The New Stage of S=−2 Hypernuclear Study Opened with a New High-resolution Spectrometer

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INPC 2016, Adelaide
12 September 2016

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Contents

- Introduction
  - Motivation of hypernuclear physics
  - Previous experiments
- Spectroscopy of Ξ-hypernuclei at J-PARC
  - Experimental setup
  - Future extension
- Status of new spectrometer
  - Design
  - Magnet construction and field measurement
- Summary

Introduction

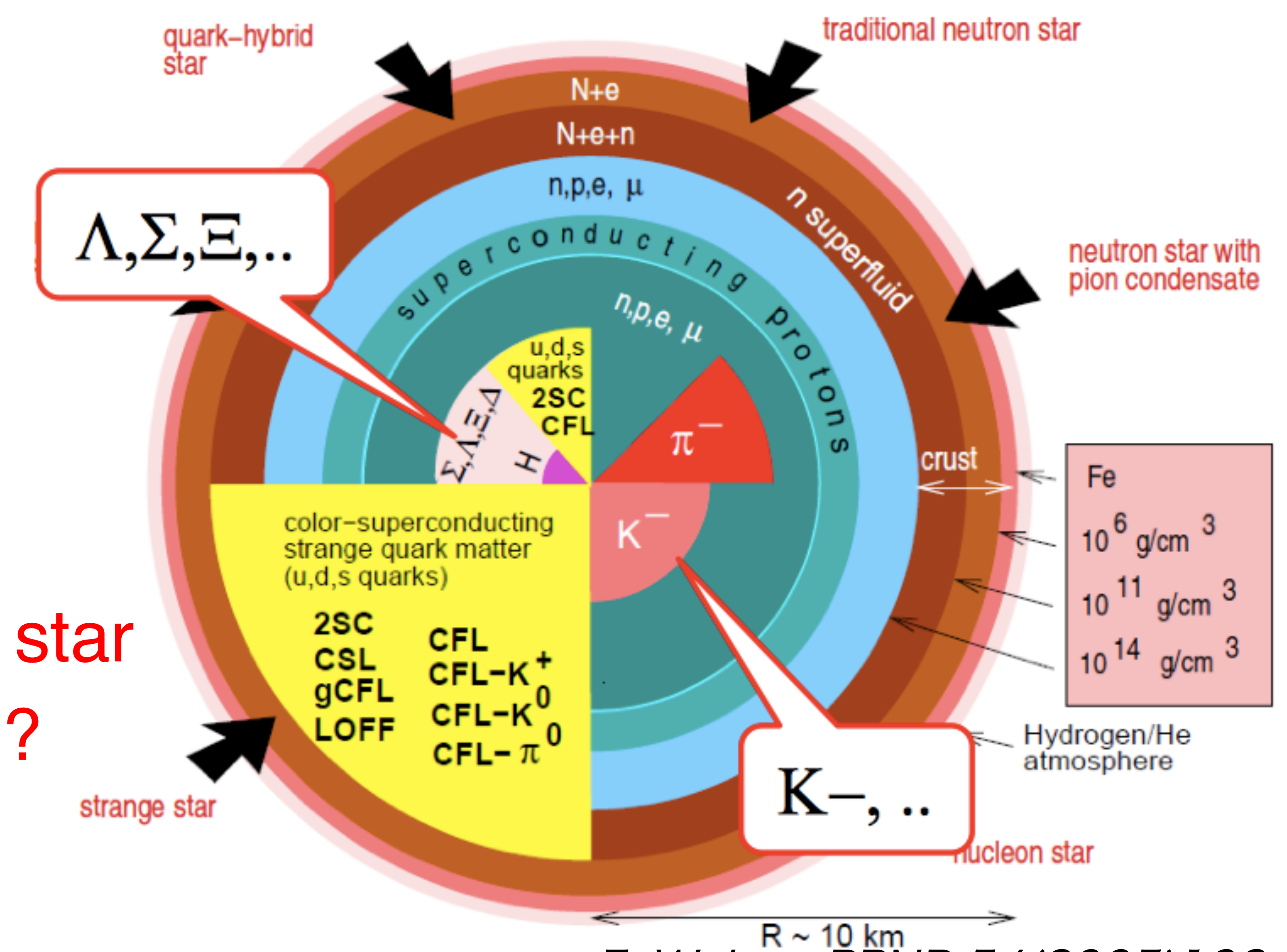
Motivation

- Baryon-baryon interaction in $SU_f(3)$
- Role of strangeness in dense nuclear matter

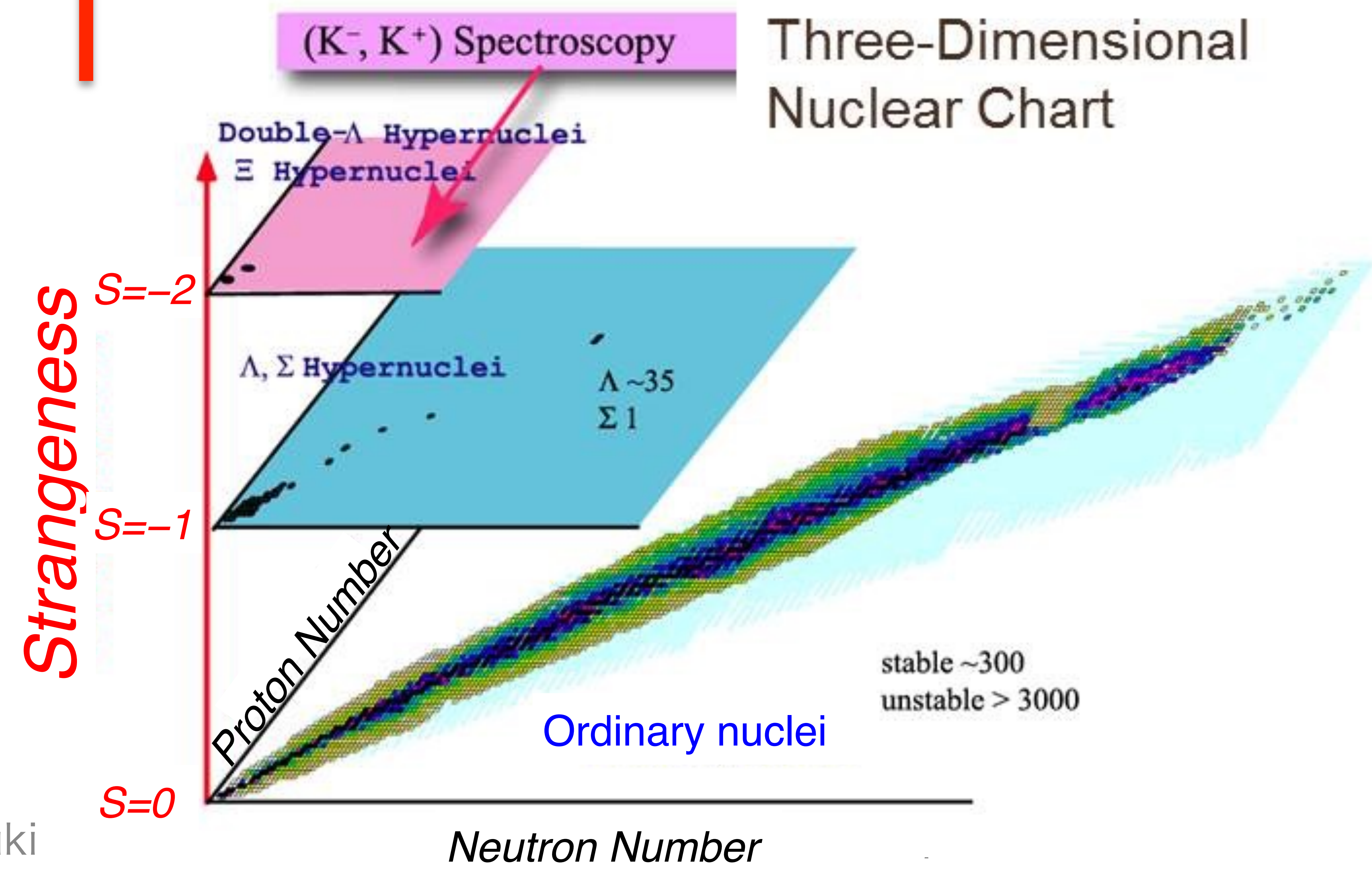
NN force → generalization → *BB* force

- S=−2 Ξ, ΛΛ
  - a few emulsion events
  - limited information
- S=−1 Λ, Σ
  - hypernuclear structure
    - (K^-, π^-), (π^+, K^+), (e,e'K^+) etc
    - γ-ray spectroscopy
  - → effective Λ*N*, Σ*N* interactions
- S= 0 *p*, *n*
  - a lot of *NN* scattering data
  - → realistic nuclear force

Core of neutron star
S=−∞ ??



F. Weber, PPNP 54(2005)193



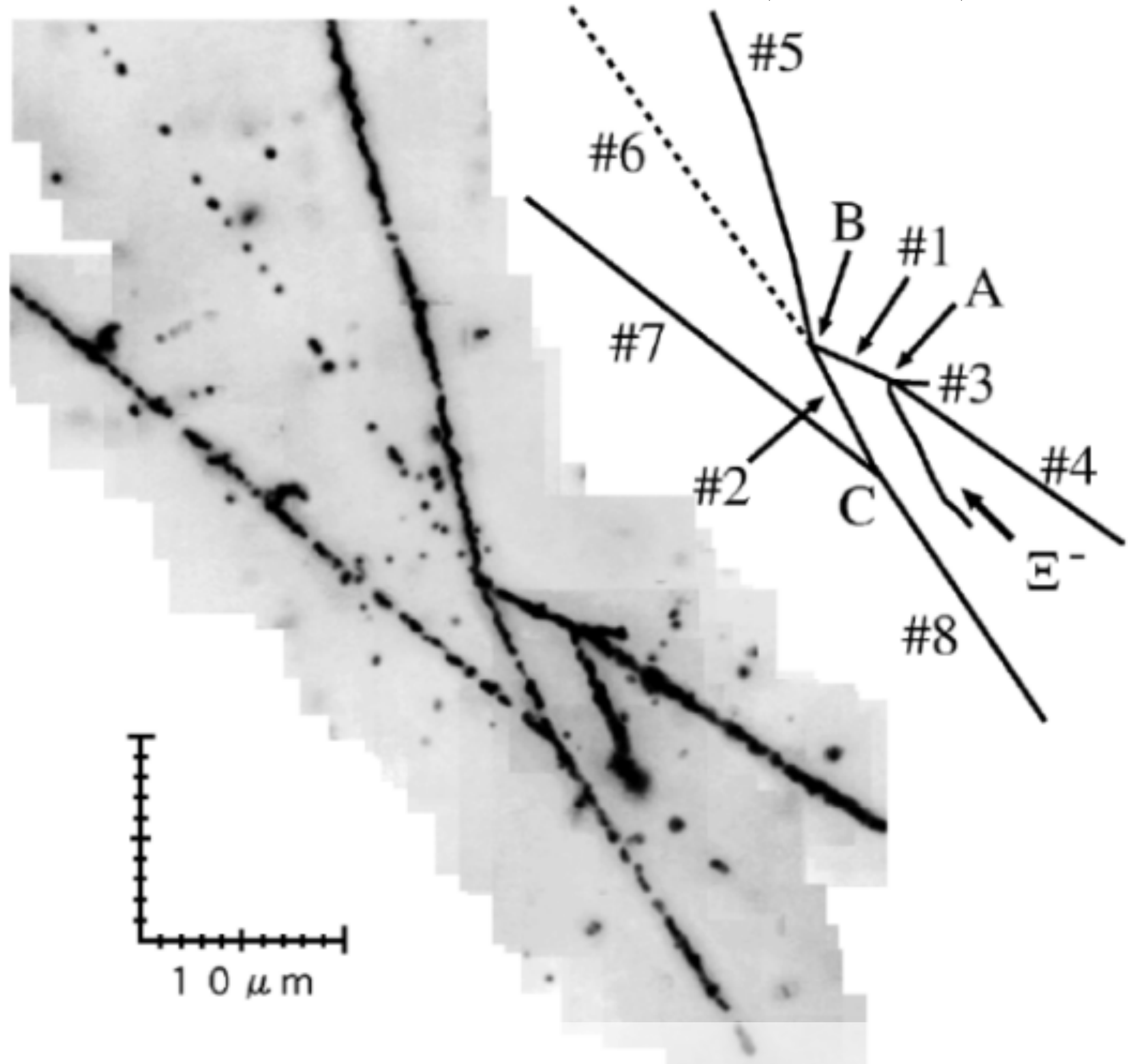
Emulsion Experiment

KEK-E373

- "NAGARA" event
  - uniquely identified as ${}_{\Lambda\Lambda}{}^{6}$He
  - $\Delta B_{\Lambda\Lambda}$ = 0.67 ± 0.17 MeV
    weakly attractive

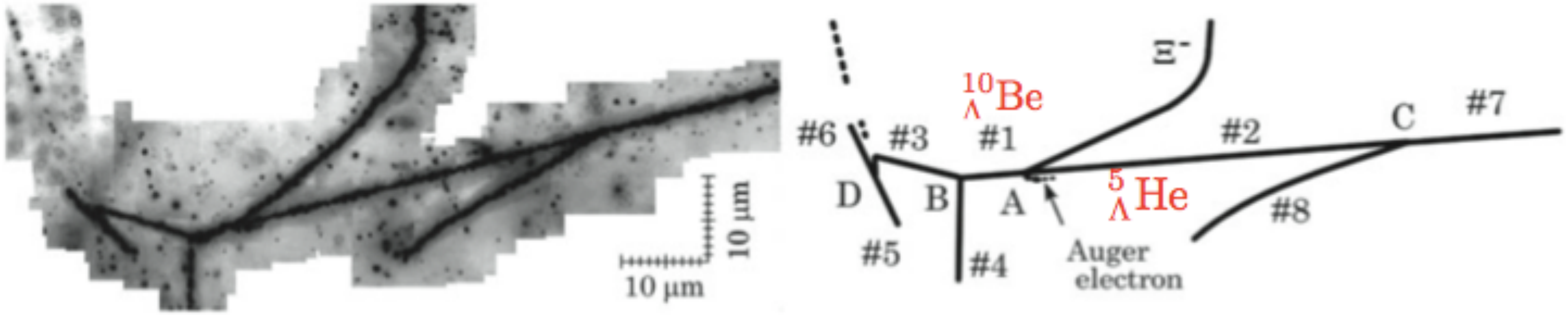
J.K. Ahn et al., PRC 88 (2013) 014003

H. Takahashi et al., PRL 87 (2001) 212502



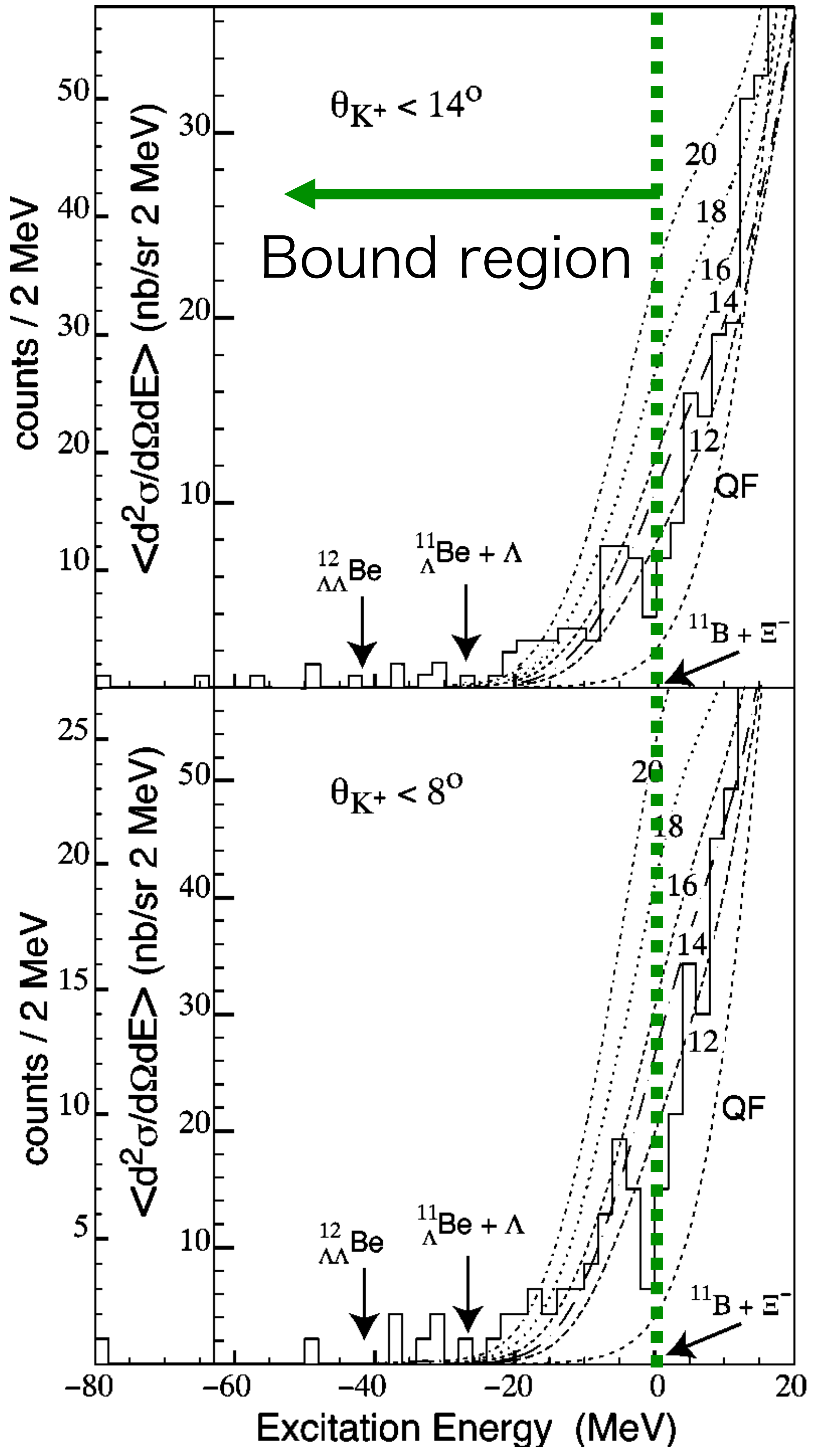
- "KISO" event
  - Ξ-^{14}N system
  - $\Xi^{-}+{}^{14}N \rightarrow {}^{10}_{\Lambda}Be + {}^{5}_{\Lambda}He$
  - B_{Ξ}=1.11 or 4.38 (±0.25) MeV **±$\Gamma_{conv.}$/2**

S=−2 hypernuclei do exist !
→ systematic study



K. Nakazawa et al., PTEP (2015) 3, 033D02

Spectroscopic Study



P. Khaustov et al., PRC 61 (2000) 054603

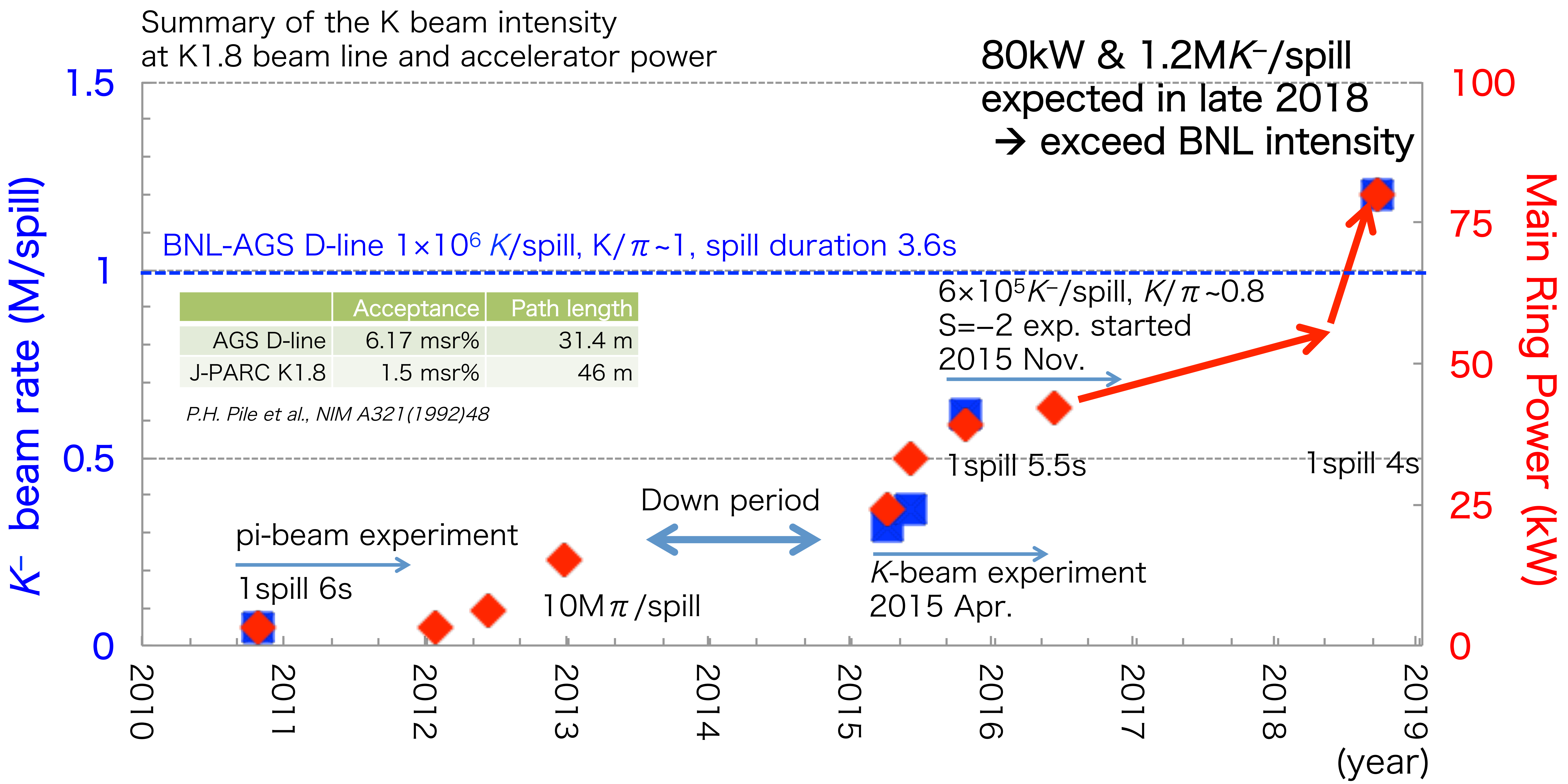
BNL-E885 : ^{12}C(K^-,K^+) at 1.8 GeV/c

- missing-mass spectroscopy
- dσ/dΩ (–20 < E < 0 MeV)
  - θ<14°: 67 events, 42±5 nb/sr
  - θ<8°: 42 events, 89±14 nb/sr
  - “evidence” of existence of Ξ bound state
- mass resolution 14 MeV_{FWHM}
  - no clear peak
  - shape analysis → V_{Ξ} ~ –14 MeV ?

Better resolution and more statistics → J-PARC

Spectroscopy Experiment at J-PARC

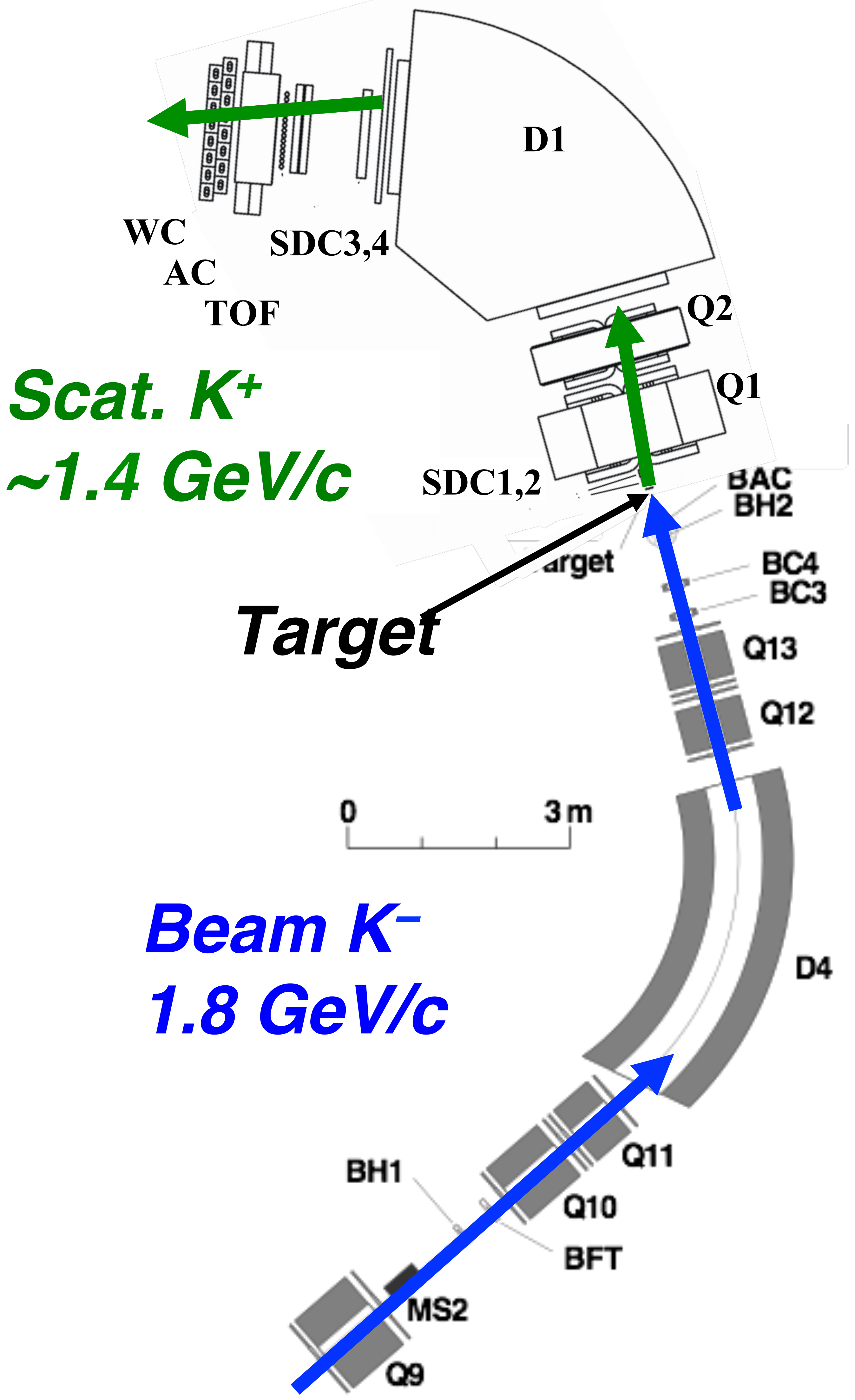
Beam Intensity at J-PARC



	Acceptance	Path length
AGS D-line	6.17 msr%	31.4 m
J-PARC K1.8	1.5 msr%	46 m

J-PARC E05 Experiment

[S–2S spectrometer]



[Beam spectrometer]

Missing-mass spectroscopy of Ξ-hypernucleus via the $^{12}C(K^-, K^+)^{12}{}_{\Xi}Be$ reaction (Nagae et al.)

- observe peaks of the bound state
  - much improved mass resolution of <2 MeV
  - deduce the information of ΞN potentials

Pilot measurement: Nov. 2015

- mass resolution ~7 MeV, w/ existing SKS spectrometer
- beam: 6×10^5 K^-/spill (Acc. 39kW) K/π ~0.8

Spectrometers

- K^- : Beam spectrometer, dp/p<1×10^{-3}
  - already working at K1.8BL
- K^+ : S-2S spectrometer, dp/p 6×10^{-4}
  - newly developed for (K^-, K^+) reaction spectroscopy
  - magnet construction completed in 2015

to be installed in 2018 → high resolution

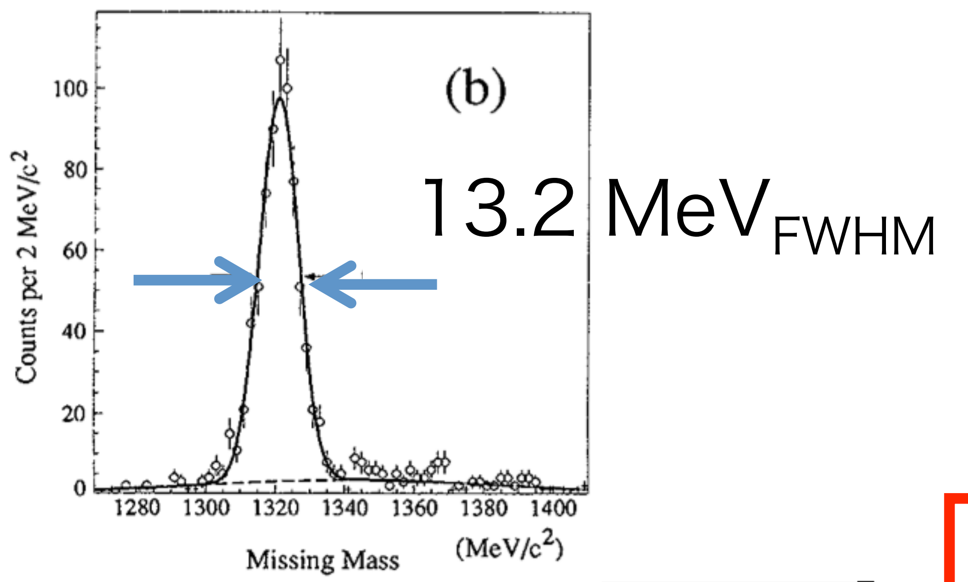
Accelerator power: 80kW in 2018? → enough statistics

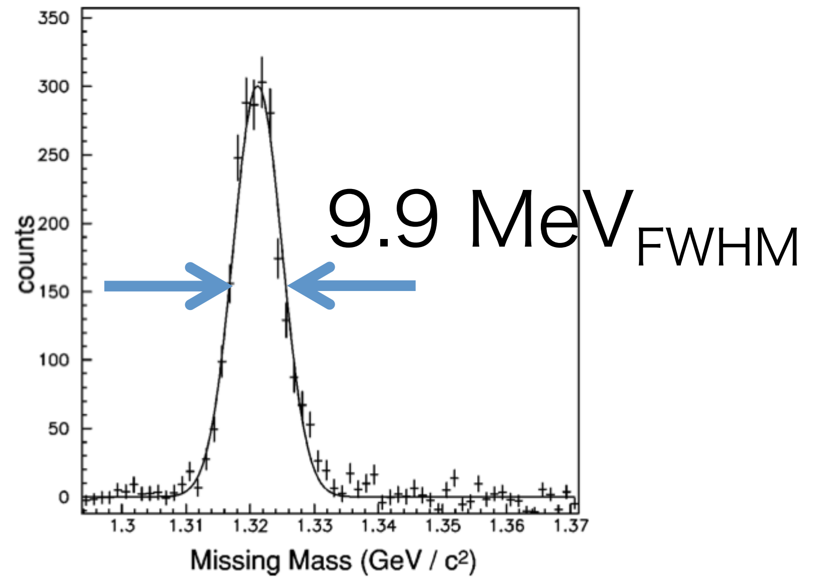
Progress of Mass Resolution

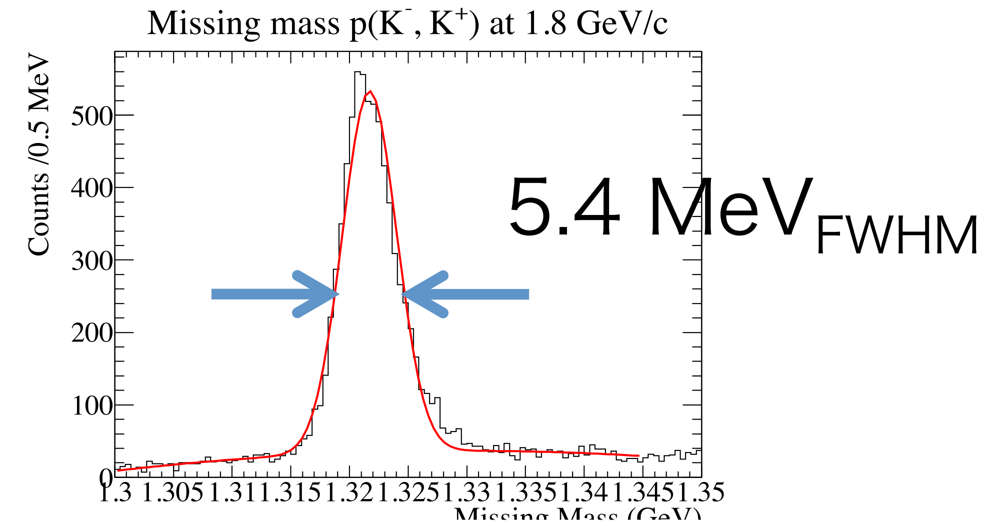
$^{12}C(K^-,K^+)$ experiments	KEK-E224	BNL-E885	J-PARC E05 (pilot run w/ SKS)	J-PARC E05 (S–2S)
ΔΩ (msr)	90	50	110	60
θ (deg)	<12	<14	<16	<8
pK^+ (GeV)	0.9 – 1.7	1.0 – ?	1.1 – 2.4	1.2 – 1.6
ΔM (MeV_{FWHM})	22 →	14 →	7 ⇢	<2

First measurement optimized for MM spectroscopy

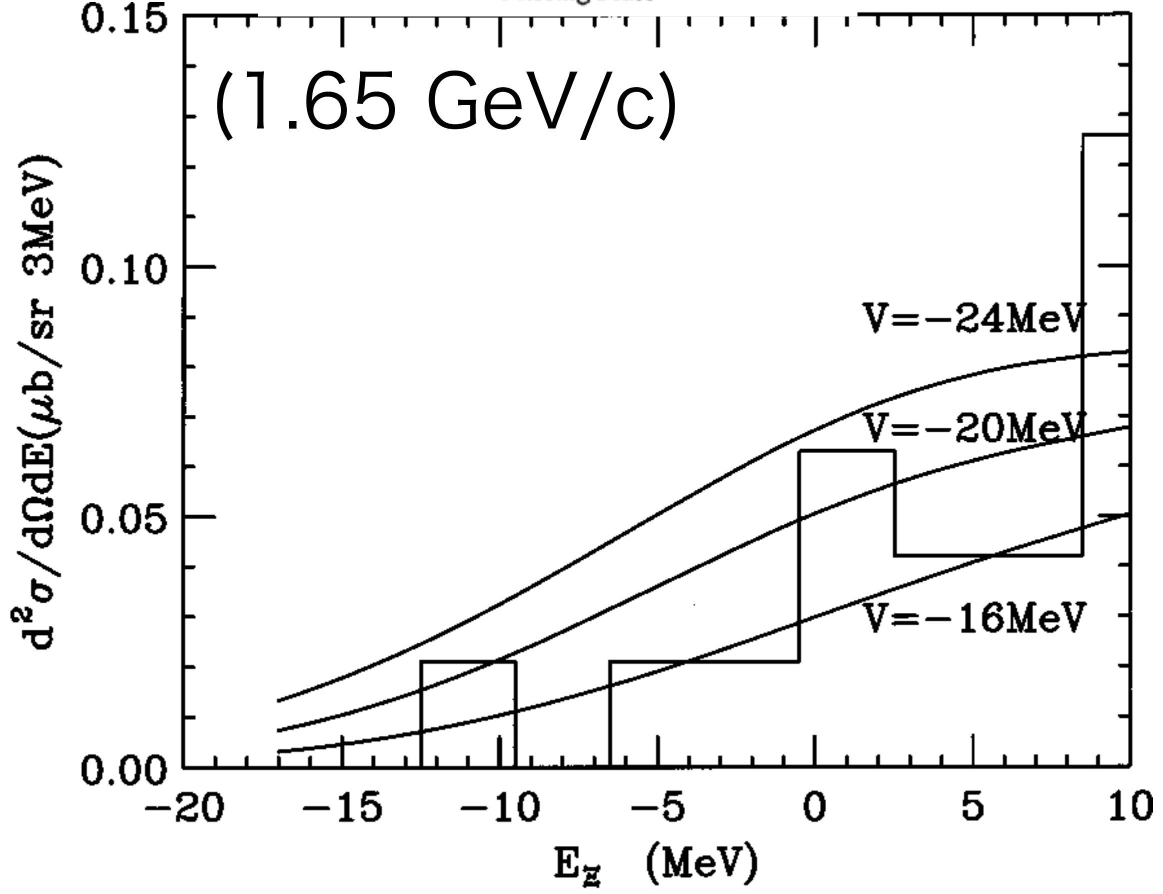
Elementary Ξ^- peak

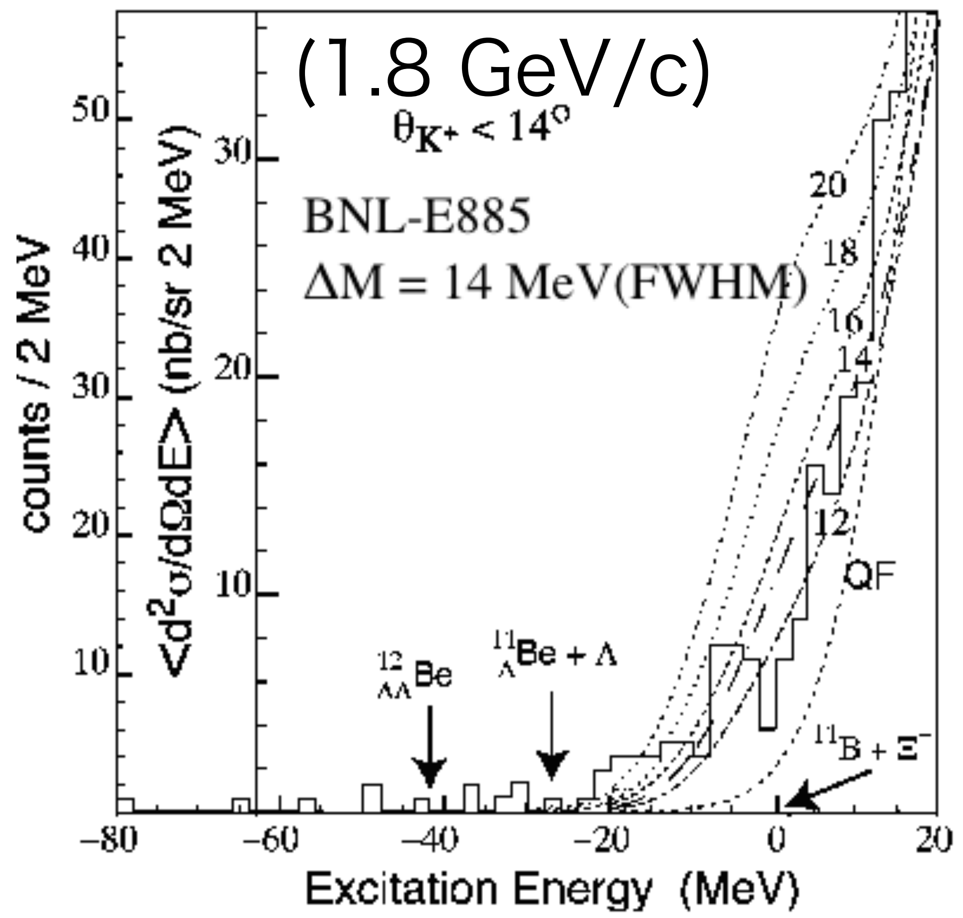


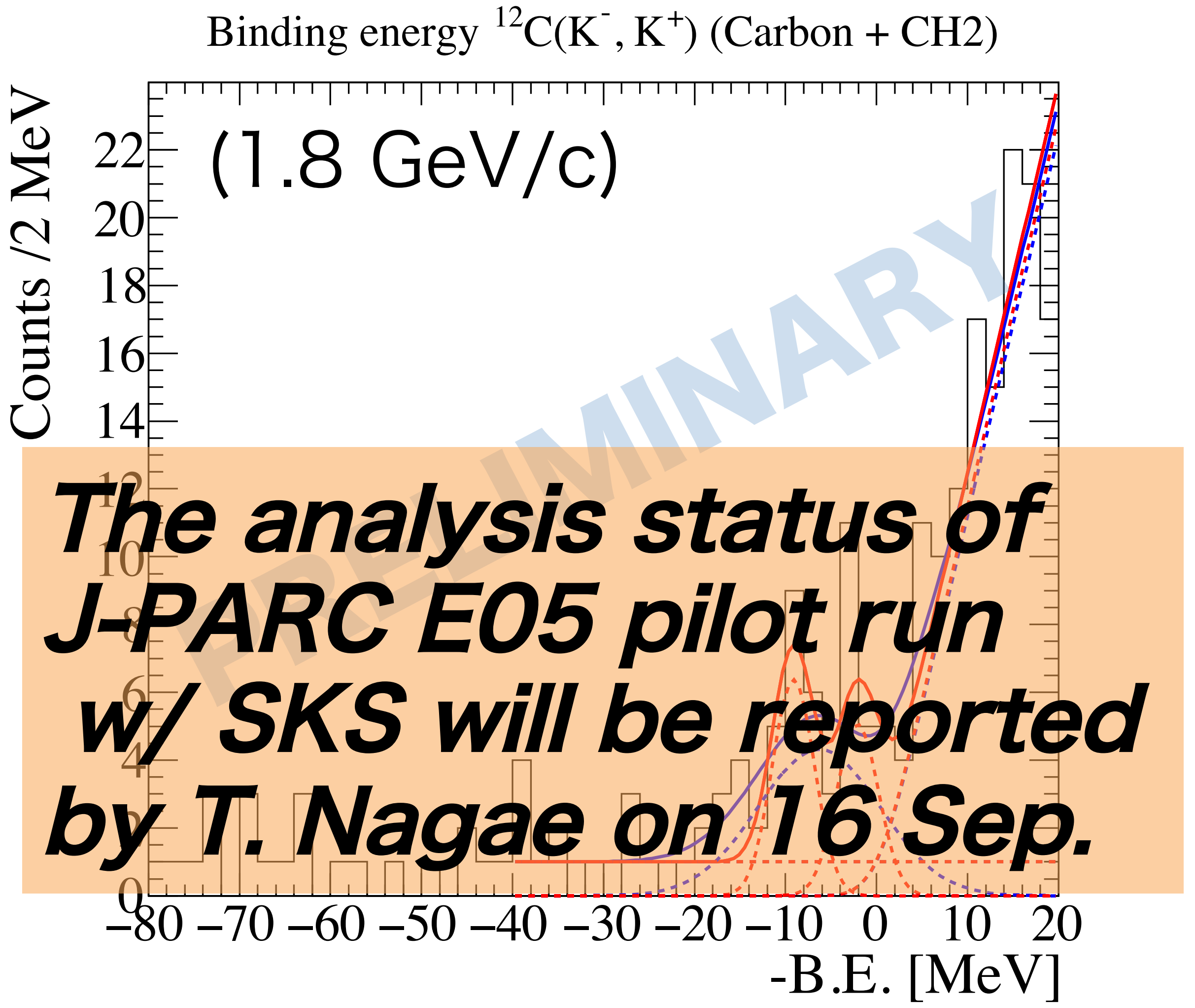




Hypernuclear Spectrum







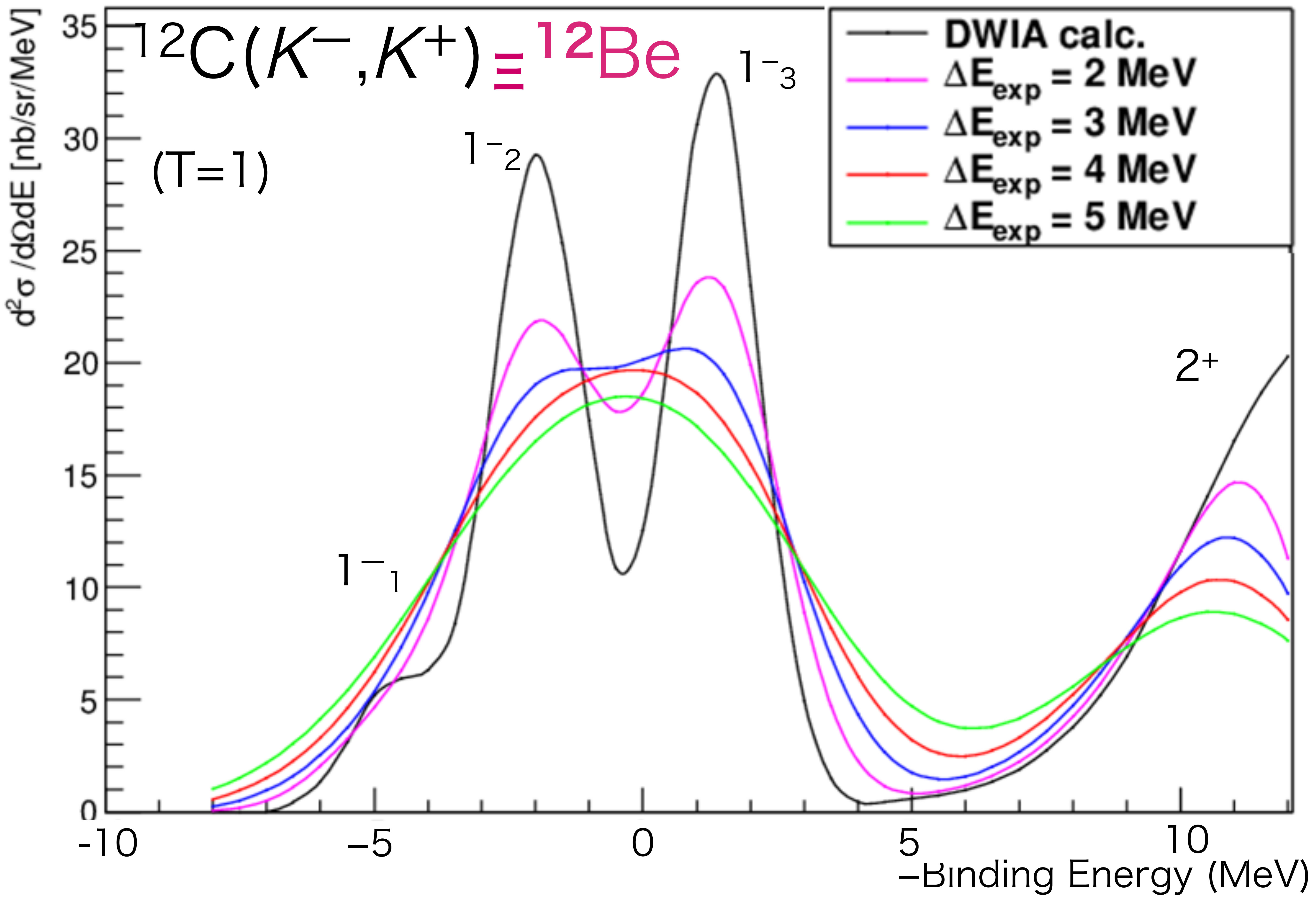
The analysis status of J-PARC E05 pilot run w/ SKS will be reported by T. Nagae on 16 Sep.

T. Fukuda et al., PRC 58 (1998) 1306

P. Khaustov et al., PRC 61 (2000) 054603

Expected Spectrum

- DWIA spectrum for ESC08a interaction
- Nuclear core excitations are taken into account.



Black line: Theoretical calculation
T. Motoba and S. Sugimoto, NPA 835 (2010) 223

Colored line : calculation convoluted with experimental resolution

To resolve these peaks, high energy resolution, ΔE < 2 MeV, is essential

Future Extension

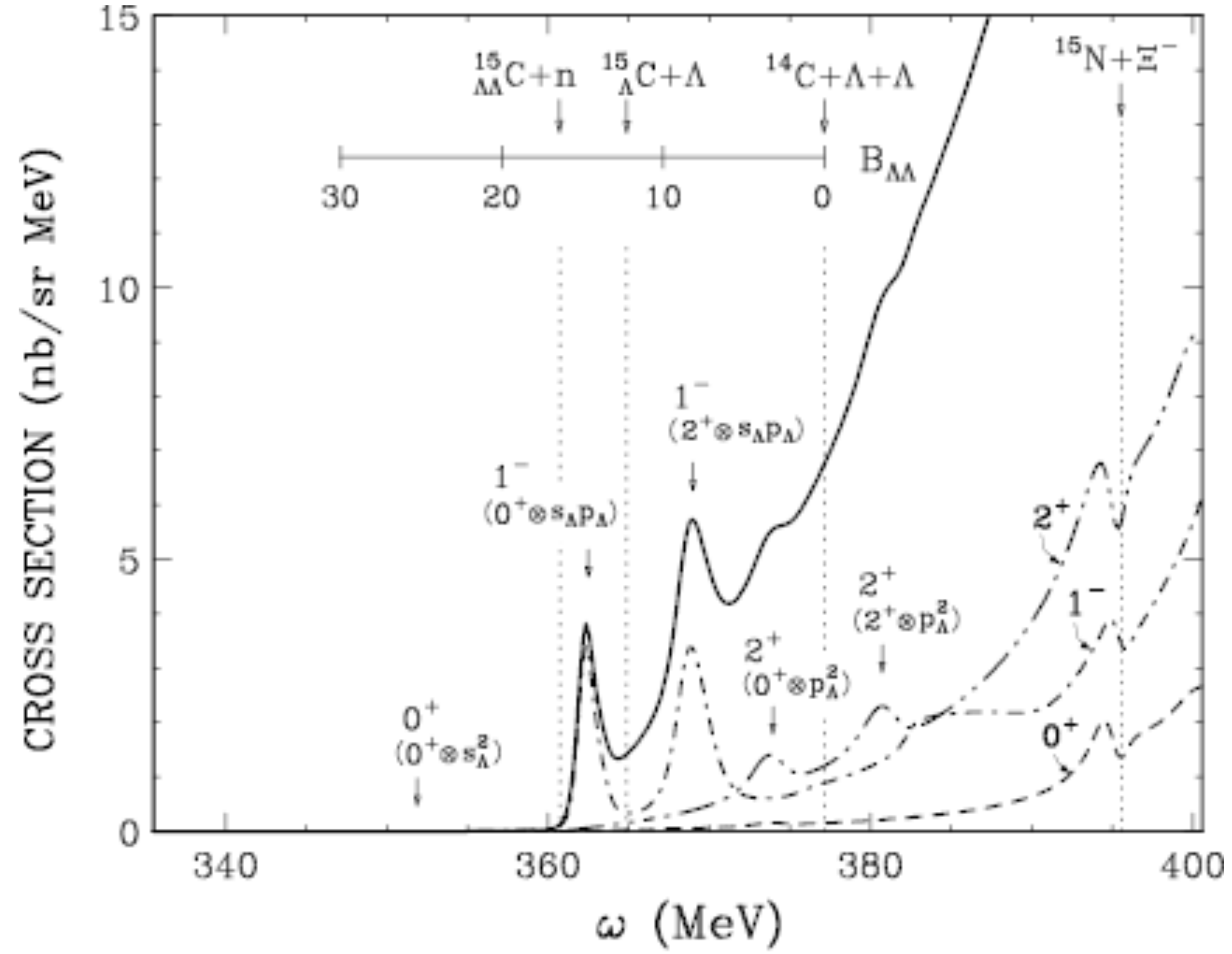
Systematic studies on S=−2 hypernuclei

- Various targets
  - light: ^{7}Li → $_{\Xi}{}^{7}$H($\alpha nn\Xi$), ^{10}B → $_{\Xi}{}^{10}$Li($\alpha\alpha n\Xi$)
    - spin-isospin dependence of ΞN potential
  - heavy: ^{89}Y→$_{\Xi}{}^{89}$Rb, etc.
    - mass dependence

$$V_{\Xi N} = V_0 + \sigma\cdot\sigma V_{\sigma\cdot\sigma} + \tau\cdot\tau V_{\tau\cdot\tau} + (\sigma\cdot\sigma)(\tau\cdot\tau)V_{\sigma\cdot\sigma\tau\cdot\tau}$$

- Double Λ-hypernuclei
  - via Ξ doorway
  - sensitive to ΞN-ΛΛ coupling strength
  - $d\sigma/d\Omega$ is expected to be several nb/sr
  - first measurements of excited states

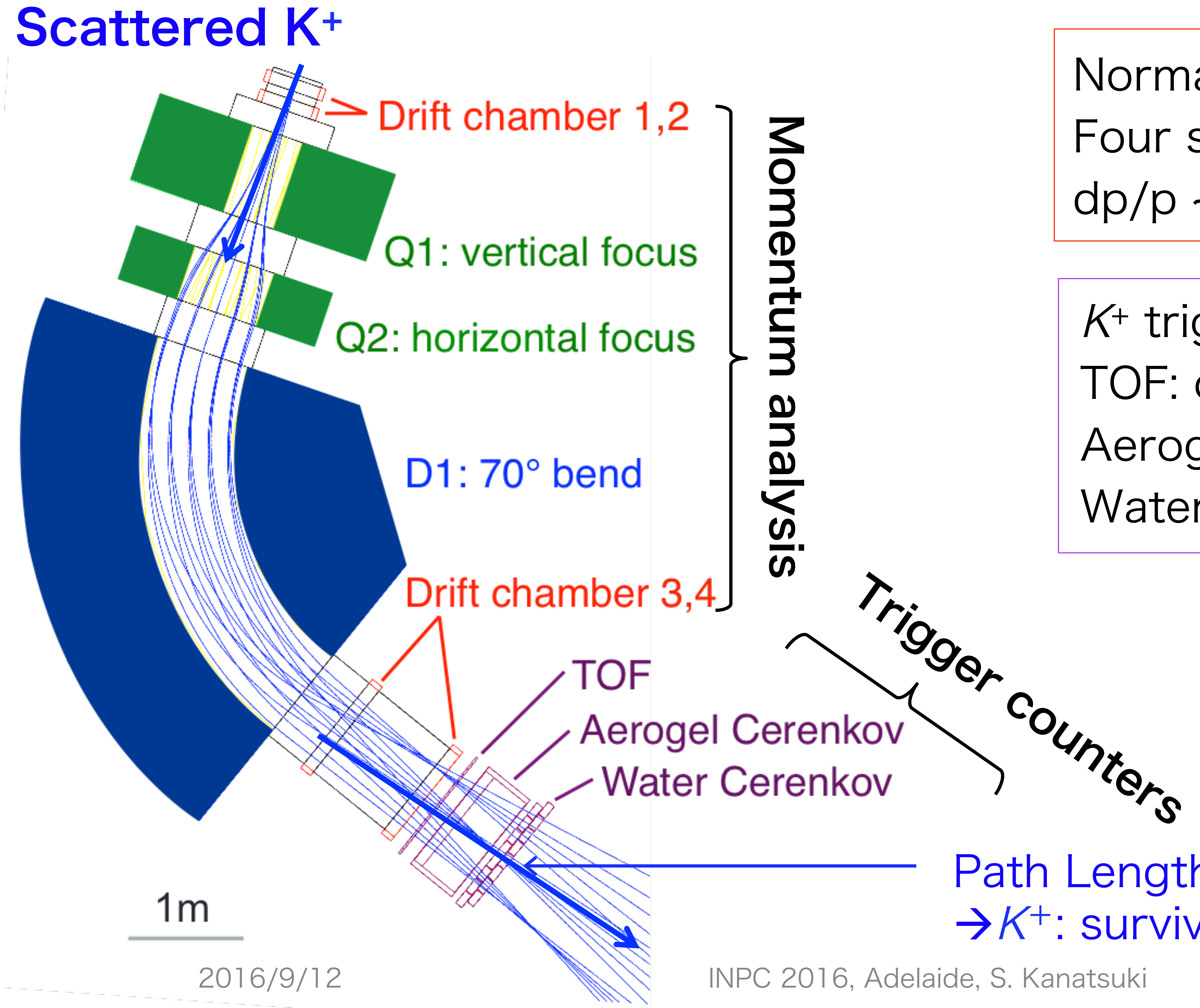
^{16}O(K$^-$, K$^+$) at 0 deg, 1.8 GeV/c



T. Harada et al., PLB 690 (2010) 363–368

S-2S spectrometer

Configuration



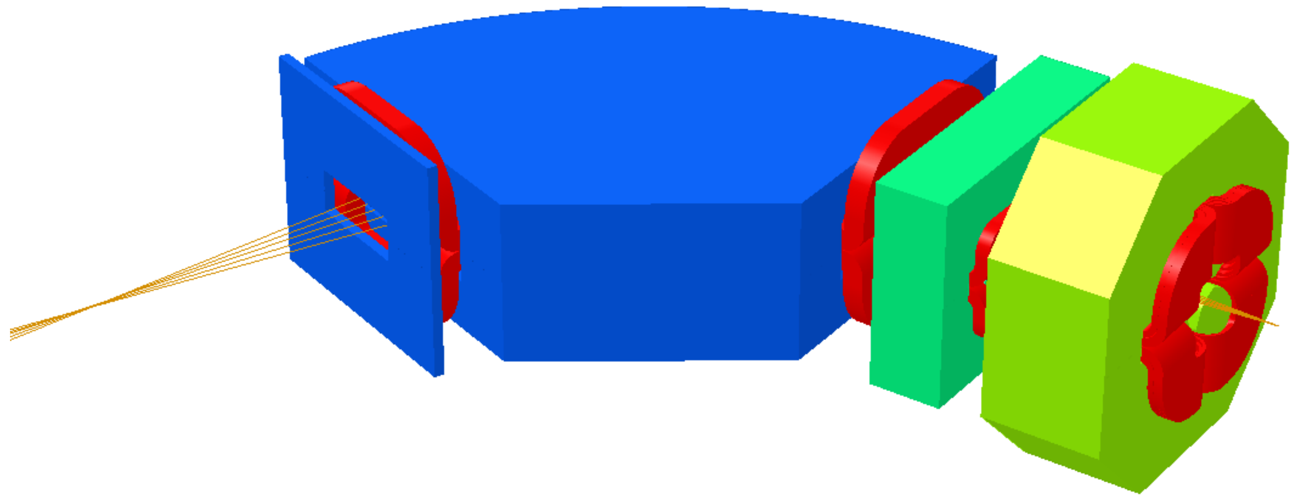
Normal conducting magnets
Four sets of wire chambers
dp/p ~$6\times10^{-4}{}_{FWHM}$, $\Delta\Omega$ 60 msr

K^+ trigger = TOF ∧ $\overline{AC}$ ∧ WC
TOF: off-line particle identification
Aerogel: n=1.06 → Pion veto
Water: n=1.33 → Proton veto

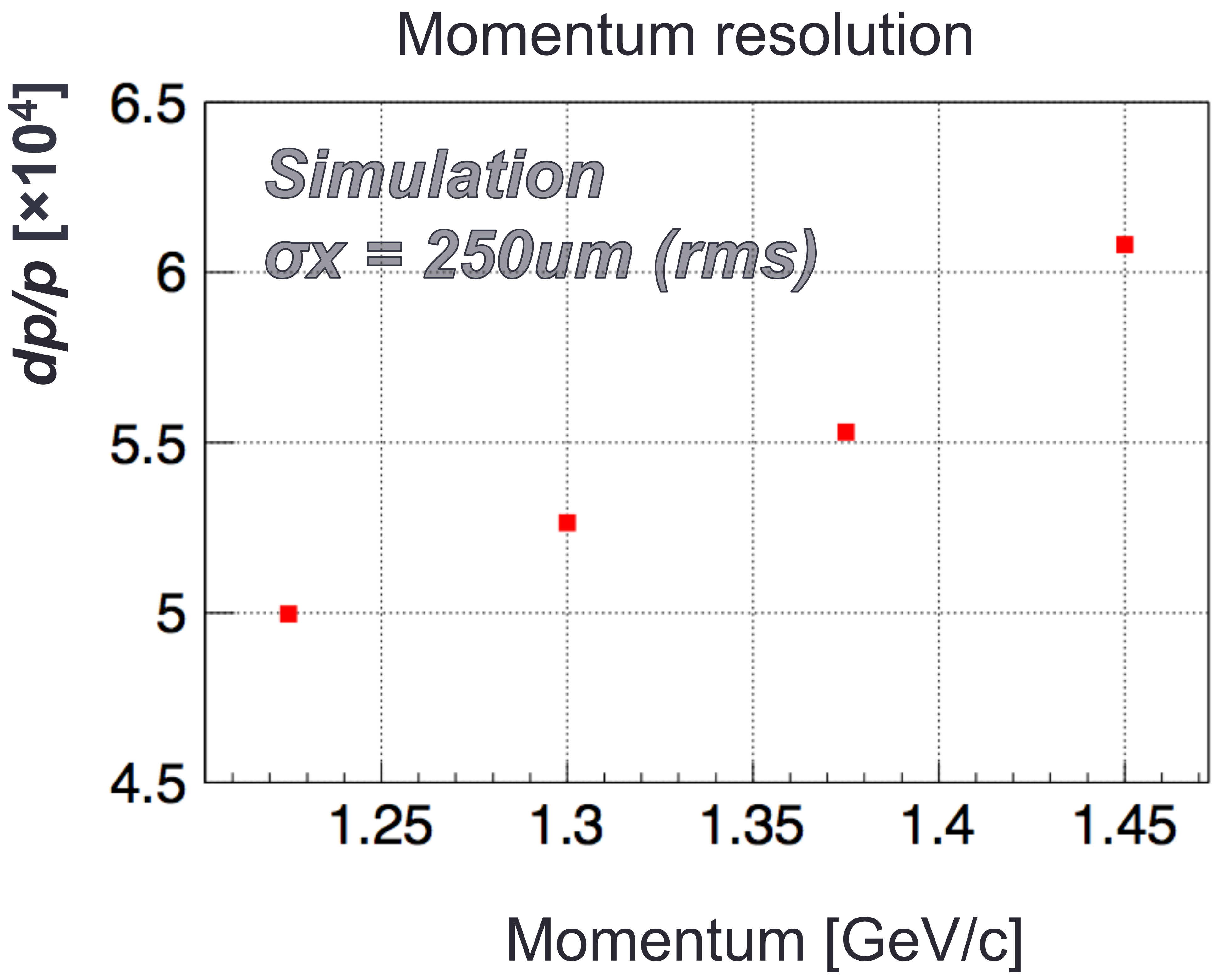
Beam = 10^6 K^-

- π^+, p : 1000
- K^+ : 1

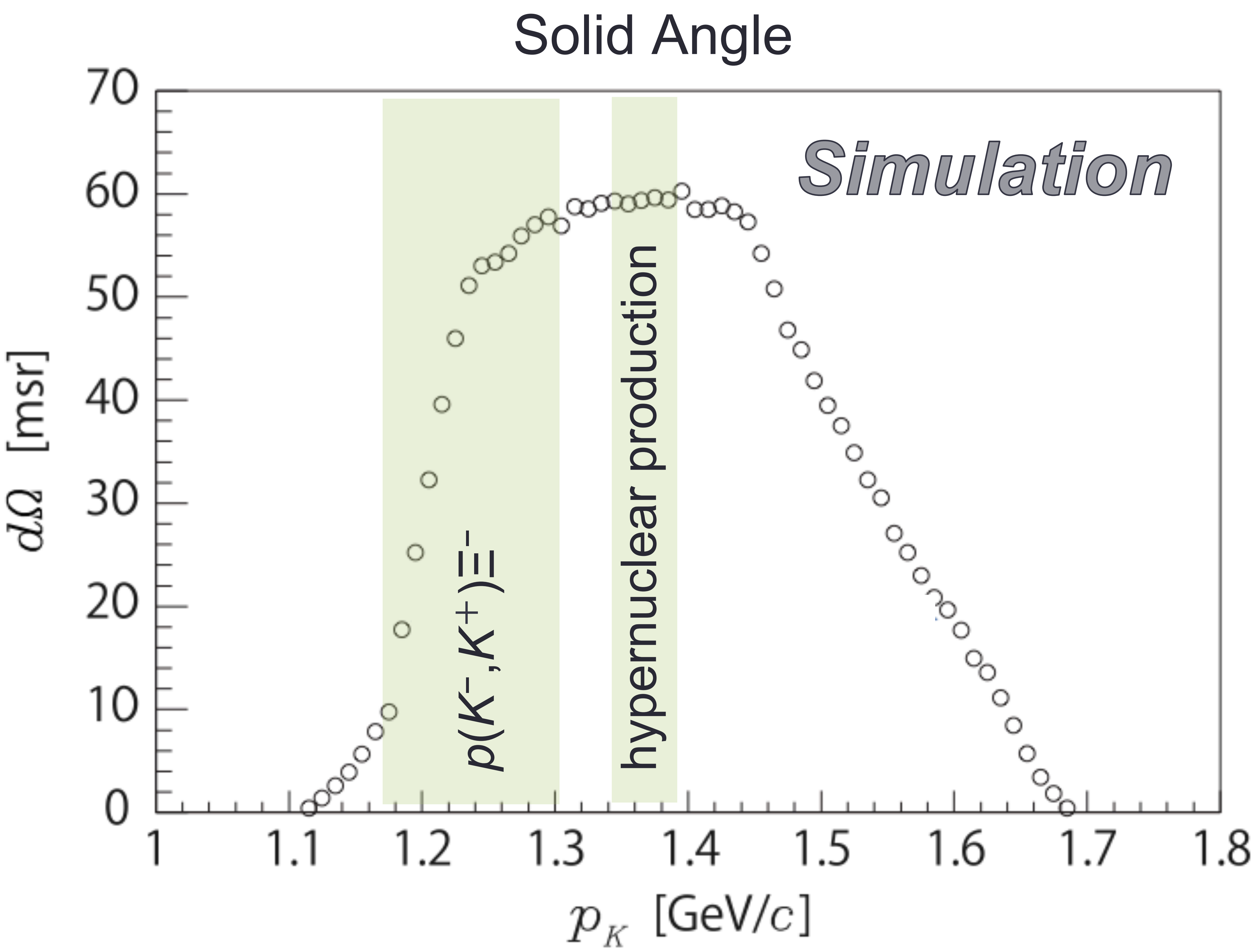
Performance Estimation



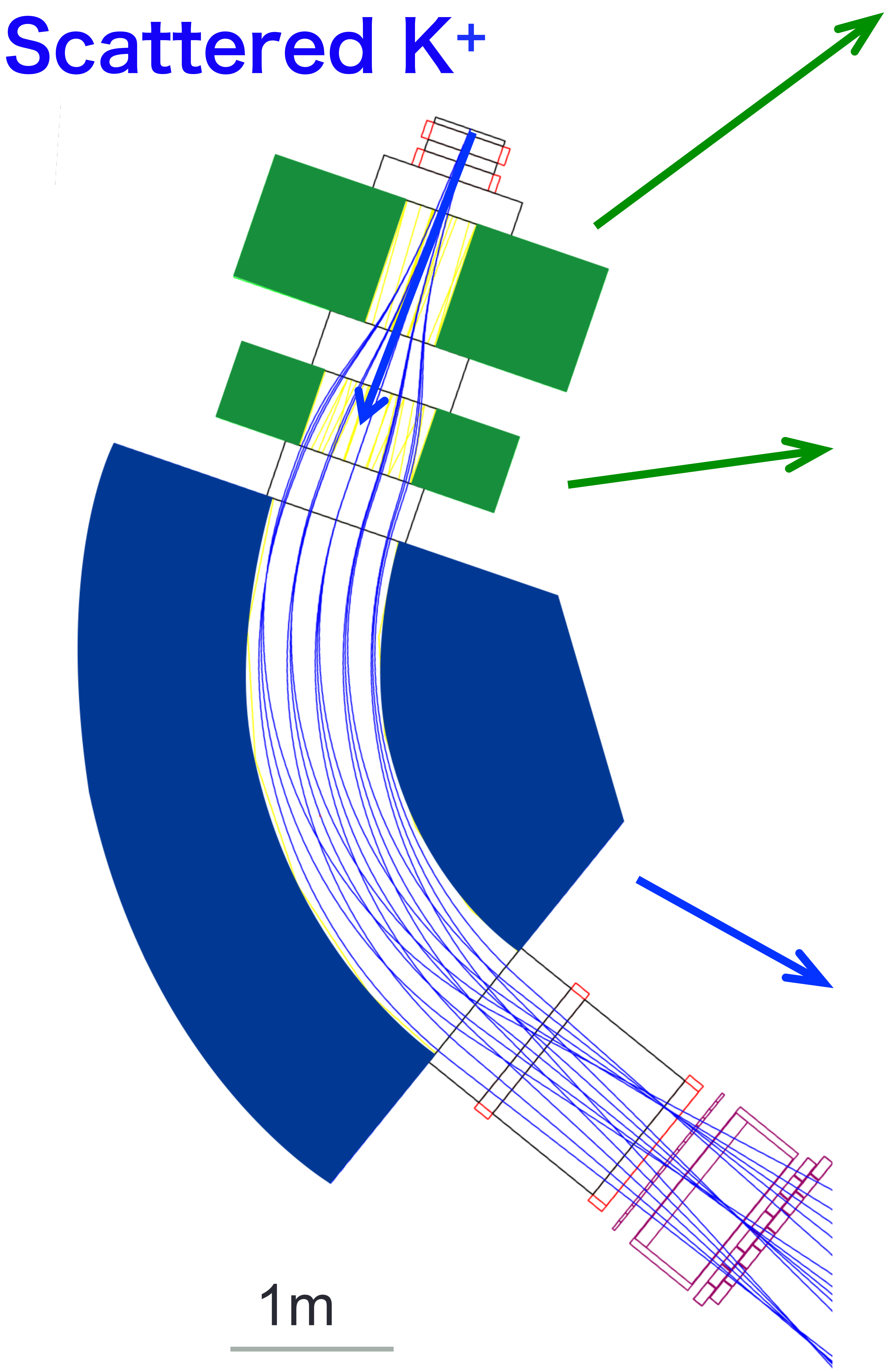
dp/p ~6×10^{-4} (FWHM)



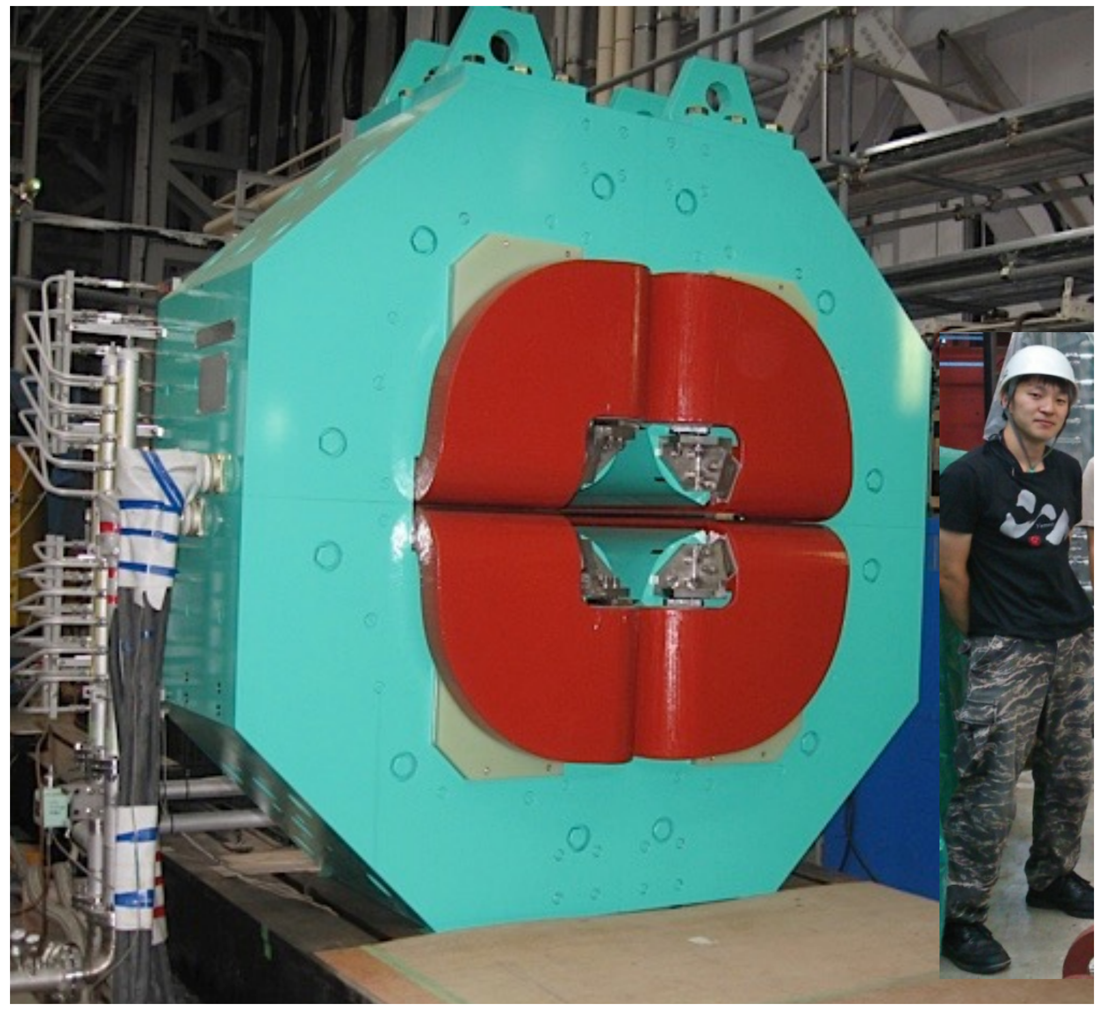
dΩ ~60 msr



Magnets

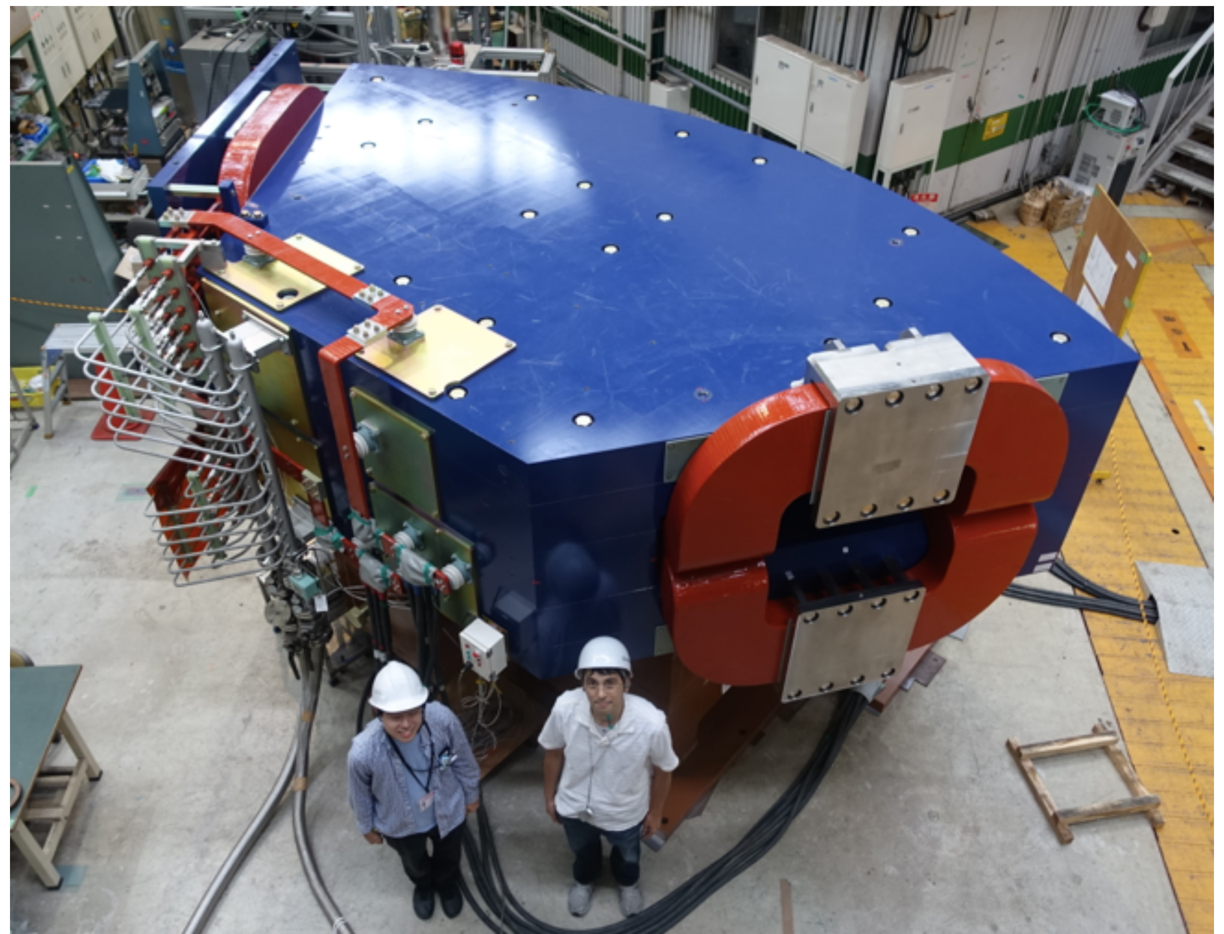


- Q1 (vertical focus)
  - 8.7 T/m
  - aperture 31 cm
  - 37 ton
  - $2.4 \times 2.4 \times 0.88\ m^3$
- Q2 (horizontal focus)
  - 5.0 T/m
  - aperture 36 cm
  - 12 ton
  - $2.1 \times 1.54 \times 0.5\ m^3$
  - renewal one with modification of poles and coils
- D1
  - 1.5 T (70° bend @ 1.37GeV/c)
  - pole gap $32 \times 80\ cm^2$
  - 86 ton
  - central trajectory 3.7 m



2013 Mar

2014 Mar

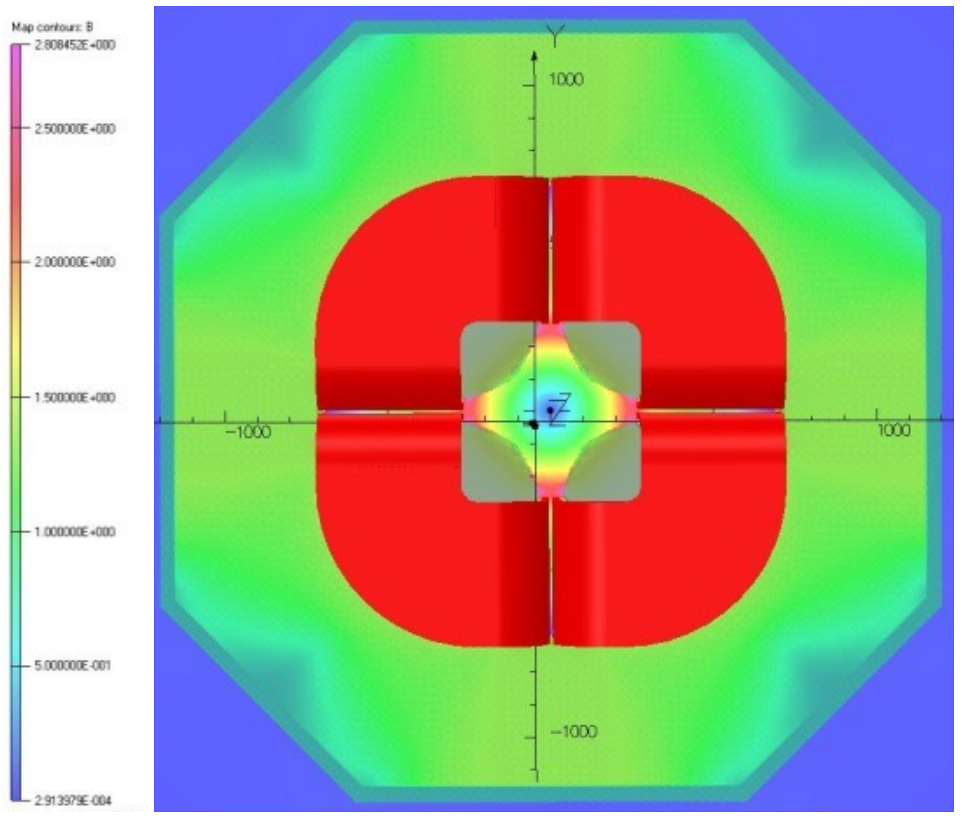


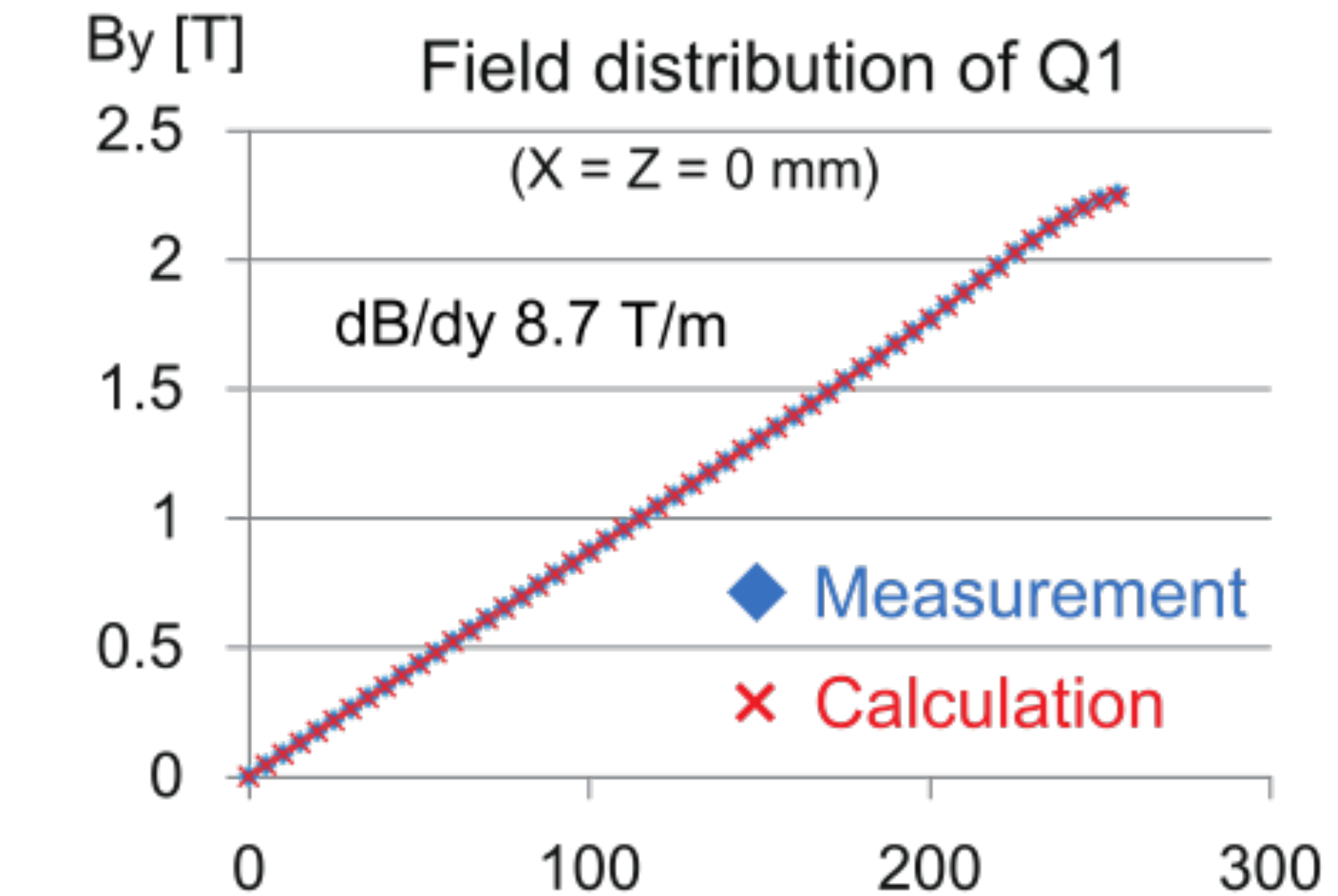
2015 May

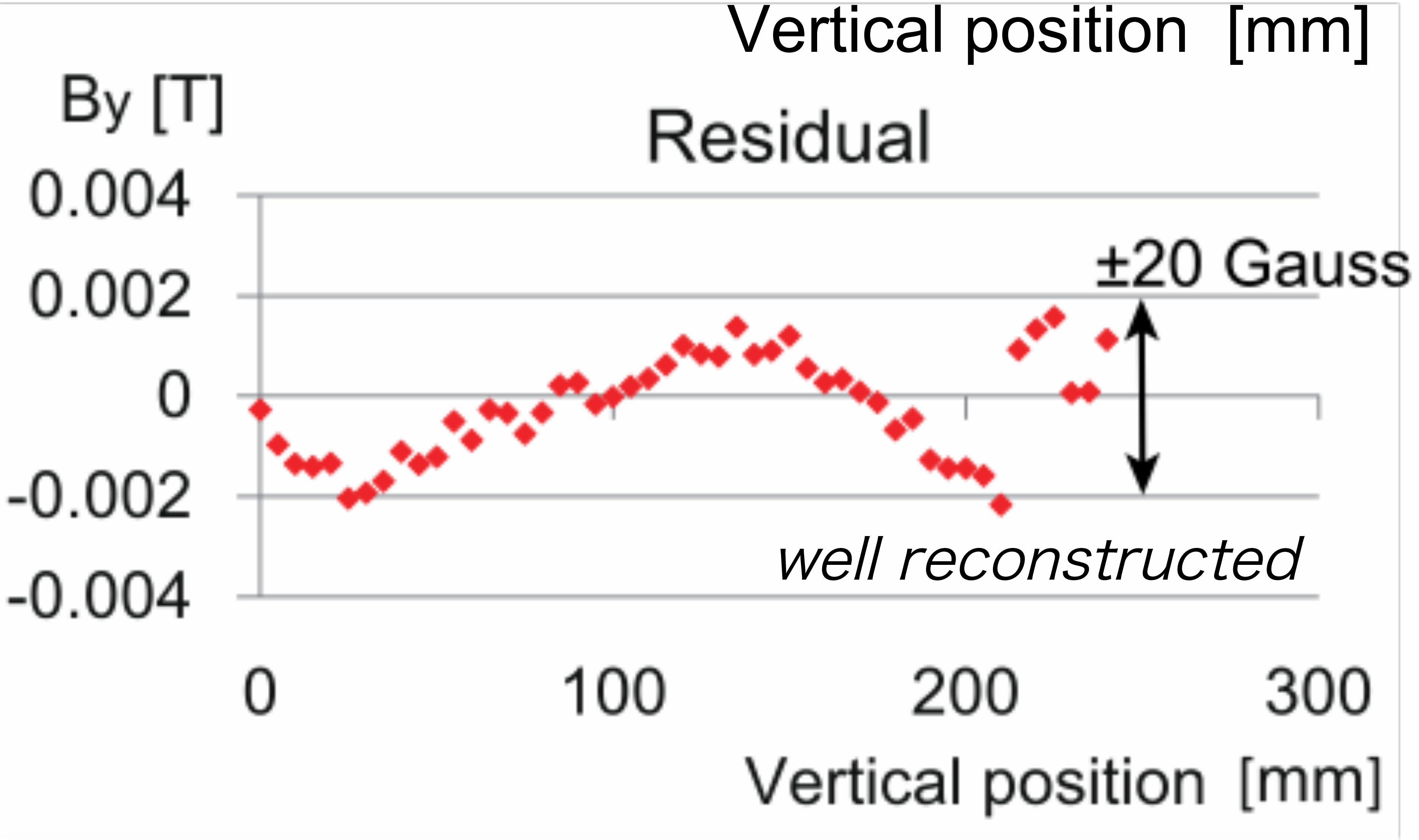
Q1, Q2 Magnet

- Field Measurement
  - with Hall probe
  - field gradient
    - Q1: 8.7 T/m, Q2: 5.0 T/m
  - enough to achieve large acceptance

- Field Calculation
  - 3D electromagnetic field calculation software Opera-3d/TOSCA

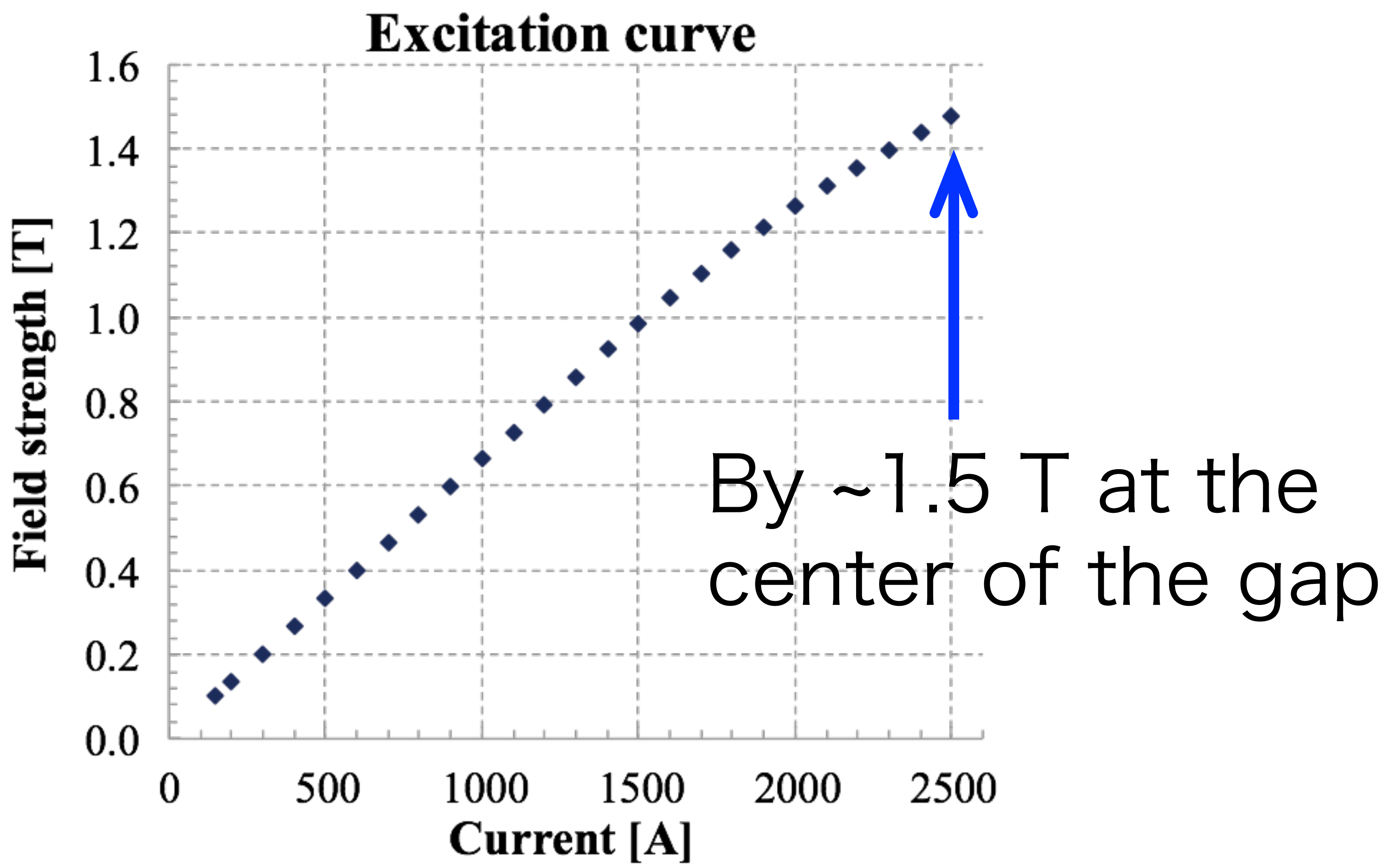


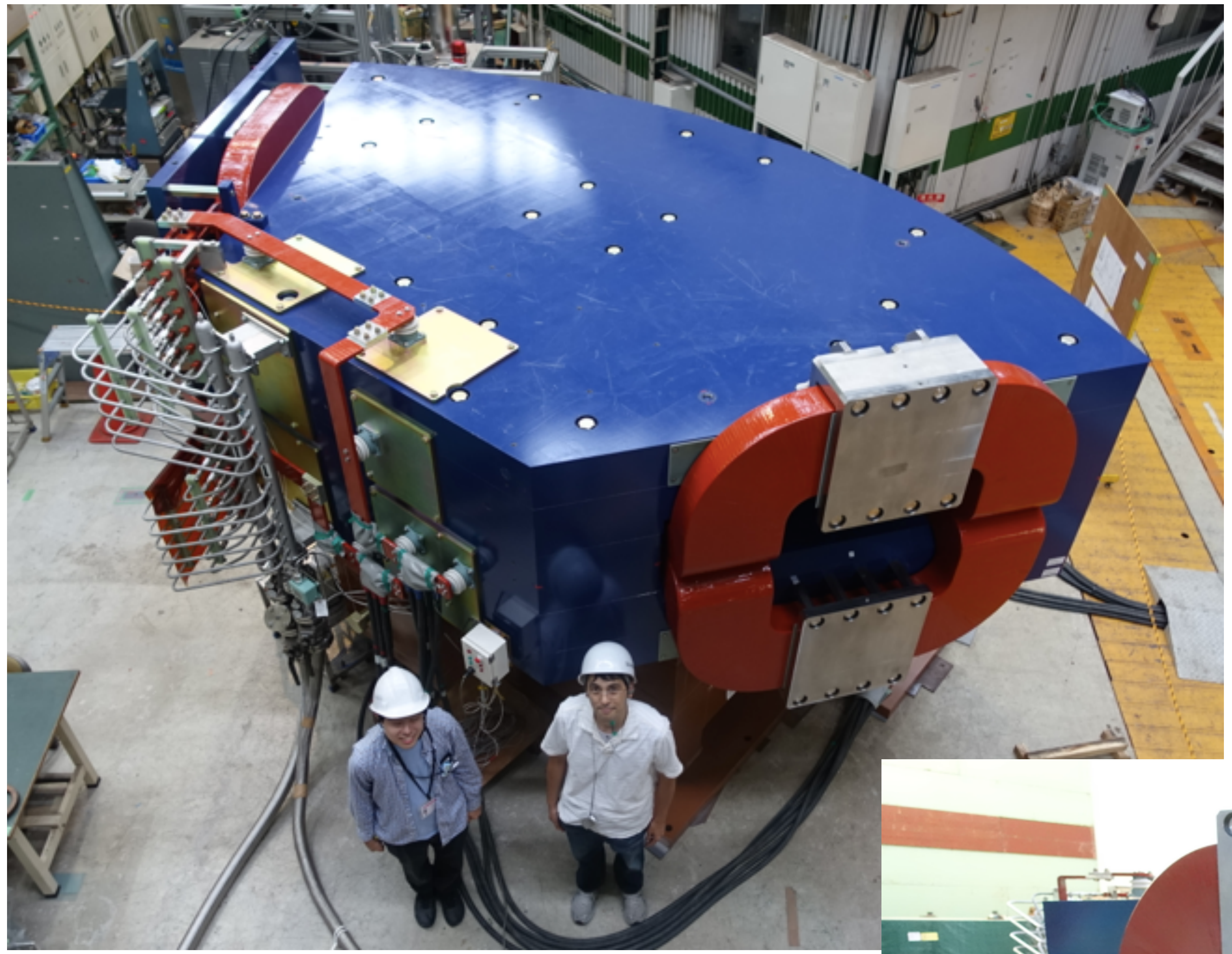


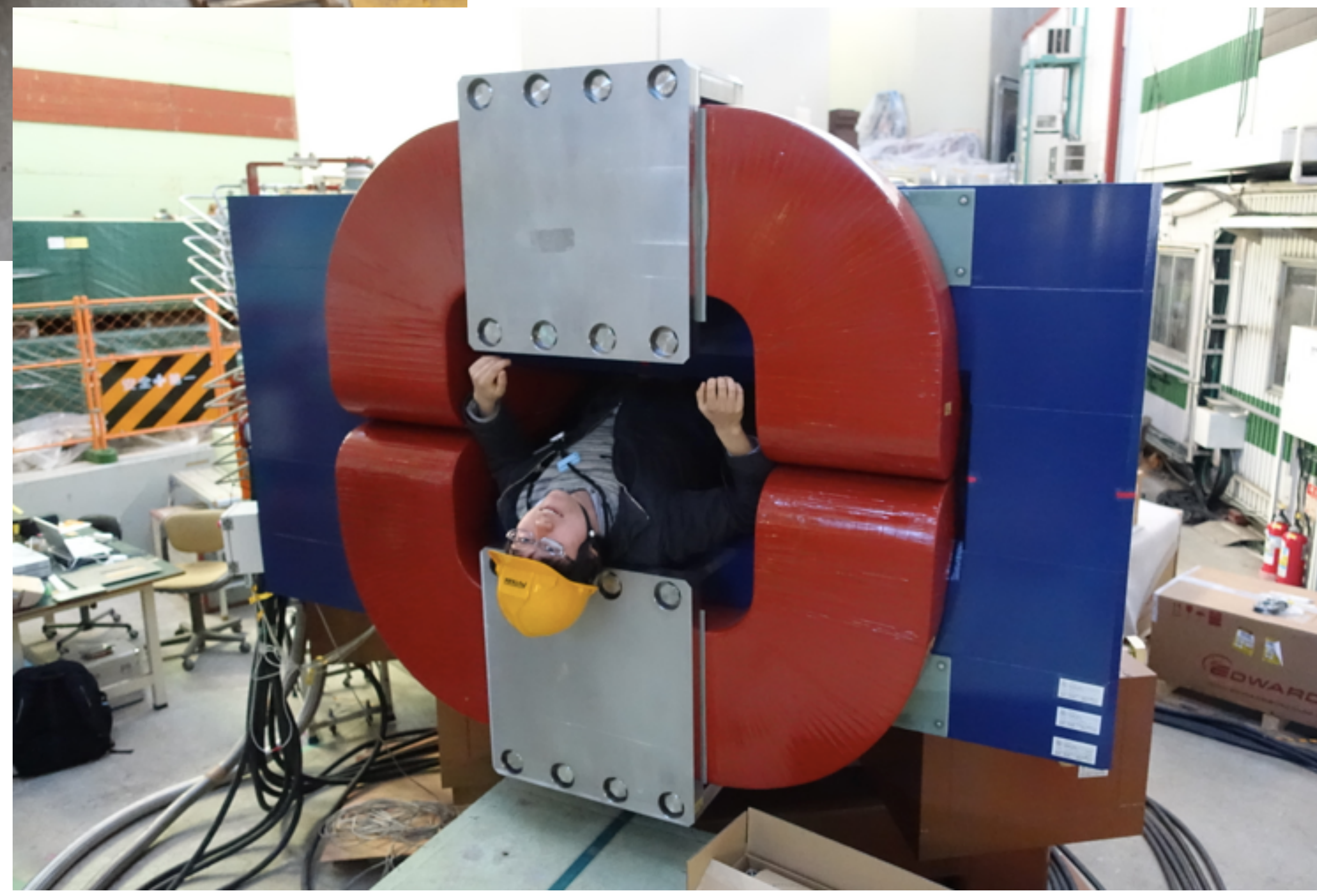


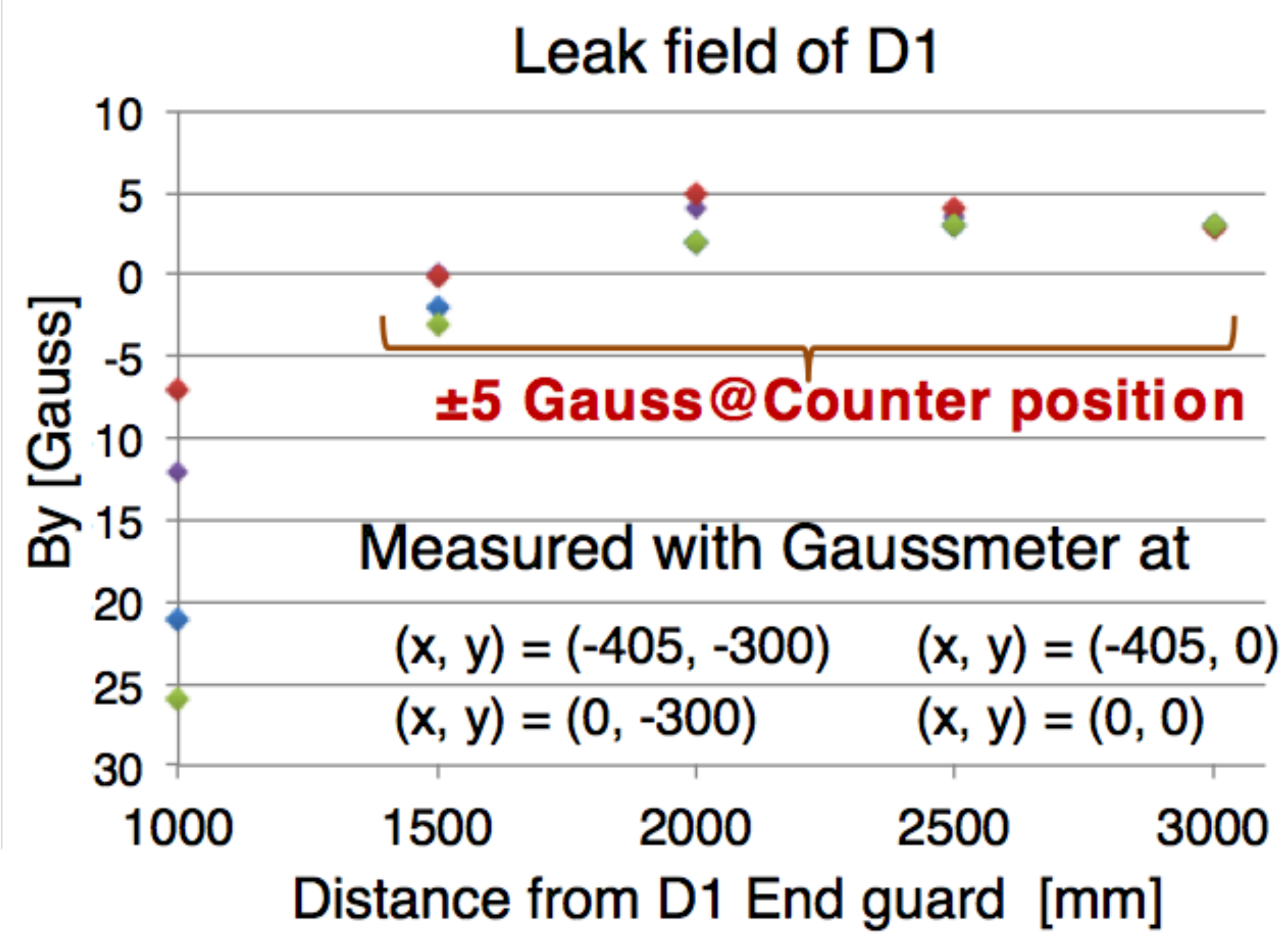
D1 Magnet

- Field Measurement
  - Excitation curve is measured by using NMR









- Field distribution
  - will be measured by using Hall probe
  - study is ongoing at KEK
- Leak field
  - measured by using gaussmeter : ～5 Gauss
  - active cancellation of leak field by using a bucking coil for PMT on the trigger counters

Summary

- Ξ hypernuclei
  - the last piece of baryon-baryon interaction in $SU_f(3)$
  - Ξ in neutron star?

- J-PARC E05 experiment
  - missing-mass spectroscopy via the $^{12}C(K^-, K^+)^{12}{}_{\Xi}Be$ reaction
  - with a new magnetic spectrometer S–2S
    - magnets and detectors are almost completed
    - to be installed in J-PARC in 2018 → E05 Run starts !
  - mass resolution of ＜2 MeV and dΩ ~60 msr → 250 events in 20 days

- Systematic study of S=–2 hypernuclei
  - high-resolution measurement of Ξ- &ΛΛ-hypernuclei with intense K^- beam
  - so far, only confirmation of the existence of bound states

    → investigation of the details of the ΞN, ΛΛ interaction

Backup

Interaction Model Dependence

T. Motoba, S. Sugimoto / Nuclear Physics A 835 (2010) 223–230 229

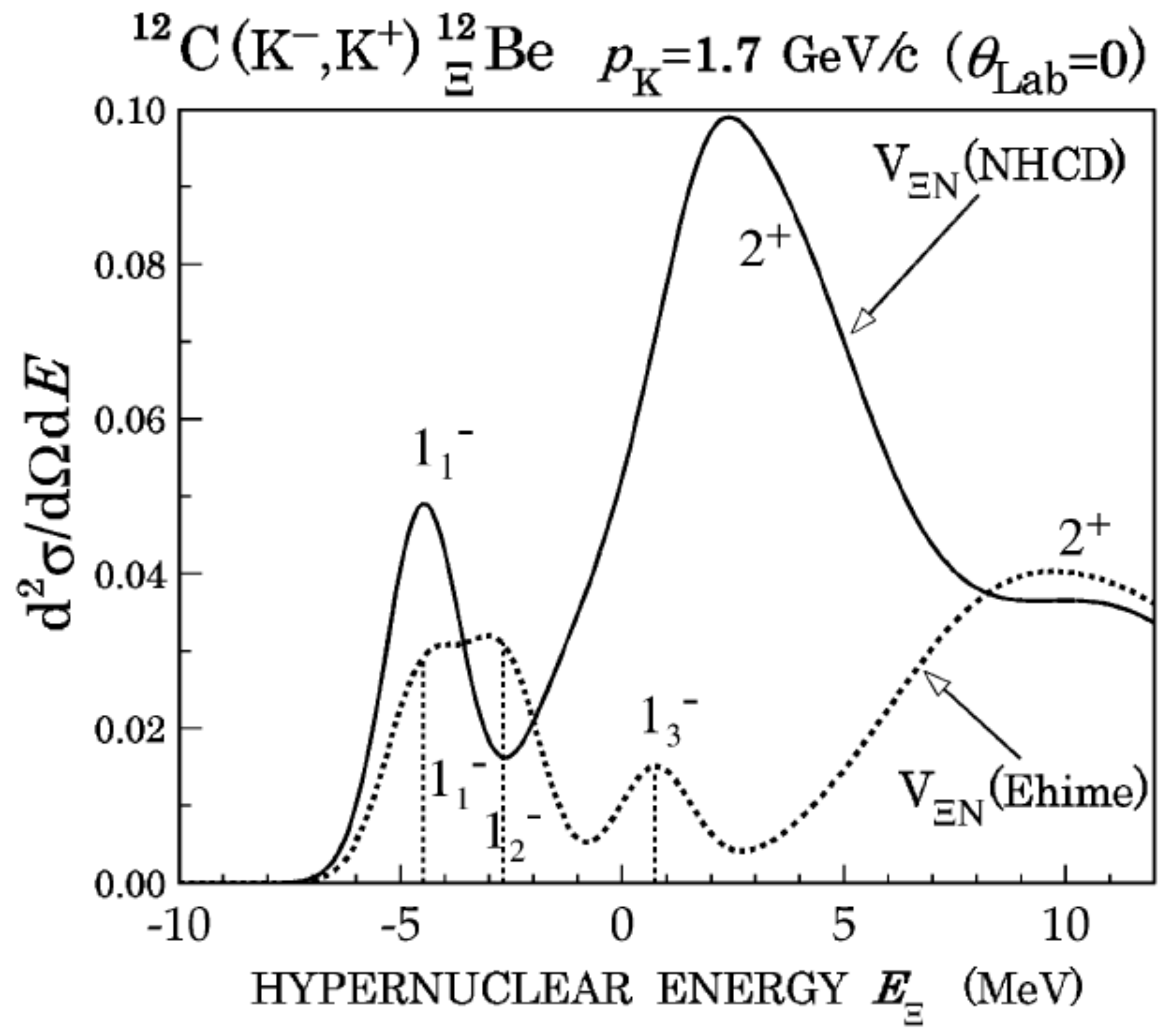


Figure 6: DWIA spectra with NHC-D and Ehime.

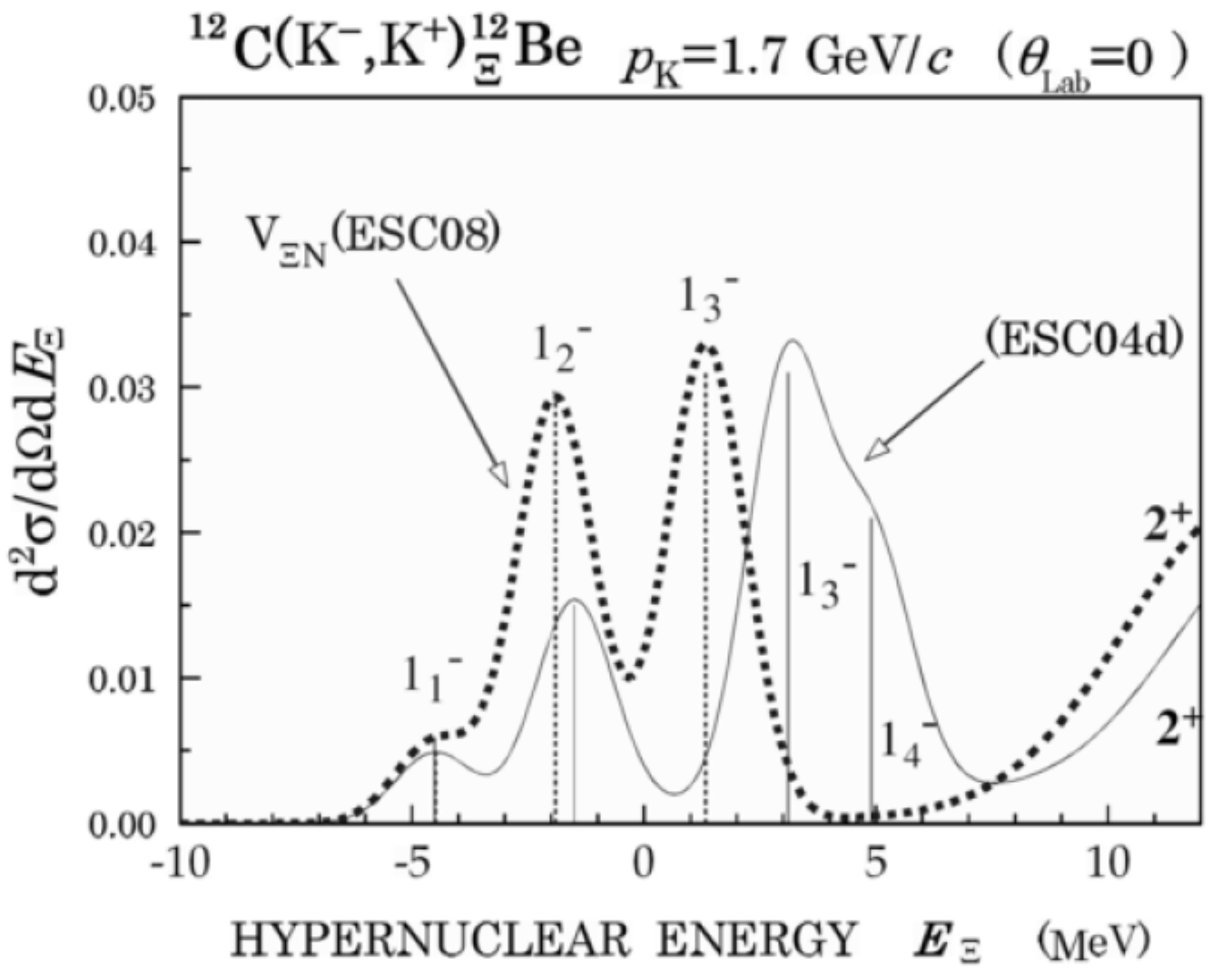
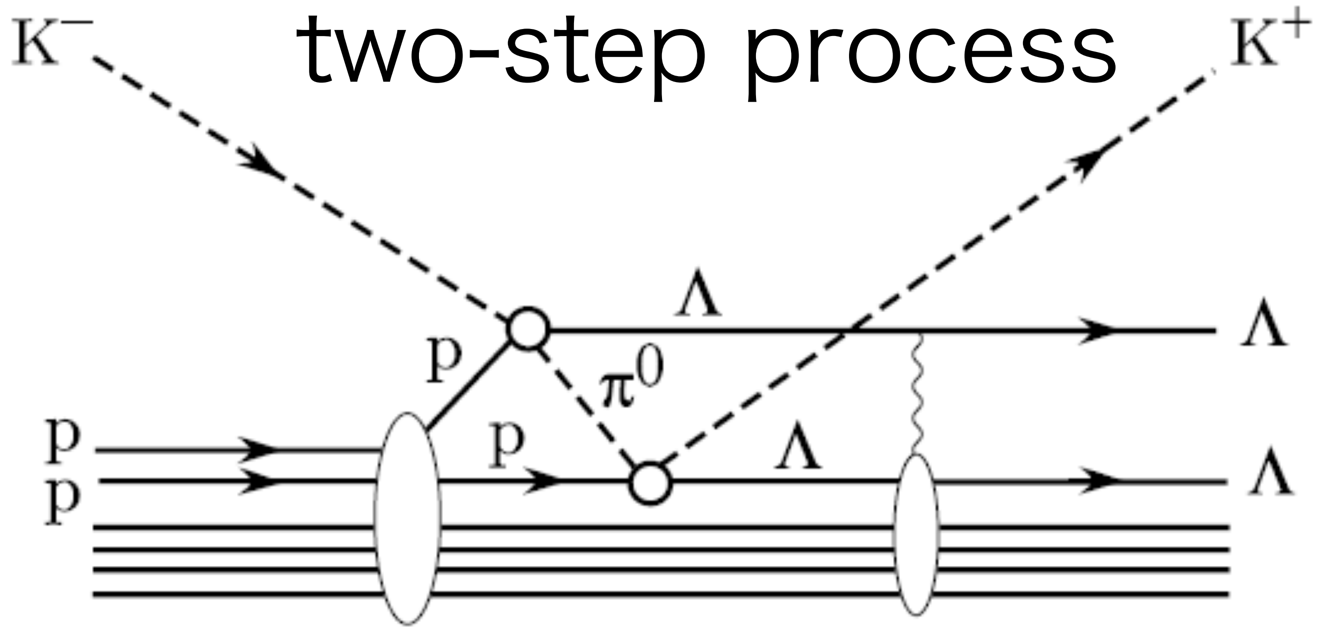


Figure 7: DWIA spectra with ESC04d and ESC08a.

The shapes of spectra depend on the properties of spin-dependent term of interaction models

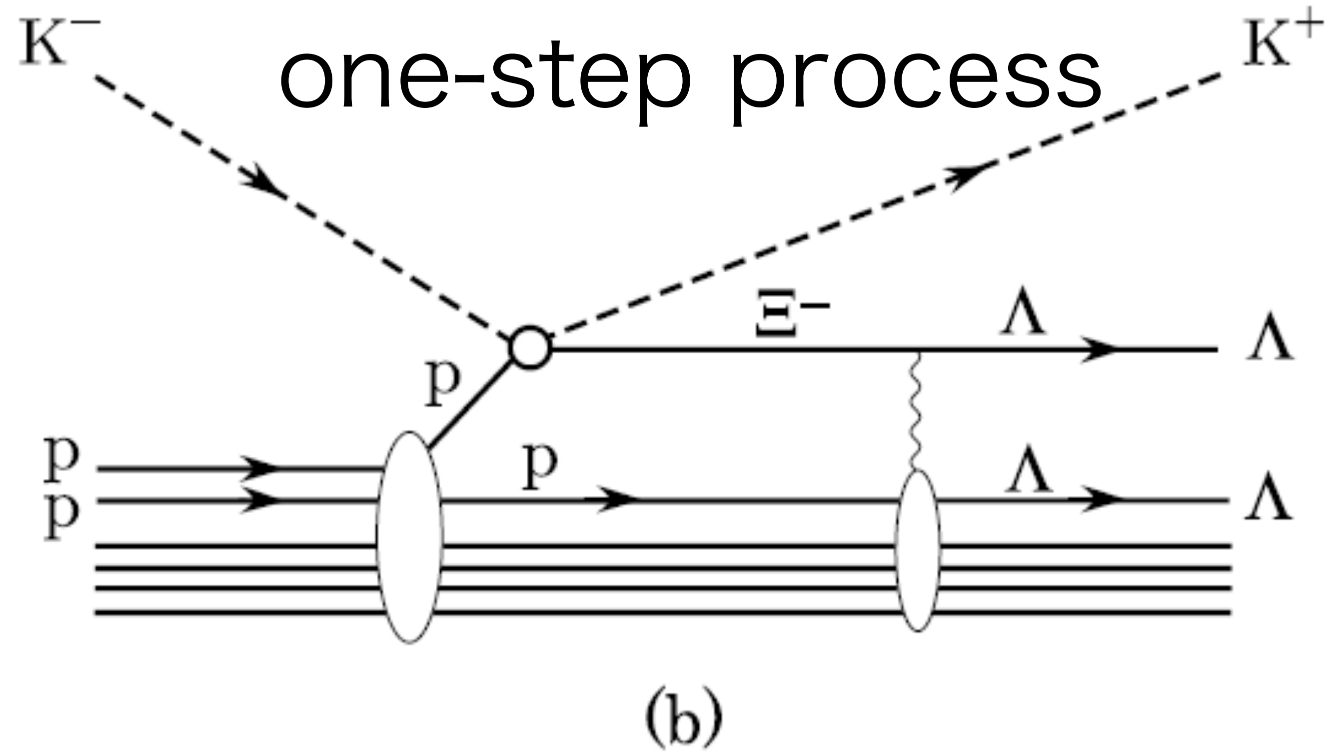
Double Λ Hypernuclei

two-step process



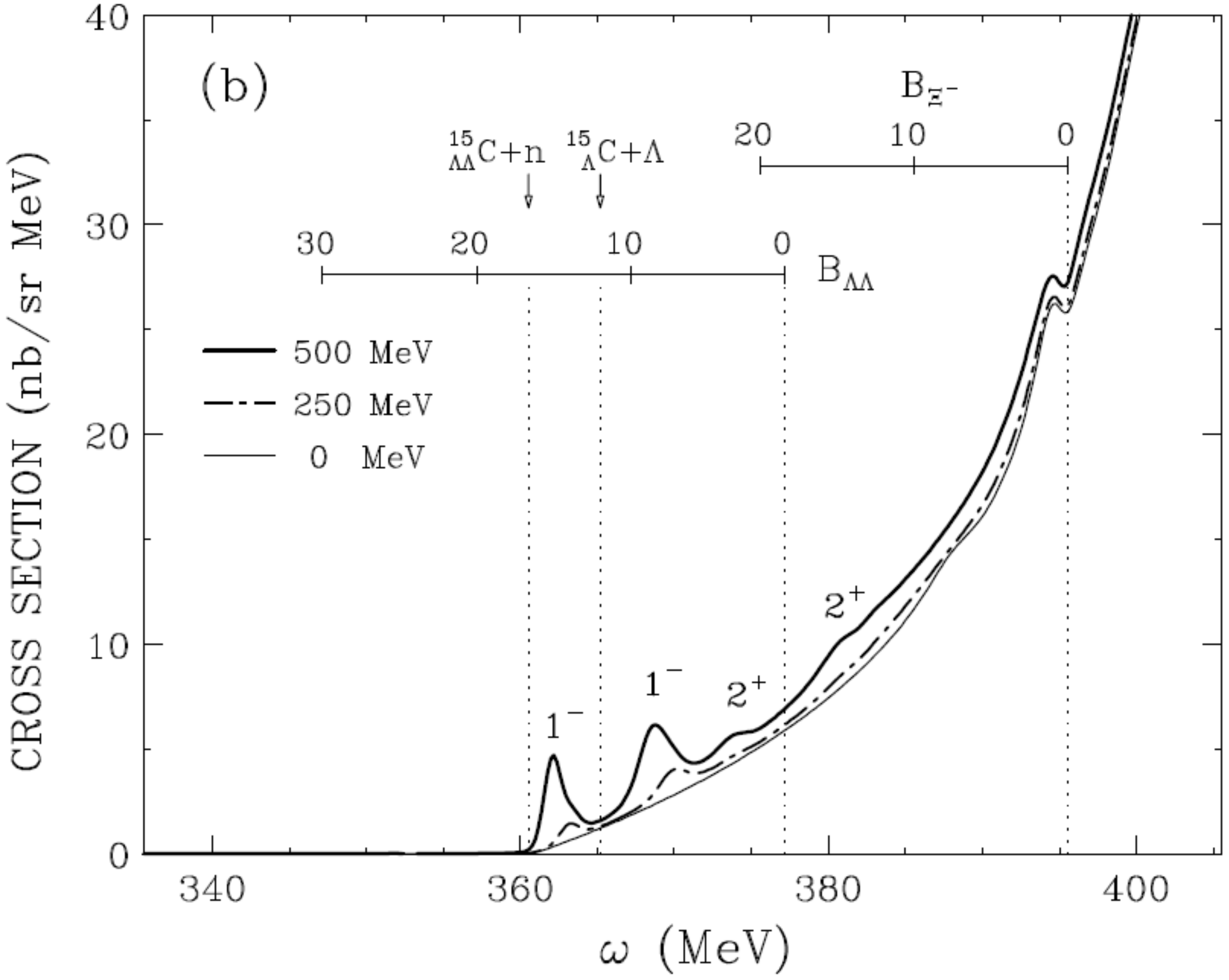
(a) ～0.1 nb/sr

one-step process



7～12 nb/sr

Sensitive to ΞN-ΛΛ coupling strength

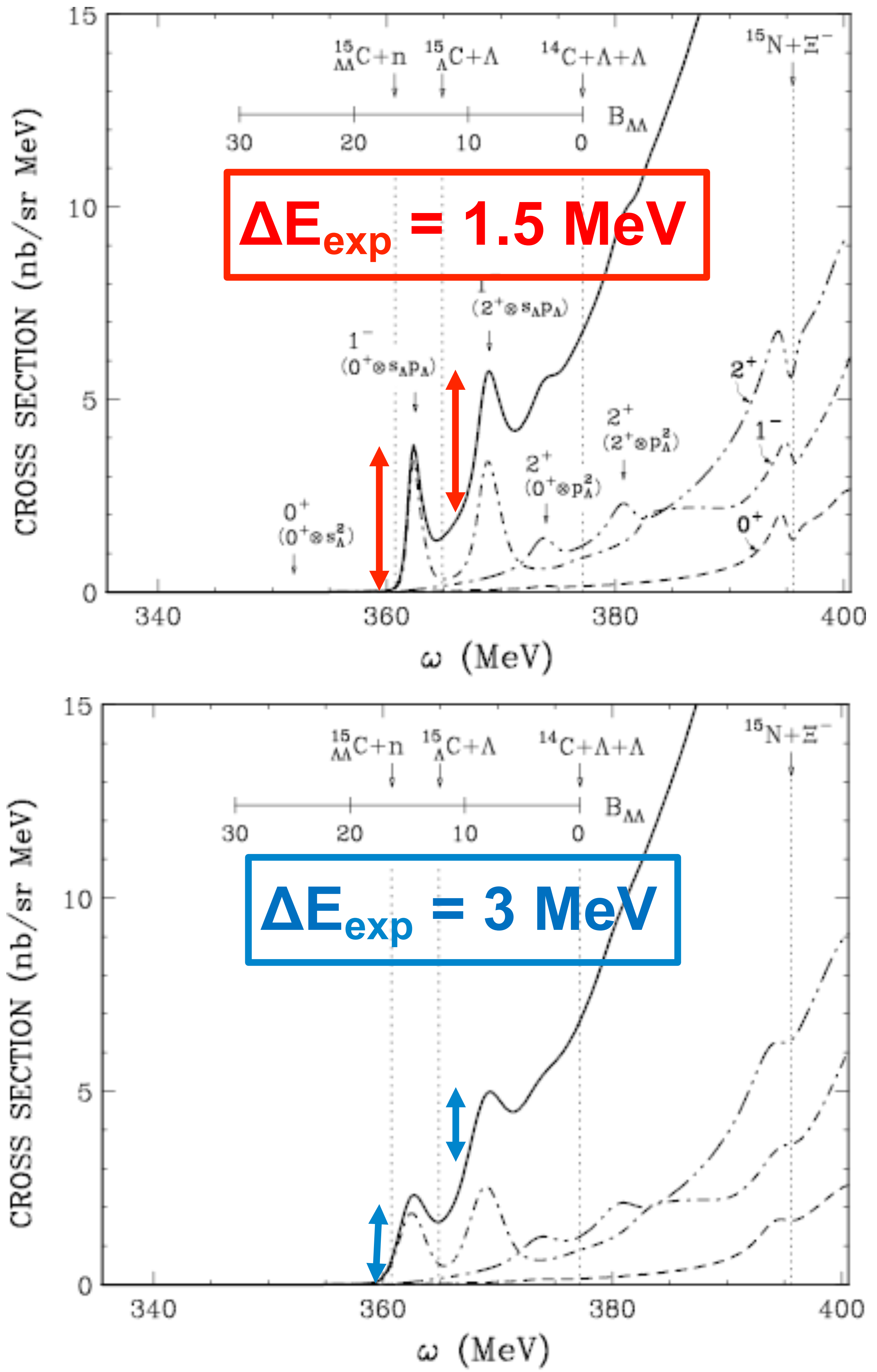


T. Harada et al., Phys. Lett. B 690, 363 (2010)

Double Λ Hypernuclei

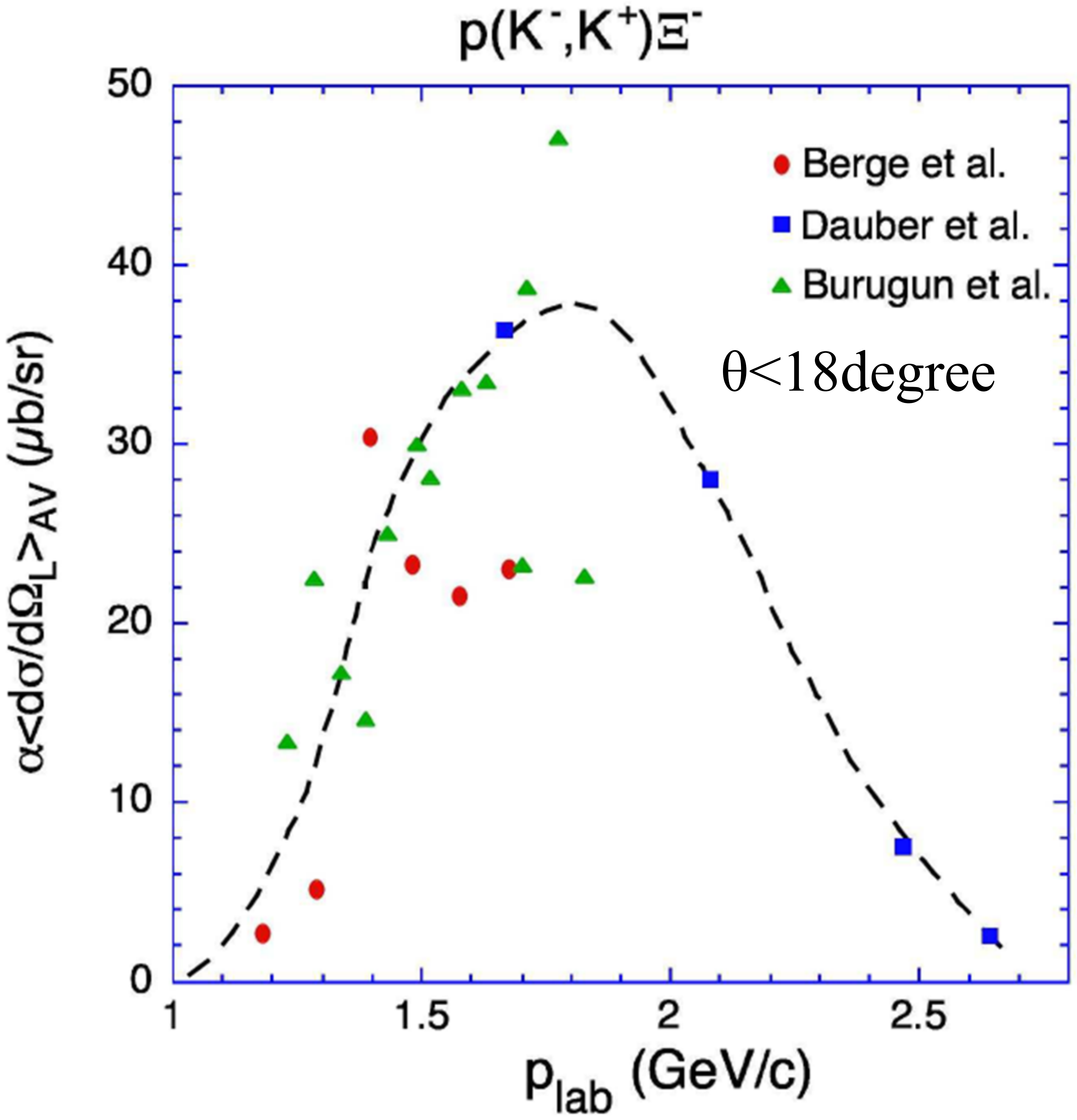
- $^{16}O\ (K^-, K^+)\ _{\Lambda\Lambda}{}^{16}C$

- $[^{15}N(1/2^-, 3/2^-) \times s_{\Xi}]_{1^-} \rightarrow [^{14}C(0^+, 2^+)] \times s_{\Lambda} p_{\Lambda}]_{1^-}$
- $[^{15}N(1/2^-, 3/2^-) \times p_{\Xi}]_{2^+} \rightarrow \quad [^{14}C(0^+, 2^+) \times p_{\Lambda}{}^2]_{2^+}$

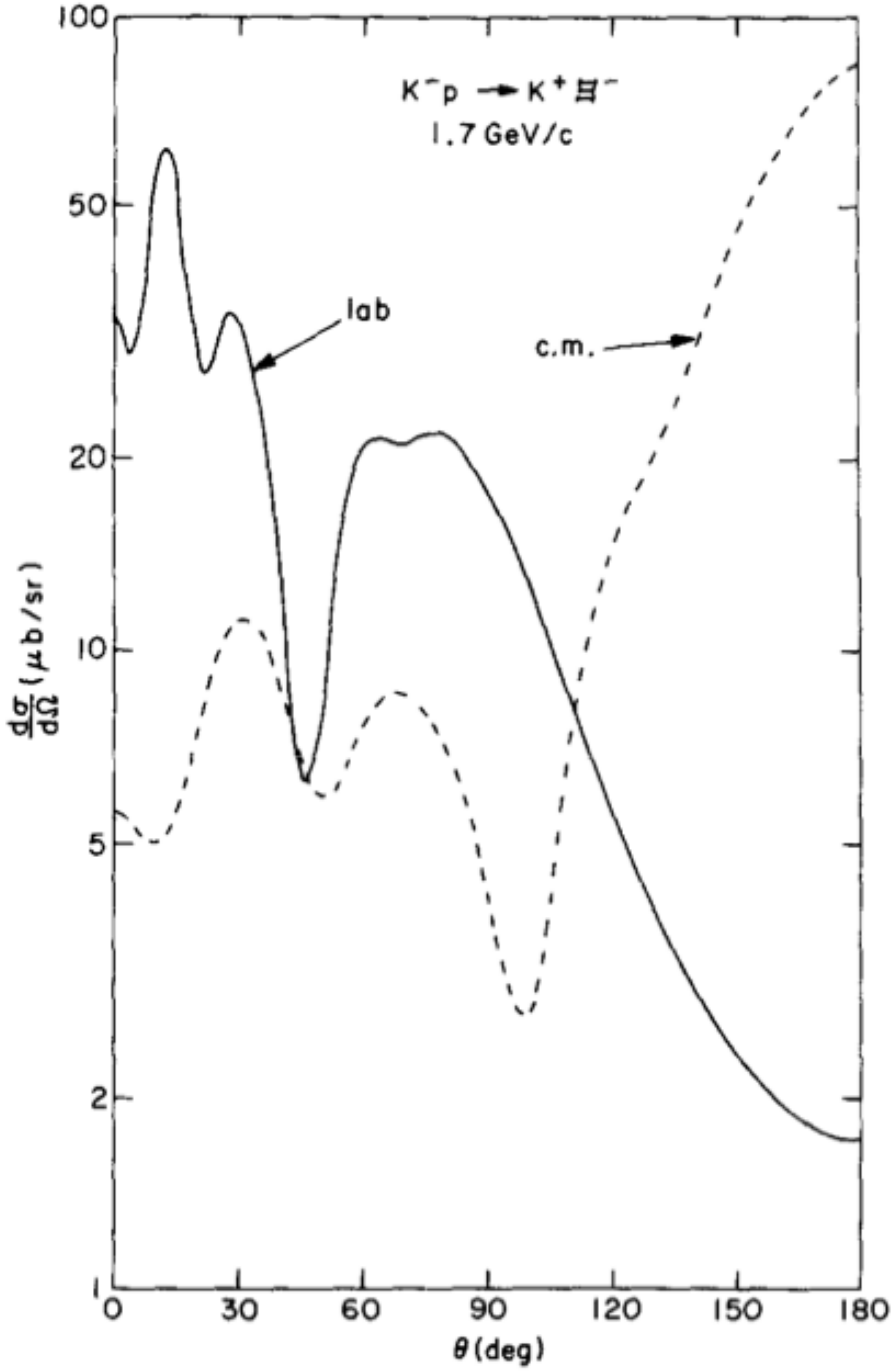


T. Harada et al., Phys. Lett. B 690, 363 (2010)

Cross section of p(K⁻, K⁺) Ξ⁻



C.B. Dover and A. Gal, Ann. Phys. 146, 309 (1983)



Mass Resolution

High-Res Spec. "S-2S" ← *SKS limits ΔMM*

$$\Delta M^2 = \left(\frac{\partial M}{\partial p_B}\right)^2 \Delta p_B^2 + \left(\frac{\partial M}{\partial p_S}\right)^2 \Delta p_S^2 + \left(\frac{\partial M}{\partial \theta}\right)^2 \Delta \theta^2 + \Delta E_{\mathrm{strag.}}^2$$

$^{12}C(K^-,K^+)\ _{\Xi}^{12}Be$, θ=5°, E_{hyp}=0 MeV, Δθ=2mrad [MeV]

	Beam	Scat	*θ*	ΔM
Design value	0.84	0.62	0.04	1.0
Realistic?	1.67	0.62	0.04	1.8
Pilot run	1.67	3.74	0.04	4.1

ΔE_{strag} ←	Target thickness
1 MeV ←	3 g/cm^2
2 MeV ←	6 g/cm^2
3 MeV ←	10 g/cm^2

- Momentum resolution dp/p (FWHM)
  - Beam: (design) <5×10^{-4}
  - (realistic?) 1×10^{-3} ← evaluation in other experiments at J-PARC
  - Scat: SKS (used in pilot run) 3×10^{-3}
  - S-2S 5×10^{-4}

Kinematics

p_{K-} = 1.8 GeV/c ⟷ p_{K+} = 1.2〜1.4 GeV/c

Recoil Momentum

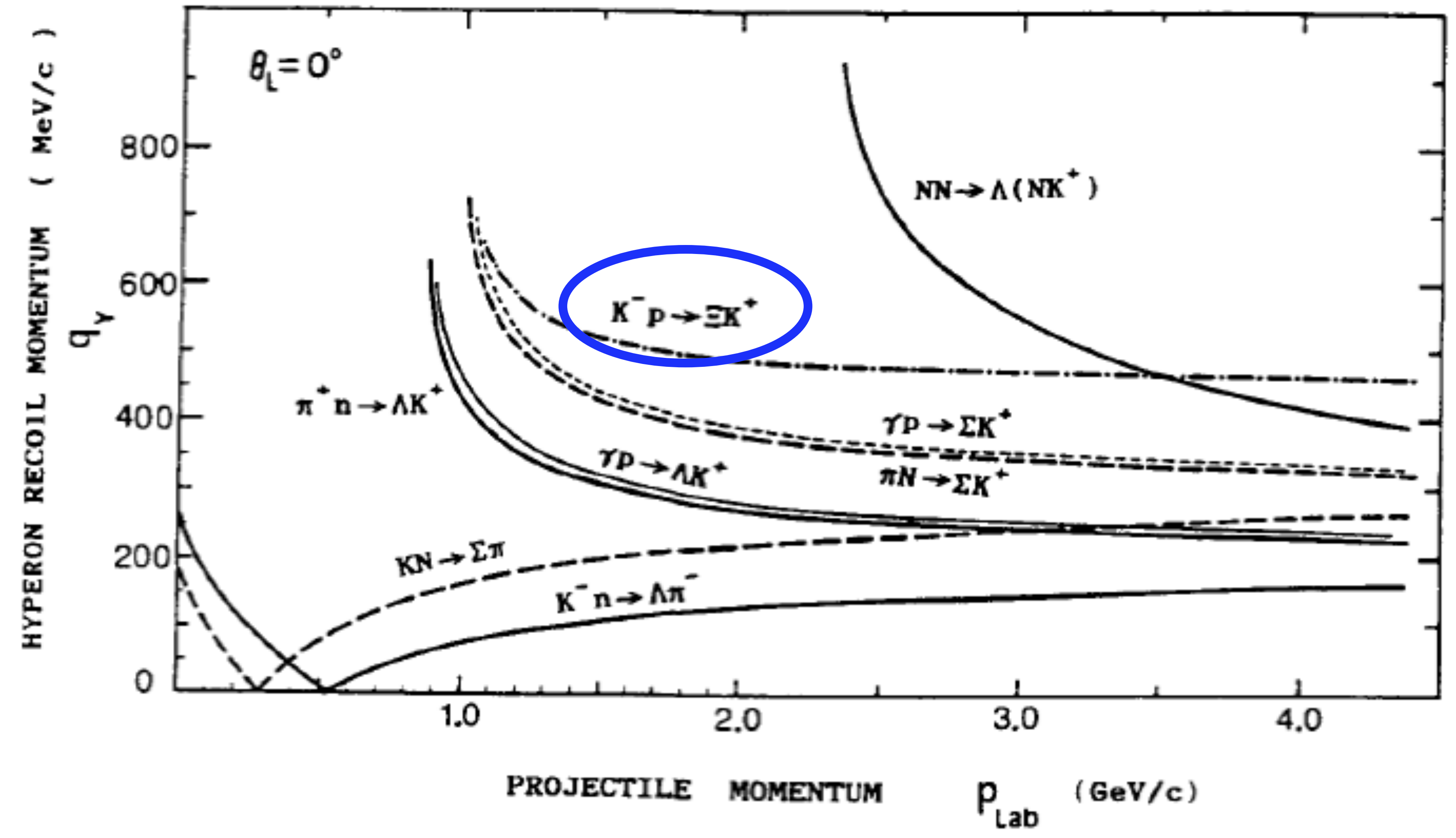
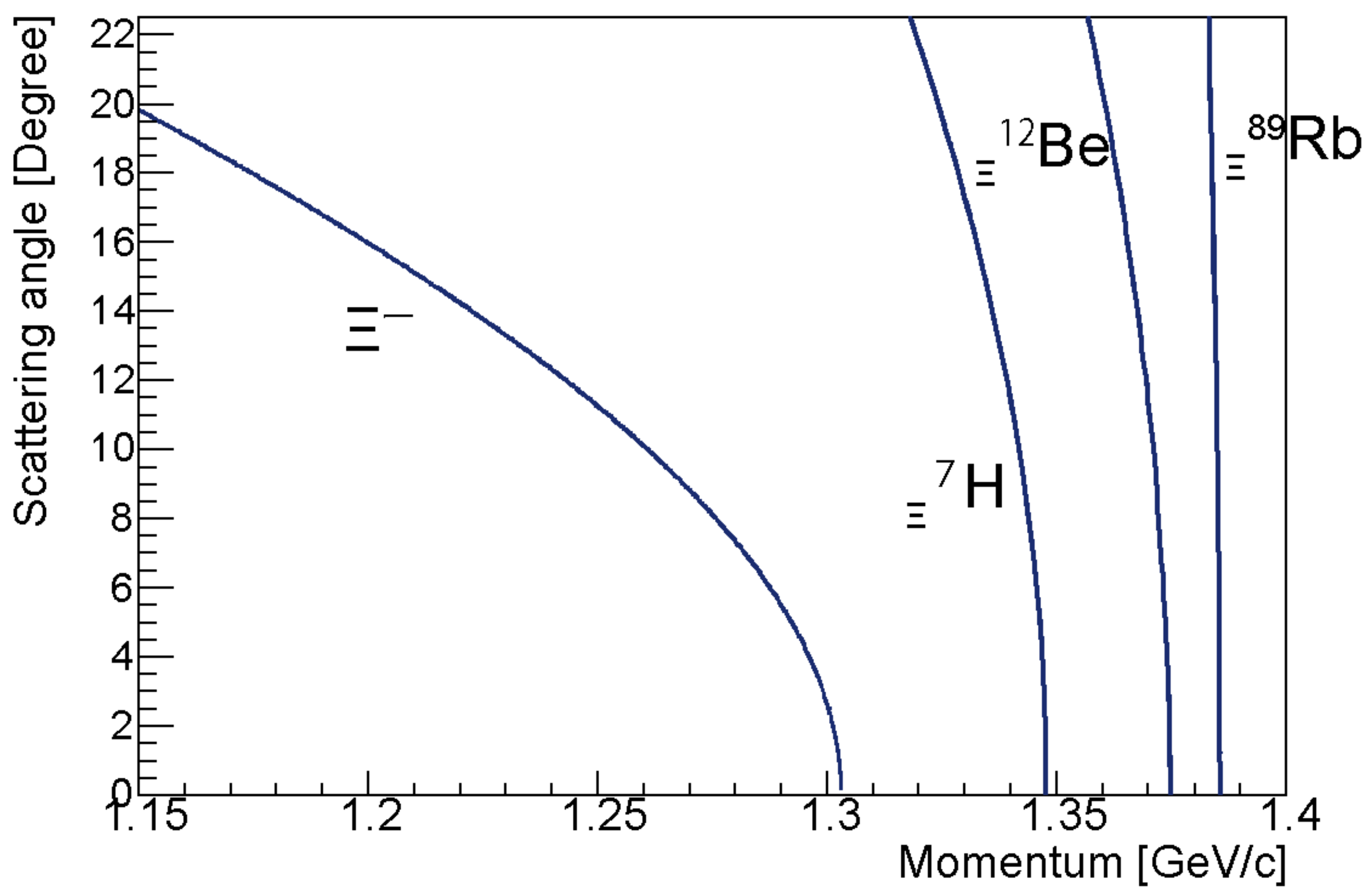


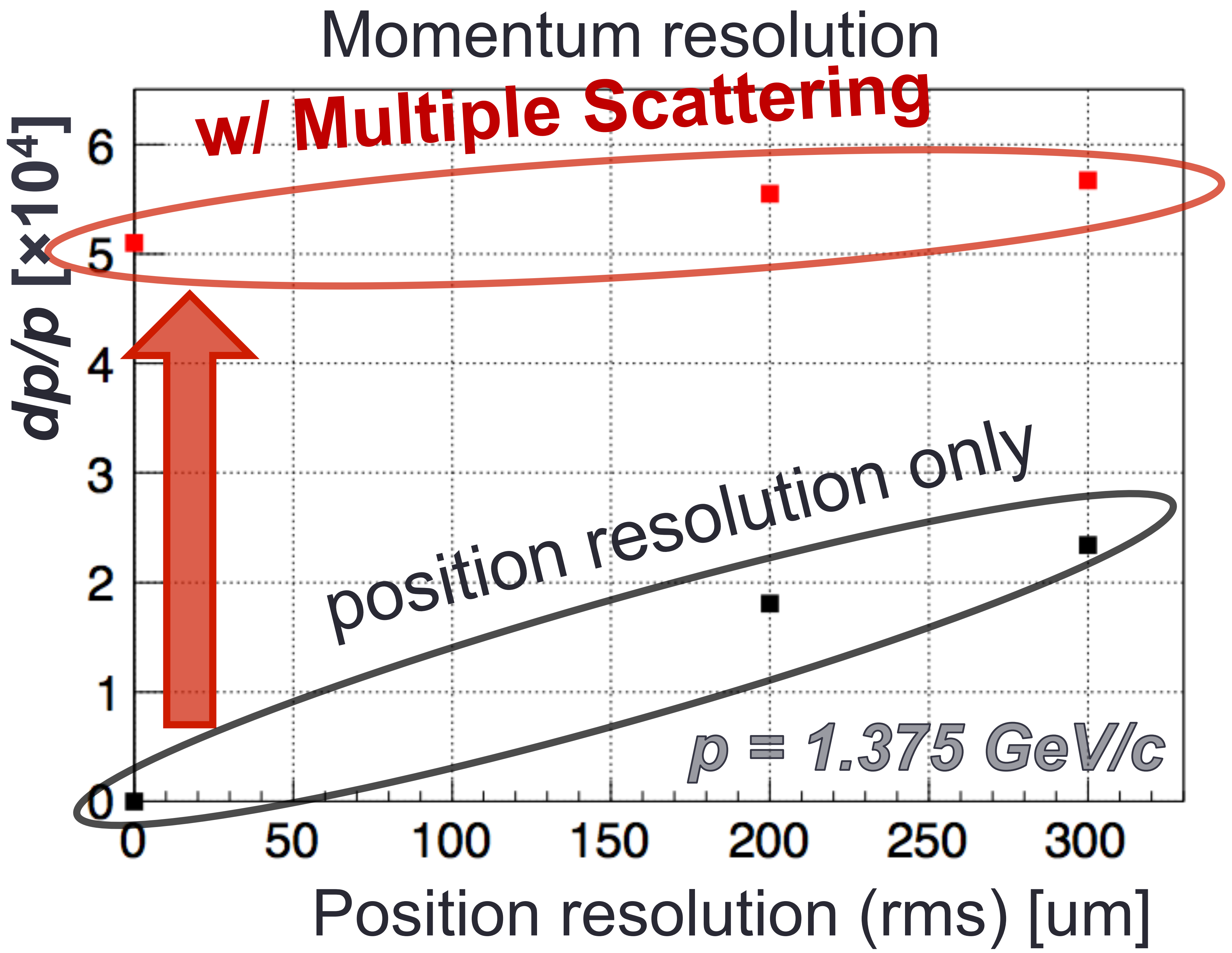
Fig. 2.3. The momentum q_Y transferred to the hyperon Y as a function of the projectile momentum $p_{proj} = p_a$ in the reaction $aN \to Yb$ at $\theta_{b,L} = 0°$.

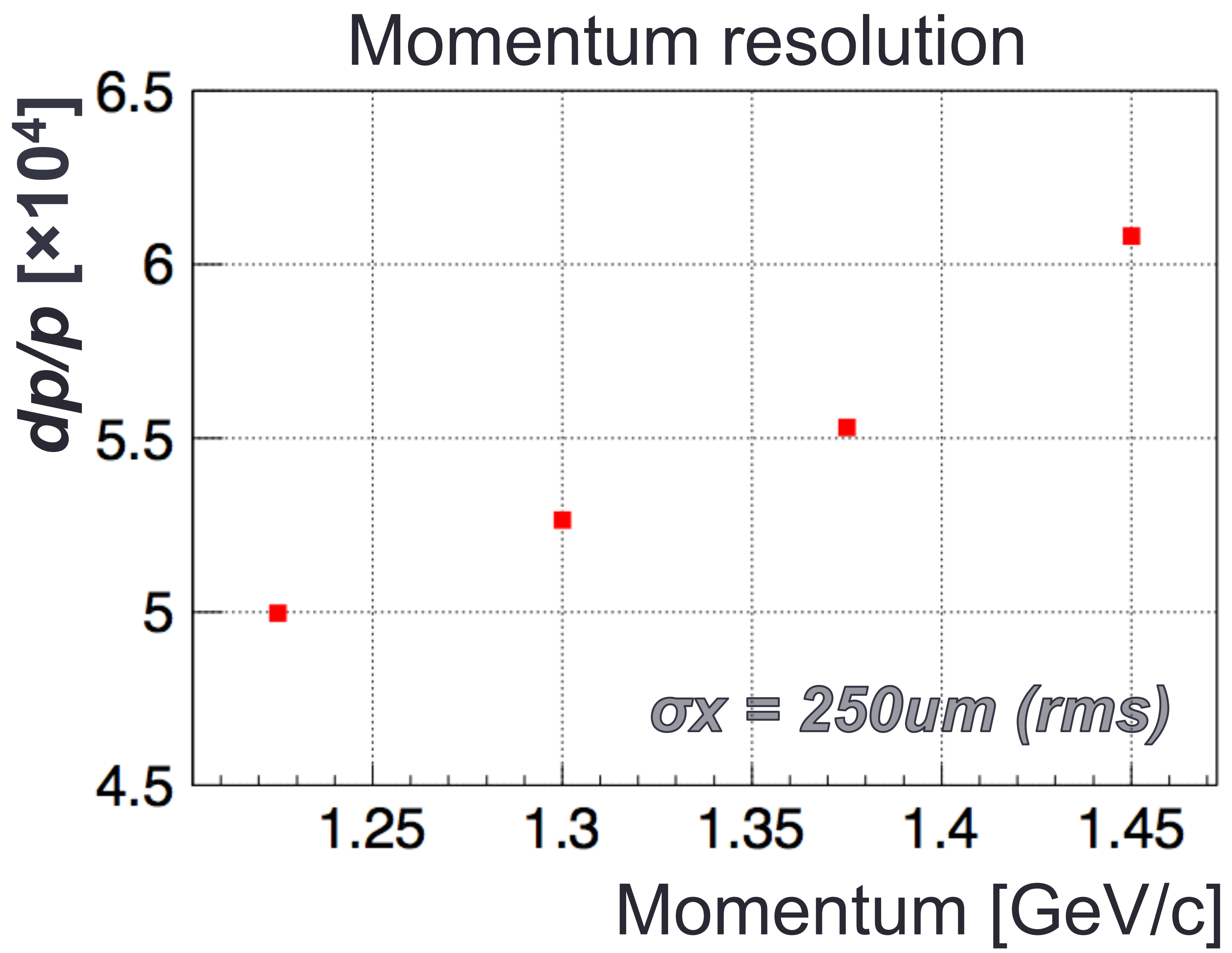
Momentum of K^+



Momentum Resolution

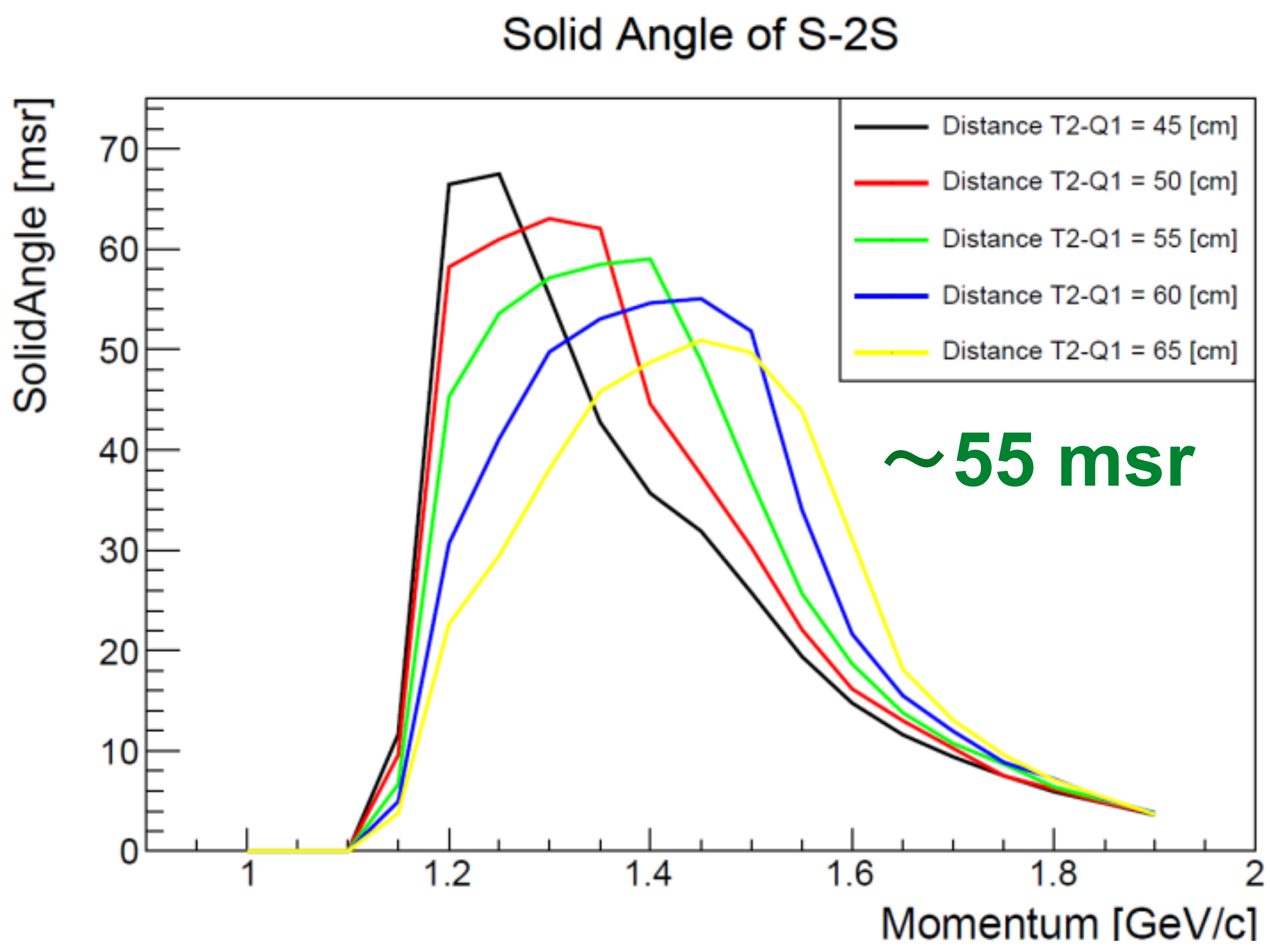
dp/p **5～6×10^{-4} (FWHM)**

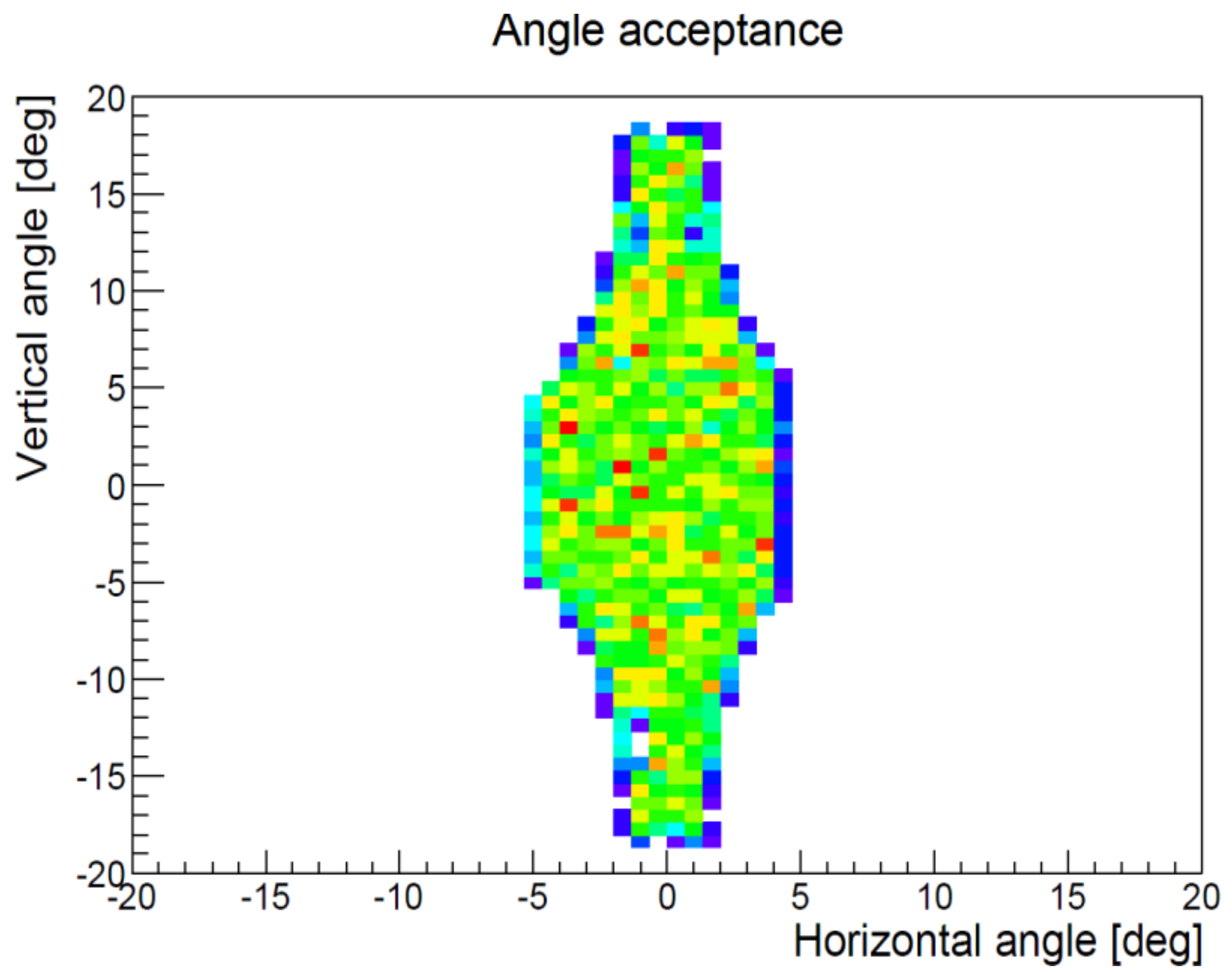


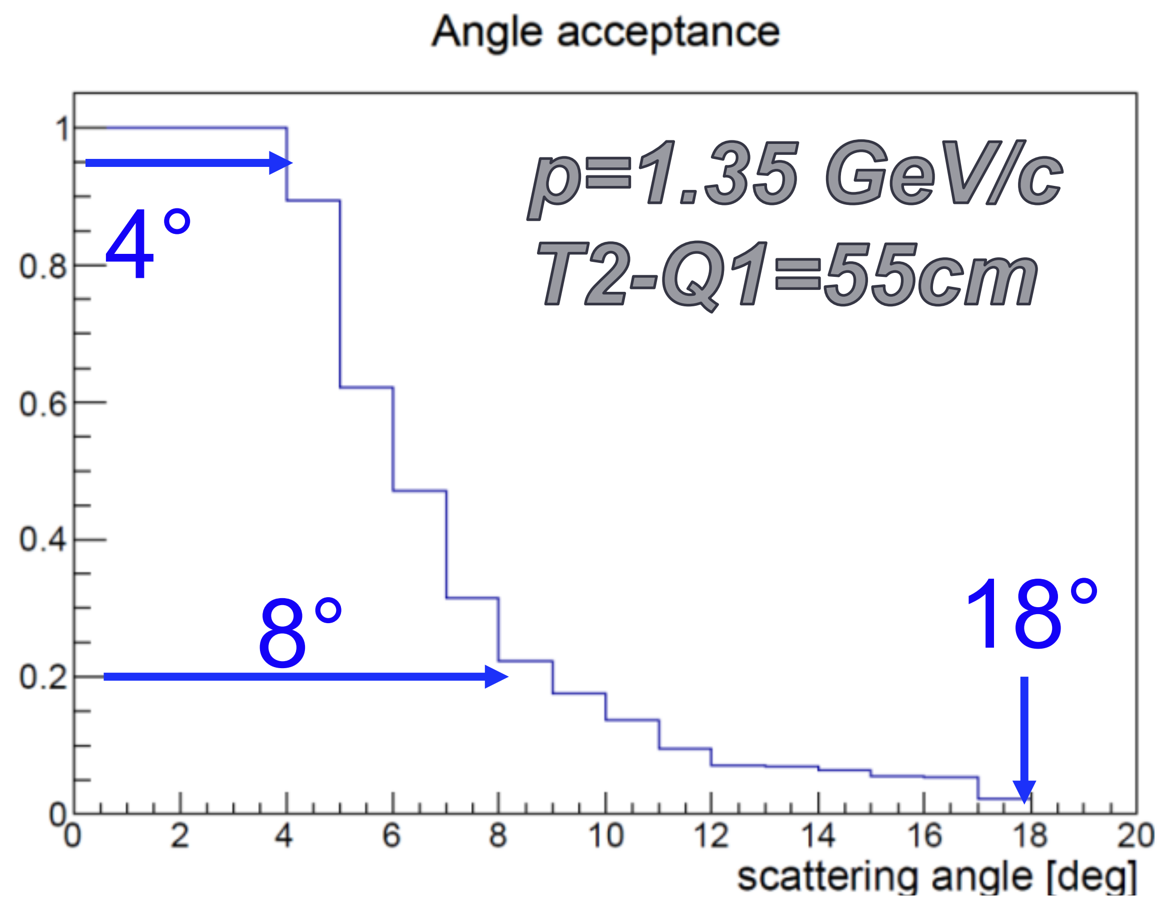


Magnet condition
Q1,Q2,D1 = 2500A (max)

Solid Angle





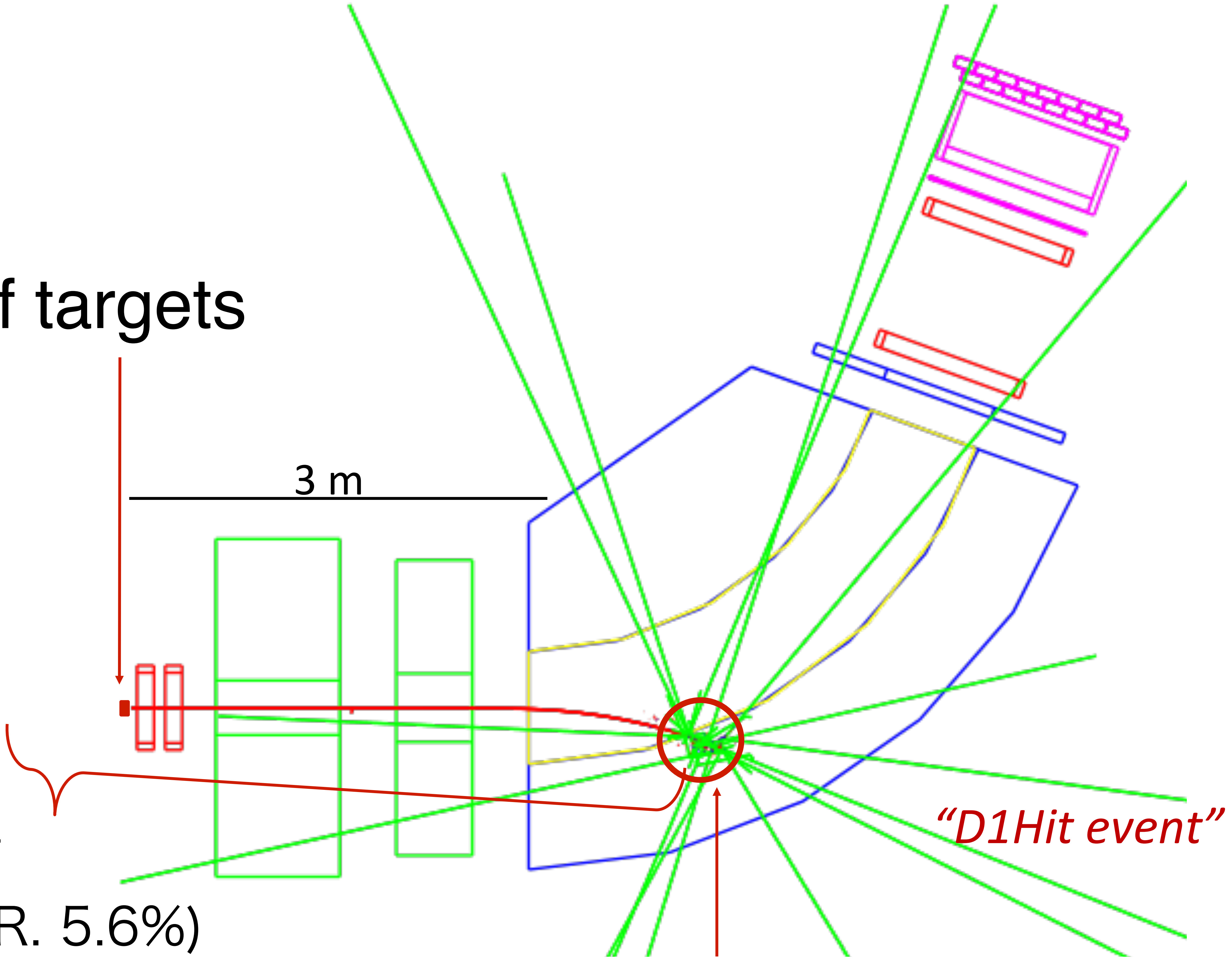


Magnetic field ← TOSCA calculation
Q1,Q2,D1 = 2500A (max)

Particles just passing through the magnets
= not including detector configuration

Backgrounds

1. Various products off targets
   - Reaction rate: ～10%



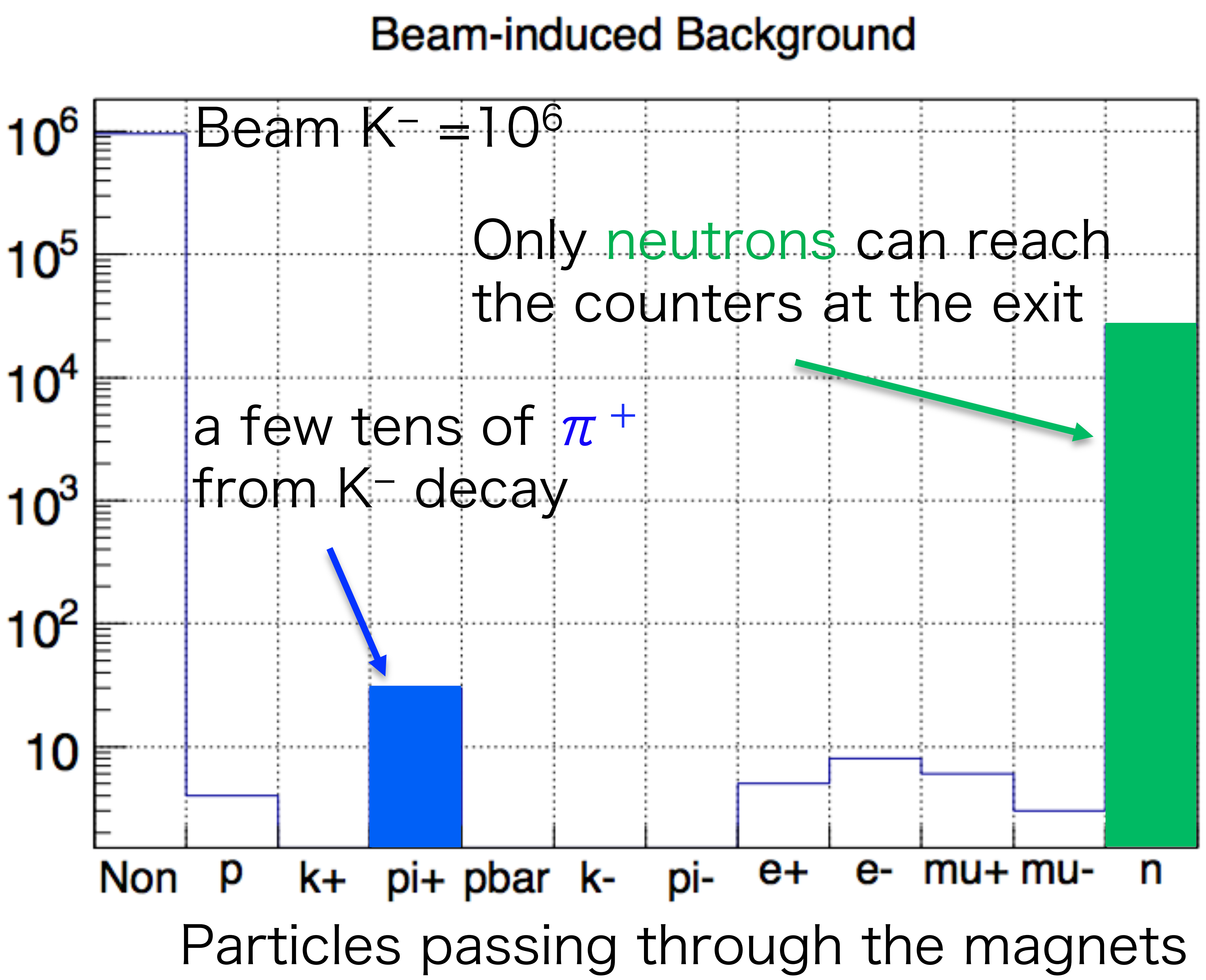
2. Decay of beam K^-
   - $K^- \rightarrow \pi^- \pi^- \boldsymbol{\pi}^+$ (B.R. 5.6%)

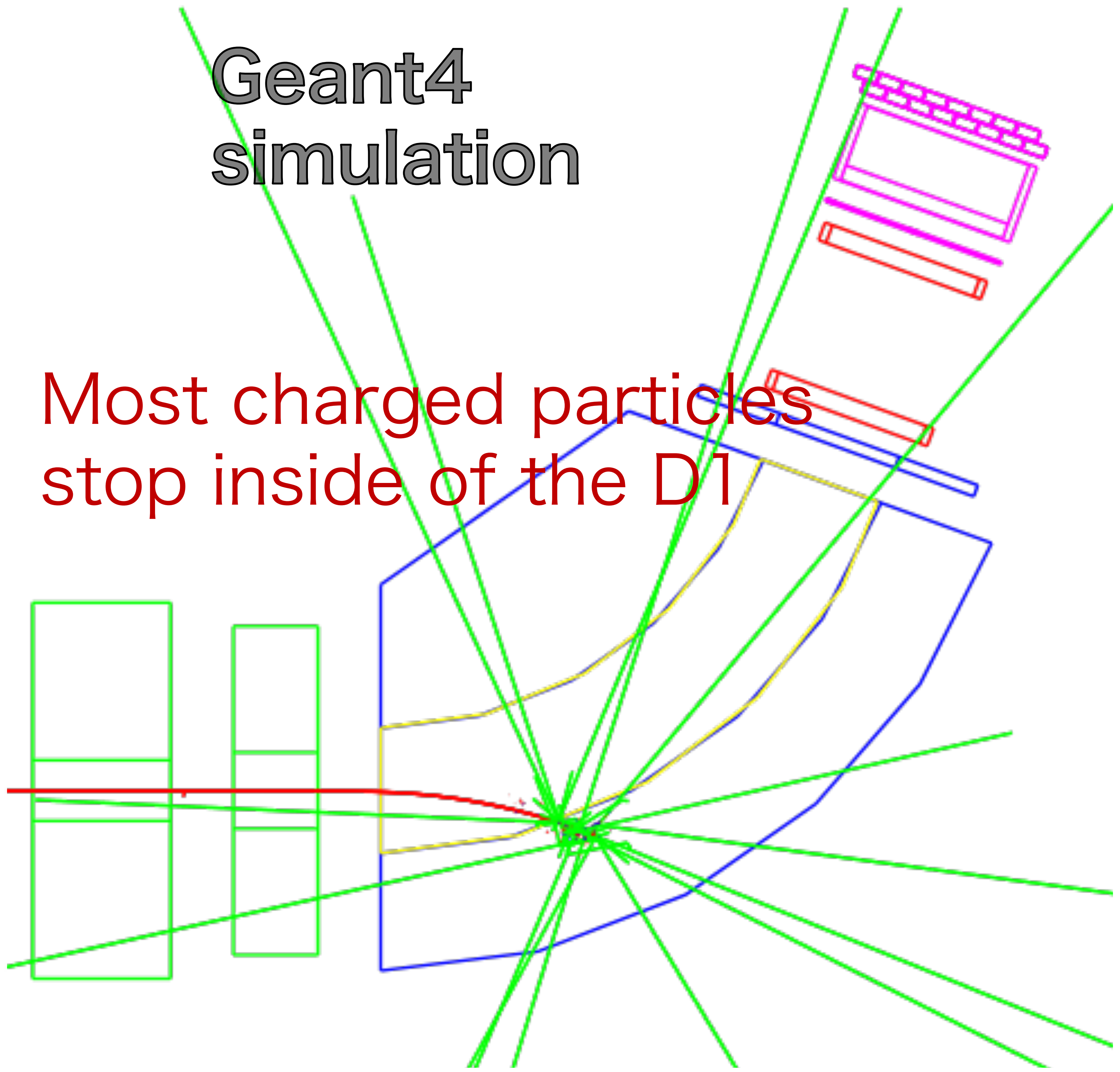
   K^-@1.8 GeV/c: $\beta \gamma c \tau$ ～13.5 m

3. Reactions on the D1 yoke
   - $K^- + Fe \rightarrow$ *many particles*

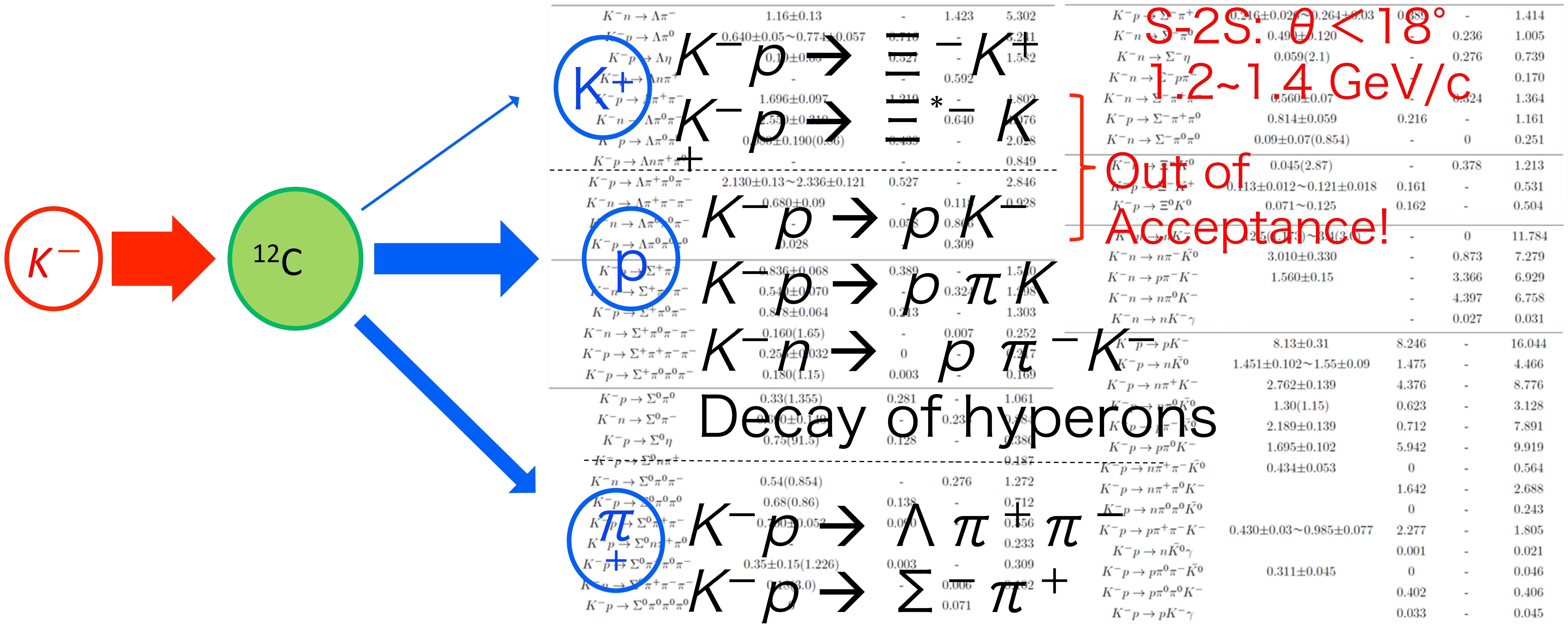
Backgrounds not from the Target

- Decay of beam K^- & Reactions on the D1yoke





Reactions in Target



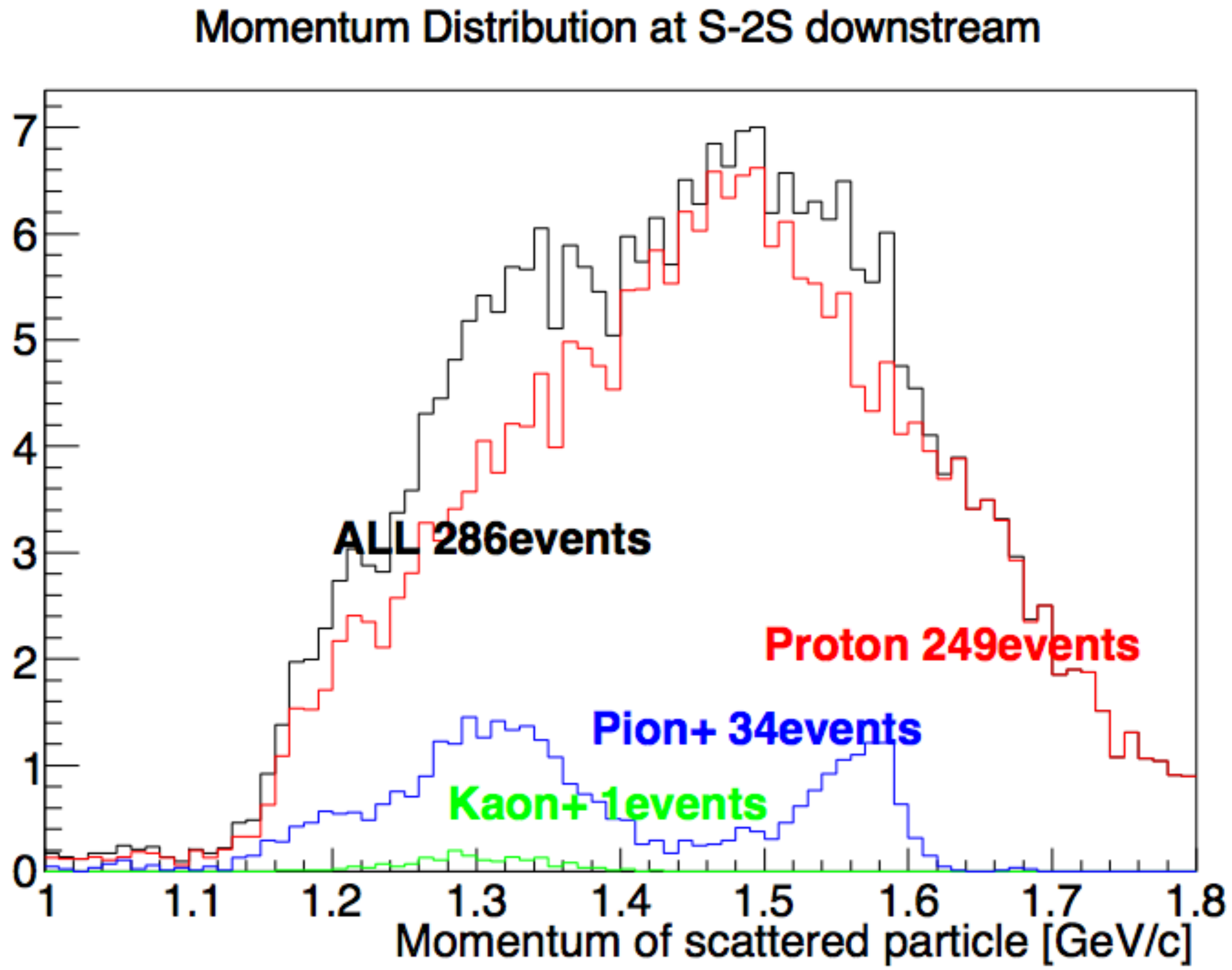
"Compilation of Cross-Sections : K± induced reactions", CERN-Library(1983)

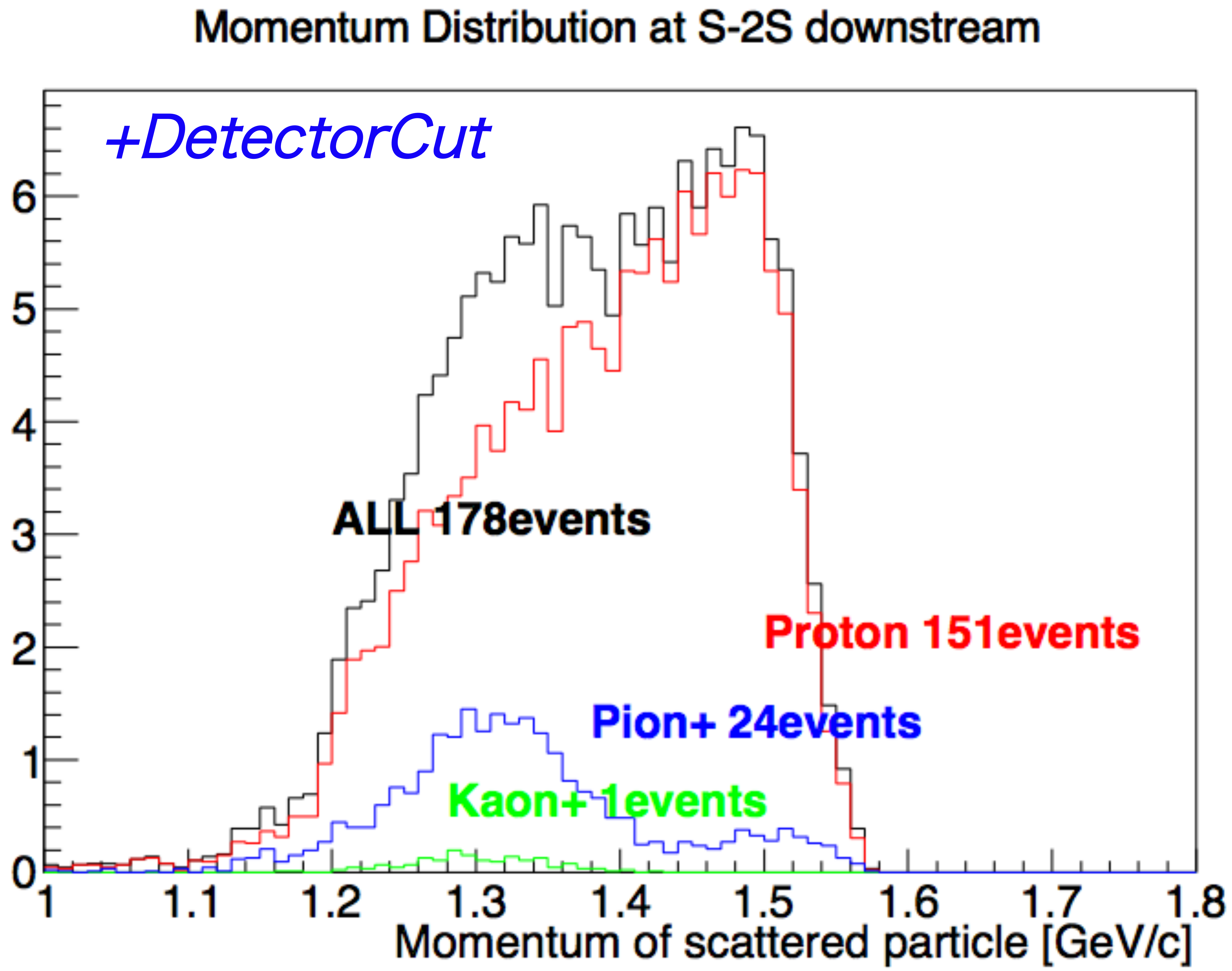
- Background estimation
  - JAM v1.210 : Jet AA Microscopic transport model

Y. Nara et.al., Phys. Rev. C61 (2000) 024901

Background Distributions

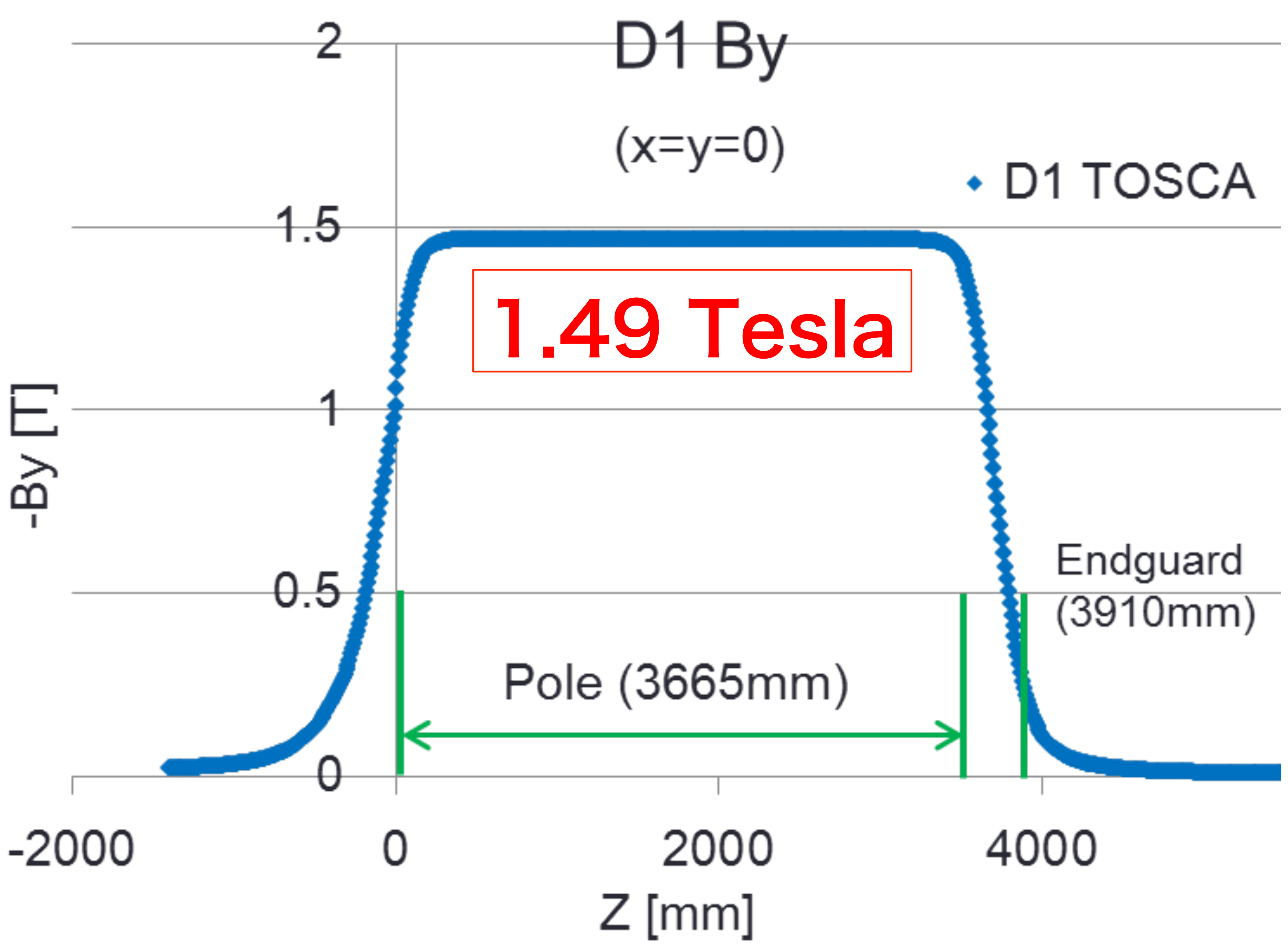
JAM simulation
$10^6 K^-$@1.8GeV/c, 3 g/cm^2, ^{12}C target

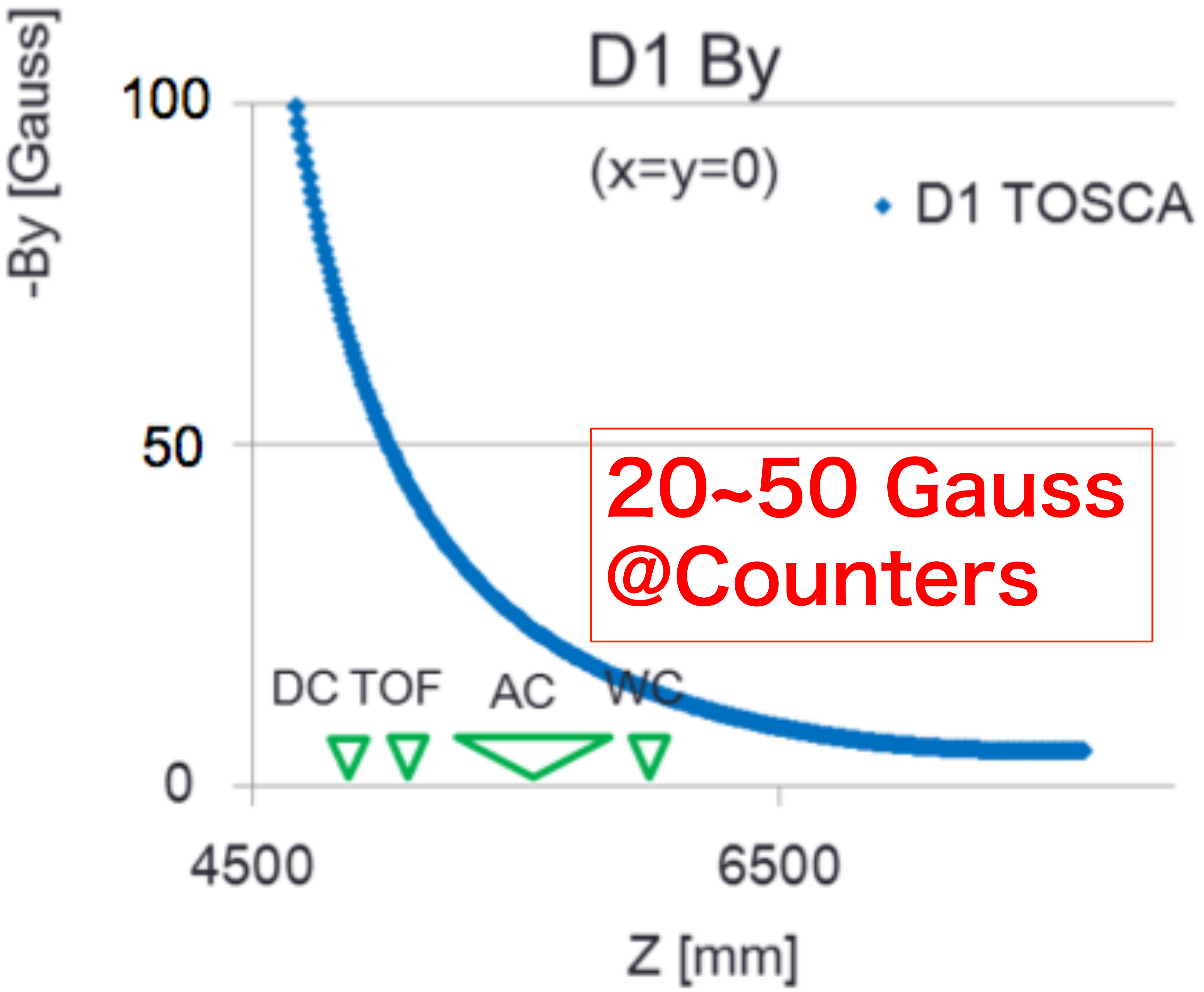




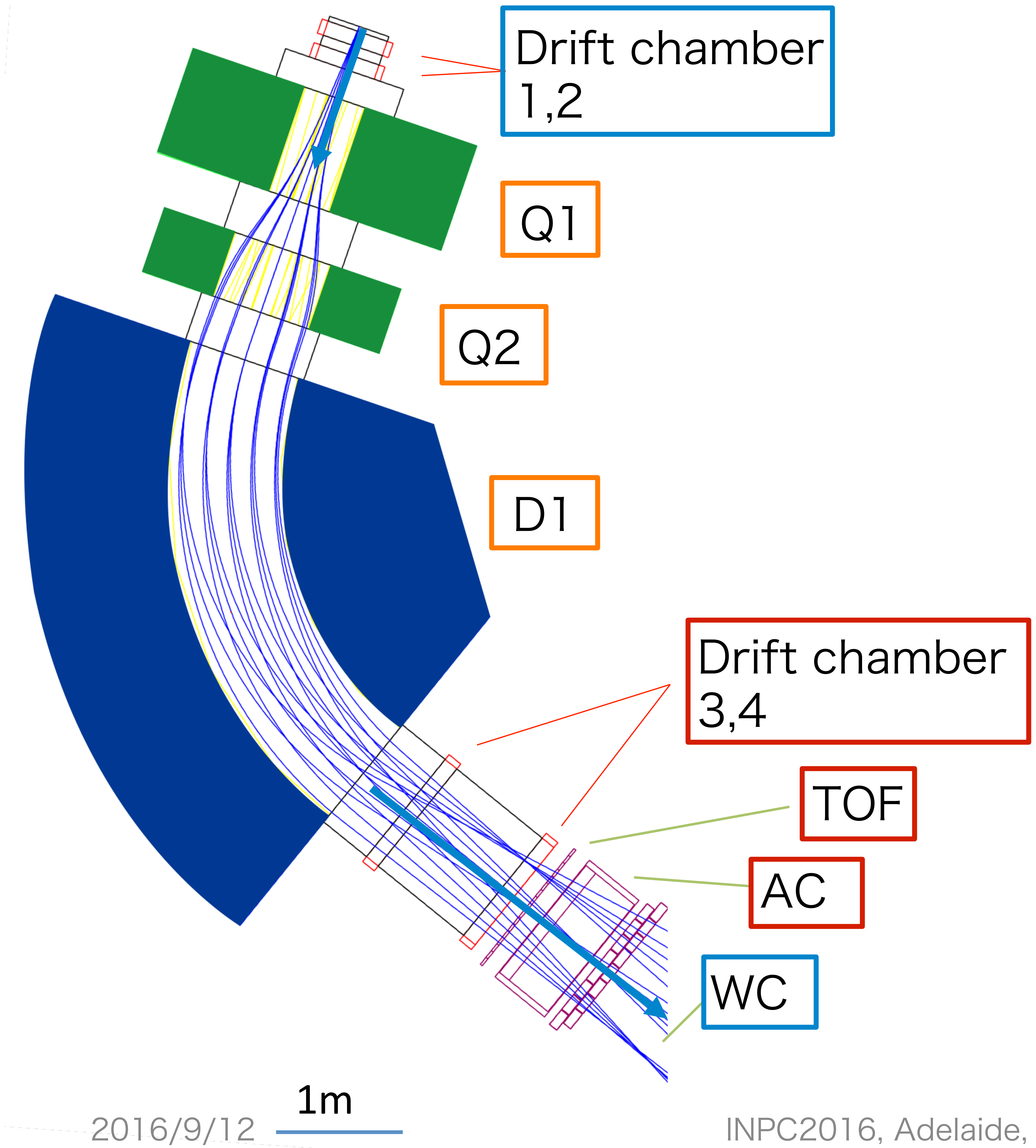
Field Calculation of D1

- Calculation by Opera/TOSCA-3d
  - Input model will be tuned after field measurement





Status Summary



Magnets

- Q1,Q2 : Ready
- D1 : Field measurement is ongoing

Existing Detectors

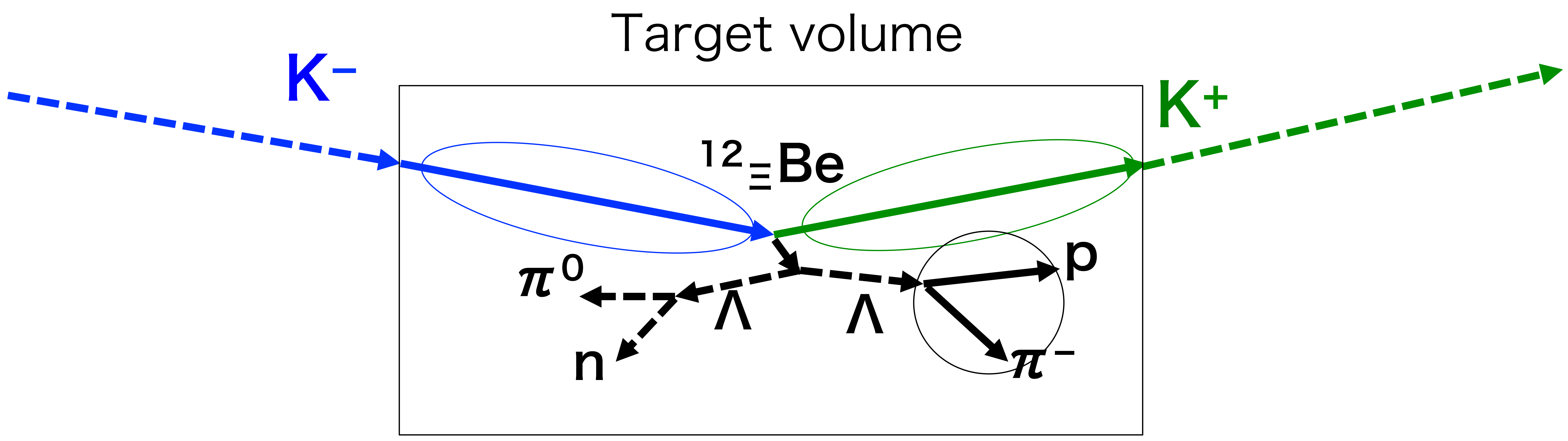
- DC 1
- DC 3,4
  - 1 m×1 m Drift chambers
  - Need some repairments
- AC
  - Ready

New Detectors

- TOF
  - plastic scintillator
- DC 2
  - 2.5mm-pitch, vertically large size
- Water Cherenkov
  - T. Gogami, et al., NIM A, 817 (2016) 70

Active Fiber Target

- Scintillating fiber
  - scintillation light yield → correction of the energy of kaons event-by-event

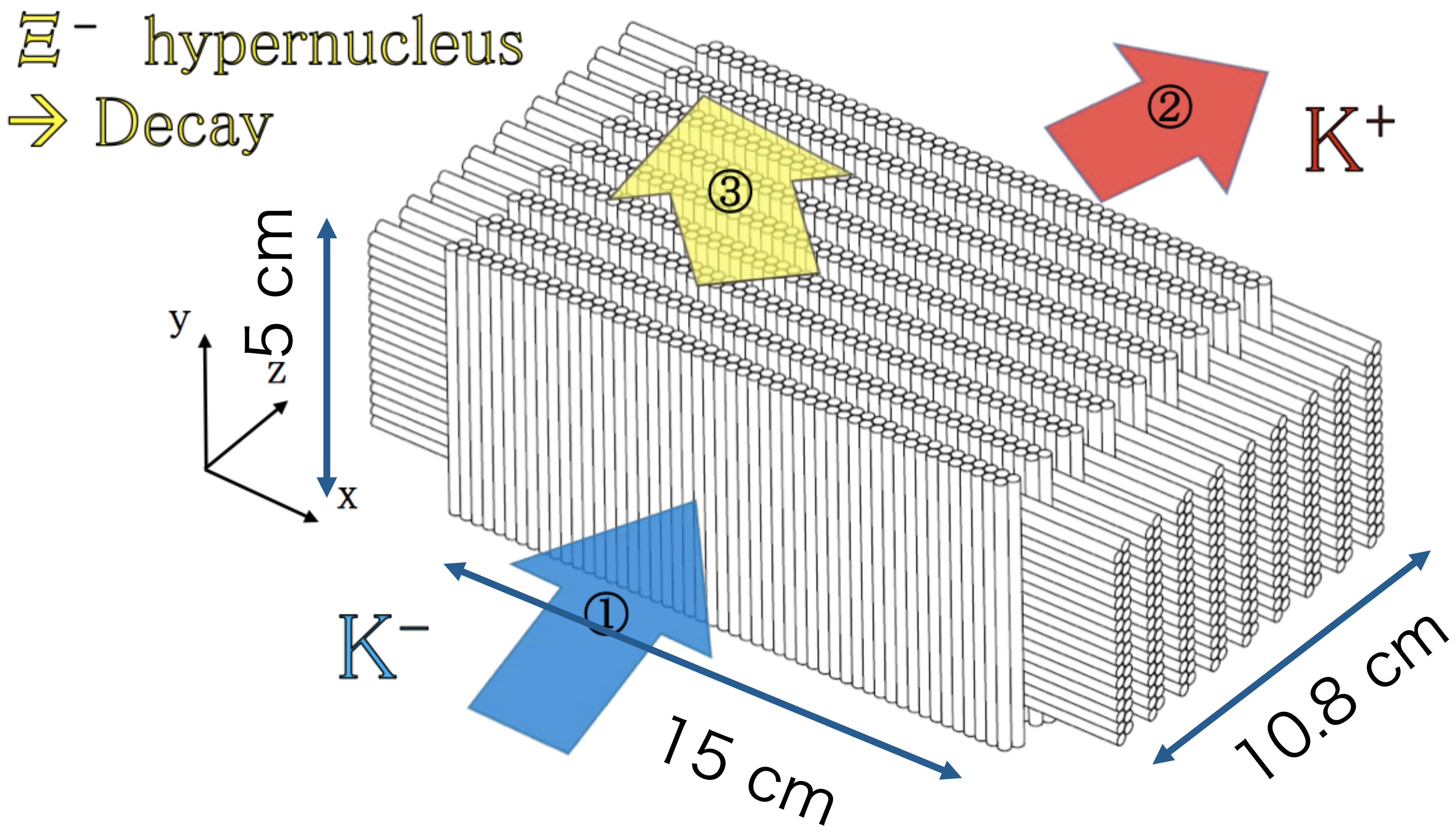


Energy losses of
- Beam K^-
- Scat. K^+
- Decay particles from hypernucleus

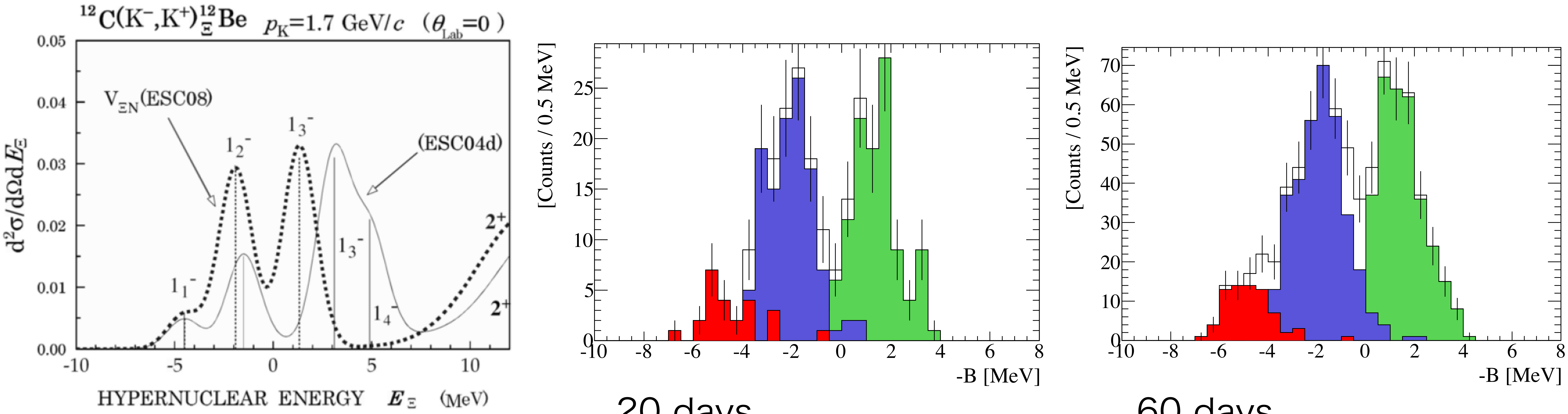
should be measured separately → Target must be segmented

Active Fiber Target

- Scintillating fiber bundle
  - 3x3 mm square or 3 mm Φ (→ 50×18+16×18 ≒ 1000)
  - MPPCs attached on the both ends of each fiber



Expected Spectrum



20 days

60 days

Three 1⁻ states with widths of 2.5 MeV_{FWHM}