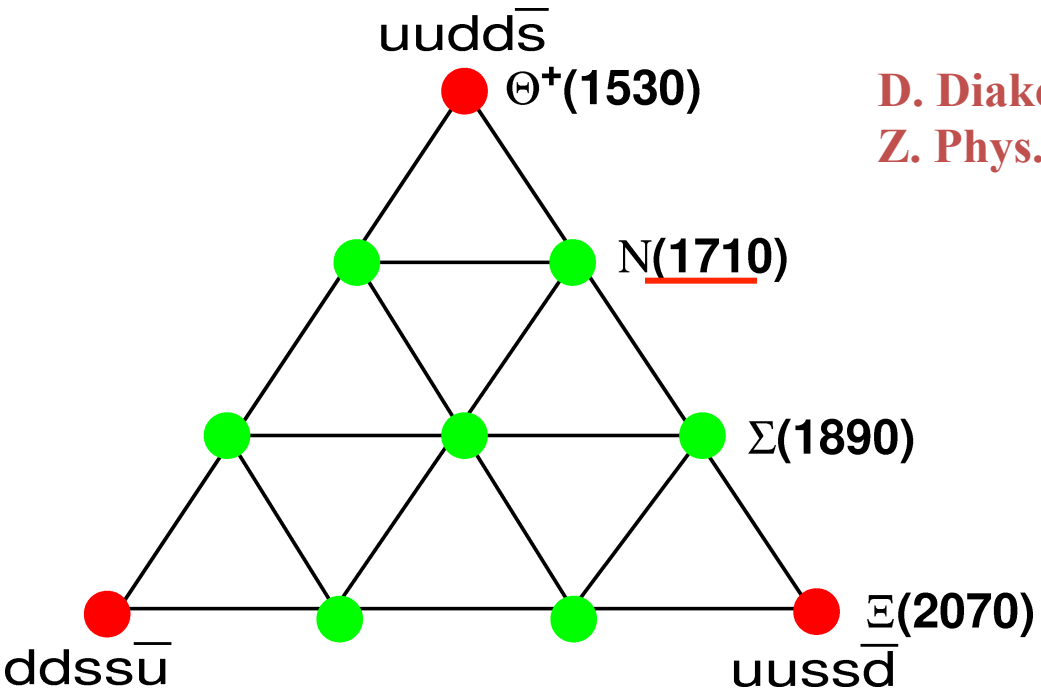
New Θ^+ results from LEPS

Takashi NAKANO
RCNP, Osaka University

2013, Jan. 25th, Riken-Wako

- Introduction
- Experiment
- Inclusive analysis – Blind analysis
- Exclusive analysis
- Summary

Prediction of the Θ^+ Baryon



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$^+$**

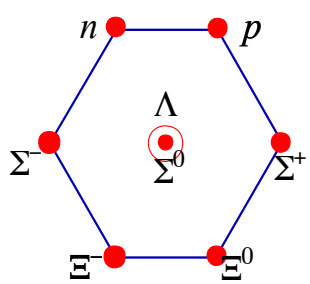
Important Q.: if $N_c \to \infty$ which is smaller, $\frac{m_s}{\Lambda}$ *or* $\frac{1}{N_c}$?

the answer:

splitting inside SU(3) multiplets is $\sim m_s$, numerically ~140 MeV

splitting between the centers of multiplets is $\sim \Lambda / N_c$, numerically ~ 230 MeV.

Hence, $m_s \leq \Lambda / N_c$ meaning that one can first put $m_s = 0$, obtain the degenerate SU(3) multiplets, and only at the final stage account for nonzero m_s, leading to splitting inside multiplets, and mixing of SU(3) multiplets.



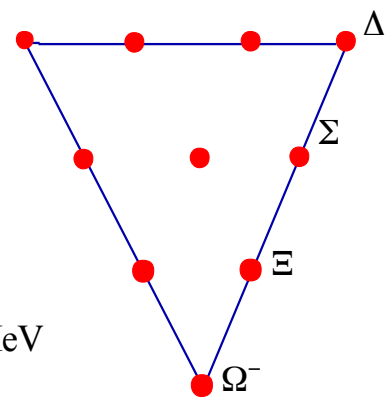
mean octet mass 1152 MeV

difference from decuplet 230 MeV

(8,1/2)

mean decuplet mass 1382 MeV

splitting inside decuplet ~ 140 MeV



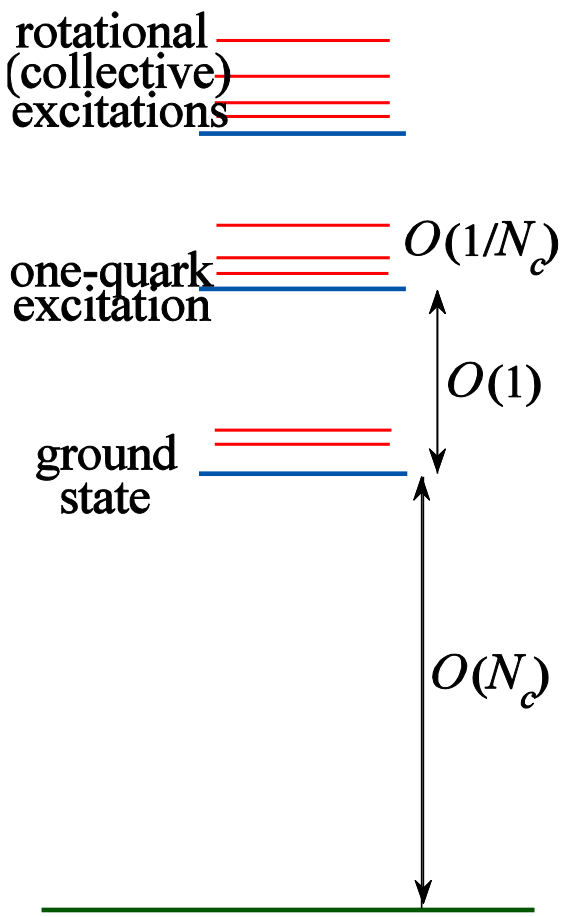
(10,3/2)

How does baryon spectrum look like at $N_c \to \infty$?

E. Witten
E. Jenkins and A. Manohar
T. Cohen and R. Lebed
…

(imagine number of colors is not 3 but 1003)

Witten (1979): Nc quarks in a baryon can be considered in a mean field (like electrons in a large-Z atom or nucleons in a large-A nucleus).



Color field fluctuates strongly and cannot serve as a mean field, but color interactions can be Fierz-transformed into quarks interacting (possibly non-locally) with mesonic fields, whose quantum fluctuations are suppressed as $O(1/N_c)$.

Examples: instanton-induced interactions, NJL model, holographic QCD…

The mean field is classical

Baryons are heavy objects, with mass $O(N_c)$.

One-particle excitations in the mean field have energy $O(1)$

Collective excitations of a baryon as a whole have energy $O(1/N_c)$

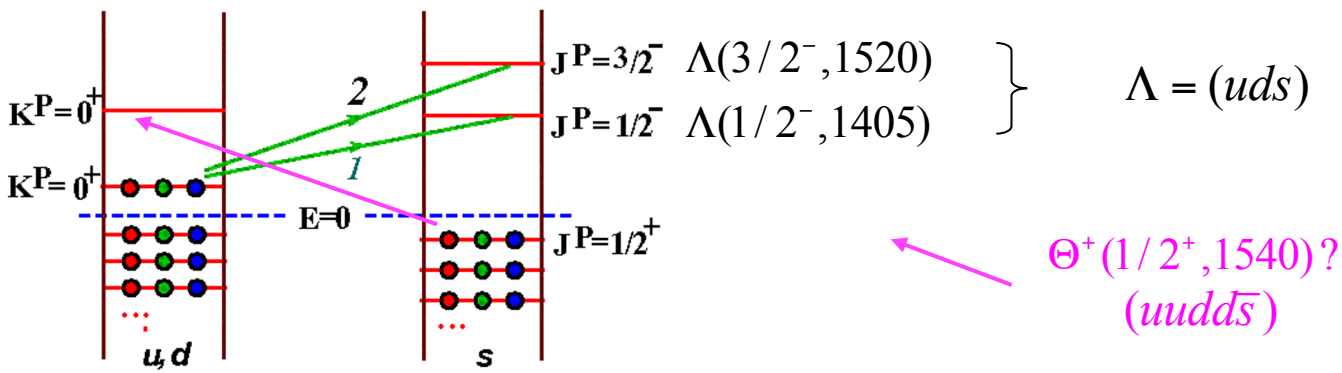
Splittings inside octets, decuplets are $O(m_s)$

Lowest one-quark excitations

The two lowest baryons resonances that do not belong to the ground-state (**8**, ½), (**10**, 3/2), are SU(3) singlets $\Lambda(1/2^-,1405)$, $\Lambda(3/2^-,1520)$.

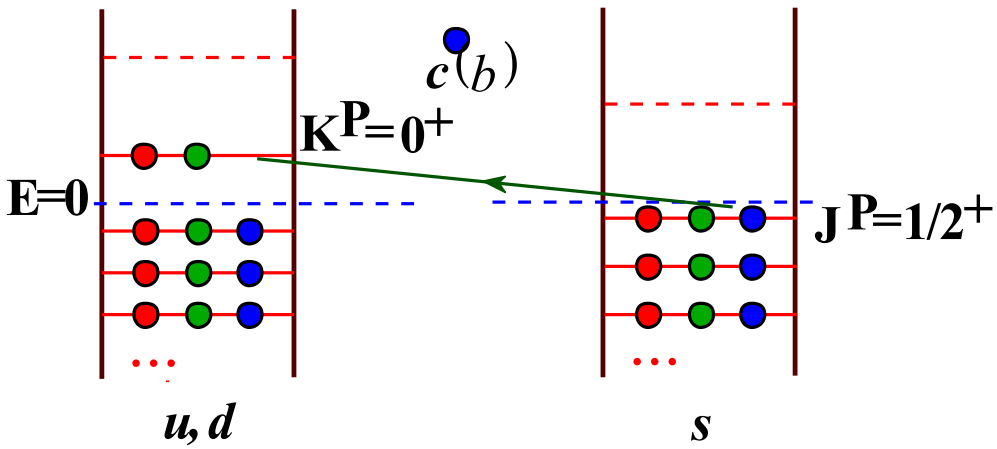
They can be explained if there are two ***s***-quark levels with $J^P = 1/2^-, 3/2^-$

Off-diagonal "Gamov – Teller" transitions

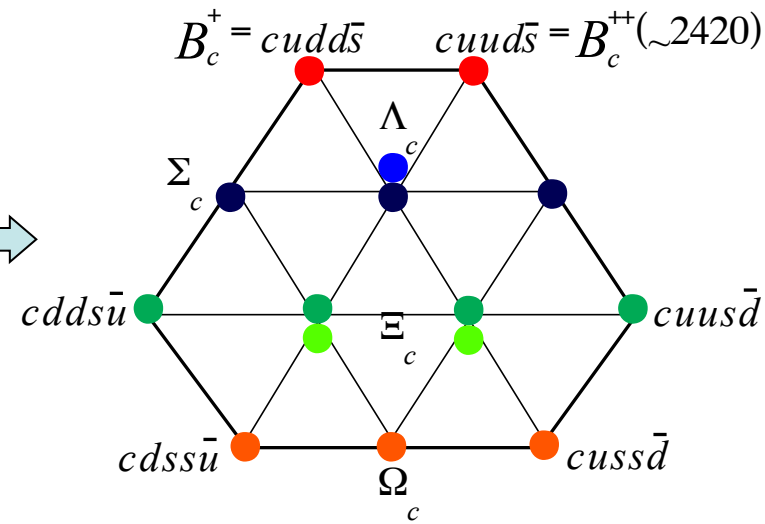


In the large Nc limit, these excitations induce two `towers' or `bands' of rotational states, but at Nc = 3 they reduce to two single rotational states: (**1**, 1/2-) and (**1**, 3/2-).

There is also a Gamov-Teller-type transition:



exotic 5-quark charmed baryons



$(\overline{15}, 1/2^+)$

anti-decapenta-plet

Exotic 5-quark charmed baryons B_c^{++}, B_c^+ are light (~2420 MeV) and can decay only weakly:

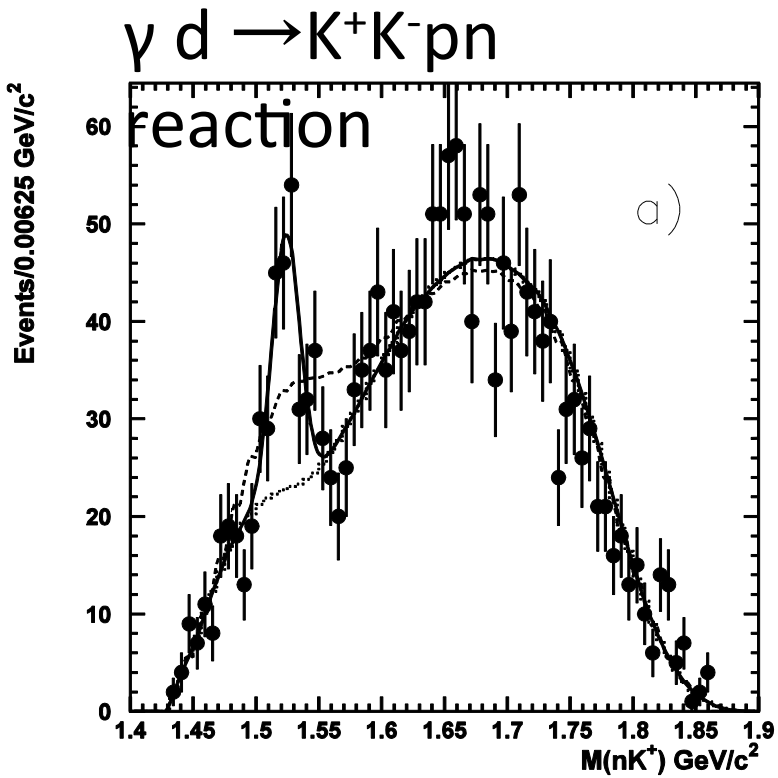
$$B_c^{++} \to p\pi^+,\ p\phi\pi^+, \ldots B_c^+ \to \Lambda K^+, \text{etc.}$$

B_c = **"Beta-sub-c"**

clear signature, especially in a vertex detector.
Life time $10^{-13}\ s$

NB: $\Theta_c = uudd\bar{c}$ is another pentaquark, hypothetized by Lipkin and Karliner; in our approach it must be ~350 MeV heavier!

Previous result of the Θ^+ search by LEPS

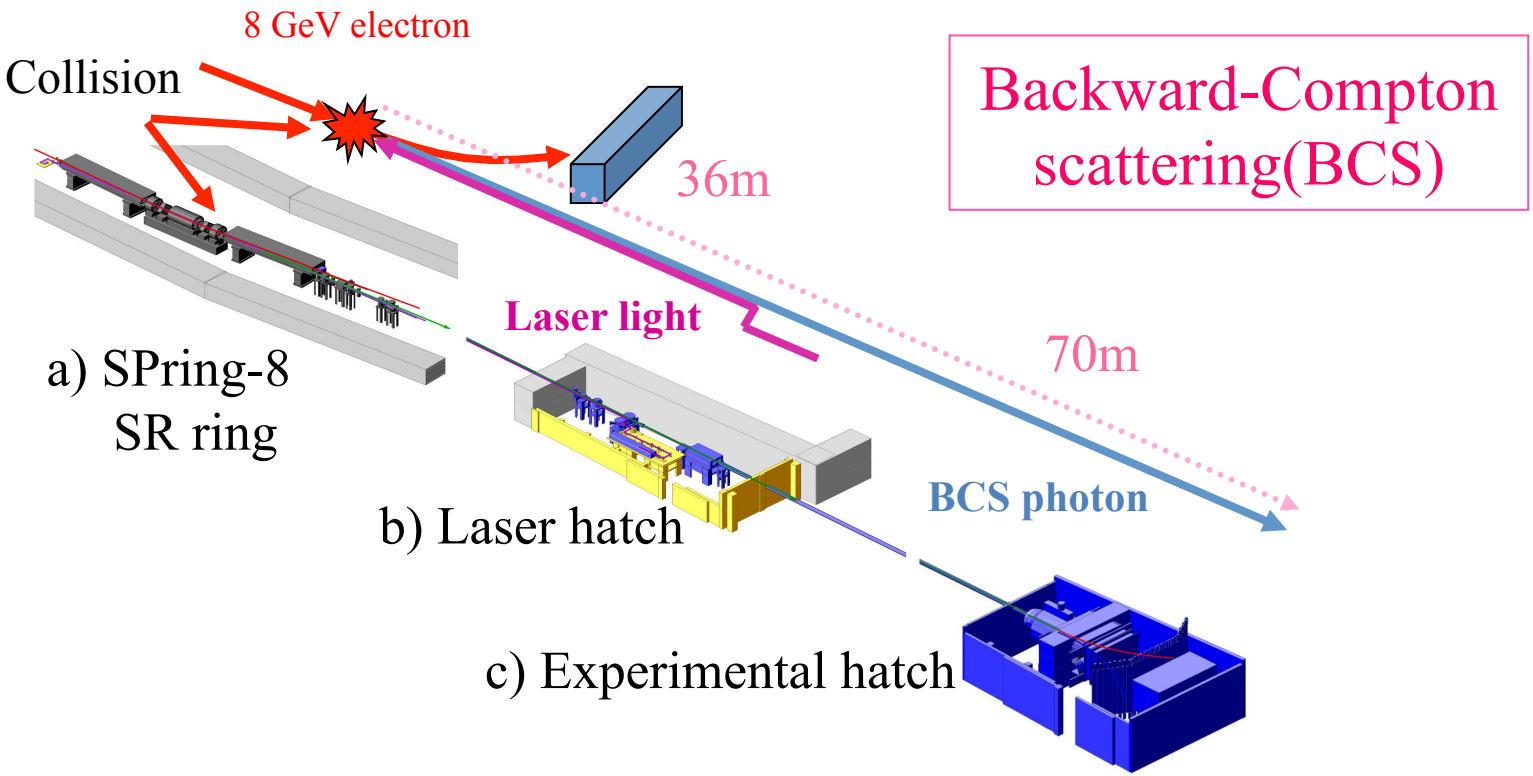


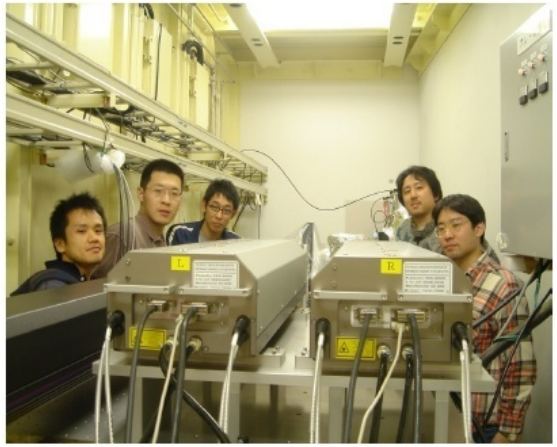
- Data taken in 2002-2003.
- $2.0<E_\gamma<2.4$ GeV.
- Significance of 5.1σ from shape analysis.
  ($\Delta(-2\ln L)$ with/without signal)
- Mass=1524±2＋3MeV/c^2.

If the peak is real,

- It should be reproducible.
- It should appear in $M(nK^+)$.
- It should not appear in $M(nK^-)$ nor in $M(pK^+)$.
- Fermi-motion correction should work.

Experiment@SPring-8/LEPS

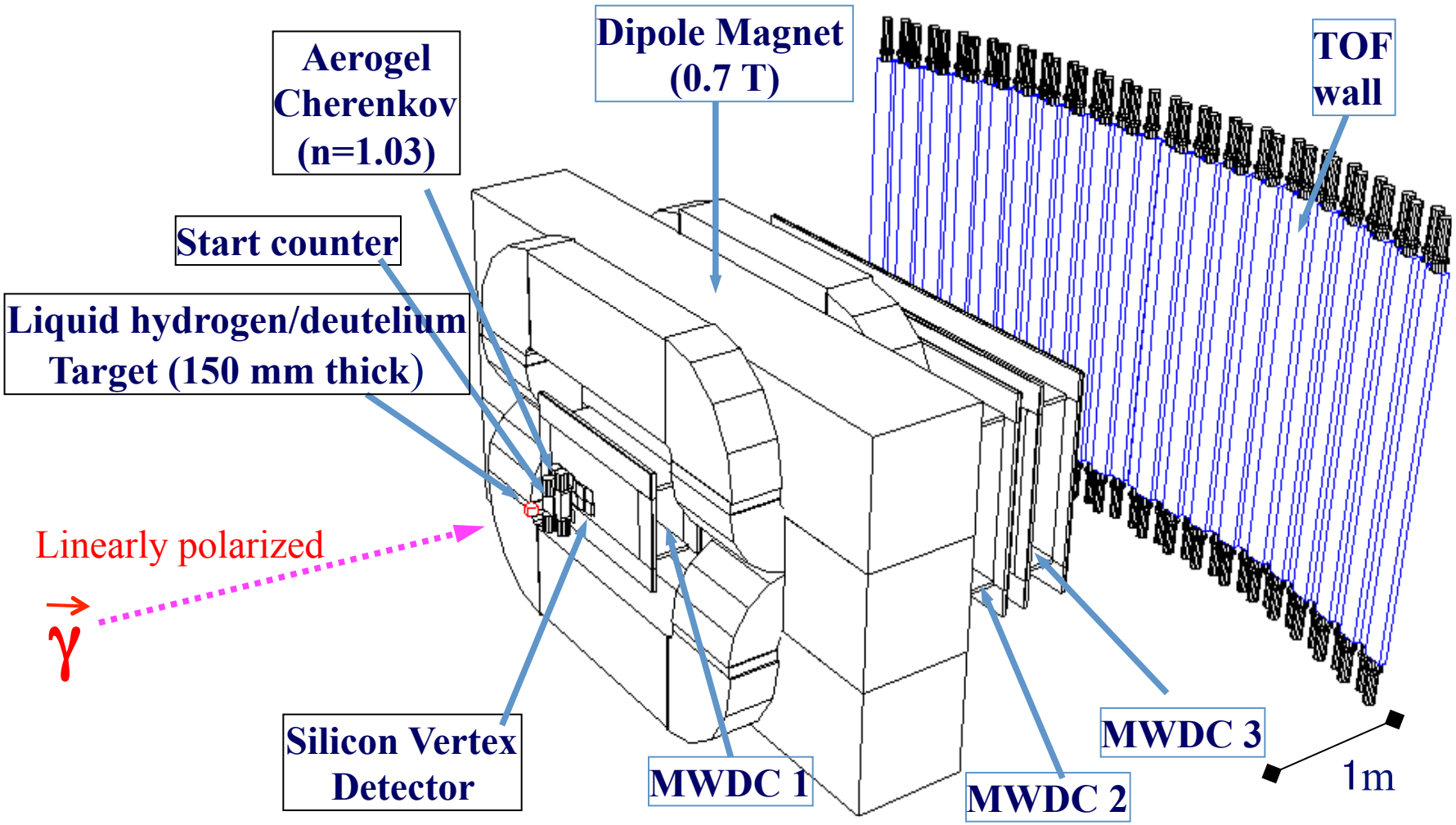




Upgrade since previous experiment

- **Two laser injection system to increase beam intensity.**
- 5W Ar laser → 8W solid state laser (Paladin by Coherent company).
- Beam intensity of 1→2Mcps was achieved at the maximum.
- About 2.6 times statistics was collected in 2006-2007.

LEPS forward spectrometer

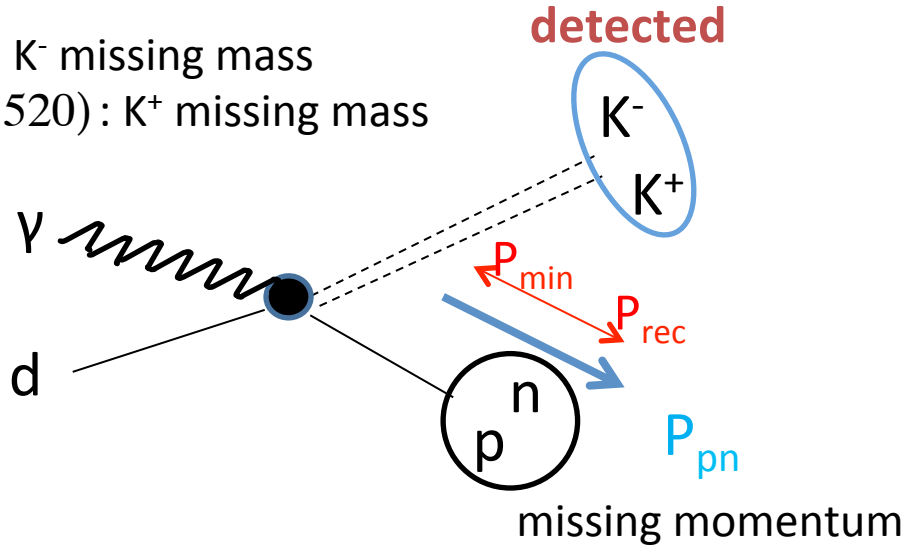


- The same setup for Common 2006-2007 data.
- Symmetric acceptance for positive/negative charged particles.

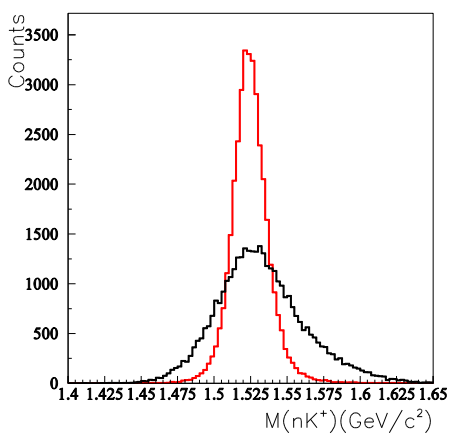
→ **symmetric acceptance for K^+ and K^- from $\Theta^+/\Lambda(1520)$ production.**

Search for Θ^+ in Fermi-motion corrected K^- missing mass

Θ^+ : K^- missing mass
$\Lambda(1520)$: K^+ missing mass



Minimum Momentum Spectator Approximation (MMSA):
Assume possible minimum momentum configuration for the spectator.



simple MMn(γ,K^-)X: 30 MeV/c^2
M(nK^+) by MMSA :11 MeV/c^2
(16 MeV/c^2 for Λ(1520))

For the further improvement

Inclusive analysis:
p/n unseparated

↓

Exclusive analysis:
p/n separated

In the previous analysis, only inclusive analysis was carried out.

Separation of the two types of K^+K^- events from neutron and proton largely improves the signal sensitivity.

Inclusive Analysis

- New data was taken in 2006-2007 with almost the same setup.
- Blind analysis was applied to check the previous result.
  (Selection cut is not changed from previous analysis.
  calibration fixed before opening the box)

Comparison of the Λ(1520) peak

- Is there any problems on new data?
- Is it possible to add two data sets?

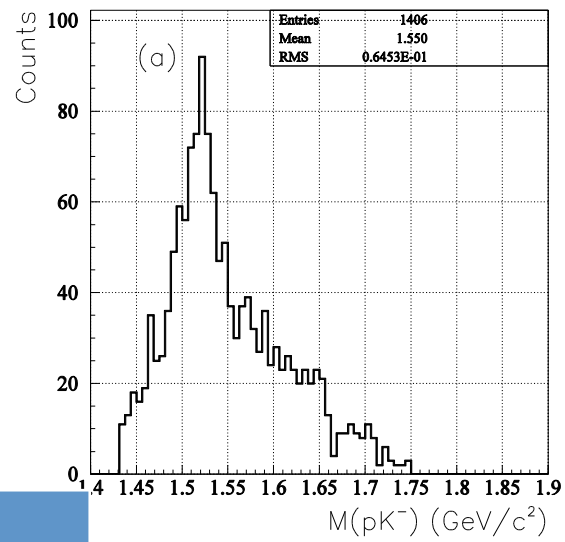
$\gamma n \rightarrow K^- \Theta^+ \rightarrow K^+ K^- n$

$K^- \Leftrightarrow K^+$

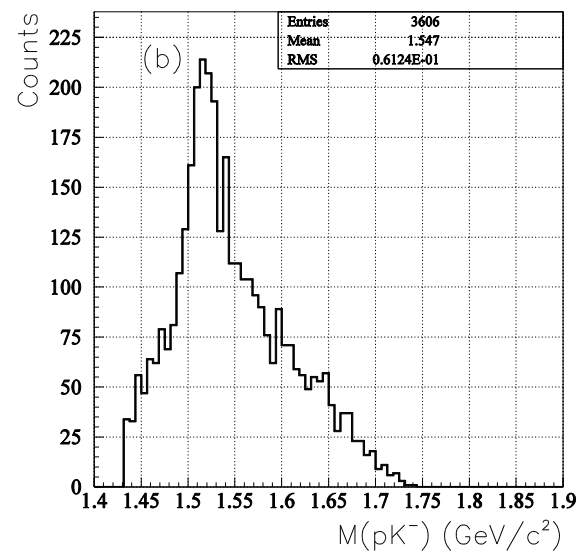
$n \Leftrightarrow p$

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

Previous data



New data



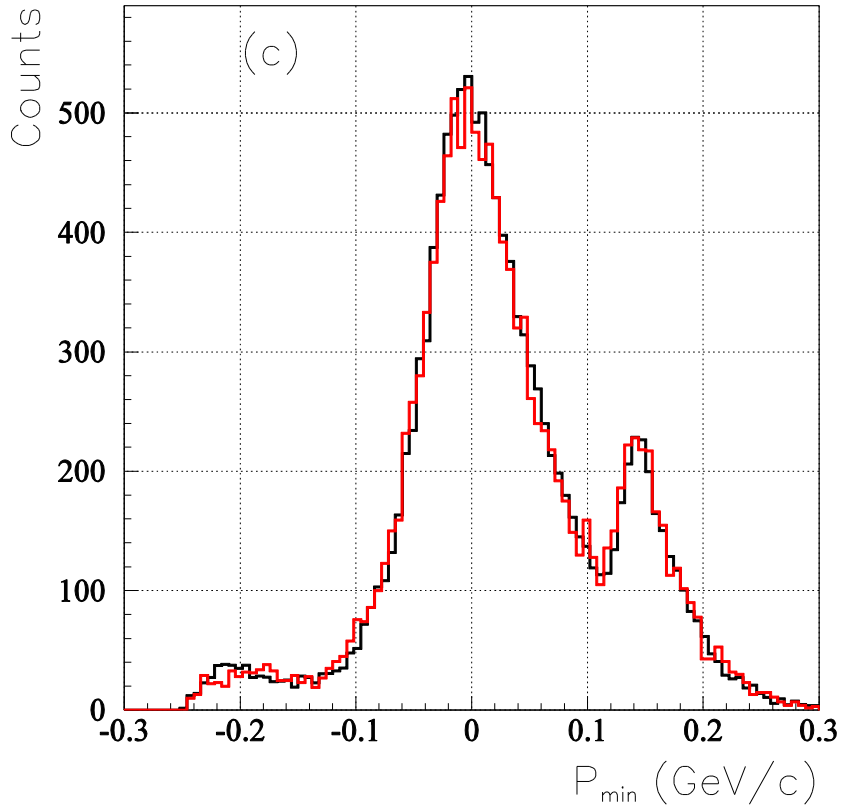
	Previous	New
Peak position(MeV)	1517.6±1.6	1517.8±1.0
Peak width (MeV)	18.5±2.2	16.8±1.6
Peak height	53.0±5.2	128.3±8.2
S/N ratio	1.74±0.22	1.55±0.15

$MMn(\gamma,K^-)X>1.6GeV/c^2$
to keep the condition of the blind analysis.

- Λ(1520) peak was found to be consistent for two data sets.

Other checks: ϕ events

P_{min} for ϕ events



New data

Previous data

(normalized by entry)

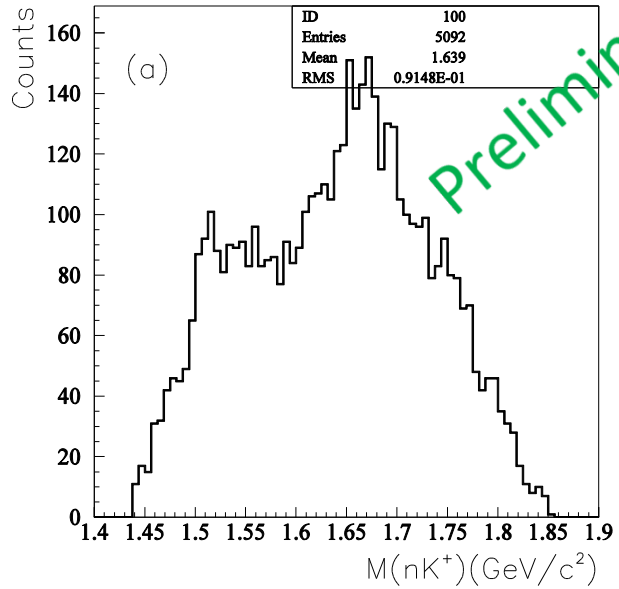
χ^2/ndf=96.6/90

K.S test 52.4%

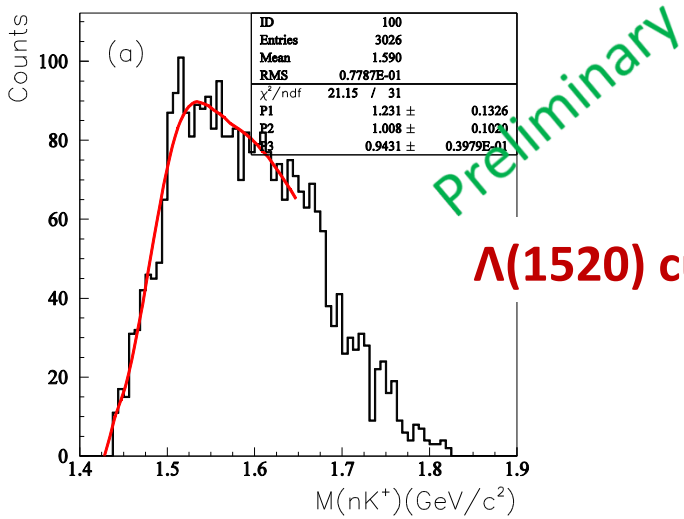
Other distributions are also checked and consistent.

We decided to add two data sets after opening the box.

Box open for new data

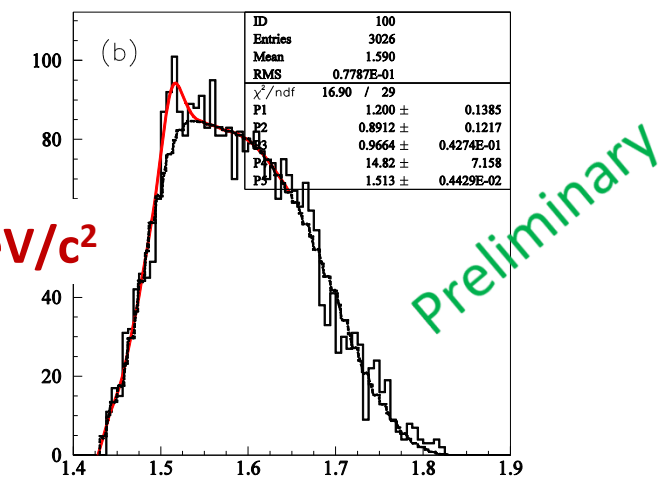


fitting w/o signal



Λ(1520) cut M(pK⁻)>1.55 GeV/c²

fitting w/signal

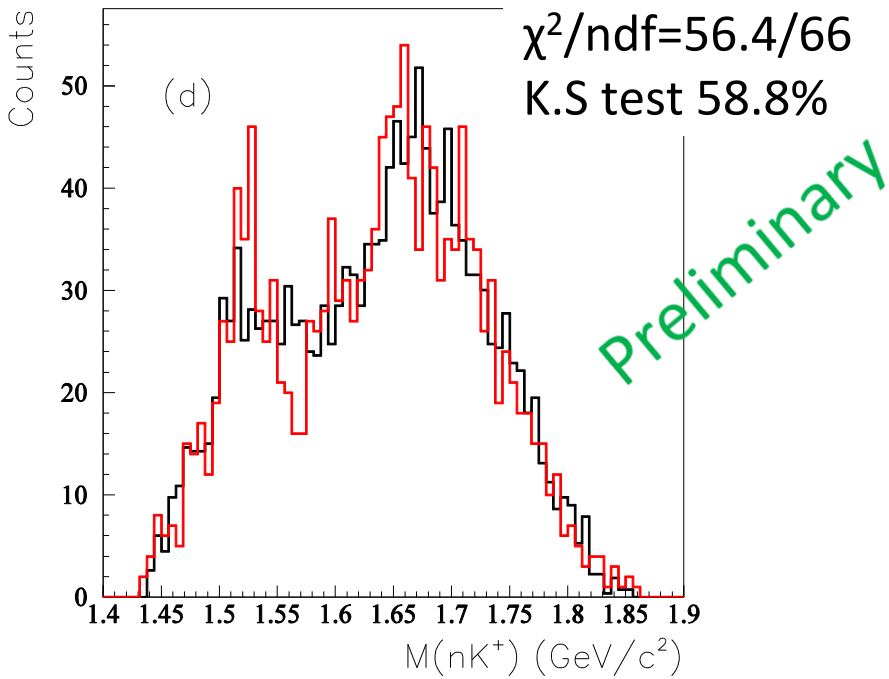


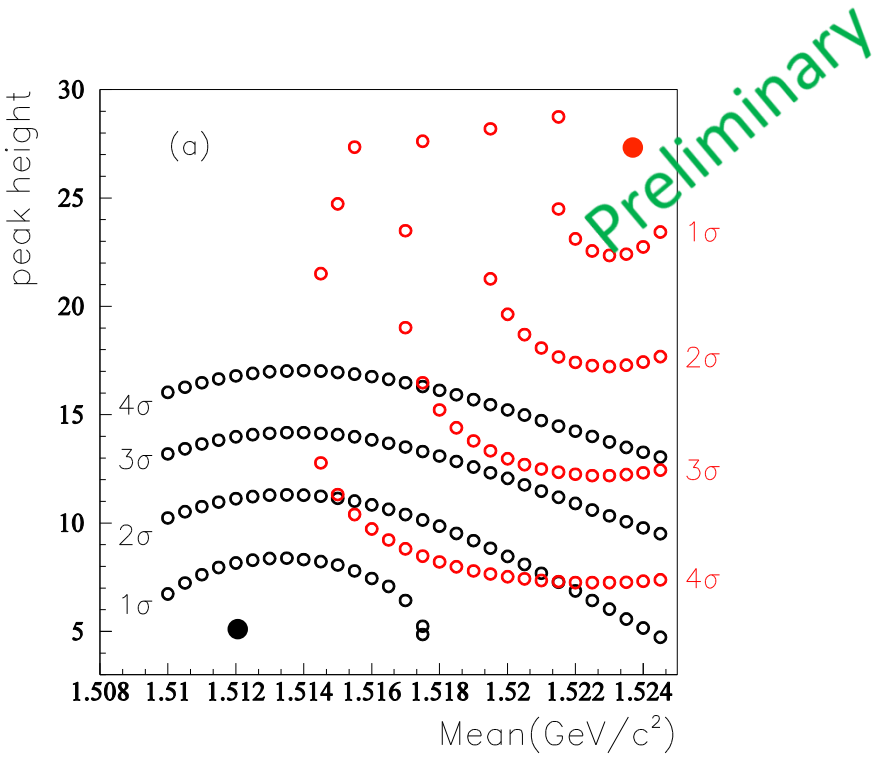
The significance is less than 2σ if we perform the same shape analysis as the previous analysis.

Consistency check of final M(NK$^+$) spectrum

New data

previous data





- Two data sets are normalized by the entry.
- In total, two data sets are consistent.

The increment of the χ^2 from the best fit in the space of peak height and position of signal.

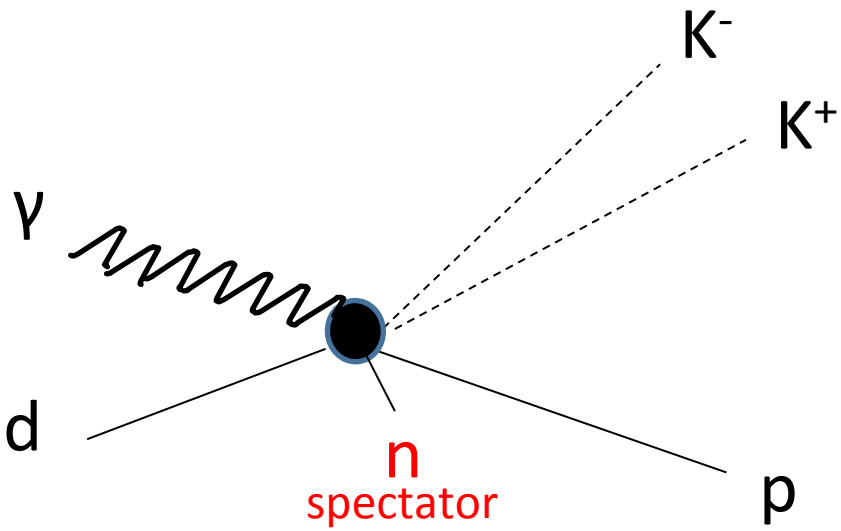
→almost 3σ deviation from two data sets.

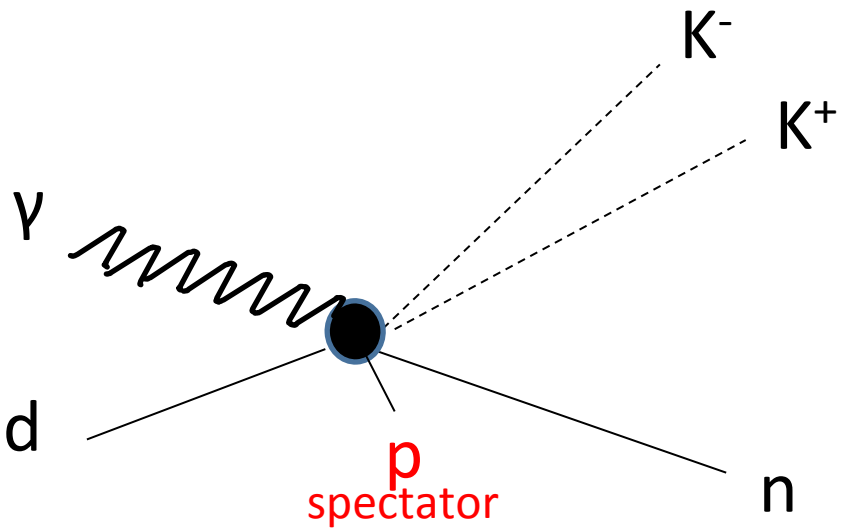
Unlikely to happen → Overestimation of significance by shape analysis.

The background shape must be the same!

Exclusive Analysis

SEPARATE

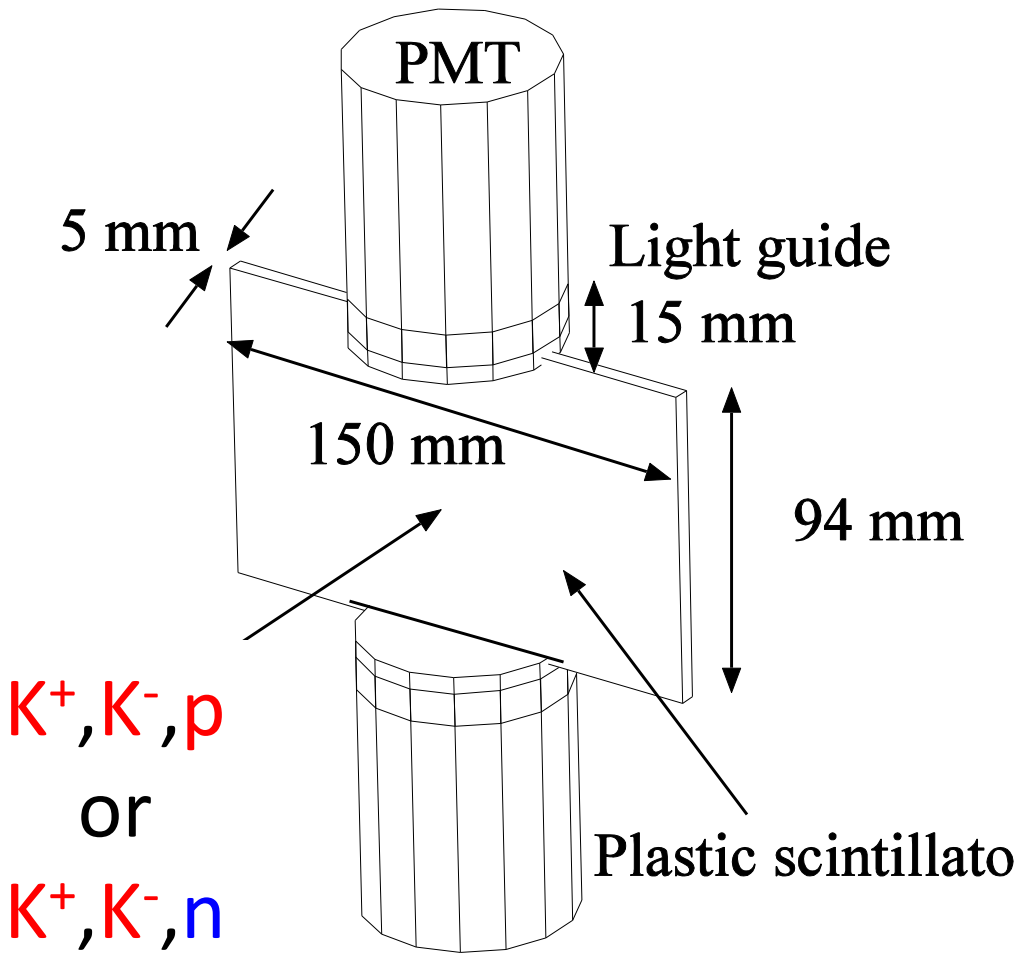




$\Lambda(1520)$, ϕ, ...

Θ^+, ϕ, ...

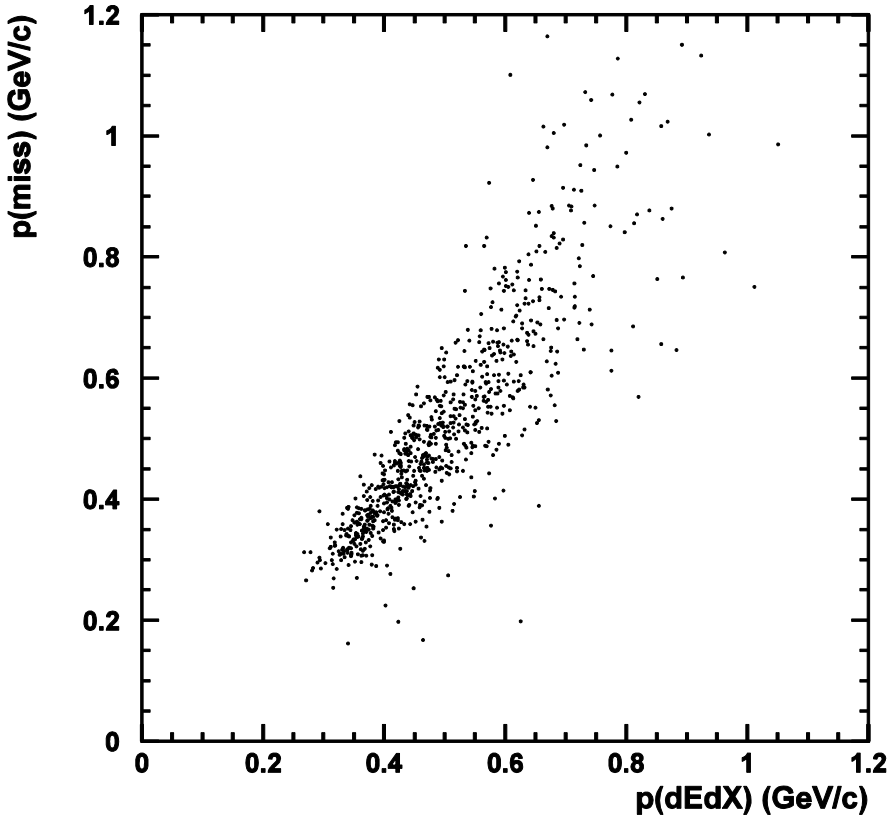
Start counter



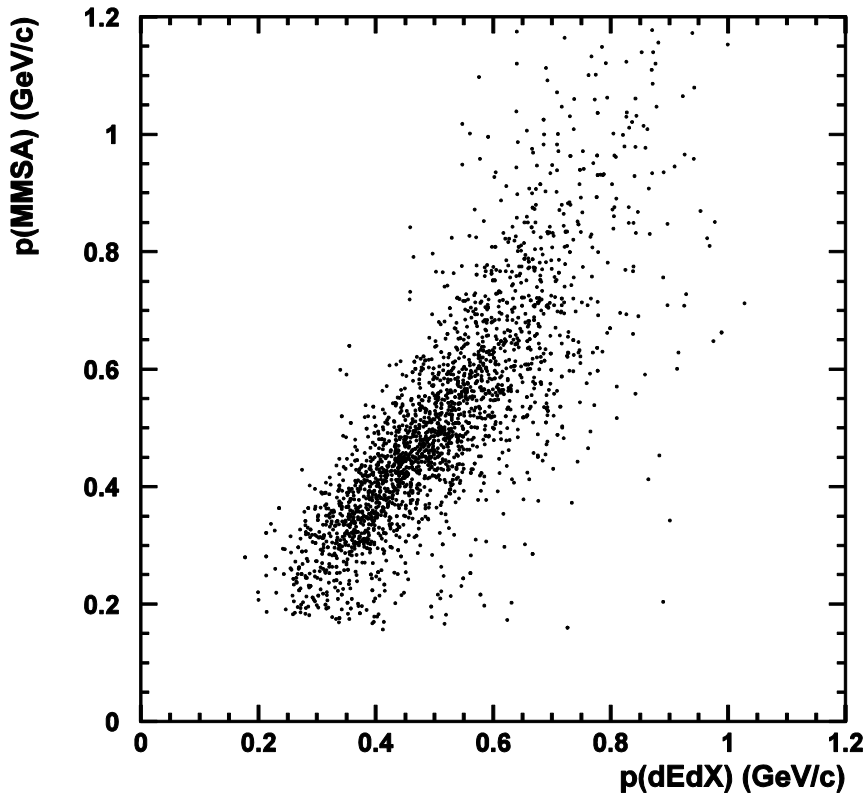
K^+,K^-,p
or
K^+,K^-,n

Light collection is not good near the edge of the counter.
→ Efficiency was estimated by using both LH_2 and LD_2 data

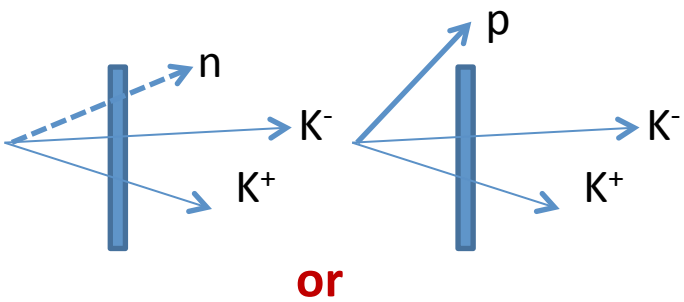
LH_2 p(miss) vs. p(dEdx)

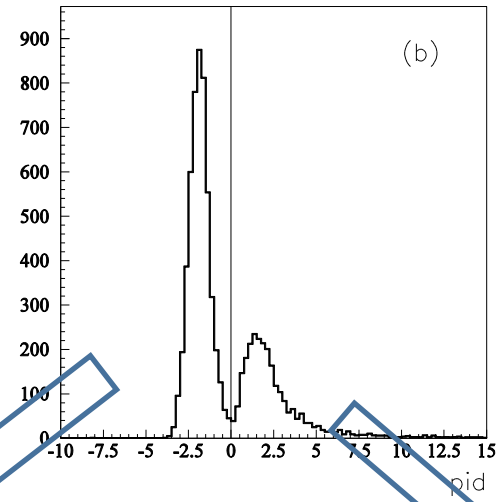


LD_2 p(MMSA) vs. p(dEdx)

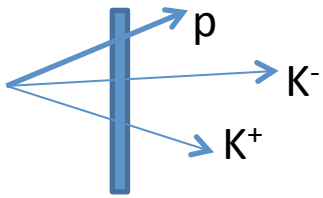


Proton detection by using dE/dx in Start Counter





Pid = (Measured energy loss in SC)
– (Expectation of KK)
– (Half of expectation of proton)

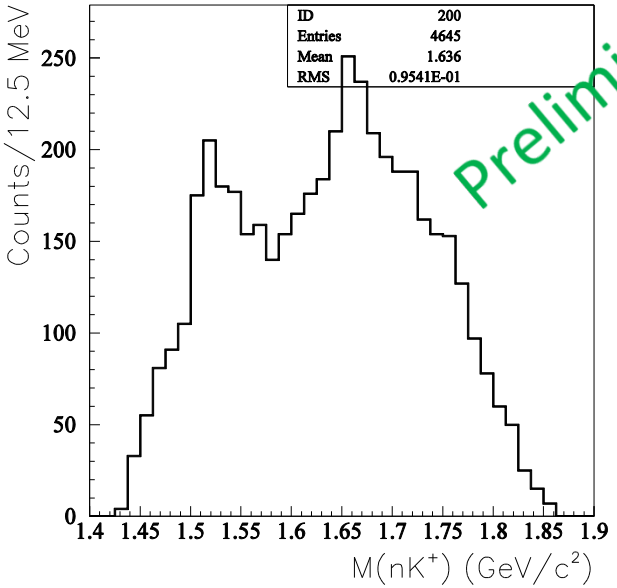


Proton not tagged (Proton rejected)

KKn and part of KKp

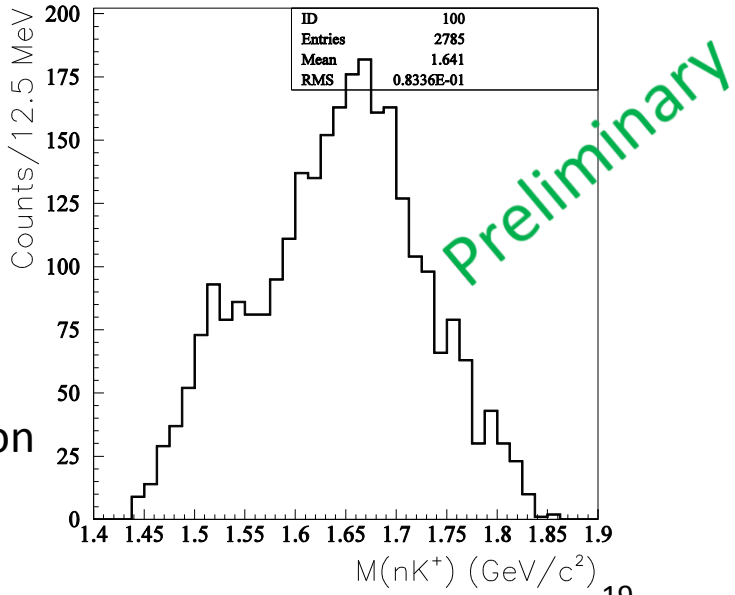
Proton tagged (ε ~60%)

KKp only

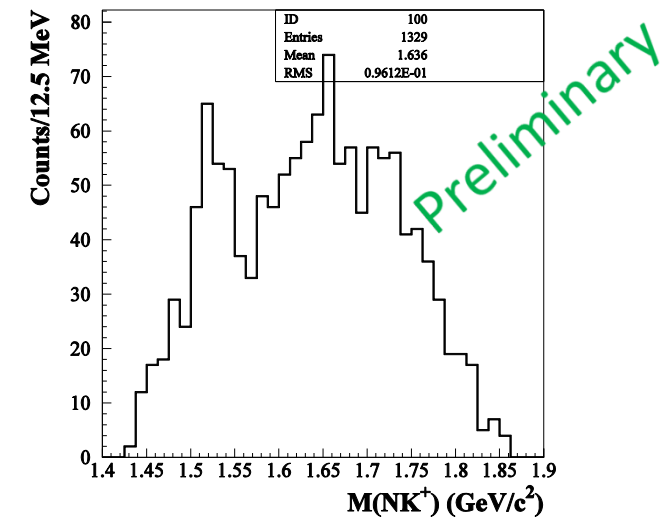


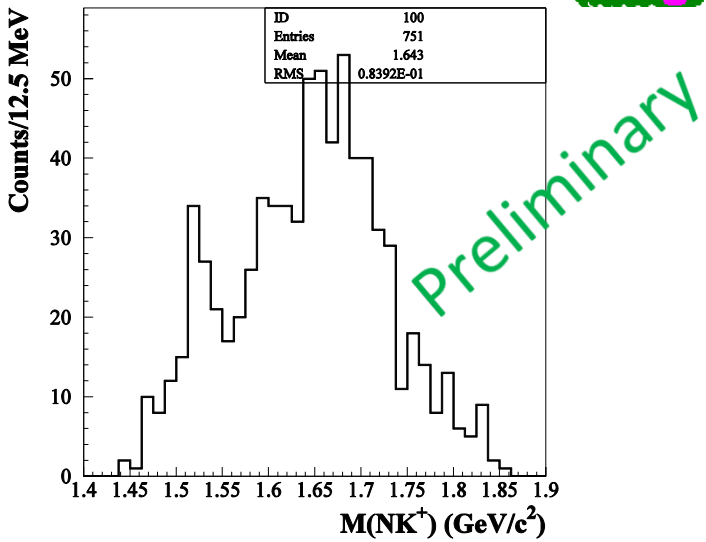
Signal enhancement is seen in proton rejected events.
→ should be associated with γn reaction.

p/n ratio:
1.6 before proton rejection
0.6 after proton rejection



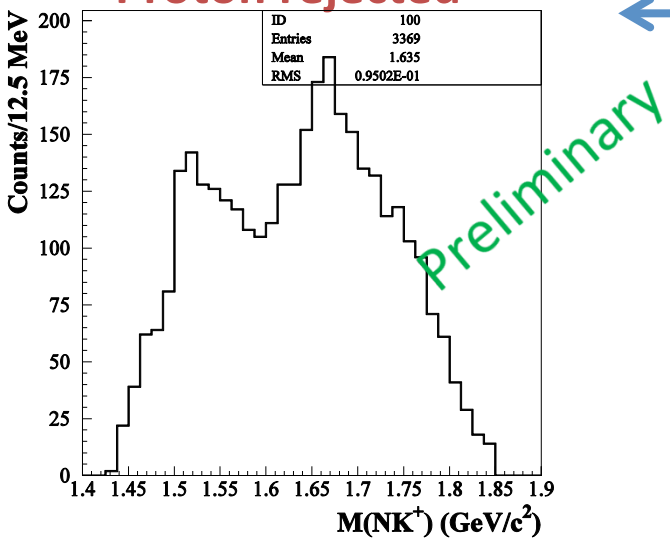
M(NK$^+$) for exclusive samples



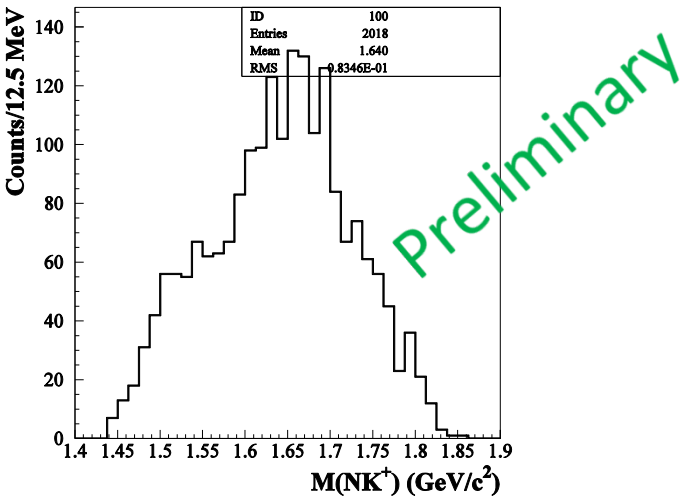


previous

Proton rejected



Proton tagged

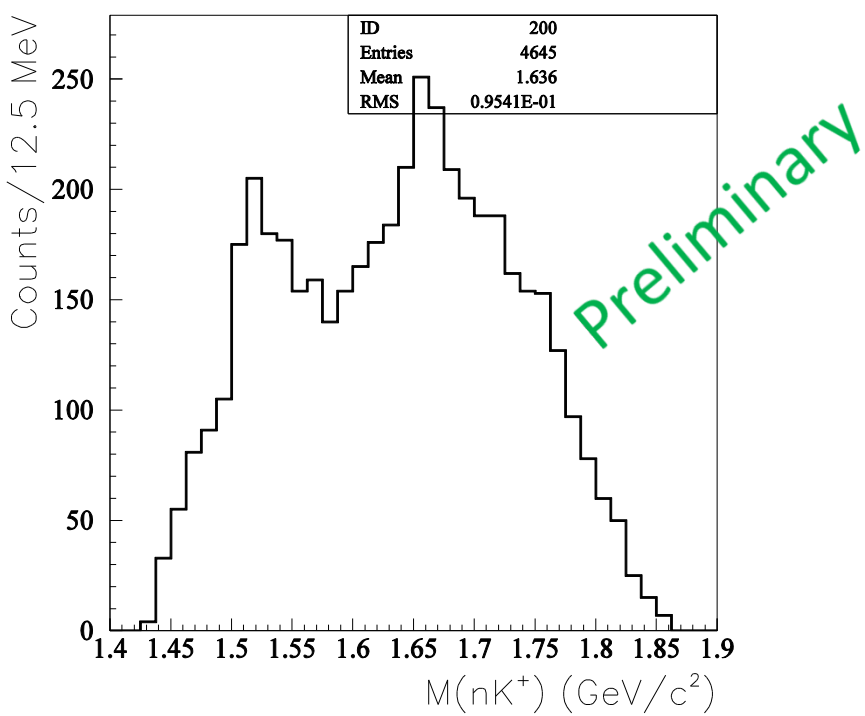


new

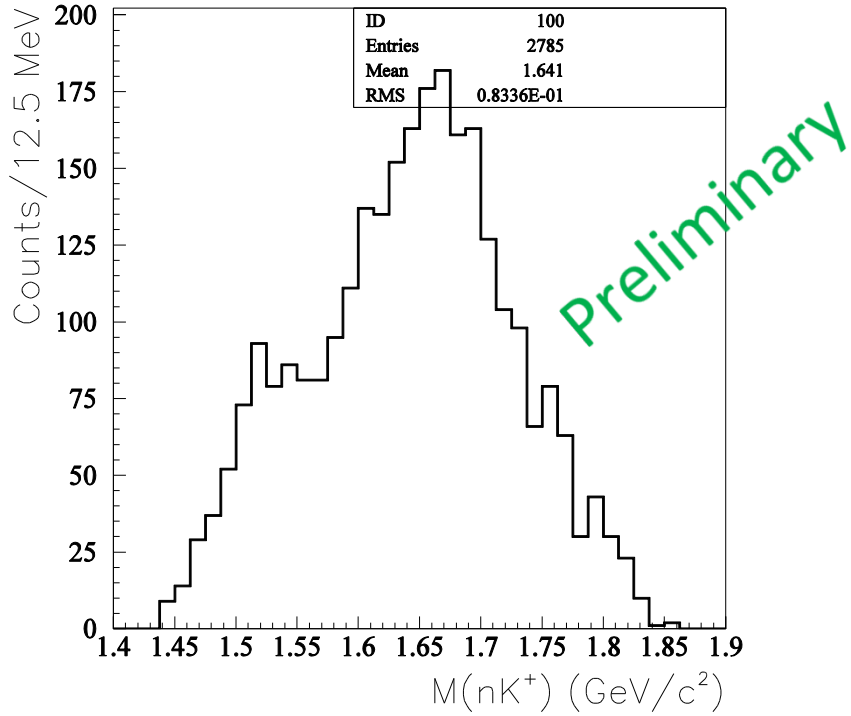
- Peak is seen in tagged events for the previous data while not seen in the new data.
- An enhancement is seen in proton rejected events in the both data.

Exclusive samples for summed data

Proton rejected



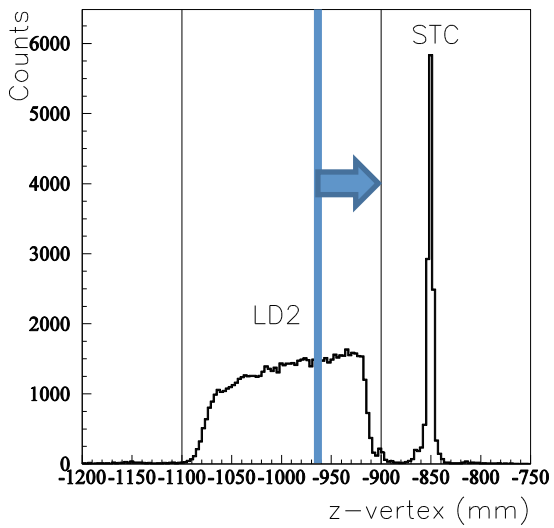
Proton tagged



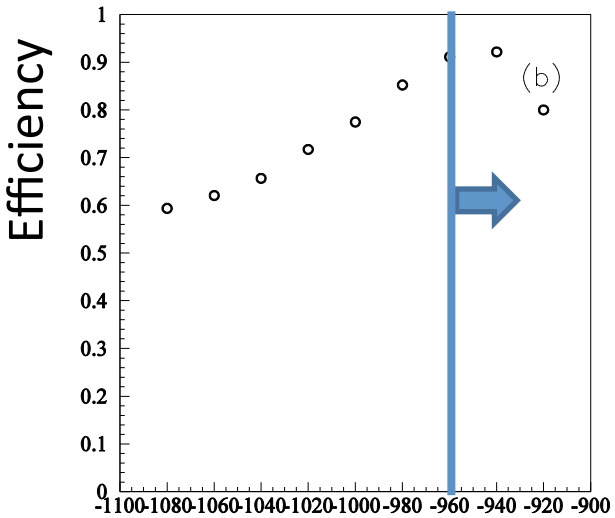
- Structure seen in proton tagging becomes much smaller.
- Enhancement is seen in proton rejected events.

→ Further rejection of the proton events.

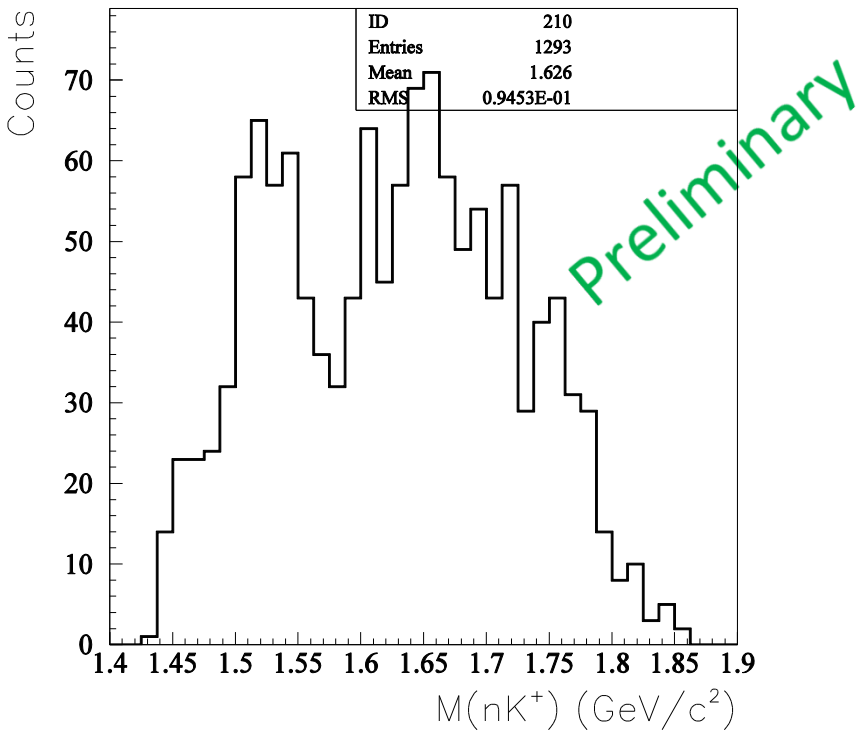
Neutron enhanced sample



Proton rejection efficiency becomes
60%→90% by selecting downstream of target

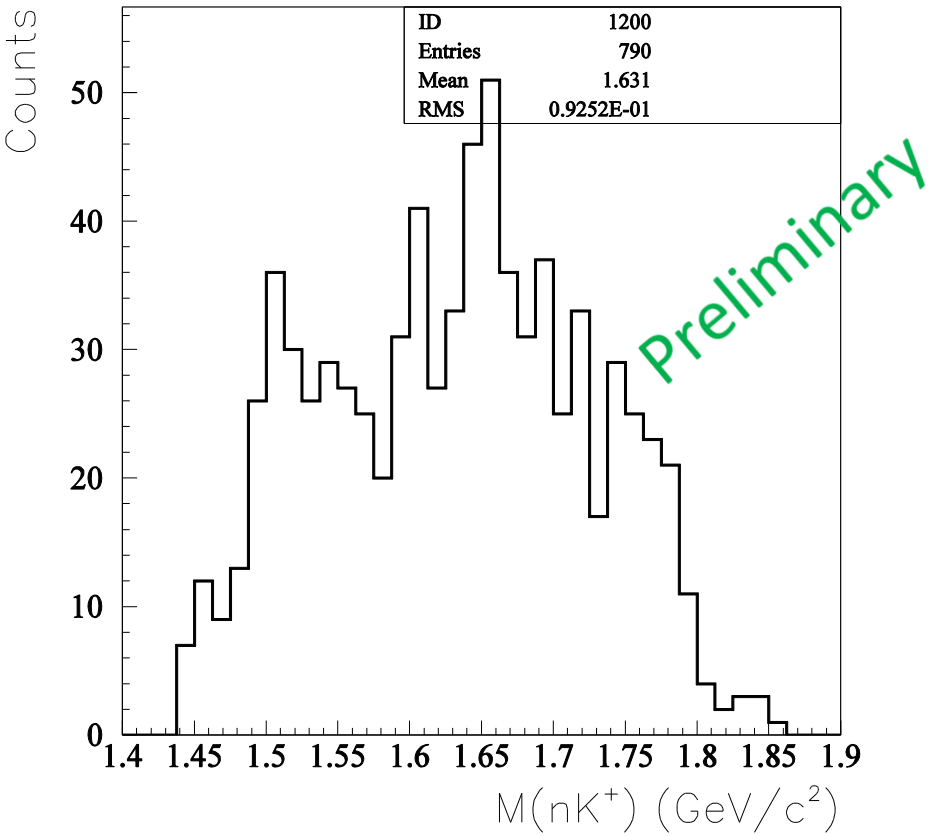


M(nK⁺)

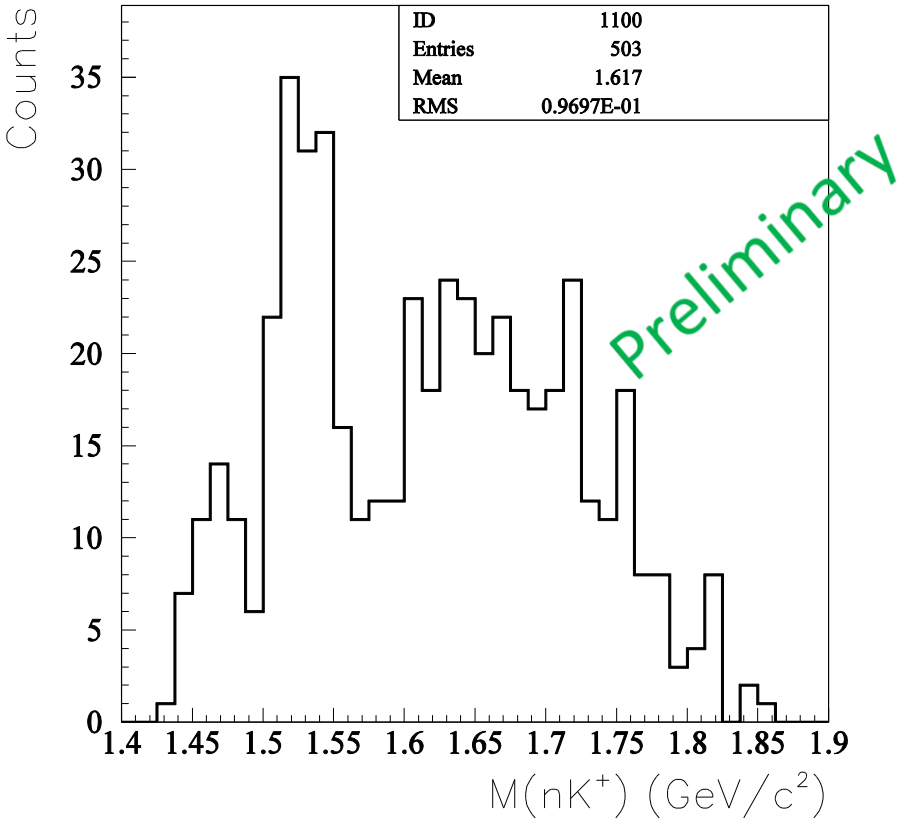


Polarization dependence of the M(nK$^+$)

Horizontal



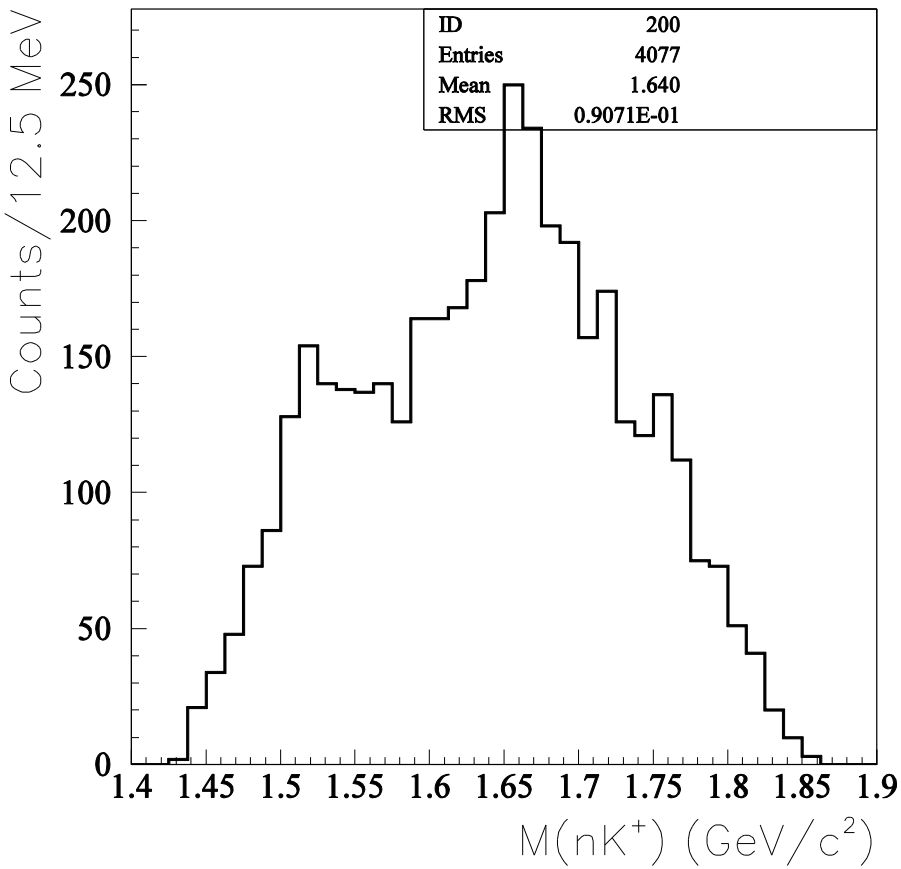
Vertical



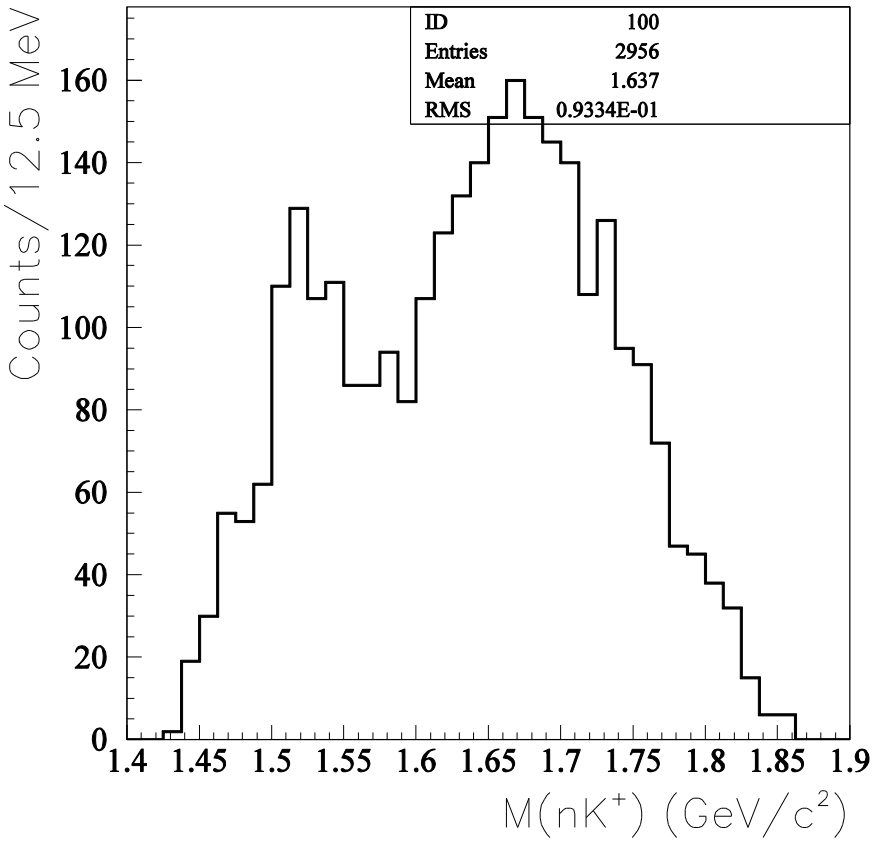
B.G strength strongly depends on the beam polarization.

Pol. dependence of inclusive spectra

Horizontal

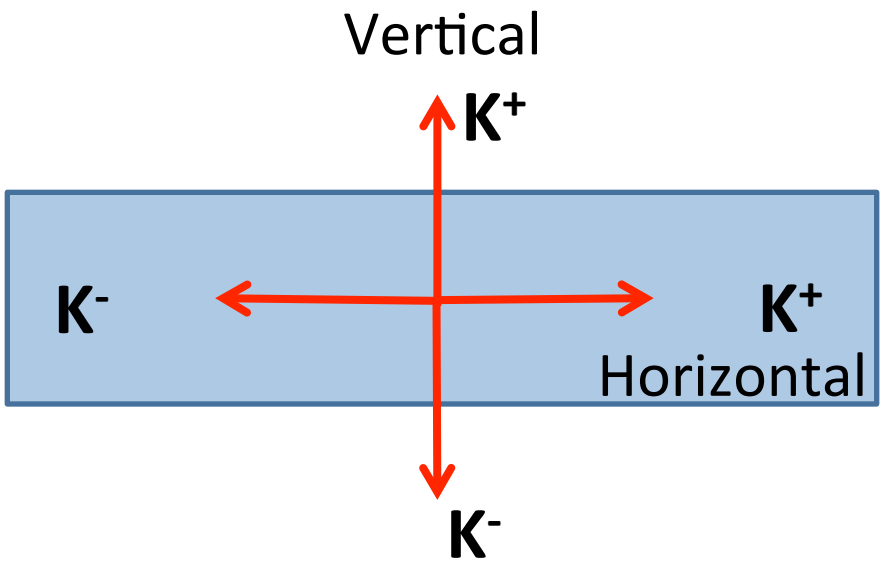


Vertical



Origin of polarization dependence

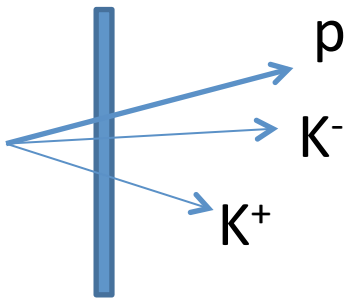
The spectrometer acceptance has approximately rectangular shape.



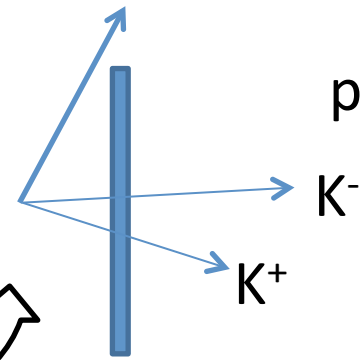
If K^+ and K^- prefer to fly parallel to the polarization,
the acceptance difference cause the difference of the strength
→ Suggesting non-resonant KK has p-wave component

Schematic explanation of MC-based exclusive analysis

proton **"tagged"** events



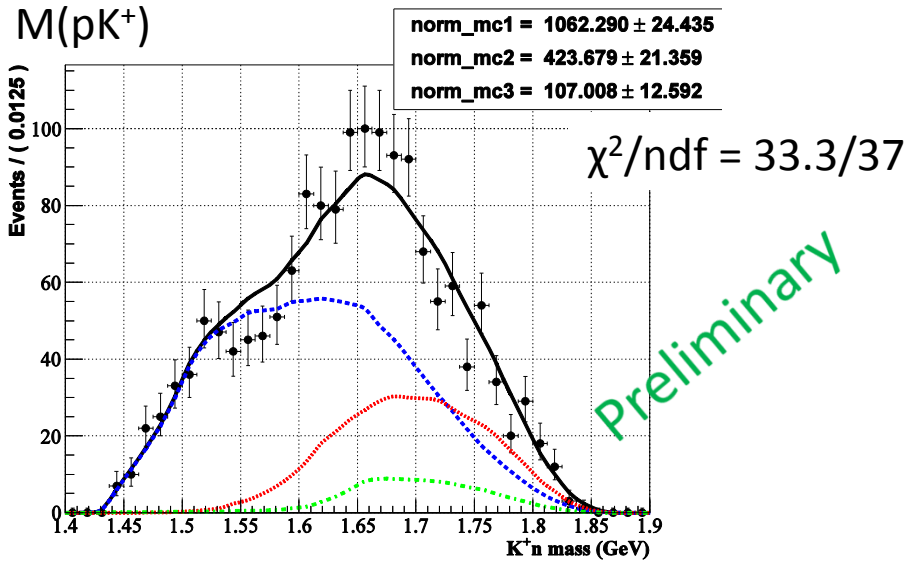
proton **"leaked"** events

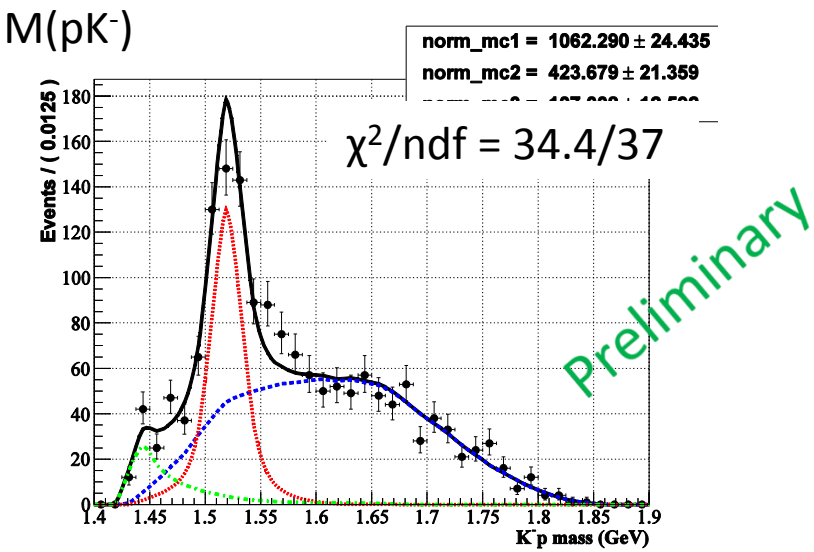


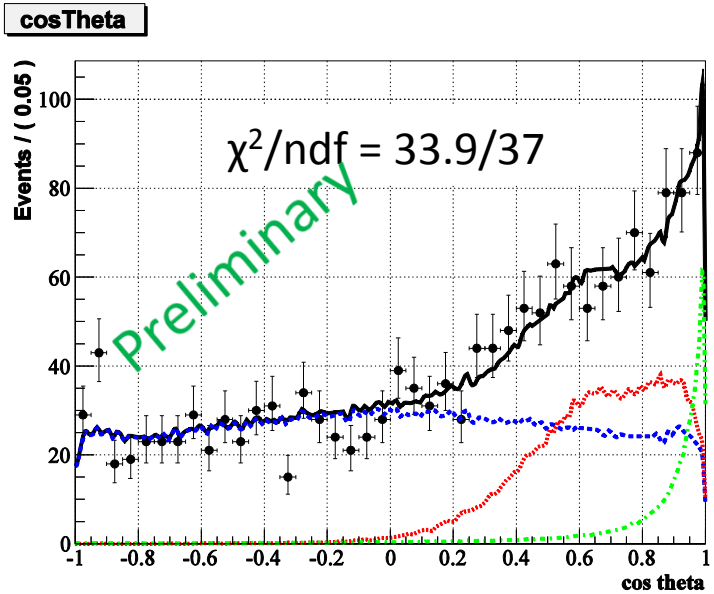
Estimation with a help of MC

Note: the fluctuation at 1.53 GeV/c^2 in M(pK^+) in the previous data is removed.

Fitting proton-tagged events







ϕ and non-resonant KK

Λ(1520)

Λ(1405)

Summed

- Extended maximum-likelihood un-binned fit.
- M(pK$^+$), M(pK$^-$), cos(Θ) of K$^+$ are simultaneously fitted.
- Ratio of ϕ to non-resonant KK is determined from M(KK).
- Λ(1405) to explain threshold enhancement of M(pK$^-$)
- χ^2/ndf is close to one.

Proton/neutron ratio from two methods

1. Ratio of estimated proton contribution to the neutron contribution for the full data sample

   → 4616/2831 = 1.61

2. Ratio of tagged proton contribution to the neutron contribution for the sample with vtz cut

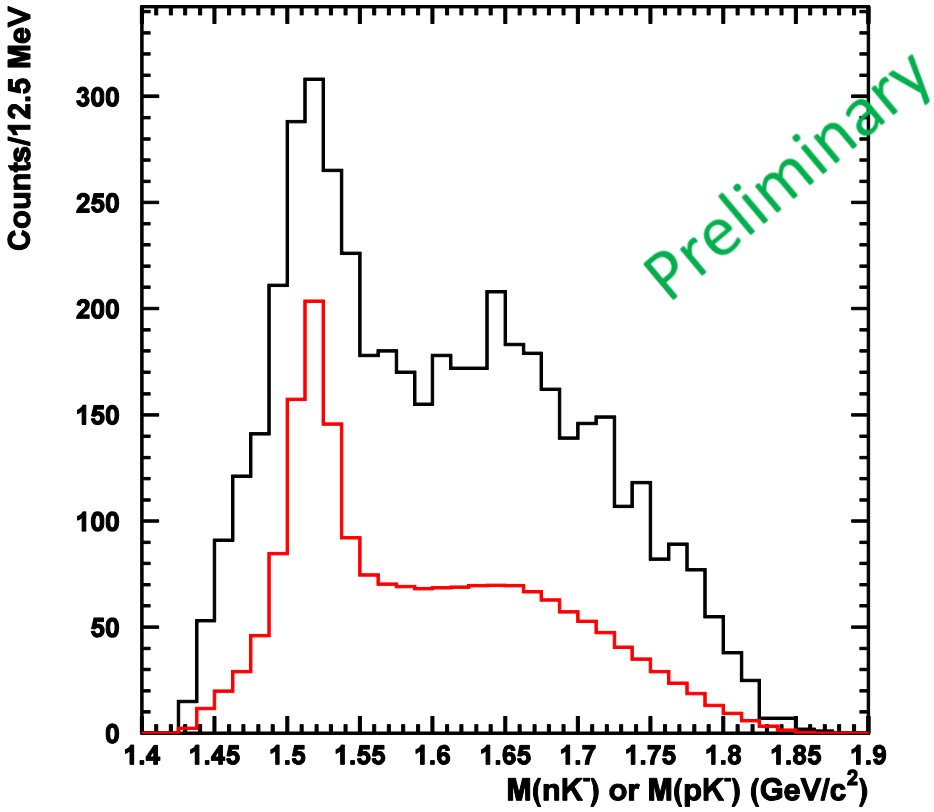
   (proton tagging efficiency of 0.9 was taken into account)

   → 1770/1119 = 1.58

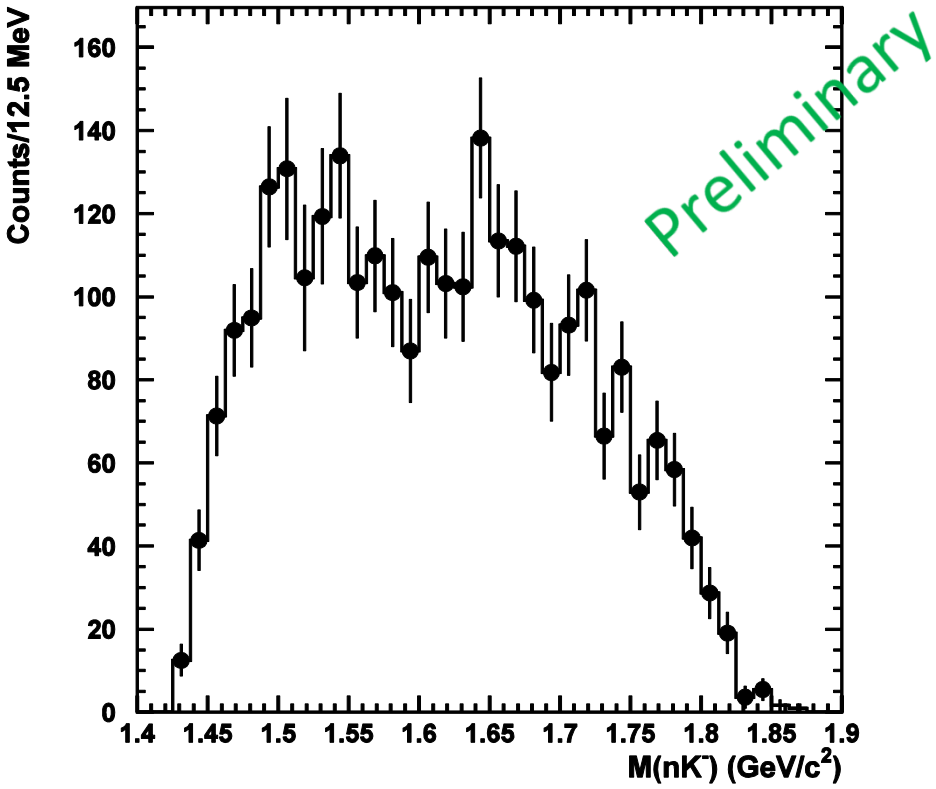
M(nK$^-$) distribution

✓The peak did not appear in M(nK$^-$)

n and p(leaked)



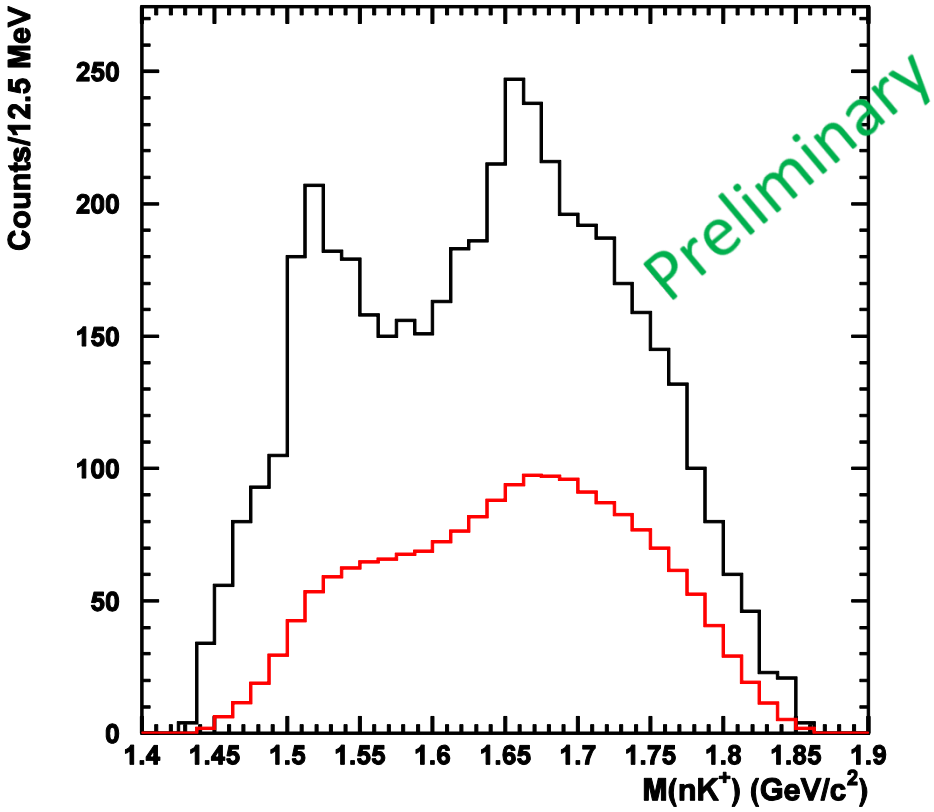
subtracted



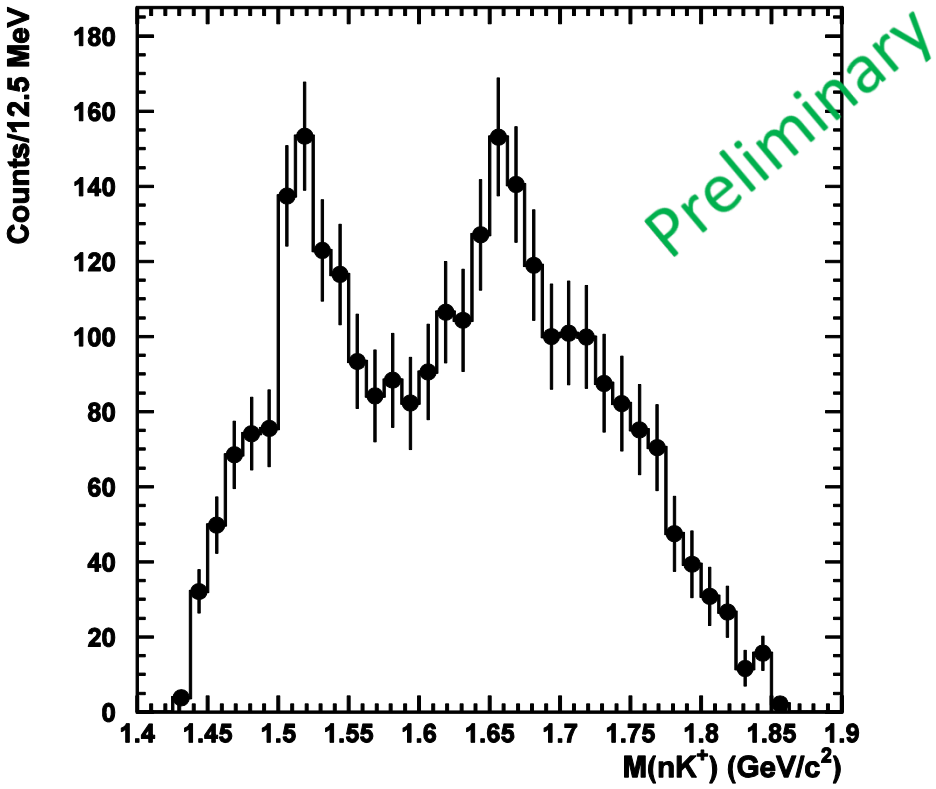
M(nK$^+$) distribution

✓The peak appeared in M(nK$^+$)

n and p(leaked)



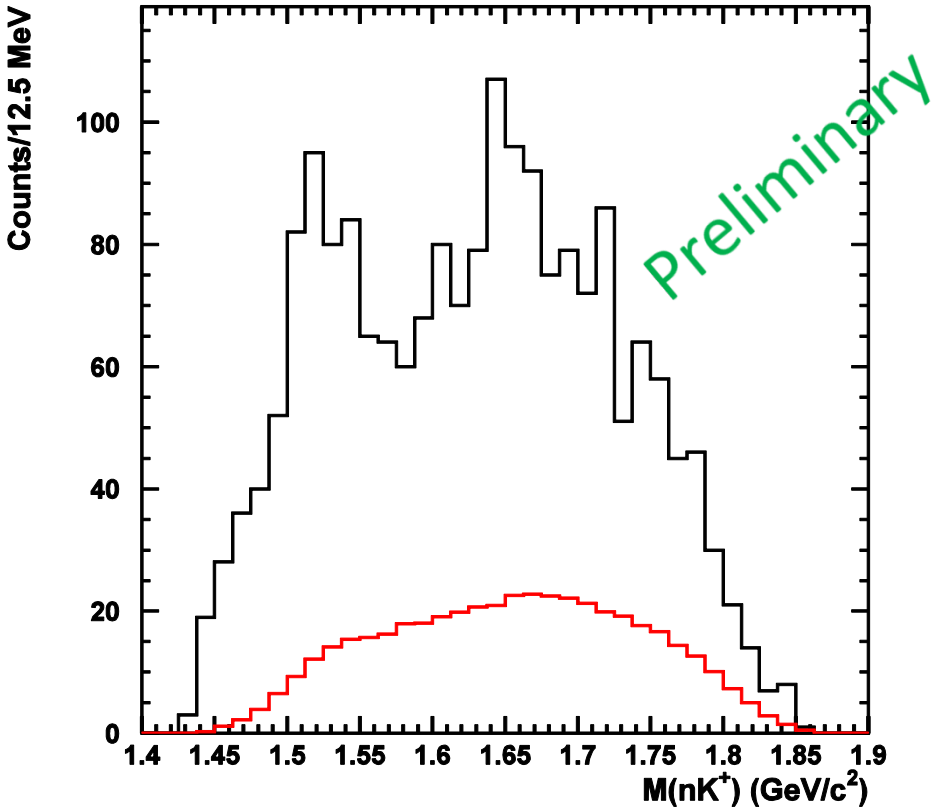
subtracted



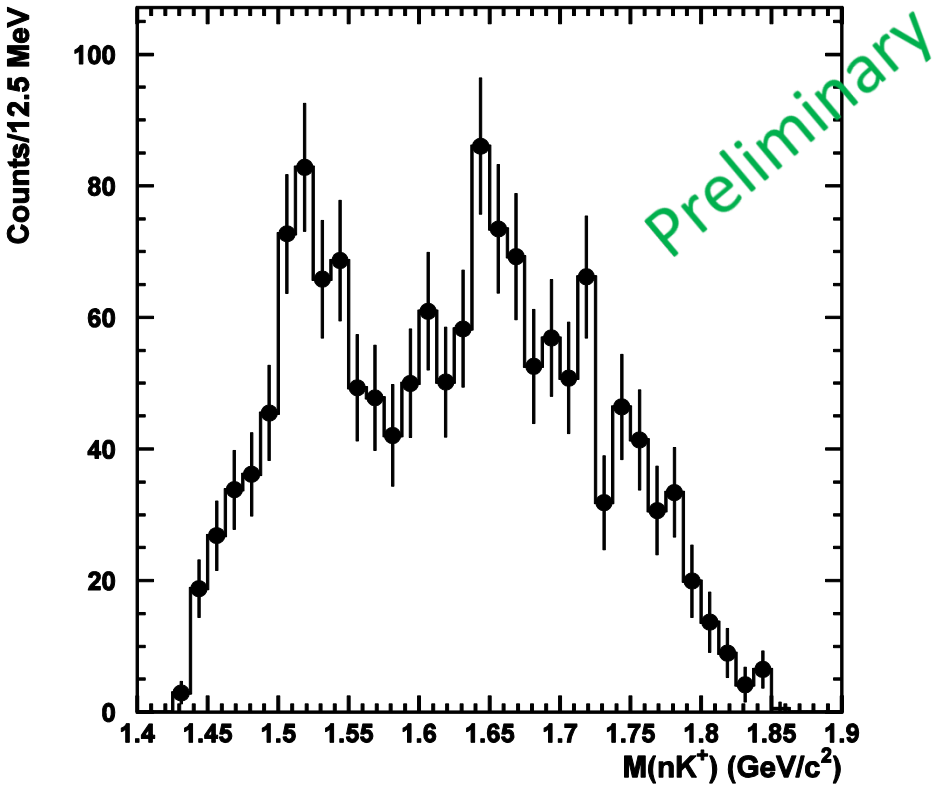
Downstream(vtz>-980 mm)

✓The peak appear in low proton-leakage region.

n and p(leaked)



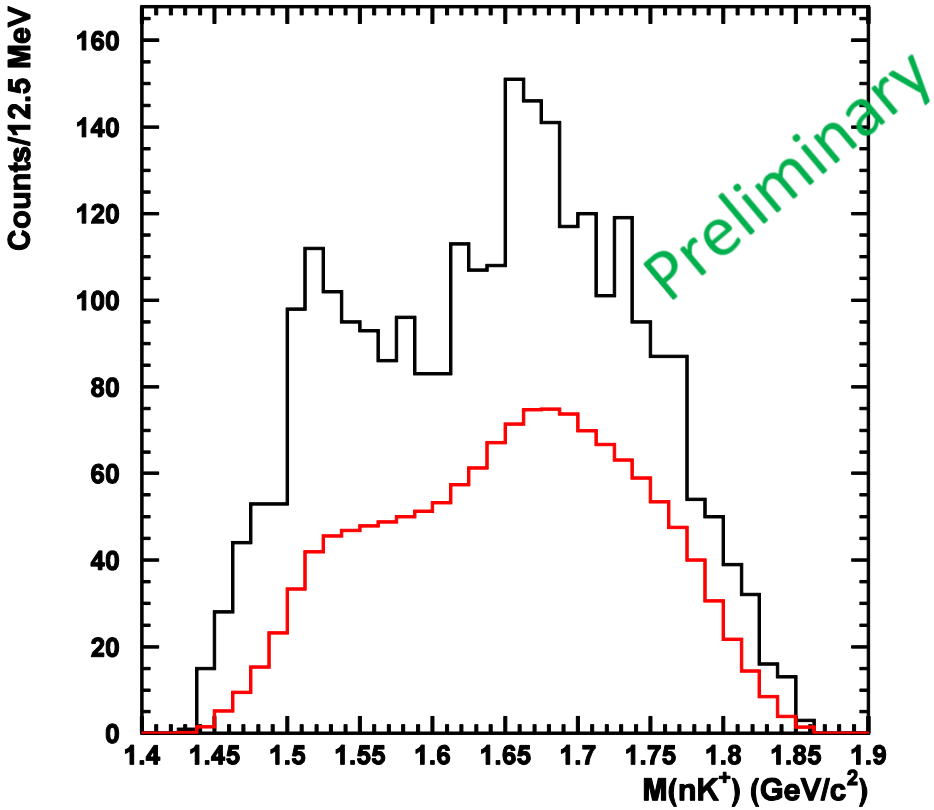
subtracted



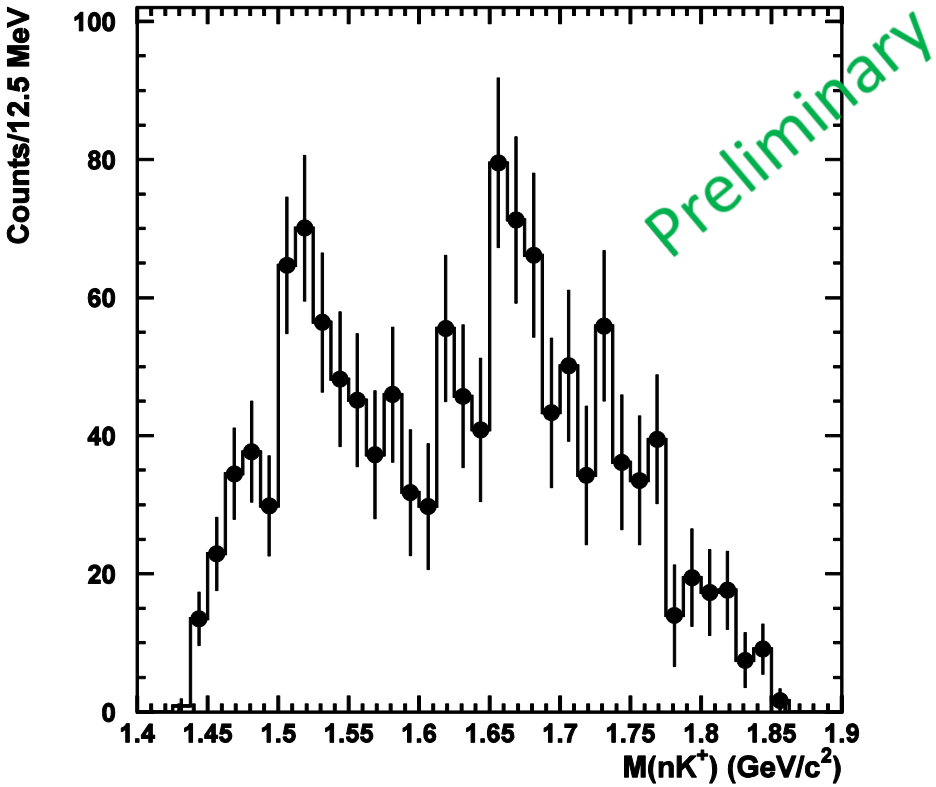
Upstream (vtz<-980 mm)

✓The peak appear in high proton-leakage region.

n and p(leaked)



subtracted

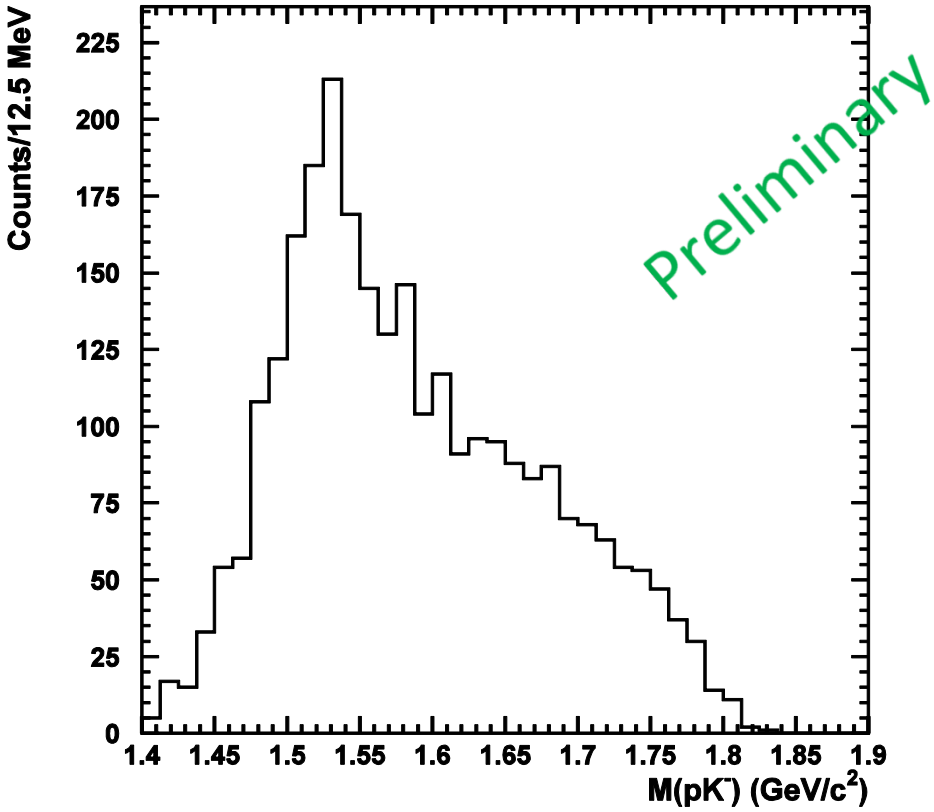


The number of neutron events is consistent with the acceptance.

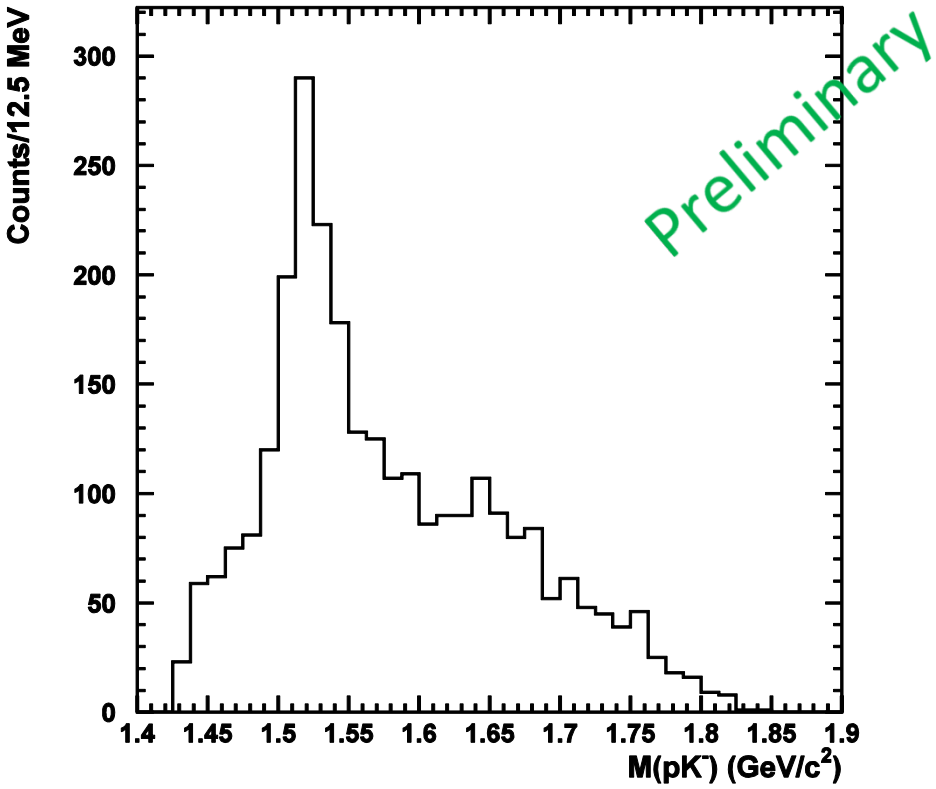
Fermi-motion correction by MMSA

✓MMSA worked for Λ(1520)

w/o correction

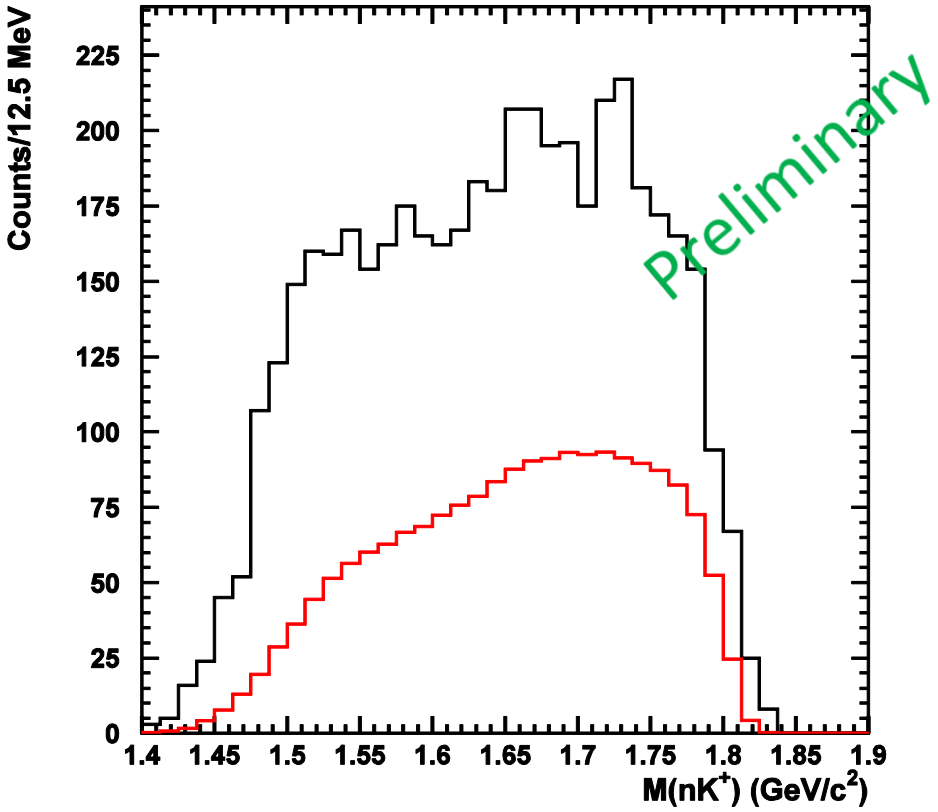


w/ correction

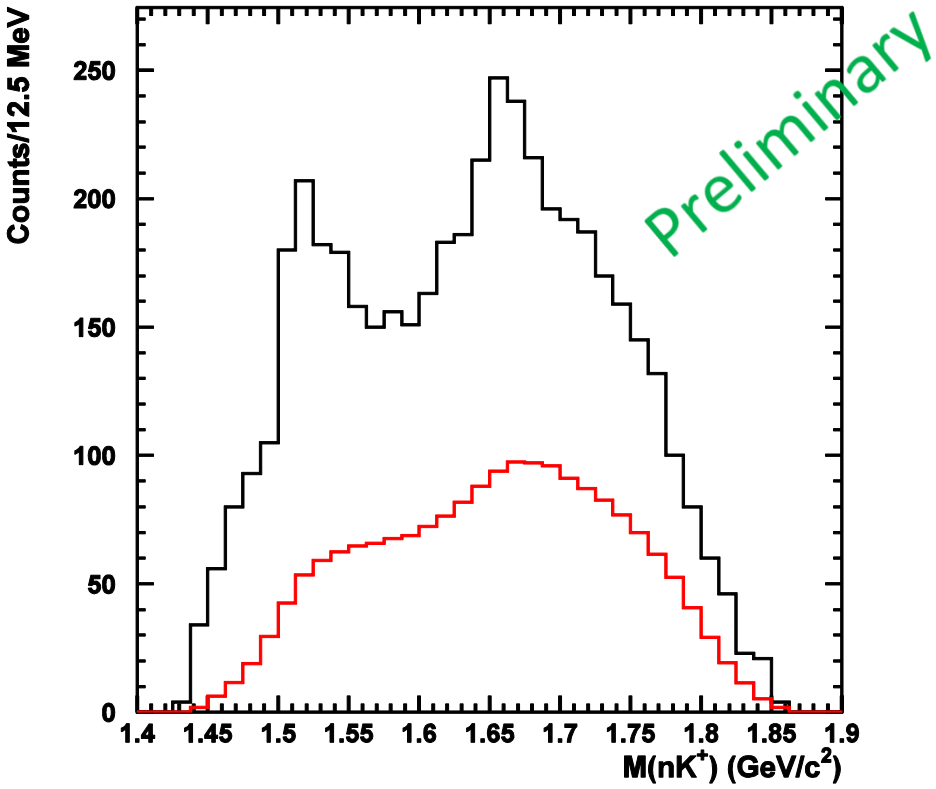


Fermi-motion correction by MMSA

w/o correction



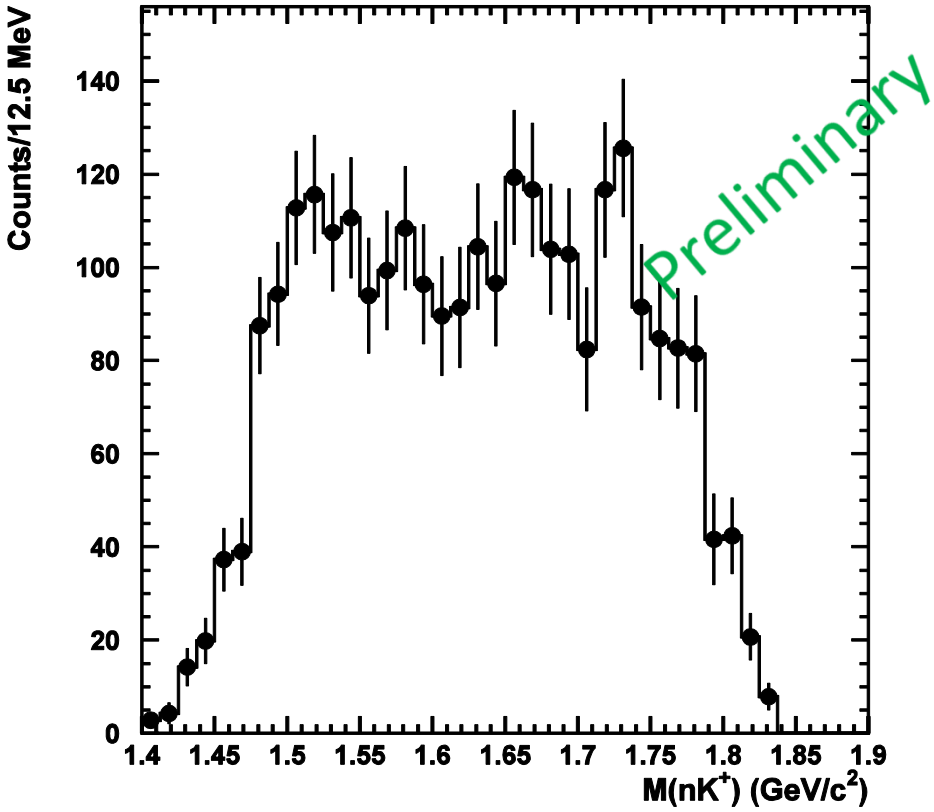
w/ correction



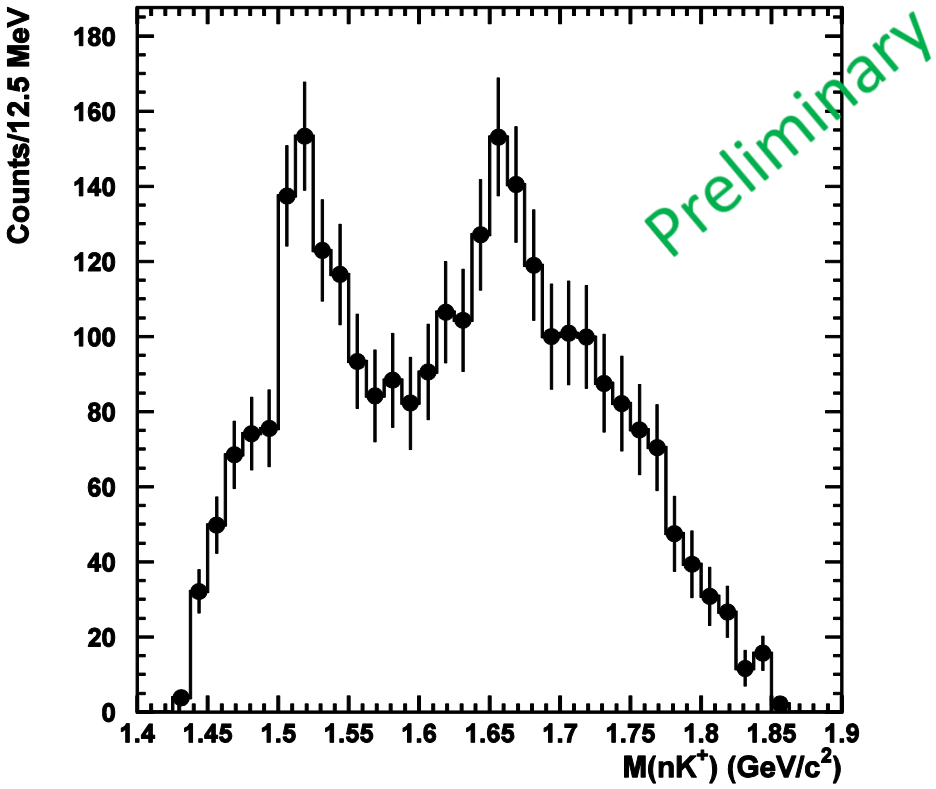
Fermi-motion correction by MMSA

✓MMSA worked for Θ^+

w/o correction



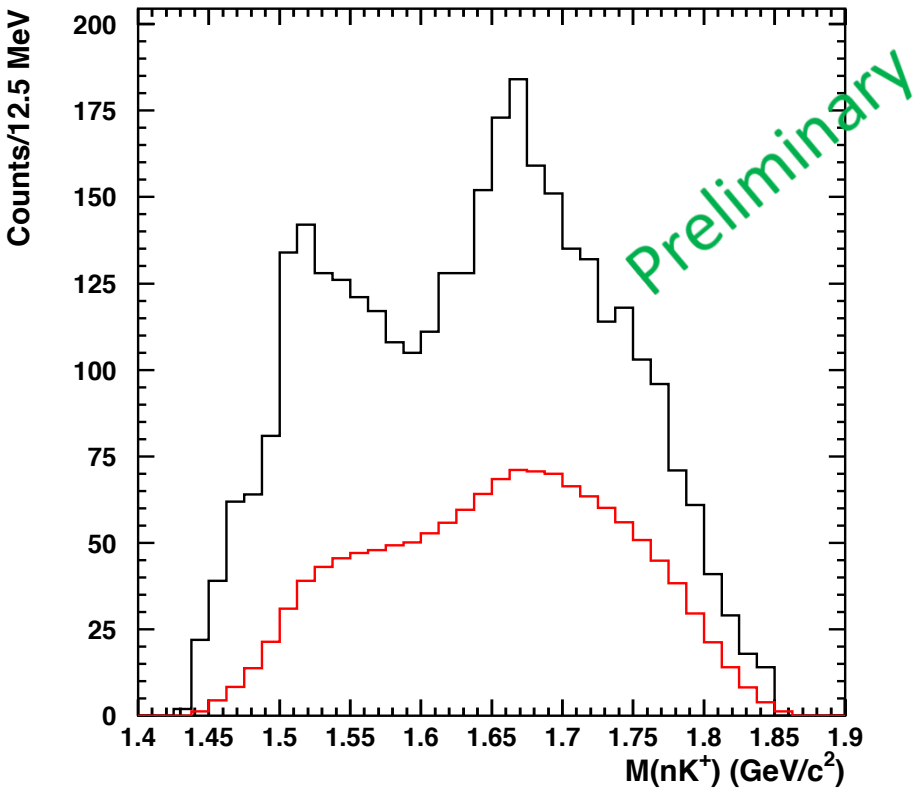
w/ correction



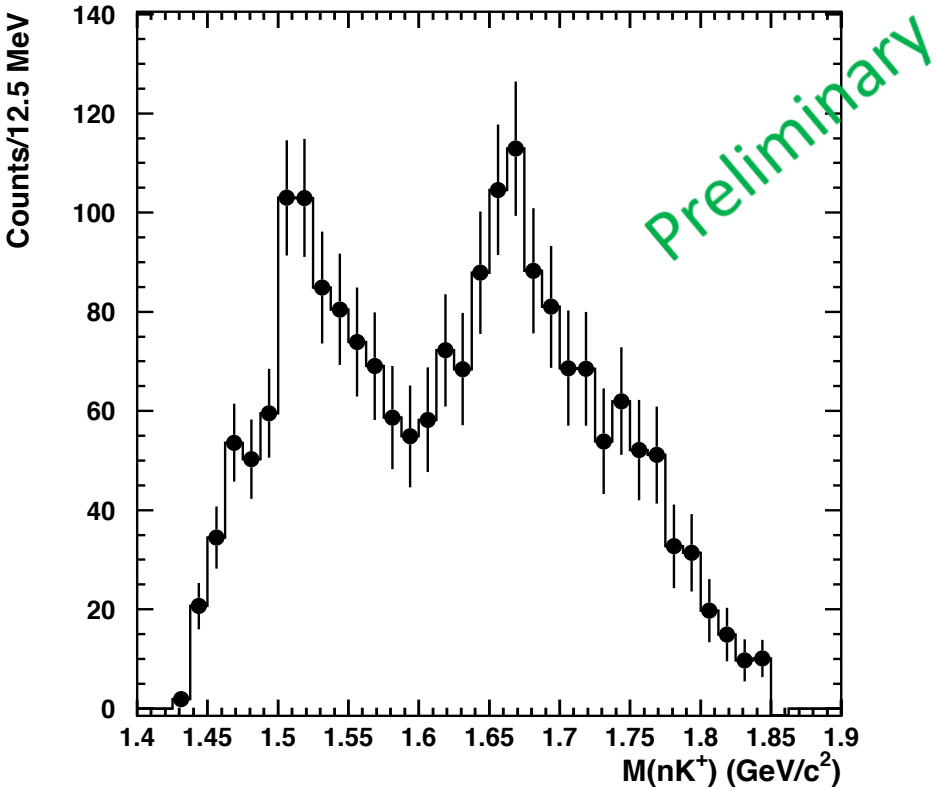
New data (2006-07)

✓The peak appeared in the new data.

n and p(leaked)



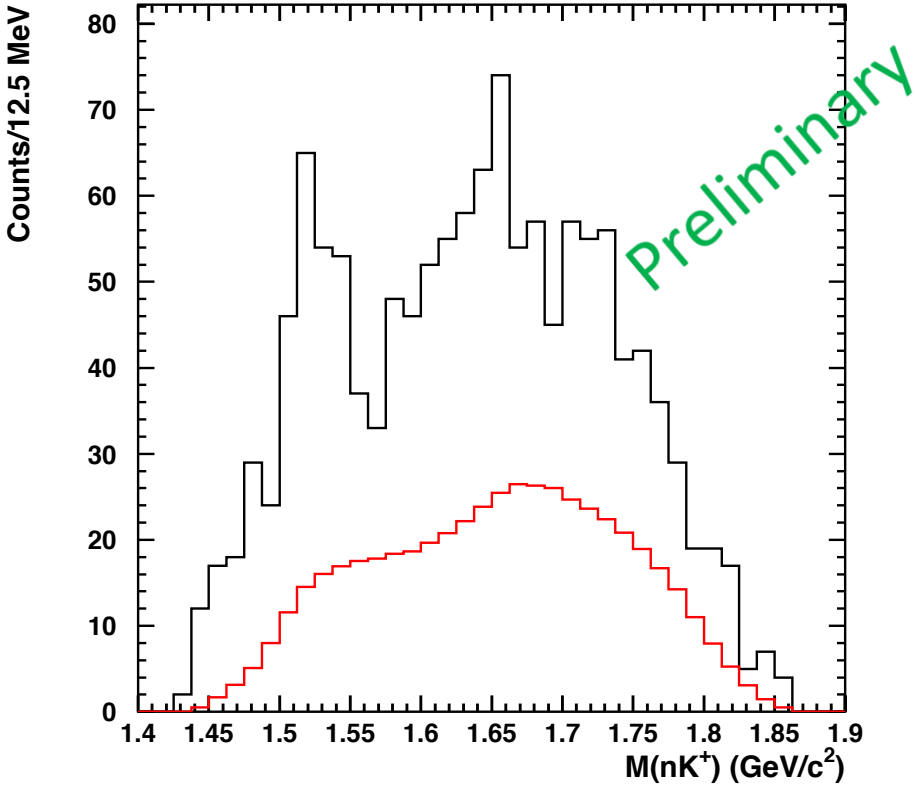
subtracted



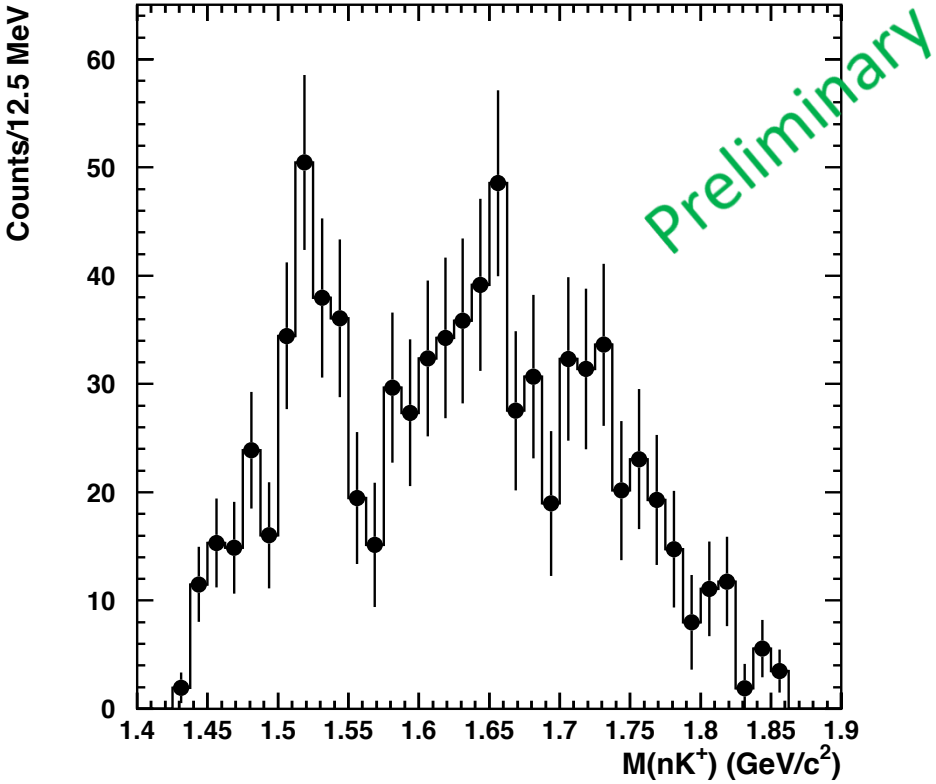
Previous data (2002-03)

✓The neutron spectrum is not much different from that of the new data.

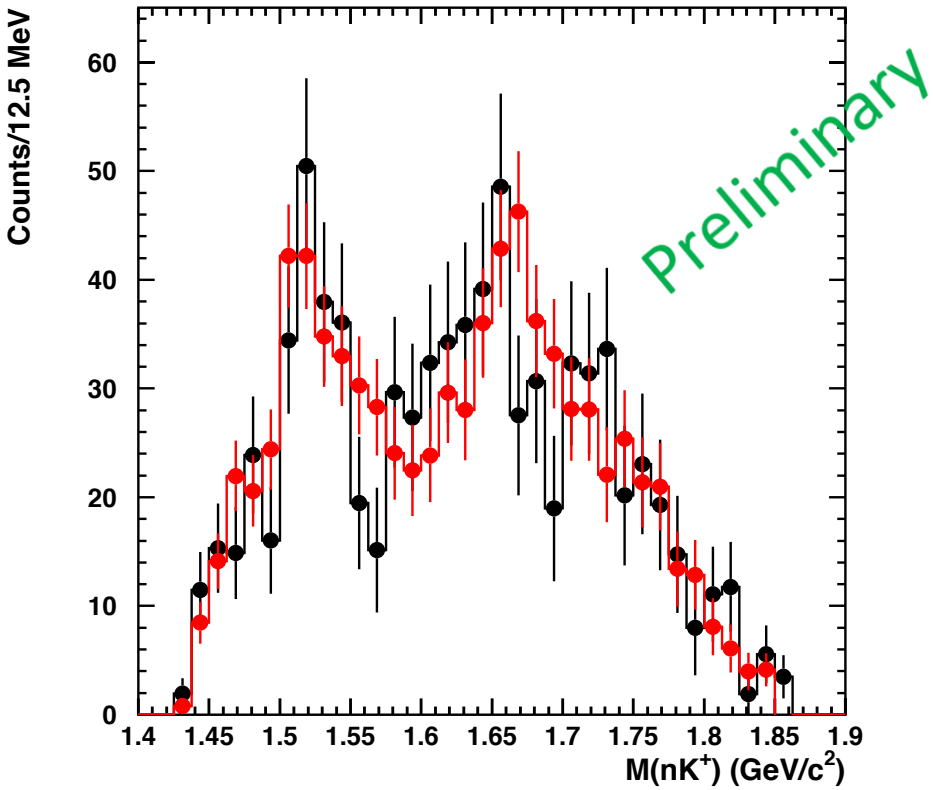
n and p(leaked)



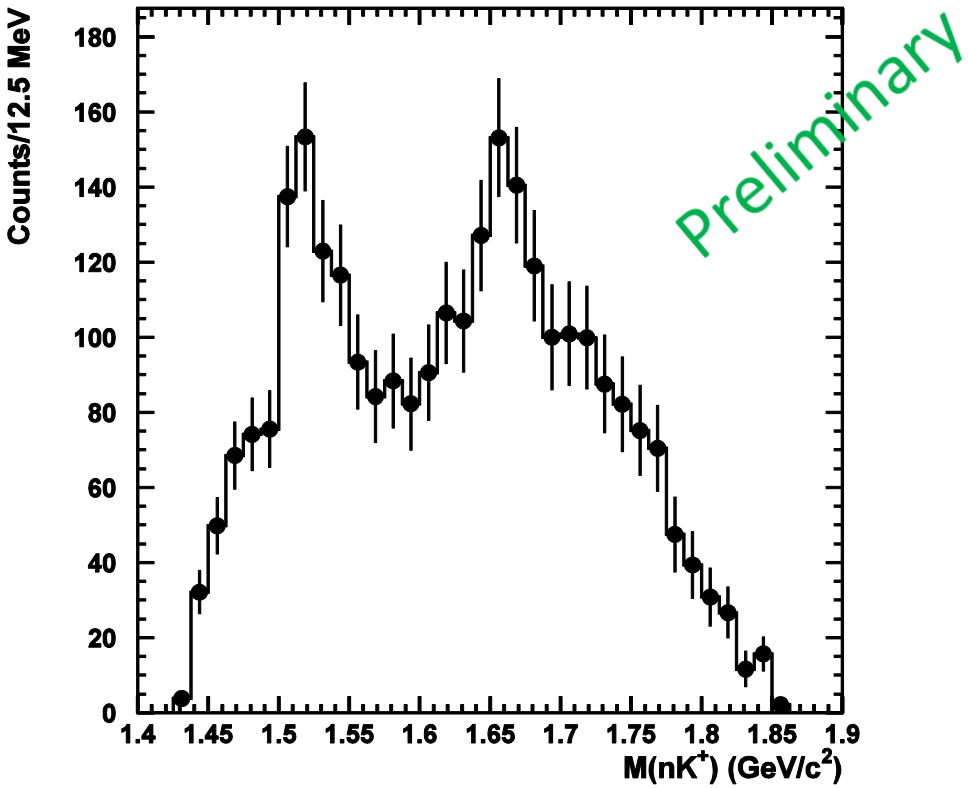
subtracted



Comparison of the previous and new results



M(nK$^+$) distribution of the summed data

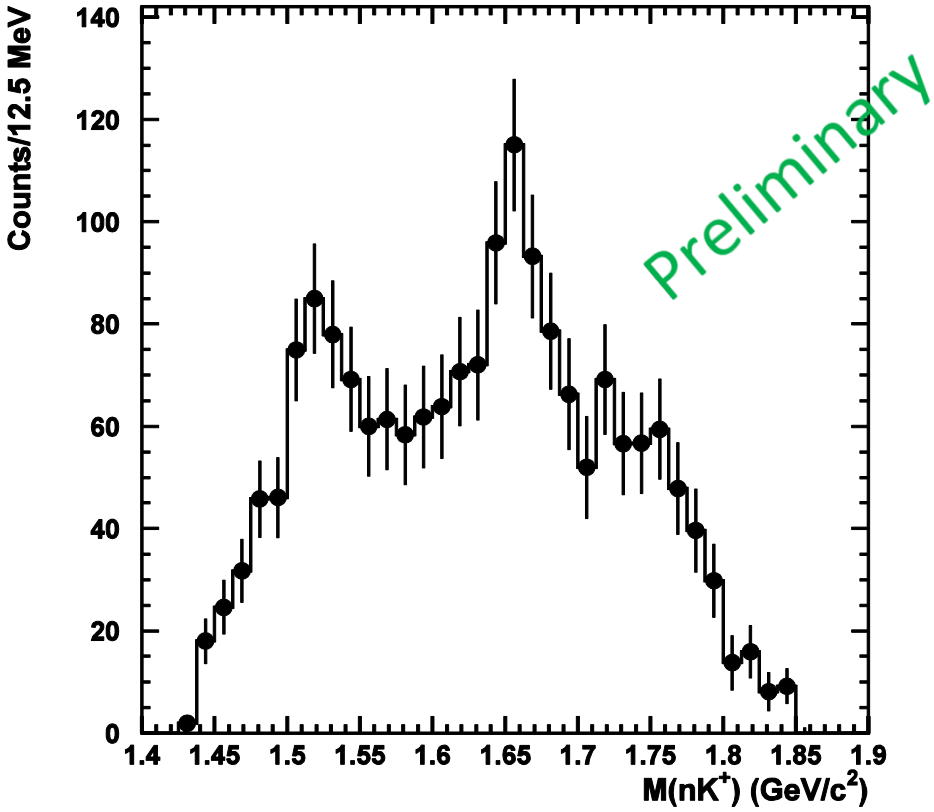


- We are now trying to understand background processes.
- Data taking with a large start counter is on going.

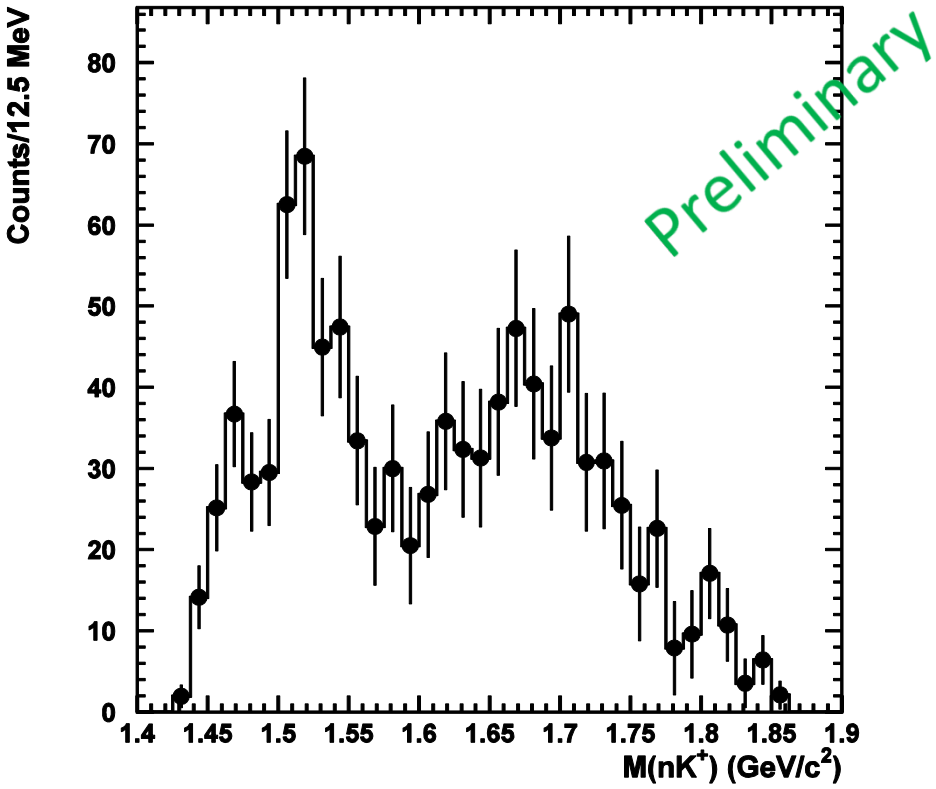
Pol. dependence

✓The large polarization dependence of the S/N ratio was seen.

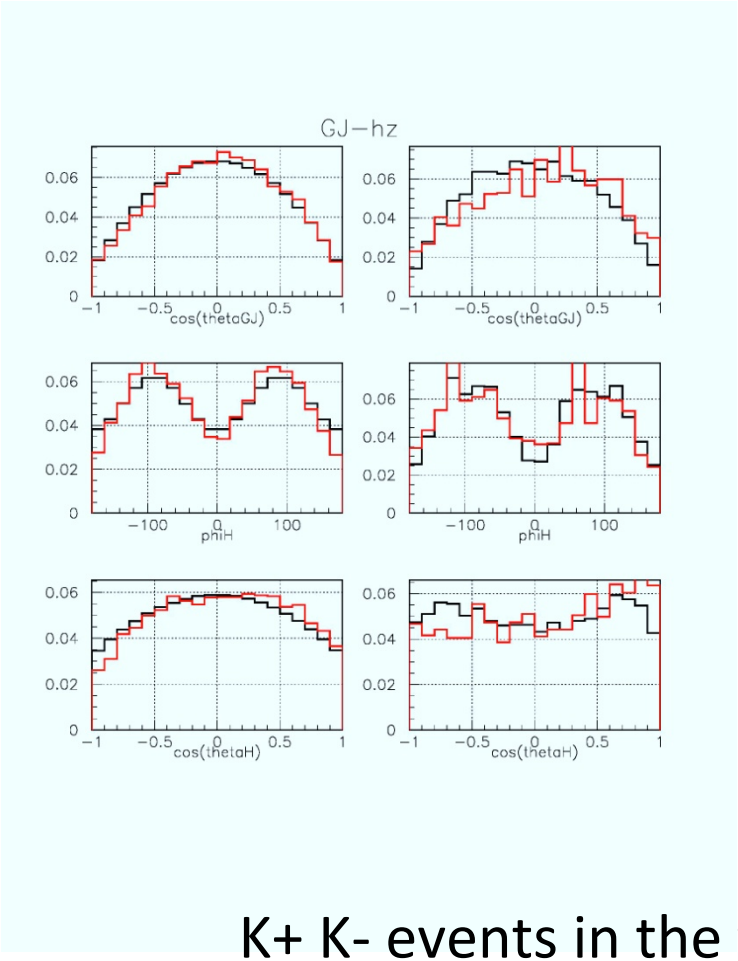
Horizontal

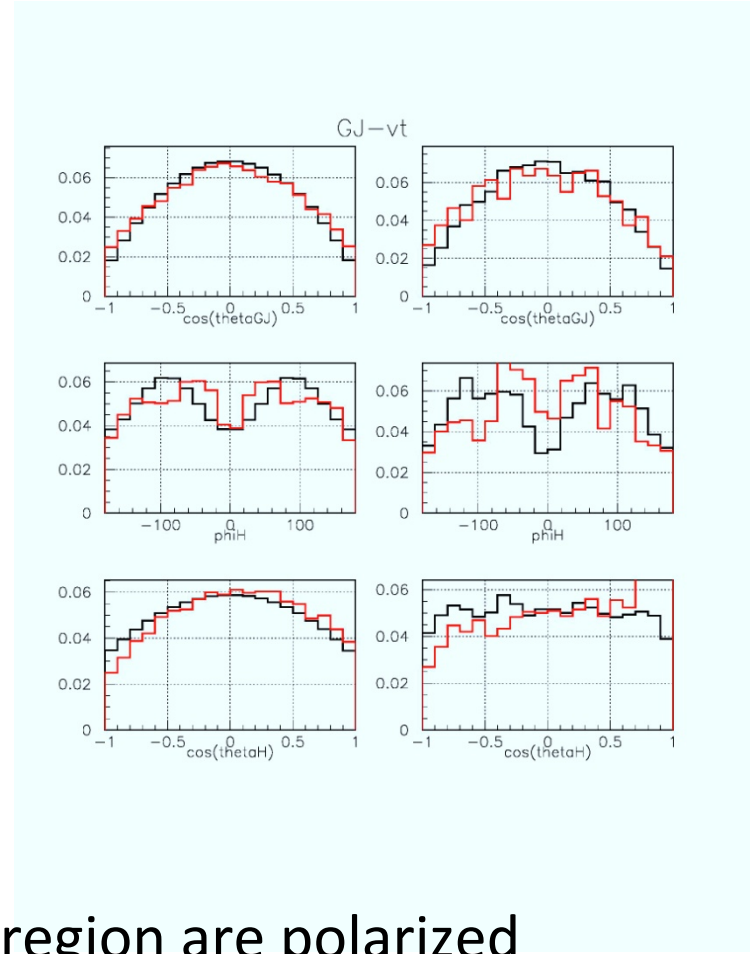


Vertical



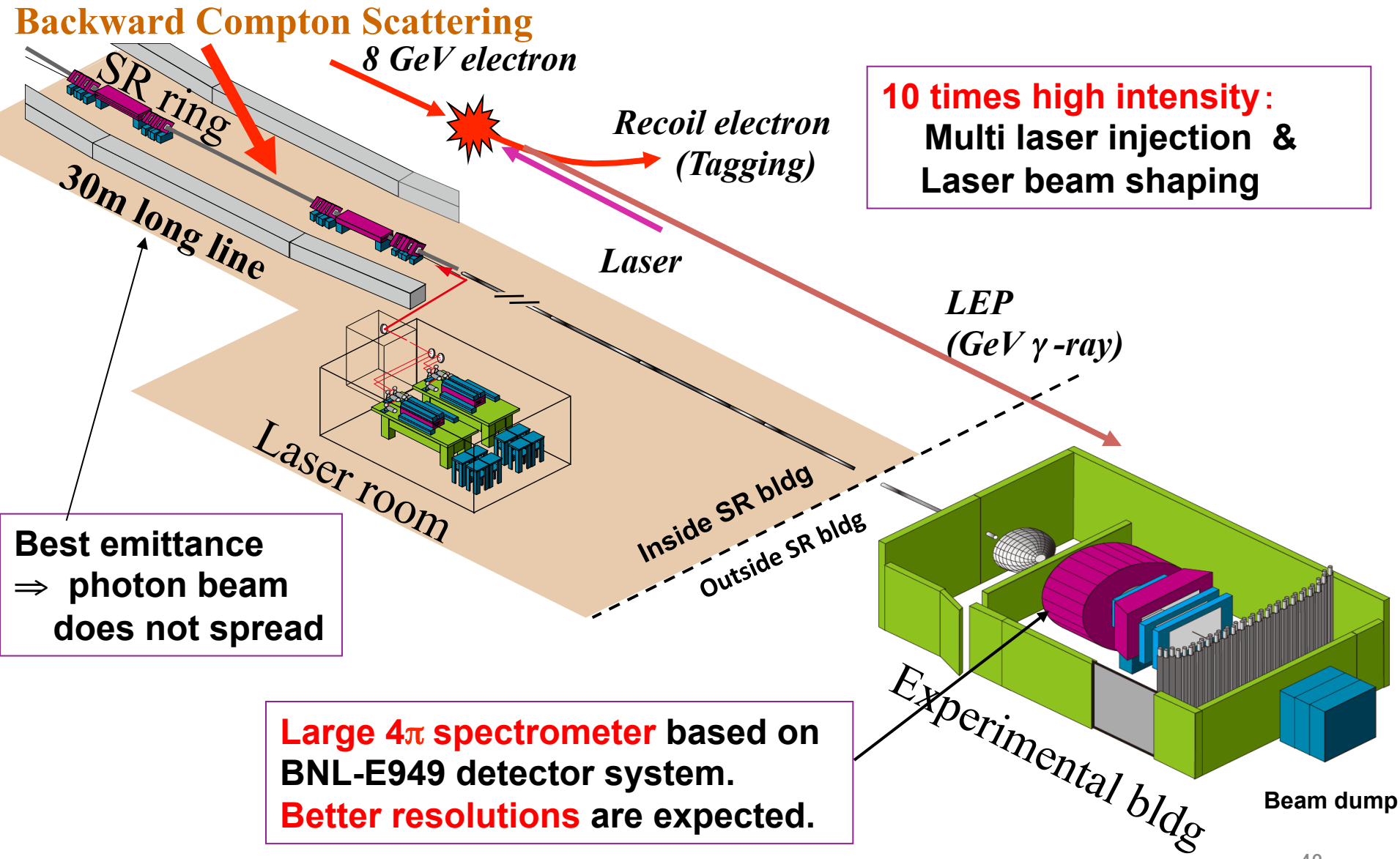
MC (black) vs. Data (red):
All (left column) – After cuts (right column)





K+ K- events in the f tail region are polarized and probably in p-wave.

LEPS2 Facility



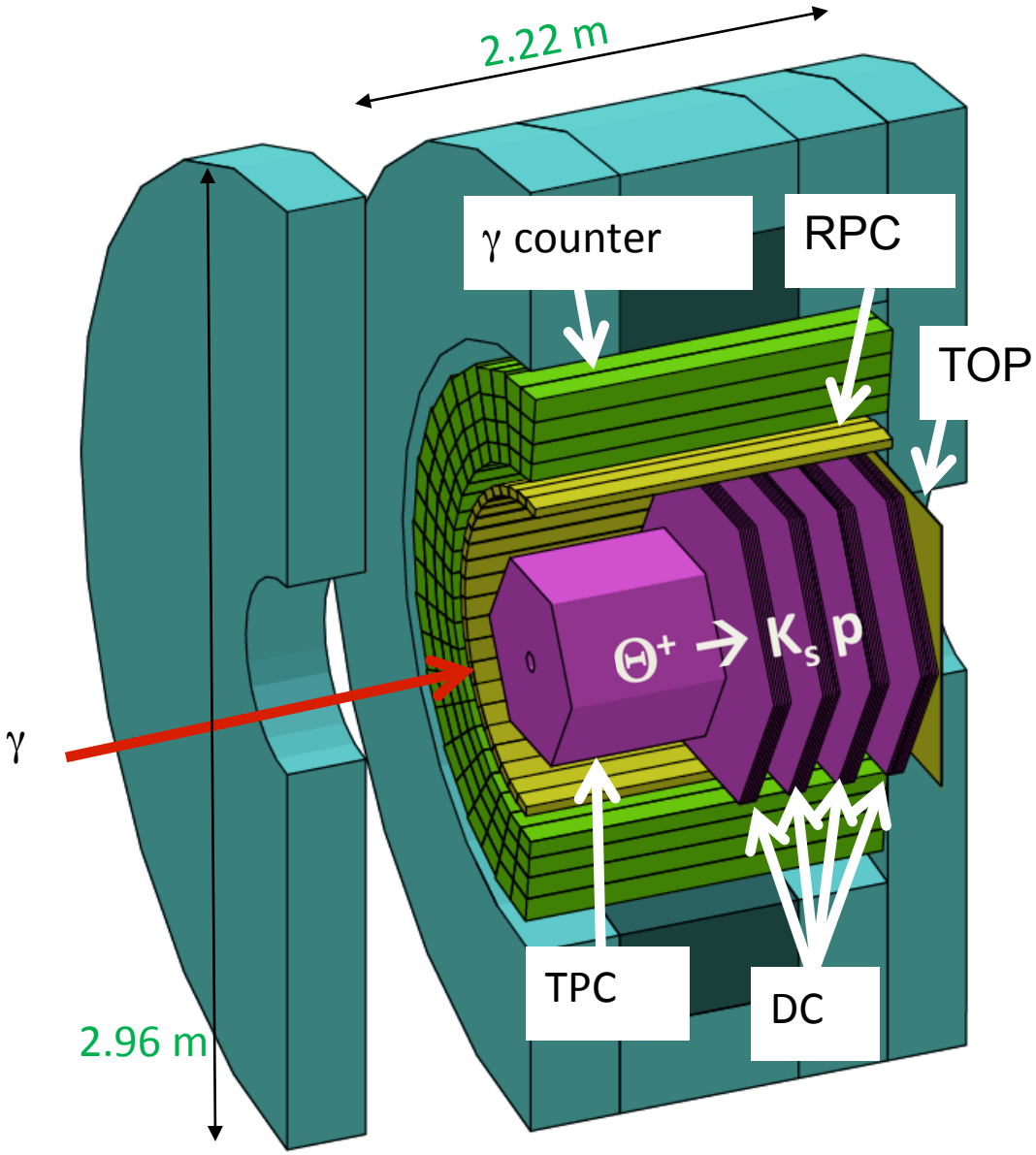
10 times high intensity:
Multi laser injection &
Laser beam shaping

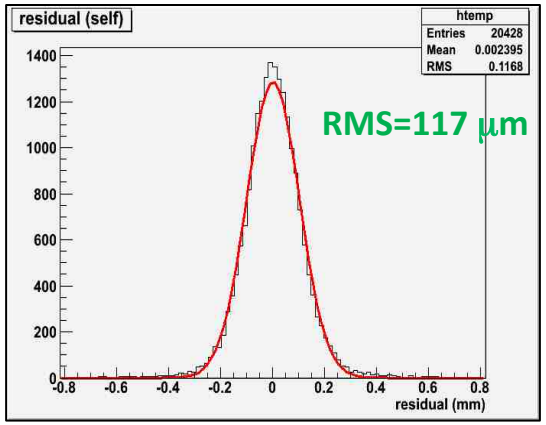
Best emittance
⇒ **photon beam**
does not spread

Large 4π spectrometer based on
BNL-E949 detector system.
Better resolutions are expected.

LEPS2 Detector

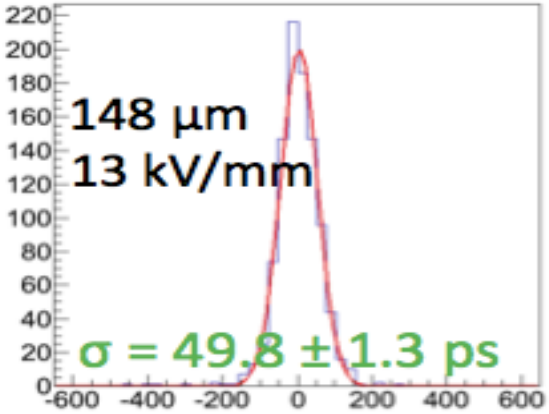
B=1 T : $\Delta p/p \sim 1\%$ for $\theta > 7°$





TPC Prototype Residual

RPC ToF time distribution



>3σ K/π separation @1.1 GeV/c^2

Exp. hall was constructed. (2010.Oct-2012Jan)

Installation of the E949 magnet (2011.Nev-Dec)

γ counters were installed. (2012.June)

Beam pipe (2012.May)

Comparison of LEPS and LEPS2

	LEPS	LEPS2
Beam Intensity (~2.4 GeV)	2~3x10^6 (2 lasers)	<10^7 (4 high-power lasers)
Beam Intensity (~2.9 GeV)	2~3x10^5 (2 lasers)	<10^6 (4 high-power lasers)
Polarization	Linear/Circular	Linear/Circular
Detector Area	42m^2 x 3m(h)	198m^2 x 10m(h)
Charged Particle Acceptance	0~30 degrees	7~120 degrees
Momentum Resolution	0.5% (for 1-GeV kaon)	1~1.5% (for 1-GeV kaon)
Photon Coverage	none	30~110 degrees

We expect to have the first beam at LEPS2 on January 27th.

Summary

•The Θ^+ is studied via $\gamma d \rightarrow K^+K^-pn$ reaction with high statistics data at SPring-8/LEPS.2.6 times higher statistics compared with previous data are collected.

•The inclusive $M(NK^+)$ spectrum for new data does not show a strong narrow peak, which is inconsistent with the previous shape analysis.

-The significance of the peak in new data is less than 2 σ by the shape analysis.

- ❖ The background shapes were not the same.
- ❖ A fluctuation was seen in proton tagged events of the previous data.

Summary

•Exclusive analysis is performed by identifying the proton contribution using energy loss in SC.

-A part of the inconsistency was due to fluctuation in proton tagged events.

-Enhancement of events are seen in the region of $1.5<M(nK^{+})<1.55$ GeV/c^2 for proton rejected events.

-The enhancement is seen in the both new and previous data.

-S/N ratio strongly depends on the beam polarization.

• These results are checked and confirmed by MC-based exclusive analysis.

• Mass and significance estimation of the enhancement is underway.

• LEPS collaboration just started new experiment with a large SC.

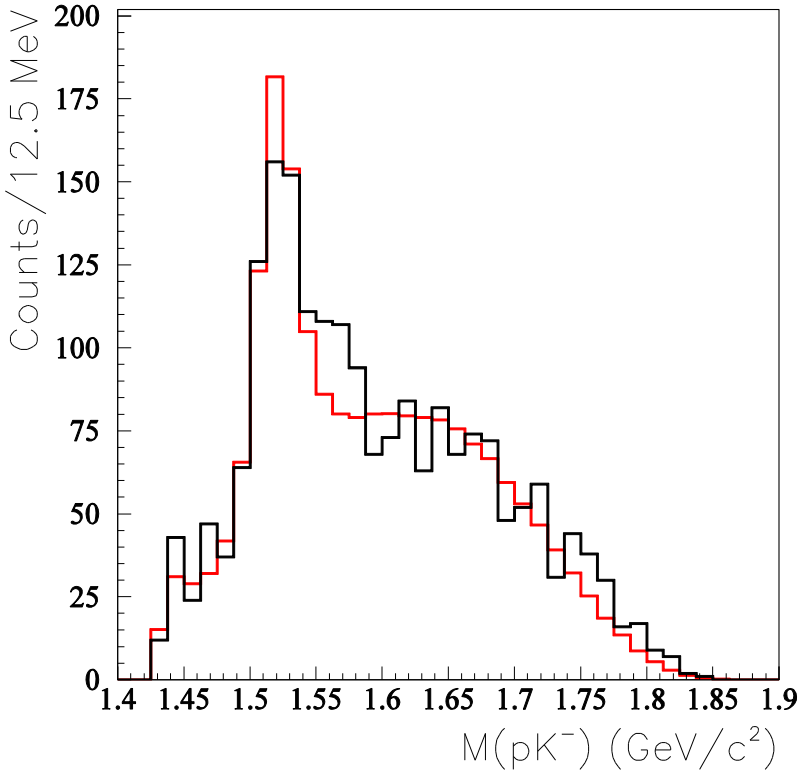
Backup

Comparison of data and MC with loose ϕ cut

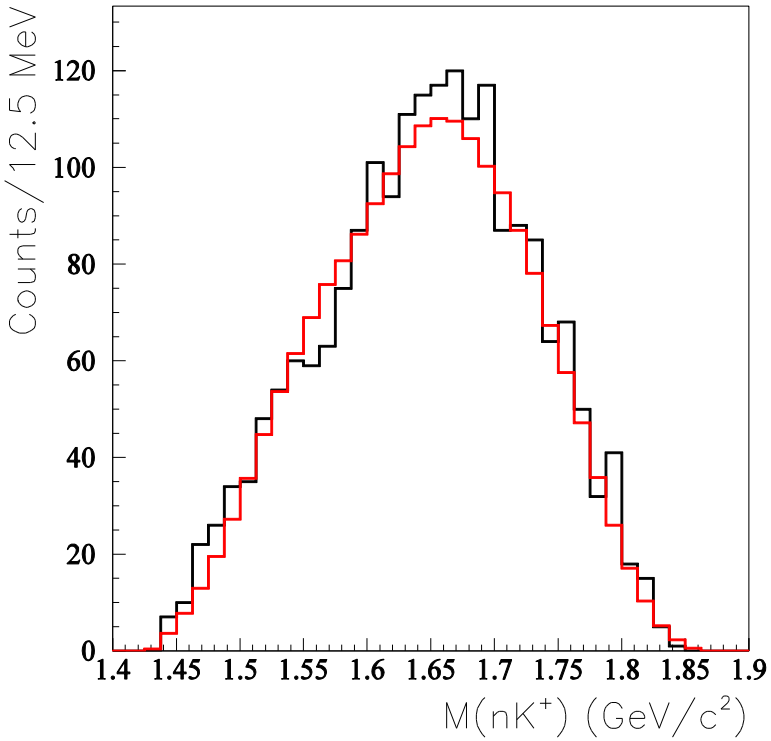
Data

MC

M(pK$^-$)

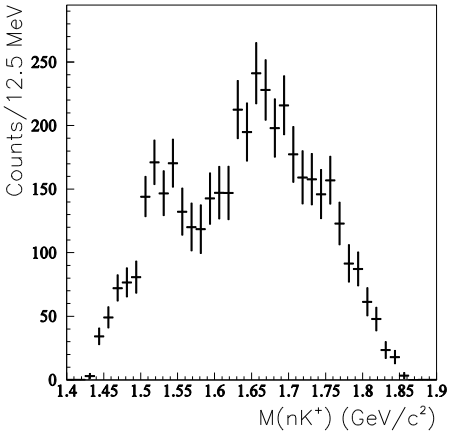


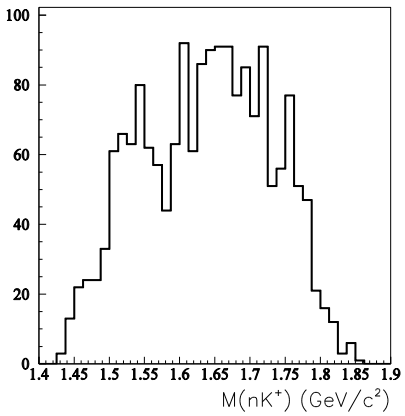
M(nK$^+$)



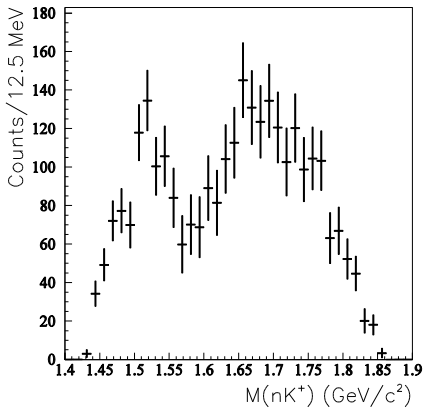
- ϕ events are excluded by M(KK)>1.03 GeV/c^2
- z-vertex, proton tagging cut is applied
- Good consistency between data and MC

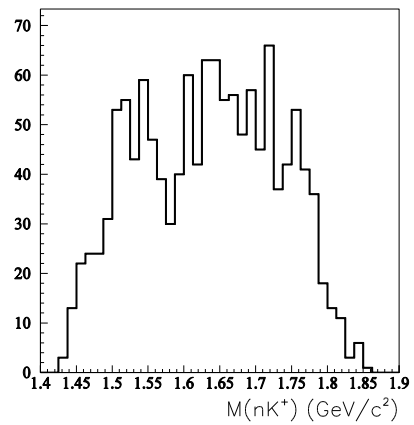
dE/dX based and MC based M(nK+) with constant ϕ cut



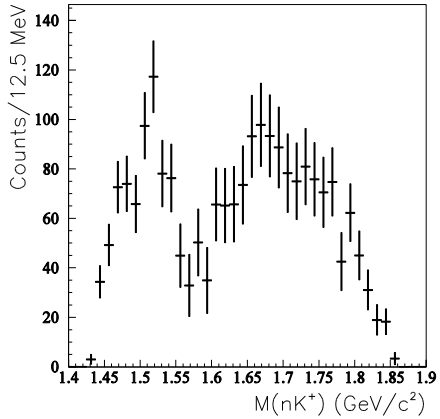


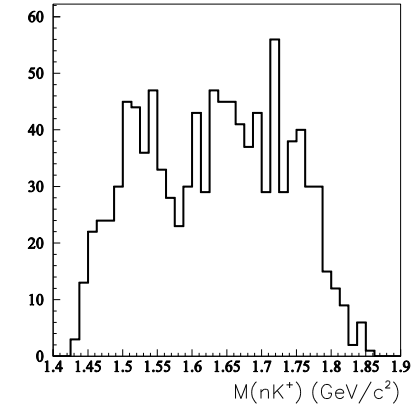
M(KK)>1.03 GeV/c^2





M(KK)>1.04 GeV/c^2



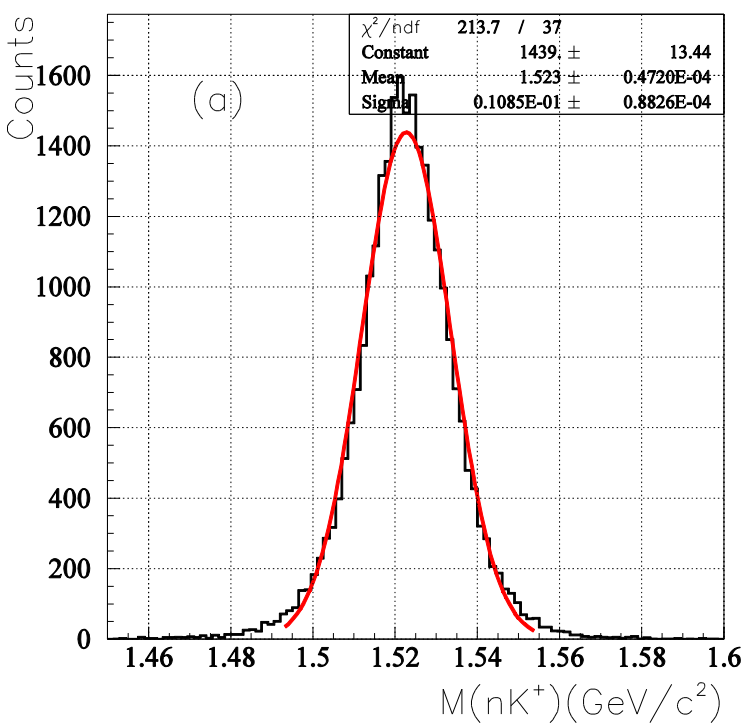


M(KK)>1.05 GeV/c^2

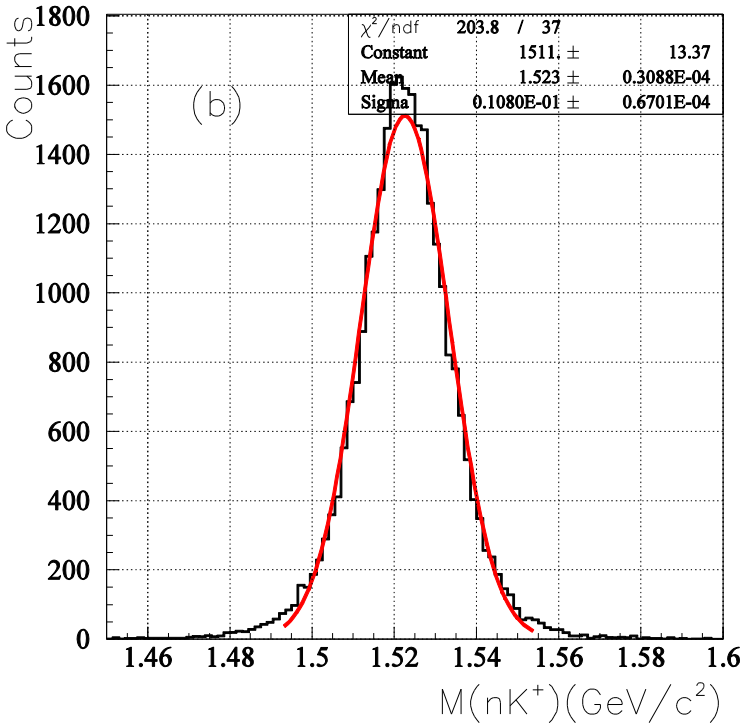
Expected mass resolution for Θ^+

Signal MC with realistic DC and E_γ resolution

Previous data 10.9±0.1 MeV/c^2

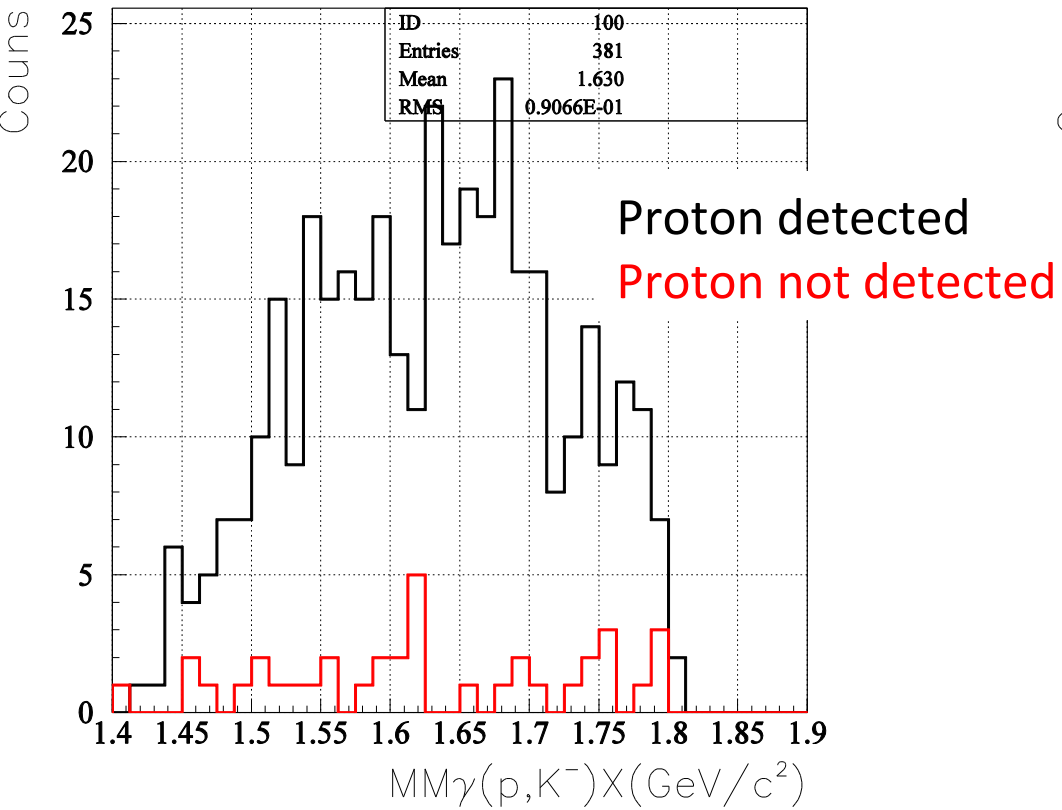


New data 10.8±0.1 MeV/c^2

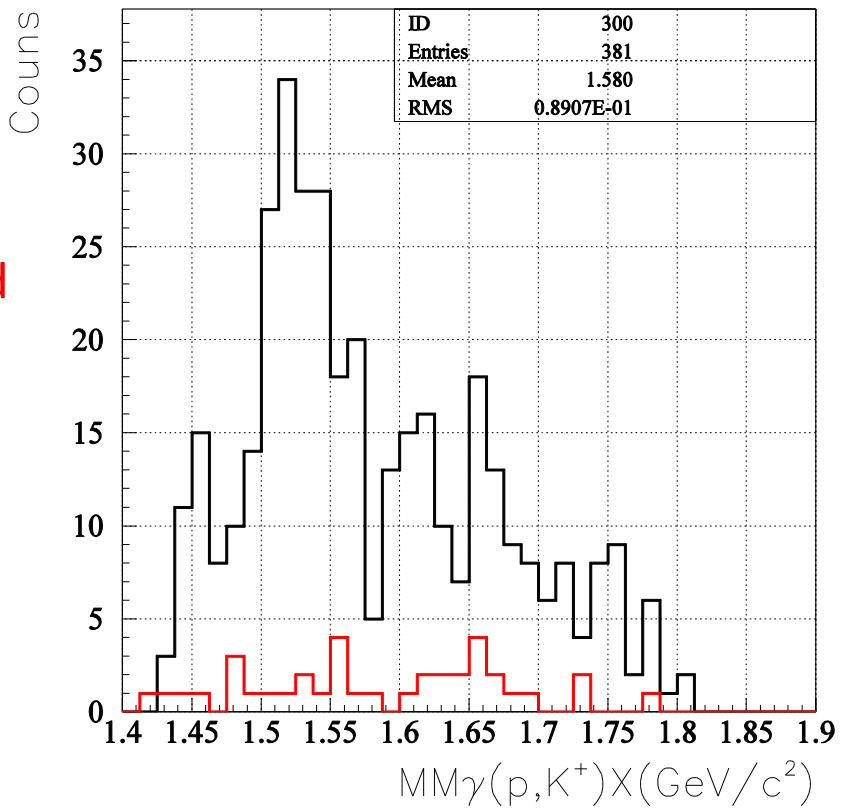


Check the bias of proton tagging by LH2 data

MMγ(p,K⁻)X



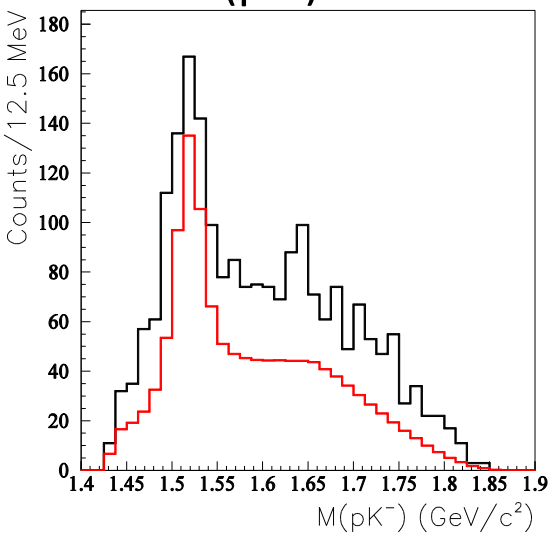
MMγ(p,K⁺)X



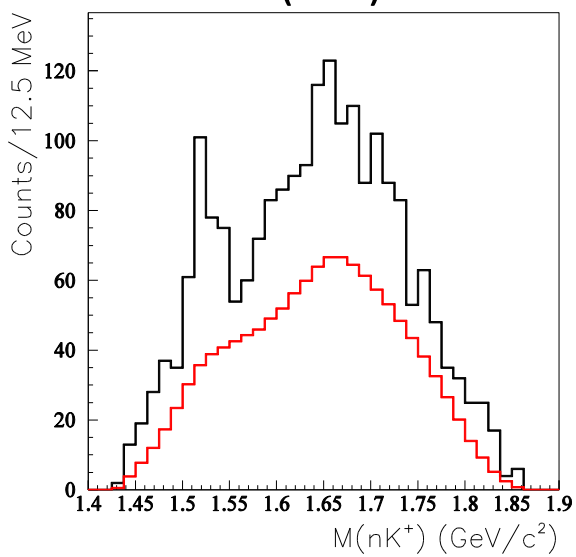
- No significant structure for un-tagged events
- Number of events are actually very small

Subtract proton contribution for previous data

M(pK⁻)



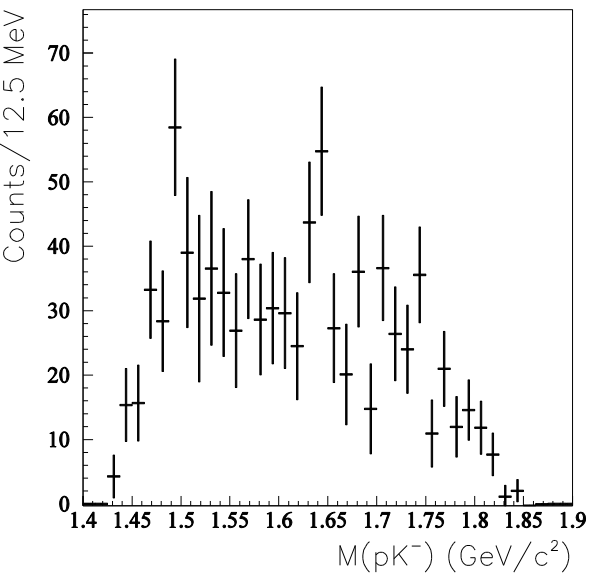
M(nK⁺)



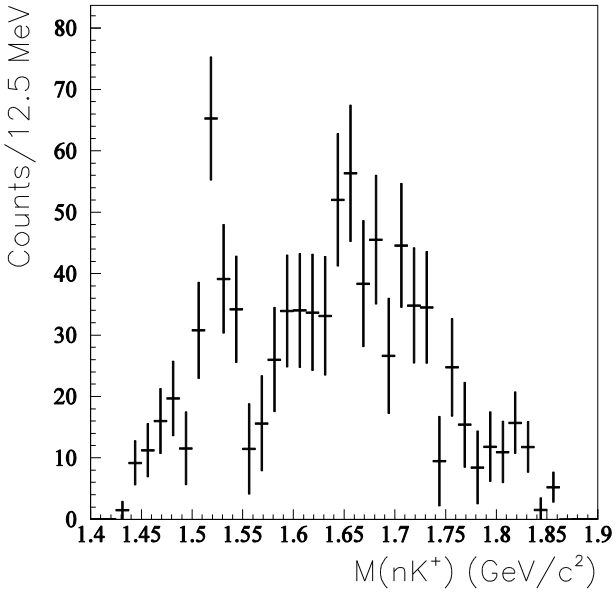
Real data

Proton events from MC

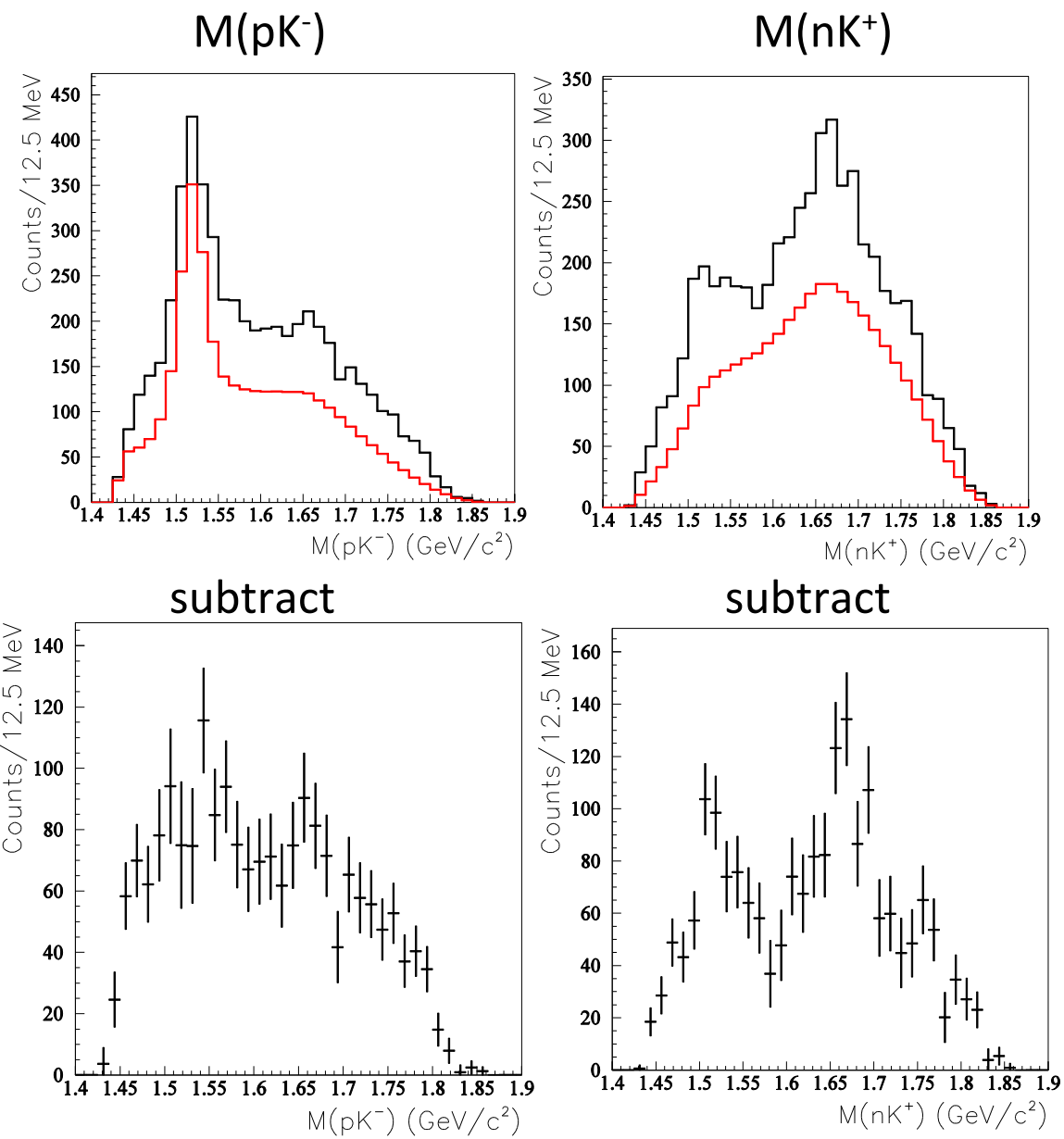
subtract



subtract



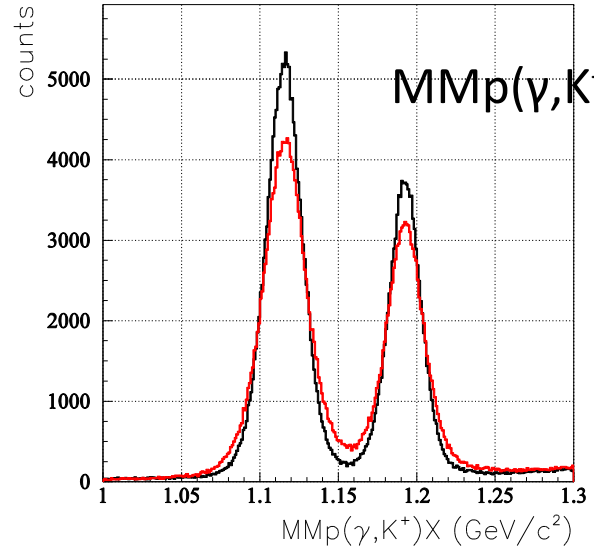
Subtract proton contribution for 06-07 data

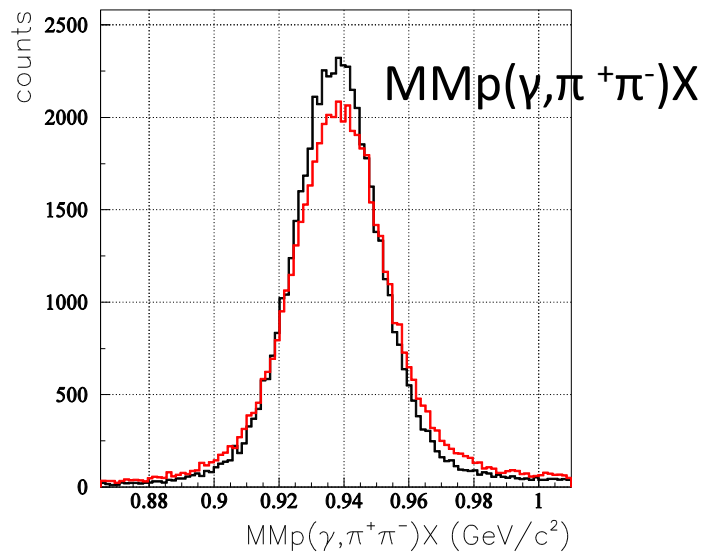


Real data

Proton events from MC

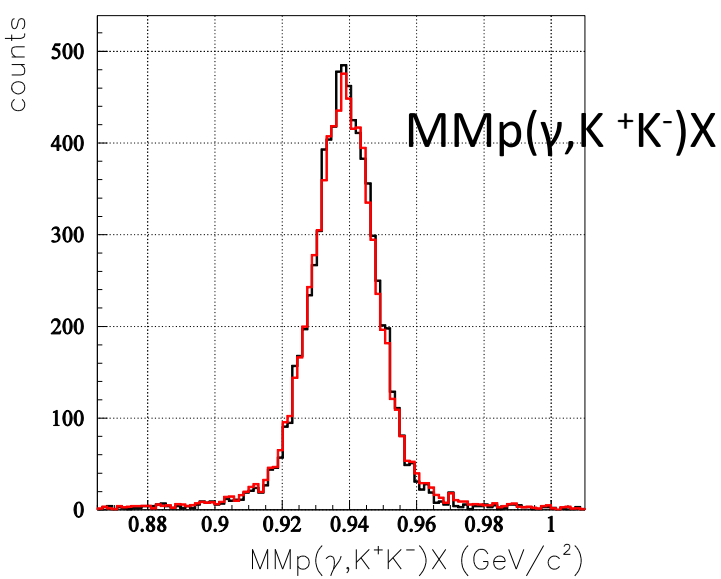
Comparison of the missing mass spectrum for LH2 data

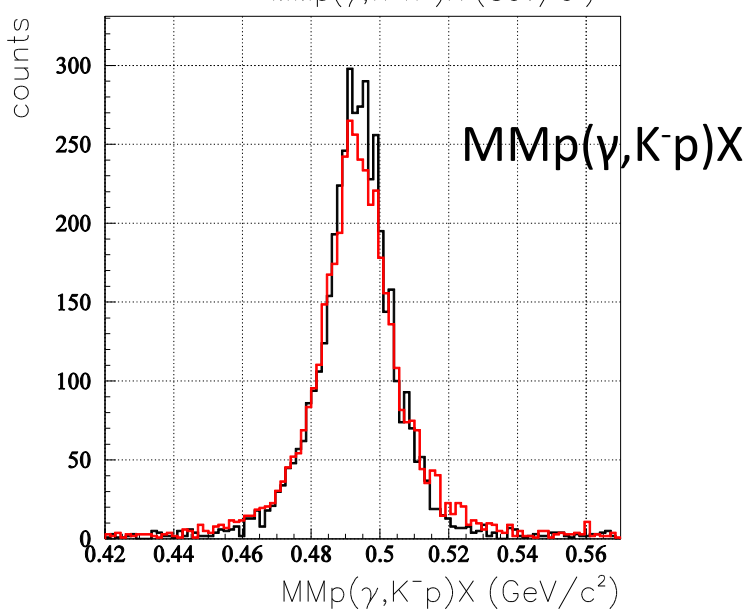




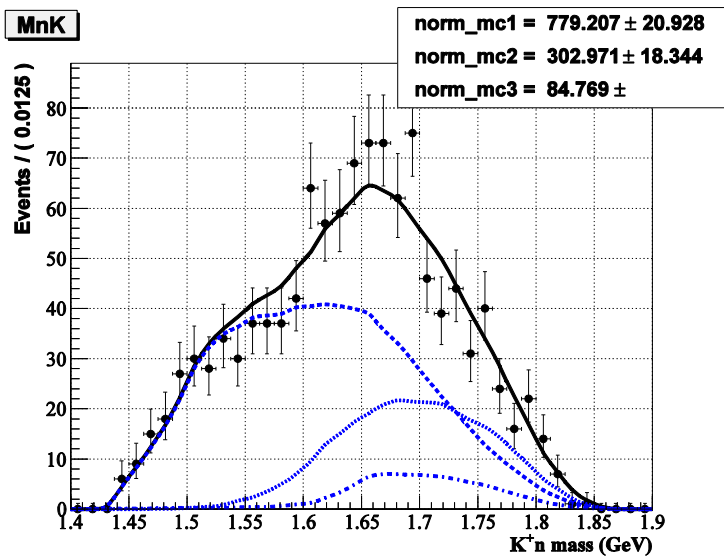
New

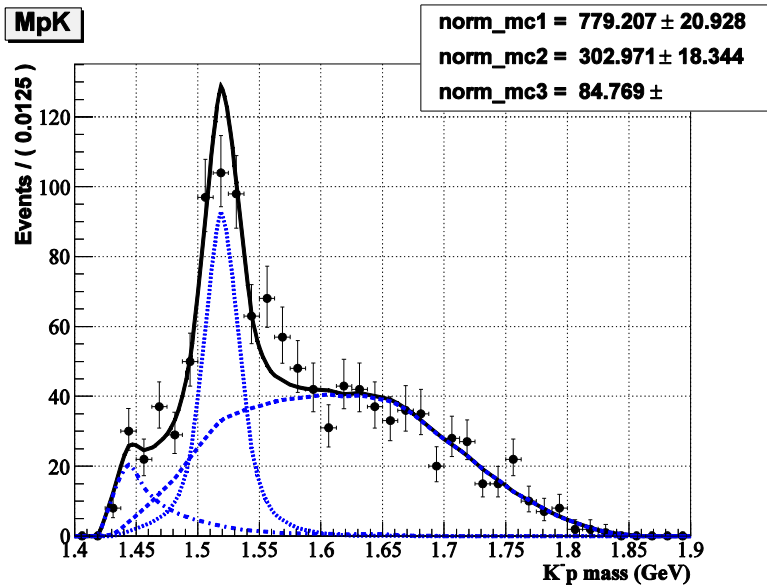
Previous

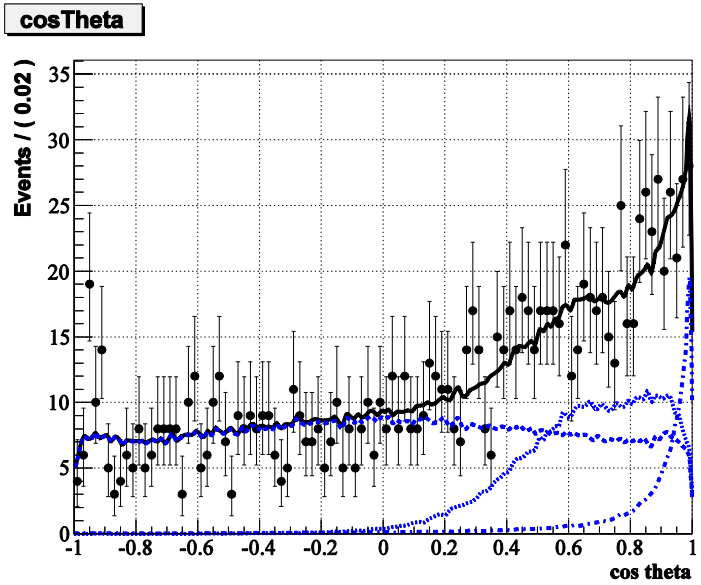




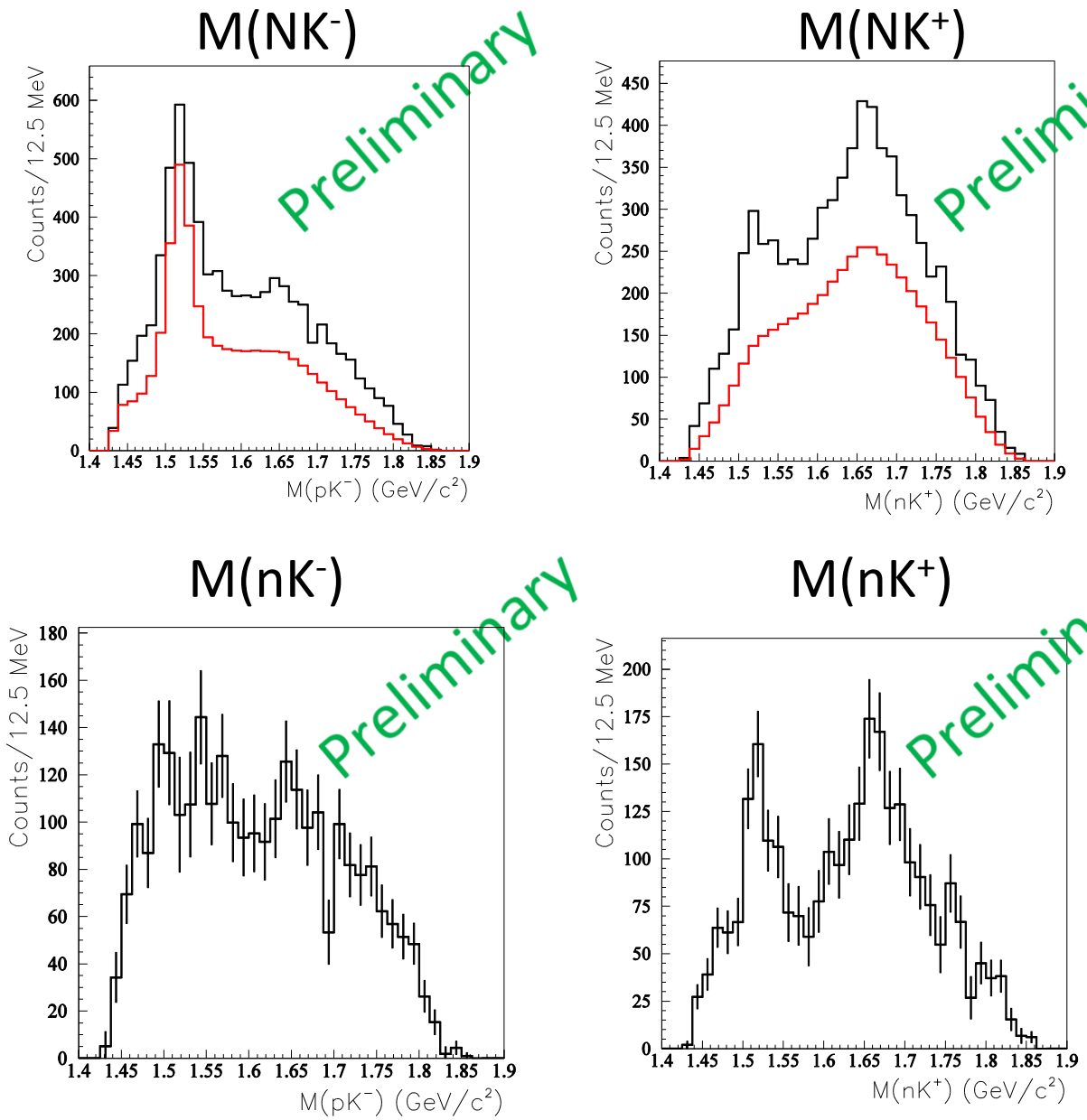
Fitting new data only







Subtract proton contribution from full data sample (B.G from new data)



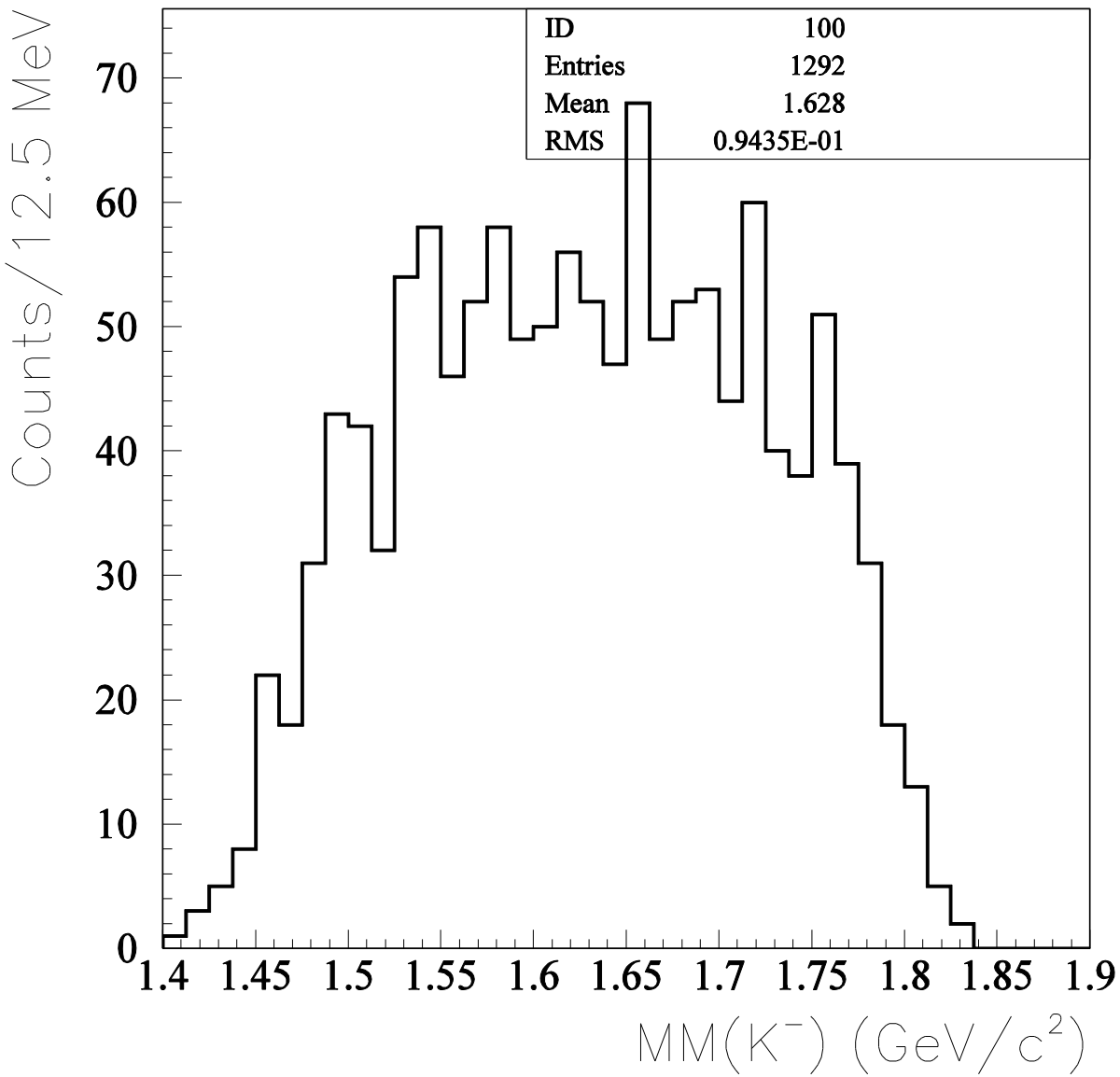
Real data

Estimated proton contribution from **new data**

Subtract proton contribution

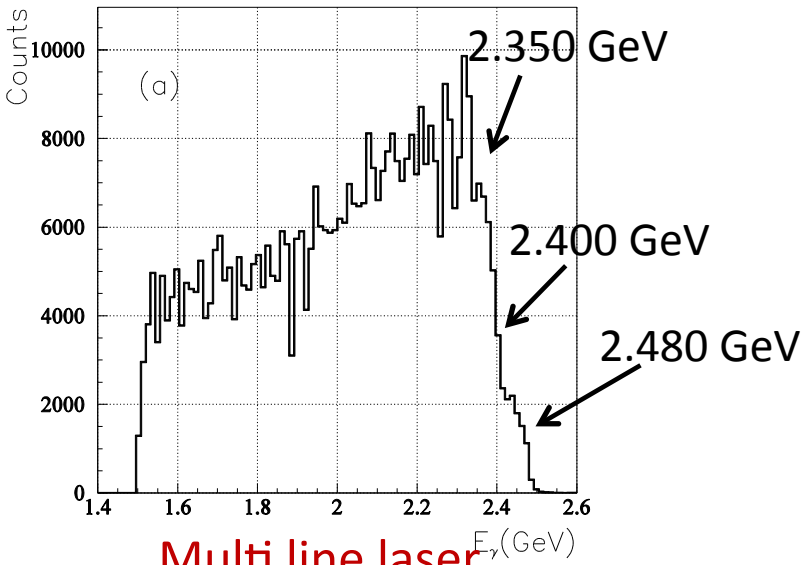
Y. Kato FB20 2012/8/23

Simple K^- missing mass for proton rejected sample



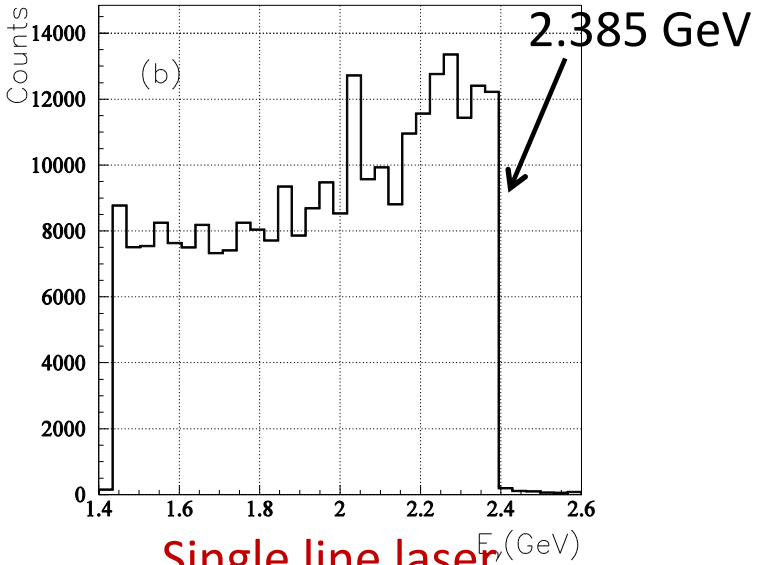
Photon energy spectrum

previous data



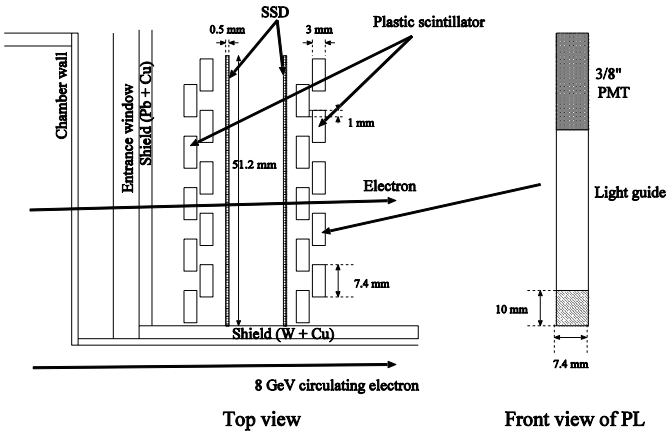
Multi line laser

new data



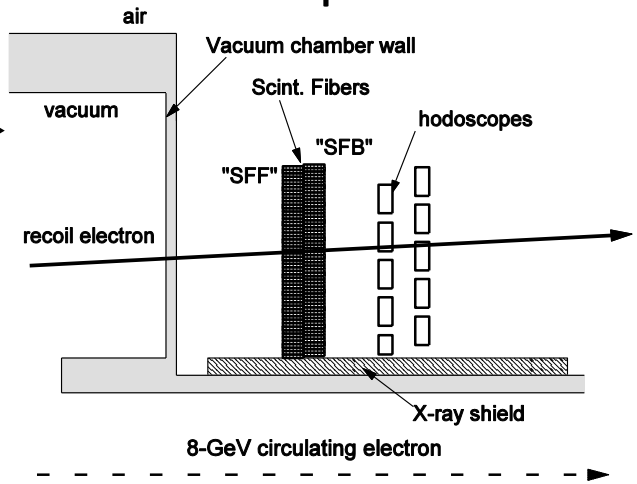
Single line laser

0.1mm pitch SSD



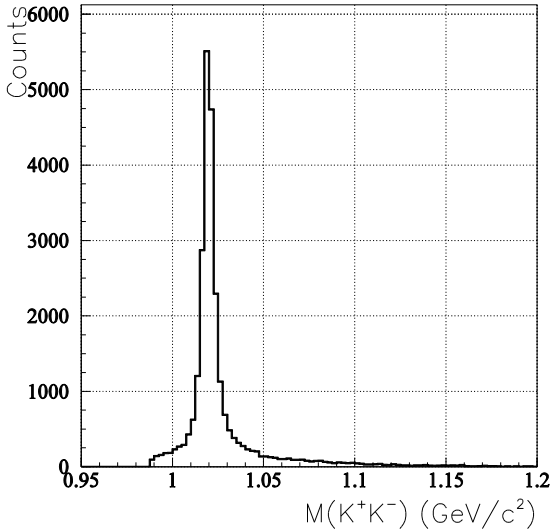
Tagger

1mm pitch SF

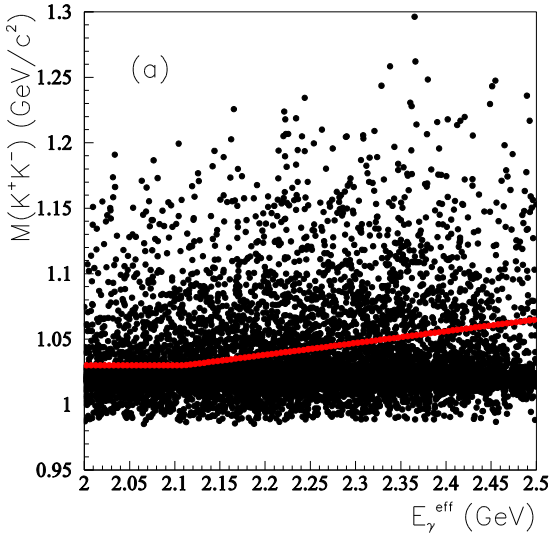


φ exclusion cut

M(K⁺K⁻) for real data



E_γ^{eff} VS M(nK⁺)

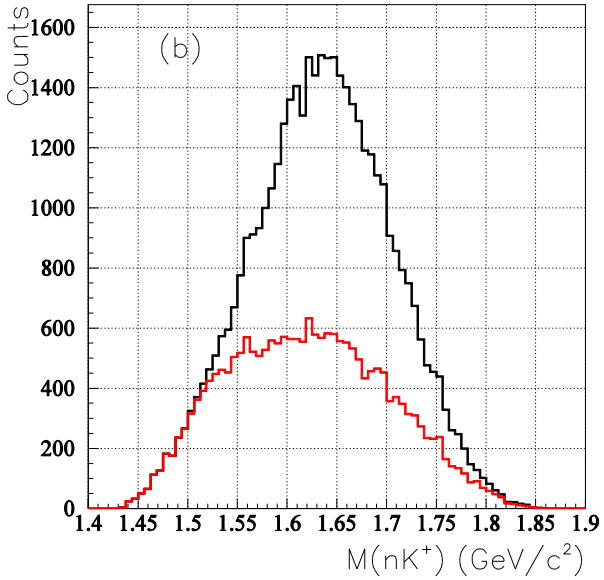


$$M(K^+K^-) > Offset + Slope(E_\gamma^{eff} - 2.0)$$

$$M(K^+K^-) > 1.03$$

Offset=1.02, slope=0.09

non-resonant KKn MC



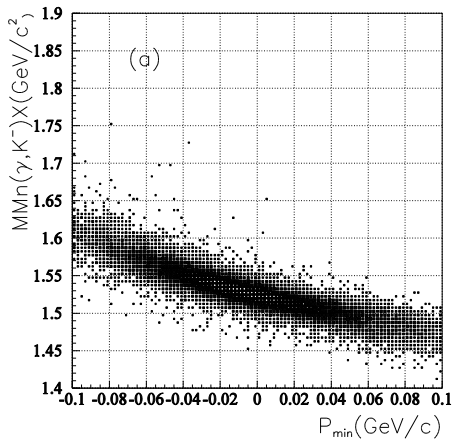
Reject medium mass region.
Do not create a peak by the cut.

Before cut
After cut

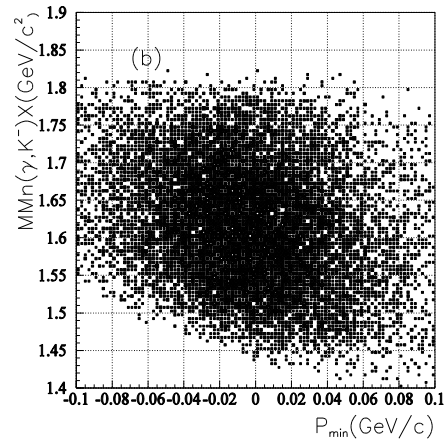
Randomized minimum momentum method for BG estimation

P_{min} VS MMγ(n,K⁻)X

signal MC

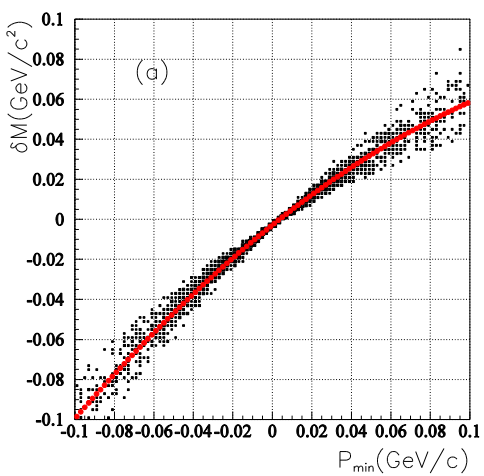


non-resonant KKN MC

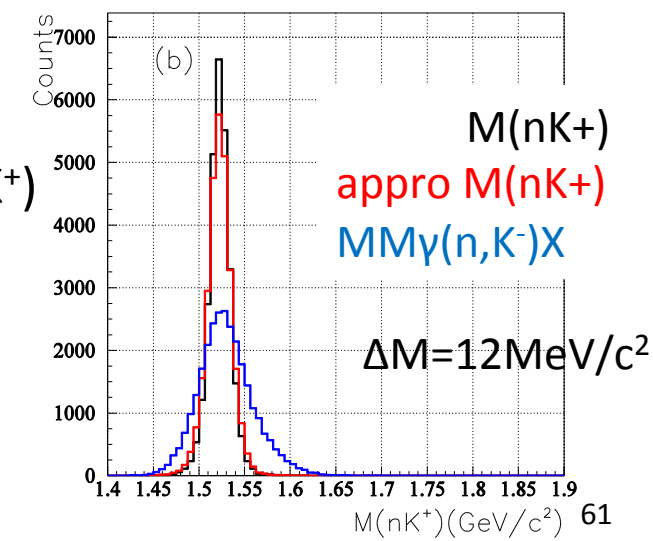


Signal events has strong correlation between Pmin and MMγ(n,K⁻)X

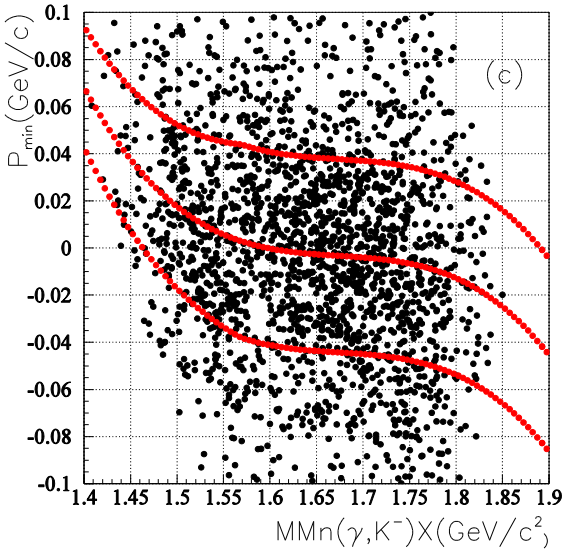
P_{min} VS magnitude of Fermi correction



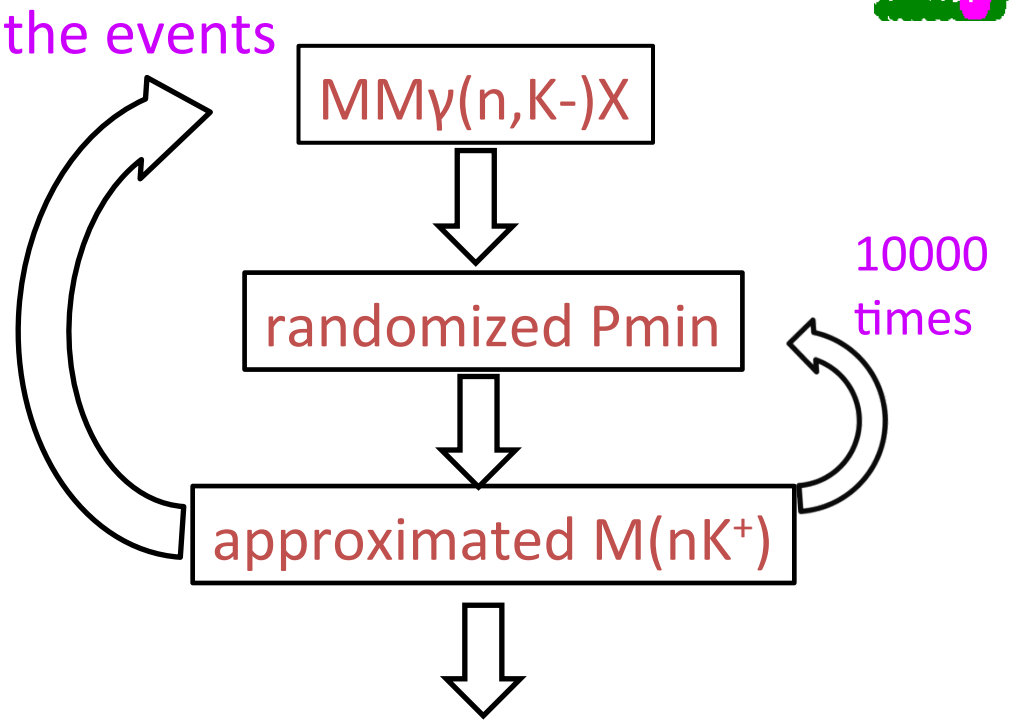
approximated M(nK⁺)



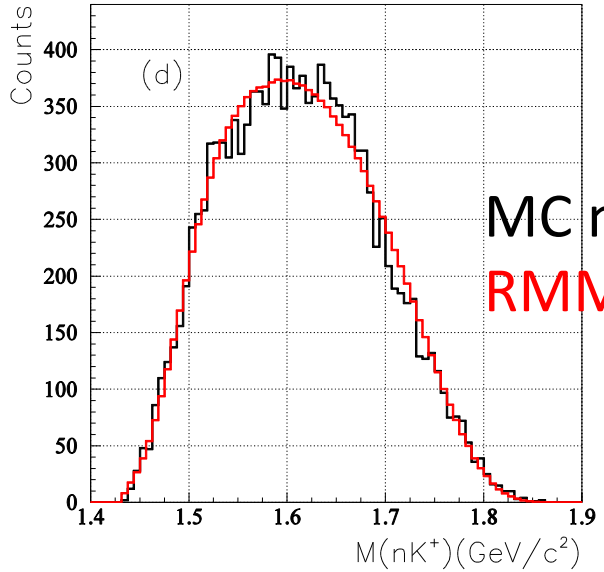
Real data MMn(γ,K⁻)X P_{min}



Mean±1σ



RMM spectrum

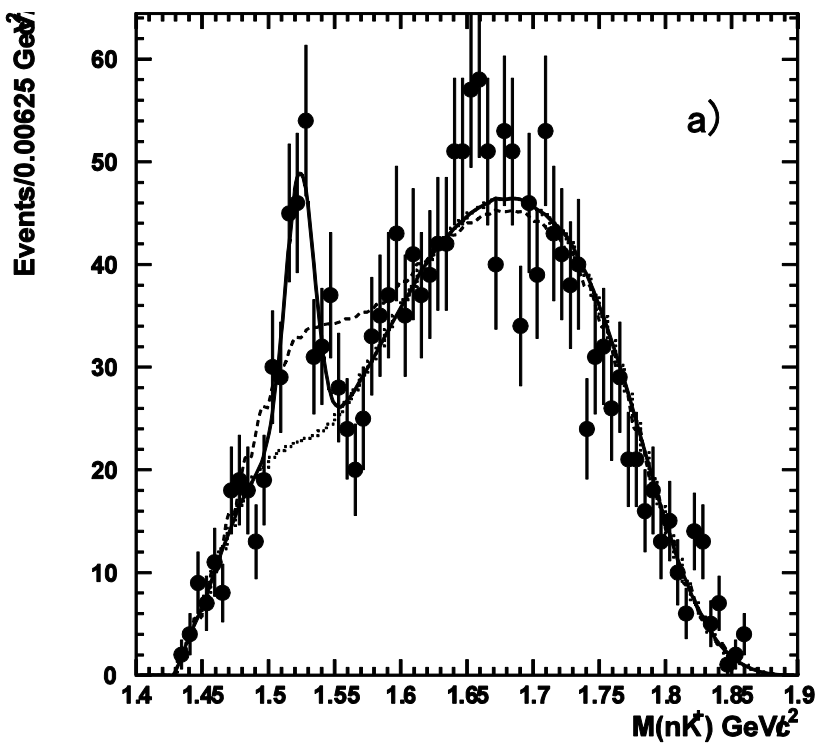


MC non-resonant KKN

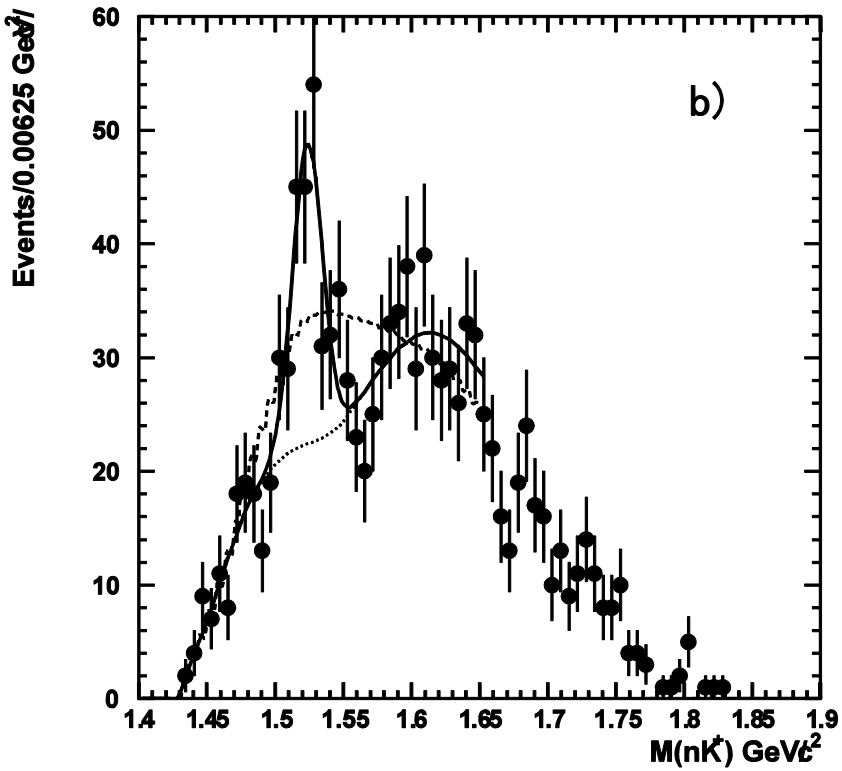
RMM spectrum

Application of the RMM to previous data

w/o Λ(1520) cut



w Λ(1520) cut



- RMM spectrum is divided into three regions.
- Significance is obtained from Δ-2ln(L) with and without the Gaussian
- The peak height is 27.5±5.0, Δχ2/ndf=30.4/2 = 5.1σ. peak position 1524.±2＋3MeV

Summary of the cut statistics

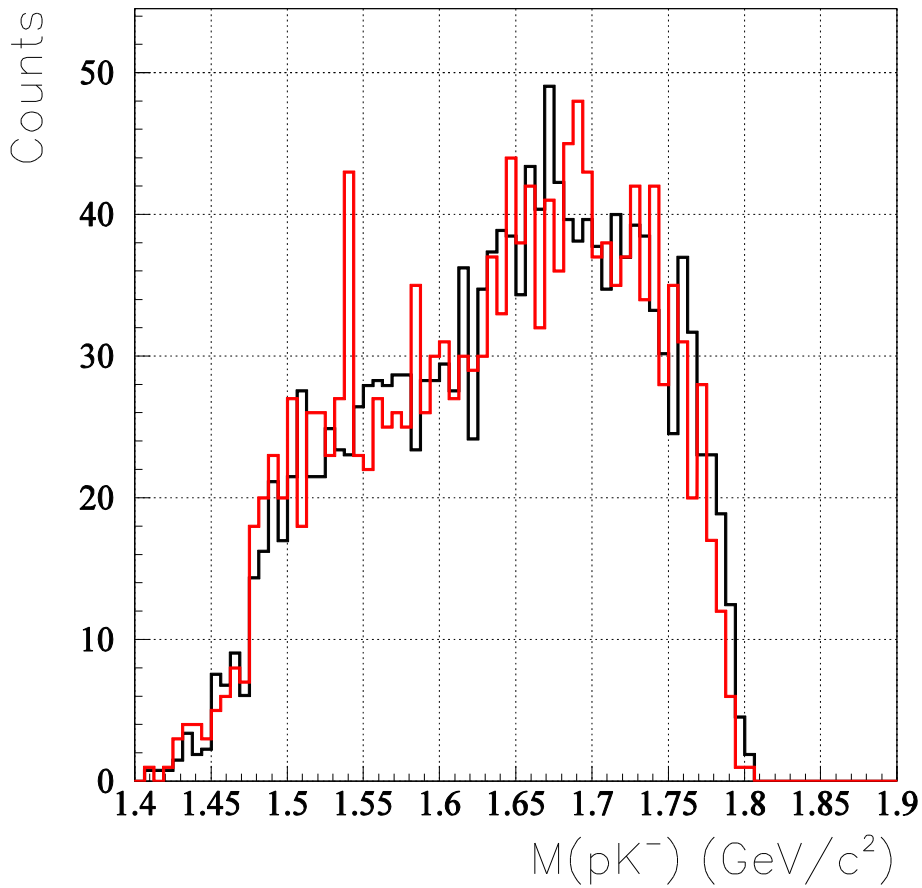
previous data

Cut	Examined	Passed	Rejection
KK ID	-	37172	-
Vertex	37172	30838	1.20
DIF	30838	27059	1.14
Tagger	27059	25818	1.05
P_{min}	25818	18569	1.39
E_{γ}^{eff}	18569	14912	1.24
ϕ	14912	2080	7.17
Ntrk=2	2080	1969	1.06
Unphy	1969	1969	1.00

New data

Cut	Examined	Passed	Rejection
KK ID	-	103336	
Vertex	103336	86233	1.20
DIF	86233	80755	1.07
Tagger	80755	65750	1.23
P_{min}	65750	49070	1.34
E_{γ}^{eff}	49070	39226	1.25
ϕ	39226	5388	7.28
Ntrk=2	5388	5106	1.06
Unphy	5106	5092	1.003

K^- missing mass with all cuts



χ^2/ndf=53.9/62

K.S test 57.6%