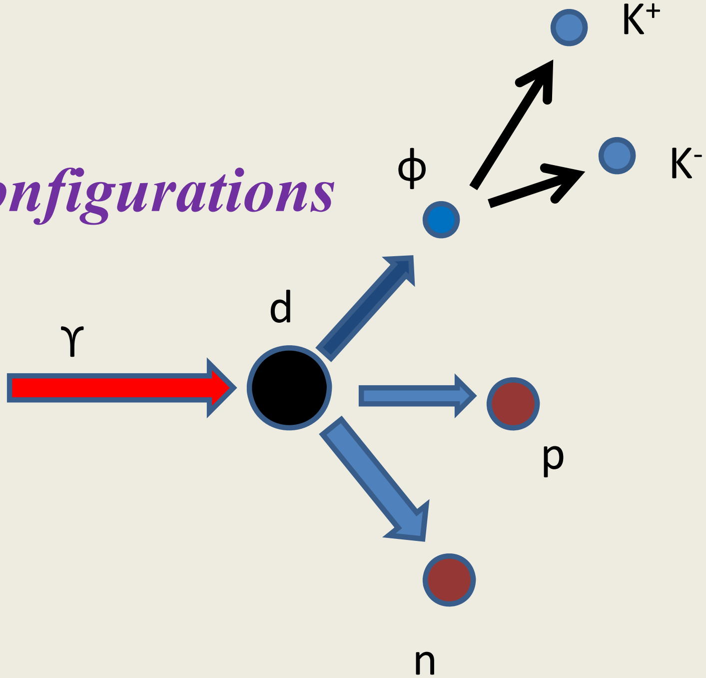
Φ-meson photo-production on deuteron and future studies using heavier nuclear targets

Haiyan Gao
Duke University, TUNL

Workshop on probing small-size configurations
In high-t photo/electroproduction
March 25-26, 2011, Jefferson Lab



Outline

- **Φ photo-production on deuteron from γ(d,p k^+k^-)n process**
- **Φ photo-production from deuteron below CLAS threshold from γ(d,pk^+k^-)n process**
- **Φ photo-production from heavy nuclear targets and search for Φ-N bound state**
- *Search for small configuration at large-t?*

Φ-N Total Cross-section (I)

- Vector meson dominance

$$T_{\gamma N \to \phi N} = \alpha_{\gamma\phi}\, T_{\phi N \to \phi N}$$

- Optical model

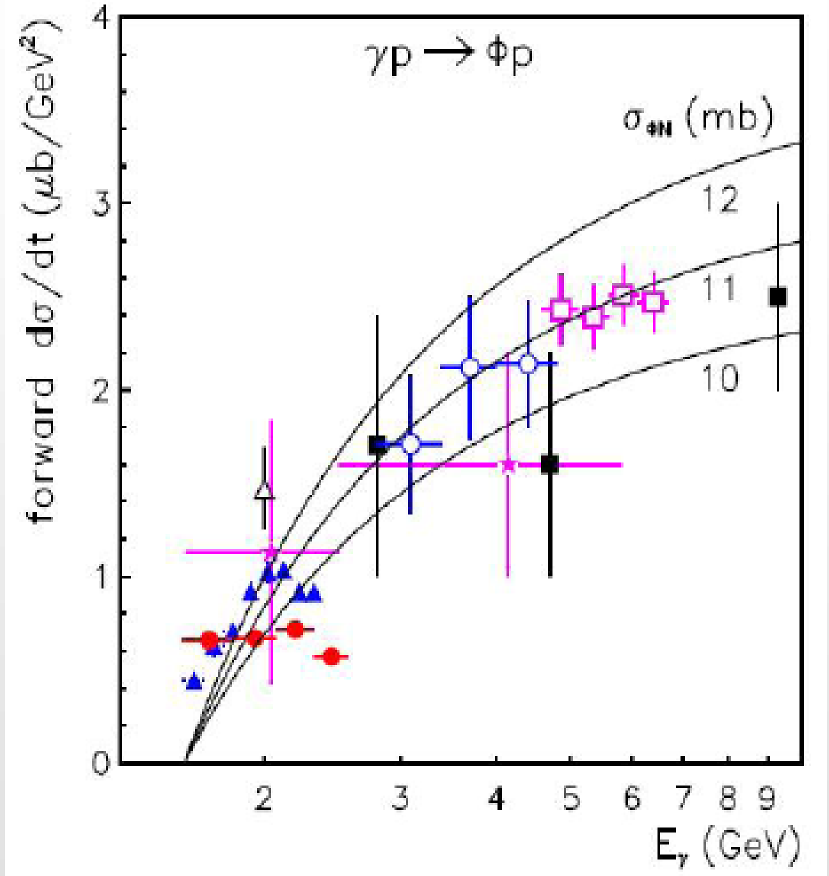
$$\sigma_{\phi N} = 4\pi\, \mathrm{Im}(T_{\phi N \to \phi N})$$

- Differential cross-section at t=0

$$\left.\frac{d\sigma_{\gamma N \to \phi N}}{dt}\right|_{t=0} = \alpha_{\gamma\phi}^2 \frac{p_\phi^2}{p_\gamma^2}\left(1-\beta^2\right)\sigma_{\phi N}^2$$

- VMD estimate $\sigma_{\Phi\text{-}N}$ = 10-12 mb

Sibirtsev et al.,EPJ. A 29 (2006) 209



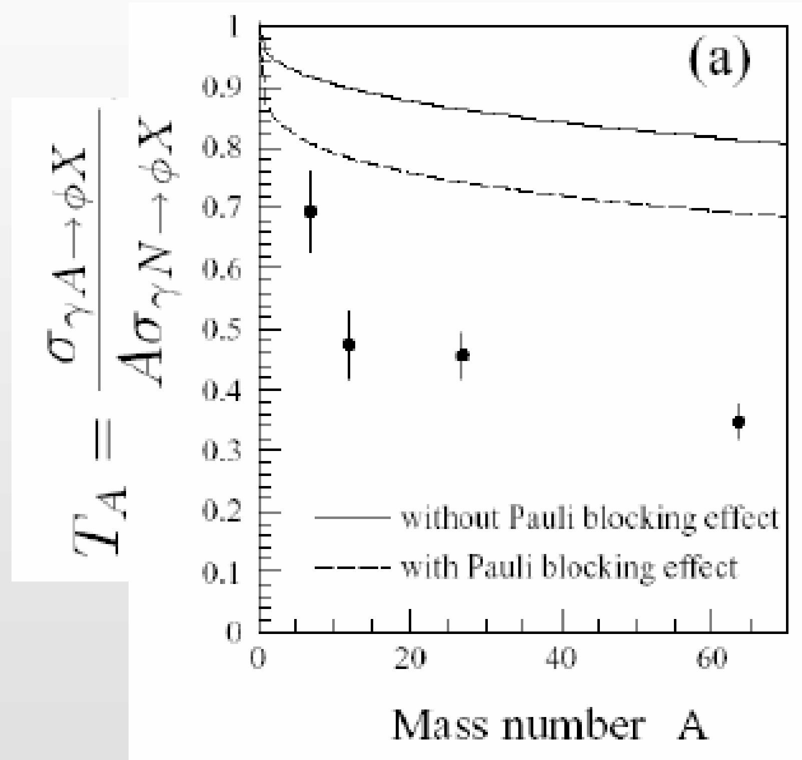
Φ-N Total Cross-section (II)

- $\sigma_{\Phi\text{-}N}^{inelastic}$ is measured through nuclear transparency

$$T_A = \frac{\sigma_{\gamma A \to \phi X}}{A\sigma_{\gamma N \to \phi X}}$$

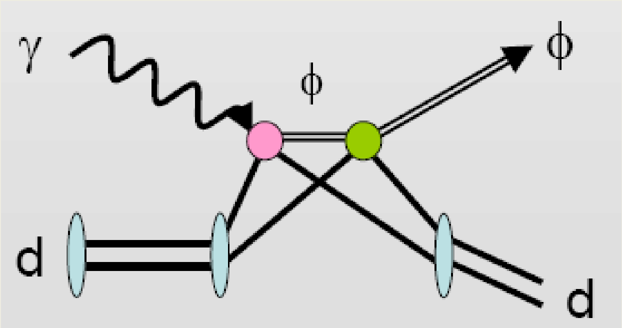
- Spring-8 data gives $\sigma_{\Phi\text{-}N}^{inelastic} = 35^{+17}_{-11}$ mb
- Much larger than $\sigma_{\Phi\text{-}N} = \sigma_{\Phi\text{-}N}^{inelas} + \sigma_{\Phi\text{-}N}^{elas}$ = 10-12 mb

T. Ishikawa et. al (LEPS)
Phys.Lett. B608 (2005) 215

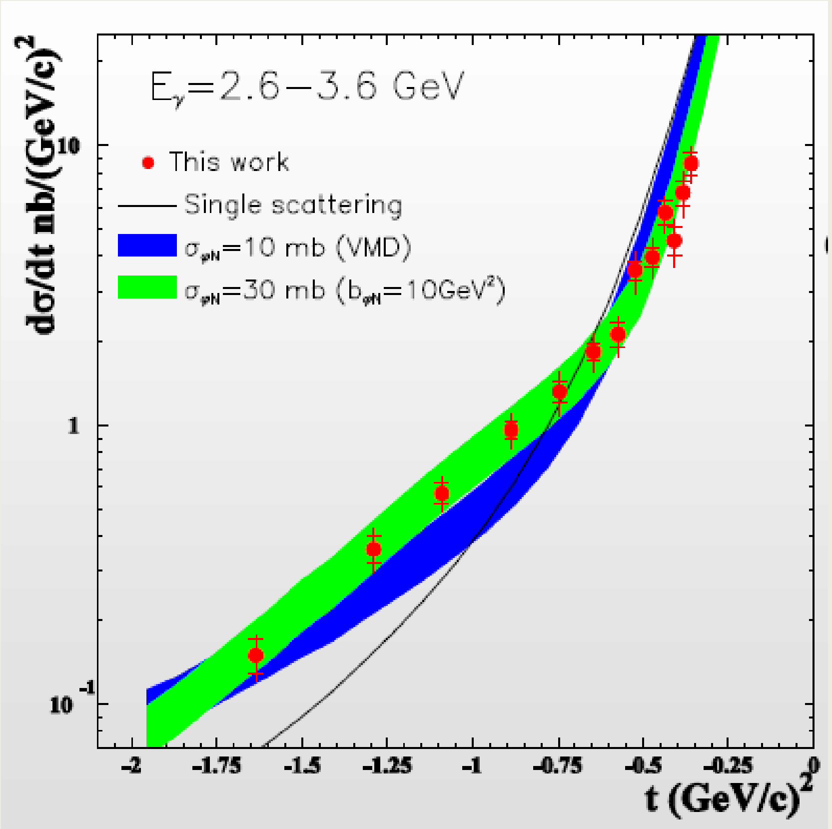


Φ-N Total Cross-section (III)

- $\sigma_{\Phi\text{-}N}$ can be extracted from high |t| region of coherent Φ production on deuteron



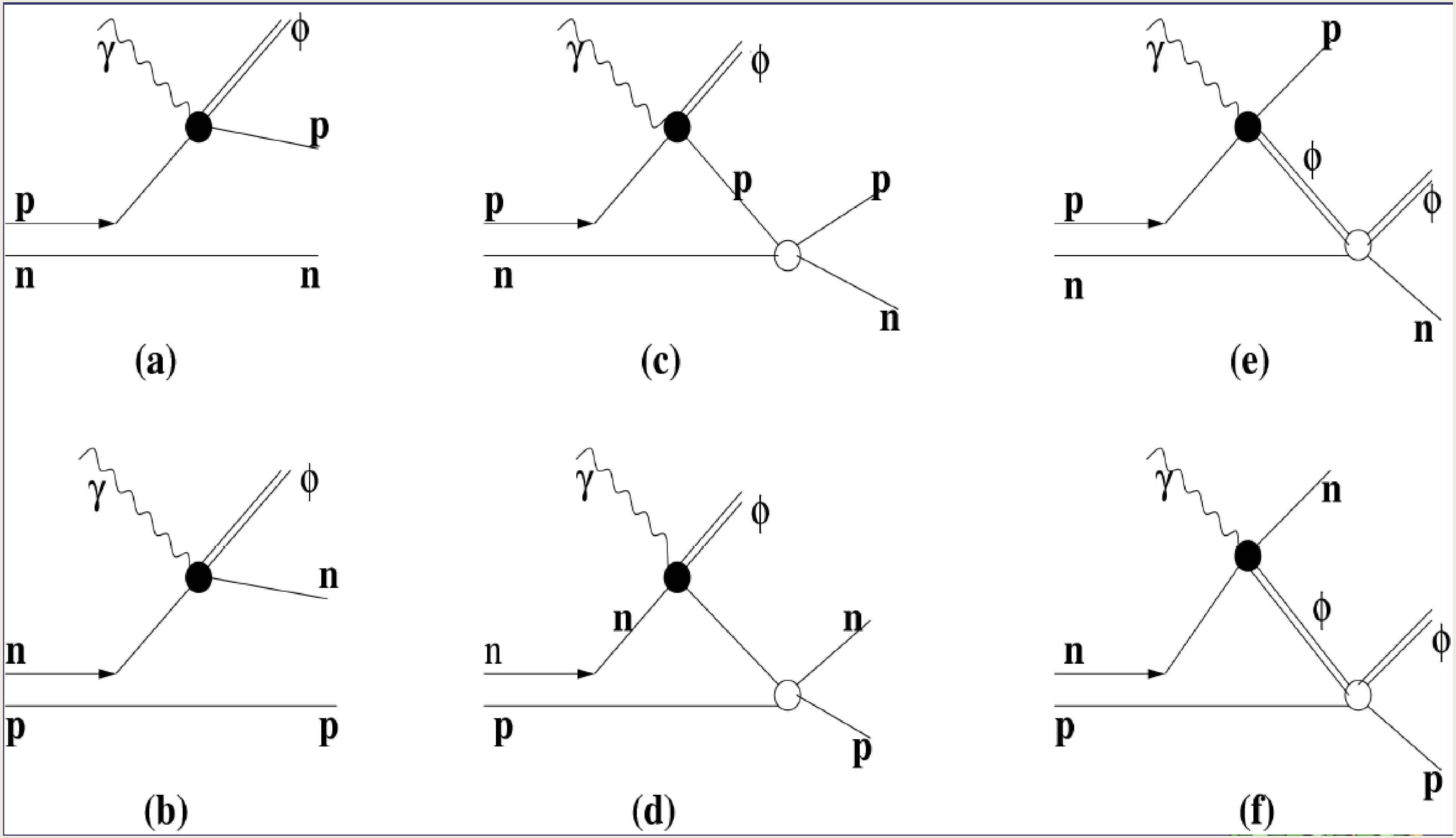
- Agrees with $\sigma_{\Phi\text{-}N}$ = 10 or 30 mb, favors 30 mb



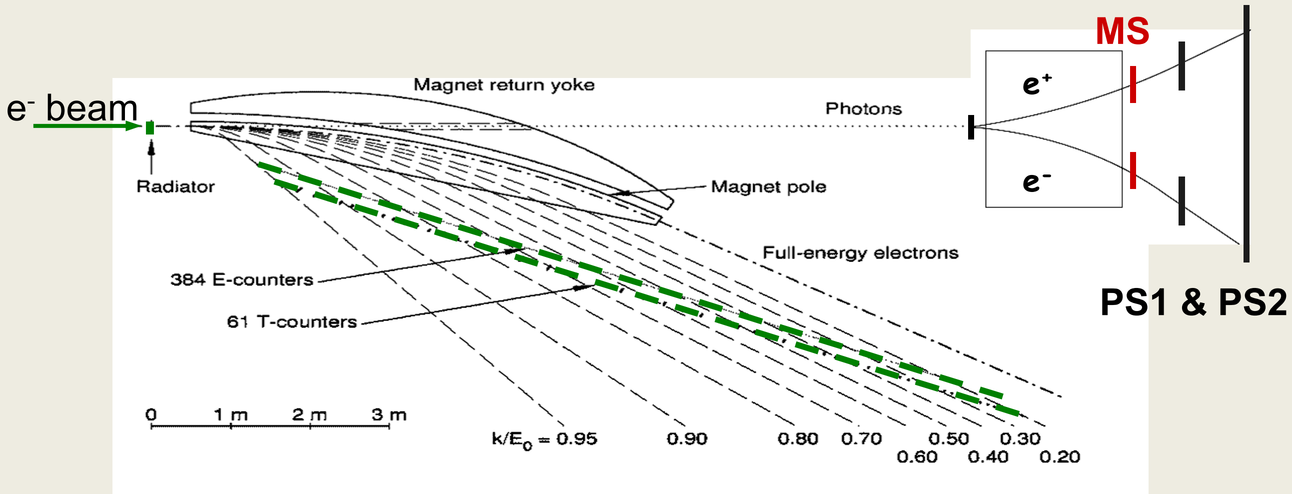
T. Mibe , et al. Phys. Rev. C76, 052202R (2007) (CLAS Collaboration)

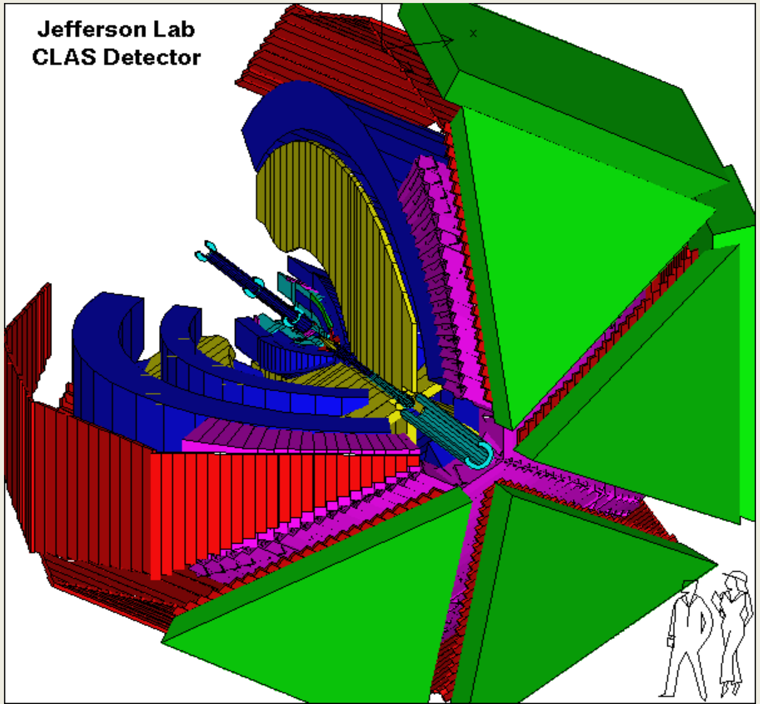
Calculations: M. Sargsian et al.

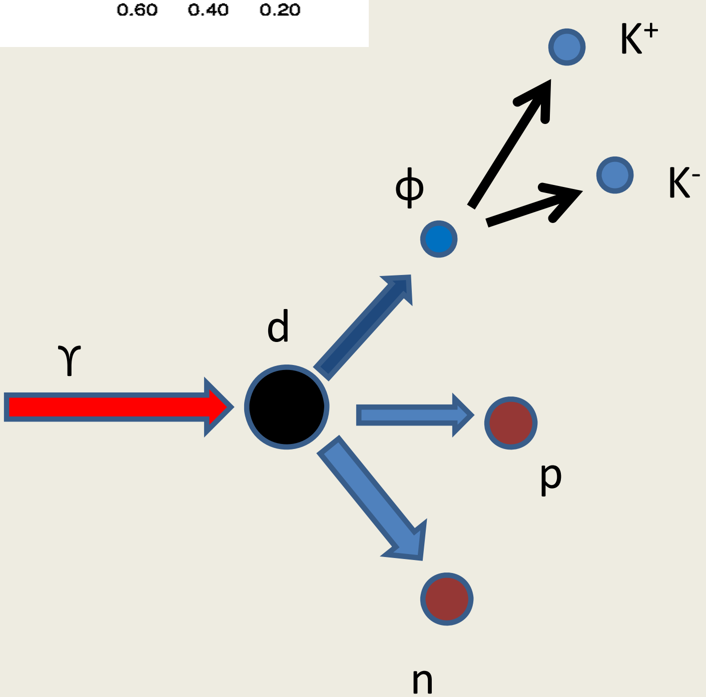
γ(d,pΦ)n Process in CLAS



Φ Production on Deuteron above CLAS threshold





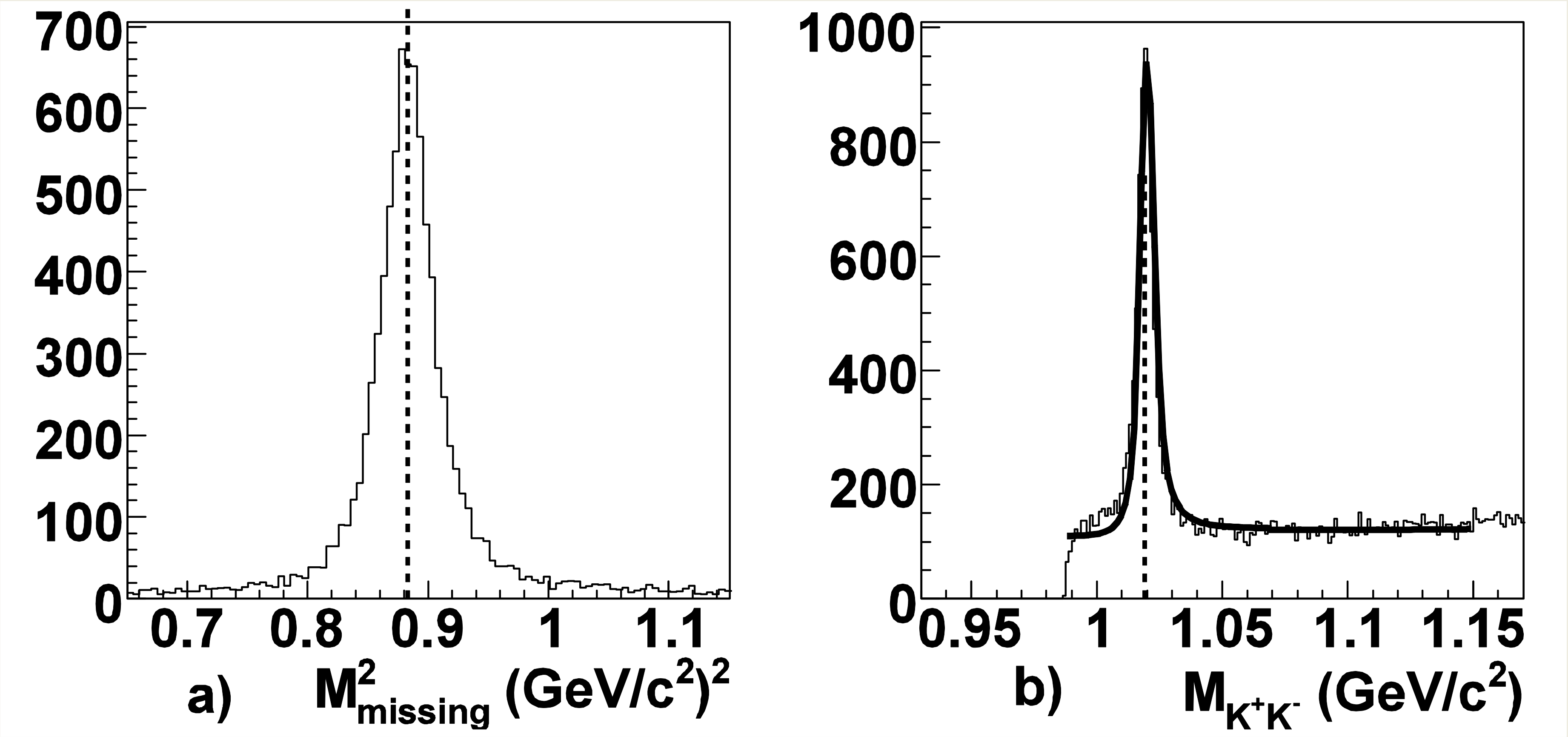


Event Selection

A triple coincidence detection of proton, K^+ and K^-.

Missing Mass to identify undetected neutrons

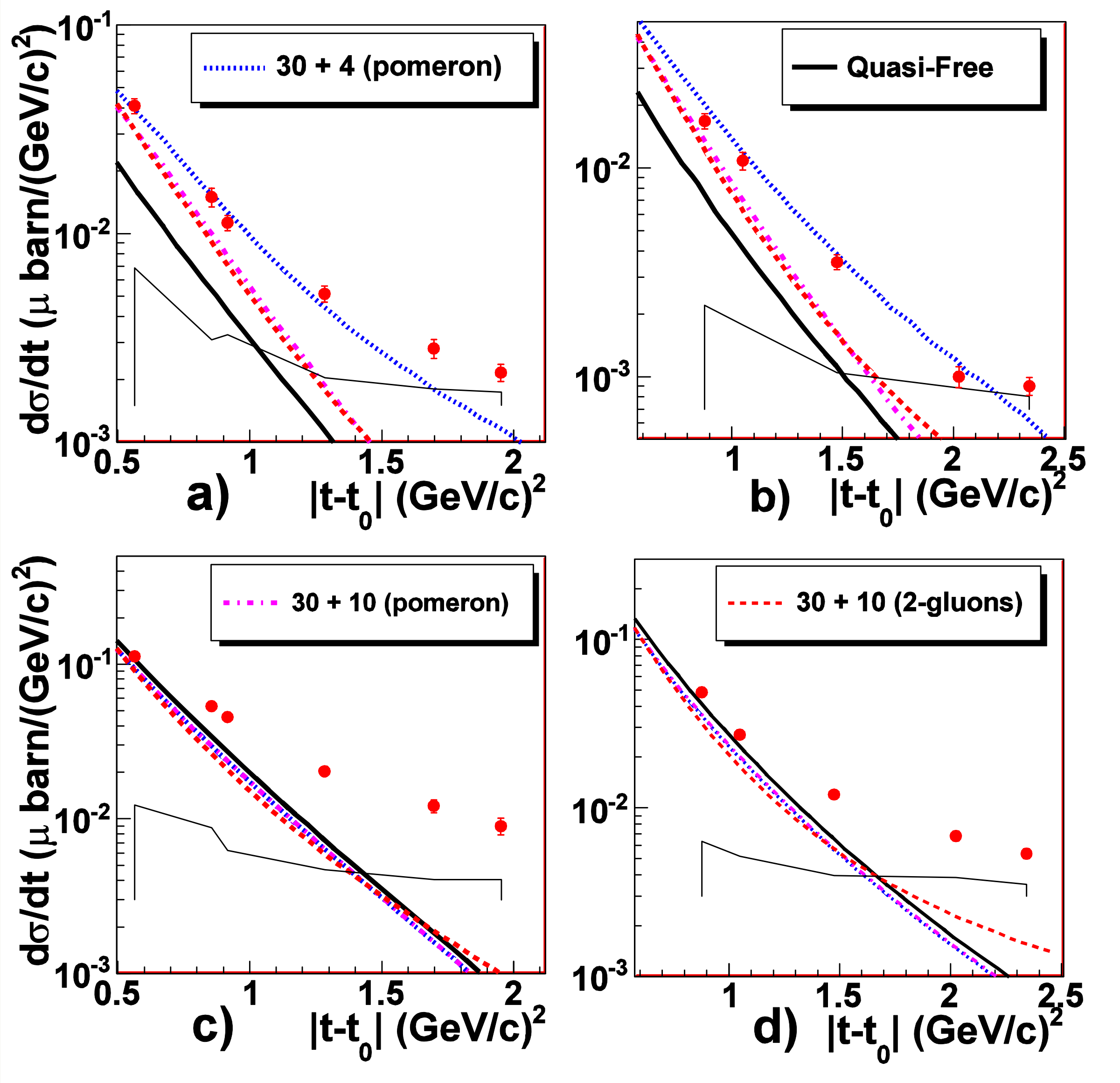
Invariant mass of K^+ and K^- to select ϕ



Results at high missing momentum

- Calculations underestimate data at low spectator nucleon momentum
- Calculation (J. M. Laget, Phys. Rev. C73, 044003 (2006))
- The N-P FSI is under control. (J. M. Laget, Phys. Lett. B609, 49 (2005))

X. Qian et al, PLB 680, 417 (2009)



(a) ,(c), 1.65-2.62 GeV; (b), (d):2.62-3.59 GeV

In (a) and (b), missing momentum higher than 180 MeV/c

Ratio

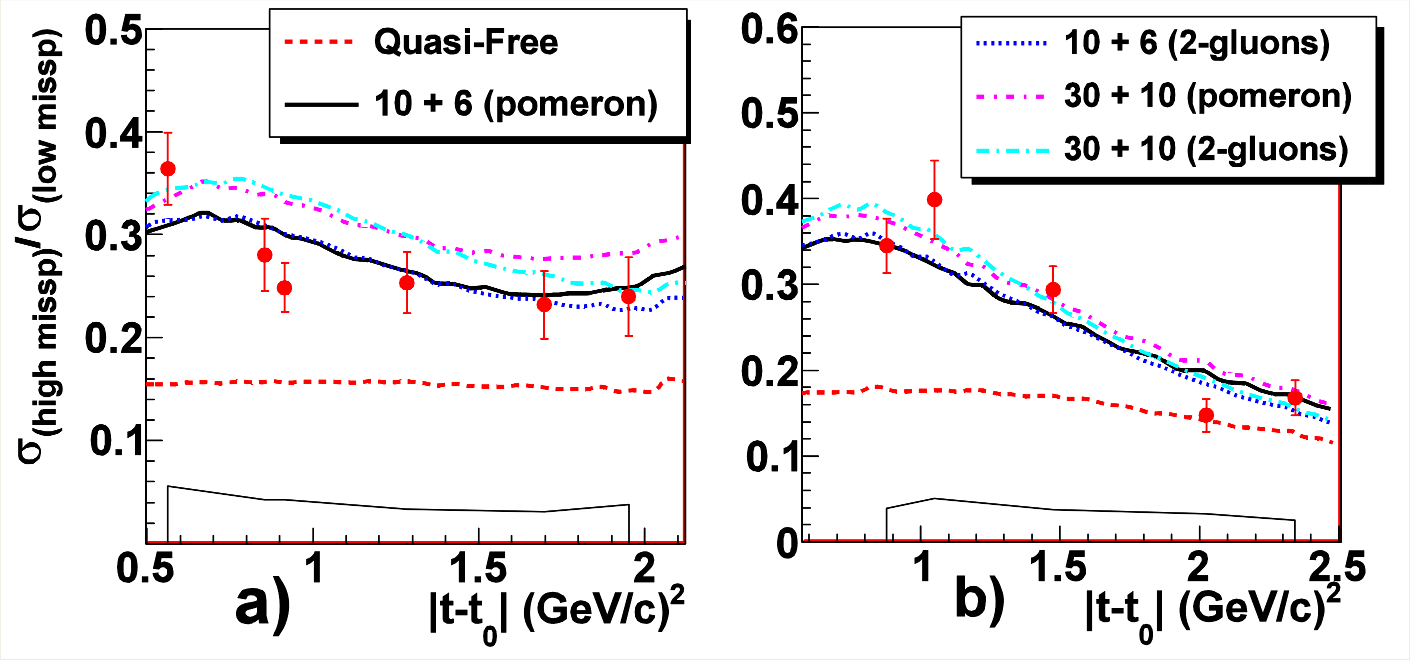
G10 exclusive channel results suggest a larger value of $\sigma_{\Phi\text{-}N}$

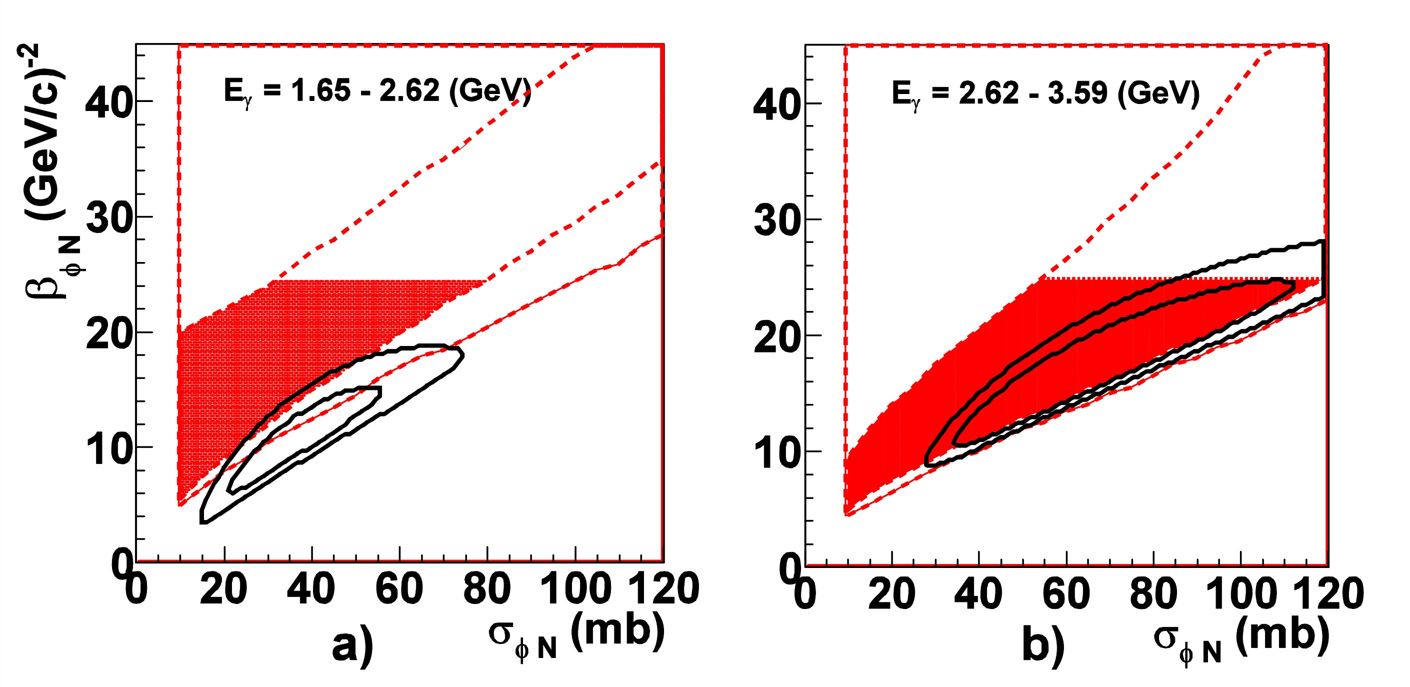
Possible explanations

Failure of VMD?

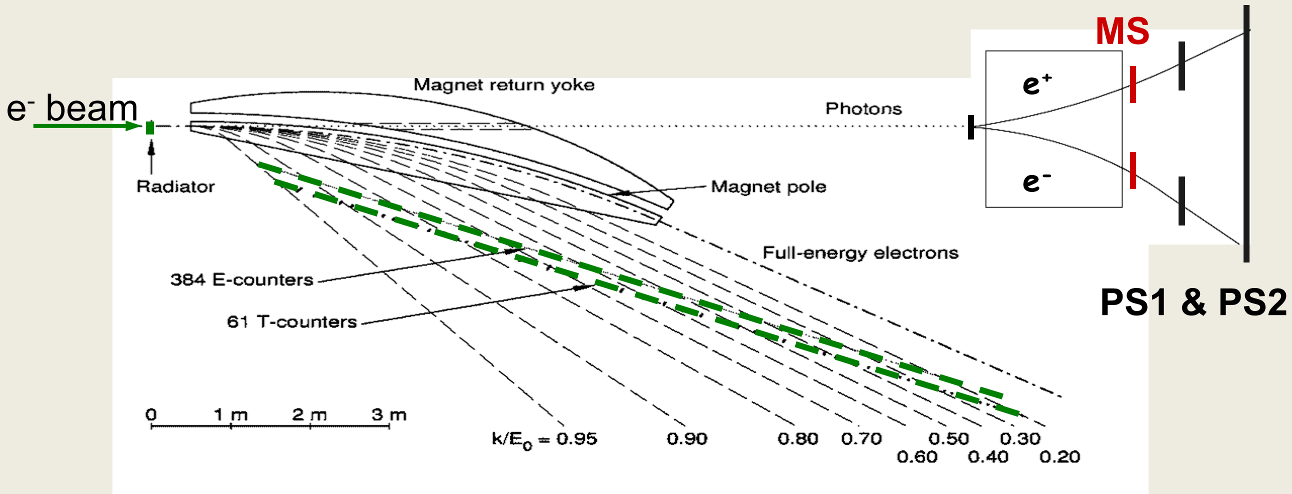
ω-ϕ mixing? : ω is generated in the first step, followed by a re-scattering.

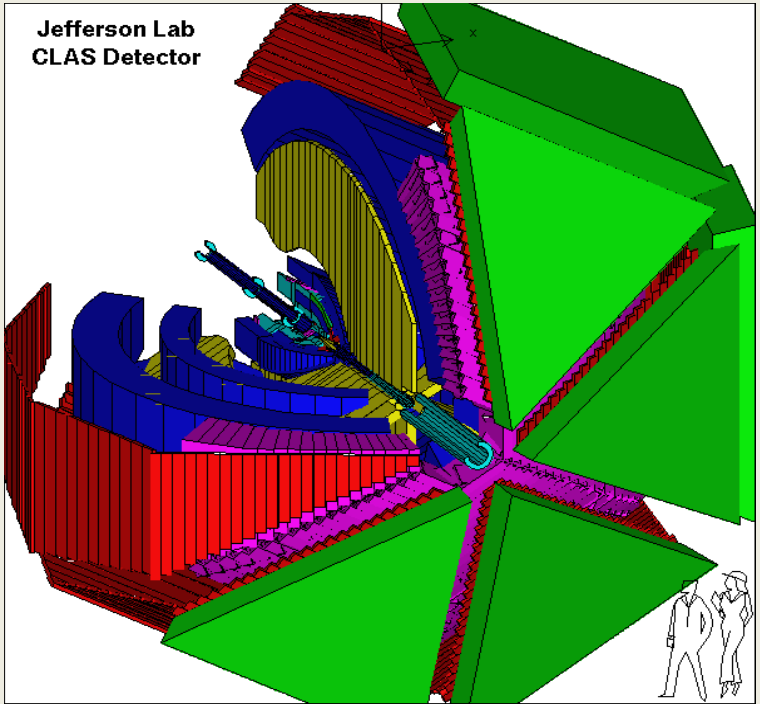
(a): 1.65-2.62 GeV
(b): 2.62-3.59 GeV

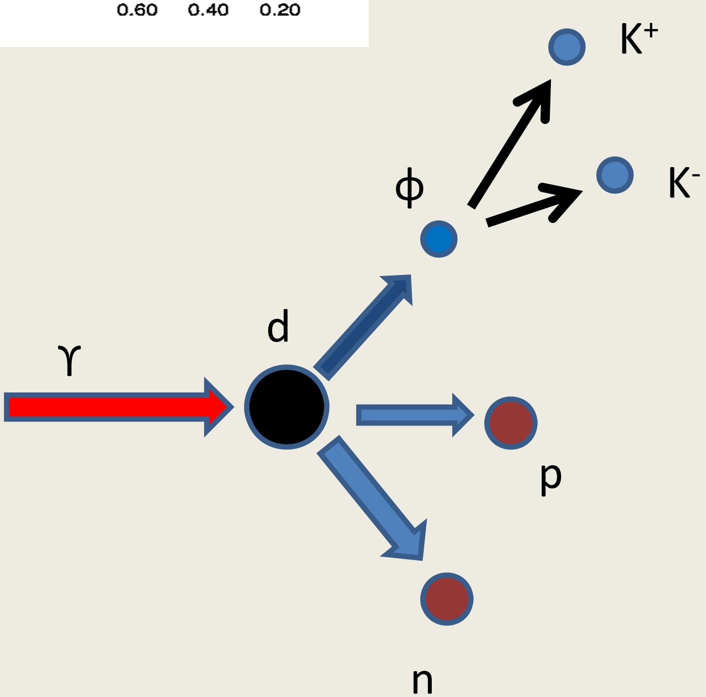




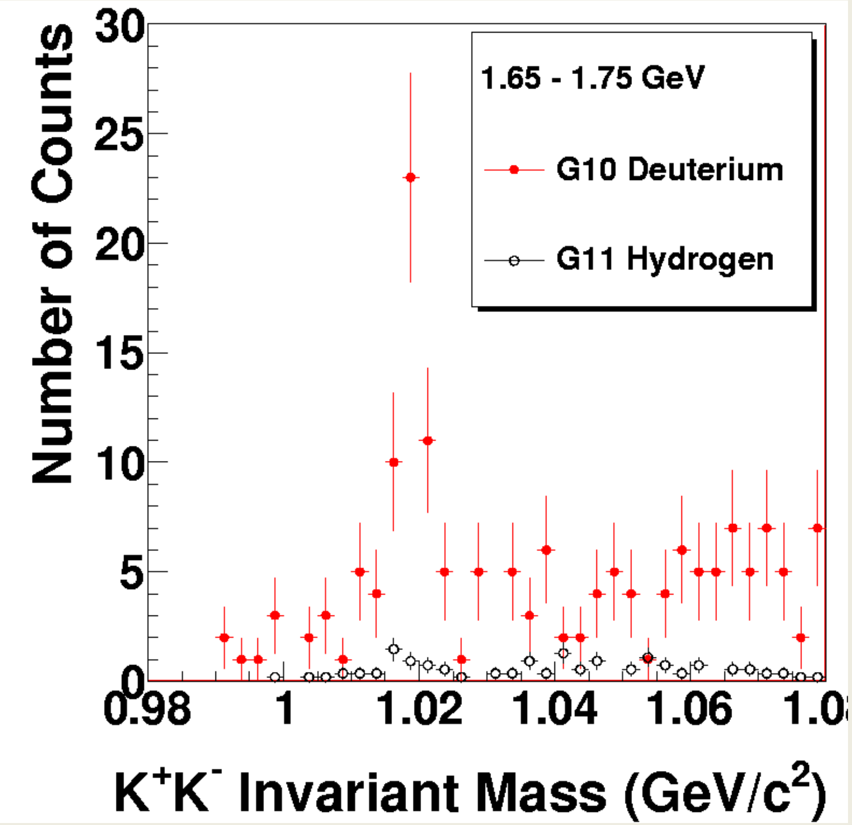
Φ Production on Deuteron below CLAS threshold

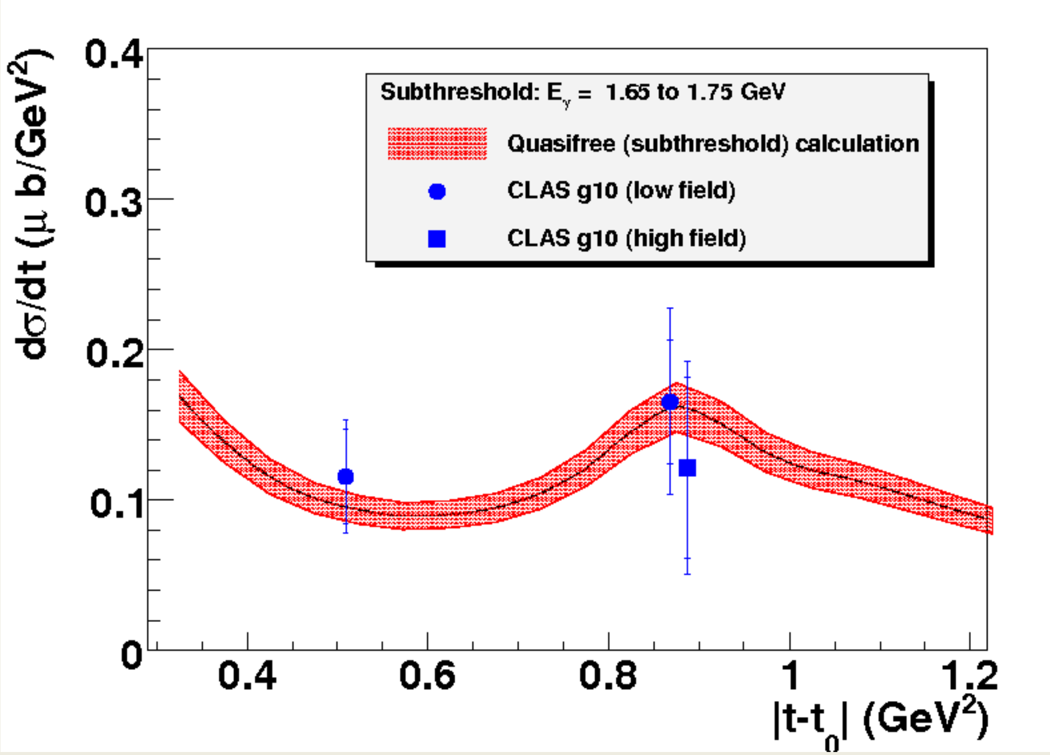






CLAS g10 results: Φ Production on Deuteron below CLAS threshold



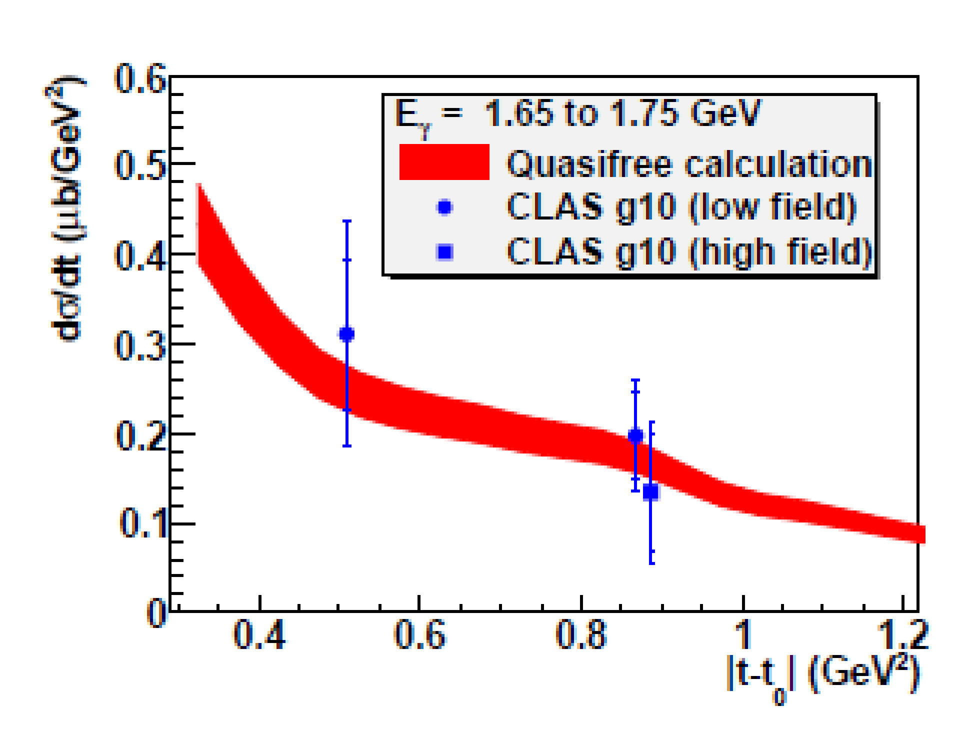


Introduce E_γ^{boost} > 1.75 GeV cut to ensure subthreshold

E_γ^{boost} is photon energy in the proton-at-rest frame

Conclusion

- See "near-threshold" events,
  - Validity of phi-N bound state search technique, which is to generate a slow phi using fermi momentum of nucleon.
- Differential cross section is consistent with simple quasi-free calculation.
  - Did not rule out any exotic behavior since data is limited by statistics.
  - Good for future design of experiment.



Near threshold results

without $E_\gamma^{boost} > 1.75$ GeV cut

X. Qian et al, PLB 696, 338 (2011)

T. Sekihara, et al., arXiv:1008.4422

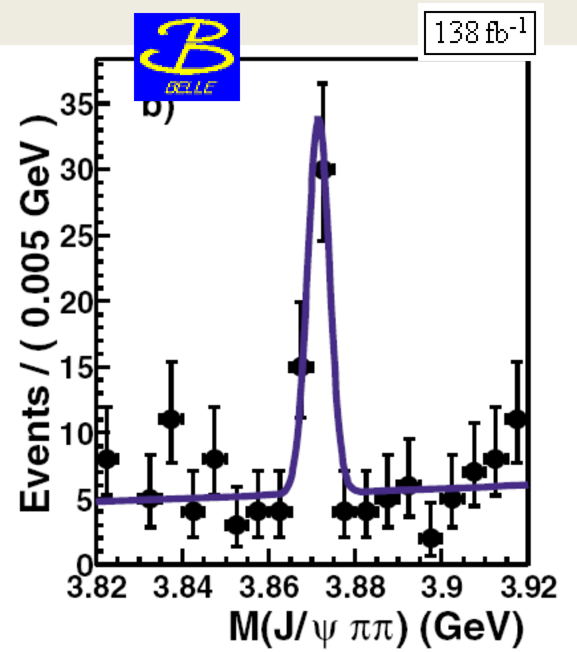
Results different from W.C. Chang et al. PLB684(2010)6, though different kinematics

Question: are there any QCD molecular states?

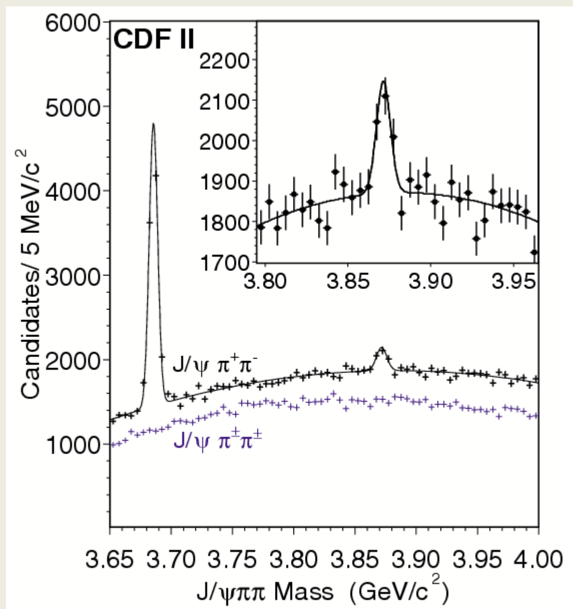
Answer: maybe

Discovery of the X(3872)

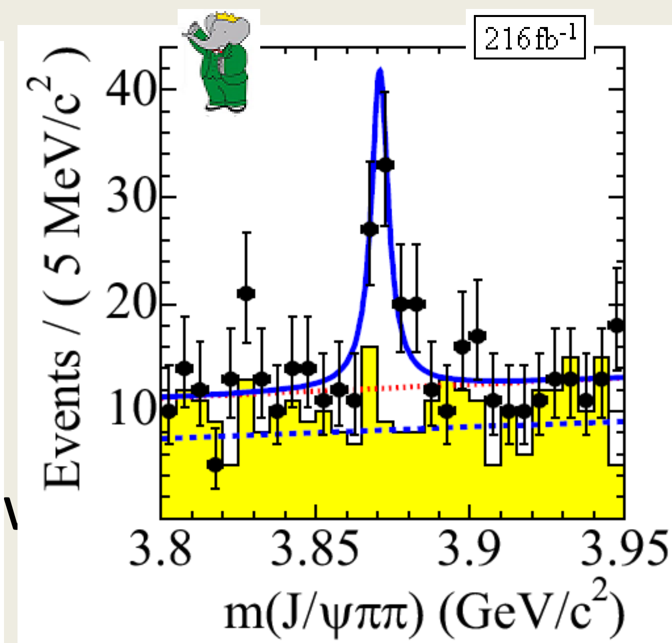
- In 2003, Belle discovered a new signal in $B^+ \rightarrow X K^+$, $X \rightarrow J/\psi \pi^+ \pi^-$
- Narrow (Γ<2.3MeV) particle with mass m(X)=3871.2+/-0.6 MeV/c^2



Phys. Rev. Lett. 91, 262001 (2003)



Phys. Rev. Lett. 93, 072001 (2004)
Phys. Rev. Lett. 93, 162002 (2004)



Phys. Rev. D 71, 071103 (2005)
Phys. Rev. D 73, 011101 (2006)

Confirmed by CDF, D0 and BaBar

X(3872) Interpretation

- X(3872) is puzzling
  - Similar to charmonium, ie: narrow state decaying to $J/\psi\pi^+\pi^-$
  - However, above DD threshold expect to be wide and X→DD dominant
  - Quantum numbers established: 1^{++}
  - It does not fit into the charmonium model
- Note: $$m(X) \approx m(D) + m(\overline{D}^{*0})$$
- Leading contender: a bound state of two D mesons
  - i.e.: a D^0D^{*0} molecule
  - Supported by predictions of mass, decay modes, J^{PC}, branching fractions
- Other exotic predictions:
  - "Tetraquark" 4-quark bound state
  - "Glueball" gluon bound state, charmonium-gluon hybrid

Nuclear-Bound Quarkonium

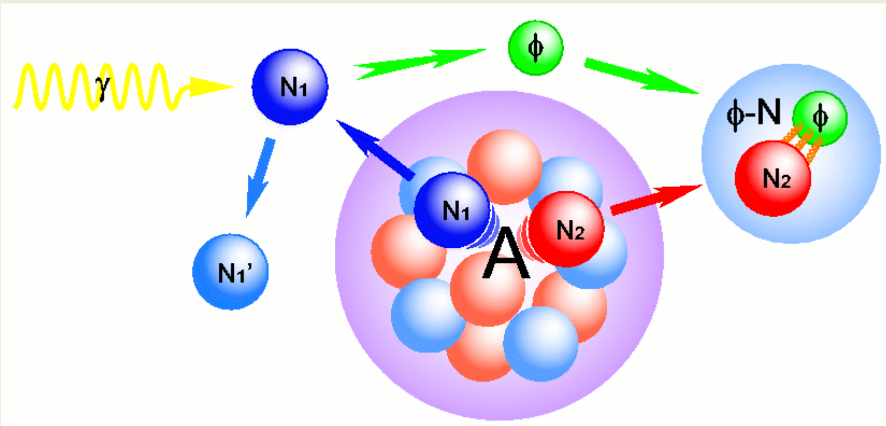
- **Proton-proton scattering:** intriguing behavior in spin correlation, nuclear transparency
- **QCD van der Waals interaction**, mediated by *multi-gluon exchanges*, is dominant when the two interacting color singlet hadrons have **no common quarks**. ***QCD analog*** of the attractive QED van der Waals potential
- No Pauli blocking, effective quarkonium-nuclear interaction will not have a short-range repulsion
- S. J. Brodsky, I. A. Schmidt, and G.F. de Teramond, Phys. Rev. Lett. **64**, 1011 (1990); Luke, Manohar and Savage
- Suggested a bound state of charm quarkonium to ^{3}He nucleus: η_c-^{3}He by studying proton capture on deuteron
- Binding energy ~ 20 MeV, width ~ tens of keV.
- D. A. Wasson, Phys. Rev. Lett. **67**, 2237 (1991).

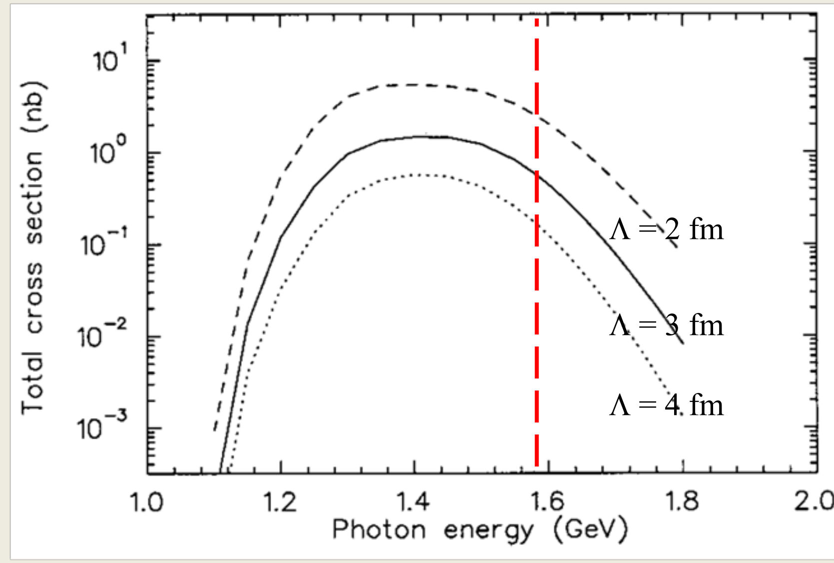
ϕ-N Bound State (suggested by Isgur)?

- H. Gao, T.-S. H. Lee, and V. Marinov, Phys. Rev. C **63**, 022201R (2001).
  - The interaction is expected to be enhanced by $(m_c/m_s)^3$, following Brodsky *et al.* PRL 64, 1011 (1990) $V_{(q\bar{q})A} = -\frac{\alpha e^{-\mu r}}{r}, \ \alpha = 1.25, \ \mu = 0.6$
  - Varitional method with
  - ***Binding energy ~ 2 MeV***
  - ϕ-N can be formed inside heavy nuclei through quasi-free ϕ photoproduction.

Creation of ϕ-N Bound State in Heavy Nuclei

ϕ production threshold
on Hydrogen target





H. Gao, T.-S. H. Lee, and V. Marinov,
Phys. Rev. C **63**, 022201 (2001)

- "Sub-threshold" generated ϕ is slow enough to bound with nucleon
- $\sigma^{tot} \sim 1.4$ nb on ^{12}C nucleus.

ϕ-N bound state in chiral quark model

- Huang, Zhang and Yu, Phys. Rev. C **73**, 025207 (2006)
- Chiral SU(3) quark model and the extended chiral SU(3) quark model solving the Resonant Group Method (RGM) equation
- Model parameters from previous work give good descriptions of
  - Baryon ground states
  - Deuteron binding energy
  - NN scattering phase shifts
- Extended chiral quark model plus channel coupling effect $\rightarrow$ ϕ-N quasi-bound state with several MeV of binding energy

Possible Way to Detect ϕ-N

- "Sub-threshold" ϕ production in nuclei.
  - Can use real photon, electron or proton beam.
  - Need to tag energy of real/virtual photon.
- Detect all final states of ϕ-N bound state decay to reconstruct its invariant mass.
  - $\phi\text{-}N \rightarrow p_2' + K^+ + K^-$: triple coincidence
  - Other decay channels (suggested by M. Strikman)
- Jefferson Lab Hall B CLAS12 is a possible place to search for such particle:
  - Large acceptance detector and tagged photon beam.
  - Good particle identification.

Background Channels

- Four major background channels
  - Direct production:

$$\gamma + p_1 \rightarrow p_1' + K^+ + K^-$$

  - No Bound State:

$$\gamma + p_1 \rightarrow p_1' + \phi \rightarrow p_1' + K^+ + K^-$$

  - Λ(1520) Production:

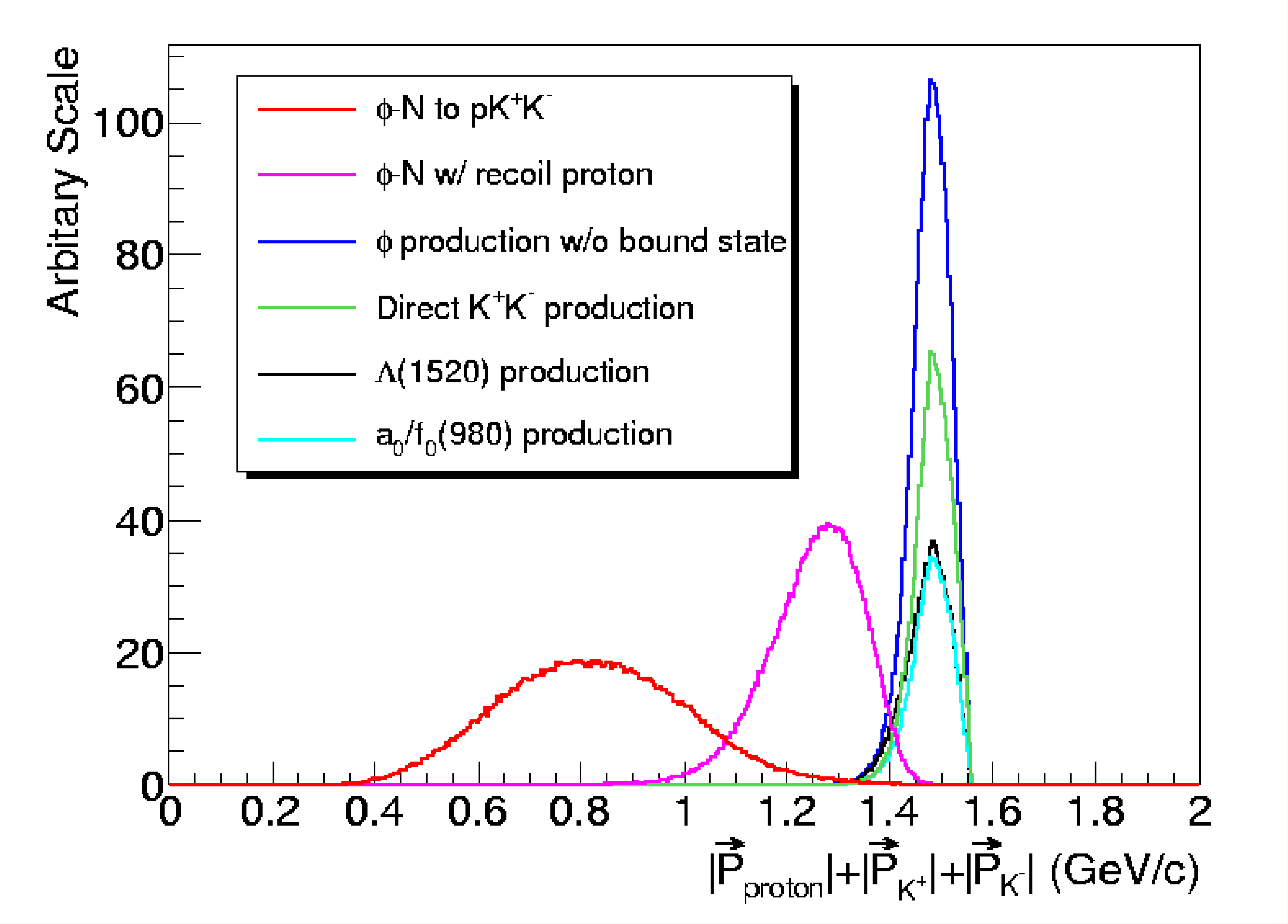
$$\gamma + p_1 \rightarrow \Lambda(1520) + K^+ \rightarrow p_1' + K^- + K^+$$

  - a_0/f_0 production

$$\gamma + p_1 \rightarrow p_1' + a_0 / f_0 \rightarrow p_1' + K^+ + K^-$$

- Bound state formed but K^+ K coincide with the recoil proton p_1'.

Phase Space simulation results



5 MeV width assumed for the bound state, photon energy 1.5-1.55 MeV, Cu target

Other decay channels of phi-N?

- Two channels have larger phase spaces
  - Decay into Lambda and kaon:

$$\phi - N \rightarrow \Lambda^0 + K^+ \rightarrow p + \pi^- + K^+$$

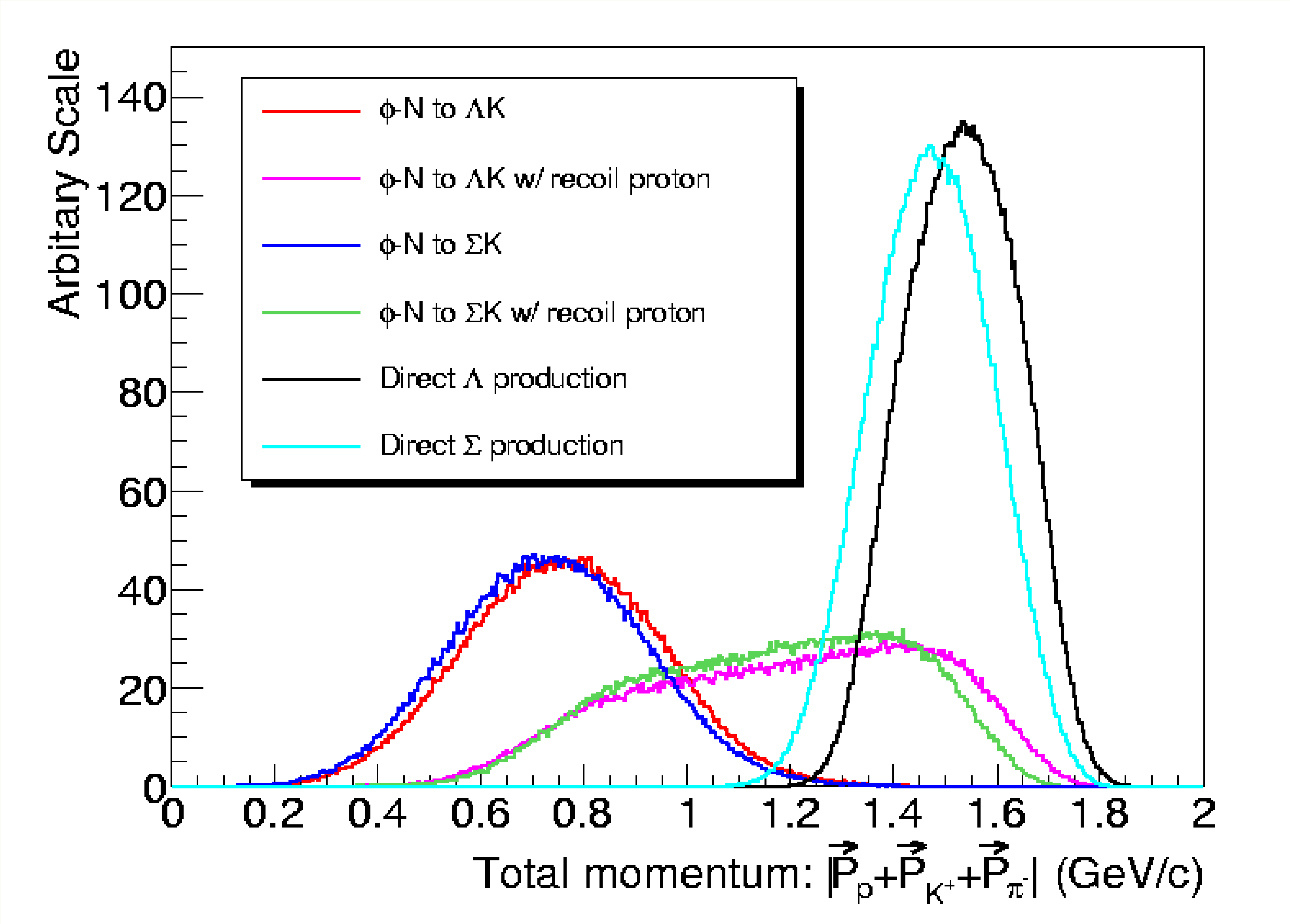
  - Decay into Sigma and kaon:

$$\phi - N \rightarrow \Sigma^0 + K^+ \rightarrow \Lambda^0 + \gamma + K^+ \rightarrow p + \pi^- + \gamma + K^+$$

- Simulations carried for these two decay channels

Phase Space Simulation

- Performed by Y. Qiang.
- One nuclear target as a test case: ^{63}Cu.
- Fermi motion and missing energy distributions were taken into account in the simulation of quasi-free process.
- Simulations also taken into account two phi-N state widths: 5 MeV and 50 MeV
- The following results were from ^{63}Cu target with photon energy $E\gamma = 1.50 \sim 1.55$ GeV.



Results shown with 5 MeV width

Theoretical issues and help needed

- Final state interaction of the bound state with other nucleons inside the nucleus
  - **Light nuclei better suggested by Strikman**
  - **CLAS g3 (S. Malace et al.)**
- Theoretical investigation of the width and the decay branching ratio of the bound state
- More theoretical study of the production cross section
- Can one observe such a state on the lattice (private communications with K.F. Liu)?

Summary

- **Φ –meson production from nuclear targets is a rich area of research**
  - **Larger ϕ-N total cross section**
  - **Observed below CLAS threshold phi-meson production**
- ***ϕ-N* bound state predicted to have moderate cross section in sub-threshold *ϕ* photo-production**
- **Potential decay channels of KK, KLambda, and KSigma investigated, promising for identifying the bound state**
- **Jefferson Lab Hall B CLAS12- an excellent place to carry out the search**
- **Ongoing study with Anke at COSY (Q.J. Ye, H. Gao, M. Hartmann)**
- **Study of smalll configuration at high t**

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