Quark Nuclear Physics at LEPS/SPring-8

T. Nakano

Colloquium@IFIC, June 2, 2006

Outline

- Introduction
- Λ(1405) study
- ϕ photo-production
- K^+ photo-production
- Θ^+ study

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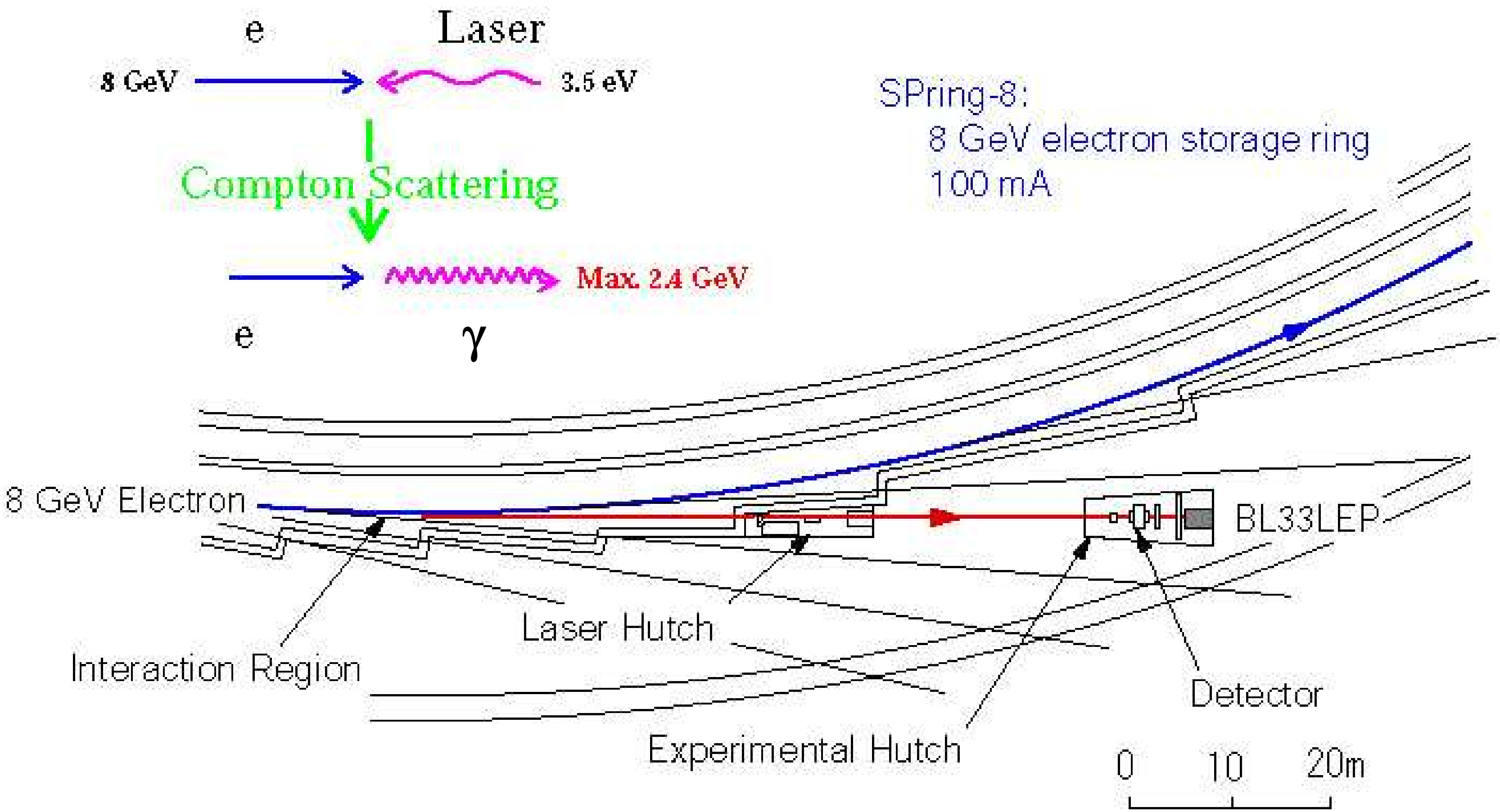
Laser Electron Photon facility at SPring-8

in operation since 2000



Laser Electron Photon (LEP) Beam

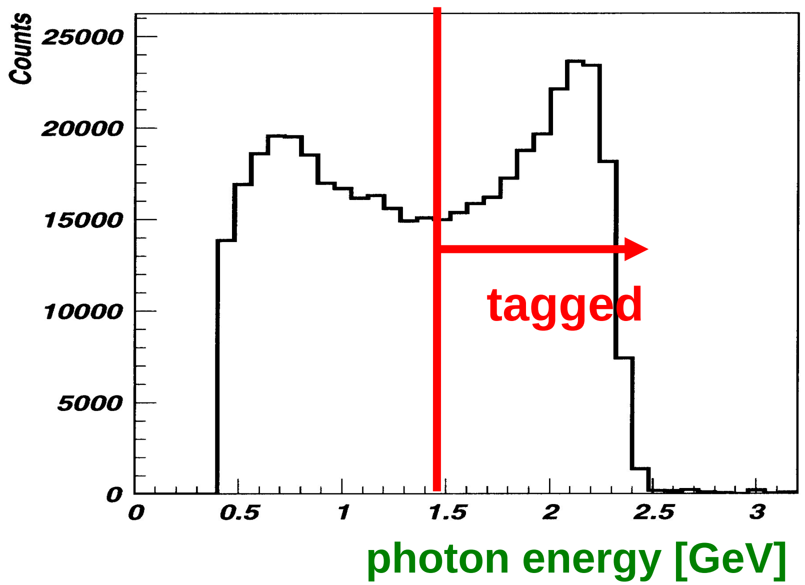
8 GeV electrons in SPring-8 + 351nm Ar laser (3.5eV)

⇒ maximumly 2.4 GeV photons (Backward Compton Scattering)

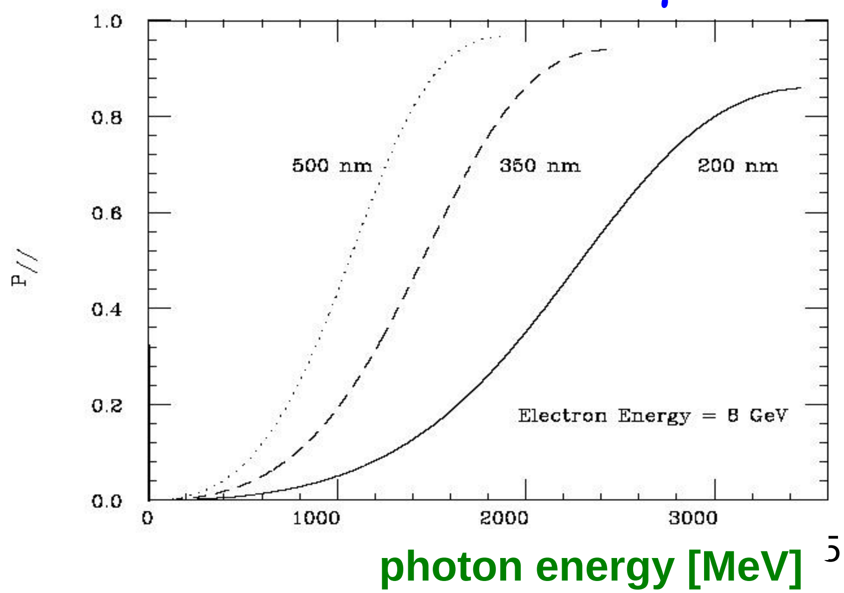
- E_γ measured by tagging a recoil electron ⇒ E_γ>1.5 GeV, ΔE_γ ~10 MeV
- Laser Power ~6 W ⇒ Photon Flux ~1 Mcps
- Laser linear polarization 95-100% ⇒ Highly polarized γ beam

Most of physics programs including photoproductions of Θ^+, ϕ, hyperon, … have used this photon beam.

PWO measurement



Linear Polarization of γ baem



Photon Energy Upgrade

Maximum Energy of LEP beam

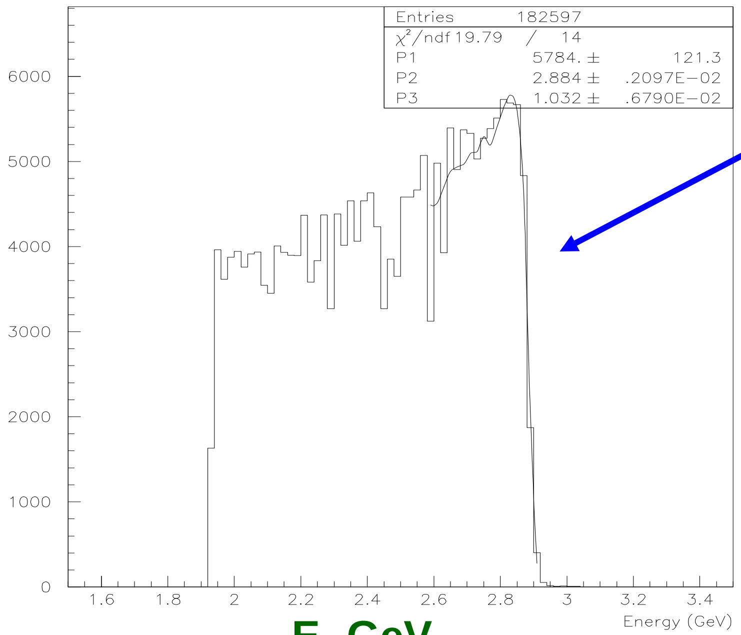
$$k_{\max} = \frac{(E_e + P_e)\, k_{laser}}{E_e - P_e + 2k_{laser}} \cong \frac{4E_e^2 k_{laser}}{m_e^2 + 4E_e k_{laser}}$$

E_e = 7.960 GeV, m_e = 0.5110 MeV/c^2

Ar laser (**351 nm**) k_{laser} = **3.53 eV** ⇒ k_{max} = **2.40 GeV**

Deep UV laser (**257 nm**) k_{laser} = **4.82 eV** ⇒ k_{max} = **2.95 GeV**

Laser Power ~1.2 W ⇒ γ Beam Intensity ~200 Kcps



E_γ GeV

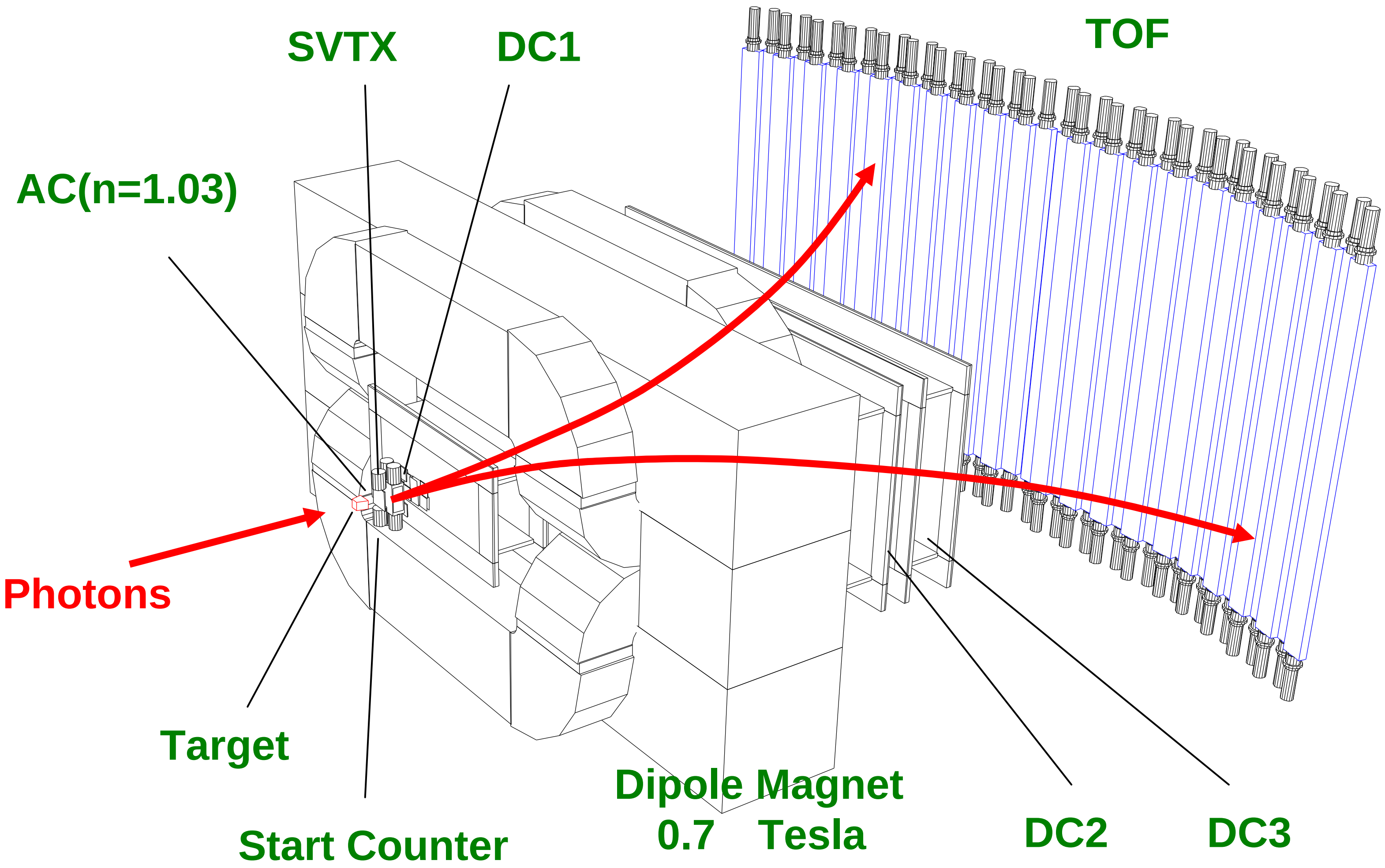
LEP energy spectrum measured by tagging system

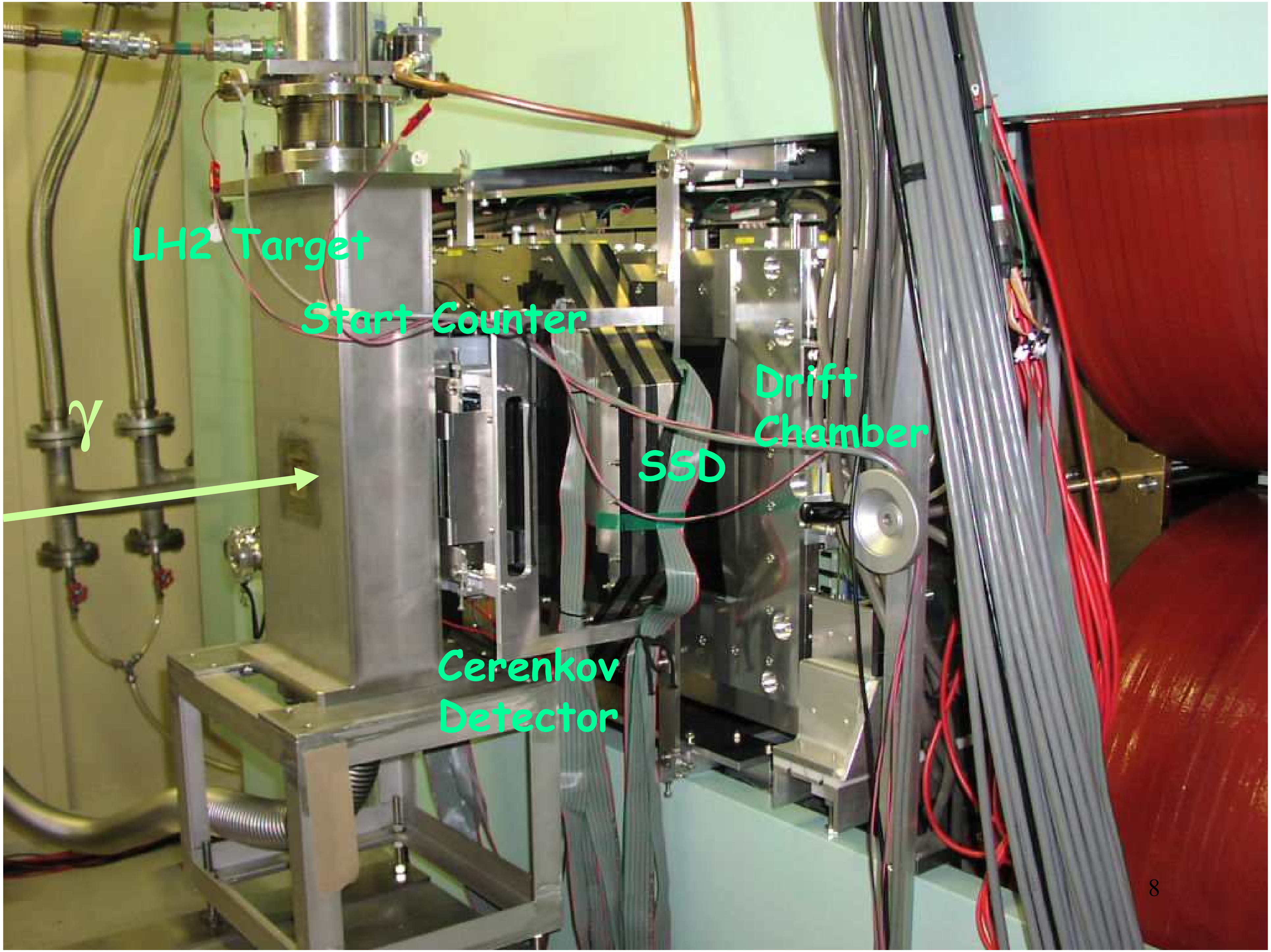
Physics possibilities have been increased.

- ω-mesic nuclei
- γp→K*Λ(1405)
- γN→K*Θ^+

LEPS spectrometer

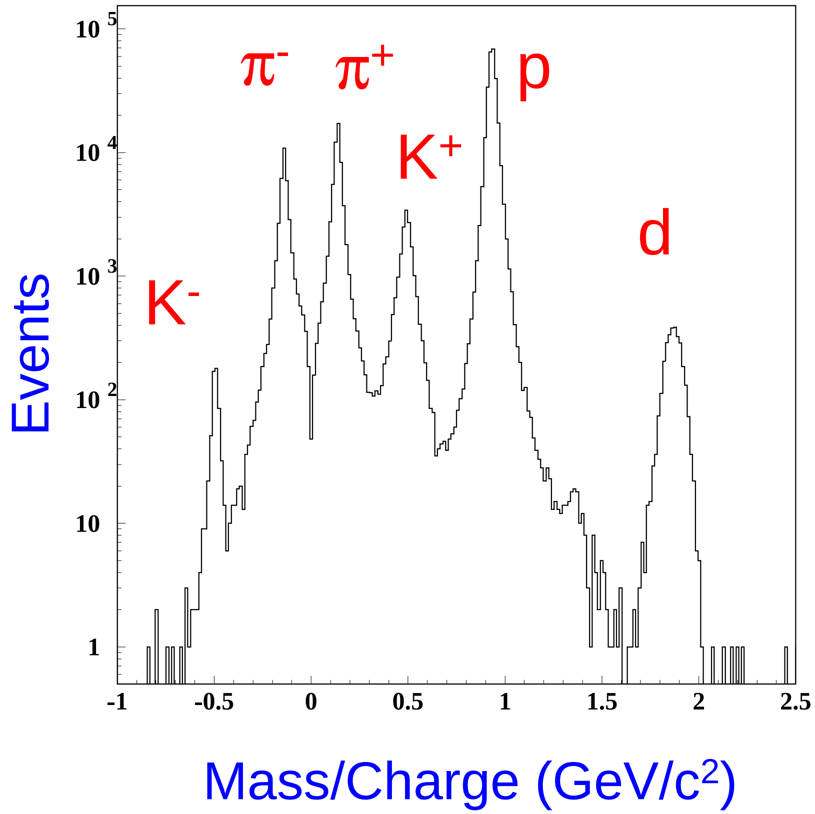
Charged particle spectrometer with forward acceptance
PID from momentum and time-of-flight measurements



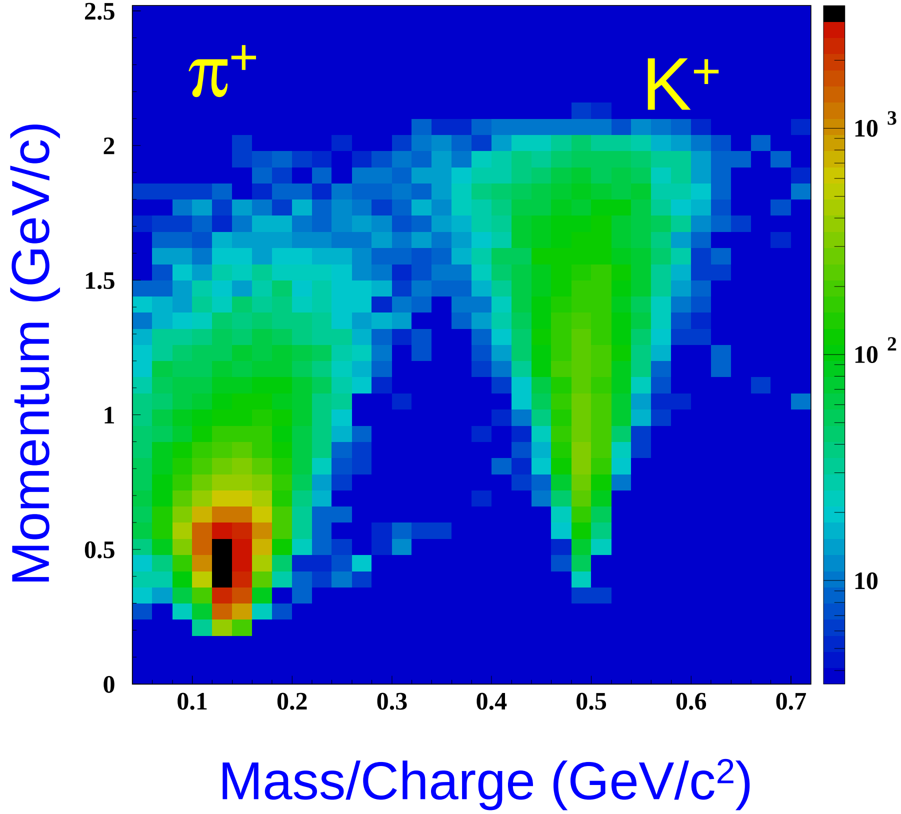

LH2 Target
Start Counter
γ
Drift Chamber
SSD
Cerenkov Detector

Particle Identification

Reconstructed mass



K/π separation



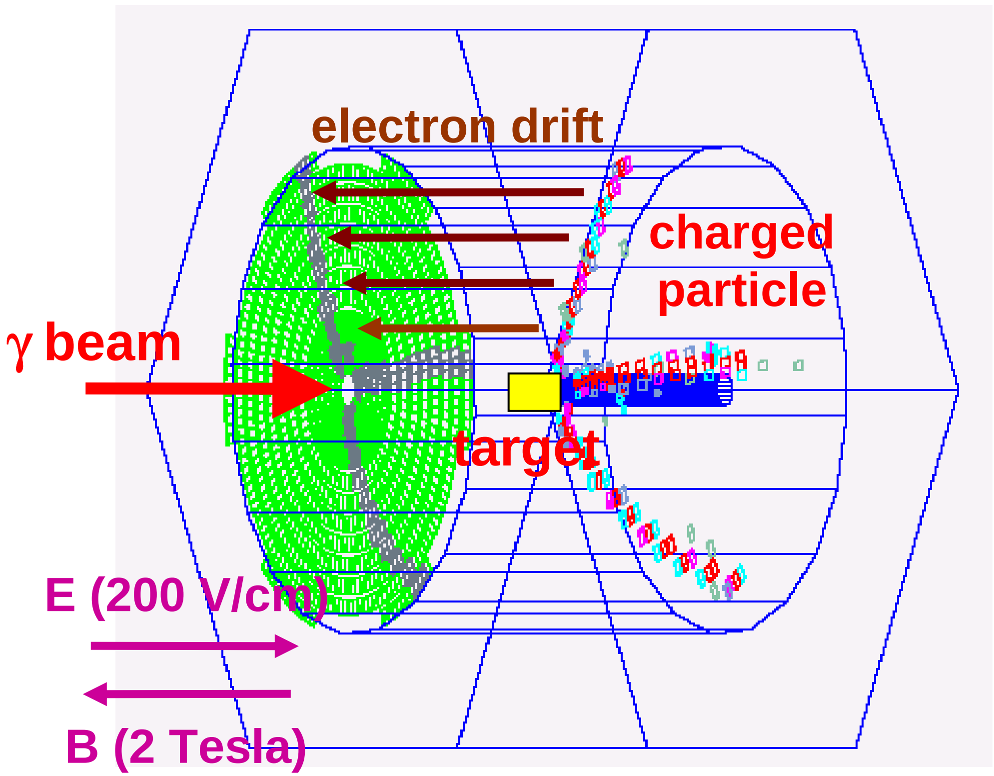
σ_P ~6 MeV/c for 1 GeV/c, σ_{TOF} ~150 ps,
σ_{MASS} ~30 MeV/c^2 for 1 GeV/c Kaon

Time Projection Chamber

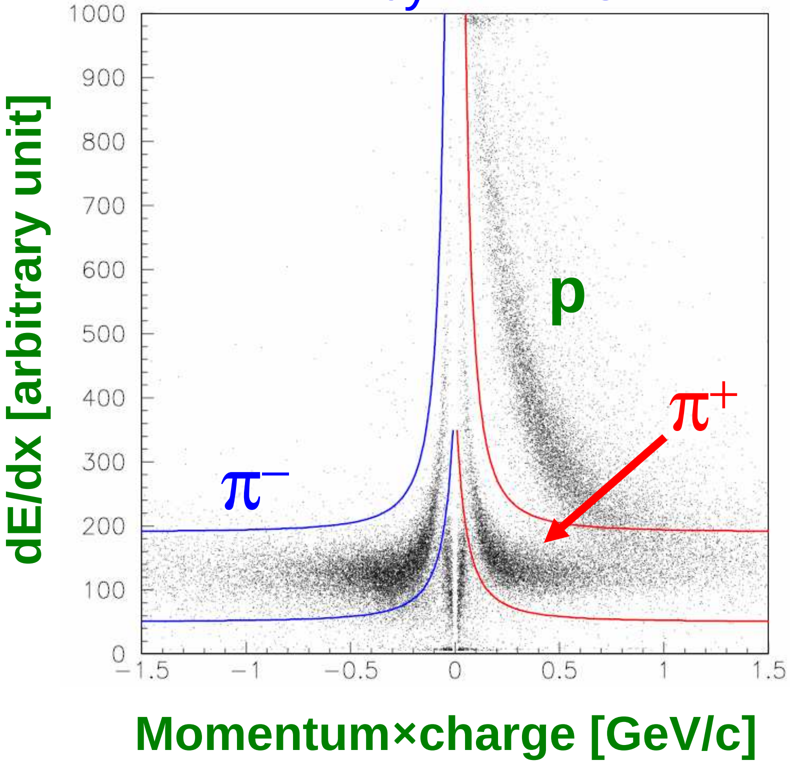
Geometrical acceptance can be expanded by setting TPC in front of forward spectrometer.

1st TPC for nuclear targets : Physics runs for $\Lambda(1405)$ photoproduction etc

2nd TPC for LH_2/LD_2 targets : Being prepared for Θ^+ photoproduction etc



PID by 1st TPC



Summary of Collected Data

Dec. 2000 – June 2001 LH_2 50 mm ~5×10^{12} photons

Photoproductions of ϕ, Λ, Σ^0, … from proton

5 mm-thick plastic counter $\Rightarrow$ 1st evidence of Θ^+

2001-2002 Gamma Exp. [w/o forward spectrometer]

Nuclear tgt exp. w/ forward spectrometer (A-dep.)

May 2002 – Apr. 2003 LH_2 150 mm ~1.4×10^{12} photons

Oct. 2002 – June 2003 LD_2 150 mm ~2×10^{12} photons

Θ^+ : #neutron×#photons in K^+K^- detection mode

($\gamma n \rightarrow \Theta^+ K^- \rightarrow K^+ n K^-$) = 5×short LH_2 runs

K^-p detection mode ($\gamma d \rightarrow \Theta^+ \Lambda^* \rightarrow \Theta^+ K^- p$) is available.

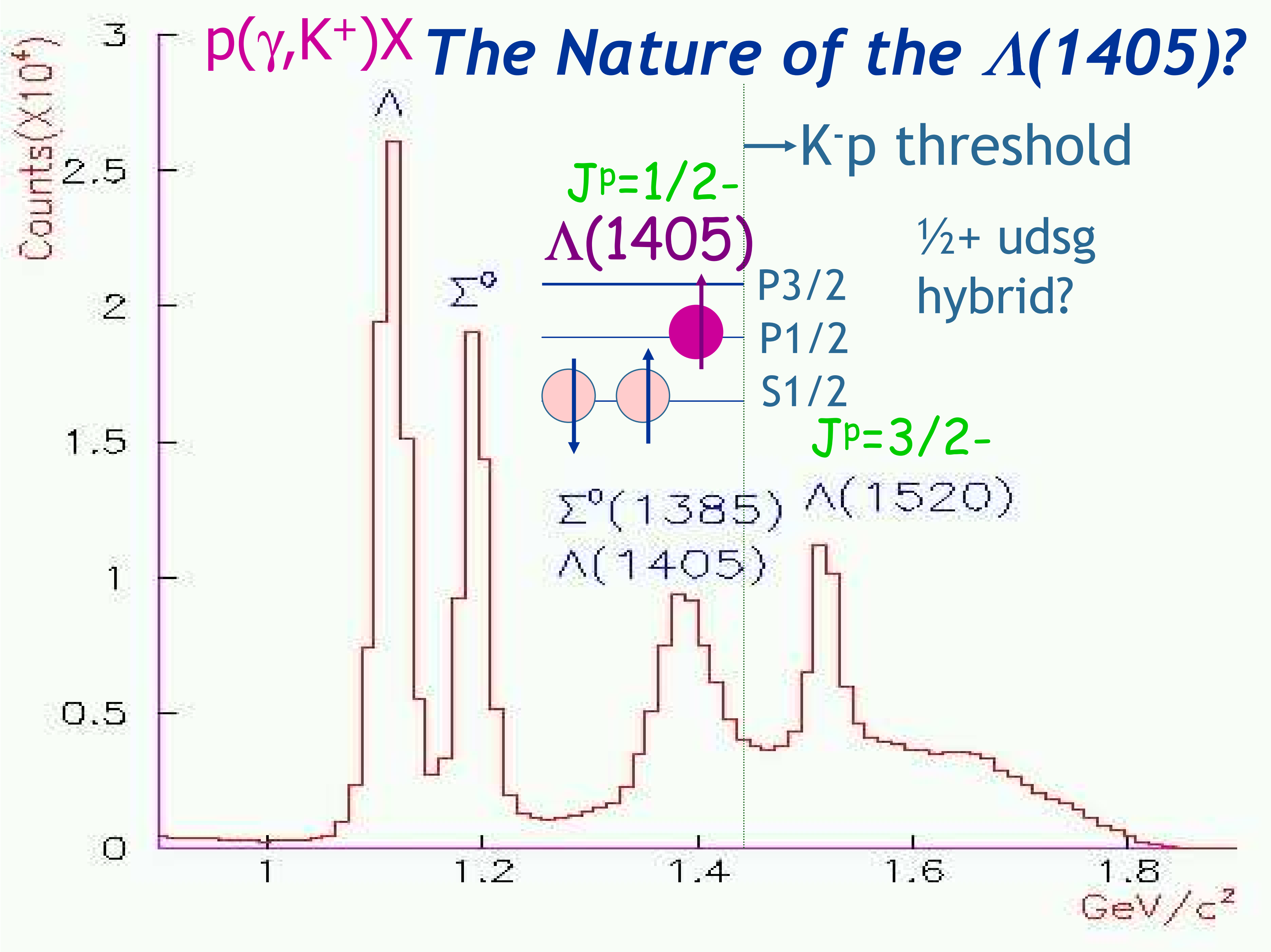
Photoproductions of ϕ, Σ^-, … from deuteron

2003 K^0 Exp. [AC $\rightarrow$ Gas Cherenkov to accept pions]

2004 1st TPC operated, C / CH_2 / Cu target

2005 3-GeV upgrade, C / CH_2 target w/ spectrometer+TPC

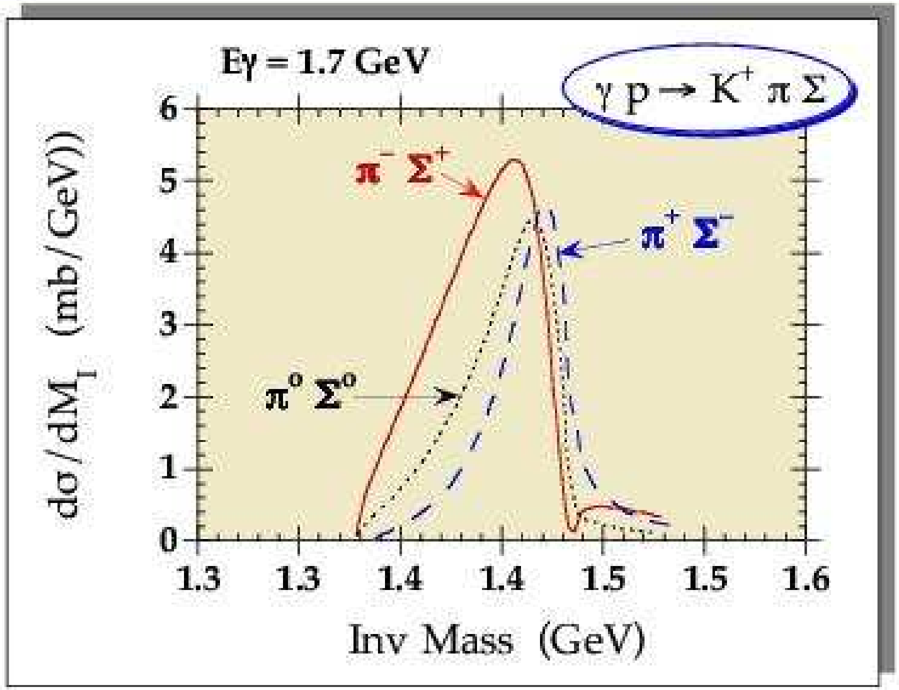
The Nature of the Λ(1405)?



The Nature of the Λ(1405) ?

- uds g **hybrid ?**
- **SU(3) – singlet 3q state ?**
- ***sub-threshold* $\bar{K}N$ bound state ?**

Nacher, Oset, Toki, Ramos
Phys. Lett. B 455 (1999) 55
(χLagrangians + mB FSI + cc)



$$\gamma \quad p \quad \rightarrow \quad K^+ \quad \pi \quad \Sigma$$

$$I = \quad 1/2 \qquad 1/2 \quad 1 \quad 1$$

$$\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(o)}\right|^2 + \frac{2}{\sqrt{6}}\Re e\left(T^{(o)}T^{(1)^*}\right) + \Theta\left(T^{(2)}\right)$$

$$\updownarrow$$

$$\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(o)}\right|^2 - \frac{2}{\sqrt{6}}\Re e\left(T^{(o)}T^{(1)^*}\right) + \Theta\left(T^{(2)}\right)$$

Λ(1405) photoproduction

- 3-quark state or KN bound state?

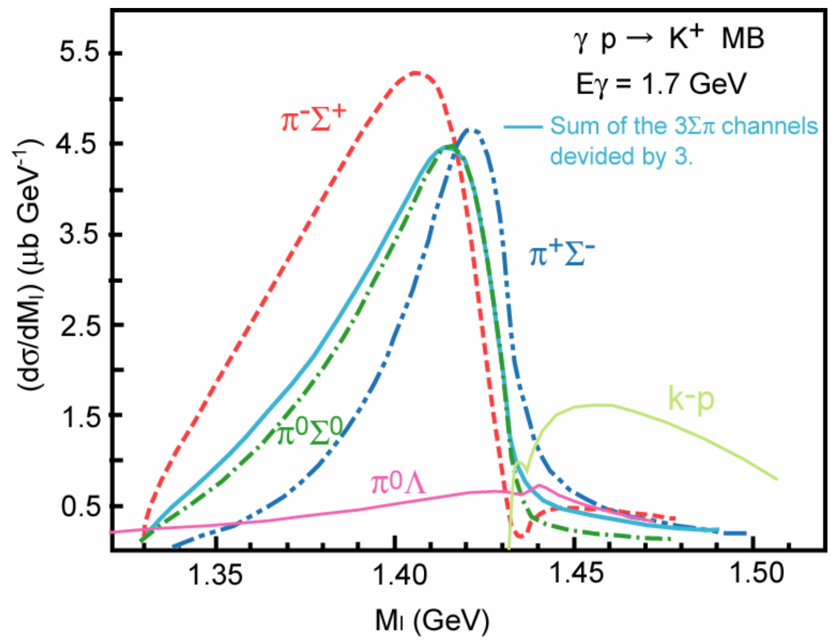
  Chiral unitary model

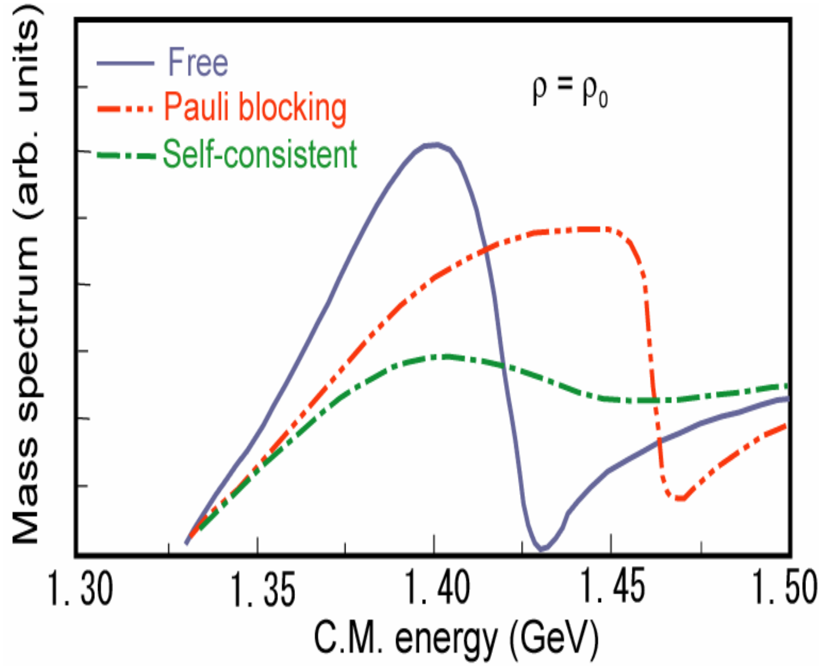
  ⇒ Different spectrum shapes between $\pi^+\Sigma^-$ & $\pi^-\Sigma^+$ channels.

  ⇒ Modification of invariant mass distribution in nuclear matter.

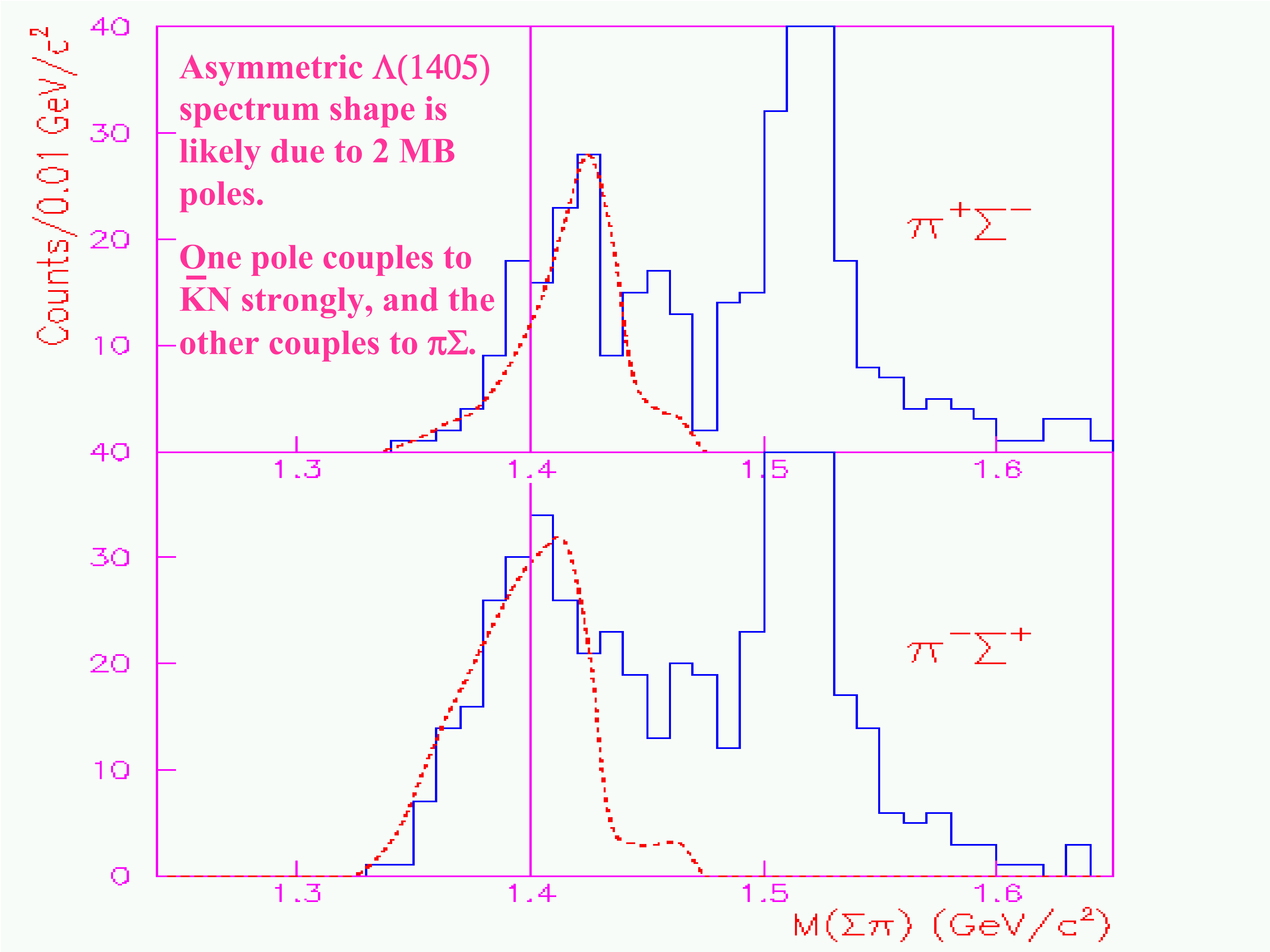
- Λ(1405) and Σ(1385) are not separated in MMp(γ,K^+).

  ⇒ Need to detect Σ→πN to select Λ(1405) w/ large acc. TPC

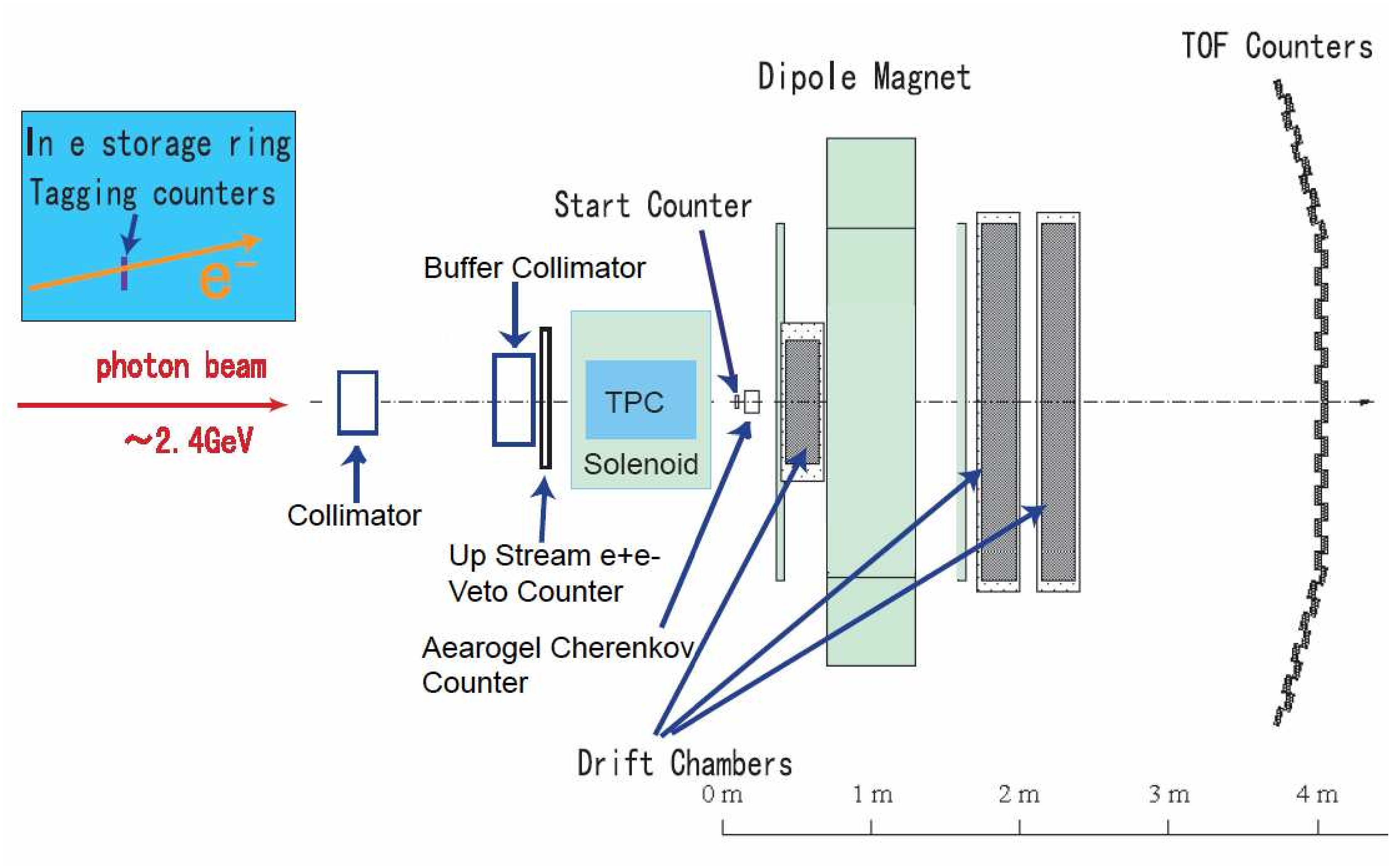




J.C. Nacher, E. Oset, H. Toki and A. Ramos, Phys. Lett. B455 (1999), 55


Asymmetric Λ(1405) spectrum shape is likely due to 2 MB poles.
One pole couples to $\bar{K}N$ strongly, and the other couples to πΣ.
Counts/0.01 GeV/c^2
40
30
20
10
0
1.3
1.4
1.5
1.6
$\pi^+\Sigma^-$
$\pi^-\Sigma^+$
M(Σπ) (GeV/c^2)

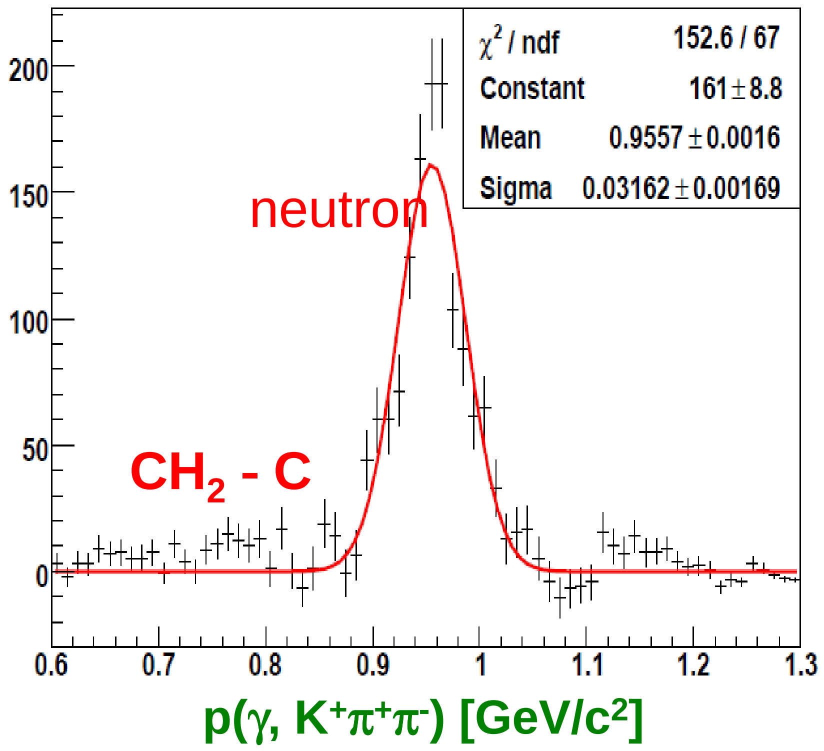
Setup of TPC experiment

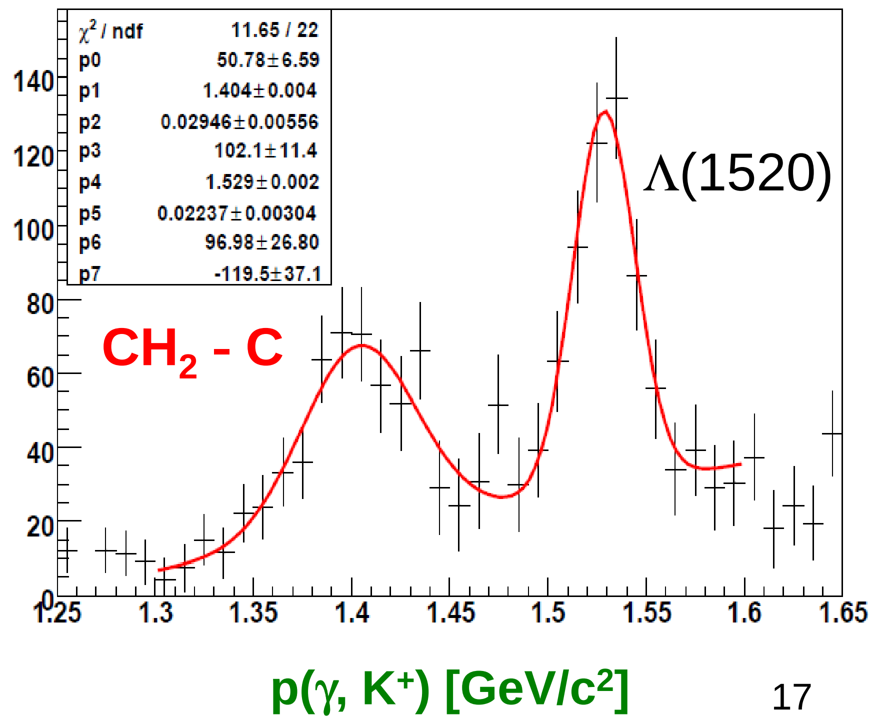


Nuclear Target Data w/ TPC

- $\gamma p \rightarrow K^+ \Lambda(1405) \rightarrow K^+ \Sigma^\pm \pi^\mp \rightarrow K^+ n \pi^\pm \pi^\mp$

  Spectrometer **TPC**
- Different charge combinations ($\Sigma^\pm \pi^\mp$) will be compared.
- Spectrum from nuclear target will be examined.





Jido, Oller, Oset, Ramos, Meißner, NPA725, 181 ('03)

SU(3) symmetry considerations

The existence of the three poles in the scattering amplitude with $I = 0$ can be understood in consideration of the SU(3) flavor structure of the meson baryon scattering.

Scattering of octet meson and octet baryon

states

$$\underset{\text{meson}}{8} \otimes \underset{\text{baryon}}{8} = 1 \oplus 8_s \oplus 8_a \oplus 10 \oplus \overline{10} \oplus 27$$

Elementary vertex (TW term)

$$V_{ij} = -C_{ij}\frac{1}{4f^2}\left(k_\mu - k'_\mu\right)\bar{u}(p')\gamma^\mu u(p)$$

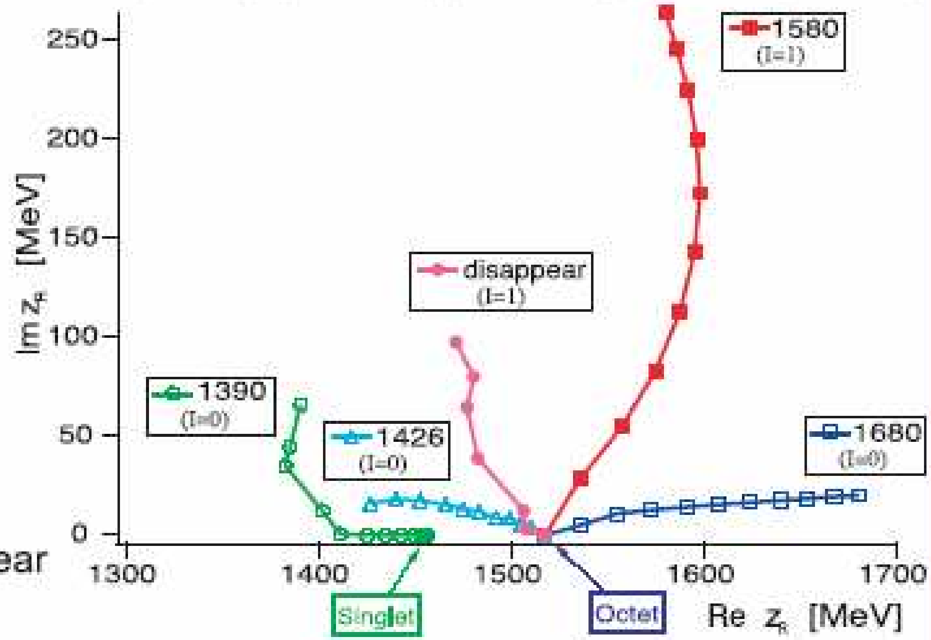
Coefficient in SU(3) basis

$$C_{ij} = \mathrm{diag}(\underset{1}{6}, \underset{8_s}{3}, \underset{8_a}{3}, \underset{10}{0}, \underset{\overline{10}}{0}, \underset{27}{-2})$$

$1,\ 8_s,\ 8_a$	attraction
27	repulsion

One singlet and two octets should appear after the unitary resummation.

Trajectories of the poles in the amplitudes obtained by changing the SU(3) breaking parameter gradually



Note that the singlet and the octet states are lying nearby in energy and what we see in experiment is a combination of these two resonance.

Λ(1405) production in $\overline{K}N$ channel

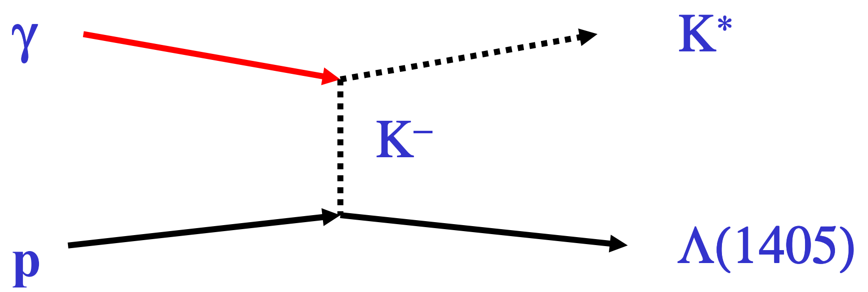
- Radiative Capture of K^-: $K^- p \rightarrow \Lambda(1405)\,\gamma$ (Ramos, Oset,,,)

  Large background from $K^- p \rightarrow \Lambda\,\pi^0$
- $\overline{K}^0$ exchange in t channel.

  $\gamma\ \ p \rightarrow \Lambda(1405)\,K^*$

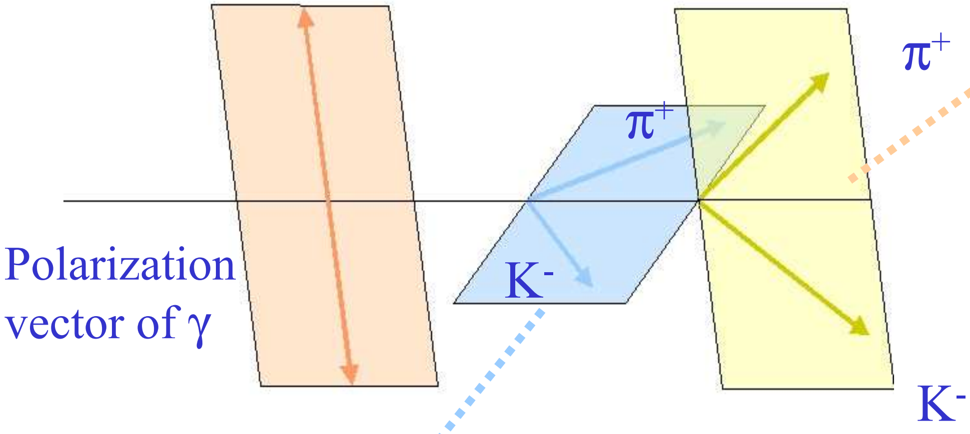
  Small momentum transfer → Forward peak

  K* decays into 3 π with large opening angles.



Photoproducion by linearly polarized photon

In K^* rest frame (Helicity frame)



Decay Plane $// \vec{\gamma}$

if natural parity exchange $(-1)^J$

Decay Plane $\perp \vec{\gamma}$

if unnatural parity exchange $-(-1)^J$ (Pseudoscaler mesons)

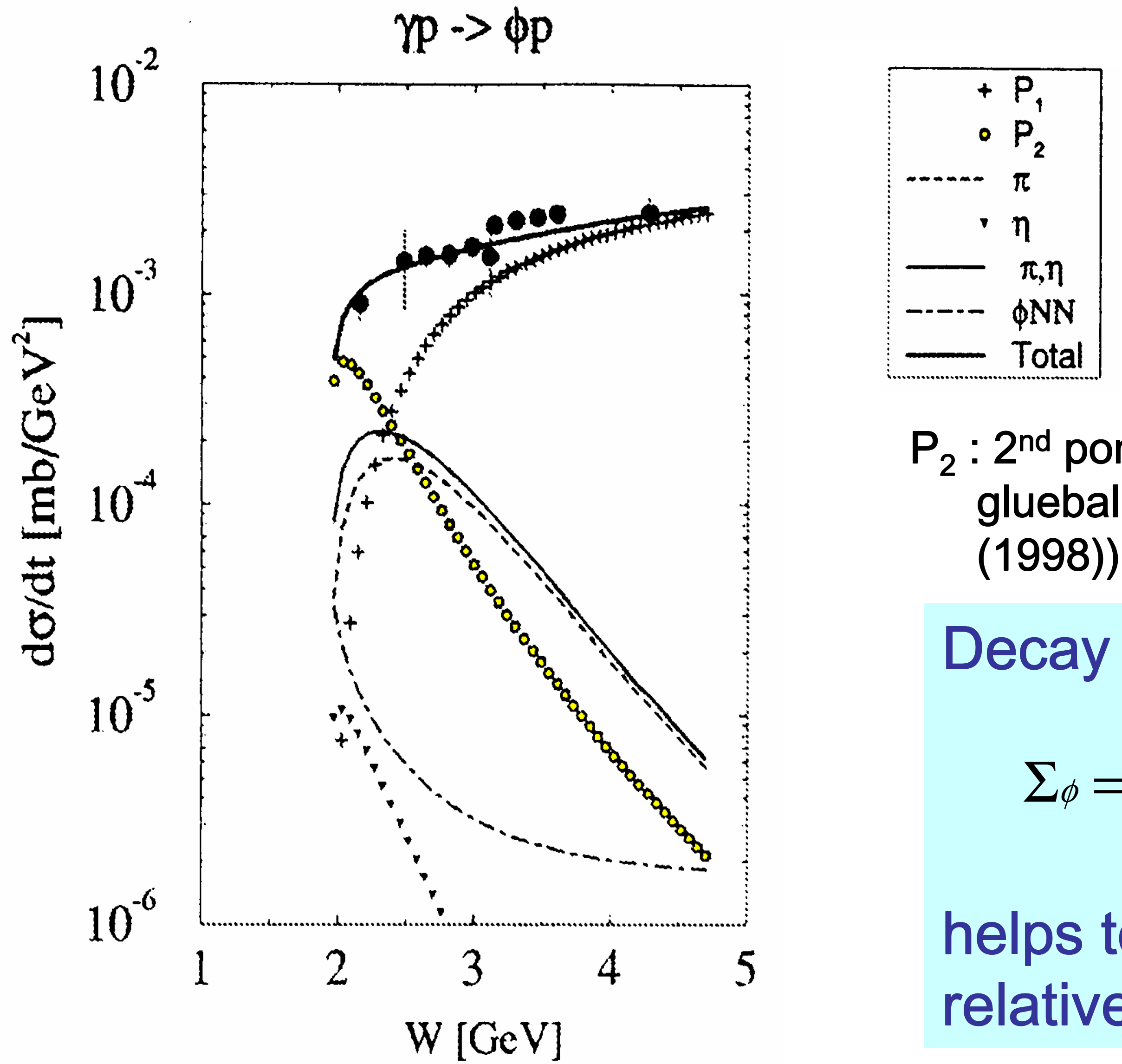
Decay Angular distribution of K^*

↓

Decomposition of

- natural parity exchange
- unnatural parity exchange

ϕ photoproduction near production threshold



Titov, Lee, Toki
Phys.Rev C59(1999) 2993

Data from: SLAC('73), Bonn('74),DESY('78)

P_2 : 2nd pomeron ~ 0^+ glueball (Nakano, Toki (1998))

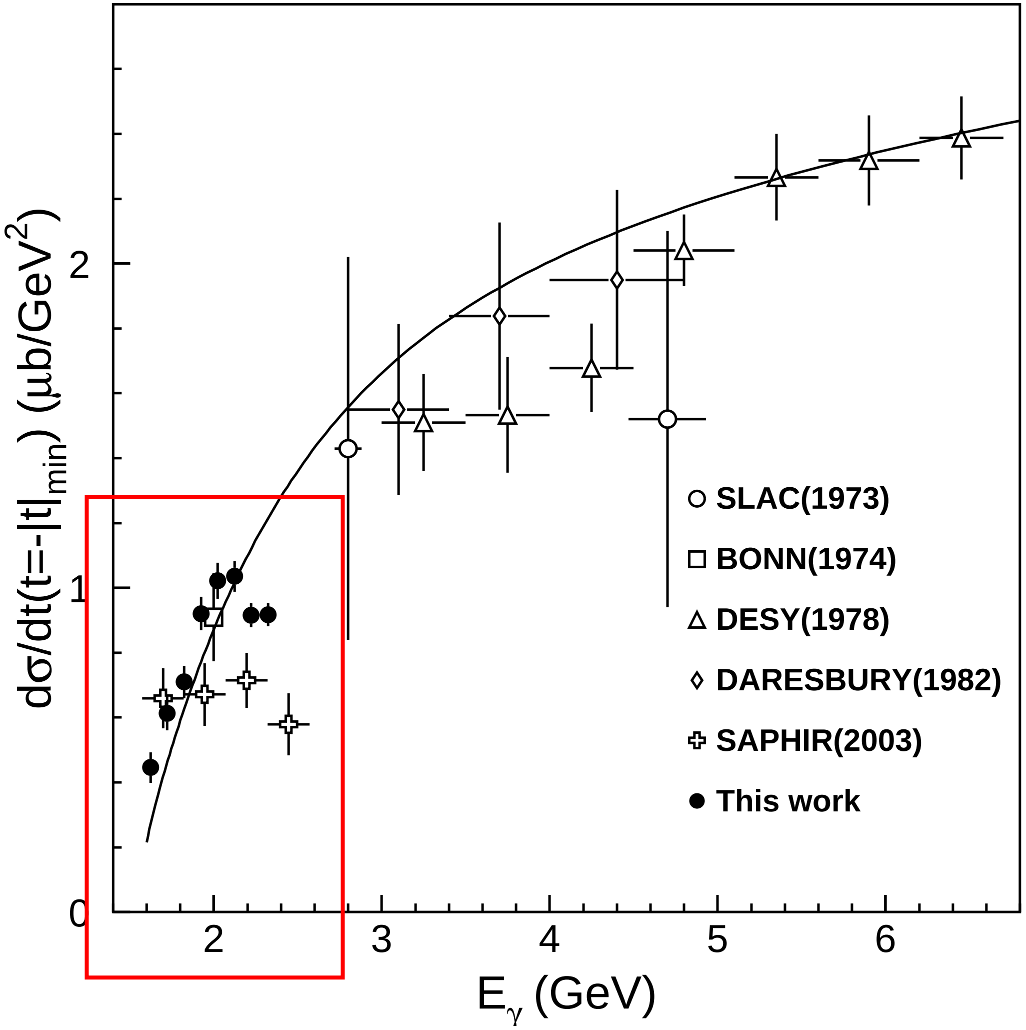
Decay asymmetry

$$\Sigma_\phi = \frac{\sigma_{//} - \sigma_{\perp}}{\sigma_{//} + \sigma_{\perp}} \cong \frac{\sigma_n - \sigma_{un}}{\sigma_n + \sigma_{un}}$$

helps to disentangle relative contributions

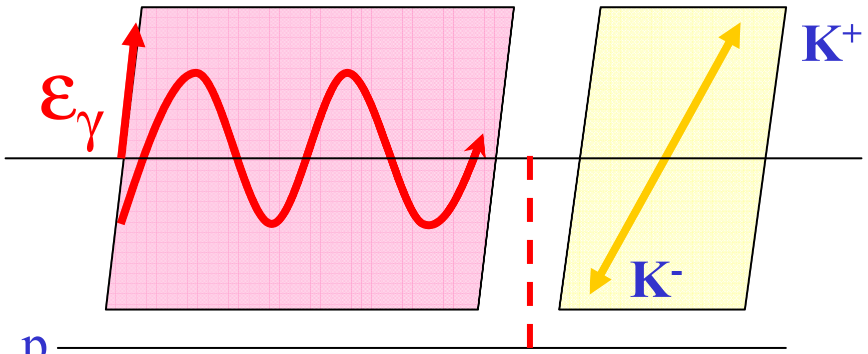
Differential cross section at $t=-|t|_{min}$

Phys. Rev. Lett. 95, 182001 (2005)

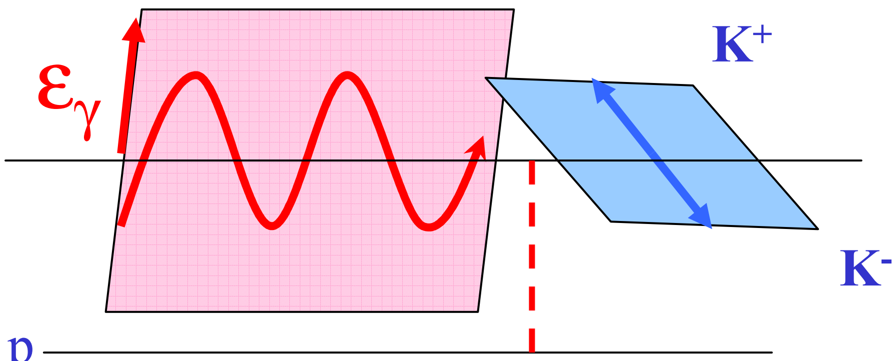


Polarization observables with linearly polarized photon

ϕ meson rest frame



Decay Plane // $\vec{\gamma}$
natural parity exchange $(-1)^J$
(Pomeron, Scalar Glueball, Scalar mesons)

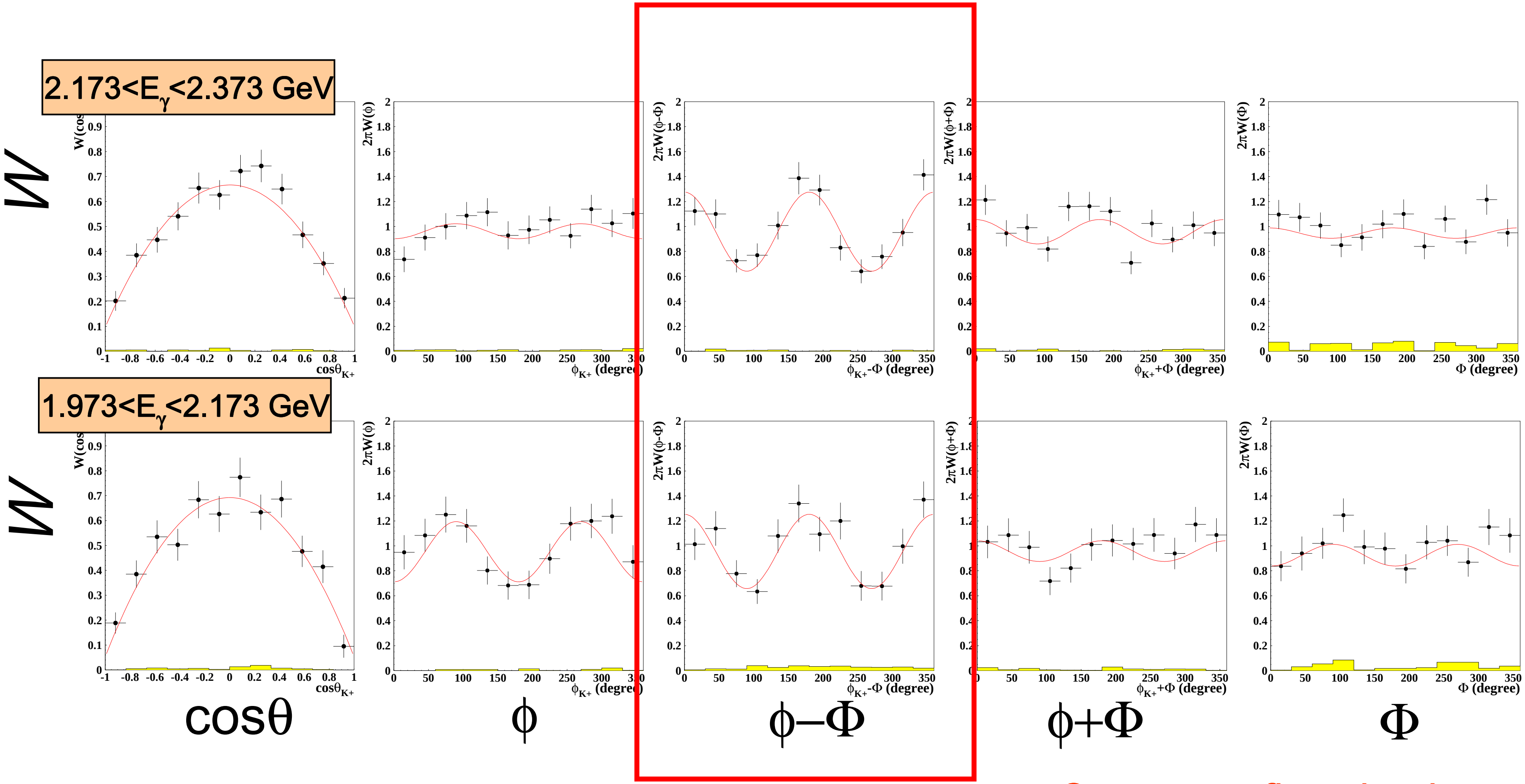


Decay Plane $\perp$ $\vec{\gamma}$
unnatural parity exchange $-(-1)^J$
(Pseudoscalar mesons π,η)

Decay angular distribution of ϕ → **Relative contributions from natural, unnatural parity exchanges**

The same technique will be used to study $\Lambda(1405)$.

Decay angular distribution

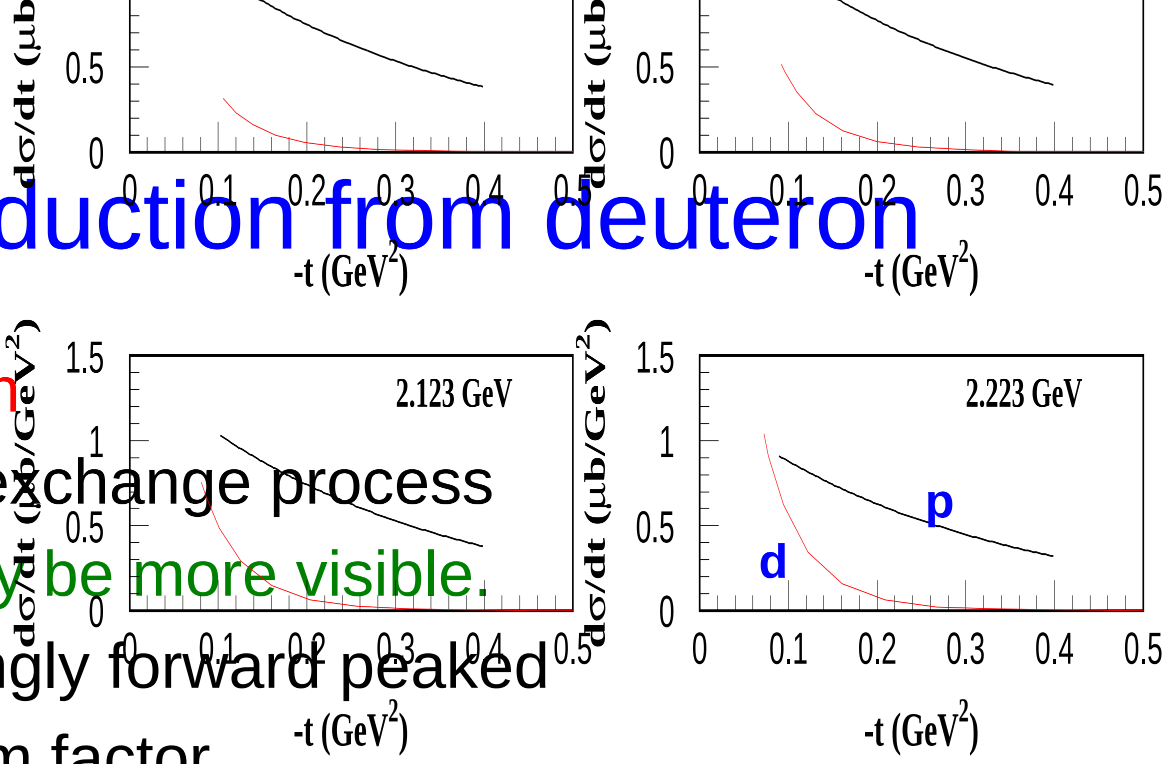


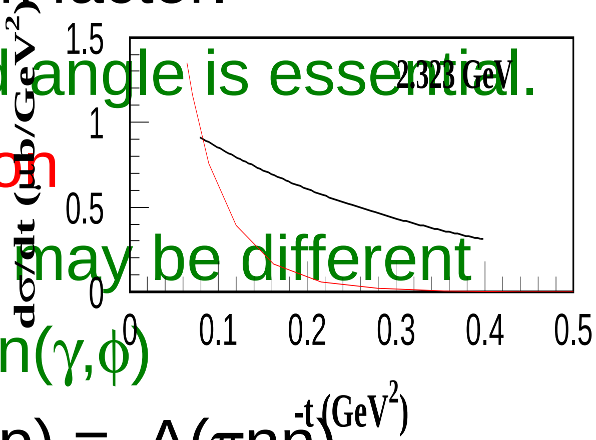
Curves are fit to the data.

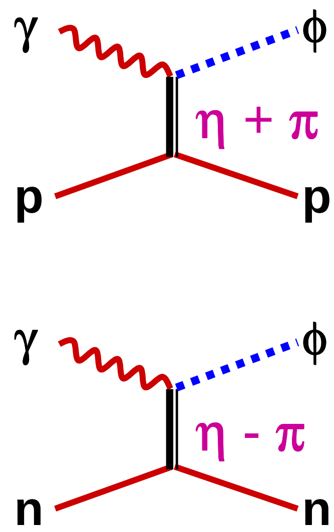
No energy dependence, except for ϕ distribution.
Natural parity exchange is dominant.

ϕ photoproduction from deuteron

- Coherent production
  - d: isospin=0 No p exchange process
    Exotics process may be more visible.
  - t dependence: strongly forward peaked
    due to deuteron form factor.
    Detection at forward angle is essential.
- Incoherent production
  - ϕ decay asymmetry may be different
    between p(γ,ϕ) and n(γ,ϕ)
    π: isovector $\Rightarrow$ A(πpp) = A(πnn)
    η:isoscalar $\Rightarrow$ A(ηpp) = -A(ηnn)

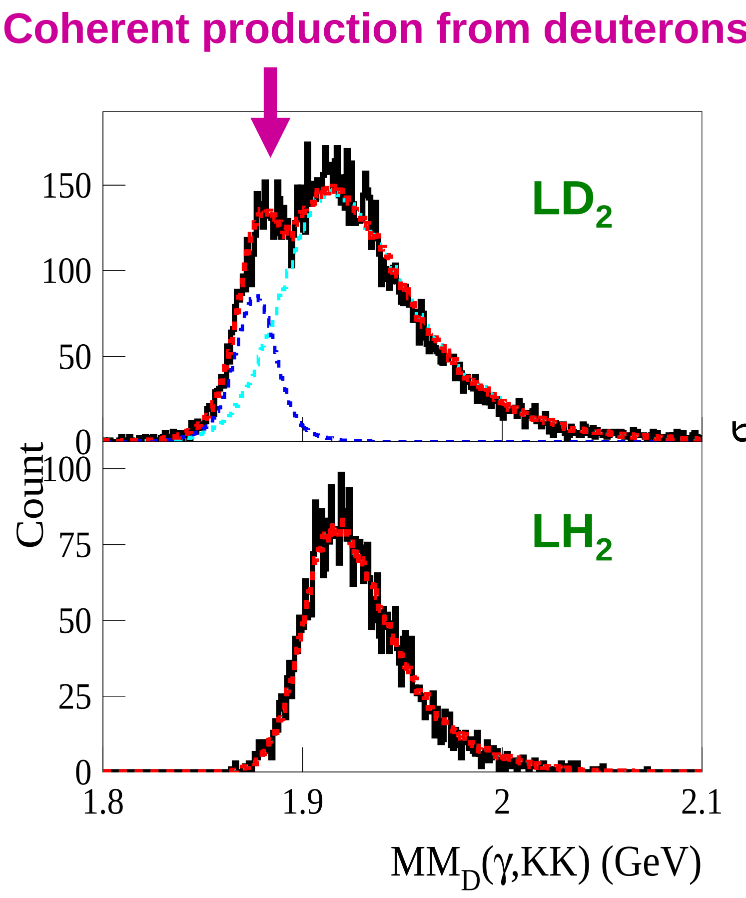


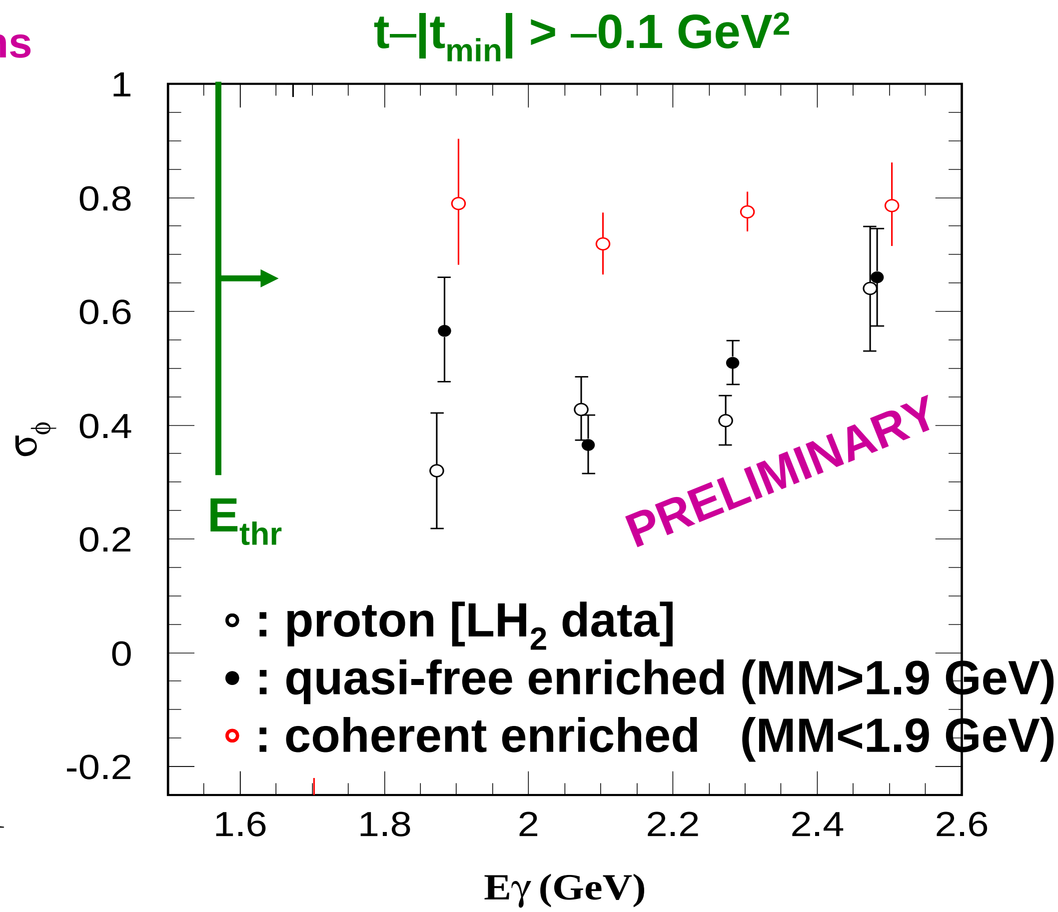




Titov.,Lee,Toki, Streltsova
PRC, 60 (1999)

Decay Asymmetry in LD_2 data





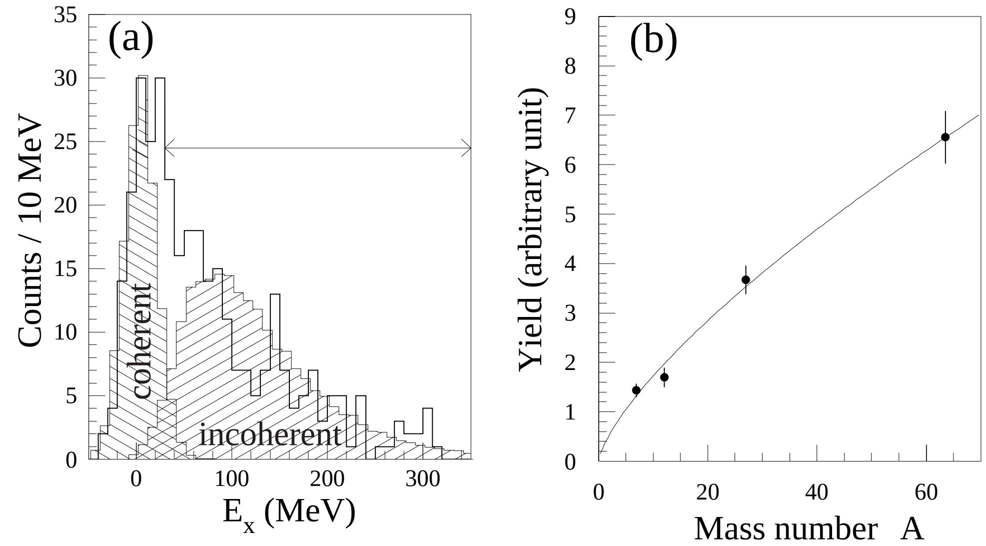
Natural parity exchange is dominant for N(γ,ϕ)N and d(γ,ϕ)d.

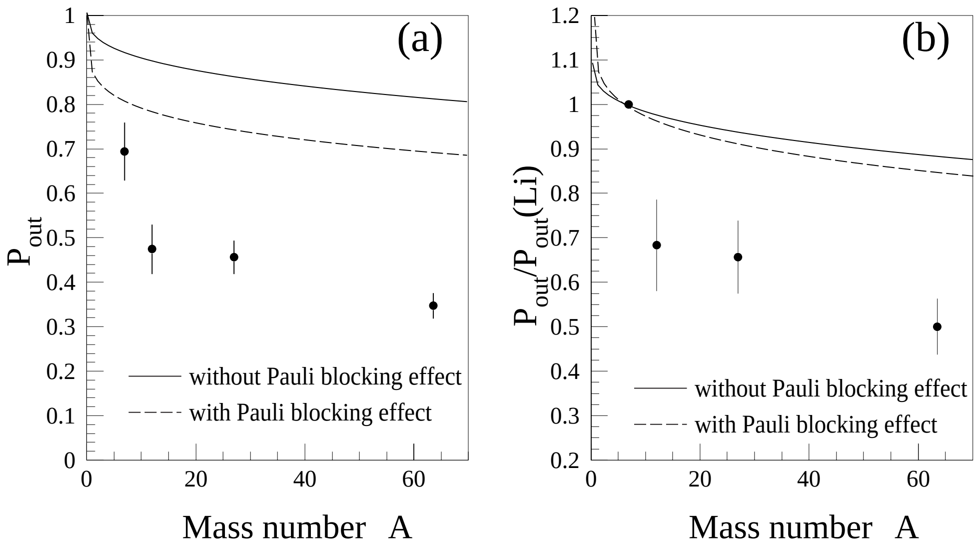
Decay asymmetries of p and quasi-free components are consistent.

Decay asymmetry of coherent component is higher than that of nucleon.

ϕ photoproduction from nuclei

Phys. Lett. B 608, 215 (2005)





OZI rule → Total ϕ-N cross section $\sigma_{\phi N}$ should be small.

If $\sigma_{\phi N}$ is small, the cross section from a nucleus, σ_{A}^{inc}, is approximately proportional to the target mass number *A*.

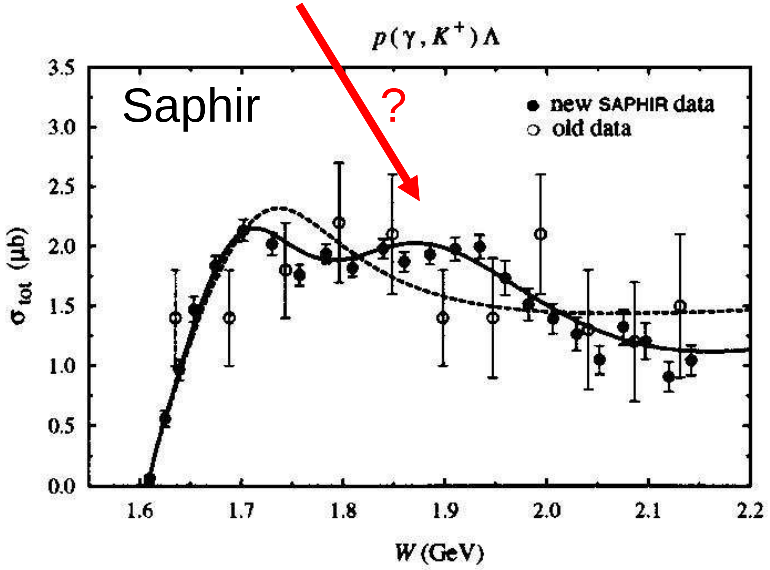
(a) $P_{out} = \sigma_{A}/(A\sigma_{N})$

(b) $P_{out}/P_{out}(\mathrm{Li})$

The data indicates large $\sigma_{\phi N}$ and/or large in-medium modification of f meson.

Study of p(γ,K⁺)Λ,Σ⁰ reactions

- **Available data is not sufficient to fix models and draw conclusions on the reaction process and presence of 'missing' nucleon resonances e.g. D_{13}(1900)**



Measurement of additional observables is needed:

At LEPS/SPring-8:

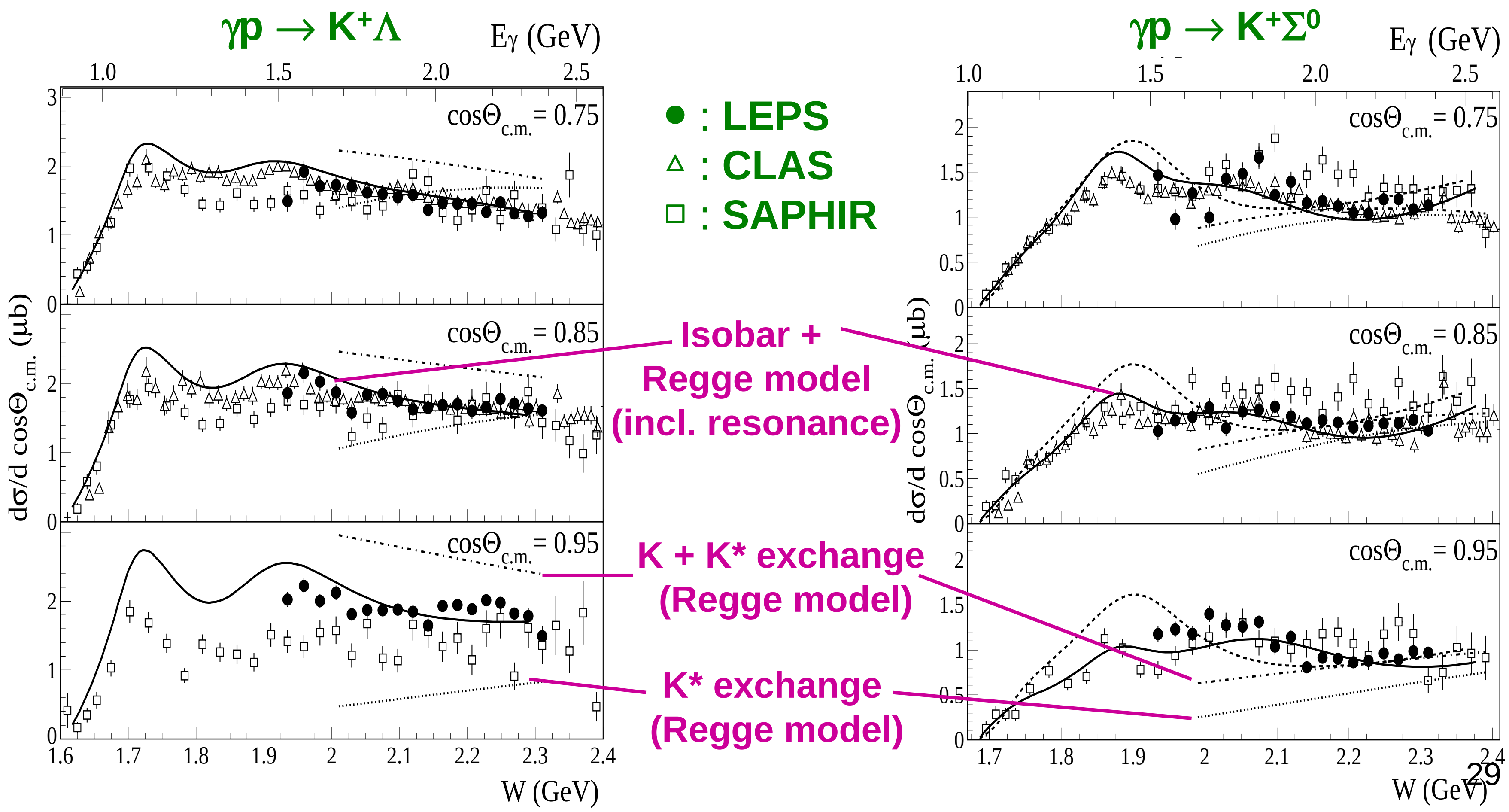
- **Single polarization observables**
  - **Photon polarization asymmetry (Σ)**

$$\frac{d\sigma}{d\Omega}_{POL} = \frac{d\sigma}{d\Omega}\left[1 + \Sigma P \cos(2\phi)\right]$$

  - Recoil polarization
- Double Polarization observables
  - Beam-recoil asymmetry
- Cross sections:
  - Forward angles (t_{max}>t>-0.6) (t-channel K/K* interference)

Differential cross sections [LH_2 target]

- Resonance structure at W=1.96 GeV in $\gamma p \rightarrow K^+\Lambda$: $D_{13}(1900)$
- Large contribution of t-channel K/K* exchange in $\gamma p \rightarrow K^+\Lambda$
- Small enhancement at W=2.05 GeV in $\gamma p \rightarrow K^+\Sigma^0$: $P_{31}(1910)$ Δ^* ?



Beam Asymmetry [LH_2 target]

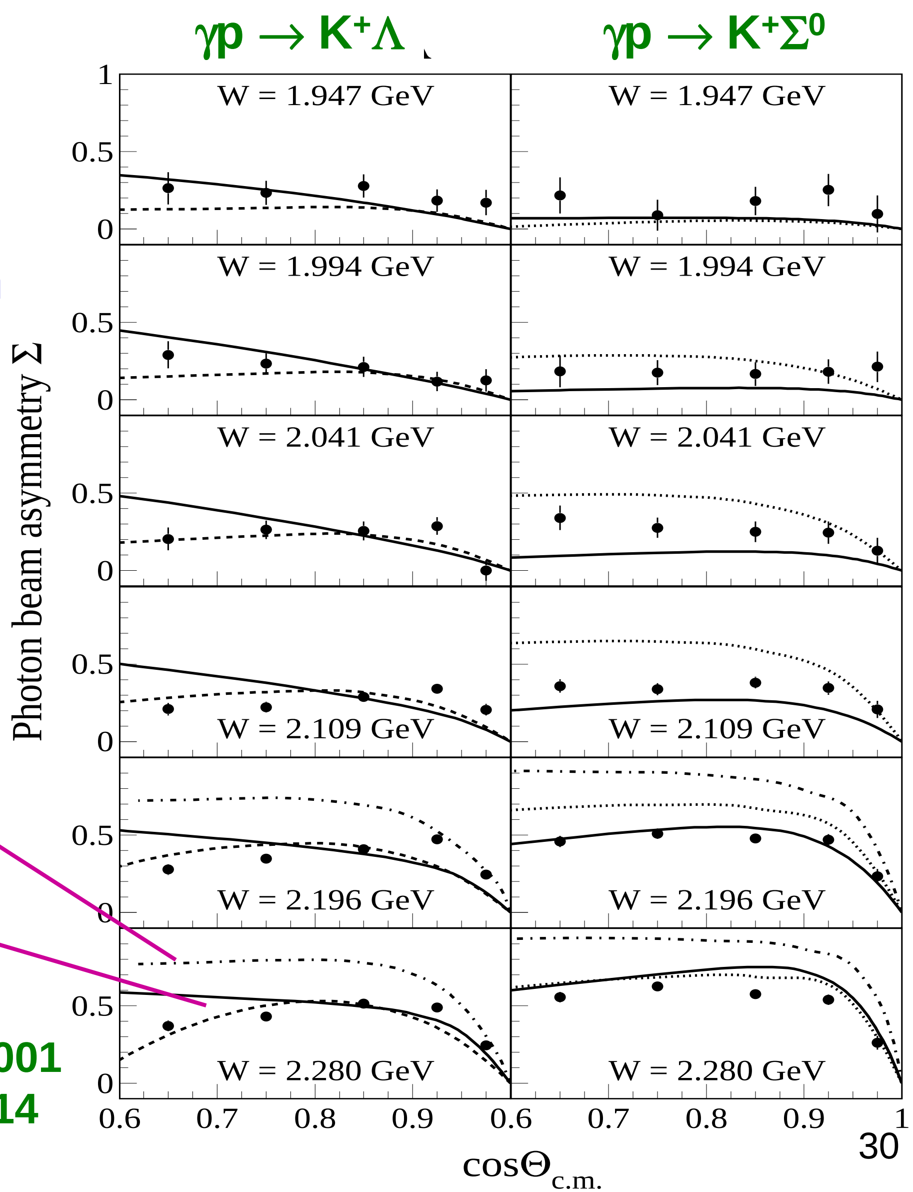
$P_\gamma \Sigma \cos(2\Phi) = [N_V - N_H]/[N_V + N_H]$

Positive Asymmetries observed

⇒ K^+Y tends to go to the direction in parallel to polarization vector.

Smaller asymmetries than Regge model

⇒ s-channel resonance effect ?



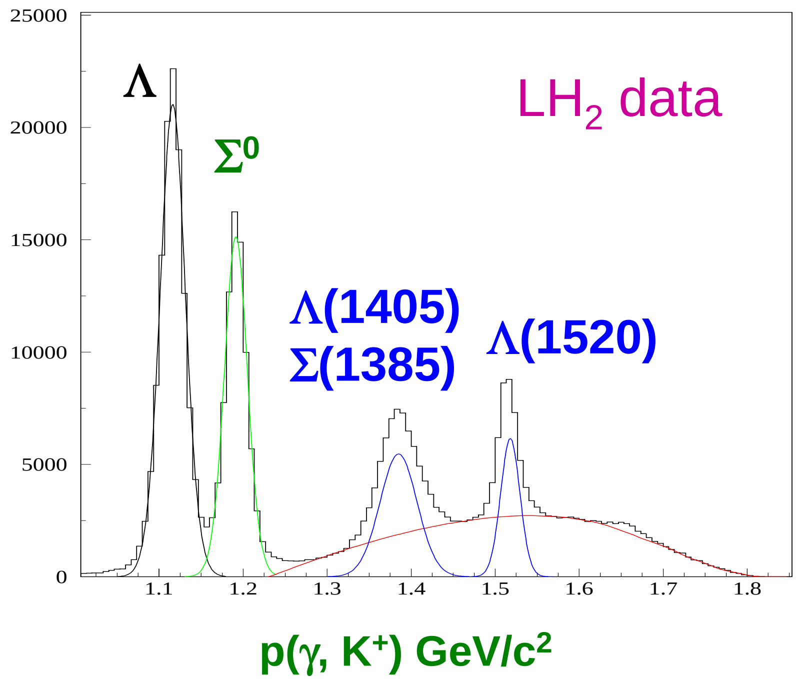
R.G.T. Zeggers et. al., PRL 91 (2003), 092001
M. Sumihama et. al., PRC 73 (2006), 035214

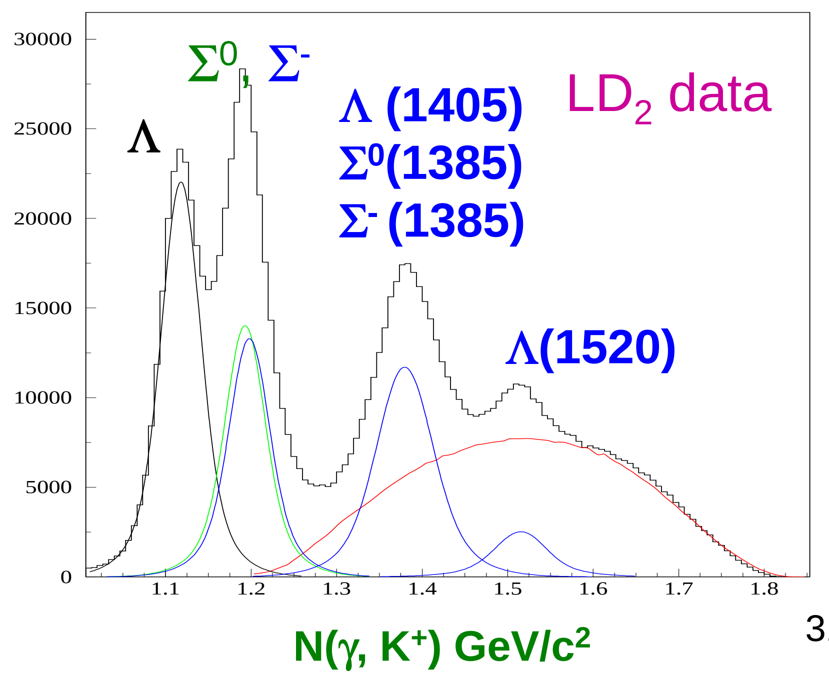
Ground-State Λ and Σ Photoproduction from Proton / Deuteron

- Hyperons are identified by K^+ missing mass
- Differential cross sections & photon beam asymmetry

⇒ Missing baryon resonance which couples to KY (D_{13}, …)

Meson exchange in t-channel (K, K*, …)

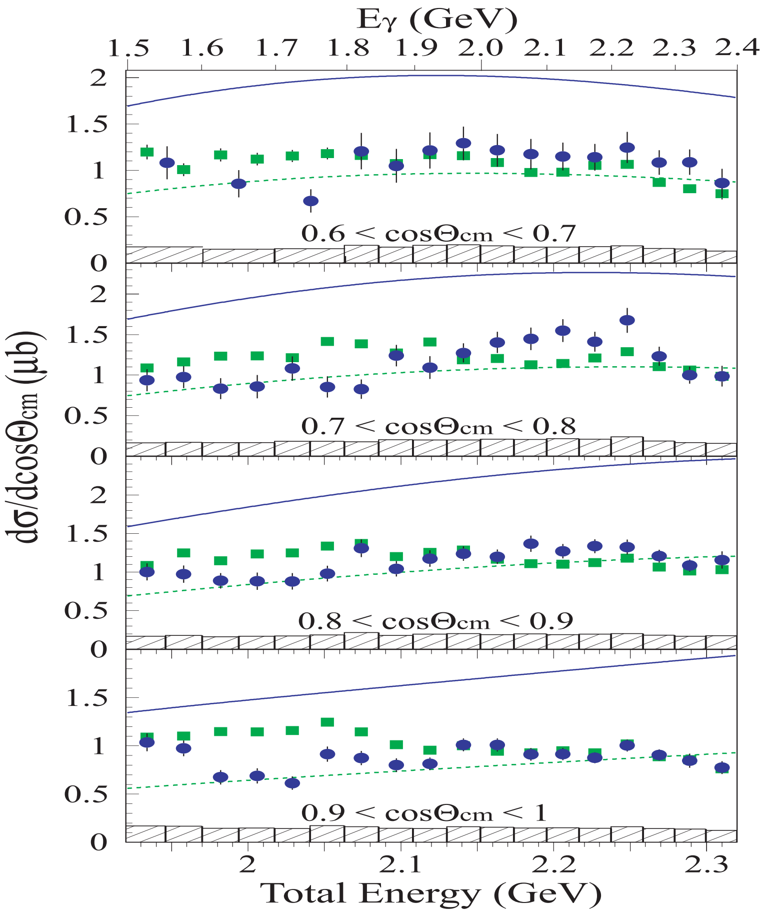




Σ^- photoproduction from LD_2 target

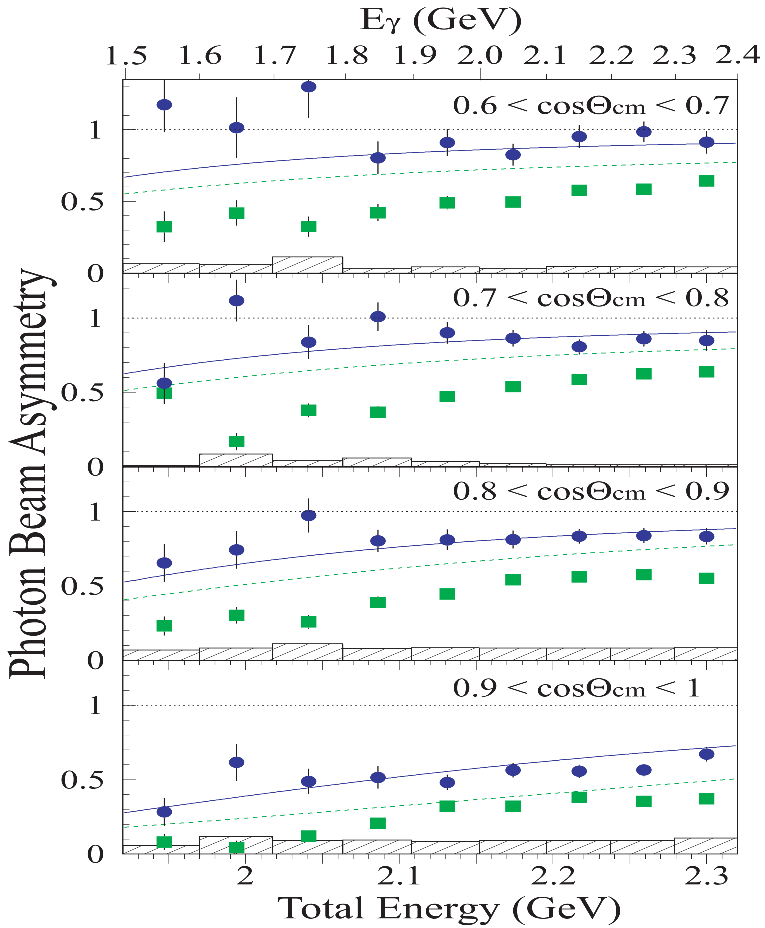
Differential cross sections

Enhancement in $K^+\Sigma^0$ relative to $K^+\Sigma^-$ around W=2 GeV ⇒ P_{31} Δ^* resonance ?



Blue : $K^+\Sigma^-$
Green: $K^+\Sigma^0$
Lines: Regge model

Kohri et. al., hep-ex/0602015



Beam Asymmetries

- Large asymmetries in $K^+\Sigma^-$

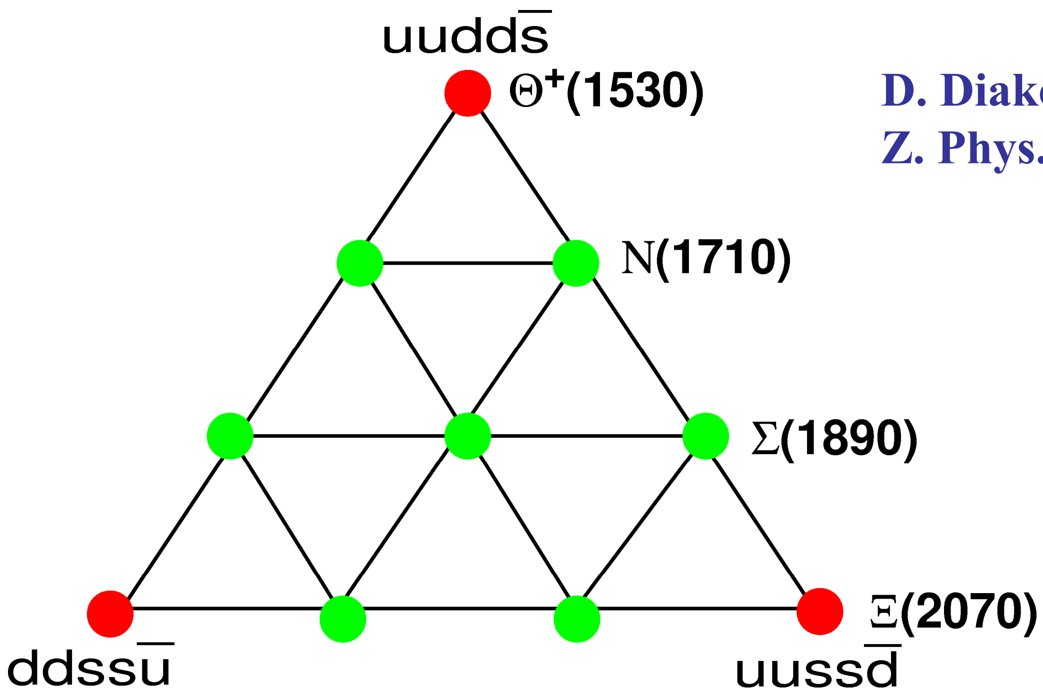
⇒ K^* exchange in t-channel.

- Large difference of asymmetries in $K^+\Sigma^-$ and $K^+\Sigma^0$ channels.

⇒ Inclusion of Δ^* resonance ?
Or inclusion of additional effects ?

Pentaquark

The antiquark has a different flavor than the other 4 quarks.



M = [1890-180*Y] MeV

D. Diakonov, V. Petrov, and M. Polyakov, Z. Phys. A 359 (1997) 305.

- **Exotic: S=+1**
- **Low mass: 1530 MeV**
- **Narrow width: ~ 15 MeV**
- **J^p=1/2$^+$**

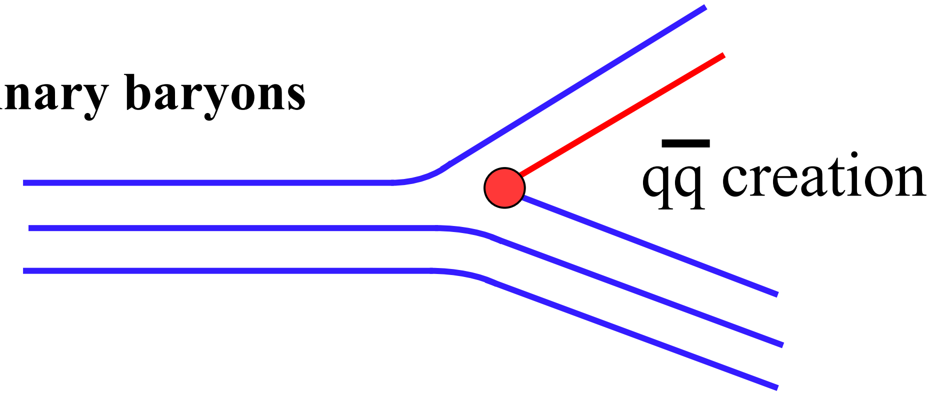
Theory

•DPP predicted the Θ^+ with M=1530MeV, Γ<15MeV, and $J^p=1/2^+$.

•Naïve QM (and many Lattice calc.) gives M=1700~1900MeV with $J^p=1/2^-$.

•But the negative parity state must have very wide width (~1 GeV) due to "fall apart" decay.

Ordinary baryons



Positive Parity?

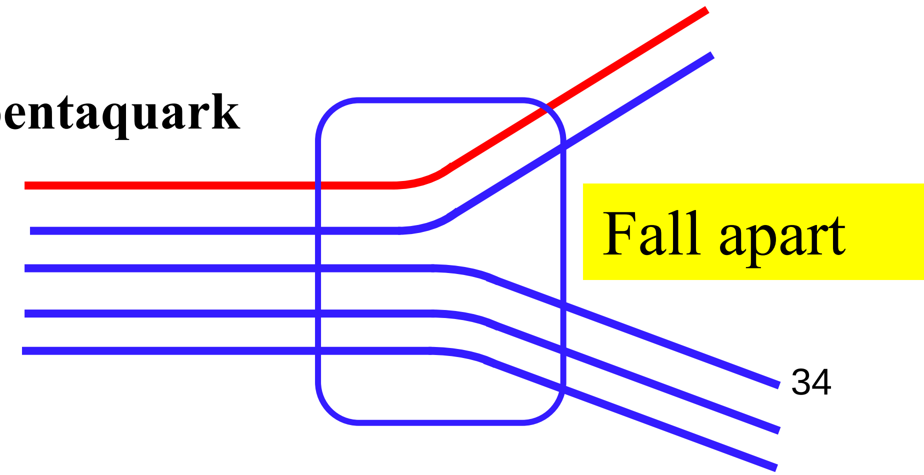
•Positive parity requires P-state excitation.

•Expect state to get heavier.

•Need counter mechanism.

diquark-diquark, diquark-triquark, or strong interaction with "pion" cloud?

For pentaquark

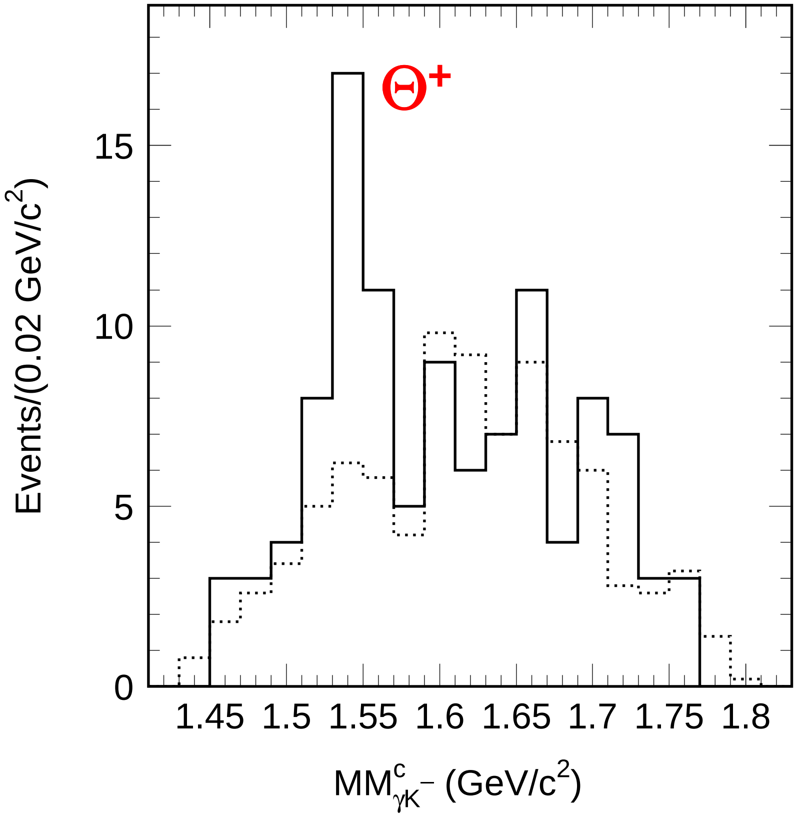


First evidence from LEPS

$\gamma\, n \rightarrow K^+ K^- n$

Phys.Rev.Lett. 91 (2003) 012002

hep-ex/0301020



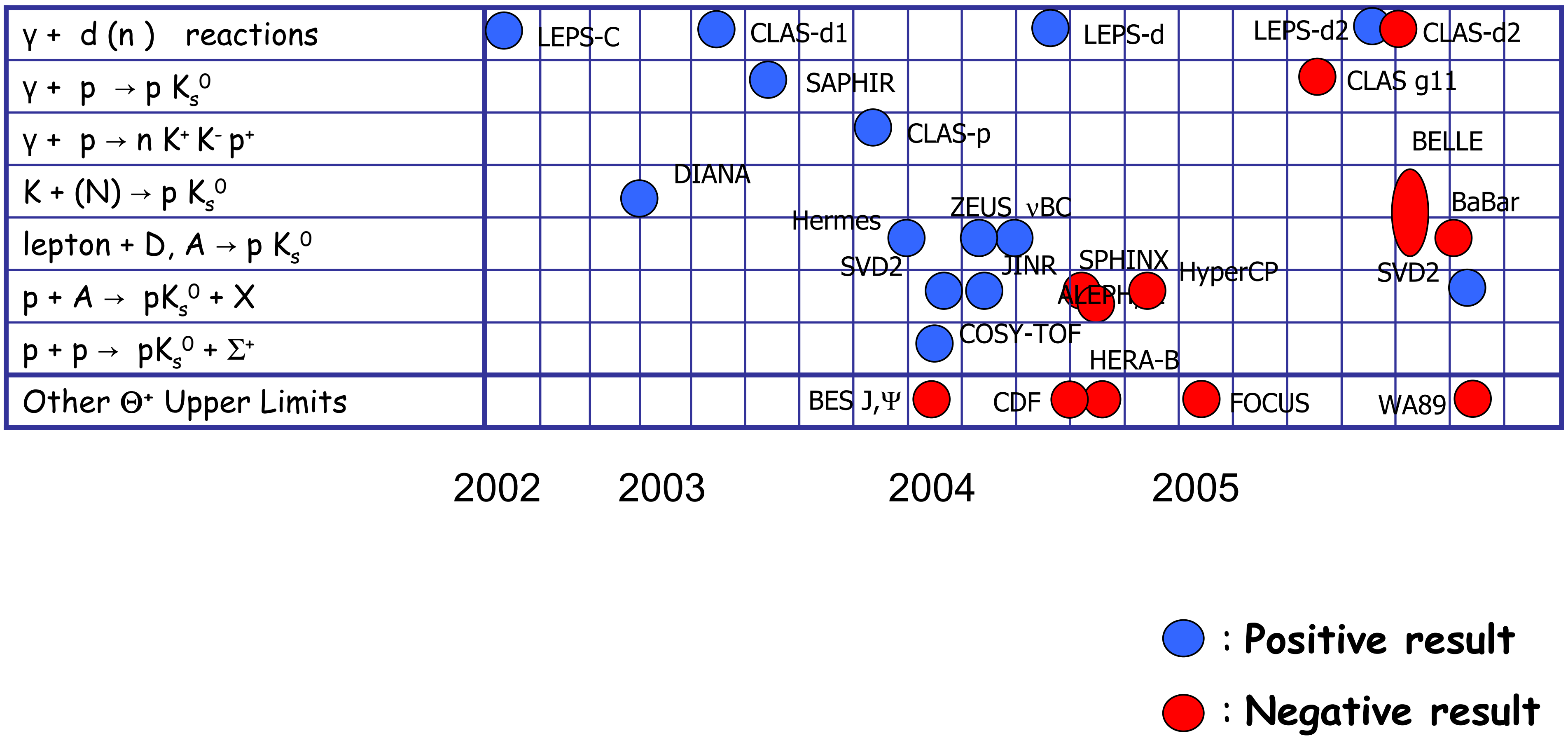
Low statistics: $\frac{S}{\sqrt{B}} = 4.6$ **but** $\frac{S}{\sqrt{S+B}} = 3.2$

Tight cut: 85% of events are rejected by the ϕ exclusion cut.

Unknown background: BG shape is not well understood. Events from a LH2 target were used to estimate it. Possible kinematical reflections.

Correction: Fermi motion correction is necessary.

Time dependent experimental status of Θ^+



From Carl Carlson’s talk at Hawaii pentaquark workshop

Don’t give up so easily...

Θ^+ searches with LD_2 target

- Search in $\gamma\, d \rightarrow K^+ K^- X$
- Search in $\gamma\, d \rightarrow \Lambda(1520)\ X$
- Search in $\gamma\, d \rightarrow \Lambda(1116)\ X$
- Near-term plan

LEPS LD_2 runs

- Collected Data (LH_2 and LD_2 runs)

  Dec.2000 – June 2001 LH_2 50 mm ~5×10^{12} photons

  published data

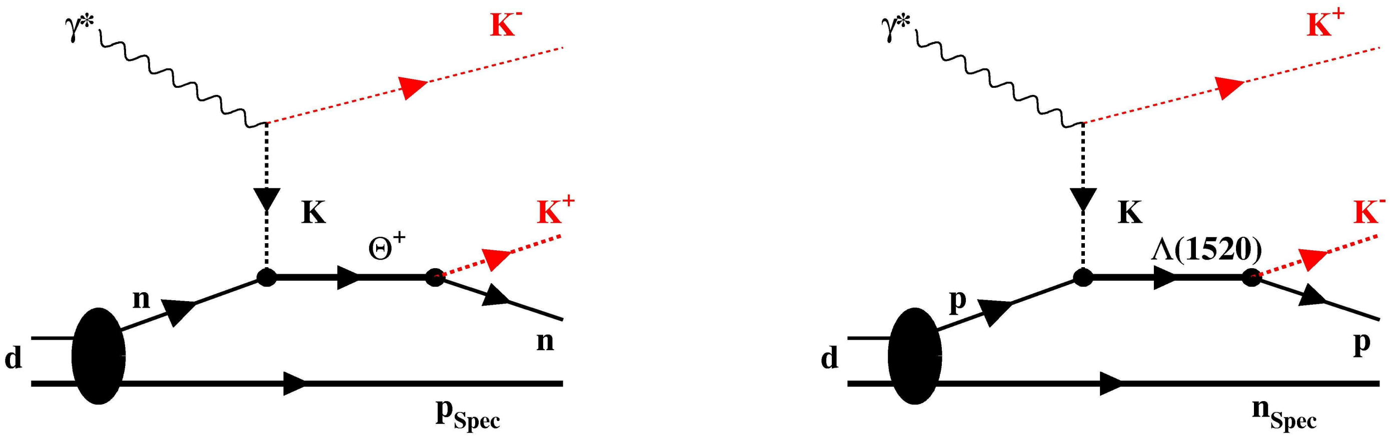
  May 2002 – Apr 2003 LH_2 150 mm ~1.4×10^{12} photons

  Oct. 2002 – June 2003 LD_2 150 mm ~2×10^{12} photons

- #neutrons × #photons in K^+K^- detection mode

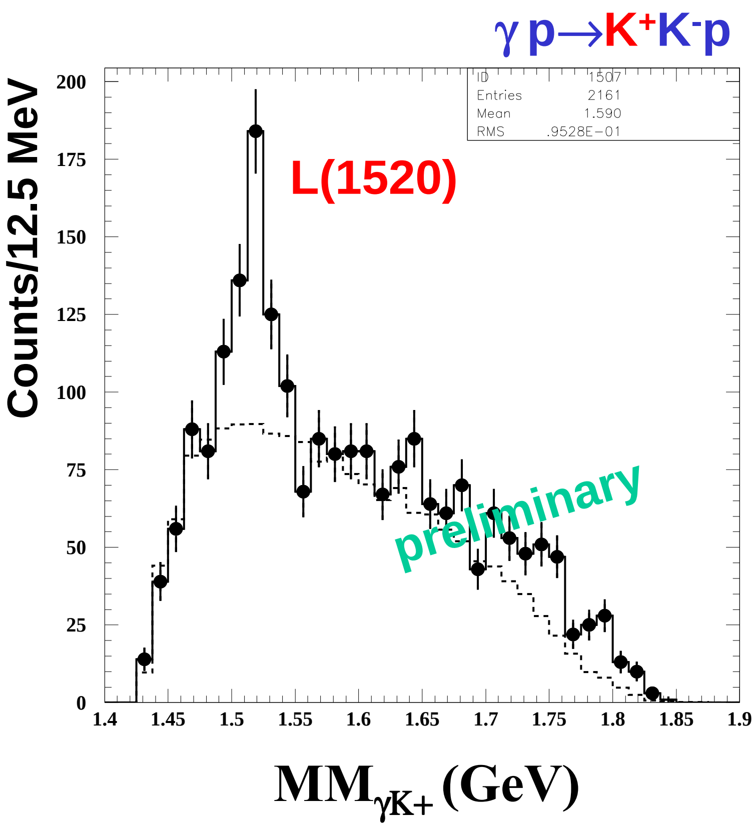
  LD_2 runs = 5mm-thick STC in short LH_2 runs × ~5

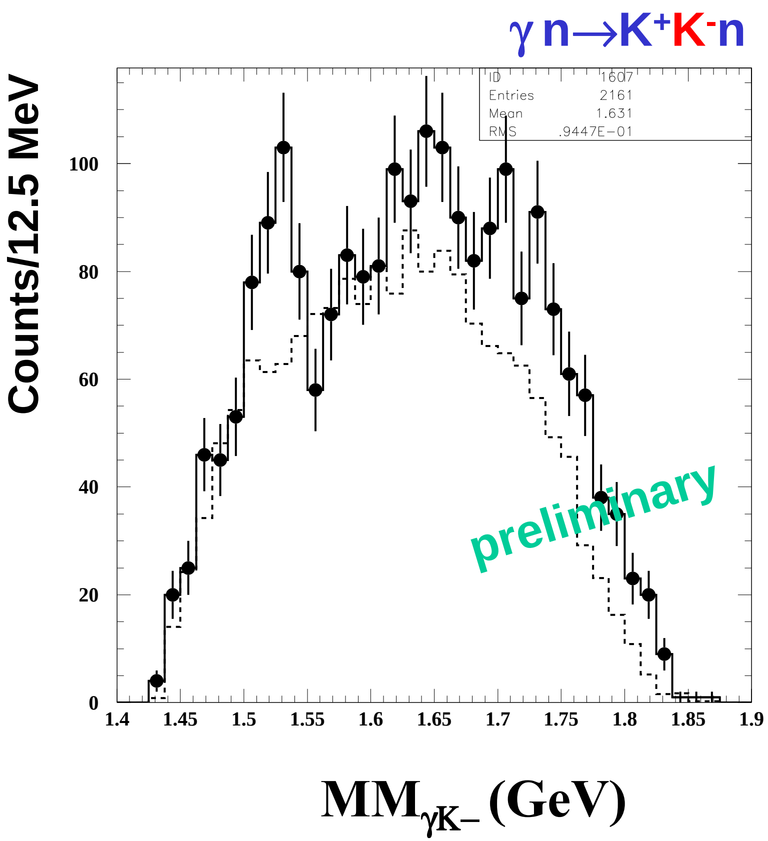
Θ^+ and $\Lambda(1520)$ production from deuteron



Search for Θ^+ in $\gamma n \to K^+K^-n$

- A proton is a spectator (undetected).
- Fermi motion is corrected to get the missing mass spectra.
- Tight ϕ exclusion cut is essential.
- Background is estimated by mixed events.



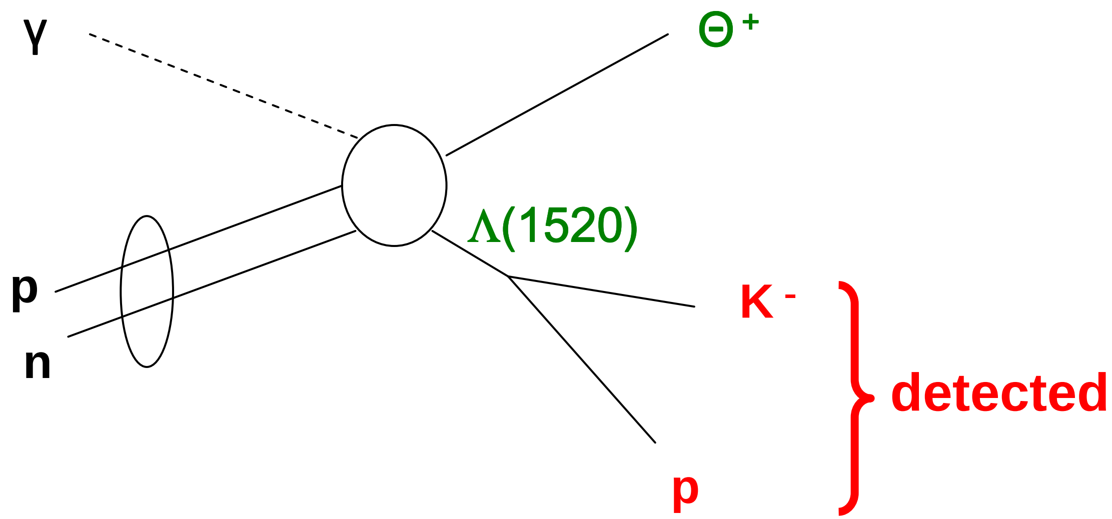


Θ^+ search in $\gamma d \rightarrow \Lambda(1520)$ KN reaction

Θ^+ is identified by K^-p missing mass from deuteron. $\Rightarrow$
No Fermi correction is needed.

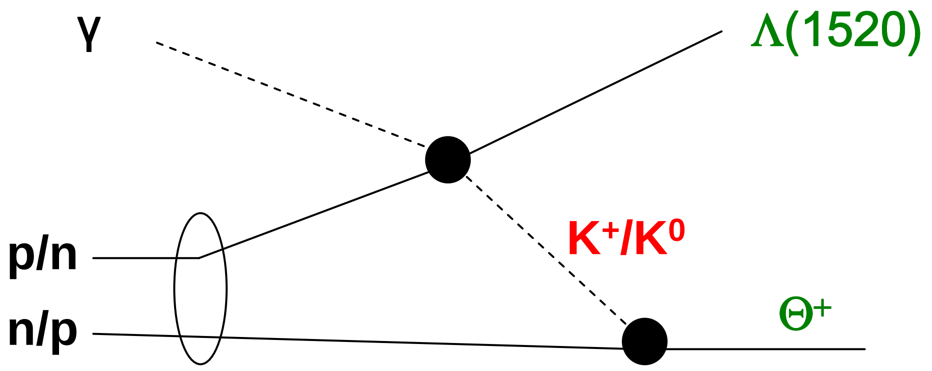
K^-n and pn final state interactions are suppressed.

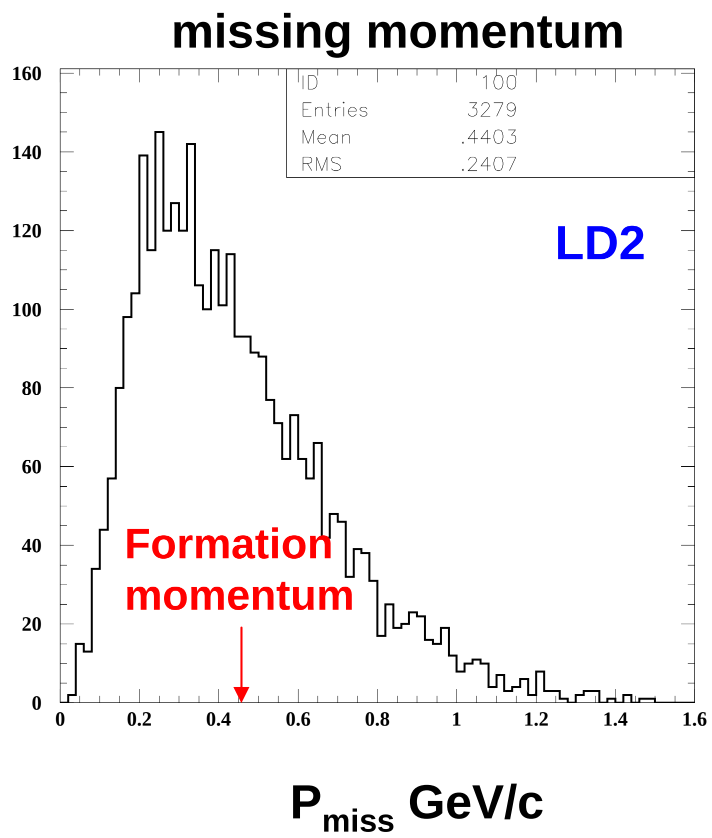
If $s\bar{s}$(I=0) component of a γ is dominant in the reaction, the final state KN has I=0. (Lipkin)



A possible reaction mechanism

- Θ^+ can be produced by re-scattering of K^+.
- K momentum spectrum is soft for forward going $\Lambda(1520)$.



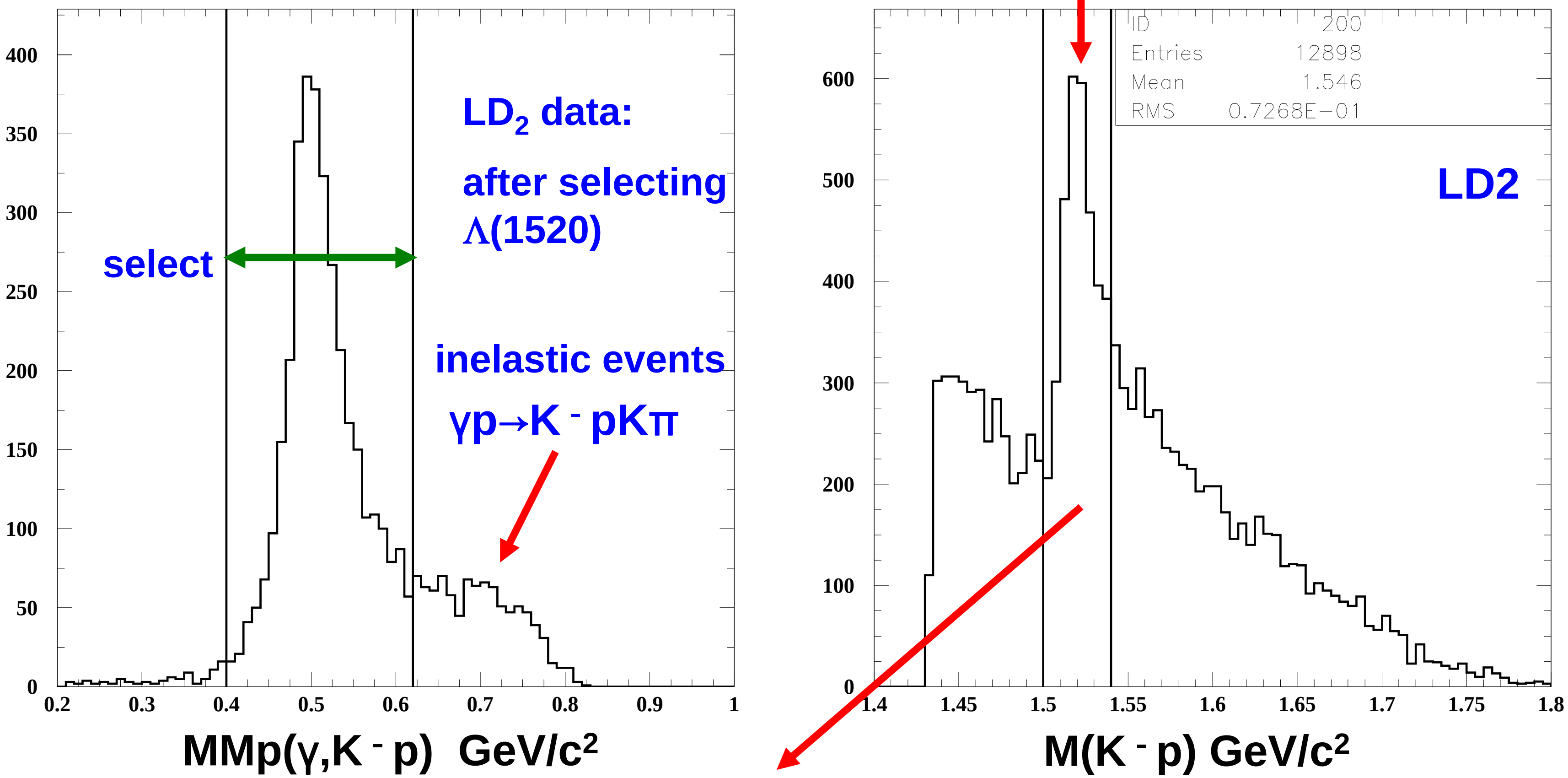


- **LEPS acceptance has little overlap with CLAS acceptance.**
- **Exchanged kaon can be on-shell.**

Event selection

K mass is smeared by Fermi motion.
(assumed proton at rest)

Λ(1520)

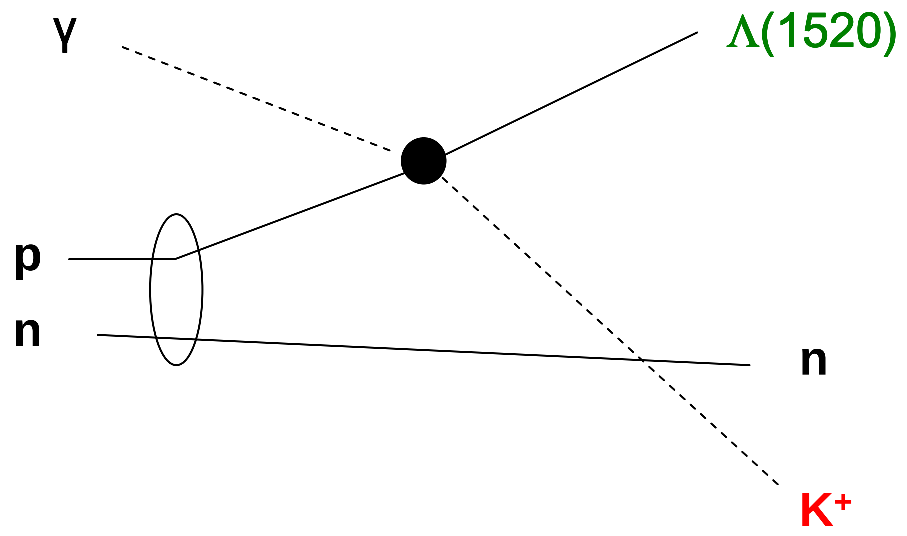


Select Λ(1520) in 1.50–1.54 GeV/c^2

⇒ calculate K$^-$ p missing mass of γ d → K$^-$ p X reaction

Background process

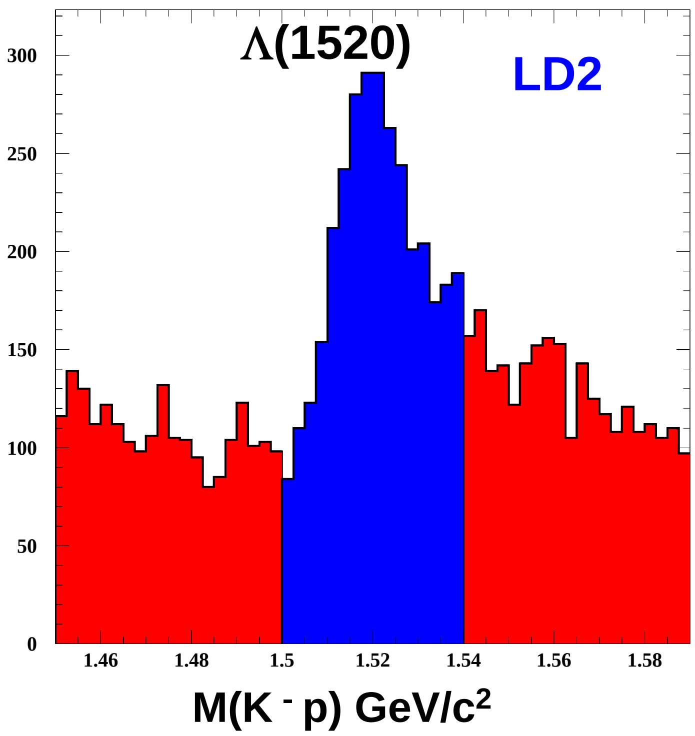
- Quasi-free Λ(1520) production must be the major background.
- The effect can be estimated from the LH2 data.

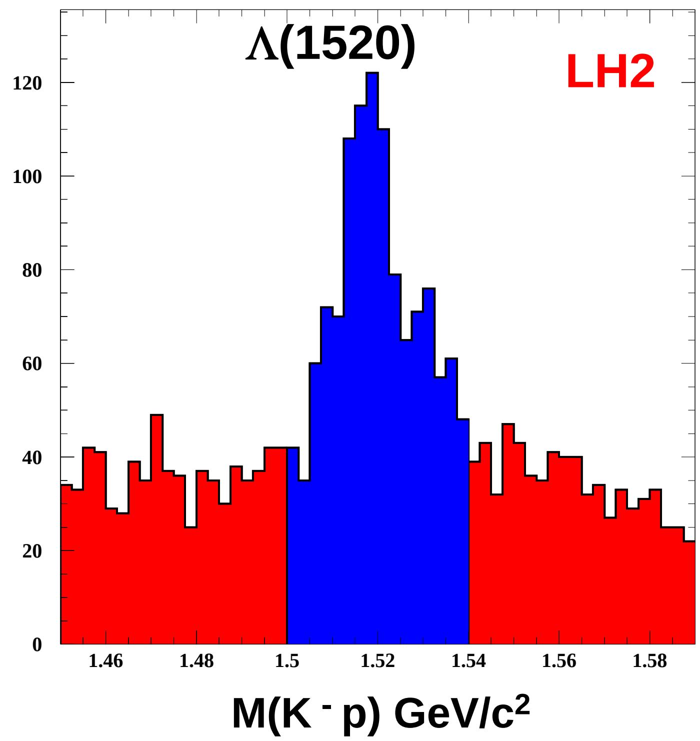


- The other background processes which do not have a strong pK^- invariant mass dependence can be removed by sideband subtraction.

Sideband subtraction to remove non-resonant background

$E\gamma > 1.75$ GeV



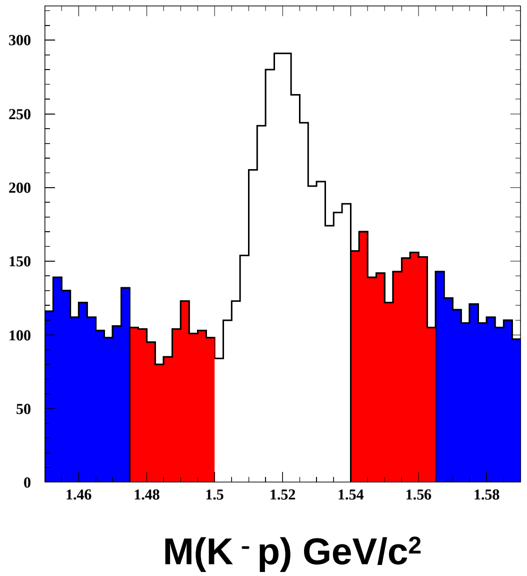


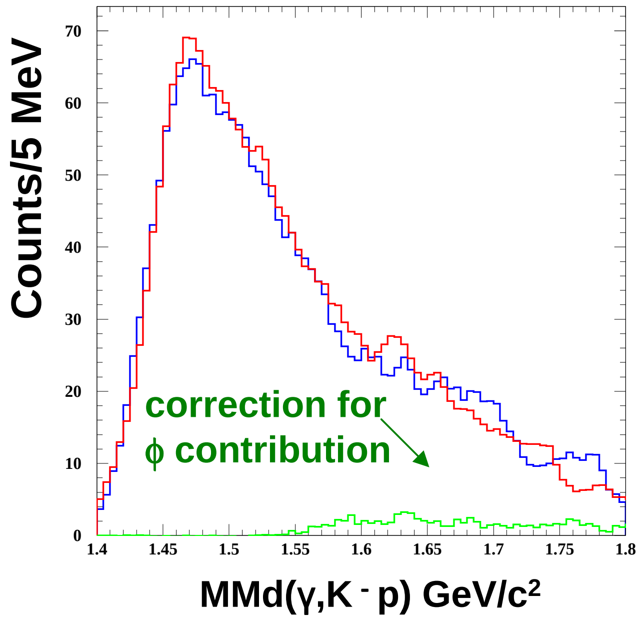
$1.50 < M(K^- p) < 1.54$

$1.45 < M(K^- p) < 1.50$ or $1.54 < M(K^- p) < 1.59$

S =  - 0.4 

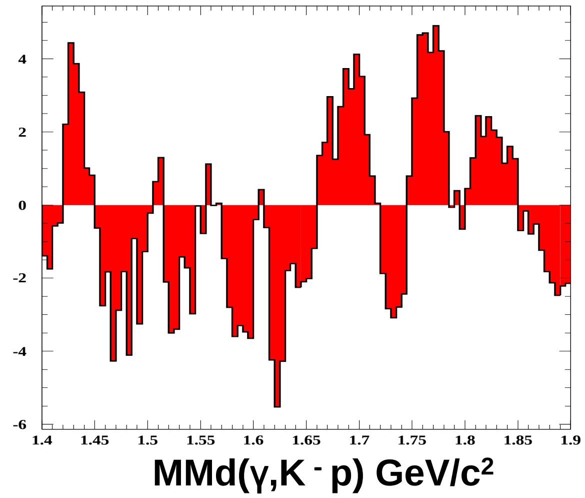
BG estimation with two independent sideband regions



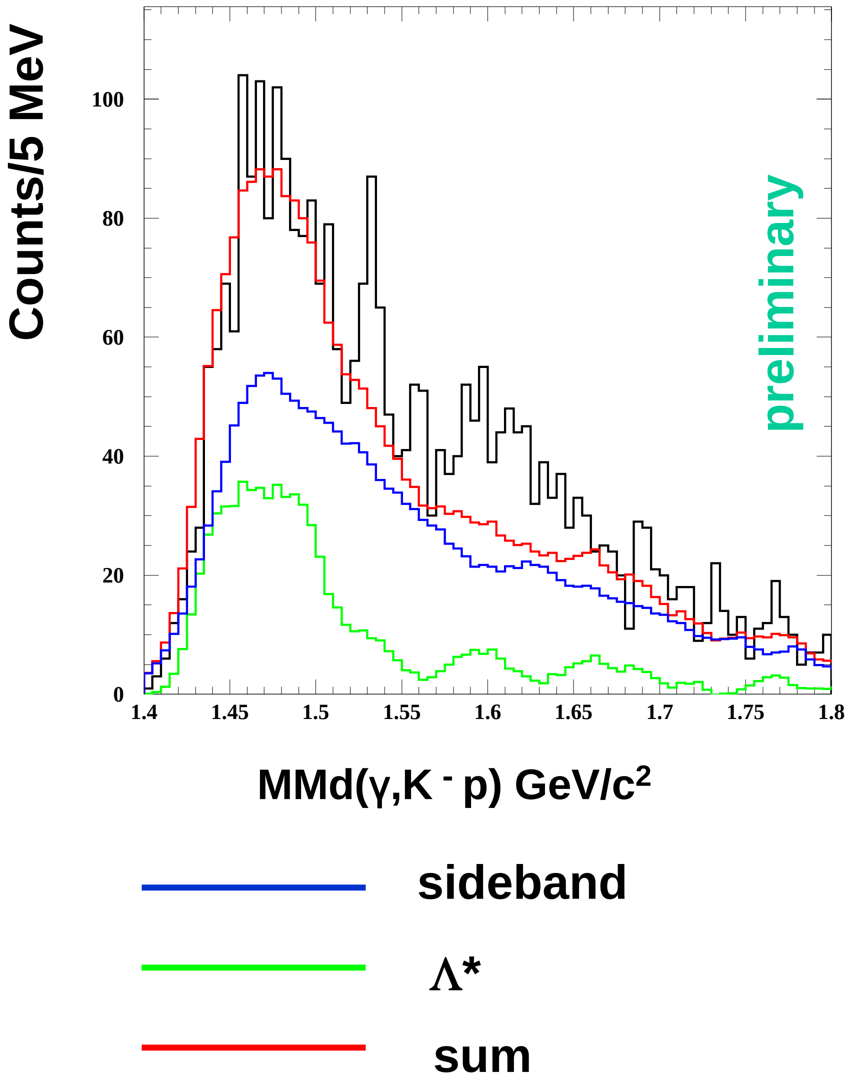


- Validity of the sideband method with Eγ smearing was checked by using two independent regions of the sideband.
- Channel-to-channel comparison gives

mean=-0.04 and RMS=2.0.

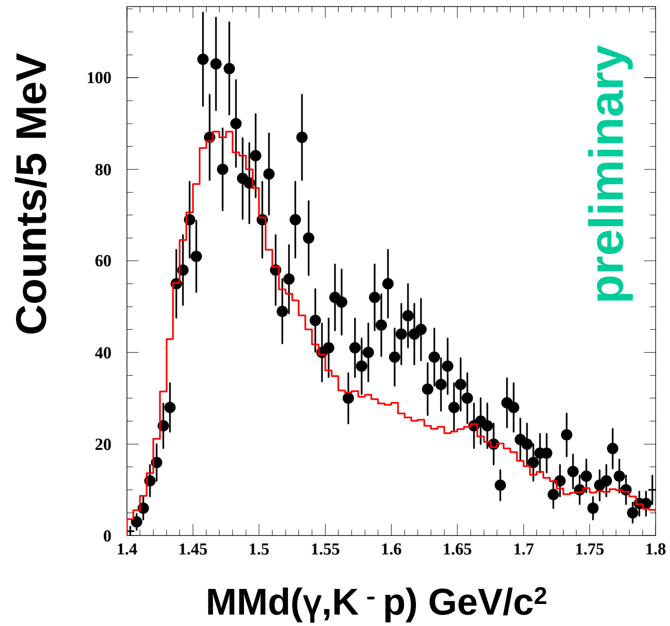


K $^-$ p missing mass spectrum



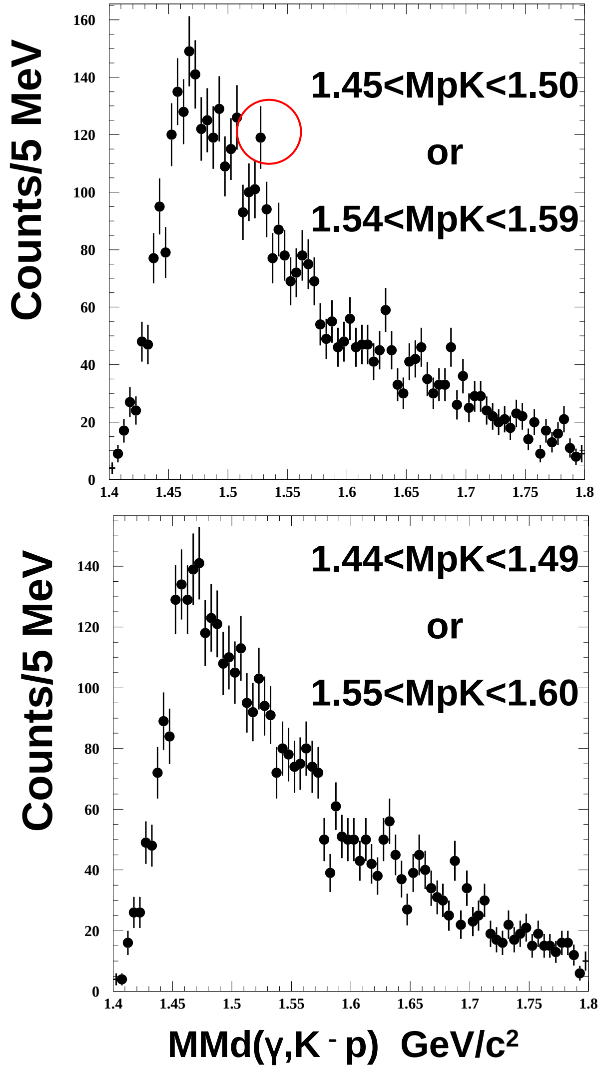
Excesses are seen at 1.53 GeV and at 1.6 GeV above the background level.

1.53-GeV peak: $\frac{S}{\sqrt{S+B}} \approx 5$
(in the 5 bin = 25 MeV)

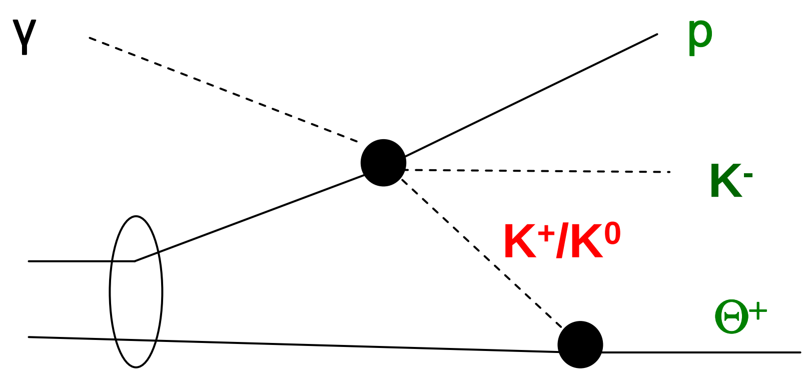


Normalization of Λ* is obtained by fit in the region of MMd < 1.52 GeV.

K ⁻ p missing mass in sideband regions



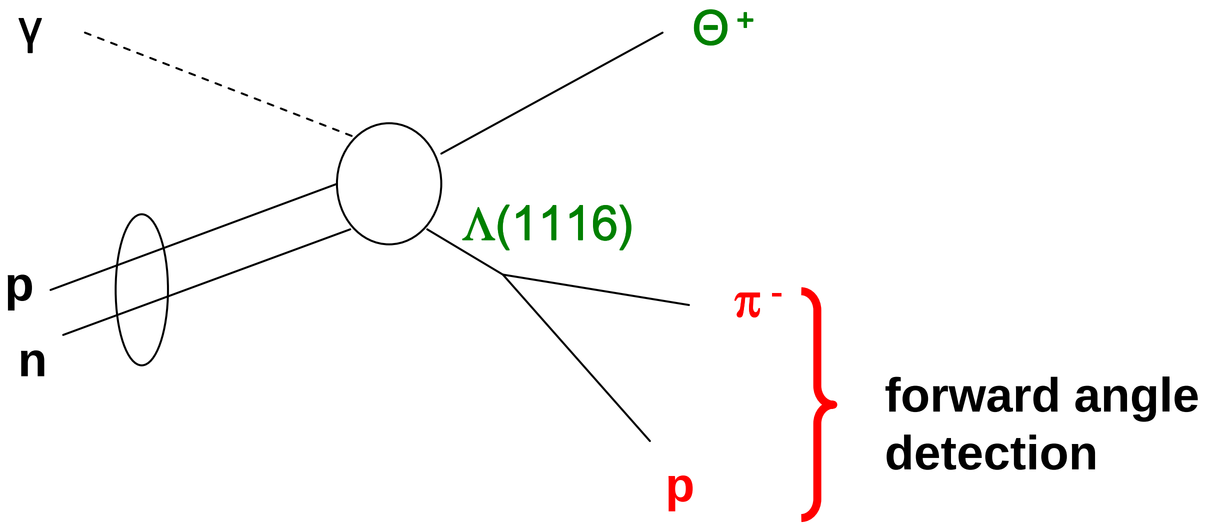
10 MeV away from the Λ* region



Θ^+ formation cross-section by simple kaon re-scattering is small.

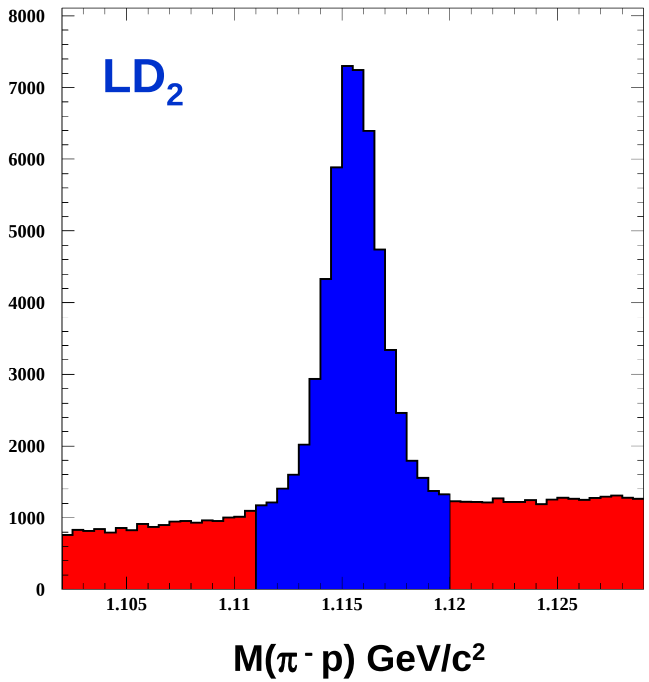
A theoretical estimation by Titov is small (nucl-th/0506072) .

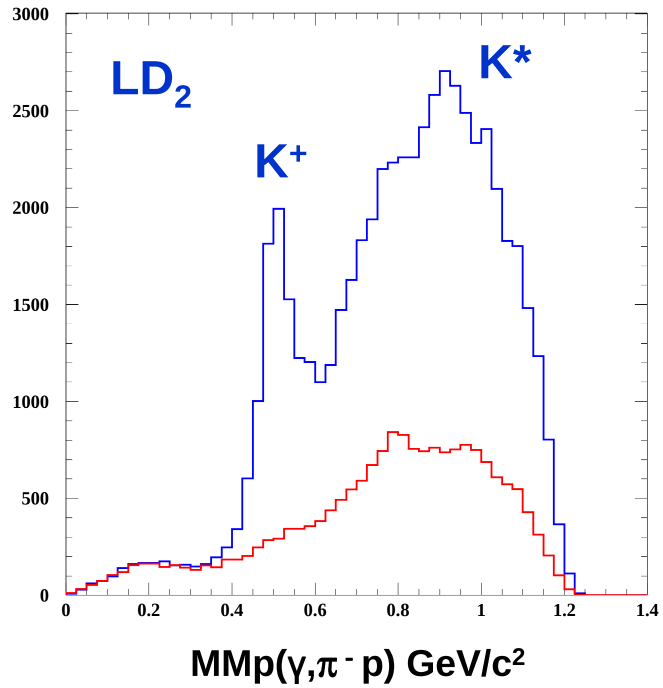
Search for $\gamma\, d \rightarrow \Lambda(1116)\, \Theta^{+}$



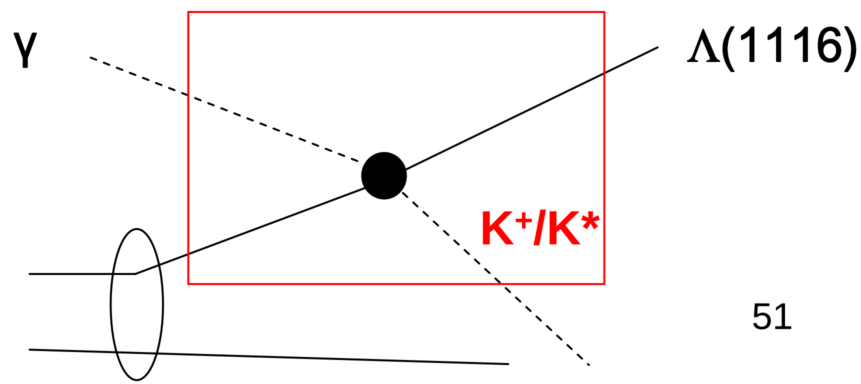
1.5 GeV < Eγ < 2.4 GeV

γ d → Λ(1116) X

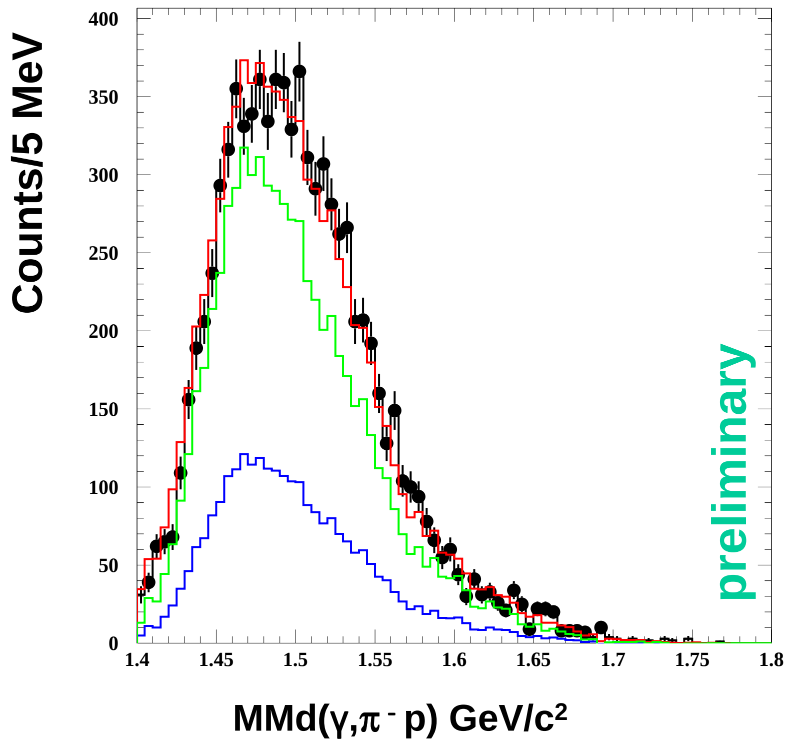




- ~100k Λ events are identified in the deuteron data.
- The missing mass was calculated by assuming a nucleon at rest.

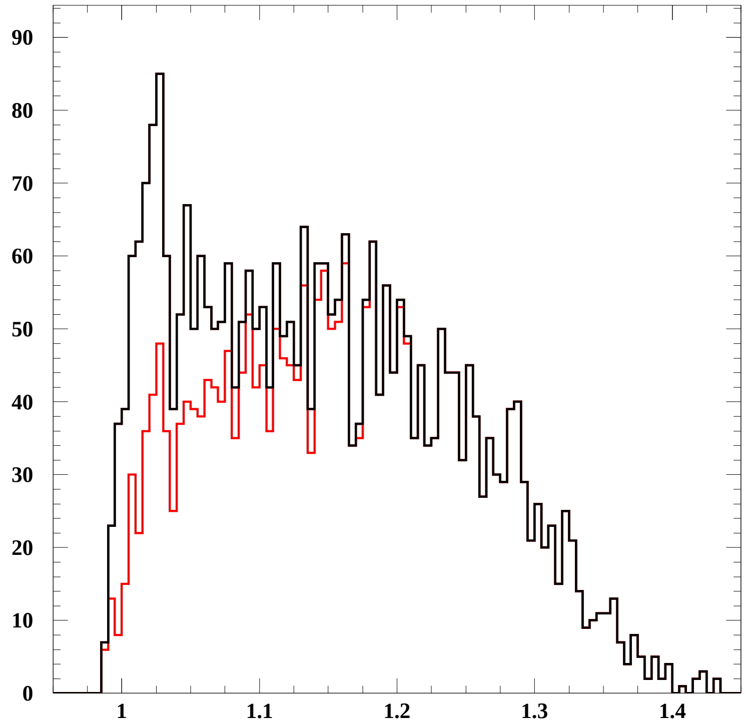


MMd(γ,π^{-}p) spectra



- Normalization factor for LH2 data (green line) is 2.6. → No large p/n asymmetry.
- No excess at 1.53 GeV nor 1.6 GeV.
- Quasi-free process can be reproduced by free process. → small effect from Fermi motion.
- Large cross-section compared with Λ(1520).
- Missing Mass resolution is worse.

Remove ϕ background by rejecting events with P_p<0.55 GeV/c



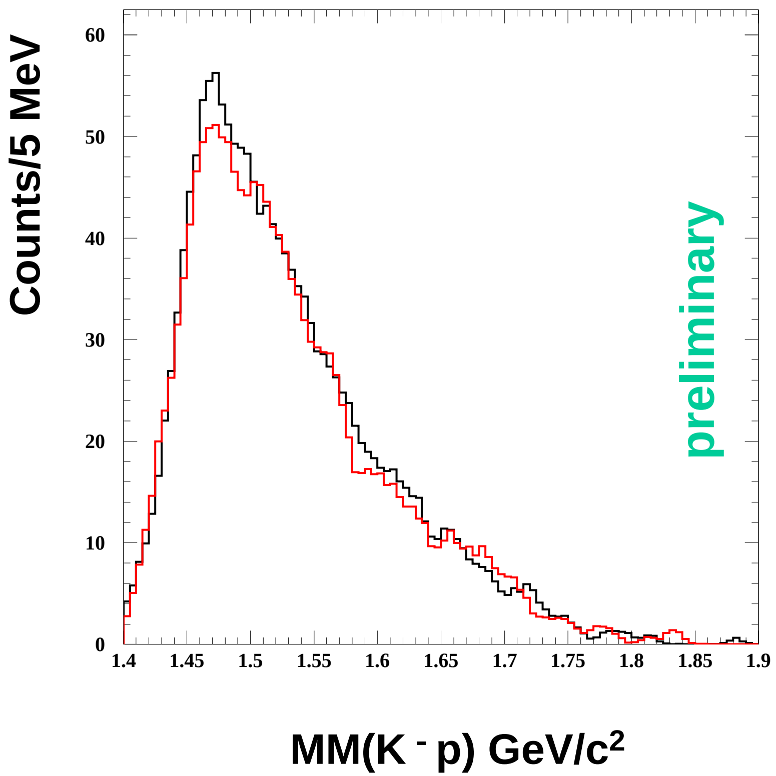
$M(K^+K^-)$ GeV/c^2

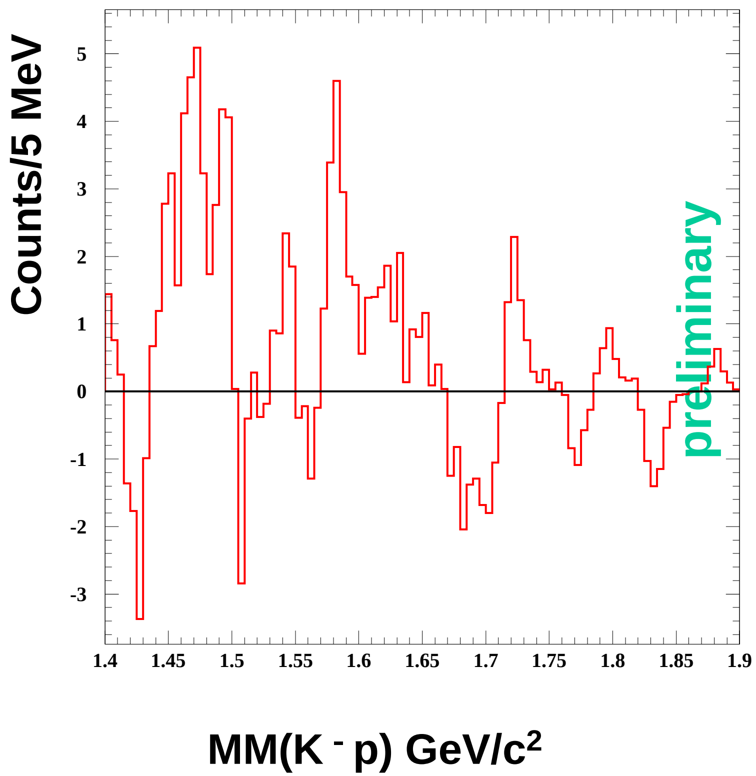
Remove high frequency fluctuations by 10-MeV Eγ smearing

near side: $1.48<M_{Kp}<1.50$ or $1.54<M_{Kp}<1.56$

far side: $1.46<M_{Kp}<1.48$ or $1.56<M_{Kp}<1.58$

difference: far - near



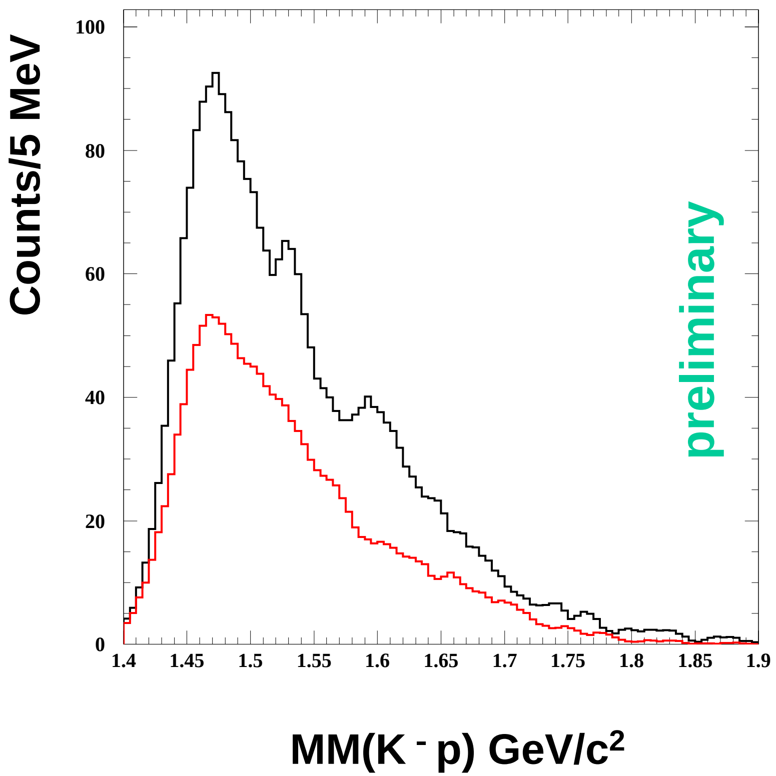


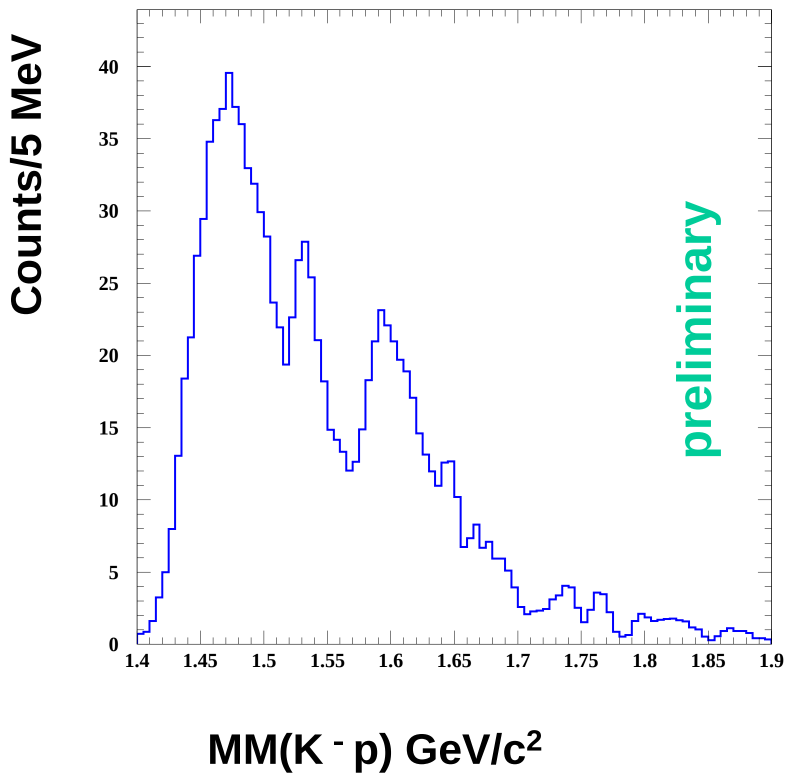
LD_2 spectrum after ϕ exclusion

signal region: $1.50<M_{Kp}<1.58$

side band: $1.46<M_{Kp}<1.50$ or $1.54<M_{Kp}<1.58$

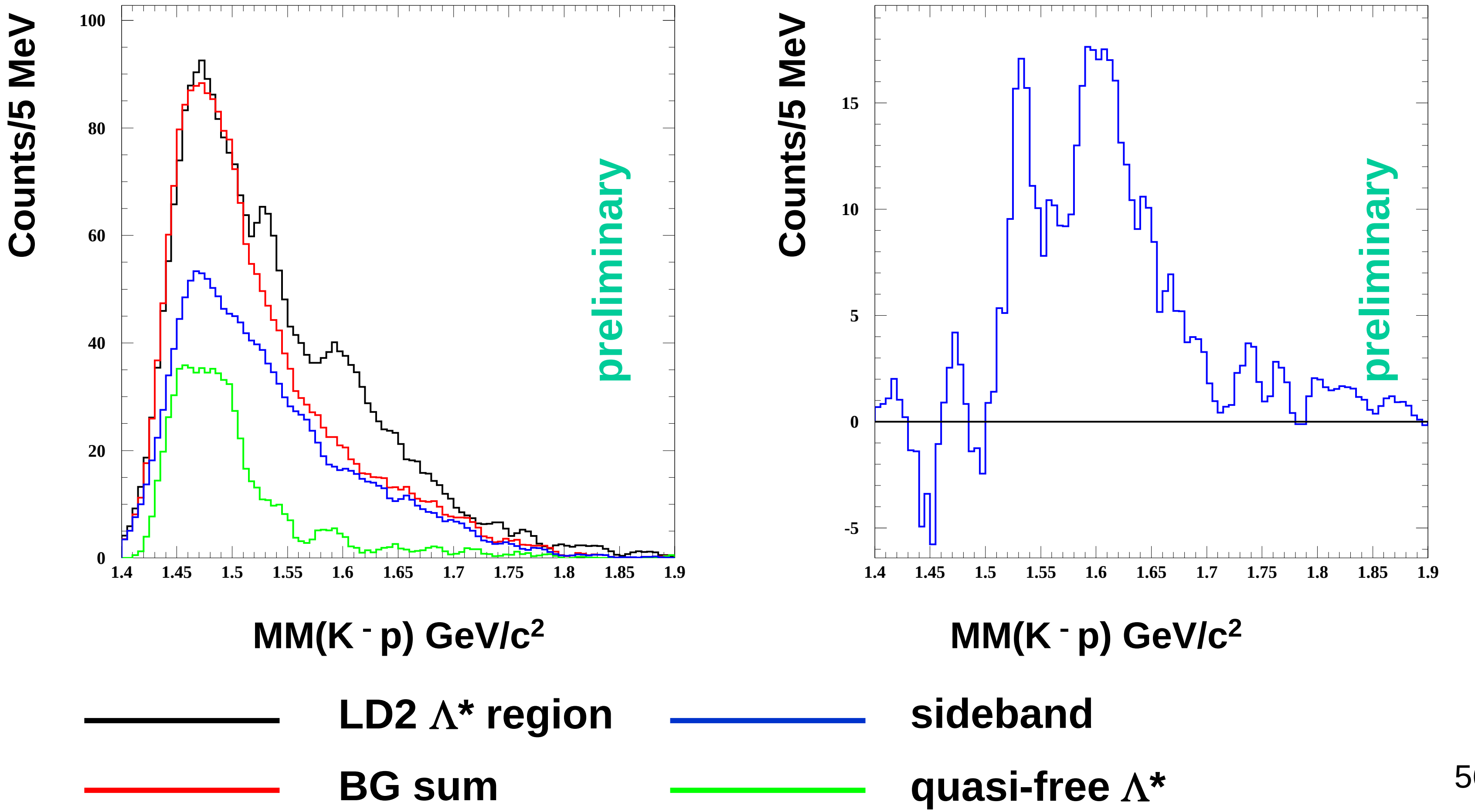
$\Lambda^*(1520)$: signal – side band





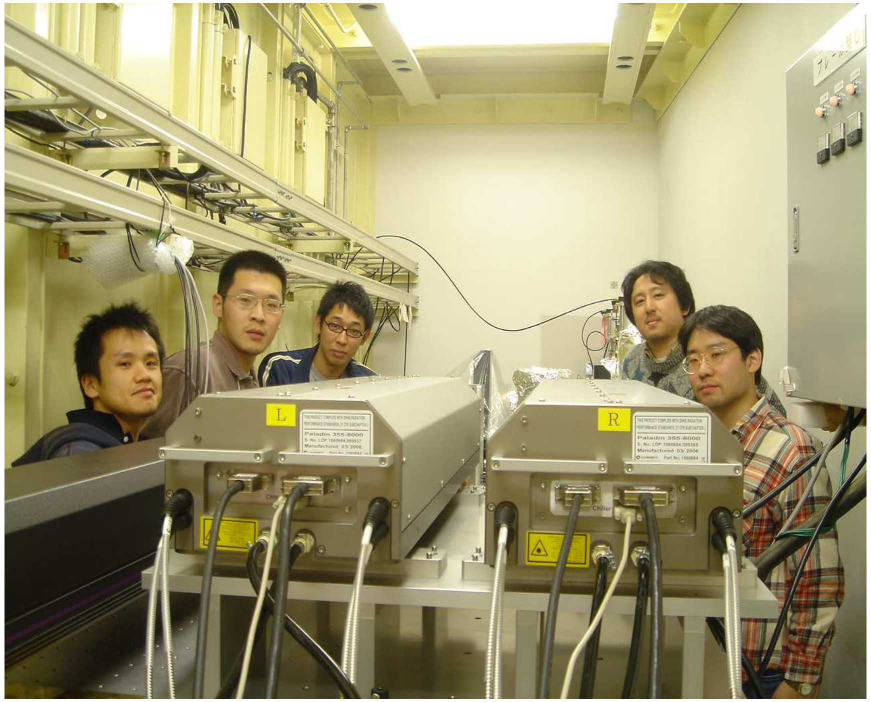
The Θ^+ peak and the bump at 1.6 GeV are robust. and they are not associated with ϕ events.

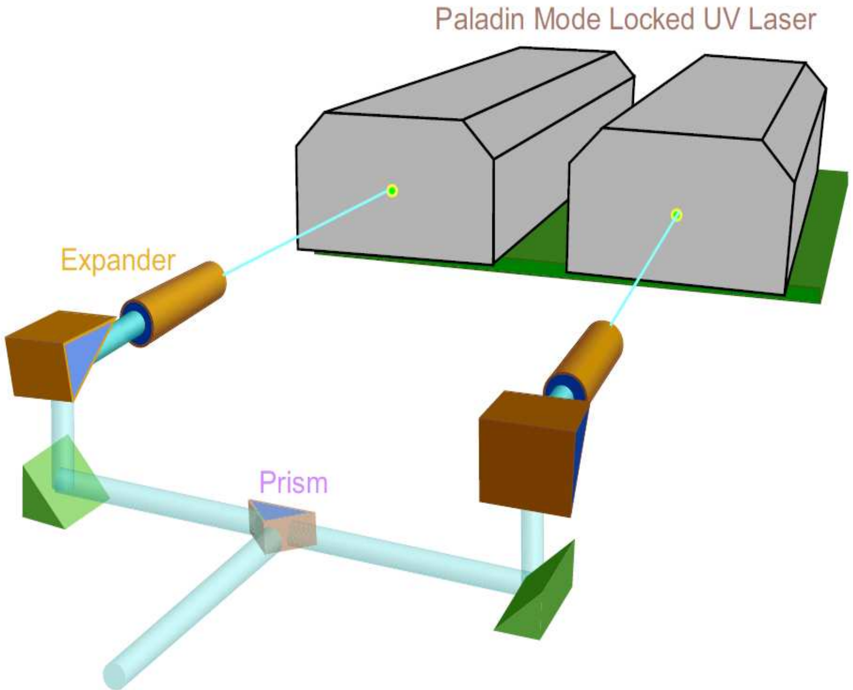
K⁻ p missing mass spectrum (smeared)



Near-Future Prospects on Θ^+

- Take **another data set with LD_2 target and the forward spectrometer (exactly same as the previous setup) this year**. Photon beam intensity will be twice by injecting two lasers. Basic test was succeeded.
- **2nd Time Projection Chamber** is being prepared to increase acceptance coverage. CLAS region can be covered.





Near-term plan

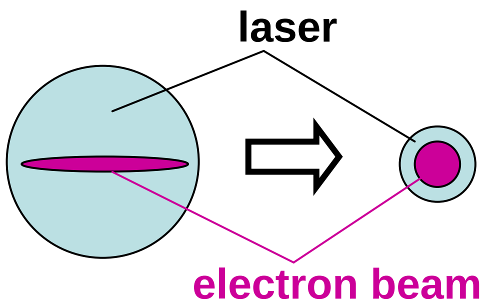
- **MC based BG study and cross-section estimation are in progress.**
- **Re-measurement with the same setup and improved beam intensity was just started in June, 2006.**
- **Experiment with improved acceptance will start in 2007 after installing a new TPC.**

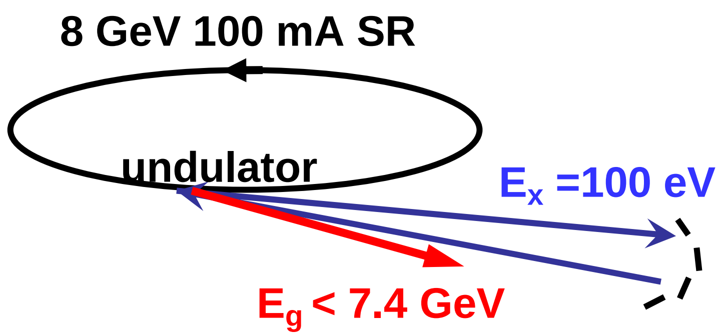
New beamline at SPring-8

Motivation :

- Better kinematical coverage w/ better resolutions and energy extension are desired for Θ^+ studies.
- glueball, hybrids and many other physics possibilities can be explored.

- Higher intensities for precise measurements and exotics searches (vs. LEPS intensity ~10^6 /sec)
  - Multi-laser injection (≥2 lasers w/ large apperture)
  - Round electron beam
- Higher energies for heavier hadrons (vs. LEPS energy ≤2.4 or 3.0 GeV)
  - x-ray injection by undulator





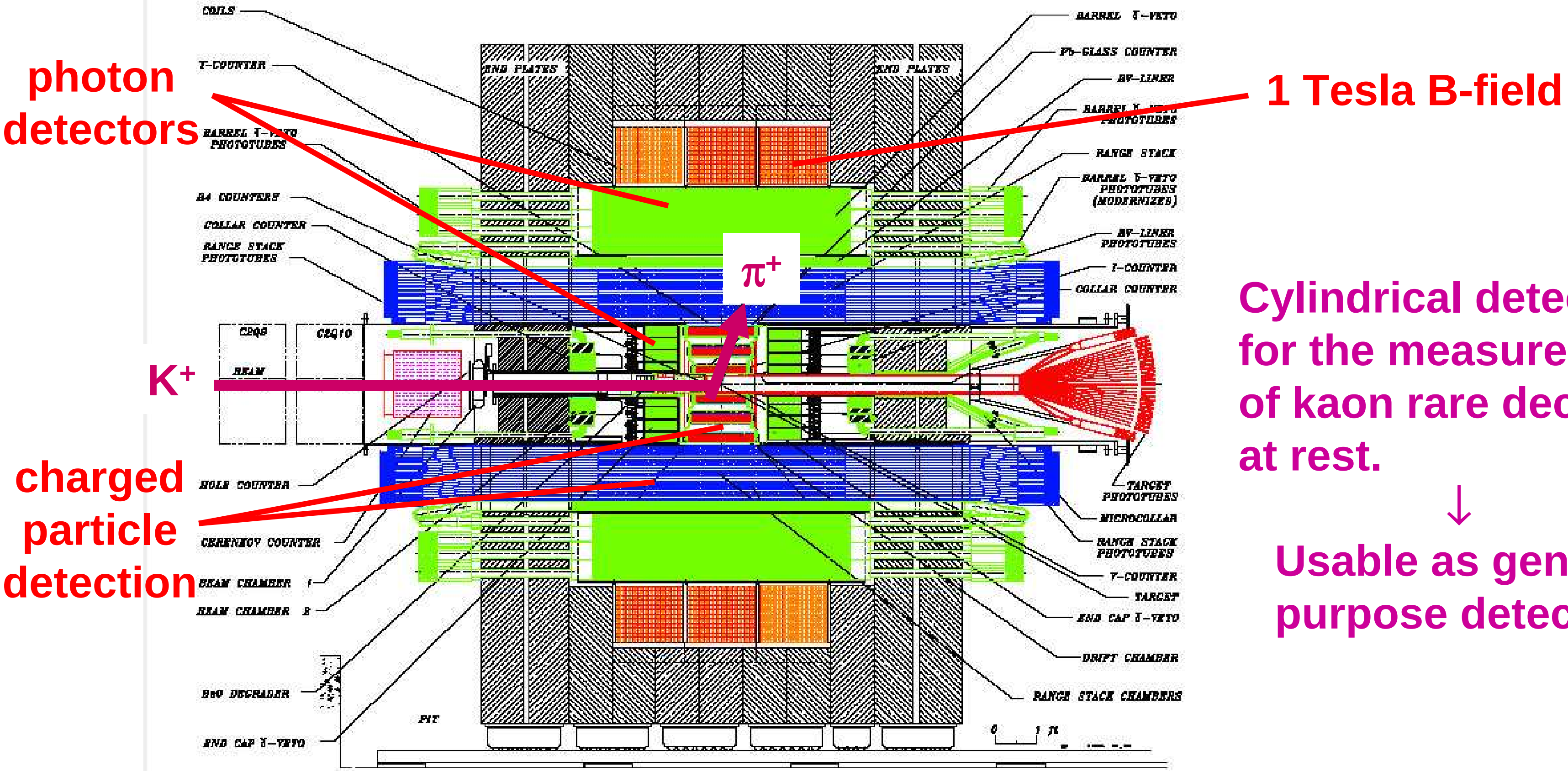
Moving BNL-E949 detector

- Large volume 4π detector to cover both charged particles and photons.

  (vs. LEPS forward spectrometer. Gamma experiments were separated.)
- E949 detector → SPring-8 (Basic consensus has been obtained.)

  In future, → J-PARC hadron physics and kaon rare decay

  e.g. $K^+ n \rightarrow \Theta^+ \rightarrow K_S^0 p \rightarrow \pi^+ \pi^- p$



Cylindrical detector for the measurement of kaon rare decay at rest.

↓

Usable as general purpose detector

A Possibility of Schedule

- Gathering collaborators in addition to LEPS group
- Now we are requesting budget.
- LOI will be submitted soon.
- If budget is approved,

2007-2008 Construction & Developments of Beamline,
Exp. Hutches, Laser Injection System,
Forward Spectrometer, High Speed DAQ, …
Moving E949 detector
2009 Hopefully starting the new experiment
Preparations for higher energy option