High precision measurement of phi-nucleon cross-section and tensor asymmetry with a tensor polarized deuteron target

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Jefferson Lab

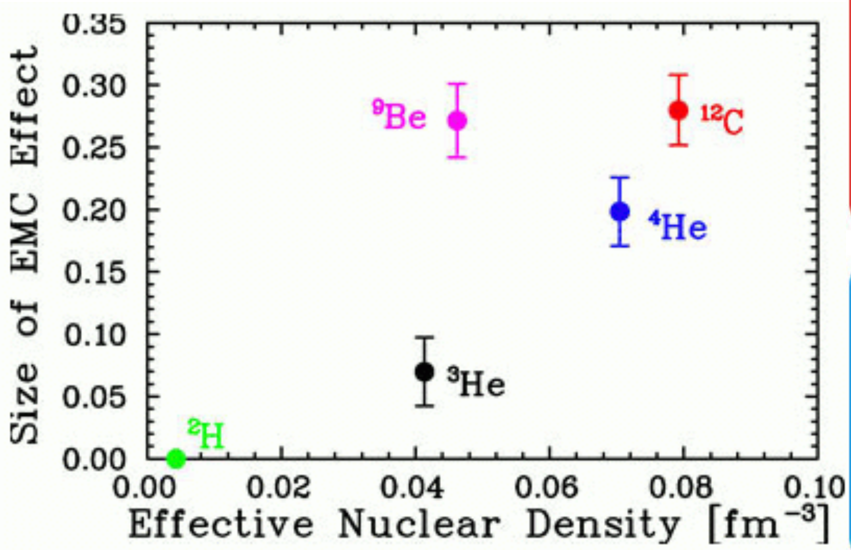
GlueX

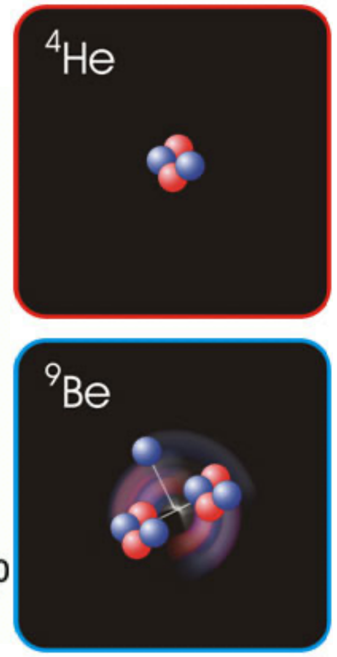
GlueX Acknowledgements: gluex.org/thanks

Hadronic Interactions with Nuclear Medium

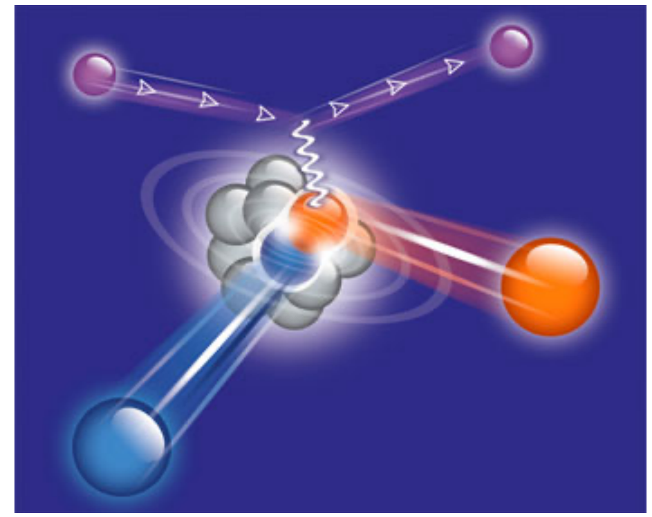
Cold QCD matter

EMC Effect





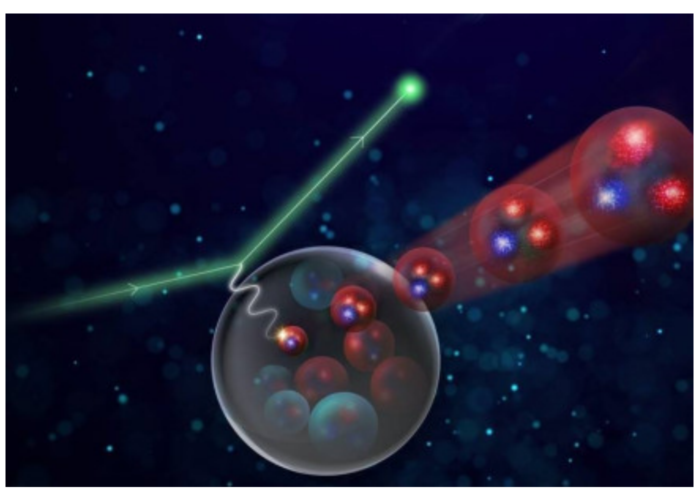
Short Range Configurations



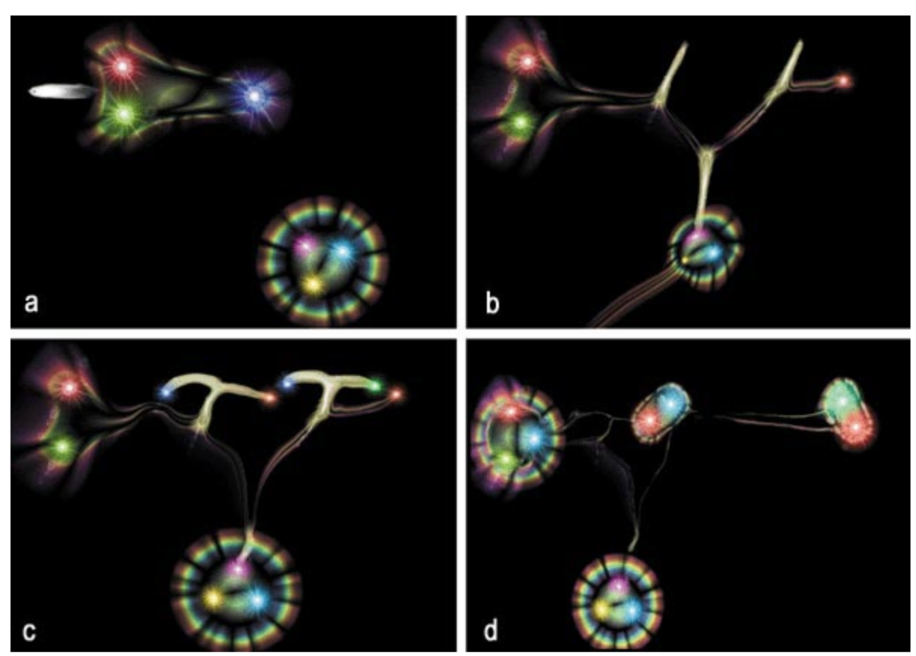
Medium Modifications

- Particle masses
- Particle widths
- Fragmentation functions
- Form factors
- …

Color Transparency



hadronization in medium

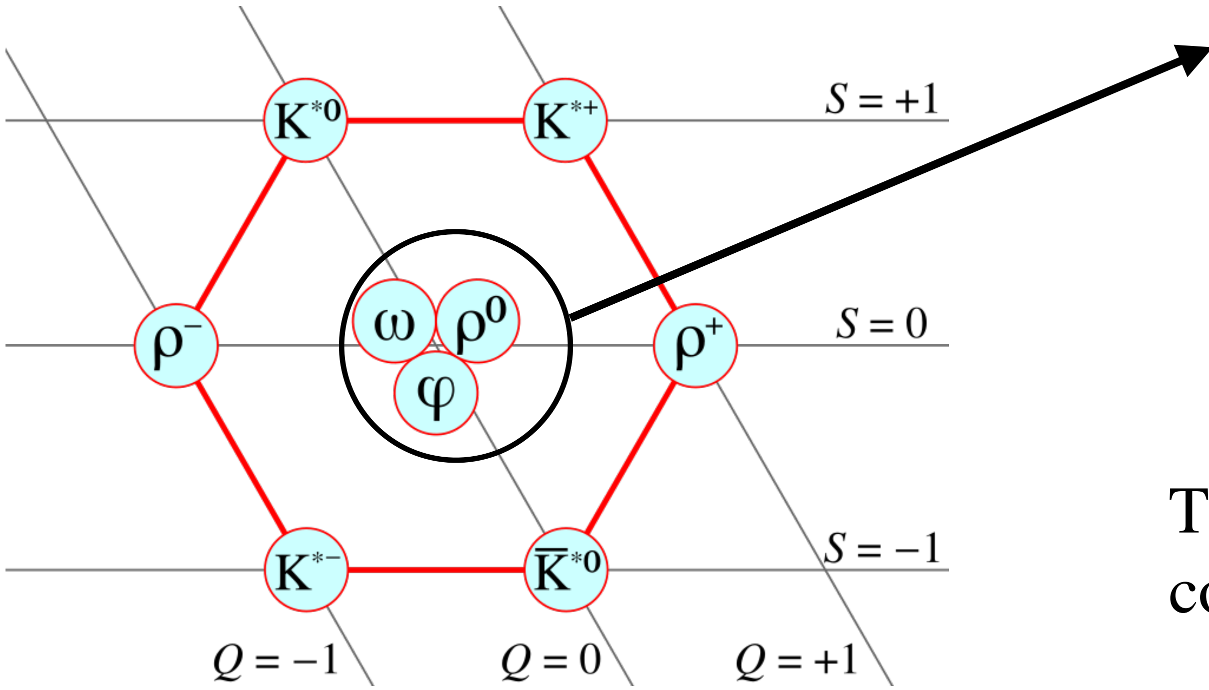


What is the cross section for $\phi N \to \phi N$?

Does it change in medium?

$\phi - N$ interaction

nonet of vector mesons



$J^{PC} = 1^{--}$, $Q = B = S = 0$

same quantum numbers as the photon

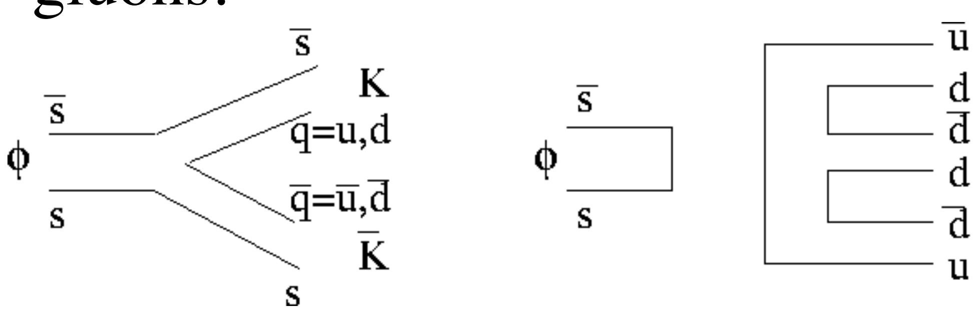
$$\rho = (u\bar{u} - d\bar{d})/\sqrt{2}$$
$$\omega \approx (u\bar{u} + d\bar{d})$$
$$\phi \approx s\bar{s}$$

Vector Meson Dominance (VMD) model

The hadronic components of the physical photon consist of the lightest vector mesons ρ, ω and ϕ.

OZI rule

A decay is suppressed if initial and final states only connected by gluons.

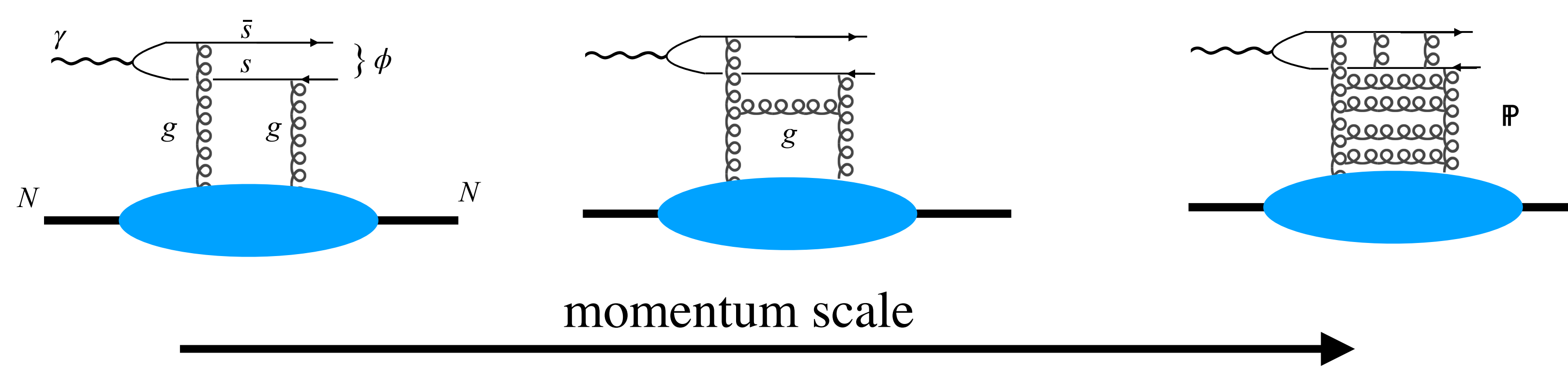


$$\frac{g^2_{\phi\rho\pi}}{g^2_{\omega\rho\pi}} = \frac{g^2_{\phi NN}}{g^2_{\omega NN}} \stackrel{?}{=} \tan^2 \delta V = 0.0042$$

Suggests that $\phi - N$ interaction will also be suppressed.

Quark interchange between ϕ and nucleon suppressed.

Multi-gluon (pomeron) exchange dominates at all energies.



$\phi - N$ cross section in free space

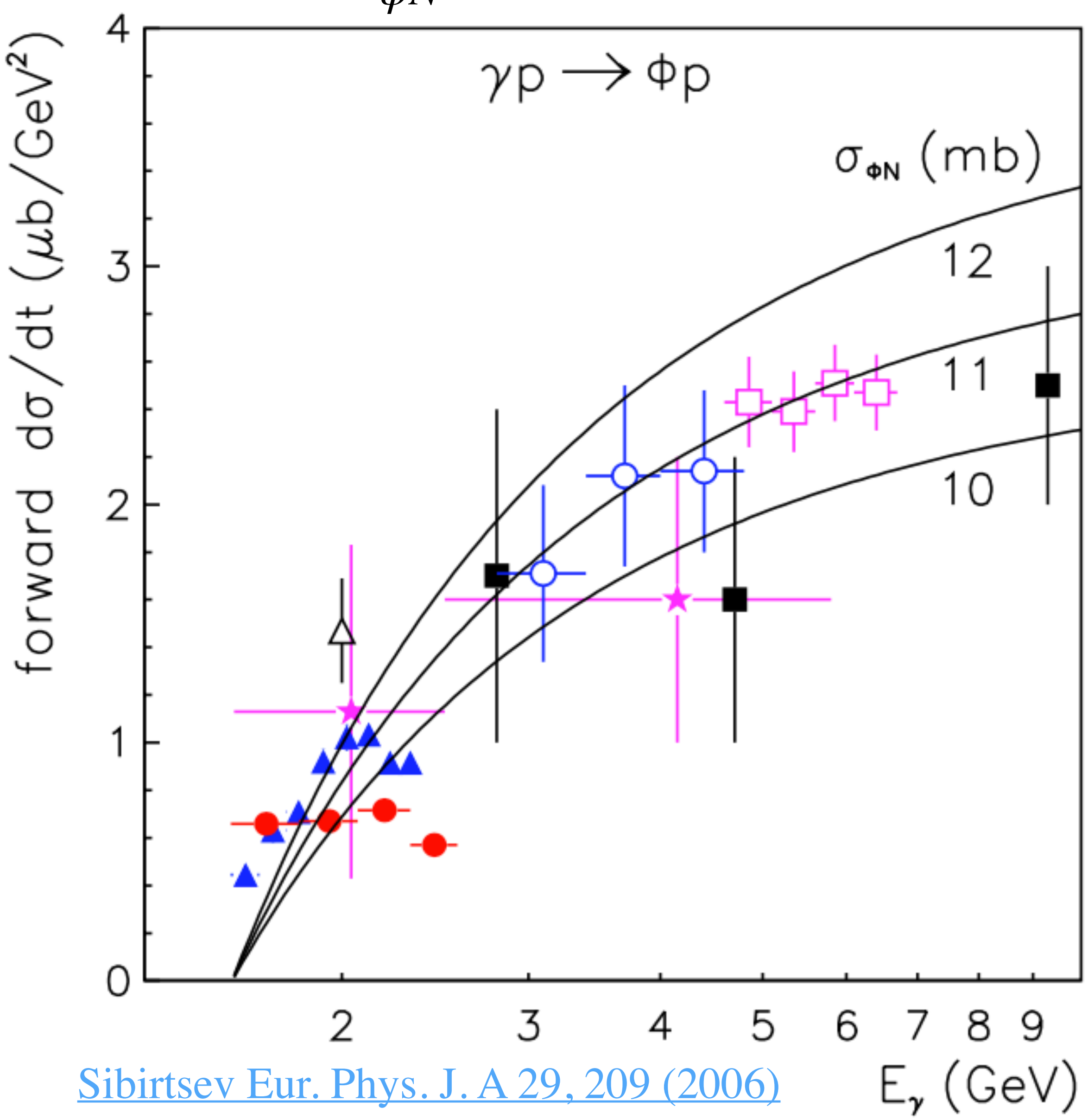
Studying hadronic interactions of unstable particles is difficult.

$$\phi N \to \phi N$$

$$\gamma p \to \phi p$$

using vector meson dominance

$$\sigma_{\phi N} \simeq 10 - 12 \text{ mb}$$



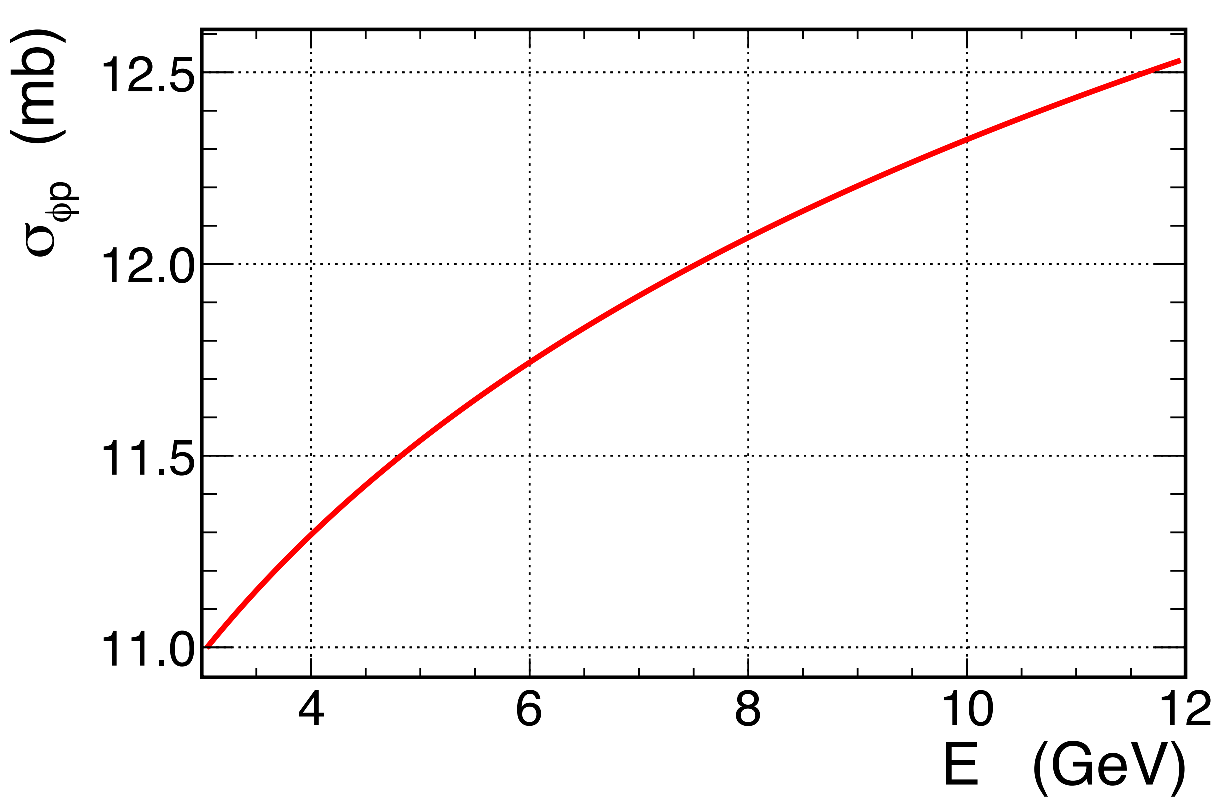
Sibirtsev Eur. Phys. J. A 29, 209 (2006)

Muhlich Nucl. Phys. A 765, 188 (2006)

Additive quark model

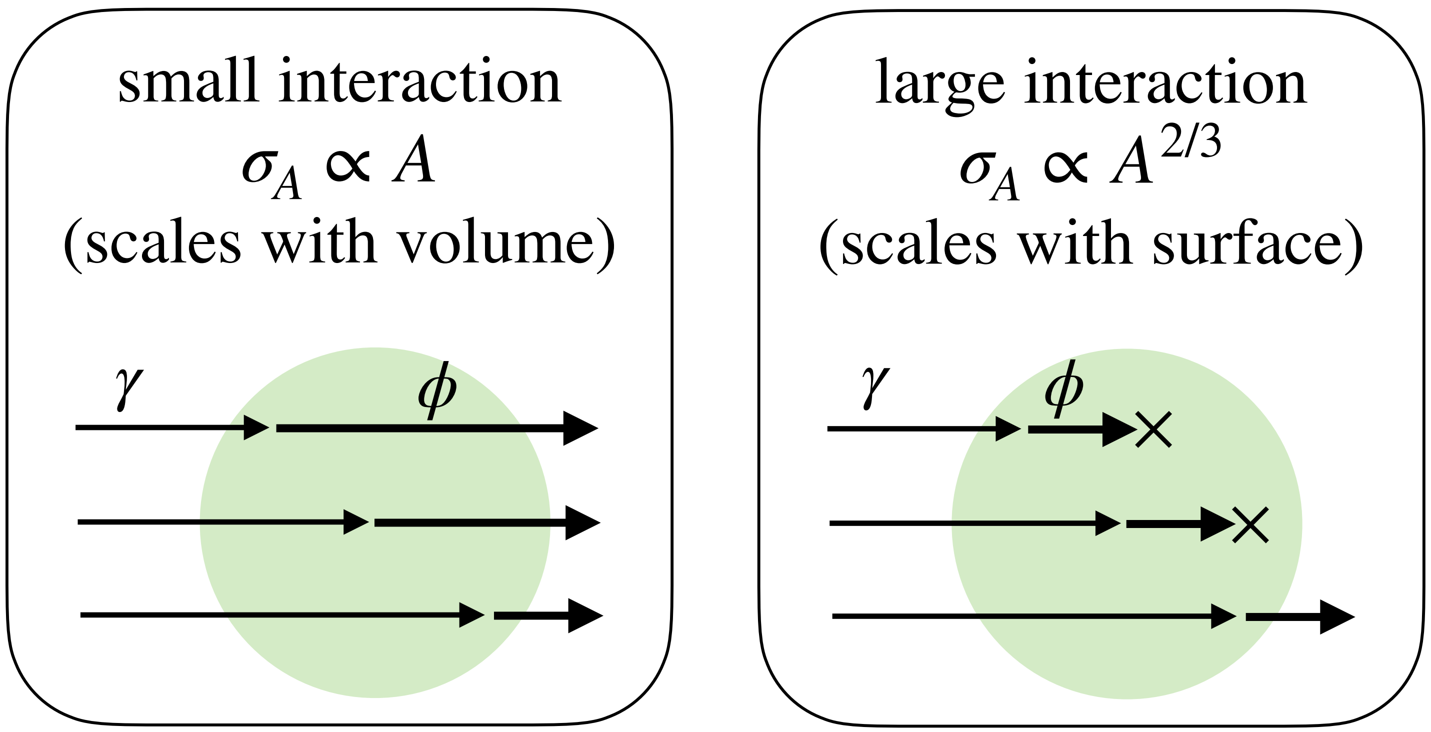
$$\sigma_{\phi p} \simeq \sigma_{K^+p} + \sigma_{K^-p} - \sigma_{\pi^+p}$$

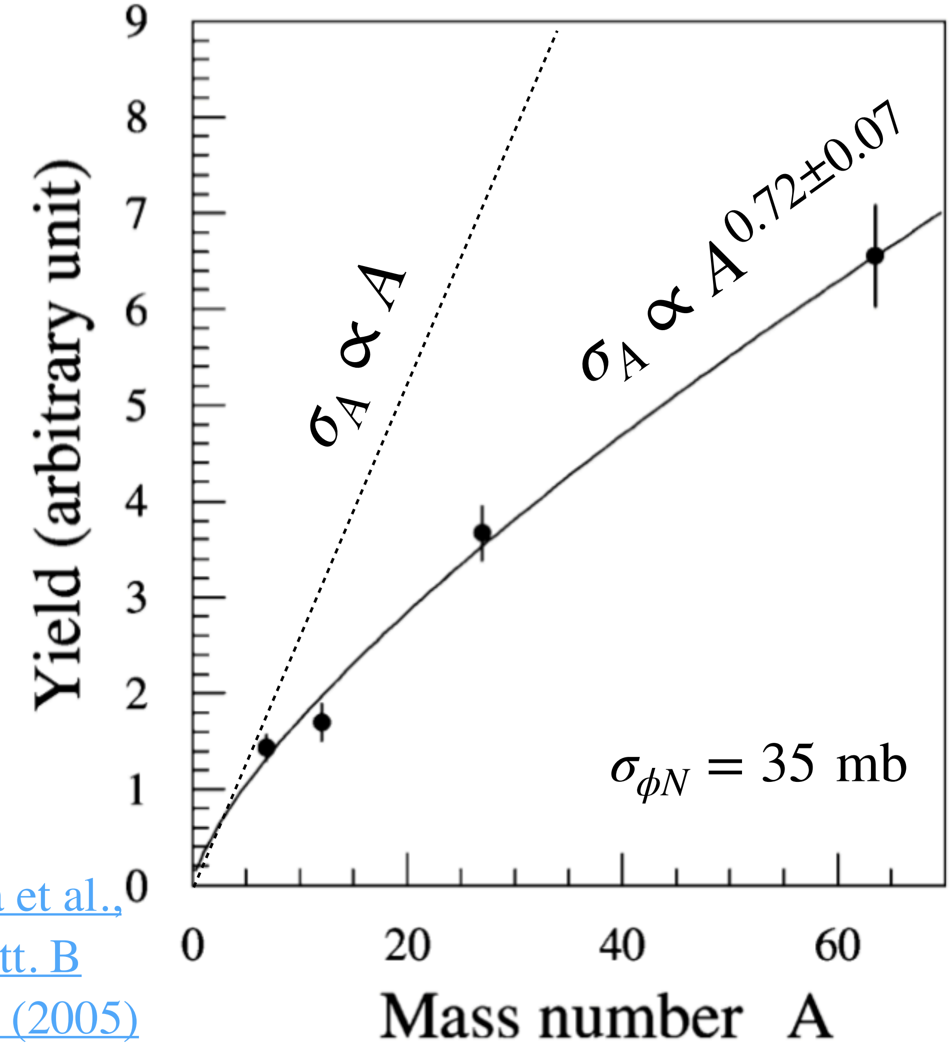
$$\sigma_{\phi p} \simeq (10s^{0.0808} - 1.52s^{-0.4525}) \text{ mb}$$



$\phi - N$ cross section in nuclei

Study scaling of ϕ with mass number A.
Too few ϕ detected $\Longrightarrow$ ϕ absorbed $\Longrightarrow$ large cross section for rescattering or absorption

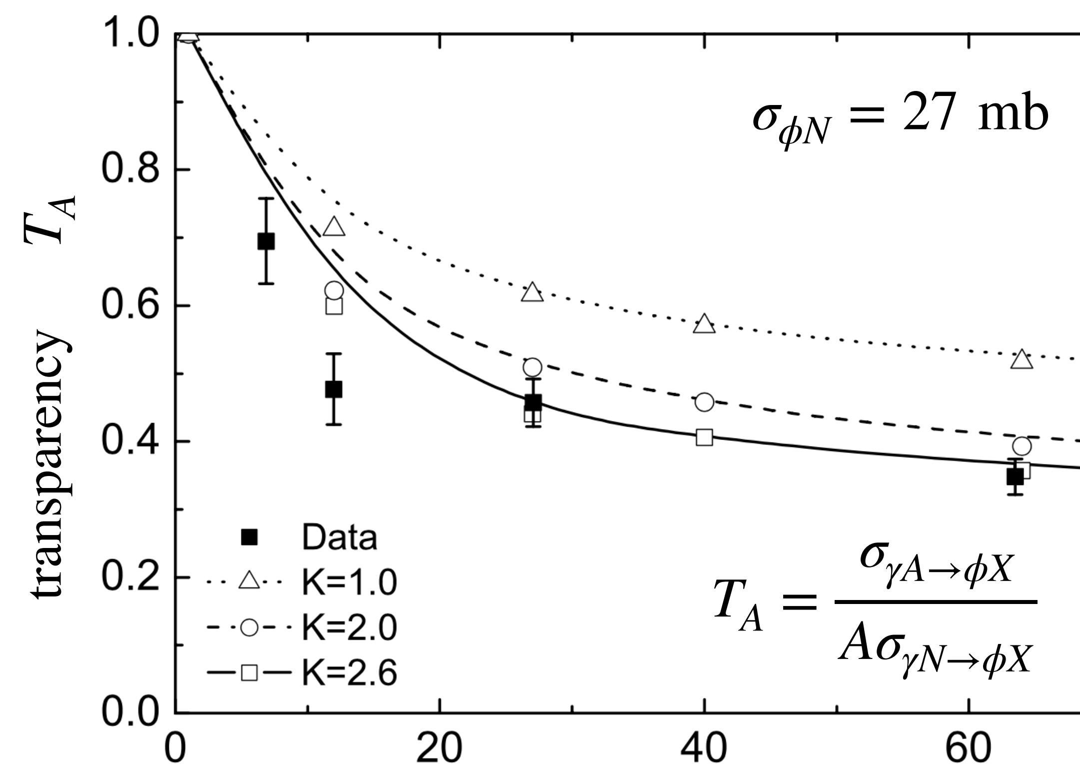




Ishikawa et al., Phys. Lett. B 608, 215 (2005)

Sophisticated models need $\sigma_{\phi N} \simeq 30$ mb

semi-classical BUU transport model with coupled-channel final state dynamics, Fermi motion, Pauli blocking, shadowing, elastic and inelastic scattering including sidefeeding and regeneration of all produced particles, decays of unstable particles, collisional broadening, kaon self energies.



Muhlich Nucl. Phys. A 765, 188 (2006)

Potential Explanations

coupled channel effect (2 step process):
$\gamma N \rightarrow \omega N$ followed by $\omega N \rightarrow \phi N$ OR
$\gamma N \rightarrow \pi N$ followed by $\pi N \rightarrow \phi N$
no absolute cross sections and no t-slopes available $\Longrightarrow$ more data needed

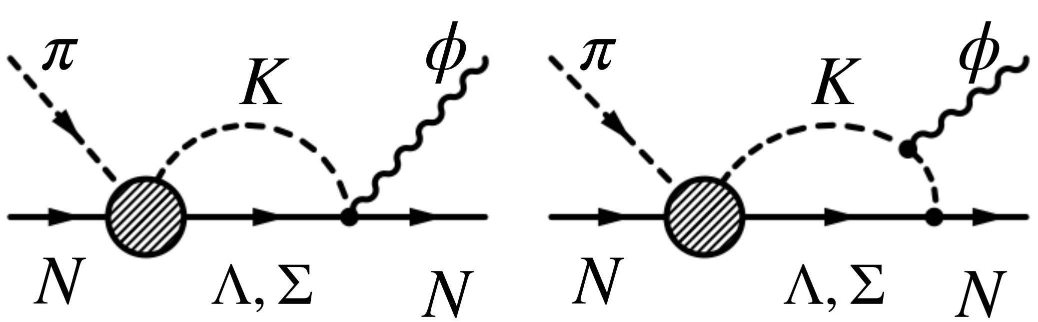
Sibirtsev Eur. Phys. J. A 29, 209 (2006)

$\phi - N$ bound state in the nucleus?

QCD van der Waals attractive potential

Gao et al. PRC 63, 022201 (2000)

Box diagrams with open strangeness



Doring et al. PRC78, 025207 (2008)

Cryptoexotic baryon B_ϕ

🤔

Sibirtsev Eur. Phys. J. A 29, 209 (2006)

ϕ is modified in nucleus but ρ, ω are not.

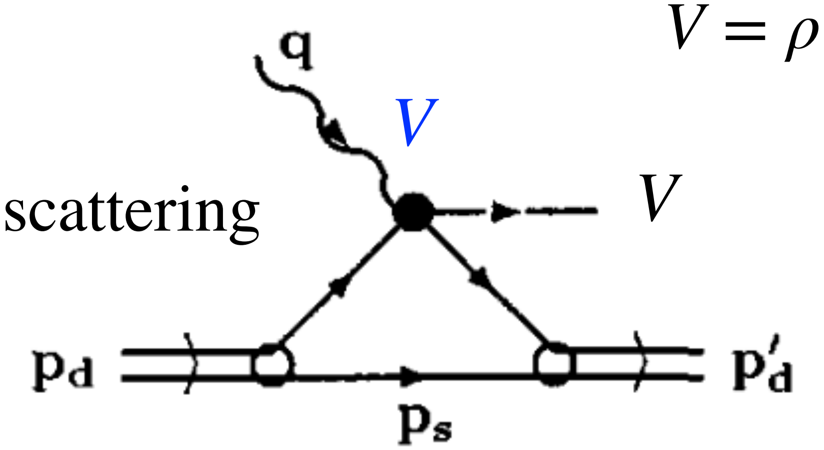
ϕ is created as a $s\bar{s}$ point-like configuration, which transitions into ϕ as eigenstate of QCD Hamiltonian.

Enter the deuteron $\gamma d \to Vd$

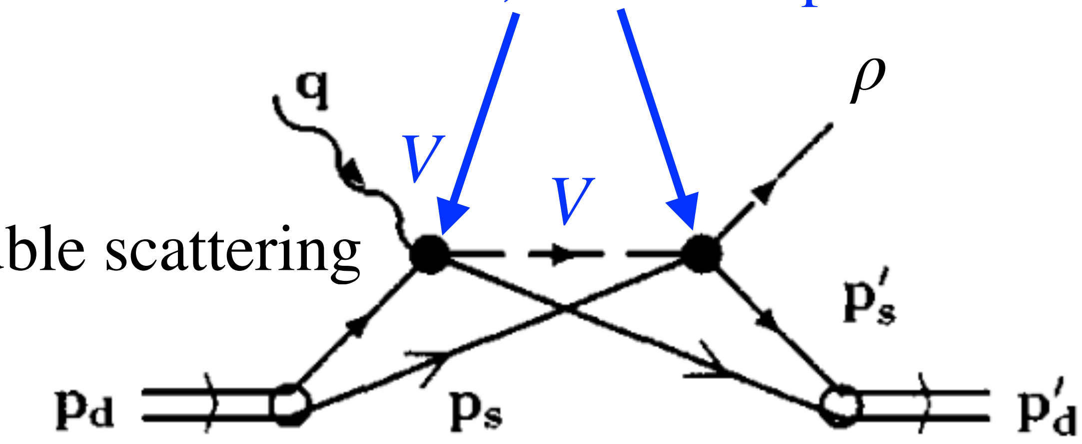
VMD: same cross section, same t-slope

$V = \rho, \omega, \phi$

single scattering



double scattering

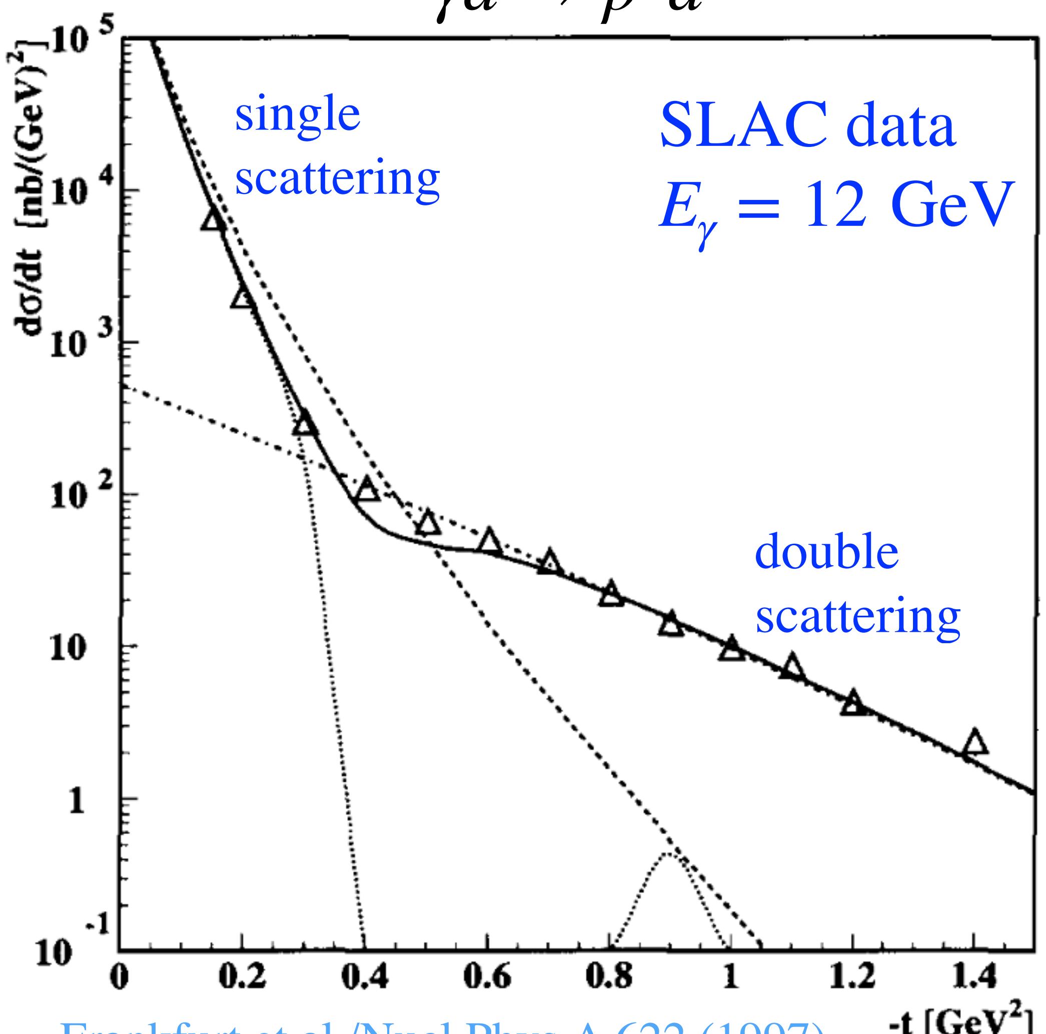


Double scattering contains information about the initially produced ejectile and its evolution through the target.

single scattering
- full momentum transferred to single nucleon → steep t-slope

double scattering:
- ≈½ momentum transferred to each nucleon → shallower effective t-slope (dominates at high-t, low rate)

$\gamma d \to \rho^0 d$



Frankfurt et al./Nucl.Phys.A 622 (1997)

Model of coherent vector meson photoproduction

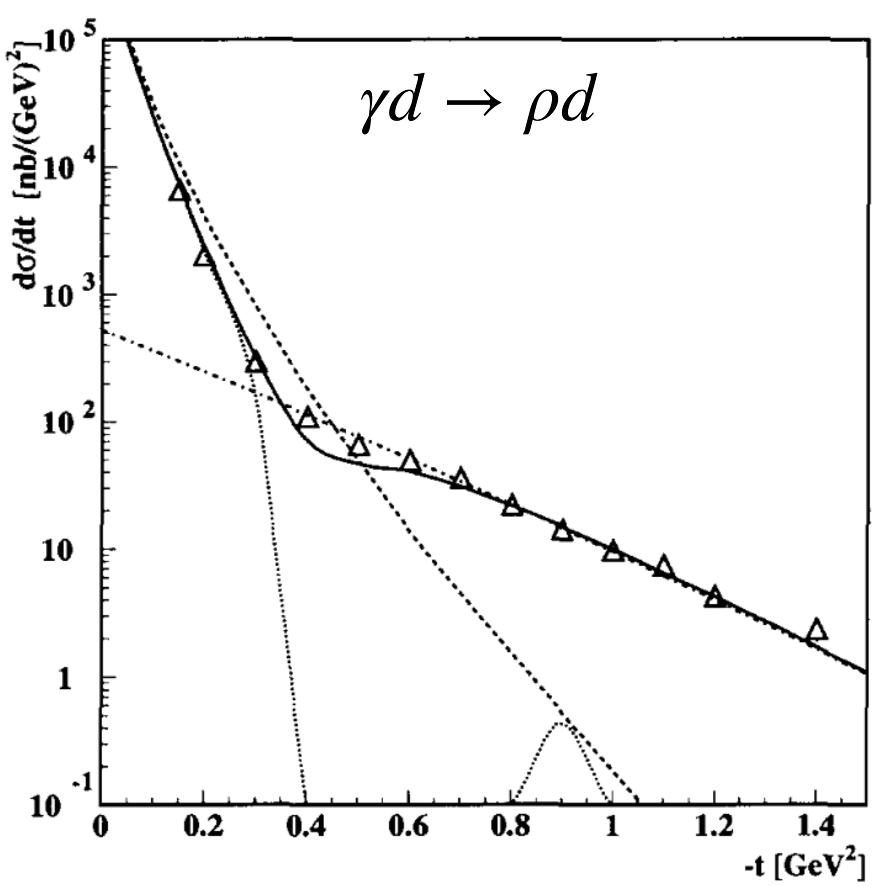
Model of single and double scattering describes the differential cross sections for ρ, ω and ϕ

Frankfurt et al./Nucl.Phys.A 622 (1997)

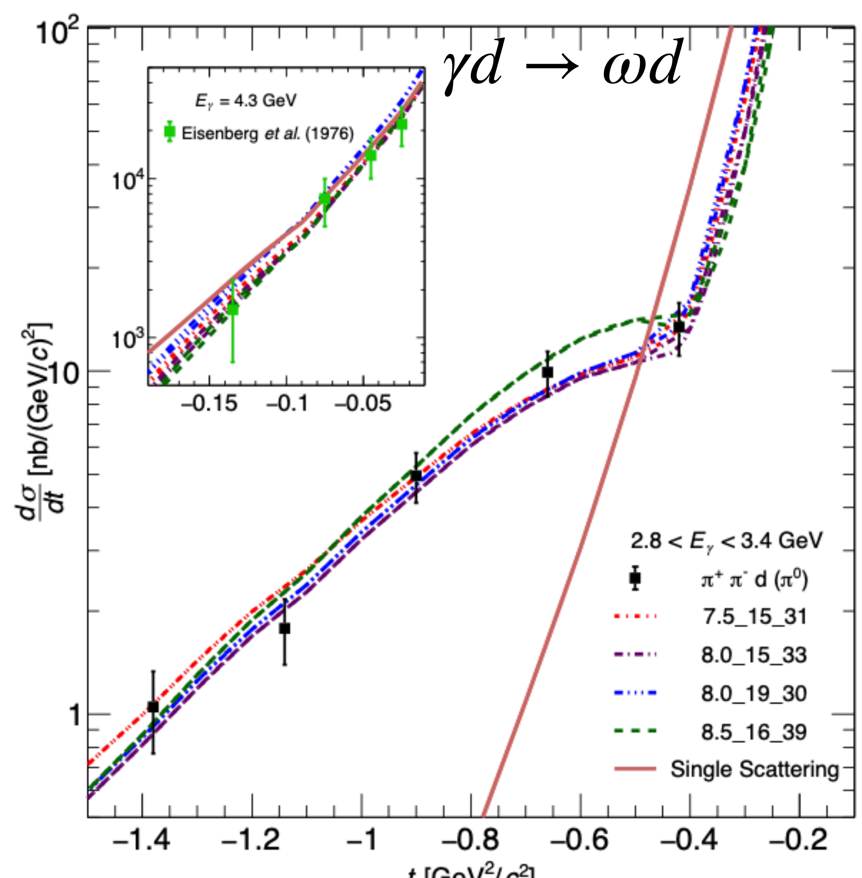
Very standard ingredients

- Glauber theory with relativistic/recoil corrections,
- hadronic structure of the photon (vector meson dominance),
- Paris Potential for deuteron structure,
- longitudinal interaction length of the photon l_c.

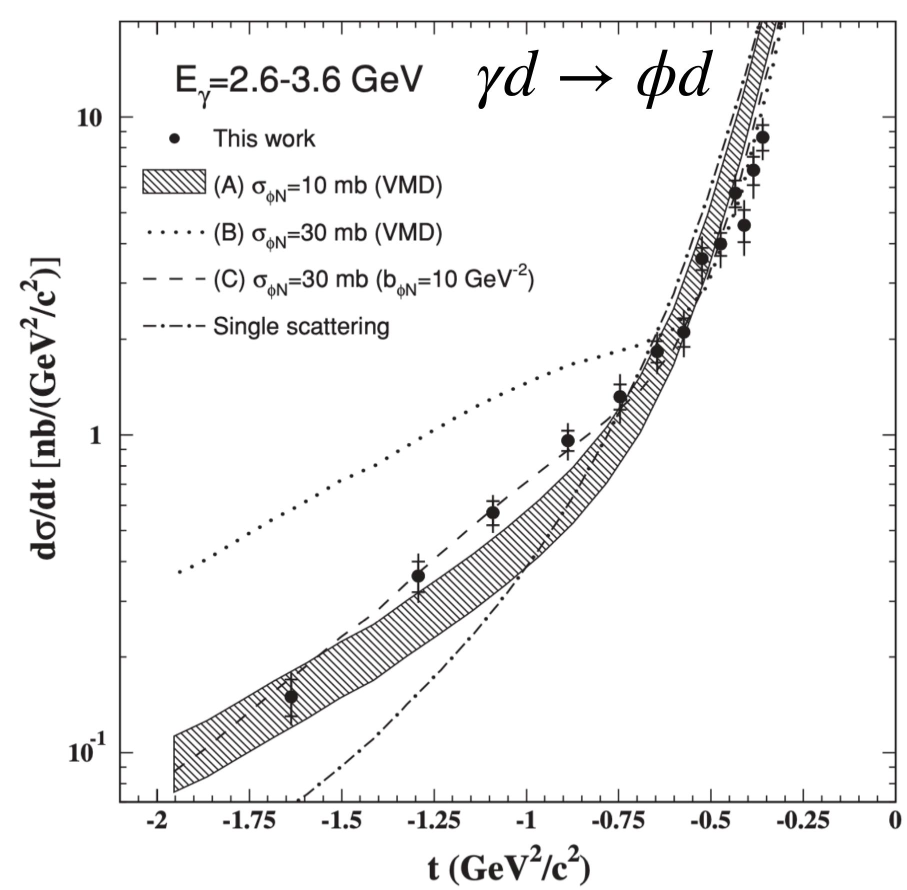
All of ρ, ω and ϕ provide interesting systems for study.



Frankfurt et al./Nucl.Phys.A 622 (1997)

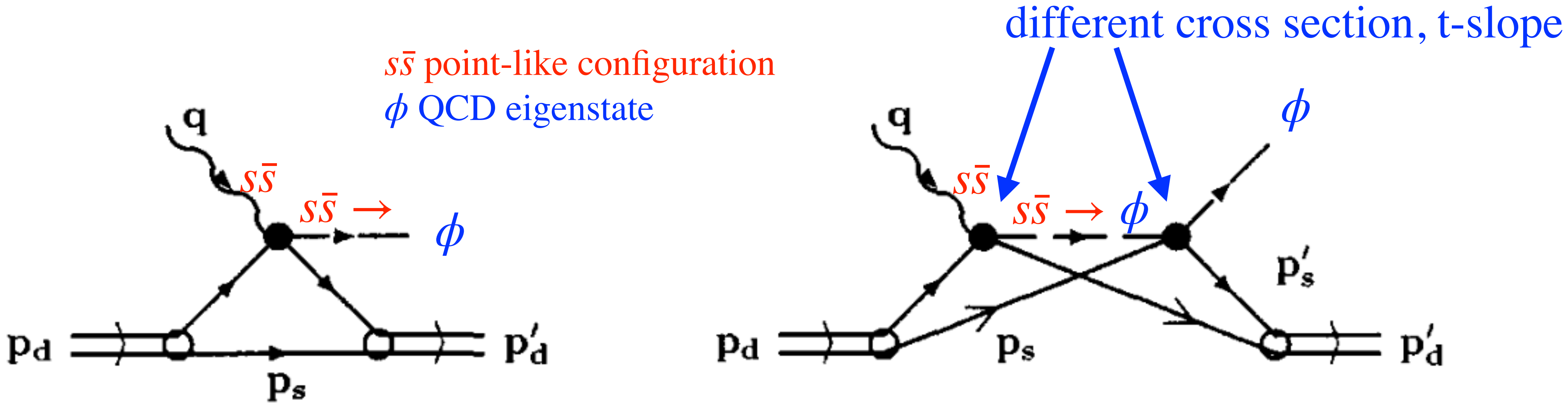


Chetry Physics Letters B 782 2018



Mibe Phys. Rev. C 76, 052202 2007

Measurement of $\phi - N$ cross section $\sigma_{\phi N}$

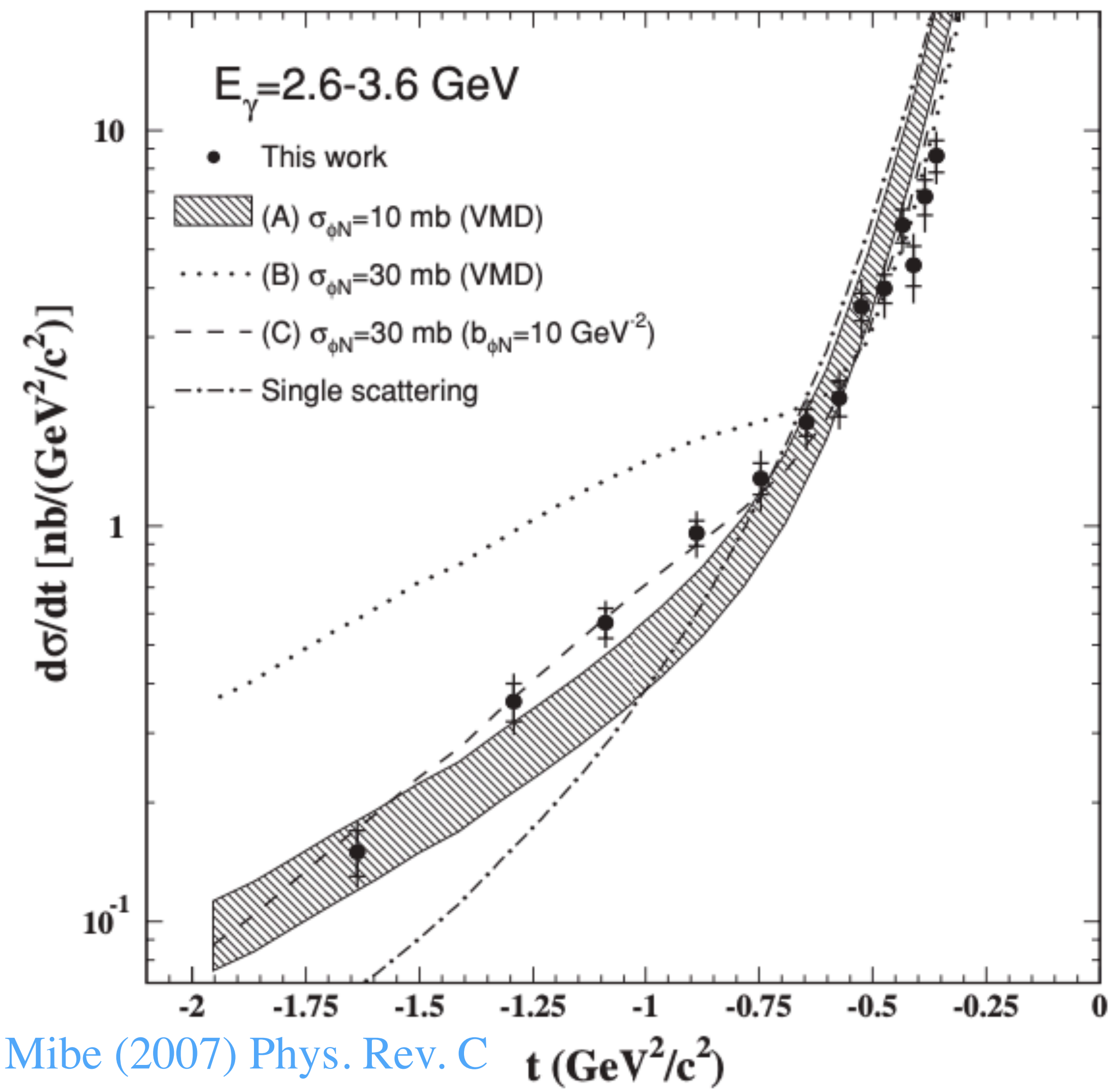


attenuation of ϕ photoproduction off heavy nuclei
$\Longrightarrow \sigma_{\phi N} \simeq 30$ mb

exclusive ϕ photoproduction analyzed with
vector meson dominance $\Longrightarrow \sigma_{\phi N} \simeq 10$ mb

CLAS data ambiguous depending on analysis method.
consistent with $\sigma_{\phi N} \simeq 10$ mb using VMD
consistent with $\sigma_{\phi N} \simeq 30$ mb if t-slope larger

Tensor polarization of the deuterium will provide a handle to disambiguate $\sigma_{\phi N}$ puzzle.



T. Mibe (2007) Phys. Rev. C

Tensor Polarization

Spin-1 in a magnetic field
Zeeman splitting results in 3 energy levels
$m = -1, 0, +1$

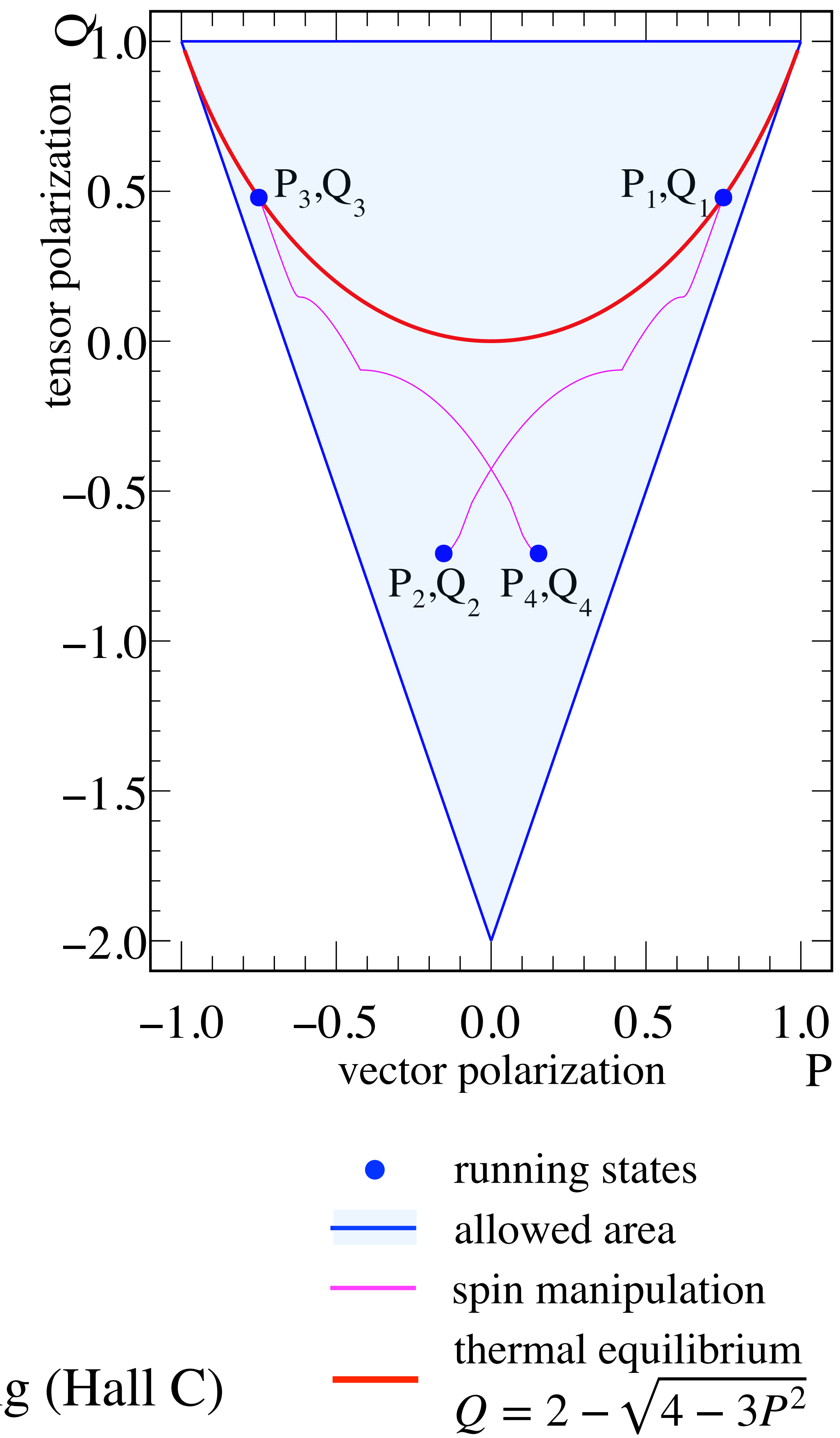
$N_+ + N_- + N_0 = 1$

Vector Polarization
$P = N_+ - N_-$
$-1 \leq P \leq +1$

Tensor Polarization (Alignment)
$Q = 1 - 3N_0$
$-2 \leq Q \leq +1$

$Q_+ = Q_1 = Q_3$
$Q_- = Q_2 = Q_4$

At thermal equilibrium
$Q = 2 - \sqrt{4 - 3P^2}$



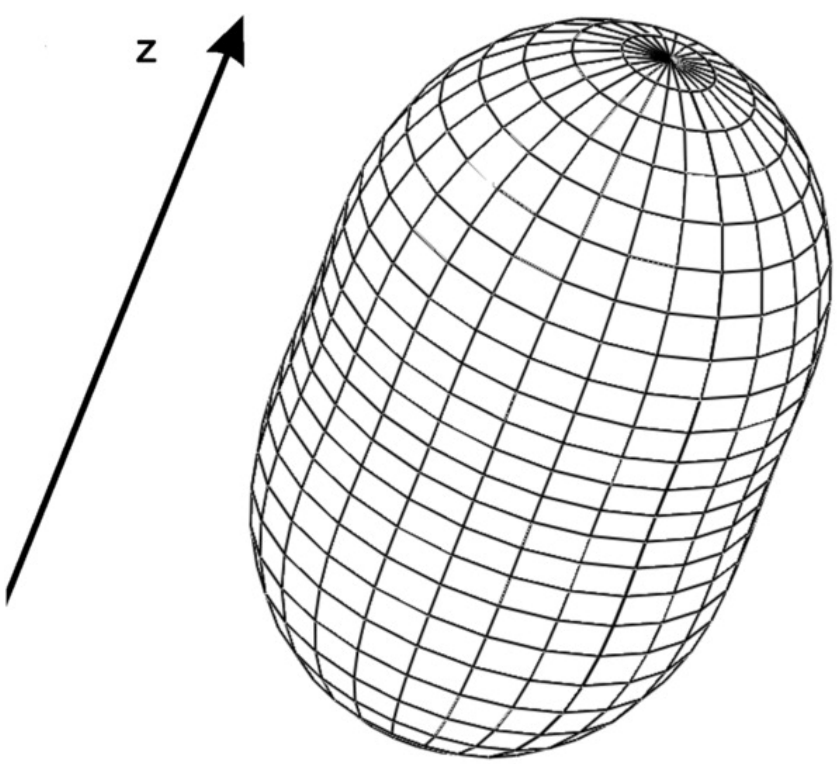
Tensor polarization: 2 approved experiments at JLab.
E12-13-011 b_1 structure function (Hall C)
E12-15-005 t_{20} form factor and A_{zz} in quasi-elastic scattering (Hall C)

Tensor Polarization

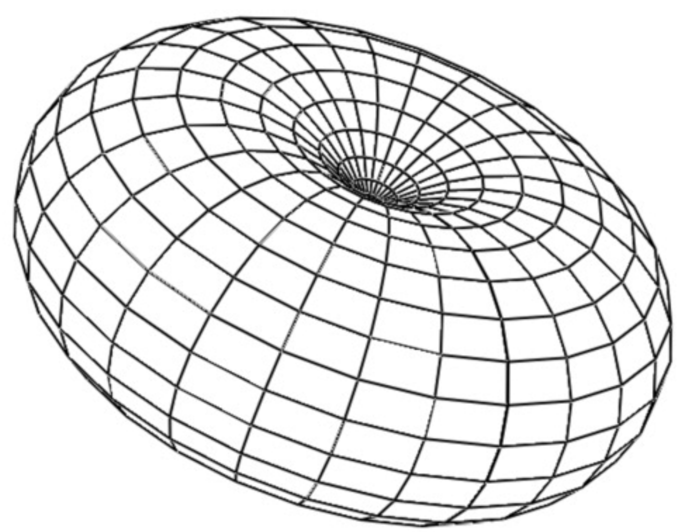
Deuteron spin states have different spatial density distributions

- Change the amount of material traversed by the ϕ. 👋👋👋
- Changes the relative orientation of nucleons and the likelihood of hitting both and leaving deuteron intact. 👋👋

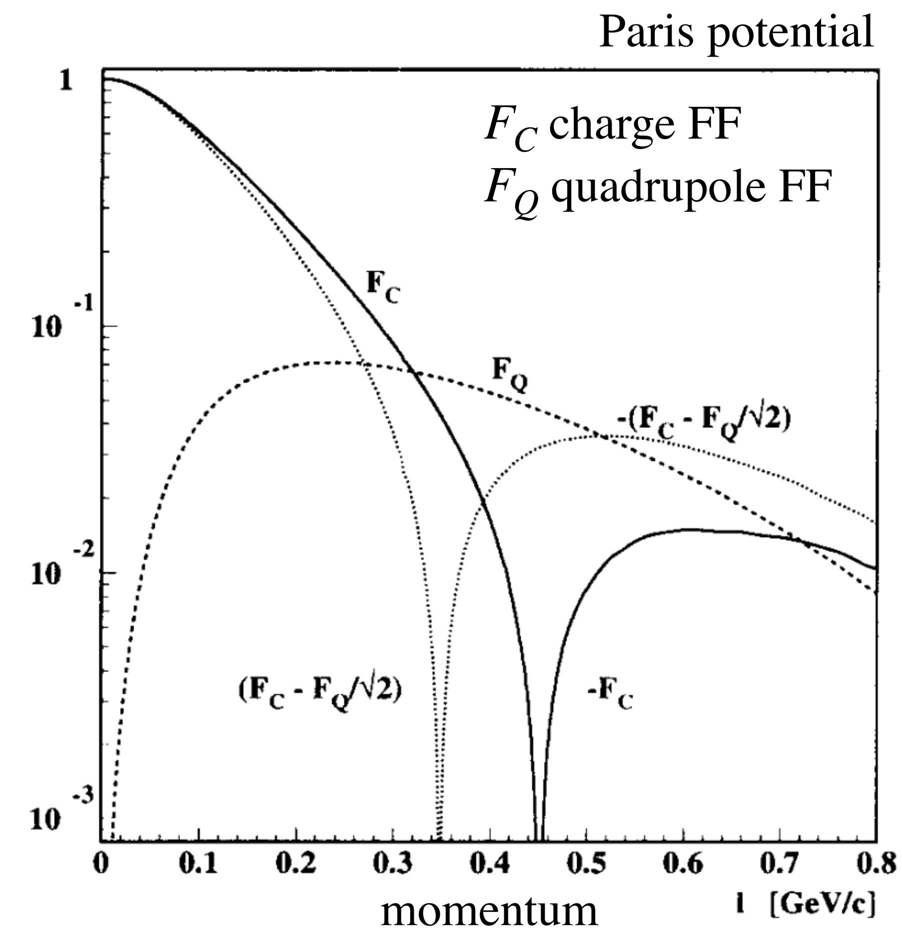
$m = \pm 1$



$m = 0$



hole associated with node in the charge form factor



$$A_{zz} = 2A_d^T = 2\frac{\sigma_+ - \sigma_-}{Q_+\sigma_- - Q_+\sigma_-}$$

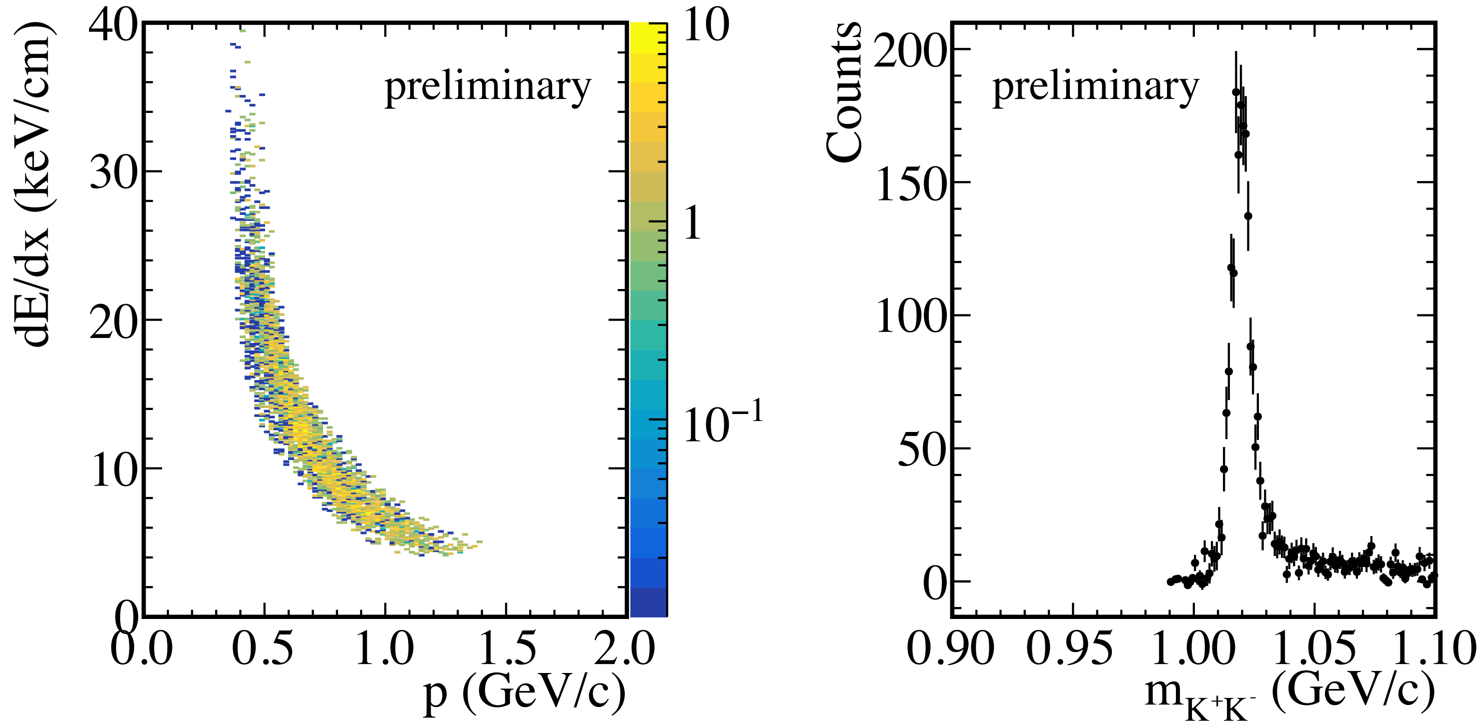
asymmetry benefit:
many systematics cancel

Projection of Statistics

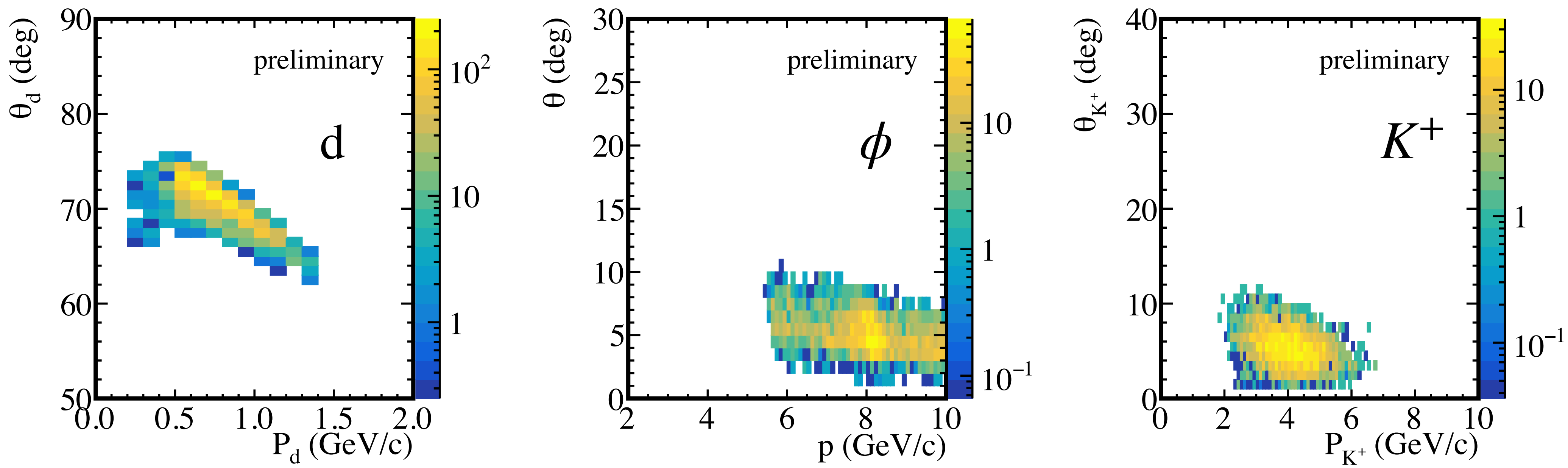
Extrapolate using preliminary data from 2.9 PAC days of deuteron data from SRC/CT running in 2021 in Hall D. Same apparatus and data analysis.

- very clean signal for exclusive ϕd final states
- use measured distribution, remove statistical fluctuations, and scale to account for luminosity and time.

direct detection of intact deuteron, very clean ϕ signal



kinematics of 2 body scattering



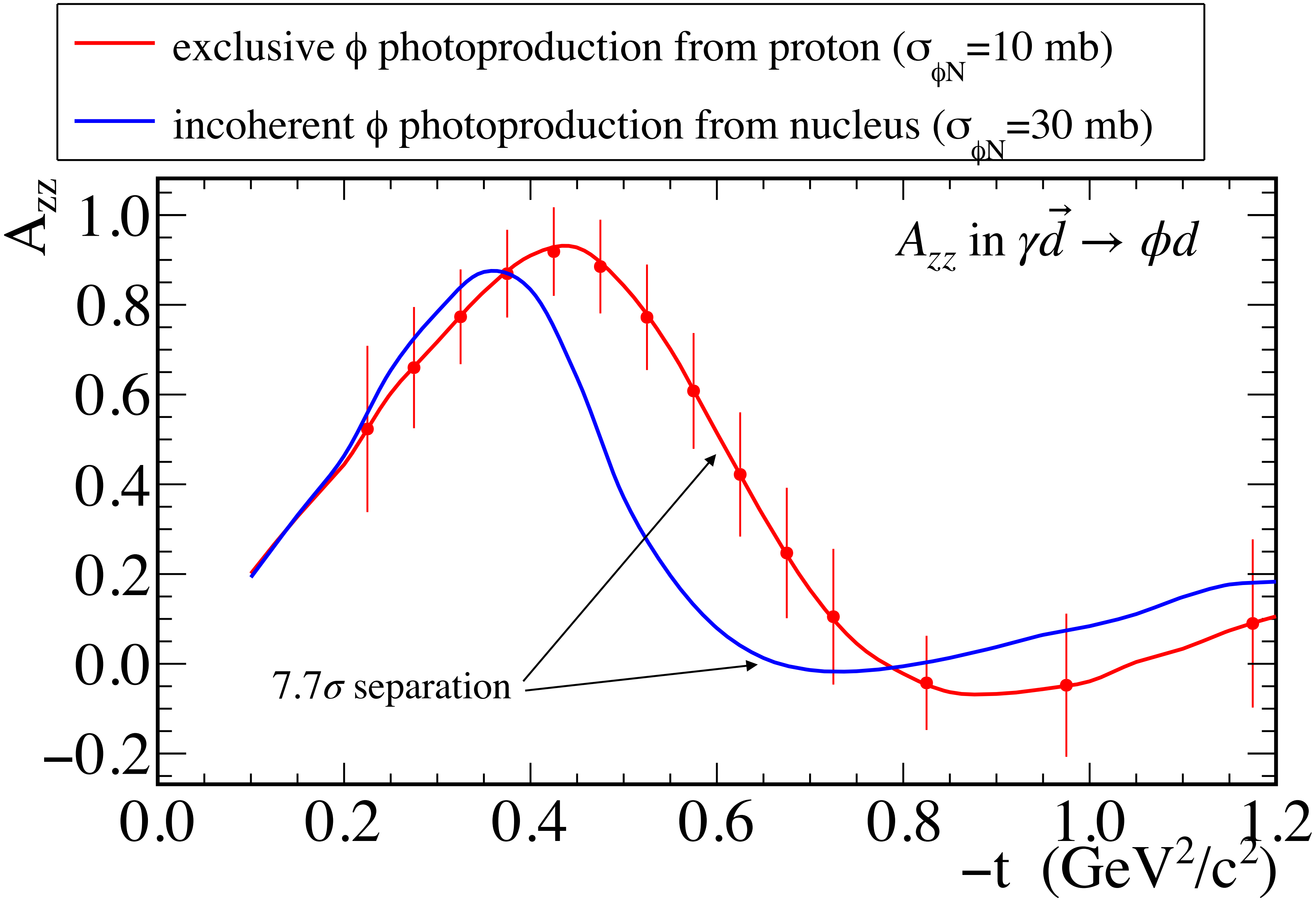
Preliminary data courtesy Bo Yu, Duke University.

Projected Uncertainties

$$A_{zz} = 2A_d^T = 2\frac{\sigma_1 - \sigma_2}{Q_1\sigma_2 - Q_2\sigma_1}$$

Asymmetry curves from Frankfurt et al.
using scenarios consistent with cross section data

Obtain 7.7σ separation



Statistics assuming
60 PAC days of beam
$Q_1 = 0.35$ and
$Q_2 = -0.38$

Systematics: 8% from measurement of target polarization

shape discrimination, normalization uncertainties not important.

Coherence Length of the Photon l_c

Real and virtual photons

Photon fluctuates into $q\bar{q}$ with lifetime l_c, estimated with uncertainty relation $\sim 1/m_N x_{\mathrm{Bj}}$

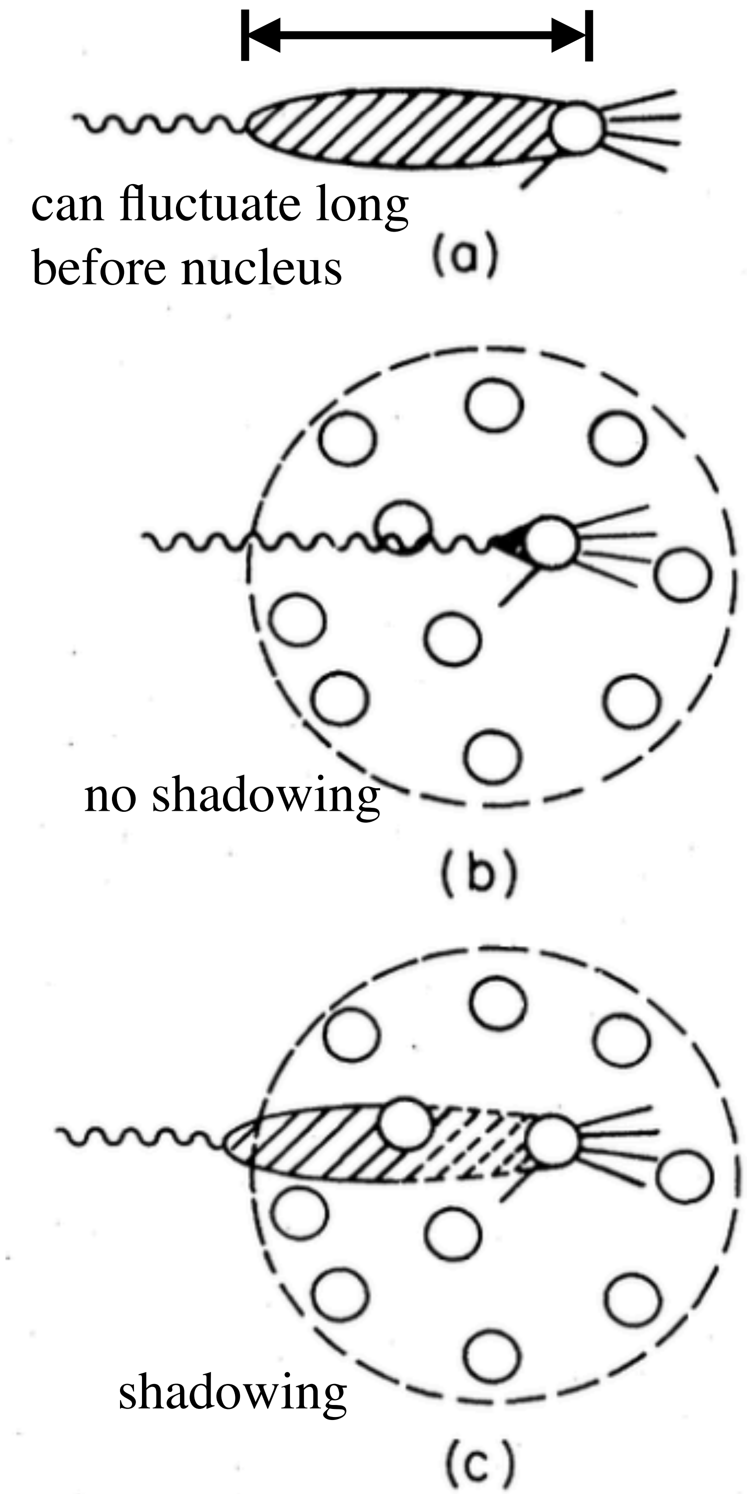
Shadowing in nuclear-DIS at $x \ll 0.1$ evidence of this phenomenon.

Deuteron is small so $l_c \gtrsim$ deuteron size at intermediate energies.

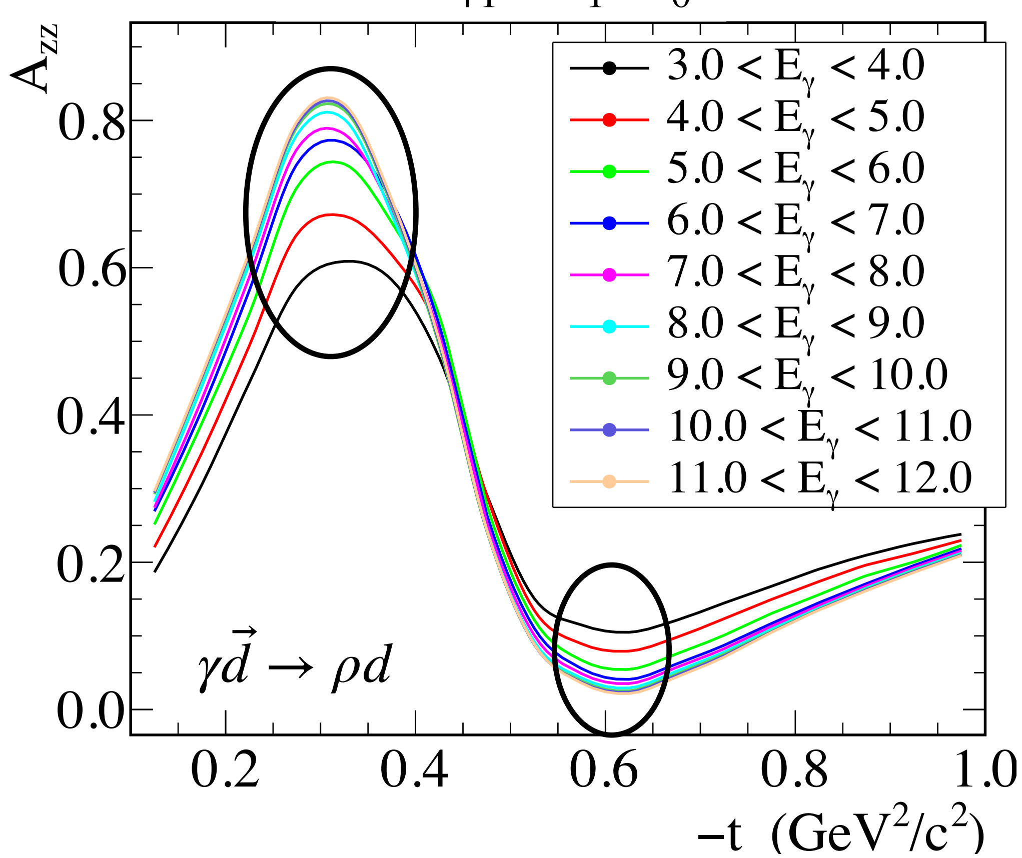
Test predictions for energy ν and mass m_V dependence with

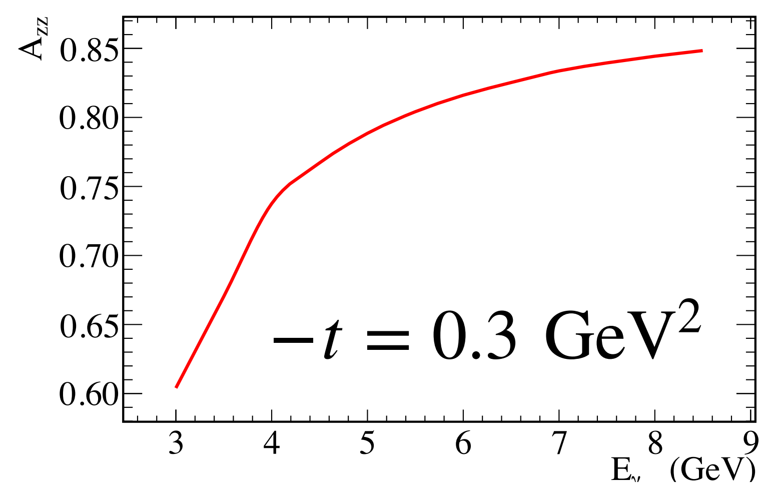
$\gamma\vec{d} \to \rho d$ and $\gamma\vec{d} \to \omega d$

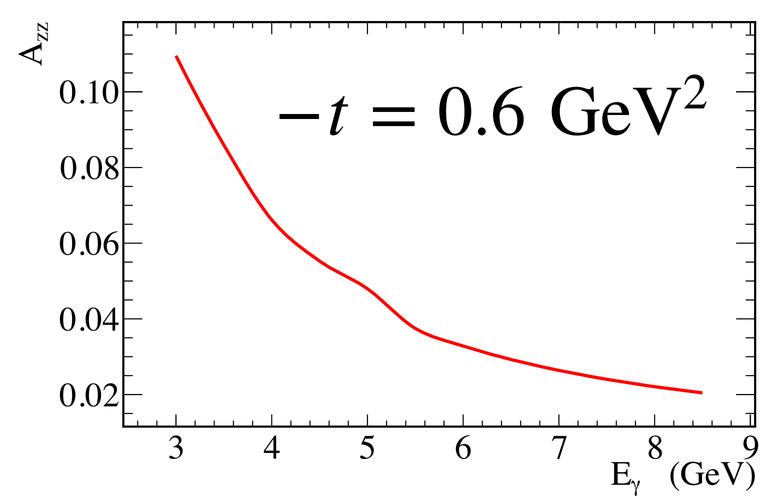
$$l_c \approx 2\nu/(m_V^2 + Q^2)$$



$$A_{zz} = \frac{\sigma_{+1} + \sigma_{-1} - 2\sigma_0}{\sigma_{+1} + \sigma_{-1} + \sigma_0}$$



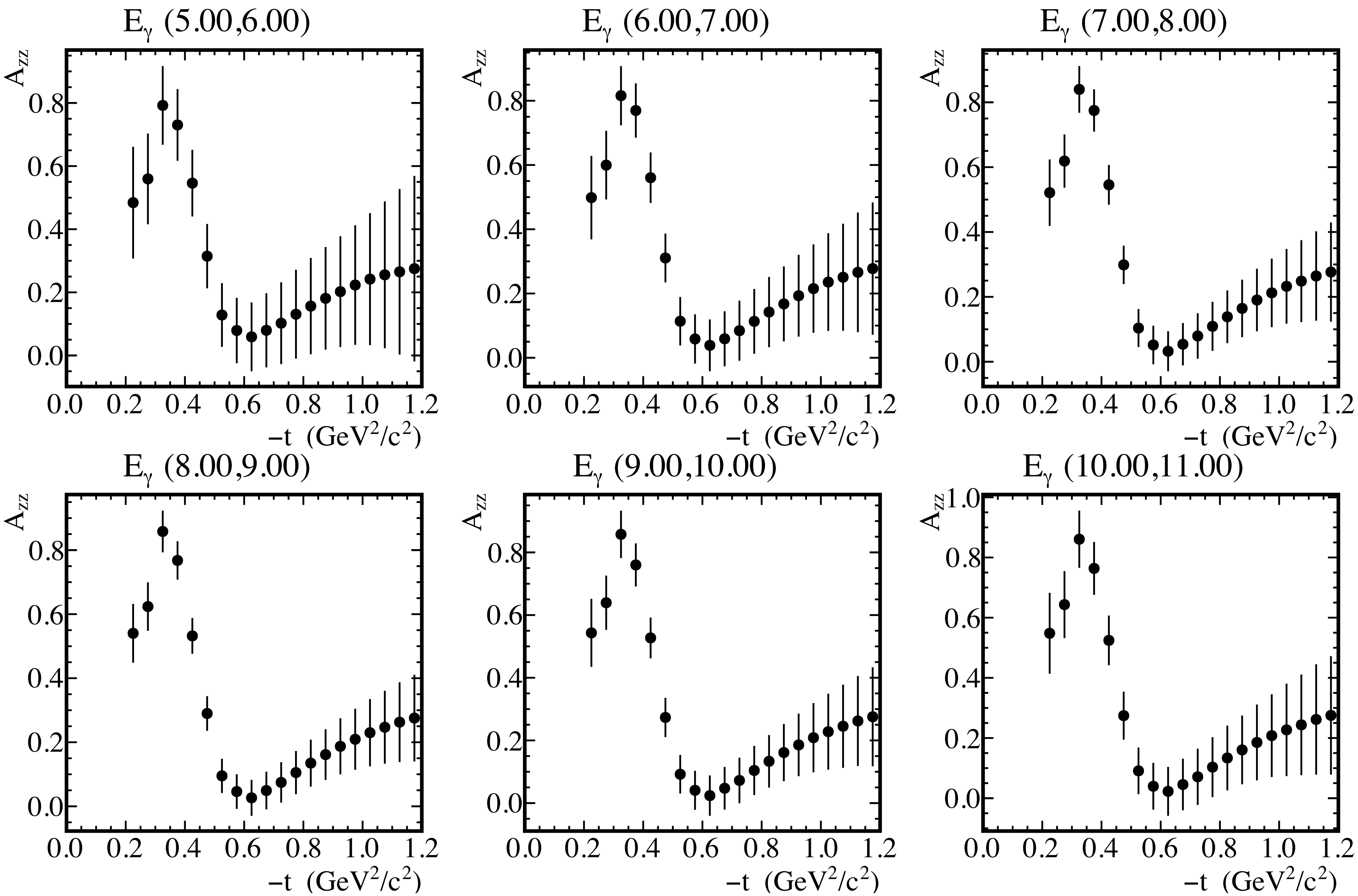




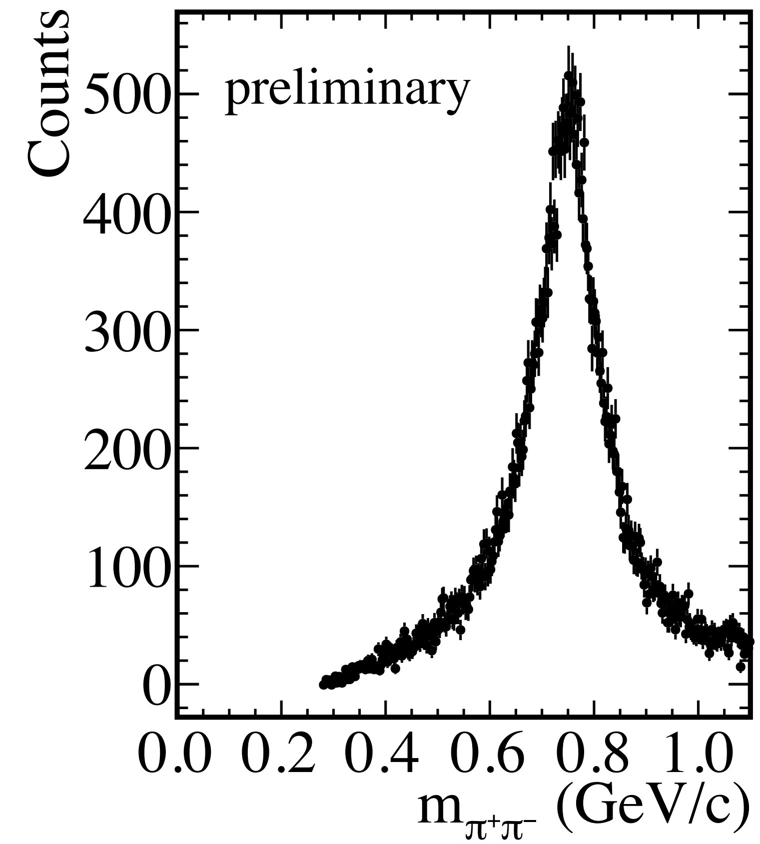
Bauer et al. Rev.Mod.Phys. v50 (1978)

Projected Uncertainties in $\gamma\vec{d} \rightarrow \rho d$

significantly higher statistics for ρ, can study energy dependent effects, such as coherence length of process



direct detection of intact deuteron, very clean ρ signal



60 PAC days of beam
$Q_+ = 0.35$ and
$Q_- = -0.38$

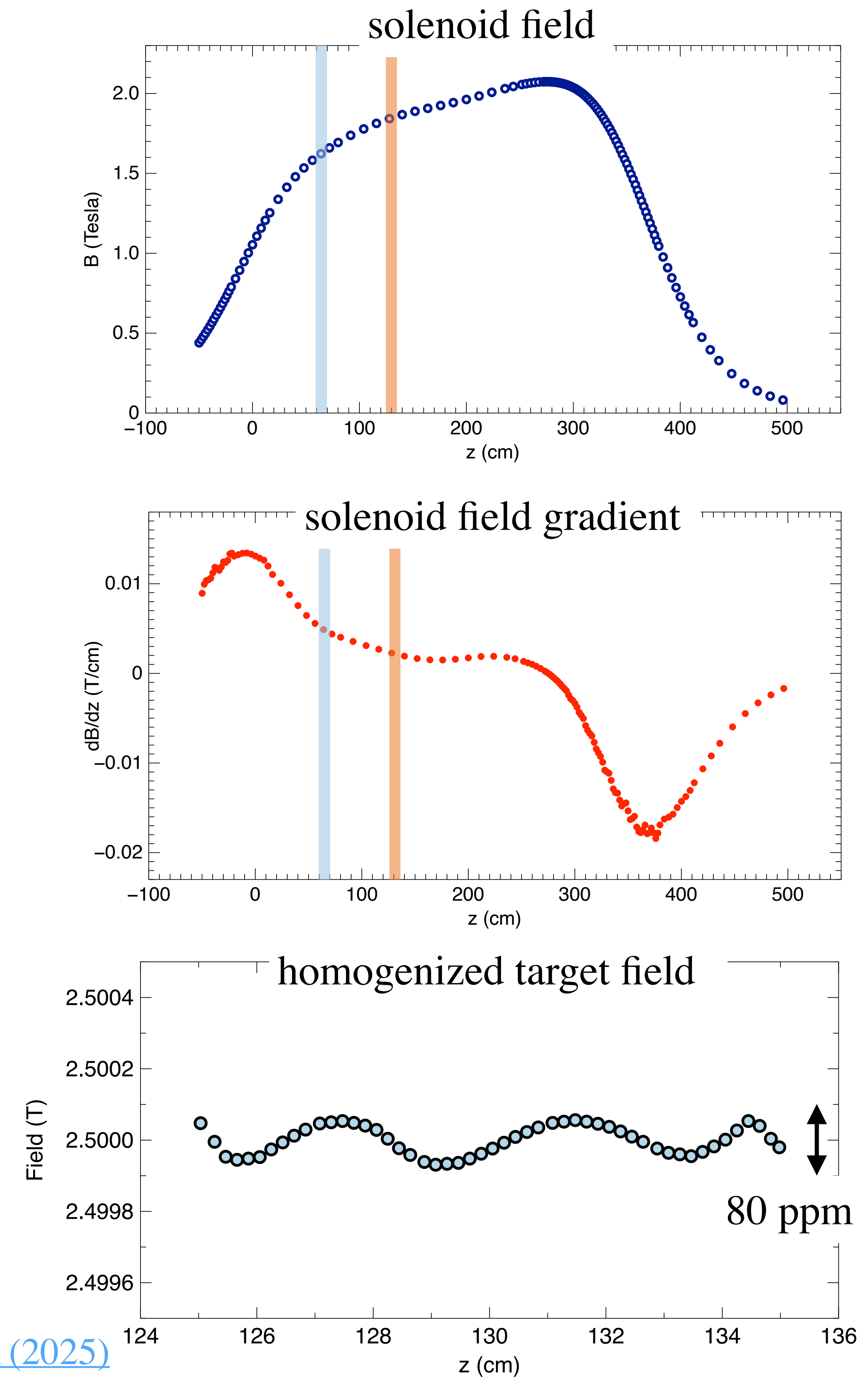
FROST-D ☃️ Hall D Polarized Target

The only non-standard equipment is the target.

This experiment will use the polarized target already approved for E12-20-011 REGGE (Real Gamma GDH Experiment)

Same principles as the FROST target which ran twice in Hall B, and other targets at CERN, Mainz, KEK, JINR, etc.

- Dynamically polarized target
- 10 cm long to reduce tagger accidentals.
- Use Hall D solenoid field plus thin, superconducting coils inside the target cryostat to increase field to 2.5 T and decrease gradient <100 ppm.
- ^3He-^4He dilution refrigerator, base temperature 50 mK and 300 mK with microwaves on.
- Allows continuous polarization and frozen spin modes.



Dalton et al. Eur. Phys. J. A (2025)

Advantage of a photon beam

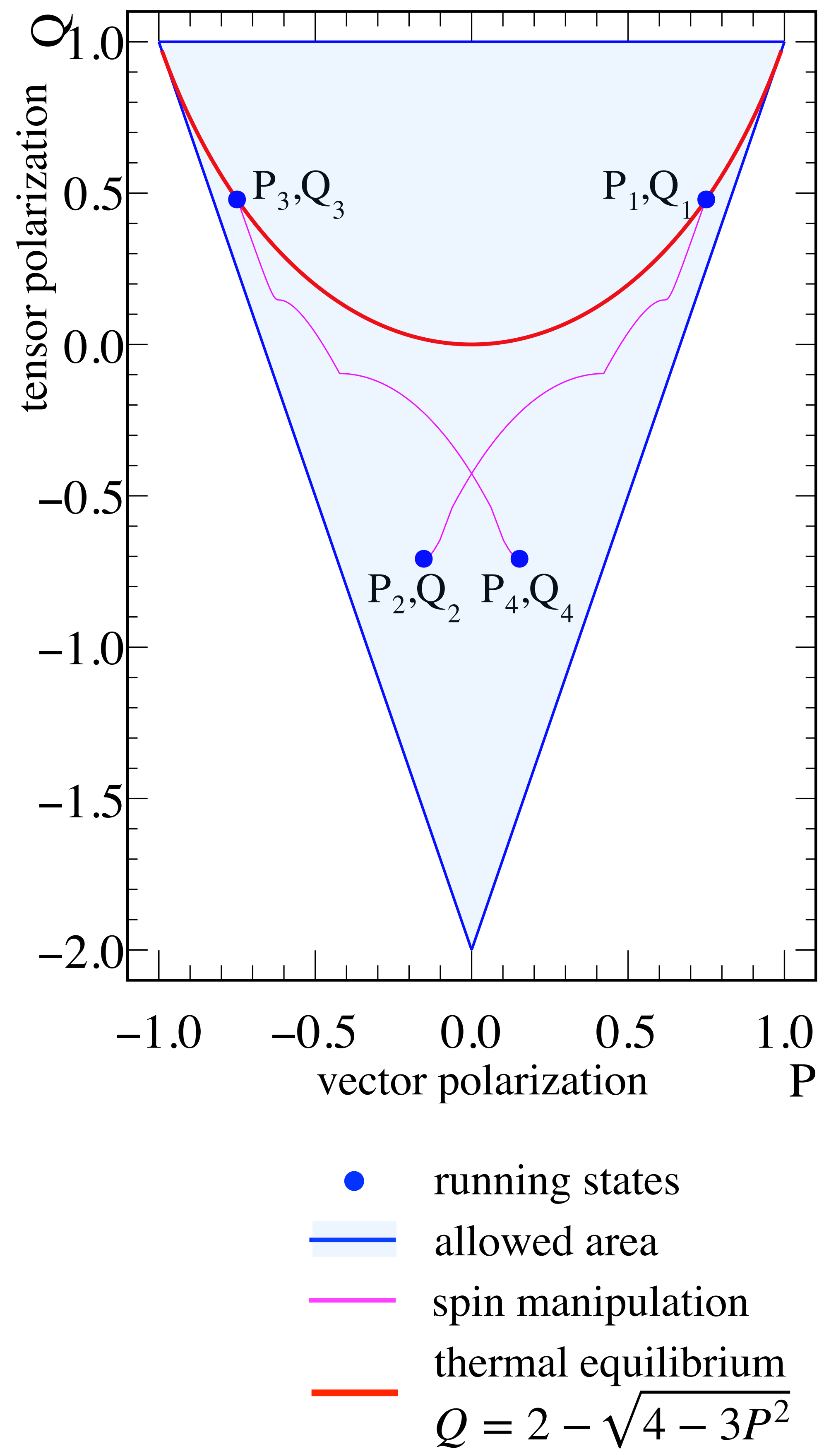
A photon beam adds very little heat allowing a much higher polarization than is possible with an electron beam. We conservatively assume $P = 0.75$ but higher has been achieved.

Using the frozen spin mode allows manipulations that take the spin states of the deuterium out of thermal equilibrium. This allows negative Q. [Dalton et al. Eur. Phys. J. A (2025)]

$Q_+ = 0.48$ and $Q_- = -0.71$ are possible in ideal circumstances.

A large lever arm is therefore available to measure the asymmetry wrt Q. Compare to $Q_+ = 0.3$ and $Q_- = 0$ for electron beam.

Vector polarization will be reversed to cancel but vector measurements will be taken concurrently.

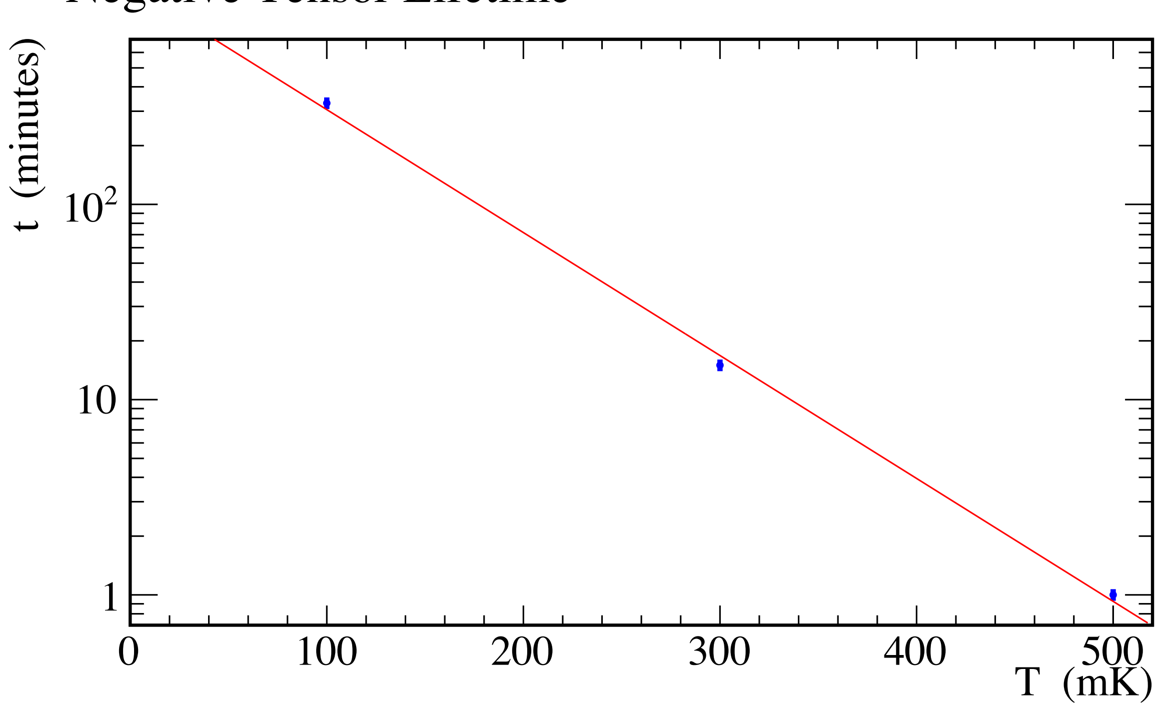


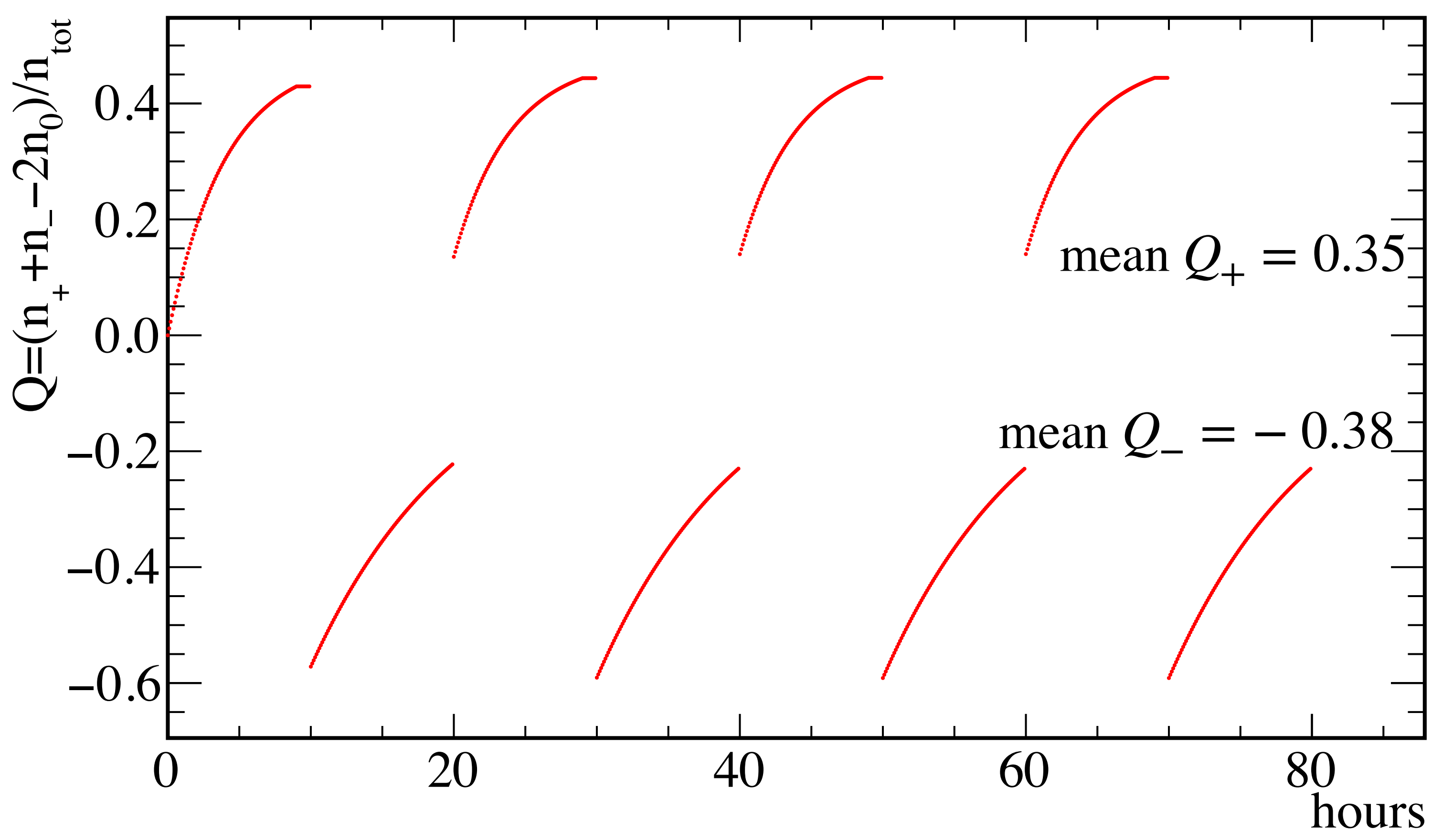
Target polarization cycle

In practice the target must be polarized in positive tensor mode (DNP), assumed $\tau = 6$ hrs, which takes time and will depolarize in negative tensor mode (frozen spin), assumed $\tau = 10$ hrs.

Averages of $Q_+ = 0.35$ and $Q_- = -0.38$ were used in the proposal.

"Worst case scenario" we run with
$Q_+ = 0.48$ and $Q_- = 0$
Decrease the separation to 4.9σ





Beamtime Request

60 Days data taking with polarized beam

5 Days overhead
- Beamline commissioning
  - Tracking calibration - straight track runs
  - Pair Spectrometer (PS) calibration - total absorption counter (TAC)
  - Luminosity calibration - Compton events vs PS
- Polarized target commissioning and running
  - Empty target running
  - Measure the polarization - regular NMR calibration

GlueX endorsed: commitment by the GlueX collaboration to operate the detector, staff shifts, calibrate and process the data, as well as provide support for data analysis.

Summary

We will measure A_{zz} for $\gamma d \rightarrow \phi d$ with sufficient precision to determine decisively whether $\sigma_{\phi N} \approx 10$ mb or $\sigma_{\phi N} \approx 30$ mb, thereby solving a longstanding puzzle (e.g. Feynman's "Photon-hadron interaction, 1972)

High statistical significance in A_{zz} for $\gamma d \rightarrow \rho^0 d$ and $\gamma d \rightarrow \omega d$,
related to the deuteron charge form factor, single and double scattering and photon coherence length.

Tensor polarized D with a real photon beam is a new thing never been done before.
Easier than with electron beam.
Good surprises are possible.

GlueX has a hermetic detector with an open trigger so will capture a broad range of final states not mentioned here.

Theory Report: Solving the $\sigma_{\phi N}$ puzzle is an important endeavor to understand the limits of the applicability of VMD and to better interpret incoherent photoproduction data, where various theoretical models—similar to color transparency—have been proposed to explain the phenomena. The proposal reads well and is encouraged.

GlueX Acknowledgements: gluex.org/thanks