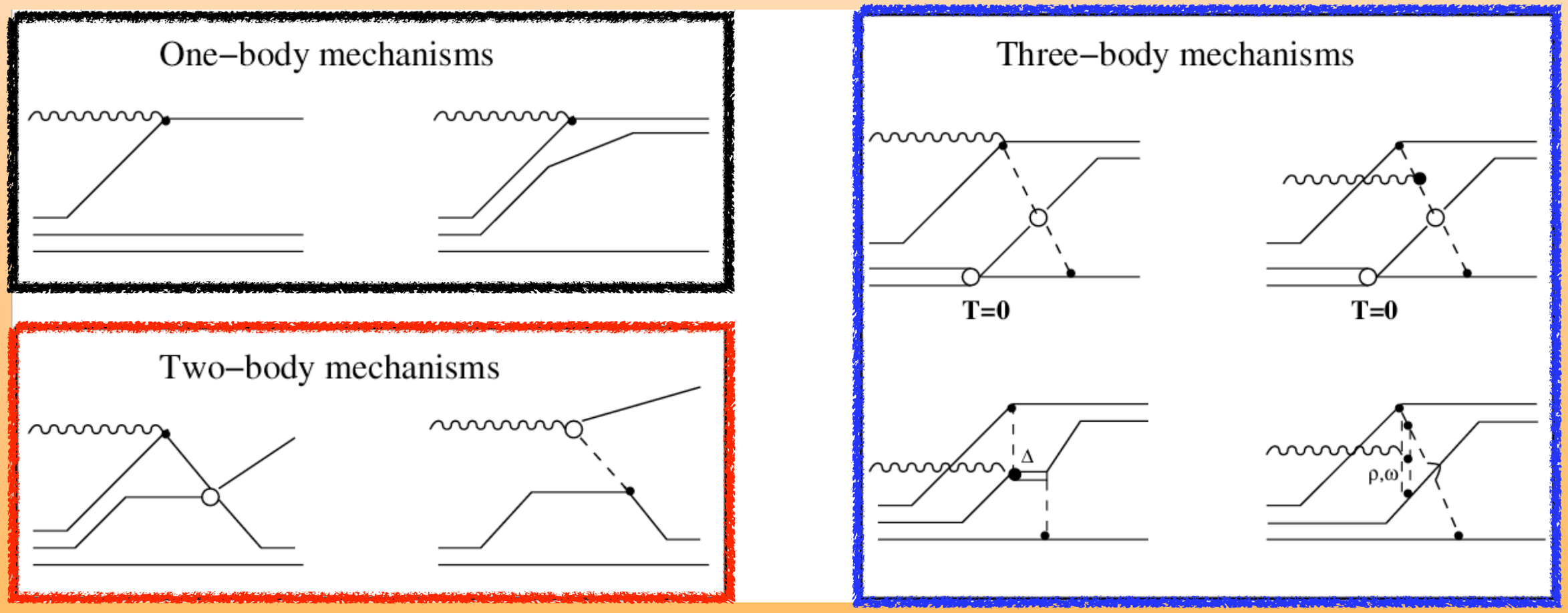
High-momentum components of the nuclear wf

- measured two-nucleon momentum distributions of correlated pn and pp pairs
- reduced FSI: leading nucleon p_T<0.3 GeV/c
- pair momentum along q is very small
- little Q^2 or isospin dependence

measured spectator correlated NN pairs

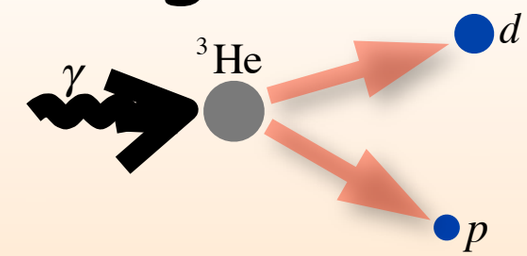
Three-Body Mechanisms in Reactions on Light Nuclei at Medium Energies

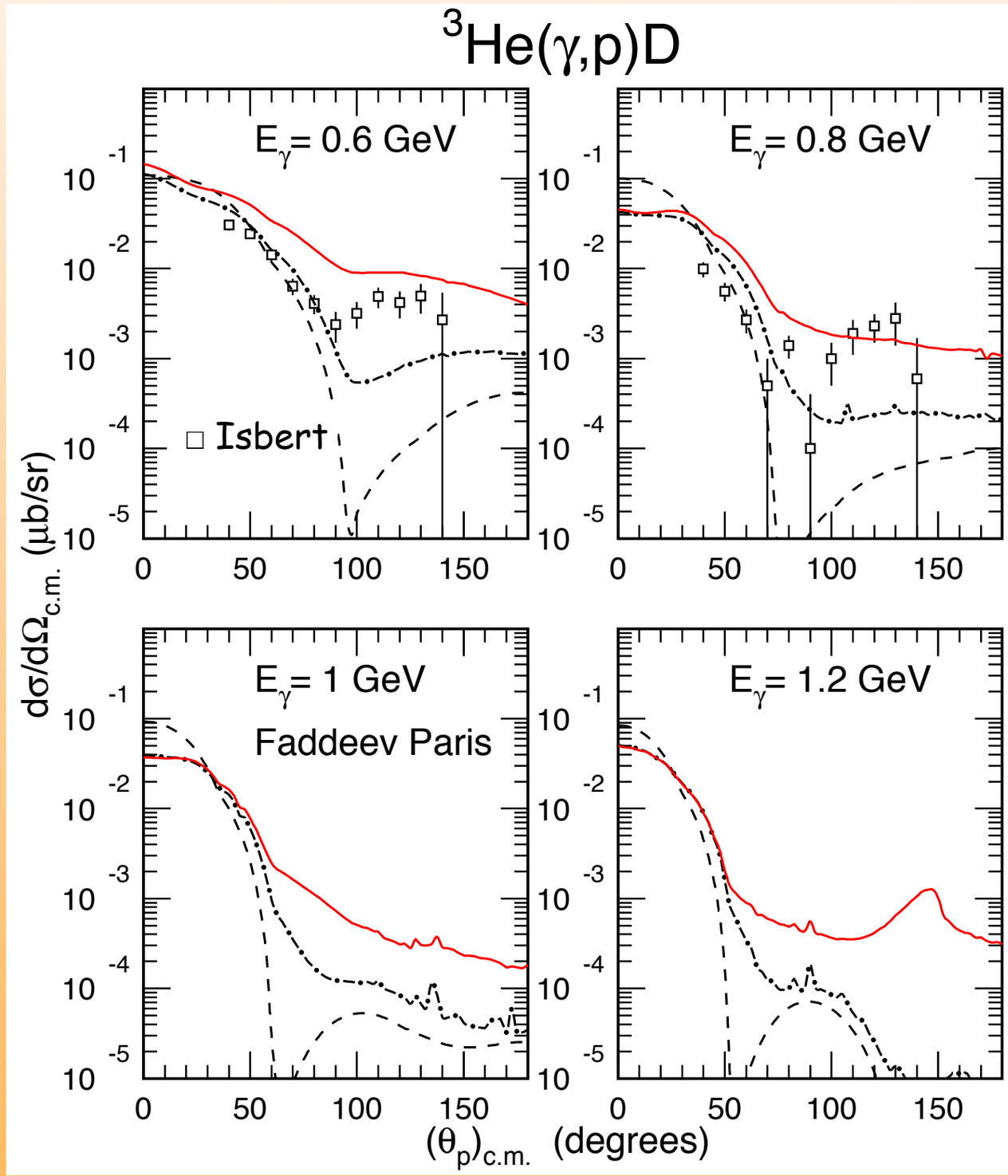
- Traditional Nuclear models: Diagrammatic approach, with one-, two-, and three-body mechanisms, is used to calculate the scattering amplitude



J. M. Laget, Phys. Rev. C **38**, 2999 (1988)

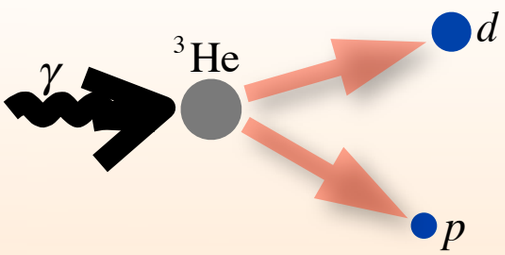
Predictions for Two-Body Photodisintegration of ^{3}He





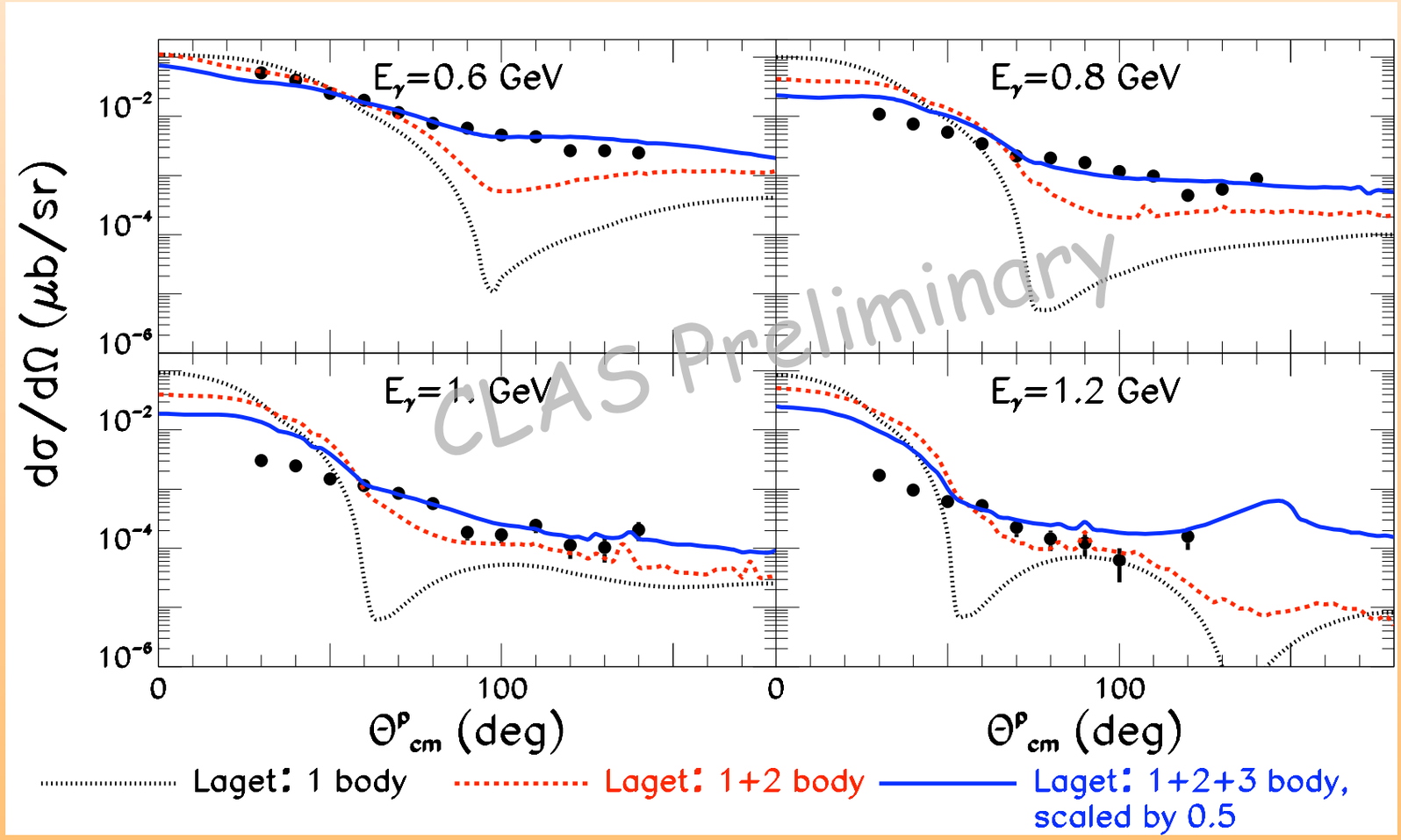
V. Isbert et al., Nucl. Phys. A **578**, 525 (1994)
J.-M. Laget, Phys. Rev. C **38**, 2999 (1988)

- Difficult to treat theoretically.
- Three-body mechanisms predicted to dominate at large t for all photon energies.
- Two-body mechanisms sufficient to describe data at low t.
- **Are three-body mechanisms dominant at large t for E_γ above 1 GeV?**



Two-Body Photodisintegration of ^{3}He

Comparison with predictions



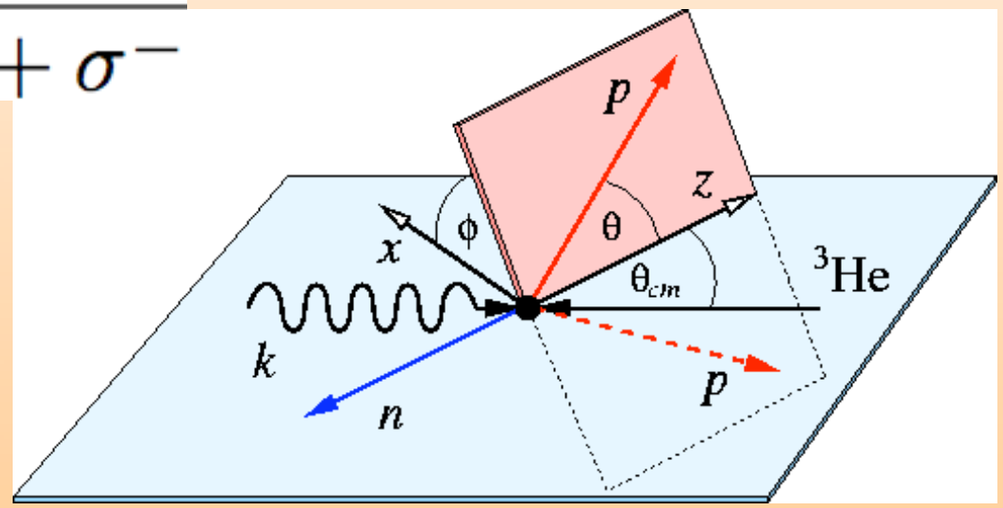
E_γ : 0.4 - 1.4 GeV

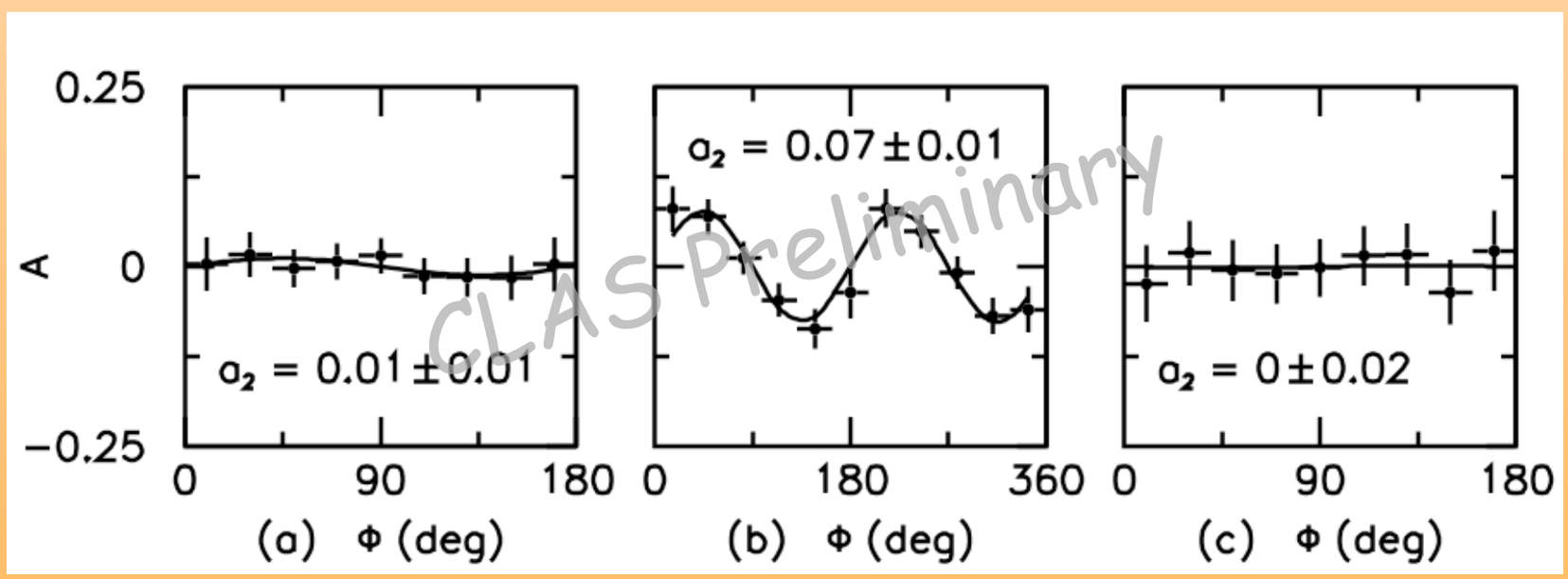
θ^*_p : 40° - 140°

- An order of magnitude forward-backward asymmetry.
- Slope of differential cross section nearly independent of Eγ.
- Relative contribution of three-body mechanisms is larger at 600-800 MeV than at higher photon energies.

Three-Body Photodisintegration of ^{3}He: Beam-Helicity Asymmetry A(φ)

$$A(\phi) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$





T.N. Ukwatta et al., AIP Conf. Proc. **884**, 454 (2007)

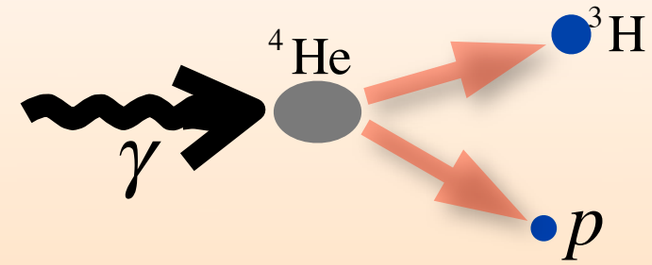
- Neutron non-spectator events:

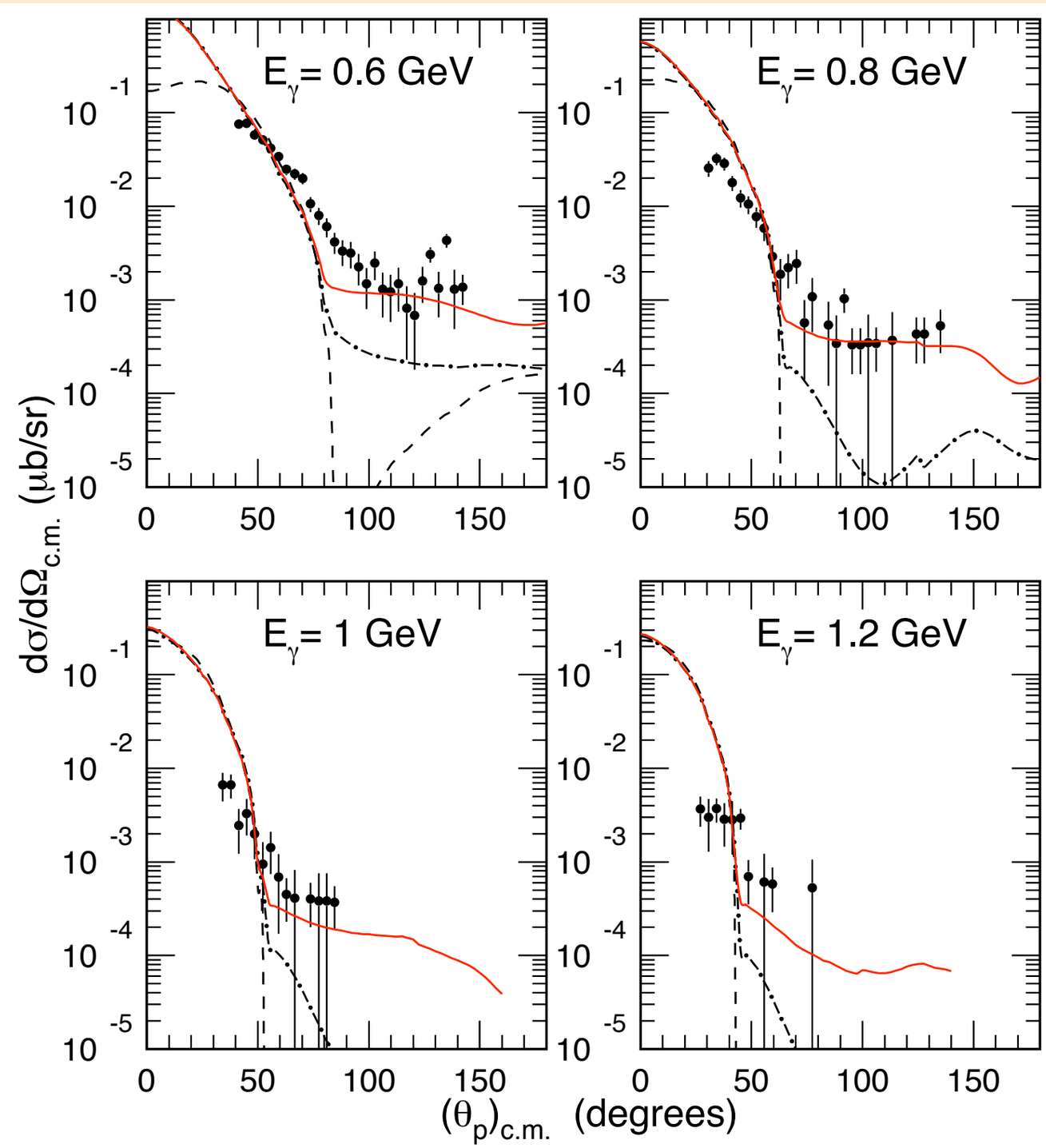
  p_n> 200 MeV/c

- Helicity asymmetry peaks between 0.6 and 1.0 GeV.
- Signature for three-body mechanisms?

Two-Body Photodisintegration of ^{4}He

Comparison with predictions





- Kinematic coverage:
  E_γ : 0.35 - 1.5 GeV
  θ^*_p : 40° - 130°
- Two orders of magnitude forward-backward asymmetry.
- Relative contribution of three-body mechanisms is large at all photon energies for θ^*_p > 60°.

R. Nasseripour et al., Phys. Rev. C **80**, 04603 (2009)

Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom

Tool: Exclusive nuclear reactions with real photons

- large momentum transfer t selects small-size configurations.

Signatures:

- scaling of invariant cross sections (Constituent Counting Rules).
- factorization (Reduced Nuclear Amplitudes).
- color transparency.

Quark Dynamics:
Constituent Counting Rules (pQCD, AdS/CFT)

- At high t, high s, and high u, the invariant cross section of an exclusive process A + B $\rightarrow$ C + D has the following asymptotic behavior:

$$\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s)$$

where n is the total number of the initial and final elementary fields.

- Examples:

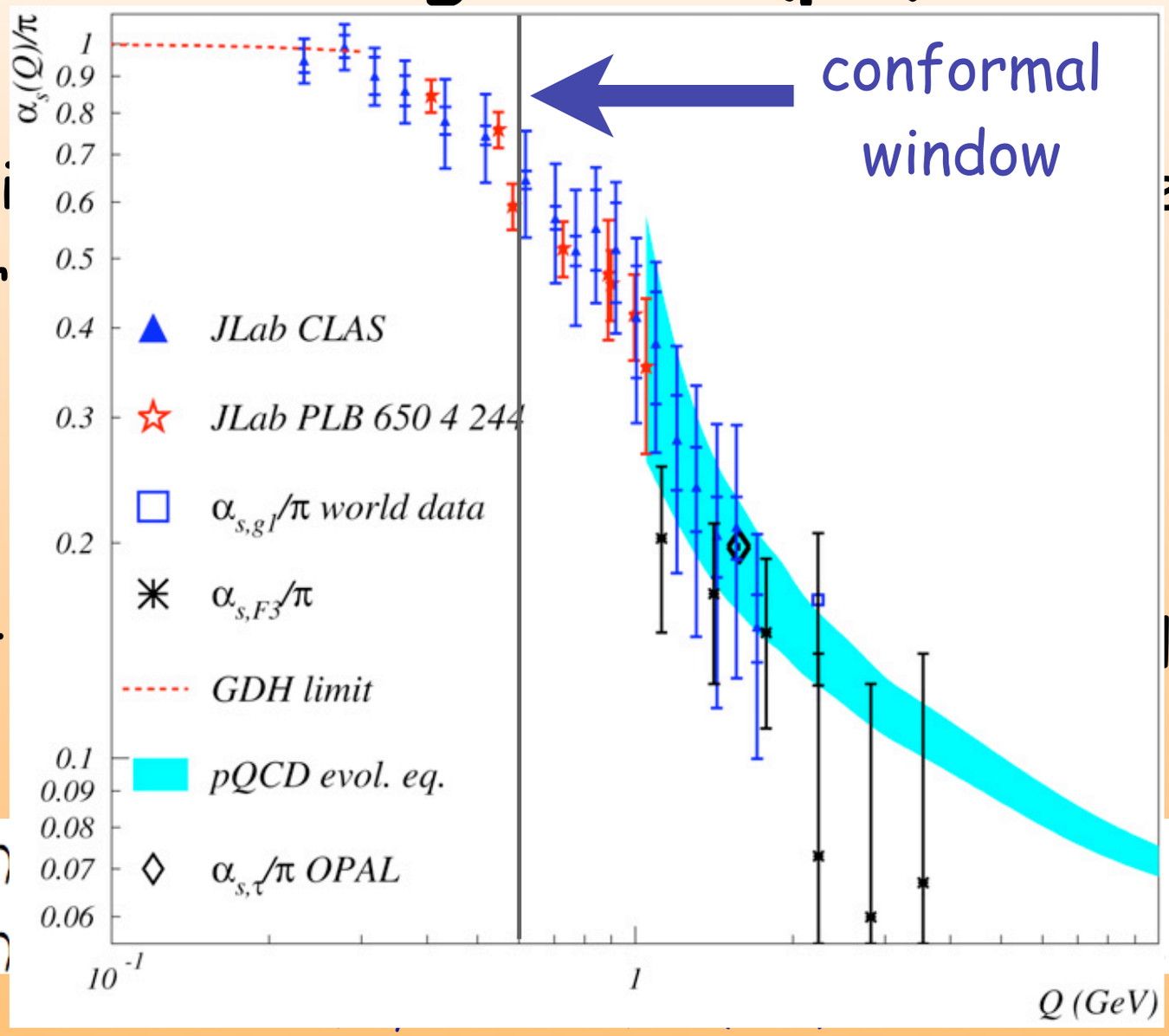
$$\begin{array}{lll} \gamma d & \rightarrow & \pi^0 d, \quad n-2=13 \\ \gamma d & \rightarrow & pn, \quad n-2=11 \end{array} \qquad \begin{array}{lll} \gamma p & \rightarrow & \pi^0 p, \quad n-2=7 \\ \gamma p & \rightarrow & K^+\Lambda, \quad n-2=7 \end{array}$$

A. Deur et al, Phys. Lett B **665**, 349 (2008)

- Reflect underlying scale free interactions (Brodsky, DeTeramond): scale independence of α_s.

S.J. Brodsky and G.R. Farrar, Phys. Rev. Lett **31**, 1153 (1973); V. Matveev et al., Nuovo Cimento Lett. **7**, 719 (1973); S.J. Brodsky and J.R. Miller, Phys. Rev. C **28**, 475 (1983)

Quark Dynamics:
Constituent Counting Rules (pQCD, AdS/CFT)



- At high t, hi ... ection of an exclusive pr ... asymptotic behavior:

  where n is t ... l elementary fields.

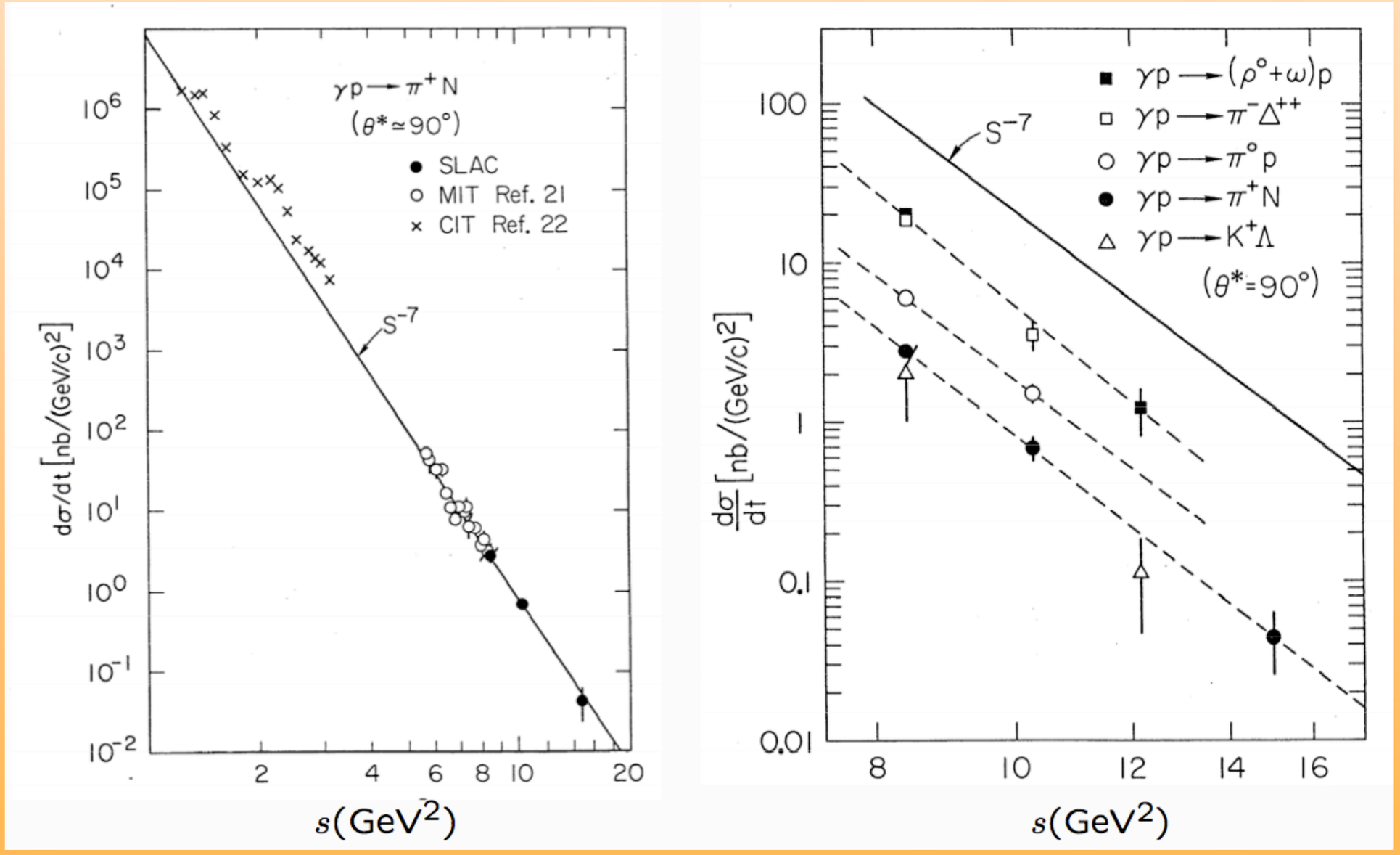
- Examples: ... $n-2=7$ ... , $n-2=7$

- Reflect underlying scale free interactions (Brodsky, DeTeramond): scale independence of α_s.

S.J. Brodsky and G.R. Farrar, Phys. Rev. Lett **31**, 1153 (1973); V. Matveev et al., Nuovo Cimento Lett. **7**, 719 (1973); S.J. Brodsky and J.R. Miller, Phys. Rev. C **28**, 475 (1983)

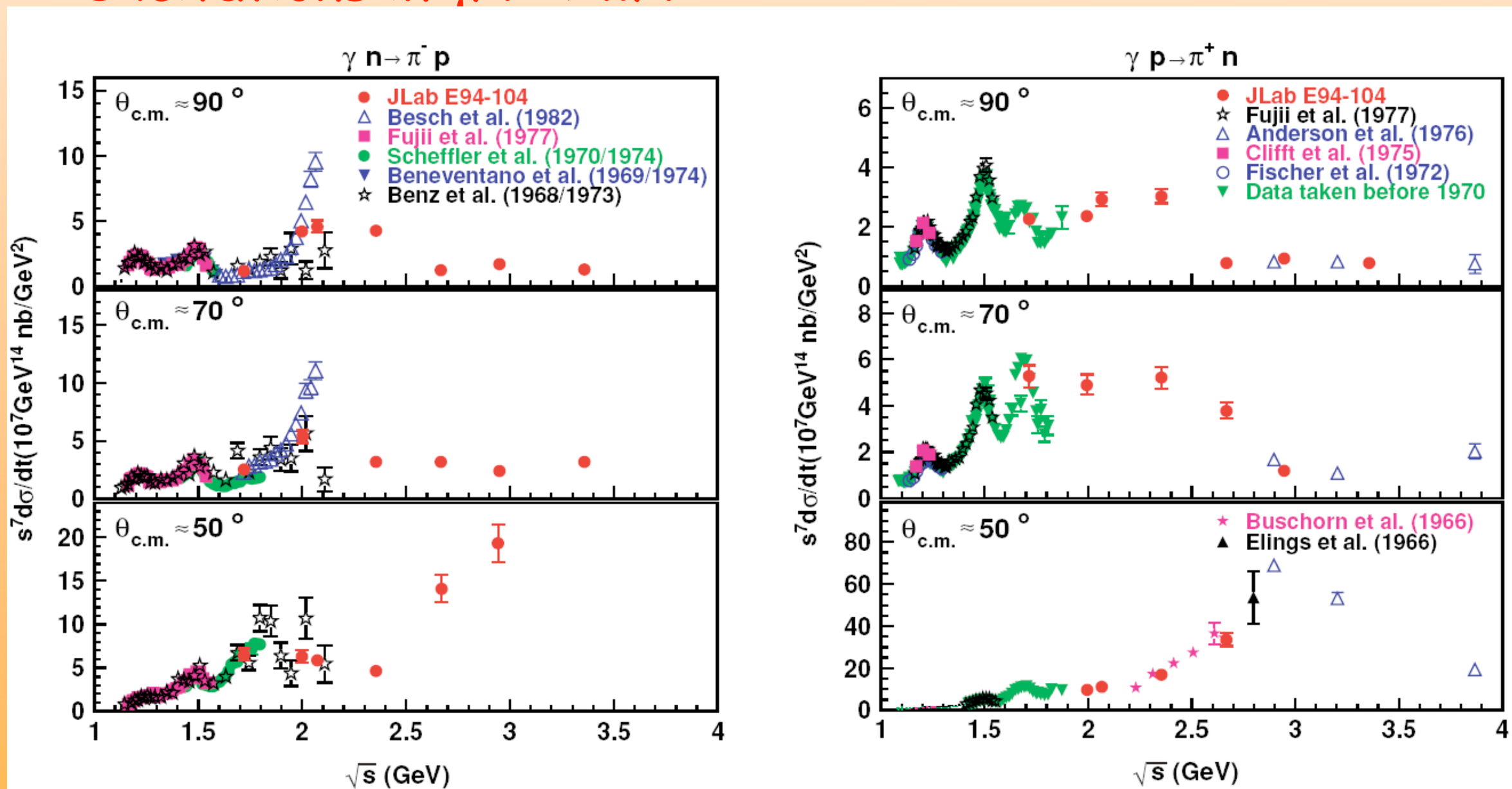
Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom in the Nucleon

- Many exclusive processes on nucleon targets show scaling already at moderate momentum transfer



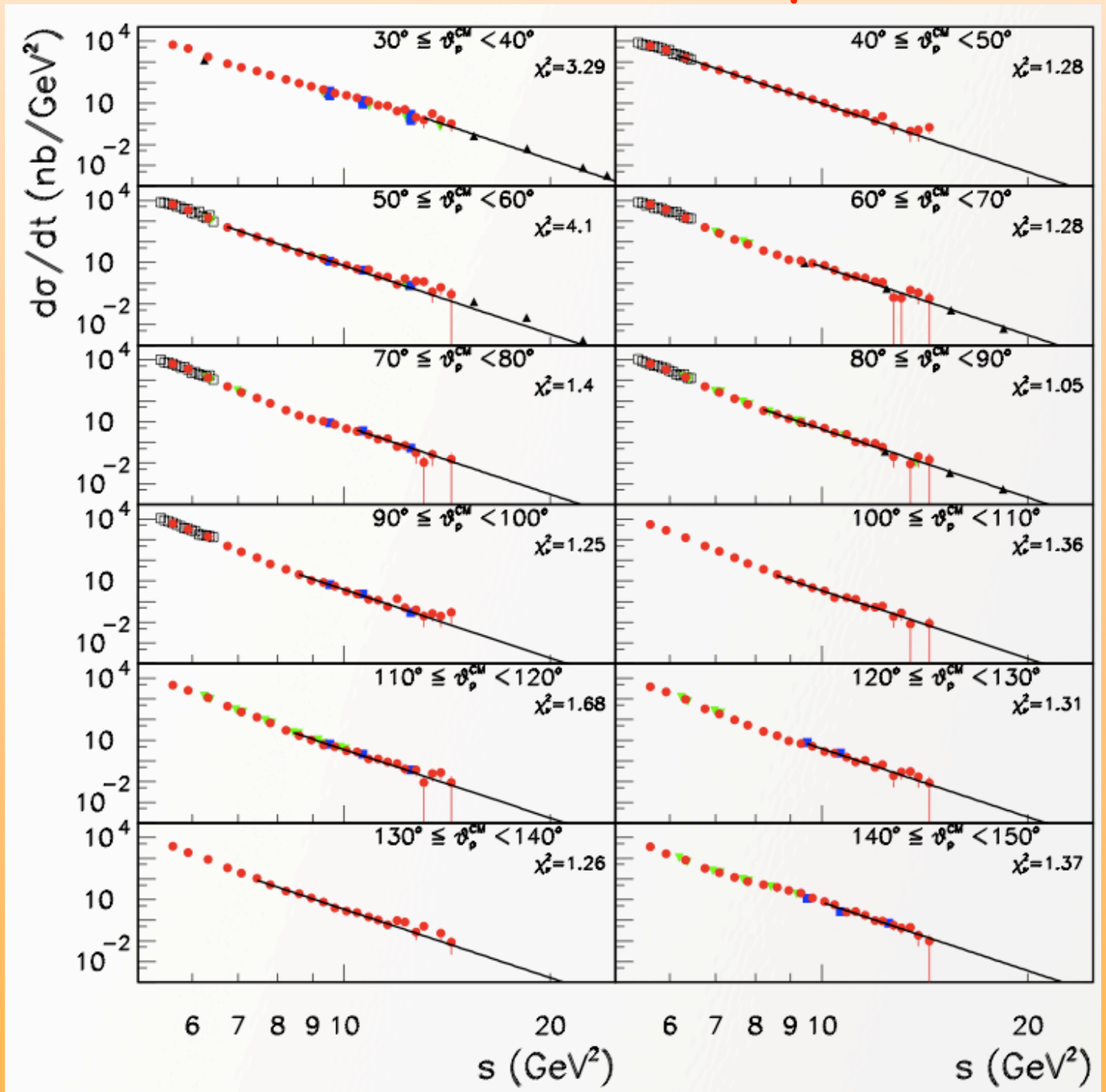
Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom in the Nucleon

Oscillating scaling: scale invariance broken by resonance excitations in $\gamma N \rightarrow \pi N$



Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom in the Nucleus

What about exclusive processes on nuclear targets?



Deuteron Photodisintegration

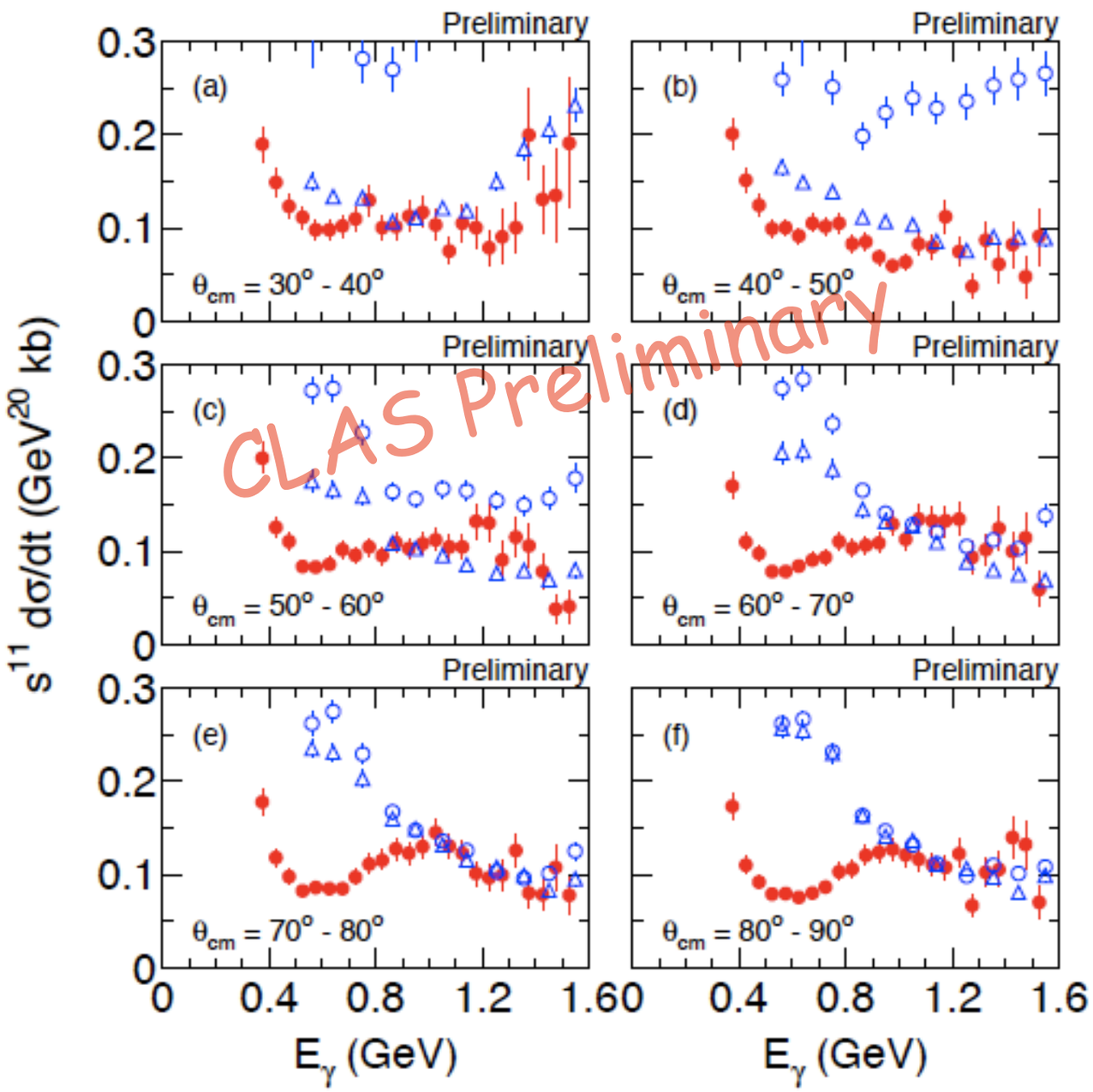
$$\frac{d\sigma}{dt} = \frac{1}{s^{11}} f(t/s)$$

- Fits of dσ/dt data at $p_T > 1.1$ GeV/c with As^{-11}
- All but two fits have $\chi^2 \leq 1.34$

P. Rossi et al., Phys. Rev. Lett. **94**, 012301 (2005)

Photodisintegration of a pp pair

What about exclusive processes on nuclear targets?



Mirazita *et al.*, Phys. Rev. C **70**, 014005 (2004)

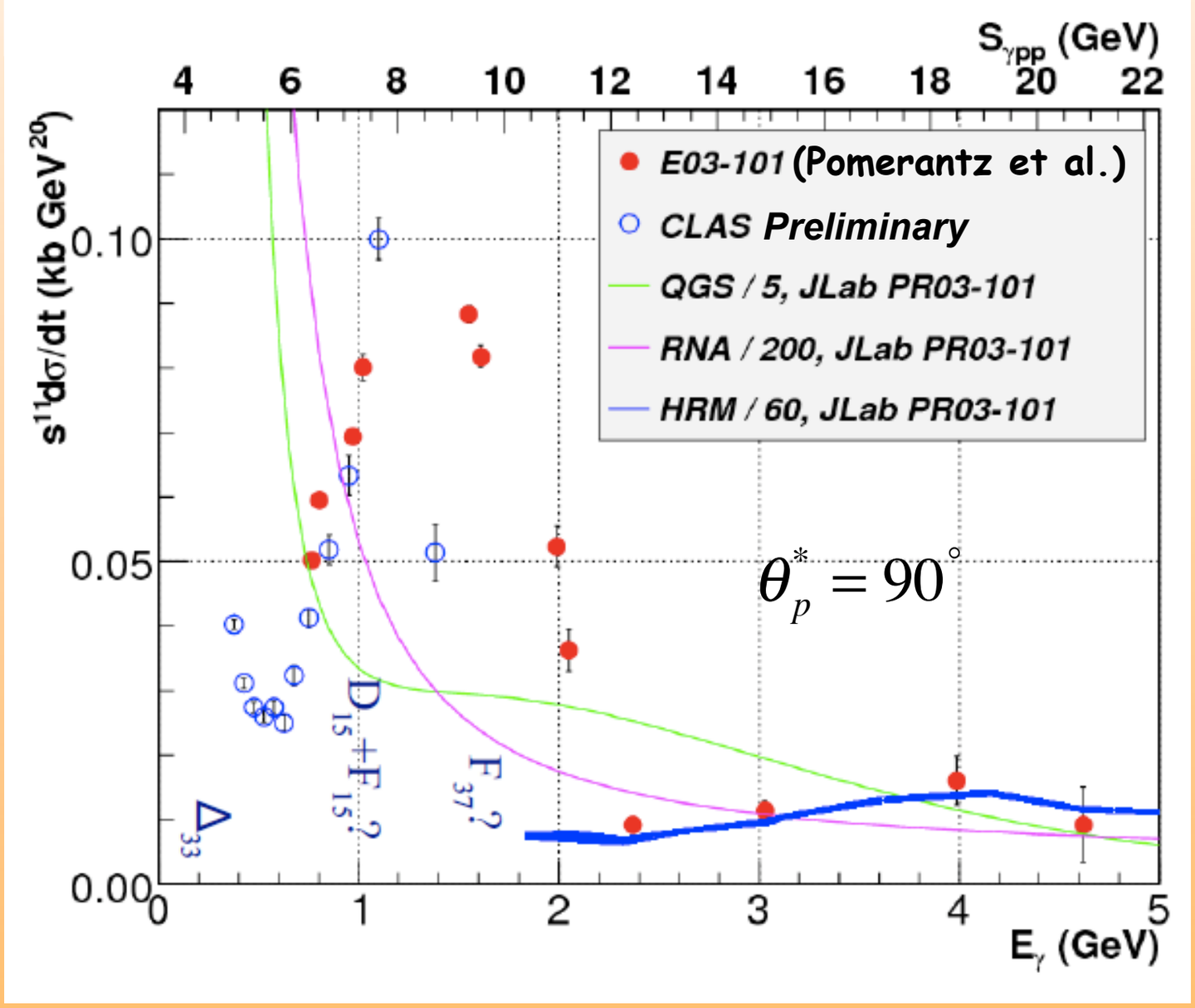
p_n < 0.25 GeV/c

- Cross section scales approximately as s^{-11}
- γ pp → p + p is symmetric about 90°
- Scaled deuteron photodisintegration (×1/4);
  ○ forward angles
  △ backward angles

Steffen Strauch, private communication, 2010

Photodisintegration of a pp pair

What about exclusive processes on nuclear targets?



$p_n < 0.1$ GeV/c

- Hall-A new data extend to higher energies.
- Hall-A and Hall-B data in very good agreement.
- Cross section scales as s^{-11} for $E_\gamma > 2$ GeV. Deuteron photodisintegration scales already at $E_\gamma > 1$ GeV.
- Large structure between 1 and 2 GeV. Not observed in deuteron photodisintegration.

I. Pomerantz et al., Phys. Lett. B **684**, 106 (2010)
Figure from R. Gilman, talk given at High-Energy Nuclear Physics and QCD, FIU, Miami, FL, 2010

Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom in the Nucleus

What about exclusive processes on nuclear targets?

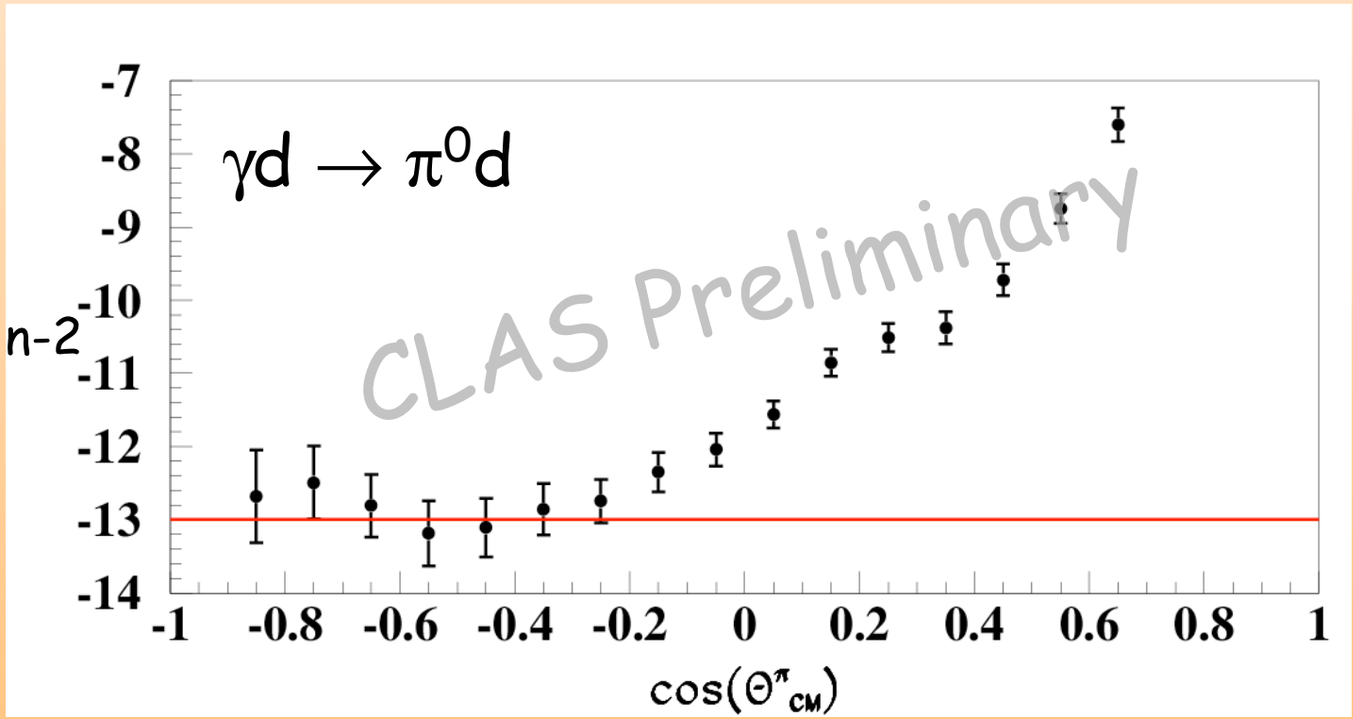
Coherent Pion Photoproduction off the Deuteron

$$\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s)$$

CCR Predict n-2=-13

Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom in the Nucleus

What about exclusive processes on nuclear targets?



Coherent Pion Photoproduction off the Deuteron

$$\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s)$$

CCR Predict n-2=-13

- CLAS data generally consistent with scaling for $\cos\theta_\pi < -0.25$. This is consistent with previous results.

Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom in the Nucleus

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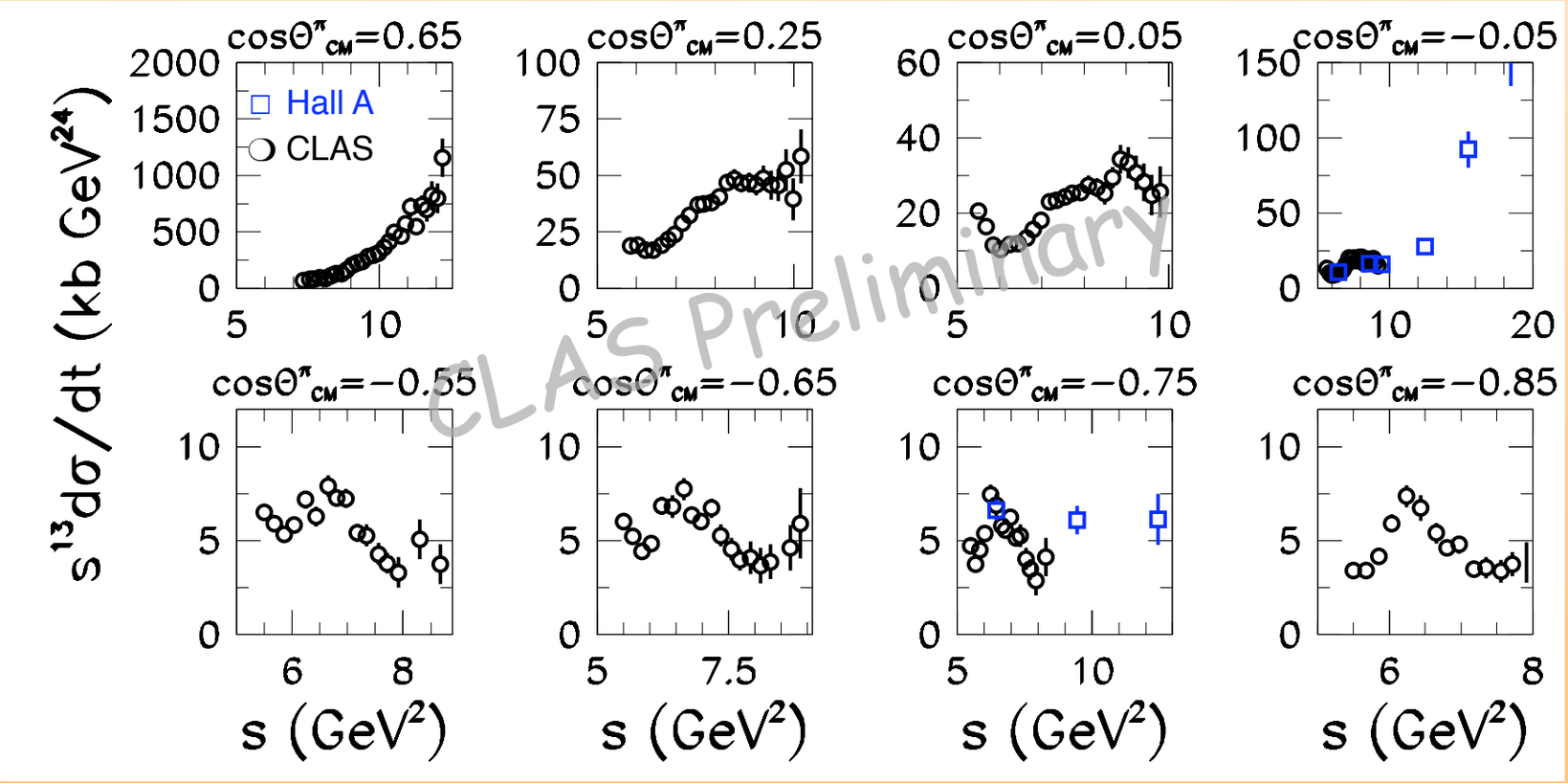

$\gamma d \rightarrow \pi^0 d$

$$\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s)$$

CCR Predict n-2=-13

Meekins et al., Phys. Rev. C **60**, 052201 (1999)

Transition from Meson-Nucleon to Quark-Gluon Degrees of Freedom in the Nucleus

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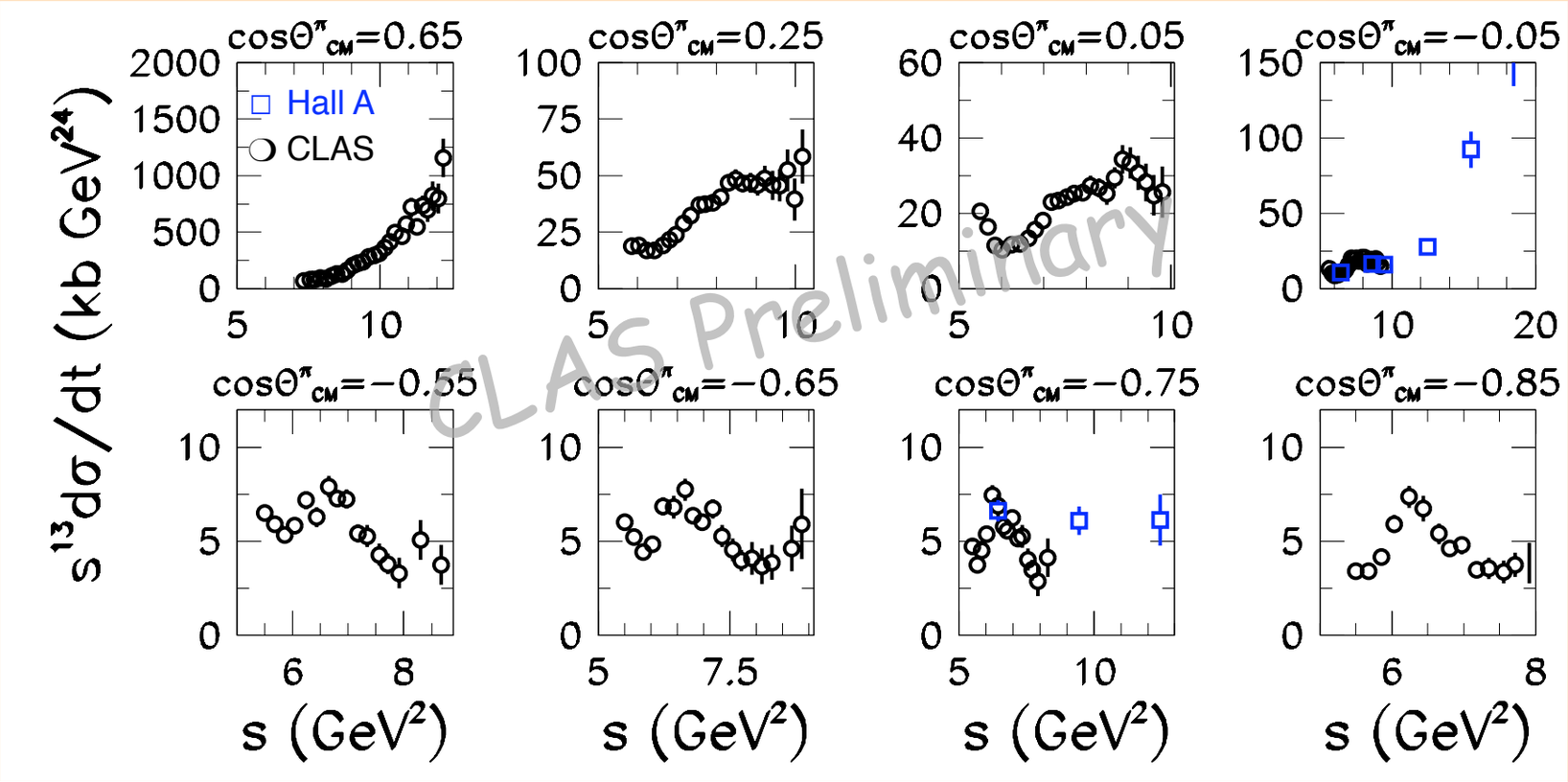


$\gamma d \rightarrow \pi^0 d$

$$\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s)$$

CCR Predict n-2=-13

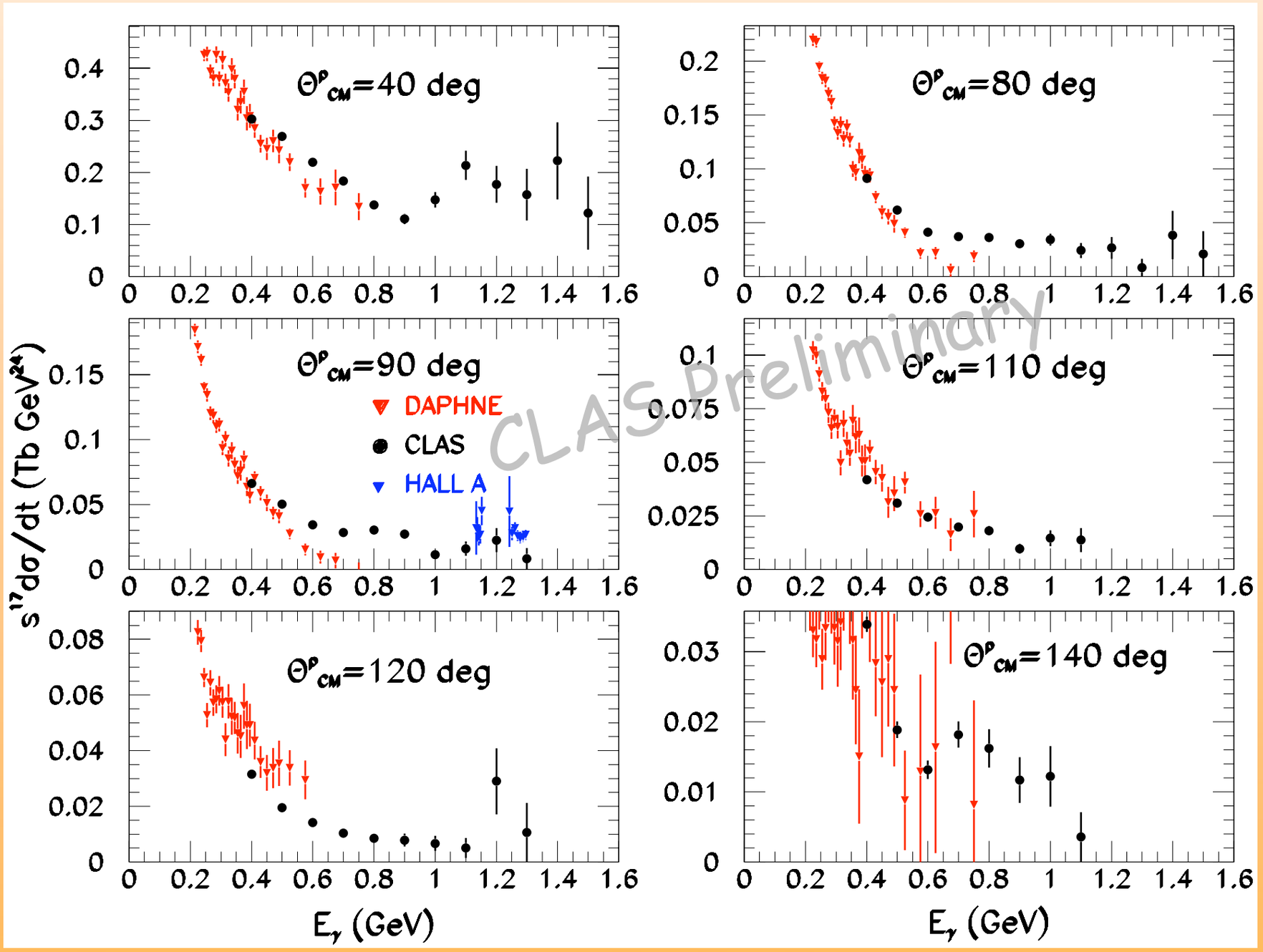
- Oscillating scaling: scale invariance broken by non-perturbative rescattering subprocesses in $\gamma d \rightarrow \pi^0 d$.

Meekins et al., Phys. Rev. C **60**, 052201 (1999)

Two-Body Photodisintegration of ^{3}He

Scaling of invariant cross sections

$$\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s)$$



- CCR Predict n-2=-17
- Indication that above ~0.7 GeV data consistent with scale invariance for all CM angles
- $p_{\perp,d} > 0.65$ GeV/c and large range of |t|

V. Isbert et al., Nucl. Phys. A **578**, 525 (1994)

I. Pomerantz et al., private communication (2010)

Conclusions

- Indication for Short-Range Tensor Correlations in e ^{3}He→e'ppn
- Two-Body Mechanisms in Photodisintegration of ^{3}He and ^{4}He
  - measured differential cross sections for E_γ = 0.4 - 1.4 GeV and θ^*_p = 40° - 140°.
  - established optimum kinematic range to probe three-body dynamics in photoreactions on ^{3}He and ^{4}He
- Transition from meson-nucleon to quark-gluon df
  - γ pp(n)$_s$→pp(n)$_s$
    - at 90 deg, CCR scaling for E_γ > 2 GeV.
    - scale invariance is broken below E_γ of 2 GeV
  - γ d→π^0d
    - oscillating CCR scaling at cos θ^*_π < -0.25
    - oscillations mostly due to re-scattering mechanisms
  - γ ^{3}He→pd
    - data consistent with scale invariance for E_γ > 0.7 GeV
  - γ ^{4}He→pt
    - no evidence for CCR scaling