Recent Θ^+ and Gamma experiments at the SPring-8/LEPS

Koichi Kino (RCNP)

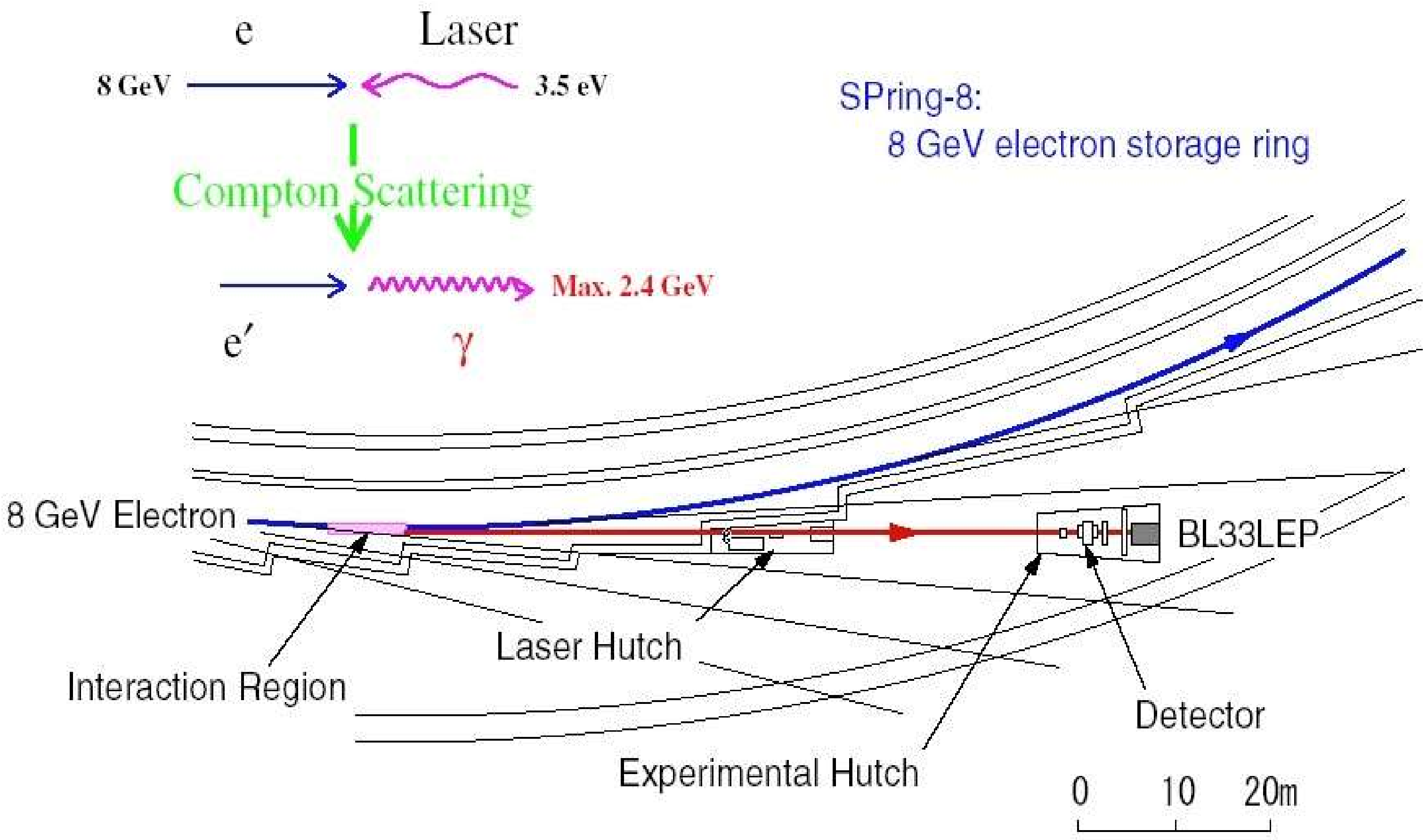
- **Θ^+experiment**
  - **LD2 target data**
  - **2002 Oct. - 2003 Jun.**
- **Gamma experiment**
  - **2003 Oct. - Nov.**
  - **Forward gamma detector**
  - **Preliminary γ+p → η+p' analysis**

LEPS beam line

SPring-8 (SuperPhotonRing 8GeV)

8 GeV electron storage ring

Current=100mA
62 beam lines
Bunch=every 2nsec



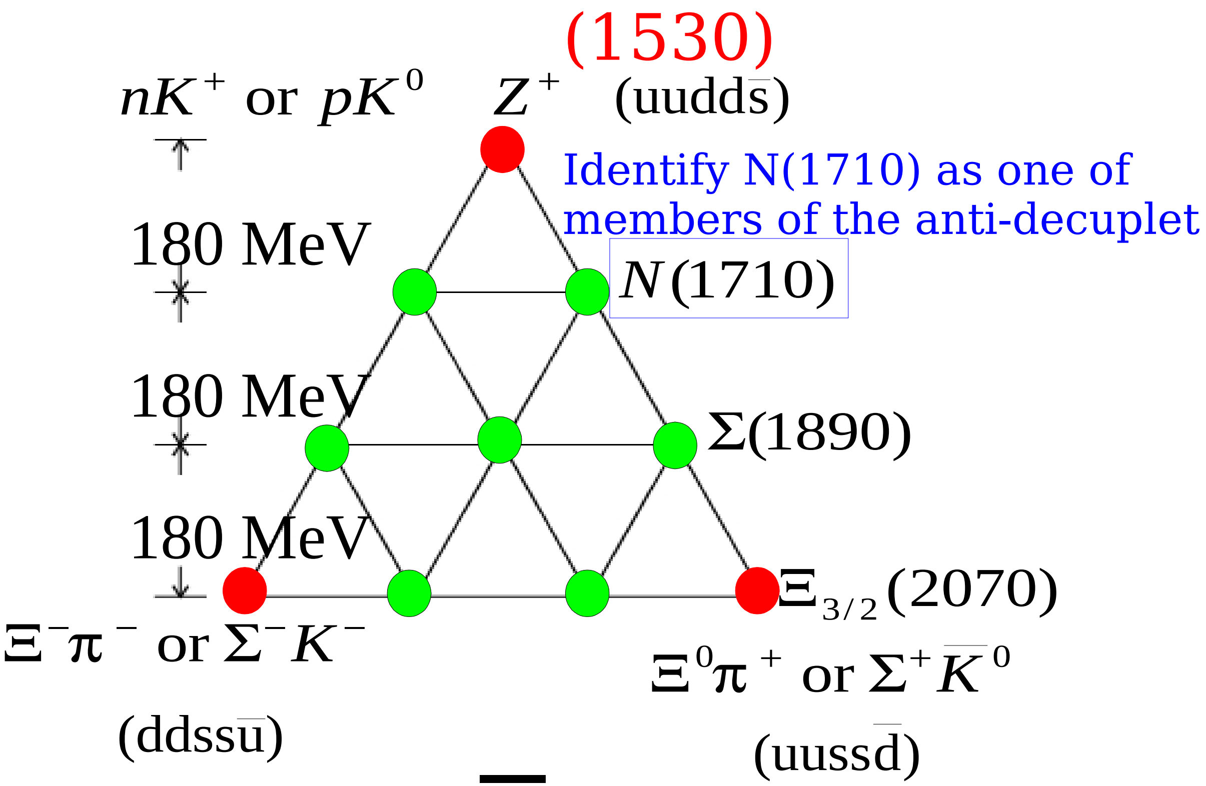
1.5 – 2.4 GeV real photon available

Θ^+ experiment

LEPS Θ^+ first data

- **Prediction from the chiral soliton model**

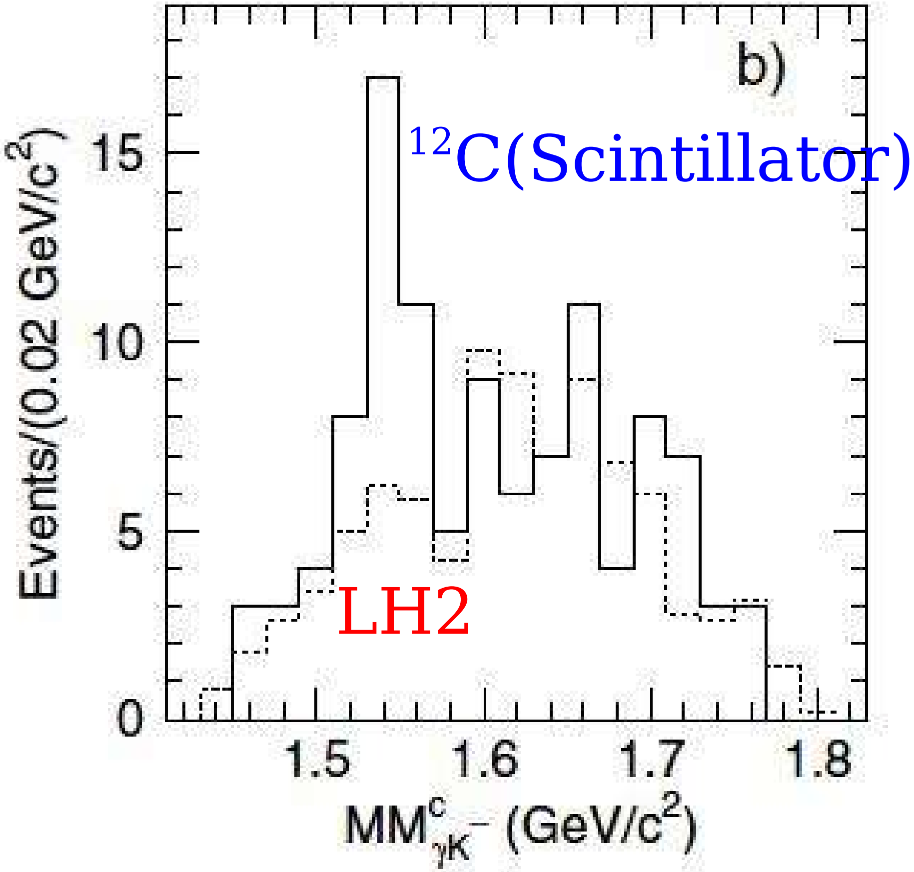
[Diakonov et al. Z.Phys.A359(1997)305]



$q^4\bar{q}$ $\overline{10}$ state

- $\gamma + n(^{12}C) \rightarrow K^+K^-n$

[Nakano et al. Phys.Rev.Lett 91(2003)012002]



peak = 1.54±0.01 GeV/c^2
width < 25 MeV/c^2
Gaussian significance = 4.6σ

Data from other Labs

- **Optimistic data**

LEPS	$\gamma+n(^{12}\mathrm{C}) \rightarrow nK^{+}+K^{-}$
CLAS	$\gamma+d \rightarrow nK^{+}+p+K^{-}$
CLAS	$\gamma+p \rightarrow nK^{+}+\pi^{+}+K^{-}$
SAPHIR	$\gamma+p \rightarrow nK^{+}+K_s^0$
HERMES	$e+d \rightarrow pK_s^0+X$
ZEUS	$e+p \rightarrow pK_s^0+X$
COSY	$p+p \rightarrow pK_s^0+\Sigma^{+}$
DIANA	$K^{+}+Xe \rightarrow pK_s^0+Xe'$
JINR	$n+p \rightarrow nK^{+}+p+K^{-}$
SVD	$p+A \rightarrow pK_s^0+X$
$\nu+A$	$\nu+A \rightarrow pK_s^0+X$

- **Pessimistic data**

BaBar	$e^{+}+e^{-} \rightarrow pK_s^0+X$
E690(Fermi)	$p+p_{rest} \rightarrow p_{slow}K_s^0+K^{-}+\pi^{+}+p_{fast}$
CDF	$p+\bar{p} \rightarrow pK_s^0+X$
Belle	$K+N \rightarrow pK_s^0$
Belle	$B^0 \rightarrow pK_s^0+\bar{p}$
HERA-B	$p+A \rightarrow pK_s^0+X$
ALEPH	$e^{+}+e^{-} \rightarrow pK_s^0+X$
DELPHI	$e^{+}+e^{-} \rightarrow pK_s^0+X$
HyperCP	$p+A \rightarrow pK_s^0+X$
BES	$\psi(2S) \rightarrow pK_s^0 + \bar{n}K^{-}, \bar{p}K_s^0 + nK^{+}$
BES	$J/\psi \rightarrow pK_s^0 + \bar{n}K^{-}, \bar{p}K_s^0 + nK^{+}$

etc.

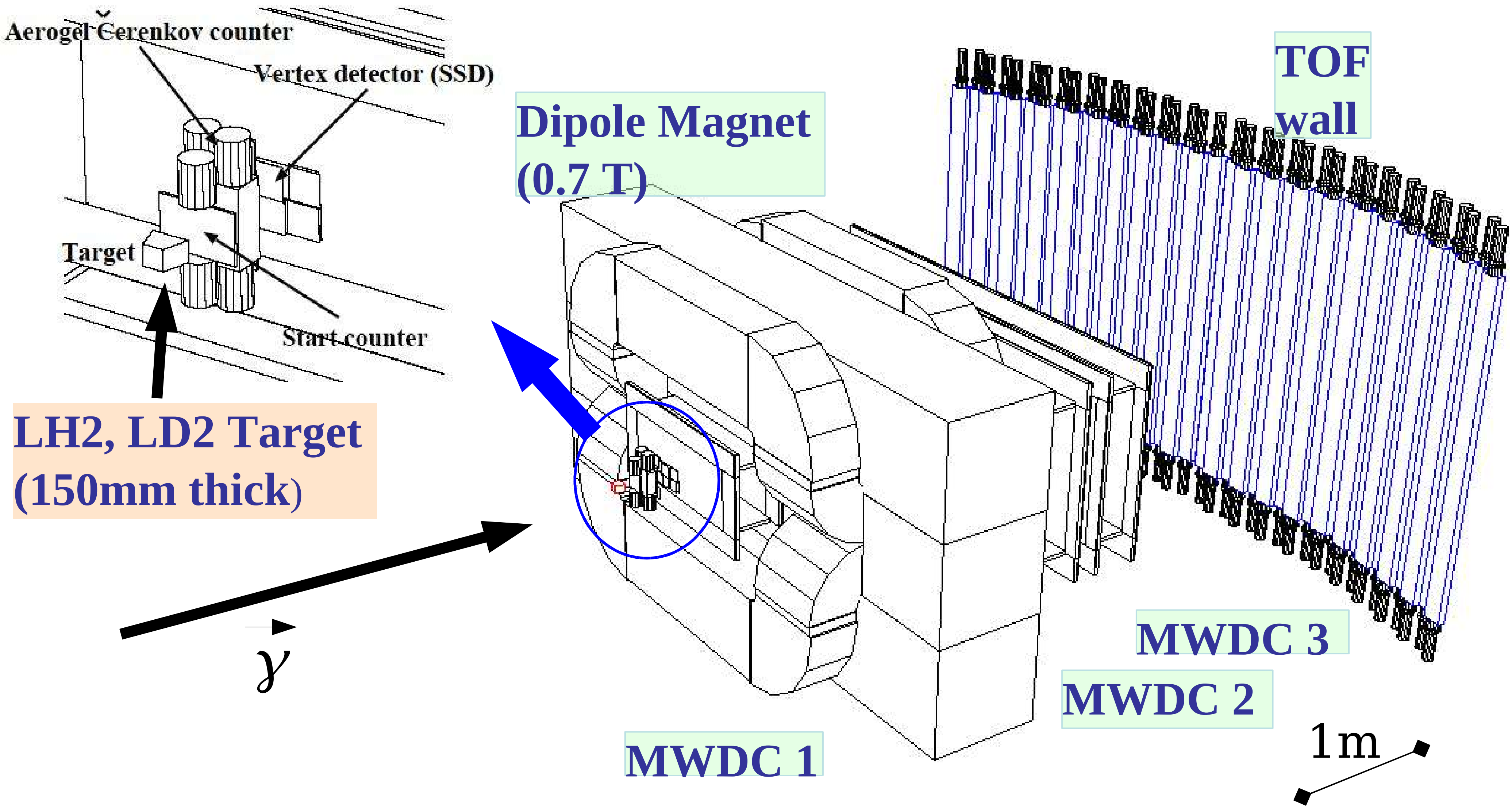
E522(KEK) $\pi^{-}+p \rightarrow X+K^{-}$

- **Can the peak seen in the previous LEPS data be seen in the new data again ?**

LEPS new LD2 and LH2 data

- **Oct. 2002 – Jun. 2003**
- **15cm-long target cell**
- **$\sim 2 \cdot 10^{12}$ photons on the LD2 target**
  - **Less Fermi motion effect**
- **$\sim 1.4 \cdot 10^{12}$ photons on the LH2 target**

LEPS Detector

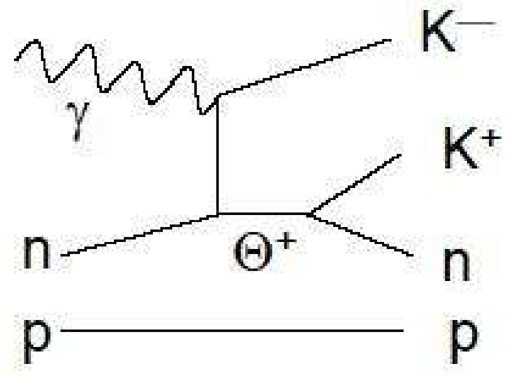


Expected reactions

$\gamma n(p) \rightarrow \Theta^{+}K^{-}(p)$

$\Theta^{+} \rightarrow K^{+}n$

Exotic

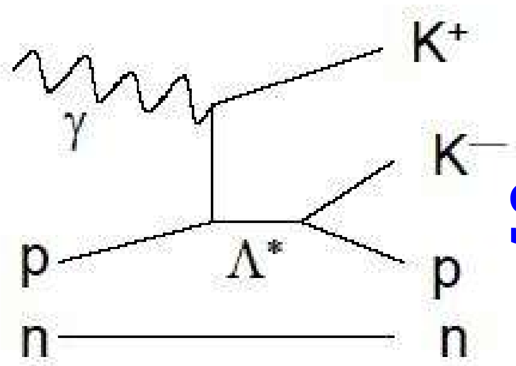


S=+1

$\gamma p(n) \rightarrow \Lambda^{*}(1520)K^{+}(n)$

$\Lambda^{*}(1520) \rightarrow K^{-}p$

Standard baryon



S=–1

$\gamma N \rightarrow \phi(1020)N \rightarrow K^{+}K^{-}N$

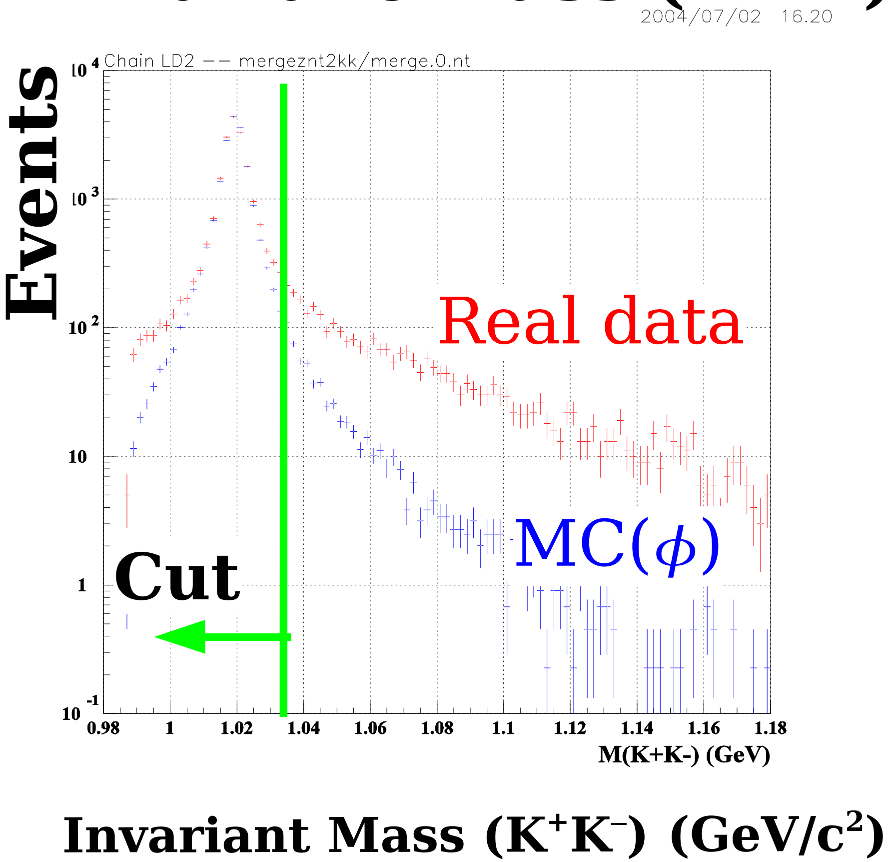
Mason resonance

Applied cuts and correction

- ϕ **meson exclusion cut**
- **Deuteron elastic reaction cut**
- **Missing mass cut**
- **Fermi motion correction**

ϕ meson exclusion cut

- **Invariant Mass (K^+K^-)**

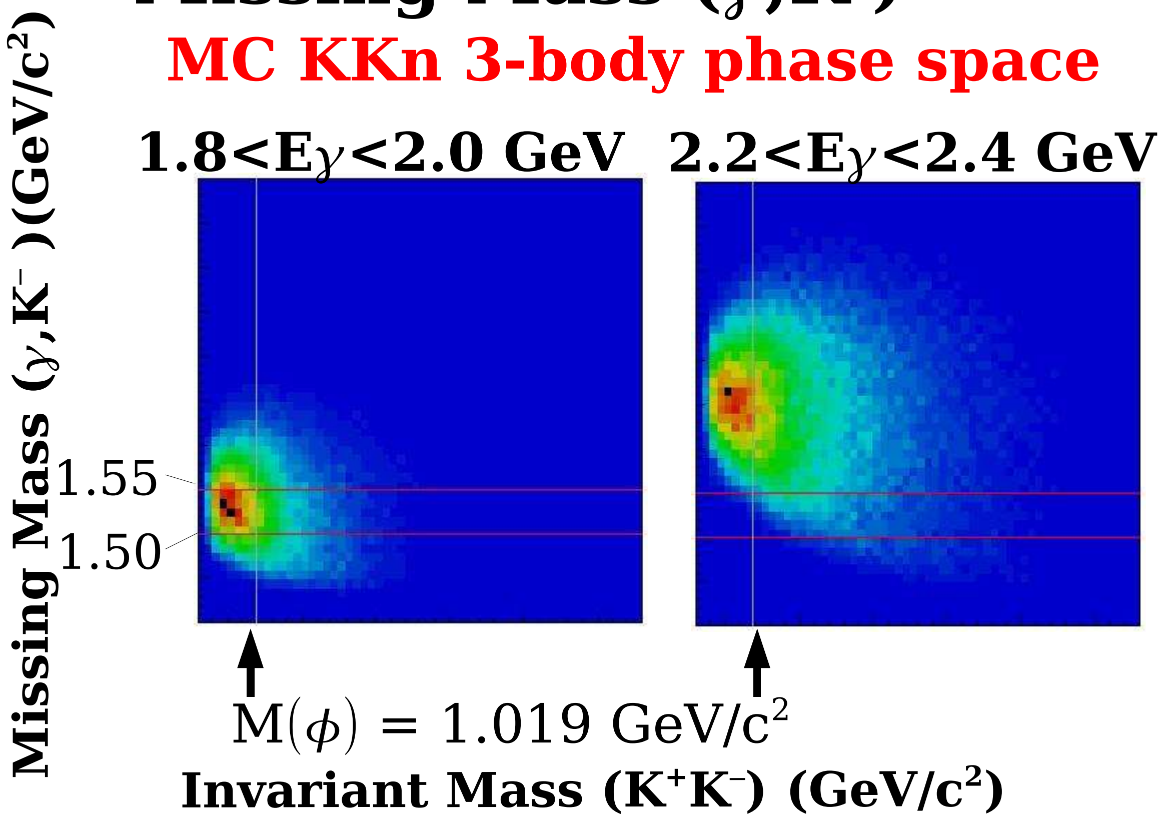


Ratio = (Real – MC) / MC

Almost $E\gamma$ independent

- **Missing Mass (γ,K^-)**

MC KKn 3-body phase space



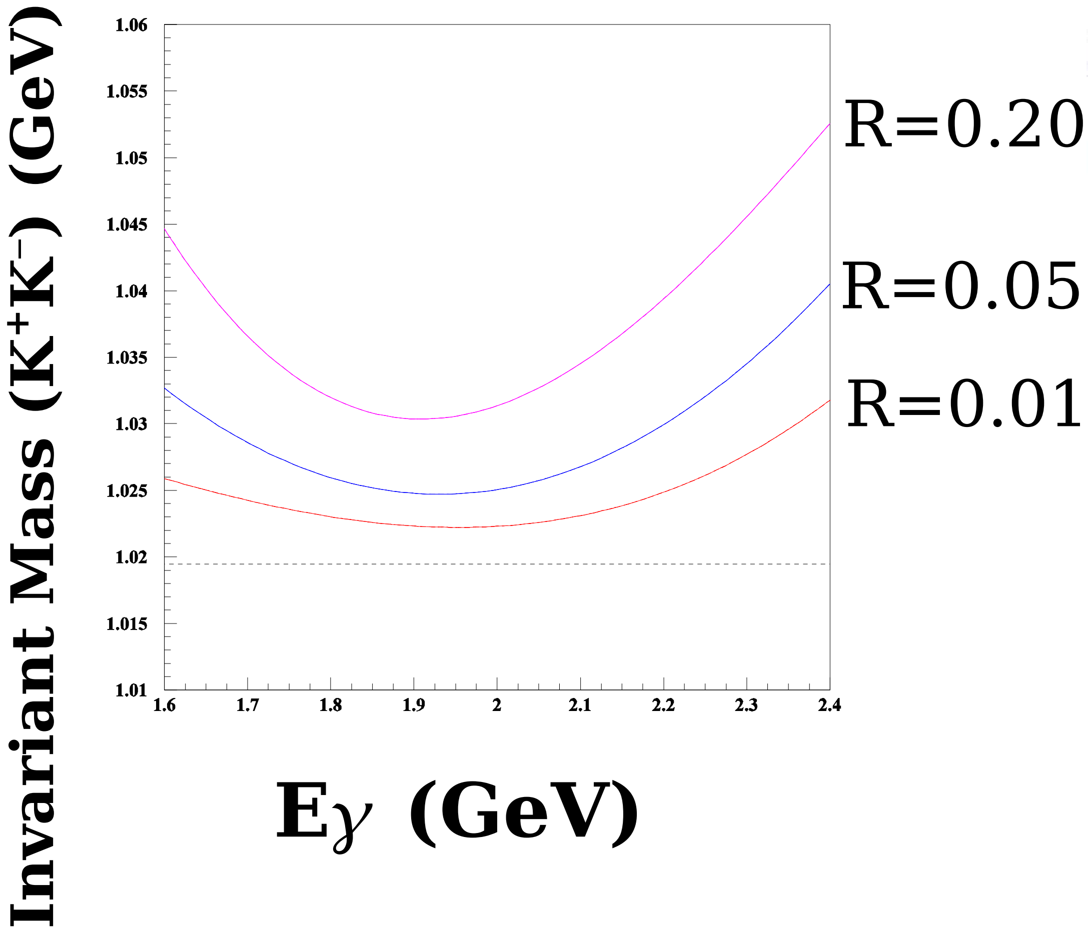
Relative acceptance
= N(1.50<MM(γ,K^-)<1.55) / N(all)

$E\gamma$ dependent

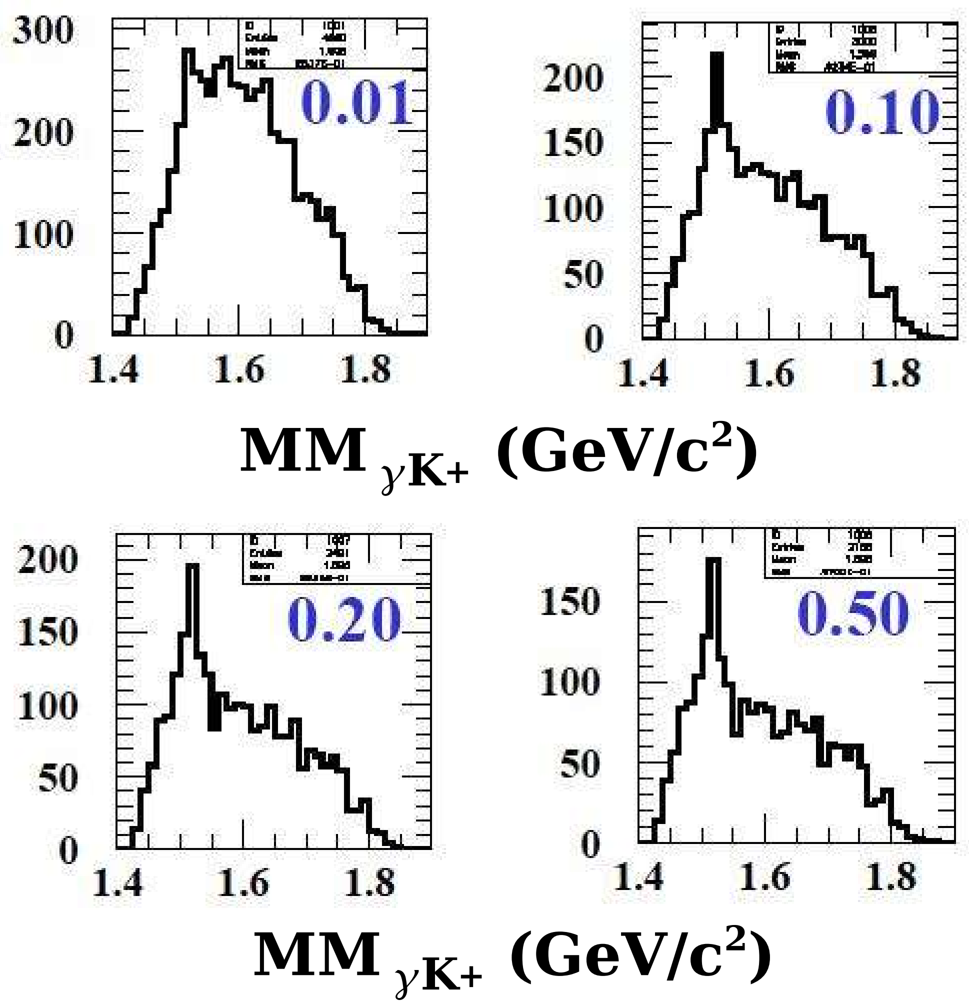
R = "Ratio" × "Relative acceptance"

ϕ meson exclusion cut

- **Energy dependent ϕ exclusion cut function**

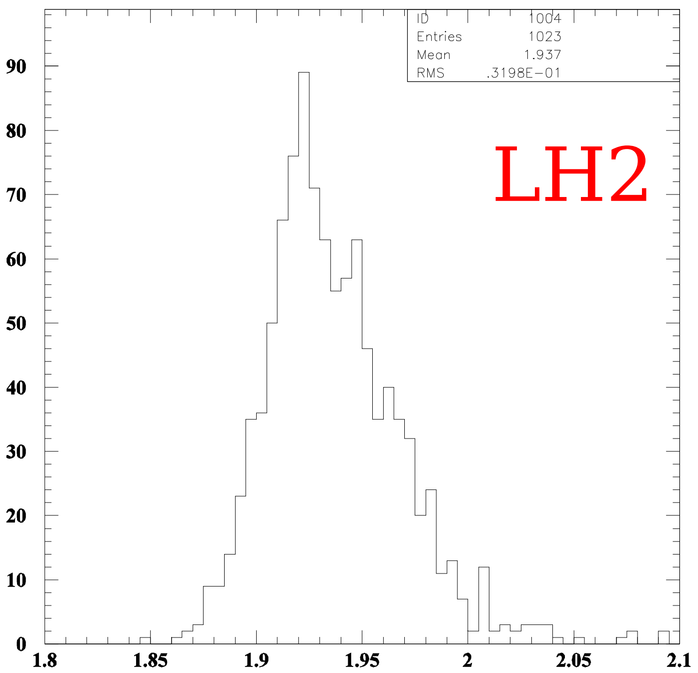


- **Effect on MM (γ,K^+)**

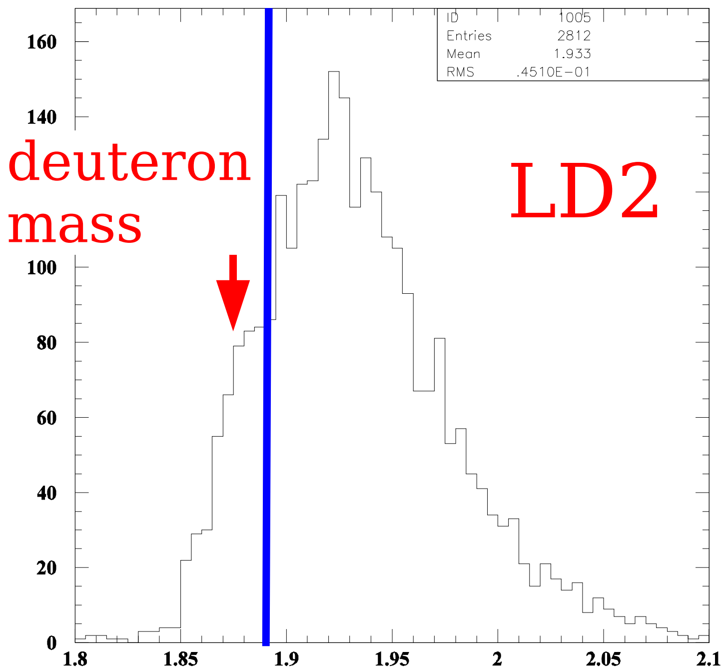


deuteron elastic reaction cut

- **Remove $\gamma d \to K^+K^- d$ reaction**
- **Cut MM $d(\gamma, K^+K^-) < 1.89$ GeV/c^2**



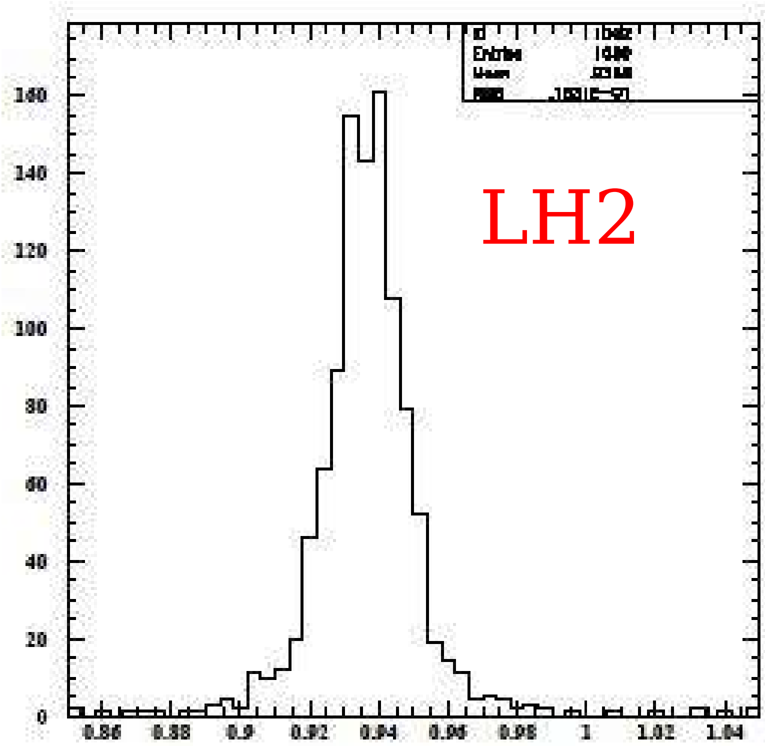
MM $d(\gamma, K^+K^-)$ (GeV/c^2)



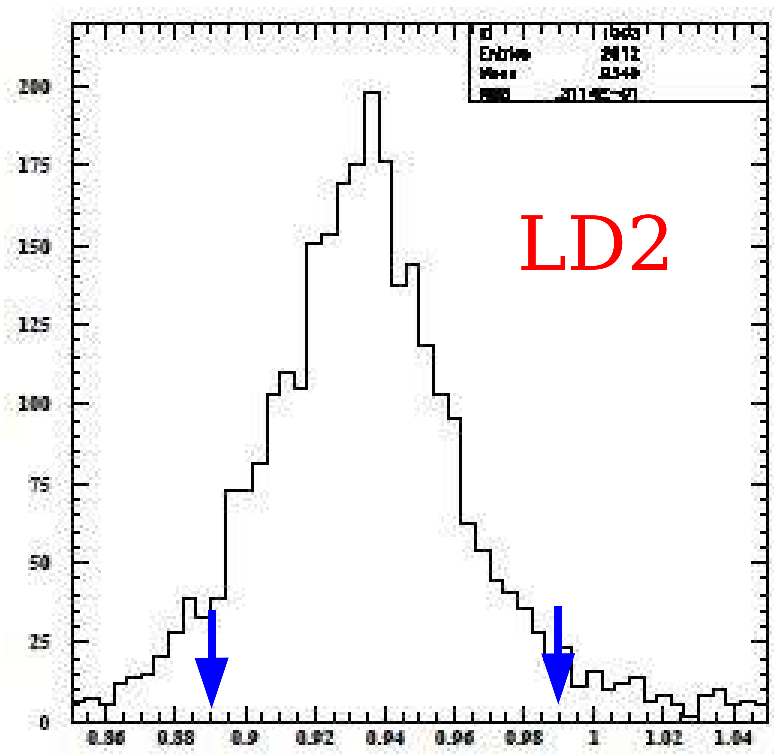
MM $d(\gamma, K^+K^-)$ (GeV/c^2)

MM n(γ,K$^+$K$^-$) cut

- **Coose 0.89 < MM n(γ,K$^+$K$^-$) < 0.99 GeV/c^2**



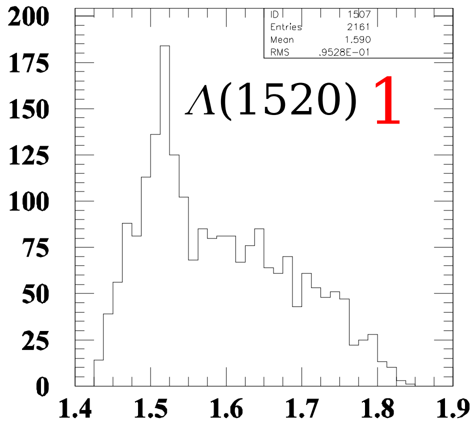
MM n(γ,K$^+$K$^-$) (GeV/c^2)

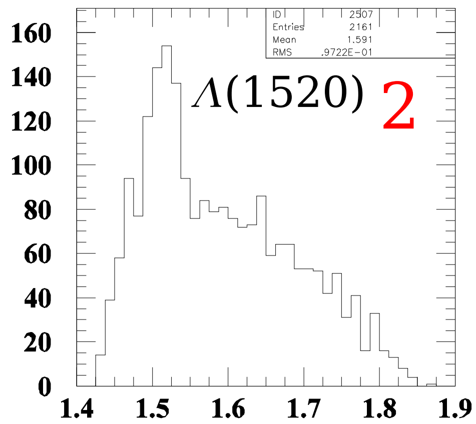


MM n(γ,K$^+$K$^-$) (GeV/c^2)

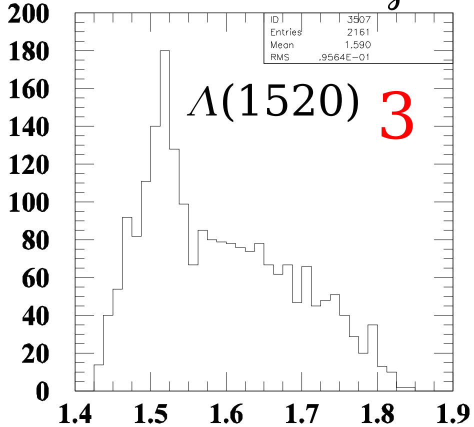
Fermi motion correction

- 1 : $MM^{c}_{\gamma K-} = MM_{\gamma K-} - MM_{\gamma K+K-} + M_{n}$
- 2 : $(MM^{c}_{\gamma K-})^{2} = (MM_{\gamma K-})^{2} - P_{(K+n)}/P_{n}(MM^{2}_{\gamma K+K-} - M_{n}^{2})$
- 3 : n(p) momentum = missing momentum





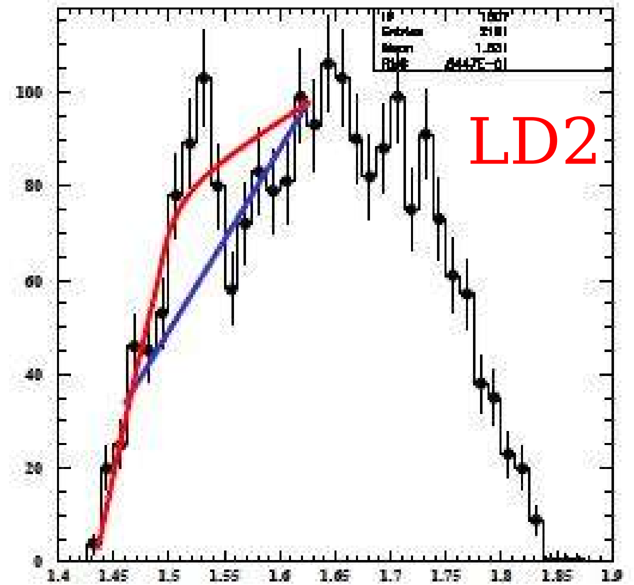
$MM_{\gamma K+}$ (GeV/c^2)



$MM_{\gamma K+}$ (GeV/c^2)

Result of LD2 data and summary

- K^+K^- from LD2 target
- ϕ exclusion cut at R=0.2
- MM d(γ,K^+K^-)>1.89 GeV/c^2
- 0.89<MM n(γ,K^+K^-)<0.99 GeV/c^2
- Fermi motion correction

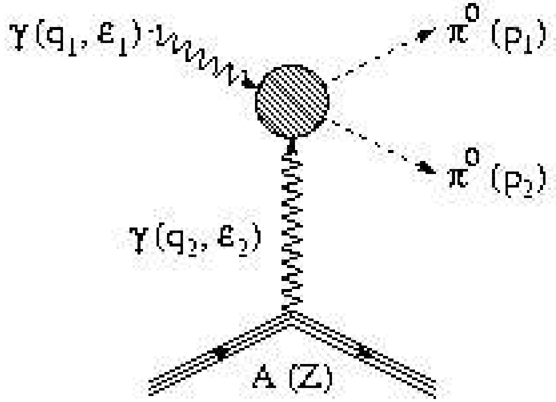


Missing Mass (γ,K^-)(GeV/c^2)

- LEPS took new data with LD2 target for the search of the Θ^+.
- Energy dependent ϕ exclusion cut was designed and its validity was checked with Λ(1520) study.
- The "Θ^+" peak was reproduced in the K^- missing mass of LD2 data.

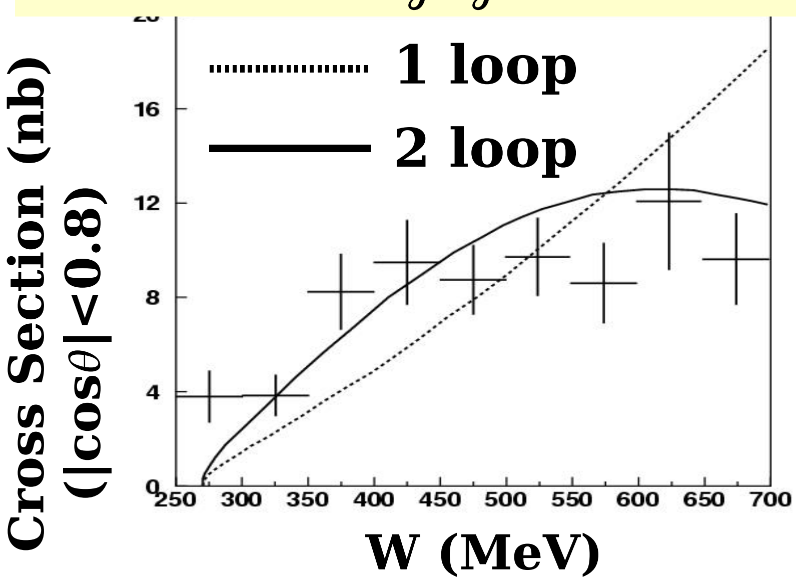
Gamma experiment

Primakov $2\pi^0$ production

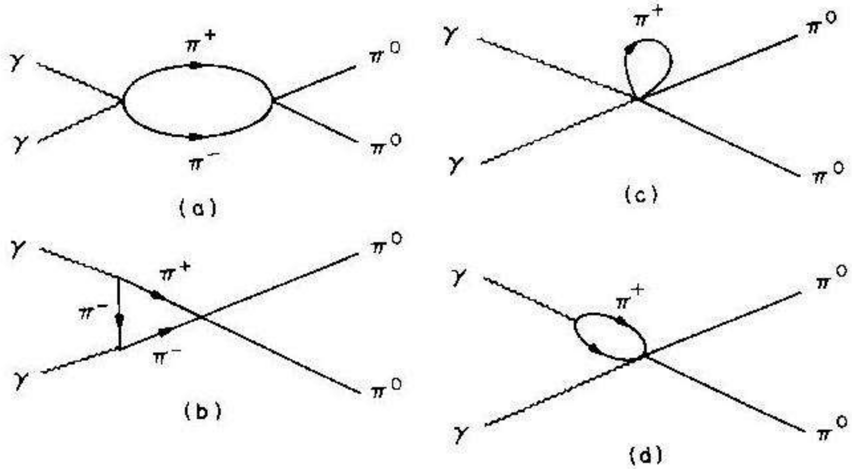


- **Only one similar reaction data exists**

$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0\pi^0$



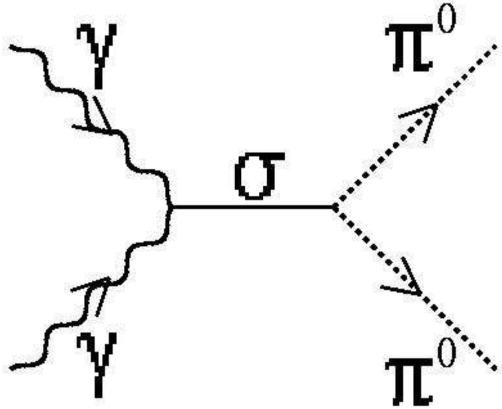
- **Polarizability** (10^{-4}fm^3)
  - $\alpha-\beta=-1.4\pm1.7$ (exp.)
  - $\alpha-\beta=-1.9\pm0.2$ (χPT.)
- **Loop structure in the χPT theory**
  - **No tree diagram because of no charge**



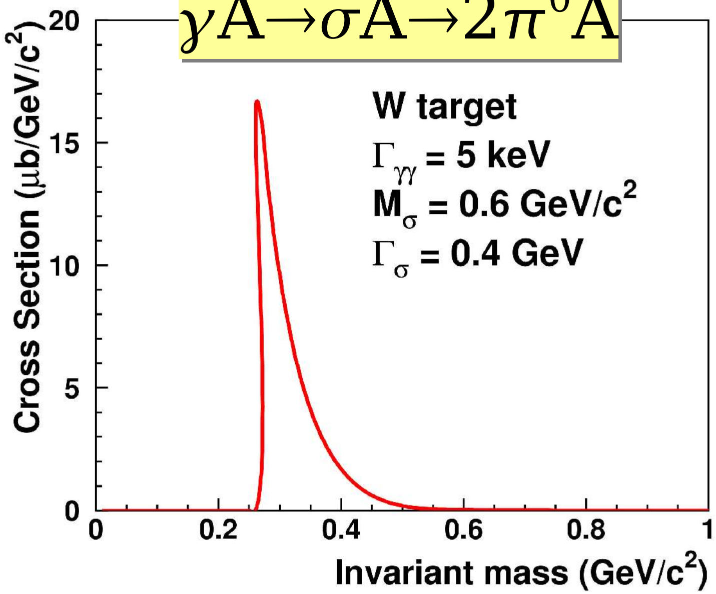
1 loop diagrams

Primakov $2\pi^0$ production

- **Contribution of σ meson**
  - **inverse process of $\sigma \to 2\gamma$ decay**
  - **f₀(400-1200)**
    - $2\pi^0$**decay : dominant**
    - $\Gamma_{\gamma\gamma}$ = 10±6 keV (PDG)
    - $\Gamma_{\gamma\gamma}$ = 3.8±1.5 keV (Pennington hep-ph9905241)



$\gamma A \to \sigma A \to 2\pi^0 A$



$$\frac{d\sigma}{d\Omega} = \Gamma_{\gamma\gamma}\frac{8\alpha Z^2}{M^3}\frac{\beta^3 E_\gamma^4}{q^4}|F_{e.m.}(q)|^2\sin^2(\theta)$$

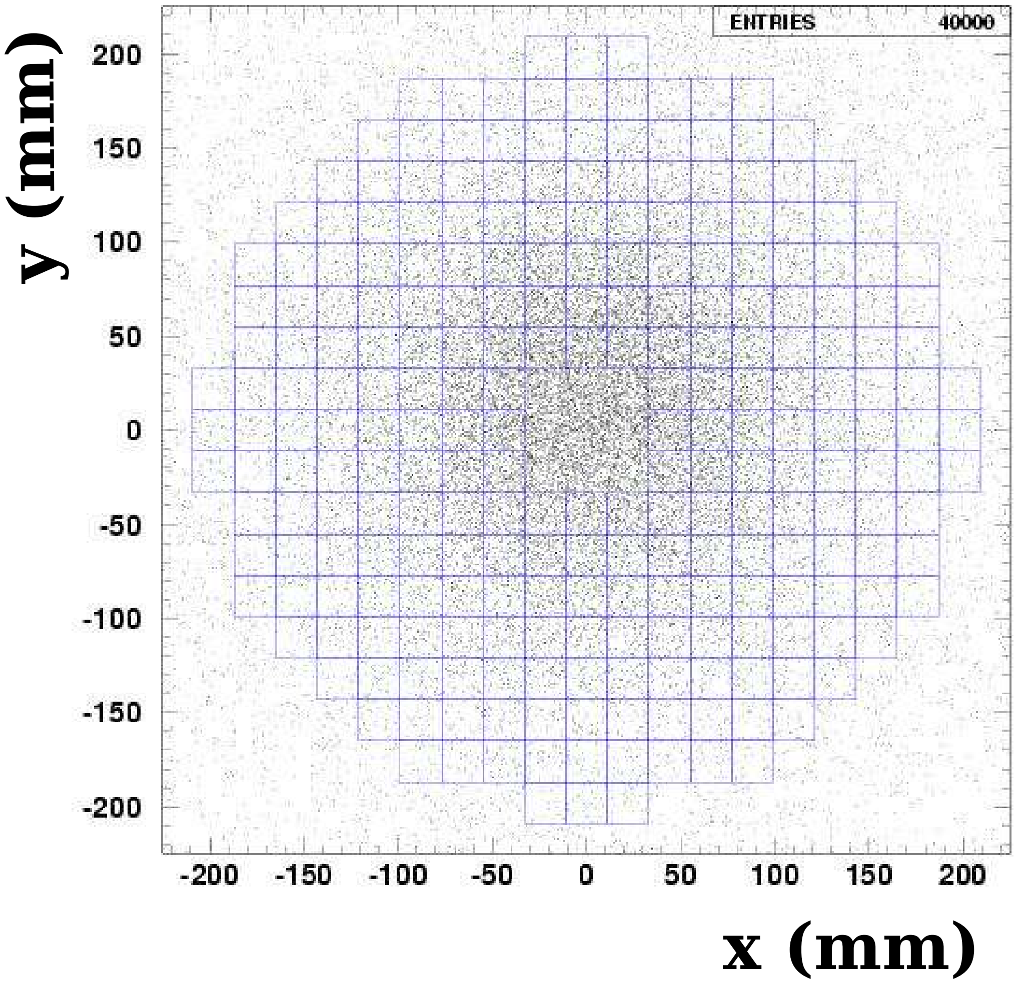
σ Mass

momentum transfer

Total Cross Section = 1.0μbarn
Eγ=0.5Mcps ⊗ DAQ Live time
➔ 0.3 event/hr

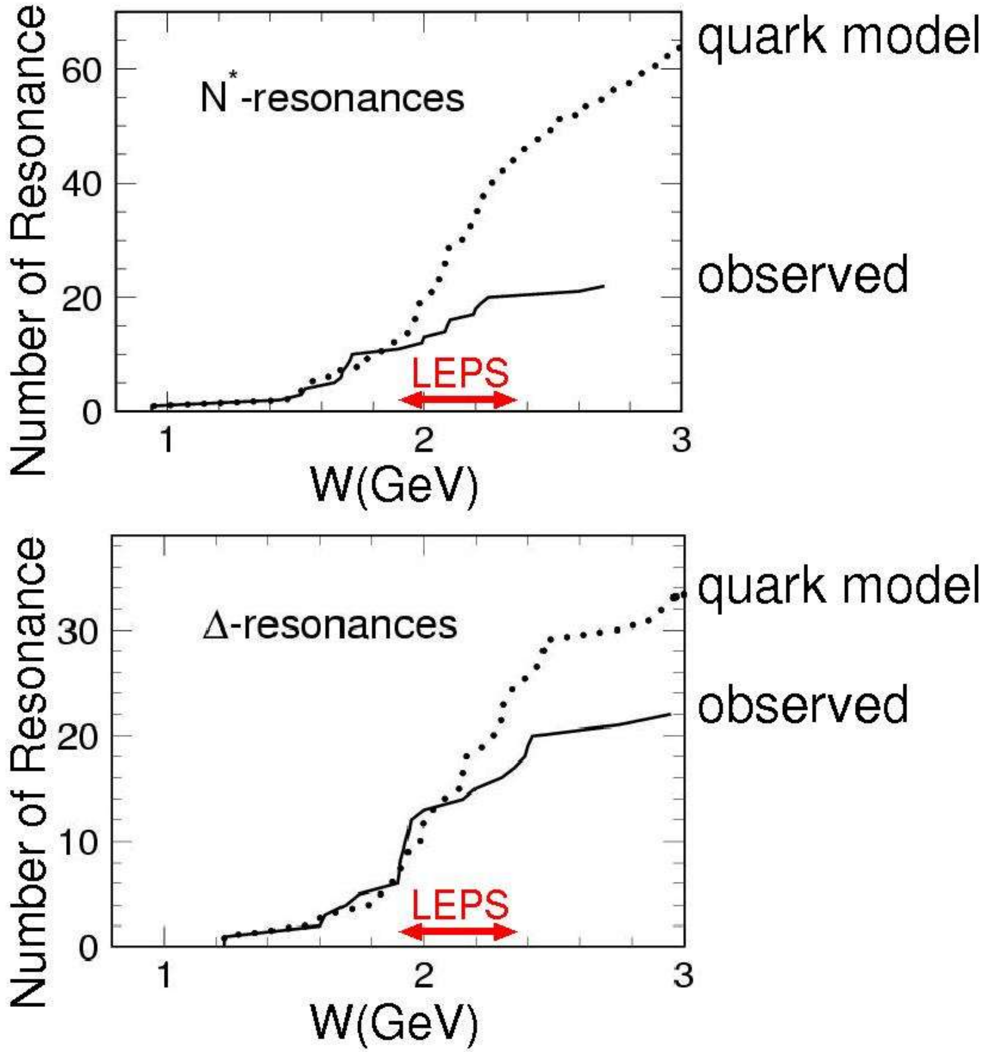
Gamm-rays distribution

- **Simulation of Primakov $2\pi^0$ production**

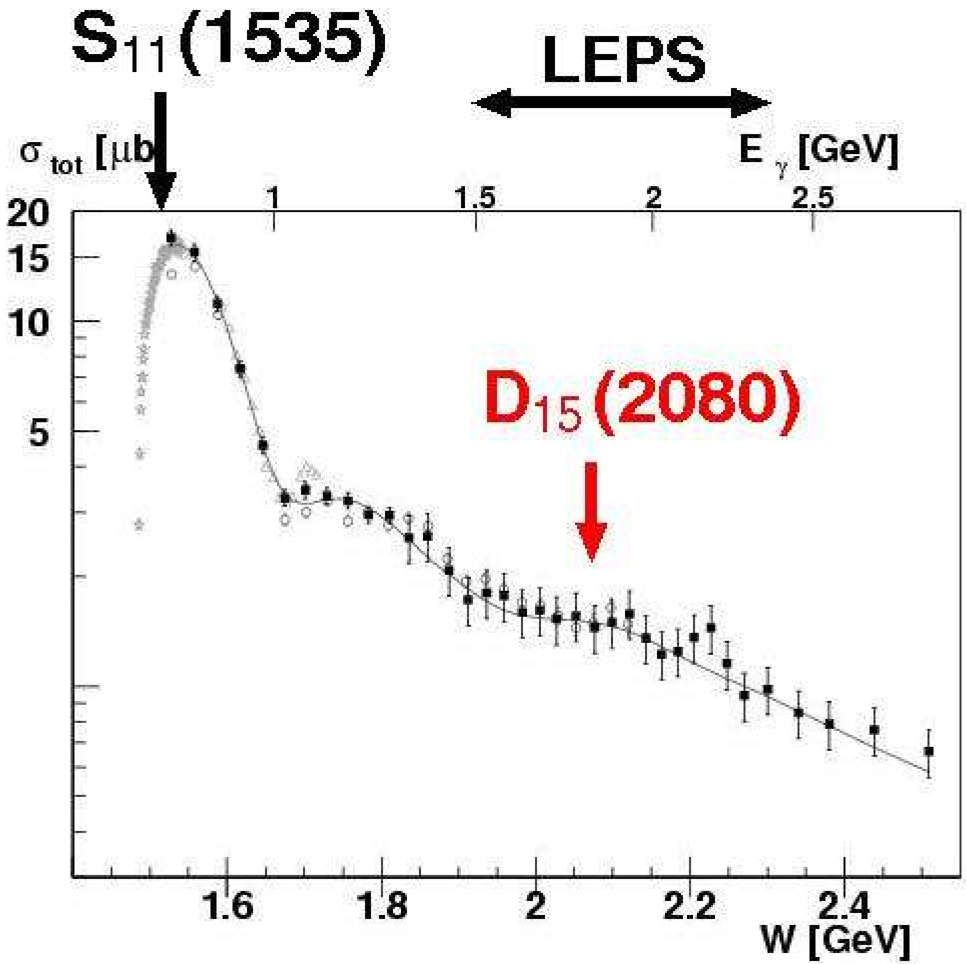


Nucleon resonances

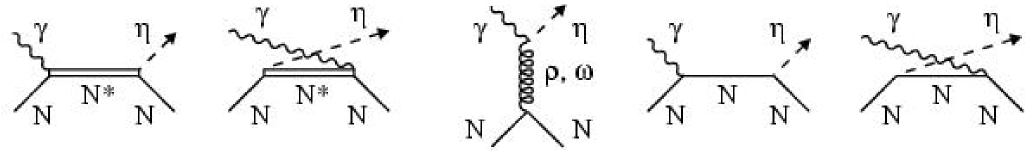
- **Gap between theory and experiment**
  - πN **scattering and** π **decay**
  - **data with other channels and isospin selectivity needed**
- **This experiment**
  - **suitable energy**
  - **various channels** $\eta,\omega,\eta',\ldots$
  - **photon beam asymmetry**



$\gamma p \rightarrow \eta p'$ data by ELSA



[hep-ex/0311045]



Included diagrams

N^*	M (MeV)	Γ (MeV)	$A_{3/2}/A_{1/2}$	$P_{in/out}$
$N(1520)D_{13}$	1530 ± 7	102 ± 15	< -2.4	$0.027^{+0.015}_{-0.010}$
PDG	1520^{+10}_{-5}	120^{+15}_{-10}	-6.9 ± 2.6	< 0.07
$N(1535)S_{11}$	1505 ± 12	152 ± 15		1
PDG	1505 ± 10	170 ± 80		1
$N(1650)S_{11}$	1626 ± 10	188 ± 30		$0.2^{+0.06}_{-0.07}$
PDG	1660 ± 20	160 ± 10		$0.01 - 0.4$
$N(1680)F_{15}$	1673 ± 8	98 ± 17	large	0.009 ± 0.007
PDG	1680^{+10}_{-5}	130 ± 10	-8.9 ± 3.6	< 0.05
$N(1720)P_{13}$	1734 ± 23	275^{+70}_{-40}	$-4.5^{+1.7}_{-2.5}$	$0.2^{+0.28}_{-0.10}$
PDG	1720^{+30}_{-70}	250 ± 50	-1.1 ± 2.1	< 0.1
$N(2080)D_{15}$	2079 ± 40	368^{+100}_{-50}	-0.5 ± 0.3	0.20 ± 0.03

Fit result

D_{15} → **$5/2^-$** χ^2=676/630

$3/2^-$ $\Delta\chi^2$=59

$1/2^+$ $\Delta\chi^2$=73

$5/2^+$ $\Delta\chi^2$=91

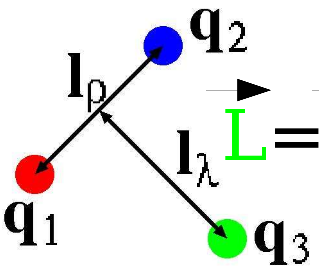
What kind of state ?

D$_{15}$
- 1 ← isospin 1/2
- 5 ← spin 5/2
- D ← π+N decay relative angular momentum

$J^{\pi}=5/2^{-}$

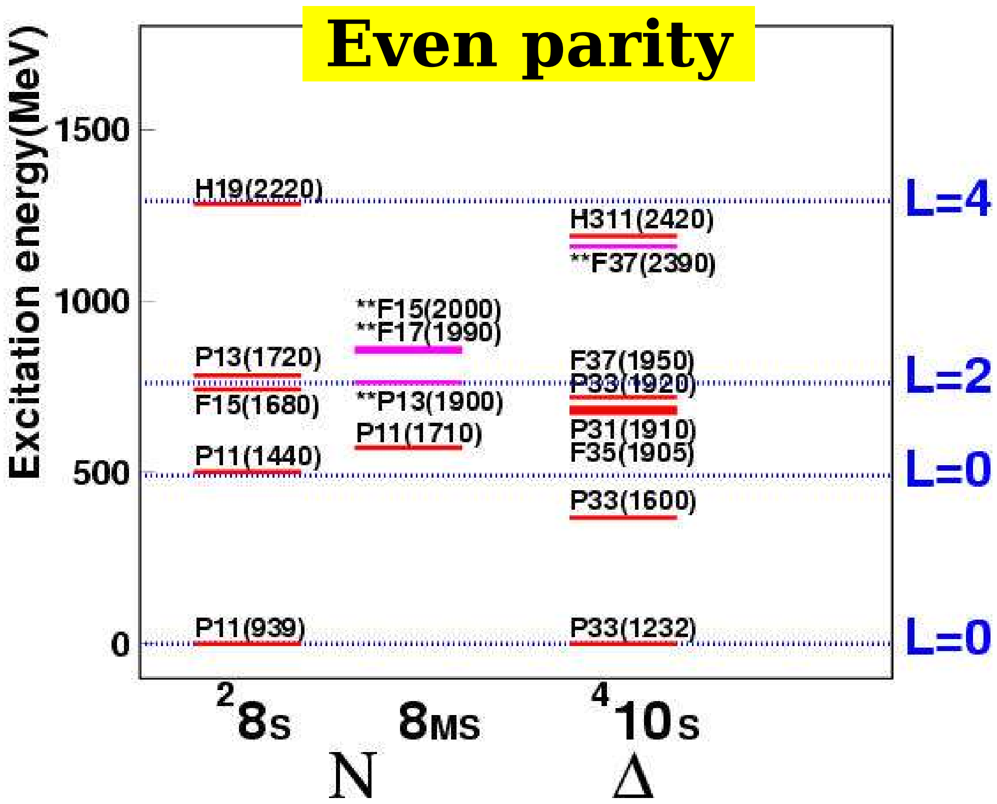
→ **L=1 or 3**

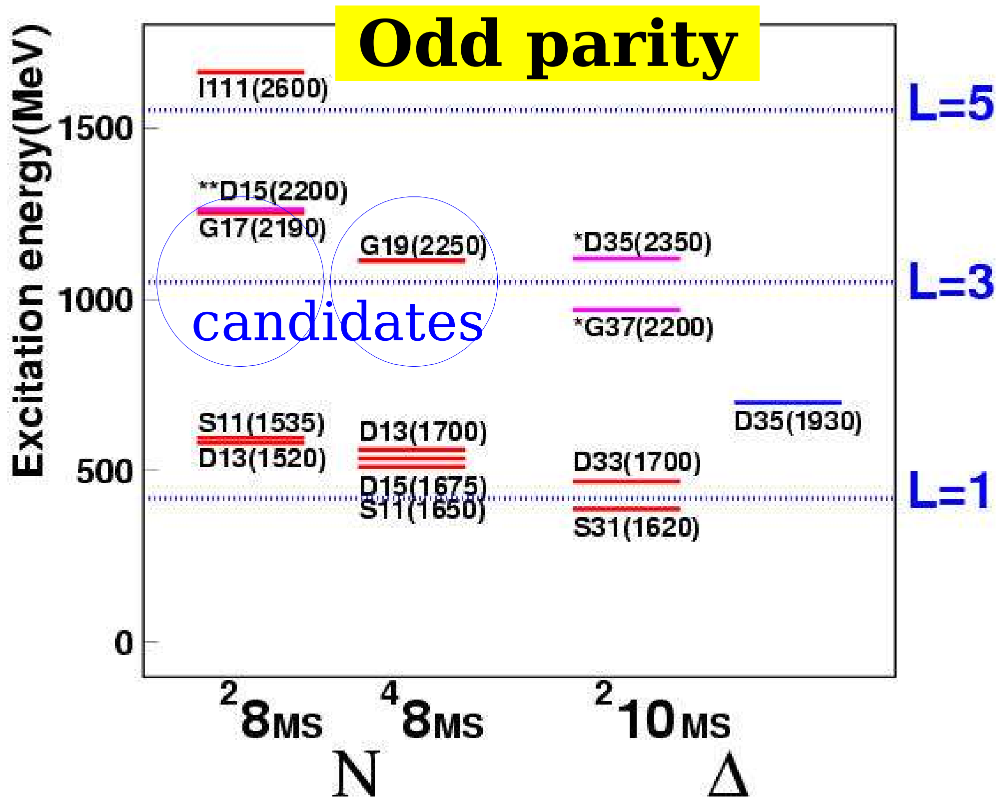
- **Deformed Oscillator Quark Model**



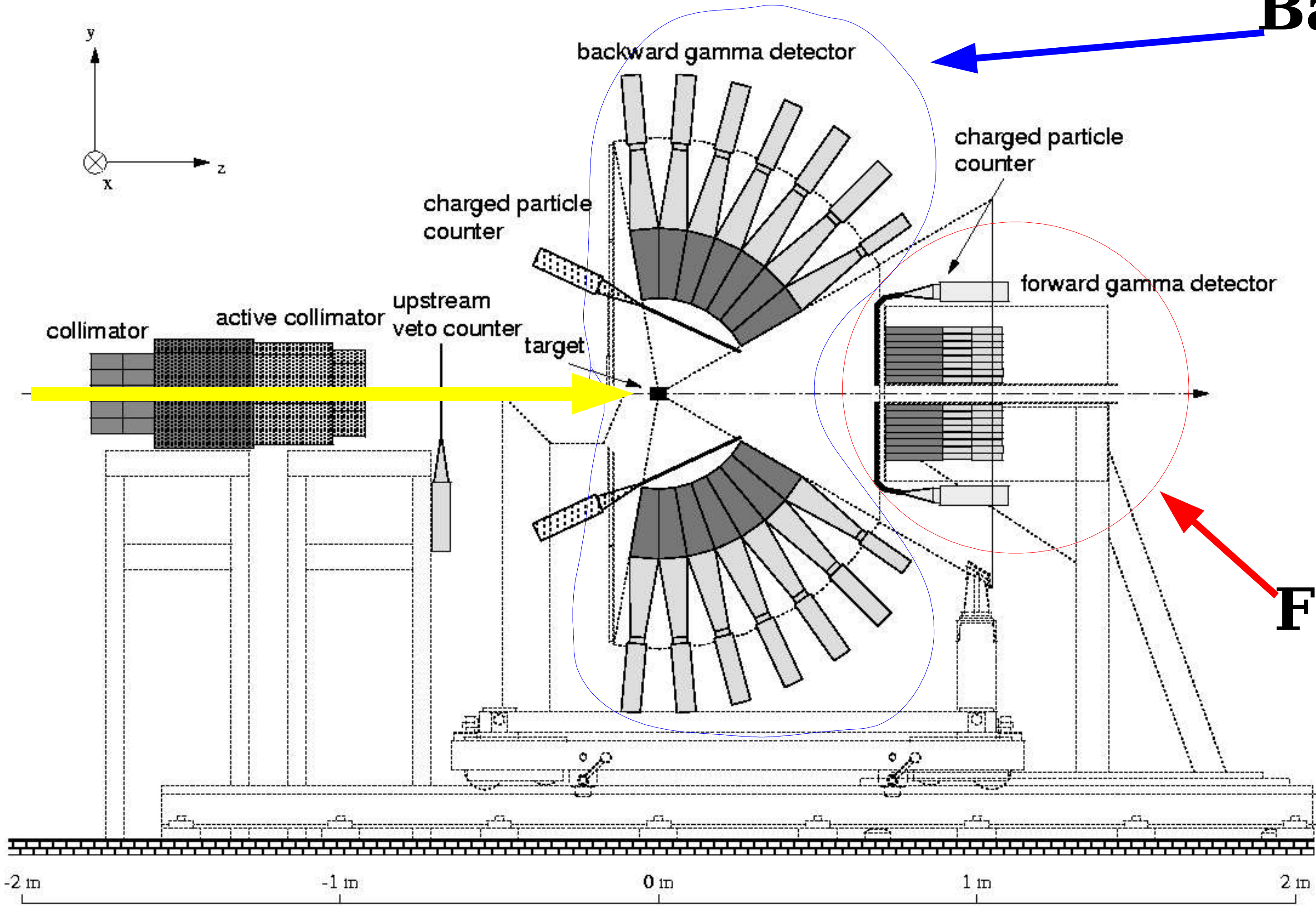
$$\vec{L}=\vec{l}_\rho+\vec{l}_\lambda$$

$$E_{DOQ}(L,N)=E_{int}(N)+\frac{L(L+1)}{2I}-\frac{\langle L^2\rangle}{2I}$$

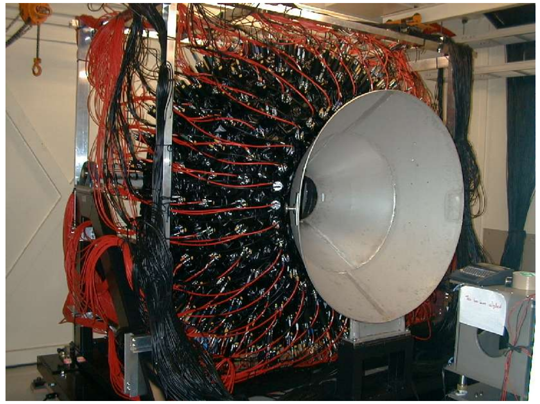




Detector Setup



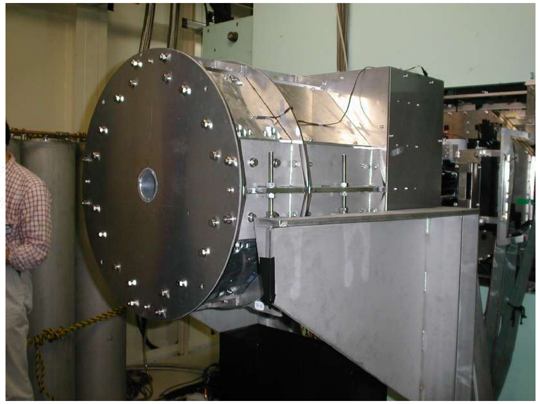
Backward Detector



θ = 30-100 deg

ϕ = 0-360 deg

Forward Detector

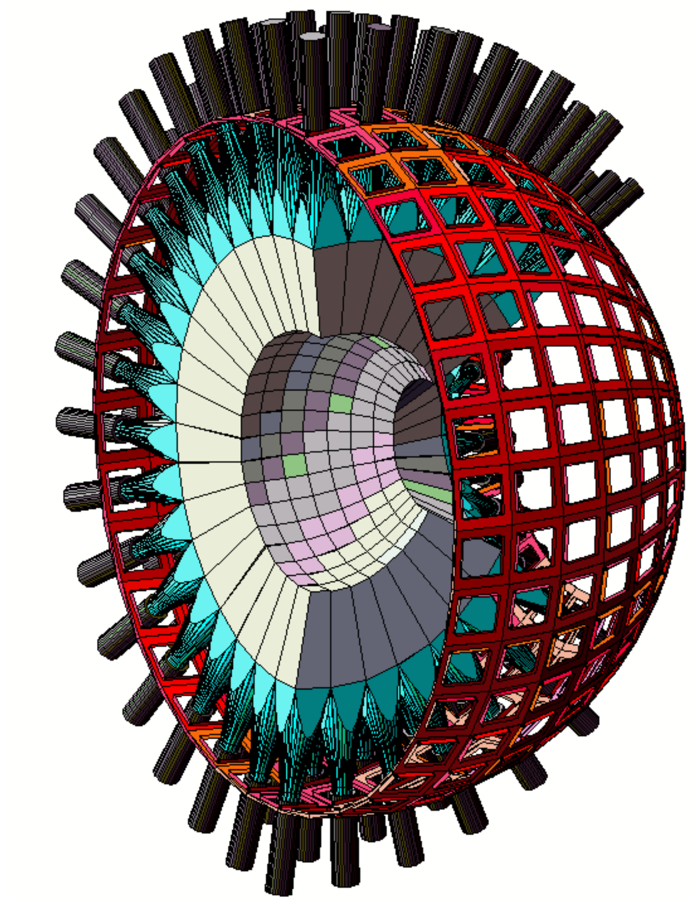


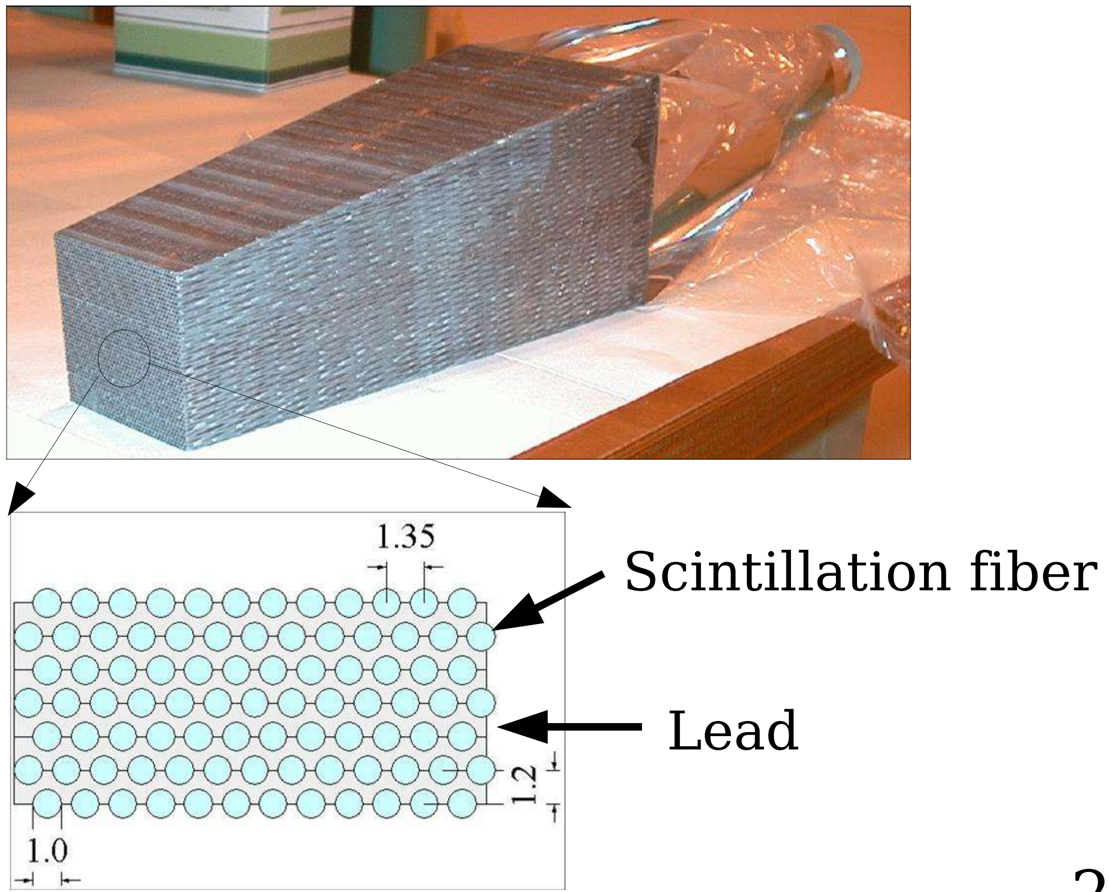
θ = 3-15 deg

ϕ = 0-360 deg

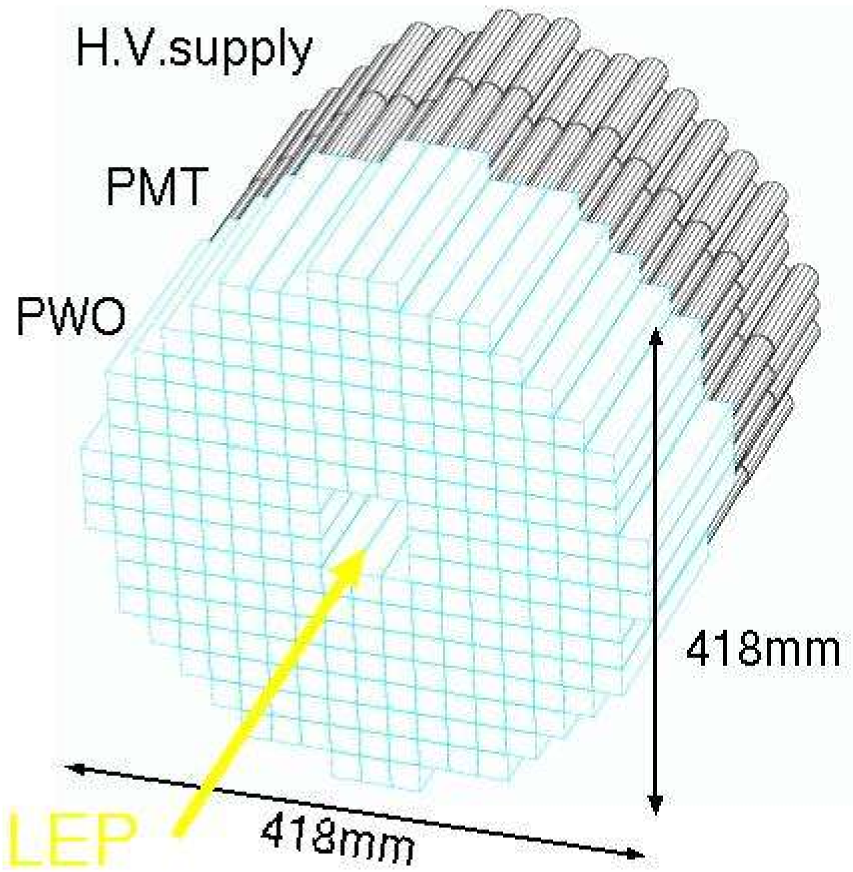
Backward Gamma Detector

- **Lead/SCIFI 252 modules**
- **Energy resolution 6% @ 1 GeV Gamma-ray**
- **Each length = 22cm → 13.7 X_0**



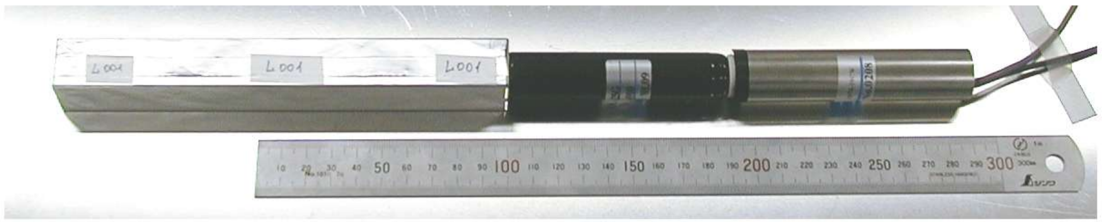


Forward Gamma Detector



- **252 PWO crystals**
  - **22×22×180mm 19.5X_0**
- **¾ in. PMT**
- **Cockcroft-Walton type H.V. supplier**
- **Energy resolution 3% @ 1GeV gamma-ray**

PWO **PMT** **H.V.Supplier**



$PbWO_4$ Crystal

- **Development started in 1992**
- **Property**
  - **high density**
  - **short radiation length**
  - **small Moliere radius**
  - **fast decay time**
  - **small light output**

	PWO	BGO	NaI(Tl)
density (g/cm^3)	8.2	7.13	3.67
radiation length (cm)	0.92	1.12	2.59
Moliere radius (cm)	2.2	2.4	4.5
decay constant (ns)	10	300	230
light yield (%)	~0.5	7 – 10	100
wave length (nm)	430	480	415
index	2.2	2.15	1.85

- **Recent development(1999~)**
  - **La^{3+},Y^{3+},... doped**
    - **To suppress 350 and 420nm absorption bands due to Pb^{3+},O^{-} color centers**

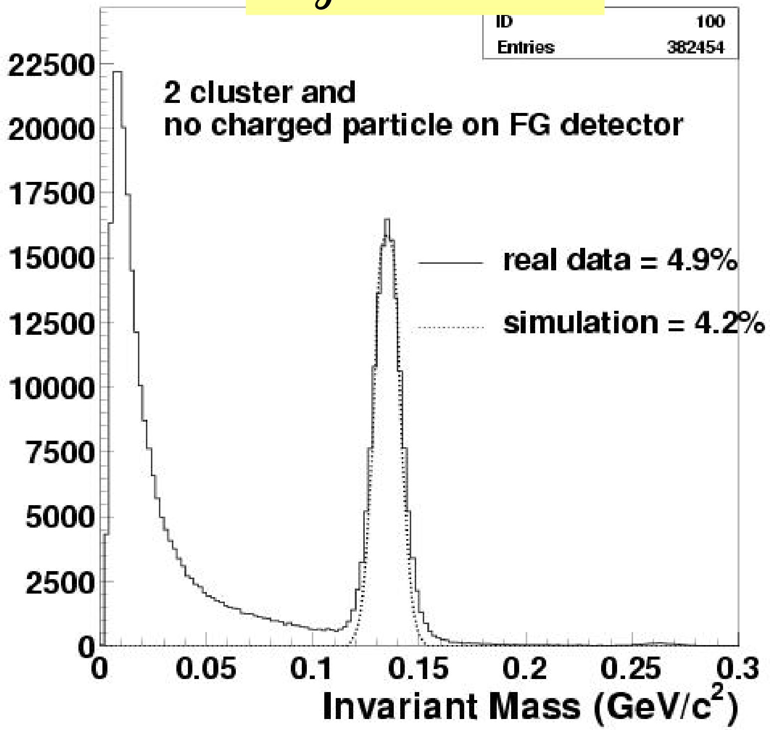
Experiment

- **Target**
  - **CH2(0.10X_0), C(0.17X_0), W(0.20X_0)**
- **Event Trigger**
  - **(FGor $\oplus$ BGor) $\otimes$ TaggerHit $\otimes$ Bar(VetoCounters)**
    - **FGor: 30MeV deposit at least in 1 crystal**
    - **BGor: 10MeV deposit at least in 1 module**
- **Incident gamma intensity**
  - **500-600 kcps**
- **Trigger rate**
  - **350-750 cps**
  - **70-80% DAQ live time**

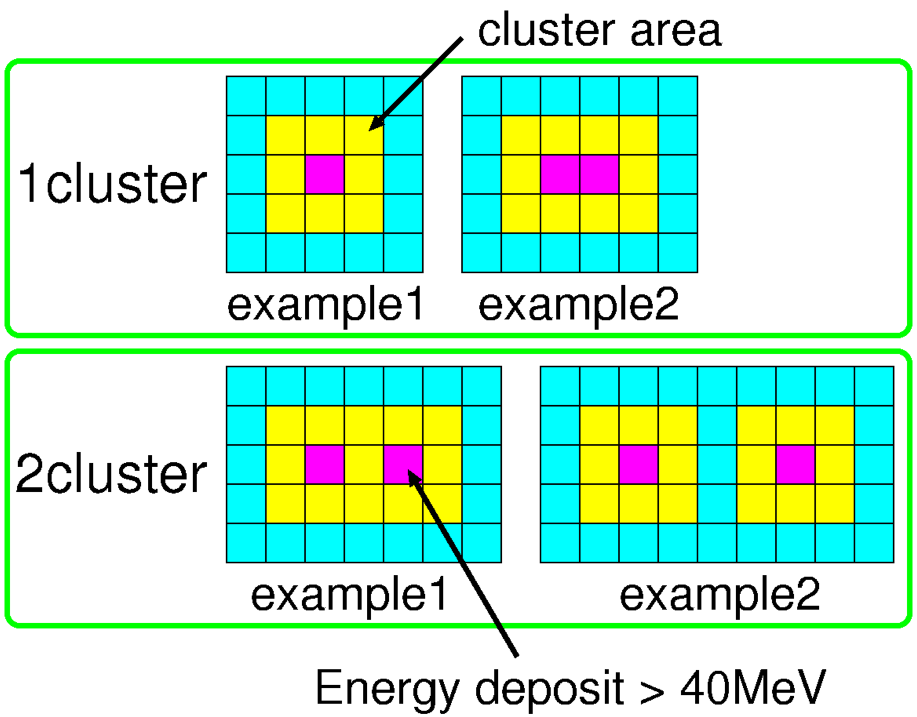
FG Base analysis(1)

- **Energy calibration**
  - **(1) cosmic-ray MIP**
  - **(2) iteration method using $\pi^0 \rightarrow 2\gamma$ events**

2γ event



- **Clustering**
  - **Energy deposit @ 1 GeV gamma-ray**
    - **80% center PWO**
    - **20% periferal 8PWOs**



FG Base analysis(2)

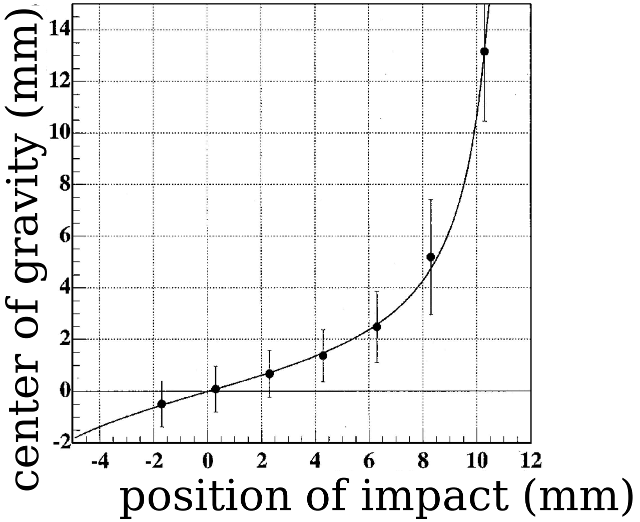
- **Position reconstruction**
  - **center of gravity method**
  - **logarithmic weighting**

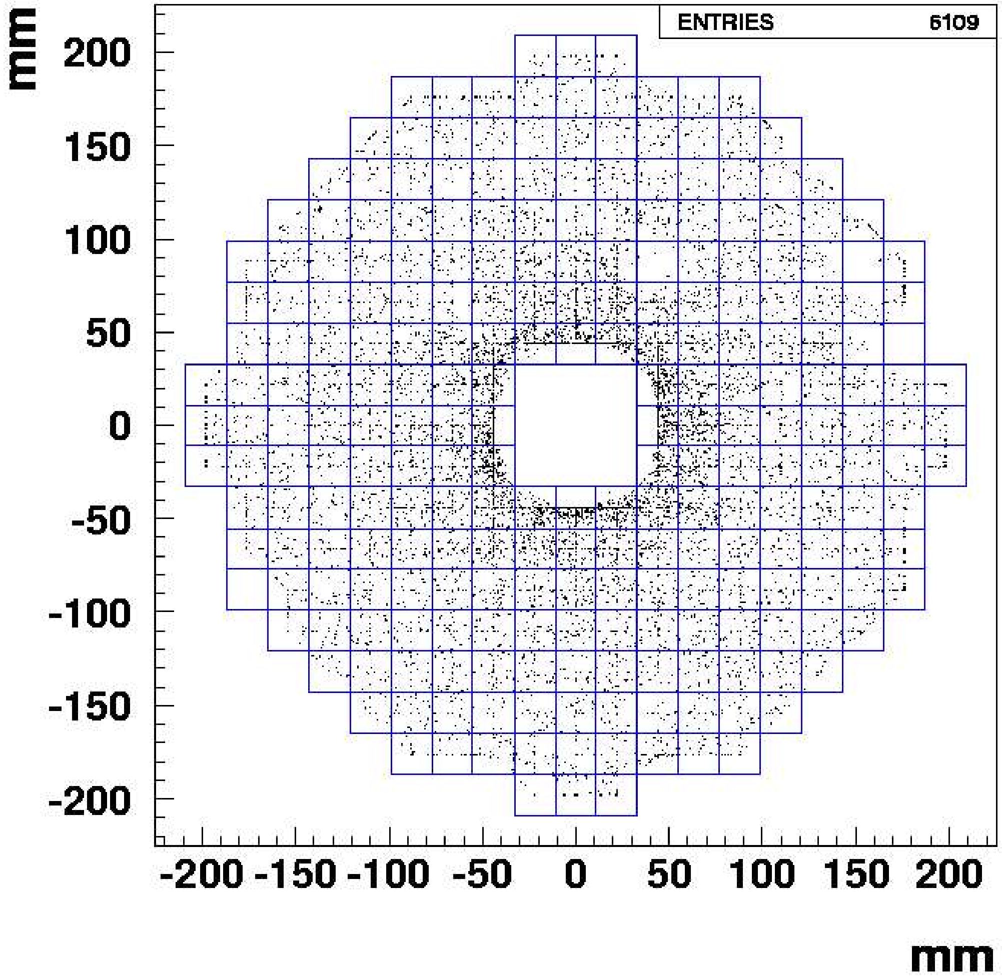
[NIM A311 (1992) 130.]

$$X=\frac{\sum w_i x_i}{\sum w_i} \qquad Y=\frac{\sum w_i y_i}{\sum w_i}$$

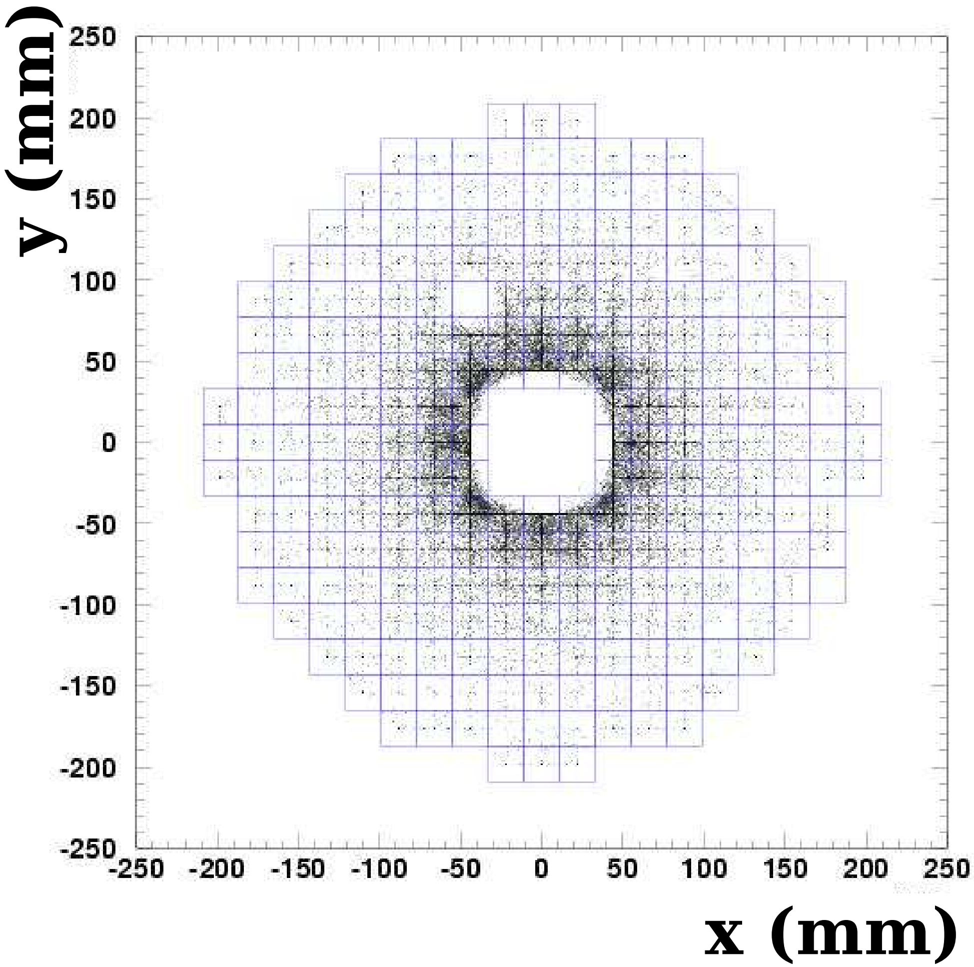
$$w_i=\max\left\{0,\left[W_0+\ln\left(\frac{E_i}{E_{tot}}\right)\right]\right\}$$

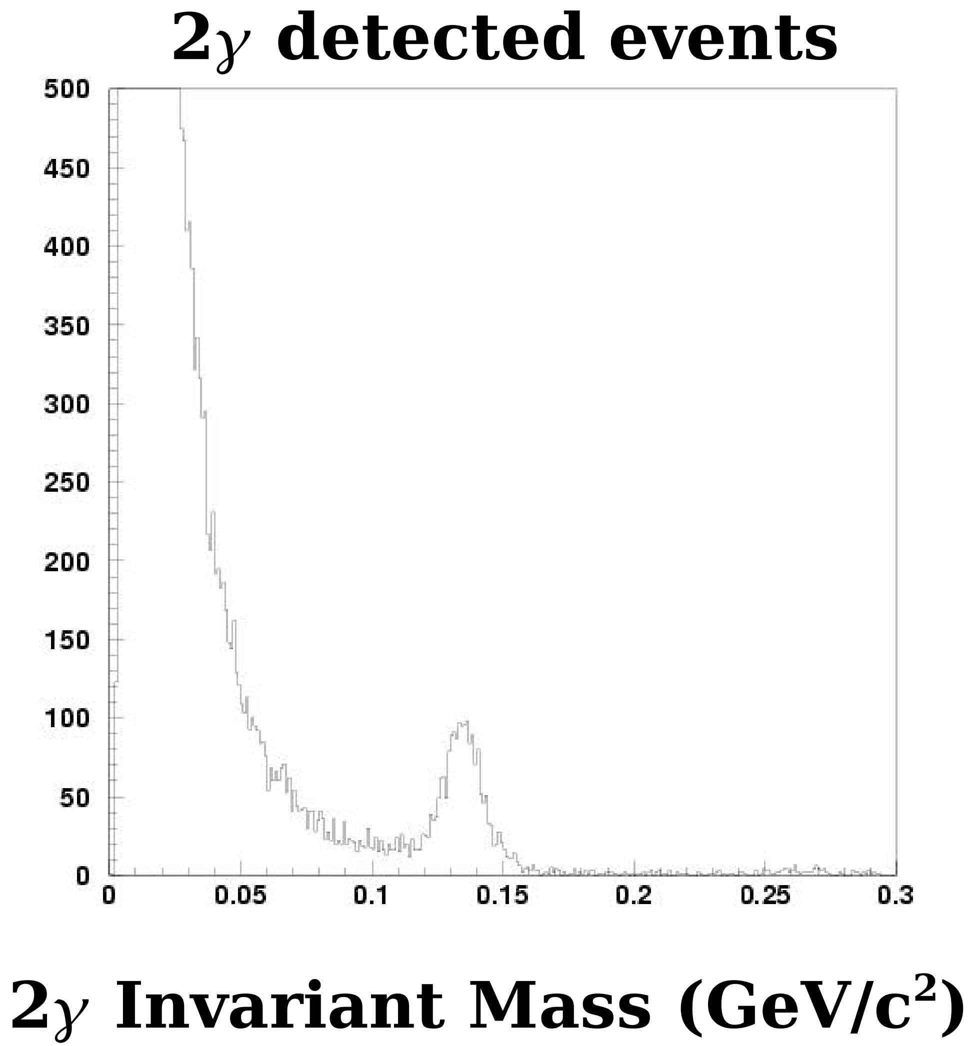
Experimental result using e- beam





W target


y (mm)
250
200
150
100
50
0
-50
-100
-150
-200
-250
-250 -200 -150 -100 -50 0 50 100 150 200 250
x (mm)


2γ detected events
500
450
400
350
300
250
200
150
100
50
0
0 0.05 0.1 0.15 0.2 0.25 0.3
2γ Invariant Mass (GeV/c²)

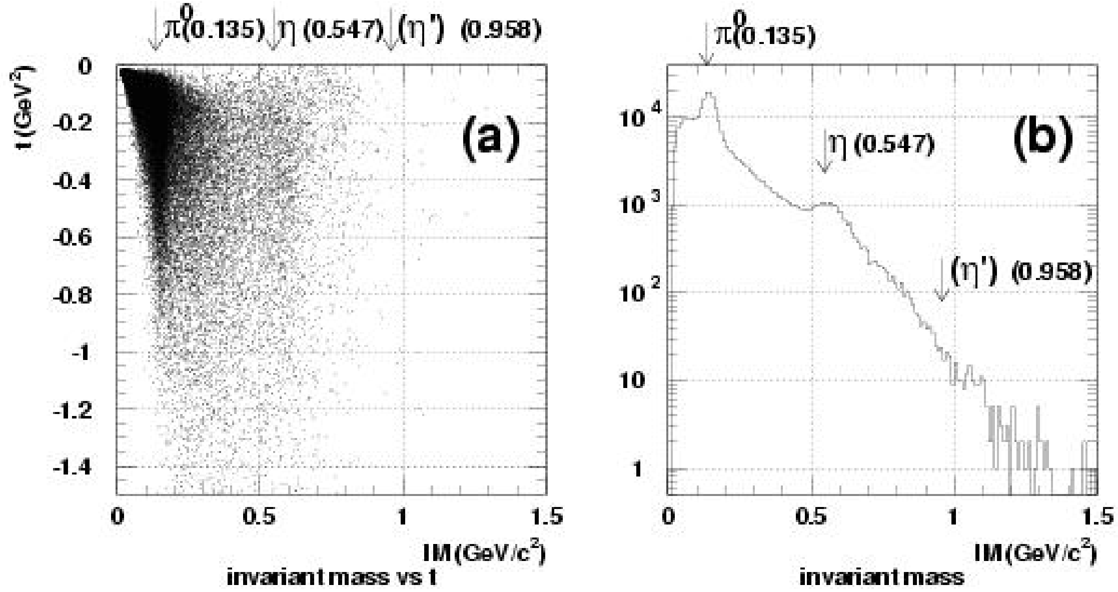
Examples of invariant mass

2γevent

$\pi^0 \to 2\gamma$ (99%)

$\eta \to 2\gamma$ (39%)

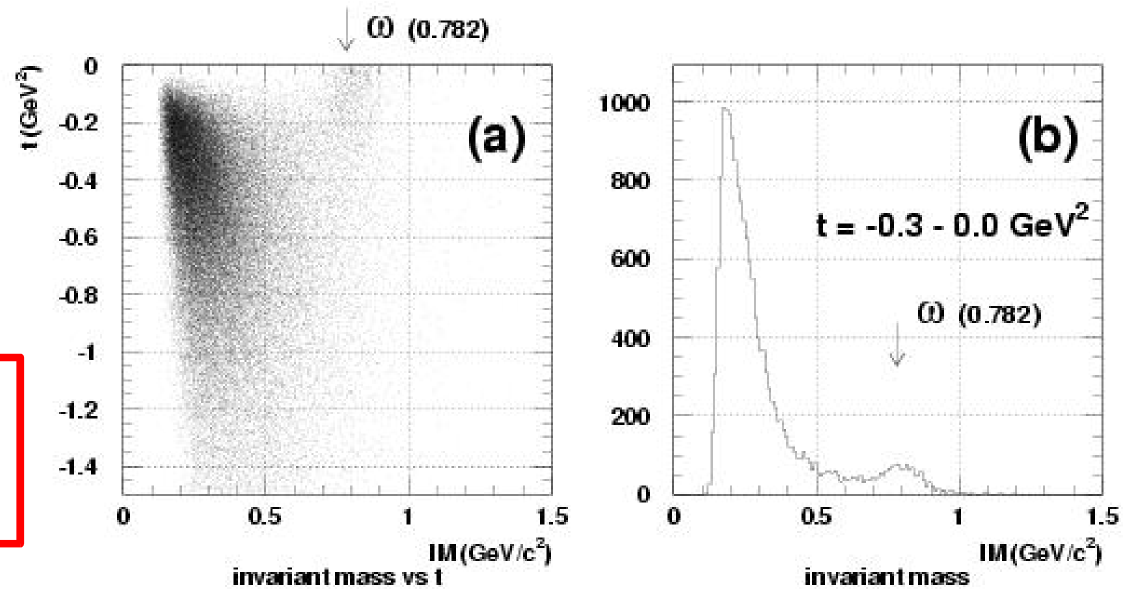
$\eta' \to 2\gamma$ (2%)



3γevent

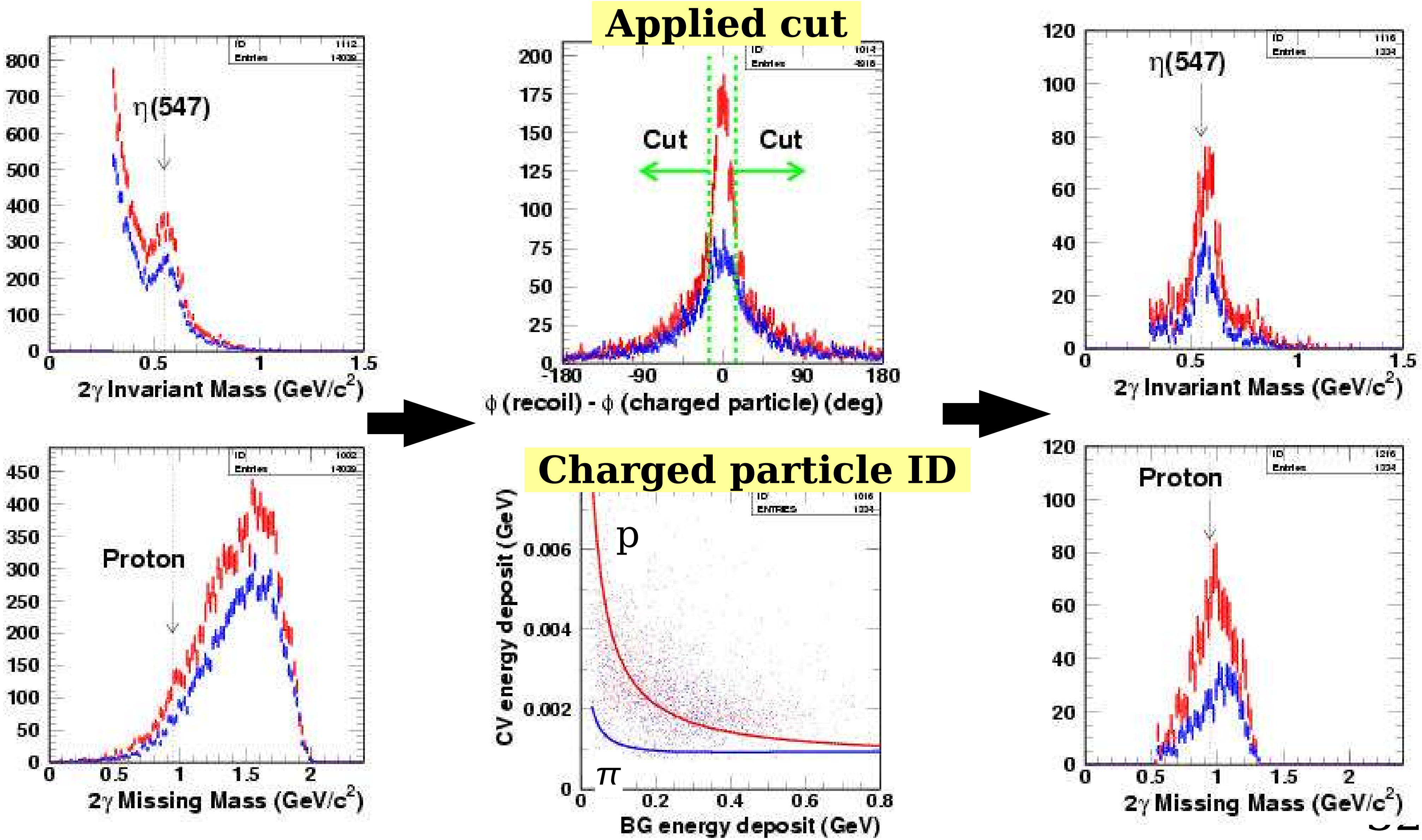
$\omega \to \gamma\pi^0 \to 3\gamma$ (9%)

kinematical fit applied



$\gamma p \rightarrow \eta p'$ event selection

- **2γ and 1 charged particle detected events**



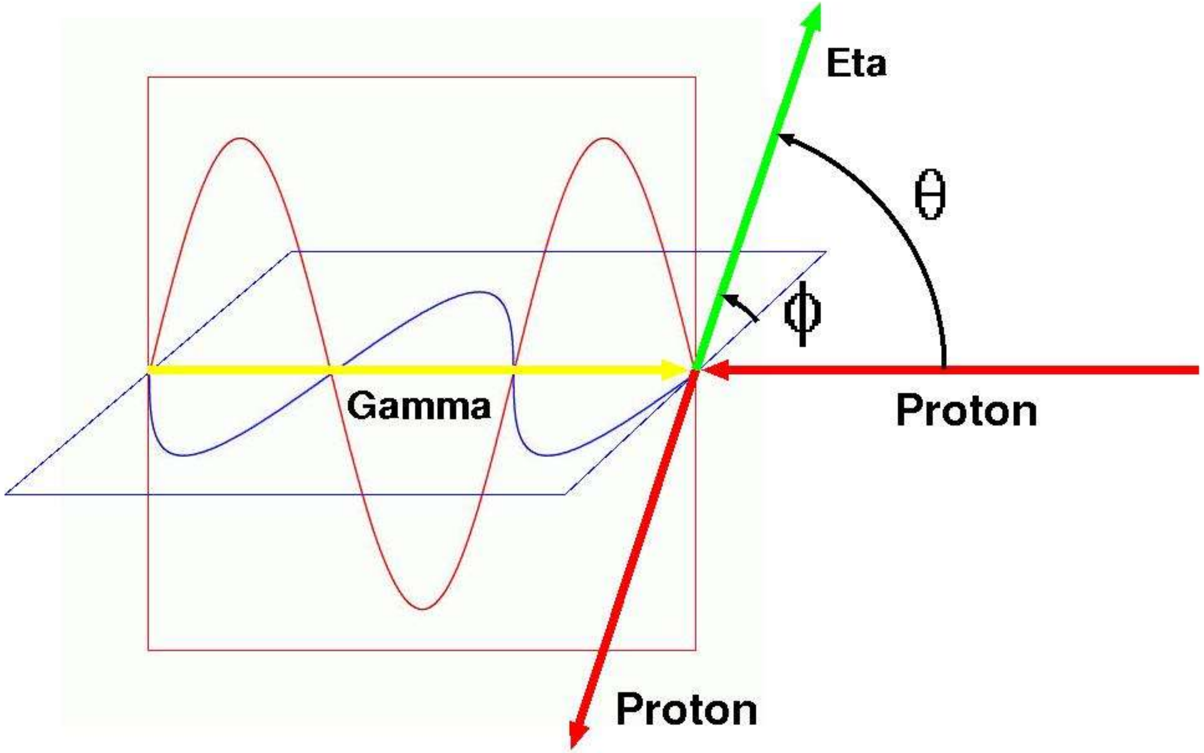
Photon Beam Asymmetry(1)

- **Photon beam asymmetry : Σ**

$$\sigma_{\perp} = \sigma + \Sigma\cos(2\phi)$$

$$\sigma_{\parallel} = \sigma - \Sigma\cos(2\phi)$$

$$\Sigma\cos(2\phi) = \frac{\sigma_{\perp} - \sigma_{\parallel}}{\sigma_{\perp} + \sigma_{\parallel}}$$



CM system of $\gamma p \rightarrow \eta p'$ reaction

Photon Beam Asymmetry(2)

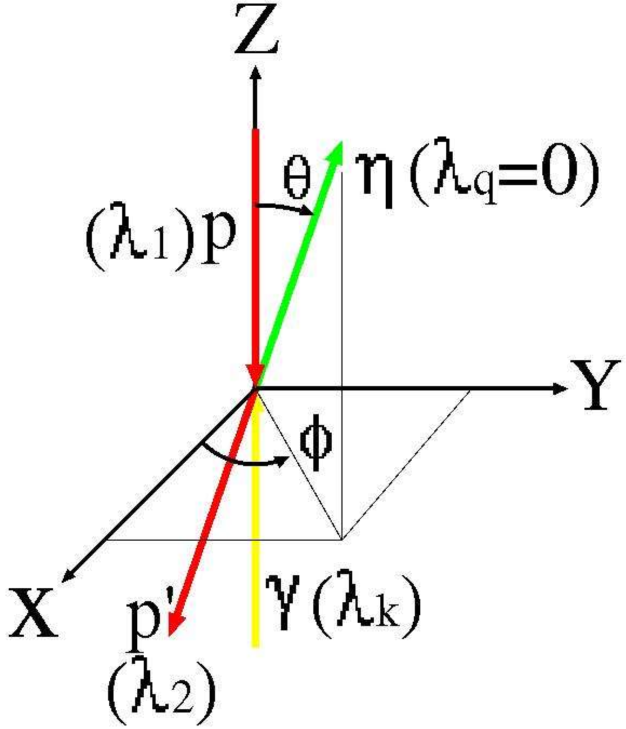
- **Helicity representation**

$$A_{\mu\lambda}(\theta,\phi) = \sum_j A^j_{\mu\lambda}(2j+1)d^j_{\lambda\mu}(\theta)e^{i(\lambda-\mu)\phi}$$

initial helicity $\lambda = \lambda_k - \lambda_1$

final helicity $\mu = \lambda_q - \lambda_2 = -\lambda_2$

resonance spin j



All amplitudes

	$\lambda_k = +1$		$\lambda_k = -1$	
$\lambda_1(\lambda)$	$-\frac{1}{2}(\frac{3}{2})$	$\frac{1}{2}(\frac{1}{2})$	$-\frac{1}{2}(-\frac{1}{2})$	$\frac{1}{2}(-\frac{3}{2})$
$\mu = \frac{1}{2}$	$A_{\frac{1}{2},\frac{3}{2}}$	$A_{\frac{1}{2},\frac{1}{2}}$	$A_{\frac{1}{2},-\frac{1}{2}}$	$A_{\frac{1}{2},-\frac{3}{2}}$
$\mu = -\frac{1}{2}$	$A_{-\frac{1}{2},\frac{3}{2}}$	$A_{-\frac{1}{2},\frac{1}{2}}$	$A_{-\frac{1}{2},-\frac{1}{2}}$	$A_{-\frac{1}{2},-\frac{3}{2}}$

Photon Beam Asymmetry(3)

Using property $A_{-\mu,-\lambda} = -e^{i(\lambda-\mu)(\pi-2\phi)} A_{\mu,\lambda}(\theta,\phi)$

- $\varepsilon_{\perp} = \frac{i}{\sqrt{2}}(\varepsilon_{+} + \varepsilon_{-})$ **Vertical linear polarization**

$$
\begin{array}{cc|lcl}
\lambda_1 & \mu & & & \\
-\frac{1}{2} & \frac{1}{2} & A_{\frac{1}{2},\frac{3}{2}} + A_{\frac{1}{2},-\frac{1}{2}} & \rightarrow & \left[\sum_j A^j_{\frac{1}{2},\frac{3}{2}}(2j+1)d^j_{\frac{3}{2},\frac{1}{2}}(\theta)\right] e^{i\phi} + \left[\sum_j A^j_{-\frac{1}{2},\frac{1}{2}}(2j+1)d^j_{\frac{1}{2},-\frac{1}{2}}(\theta)\right] e^{-i\phi} \\
-\frac{1}{2} & \frac{1}{2} & A_{-\frac{1}{2},\frac{1}{2}} + A_{-\frac{1}{2},-\frac{3}{2}} & \rightarrow & \left[\sum_j A^j_{-\frac{1}{2},\frac{1}{2}}(2j+1)d^j_{\frac{1}{2},-\frac{1}{2}}(\theta)\right] e^{i\phi} + \left[\sum_j A^j_{\frac{1}{2},\frac{3}{2}}(2j+1)d^j_{\frac{3}{2},\frac{1}{2}}(\theta)\right] e^{-i\phi} \\
\frac{1}{2} & \frac{1}{2} & A_{\frac{1}{2},\frac{1}{2}} + A_{\frac{1}{2},-\frac{3}{2}} & \rightarrow & \left[\sum_j A^j_{\frac{1}{2},\frac{1}{2}}(2j+1)d^j_{\frac{1}{2},\frac{1}{2}}(\theta)\right] - \left[\sum_j A^j_{-\frac{1}{2},\frac{3}{2}}(2j+1)d^j_{\frac{3}{2},-\frac{1}{2}}(\theta)\right] e^{-2i\phi} \\
-\frac{1}{2} & -\frac{1}{2} & A_{-\frac{1}{2},\frac{3}{2}} + A_{-\frac{1}{2},-\frac{1}{2}} & \rightarrow & \left[\sum_j A^j_{-\frac{1}{2},\frac{3}{2}}(2j+1)d^j_{\frac{3}{2},-\frac{1}{2}}(\theta)\right] - \left[\sum_j A^j_{\frac{1}{2},\frac{1}{2}}(2j+1)d^j_{\frac{1}{2},\frac{1}{2}}(\theta)\right] e^{-2i\phi}
\end{array}
$$

Interference terms in the cross section

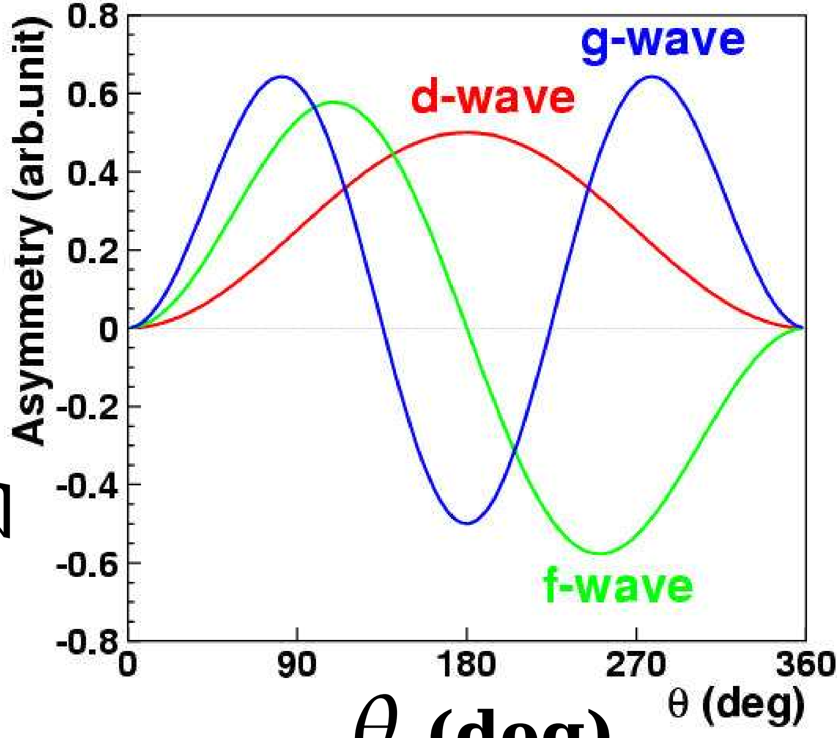
$$
= 2Re\left[\left(\sum_j A^j_{\frac{1}{2},\frac{3}{2}}(2j+1)d^j_{\frac{3}{2},\frac{1}{2}}(\theta)\right)\left(\sum_j A^j_{-\frac{1}{2},\frac{1}{2}}(2j+1)d^j_{\frac{1}{2},-\frac{1}{2}}(\theta)\right)^*\right]\cos(2\phi)
$$

$$
-2Re\left[\left(\sum_j A^j_{\frac{1}{2},\frac{1}{2}}(2j+1)d^j_{\frac{1}{2},\frac{1}{2}}(\theta)\right)\left(\sum_j A^j_{-\frac{1}{2},\frac{3}{2}}(2j+1)d^j_{\frac{3}{2},-\frac{1}{2}}(\theta)\right)^*\right]\cos(2\phi)
$$

- $\varepsilon_{\parallel} = -\frac{1}{\sqrt{2}}(\varepsilon_{+} - \varepsilon_{-})$ **Horizontal linear polarization**

Interference terms → inverse signs

Example $\gamma p \to \eta p$'@low energy

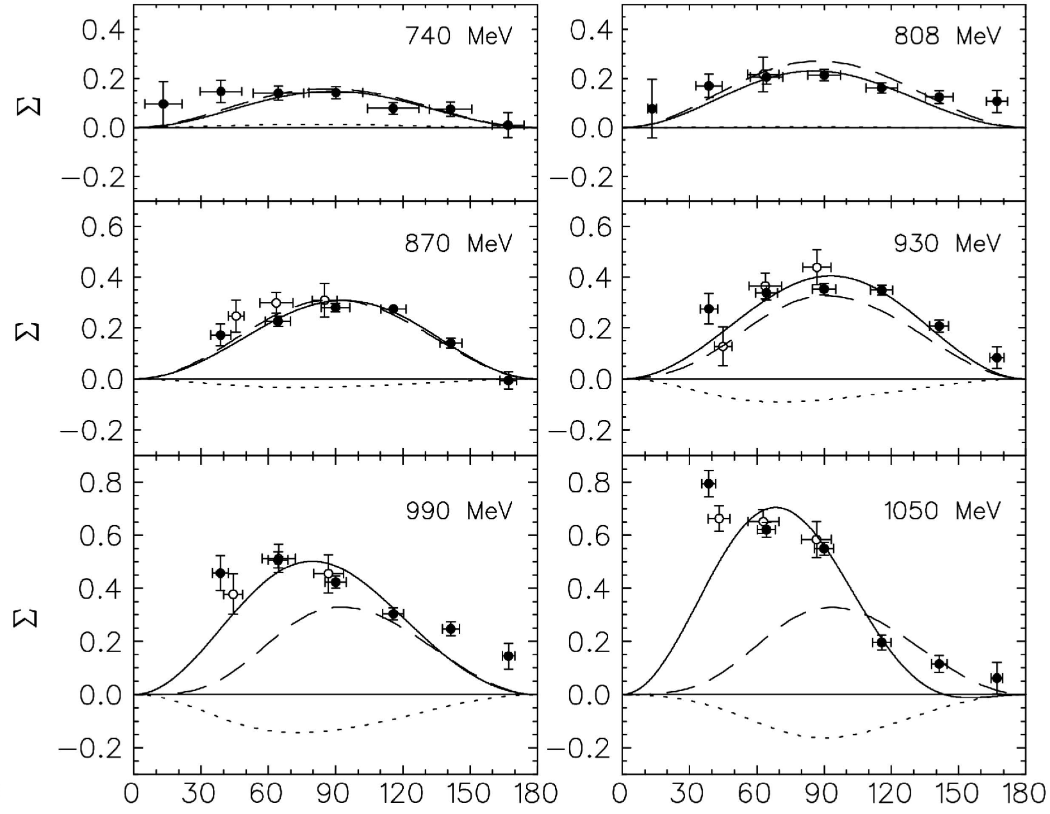


Σ θ (deg)

$S_{11} \otimes$ (D or F or G)

↑
Large Cross Section

GRAAL data

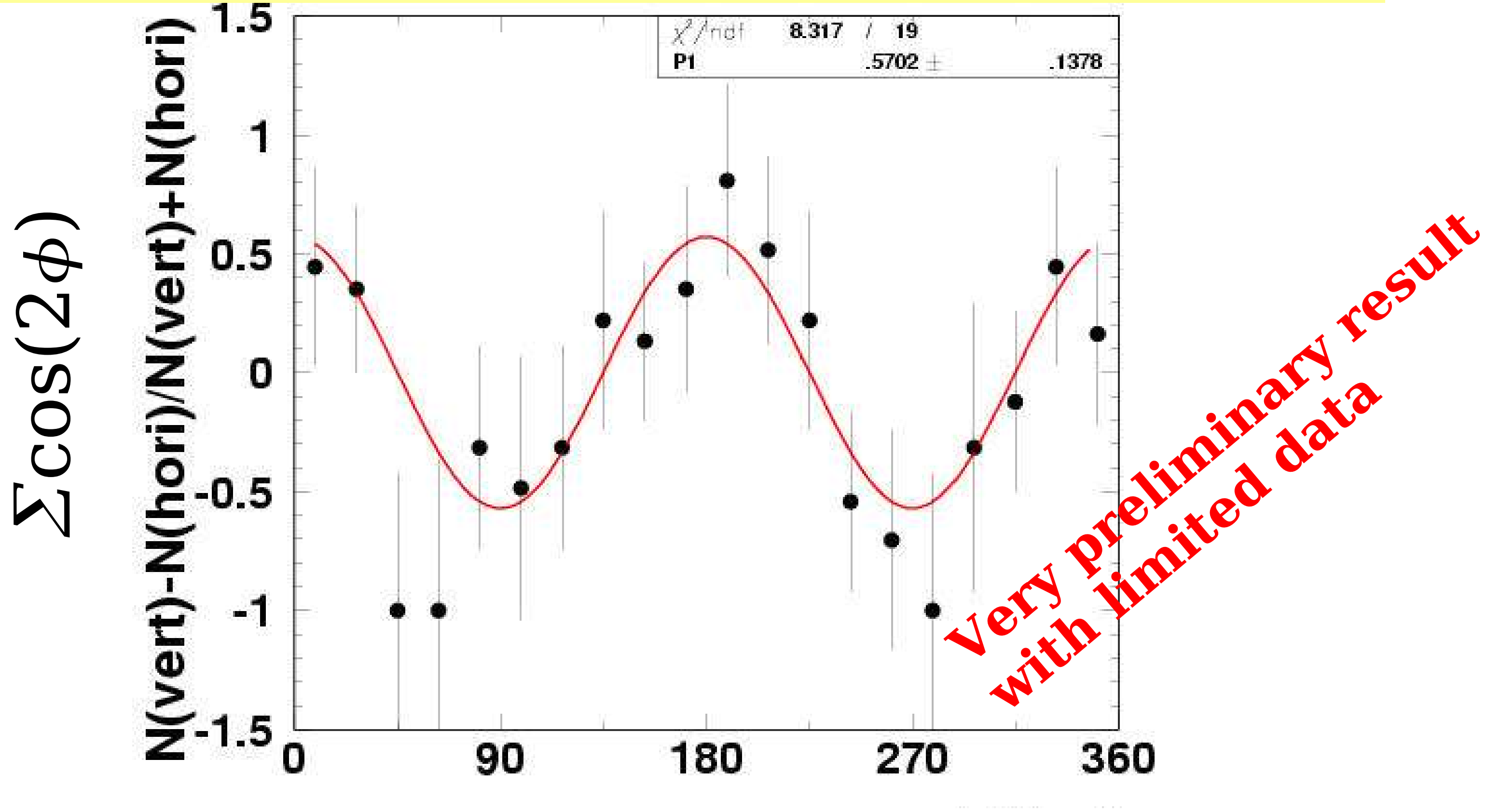


Σ θ (deg) θ (deg)

- .... isobar-model w/o D13(1520)
- – – isobar-model w/ D13(1520)
- —— fit to the data w/ F15(1680)

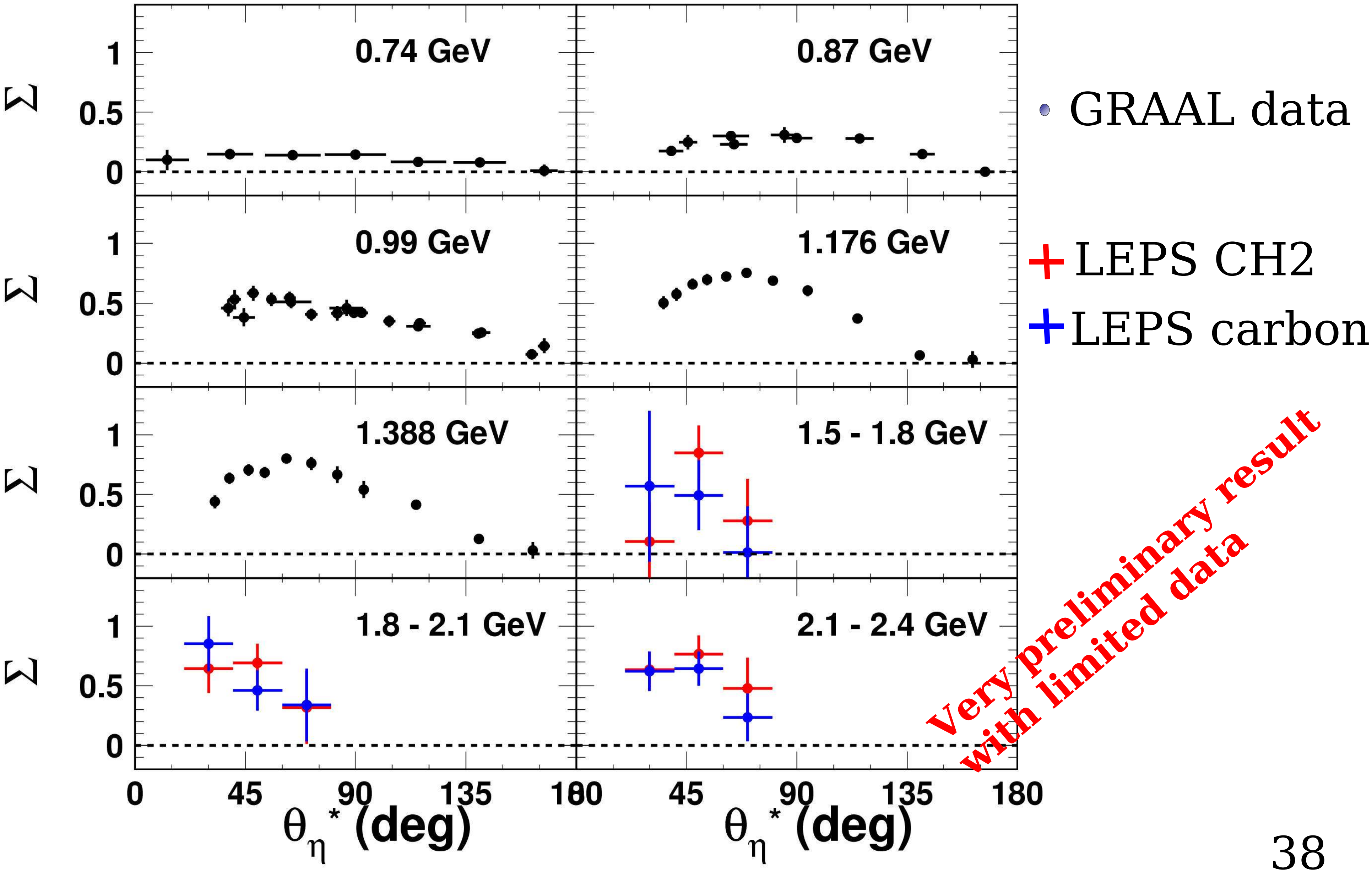
cos(2ϕ) dependence

Example: CH2 target, FG1γ,BG1γ
Eγ=1.8-2.1GeV, $\theta^{*}\eta$=40-60deg



ϕ (deg)

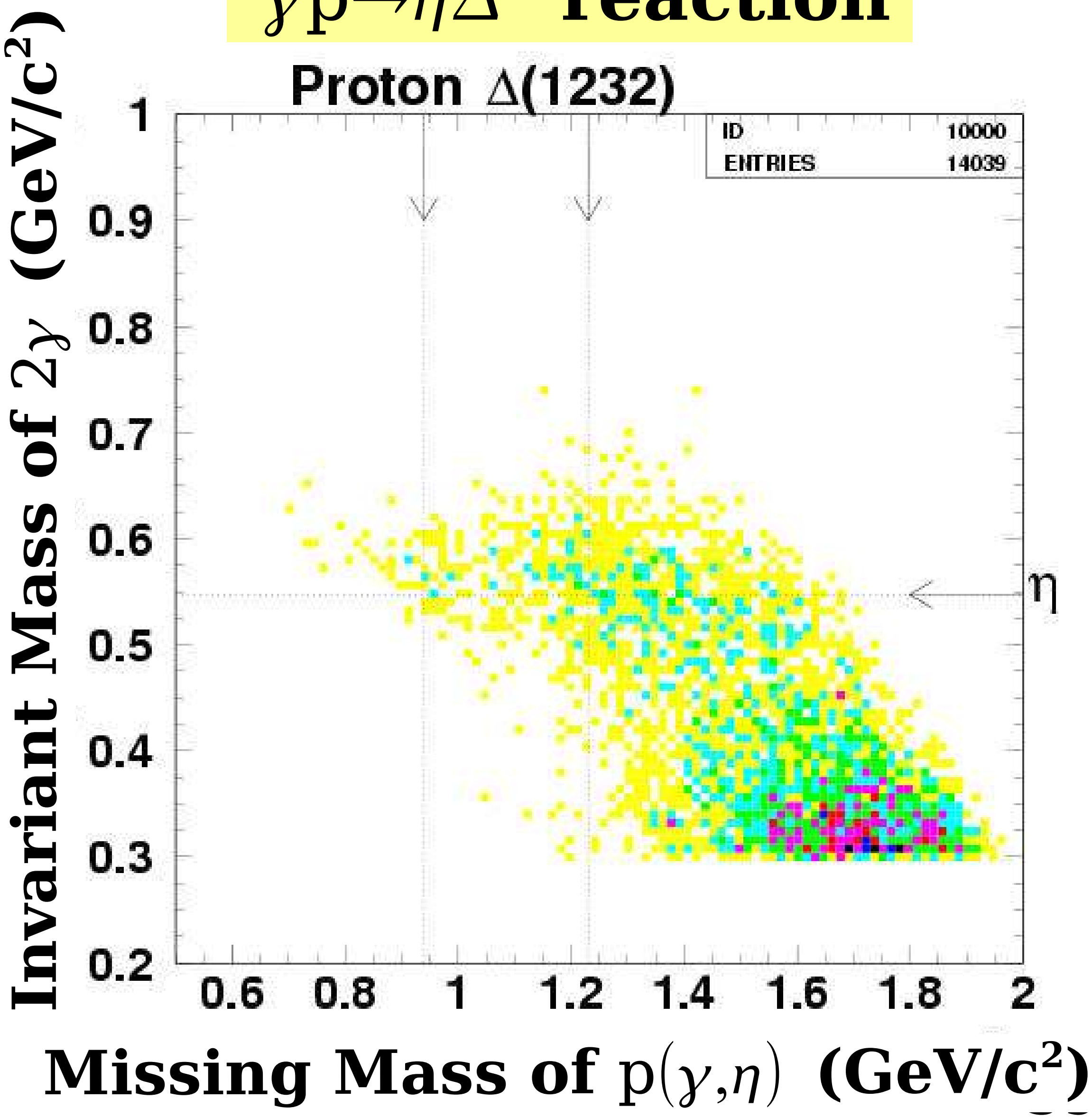
Obtained Asymmetry



Possibility of Δ^* study

- **Resonance isospin 3/2 selectivity**
- **Quark model prediction**
  - $F_{35}(1990)$
  - $D_{35}(2165)$
- **2 neutral particles in final state**
  - $\eta+\pi^0$ **or** η+n ($\Delta^+ \to p\pi^0, n\pi^+$)
  - η **detection is important**

$\gamma p \to \eta \Delta^+$ reaction

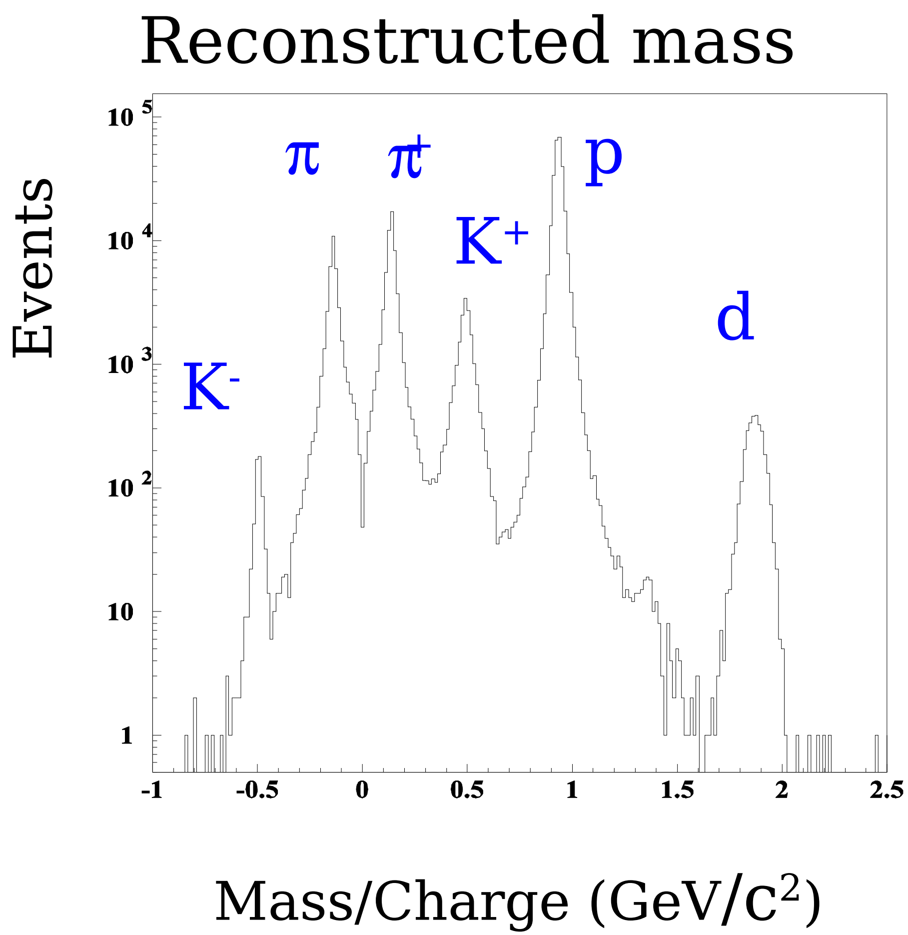


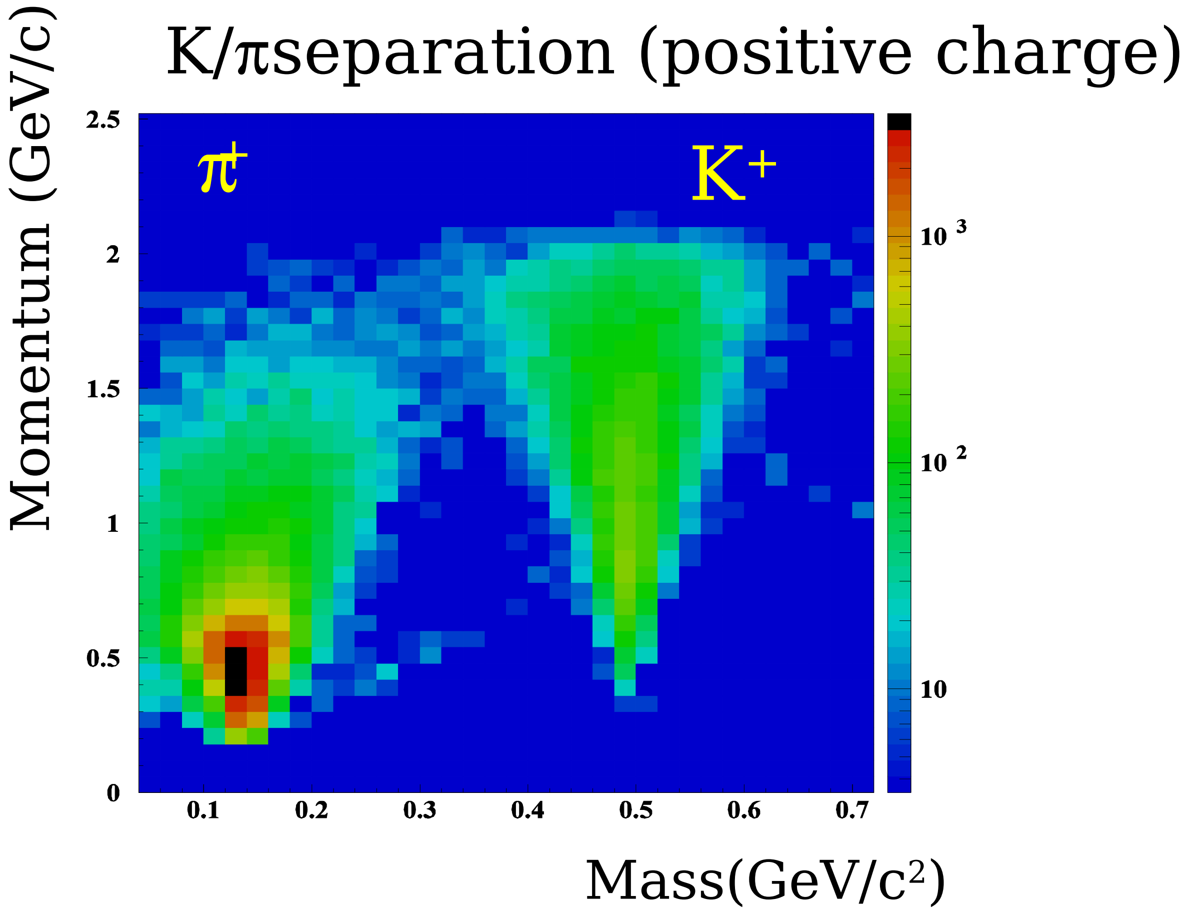
Summary

- **Photoreaction experiment was performed to study Primakov $2\pi^0$ production and nuclear resonances at the SPring-8/LEPS beam line.**
- **Forward gamma detector was constructed to detect gamma-rays at a forward direction with a minimum angle of 3 degree.**
- **Preliminary result of $\gamma\mathrm{p}\rightarrow\eta\mathrm{p}'$ reaction was shown. Photon beam asymmetries have tendency of a forward peaking distribution.**
- **Data analysis for precise calibration and various physics channels are in progress.**

additional pages

Charged particle identification

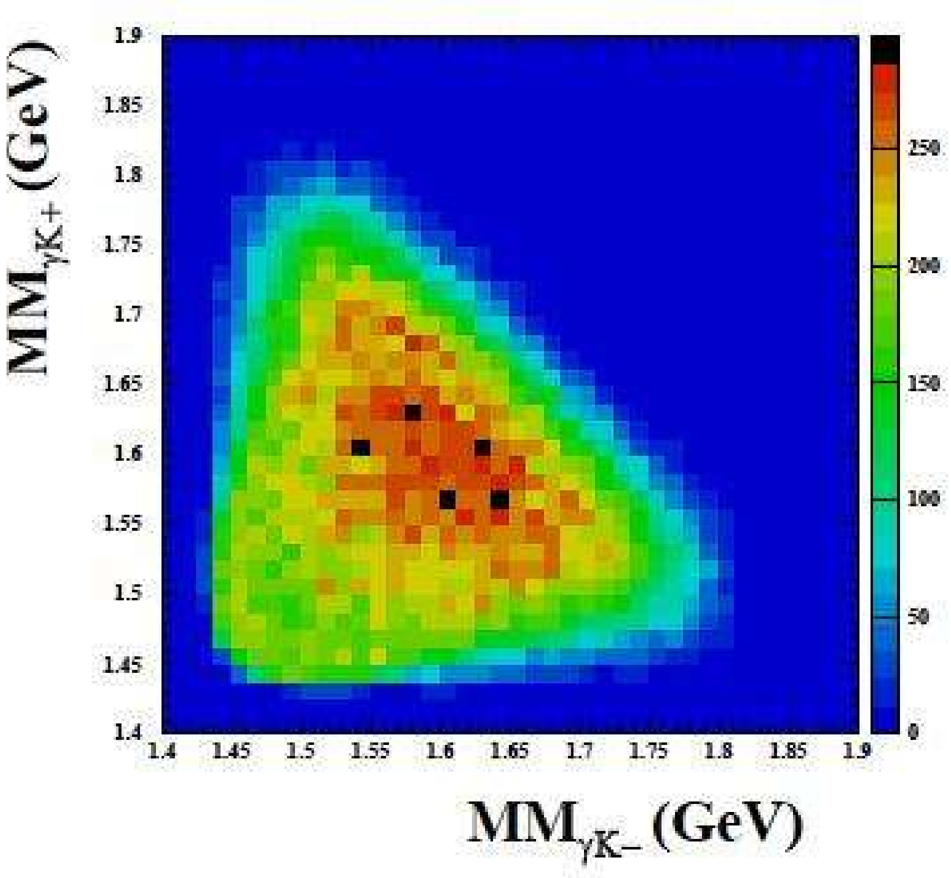


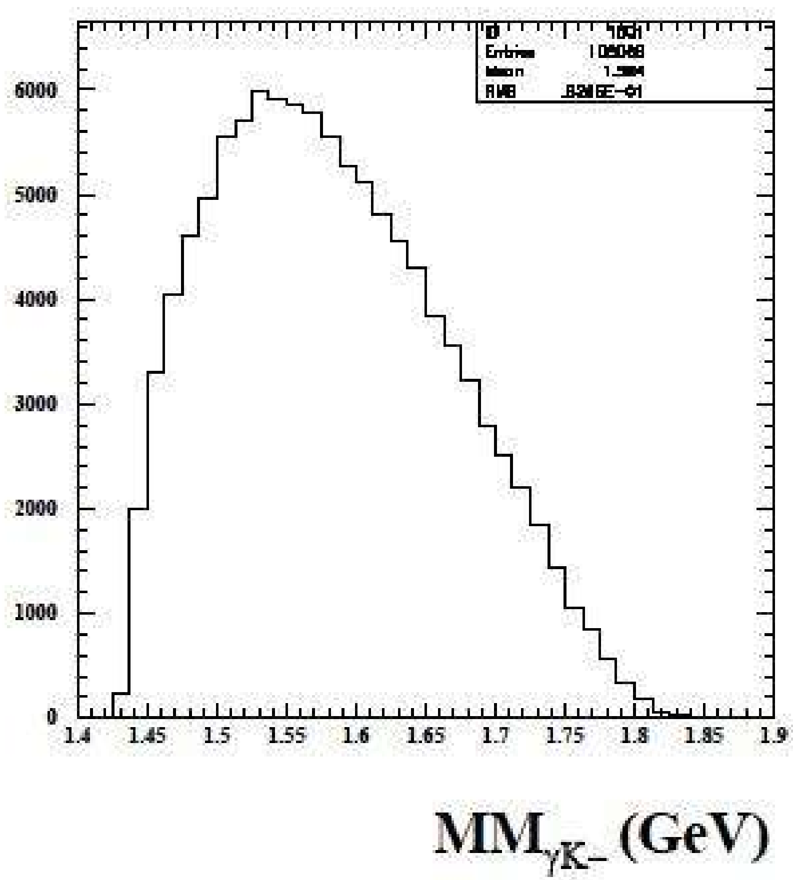


σ_{Mass} = 30 MeV/c^2(typ.) for 1GeV/c Kaon

KKN phase space MC data

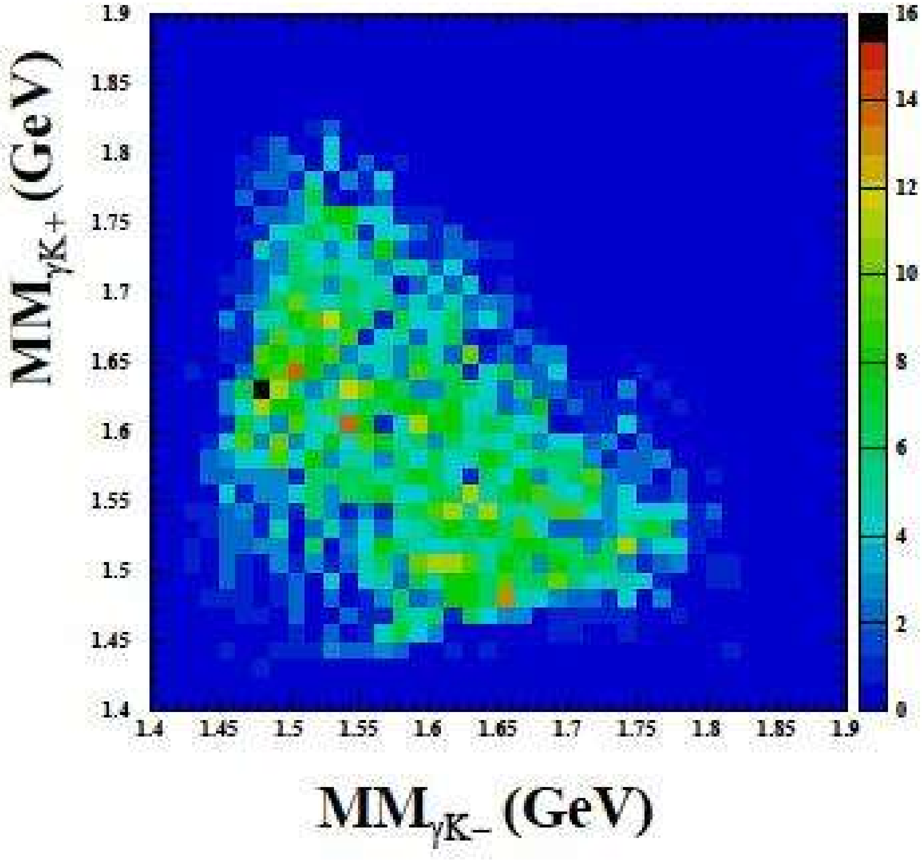
- After applying the same cuts

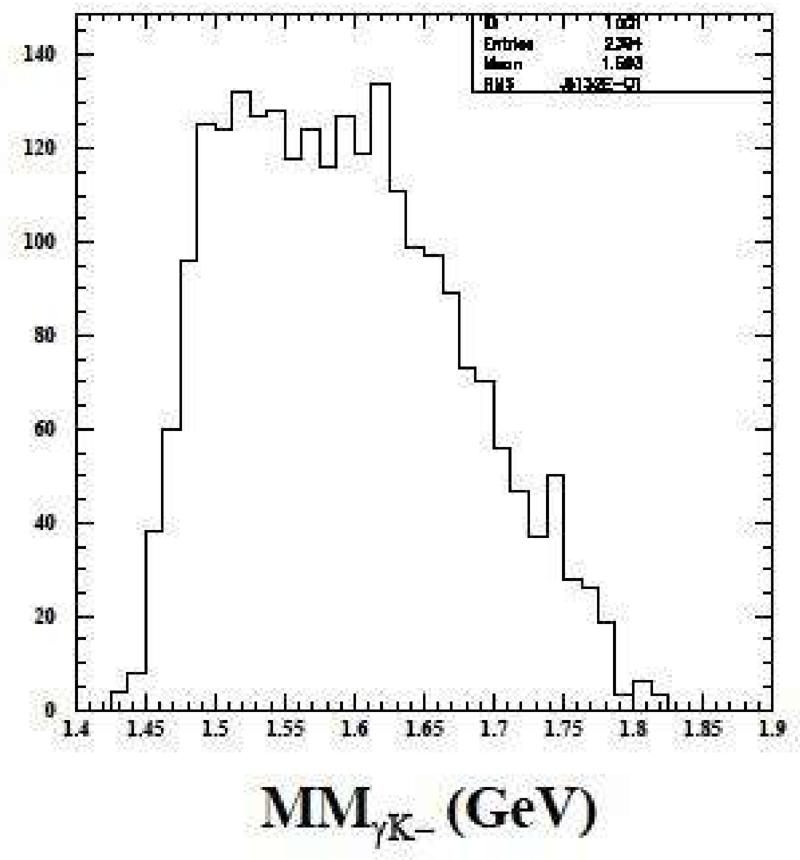




ϕ MC

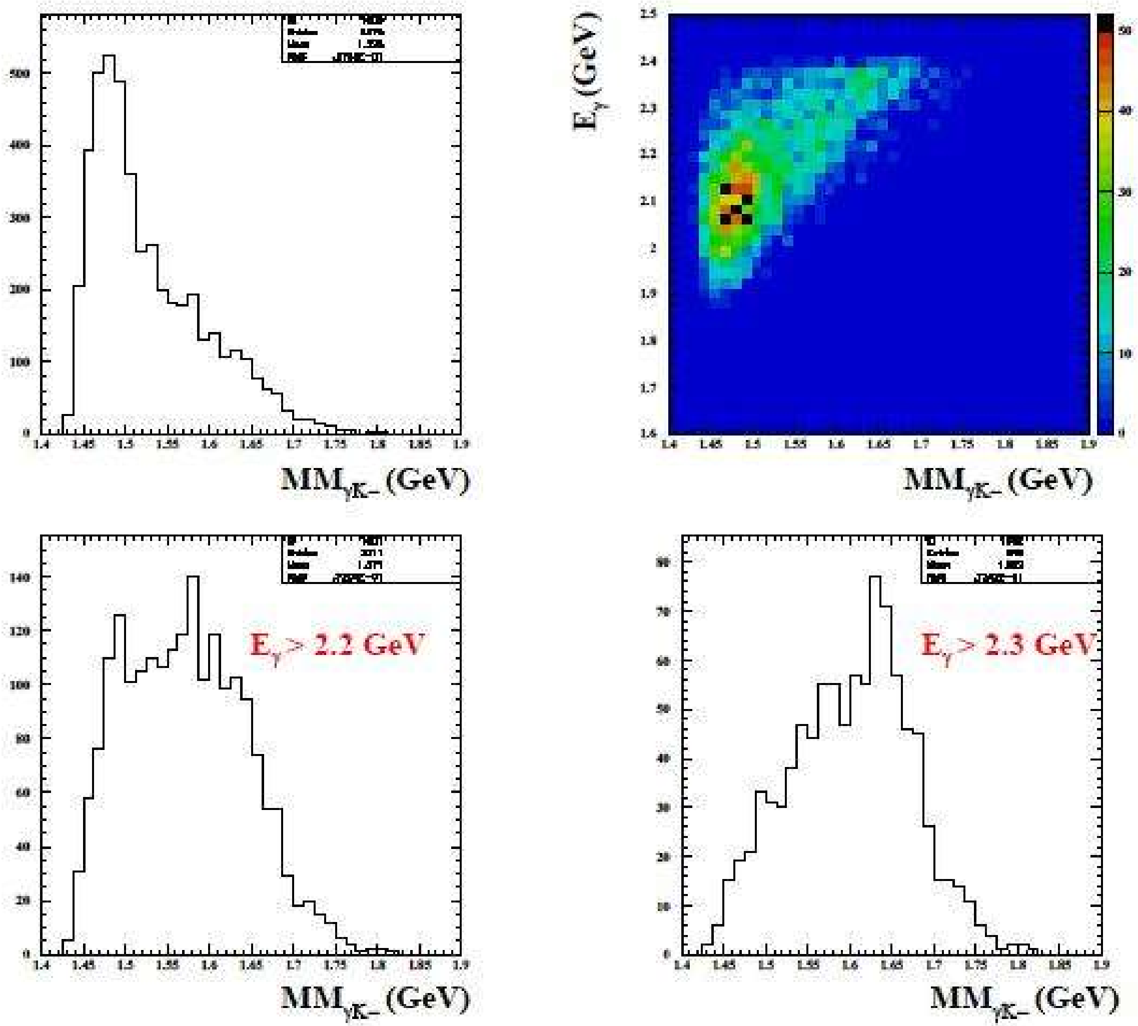
- **After applying the same cuts**





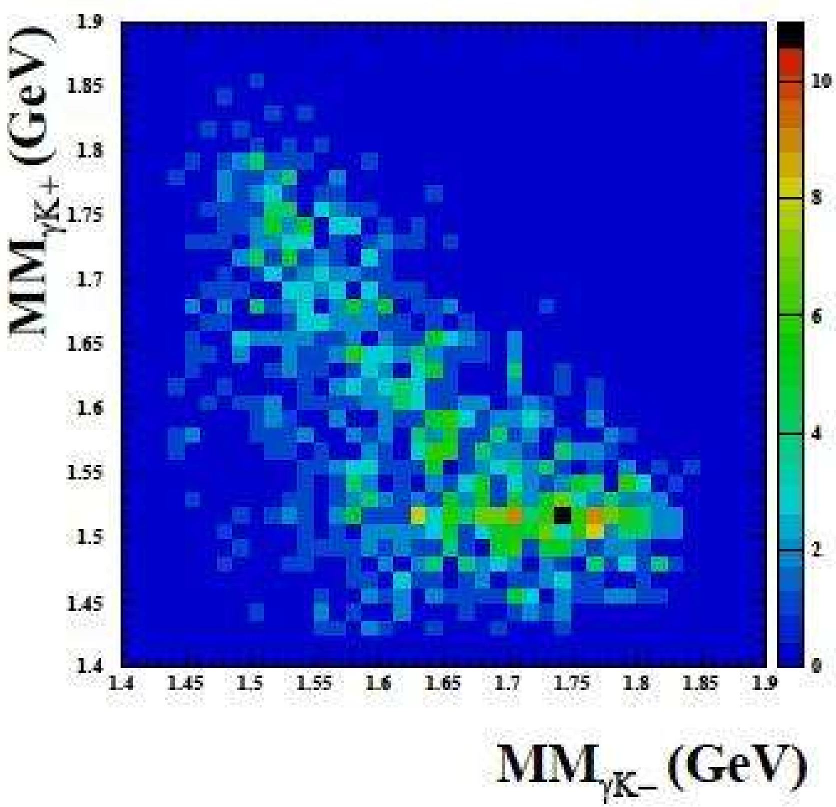
$\Lambda^*(1670)$ **MC**

- **After applying the same cuts**



MM(γ,K^+) vs MM(γ,K^-)

LH2



LD2