Results and Prospects of Θ^+ Study at LEPS

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Outline

- Introduction
- Signal identification and examination
- Significance and Cross-section
- Θ^+ signal under ϕ background
- Summary and Prospects

@ Univ. of Tsukuba, January 11th, 2008.

ペンタクウォークとは何か?

- ４つのクォークと一つの反クォークでできている。
  - 記号では: $\left(qqqq\overline{Q}\right)$
- "エキゾティック" なペンタクウォークでは、反クォークのフレーバー(種類)は他の4つ クォークのフレーバーと異なる。

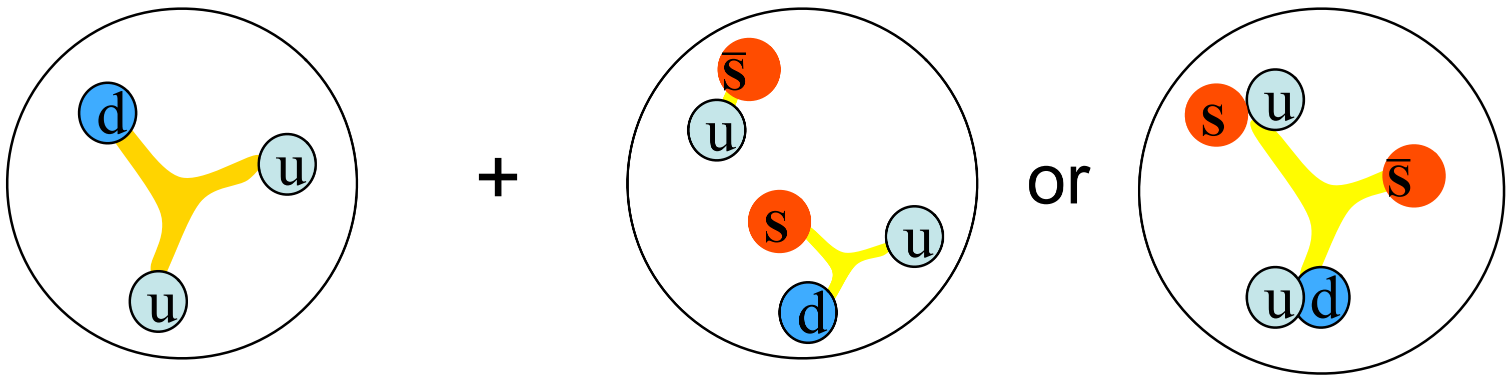
ペンタクウォークの例: **uudd$\bar{\text{s}}$**

→ ２個の **up** クォークと ２個の **down** クォーク と1個の 反 **strange** クォーク.

ストレンジネス数 = 0 + 0 + 0 + 0 + 1 = +1

ペンタクウォークは閉じ込められたクォークの全く新しい形態!

陽子の5クォーク成分



Meson cloud picture: Thomas, Speth, Weise, Oset, Jido,Brodsky, Ma, …

$$| p > \sim | uud > + \varepsilon_1 | n (udd) \pi^+ (\bar{d}u) >$$
$$+ \varepsilon_2 | \Delta^{++} (uuu) \pi^- (\bar{u}d) > + \varepsilon' | \Lambda (uds) K^+ (\bar{s}u) > \dots$$

Di-quark cluster (5-quark) picture: Zou, Riska,Jaffe,Wilczek

$$| p > \sim | uud > + \varepsilon_1 | [ud][ud]\bar{d} > + \varepsilon_2 | [ud][us]\bar{s} > + \dots$$

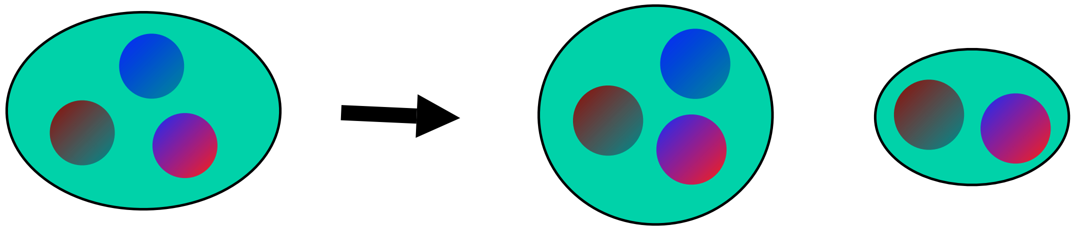
$$| \Theta^+ > \sim | [ud][ud]\bar{s} > + \dots$$

クォークモデル

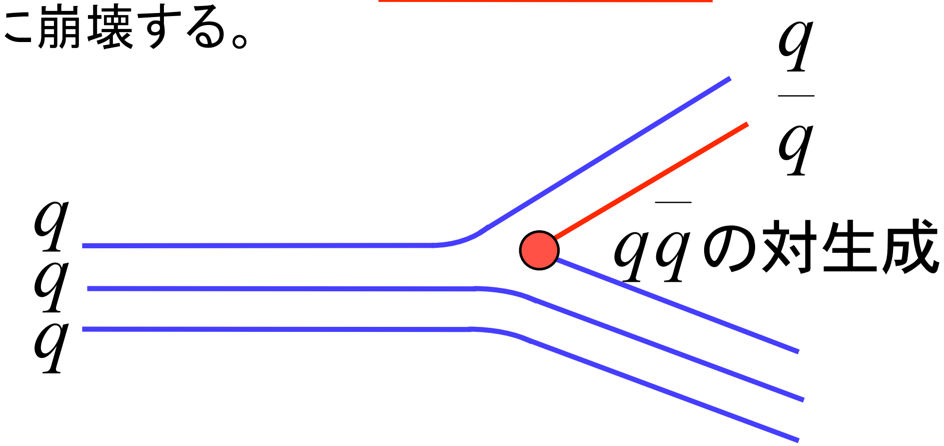
$m_u \sim m_d$ = 300 ~ 350 MeV, m_s=$m_{u(d)}$+130~180 MeV

- 主に3クォーク(qqq): バリオン
  - $m_B \sim 3m_q$ + (ストレンジネス)+(対称性)
- クォーク・反クォーク対($q\bar{q}$): メソン
  - $m_M \sim 2m_q$ + (ストレンジネス)+(対称性)
- 軽いメソンの存在: π, K, η
  - カイラル対称性の自発的破れに伴う南部・ゴールドストン・ボソン（構成要素としては$q\bar{q}$）
- 5クォーク($qqqq\bar{Q}$): ペンタクォーク
  - $m_P \sim 5m_q$ + (ストレンジネス)+(対称性)
  - 1700~1900 MeV for Θ^+ ($uudd\bar{s}$) ← ナイーブな予想

バリオンの崩壊



重いバリオンはメソン(主に軽いπやK)を放出して軽いバリオンに崩壊する。



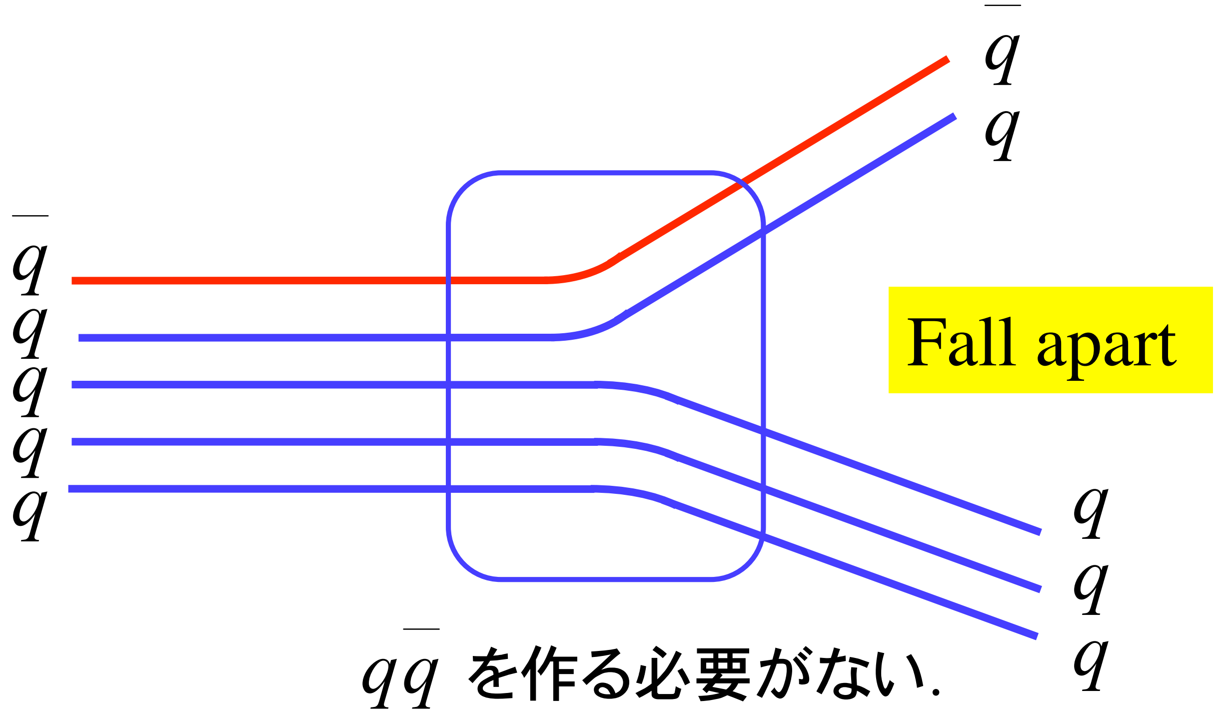
寿命

$$\tau \propto \frac{1}{\Gamma}$$

崩壊巾

π崩壊が可能なバリオンはとても不安定(寿命が短い)で質量の不定性(崩壊幅)が大きい。

ペンタクォークの崩壊



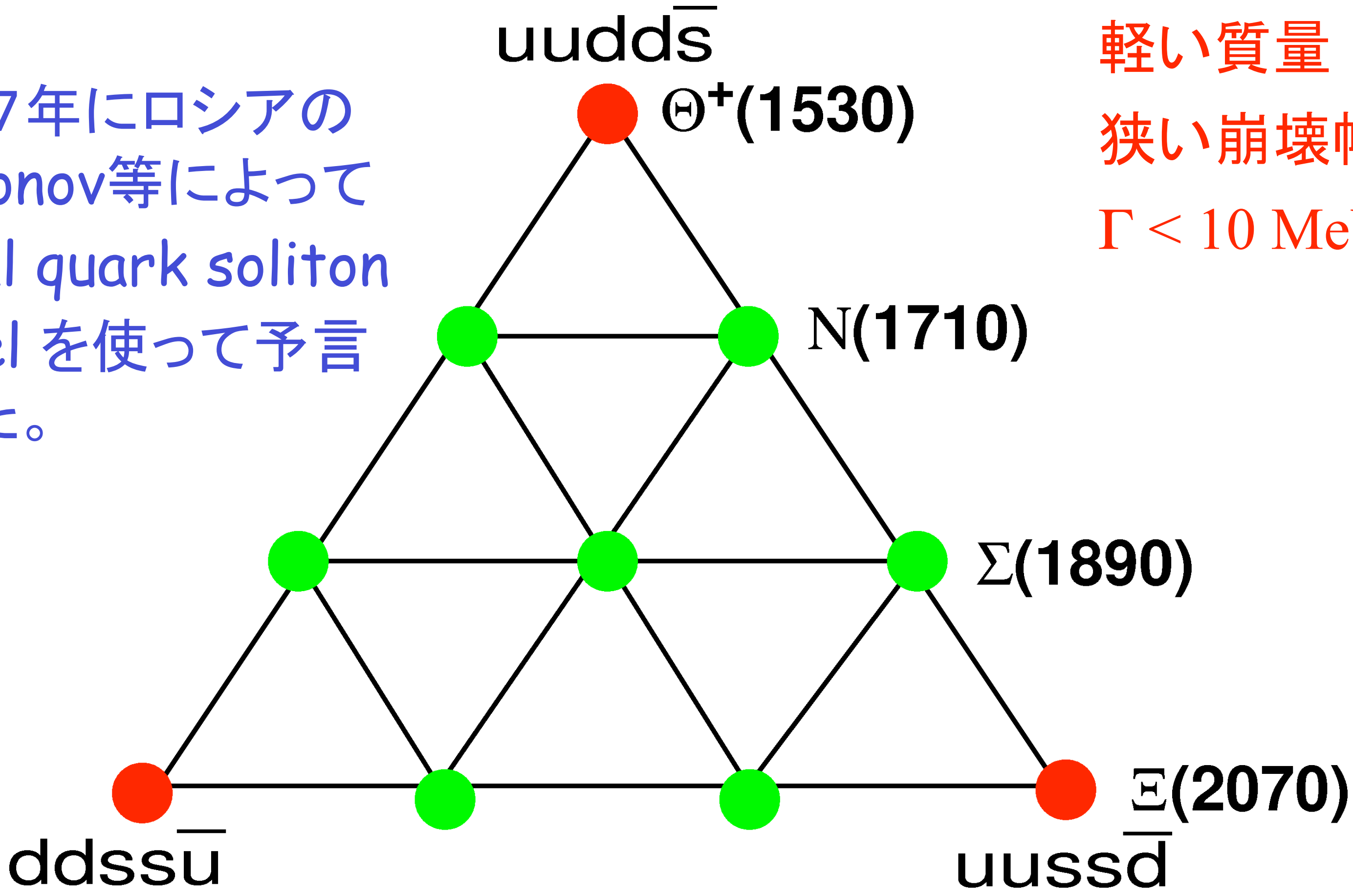
$q\bar{q}$ を作る必要がない.

ペンタクォークはとても不安定なはず

短い寿命、大きな崩壊巾.

シータ粒子(Θ^+)

1997年にロシアのDiakonov等によってchiral quark soliton model を使って予言された。



軽い質量！

狭い崩壊幅

$\Gamma < 10$ MeV

Updated experimental status

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

- No published positive result from dedicated experiments CLAS γp γd, COSY-TOF pp, KEK-PS (π^-,K^-), (K^+,π^+)

- The coupling to K^* must be small: If not, it should be seen in CLAS γp experiment and KEK (K^+,π^+) experiment.

- The width must be less than 1 MeV. (DIANA and KEK-B)

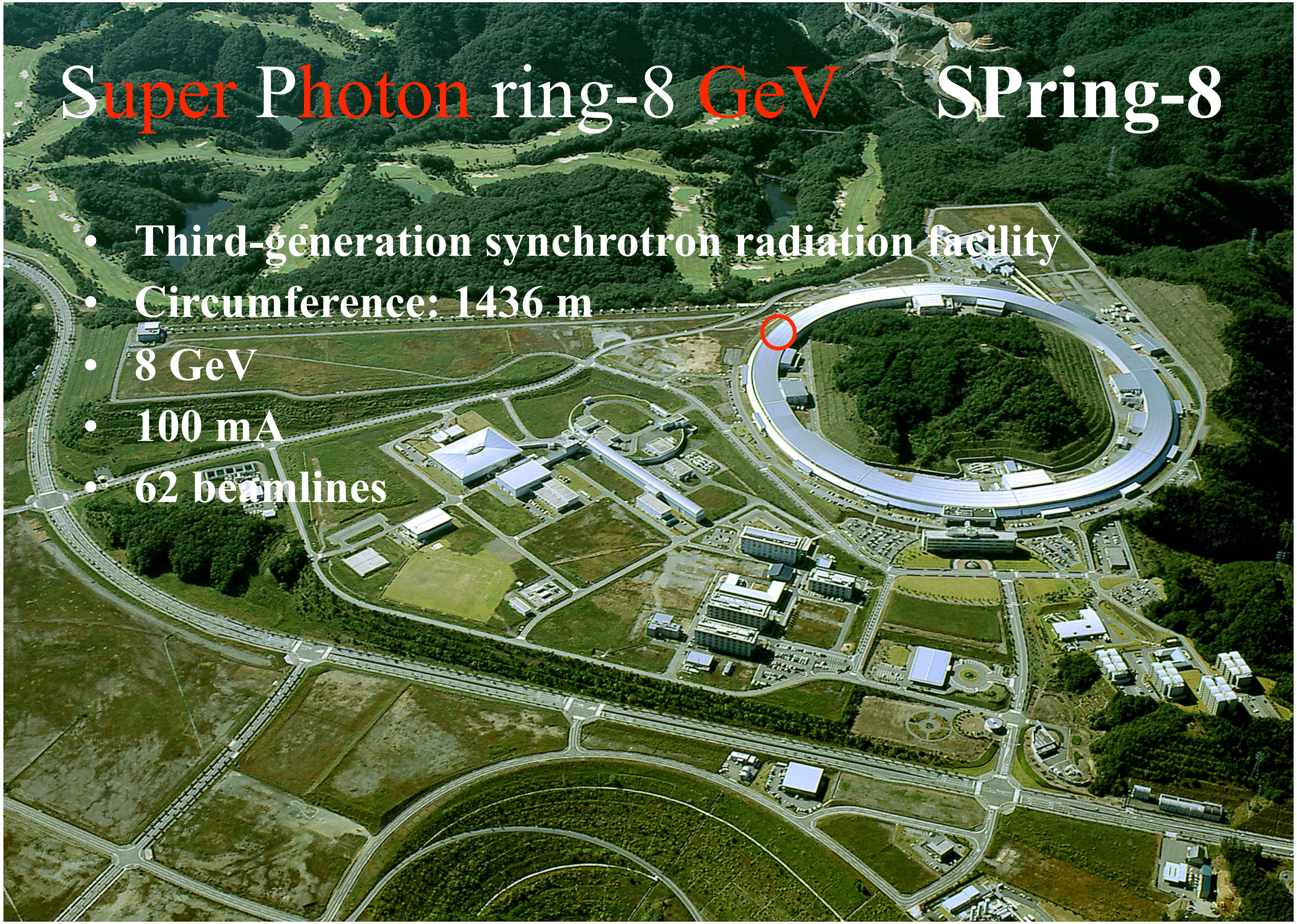
- Difficult to explain its light mass and very narrow width theoretically.

- LEPS observed signals in $\gamma\, n \to K^+K^-n$ and $\gamma d \to \Lambda(1520)KN$ reactions, which could be inconsistent with CLAS γd experiment (CLAS-g10).

"Why do we still believe in the existence of Θ^{+}?"

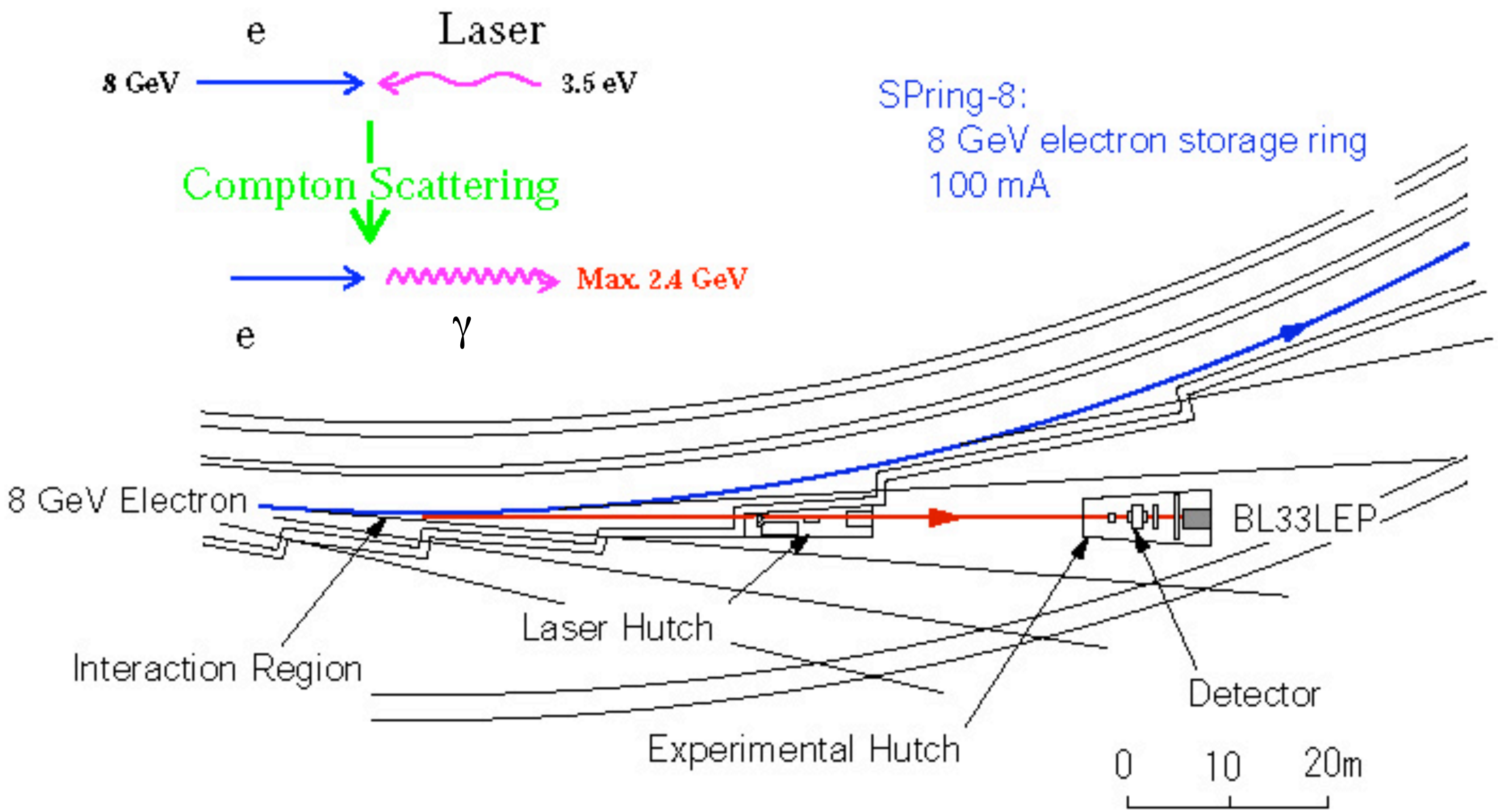
"How can our results be consistent with the CLAS result?"

"When will the study at LEPS be completed?"


Super Photon ring-8 GeV SPring-8
• Third-generation synchrotron radiation facility
• Circumference: 1436 m
• 8 GeV
• 100 mA
• 62 beamlines

レーザー電子光(LEPS)ビームライン

in operation since 2000



Laser Electron Photon (LEP) Beam

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

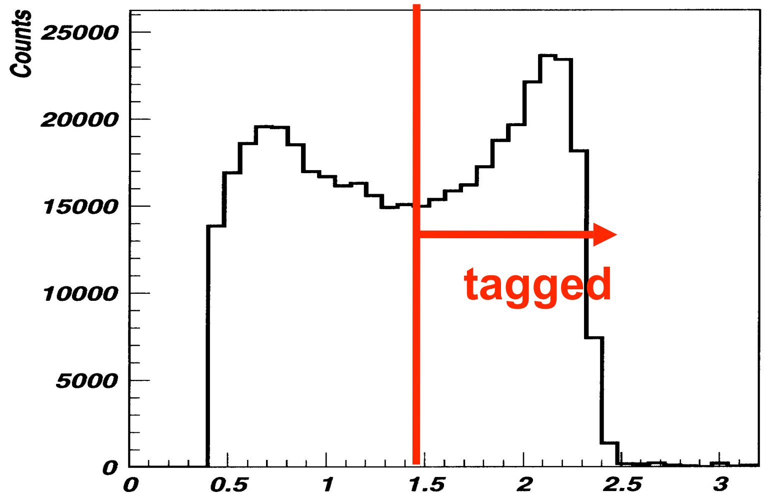
⇒ maximumly 2.4 GeV photons (Backward Compton Scattering)

— 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

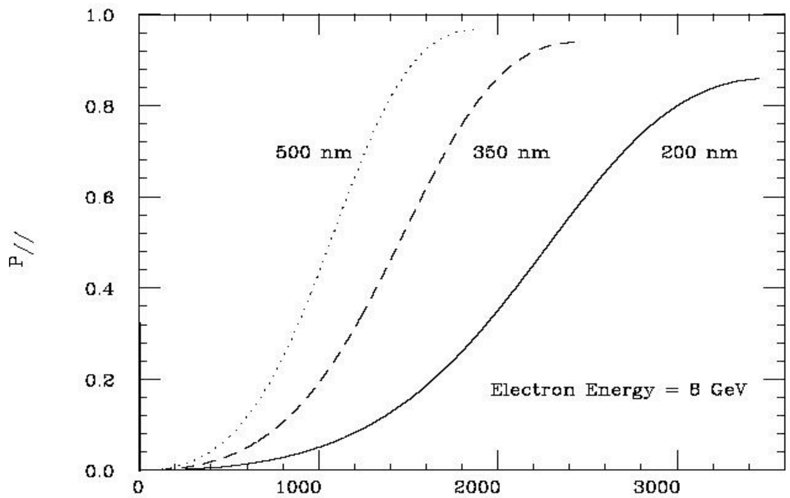
— Laser linear polarization 95-100% ⇒ Highly polarized γ beam

PWO measurement



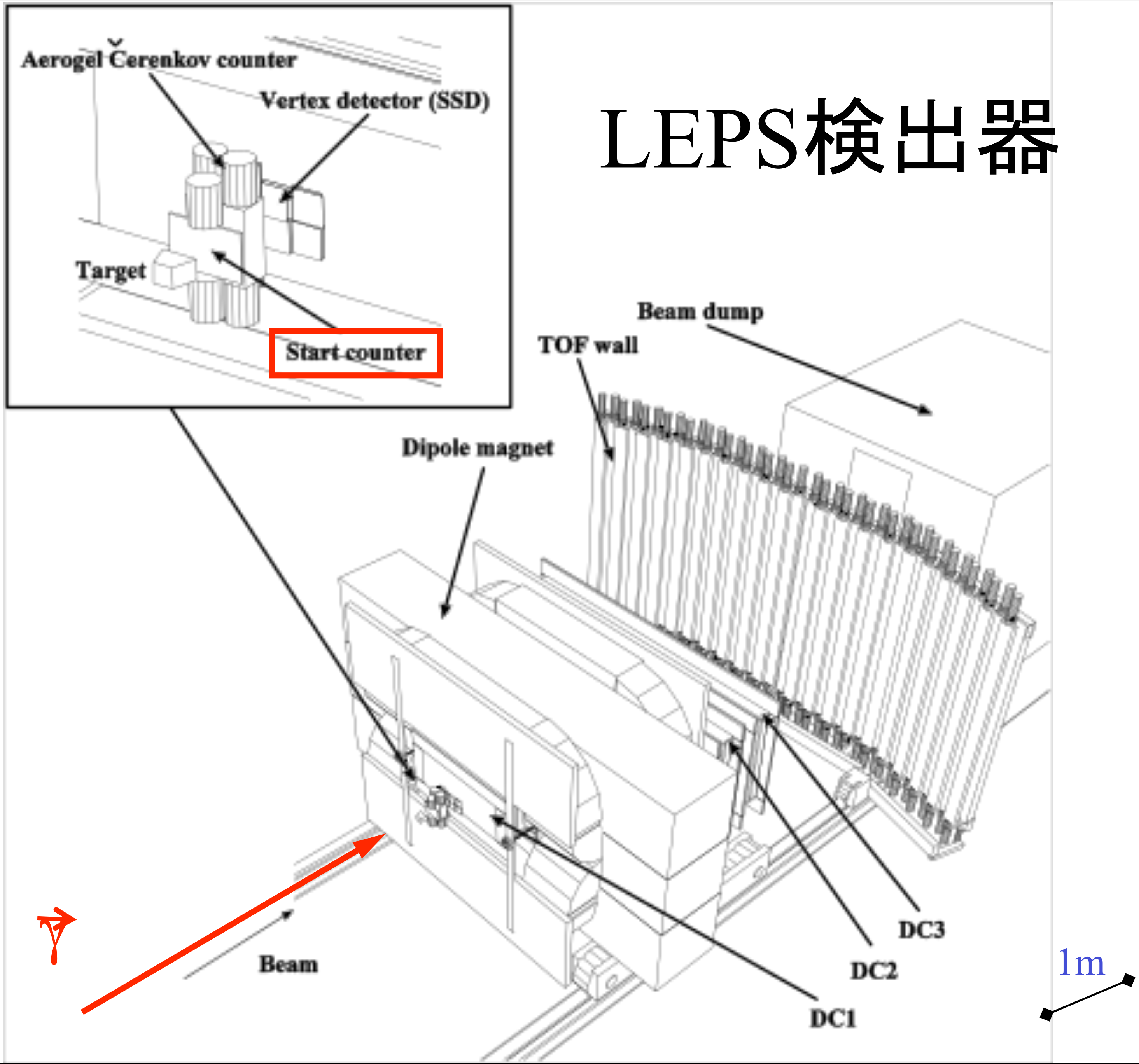
photon energy [GeV]

Linear Polarization of γ baem

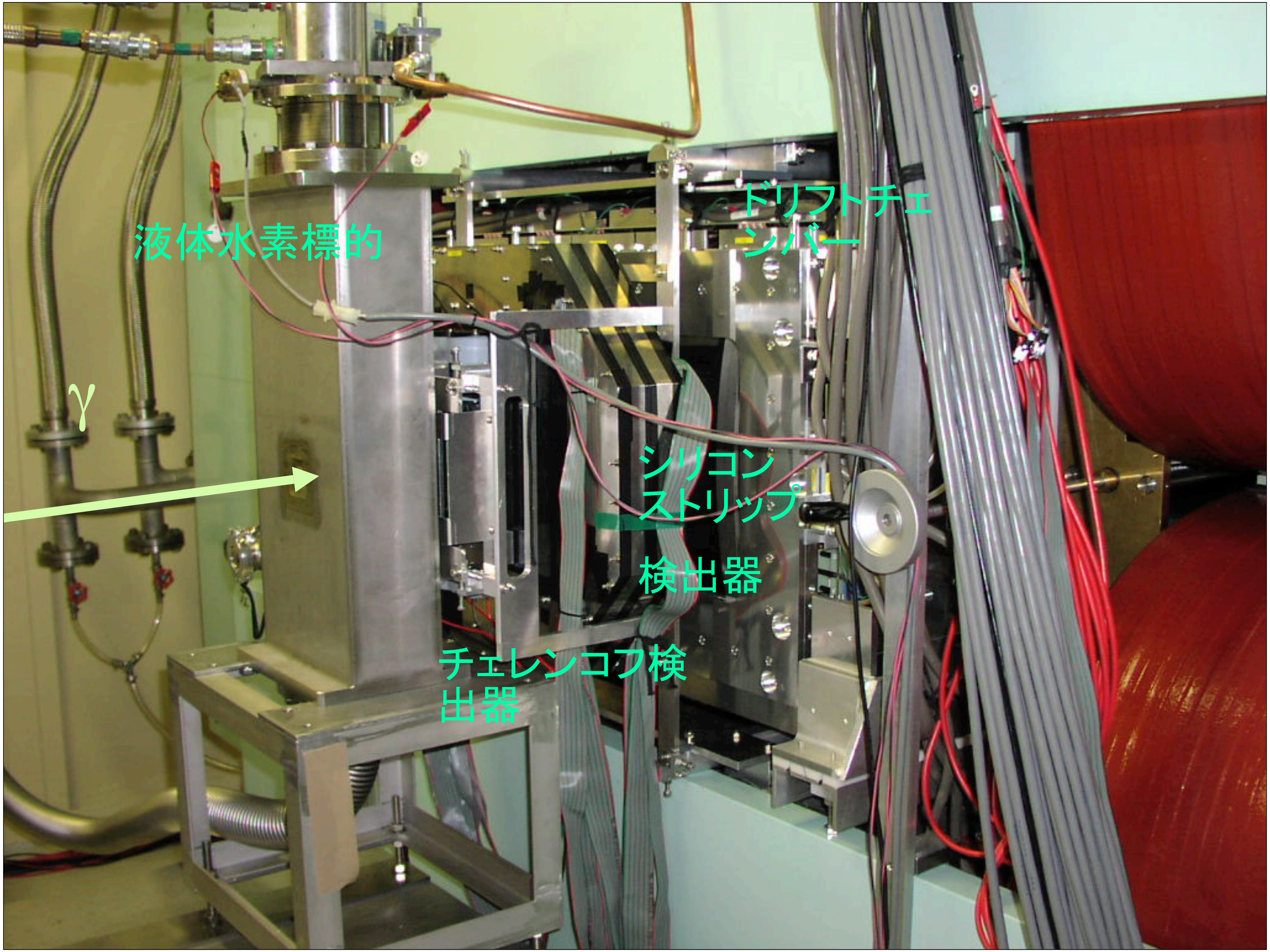


photon energy [MeV]

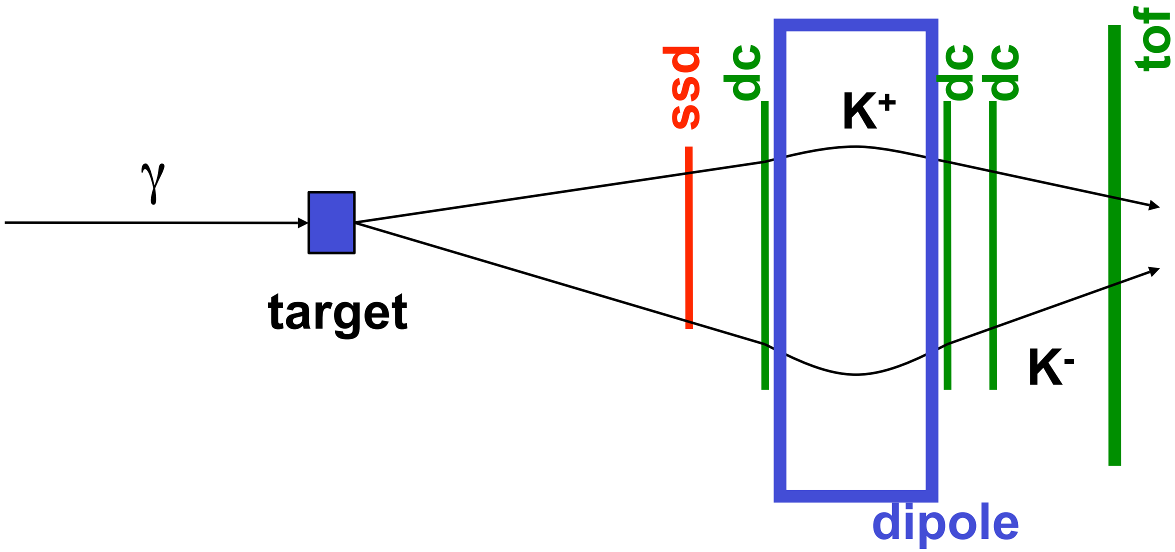
LEPS検出器



Aerogel Čerenkov counter
Vertex detector (SSD)
Target
Start counter
Beam dump
TOF wall
Dipole magnet
Beam
γ
DC1
DC2
DC3
1m


液体水素標的
γ
ドリフトチェンバー
シリコンストリップ検出器
チェレンコフ検出器

運動量とエネルギーの測定



磁石中での粒子の軌跡の曲率から運動量pがわかる

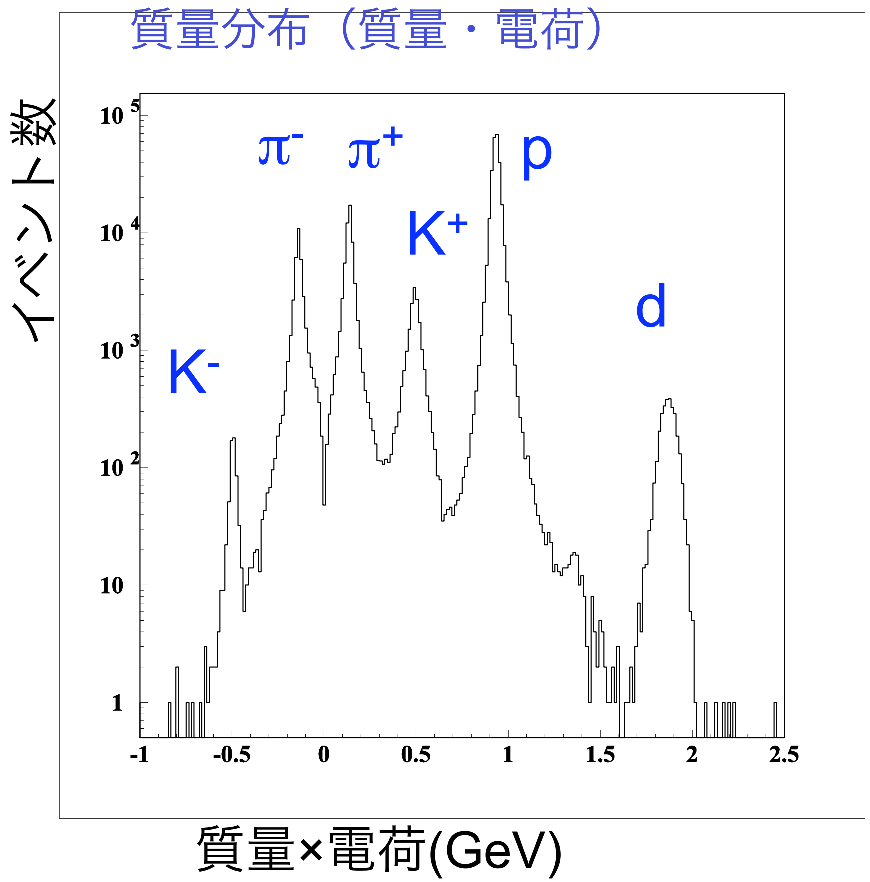
粒子の軌跡の距離と飛行時間から粒子の速さvがわかる

$v = \Delta x/\Delta t = p/E$

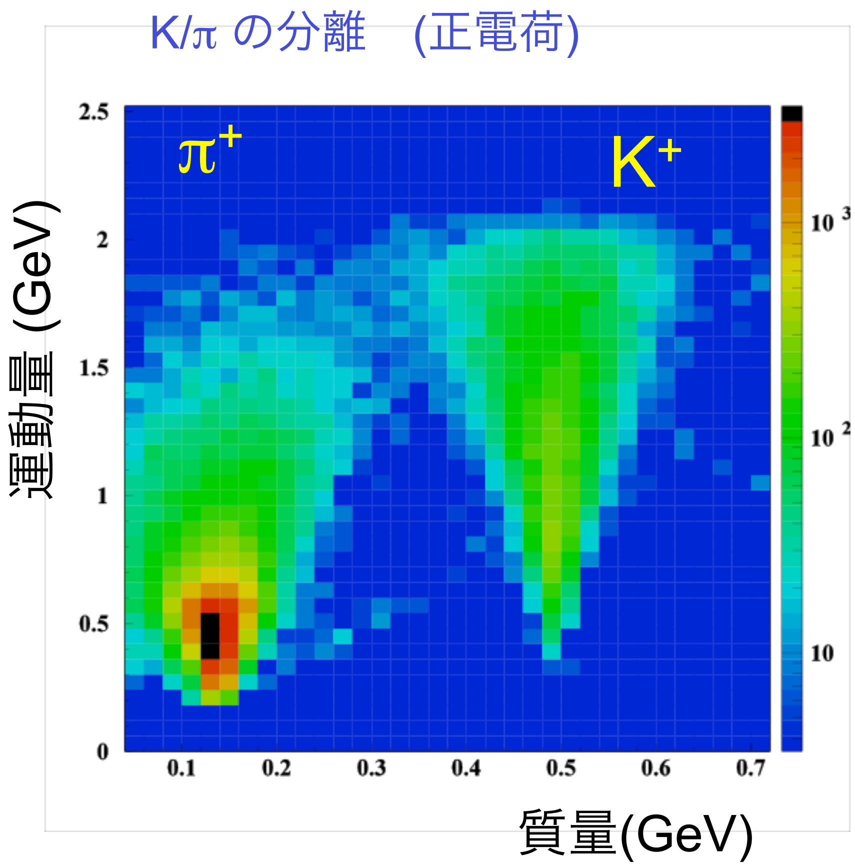
$m^2 = E^2 - p^2$

→ $m^2 = (1/v^2 - 1) \cdot p^2$

荷電粒子の検出

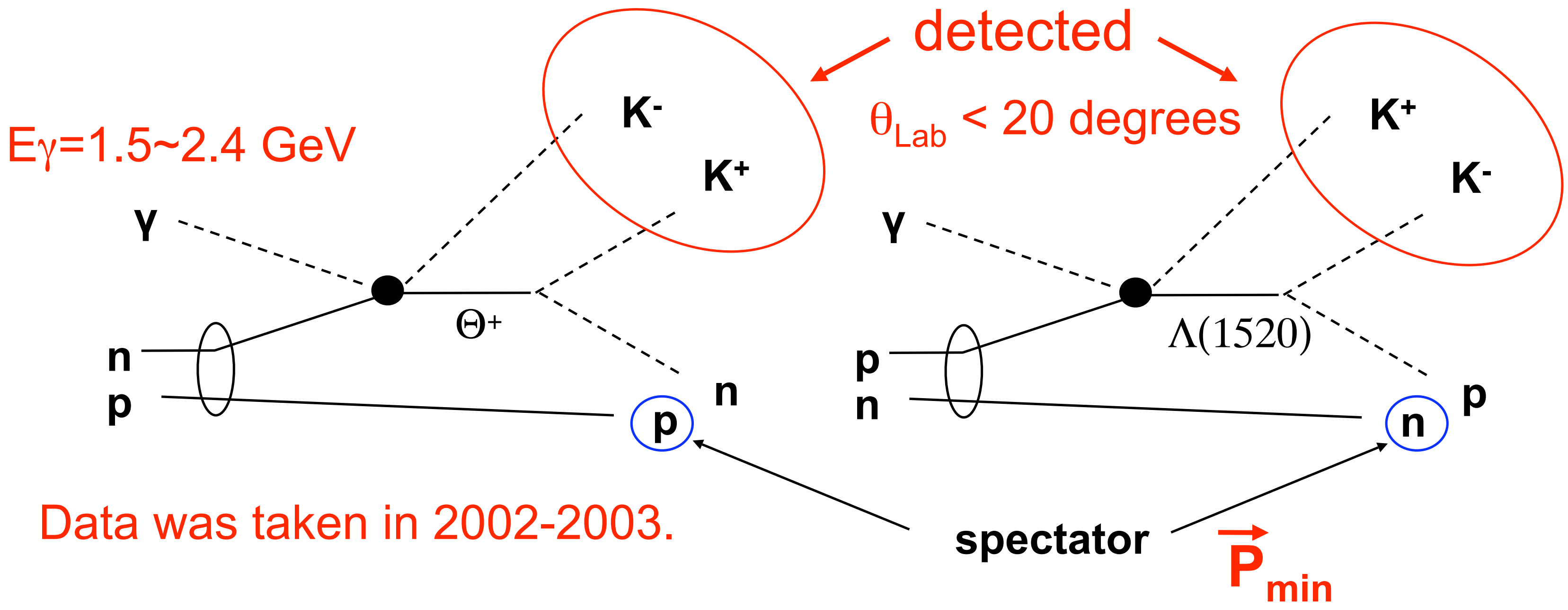


質量分布（質量・電荷）
イベント数
π-
π+
K+
p
K-
d
10 5
10 4
10 3
10 2
10
1
-1
-0.5
0
0.5
1
1.5
2
2.5
質量×電荷(GeV)



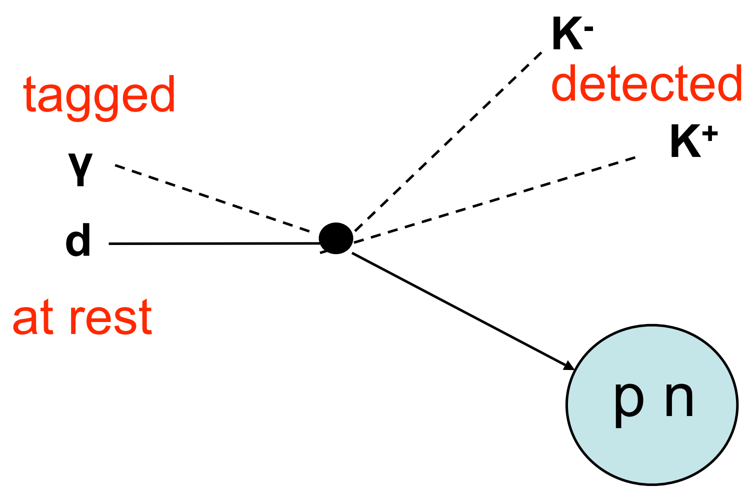
K/π の分離　(正電荷)
π+
K+
運動量 (GeV)
2.5
2
1.5
1
0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10 3
10 2
10
質量(GeV)

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



- Both reactions are quasi-free processes.
- The major BG is ϕ productions.
- Fermi-motion should be corrected.
- Existence of a spectator nucleon characterize both reactions.

Possible minimum momentum of the spectator



We know 4 momentum of *pn* system

Nucleon from decay or scattering

↓

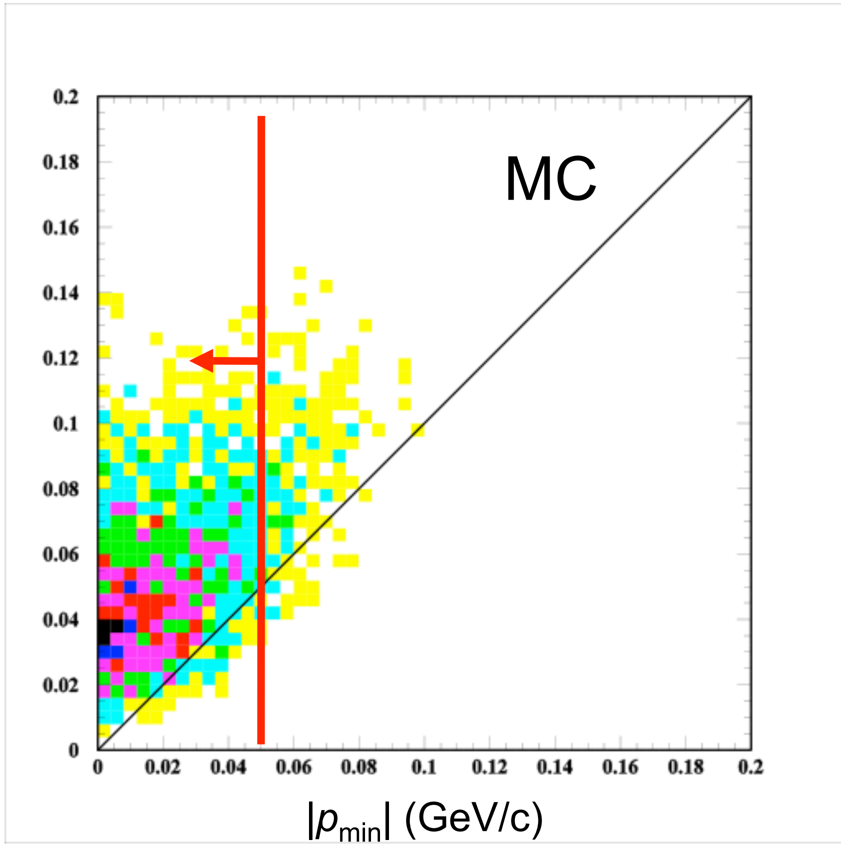
M_{pn} and $\vec{p}_{tot}$

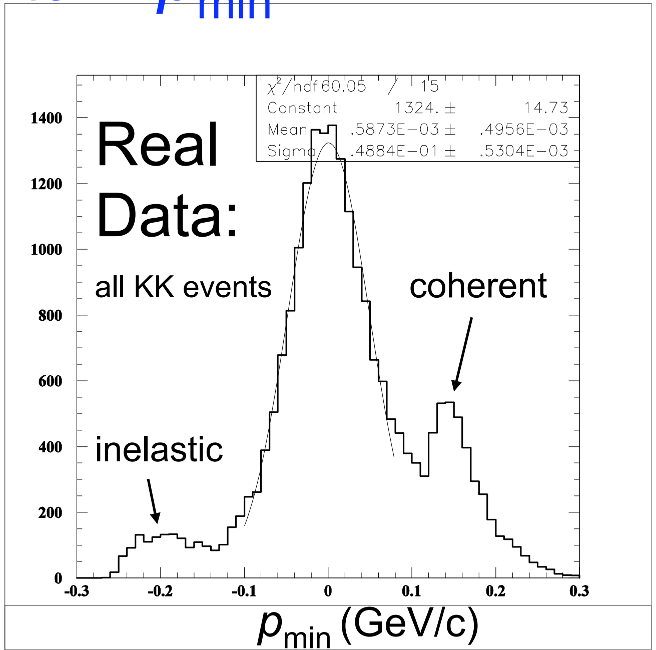
↓

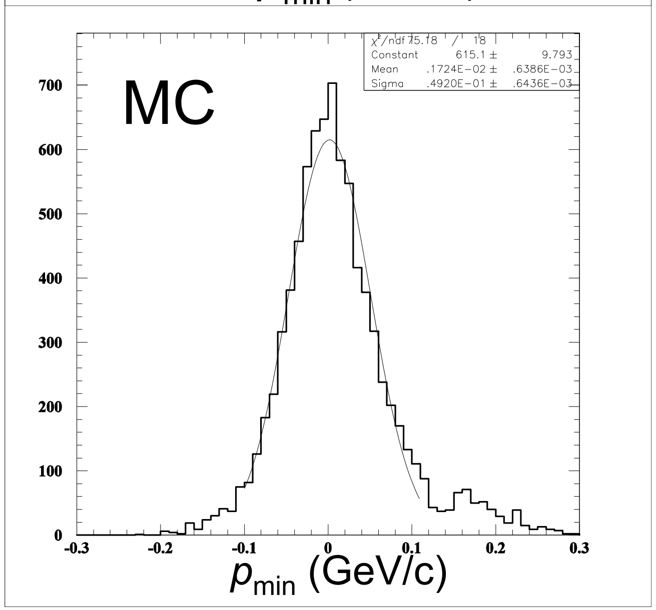
$|\vec{p}_{CM}|$ and $\vec{v}_{pn}$

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 p_{min}







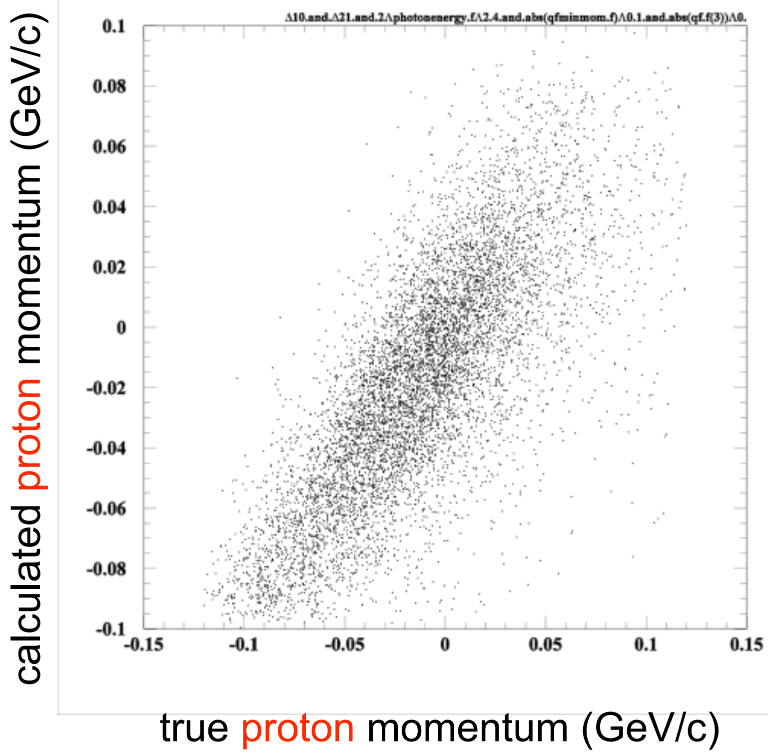
small p_{min} → small p_{Fermi}

→ less contaminations from coherent, inelastic, and re-scattering processes

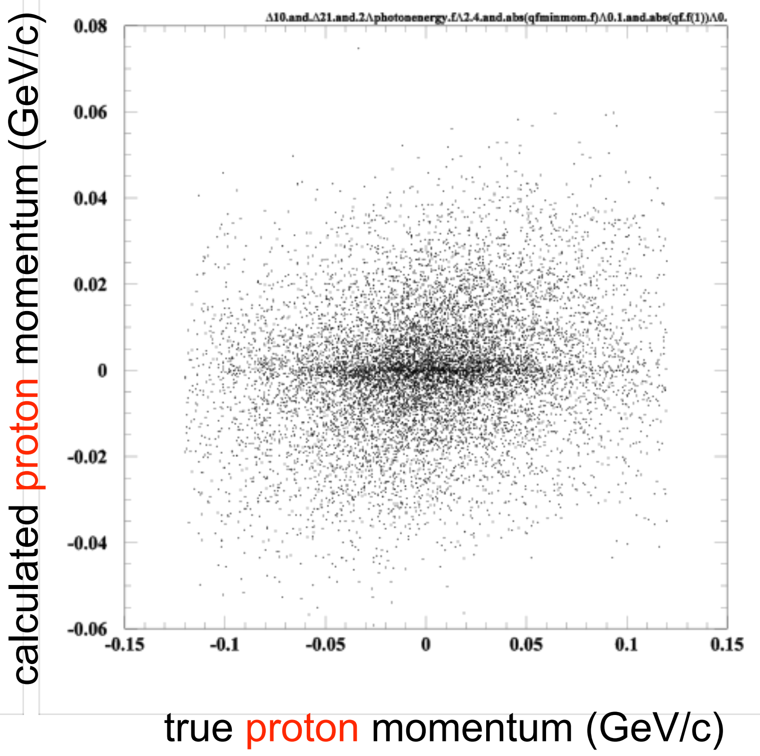
Fermi momentum

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

z component

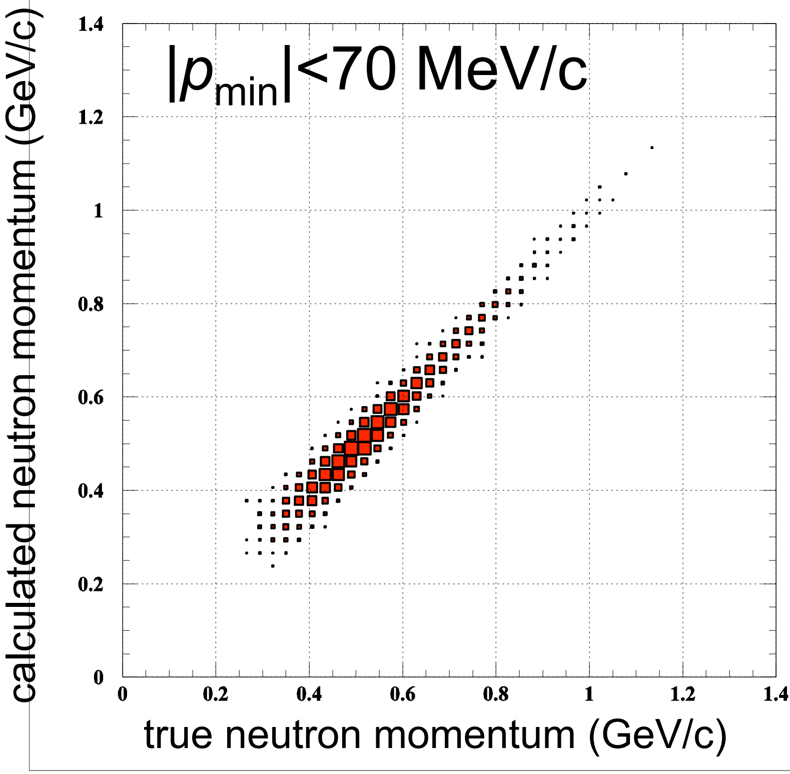


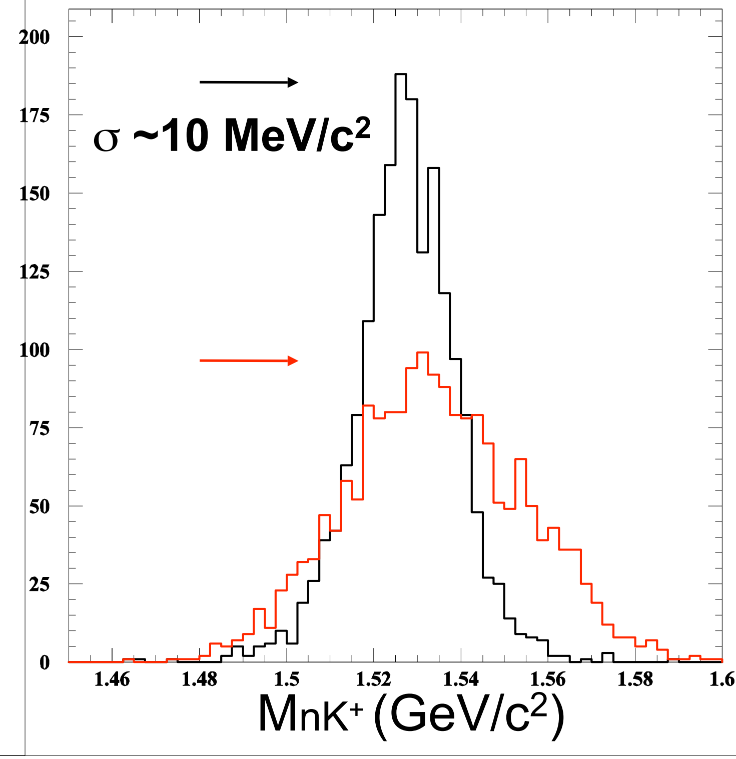
x component



Better M_{nK^+} mass resolution

MC data of γn→K⁻Θ⁺→K⁻K⁺n with Fermi motion

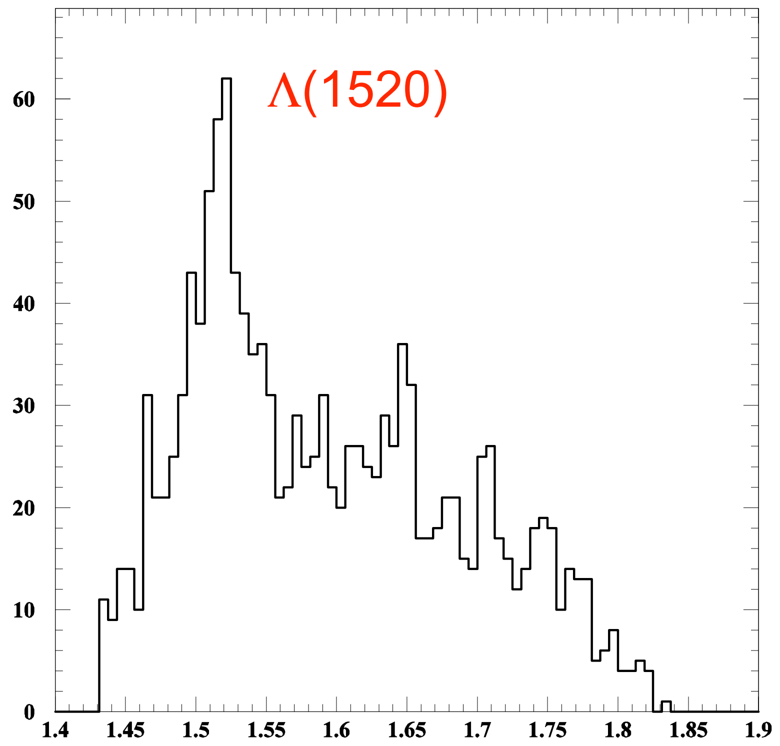




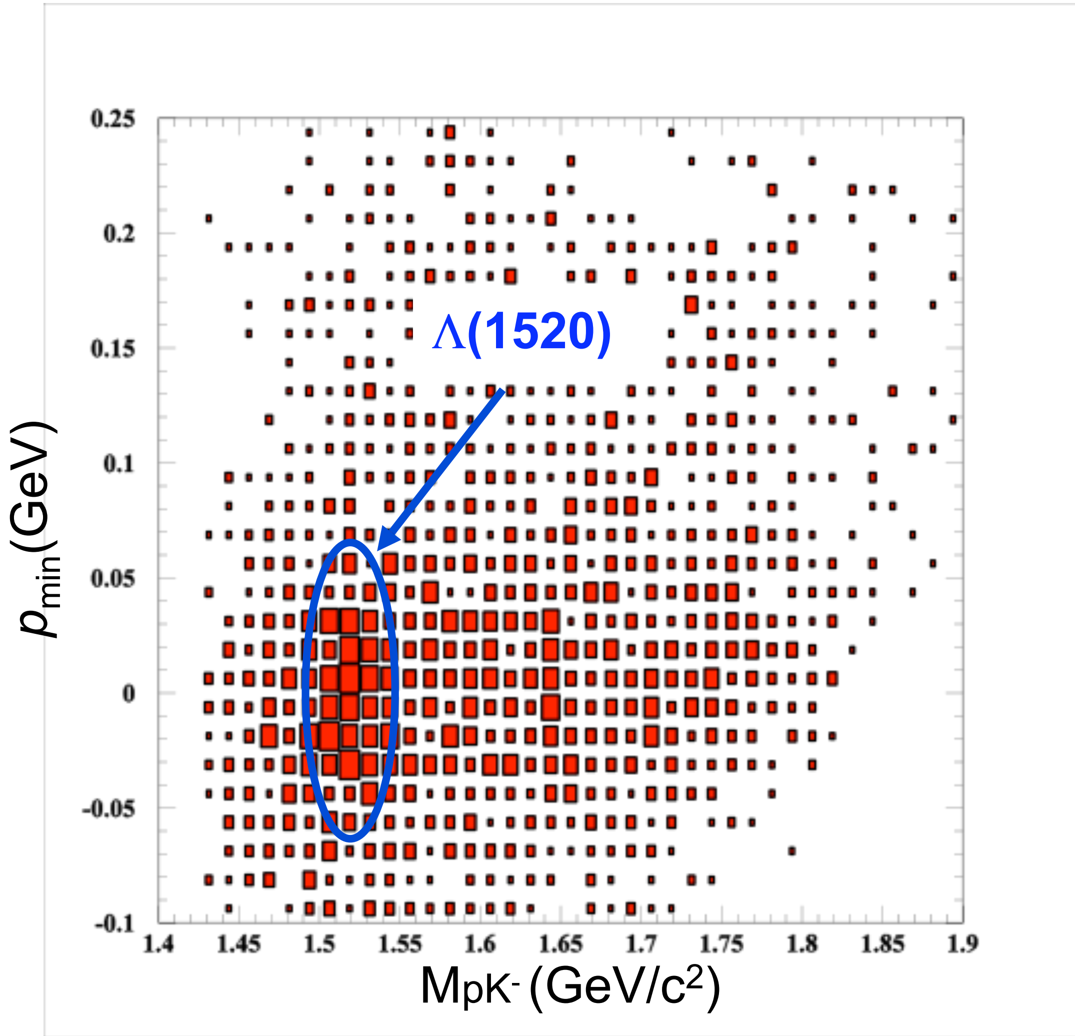
M_{nK^+} mass resolution is improved by a factor of 2 compared to a simple (γ,K⁻) missing mass resolution, where the initial neutron is assumed to be at rest.

Cut dependence of Λ(1520) peak

$|p_{min}| < 50$ MeV/c



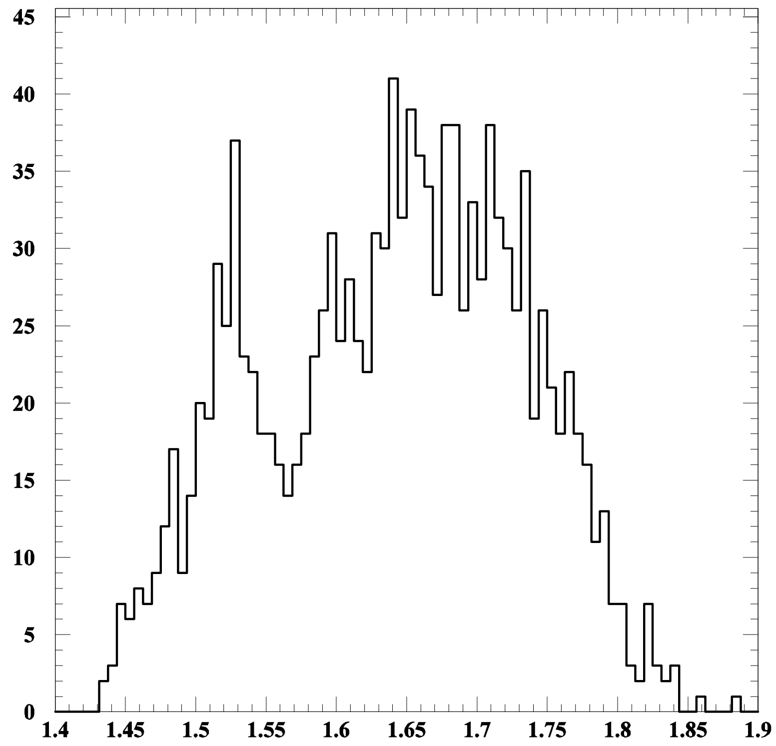
M_{pK^-} (GeV/c^2)



• Λ(1520) events have a small value for the minimum momentum.

Cut dependence of Θ^+(1530) peak

$|p_{min}| < 50$ MeV/c



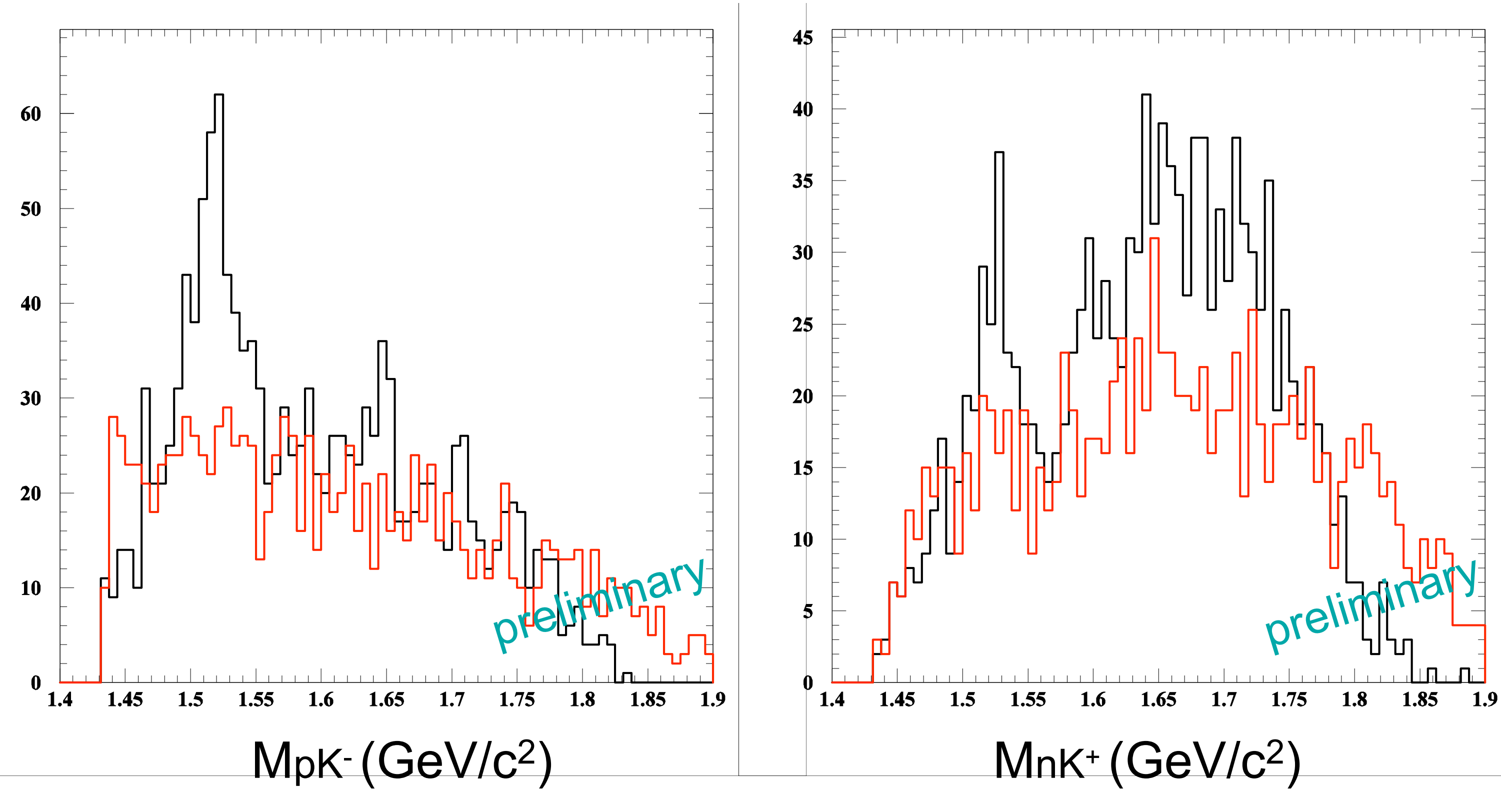
M_{nK^+} (GeV/c^2)

comparison of small and large $|p_{min}|$ regions

$|p_{min}| < 50$ MeV/c

$\sigma(p_{min})$~50MeV/c

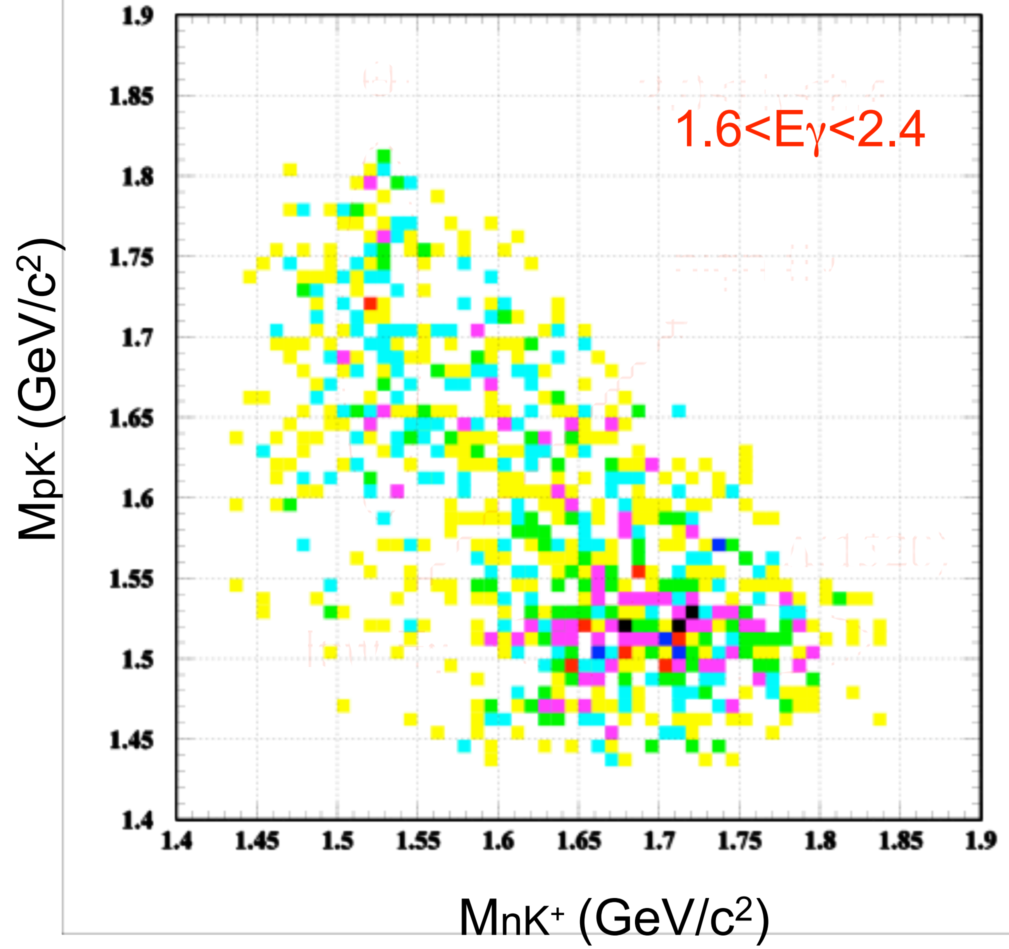
50MeV/c < $|p_{min}|$ < 300 MeV/c



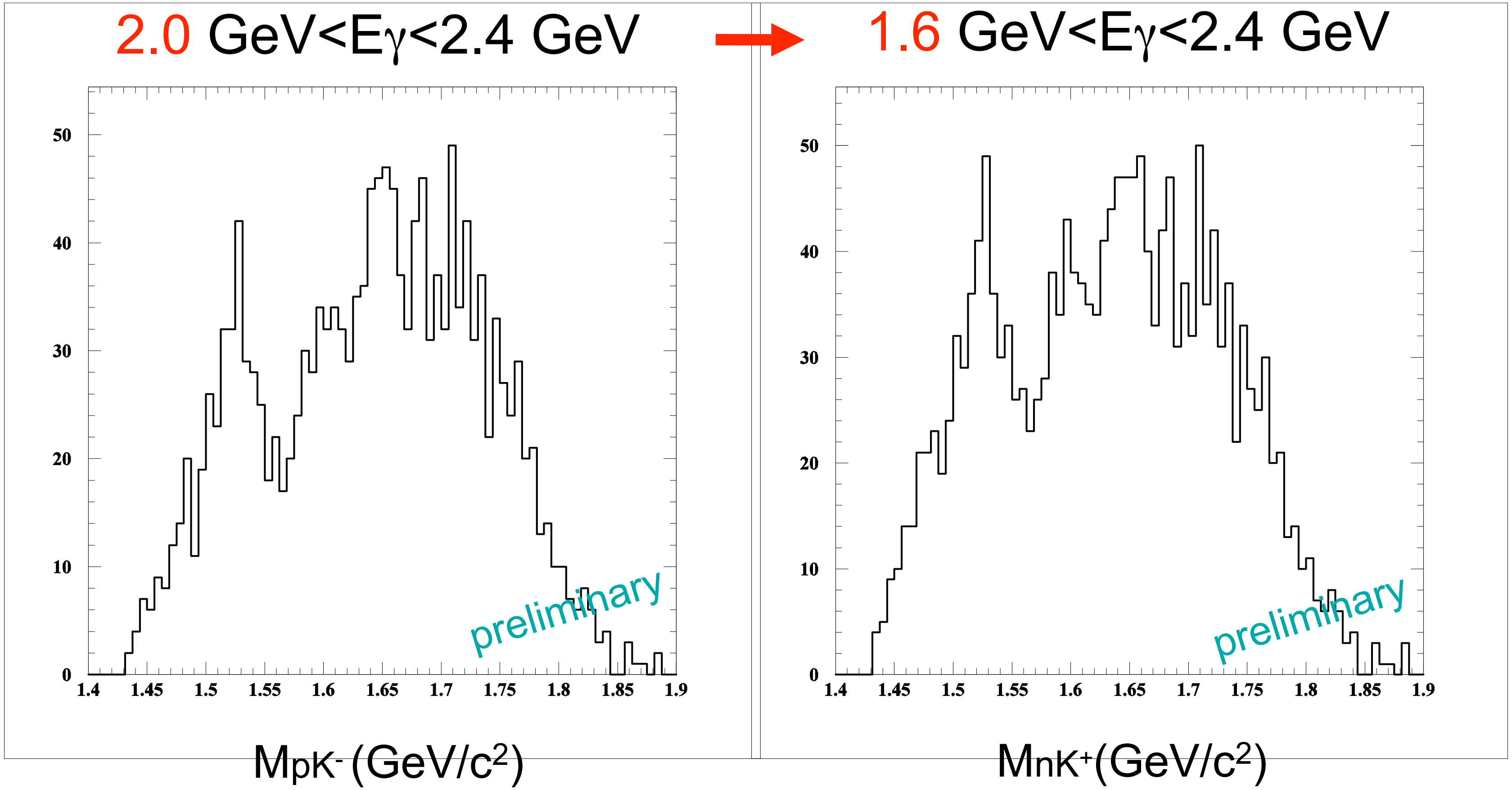
Peaks are seen only in a small $|p_{min}|$ region

→ Strong indication of the quasi-free processes.

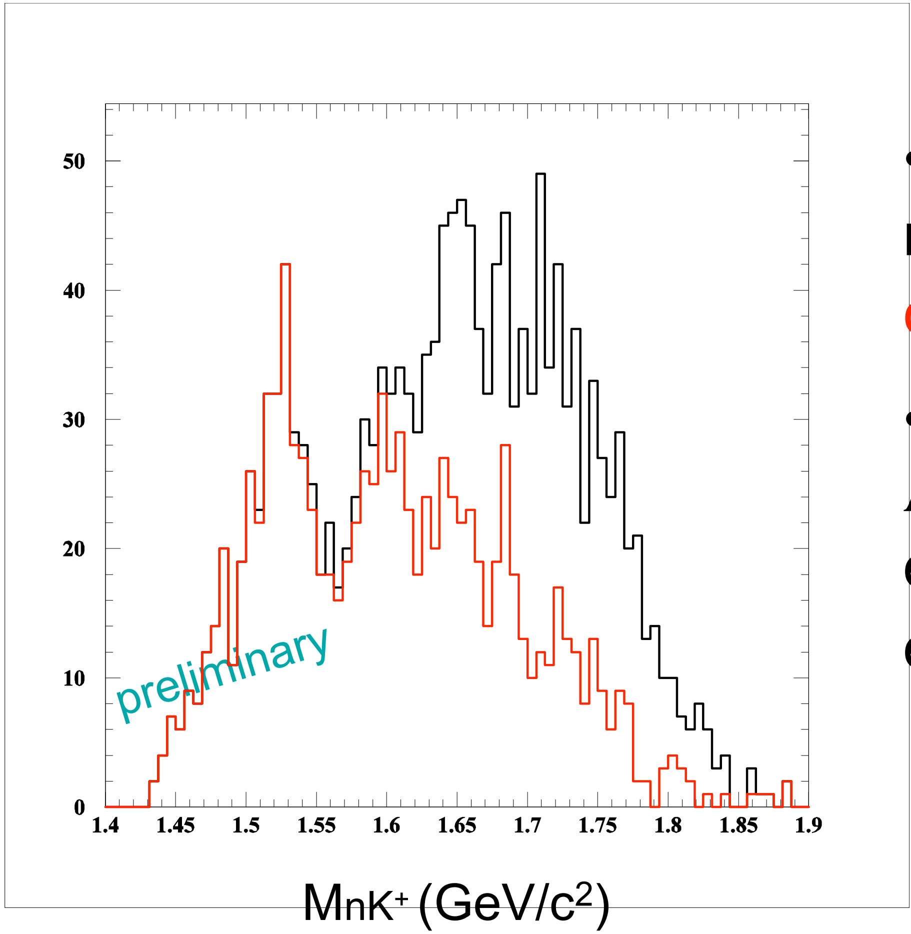
Reflection of Λ^*?



Including low Eγ events



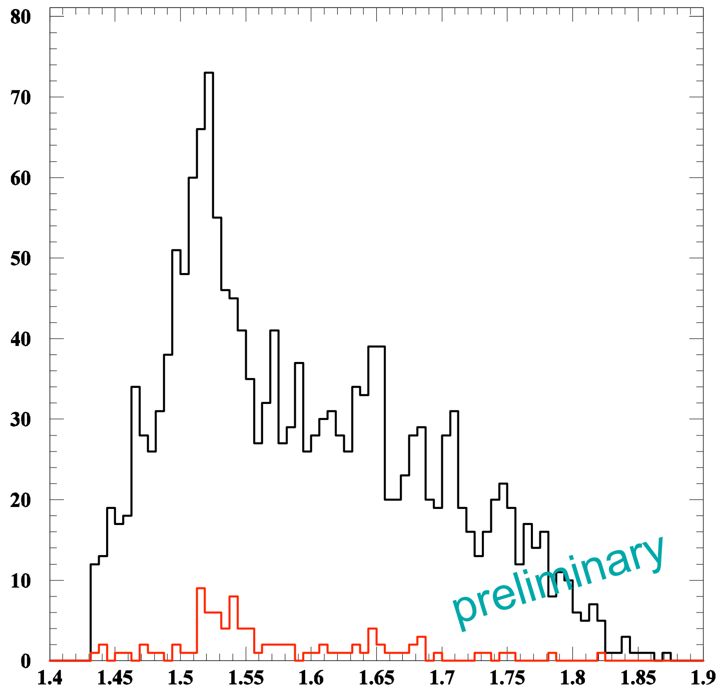
Remove Λ(1520) contribution



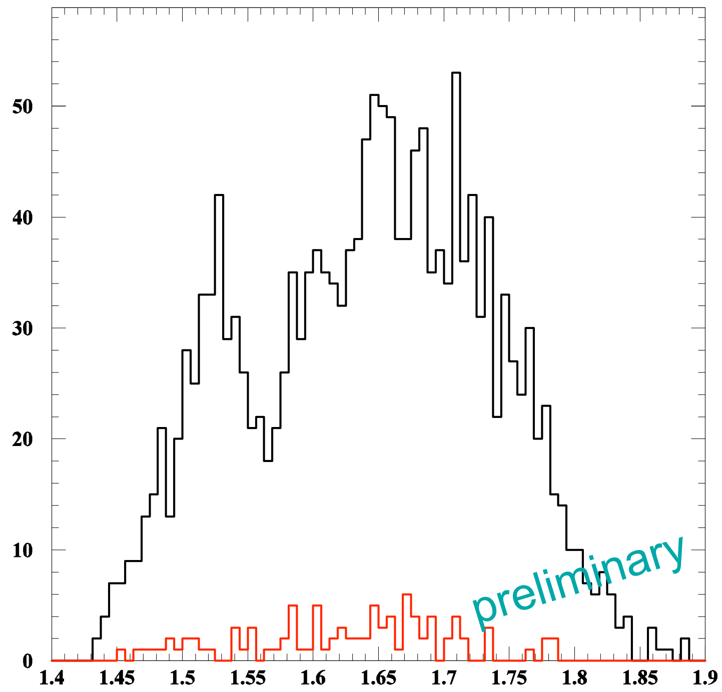
- Require M_{pK^-} > 1.54 GeV/c^2 to remove Λ(1520) events. (red curve)
- Kinematical refection of the Λ(1520) events causes enhancement of high M_{nK^+} events.

Really from a neutron?

LEPS has some acceptance for additional proton.



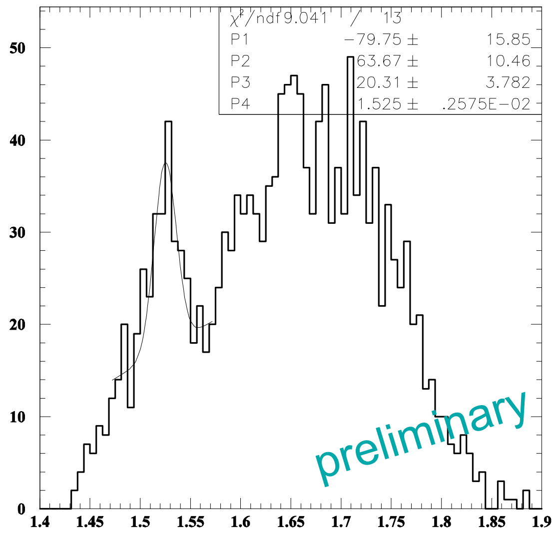
M_{pK^-} (GeV/c^2)

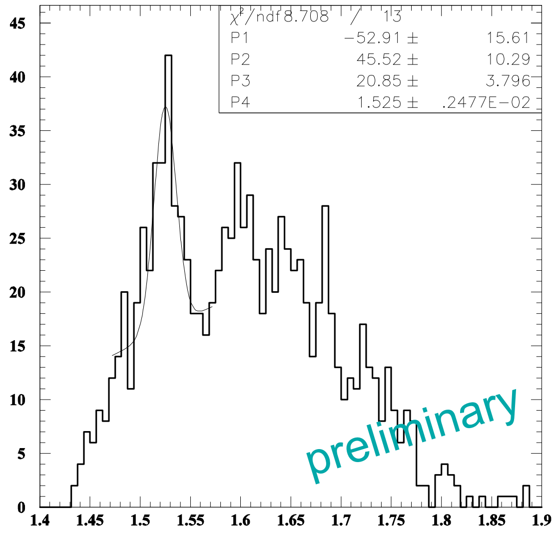


M_{nK^+}(GeV/c^2)

Although the acceptance for an additional proton is low, the Λ(1520) peak seems to be associated with the proton events while the Θ^+ peak does not.

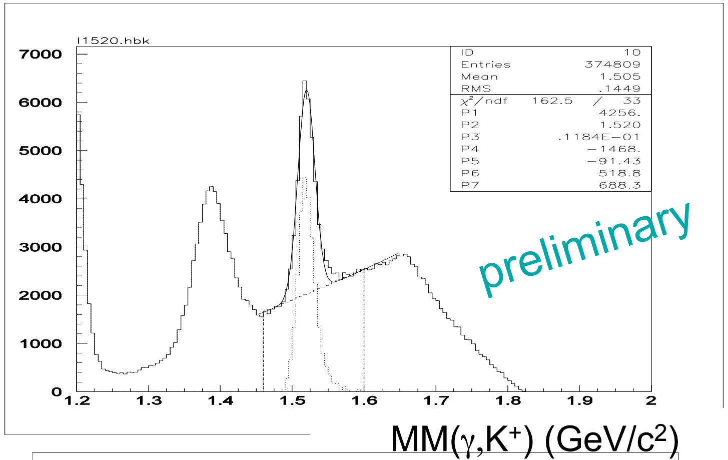
Statistical Significance

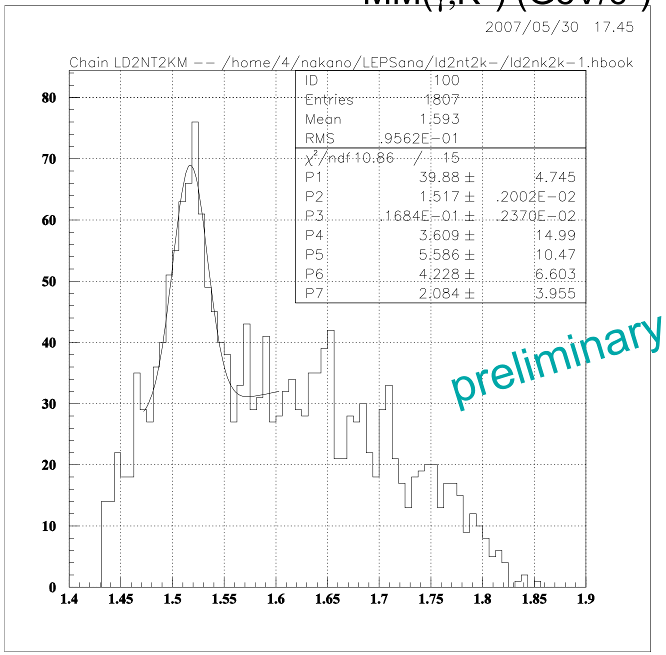




- Spectrum is fitted with a Gaussian + linear BG function with an estimated mass resolution (11 MeV/c^2).
- Significance is estimated by dividing the Gaussian peak height by its uncertainty.
- Estimated significance is ~5.

Λ(1520) Cross-section





- Single K^+ analysis of the LH2 data gives a total cross-section (σ_{tot}) of 0.9 μb for the Λ(1520) production assuming a flat angle distribution.
- KK-pair analysis of the LH2 data gives σ_{tot} ~ 0.8 μb.
- KK-pair analysis of the LD2 data gives σ_{tot} ~ 1.1 μb.
- Systematic error ~ 30%.

Θ^+ Cross-section

•Flat angle distribution and no energy dependence were assumed.

•The acceptance is higher than that of Λ(1520).

x 2 from KN partial branching ratio

x 1.17 from a narrow width

•Preliminary analysis gave $d\sigma/d\Omega$~ 0.01 μb/sr, about 10 % of the Λ(1520) production cross-section by assuming a constant matrix element. → Flat angular and energy dependence were assumed.

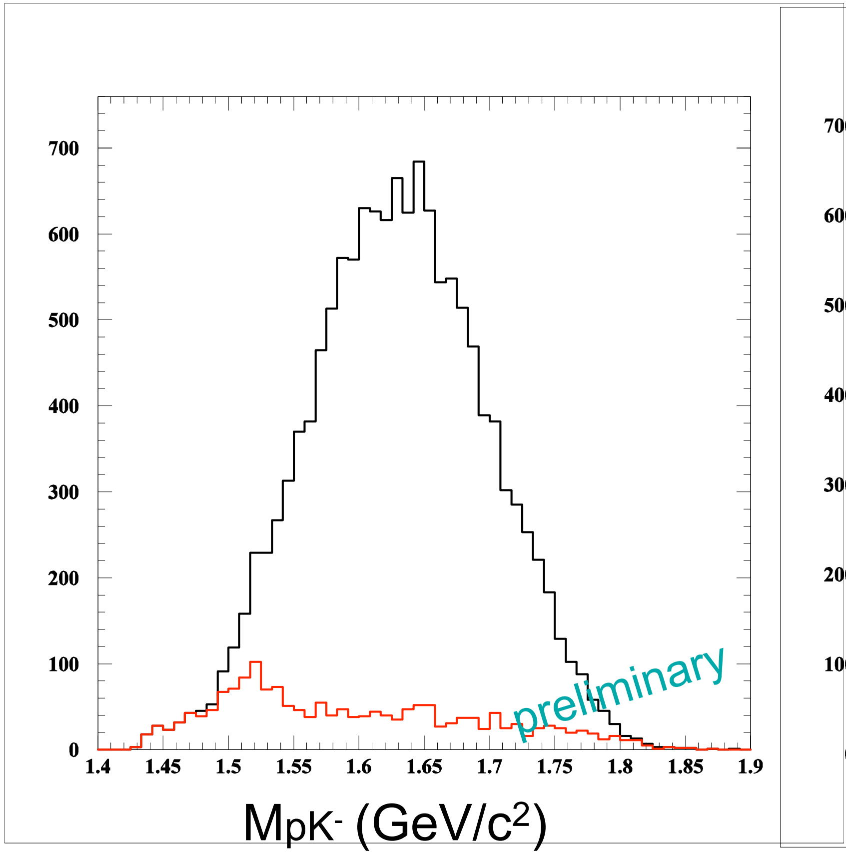
•More than one order of magnitude larger than CLAS-g10 upper limit of σ_{tot}~3 nb (95%CL).

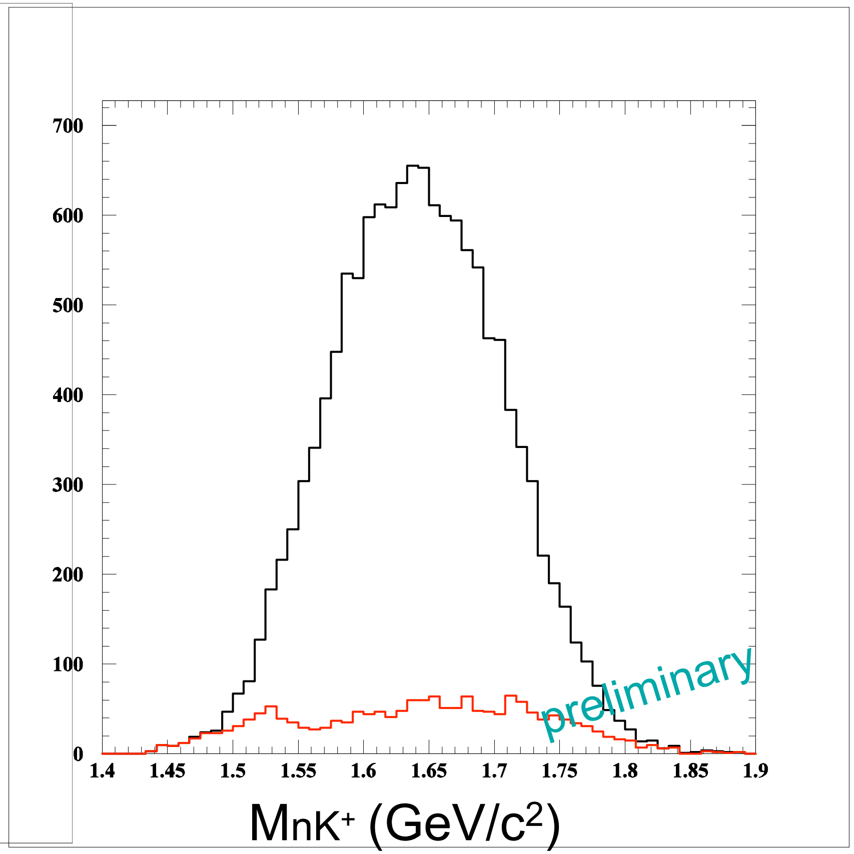
Criticism

"Didn't the ϕ exclusion cut create the peak artificially? Wasn't the cut tuned so that peak would look good?"

"How can the contradiction between CLAS and LEPS be explained?"

before and after ϕ exclusion



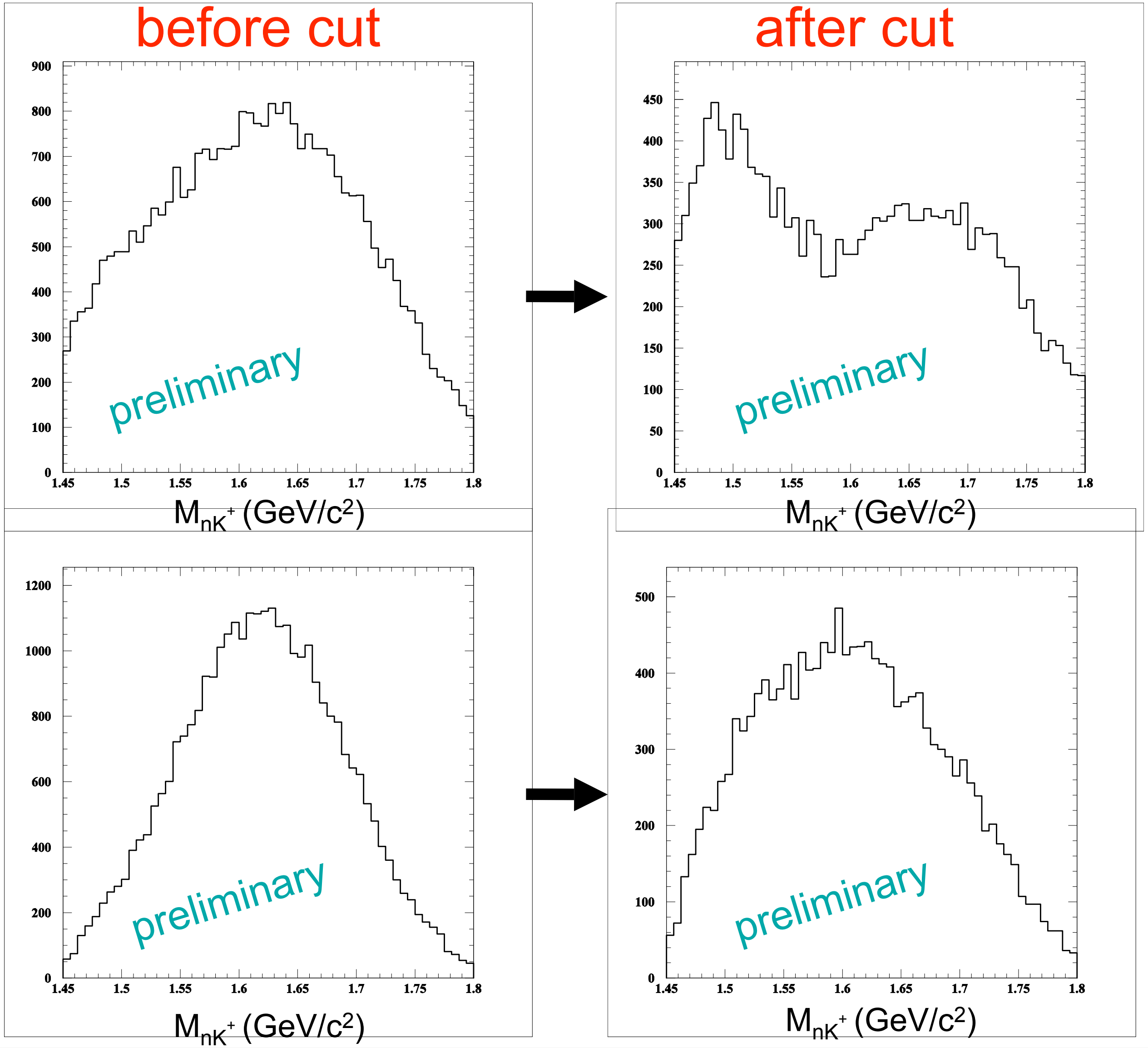


The Λ(1520) and the Θ^+ peaks can be seen only after ϕ events are excluded.

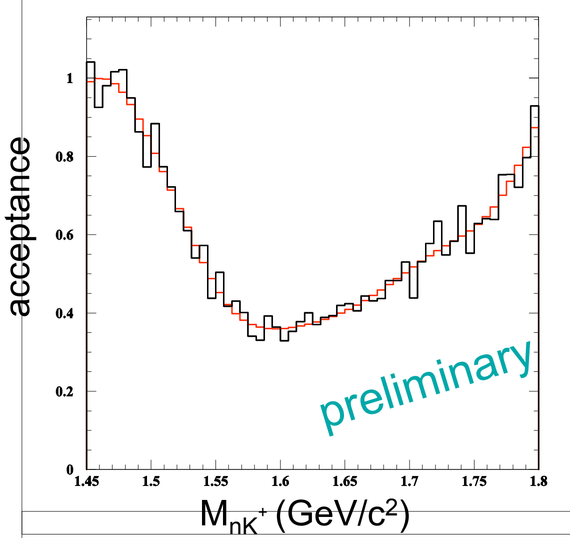
How does ϕ exclusion cut change the spectrum shape?

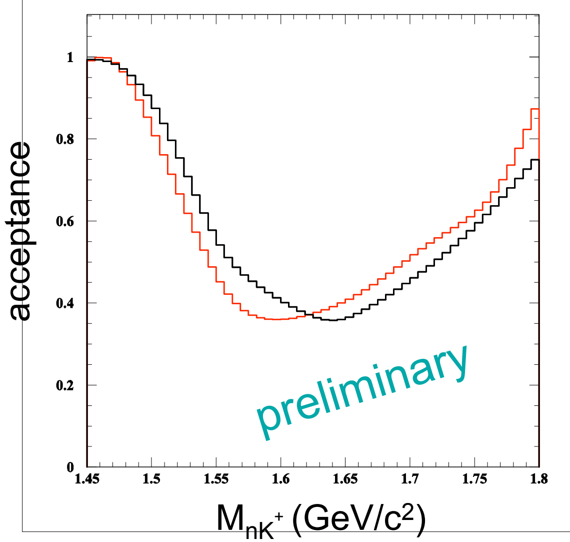
phase space

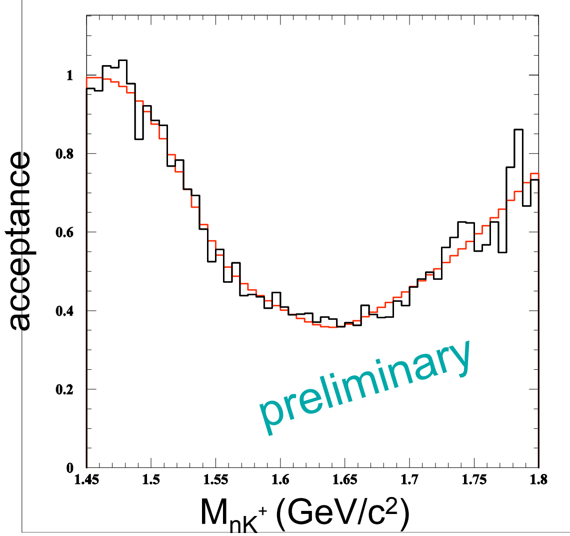
KK in p-wave (SCHC)



Yes, but the cut does not produce a narrow peak.

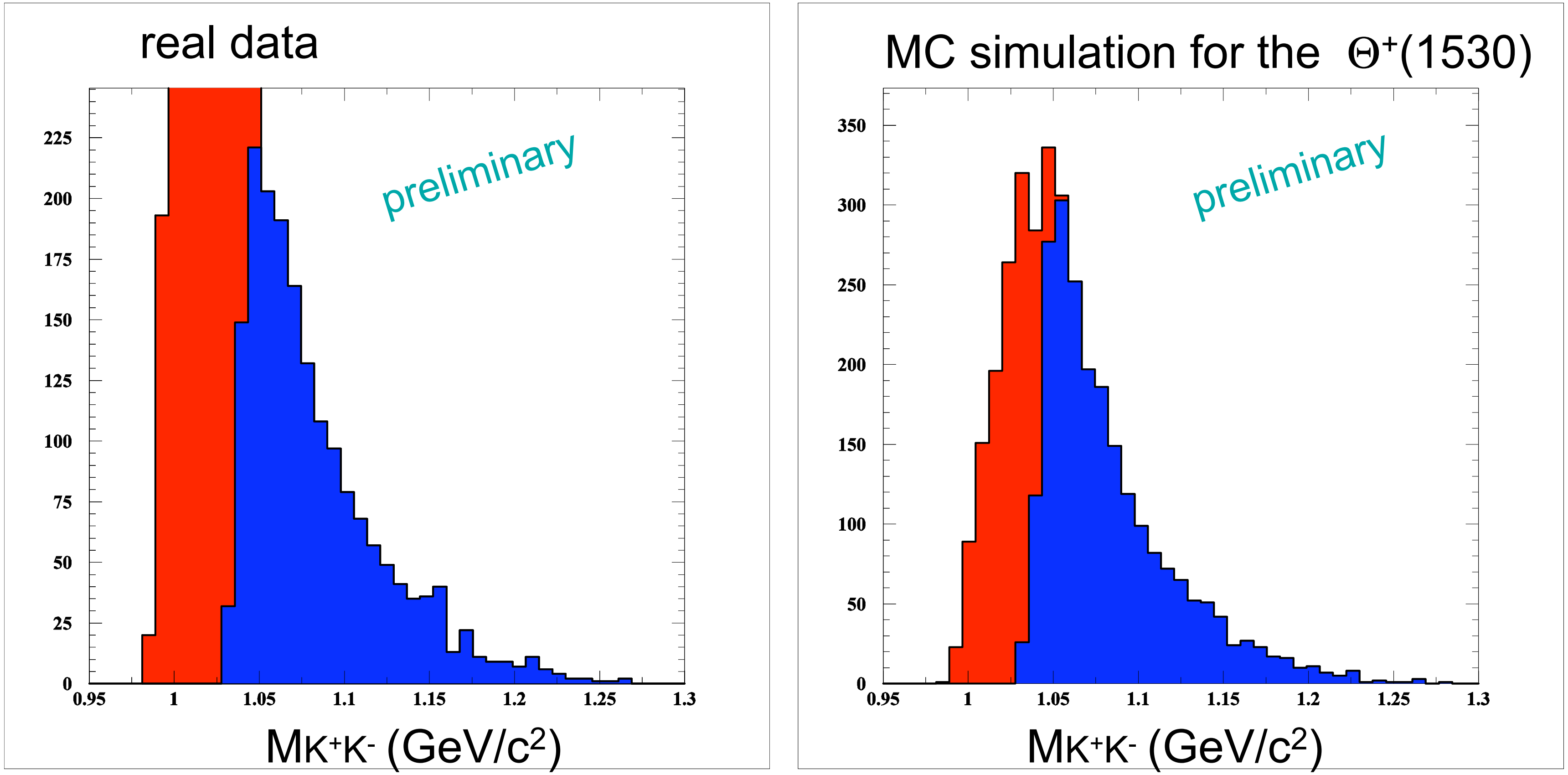






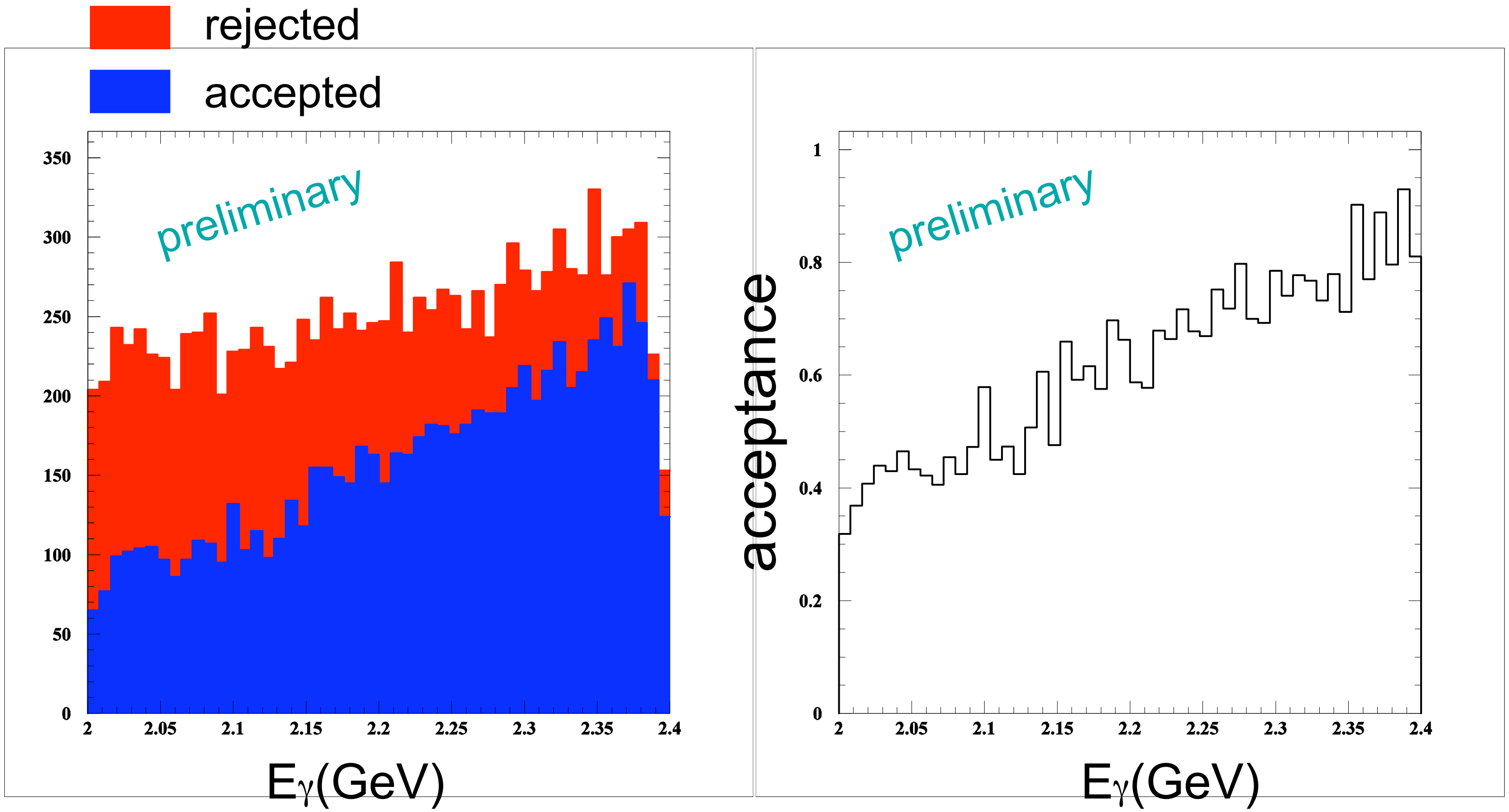
- The cuts removes events with a small KK opening angle.
- The acceptance is small when $M_{NK^+} \approx M_{NK^-}$.

Signal acceptance of ϕ exclusion cut



Acceptance of the ϕ cut for the $\Theta^+(1530)$ is ~65%.
Similar acceptance for $\Lambda(1520)$.
No structure in M_{KK} is seen above the cut.

Energy dependence of ϕ exclusion cut



Acceptance is low in low energy region.

Can be consistent with CLAS γd result?

The reaction is the same: $\gamma n \rightarrow K^- \Theta^+$

LEPS		CLAS
Good forward angle coverage	$\longleftrightarrow$	Poor forward angle coverage
Poor wide angle coverage	$\longleftrightarrow$	Good wide angle coverage
Low energy	$\longleftrightarrow$	Medium energy
Symmetric acceptance for K^+ and K^-	$\longleftrightarrow$	Asymmetric acceptance
$M_{KK} \gtrsim 1.04$ GeV/c^2	$\longleftrightarrow$	$M_{KK} > 1.07$ GeV/c^2
Select quasi-free process	$\longleftrightarrow$	Require re-scattering or large Fermi momentum of a spectator

Signal strength under/below ϕ could be large.

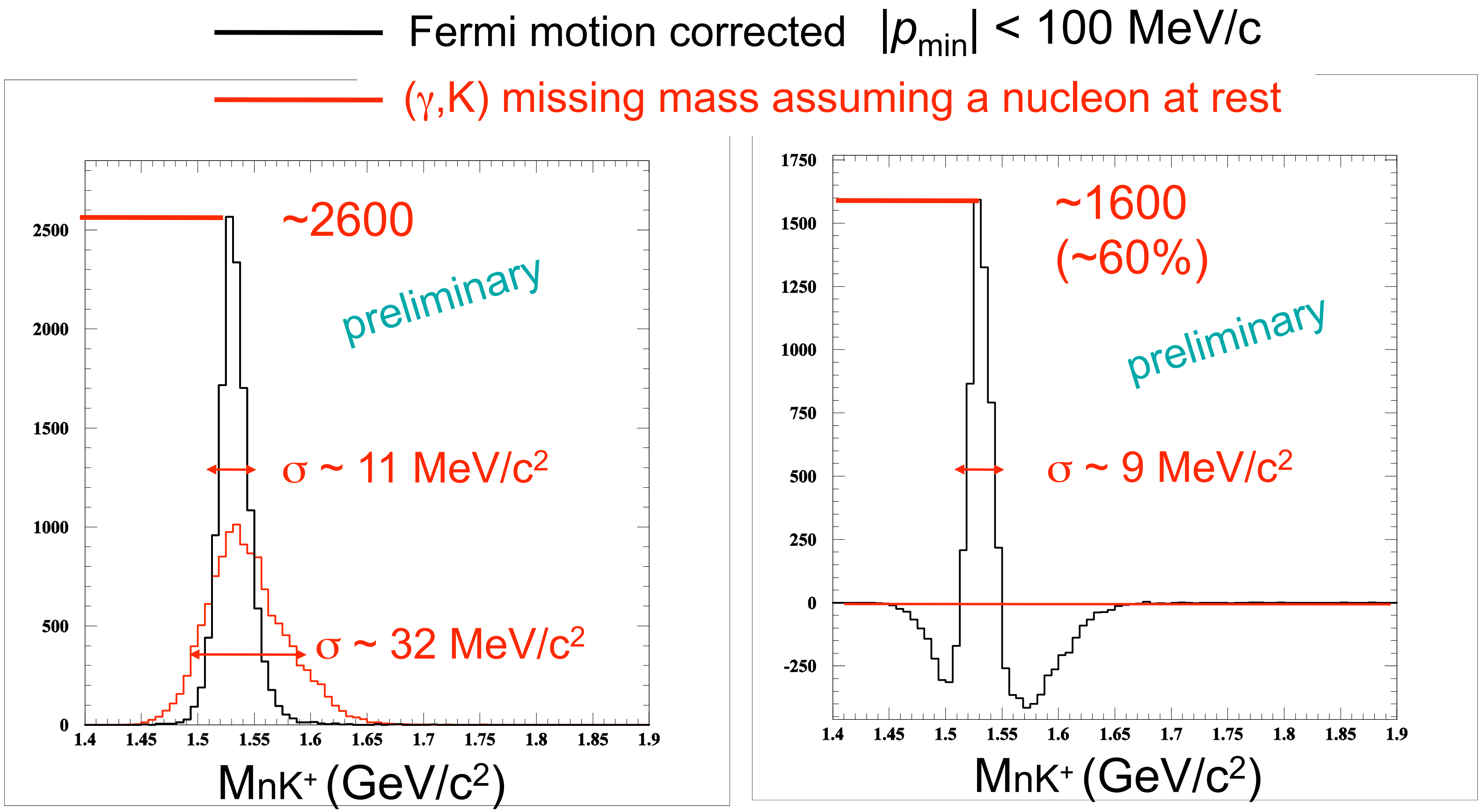
How to observe a narrow peak under ϕ background?

Subtract Fermi-motion uncorrected spectrum from Fermi-motion corrected spectrum.

-Only narrow peak will remain after the subtraction.

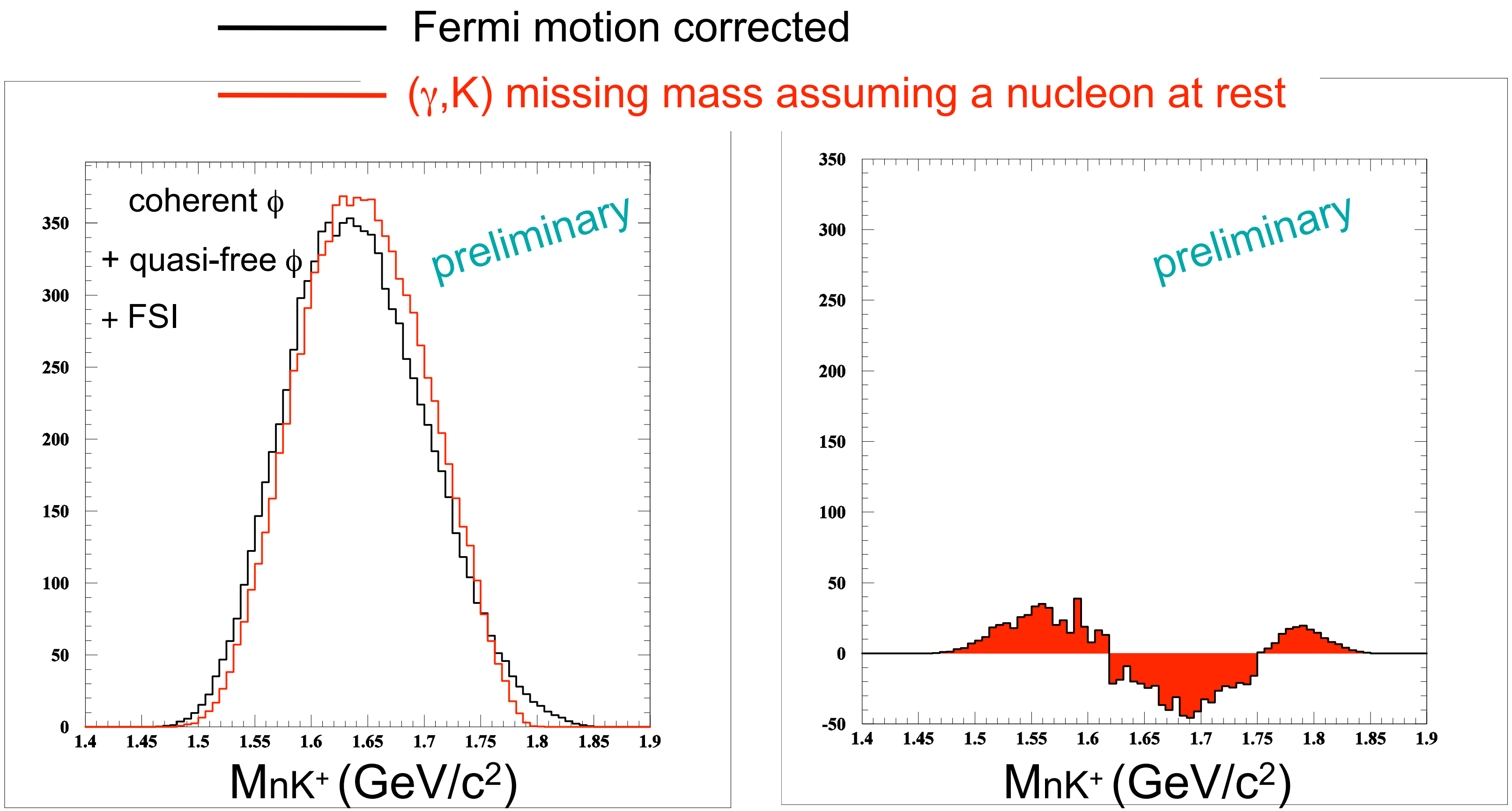
-Broad background due to ϕ contribution will be canceled largely.

M_{nK^+}(corrected) – M_{nK^+}(uncorrected): Θ^+



MC data: without ϕ exclusion cut, flat distribution

M_{nK^+}(corrected) – M_{nK^+}(uncorrected): ϕ

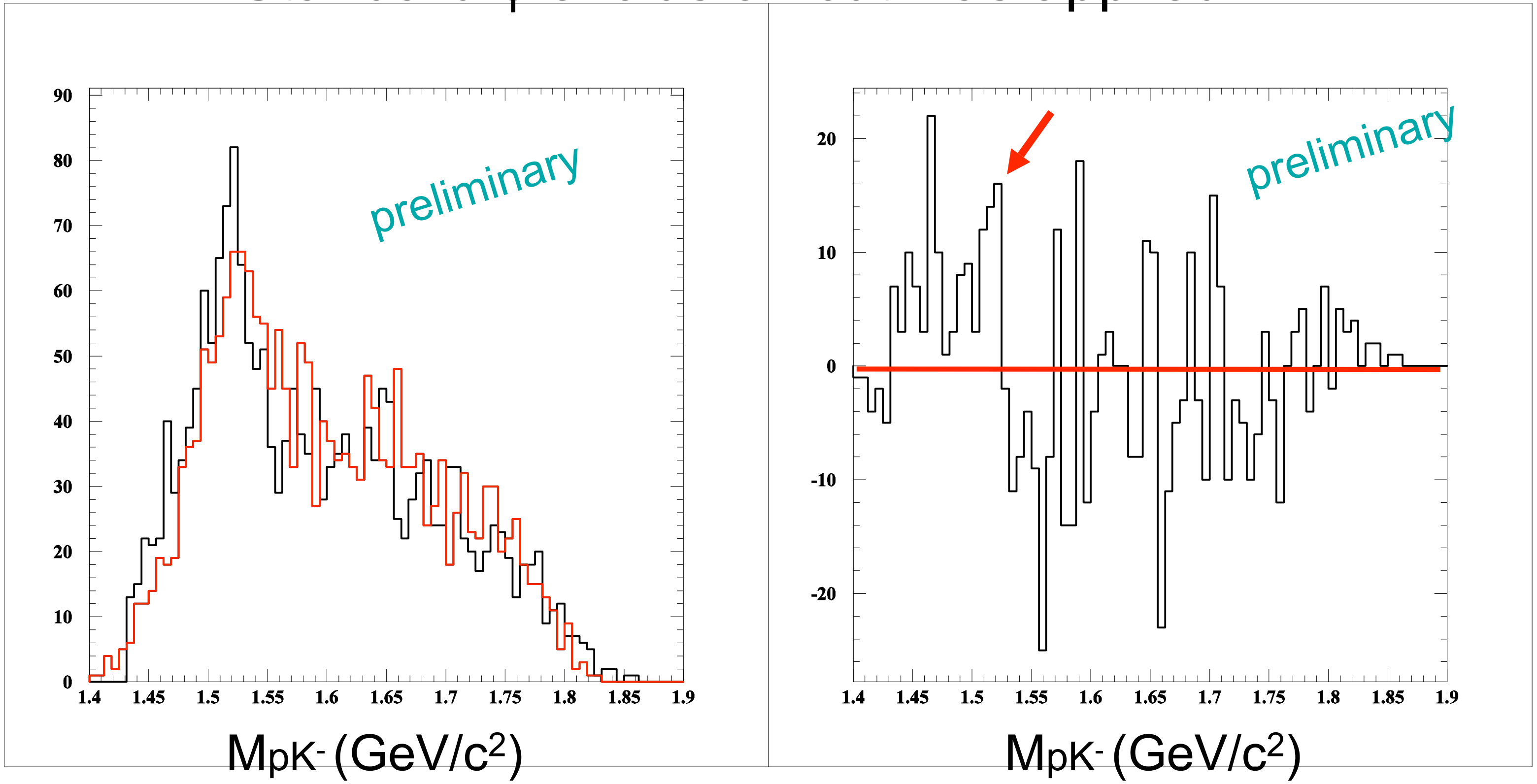


Invariant mass of K from ϕ decay and a scattered nucleon.

BG level: a factor of ~5 reduction in the signal region.

$\Lambda(1520)$ peak search under ϕ background

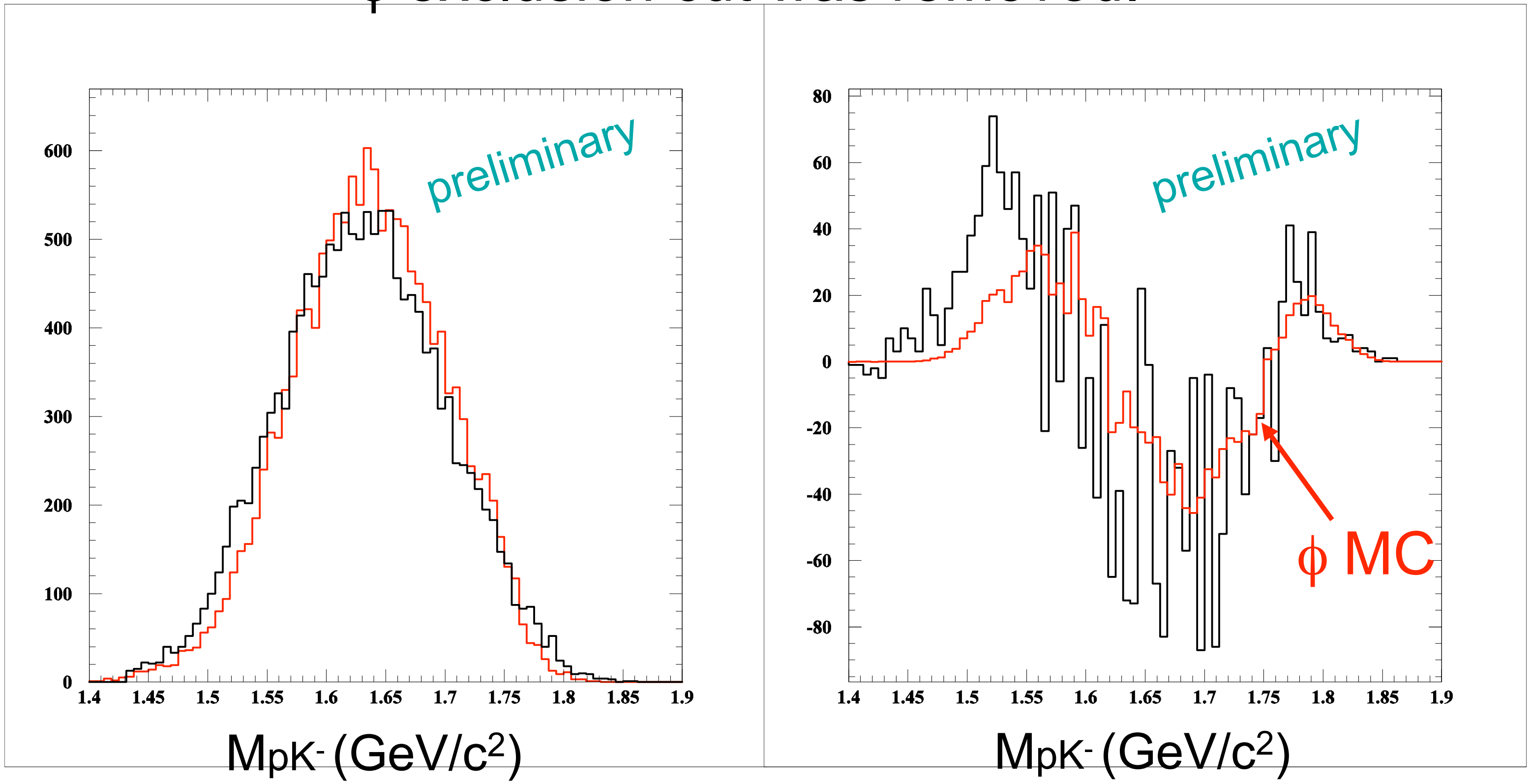
Standard ϕ exclusion cut was applied.



$|p_{min}| < 100$ MeV/c

Λ(1520) peak search under φ background

φ exclusion cut was removed.

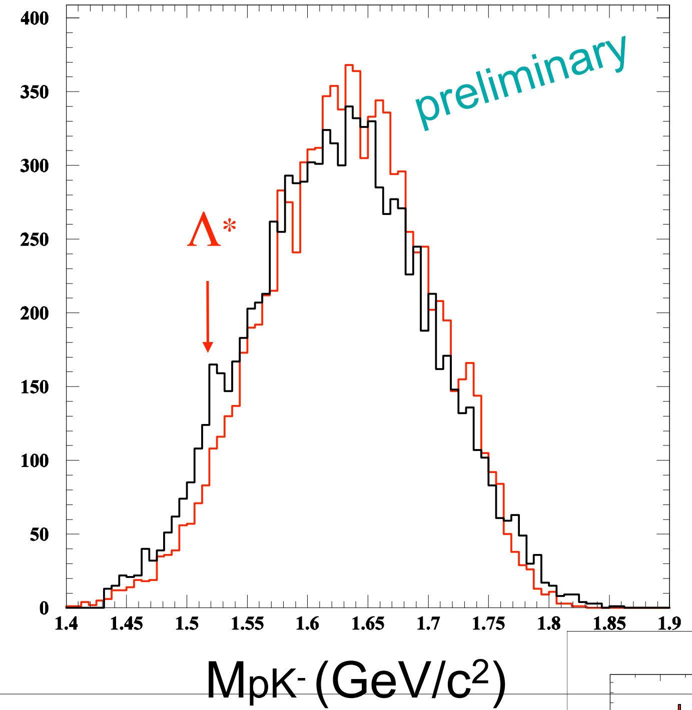


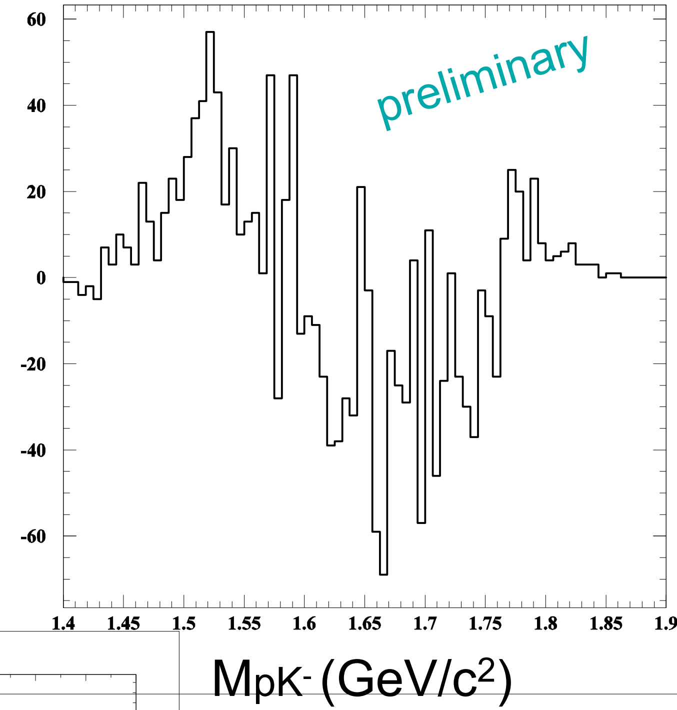
M_{pK^-} (corrected)

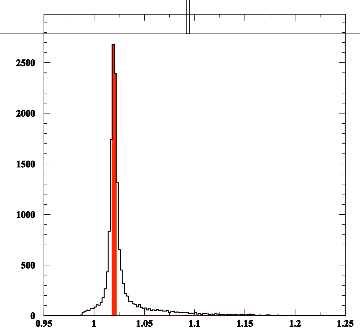
M_{pK^-} (uncorrected)

Λ(1520) peak search under φ background

φ was partially (~50%) removed.



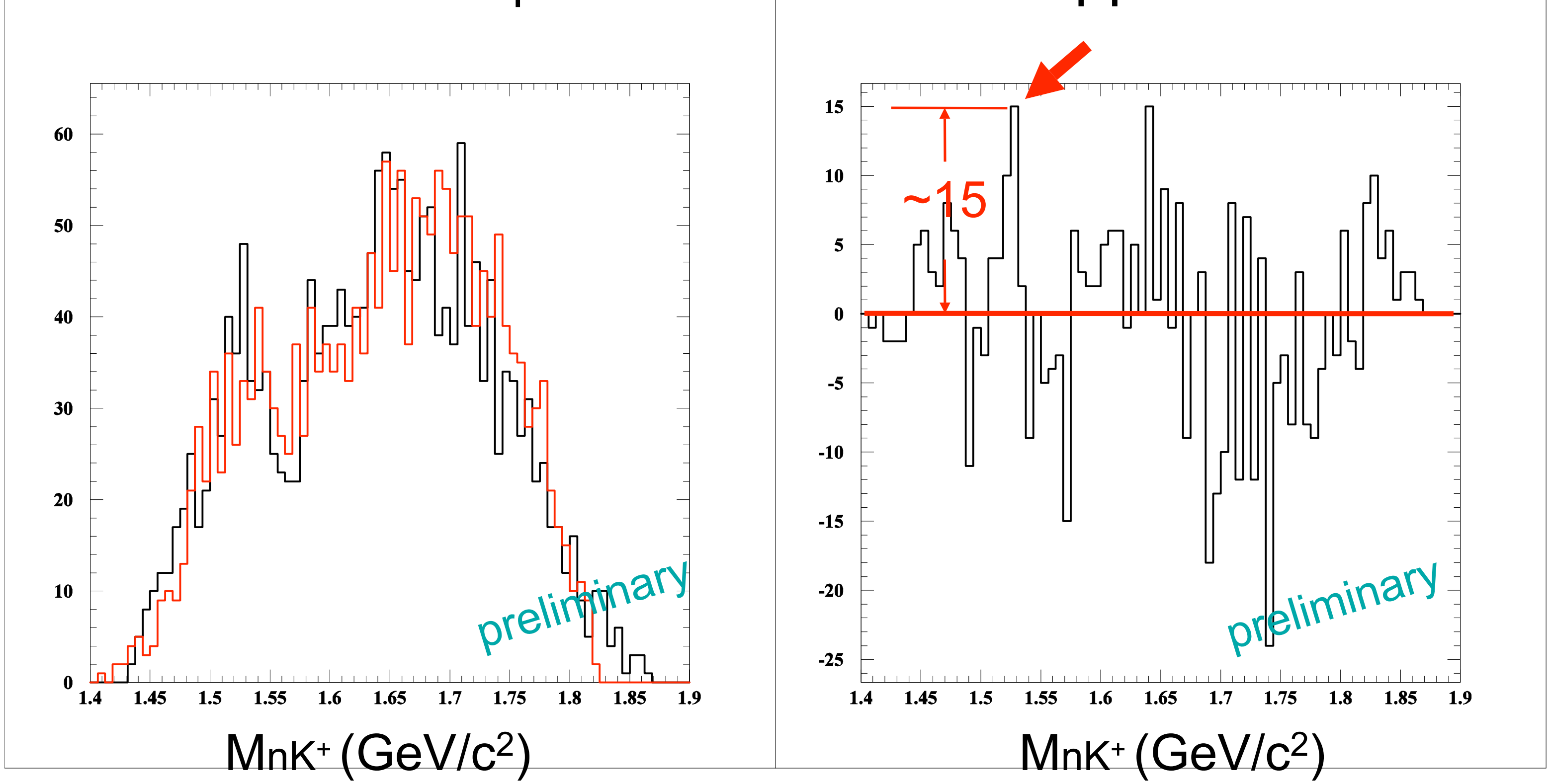




Very small acceptance loss

Θ^+ peak search under ϕ background

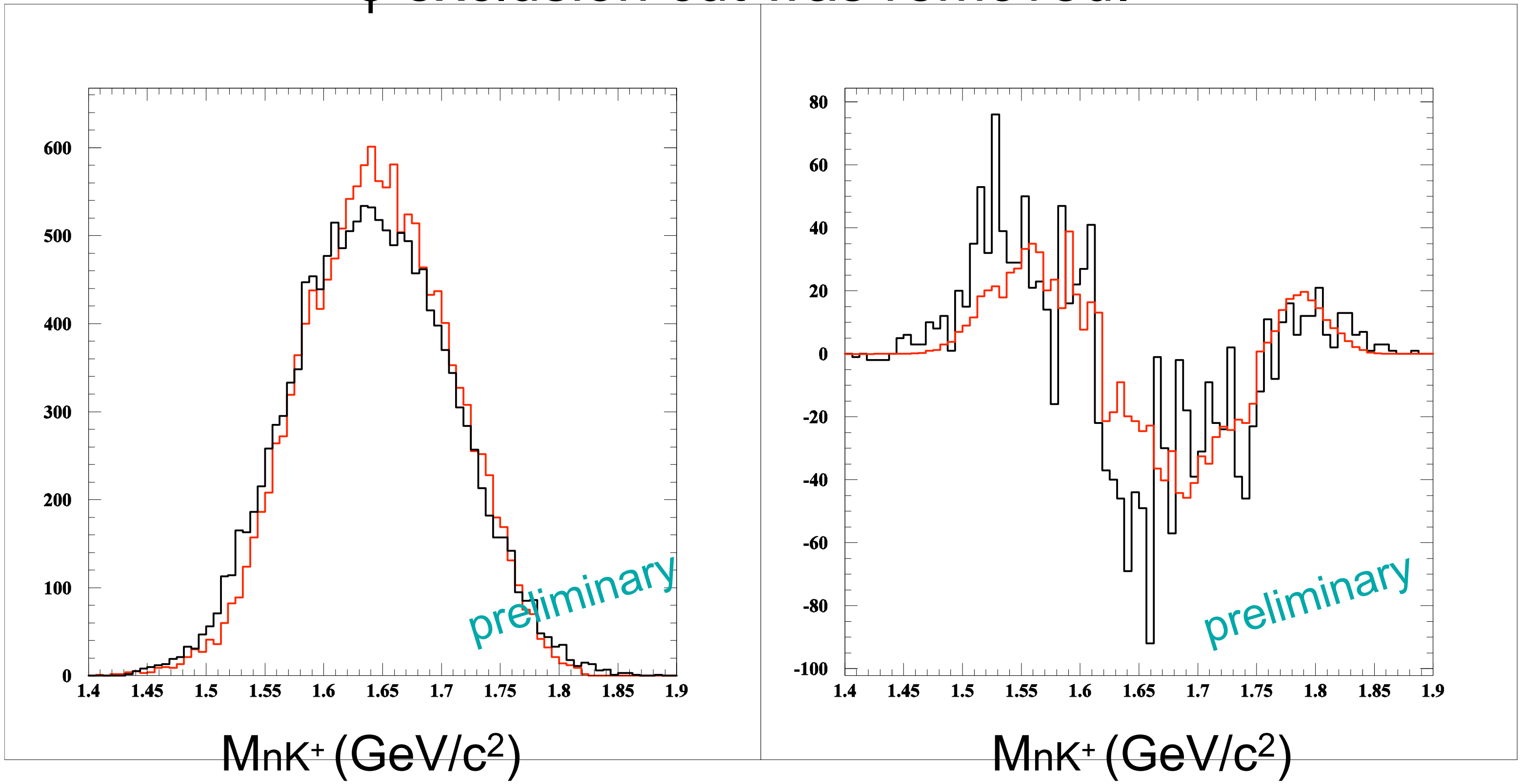
Standard ϕ exclusion cut was applied.



Acceptance of the ϕ exclusion cut is ~65% if we assume flat energy and angle dependence.

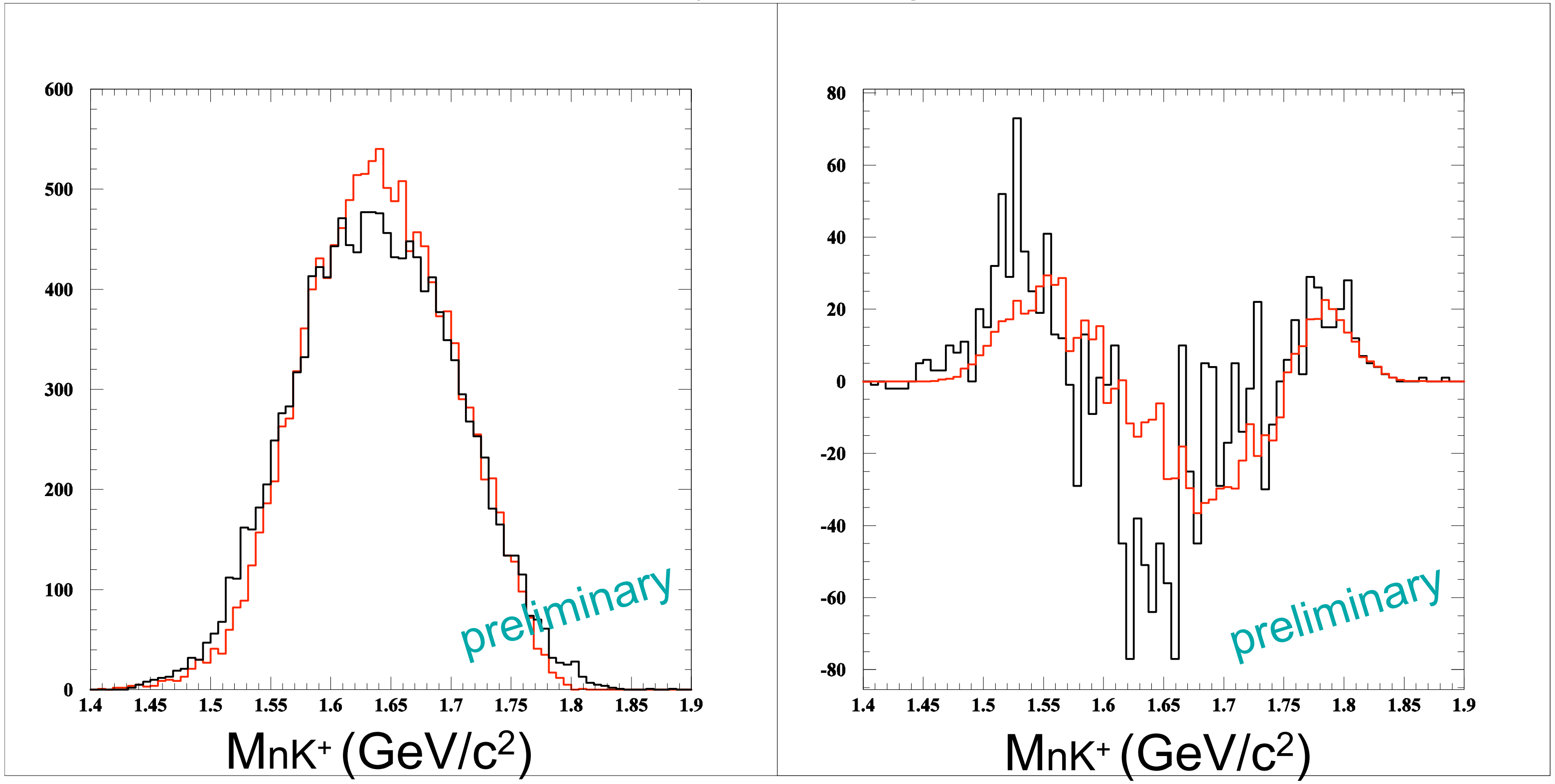
Θ^+ peak search under ϕ background

ϕ exclusion cut was removed.



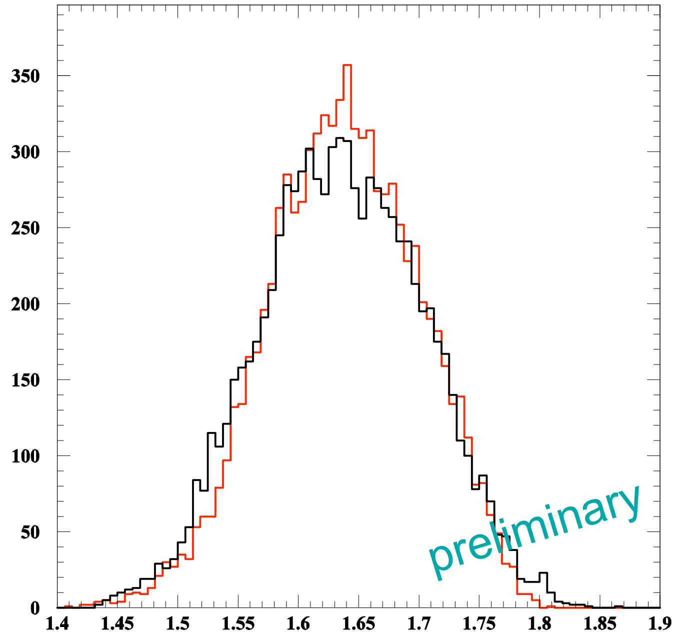
Θ^+ peak search under ϕ background

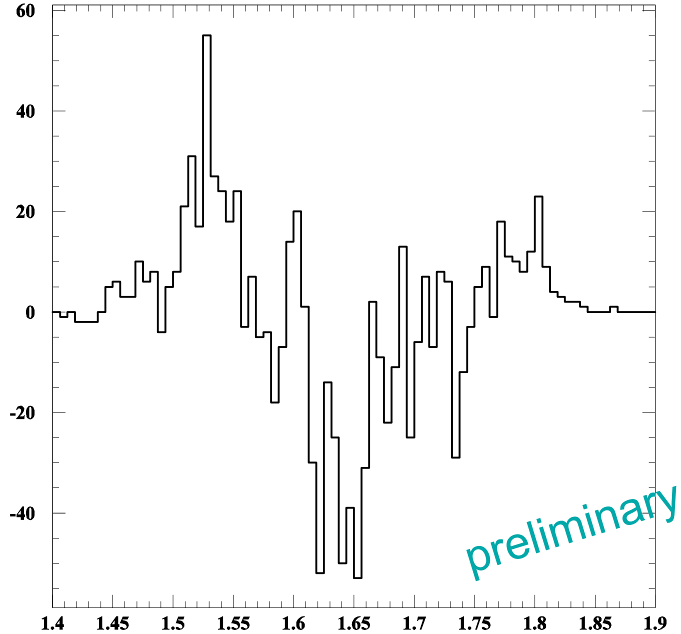
$\Lambda(1520)$ was removed by requiring Mpk- > 1.54 GeV/c^2



Θ^+ peak search under ϕ background

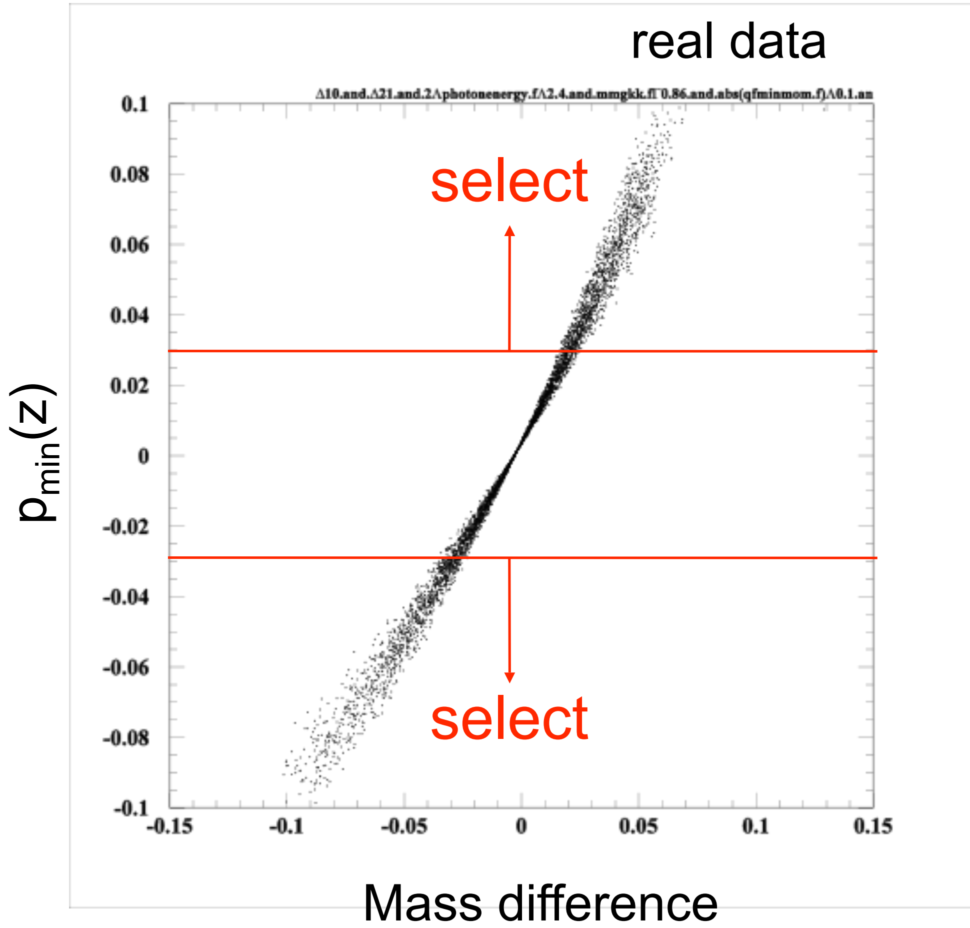
ϕ was partially (~50%) removed.





M_{nK^+} (GeV/c^2) M_{nK^+} (GeV/c^2)

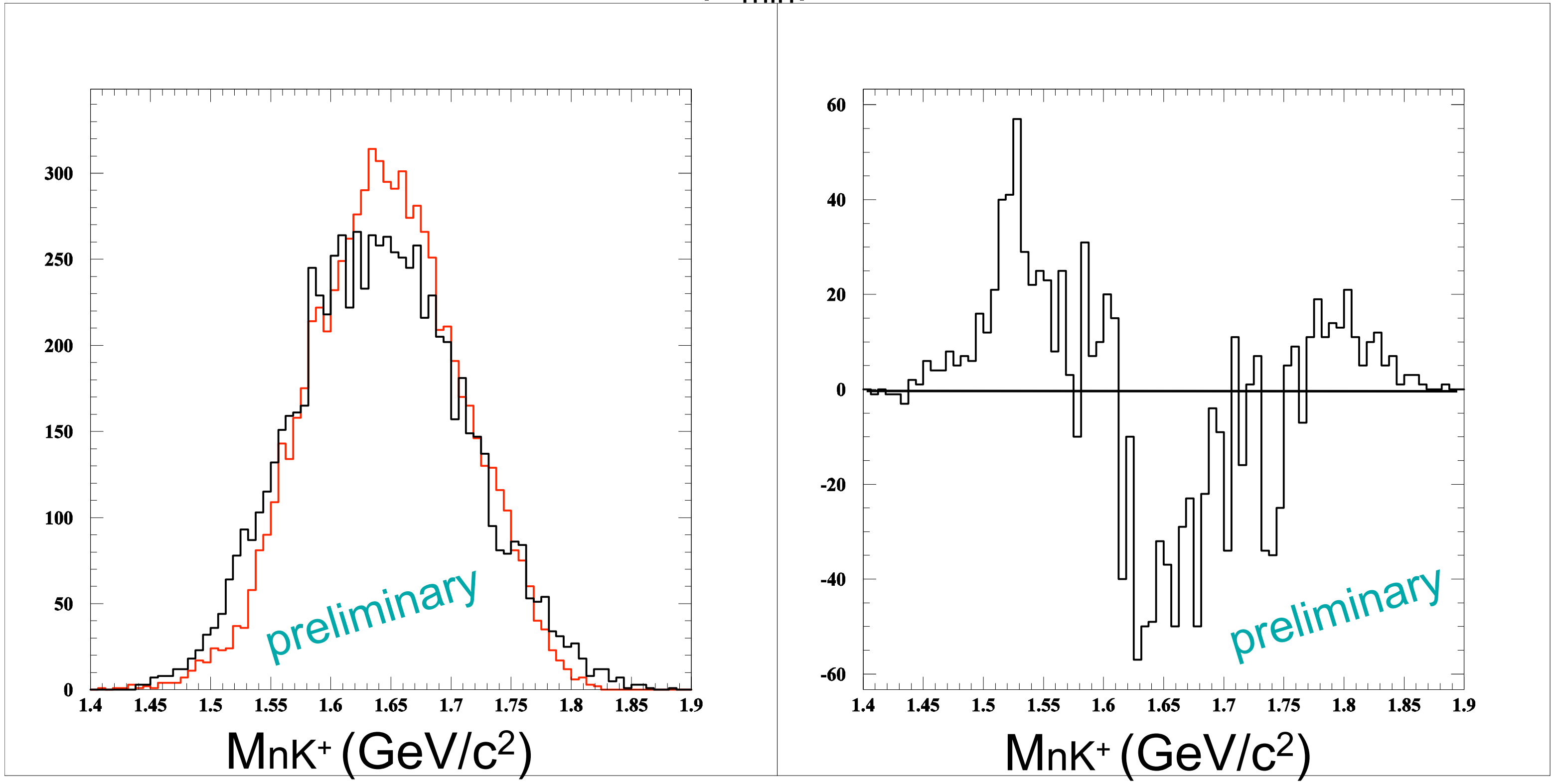
Mass difference vs. z-component of Minimum momentum (spectator momentum)



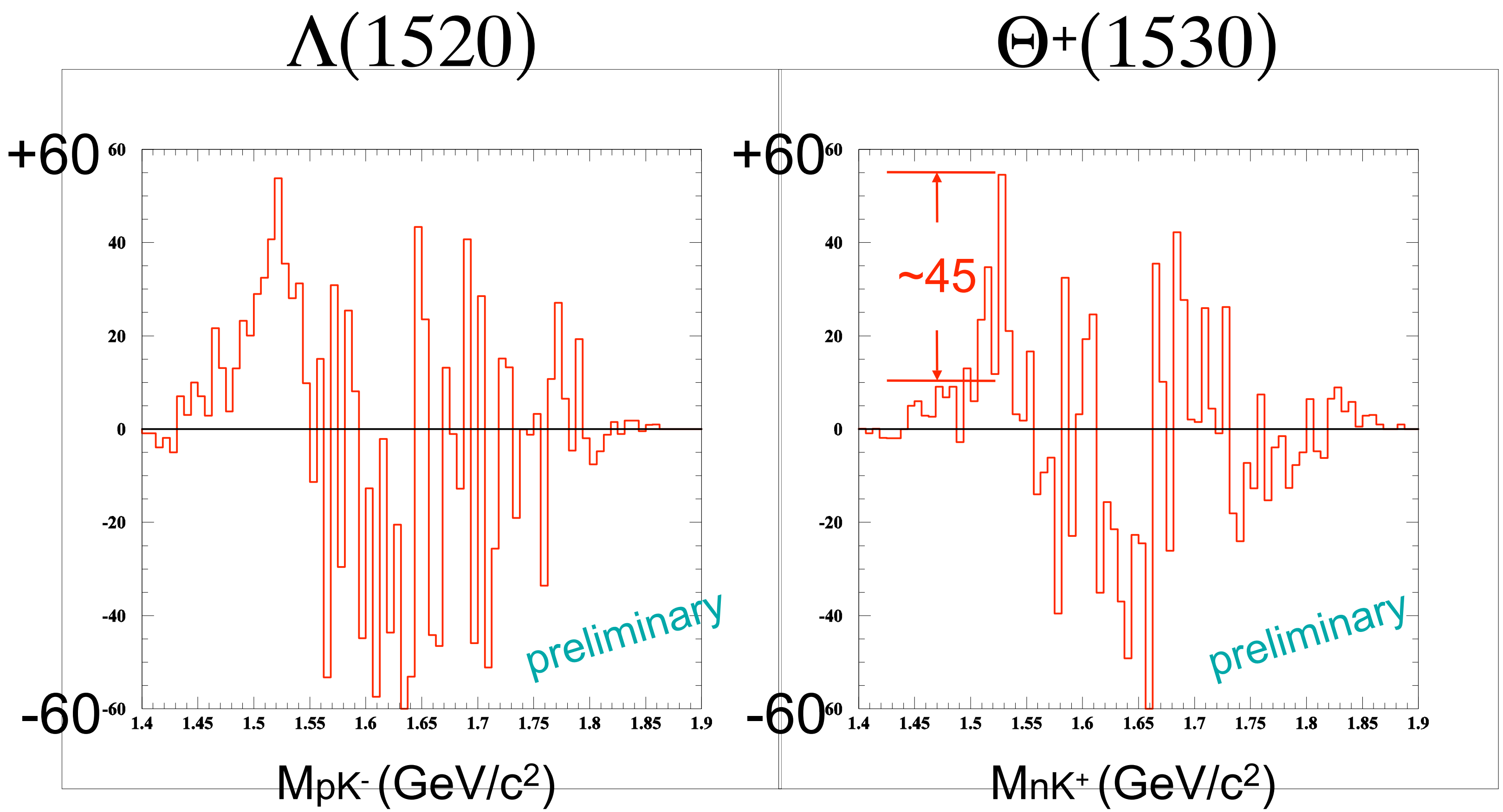
Remove events with small mass difference.

Θ^+ peak search under ϕ background

30 MeV/c<|p_{min}|<100 MeV/c



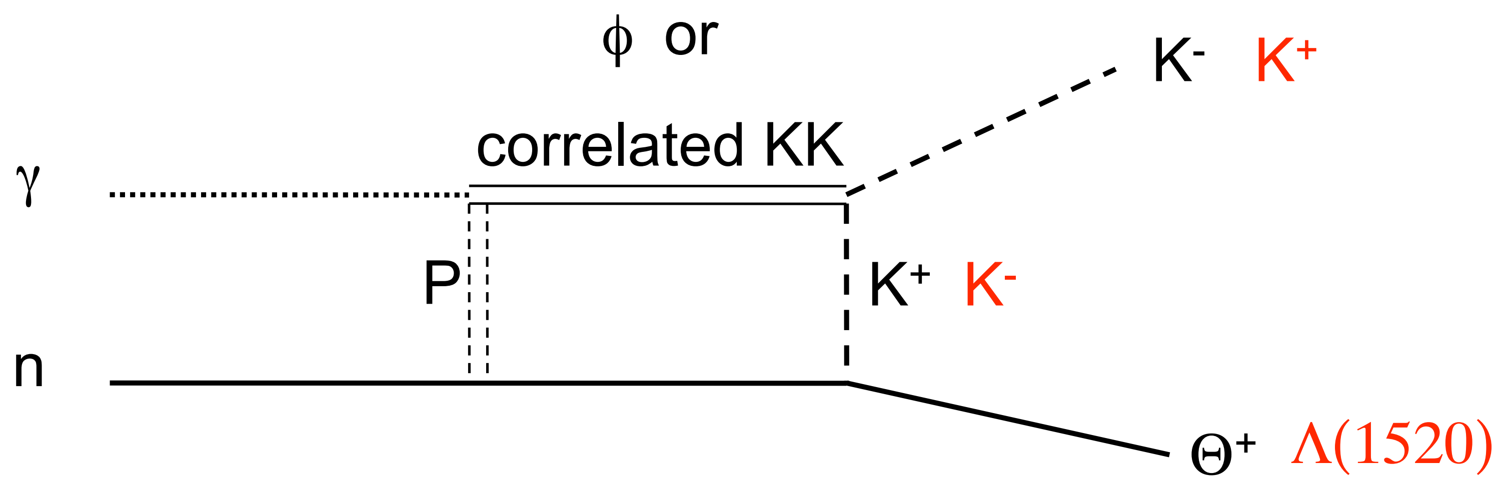
Subtract ϕ contributions



Note: Vertical scales are the same.

Θ^+ strength under/below ϕ BG seems to be LARGE.

Possible reaction mechanism which could explain the difference



ϕ is produced in forward angles.

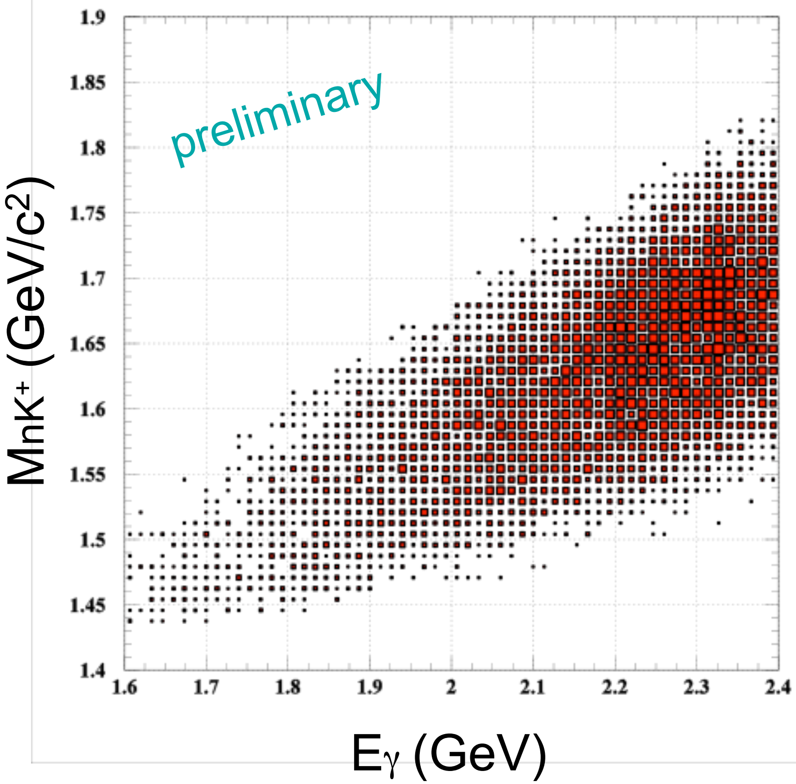
ϕ production cross-section increases with $E\gamma$.

γ couples to KK through VMD much stronger than EM.

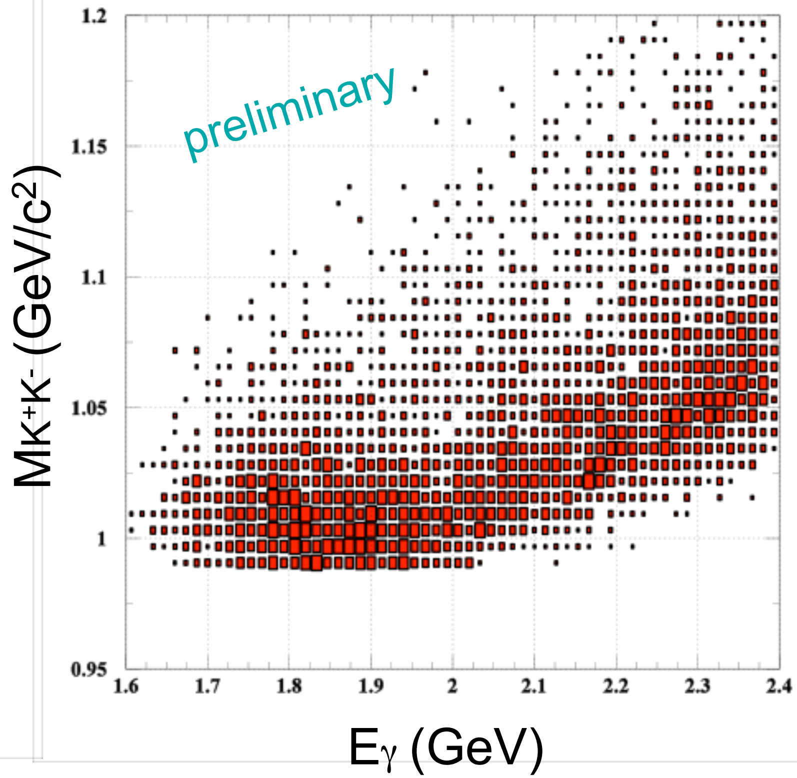
Θ^+ production amplitude is large when ϕ and K^+ close to be real.

Θ^+ production through VMD

ϕ events from real data



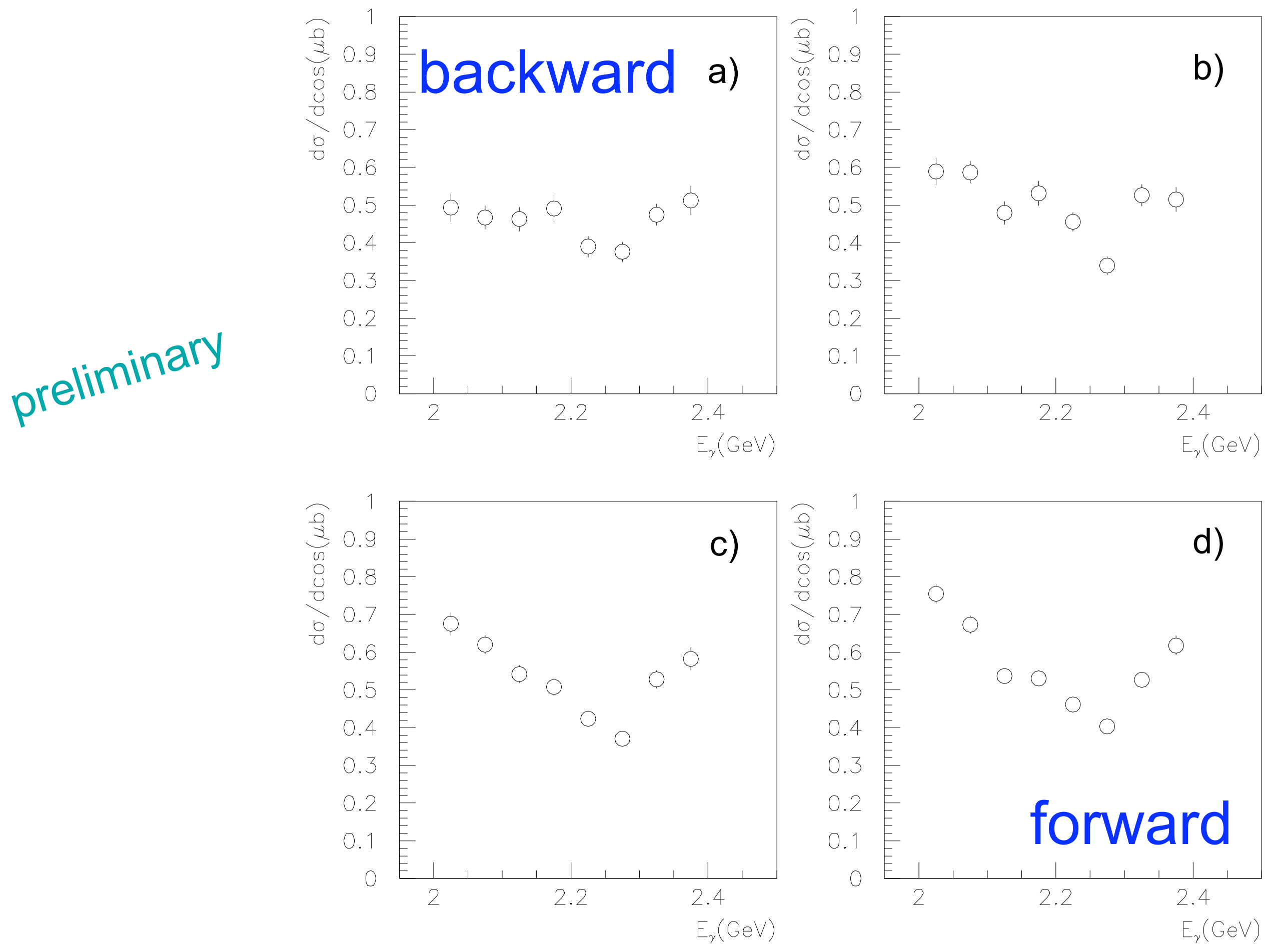
MC simulation for the $\Theta^+(1530)$



Θ^+ production through VMD should be suppressed in high $E\gamma$.

ϕ production in low energy is small. The best energy would be ~2 GeV.

Λ(1520) photo-production cross-section



Summary of Θ^+ analysis

1. Both $\Lambda(1520)$ and Θ^+ peaks are seen only in the events with small "minimum momentum" p_{min}. → indication of quasi-free processes
2. Tighter cut on p_{min} improves both mass resolutions and S/N ratios.
3. The observed peak is consistent with the expected mass resolution.
4. No sign of kinematical reflections.
5. Θ^+ seems to be produced from a neutron.
6. Statistical significance is ~5 σ.
7. Differential cross-section is ~0.01 μb/sr assuming flat distributions.
8. Require a special reaction mechanism for this result to be consistent with CLAS-g10 result.
9. Production under/below ϕ region seems to large. –may be a hint of a special reaction mechanism.

Prospects

0. Paper will come soon.

1. New data set with 3 times more statistics has been already taken.

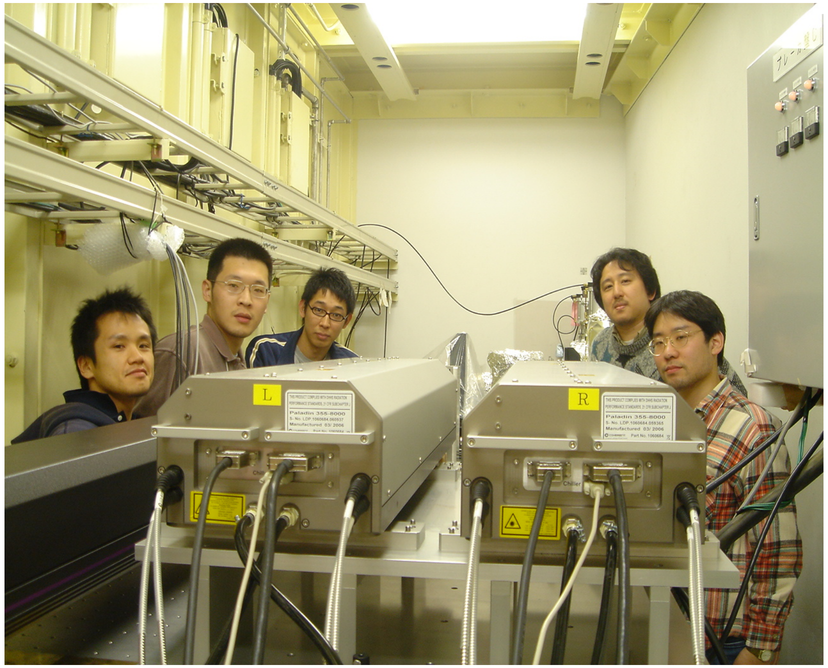
2. Blind analysis will be carried out to check the peak (by early 2008).

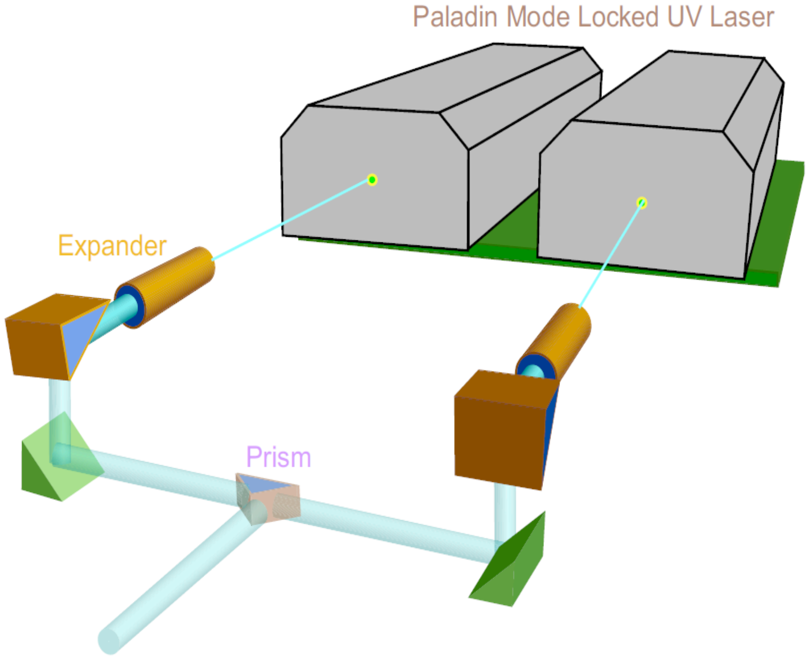
3. If the peak is confirmed, a new experiment with a Time Projection Chamber will be carried out (from Jan/Feb 2008). → wider angle coverage and Θ^+ reconstruction in pK_s decay mode.

4. If the peak is confirmed, the study will be expanded at LEPS2. We will also submit a proposal to do a complete search for Θ^+ by using a low energy K^+ beam at J-PARC.

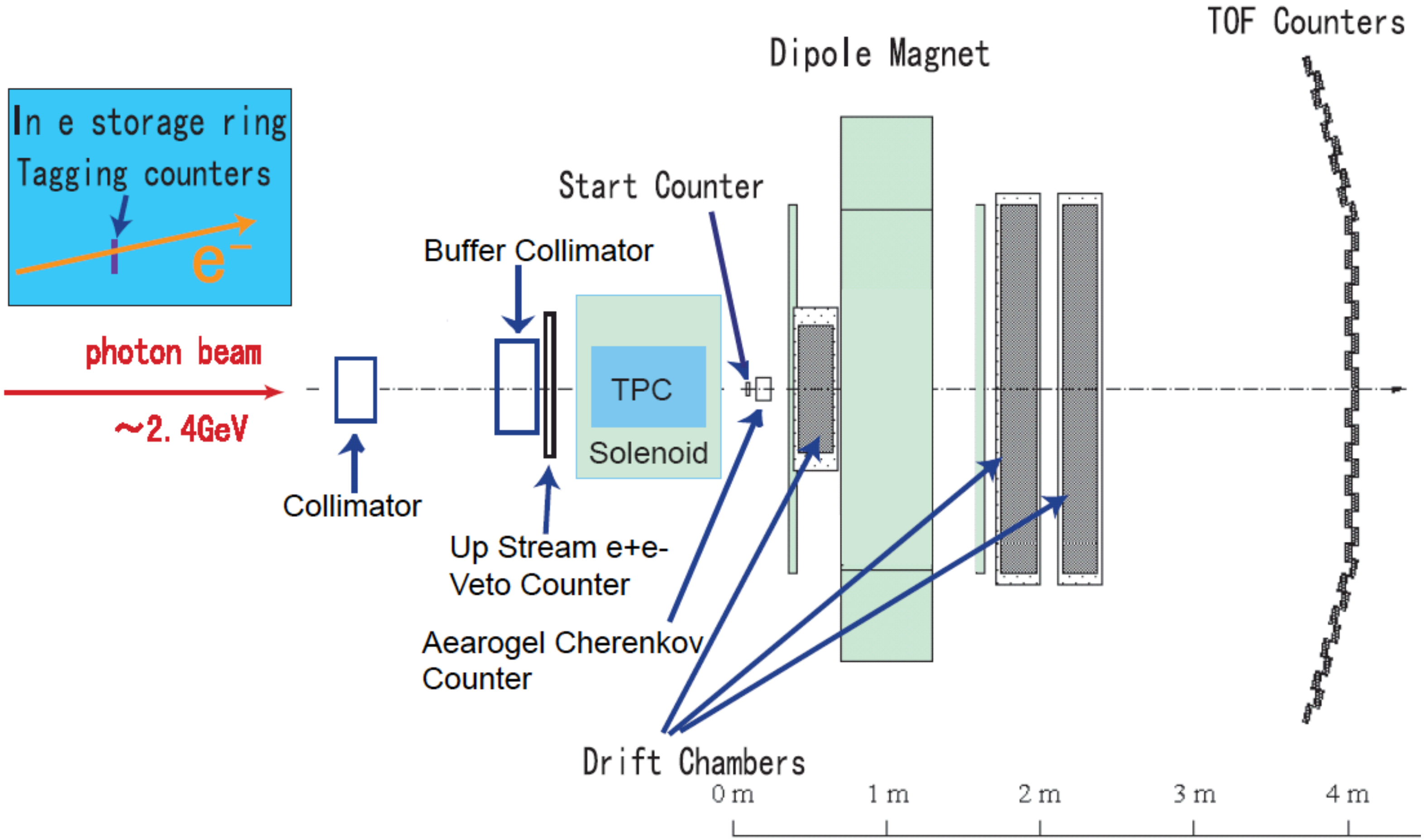
LEPS upgrade

- **Photon beam intensity was doubled by injecting two 8W lasers.**
- **Development of stable optical system is in progress.**
- **Beam Intensity will be further doubled by installing 16W lasers in 2008.**





Setup of TPC experiment



Test experiment with a new TPC and a new LH2 target was done in September, 2007.

まとめ

Pentaquark returns

stay tuned!