A search for double anti-kaon production in antiproton-^{3}He annihilation at J-PARC

F.Sakuma, RIKEN

Tum-Riken Kick-Off Meeting @ TUM, May 10-11, 2010.

This talk is based on the LoI submitted in June, 2009.

Letter of Intent for J-PARC

Double Anti-kaon Production in Nuclei by Stopped Anti-proton Annihilation

dated on 17 / 06 / 2009

M. Iwasaki[1], P. Kienle[2,3], H. Ohnishi[1], F. Sakuma[1*], and J. Zmeskal[2]
[1] *RIKEN, Japan*
[2] *Stefan Meyer Institut für subatomare Physik, Austria*
[3] *Technische Universitat Munchen, Germany*

Abstract

We propose to search for double strangeness production by $\bar{p}$ annihilation on helium nuclei at rest. The proposed experiment will provide significant information on double strangeness production and double strangeness cluster states.

Contents

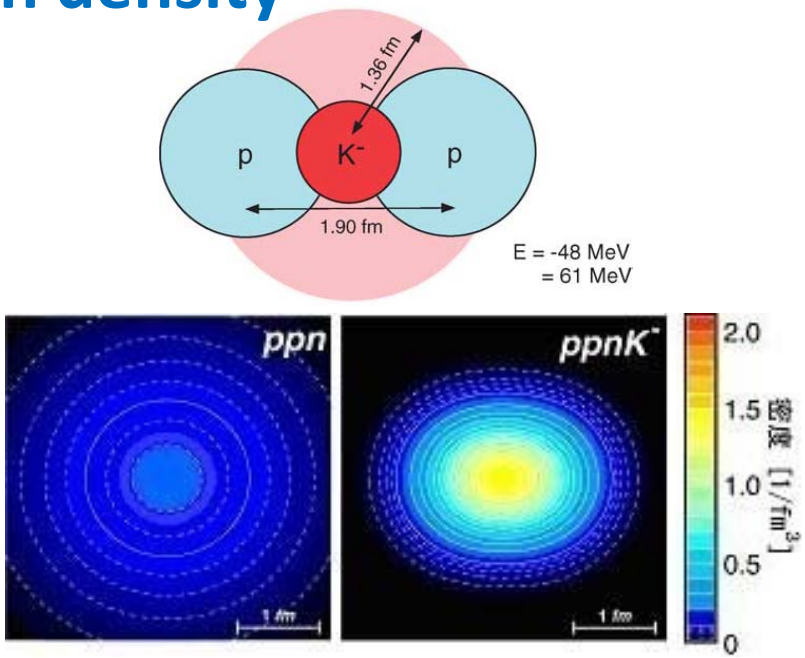
- (brief) Introduction of
  "Kaonic Nuclear Cluster"
- Possibility of
  "Double-Kaonic Nuclear Cluster"
  by Stopped-p^{bar} Annihilation
- Experimental Approach
- Summary

Kaonic Nuclear Cluster (KNC)

the existence of deeply-bound kaonic nuclear cluster is predicted from strongly attractive $K^{bar}N$ interaction

the density of kaonic nuclei is predicted to be extreme high density

Kaonic Nuclei	Binding Energy [MeV]	Width [MeV]	Central Density
K^-p	27	40	**$3.5\rho_0$**
K^-pp	48	61	**$3.1\rho_0$**
K^-ppp	97	13	**$9.2\rho_0$**
K^-ppn	118	21	**$8.8\rho_0$**



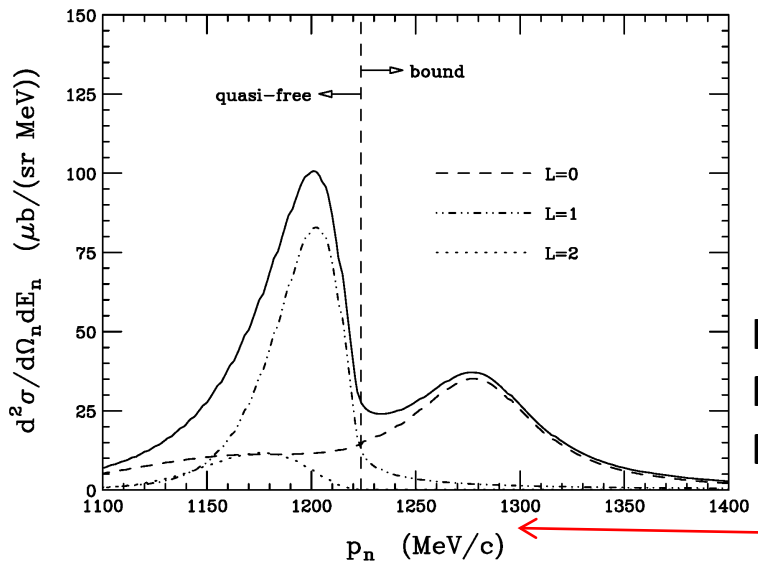
T.Yamazaki, A.Dote, Y.Akiaishi, PLB587, 167 (2004).

we will open new door to the high density matter physics, like the inside of neutron stars

Theoretical Situation of KNC

theoretical predictions for kaonic nuclei, e.g., K^-pp

	Method	Binding Energy (MeV)	Width (MeV)
Akaishi, Yamazaki PLB533, 70 (2002).	ATMS	48	61
Shevchenko, Gal, Mares PRL98, 082301 (2007).	Faddeev	55-70	90-110
Ikeda, Sato PRC76, 035203 (2007).	Faddeev	79	74
Dote, Hyodo, Weise NPA804,197(2008).	chiral SU(3)	19+/-3	40-70 ($\pi\Sigma$N-decay)



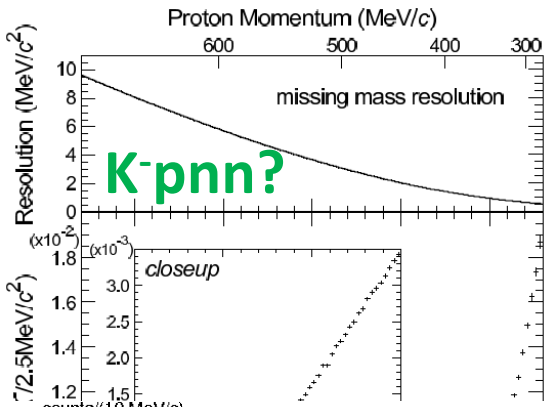
Koike, Harada
PLB652, 262 (2007).
DWIA
^{3}He(K-,n)

- **whether the binding energy is *deep* or *shallow***
- **how *broad* is the width ?**

Experimental Situation of KNC

E549@KEK-PS

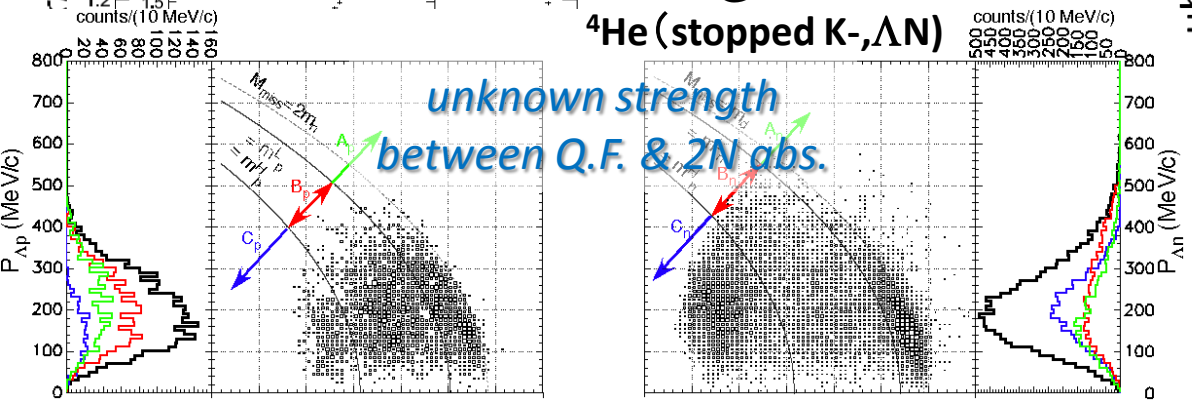
^{4}He (stopped K-,p)



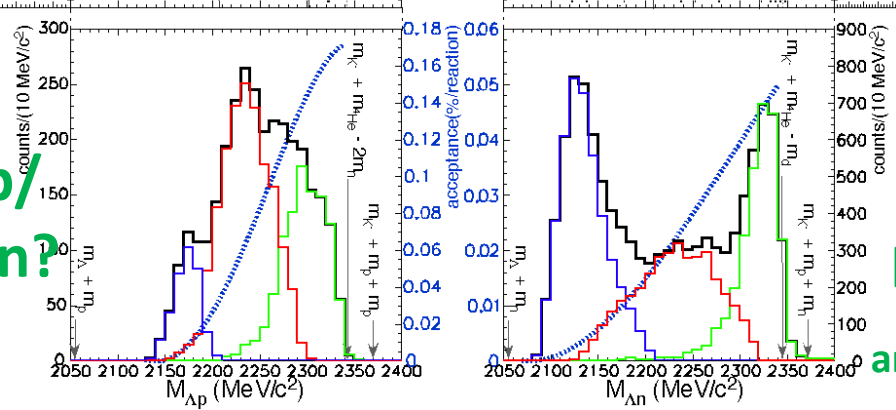
K⁻pnn?

E549@KEK-PS

^{4}He (stopped K-,ΛN)



unknown strength between Q.F. & 2N abs.

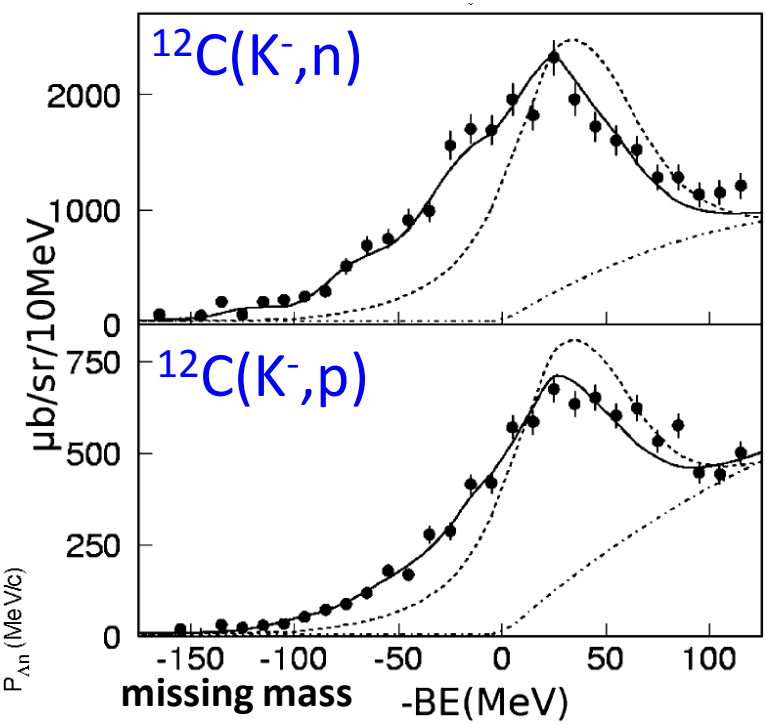


K⁻pp/ K⁻pnn?

K⁻pn/ K⁻ppn?

arXiv:0711.4943

E548@KEK-PS

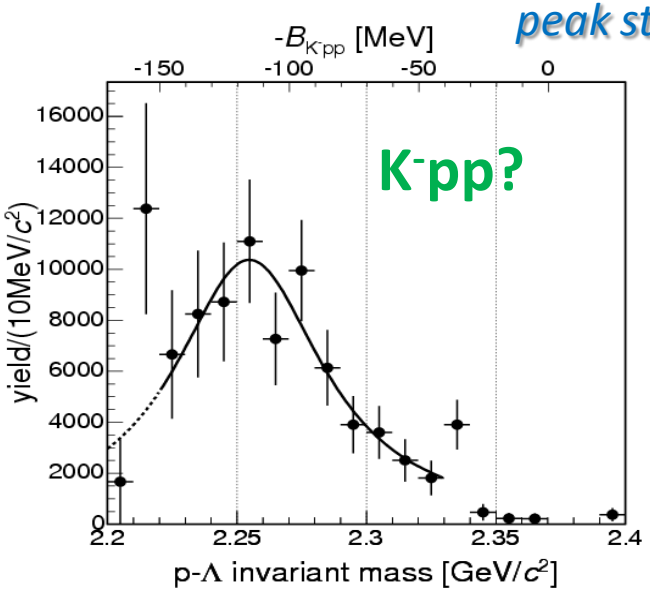


Prog.Theor.Phys.118:181-186,2007.

deep $\bar{K}$-nucleus potential of ~200MeV

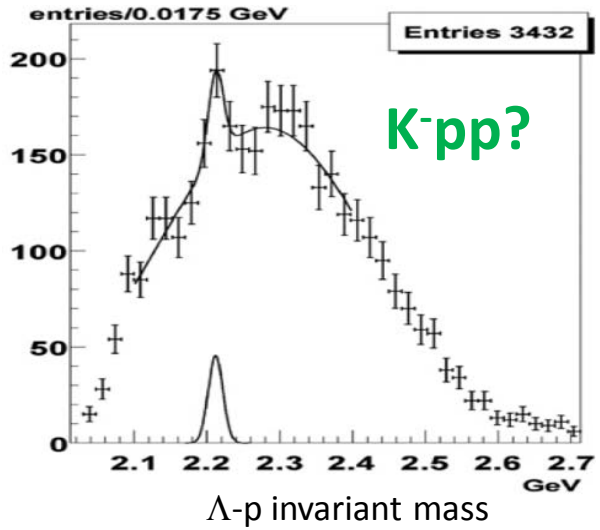
Experimental Situation of KNC (Cont'd)

peak structure → signature of kaonic nuclei ?



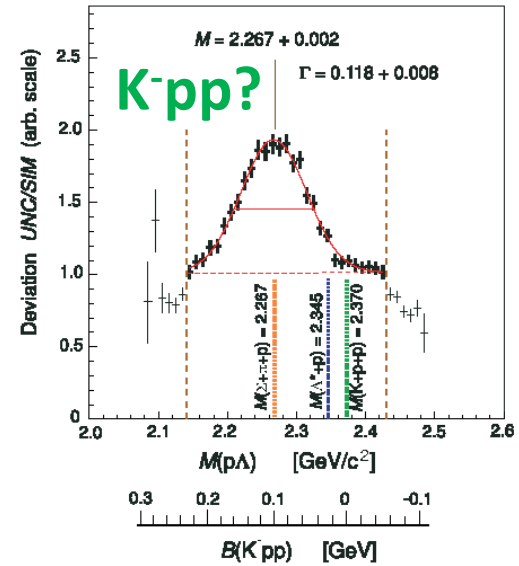
FINUDA@DAΦNE

PRL, 94, 212303 (2005)



OBELIX@CERN-LEAR

NP, A789, 222 (2007)



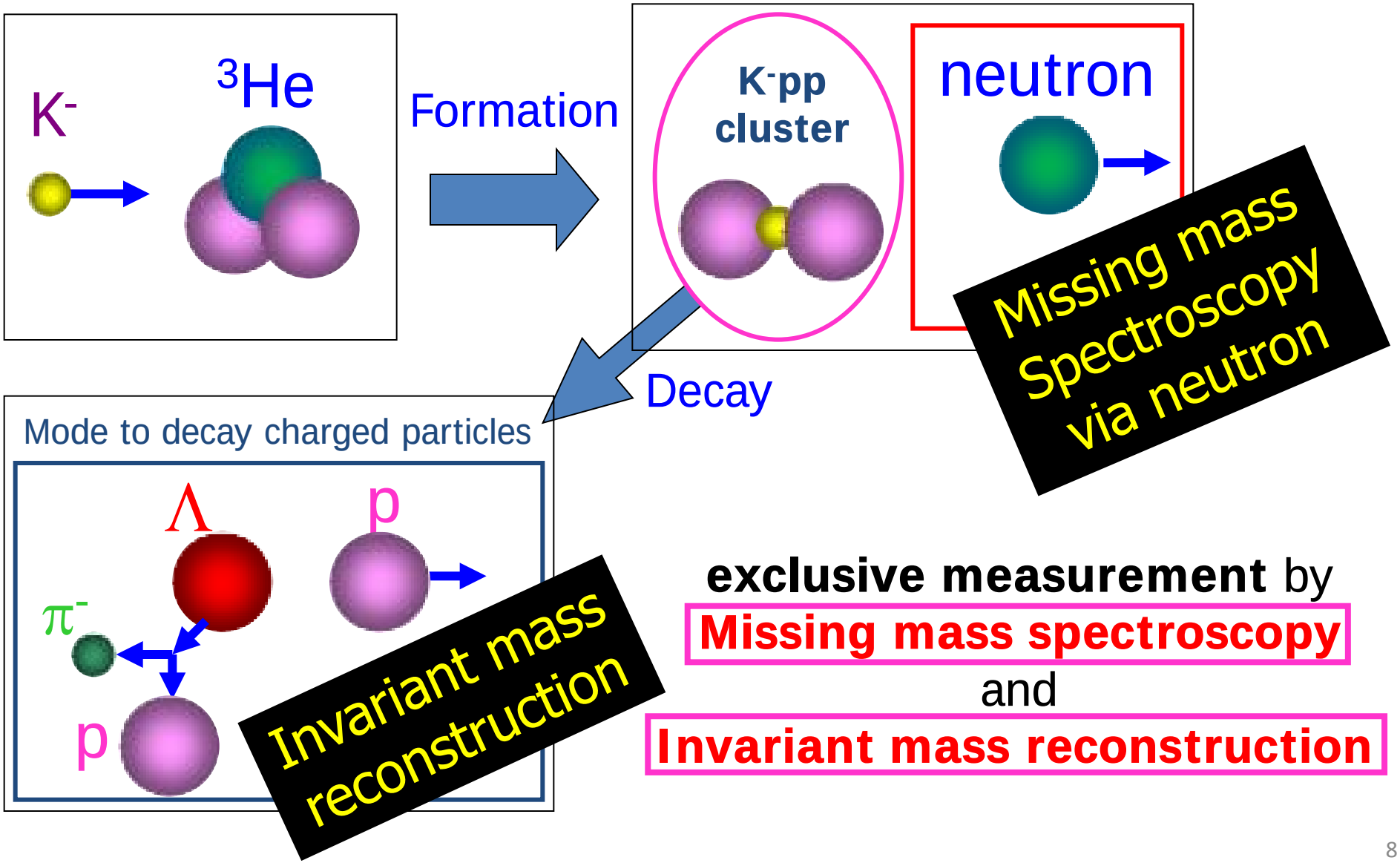
DISTO@SATUREN

PRL,104,132502 (2010)

We need conclusive evidence with observation of *formation* and *decay* !

Experimental Principle of J-PARC E15

search for K-pp bound state using $^3He(K^-,n)$ reaction



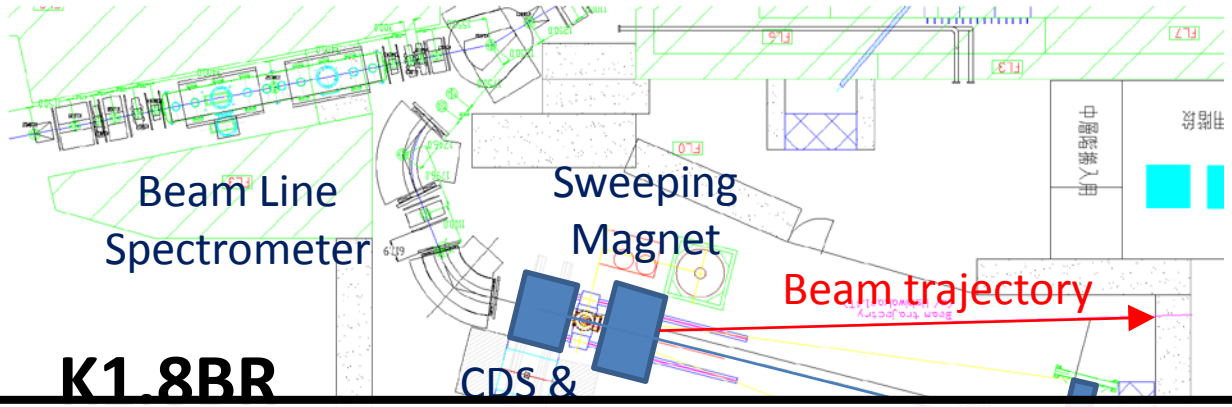
exclusive measurement by

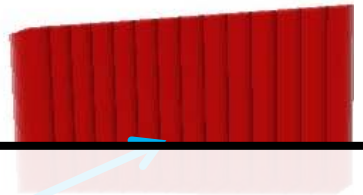
Missing mass spectroscopy

and

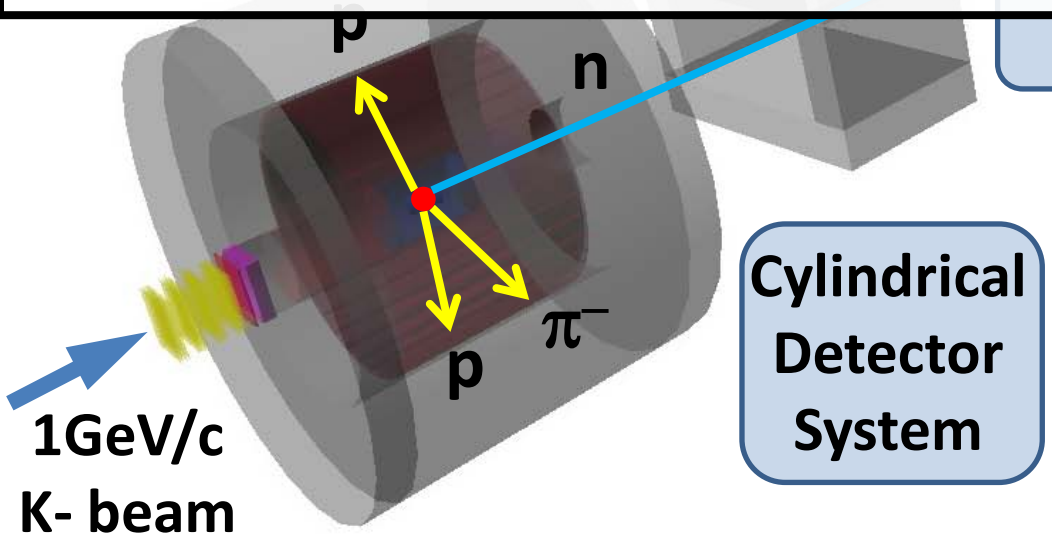
Invariant mass reconstruction

J-PARC E15 Setup



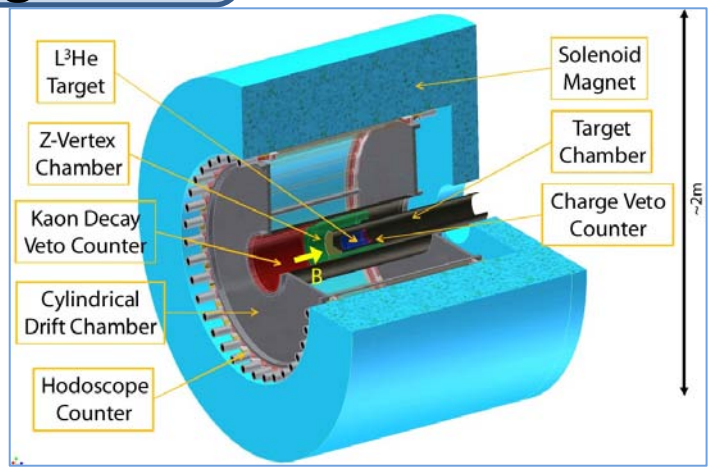


E15 will provide the conclusive evidence of K^-pp



Cylindrical Detector System

Magnet



What will happen to put one more kaon in the kaonic nuclear cluster?

Possibility of "Double-Kaonic Nuclear Cluster" by Stopped-p^{bar} Annihilation

Double-Kaonic Nuclear Cluster

- The double-kaonic nuclear clusters have been predicted theoretically.
- The double-kaonic clusters have much stronger binding energy and a much higher density than single ones.

	B.E. [MeV]	Width [MeV]	Central-Density
K-K-pp	-117	35	
K-K-ppn	-221	37	$17\rho_0$
K-K-ppp	-103	-	
K-K-pppn	-230	61	$14\rho_0$
K-K-pppp	-109	-	

PL,B587,167 (2004). & NP, A754, 391c (2005).

How to produce the double-kaonic nuclear cluster?

- heavy ion collision
- (K^-,K^+) reaction
- $p^{bar}A$ annihilation

We use $p^{bar}A$ annihilation

Double-Strangeness Production with p^{bar}

The elementary p^{bar}-p annihilation reaction with double-strangeness production:

$$\bar{p} + p \rightarrow K + \bar{K} + K + \bar{K} \ \mathbf{-98MeV}$$

This reaction is **forbidden for stopped p^{bar}**, because of a negative Q-value of 98MeV

However, if multi kaonic nuclear exists with deep bound energy, following p^{bar} annihilation reactions **will be possible**!

theoretical prediction

$$\bar{p} + {}^{3}He \rightarrow K^{+} + K^{+} + K^{-}K^{-}pn + B_{KK}^{pn} - 106\text{MeV}$$

$$\bar{p} + {}^{3}He \rightarrow K^{+} + K^{0} + K^{-}K^{-}pp + B_{KK}^{pp} - 109\text{MeV}$$

→ ***B.E.=117MeV***, ***Γ=35MeV***

$$\bar{p} + {}^{4}He \rightarrow K^{+} + K^{+} + K^{-}K^{-}pnn + B_{KK}^{pnn} - 126\text{MeV}$$

$$\bar{p} + {}^{4}He \rightarrow K^{+} + K^{0} + K^{-}K^{-}ppn + B_{KK}^{ppn} - 129\text{MeV}$$

→ ***B.E.=221MeV***, ***Γ=37MeV***

Production Mechanism of K^-K^-pp with $p^{bar}+{}^3He$?

For example, the possible K^-K^-pp production mechanisms are as follows:

with stopped p^{bar}

① direct K^-K^-pp production with 3N annihilation

② $\Lambda^*\Lambda^*$ production with 3N annihilation followed by K^-K^-pp formation

with in-flight p^{bar}

in addition above 2ways,

③ elementally $p^{bar}+p \rightarrow KKKK$ production followed by K^-K^-pp formation

- ***Some theorist's comment: If the K^-K^-pp bound system can be exist, such system could be $\Lambda^*\Lambda^*$ molecular system by analogy between Λ^* K^-p. Then the binding energy could be small of about from 30 to 60 MeV.***
- ***it has been observed that cross section of $p^{bar}+p \rightarrow KKKK$ with around 1GeV/c p^{bar}-beam is very small of less than 1μb, so it would be very difficult experimentally.***

It's worthwhile to explore these exotic system with p^{bar}, although the mechanism is NOT completely investigated!

A theoretical problem: The K^-K^- interactions have been calculated in lattice QCD as strongly repulsive interaction. However, these K-K- interactions are neglected simply in the PLB587,167 calculation which only shows the K-K-pp bound system.

Double-Strangeness Production Yield by Stopped-p^{bar} Annihilation

From several stopped-p^{bar} experiments, the inclusive production yields are:

$$R(\bar{p}p \rightarrow K\bar{K}) \sim 5\times10^{-2}$$

$$R(\bar{p}\,^3He \rightarrow \Lambda(\Sigma^0)) \sim 0.6\times10^{-2}$$

$$R(\bar{p}\,^4He \rightarrow \Lambda(\Sigma^0)) \sim 1.1\times10^{-2}$$

Naively, the double-strangeness production yield would be considered as:

$$R(\bar{p}A \rightarrow K\bar{K}K\bar{K})$$

$$= R(\bar{p}p \rightarrow K\bar{K})^2 \times \gamma \sim 10^{-5}$$

γ : reduction factor ~ 10^{-2}

Past Experiments of Double-Strangeness Production in Stopped-p^{bar} Annihilation

Observations of the double-strangeness production in stopped p^{bar} annihilation have been reported by **only 2 groups**, DIANA@ITEP and OBELIX@CERN/LEAR.

experiment	channel	events	yield (10^{-4})
DIANA	K^+K^+X	4	0.31+/-0.16
[p^{bar}+Xe]	K^+K^0X	3	2.1+/-1.2
	$K^+K^+\Sigma^-\Sigma^-p_s$	34+/-8	0.17+/-0.04
OBELIX	$K^+K^+\Sigma^-\Sigma^+n\pi^-$	36+/-6	2.71+/-0.47
[p^{bar}+^{4}He]	$K^+K^+\Sigma^-\Lambda n$	16+/-4	1.21+/-0.29
	$K^+K^+K^-\Lambda nn$	4+/-2	0.28+/-0.14

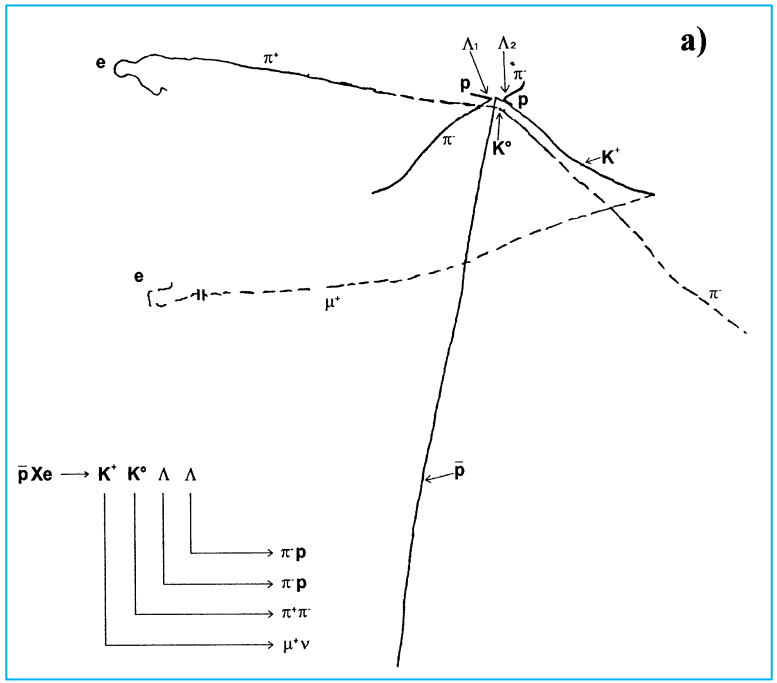
Although observed statistics are very small, their results have indicated a high yield of ~10^{-4}

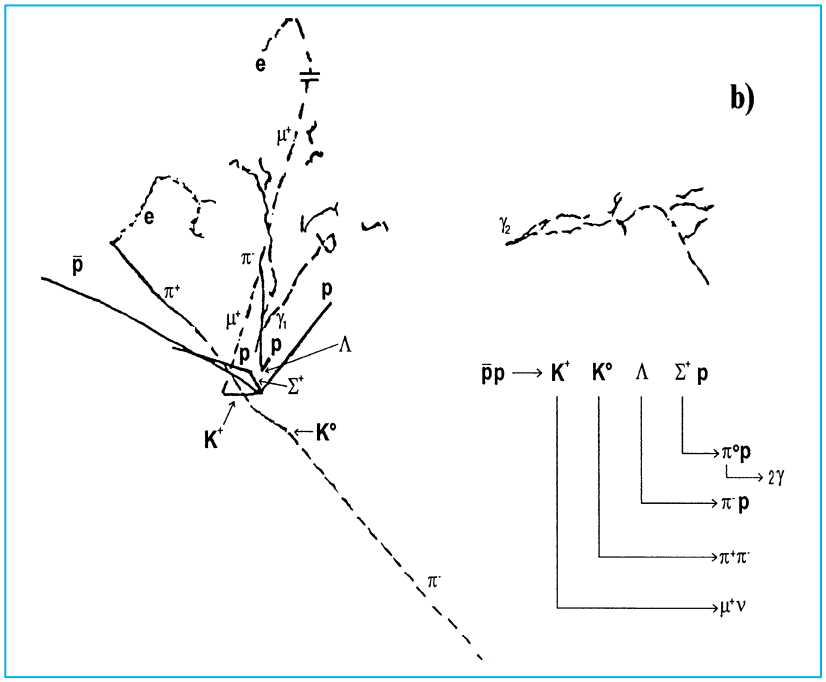
Past Experiments (Cont'd)

DIANA [Phys.Lett., **B464**, 323 (1999).]

- $p^{bar}Xe$ annihilation
- p=<1GeV/c p^{bar}-beam @ ITEP 10GeV-PS
- **700-liter Xenon bubble chamber, w/o B-field**
- 10^6 pictures →7.8×10^5 $p^{bar}Xe$ inelastic → 2.8×10^5 $p^{bar}Xe$ @ 0-0.4GeV/c

Channel	events	yield (10^{-4})
K^+K^+X	4	0.31+/-0.16
K^+K^0X	3	2.1+/-1.2



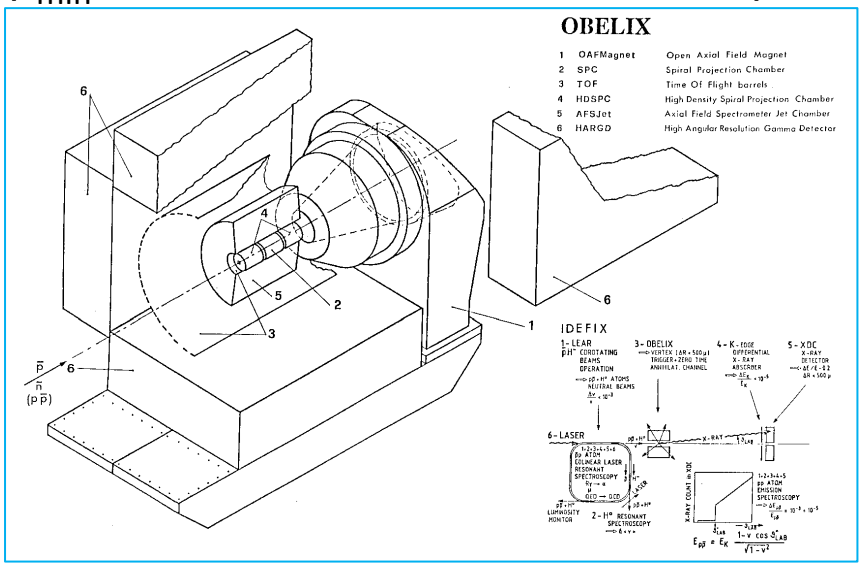


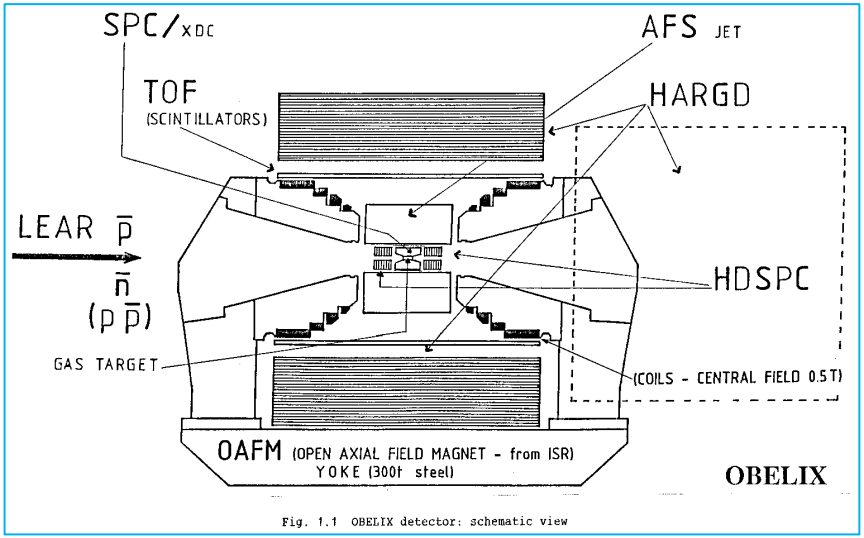
Past Experiments (Cont'd)

OBELIX ('86~'96) [Nucl. Phys., **A797**, 109 (2007).]

- $p^{bar}{}^4He$ annihilation
- stopped p^{bar} @ CERN/LEAR
- gas target (^4He@NTP, H_2@3atm)
- **cylindrical spectrometer w/ B-field**
- spiral projection chamber, scintillator barrels, jet-drift chambers
- $2.4\times10^5/4.7\times10^4$ events of 4/5-prong in ^4He
- p_{min} = 100/150/300MeV/c for $\pi/K/p$

channel	events	yield (10^{-4})
$K^+K^+\Sigma^-\Sigma^-p_s$	34+/-8	0.17+/-0.04
$K^+K^+\Sigma^-\Sigma^+n\pi^-$	36+/-6	2.71+/-0.47
$K^+K^+\Sigma^-\Lambda n$	16+/-4	1.21+/-0.29
$K^+K^+K^-\Lambda nn$	4+/-2	0.28+/-0.14





they discuss the possibility of formation and decay of K^-K^-nn and K^-K^-pnn bound system

The double-strangeness production yield of ~10^{-4} makes it possible to explore the exotic systems.

Experimental Approach

How to Measure?

we focus the reaction:

$$\overline{p} + {}^{3}He \rightarrow K^{+} + K^{0} + K^{-}K^{-}pp$$

(although K^-K^-pp decay modes are not known at all,)

we assume the most energetic favored decay mode:

$$K^{-}K^{-}pp \rightarrow \Lambda + \Lambda$$

final state = $K^+K^0\Lambda\Lambda$

We can measure the K^-K^-pp signal **exclusively** by detection of all particles, $K^+K^0\Lambda\Lambda$, using $K^0 \rightarrow \pi^+\pi^-$ mode

We need wide-acceptance detectors.

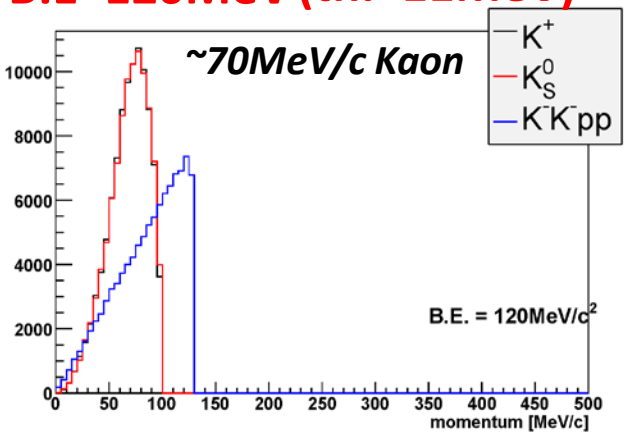
Expected Kinematics

K^+K^0X momentum spectra

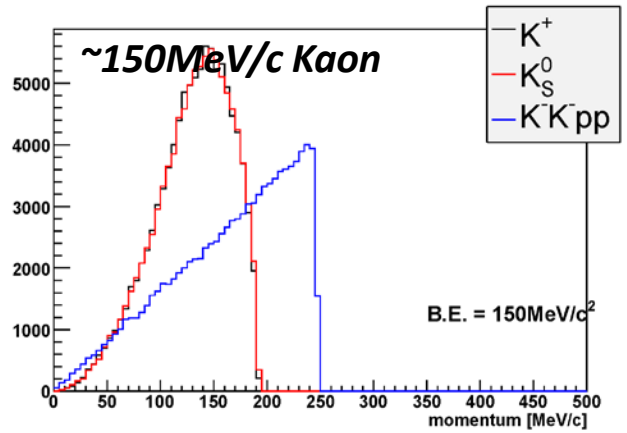
$$\bar{p} + {}^3He \rightarrow K^+ + K_S^0 + K^-K^-pp$$

assumptions:
- ✓widths of K^-K^-pp = 0
- ✓isotropic decay

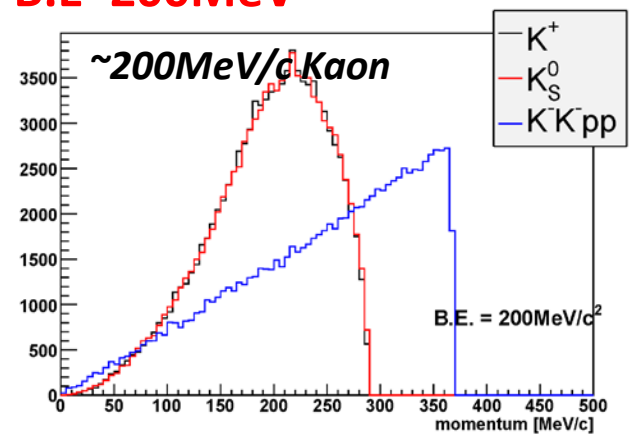
B.E=120MeV (th.+11MeV)



B.E=150MeV



B.E=200MeV



In the K^-K^-pp production channel, the kaons have very small momentum of up to 300MeV/c, even if B.E.=200MeV.

We have to construct low mass material detectors.

~200MeV/c π from K^0_S, ~800MeV/c Λ, ~700MeV/c p from Λ, ~150MeV/c π from Λ

Procedure of the K^-K^-pp Measurement

Key points of the experiment

- high intensity p^{bar} beam
- wide-acceptance and low-material detector

How to measure the K-K-pp signal

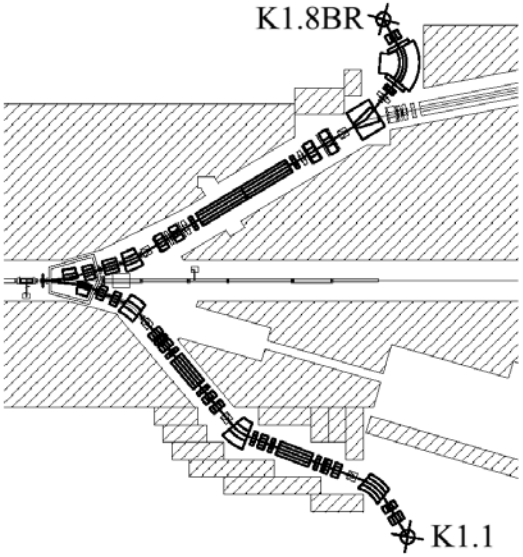
- (semi-inclusive) $K^0_S K^+$ missing-mass w/ Λ-tag
- (inclusive) $\Lambda\Lambda$ invariant mass
- (exclusive) $K^0_S K^+ \Lambda\Lambda$ detection

**1 because of the low-momentum kaon, it could be hard to detect all particles*

**2 semi-inclusive and inclusive spectra could contain background from 2N annihilation and K^-K^-pp decays, respectively*

Beam-Line

We would like to perform the proposed experiment at J-PARC K1.8BR beam line (or K1.1)



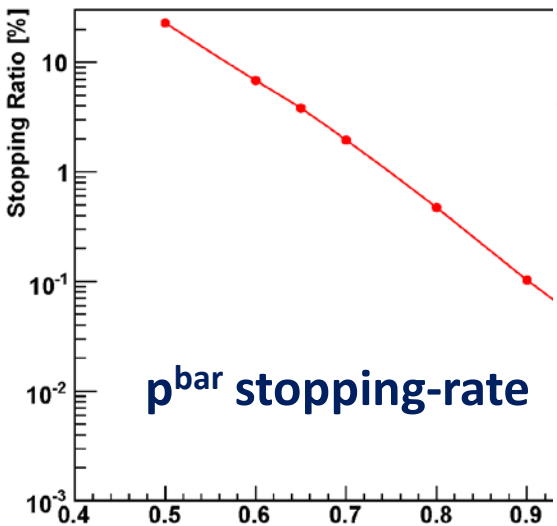
p^{bar} stopping-rate evaluation by GEANT4

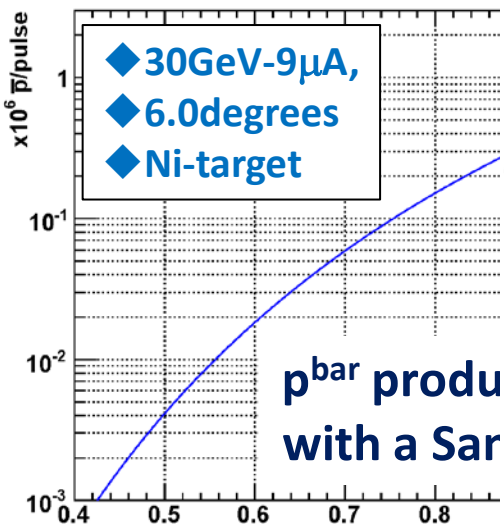
Incident Beam

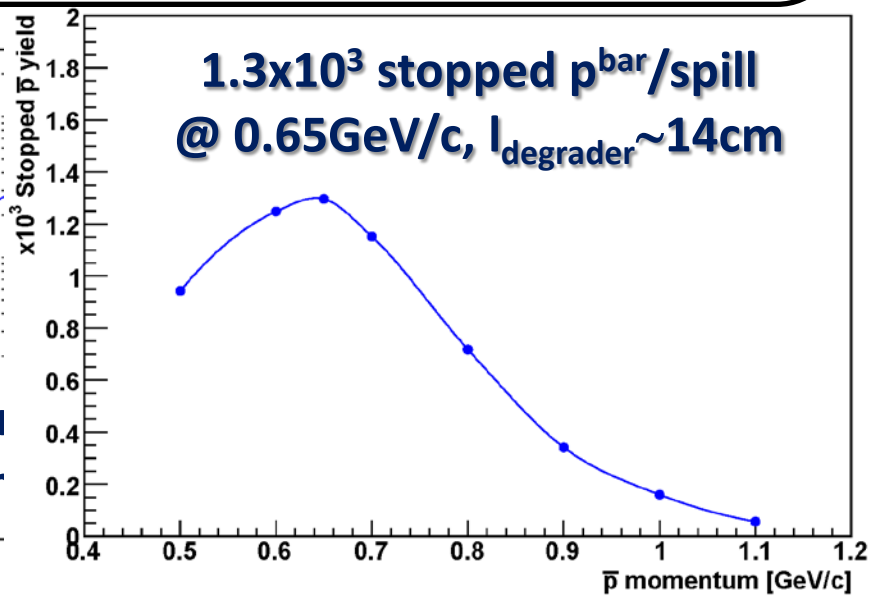
- momentum bite : +/-2.5% (flat)
- incident beam distribution : ideal

Detectors

- Carbon Degrader : 1.99*g/cm^3
- Plastic Scintillator : l=1cm, 1.032*g/cm^3
- Liquid He3 target : ϕ7cm, l=12cm, 0.080*g/cm^3







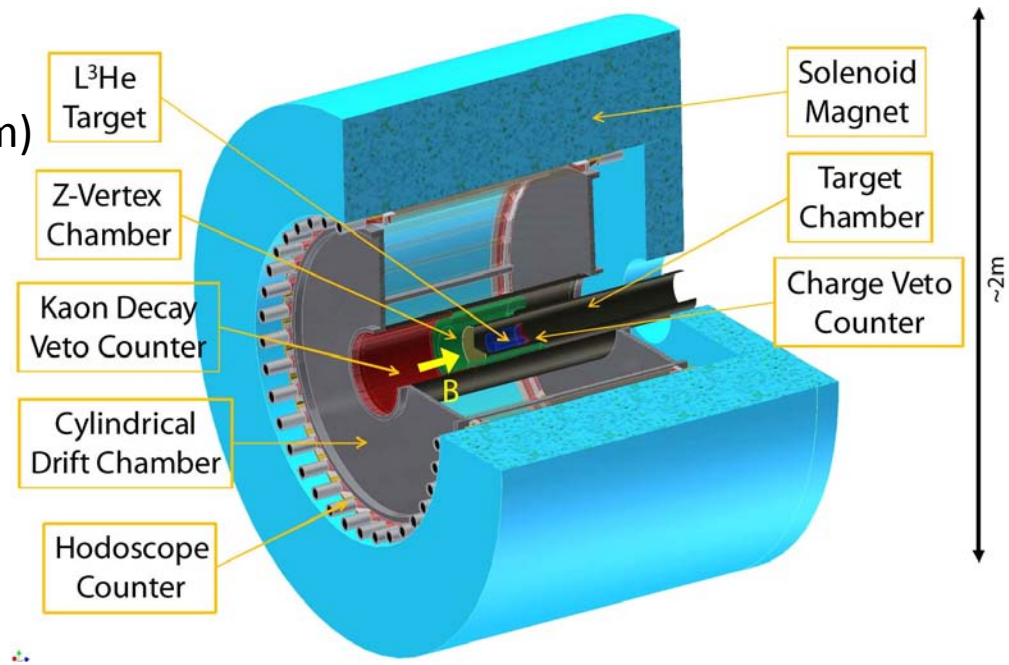
Detector Design

Key points

- low material detector system
- wide acceptance with pID

E15 CDS @ K1.8BR

- B = 0.5T
- CDC resolution : $\sigma_{r\phi}$ = 0.2mm
  σ_z's depend on the tilt angles (~3mm)
- ZTPC resolution : σ_z = 1mm
  $\sigma_{r\phi}$ is not used for present setup



ZTPC				
Layer	1	2	3	4
radius	92.5	97.5	102.5	107.5

CDC															
Type	A	A'	A	U	U'	V	V'	A	A'	U	U'	V	V'	A	A'
Layer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
radius	190.5	204.0	217.5	248.5	262.0	293.0	306.5	337.5	351.0	382.0	395.5	426.5	440.0	471.0	484.5

Trigger Scheme

expected stopped-p^{bar} yield = 1.3×10^3/spill

All events with a scintillator hit can be accumulated

$p^{bar}{}^3$He charged particle multiplicity at rest

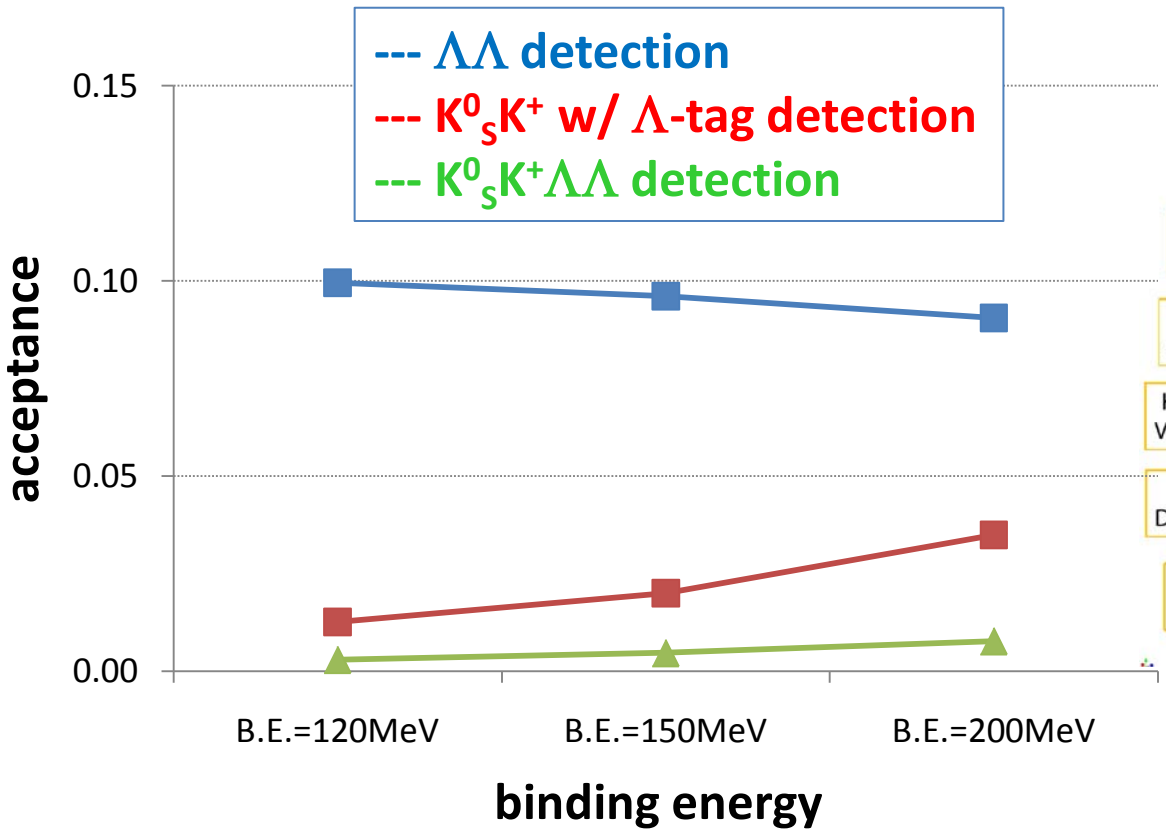
CERN LEAR, streamer chamber exp. NPA518,683 91990).

Nc	Branch (%)
1	5.14 +/- 0.04
3	39.38 +/- 0.88
5	48.22 +/- 0.91
7	7.06 +/- 0.46
9	0.19 +/- 0.08
<Nc>	**4.16 +/- 0.06**

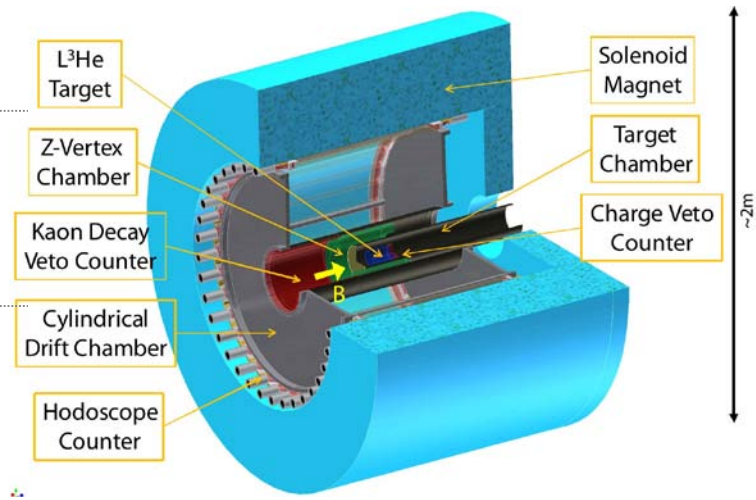
K-K-pp event

Detector Acceptance

$$P^{bar}+{}^3He \rightarrow K^+ + K^0_S + K^- K^- pp,$$
$$K^- K^- pp \rightarrow \Lambda\Lambda,$$
$$\Gamma(K^- K^- pp) = 100\text{MeV}$$



E15 CDS @ K1.8BR



Expected K^-K^-pp Production Yield

- pbar beam momentum : 0.65GeV/c
- beam intensity : 3.4×10^4/spill/3.5s @ 270kW
- pbar stopping rate : 3.9%

↓

- stopped-p^{bar} yield : 1.3×10^3/spill/3.5s

↓

we assume **K^-K^-pp production rate = 10^{-4}**

↓

K-K-pp production yield = 2.3×10^4 /week @ 270kW

↓

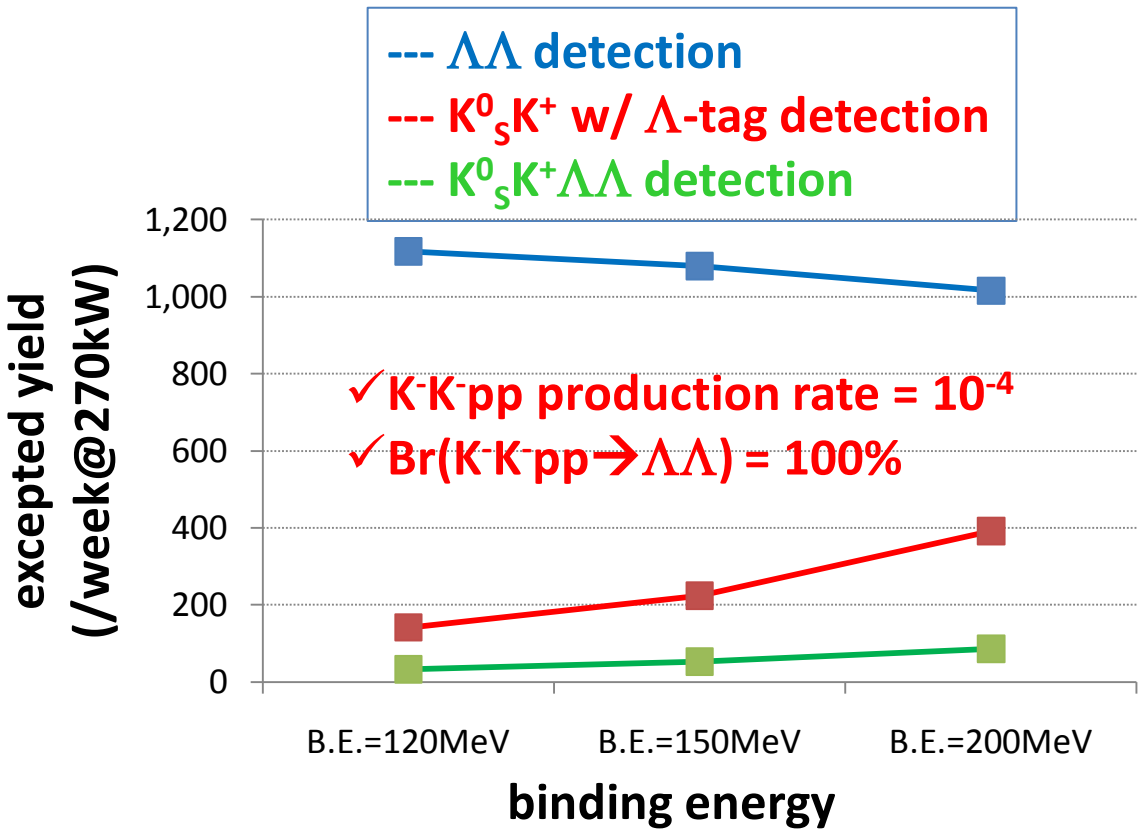
DAQ & ana efficiency = 0.7 & duty factor = 0.7

↓

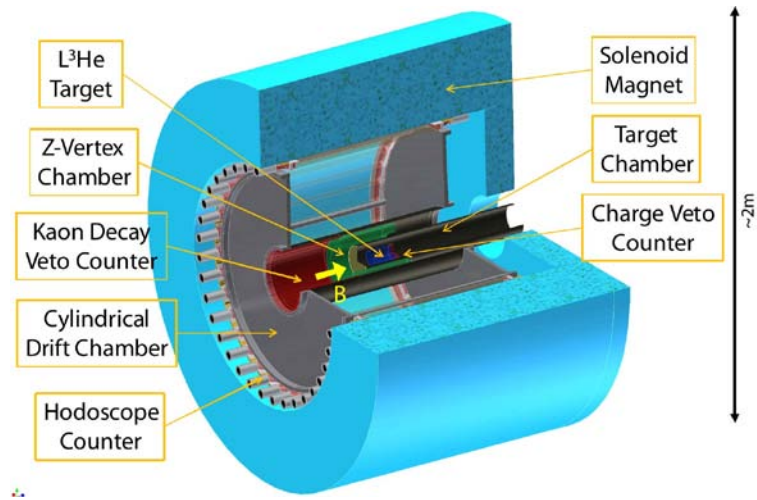
expected K^-K^-pp yield = 1.1×10^4 /week @ 270kW
w/o detector acceptance

Expected K^-K^-pp Detction Yield

$$p^{bar}+{}^3He \rightarrow K^+ + K^0_S + K^-K^-pp,$$
$$K^-K^-pp \rightarrow \Lambda\Lambda,$$
$$\Gamma(K^-K^-pp)=100MeV$$



E15 CDS @ K1.8BR



Backgrounds

- **(semi-inclusive) $K^0_S K^+$ missing-mass w/ Λ-tag**

  - **stopped-p^{bar} + ^3He → K^0_S + K^+ + K-K-pp**

3N annihilation

  - stopped-p^{bar} + ^3He → K^0_S + K^+ + Λ + Λ
  - stopped-p^{bar} + ^3He → K^0_S + K^+ + Σ^0 + Σ^0 + π^0
  - …

2N annihilation

  - stopped-p^{bar} + ^3He → K^0_S + K^+ + K^0 + Σ^0 + (n)
  - stopped-p^{bar} + ^3He → K^0_S + K^+ + K^- + Σ^0 + (p)
  - …

- **(inclusive) $\Lambda\Lambda$ invariant mass**

  - **stopped-p^{bar} + ^3He → K^0_S + K^+ + K-K-pp**
    → Λ + Λ

missing γ

  - stopped-p^{bar} + ^3He → K^0_S + K^+ + K-K-pp
    → Λ + Σ^0

missing 2γ

  - stopped-p^{bar} + ^3He → K^0_S + K^+ + K-K-pp
    → Σ^0 + Σ^0

missing π^0

  - stopped-p^{bar} + ^3He → K^0_S + K^+ + K-K-pp
    → Λ + Λ + π^0
  - …

Expected Spectra

- Monte-Carlo simulation using GEANT4 toolkit
- reaction and decay are considered to be isotropic and proportional to the phase space
- energy losses are NOT corrected in the spectra
- w/o Fermi-motion

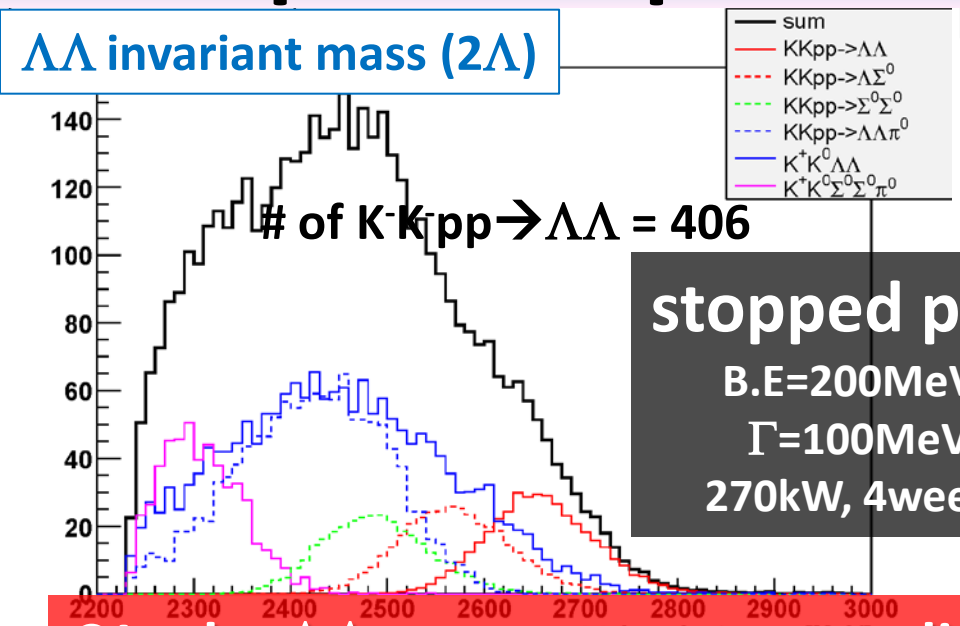
expected spectrum with the assumptions:

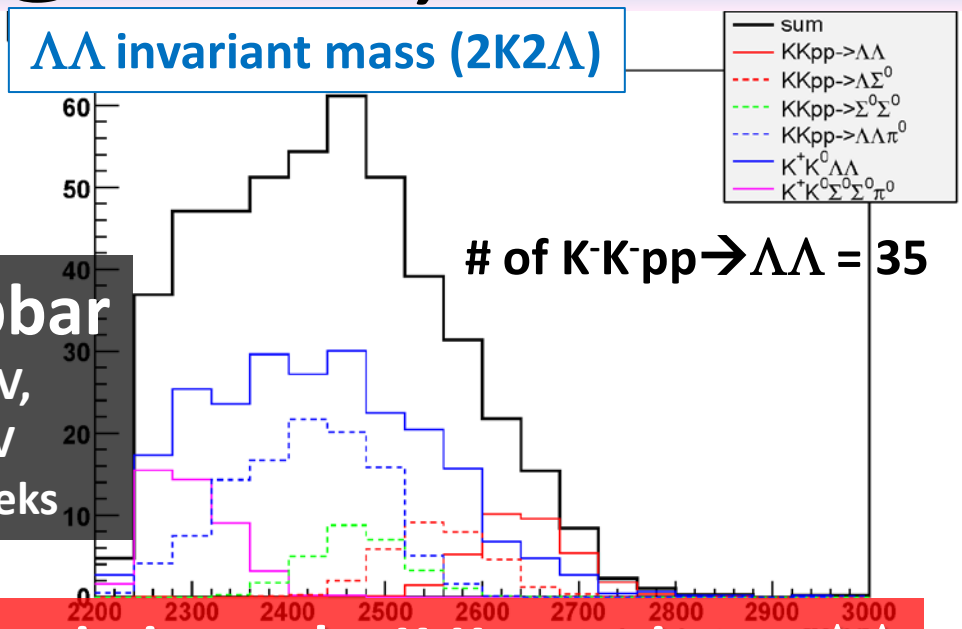
- **production rate:**
  - **K^-K^-pp bound-state = 10^{-4}**
  - **(3N) $K^-K^-\Lambda\Lambda$ phase-space = 10^{-4}**
  - **(3N) $K^+K^0\Sigma^0\Sigma^0\pi^0$ phase-space = 10^{-4}**
  - **(2N) $K^+K^0K^0\Sigma^0$(n) phase-space = 10^{-4}**
  - **(2N) $K^+K^0K^-\Sigma^0$(p) phase-space = 10^{-4}**

- **branching ratio of K^-K^-pp:**
  - **BR($K^-K^-pp \rightarrow \Lambda\Lambda$) = 0.1**
  - **BR($K^-K^-pp \rightarrow \Lambda\Sigma^0$) = 0.1**
  - **BR($K^-K^-pp \rightarrow \Sigma^0\Sigma^0$ = 0.1**
  - **BR($K^-K^-pp \rightarrow \Lambda\Lambda\pi^0$) = 0.7**

2Λ = $\Lambda\Lambda$ detection
2K = K^+K^0 w/ Λ-tag detection
2Λ2K = $K^+K^0\Lambda\Lambda$ detection

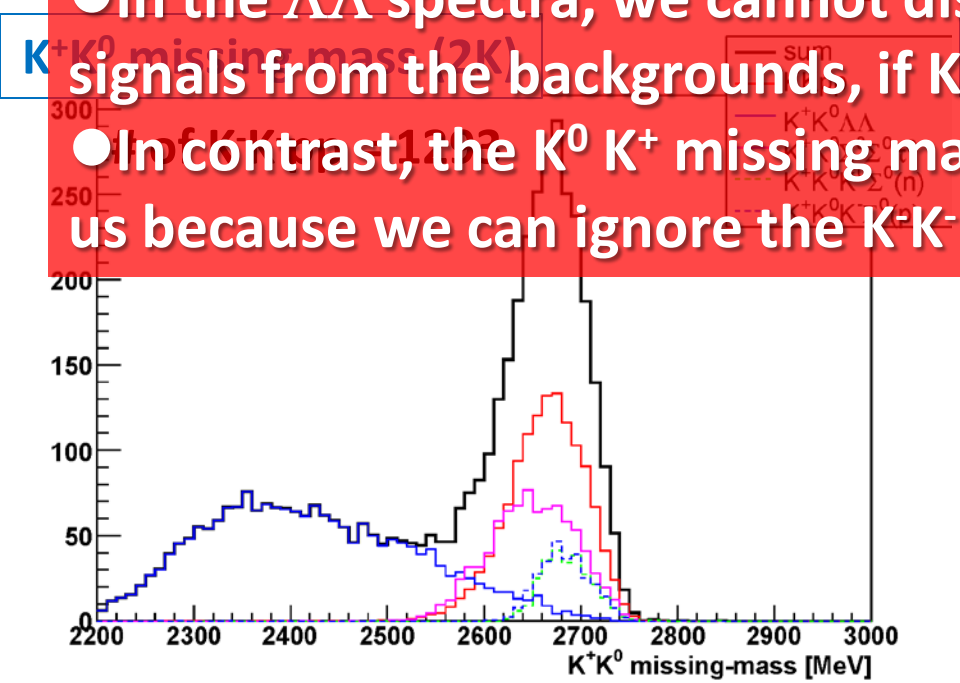
Expected Spectra @ 270kW, 4weeks

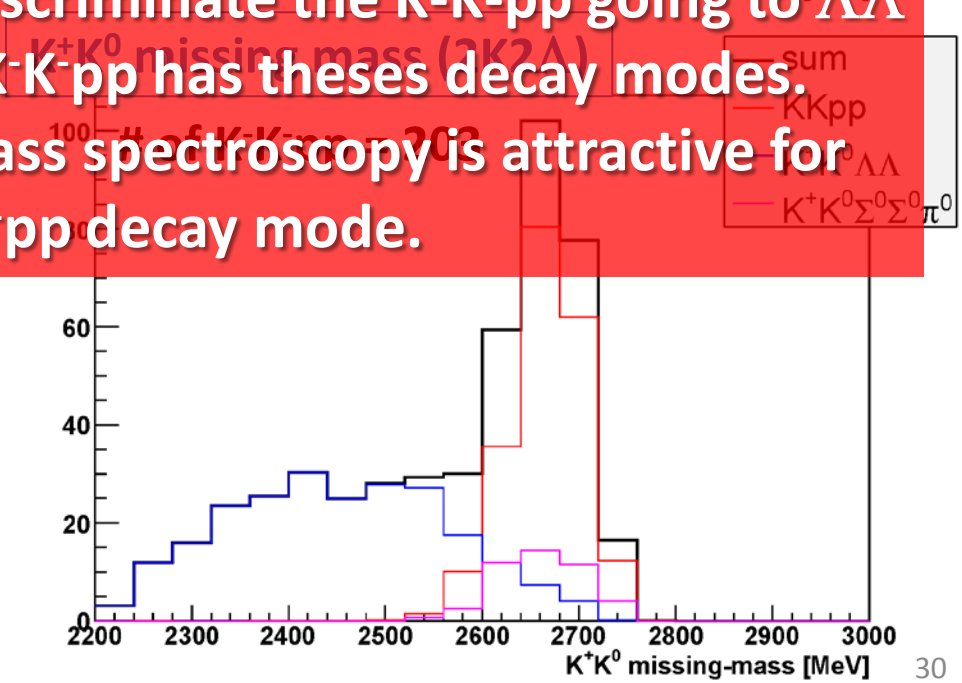




stopped pbar
B.E=200MeV,
Γ=100MeV
270kW, 4weeks

- In the ΛΛ spectra, we cannot discriminate the K-K-pp going to ΛΛ signals from the backgrounds, if K^-K^-pp has theses decay modes.
- In contrast, the K^0 K^+ missing mass spectroscopy is attractive for us because we can ignore the K^-K^-pp decay mode.





Summary

Summary

- **We propose to search for double strangeness production by p^{bar} annihilation on ^{3}He nuclei at rest.**

- The proposed experiment will provide significant information on double strangeness production and double strangeness cluster states, **K^-K^-pp**.

- The experimental key points are high-intensity p^{bar} beam and wide-acceptance/low-material detector system. We propose to perform the experiment at K1.8BR beam-line with the E15 spectrometer.

- **We are now preparing the proposal for J-PARC based on the LoI.**

Back-Up

K^-pp Production with p^{bar} at rest

Of course, we can measure K^-pp production!

$$\bar{p} + {}^3He \rightarrow K^0 + K^- pp$$

From several stopped-p^{bar} experiments, the inclusive production yields are:

$$R(\bar{p}p \rightarrow K\bar{K}) \sim 5\times10^{-2}$$

Very simply, expected K^-pp yield is 100 times larger than the K^-K^-pp production!

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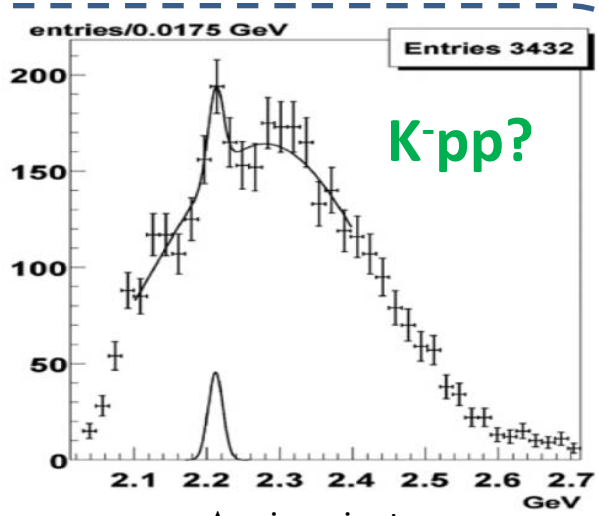
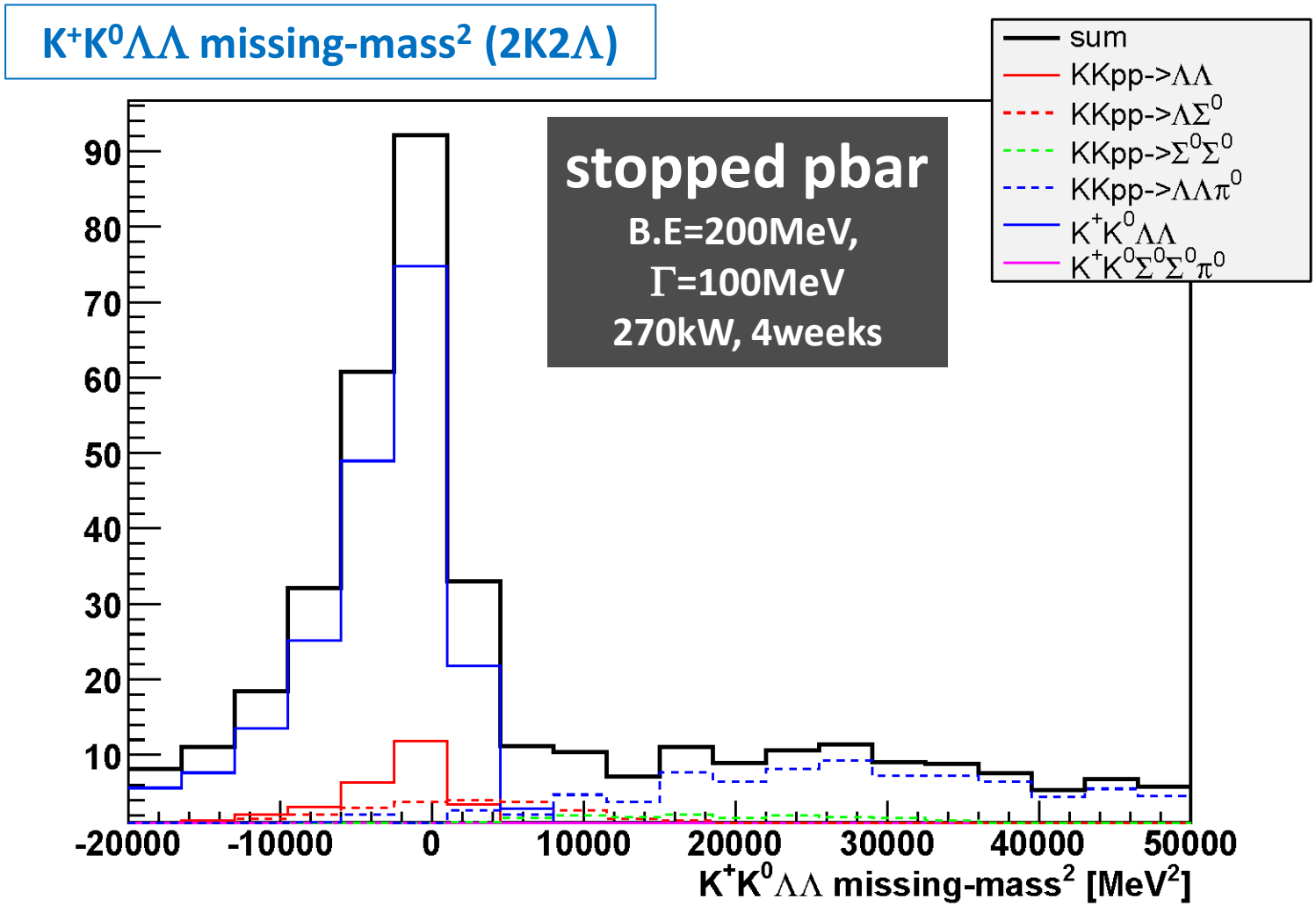
NP, A789, 222 (2007)

$$\bar{p} + {}^4He \rightarrow K^- pp + X$$
$$\rightarrow \Lambda + p$$

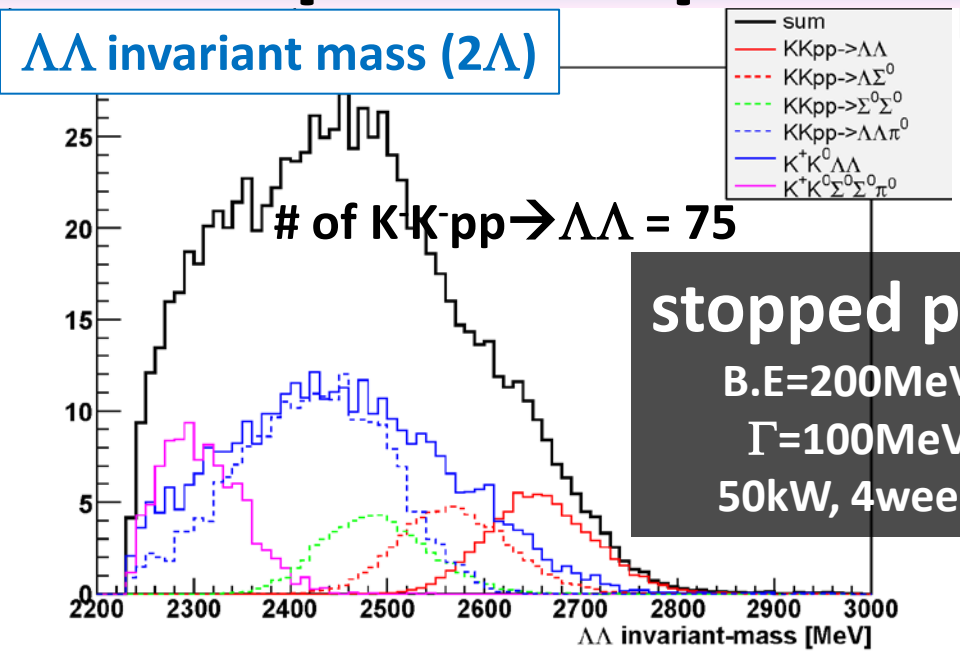


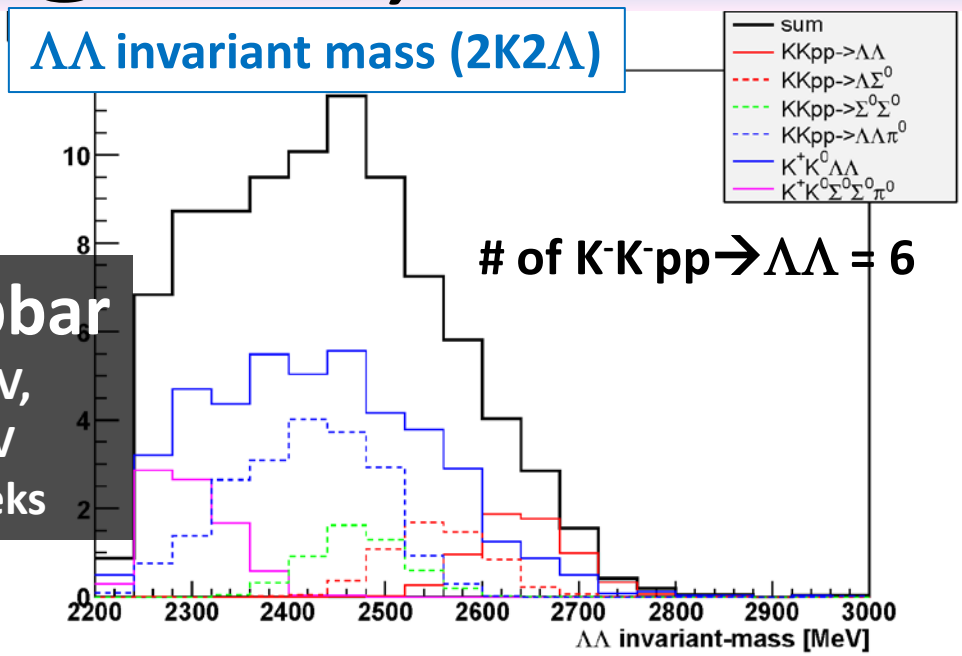
Λ-p invariant mass

Expected Spectra @ 270kW, 4weeks



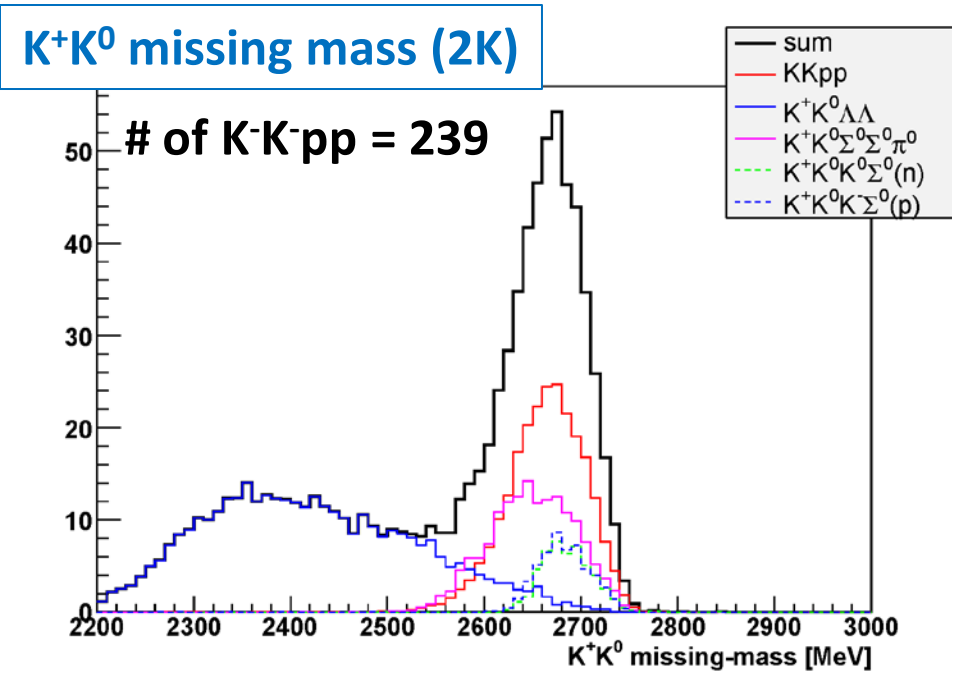
Expected Spectra @ 50kW, 4weeks

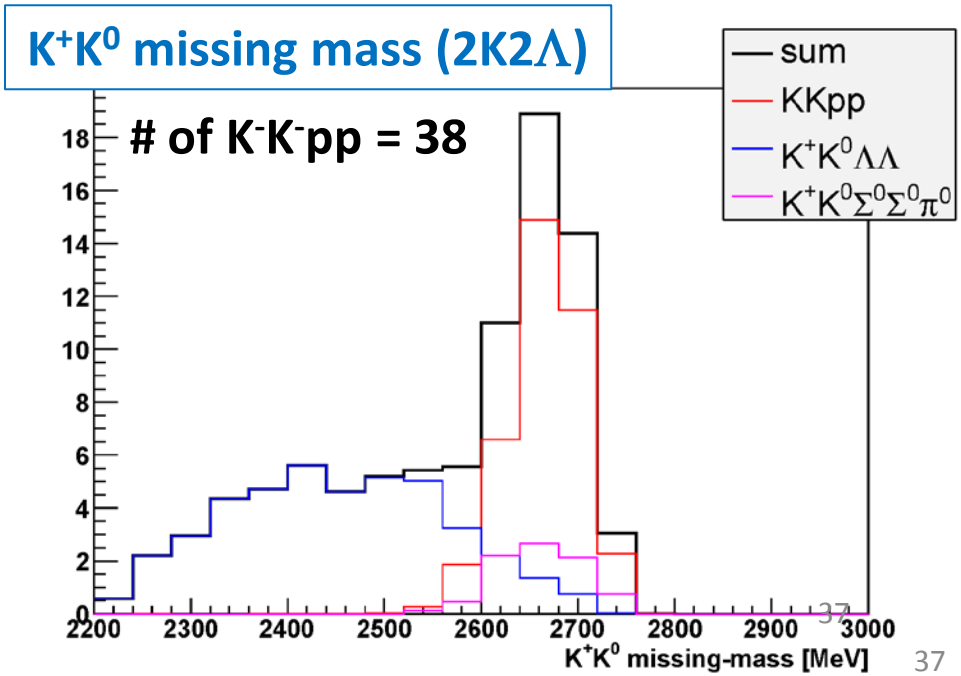




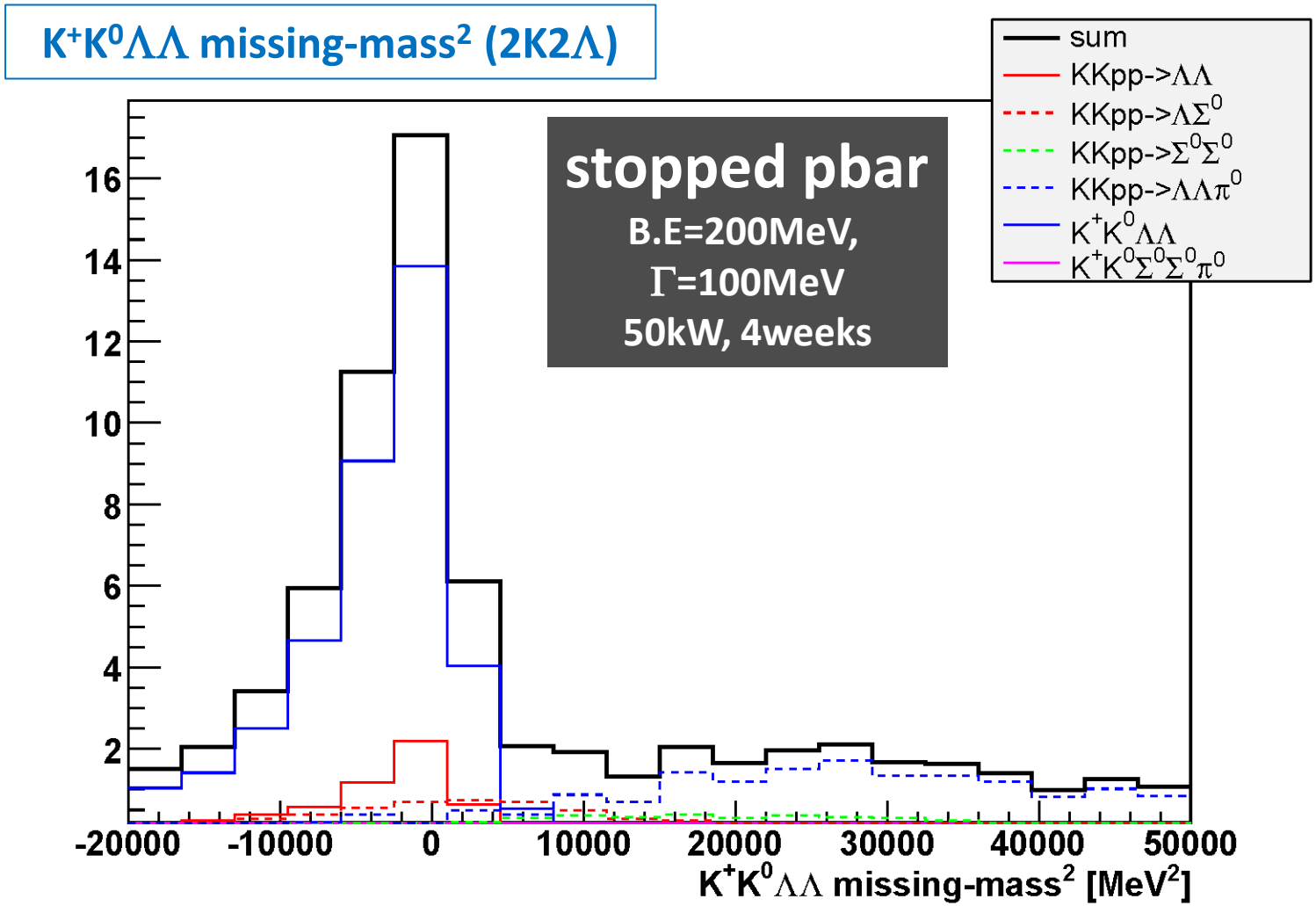
stopped pbar

B.E=200MeV,
Γ=100MeV
50kW, 4weeks





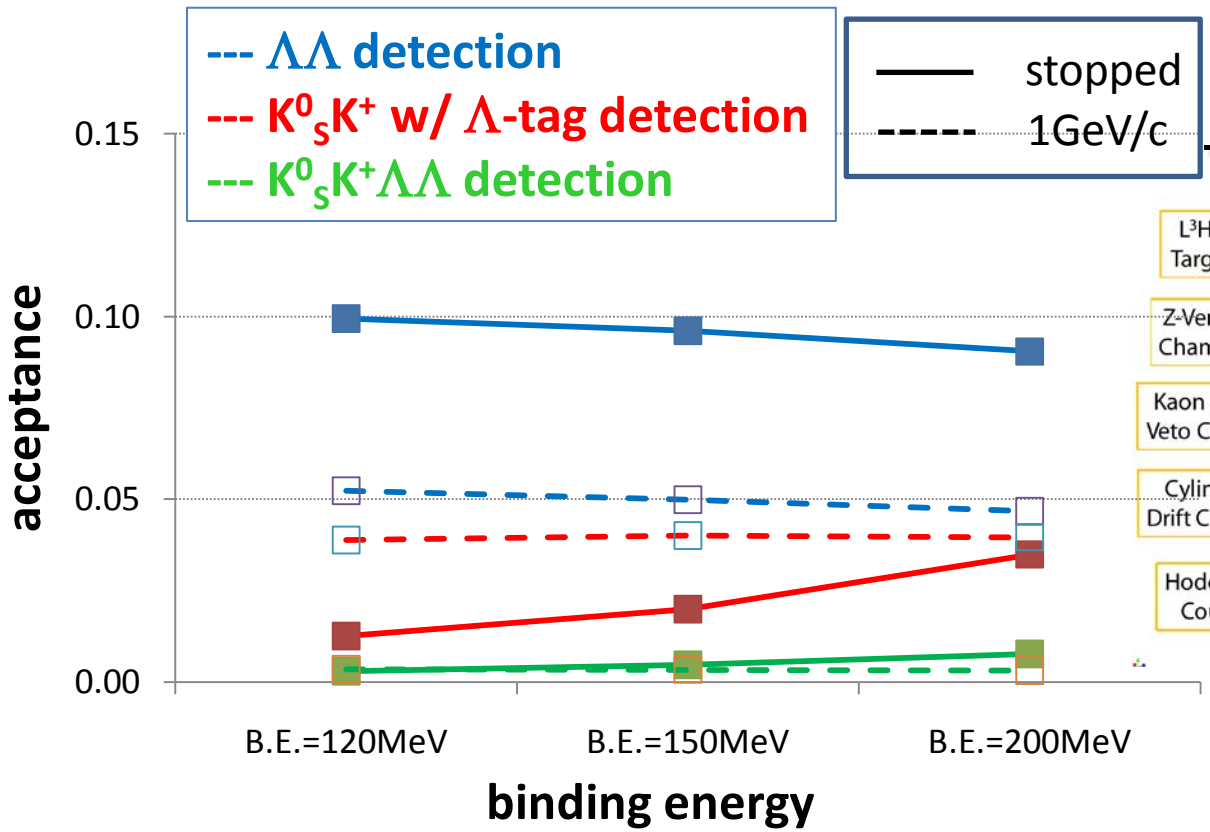
Expected Spectra @ 50kW, 4weeks



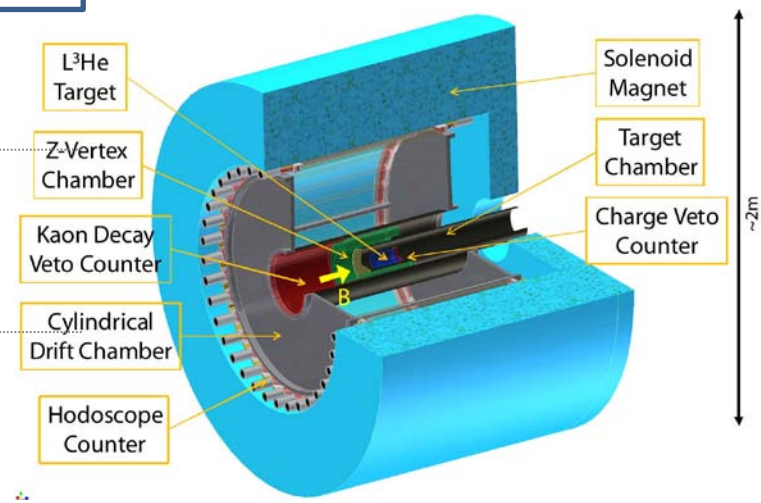
in-flight experiment

Detector Acceptance

$$p^{bar}+{}^3He \rightarrow K^+ + K^0_S + K^- K^- pp,$$
$$K^- K^- pp \rightarrow \Lambda\Lambda,$$
$$\Gamma(K^- K^- pp) = 100\text{MeV}$$



E15 CDS @ K1.8BR



Expected K^-K^-pp Production Yield

- pbar beam momentum : 1GeV/c
- beam intensity : 6.4×10^5/spill/3.5s @ 270kW

we assume **K^-K^-pp production rate = 10^{-4} for 1GeV/c pbar+p**
(analogy from the DIANA result of double-strangeness production <u>although the result are from pbar+^{131}Xe reaction</u>)

inelastic cross-section of 1GeV/c pbar+p is (117-45) = 72mb

K^-K^-pp production CS = 7.2μb for 1GeV/c pbar+p

Expected K^-K^-pp Production Yield (Cont'd)

L^3He parameters: * ρ = 0.08g/cm^3
* l = 12cm

$N = \sigma * N_B * N_T$

- N : yield
- σ : cross section
- N_B : the number of beam
- N_T : the number of density per unit area of the target

K-K-pp production yield = 1.5x10^5 /week @ 270kW

BG rate:
total CS = 117mb
pbar = 6.4x10^5/spill
BG = 1.4x10^4/spill

DAQ & ana efficiency = 0.7 & duty factor = 0.7

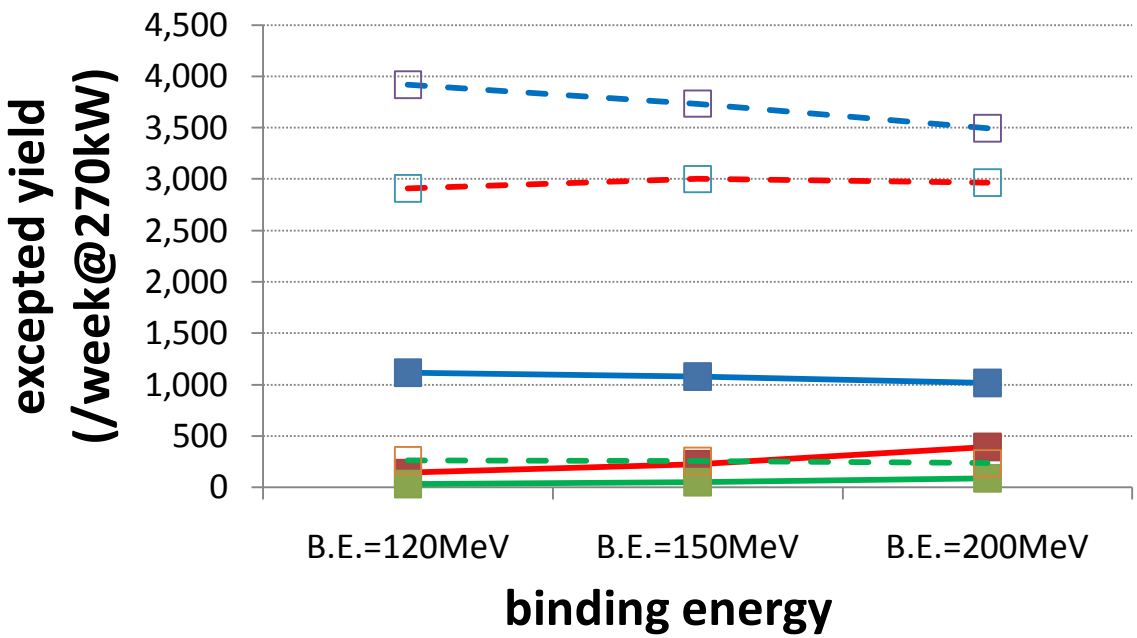
expected K^-K^-pp yield = 7.5x10^4 /week @ 270kW
w/o detector acceptance

Expected K^-K^-pp Detection Yield

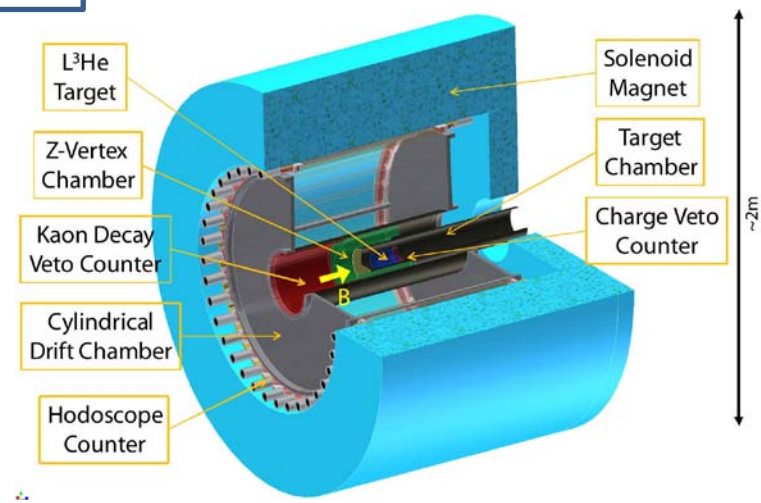
$$p^{bar}+{}^3He \rightarrow K^+ + K^0_S + K^-K^-pp,$$
$$K^-K^-pp \rightarrow \Lambda\Lambda,$$
$$\Gamma(K^-K^-pp)=100MeV$$

--- ΛΛ detection
--- $K^0_SK^+$ w/ Λ-tag detection
--- $K^0_SK^+\Lambda\Lambda$ detection

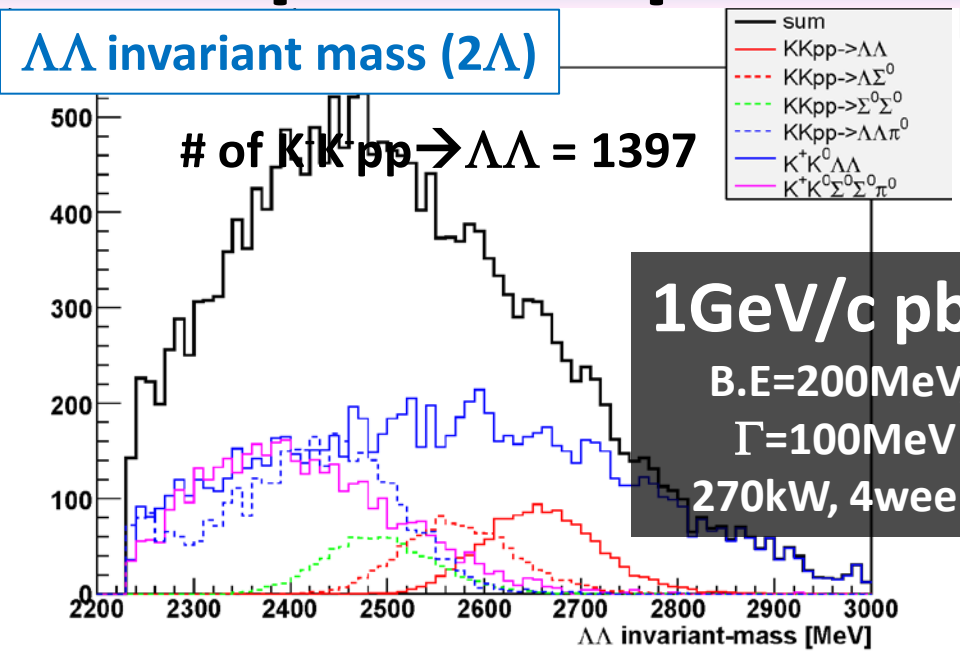
—— stopped
----- 1GeV/c

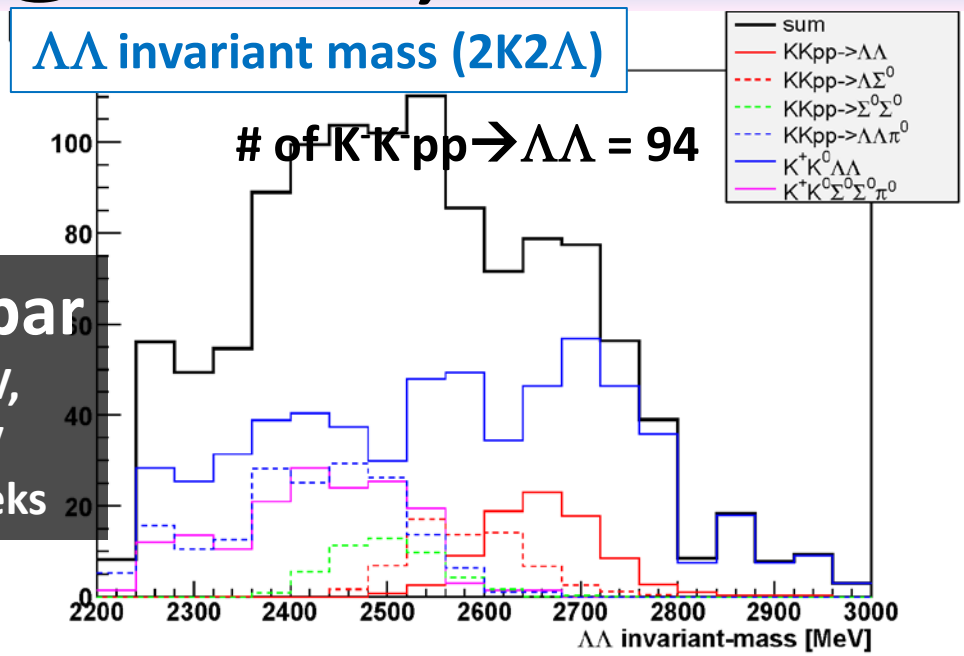


E15 CDS @ K1.8BR

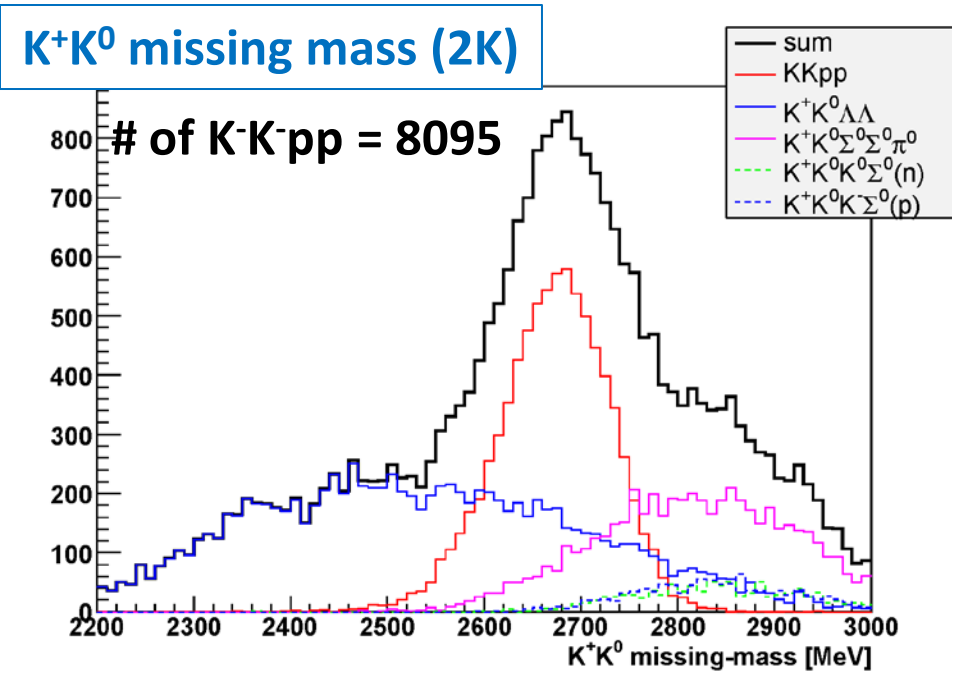


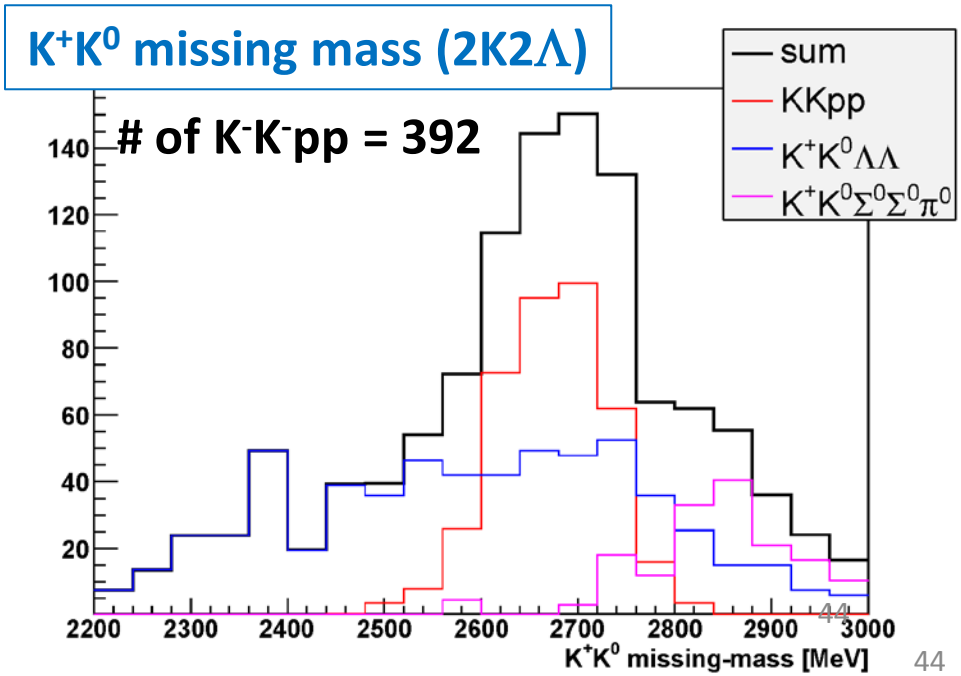
Expected Spectra @ 270kW, 4weeks



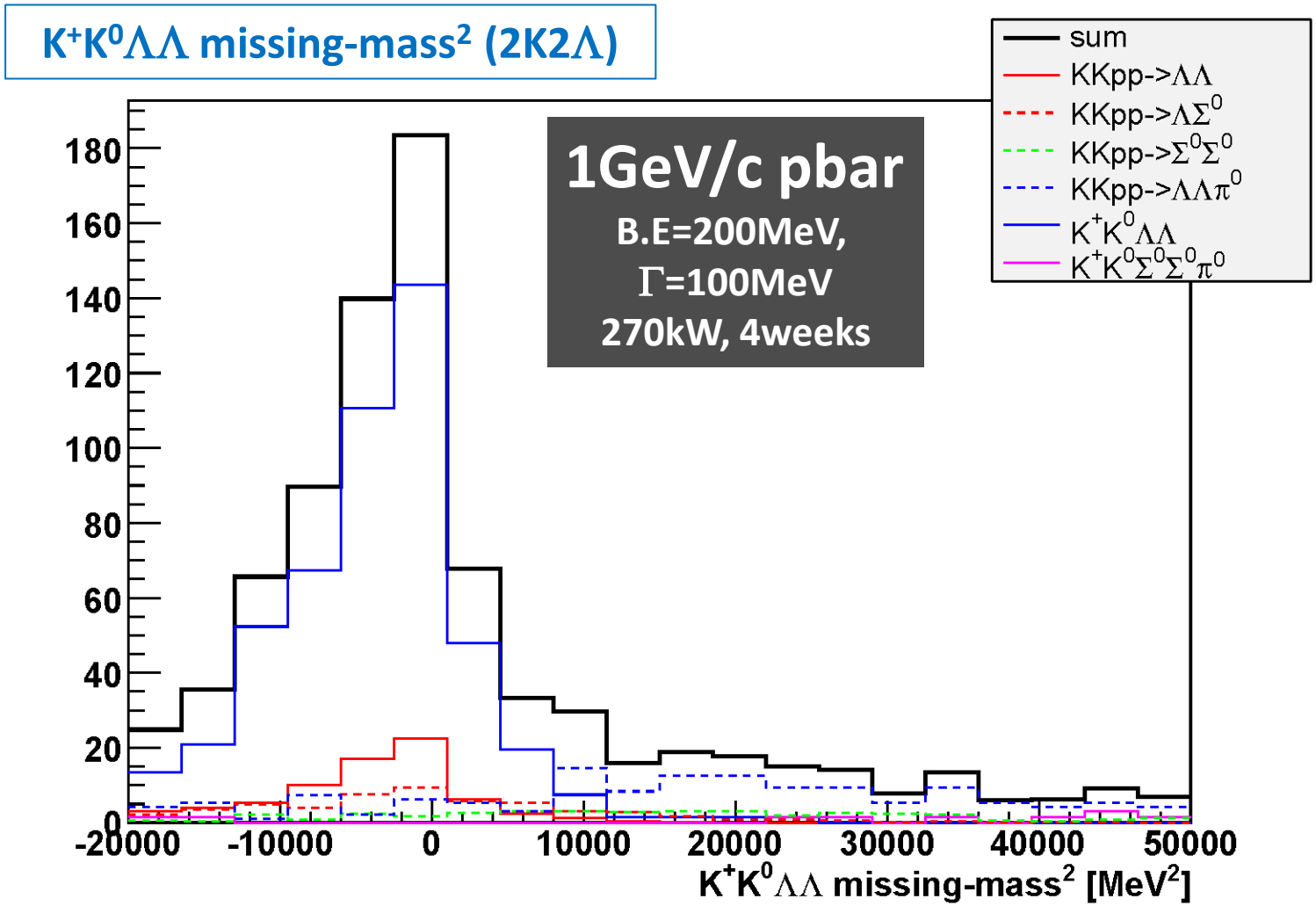


1GeV/c pbar
B.E=200MeV,
Γ=100MeV
270kW, 4weeks





Expected Spectra @ 270kW, 4weeks



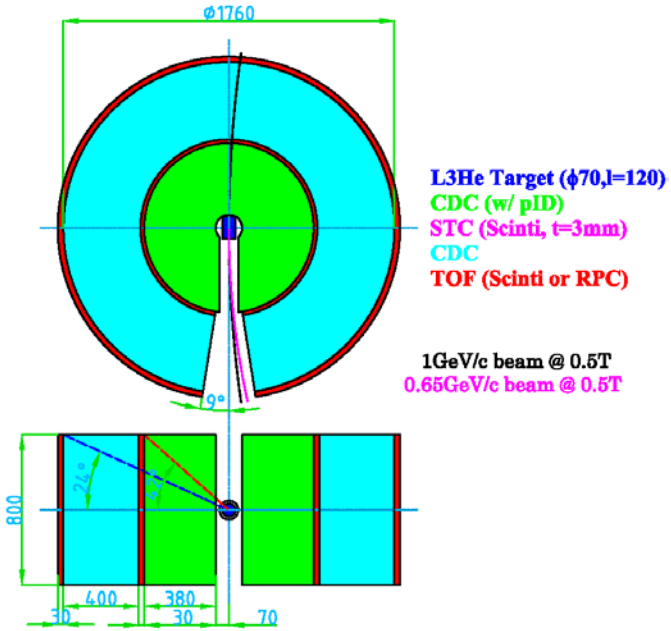
with Dipole-setup @ K1.1

Detector Design (Cont'd)

new dipole setup @ K1.1

- **The design goal is to become the common setup for the ϕ-nuclei experiment with in-flight p^{bar}-beam**
- B = 0.5T
- Double Cylindrical-Drift-Chamber setup
- pID is performed with dE/dx measurement by the INC

- INC resolution : $\sigma_{r\phi}$ = 0.2mm , σ_z = 2mm (UV)
- CDC resolution : $\sigma_{r\phi}$ = 0.2mm, σ_z = 2mm (UV)
- **CDC is NOT used for the stopped-p^{bar} experiment**



INC (wire chamber)

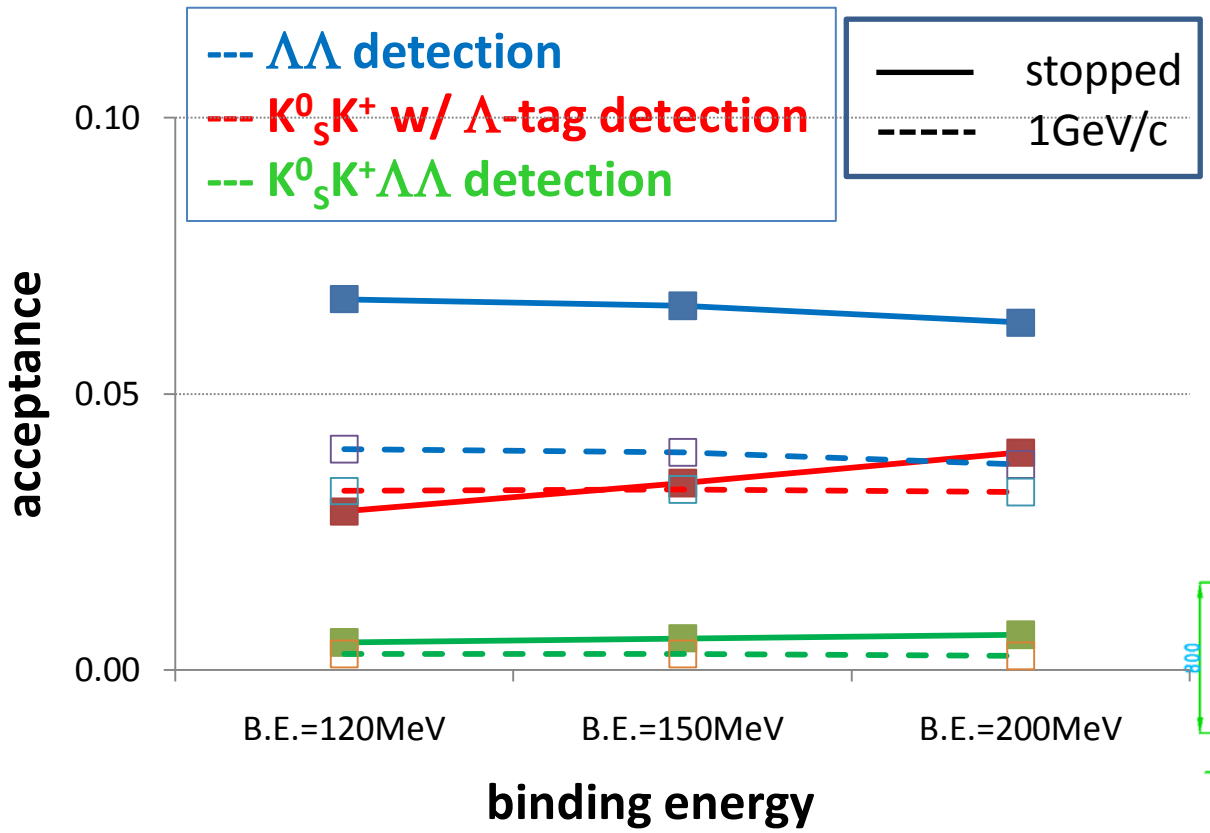
Type	A	A'	A	U	U'	V	V'	A	A'	A	U	U'	V	V'	A	A'	A
Layer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
radius	100	120	140	160	180	200	220	240	260	280	300	320	340	360	380	400	420

CDC

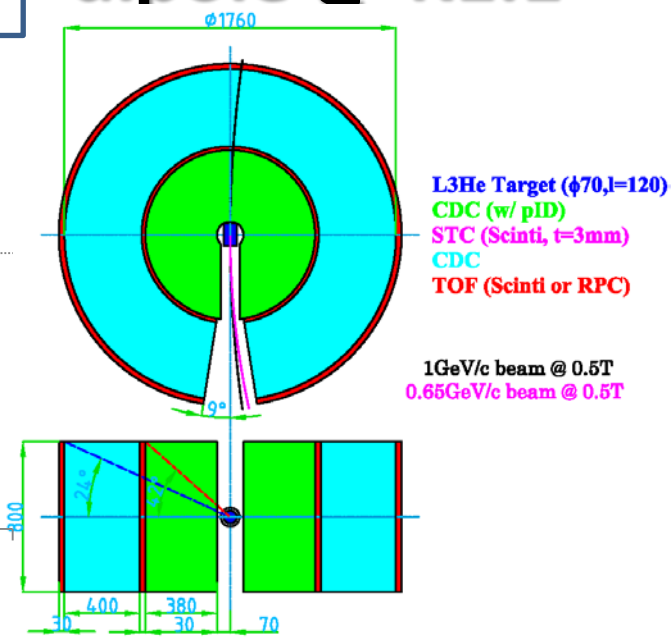
Type	A	A'	A	U	U'	V	V'	A	A'	U	U'	V	V'	A	A'
Layer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
radius	500	525	550	575	600	625	650	675	700	725	750	775	800	825	850

Detector Acceptance

$P^{bar}+{}^3He \rightarrow K^+ + K^0_S + K^- K^- pp$,
$K^- K^- pp \rightarrow \Lambda\Lambda$,
$\Gamma(K^- K^- pp)=100MeV$

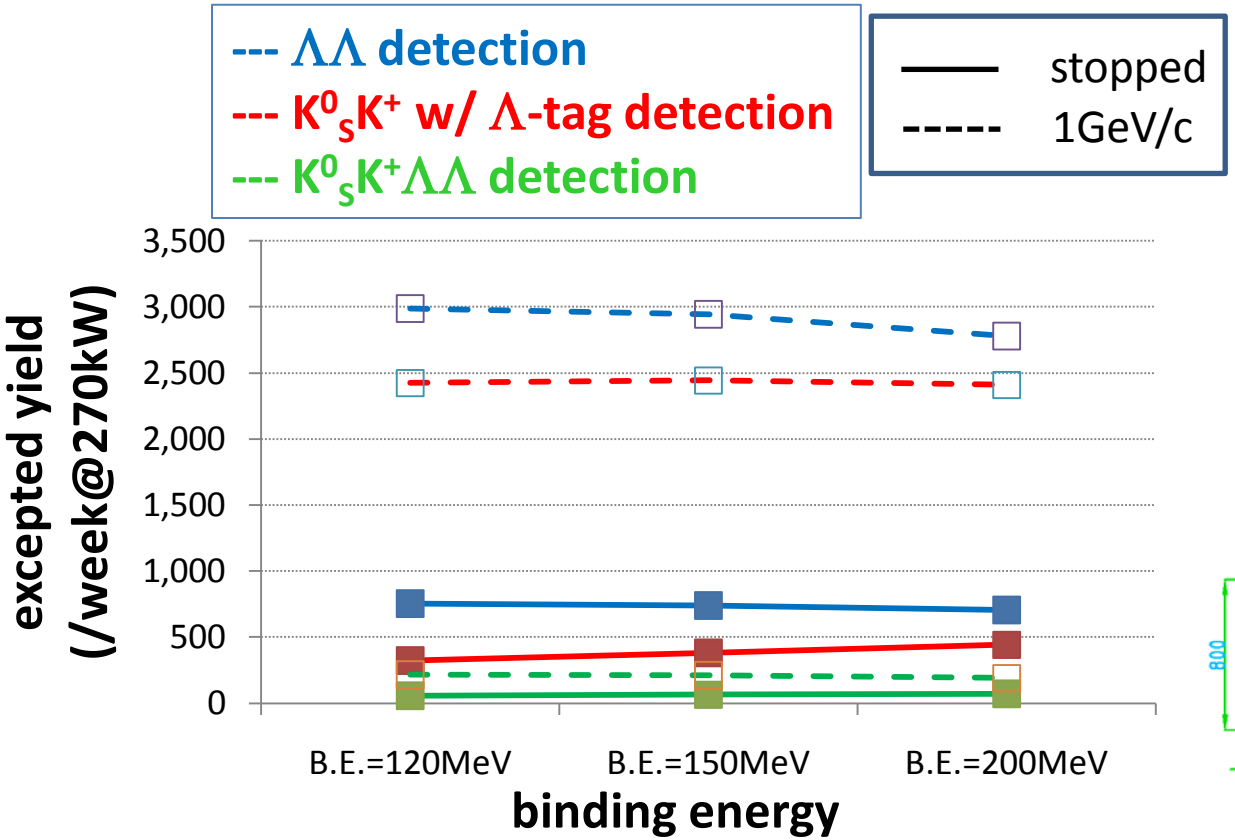


dipole @ K1.1

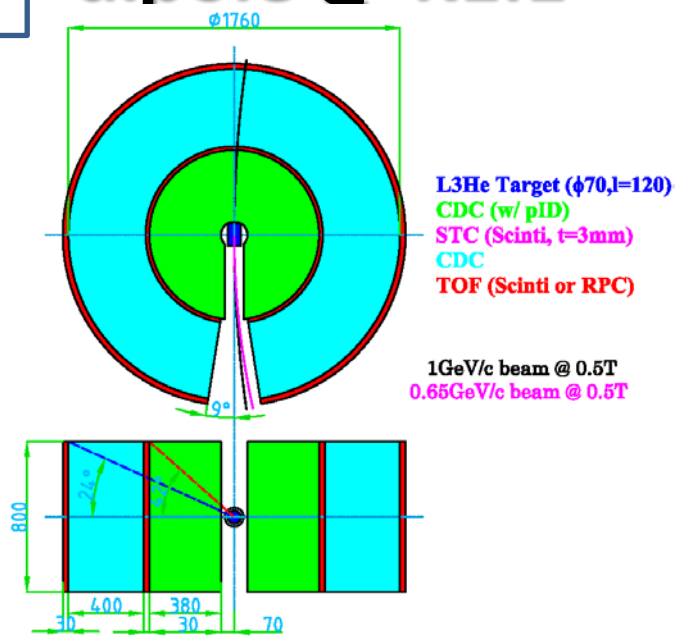


Expected K^-K^-pp Detection Yield

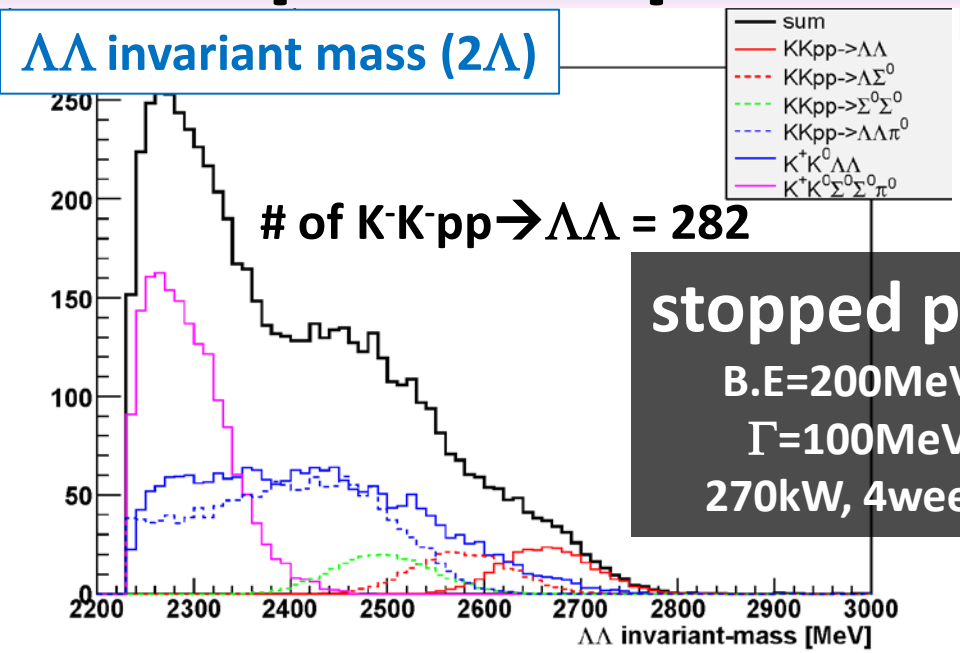
$$p^{bar}+{}^3He \rightarrow K^+ + K^0_S + K^-K^-pp,$$
$$K^-K^-pp \rightarrow \Lambda\Lambda,$$
$$\Gamma(K^-K^-pp)=100MeV$$

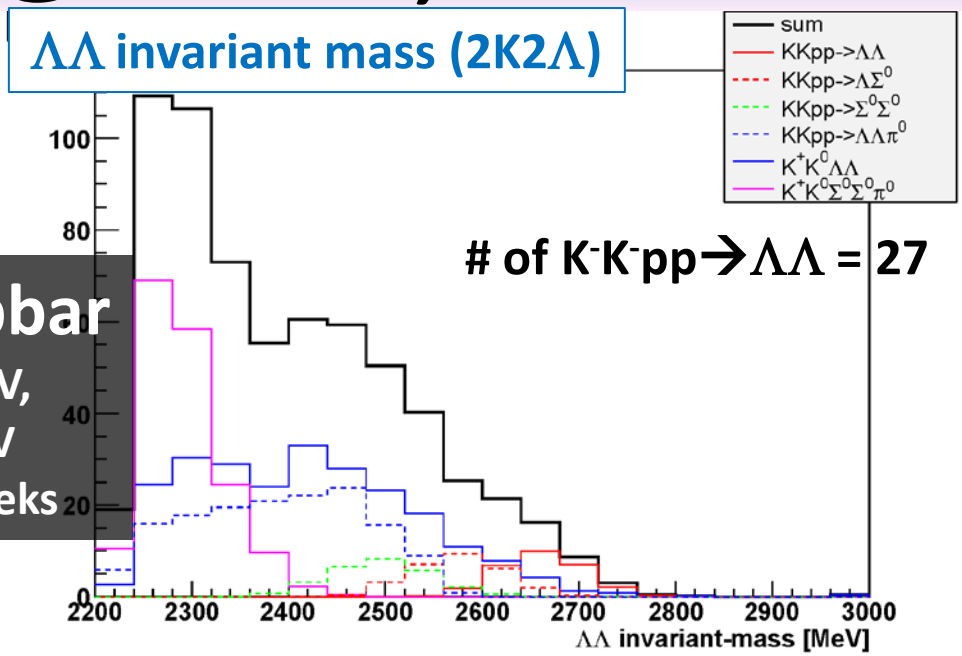


dipole @ K1.1

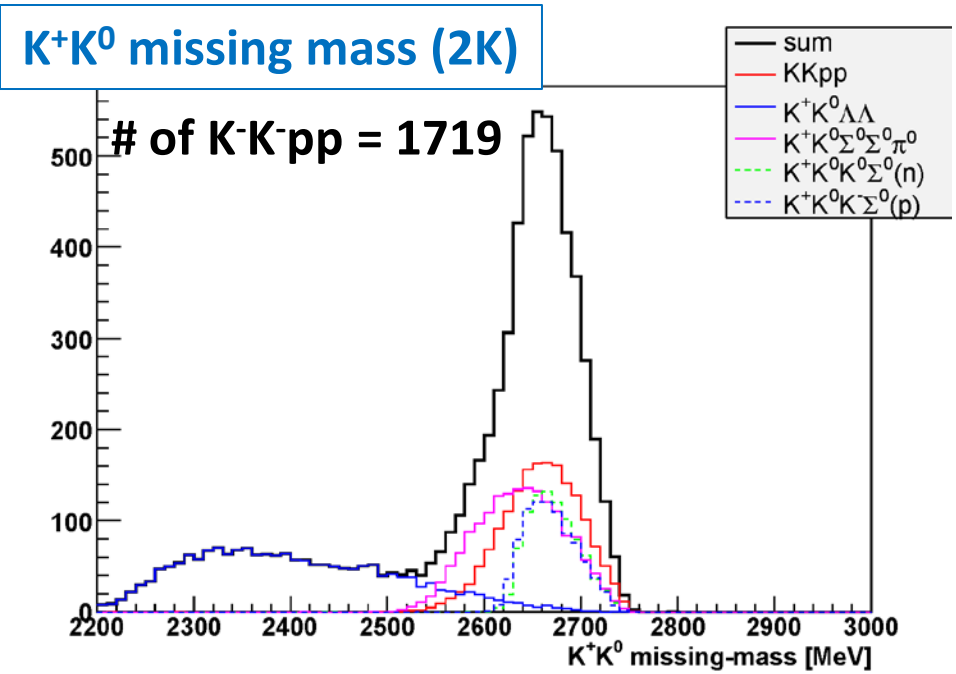


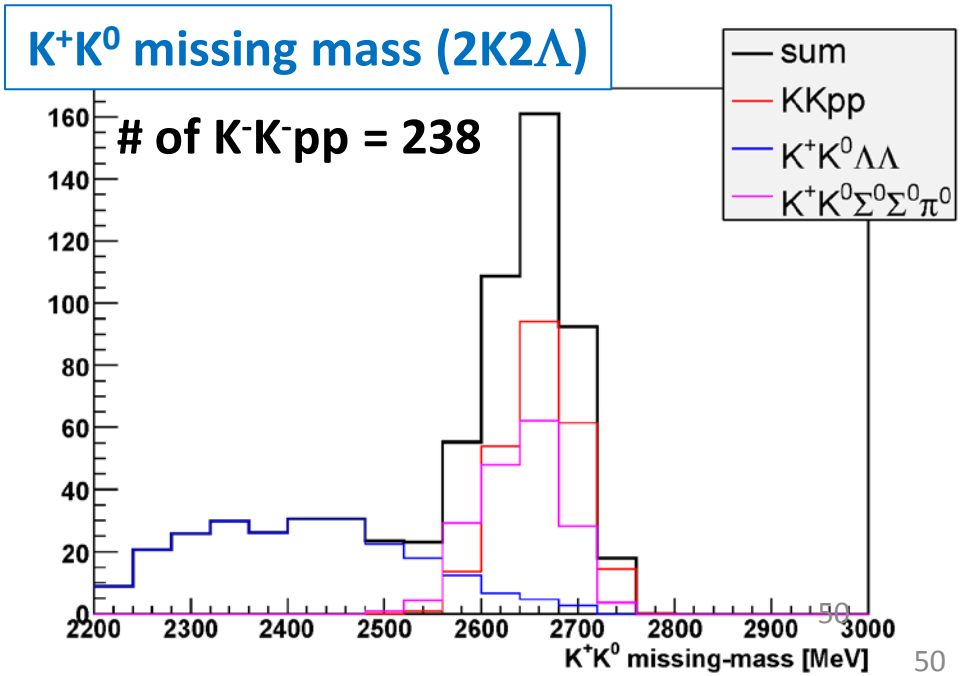
Expected Spectra @ 270kW, 4weeks



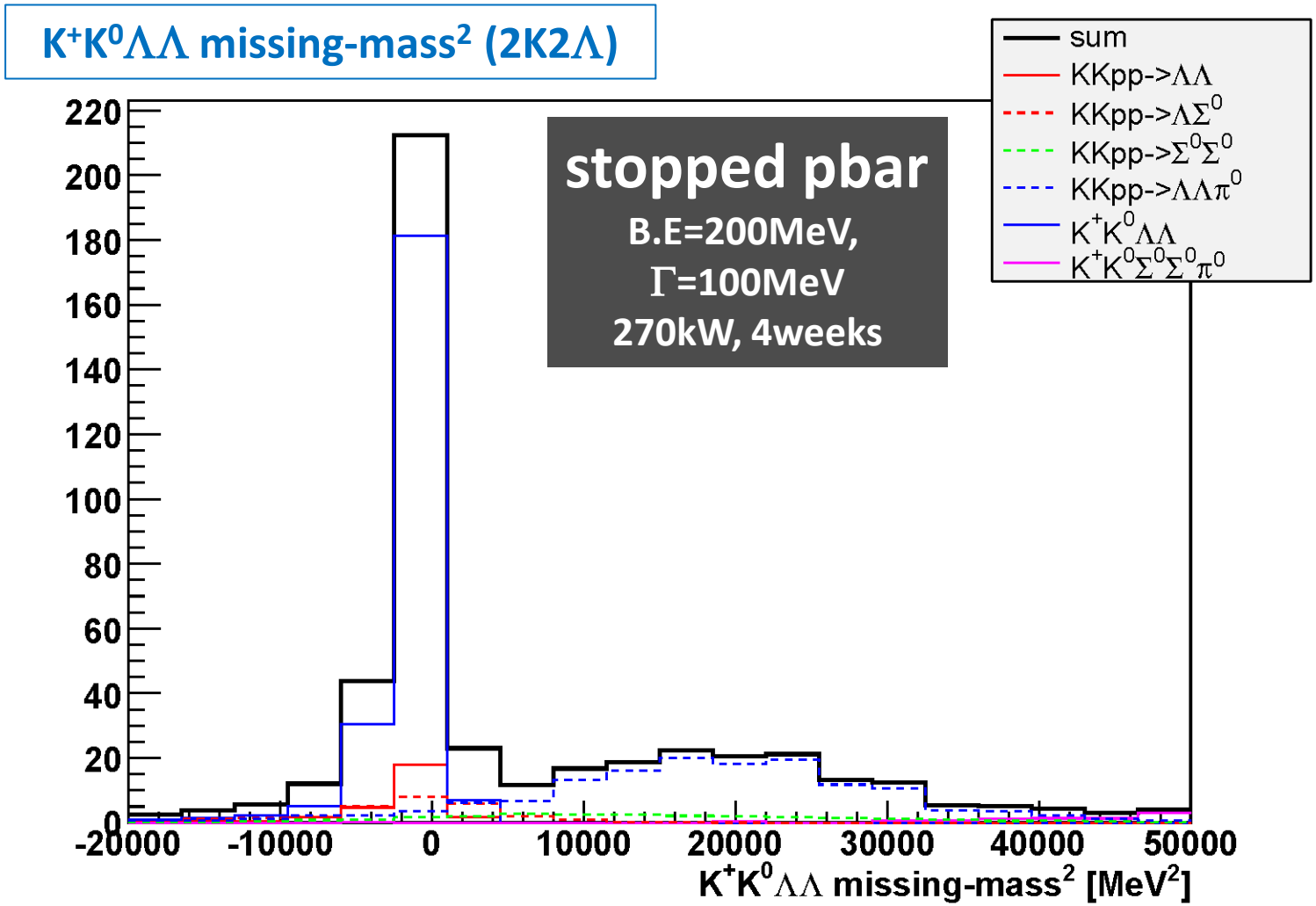


stopped pbar
B.E=200MeV,
Γ=100MeV
270kW, 4weeks

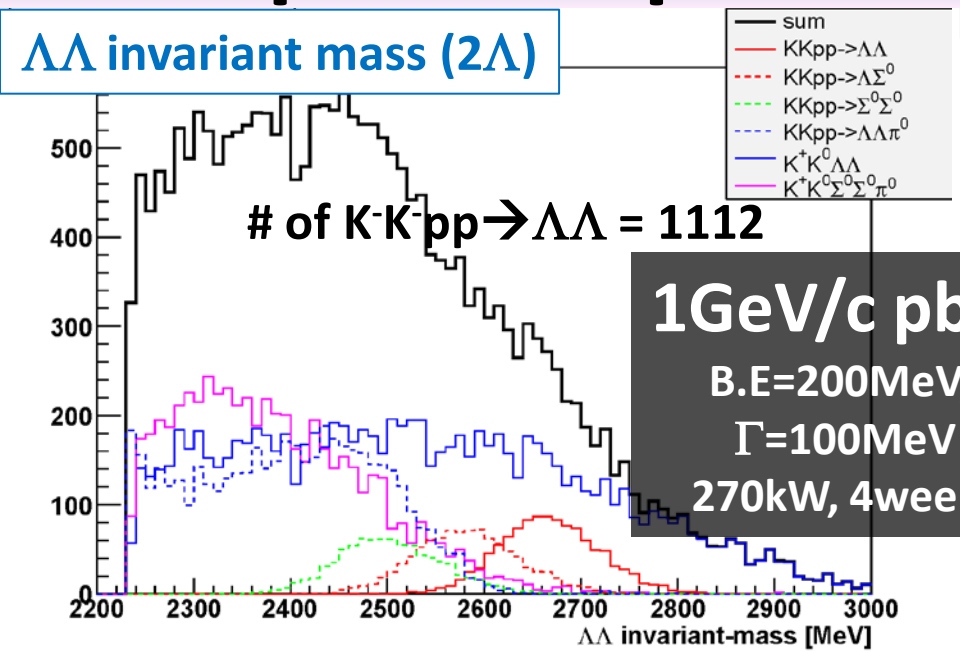


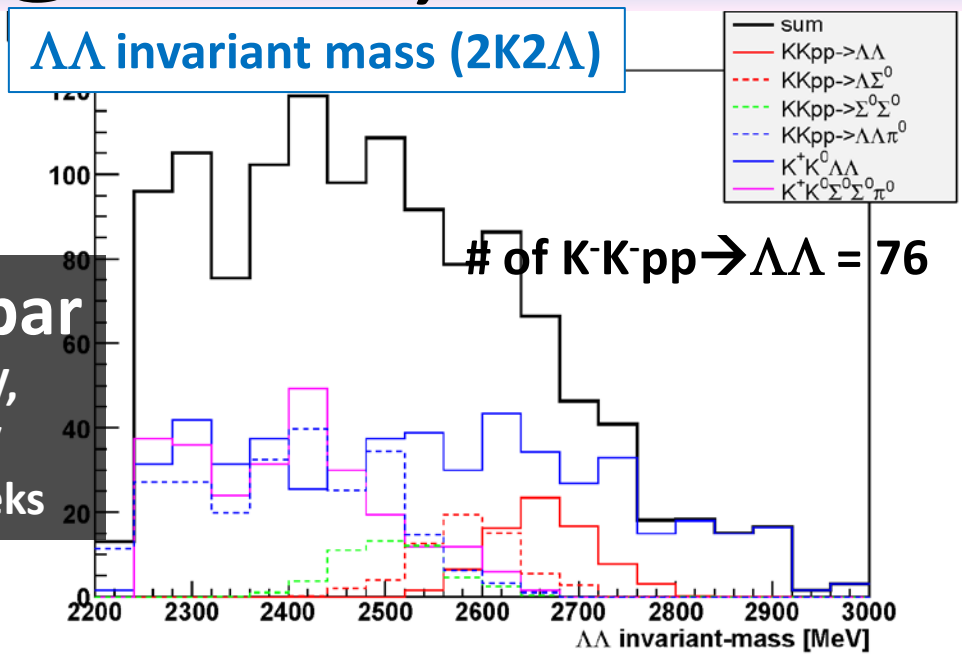


Expected Spectra @ 270kW, 4weeks

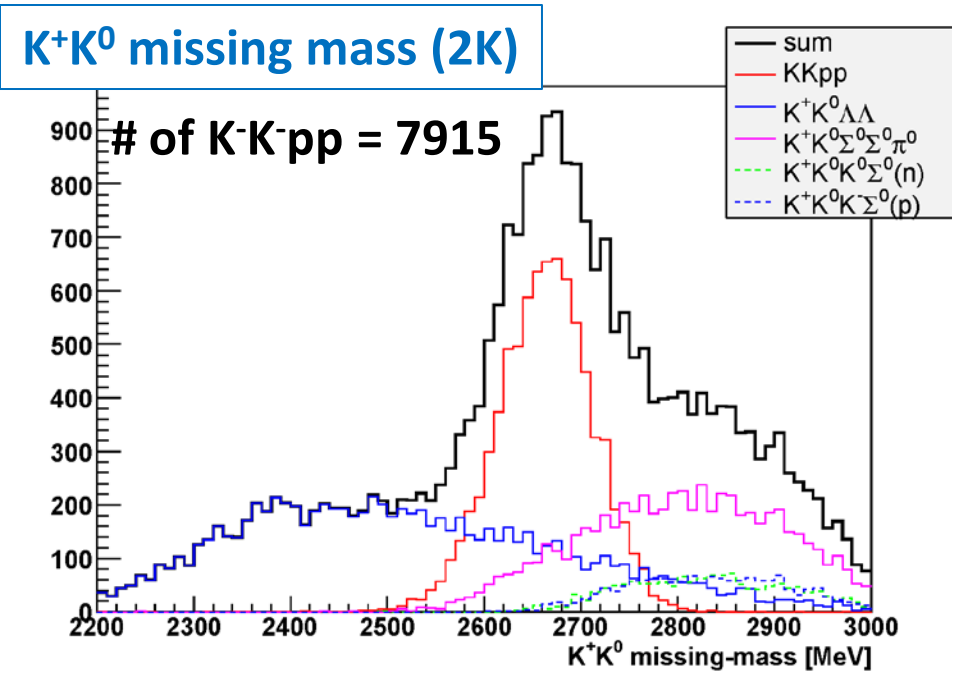


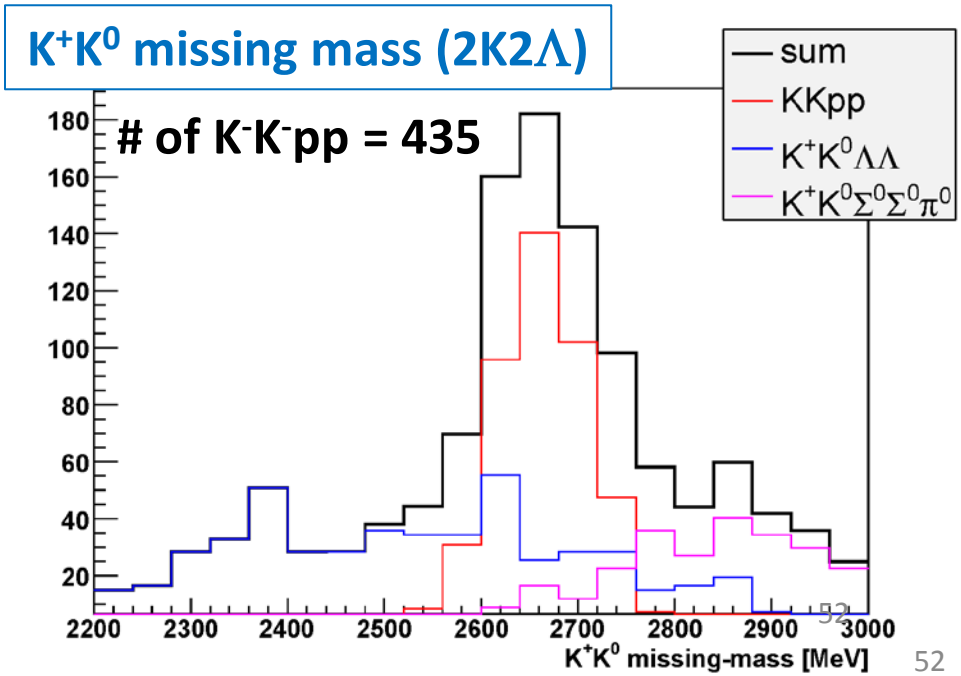
Expected Spectra @ 270kW, 4weeks



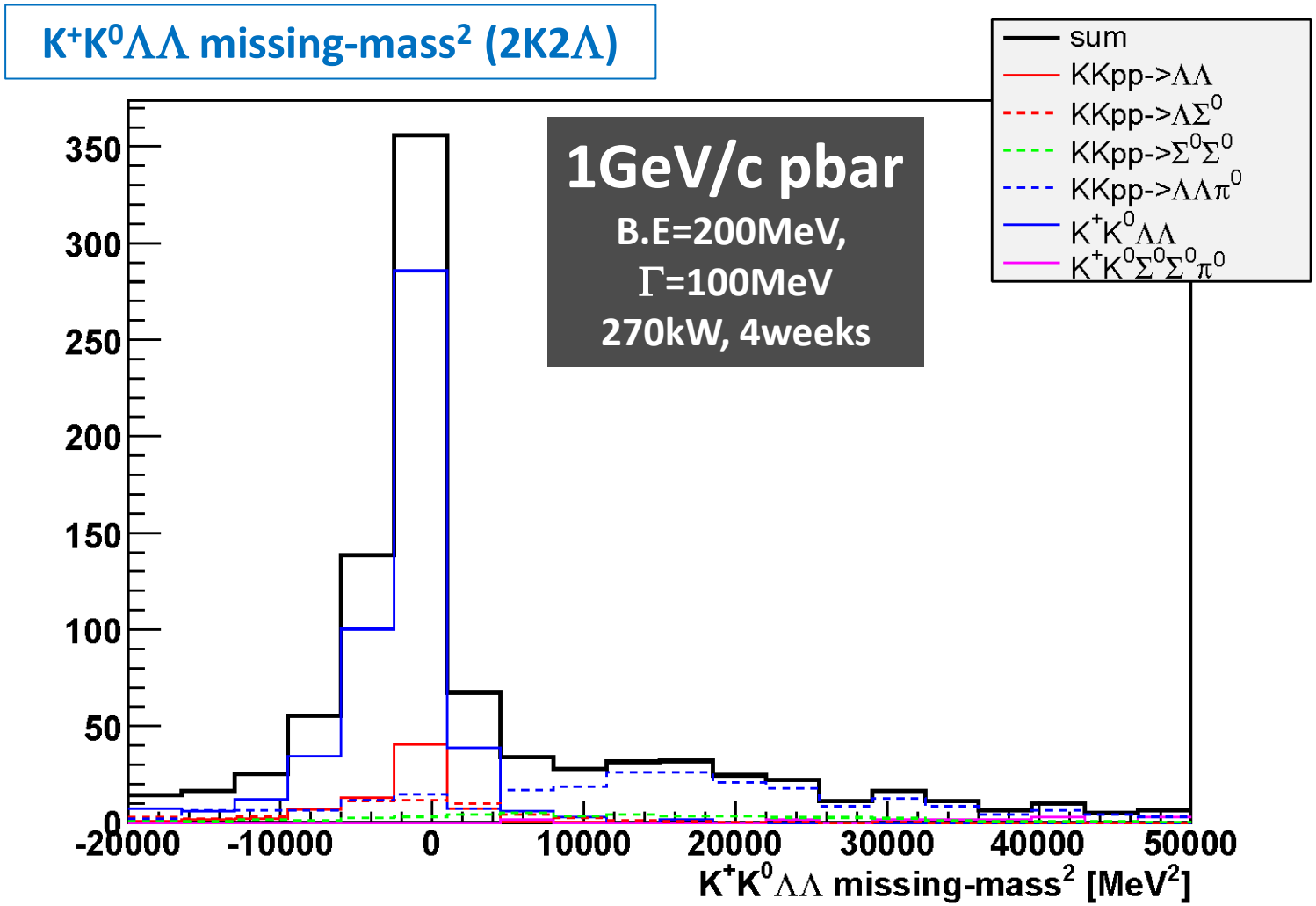


1GeV/c pbar
B.E=200MeV,
Γ=100MeV
270kW, 4weeks





Expected Spectra @ 270kW, 4weeks



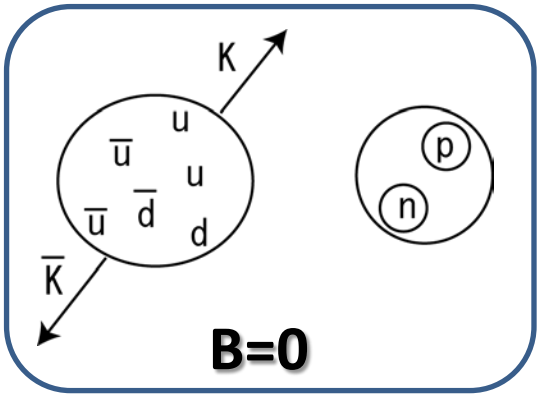
Interpretation of the Experimental Results

- Although observed statistics are very small, the results have indicated a high yield of ~10^{-4}, which is naively estimated to be ~10^{-5}.

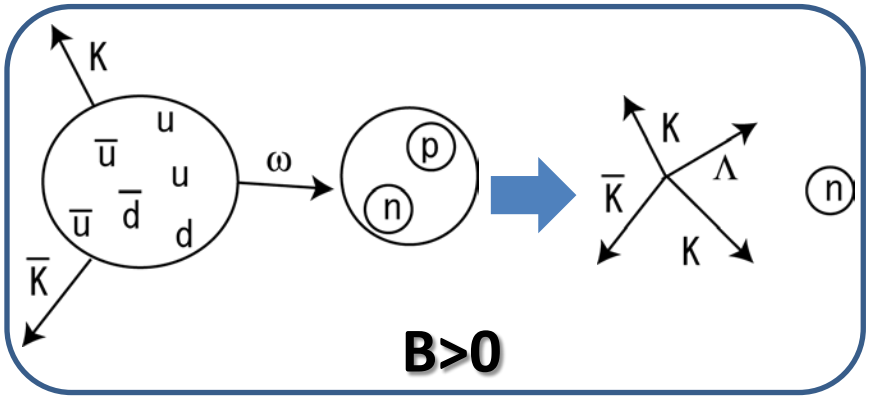
- Possible candidates of the doubl duction mechanism are:
  - rescattering
  - exoti eon annihilation)
    - *fo ly-bound kaonic nuclei,*
    - *H-p*

the mechanism is NOT known well because of low statistics of the experimental results!

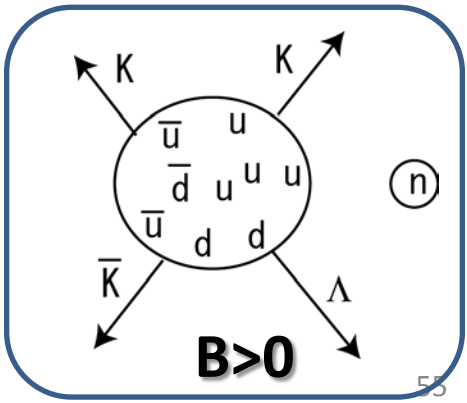
single-nucleon annihilation



rescattering cascades



multi-nucleon annihilation



$K^+K^0\Lambda\Lambda$ Final State & Background

$$\bar{p} + {}^3He \rightarrow K^+ + K^0 + X$$

$$\rightarrow K^+ + K^0 + \Lambda + \Lambda$$

This exclusive channel study is equivalent to the unbound (excited) H-dibaryon search!

	Q-value	X momentum	$\Lambda\Lambda$ mass	Λ–Λ angle
K^-K^-pp	very small	~ at rest	$M_{\Lambda\Lambda} > 2M_\Lambda$	back to back
H-dibaryon	large	boosted	$M_{\Lambda\Lambda} \sim 2M_\Lambda$	~ 0

Possible background channels

- direct $K^+K^0\Lambda\Lambda$ production channels, like:

$$\underline{\bar{p} + {}^3He \rightarrow K^+ + K^0 + \Lambda + \Lambda}$$

$$\bar{p} + {}^3He \rightarrow K^+ + K^0 + \Lambda + \Lambda + \pi^0 + \ldots$$

be distinguished by inv.-mass only → major background source

- $\Sigma^0 \rightarrow \gamma\Lambda$ contaminations, like:

$$\bar{p} + {}^3He \rightarrow K^+ + K^0 + \Lambda + \Sigma^0$$

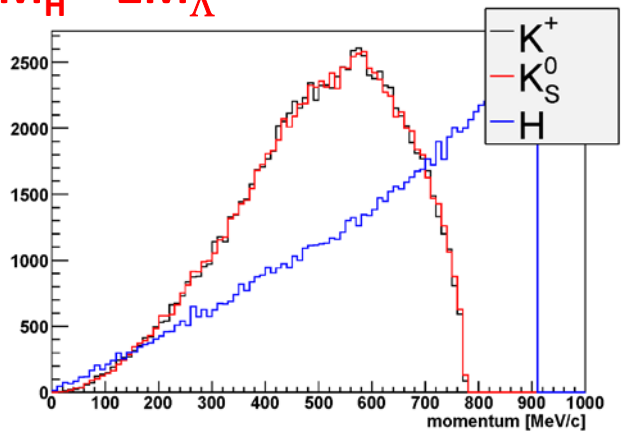
$$\rightarrow K^+ + K^0 + \Lambda + \Lambda + \gamma$$

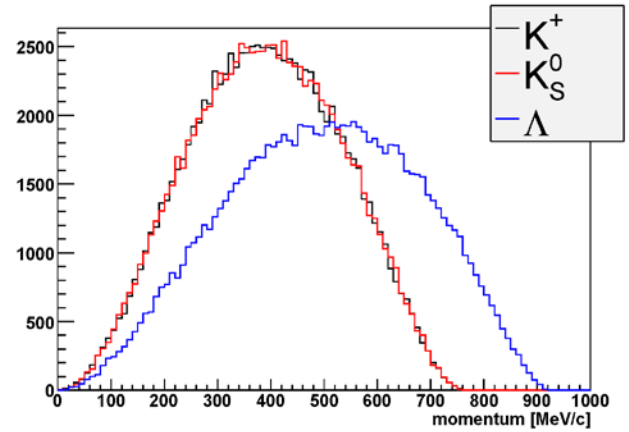
be eliminated by the kinematical constraint, *ideally*

Expected Kinematics (Cont'd)

$$\bar{p} + {}^3He \rightarrow K^+ + K^0 + H \qquad \bar{p} + {}^3He \rightarrow K^+ + K^0 + \Lambda + \Lambda$$

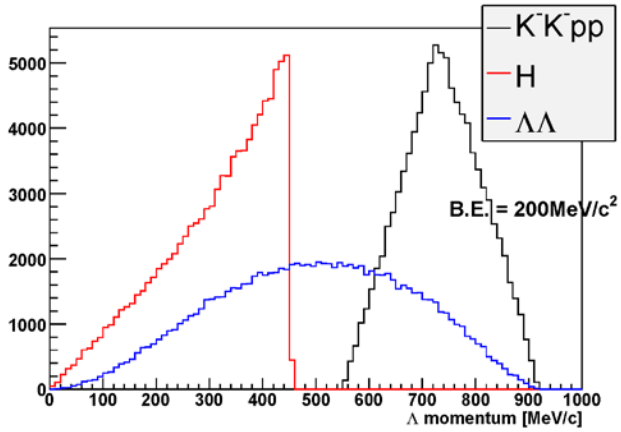
$M_H = 2M_\Lambda$



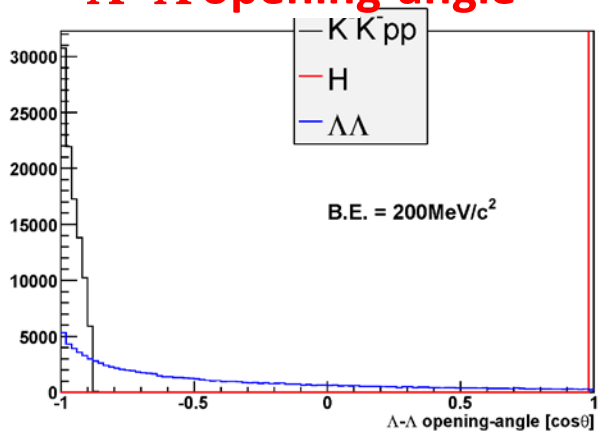


ΛΛ spectra

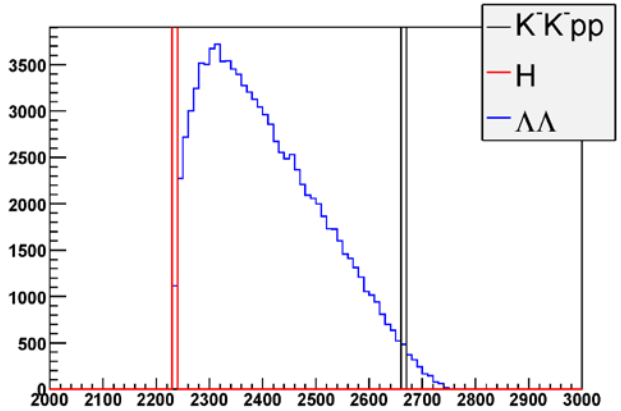
Λ momentum



Λ–Λ opening-angle



ΛΛ inv. mass



strong correlation of ΛΛ opening-angle in K^-K^-pp/H productions

Schedule

Year (JFY)	K1.8BR	K1.1 (ϕN)
2009	beam-tune	proposal
2010	E17	R&D, design
2011	E17	R&D, design
2012	E15/E31	construction
2013	E15/E31	commissioning
2014	…	data taking

The proposed experiment will be scheduled in around JFY2014, whether we conduct the experiment at K1.8BR or K1.1 beam-line.

- **K1.8BR : after E17/E15/E31?**
- **K1.1 : joint project with the ϕN experiment?**

Past Experiments of Stopped-p^{bar} Annihilation

charged particle multiplicity at rest

form Rivista Del Nuovo Cimento 17, 1 (1994).

pbar+3He charged particle multiplicity at rest

CERN LEAR, streamer chamber exp.

NP A518, 683 (1990).

nc	branch(%)
1	5.14 +−0.40
3	39.38 +−0.88
5	48.22 +−0.91
7	7.06 +−0.46
9	0.19 +−0.08
<nc>	4.155 +−0.06

pbar+4He charged particle multiplicity at rest

CERN LEAR, streamer chamber exp.

NP A465, 714 (1987).

[data in nuovo−ciment is listed below, which is a higher statistics than NPA465]

nc	branch(%)
1	3.36 +−0.35
2	5.03 +−0.42
3	33.48 +−0.92
4	12.26 +−0.63
5	35.68 +−0.93
6	3.51 +−0.36
7	6.24 +−0.47
8	0.19 +−0.08
9	0.24 +−0.10
<nc>	4.097 +−0.07

CERN LEAR streamer chamber exp.
NIM A234, 30 (1985).

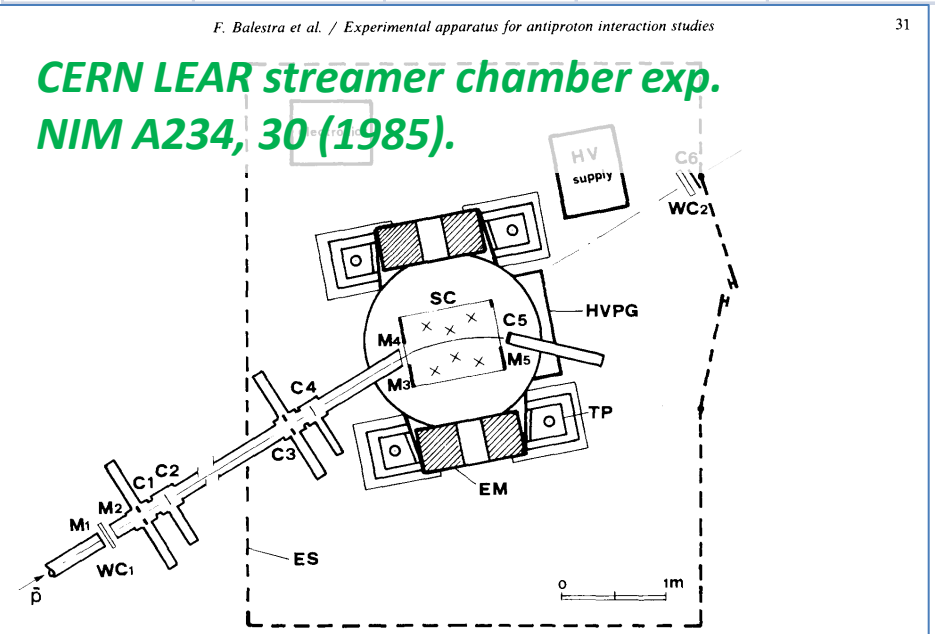


Fig. 1. Layout of the experimental apparatus. EM – electromagnet; SC–streamer chamber; HVPG–high voltage pulse generator; TP–travelling platform; ES–electrostatic screening; WC_{1-2}–wire chambers; C_{1-6}–scintillation counters; M_{1-5}–thin walls.

They obtained

$$\sigma^a(\bar{p}p) = 70.4 \pm 2.5\%$$

$$\sigma^a(\bar{p}n) = 29.6 \pm 2.5\%$$

$$\rightarrow \sigma^a(\bar{p}n)/\sigma^a(\bar{p}p) = 0.42 \pm 0.05$$

KKbar production-rate for pbar+p at rest

form Rivista Del Nuovo Cimento 17, 1 (1994).

the KKbar production-rate R for pbar+p annihilation at rest
(obtained from hydrogen bubble chamber data)

$$R\left(K^0\bar{K}^0\right) = 1.733 \pm 0.067\%$$

$$R\left(K^+K^-\right) = 1.912 \pm 0.141\%$$

$$R\left(\bar{K}^0K^+\right) + R\left(K^0K^-\right) = 1.701 \pm 0.082\%$$

$$\Rightarrow$$

$$R\left(K_S^0\right) = \tfrac{3}{4}R\left(K^0\bar{K}^0\right) + \tfrac{1}{2}\left[R\left(\bar{K}^0K^+\right) + R\left(K^0K^-\right)\right] = 2.149 \pm 0.065\%$$

$$R\left(\bar{K}K\right) = R\left(K^+K^-\right) + R\left(\bar{K}^0K^+\right) + R\left(K^0K^-\right) + R\left(K^0\bar{K}^0\right) = 5.35 \pm 0.18\%$$

There is a great deal of data on the production of strange particles on ^{1}H and ^{2}H but only few ones on heavier nuclei.

Λ/K^0_s production-rate and multiplicity for pbar+A at rest

form Rivista Del Nuovo Cimento 17, 1 (1994).

pbar+A experimental yields and charge multiplicities of $\Lambda(\Sigma^0)$ and K^0_s at rest

He data is from CERN LEAR, streamer chamber exp.

NP A526, 415 (1991).

	$R_a(\Lambda)$ (%)		$R_a(K^0_s)$ (%)		$\langle nc(\Lambda)\rangle$		$\langle nc(K^0_s)\rangle$		$\langle nc(\text{all events})\rangle$	
^1H			2.15	+-0.07						
^2H	0.30	+-0.04	2.02	+-0.10						
^3He	0.55	+-0.11	1.59	+-0.20	2.76	+-0.27	2.97	+-0.14	4.17	+-0.08
^4He	1.12	+-0.12	1.07	+-0.11	3.03	+-0.08	2.72	+-0.07	4.10	+-0.13

charge multiplicities decrease by ~1 when Λ/K^0_S is produced

DIANA [Phys.Lett., **B464**, 323 (1999).]

- $p^{bar}Xe$ annihilation
- p=<1GeV/c p^{bar}-beam @ ITEP 10GeV-PS
- 700-liter Xenon bubble chamber, w/o B-field
- 10^6 pictures → 7.8×10^5 $p^{bar}Xe$ inelastic → 2.8×10^5 $p^{bar}Xe$ @ 0-0.4GeV/c
- **$p^{bar}Xe \rightarrow K^+K^+X$: 4 events → $(0.31+/-0.16)\times10^{-4}$**
- **$p^{bar}Xe \rightarrow K^+K^0\Lambda X$: 3 events → $(2.1+/-1.2)\times10^{-4}$**

Table 1
List of observed $\bar{p}Xe$ annihilation events containing two or more strange particles in the final state (Λ_n: $\Lambda \rightarrow n\pi^0$; $K_n^0(\bar{K}_n^0)$: $K^0(\bar{K}^0) \rightarrow \pi^0\pi^0$; h: ambiguously identified meson (π or K)). $*$ denotes special scanning (see text)

$\bar{p}$ mom. interval, GeV/c	Events containing two K^+-mesons	Yield (10^{-4})	Events containing $K^+K^0(\bar{K}^0)$-pairs and Λ - hyperons	Yield (10^{-4})	Events containing other strange particles
0.0–0.4	K^+K^+h $K^+K^+\pi^0h$ $K^+K^+\Lambda_n4\gamma$ $K^+K^+4\gamma$	0.31 ± 0.16	$K^+K^0\Lambda\Lambda$ $K^+K^0\Lambda\Sigma^+p$ $K^+K^0(\bar{K}^0)\Lambda$	2.1 ± 1.2	$K^+K^-\Lambda_n\pi^-\pi^0$ $K^+\Lambda\Lambda4p$ $K^0\Lambda K^-ph$ $*$ $K_n^0\Lambda\Sigma\gamma2h$ $*$
0.4–0.65	$K^+K^+\pi^-4p\gamma$ $K^+K^+\pi^0hp$ K^+K^+2h K^+K^+4p	0.42 ± 0.21	$K^+K^0\Lambda\Lambda_np$ $K^+K^0\Lambda\Lambda_np$ $K^+K^0\Lambda\Lambda_n2p$	3.0 ± 1.7	
0.65–0.9	$K^+K^+\Lambda\Lambda_n2p$ $K^+K^+\Lambda\Lambda_n$ $K^+K^+3p\Lambda$ $K^+K^+\Sigma^-\Lambda p$	0.26 ± 0.13	$K^+K^0\Lambda\Lambda2p\pi^-$ $K^+K^0(\bar{K}^0)\Lambda\gamma2p$ $K^+K_n^0(\bar{K}_n^0)\Lambda3p\pi^0$ $K^+K^0(\bar{K}^0)\Lambda3p$ $K^+K^0(\bar{K}^0)\Lambda2p\pi^-\gamma$ $K^+K^0(\bar{K}^0)\Lambda_n\pi^02p$ $K^+K^0(\bar{K}^0)\Lambda_np$	2.4 ± 0.9	$K^+\Lambda\Sigma^-ph$ $K^+K^-\Lambda p$ $K^+\Lambda\Sigma^-3ph$ $K^+K^0(\bar{K}^0)K^-p$

← 4 events

← 3 events

interpretation of the DIANA result ($p^{bar}Xe$)

from J.Cugnon *et al.,* NP, **A587**, 596 (1995).

- The observed double strangeness yield is explained by conventional processes described by the intranuclear cascade model, as listed in the following tables.

- They also show the B=2 annihilations, described with the help of the statistical model, are largely able to account for the observed yield: i.e., the branching ratio of the $\Lambda\Lambda$KK state in p^{bar}-NNN annihilation is equal to ~10^{-4} at rest (B=1 annihilations are not so helpful).

- However they claim the frequency of even B=1 annihilation is of the order of 3-5% at the most [J.Cugnon *et al*., NP, **A517**, 533 (1990).] (is it common knowledge ?), so they conclude it would be doubtful to attempt a fit of the data with a mixture of B=0 and 2 annihilations.

On the other hand, the Crystal Barrel collaboration @ CERN/LEAR concludes their $p^{bar}d \rightarrow \Lambda K^0/\Sigma^0 K^0$ measurements disagree strongly with conventional two-step model predictions and support the statistical (fireball) model.

Table 2
Possible double strangeness production processes in $B = 0$ $(\overline{N}N)$ annihilations on a nucleus

Channel	Threshold E_{cm}, p_{lab}	Primordial state	Secondary reaction	Strange content of the final state
1	1.975, 0.646	$KK\overline{K}\overline{K}$	–	$KK\overline{K}\overline{K}$
			B	$KK\overline{K}Y$
			B+B	$KKYY$
2		$K\overline{K}m$	A	$KK\overline{K}Y$
			A+B	$KKYY$
3		m	A+A	$KKYY$
4		$\overline{K}^{\star}Km$	A	$KK\overline{K}Y$
		$K^{\star}\overline{K}m$	A+B	$KKYY$
		$\overline{K}^{\star}K^{\star}m$	C	$KKYY$
5	2.039, 0.866	$\phi\phi$	–	$KK\overline{K}\overline{K}$
			D	$KK\overline{K}Y$
			D+D	$KKYY$
6		$\omega\omega$		
		$\omega\eta$	A+A	$KKYY$
		$\omega\eta'$		

Table 3
Estimate of the various double strangeness yields in $\overline{p}$Xe annihilations at antiproton momenta 0–0.4 GeV/c. The channel numbers in first row correspond to the mechanism indicated in Table 2

Channel	$KK\overline{K}\overline{K}$	$KK\overline{K}\Lambda$	$KK\Lambda\Lambda$	ΞKK
1	–	–	–	
2		1.6×10^{-4}	3.18×10^{-5}	
3	–	–	1.29×10^{-7}	
4	–	–	4.4×10^{-5}	1.9×10^{-4}
5	–	–	–	
6	–	–	3.1×10^{-6}	
total		1.6×10^{-4}	7.9×10^{-5}	1.9×10^{-4}

Table 6
Comparison of the data from Ref. [20] with our predictions. All numbers are multiplied by 10^4

Momentum	K^+K^+X		$K^+K^0\Lambda X$		Total DS
(GeV/c)	exp.	calc.	exp.	calc.	calc.
0–0.4	0.25 ± 0.14	0.16	1.2 ± 0.8	1.59	4.3
0.4–0.65	0.32 ± 0.16	0.19	2.5 ± 1.4	1.76	4.7
0.65–0.9	0.5 ± 0.4	0.22	2.5 ± 1.4	1.9	5.2

experimental values are not final values of the DIANA data

Crystal Barrel ('86~'96) [Phys. Lett., **B469**, 276 (1999).]

- $p^{bar}{}^{4}He$ annihilation
- stopped p^{bar} @ CERN/LEAR
- liquid deuteron target
- cylindrical spectrometer w/ B-field
- SVX, CDC, CsI crystals
- ~10^6 events of 2/4-prong with topological triggers

$$Br(\bar{p}d \to \Lambda K^0) = (2.35 \pm 0.45) \times 10^{-6}$$
$$Br(\bar{p}d \to \Sigma^0 K^0) = (2.15 \pm 0.45) \times 10^{-6}$$
$$Br(\bar{p}d \to p\pi^-) = (1.3 \pm 1.0) \times 10^{-5}$$

Table 1
Observed event numbers after background subtraction, deduced $\bar{p}d$ annihilation rates at rest ("branching ratios" BR) and relative branching ratios $R_{\Sigma^0\Lambda} = BR(\Sigma^0 K^0)/BR(\Lambda K^0)$. The first errors give the statistical uncertainties (1 σ), the second the systematic uncertainties

Channel	Observed mode	Events	BR [10^{-6}]
ΛK^0_L	$\Lambda \to p\pi^-$, K^0_L(noninteracting)	$107 \pm 11 \pm 6$	$1.1 \pm 0.1 \pm 0.2$
$\Sigma^0 K^0_L$	$\Sigma^0 \to \Lambda\gamma$, $\Lambda \to p\pi^-$, K^0_L(noninteracting)	$83 \pm 10 \pm 9$	$1.0 \pm 0.1 \pm 0.2$
			$R_{\Sigma^0\Lambda} = 0.90 \pm 0.13 \pm 0.13$
ΛK^0_S	$\Lambda \to p\pi^-$, $K^0_S \to \pi^+\pi^-$	$85 \pm 10 \pm 10$	$1.6 \pm 0.3 \pm 0.5$
$\Sigma^0 K^0_S$	$\Sigma^0 \to \Lambda\gamma$, $\Lambda \to p\pi^-$, $K^0_S \to \pi^+\pi^-$	$61 \pm 8 \pm 5$	$1.5 \pm 0.2 \pm 0.5$
			$R_{\Sigma^0\Lambda} = 0.95 \pm 0.17 \pm 0.16$

Table 2
Comparison of experimental results and predictions of dynamical and statistical models

	Experimental	Dynamical model		Statistical model
		Ref. [2]	Ref. [4]	Ref. [6]
(i) Absolute $\bar{p}d$ branching ratios (BR) [10^{-6}]				
ΛK^0	2.35 ± 0.45 [a]	0.3		$1.0 \times P_{B=1}$ [c]
$\Sigma^0 K^0$	2.15 ± 0.45 [a]	0.004	0.01–0.025	$1.0 \times P_{B=1}$ [c]
$p\pi^-$	13.0 ± 1.0 [b]	2–6	38	$4.7 \times P_{B=1}$ [c]
(ii) Relative branching ratios $R_{\Sigma^0\Lambda} = BR(\Sigma^0 K^0)/BR(\Lambda K^0)$				
	0.92 ± 0.15 [a]	0.012		1.0

[a] Weighted average of the results in Table 1 with quadratically added statistical and systematic errors.
[b] Weighted average of the results of Refs. [9,10], applying charge independence to the $n\pi^0$ result [10].
[c] Total probability [%] of forming a fireball with baryon number $B = 1$. Estimates yield $P_{B=1} \lesssim 10\%$ (Ref. [6]).

support the statistical model

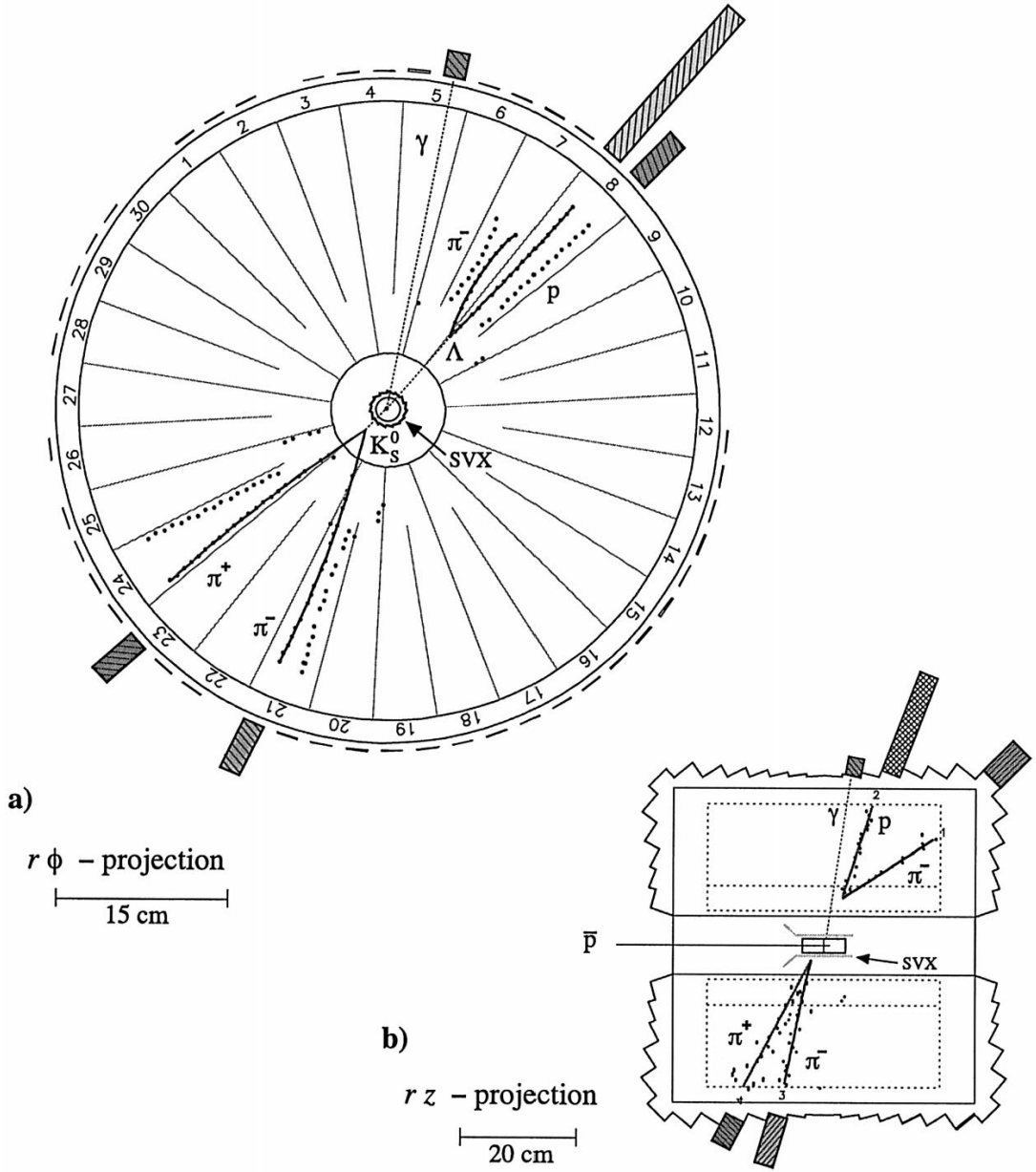


Fig. 1. Event of the Pontecorvo type, selected from the data set. With the charged-particle multiplicities 0 in the SVX and 4 in the drift chamber, it shows the complete signature of a $\bar{p}d \rightarrow \Sigma^0 K^0_S (\Sigma^0 \rightarrow \Lambda\gamma,\ \Lambda \rightarrow p\pi^-,\ K^0_S \rightarrow \pi^+\pi^-)$ event in the transverse (a) as well as in the longitudinal projections (b). The apparent left-right ambiguity of hits in the drift chamber is resolved (full line trajectories) by the sense wire staggering [13]. Clockwise and anticlockwise curvatures in (a) correspond to negative and positive charges, respectively. Energy deposits in the barrel-shaped electromagnetic calorimeter are represented by bars of proportional lengths.

OBELIX ('86~'96) [Nucl. Phys., **A797**, 109 (2007).]

- $p^{bar}{}^4He$ annihilation
- stopped p^{bar} @ CERN/LEAR
- gas target (^4He@NTP, H_2@3atm)
- cylindrical spectrometer w/ B-field
- spiral projection chamber, scintillator barrels, jet-drift chambers
- 238,746/47,299 events of 4/5-prong in ^4He
- p_{min} = 100/150/300MeV/c for π/K/p

$\bar{p}\,^4He$ ** (xx) is not observed*

4-prong $\rightarrow K^+K^+\Sigma^-\Sigma^- p_s \rightarrow K^+K^+\pi^-\pi^-(nnp_s)$

34+/-8 events → (0.17+/-0.04)x10^{-4}

5-prong $\rightarrow K^+K^+\Sigma^-\Sigma^+ n\pi^- \rightarrow K^+K^+\pi^+\pi^-\pi^-(nnn)$

36+/-6 events → (2.71+/-0.47)x10^{-4}

5-prong $\rightarrow K^+K^+\Sigma^-\Lambda n \rightarrow K^+K^+ p\pi^-\pi^-(nn)$

16+/-4 events → (1.21+/-0.29)x10^{-4}

5-prong $\rightarrow K^+K^+K^-\Lambda nn \rightarrow K^+K^+K^- p\pi^-(nn)$

4+/-2 events → (0.28+/-0.14)x10^{-4}

they discuss the possibility of formation and decay of K^-K^-nn and K^-K^-pnn bound system