光を用いたΦ中間子生成とΘ$^+$生成の研究

三部　勉

高エネルギー加速器研究機構

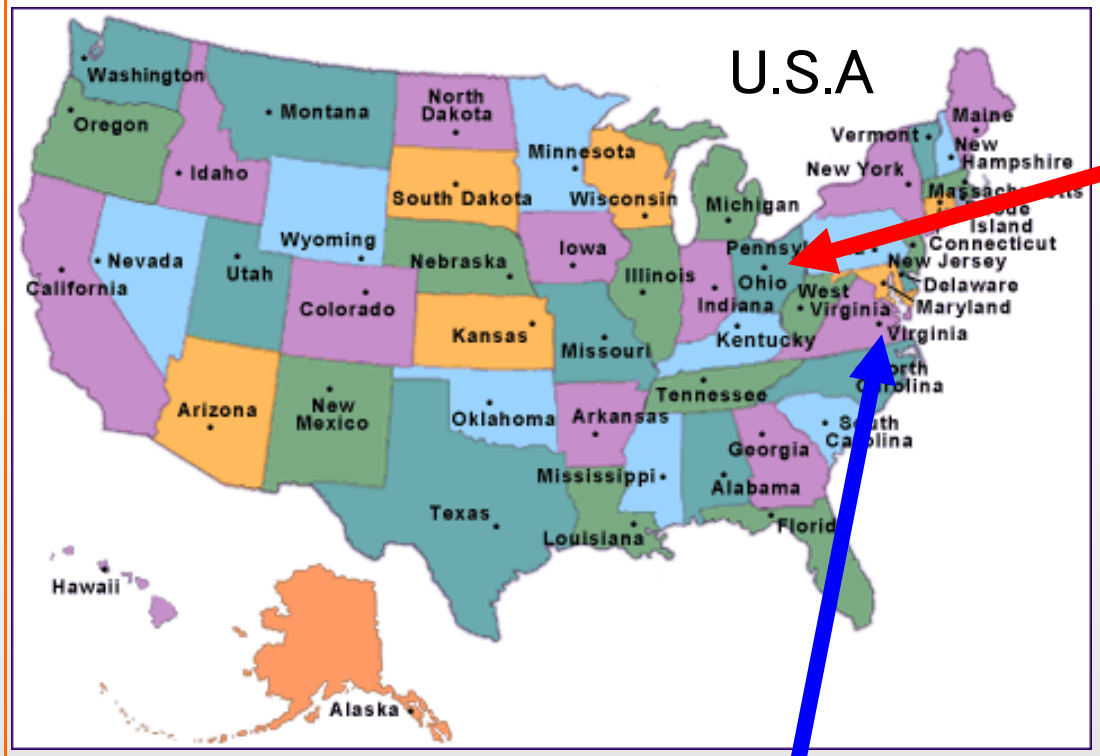
略歴

- LEPS/Spring-8 (1998-2004)
  - 大阪大学理学研究科物理学専攻博士課程
  - 日本学術振興会特別研究員（PD）
  - ハドロン光生成（Φ中間子、ペンタクォーク）
- CLAS/Jefferson Lab (2004-7007)
  - 米国オハイオ大学研究員
  - ハドロン光生成（Φ、K*、Λ(1520)、ペンタクォーク）
- PHENIX/BNL (2007-)
  - 高エネルギー加速器研究機構研究員
  - 偏極陽子衝突からのWボソン生成、MuTr FEE upgrade

概要

- Jefferson研究所
- ペンタクォーク光生成
  - $\gamma d \rightarrow \Theta^+ K^- p$ (PRL 96, 212001 (2006))
  - $\gamma d \rightarrow \Theta^+ \Lambda$ (PRL 97, 032001 (2006))
  - $\gamma d \rightarrow \Theta^+ \Lambda(1520)$
- Φ中間子光生成
  - $\gamma p \rightarrow \phi p$ (PRL 95,182001 (2005) (LEPS))
  - $\gamma d \rightarrow \phi d$ (PRC 76, 052202 (2007))
- テトラクォーク光生成 (approved by PAC in 2007)
  - $\gamma He^4 \rightarrow C(1480)He^4$, $C(1480) \rightarrow \phi\pi$
- まとめ

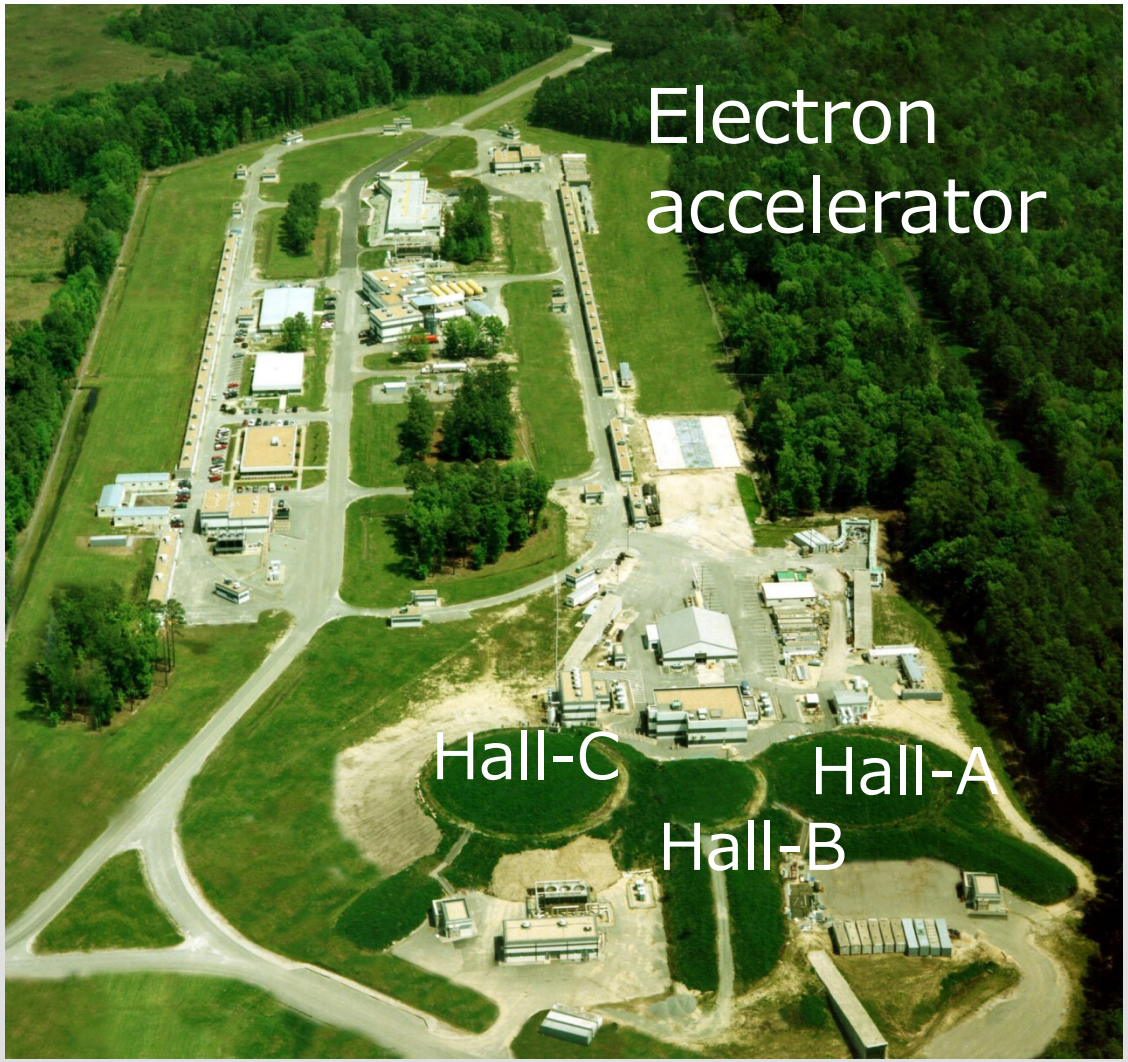
Jefferson Lab and Ohio University



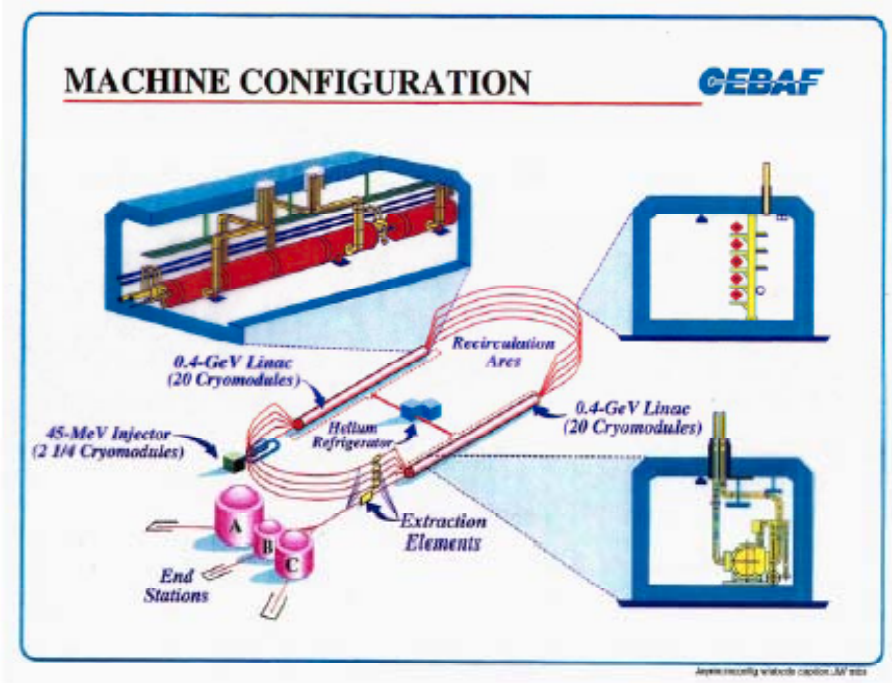
Ohio University
Athens, OH

Jefferson laboratory
Newport News, VA

Jefferson Laboratory



Jefferson Lab



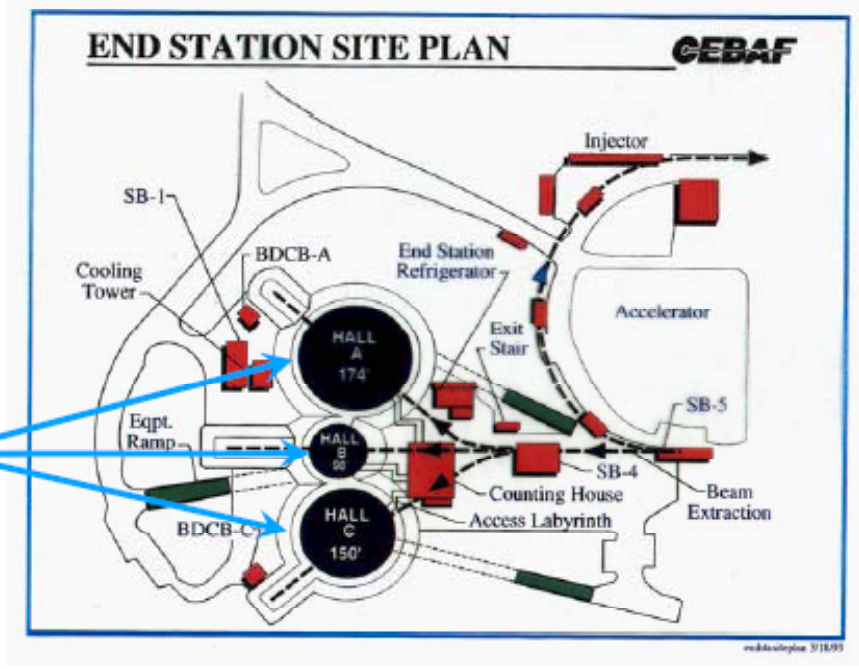
CEBAF is a superconductive electron accelerator

→ continuous beam

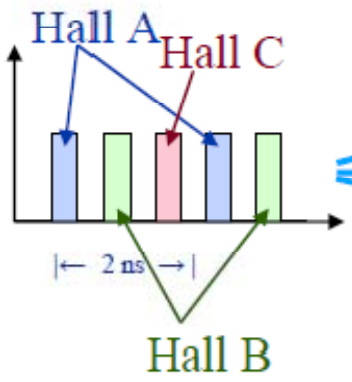
→ high longitudinal polarization

→ energy range → 0.75 –5.9 GeV

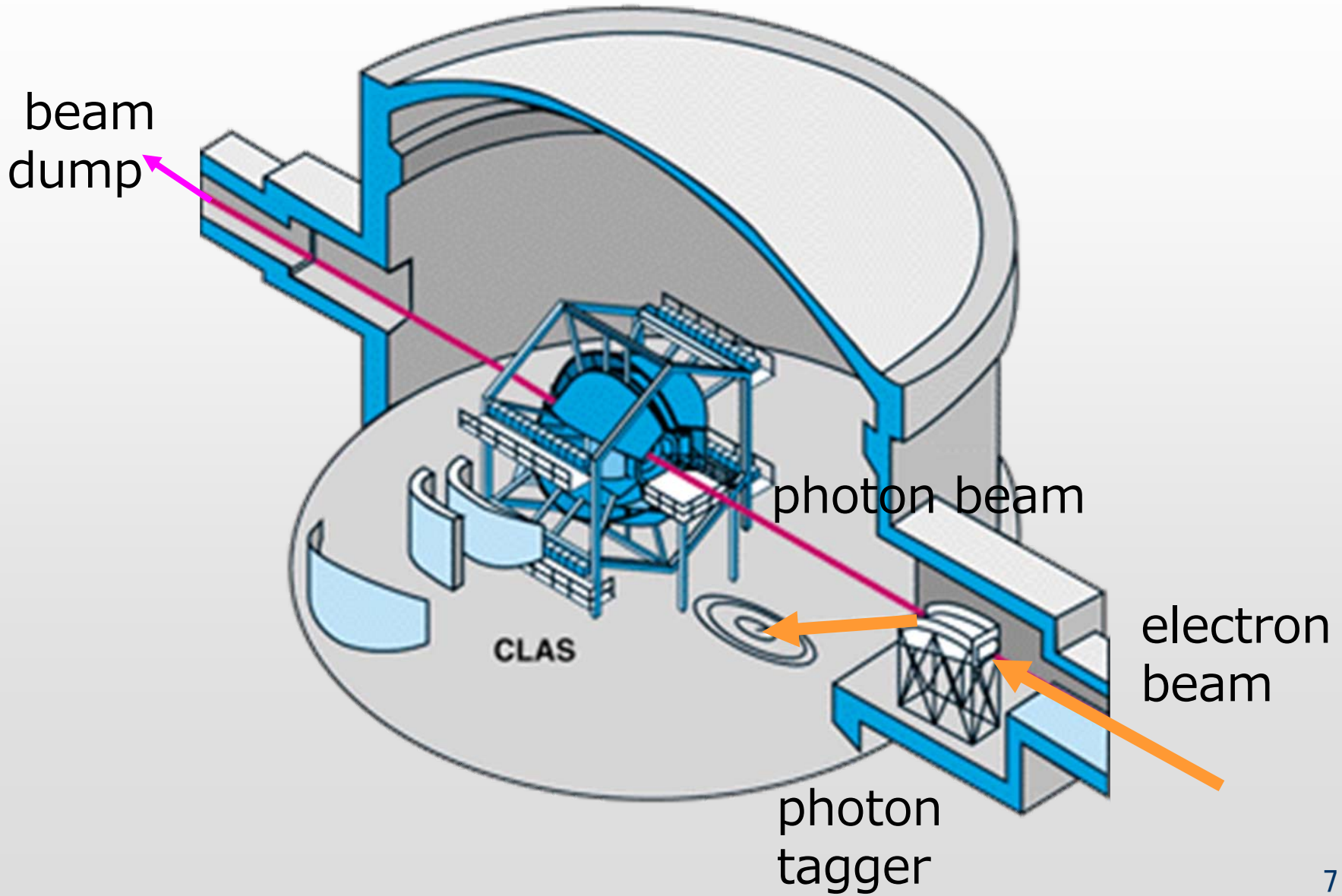
→ current range → 0.1 nA –200mA



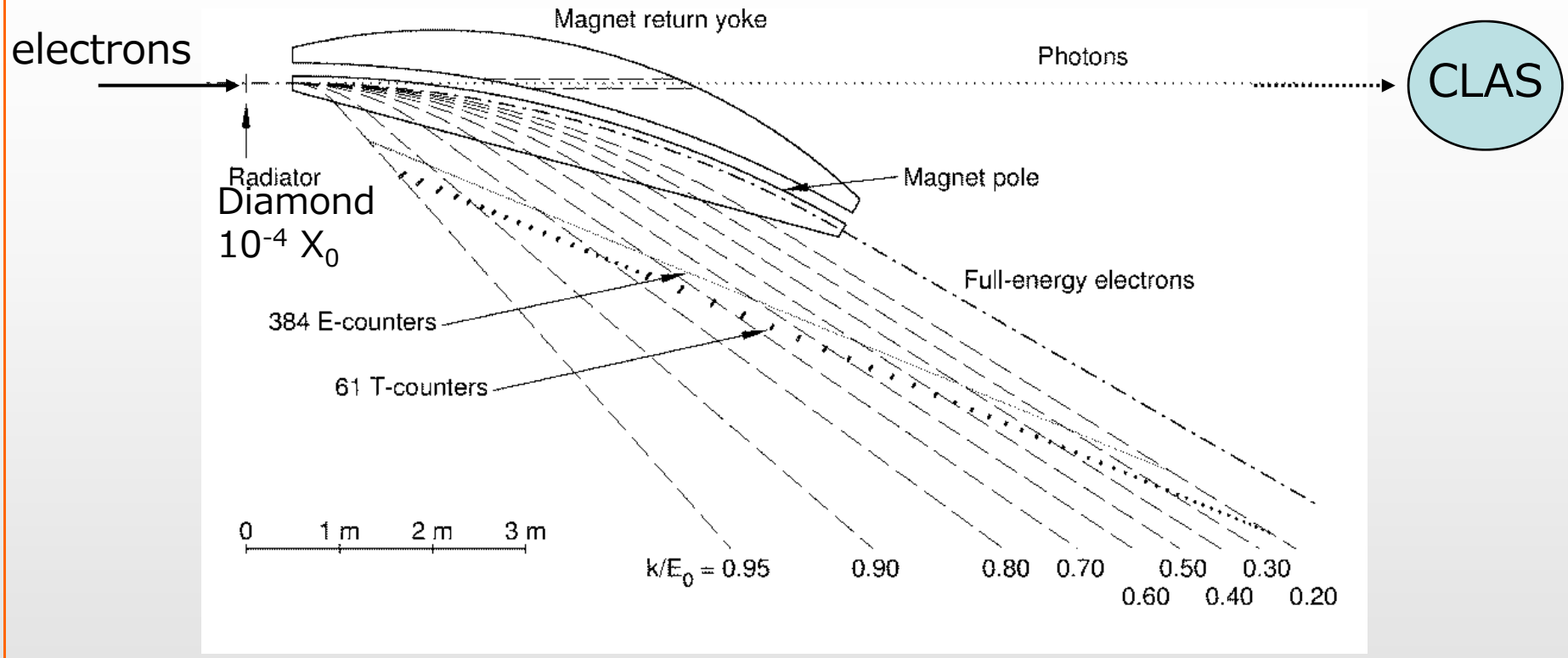
The electron beam can be delivered simultaneously to the three halls with high polarization



Experimental Hall-B



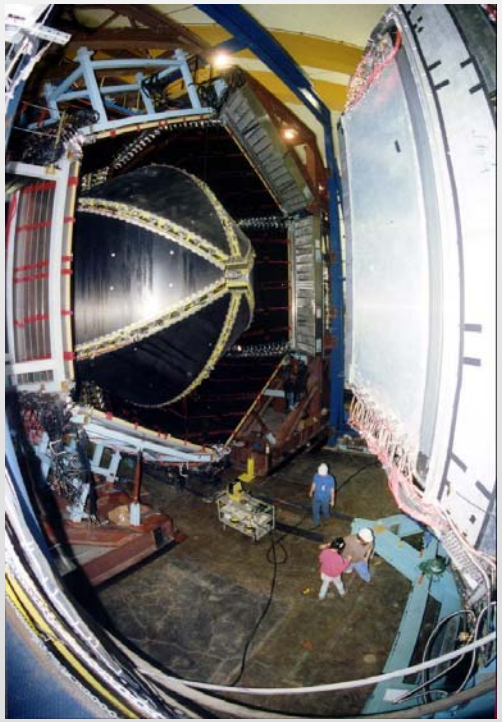
Bremsstrahlung tagged photon beam

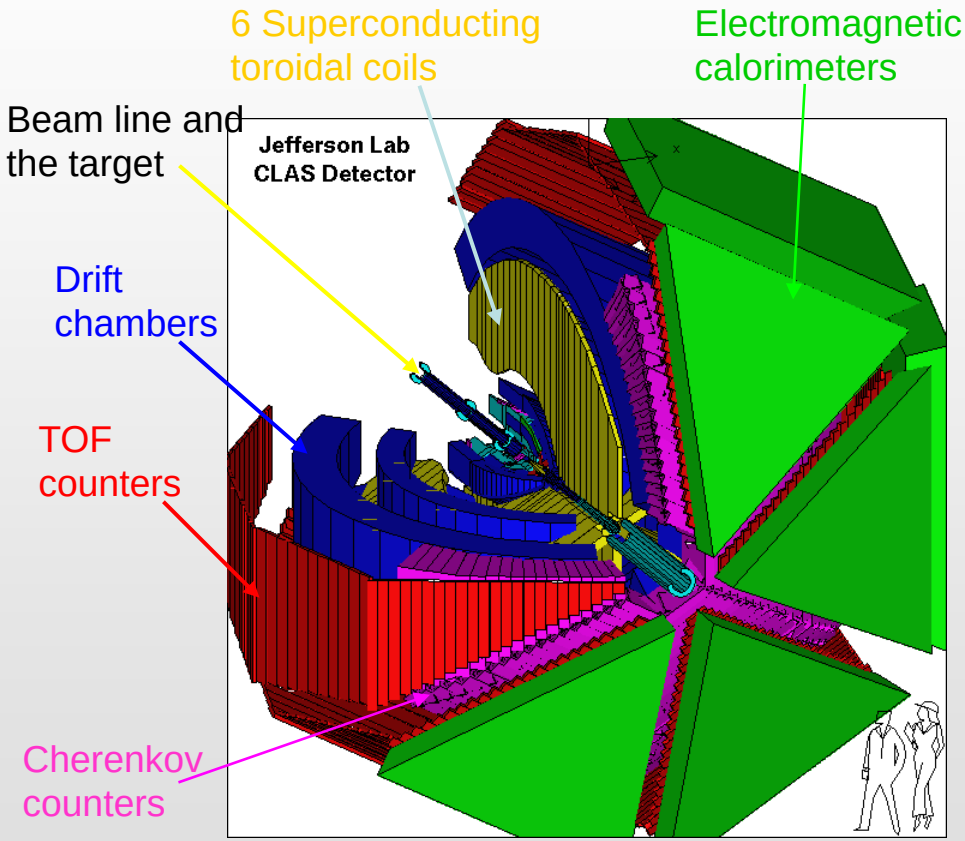


- Unpolarized/Circularly polarized photon (Linear pol. is optional)
- Tagging range: (0.2-0.95)E_e, E_e(Max) = 6 GeV
- Photon flux ~10^7/sec
- $\Delta E_\gamma / E_\gamma$ ~0.1%

Hall-B CLAS

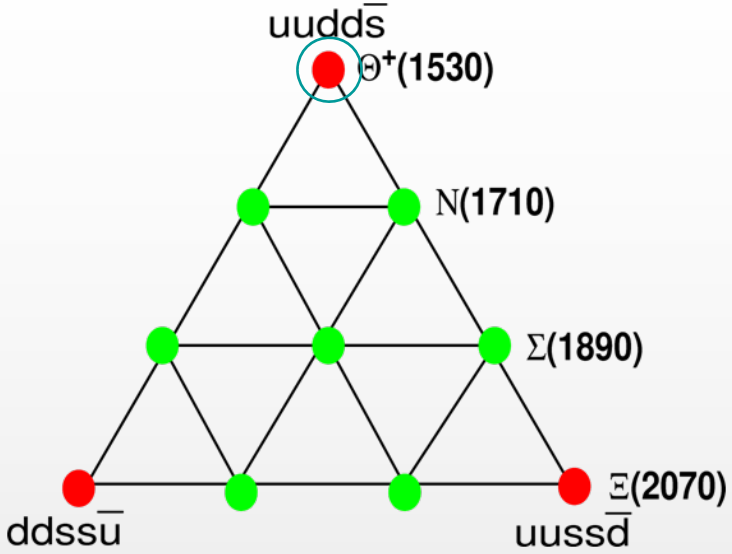
- CEBAF Large Acceptance Spectorometer
  - Large acceptance for charged particle tracks
  - TOF resolution < 0.2 ns
  - $\Delta p/p < 1$ %
  - Sensitive to neutral tracks at forward angles





ペンタクォーク光生成

What are Pentaquarks?



- Objects with 4 quarks and 1 anti-quark
- Example: $uudd\bar{s}$ (exotic); The "Θ^+"
  - Baryon number = 1/3 + 1/3 + 1/3 + 1/3 - 1/3 = 1
  - Strangeness = 0 + 0 + 0 + 0 + 1 = +1
- Early history:
  - Bag models: R.L.Jaffe (76), deSwart(80)
  - Soliton models: Diakonov, Petrov (84); Chemtob(85); Praszalowicz(87), Walliser(92)
- Experimental data
  - 12 papers claimed evidence of Θ^+
    - $\Theta^+ \rightarrow K^+ n,\ \bar{K}^0 p$
    - M = 1533.6 ± 2.4 MeV (S=2.1)
    - Γ = 0.9 ± 0.3 MeV
  - 16 papers reported negative results

PDG'04: Θ^+ *** → PDG'06 * → PDG'07 no stars

Citation: W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006) and 2007 partial update for edition 2008 (URL: http://pdg.lbl.gov)

$\Theta(1540)^+$

$I(J^P) = 0(?^?)$

OMITTED FROM SUMMARY TABLE

A REVIEW GOES HERE – Check our WWW List of Reviews

$\Theta(1540)^+$ MASS

The note below, from the 2006 Review, lists 10 papers on searches for the $\Theta(1540)$ with negative results. Since then, there have been six more such papers (four of them from the CLAS experiment) AKTAS 06B, DEVITA 06, KUBAROVSKY 06, LINK 06C, MCKINNON 06, and NICCOLAI 06. Two other papers, MIWA 06 and PANZARASA 06, did find a peak at about the right mass, but only at the 2.5-to-2.7 standard deviation level. We will summarize all these results in a table in the 2008 Review.

Since our 2004 edition, there have been several new claimed sightings of the $\Theta(1540)^+$ (see entries below marked with bars to the right), but there have also been several searches with negative results:

In general, these experiments with negative results have many more events than do the experiments with positive results. Some, but not all, involve reactions or energies different from those giving positive results.

Furthermore, the $\Theta(1540)^+$ finds no support from the claimed observations of other pentaquarks, the $\Phi(1860)$ and the $\Theta_c(3100)$; for each of these, there are several non-sightings against a single claim of sighting. (See the Listings following the $\Theta(1540)^+$.) We have reduced the status of the $\Theta(1540)^+$ to no stars.

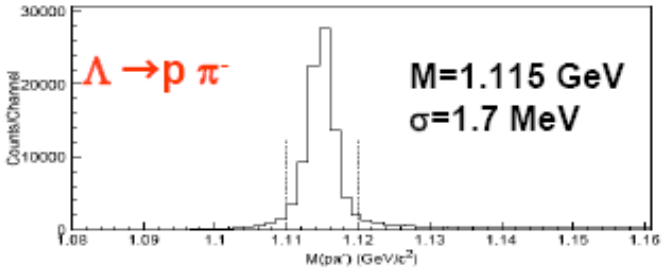
Dedicated experiments for pentaquark at CLAS

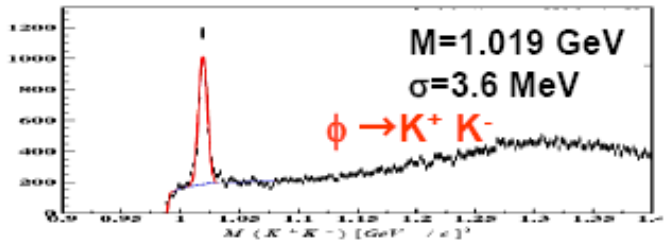
- g10
  - Photoproduction on deuterium at $E_\gamma < 3.6$ GeV
  - Completed in 2004
- g11
  - Photoproduction on proton at $E_\gamma < 3.8$ GeV
  - completed in 2004
- eg3
  - Photoproduction on deuterium at $E_\gamma < 5.6$ GeV
  - completed in 2005

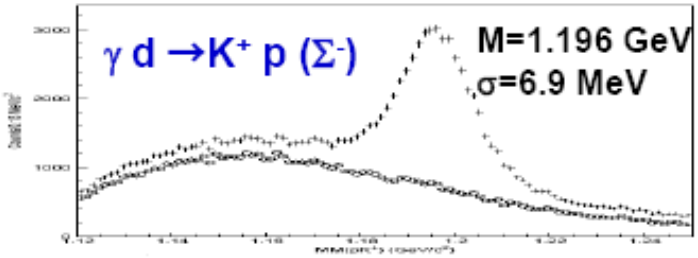
CLAS pentaquark searches

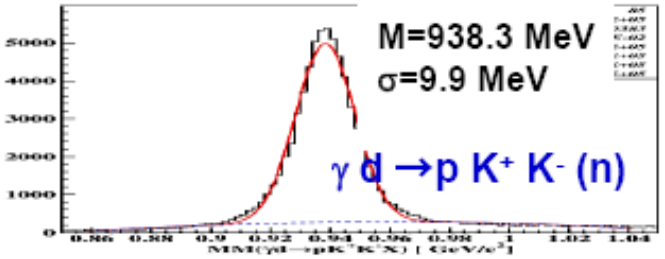
- Θ^+ pentaquark searches — **data sets**
  - $\gamma p \rightarrow \Theta^+ \overline{K}^0$, $\Theta^+ \rightarrow nK^+$, pK^0 — **g11**
  - $\gamma d \rightarrow \Theta^+ pK^-$ — **g10**
  - $\gamma d \rightarrow \Theta^+ \Lambda(1116)$ — **g10**
  - $\gamma d \rightarrow \Theta^+ \Lambda(1520)$ — **g10**
- Θ^{++} pentaquark search
  - $\gamma p \rightarrow \Theta^{++} K^-$ — **g11**
- Φ^{--} ($\Xi^{--}(1860)$) pentaquark search
  - $\gamma d \rightarrow \Phi^{--} X$, $\Phi^{--} \rightarrow \Xi^- \pi^-$, $\Xi^- \rightarrow \Lambda \pi^-$ — **eg3**

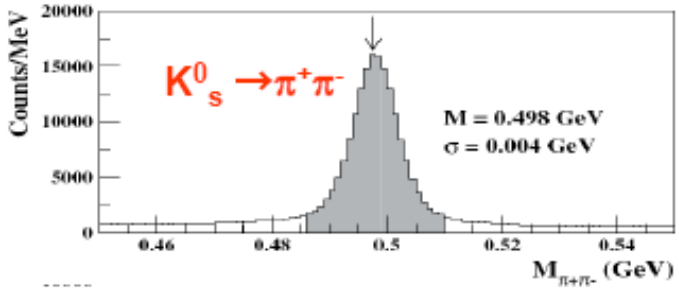
CLAS Hadron identification

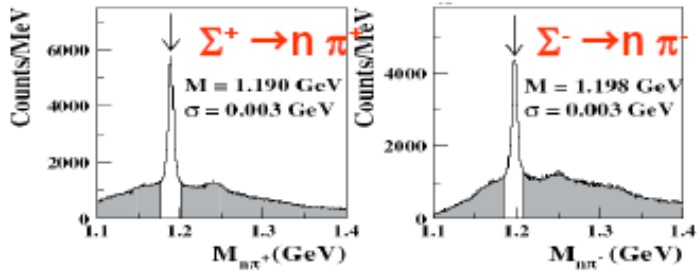


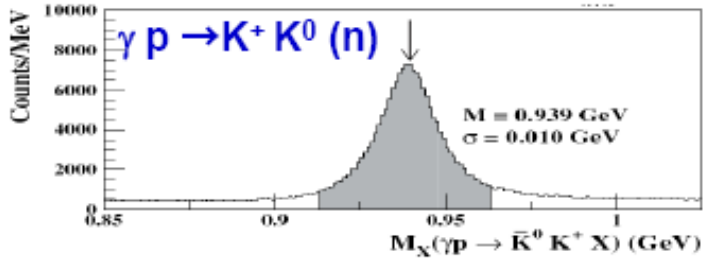












CLAS measures masses at the level of 1-2 MeV

Resolution: few MeV for invariant masses
10 MeV for missing masses

CLAS g10 experiment

$$\gamma d \rightarrow h^{\pm} h^{\pm} X$$

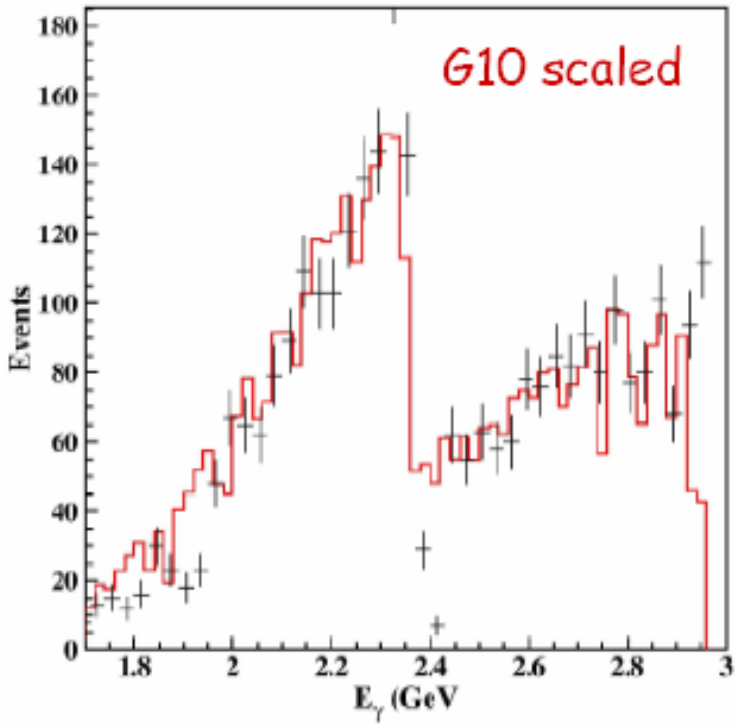
- Primary Goal : Confirmation of previously-reported CLAS Θ^+ signal with higher statistics

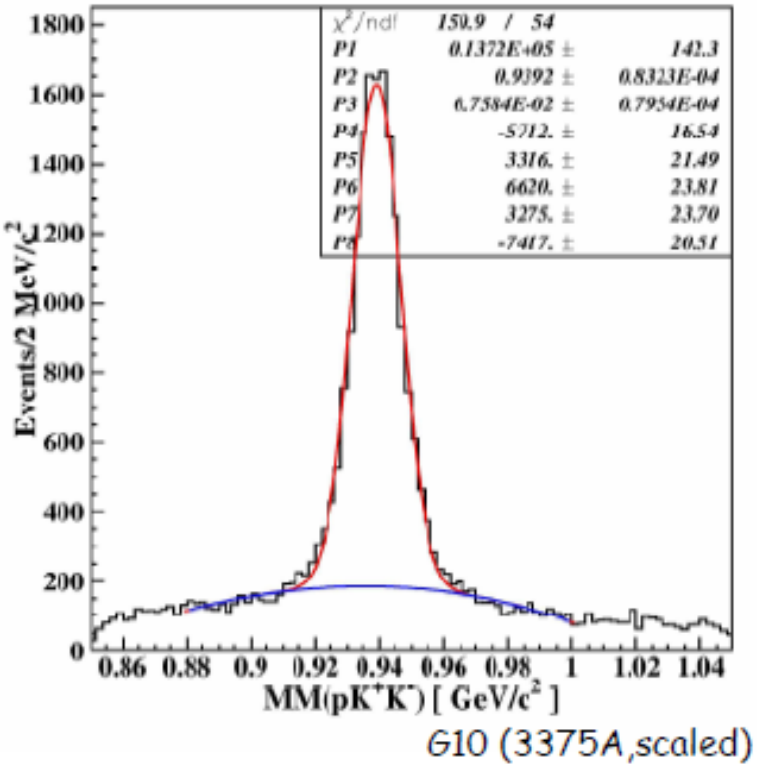
- Beam: real photon
- Target: LD_2 target (24cm-long)
- Tagged photon energy: $0.8 < E_\gamma < 3.6$ GeV
- Integrated luminosity: $50 pb^{-1}$ ($1.3 < E_\gamma < 3.6$ GeV)
- Trigger: two charged particles in different CLAS sectors.
- CLAS Torus settings: 3375 A (higher resolution) and 2250 A (larger acceptance)

$\gamma d \rightarrow \Theta^+ p K^-$, $\Theta^+ \rightarrow n K^+$

- The same photon beam energy spectrum as for previous measurements.

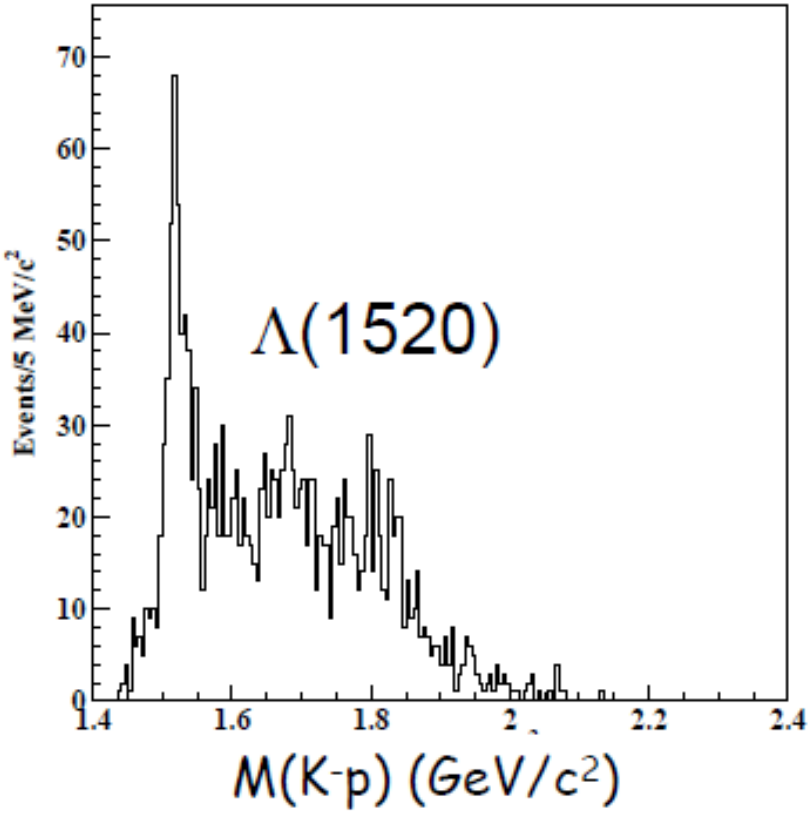
- Event selection criteria:
  - PID (using exclusivity of the channel)
  - 3σ cut on missing neutron mass peak and the neutron momentum >0.08 GeV/c



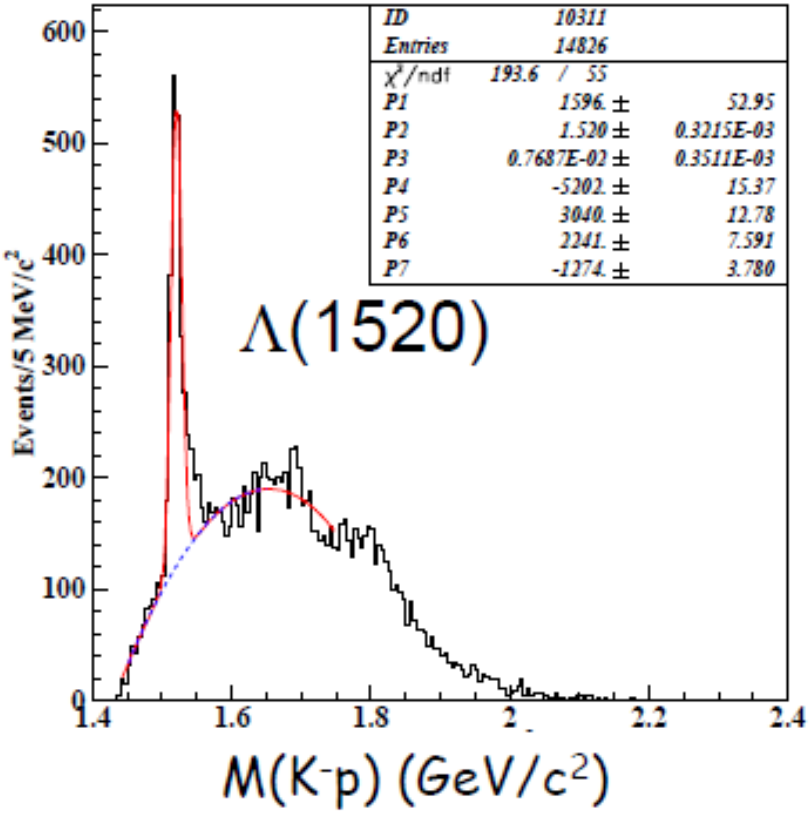


Comparison with previous data

Published data



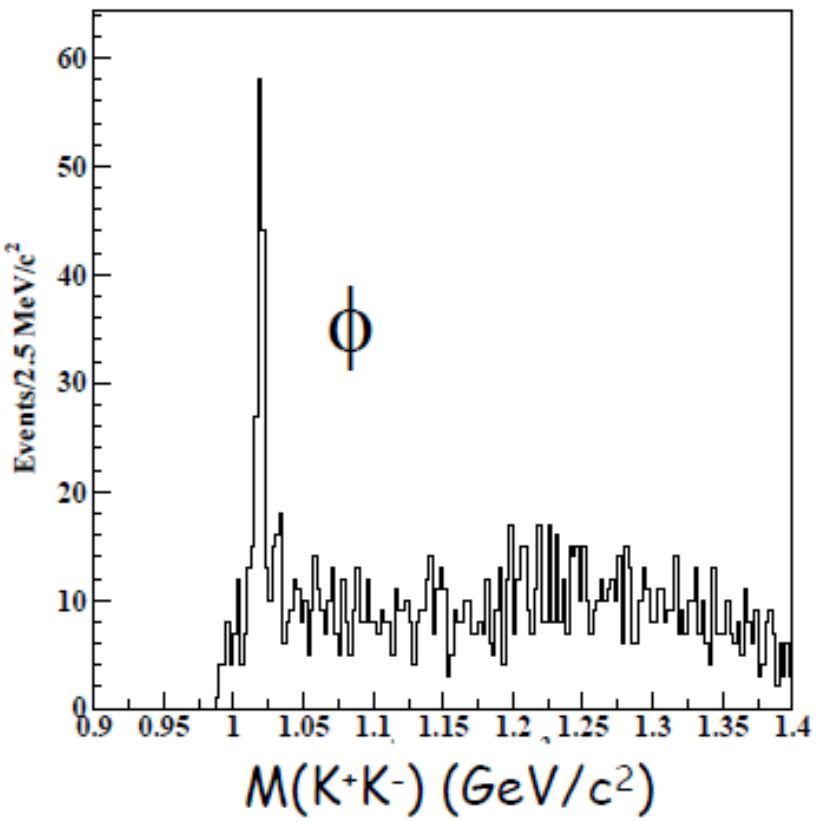
G10 (3375A,scaled)



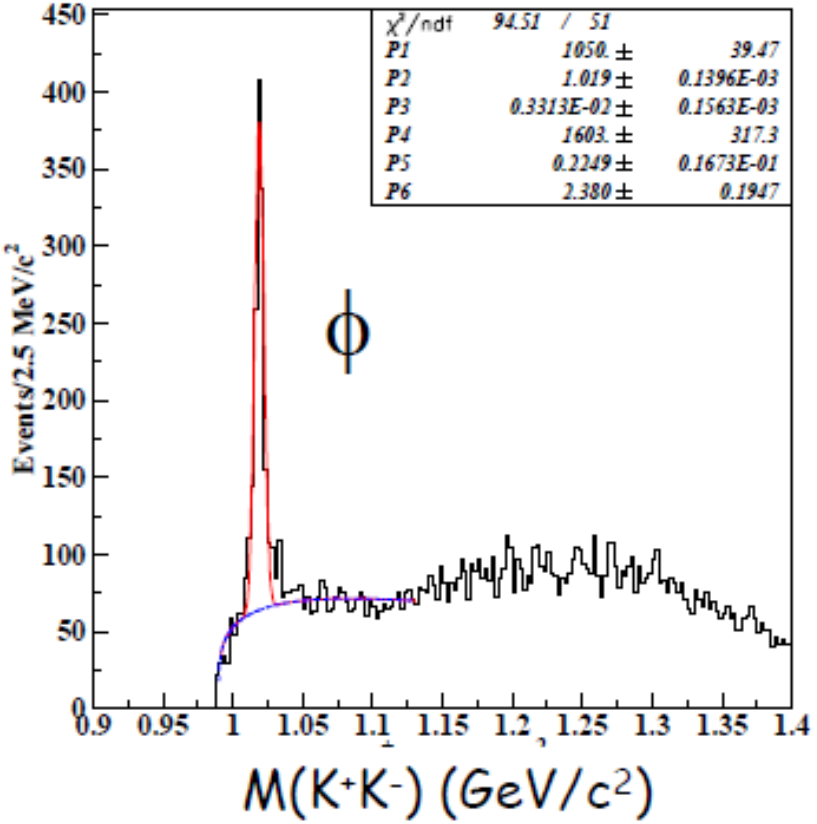
- G10 data is scaled to match the beam energy and acceptance for published data

Comparison with previous data

Published data



G10 (3375A,scaled)

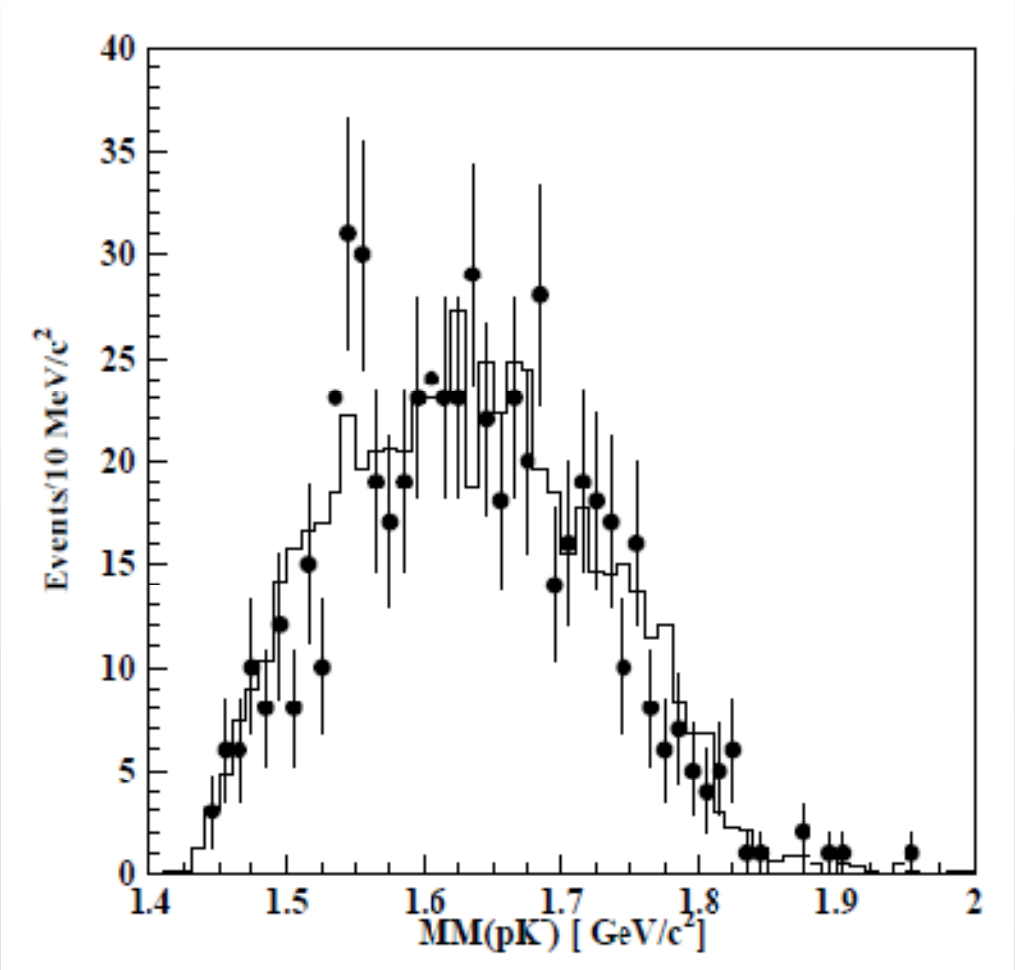


- G10 data is scaled to match the beam energy and acceptance for published data

$\gamma d \rightarrow \Theta^+ p K^-$, $\Theta^+ \rightarrow n K^+$

● : previous data

histogram : new data (scaled down by 5.9)



- Same reaction and same condition as the CLAS published paper, with much more statistics
- Previous peak could not be reproduced under similar conditions.
- Statistical significance of old peak is reduced from 5.2 σ to 3.1 σ when new data is used as background.

Bayesian analysis of CLAS Θ^+ signal

- Baye's theorem

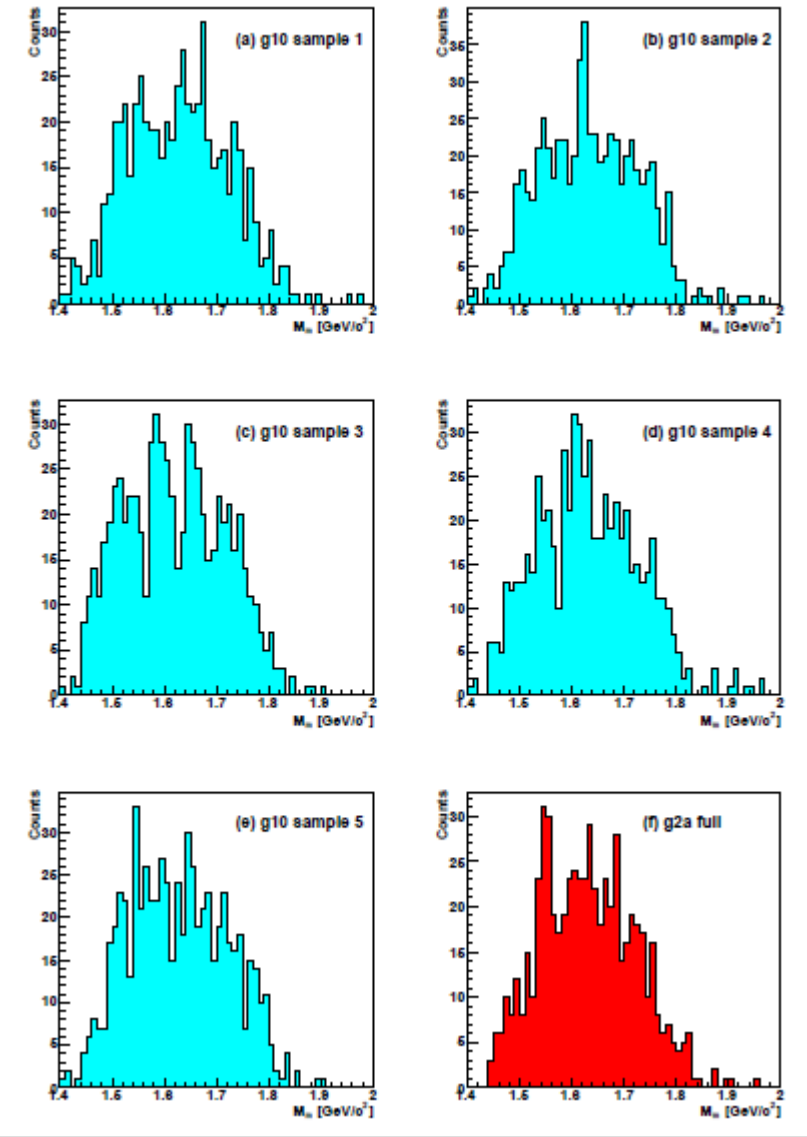
$$P(M \mid D) = \frac{P(D \mid M)\, P(M)}{P(D)},$$

  - P(M|D) : probability that model (M) is true given some observed data (D)
  - P(D|M) : probability of the data being observed given the model
  - P(M): probability of the model being correct
  - P(D): normalization constant

- Evidence ratio (~likelihood ratio)

$$R_E = \frac{P(M_P \mid D)}{P(M_0 \mid D)} = \frac{P(D \mid M_P)}{P(D \mid M_0)} \times \frac{P(M_P)}{P(M_0)}$$

$$\ln(R_E) = \ln P(D \mid M_P) - \ln P(D \mid M_0)$$

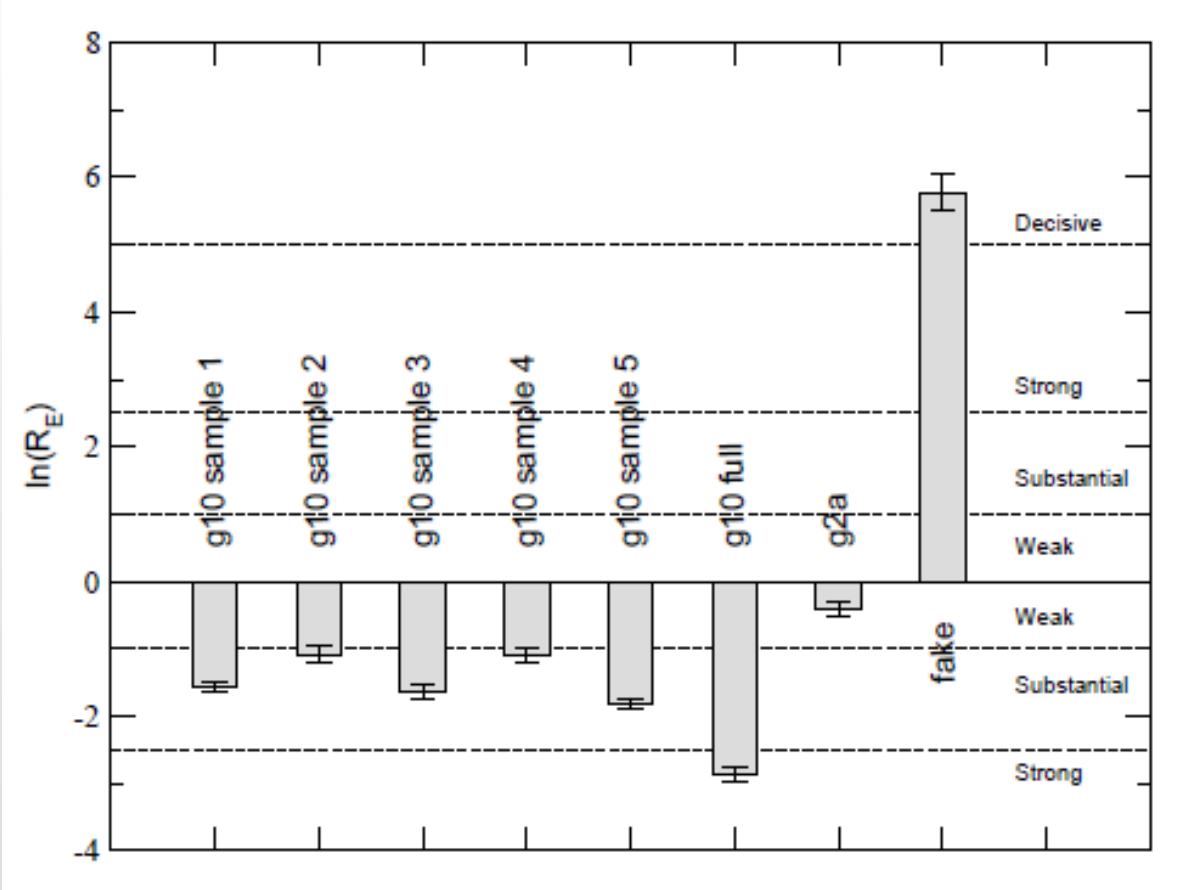


arXiv:0709.3154 [hep-ph]

Evidence ratio

$$\ln(R_E) = \ln P(D \mid M_P) - \ln P(D \mid M_0)$$

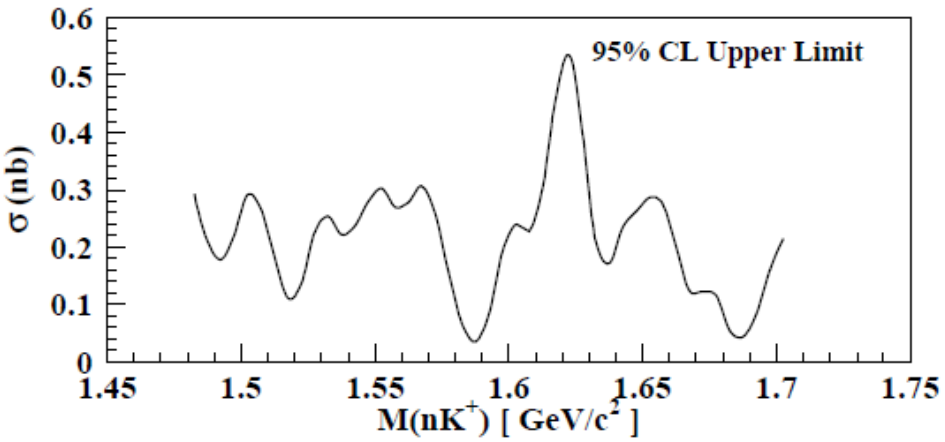
M_p : BG+narrow peak
M_0 : BG



Data sample	$\ln(R_E)$		
g10 sample 1	-1.56	±	0.07
g10 sample 2	-1.09	±	0.13
g10 sample 3	-1.64	±	0.09
g10 sample 4	-1.11	±	0.11
g10 sample 5	-1.82	±	0.07
g10 full	-2.87	±	0.11
g2a	-0.41	±	0.10
fake	5.78	±	0.27
g2a $\Lambda(1520)$	96.70	±	0.70
g10 $\Lambda(1520)$	549.12	±	2.17

arXiv:0709.3154 [hep-ph]

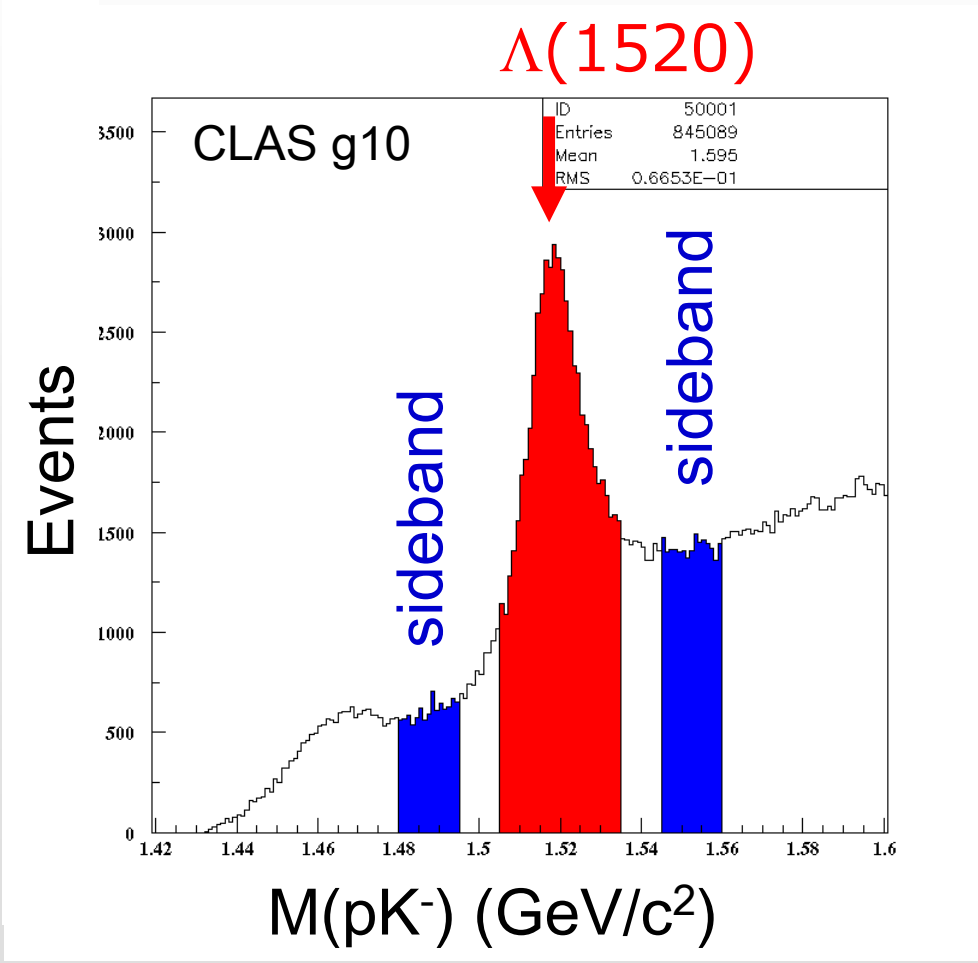
$\gamma d \rightarrow \Theta^+ p K^-$, $\Theta^+ \rightarrow n K^+$



- Cross section upper limit for $\gamma d \rightarrow K^- \Theta^+ p$ (p>350 MeV/c)
  - 0.5 nb (95%CL)
- Upper limit for the quasi-free reaction $\gamma n \rightarrow K^- \Theta^+$ (proton spectator, LEPS channel)
  - Need extrapolation from rescattering region (Fermi momentum tail) to quasi-free part. Estimated from $\Lambda(1520)$ events
  - ~3 nb (95%CL)
  - LEPS cross section 100 nb for the constant matrix element.

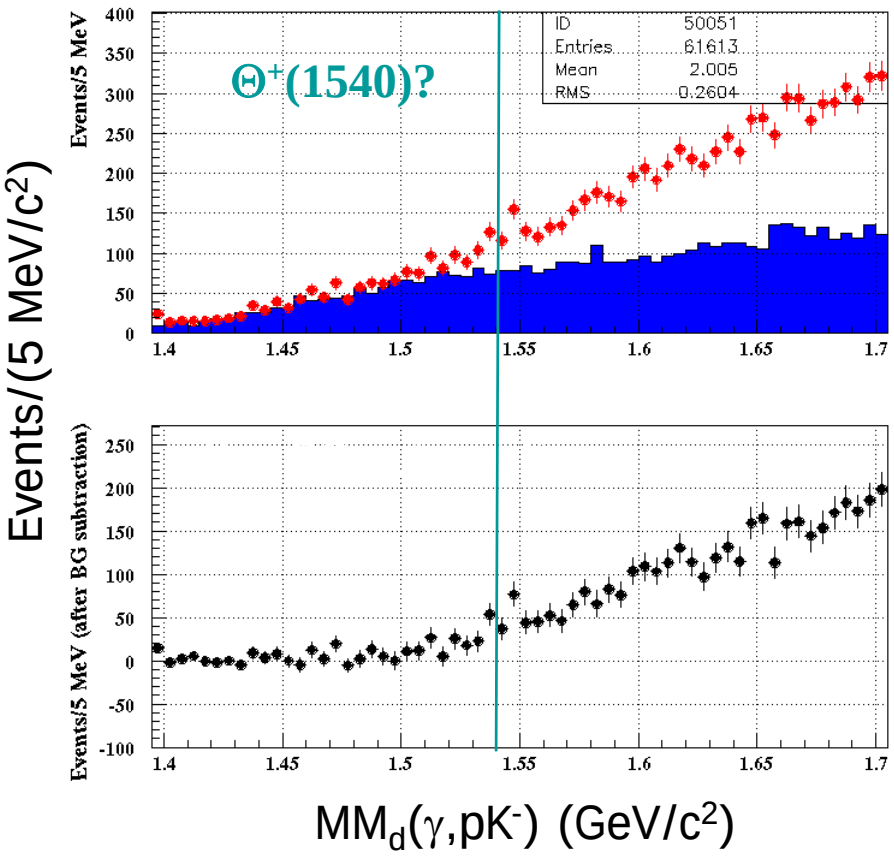
$\gamma d \rightarrow \Theta^+ \Lambda(1520)$

- Θ^+ peak was seen in the same reaction with forward going $\Lambda(1520)$ at LEPS. CLAS is sensitive to backward going $\Lambda(1520)$.
- $\Lambda(1520)$ selection : $1.505<M(pK^-)<1.535$ GeV/c^2
- Remaining BG
  - non-resonant pK^- pair from $\gamma d \rightarrow pK^-X(X=K^+n, K^0p,\ldots)$
  - $p\pi^-$ pair from 3 pion (or more) production ($\pi^+\pi^-\pi^0pn$, $\pi^+\pi^-\pi^-pp$)
- BG was subtracted based on sidebands.

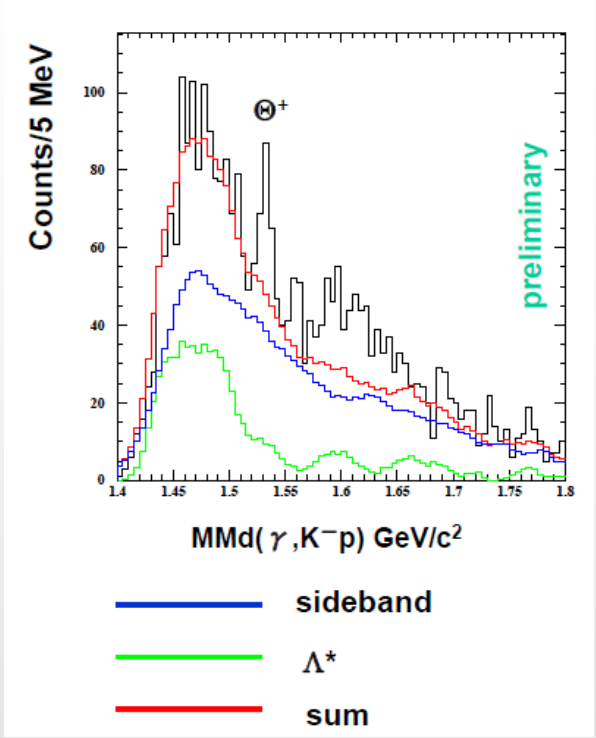


$\gamma d \rightarrow \Theta^+ \Lambda(1520)$

Red : $\Lambda(1520)$ region
Blue: sidebands



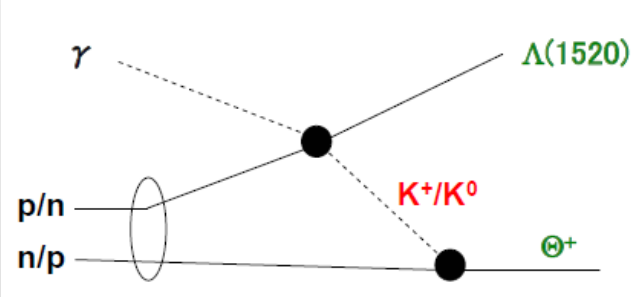
LEPS



- The LEPS Θ^+ peak could not be confirmed by CLAS.

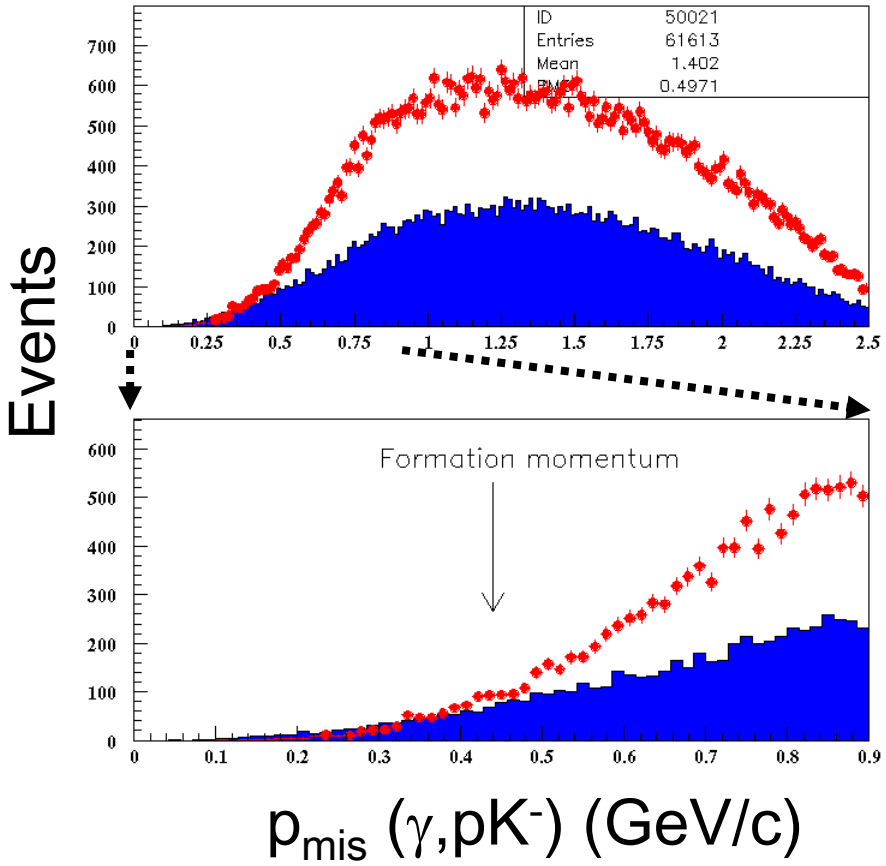
$\gamma d \rightarrow \Theta^+ \Lambda(1520)$

- Suppose Θ^+ is formed by nearly on-shell kaon exchange followed by the $\Lambda(1520)$ photo- production on nucleon, kaon momentum can be inferred from the missing momentum ($p_{mis}=p_\gamma-p_{\Lambda(1520)}$)



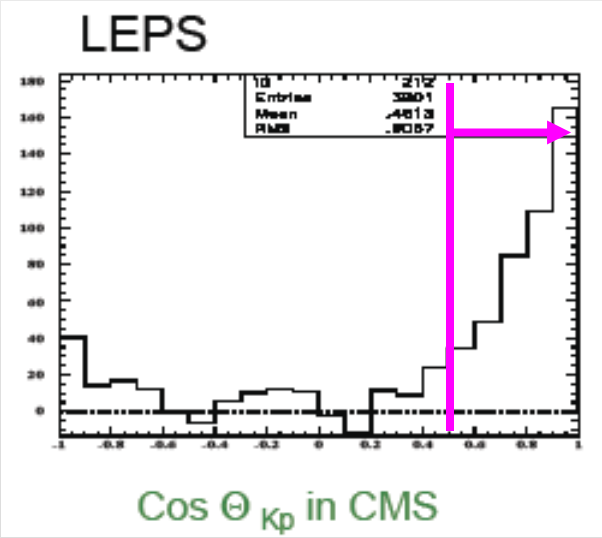
- Data poorly covers the region of the Θ^+ formation momentum.

Red : $\Lambda(1520)$ region
Blue: sidebands



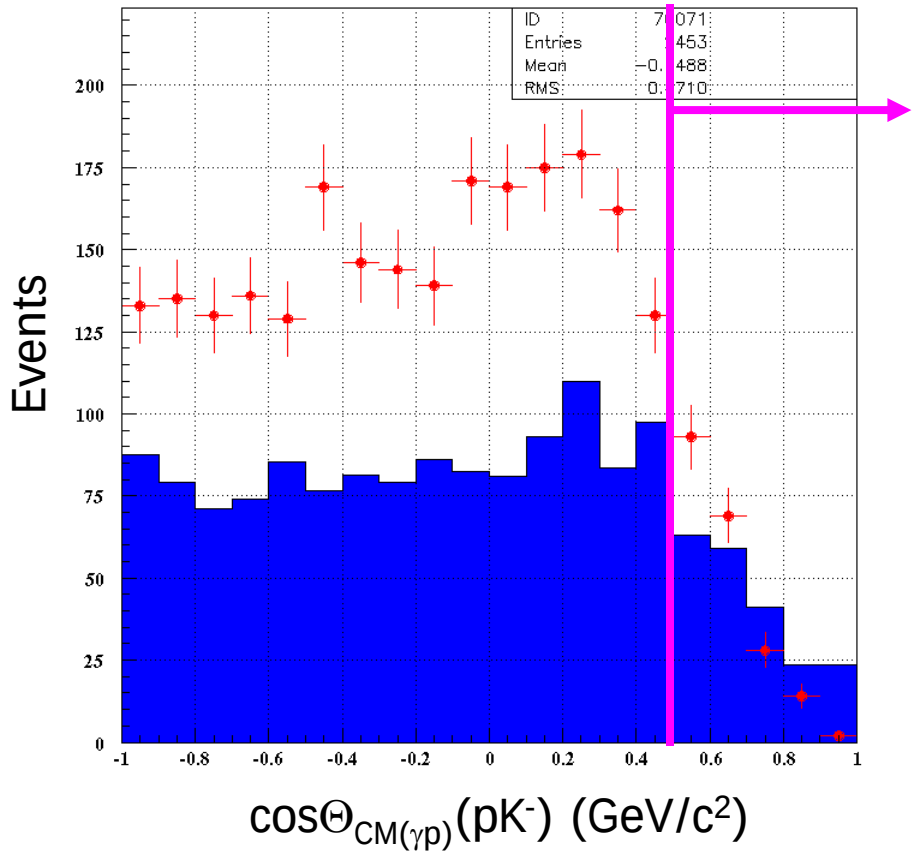
Angular distribution of Λ(1520)

- Polar angle of pK- pair in γp CM system for the events in Θ^+ mass region; $1.5<MM_d(\gamma,pK^-)<1.6$ GeV/c^2.
- CLAS acceptance drops rapidly in $\cos\Theta_{CM}>0.4$
- CLAS barely covers LEPS kinematics.



CLAS g10

Red : Λ(1520) region
Blue: sidebands



Summary : CLAS pentaquark experiments

- High-statistics data for the pentaquark photoproduction were taken at CLAS.

- No pentaquark signal was found in following reactions:
  - $\gamma p \rightarrow \Theta^+ \overline{K^0}$, $\Theta^+ \rightarrow nK^+, pK^0$ **Challenging SAPHIR result**

g10:
  - $\gamma d \rightarrow \Theta^+ pK^-$, $\Theta^+ \rightarrow nK^+$ **Supersede previous CLAS result**
  - $\gamma d \rightarrow \Theta^+ pK^-$, $\Theta^+ \rightarrow pK^0$
  - $\gamma d \rightarrow \Theta^+ \Lambda(1116)$, $\Theta^+ \rightarrow nK^+$
  - $\gamma d \rightarrow \Theta^+ \Lambda(1520)$

  - $\gamma p \rightarrow \Theta^{++} K^-$, $\Theta^{++} \rightarrow pK^+$

- Direct comparison between CLAS results and LEPS results are difficult.
  - However, an order of magnitude inconsistency between CLAS upper limit and LEPS cross section needs to be understood.

What's next ? (My personal view)

- Existence or non-existence?
  - High statistics test of initial evidences
    - Apple-to-Apple comparison.
    - CLAS Θ^+ evidence in the reaction $\gamma p \rightarrow \Theta^+ K^- \pi^+$ will be tested with the 6 GeV electron beam.
    - LEPS Θ^+ signals should be tested with LEPS data (in progress).
- Role of J-PARC as an exotic hadron research facility
  - Formation reaction $K^+ n \rightarrow \Theta^+$ with low energy K+ beam (LOI, Nakano et al)
  - Production reaction $\pi^- p \rightarrow K^- \Theta^+$ (Day 1 experiment, Naruki et al)
  - Mesonic analogues of $\Theta^+(uud\bar{u}d\bar{s})$, for example $ud\bar{s}\bar{s}$, can be searched with high energy Kaon beam in reactions $K^+ p \rightarrow \Sigma^+ X^+$ (S=+2 meson)

ϕ中間子光生成

Total cross sections

Donachie and Landshoff Phys.Lett. B296(1992)227

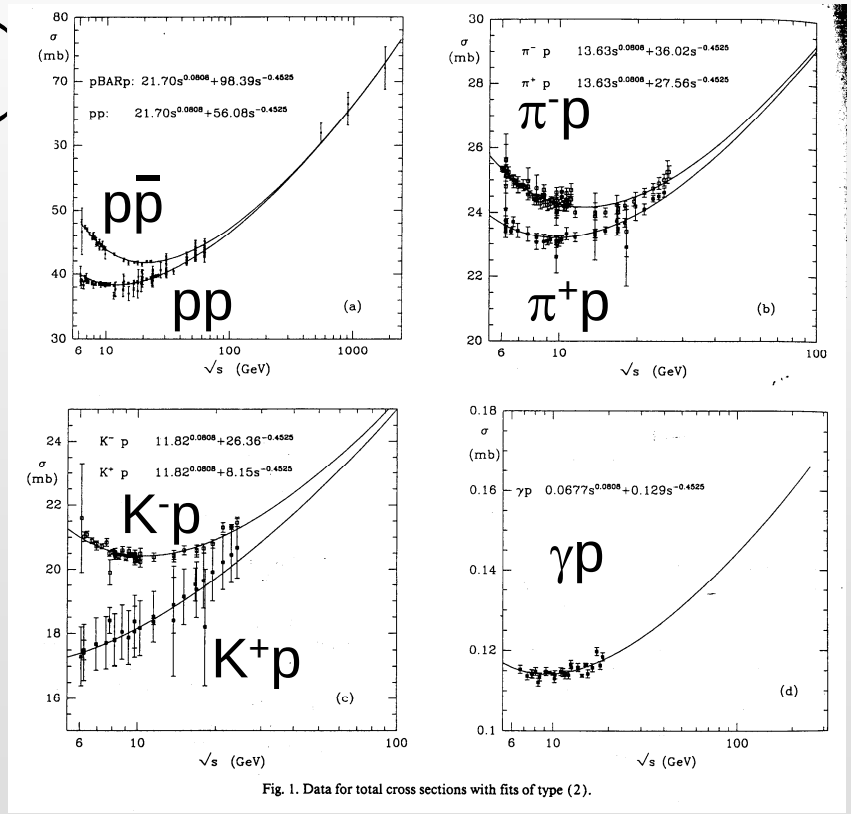


Fig. 1. Data for total cross sections with fits of type (2).

$\sqrt{s}$

Regge theory

$$\sigma_{total} = Xs^{\varepsilon} + Ys^{\eta}$$

ρ meson trajectory

$\varepsilon = a(0)-1 = -0.4525$

Pomeron trajectory

$\eta = a(0)-1 = 0.0808$

Flavor blind

$$\sigma(pp) \approx \sigma(p\bar{p}), \sigma(Kp) \approx \sigma(\pi p)$$

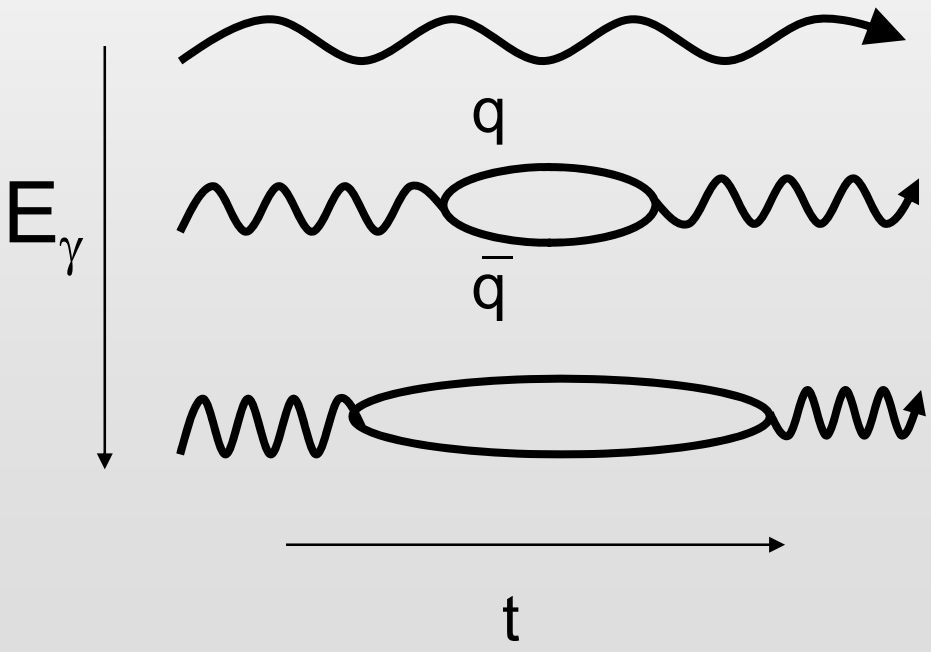
Additive-quark rule

$$\sigma(\pi p)/\sigma(pp) \approx 2/3$$

Pomeron ≈ Glueball ?

Vector Meson Dominance (VMD)

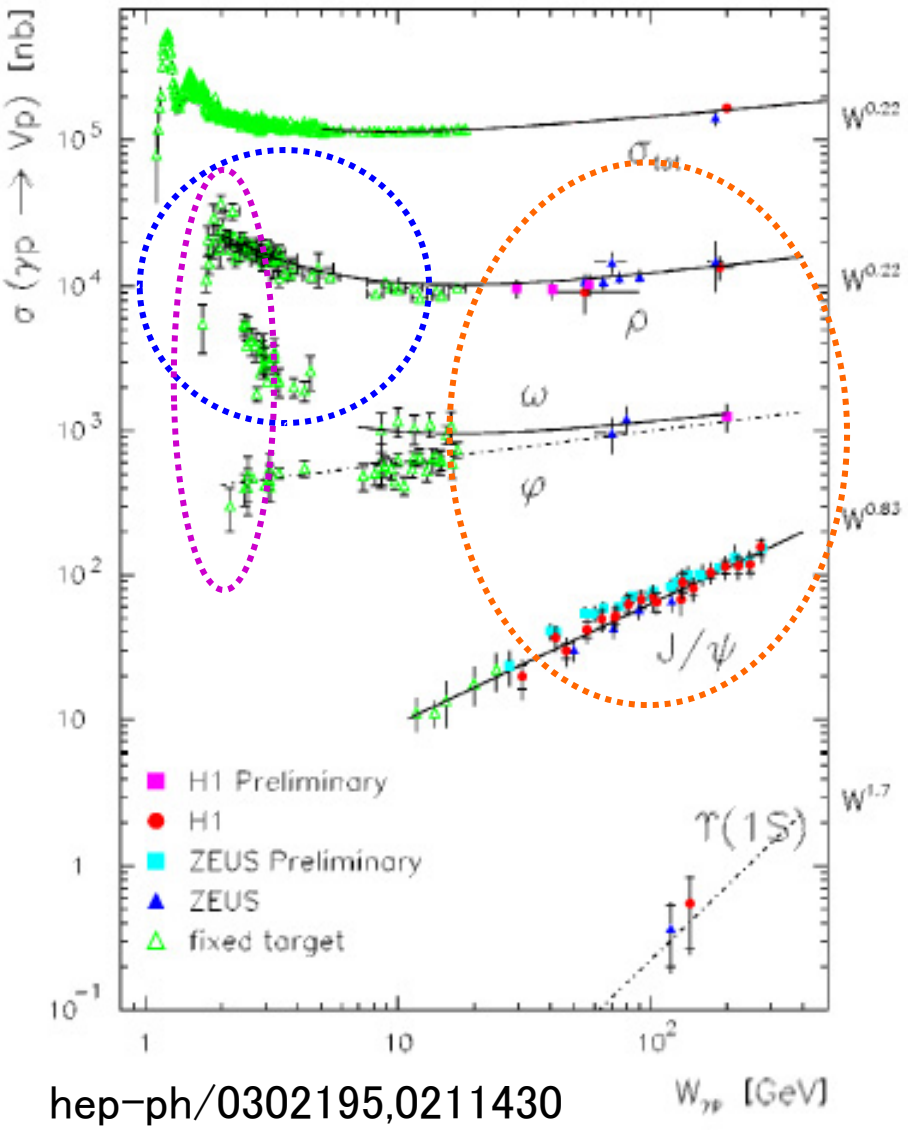
- Photon $J^{PC} = 1^{--}$
- Vector mesons ($\rho,\omega,\phi,J/\psi$ ...) $J^{PC} = 1^{--}$



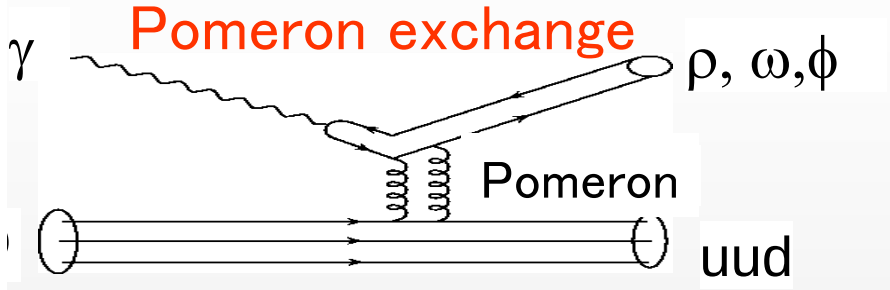
$$\Delta t \approx \frac{2E_\gamma}{m_{VM}^2} \approx 1\,fm/c$$

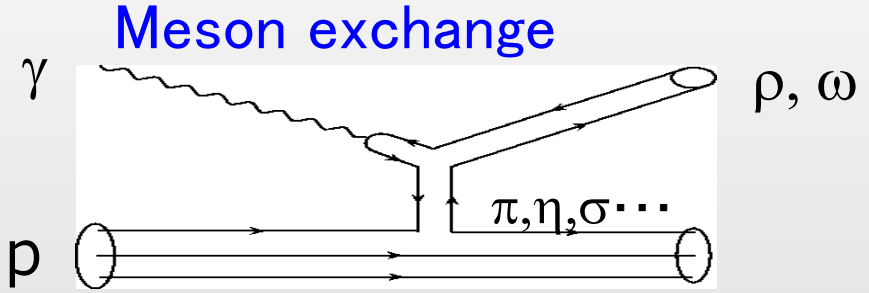
for ϕ-meson,
E_γ=3 GeV

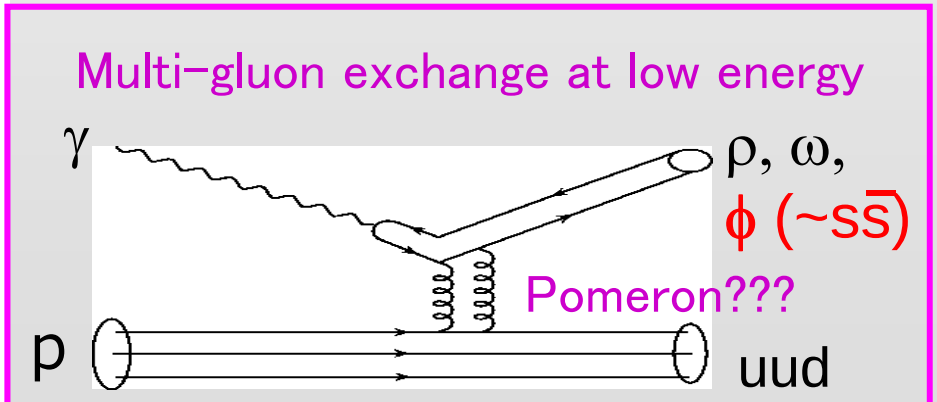
Vector Meson Photoproduction



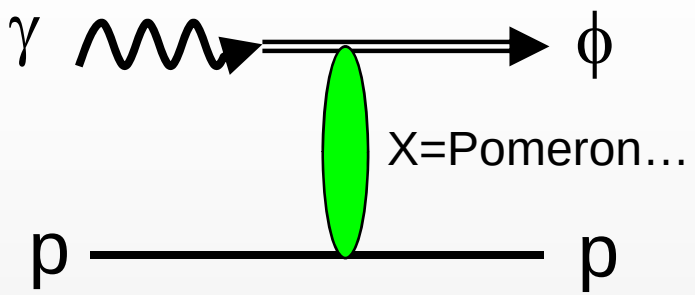
hep-ph/0302195,0211430



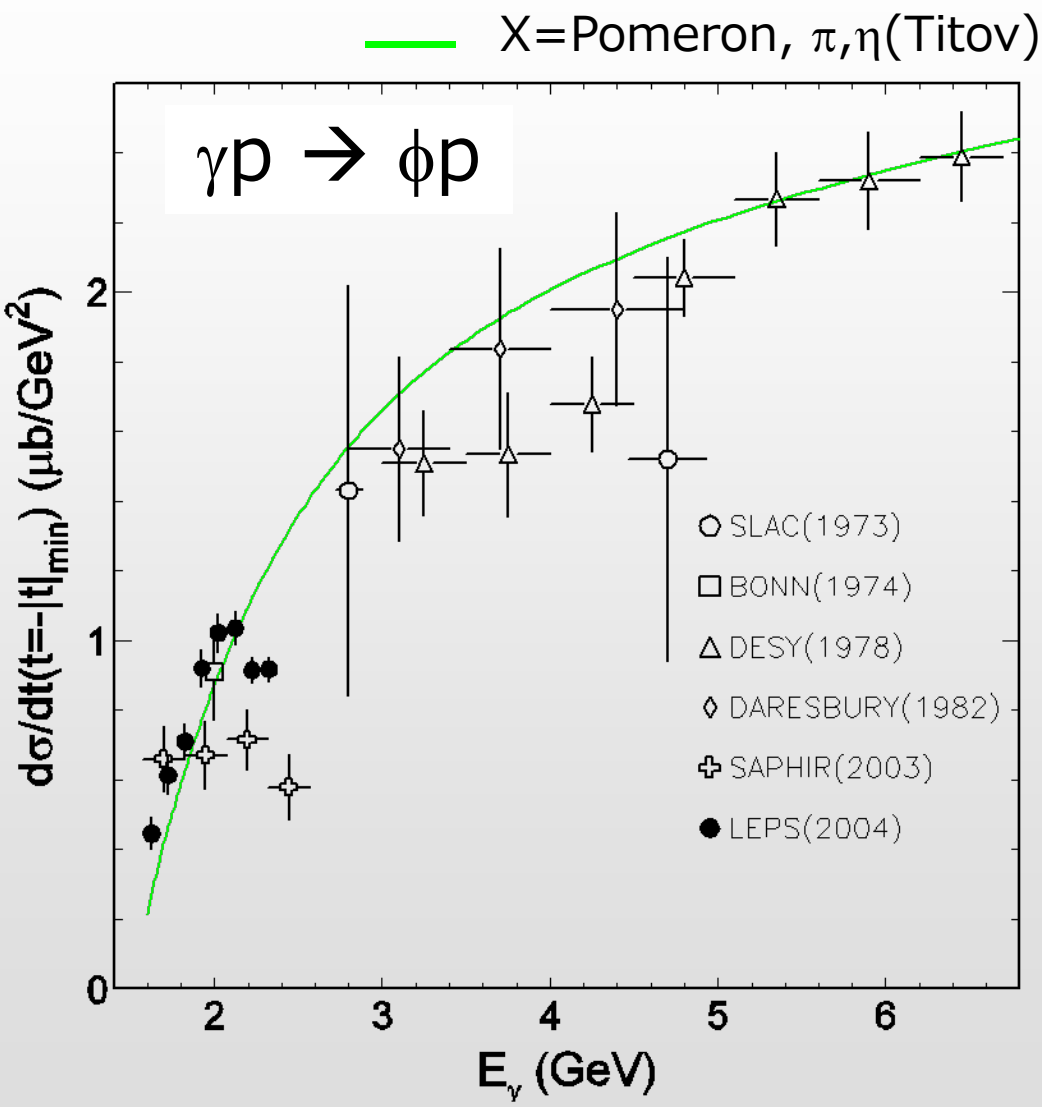




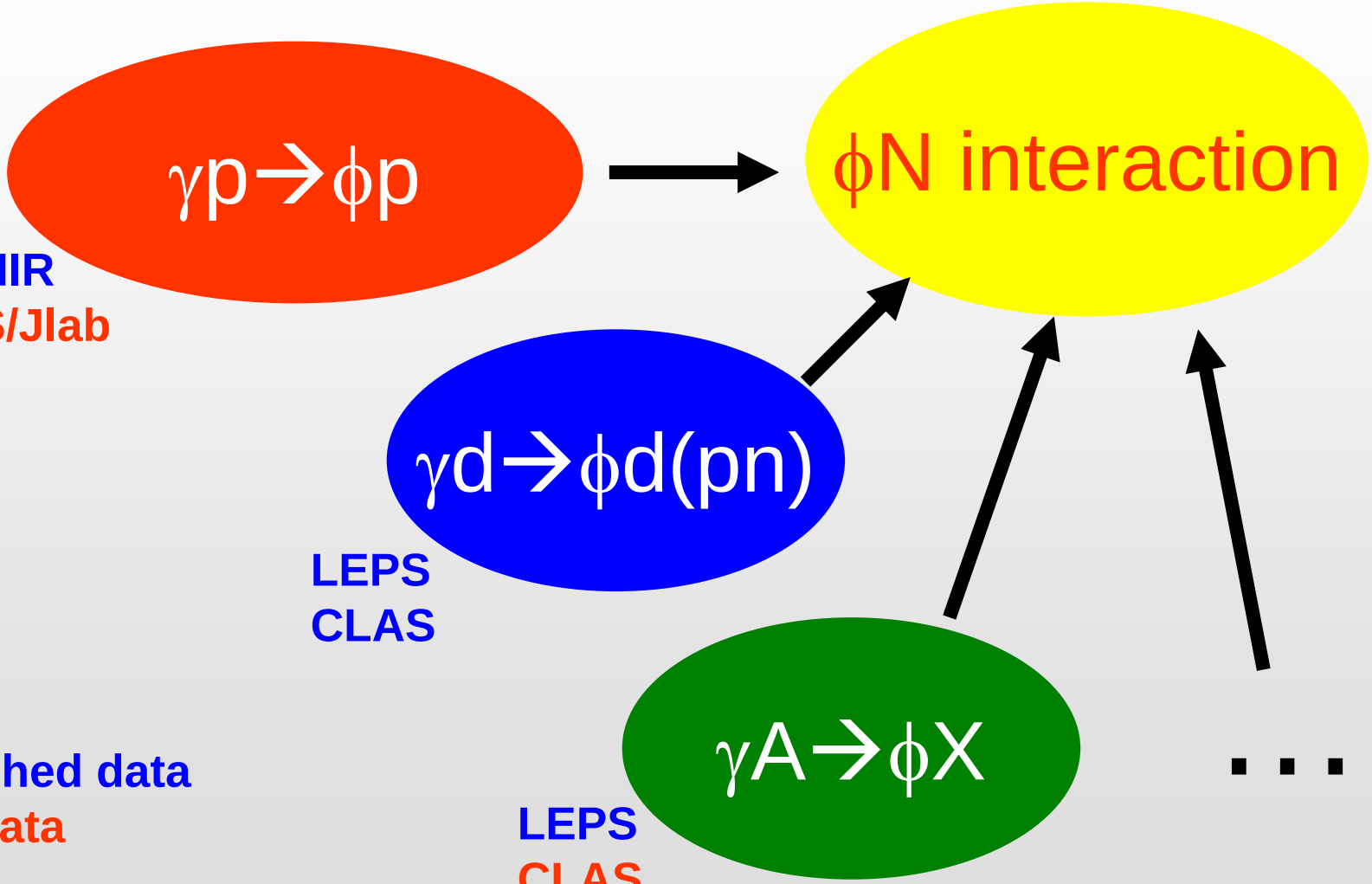
SPring-8 LEPS実験　超前方微分断面積 ($t=-|t|_{min}$)



- 超前方断面積が光子エネルギーに対して単調増加しないことを発見した。
- 崩壊角度分布によると、これはπ交換過程だけでは説明できない。
- 低エネルギーでのφN相互作用模型に疑問。0^+グルーボール交換の役割？（中野・土岐）
- データの整合性
  - LEPS vs SAPHIR ?
- 高エネルギーデータとの関係
  - $2.5<E_\gamma<3.0$ GeV領域のデータがない
- 学位論文（大阪大学2004年)



研究戦略：幅広いデータからφN相互作用をさぐる



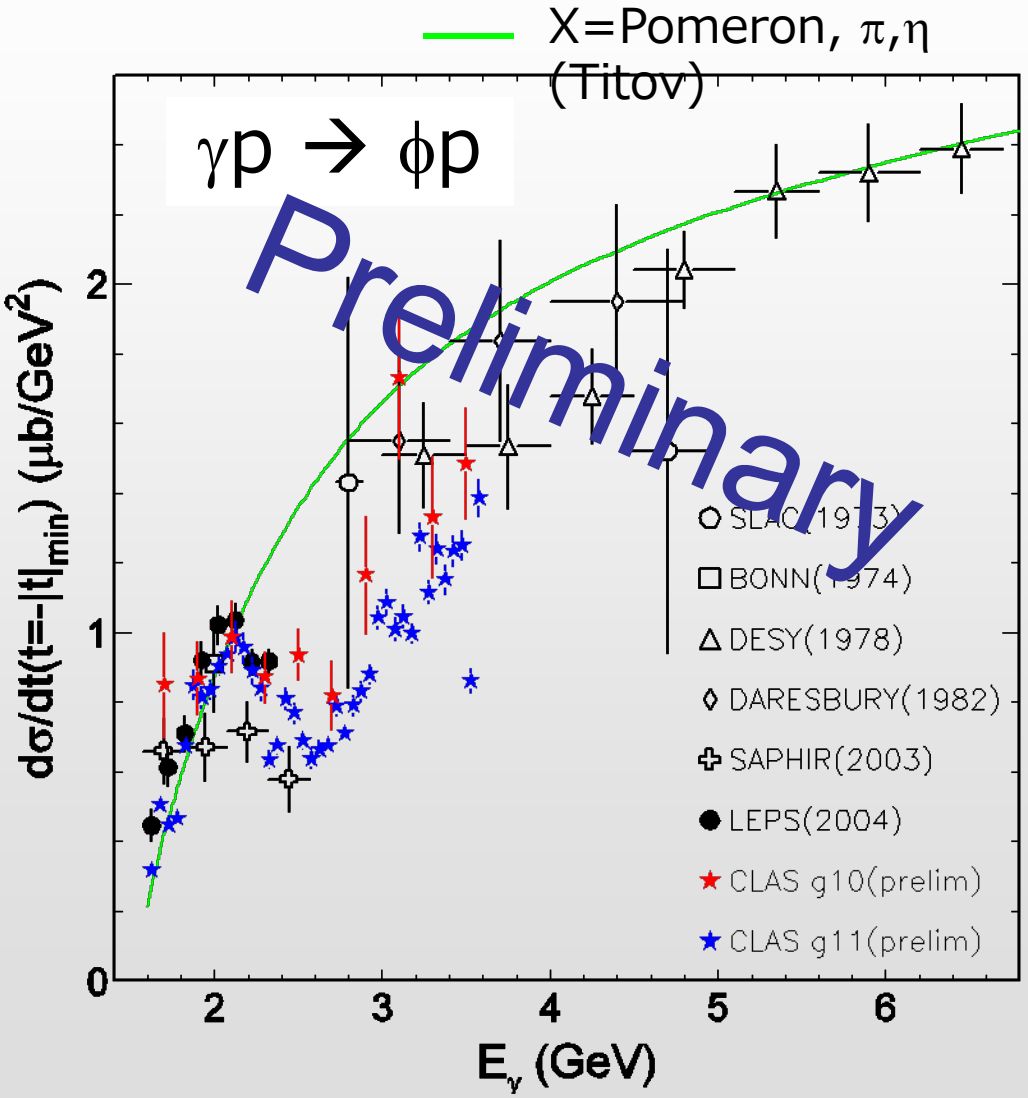
Dedicated experiments for pentaquark at CLAS

- g10
  - Photoproduction on deuterium at $E_\gamma < 3.6$ GeV
  - Completed in 2004
- g11
  - Photoproduction on proton at $E_\gamma < 3.8$ GeV
  - completed in 2004
- eg3
  - Photoproduction on deuterium at $E_\gamma < 5.6$ GeV
  - completed in 2005

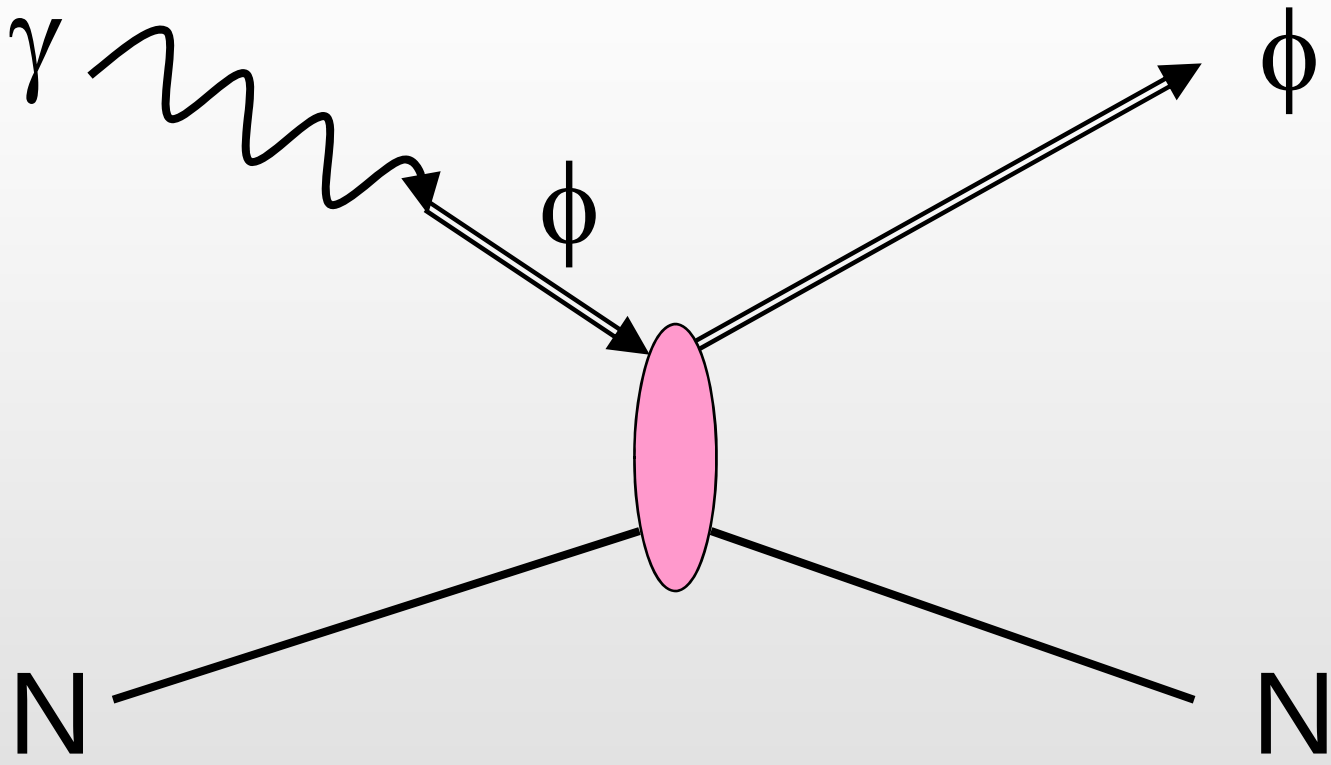
Excellent data sets for ϕ meson photoproduction too !

γp → φp at low energies (CLAS)

- Jlab/CLASにて追試を行いLEPSデータを支持する結果を得た。
- エネルギー依存性の異常は実験的に確立された
- 低エネルギーにおける多重グルーオン交換モデルの抜本的改善が必要



Is this picture valid ?



Works well for ρ and ω at higher photon energy

Another puzzle : ϕ-N cross section

- Vector meson dominance

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

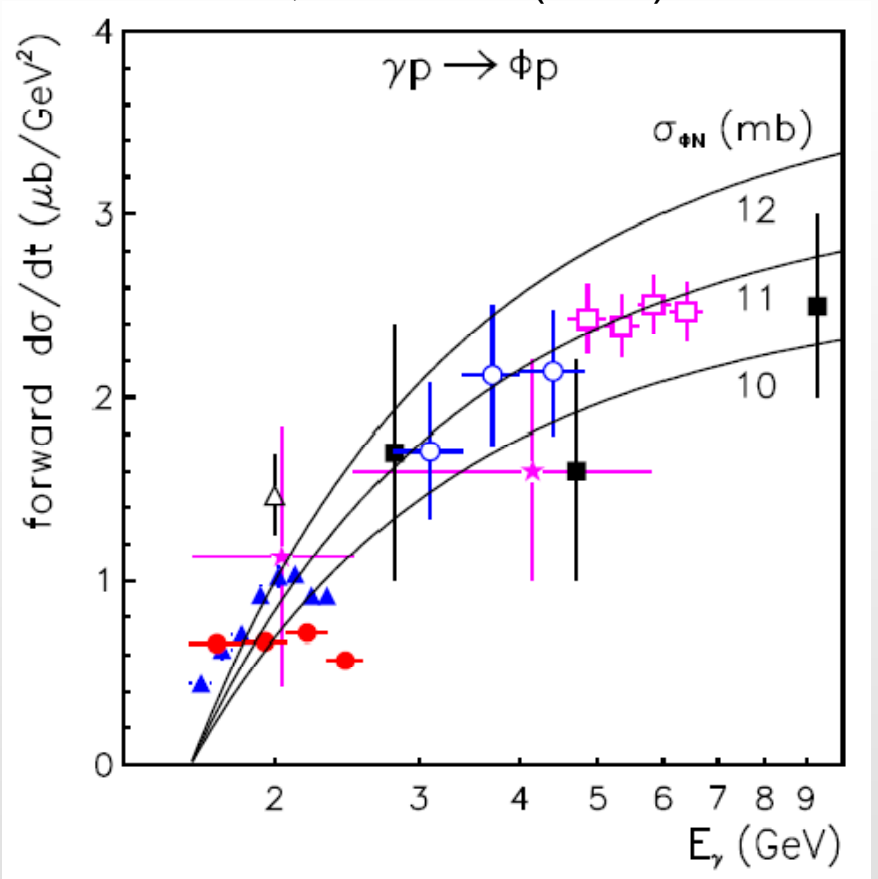
- Optical theorem

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

- Diff. cross section at t=0

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

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



- VMD estimate, $\sigma_{\phi N}$ ~10-12 mb

ϕ-N cross section from A-dependence

- $\sigma_{\phi N}^{inel}$ is measured by a nuclear transmission factor (T_A) from A-dependence:

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

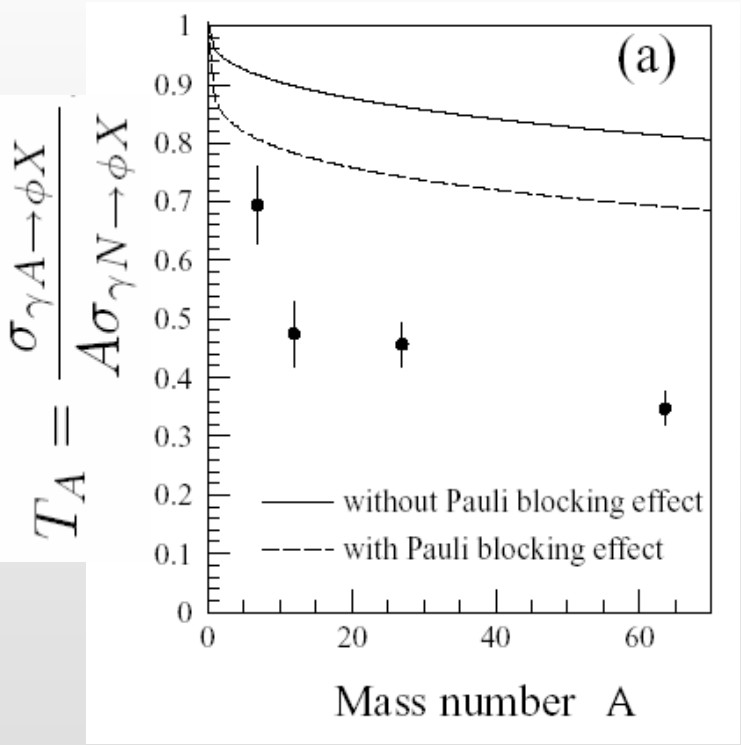
- SPring-8 data ($\phi \to K^+K^-$, E_γ=1.6-2.4 GeV) on A-dependence:

$\sigma_{\phi N}^{inel} = 35^{+17}_{-11}$ mb

- Much larger than VDM estimate

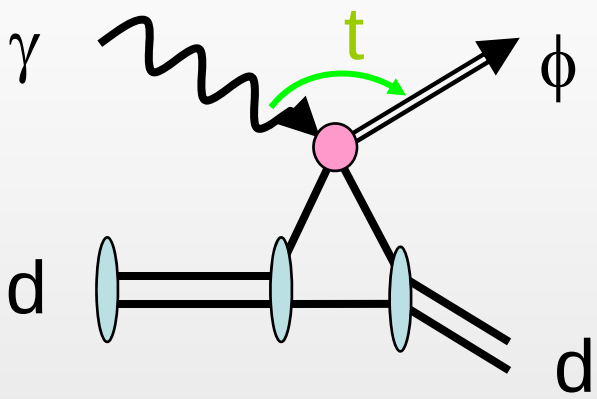
$\sigma_{\phi N} = \sigma_{\phi N}^{el} + \sigma_{\phi N}^{inel} = 10\text{-}12$ mb

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

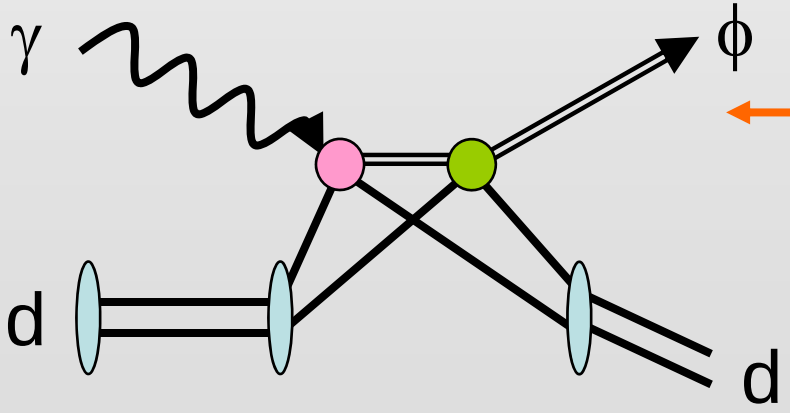


Independent measurement of ϕ-N cross section from $\gamma d \rightarrow \phi d$

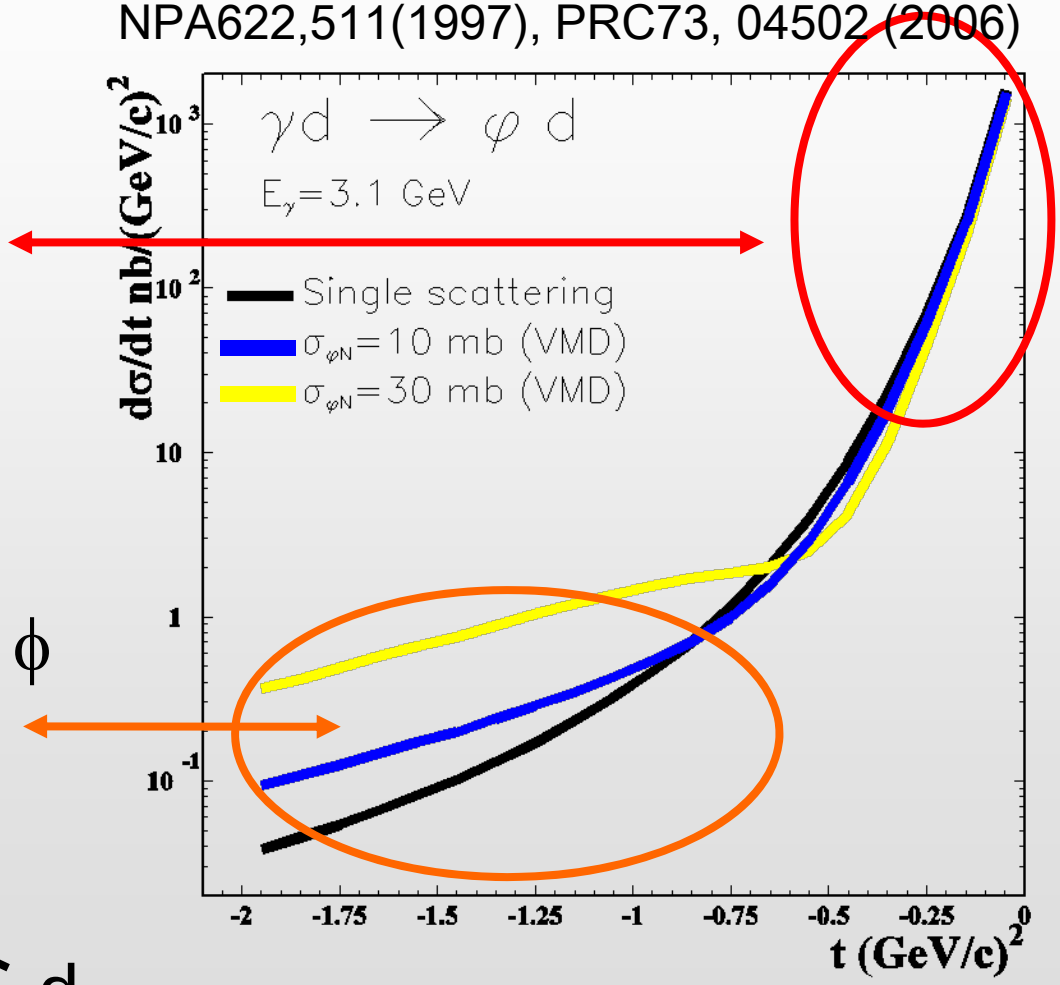
- Single scattering



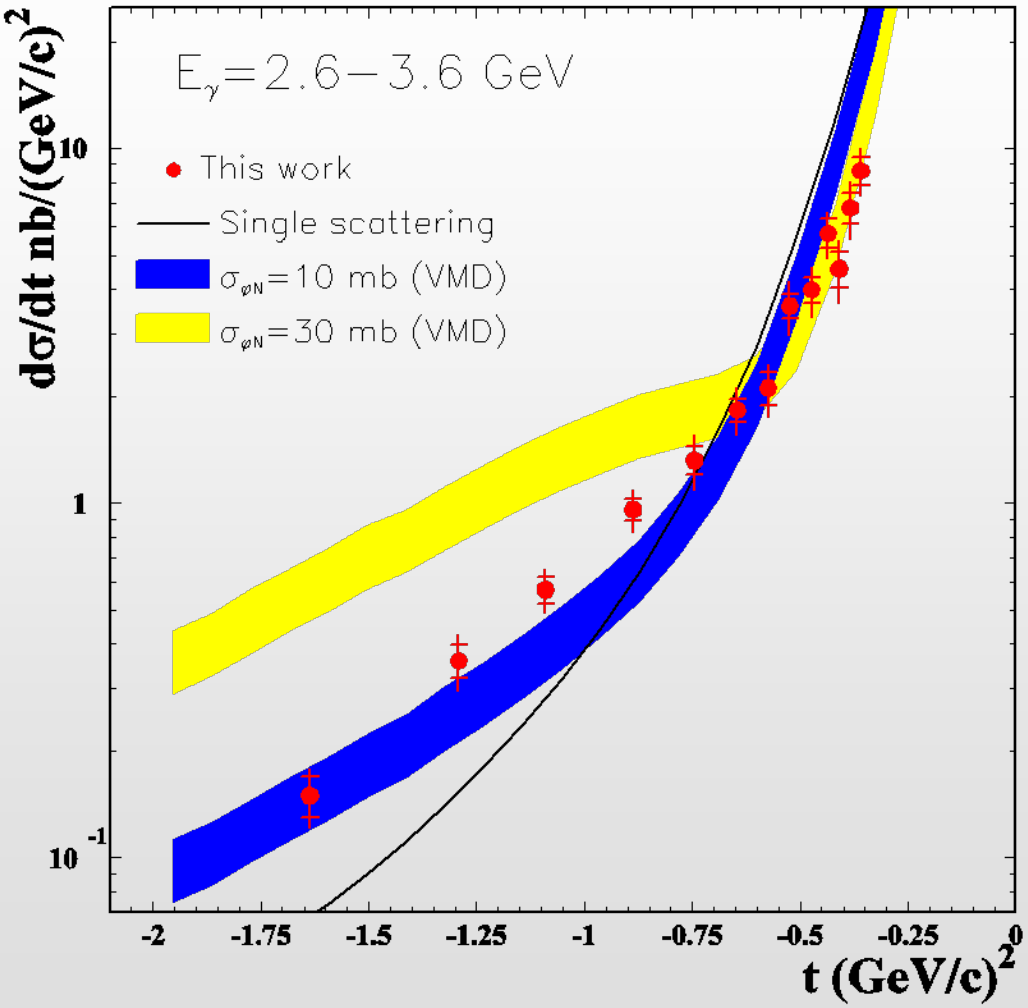
- Double scattering

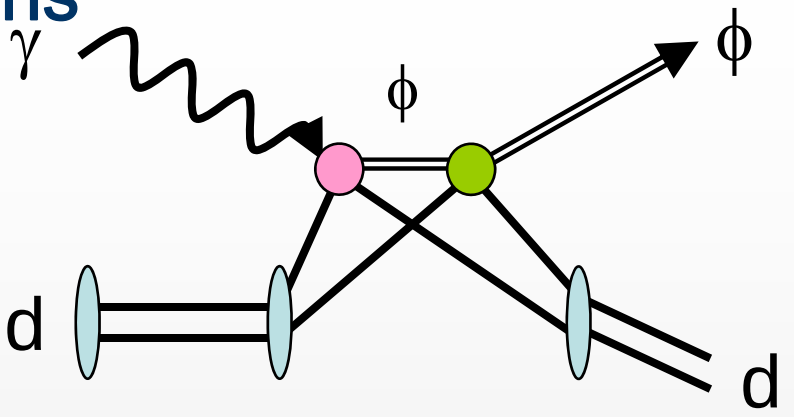


Model: T. Rogers, M. Sargsian, M. Strikman
NPA622,511(1997), PRC73, 04502 (2006)

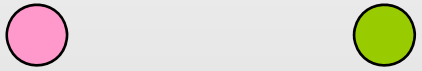


γd→φd, differential cross sections



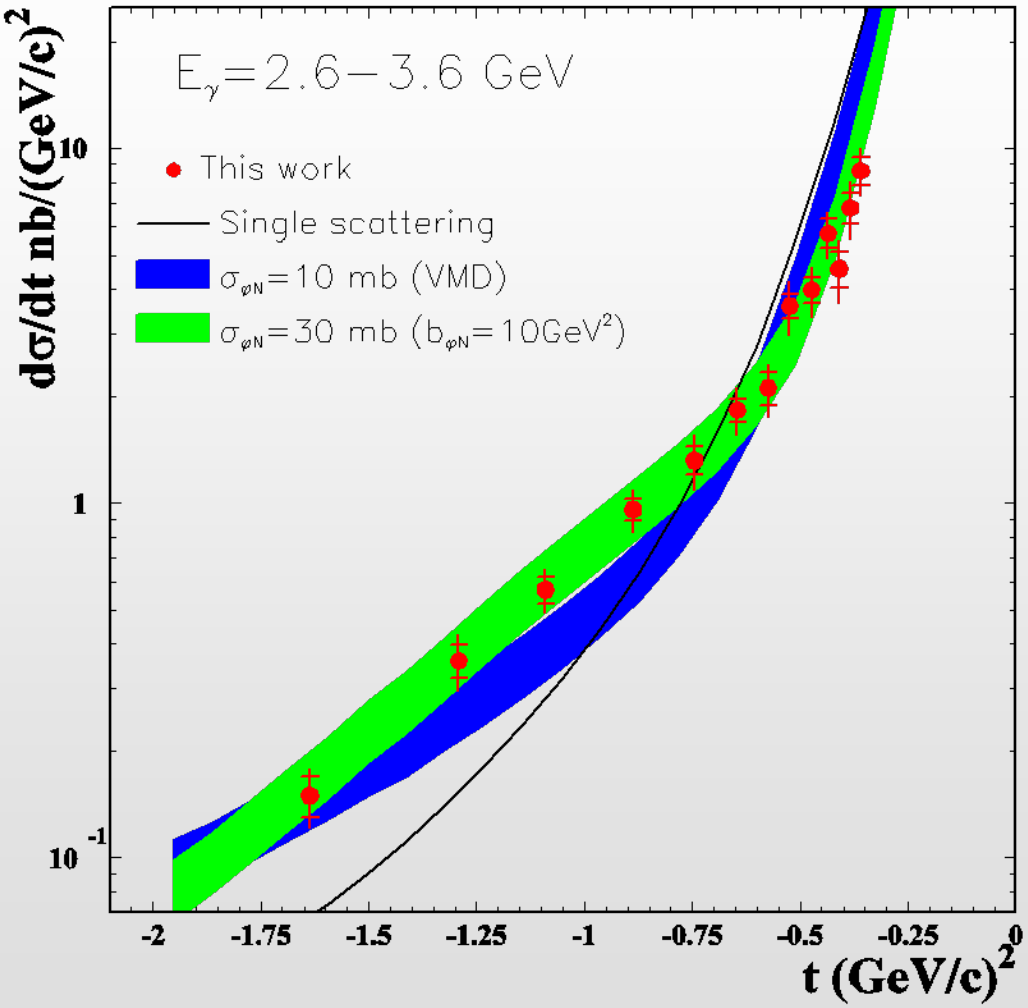


- Prediction from Vector Meson Dominance
- $T_{\gamma N \to \phi N} = \alpha_{\gamma\phi}\ T_{\phi N \to \phi N}$



- Data favors $\sigma_{\phi N}$=10 mb
  - In other words, VMD must be violated if $\sigma_{\phi N}$ is larger than 10 mb.

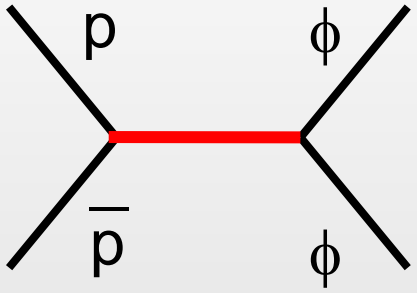
γd→φd,differential cross sections



- Non-VMD scenario
- $T_{\gamma N \to \phi N} = \alpha_{\gamma\phi}\, T_{\phi N \to \phi N}$
- $T_{\phi N \to \phi N} \neq \sigma_{\phi N}(i+\beta)e^{b/2\, t}$
- Data are described with $\sigma_{\phi N}$ = 30 mb and larger slope b=10 GeV^2 (b~4-5 in VMD)
- Another confirmation of violation of VMD, at least, in γA reaction

ϕ photoproduction summary & what's next?

- The bump structure in forward cross sections (LEPS, CLAS)
  - Iso-spin decomposition
    - New measurement from LEPS on $\gamma d \rightarrow \phi d$ at forward angles (**nucl-ex/0703034, PLB in press**)
  - s-channel formation ($p\bar{p} \rightarrow \phi\phi$)
    - New $\bar{p}$ beam line at J-PARC hadron hall (LOI, Onishi et al)



- ϕ-N cross section ($\sigma_{\phi N}(\gamma A) >> \sigma_{\phi N}(\gamma p, \gamma d + VMD)$)
  - Rescattering amplitude
    - Incoherent ϕ meson photoproduction on deuteron (LEPS, CLAS analyses in progress)
  - Recovery of VMD at high energy?
    - E_γ dependence