



Update on the Θ^+ study at LEPS

Takashi NAKANO
(RCNP, Osaka University)

Outline

- Introduction
- Data analysis and results
- Summary and Prospects

NNR2009 @ Edinburgh, June 9th, 2009.

Experimental status

- Not seen in the most of the high energy experiments: The production rate of $\Theta^+/\Lambda(1520)$ is less than 1%.

 - Production rate depends on reaction mechanism.

- No signal observation in CLAS γp , KEK-PS (π^-, K^-) , (K^+, π^+) experiments.

 - K^* coupling should be VERY small.

- The width must be less than 1 MeV. (DIANA and KEK-B) reverse reaction of the Θ^+ decay: $\Theta^+ \rightarrow n K^+$

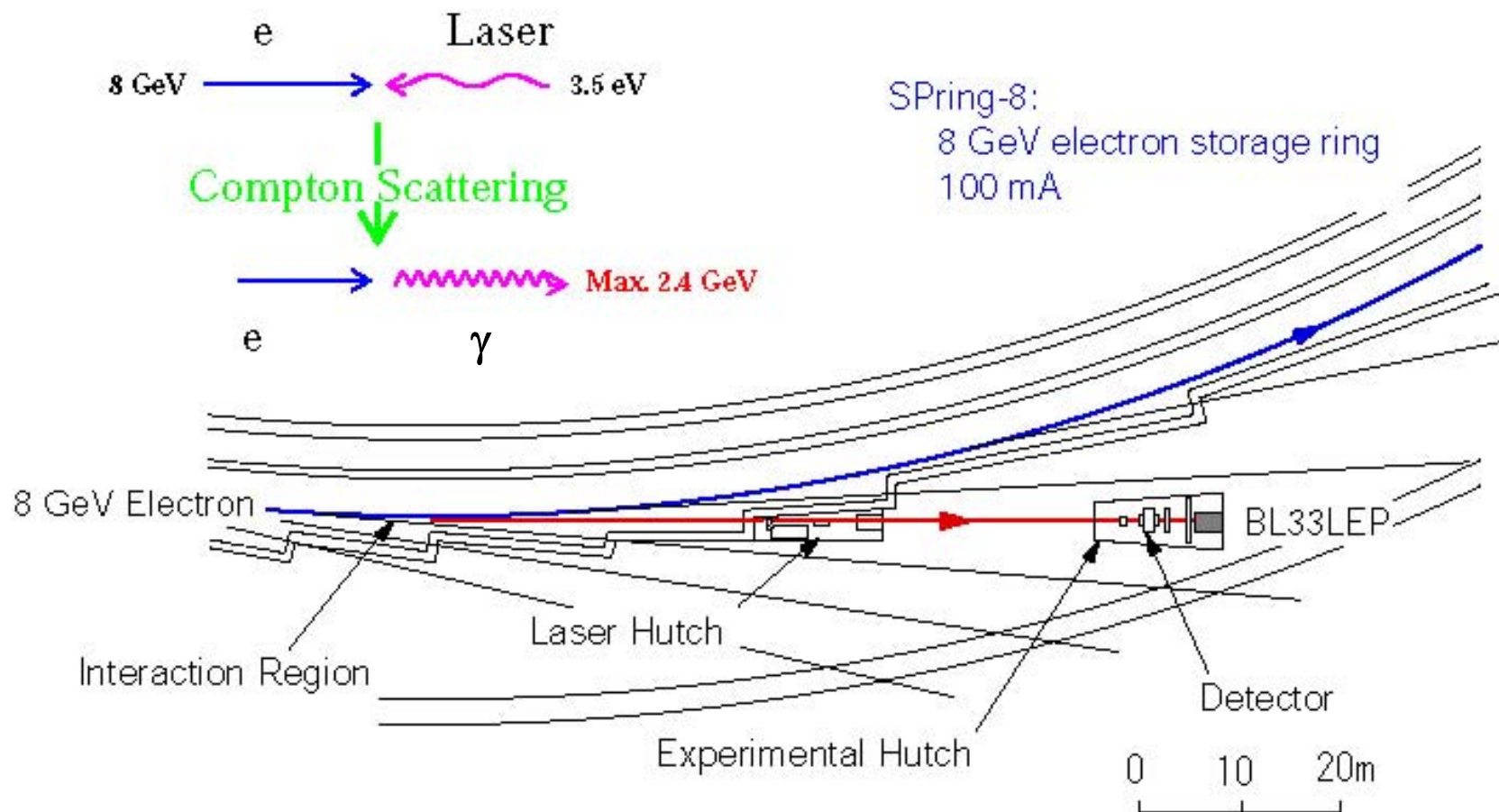
 - K coupling should be small.

- LEPS could be inconsistent with CLAS γd experiment (CLAS-g10).

 - Strong angle or energy dependence.

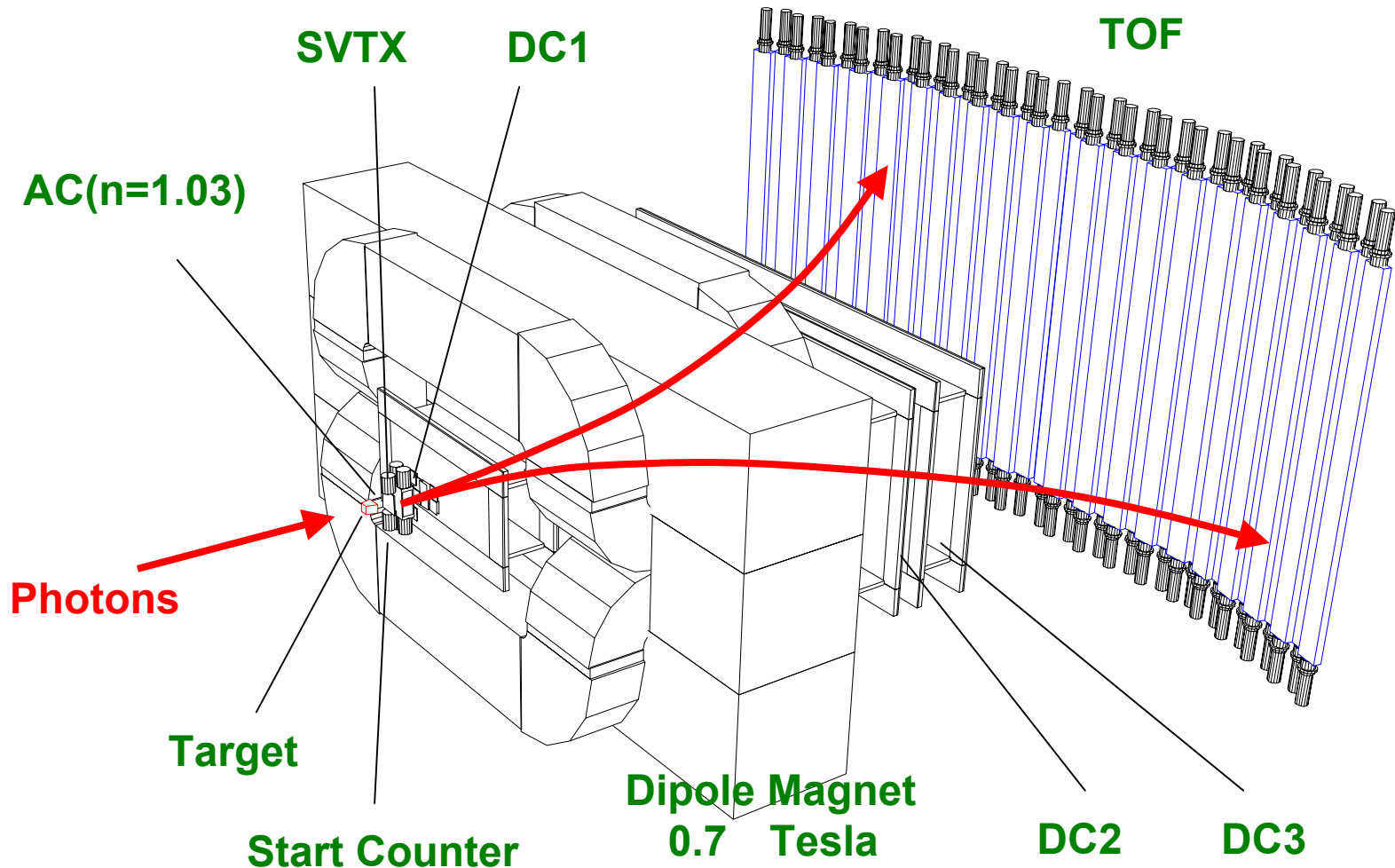
LEPS beamline

in operation since 2000

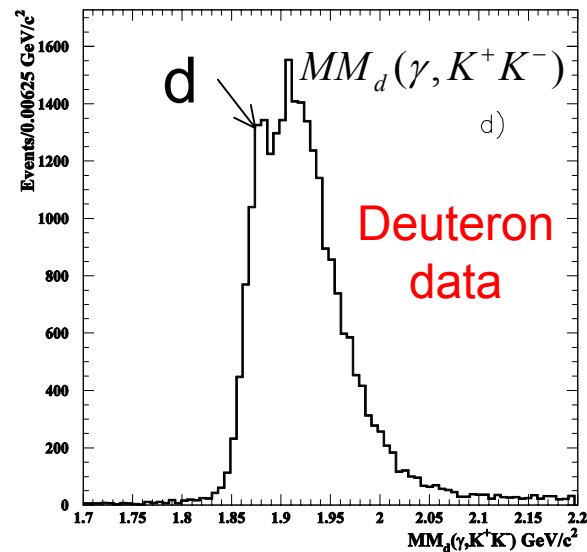
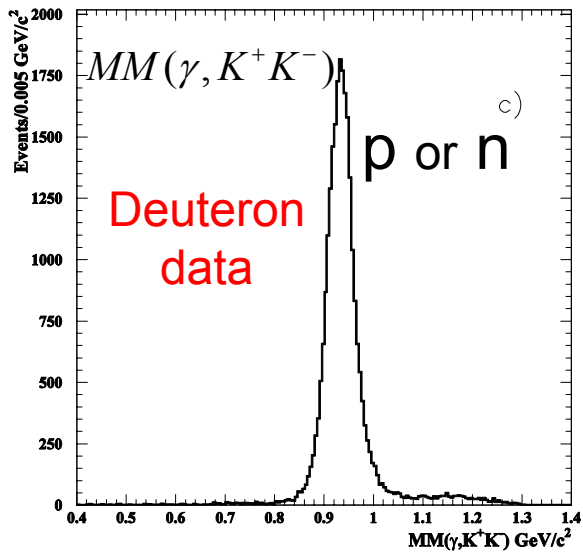
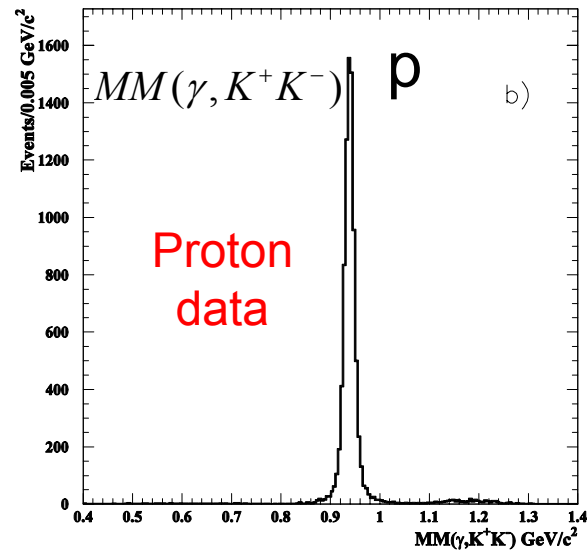
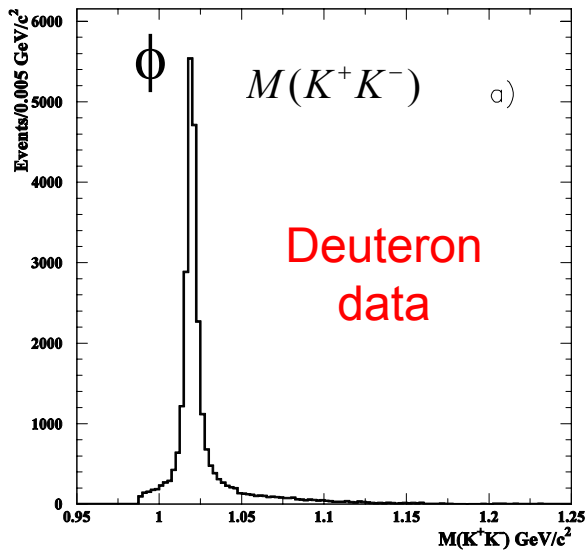


LEPS spectrometer

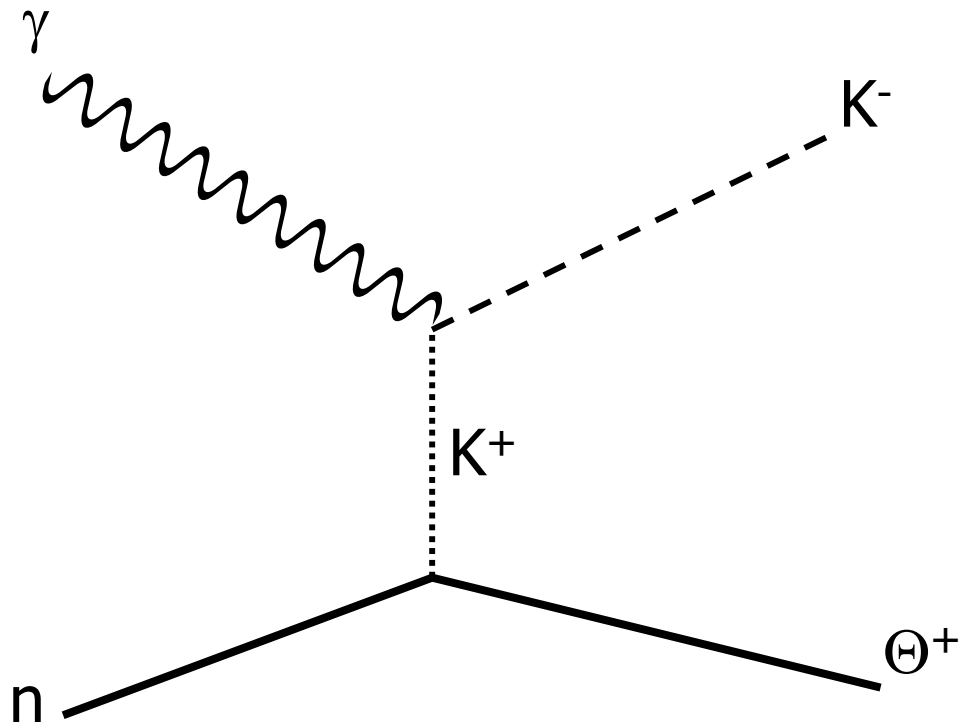
Charged particle spectrometer with **forward acceptance**
PID from **momentum** and **time-of-flight** measurements



Invariant and missing masses in (γ, K^+K^-) reactions

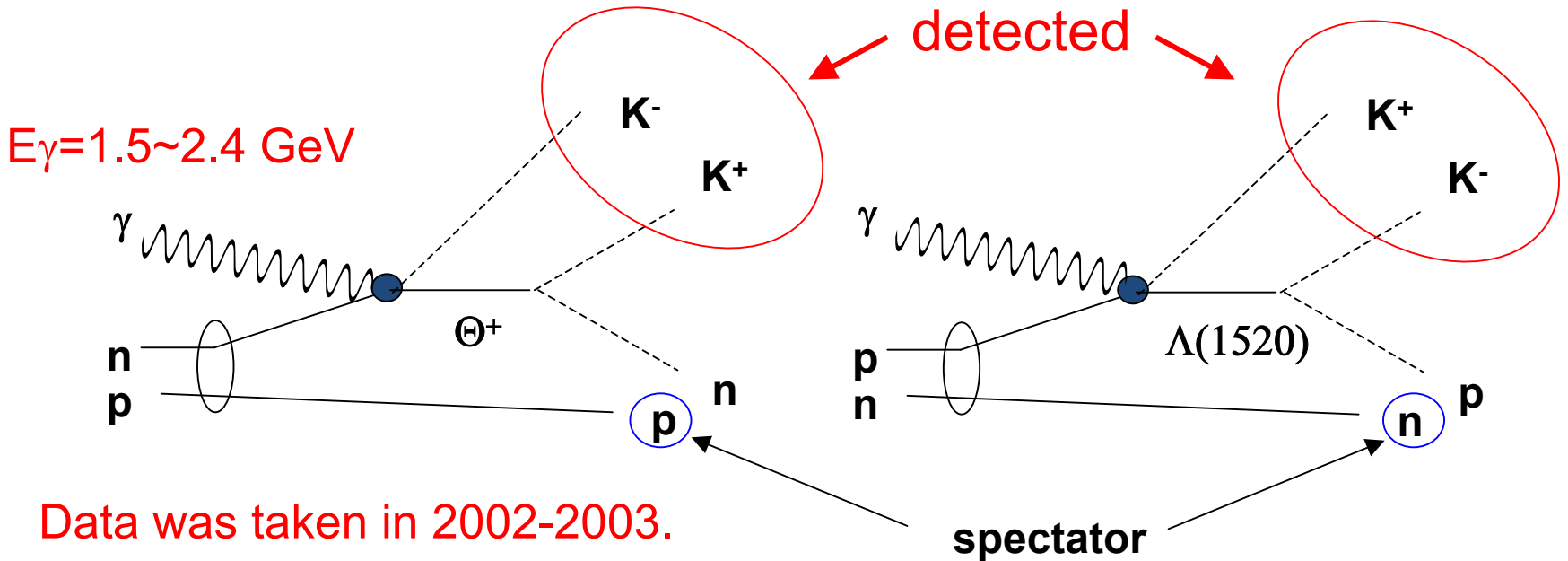


The reaction studied at LEPS



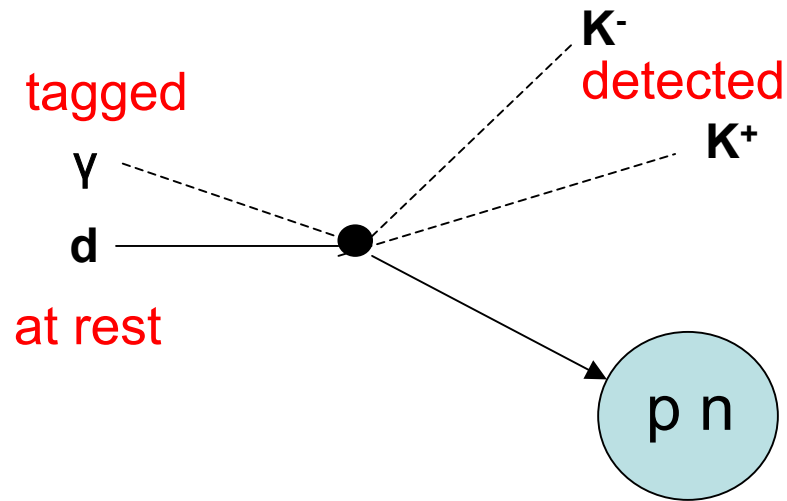
We correct and make use of Fermi motion of a neutron.

Quasi-free production of Θ^+ and $\Lambda(1520)$



- Both reactions are quasi-free processes.
- Fermi-motion should be corrected.
- Existence of a spectator nucleon characterize both reactions.

Minimum Momentum Spectator Approximation



We know 4 momentum of pn system

**Nucleon from
decay or scattering**

$$\begin{array}{c} \downarrow \\ M_{pn} \text{ and } \vec{p}_{tot} \\ \downarrow \\ |\vec{p}_{CM}| \text{ and } \vec{v}_{pn} \end{array}$$

Direction of \vec{p}_{CM} is assumed so that the spectator can have the minimum momentum for given $|\vec{p}_{CM}|$ and \vec{v}_{CM} .

Minimum Momentum Spectator Approximation (MMSA)

$$p_{pn} = p_{\text{miss}} = p_\gamma + p_d - p_{K^+} - p_{K^-}.$$

$$p_{pn} = (E_{pn}, \vec{p}_{pn})$$

$$p_d = (m_d, 0)$$

$$M_{pn}^2 = p_{pn} \cdot p_{pn}$$

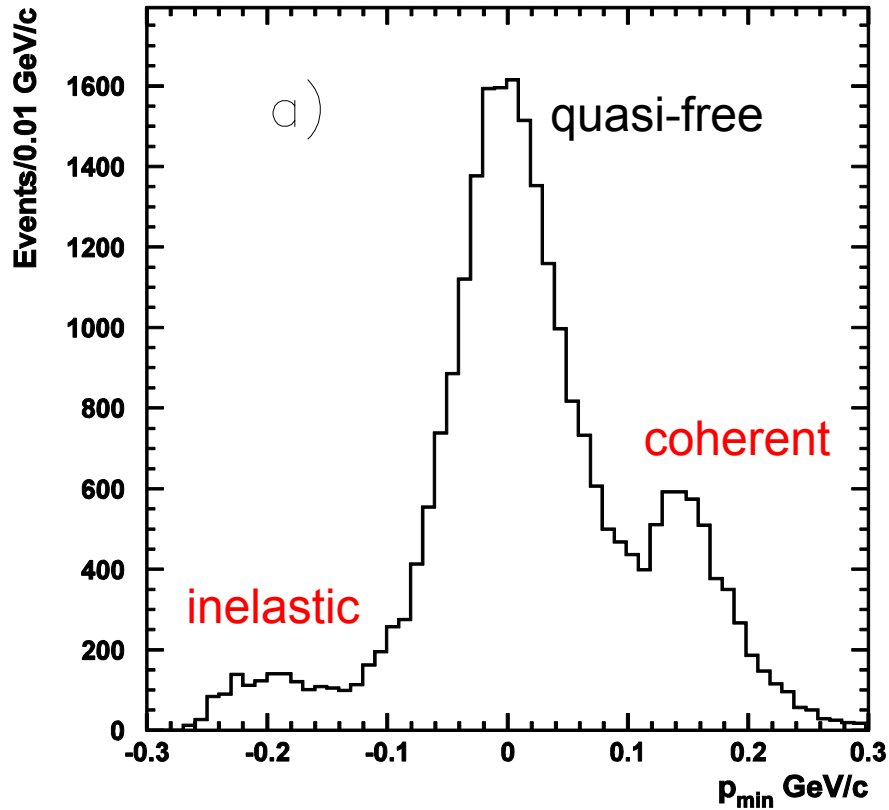
$$P_{CM} = \frac{\sqrt{(M_{pn} + m_p + m_n)(M_{pn} - m_p + m_n)(M_{pn} + m_p - m_n)(M_{pn} - m_p - m_n)}}{2M_{pn}}$$

minimum
momentum

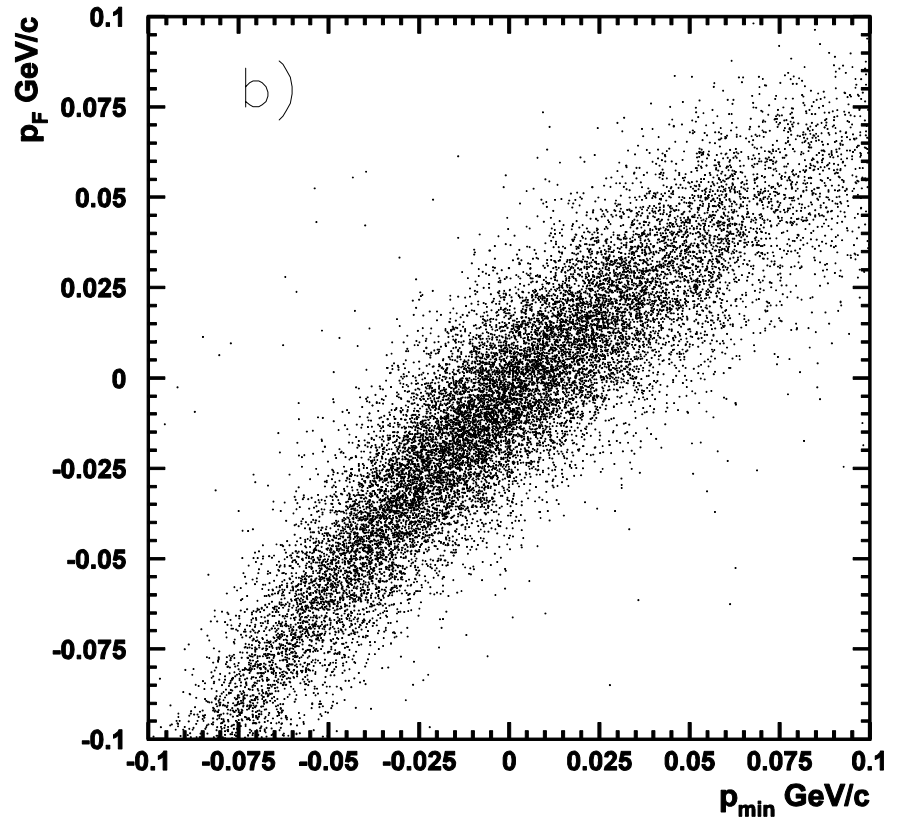
$$p_{\min} = -P_{CM} \cdot \frac{E_{\text{miss}}}{M_{pn}} + \sqrt{P_{CM}^2 + m_N^2} \cdot \frac{|\vec{p}_{\text{miss}}|}{M_{pn}},$$

$$p_{\text{res}} = |\vec{p}_{\text{miss}}| - p_{\min} \quad p_n = p_{\text{res}} \cdot \frac{|\vec{p}_{\text{miss}}|}{|\vec{p}_{\text{miss}}|}$$

2-fold roles of MMSA



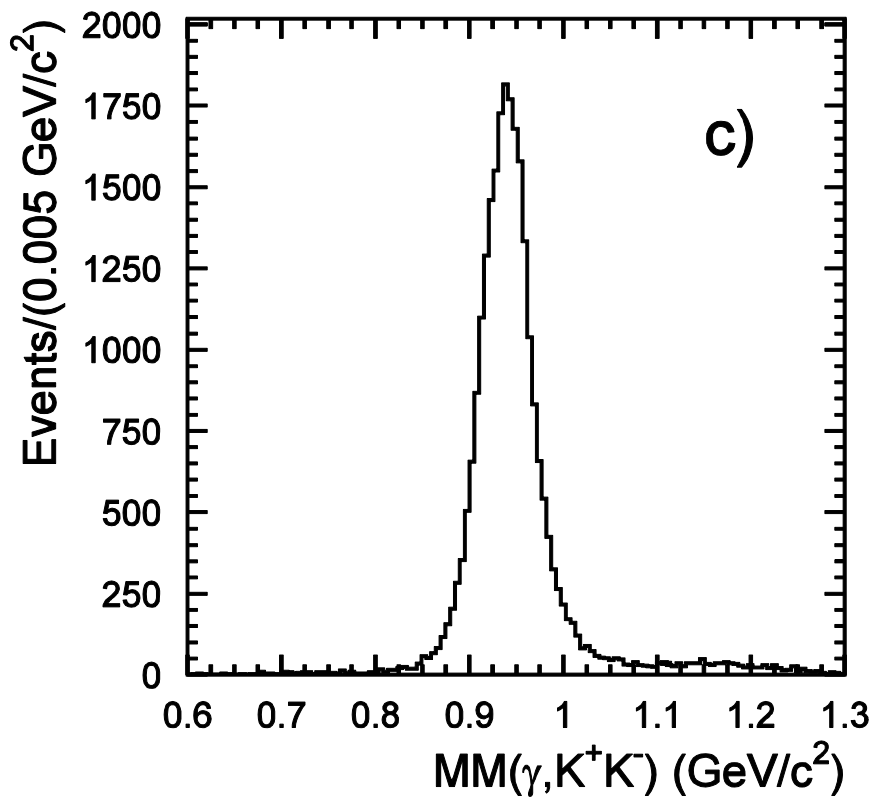
Clean-up



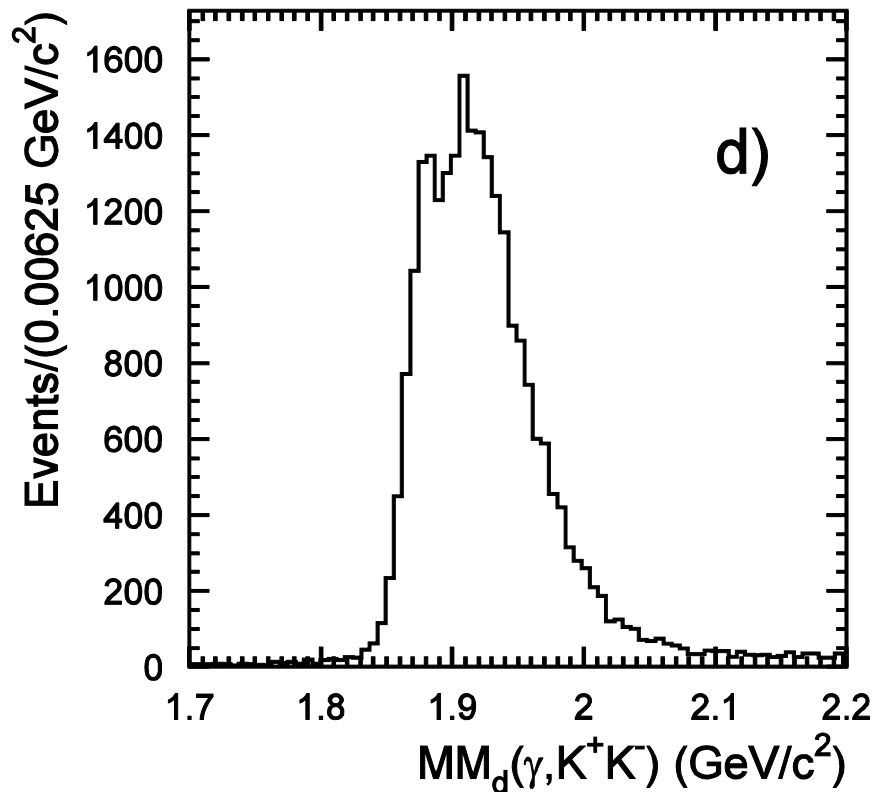
Estimation of p_F

Missing masses before p_{\min} cut

$MM(\gamma, K^+ K^-)$

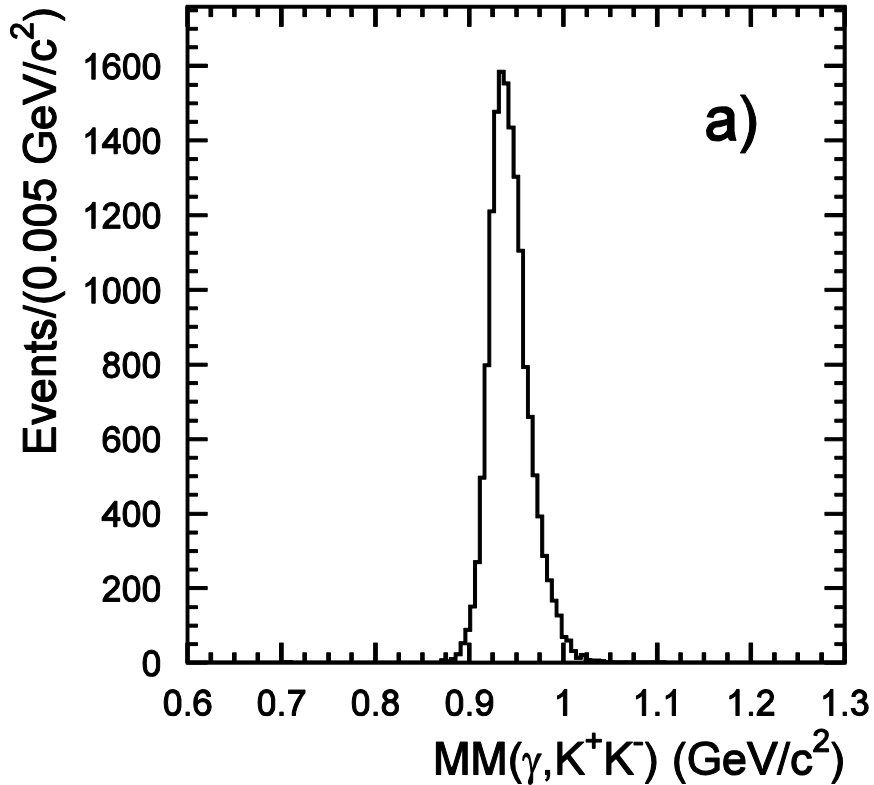


$MM_d(\gamma, K^+ K^-)$

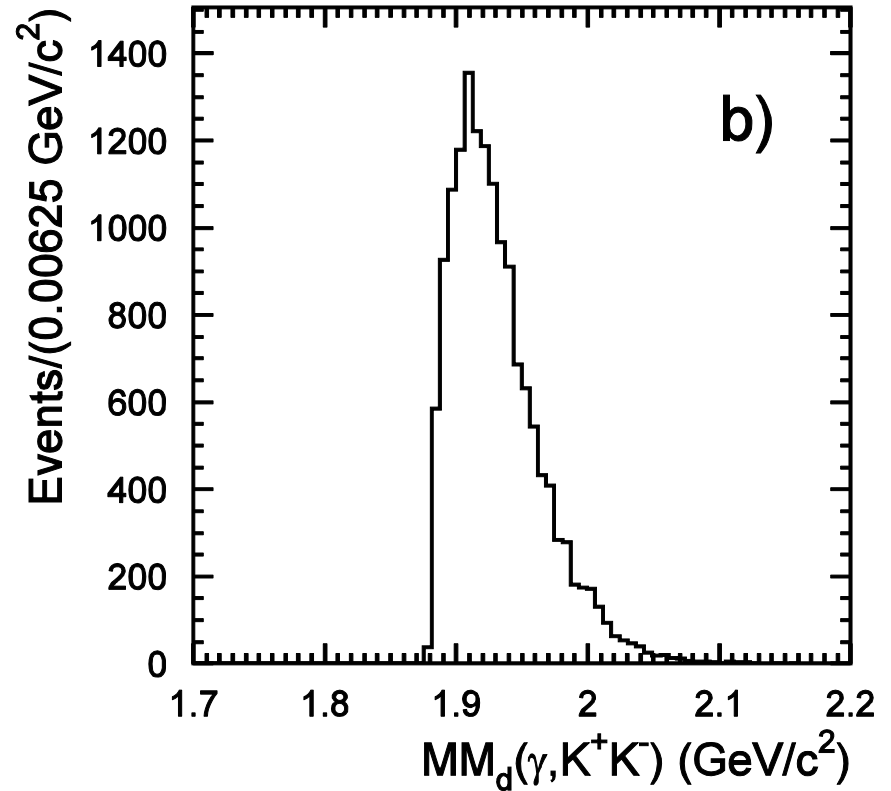


Missing masses after p_{\min} cut

$MM(\gamma, K^+ K^-)$



$MM_d(\gamma, K^+ K^-)$

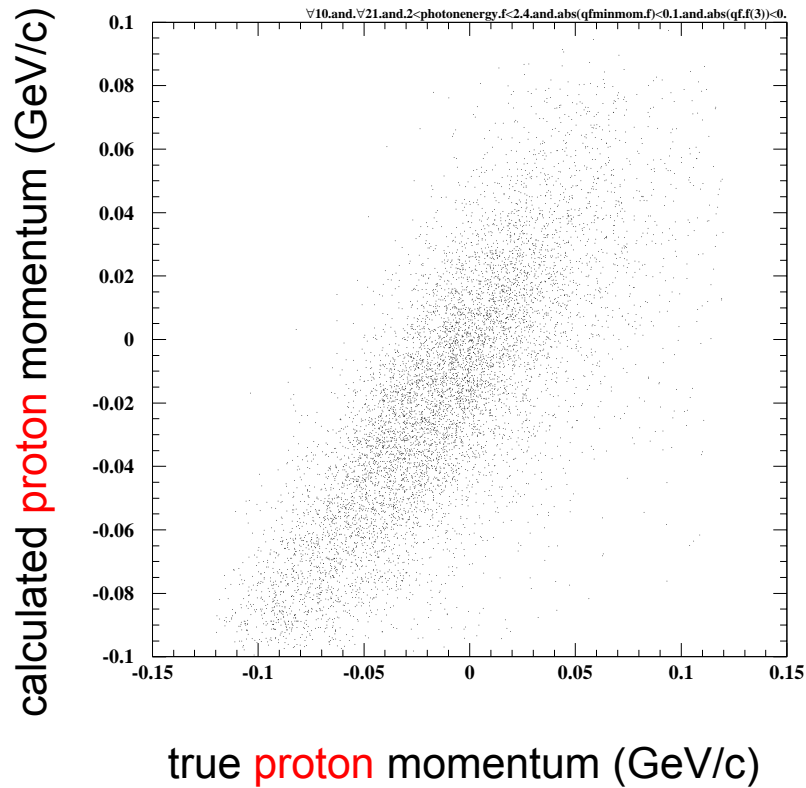


Inelastic and coherent events are removed.

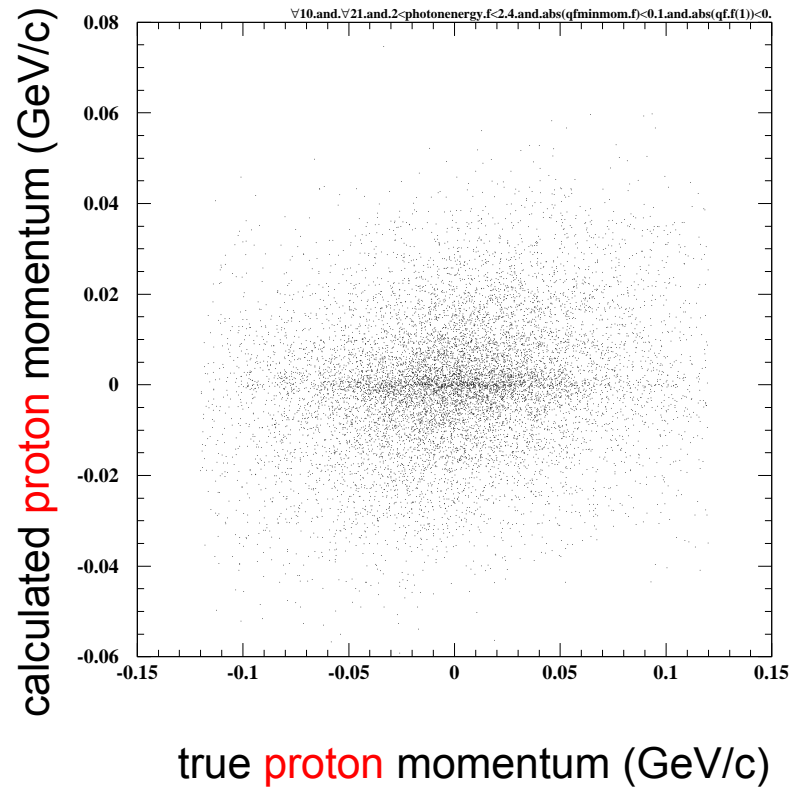
Fermi momentum

MC data of $\gamma n(\mathbf{p}) \rightarrow K^- \Theta^+(\mathbf{p}) \rightarrow K^- K^+ n(\mathbf{p})$ with Fermi motion

z component

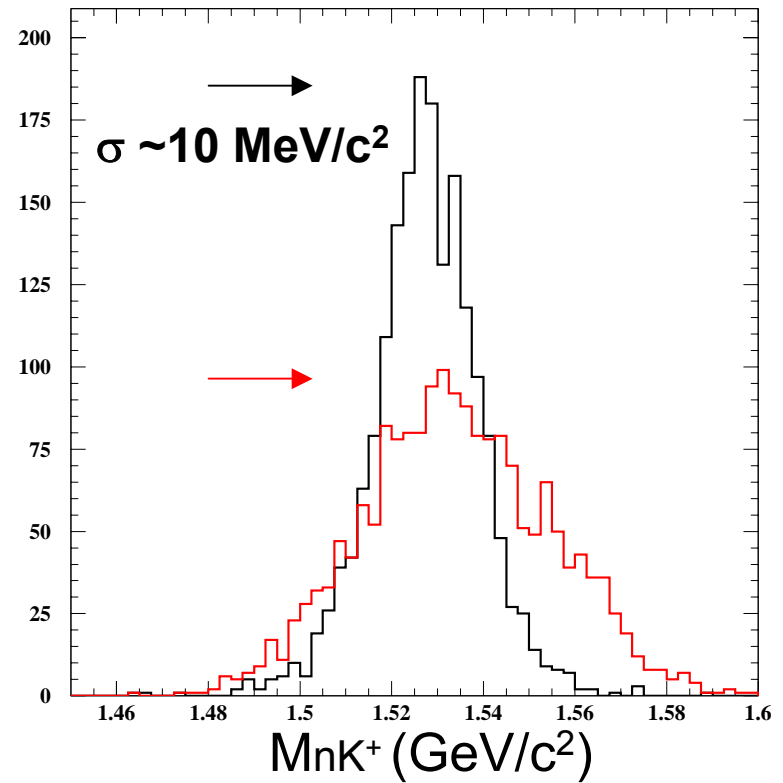
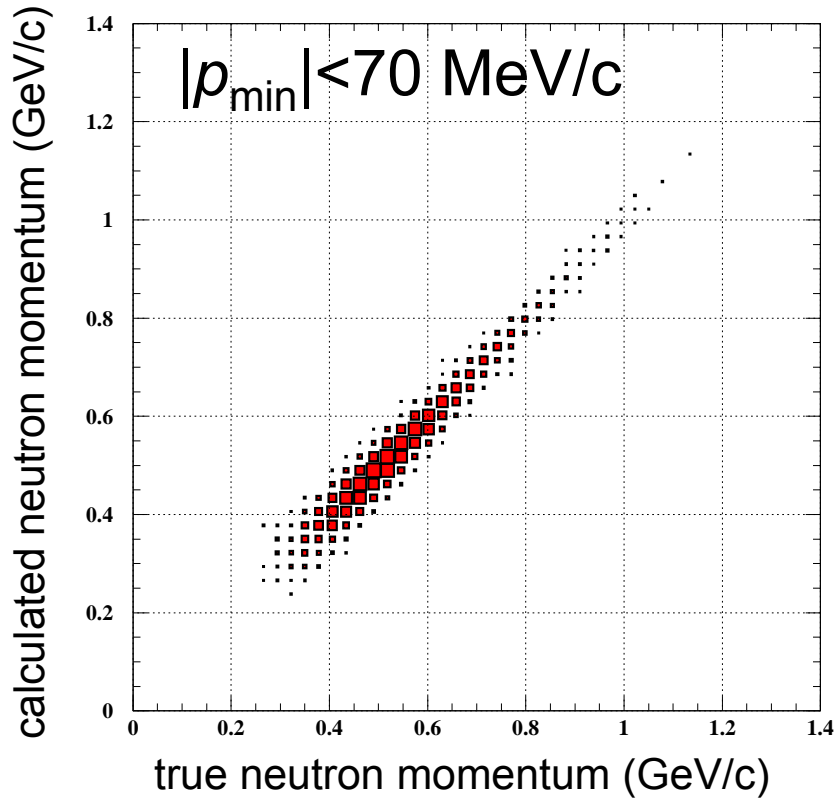


x component



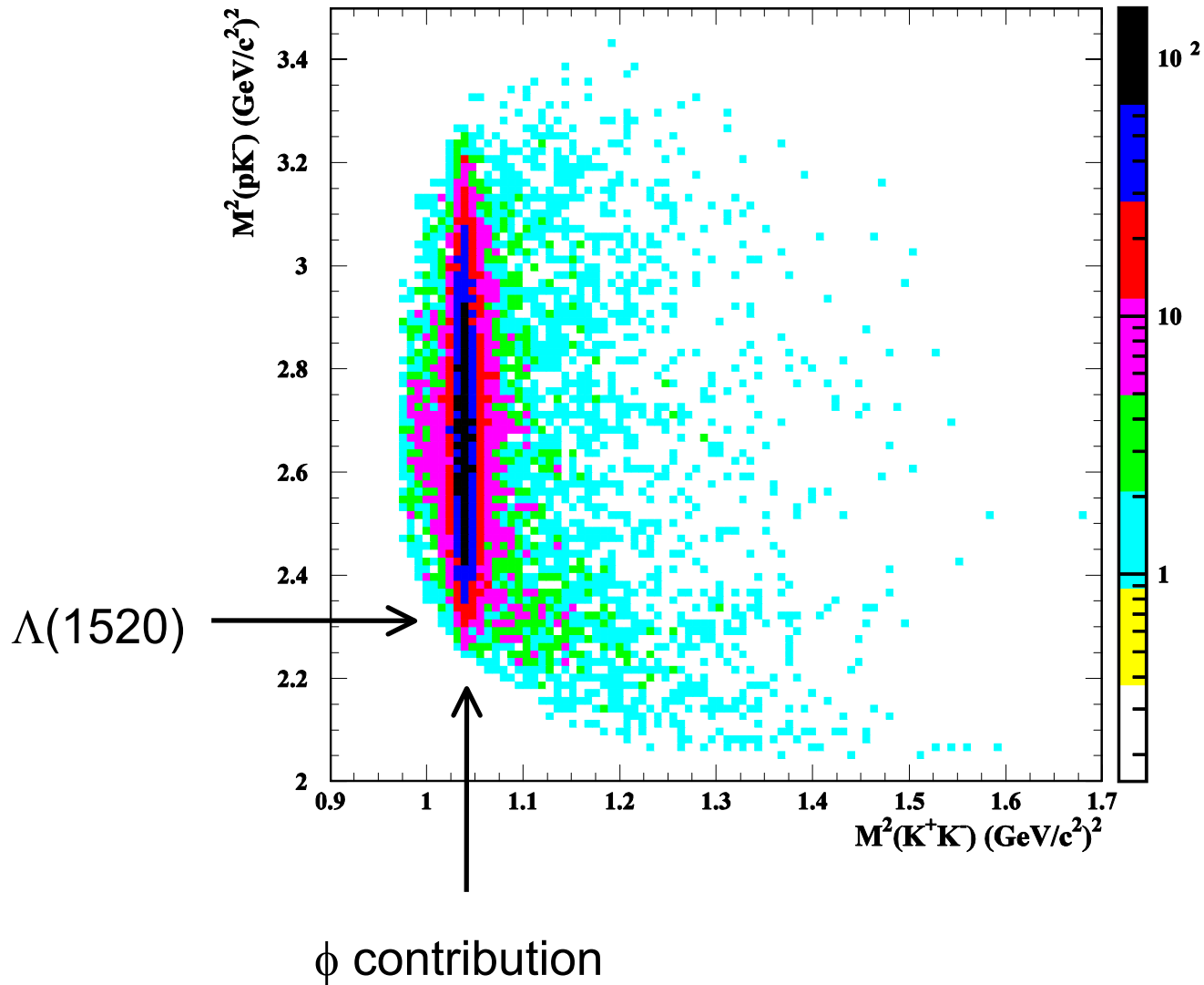
Better M_{nK^+} mass resolution with MSSA

MC data of $\gamma n \rightarrow K^- \Theta^+ \rightarrow K^- K^+ n$ with Fermi motion

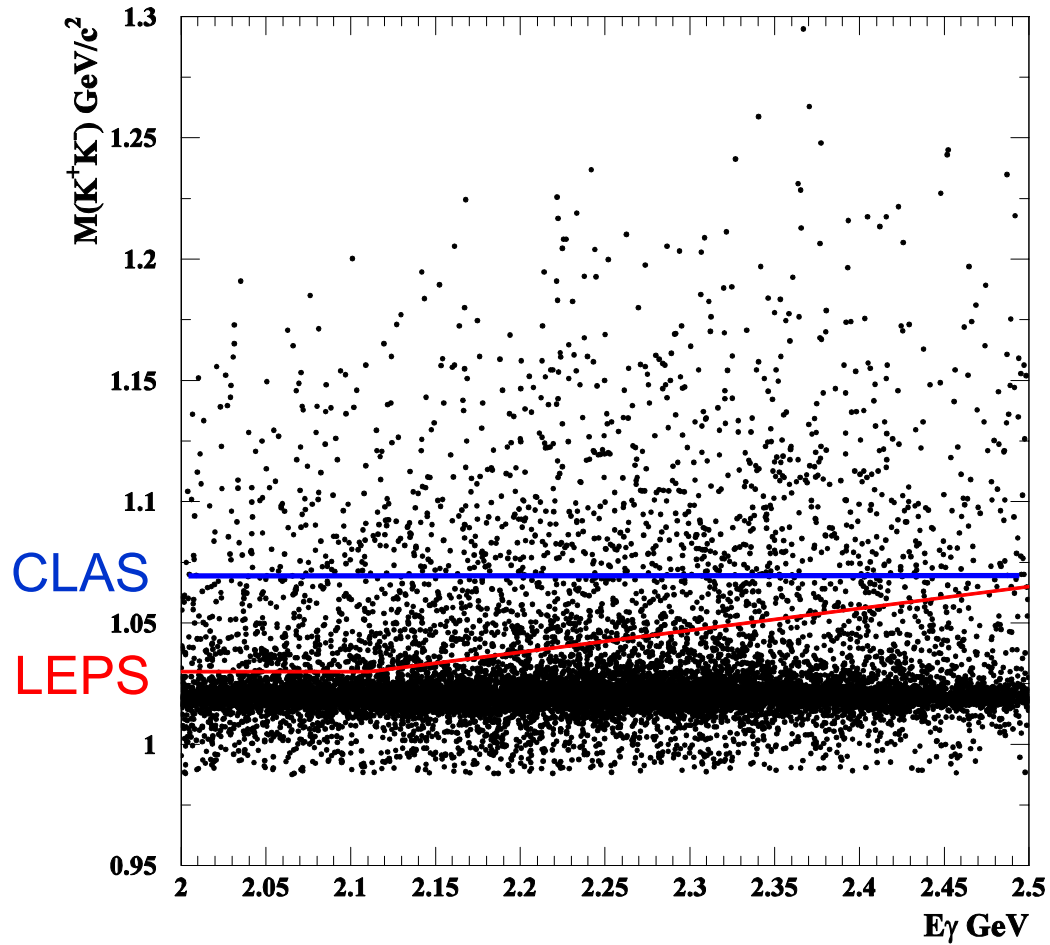


M_{nK^+} mass resolution is improved by a factor of 2 compared to a simple (γ, K^-) missing mass resolution, where the initial neutron is assumed to be at rest.

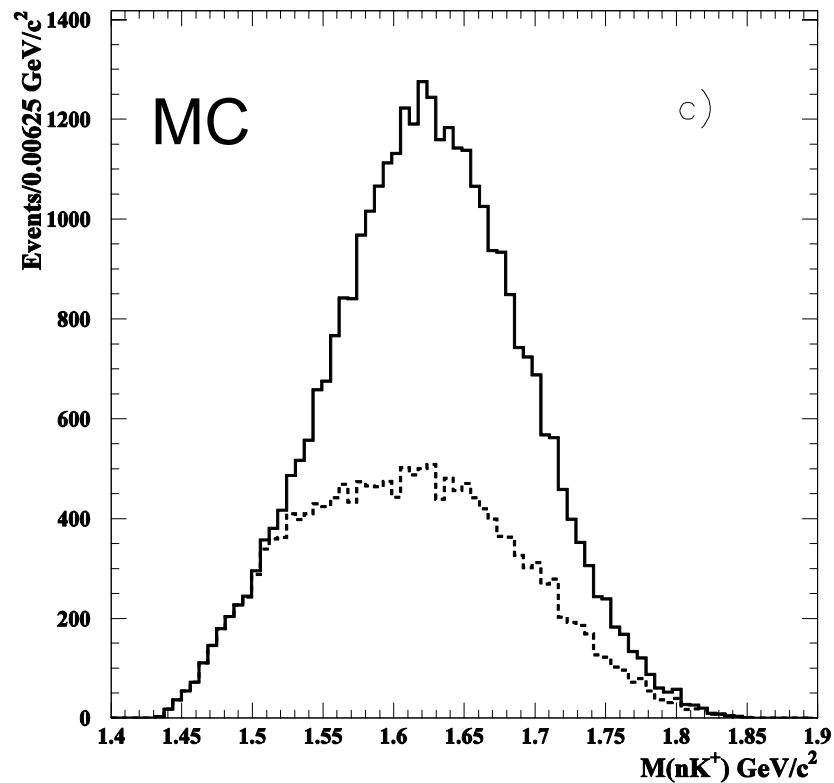
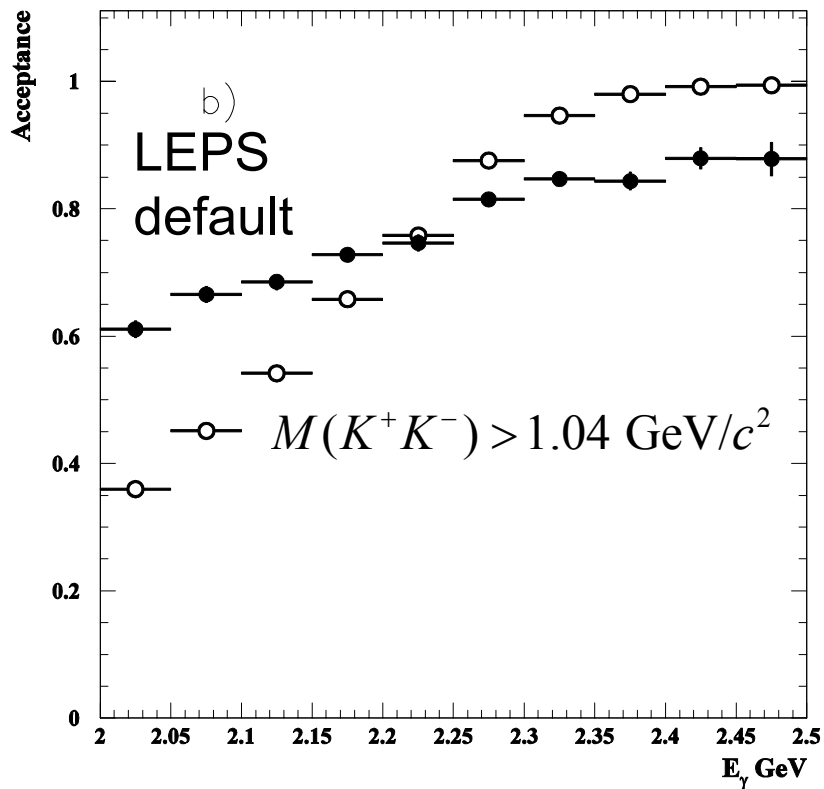
$M^2(pK^-)$ vs $M^2(K^+K^-)$



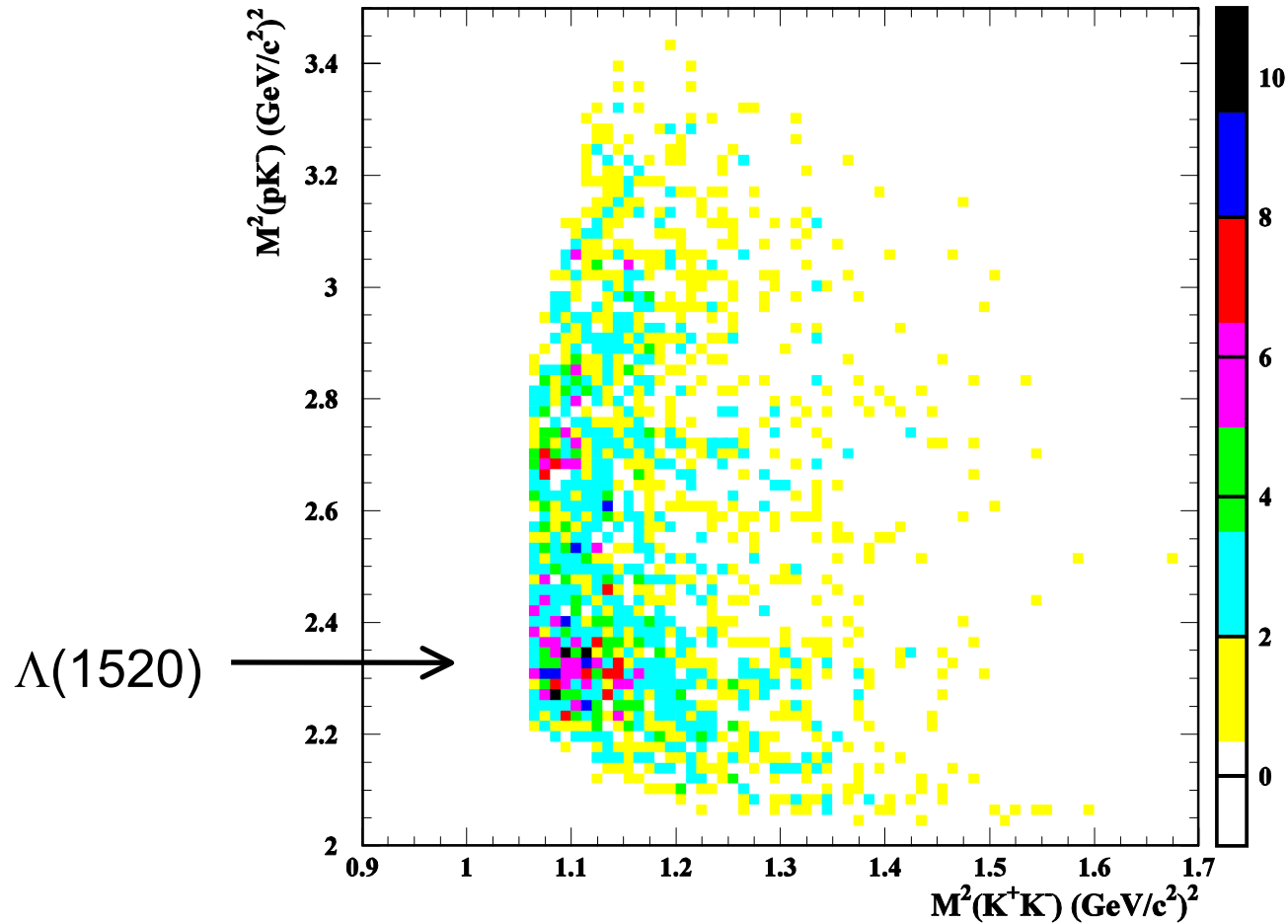
LEPS and CLAS ϕ exclusion cut condition



Signal acceptance of ϕ exclusion cut



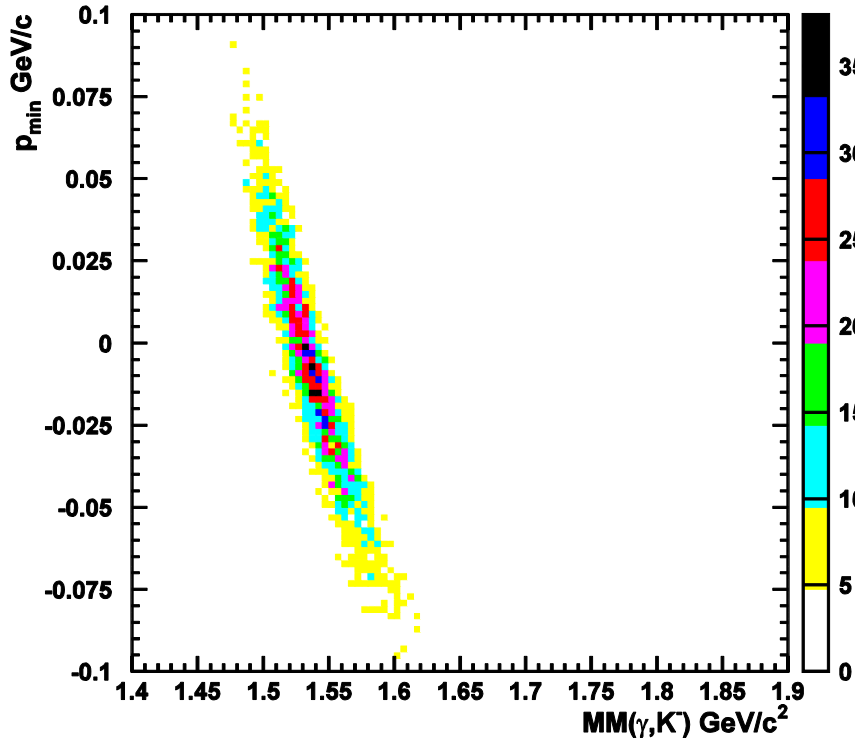
$M^2(pK^-)$ vs $M^2(K^+K^-)$ after ϕ exclusion cut



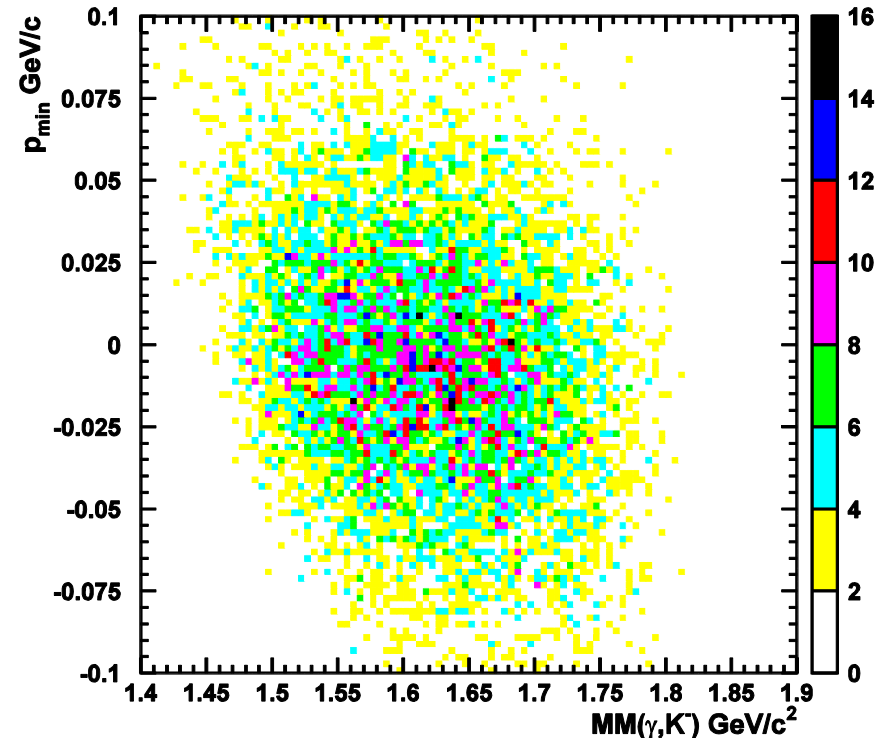
$\Lambda(1520)$ events are not concentrated near the cut boundary.

What characterize the signal and background?

a)



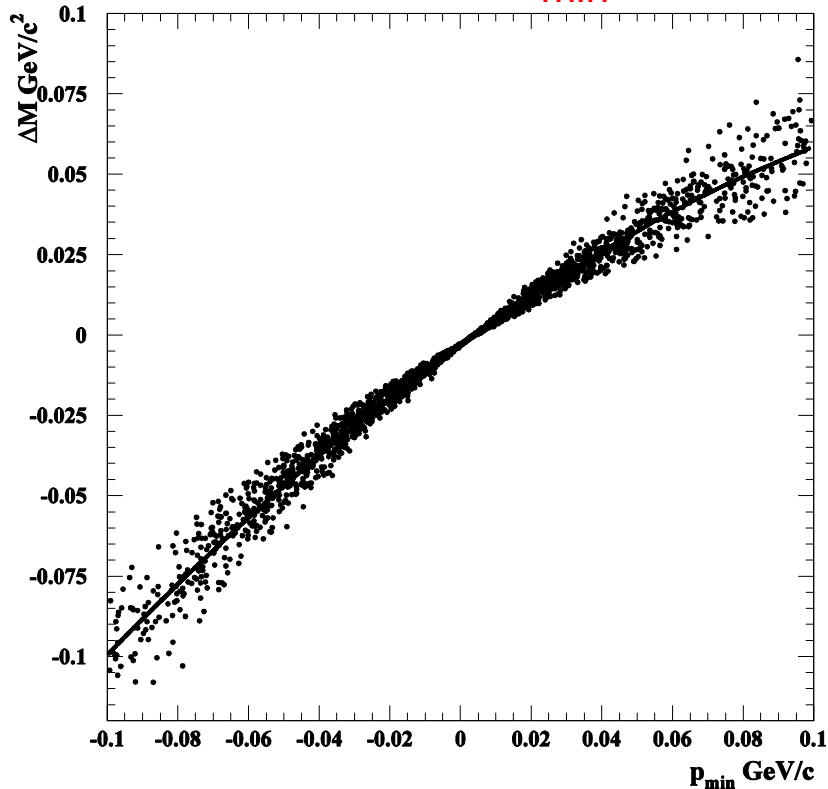
b)



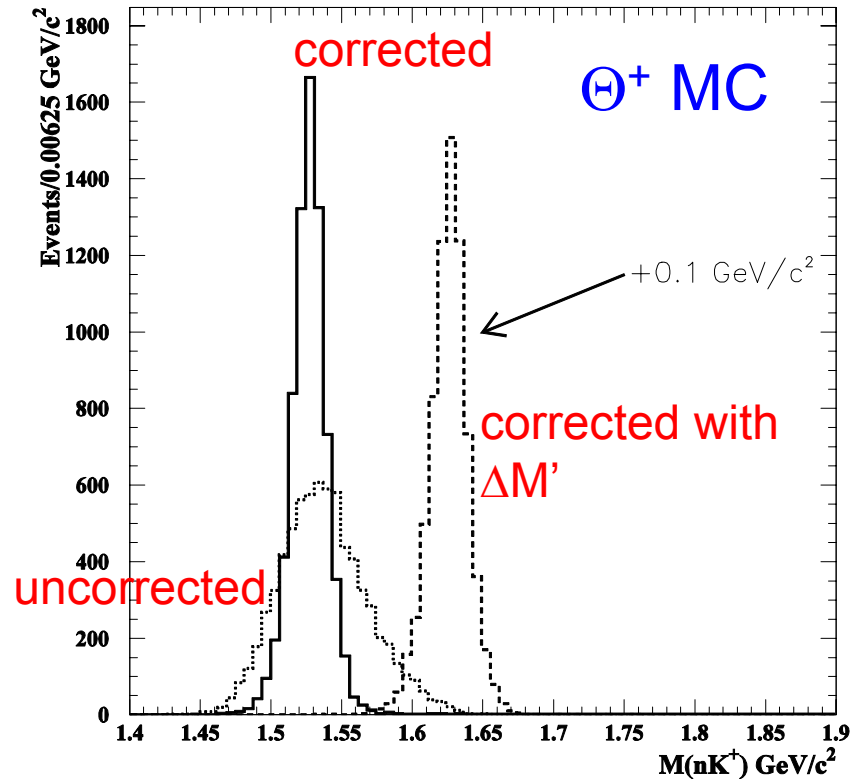
p_{\min} for background events are almost determined by Fermi motion (deuteron wave function).

Approximated $M(NK)$ calculation

ΔM vs. p_{\min}



Fermi-motion effect

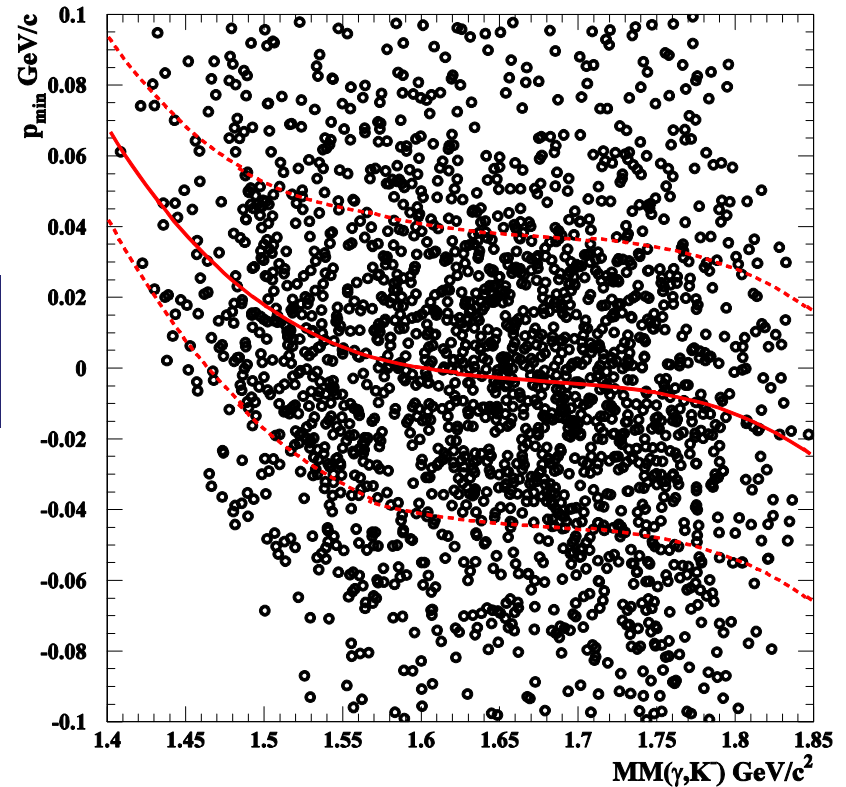
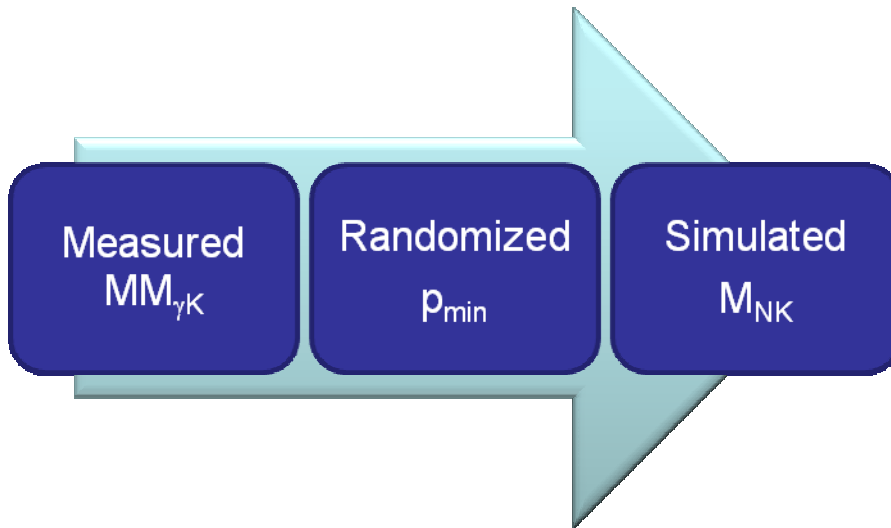


$$M(NK^m) = MM(\gamma, K^\pm) + \Delta M'(p_{\min})$$

$MM(\gamma, K^\pm)$ only depends on E_γ and p_{K^\pm} .

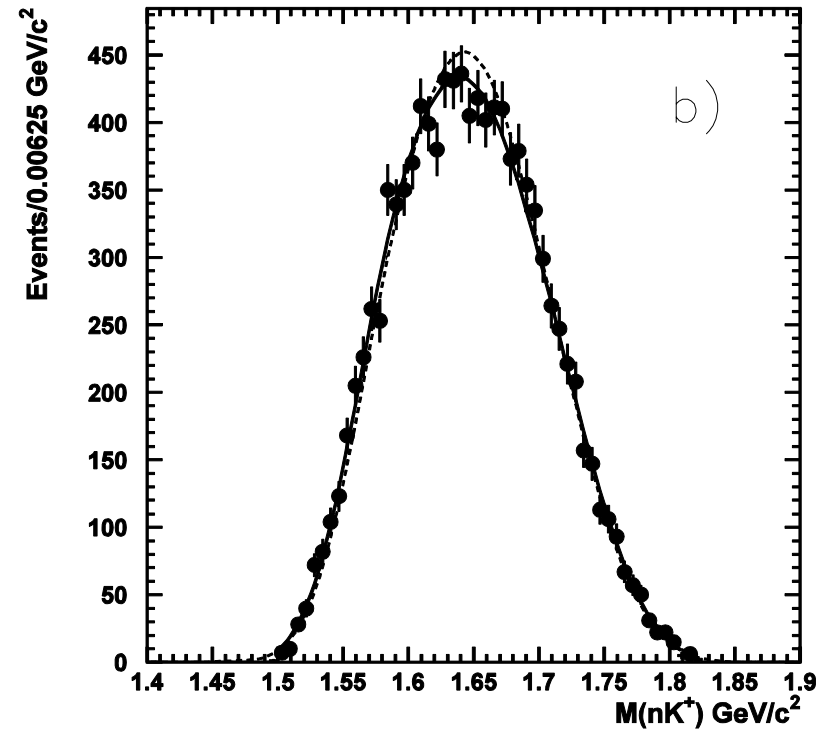
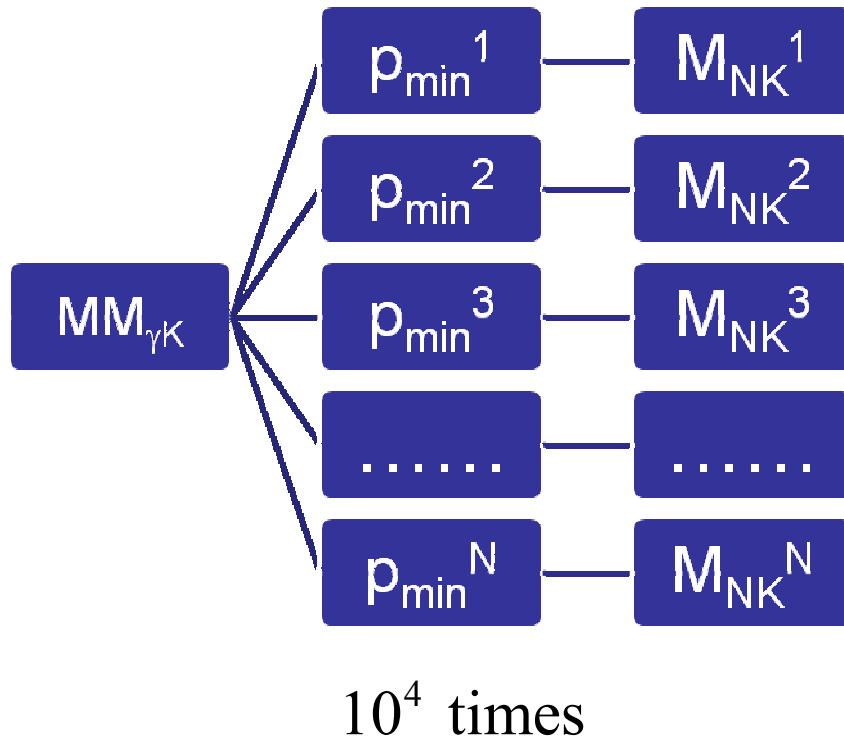
Randomized Minimum Momentum Method

“Guess a minimum momentum from a missing mass.”



Mean and σ of p_{\min} depends on $MM(\gamma, K)$, but the dependence is weak.

Statistical improvement with the RMM



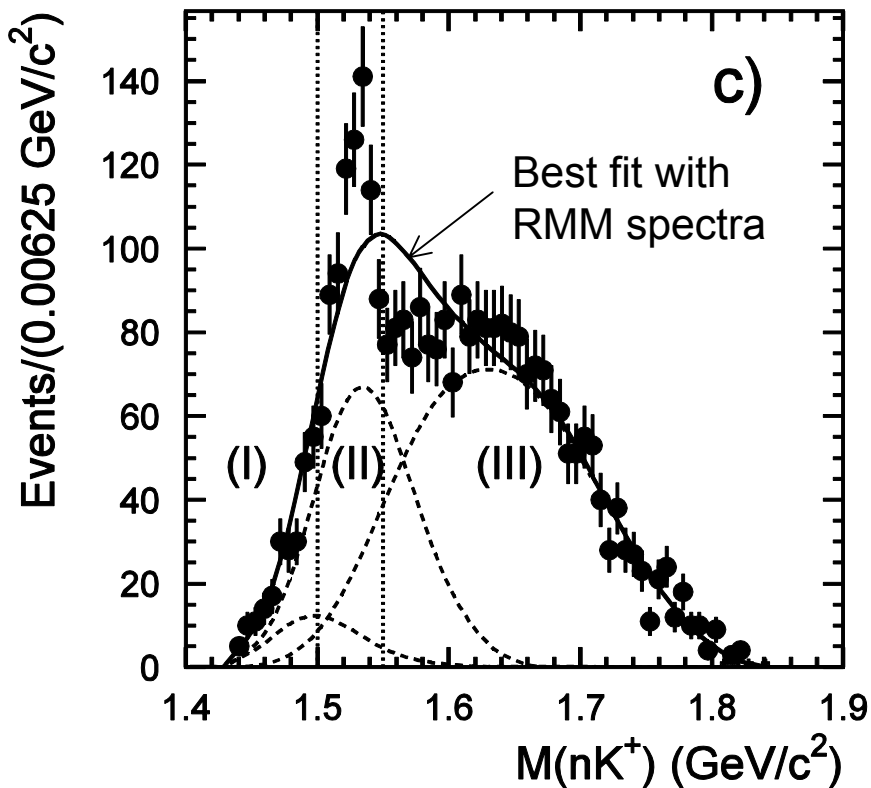
Fit to a single RMM spectrum (dashed line) and 3 RMM spectra (solid line).

How to estimate the significance?

1. Fit M(NK) distribution to mass distributions generated by the RMM with $MM(\gamma, K)$ and randomized p_{\min} .
2. Fit M(NK) distribution to mass distributions with signal contributions ($\Lambda(1520)$ or Θ^+) represented by a Gaussian function with a fixed width (σ).
3. The significance is estimated from the difference in log likelihood ($-2\ln L$) (close to χ^2 for large N) with the change in the number of degrees of freedom taken into account ($\Delta ndf=2$).

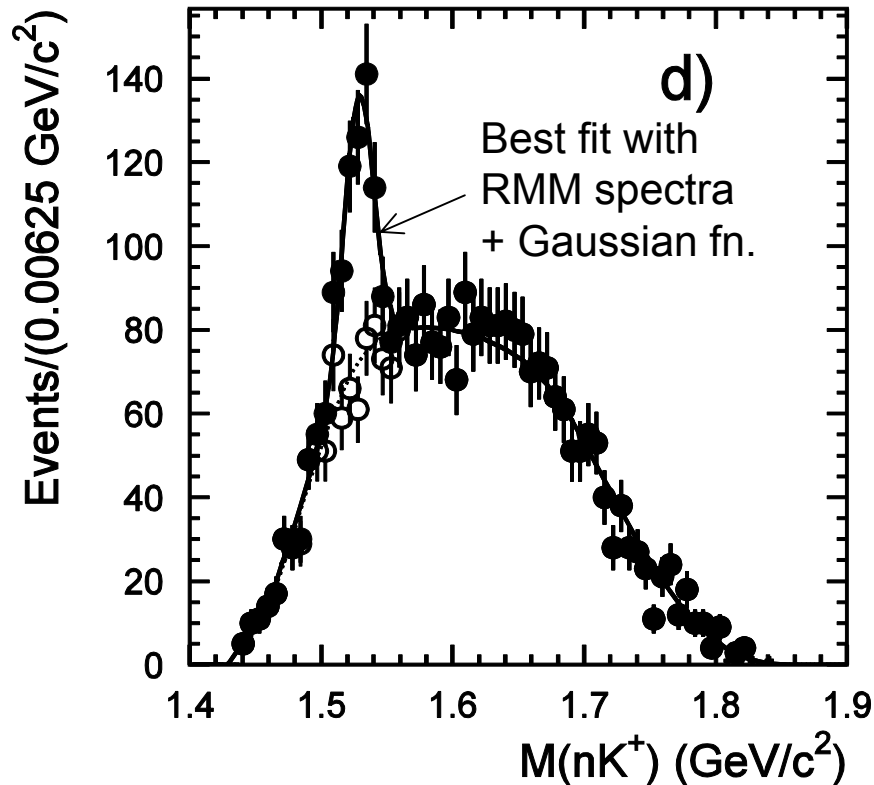
If the significance is 5σ , the probability of having the peak structure by fluctuations is $0.57 \cdot 10^{-6}$.

Test with MC data



$$-2\ln L = 114.6 \text{ for } ndf=61$$

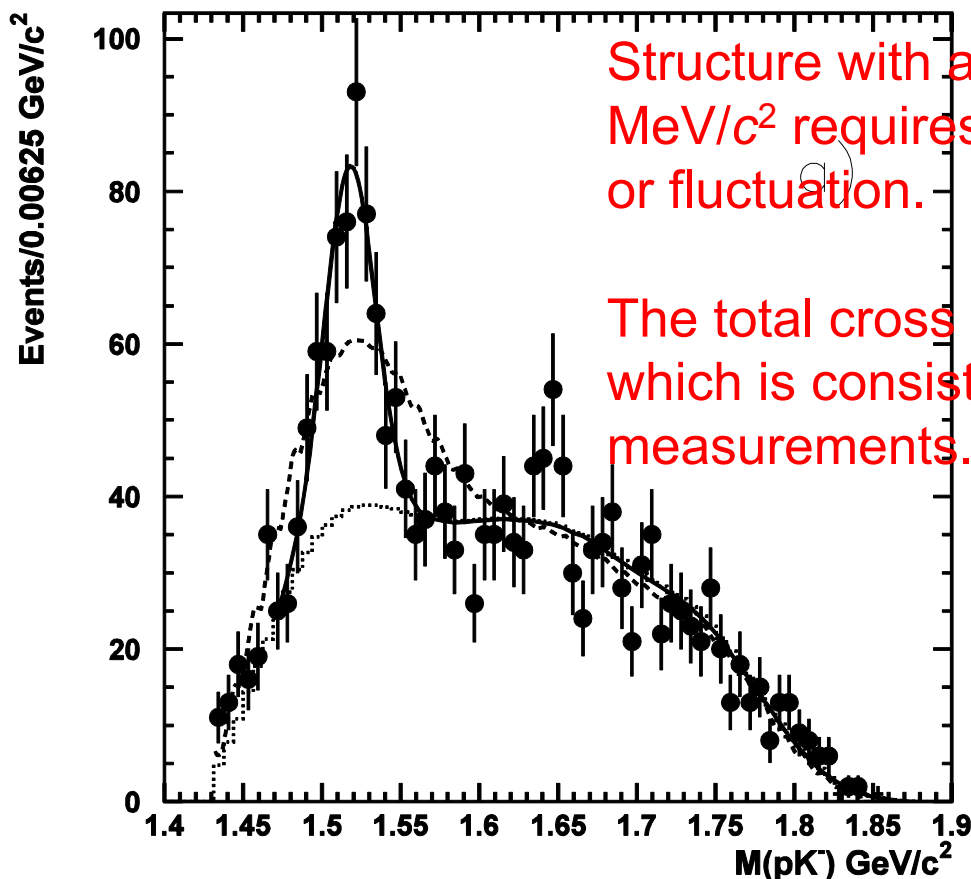
$$\Delta(-2\ln L) = 56.2 \text{ for } \Delta ndf=2 \longrightarrow 7.2\sigma$$



$$-2\ln L = 58.4 \text{ for } ndf=59$$

Results of $\Lambda(1520)$ analysis

pK⁻ invariant mass with MMSA: Fermi motion effect corrected.



Structure with a width less than 30 MeV/c² requires a physics process or fluctuation.

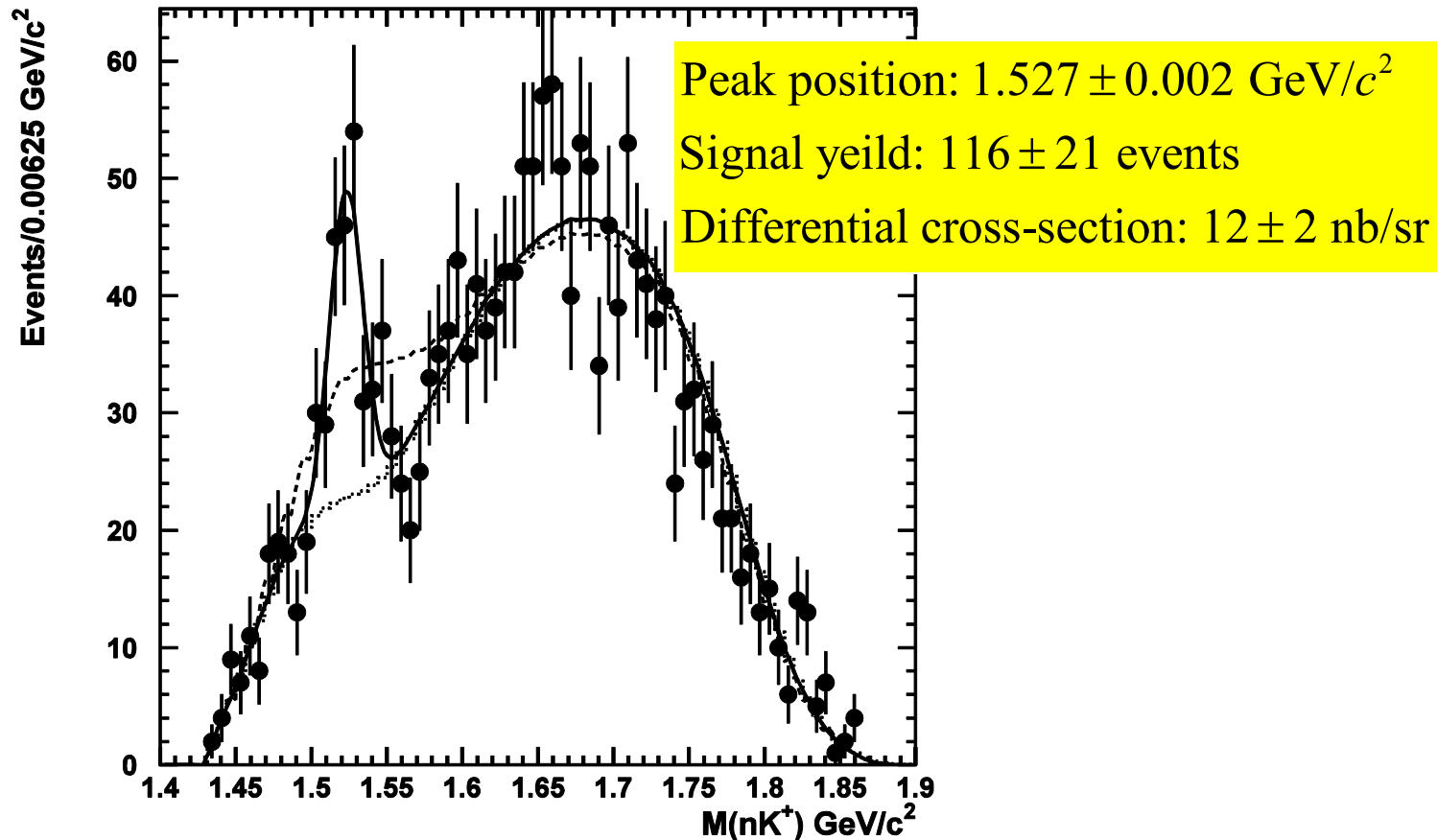
The total cross section is $\sim 1 \mu\text{b}$, which is consistent with the LAMP2 measurements.

$$\Delta(-2\ln L) = 55.1 \text{ for } \Delta ndf = 2 \longrightarrow 7.1\sigma$$

$$\text{Prob}(7.1\sigma) = 1.2 \times 10^{-10}$$

Results of Θ^+ analysis

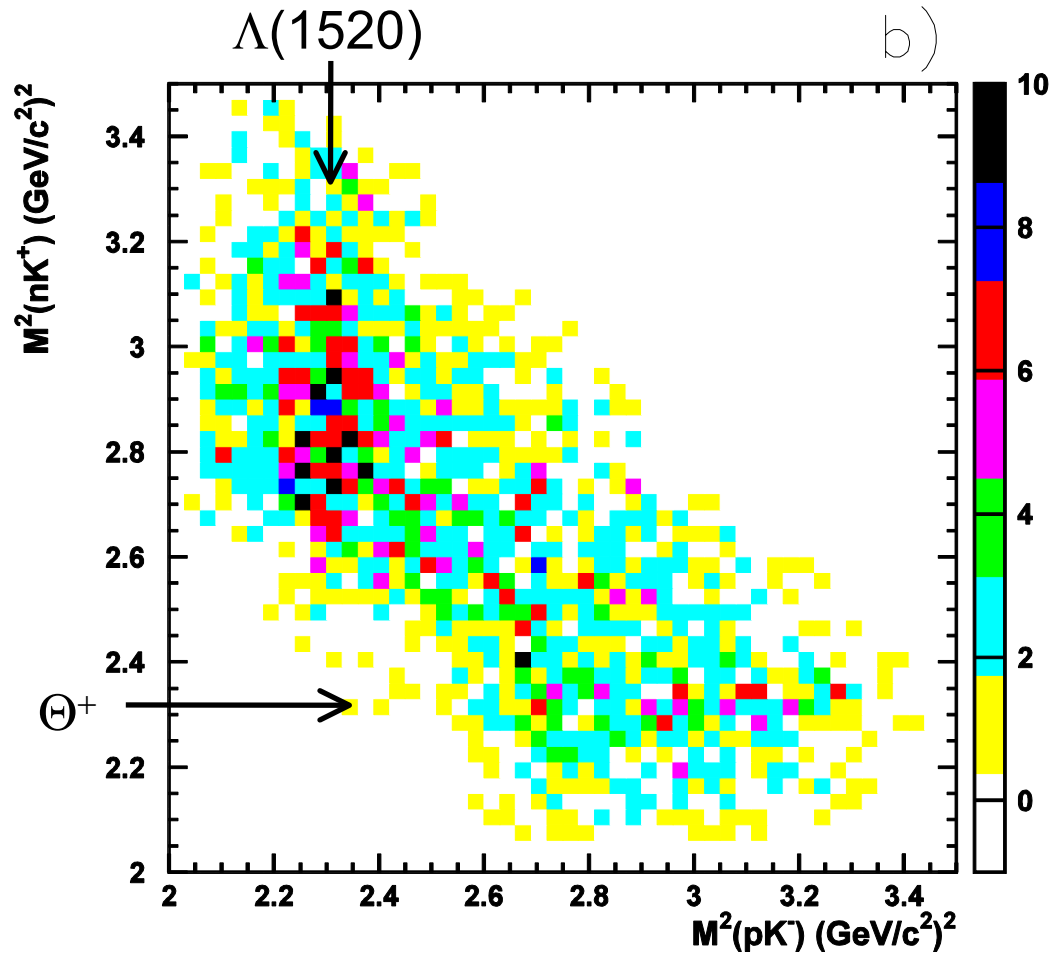
Simple (part) missing mass SN Correction effect. Fermi motion effect.



“The narrow peak appears only after Fermi motion correction.”

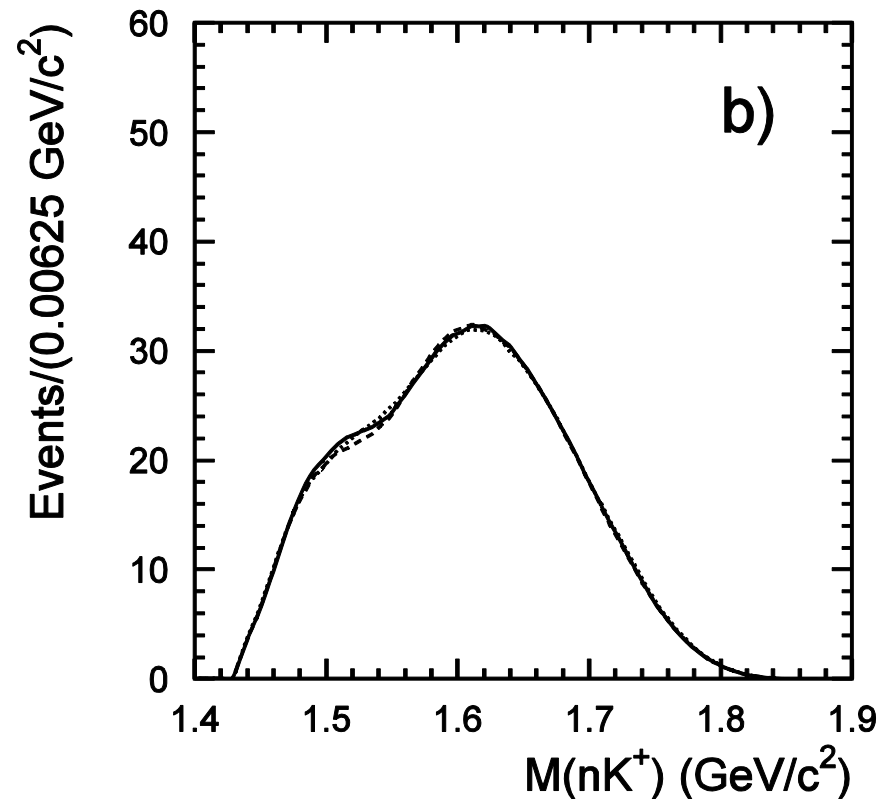
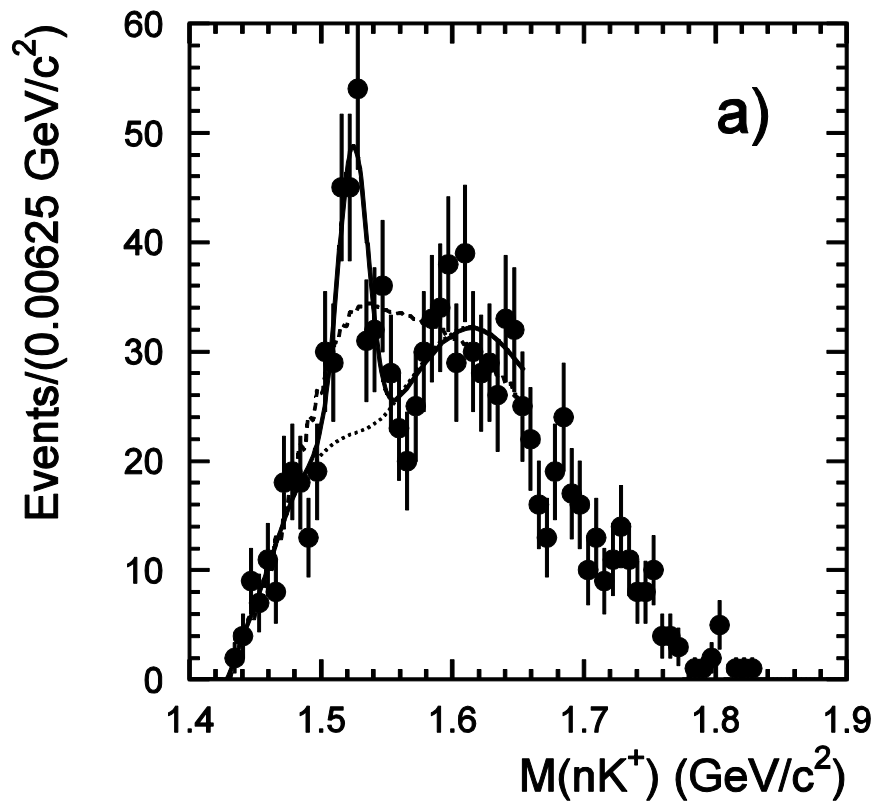
$$\Delta(-2\ln L) = 31.1 \text{ for } \Delta ndf = 2 \longrightarrow 5.2\sigma \quad \text{Prob}(5.2\sigma) = 2 \times 10^{-7}$$

$M^2(nK^+) \text{ vs. } M^2(pK^-)$



We assume a proton is a spectator for $M(nK^+)$
a neutron is a spectator for $M(pK^-)$

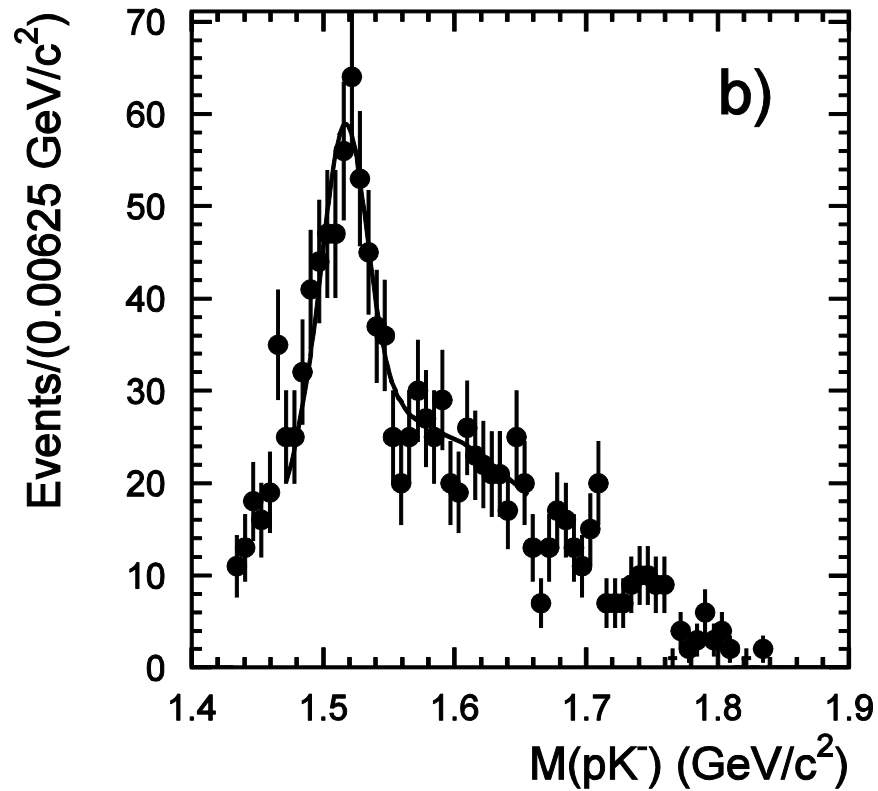
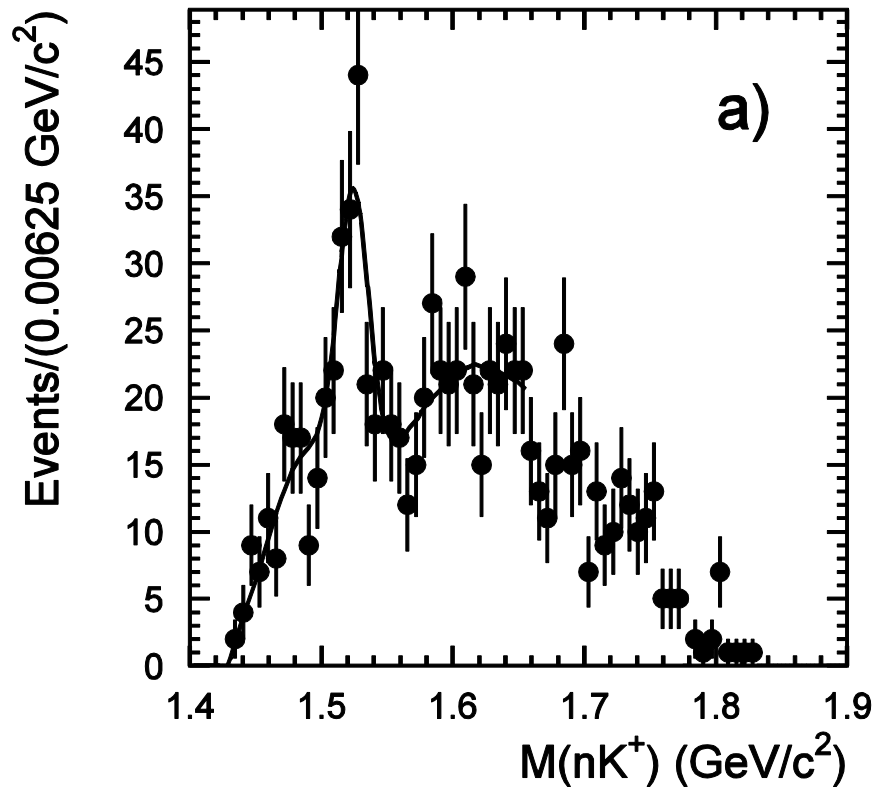
Results of Θ^+ analysis after $\Lambda(1520)$ exclusion



$$\Delta(-2\ln L) = 30.4 \text{ for } \Delta ndf = 2 \longrightarrow 5.2\sigma$$

Various BG models: minimum significance = 5.1σ

Energy independent ϕ exclusion



$$M(K^+K^-) > 1.05 \text{ GeV}/c^2$$

Next step

Probability of 1/5000000 may not be low enough.
"Extraordinary claim requires an extraordinary evidence."

High statistics data was collected in 2006-2007 with the same experimental setup.

Blind analysis is under way to check the Θ^+ peak

Difference between LEPS and CLAS for $\gamma n \rightarrow K^-\Theta^+$ study

LEPS

CLAS

Good **forward angle** coverage

↔ Poor forward angle coverage

Poor wide angle coverage

↔ Good **wide angle** coverage

Low energy

↔ **Medium energy**

Symmetric acceptance for K^+ and K^-

↔ Asymmetric acceptance

$M_{KK} \gtrsim 1.04 \text{ GeV}/c^2$

↔ **$M_{KK} > 1.07 \text{ GeV}/c^2$**

Select **quasi-free** process

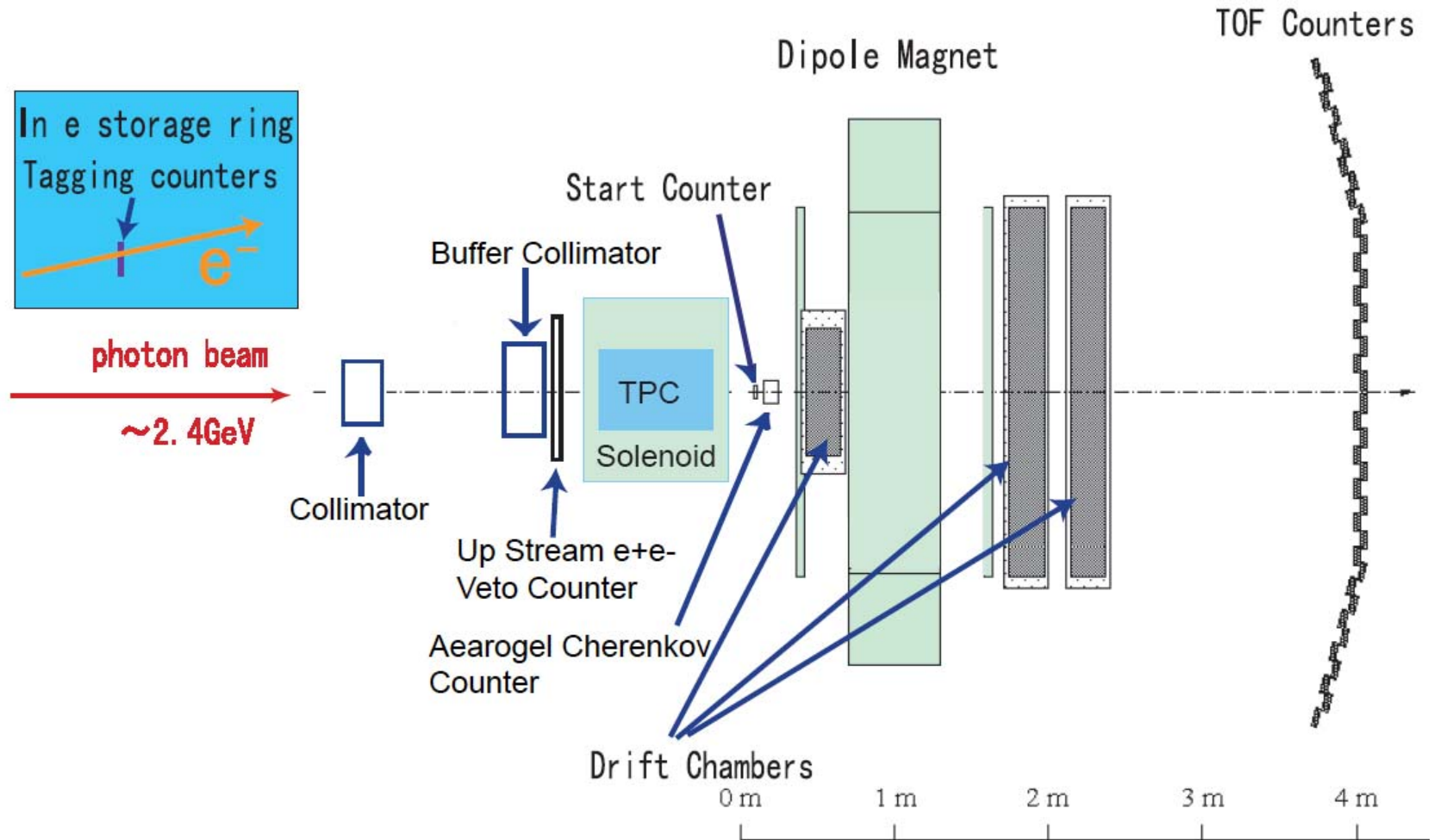
↔ Require **re-scattering** or large
Fermi momentum of a spectator

LEPS: $\theta_{\text{LAB}} < 20 \text{ degree}$ $|t| < 0.6 \text{ GeV}^2$

CLAS: $\theta_{\text{LAB}} > 20 \text{ degree}$

Θ^+ might be a soft object.

Setup of TPC experiment



Experiment with a new TPC and a new LH2/LD2 target was started in January, 2008.

Θ^+ search experiment at J-PARC

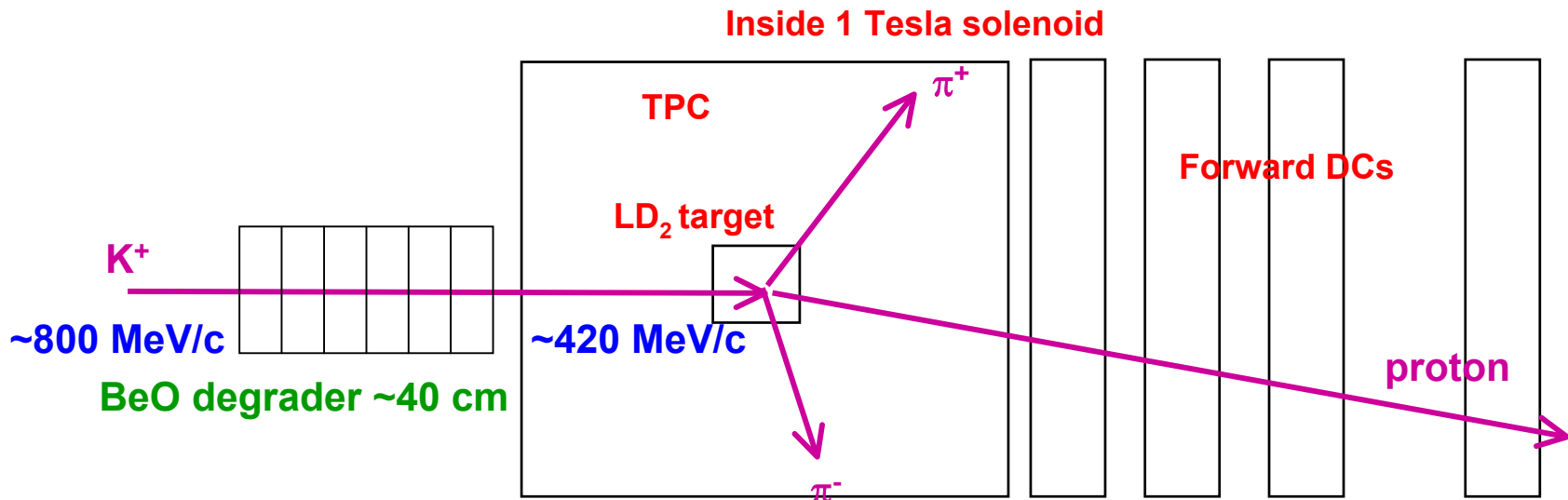
- Reverse reaction of the Θ^+ decay using a low energy K^+ beam gives an unambiguous answer.



- Cross-section depends on only the spin and the decay width.

$$\sigma = \frac{\pi}{8k^2} (2J + 1) \int \frac{\Gamma^2}{(E - M)^2 + \Gamma^2 / 4} dE \Rightarrow 26.4 \Gamma \text{ mb/MeV} \quad \text{for } J = \frac{1}{2}$$

CEX ($K^+ n \rightarrow K_S^0 p$) $\sim 7 \text{ mb}$





Summary and prospects

1. We observed a $5\text{-}\sigma$ peak in the Fermi-motion corrected nK^+ invariant mass at $1.527 \text{ GeV}/c^2$.
2. New data set with **3 times more statistics** was taken.
3. **Blind analysis** in under way to check the validity of the peak (hopefully in a few months).
4. **A new experiment with a Time Projection Chamber** has been carried out since Jan 2008. \rightarrow wider angle coverage and Θ^+ reconstruction in pK_s decay mode.
5. If the peak is confirmed, we will submit a proposal to carry out an experiment by using a low energy K^+ beam at **J-PARC**.