Study of Λ-n Interaction via FSI in γ+d Reaction

- Feasibility in the NKS2 Experiment -

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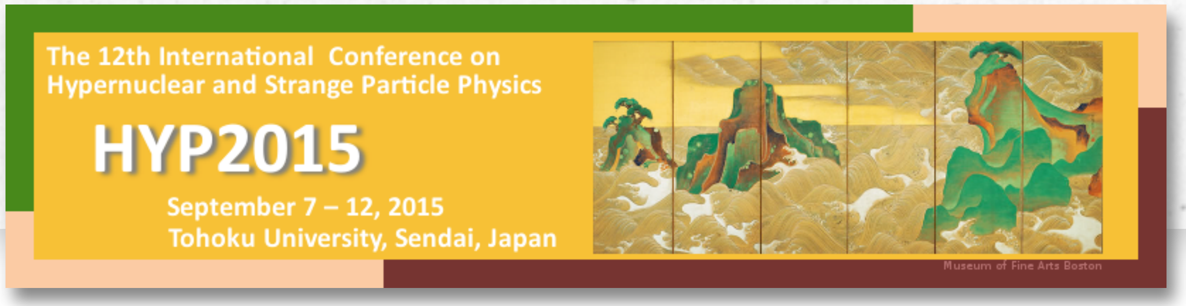
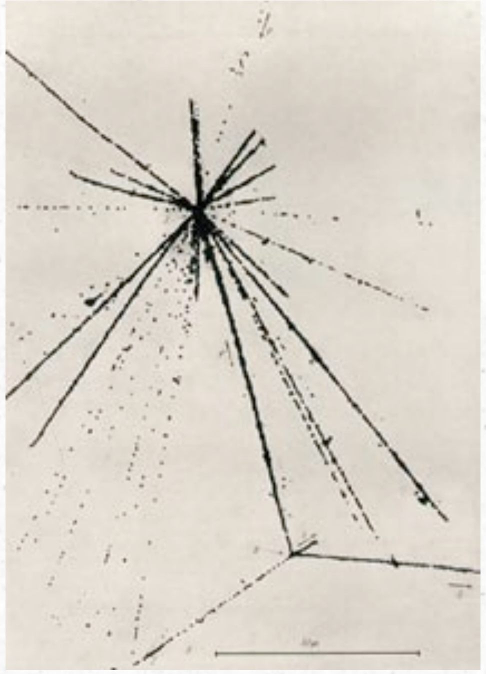
2015/9/7

TOHOKU UNIVERSITY



Motivation

- Study of nuclear force with strangeness
  - Hypernuclear experiment
    - Hadronic reaction
      - CERN-PS, BNL-AGS, KEK-PS, DAϕNE, J-PARC
    - Electro-Magnetic reaction
      - JLab, MAMI
    - Heavy ion reaction
      - GSI, BNL-RHIC, CERN-LHC
  - Hyperon-nucleon scattering
    - Λ-p at Fermi Lab, Σ-p at J-PARC
    - How about hyperon-n elastic scattering?



The first observation of a hypernucleus.

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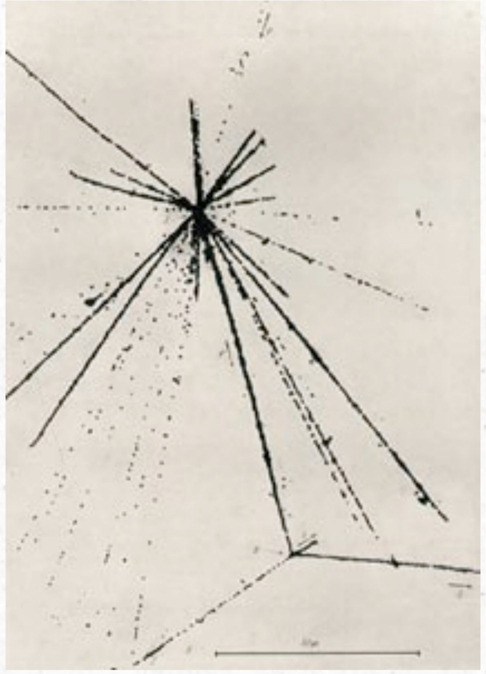

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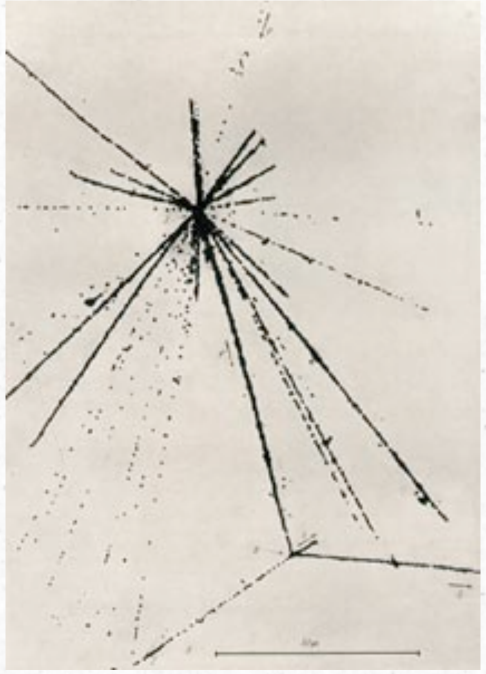
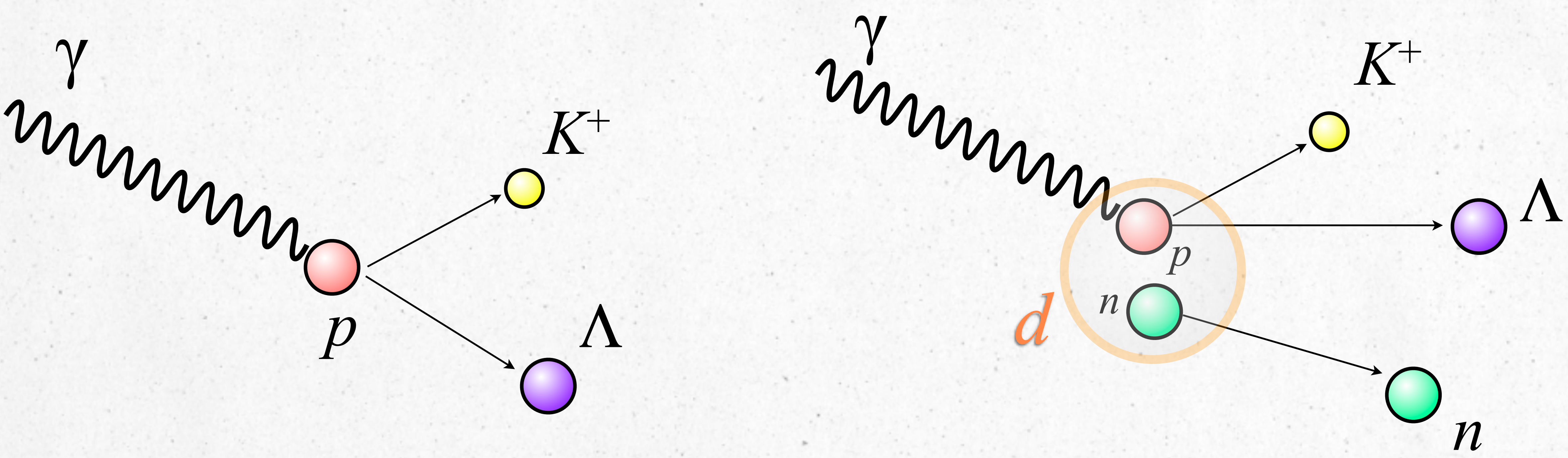


The first observation of a hypernucleus.

- We need the other data to understand NN, YN, YY force

How to Measure Λ*n* Interaction

- Using FSI in $\gamma + d$ reaction for $K^+ + \Lambda$ production



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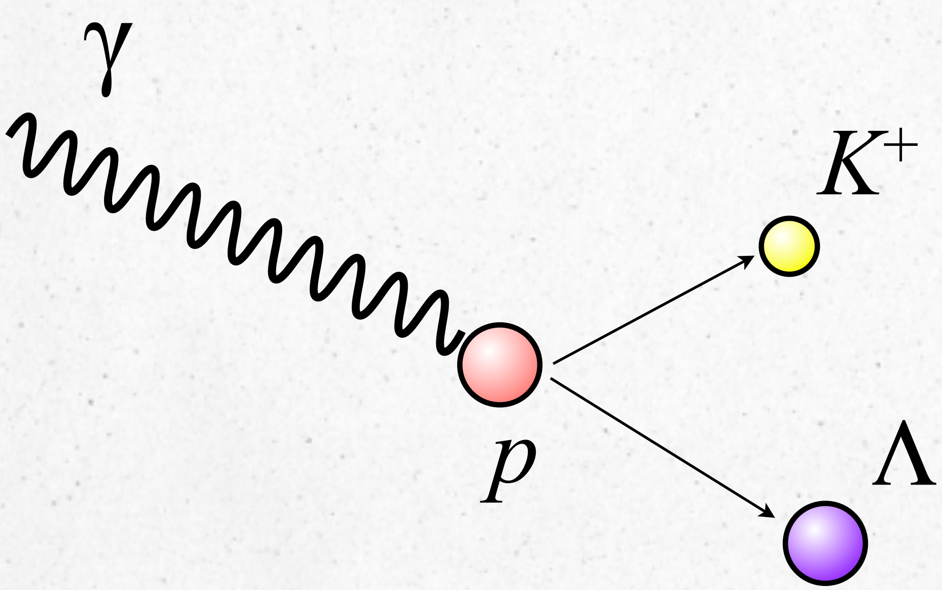

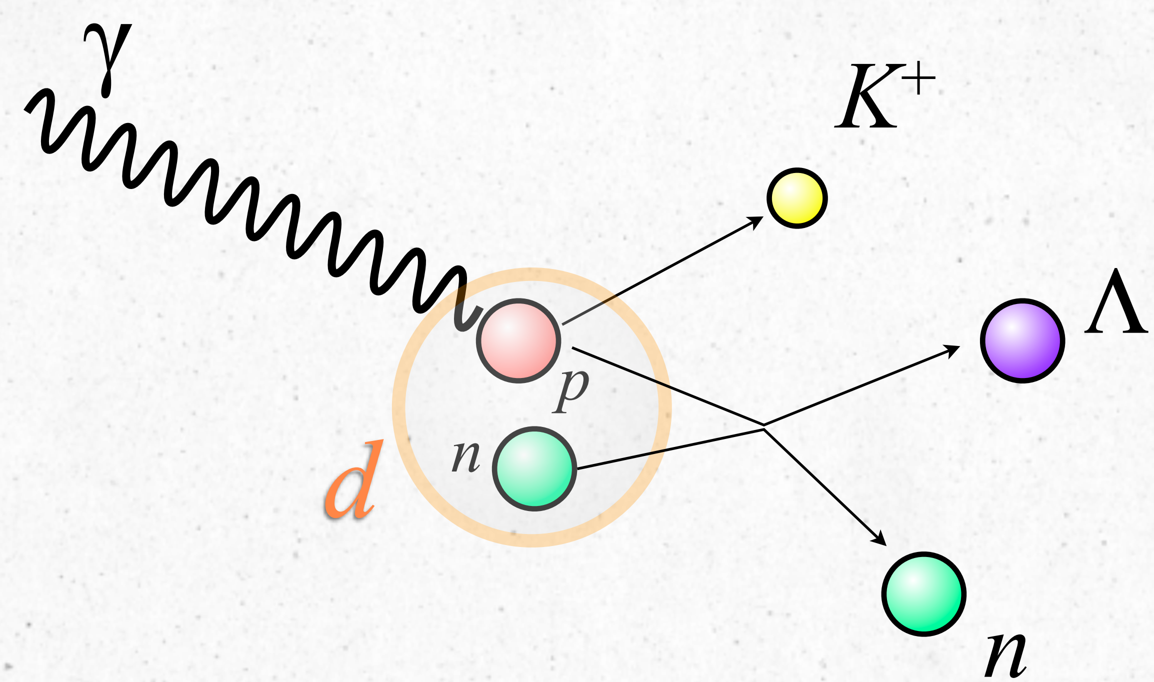

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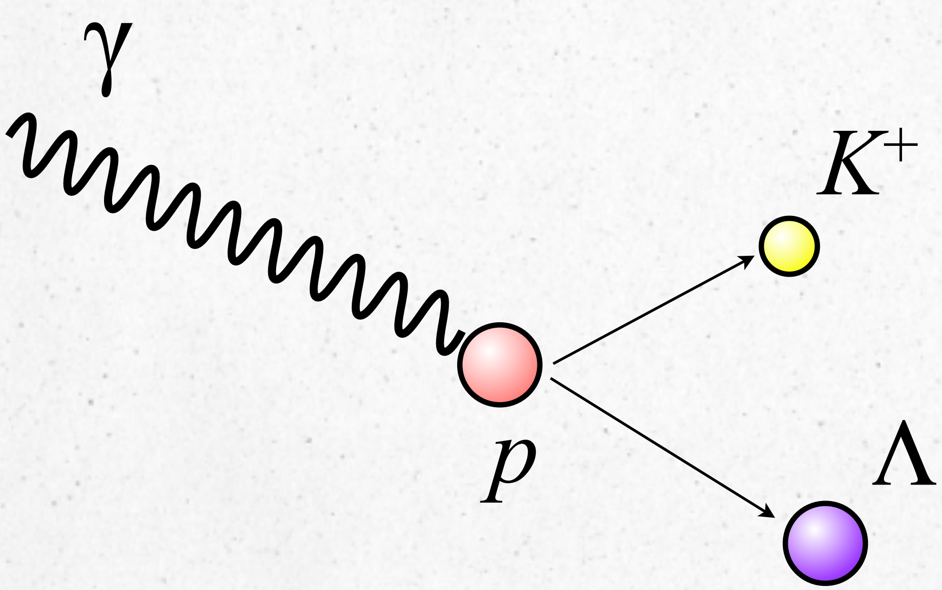

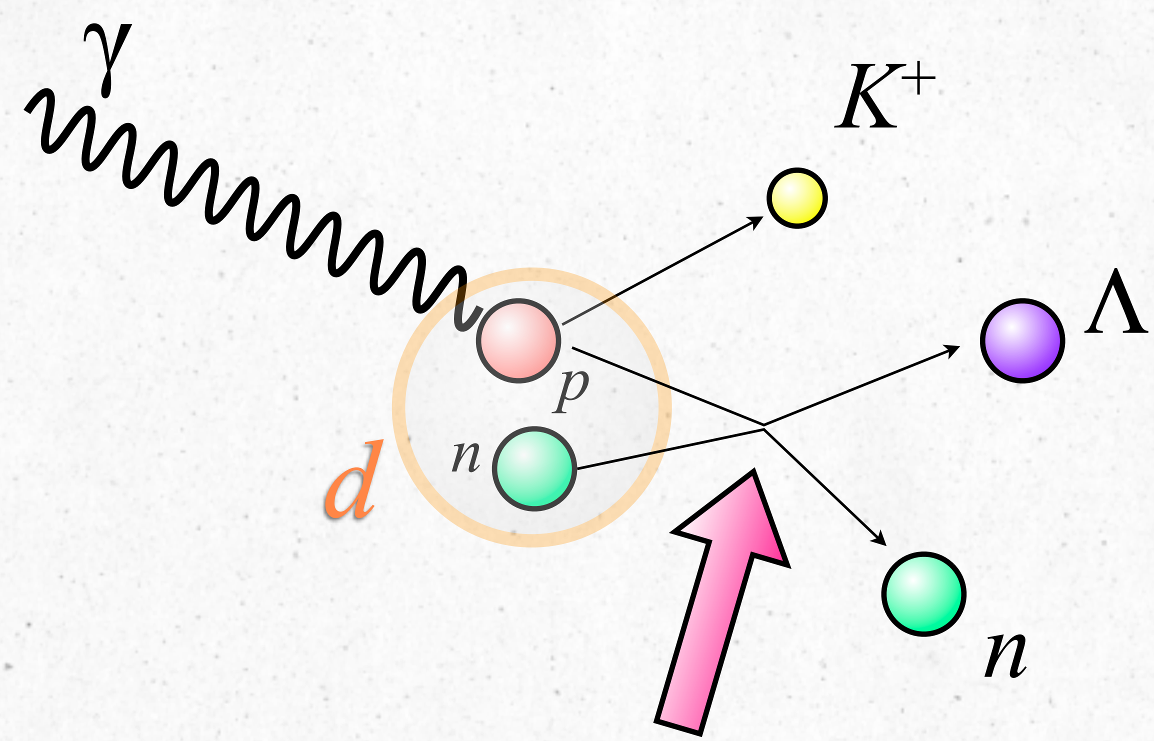

Λ*n* interaction
in Final State Interaction (FSI)

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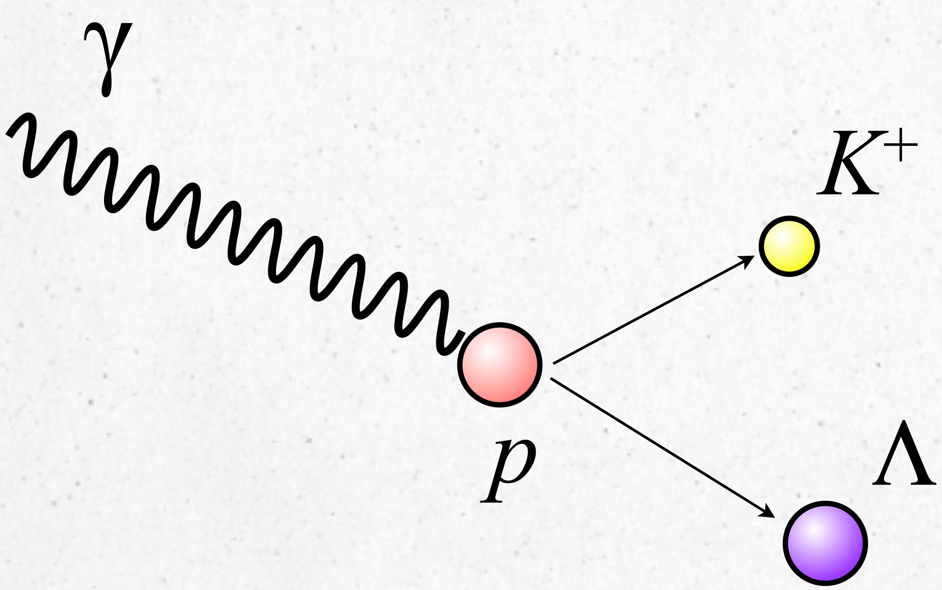
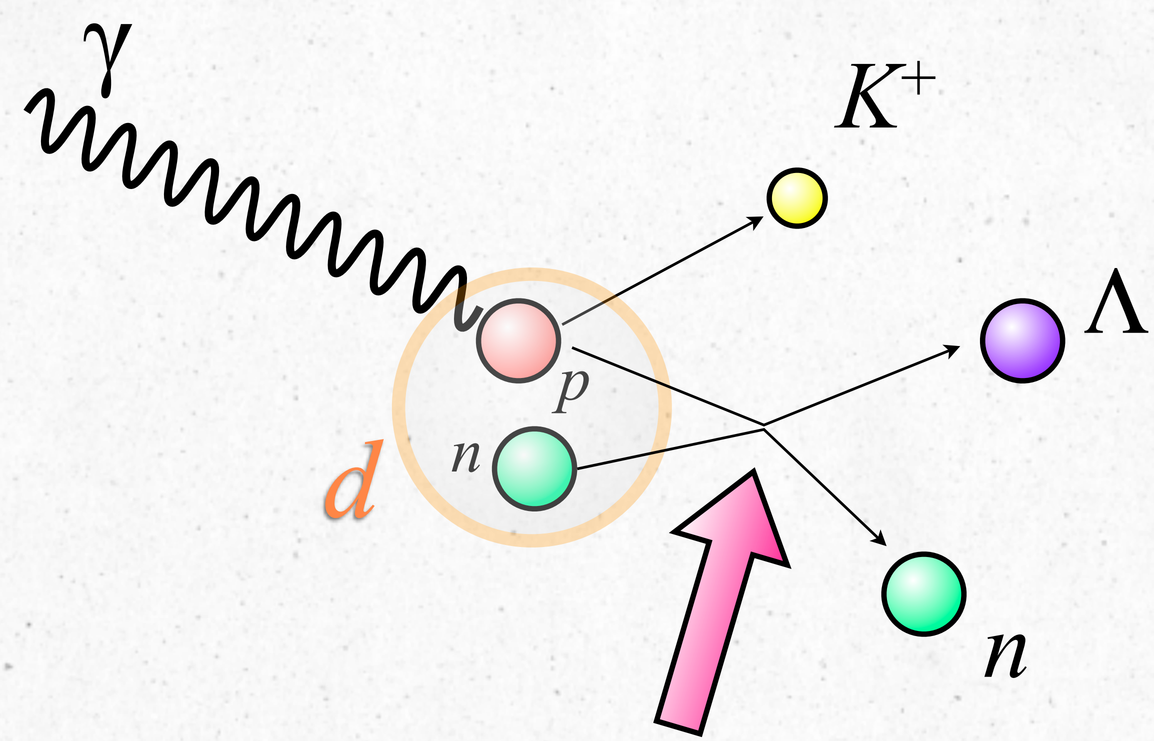




Λ*n* interaction
in Final State Interaction (FSI)

The other capability is $K^{-}+d \rightarrow \gamma + \Lambda + n$, but........

FSI Effect in the K^+ Cross-section

- The shape of the curves
  - Enhancement in forward K^+
  - variations: order of 10%
- Highly accurate measurements are required
  - in order to be able to distinguish among different potential models

R.A. Adelseck and L.E. Wright, Phys. Rev **C39** (1989) 580

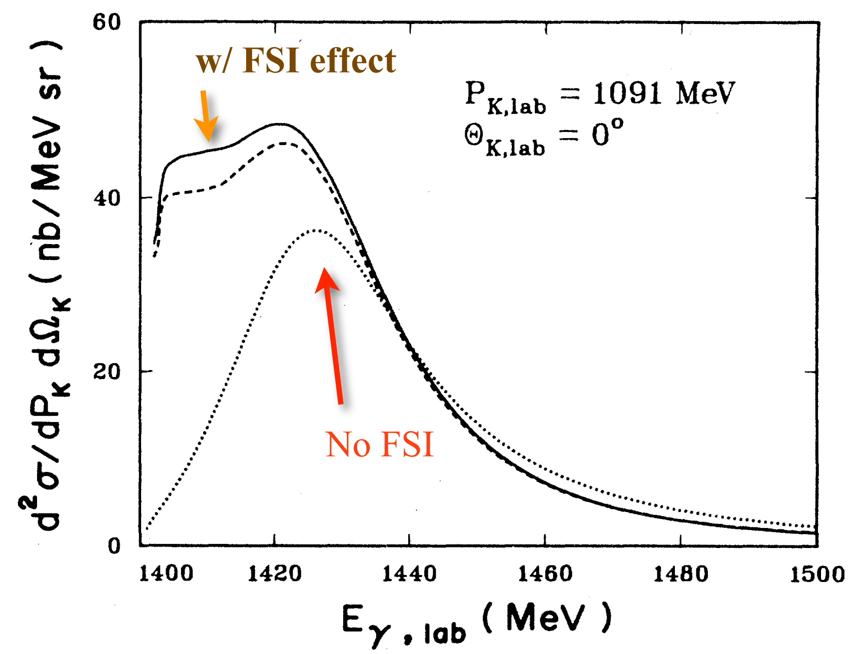


FIG. 8. Comparison of $d^2\sigma$ using the ΛN potential by Bhaduri *et al.* (— — —), the potential by Verma and Sural (——), and the plane-wave approximation (· · ·).

H.Yamamura et al., Phys. Rev **C61** (1999) 014001

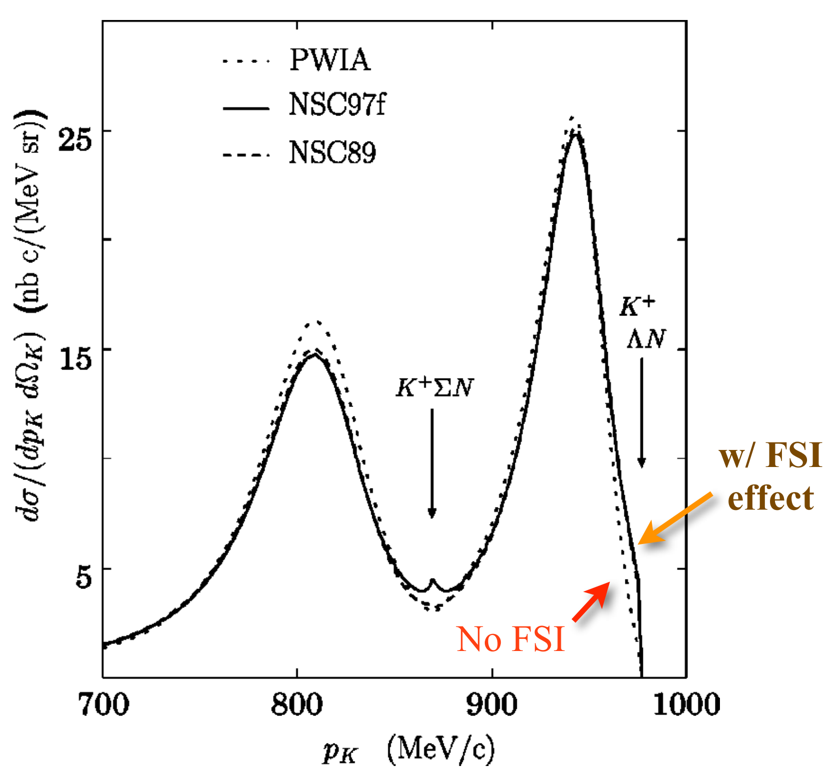
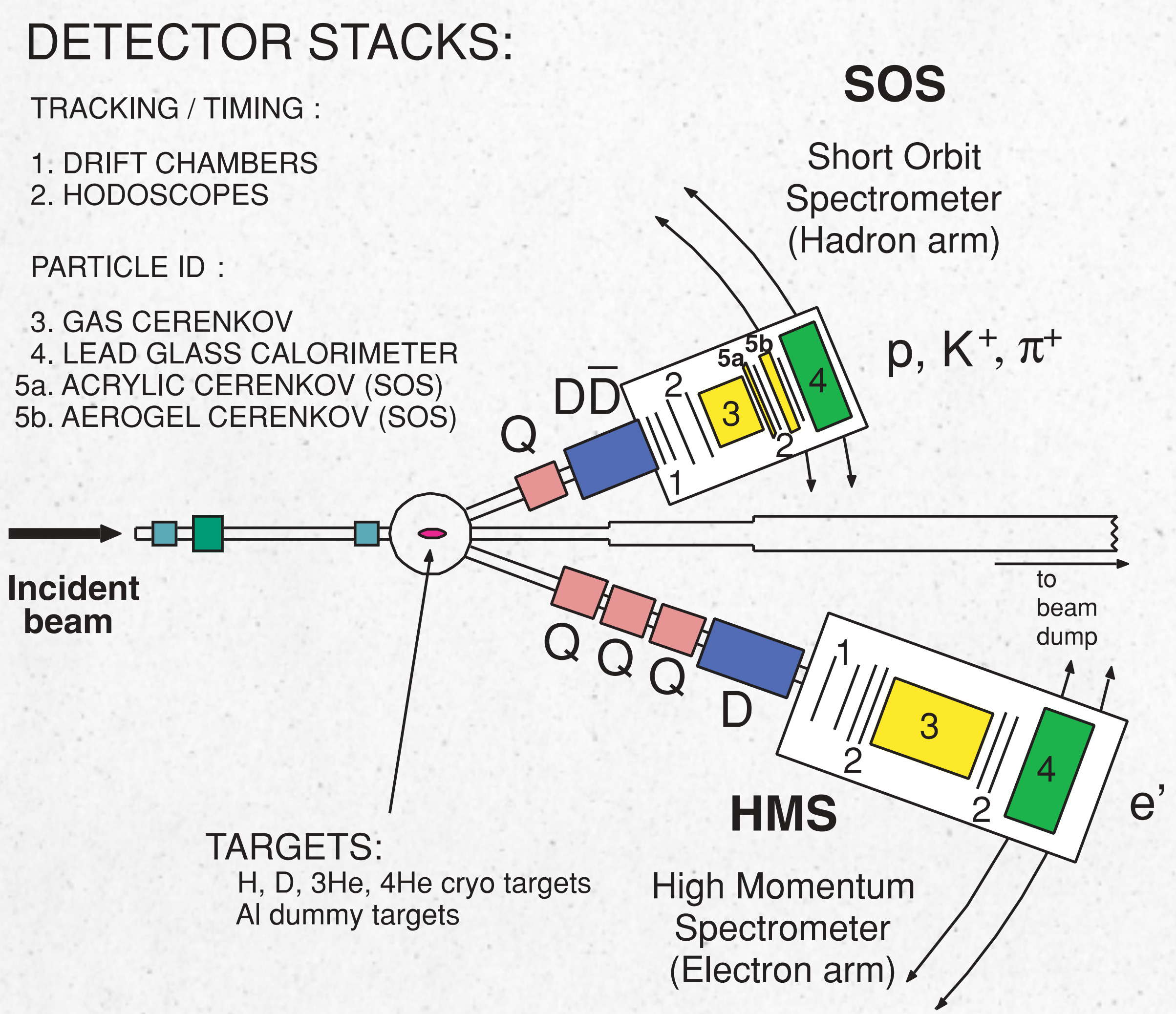


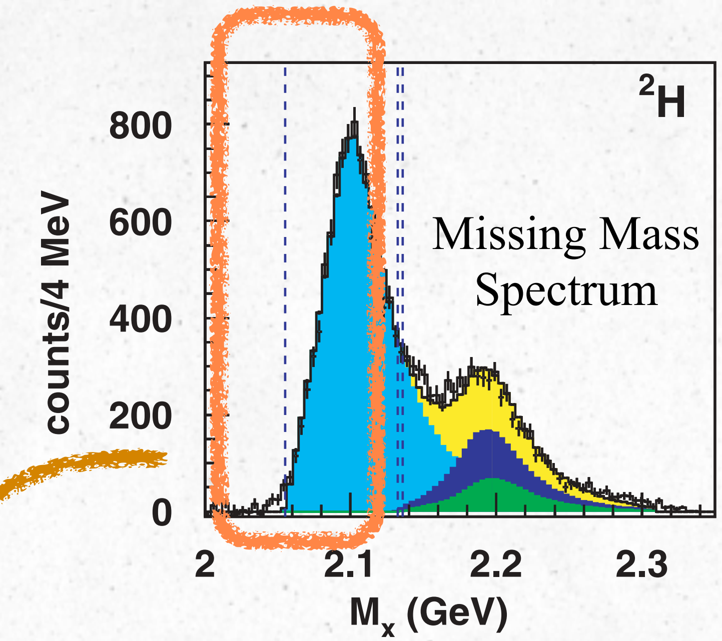
FIG. 2. The inclusive $\gamma(d,K^+)$ cross section as a function of lab momenta p_K for $\theta_K=0°$ and photon lab energy $E_\gamma=1.3$ GeV. The plane wave result is compared to two YN force predictions. The FSI effects are especially pronounced near the $K^+\Lambda N$ and $K^+\Sigma N$ thresholds, the locations of which are indicated by the arrows.

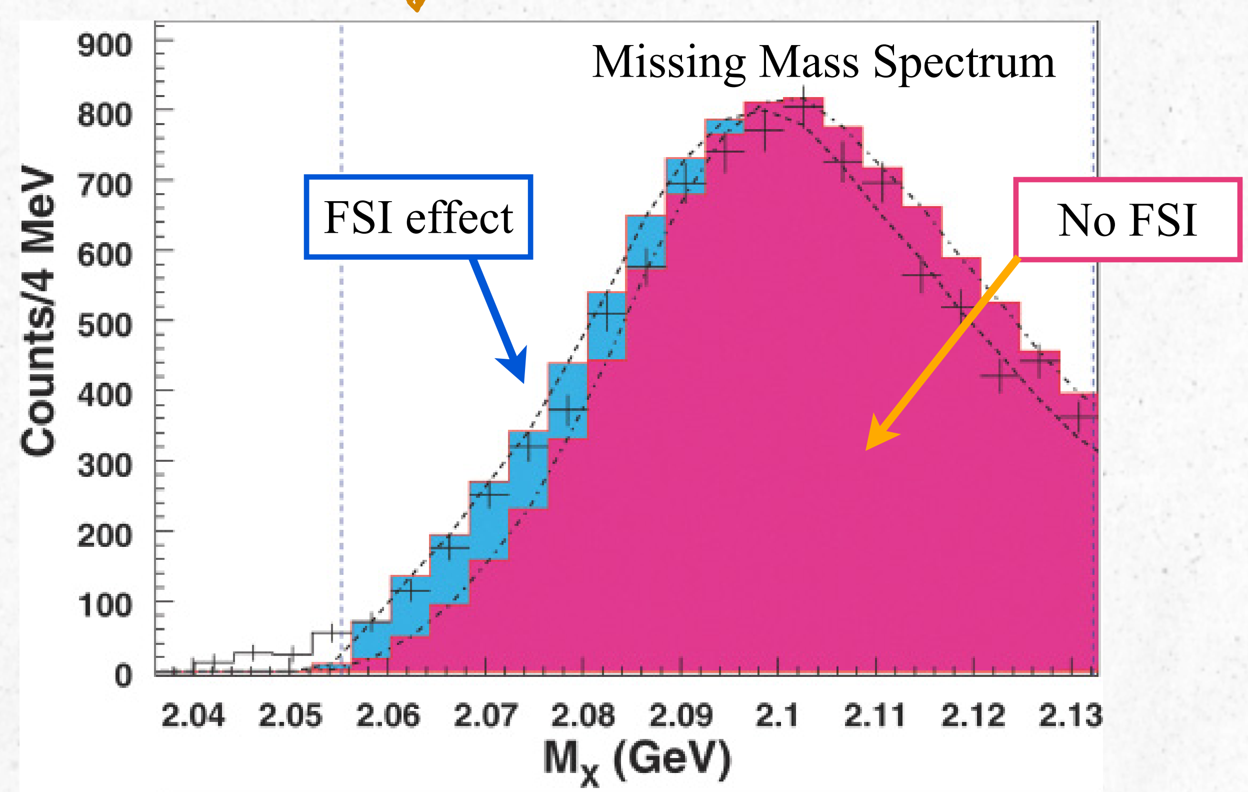
Preceded Experiment

- JLab Hall C E91-016
  - A(*e*,*e*'*K*$^+$)Λ*n* reaction
    - A = ^{1}H, ^{2}H, ^{3}He, ^{4}He
  - Q^2=0.35 (GeV/*c*)^2, W = 1.91 GeV



Phys. Rev. C76 (2007) 054004





Scattering length *a* = -2.68 [fm] (from Nijmegen 89)
Effective range *r* = 2.91[fm] (from Nijmegen 97f)
are fixed for estimation

Study about Λp Interaction

Eur. Phys. J. A **21**, 313–321 (2004)
DOI 10.1140/epja/i2003-10203-3

THE EUROPEAN PHYSICAL JOURNAL A

Analysis of the Λp final-state interaction in the reaction $p + p \rightarrow K^+(\Lambda p)$

F. Hinterberger[1,a] and A. Sibirtsev[2,3]

2.2 Final-state interaction

In the Watson-Migdal approximation [38–40] the FSI is taken into account by introducing a FSI enhancement factor $|C_{\mathrm{FSI}}|^2$,

$$\frac{d^2\sigma}{d\Omega_K dM_{\Lambda p}} = |\mathcal{M}|^2 \, |C_{\mathrm{FSI}}|^2 \, \Phi_3, \qquad (3)$$

where now $\mathcal{M}$ is a pure production matrix element and the FSI amplitude C_{FSI} depends on the internal momentum q of the Λp subsystem. It converges to 1 for $q \rightarrow \infty$ where the S-wave FSI enhancement vanishes.

$$C_{\mathrm{FSI}} = \frac{q - i\beta}{q + i\alpha}, \qquad |C_{\mathrm{FSI}}|^2 = \frac{q^2 + \beta^2}{q^2 + \alpha^2}. \qquad (4)$$

The potential parameters α and β can be used to establish phase-equivalent Bargmann potentials [44,45]. They are related to the scattering lengths a, and effective ranges r of the low-energy S-wave scattering

$$\alpha = \frac{1}{r}\left(1 - \sqrt{1 - 2\frac{r}{a}}\right), \quad \beta = \frac{1}{r}\left(1 + \sqrt{1 - 2\frac{r}{a}}\right). \qquad (5)$$

The Λp system can couple to singlet $^1S_0$ and triplet $^3S_1$ states. Near production threshold the singlet-triplet transitions due to the final-state interaction cannot occur. Therefore, the contributions of the spin-singlet and spin-triplet final states can be added incoherently. Taking the spin-statistical weights into account the unpolarized double differential cross-section may be written as

$$\frac{d^2\sigma}{d\Omega_K dM_{\Lambda p}} = \Phi_3 \left[0.25\,|\mathcal{M}_s|^2 \frac{q^2 + \beta_s^2}{q^2 + \alpha_s^2} + 0.75\,|\mathcal{M}_t|^2 \frac{q^2 + \beta_t^2}{q^2 + \alpha_t^2} \right]. \qquad (6)$$

This equation leaves six free parameters, the singlet and triplet potential parameters α_s, β_s, α_t, β_t and the production matrix elements $|\mathcal{M}_s|$ and $|\mathcal{M}_t|$. Instead of the parameters α_s, β_s, α_t and β_t one can equally well use the singlet and triplet scattering length and effective-range parameters a_s, r_s, a_t and r_t. The functional dependence on the invariant mass $M_{\Lambda p}$ can be evaluated by inserting the corresponding expression for the internal momentum q of the Λp system,

$$q = \frac{\sqrt{M_{\Lambda p}^2 - (m_\Lambda + m_p)^2}\sqrt{M_{\Lambda p}^2 - (m_\Lambda - m_p)^2}}{2M_{\Lambda p}}. \qquad (7)$$

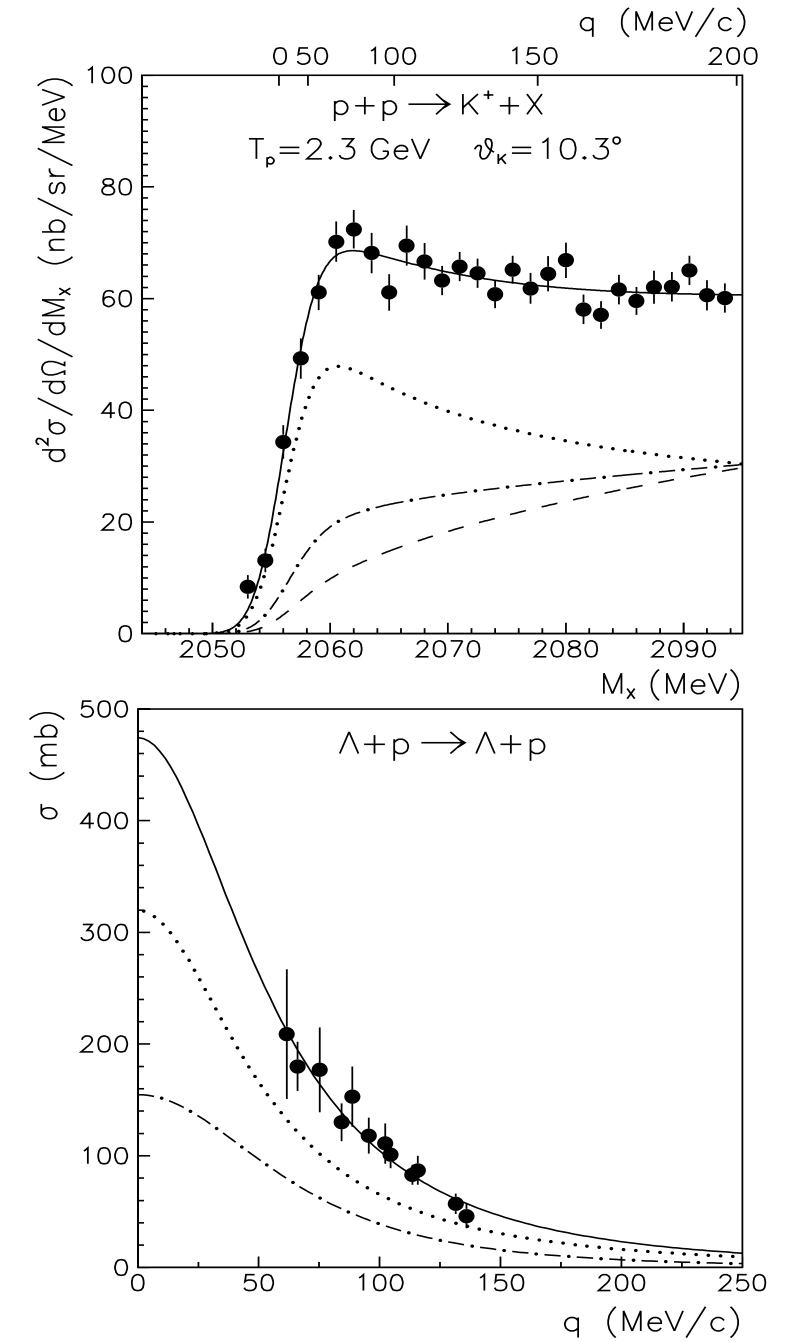
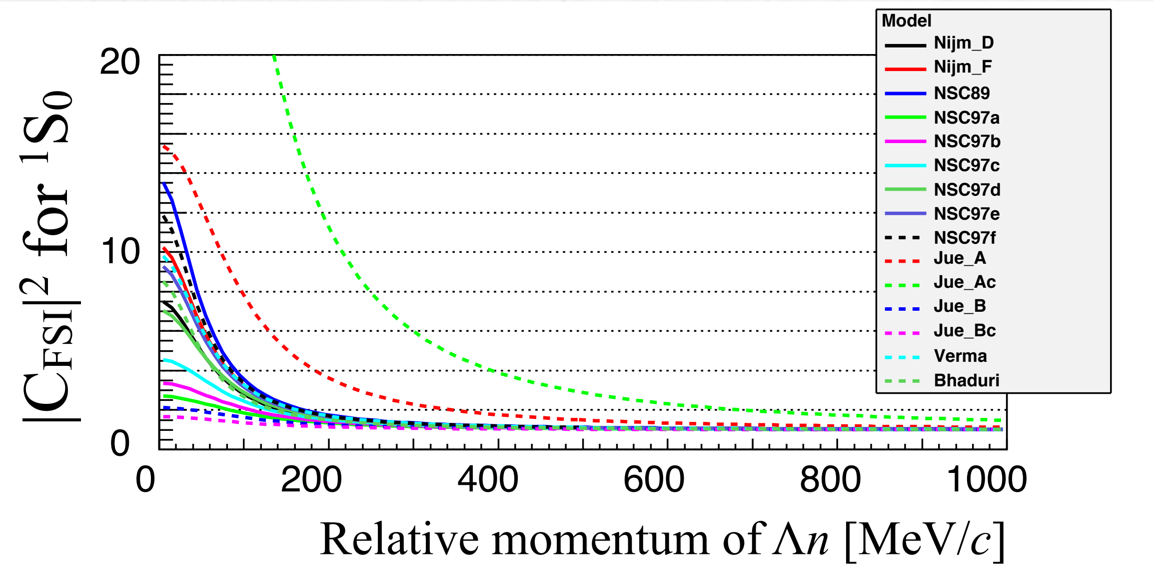


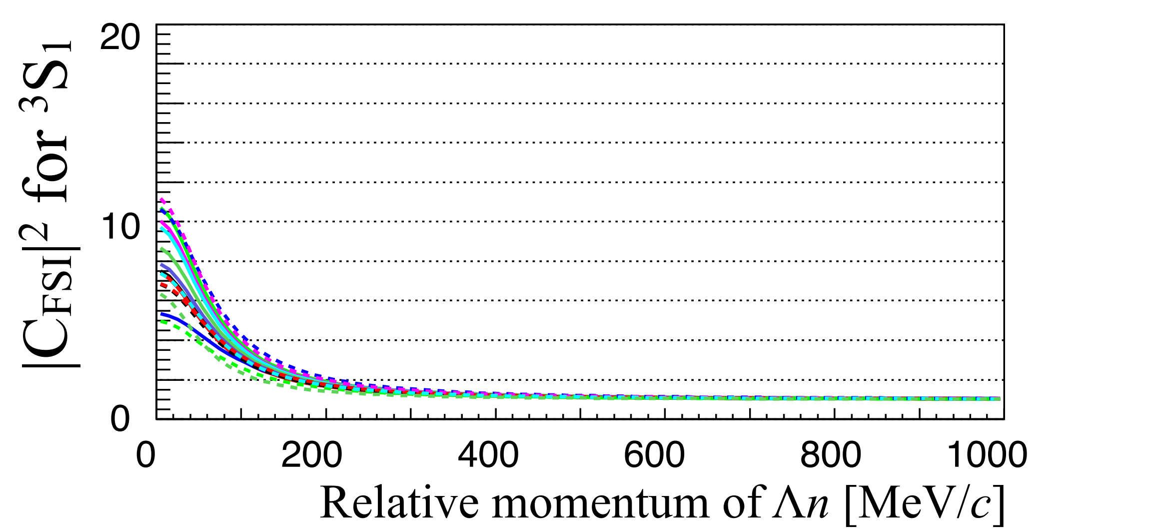
Fig. 4. Same as in fig. 1. Solid lines: Fit curves with parameters given by eq. (15) from a combined five-parameter fit of the missing-mass spectrum and the total-cross-section data, dashed line: phase space distribution, dotted lines: singlet contributions, dash-dotted lines: triplet contributions.

Enhancement Factors of Λn FSI

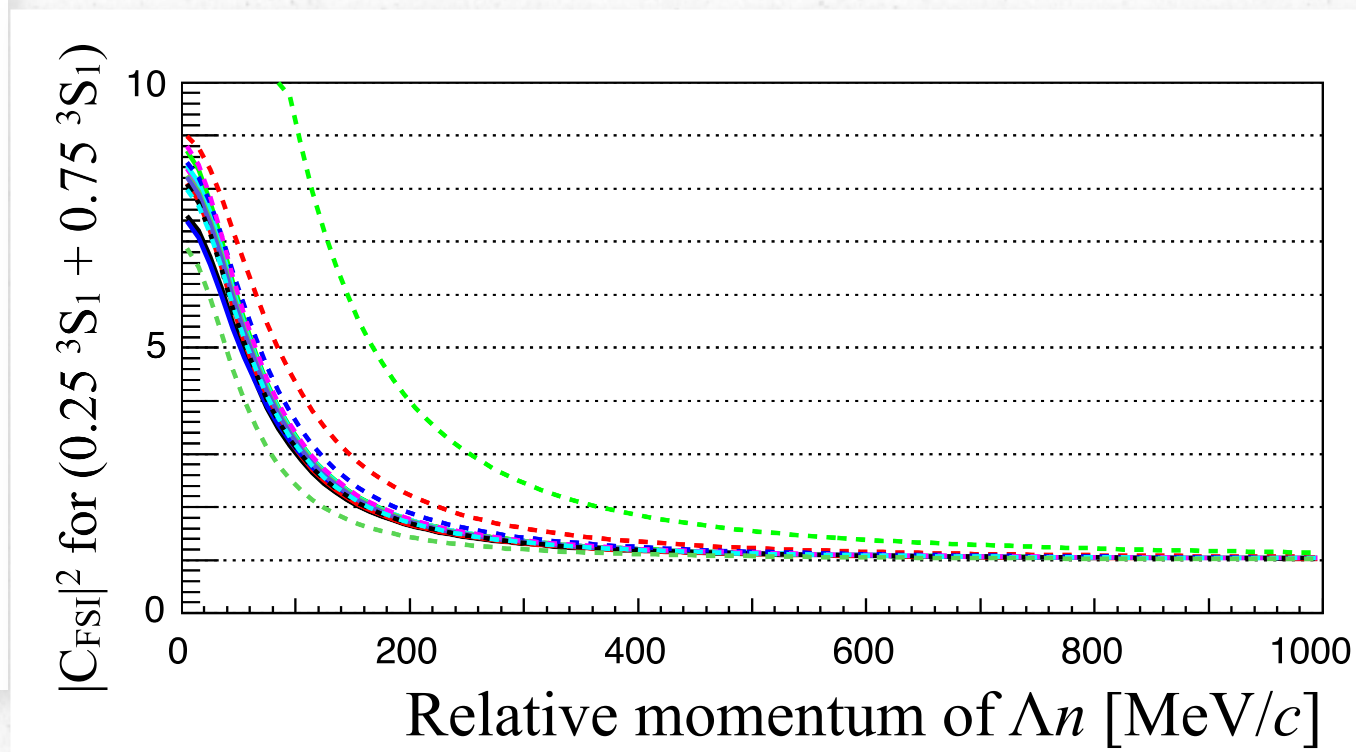
$$|C_{\mathrm{FSI}}|^2 = \frac{q^2+\beta^2}{q^2+\alpha^2}\,.$$

$$\alpha = \frac{1}{r}\left(1-\sqrt{1-2\frac{r}{a}}\right),\quad \beta = \frac{1}{r}\left(1+\sqrt{1-2\frac{r}{a}}\right).$$





	Refs.	a_s [fm]	r_s [fm]	a_t [fm]	r_t [fm]
Nijmegen D	PRD15 (1977) 2547	-2.03	3.66	-1.84	3.32
Nijmegen F	PRD20 (1979) 1633	-2.40	3.15	-1.84	3.37
NSC89	PRC40 (1989) 2226	-2.86	2.91	-1.24	3.33
NSC97a	PRC59 (1999) 3009	-0.77	6.09	-2.15	2.71
NSC97b		-0.97	5.09	-2.09	2.80
NSC97c		-1.28	4.22	-2.07	2.86
NSC97d		-1.82	3.52	-1.94	3.01
NSC97e		-2.24	3.24	-1.83	3.14
NSC97f		-2.68	3.07	-1.67	3.34
Jülich A (ΛN)	NPA570 (1994) 543	-1.56	1.43	-1.59	3.16
Jülich A~ (ΛN)		-2.04	0.64	-1.33	3.91
Jülich B (ΛN)		-0.56	7.77	-1.91	2.43
Jülich B~ (ΛN)		-0.40	12.28	-2.12	2.57
Verma	PRC22 (1980) 229	-2.29	3.14	-1.77	3.25
Bhaduri (Set I, ΛN)	PR 155 (1967) 1671	-2.46	3.87	-2.07	4.50



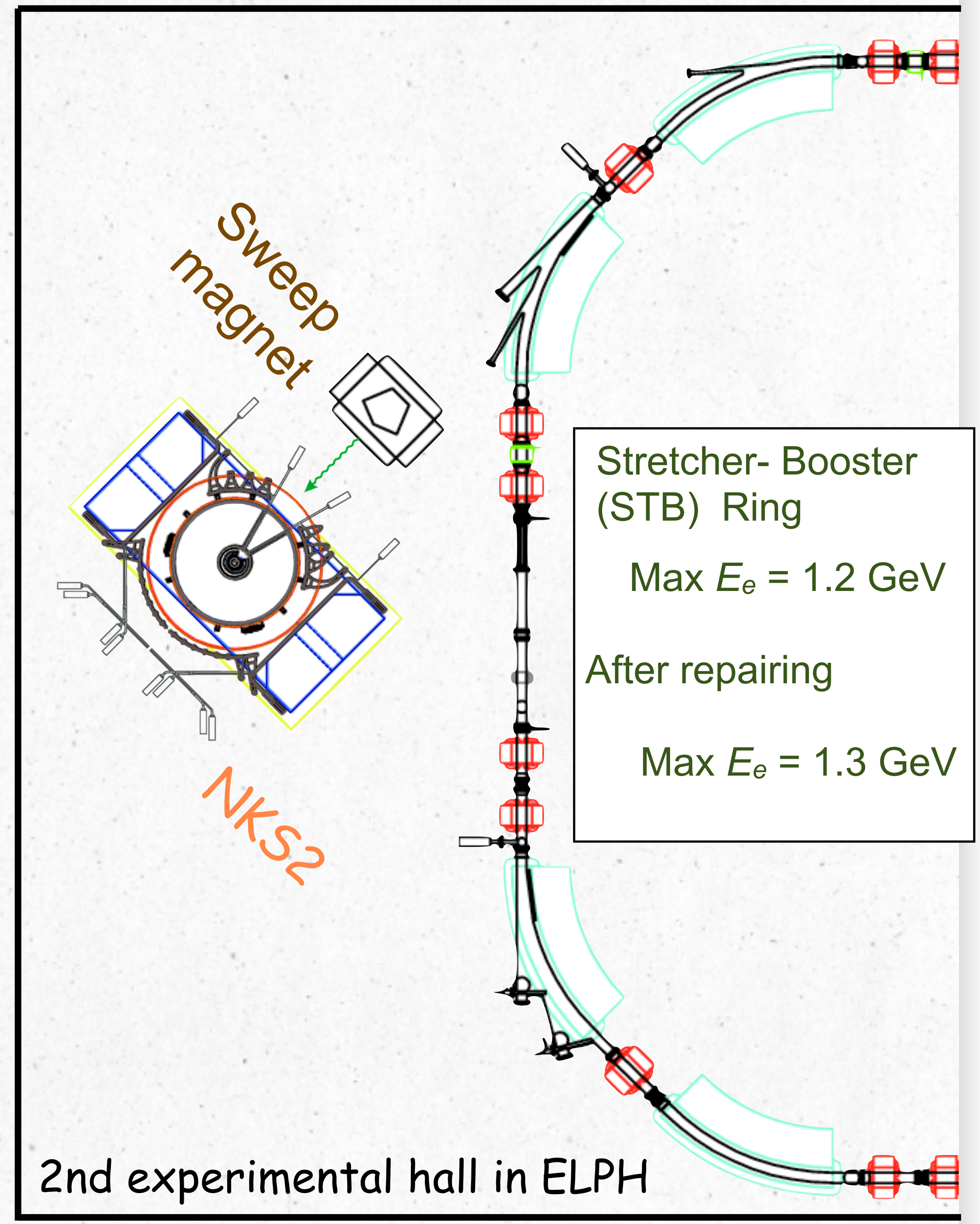
Note: It is assumed that the production matrix of single and triplet are the same.

NKS2 Experiment

(The recent results will be shown
in Parallel 2b by H. Kanda)

Photon Beam Line

in Research Center of Electron Photon Science (ELPH), Tohoku Univ.



Photon Beam Line

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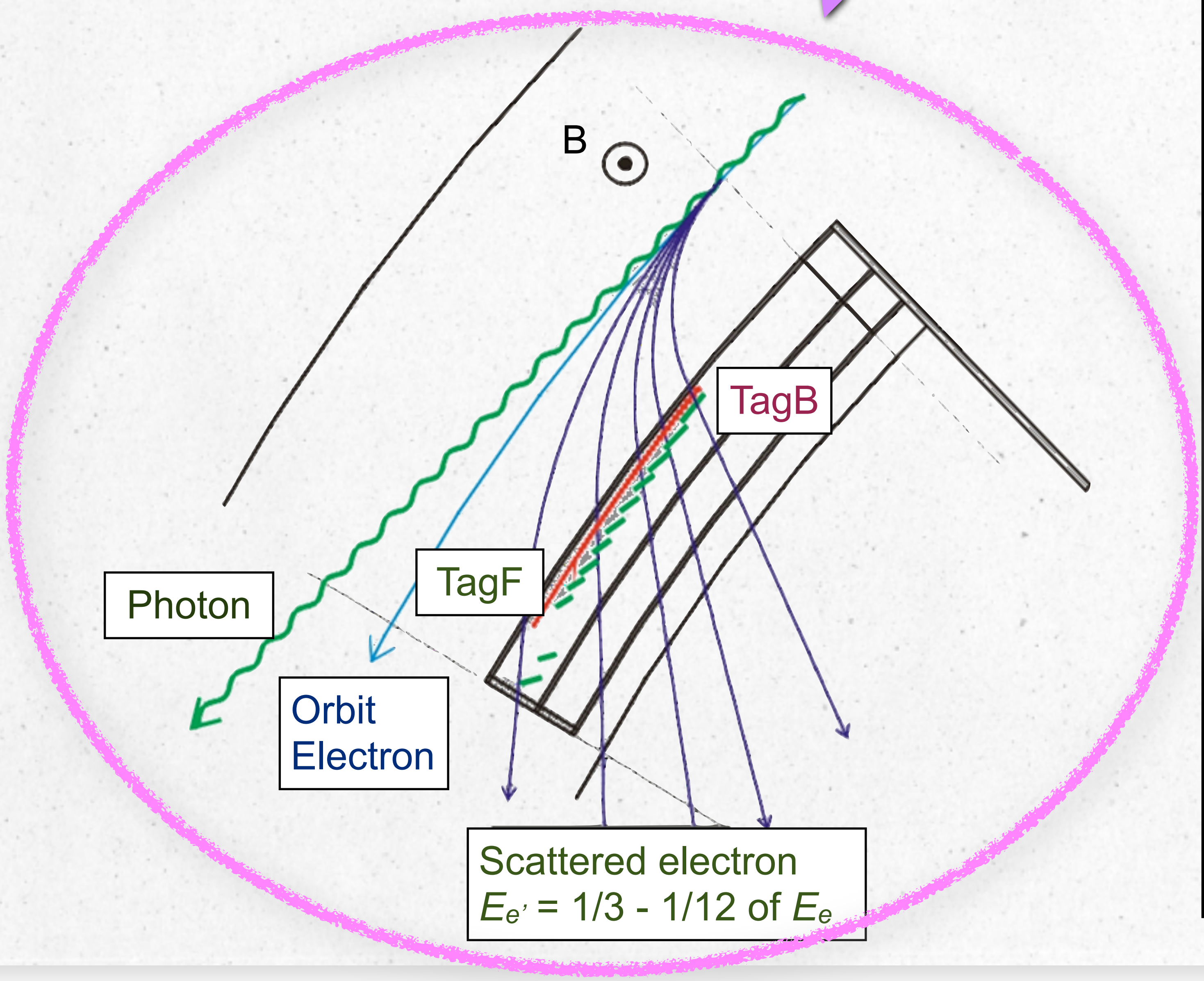
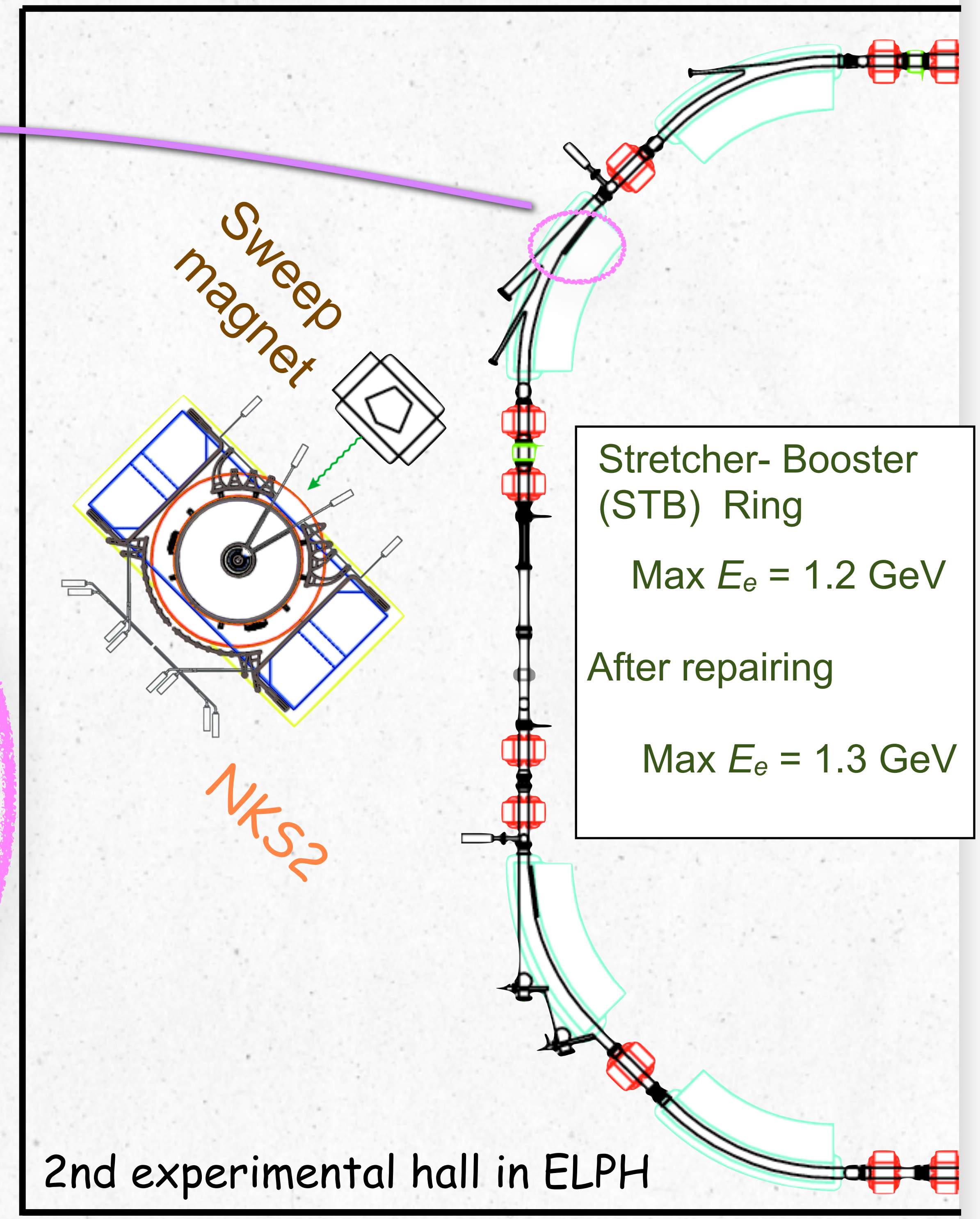
Tagged Photon Rate: 1-3 MHz

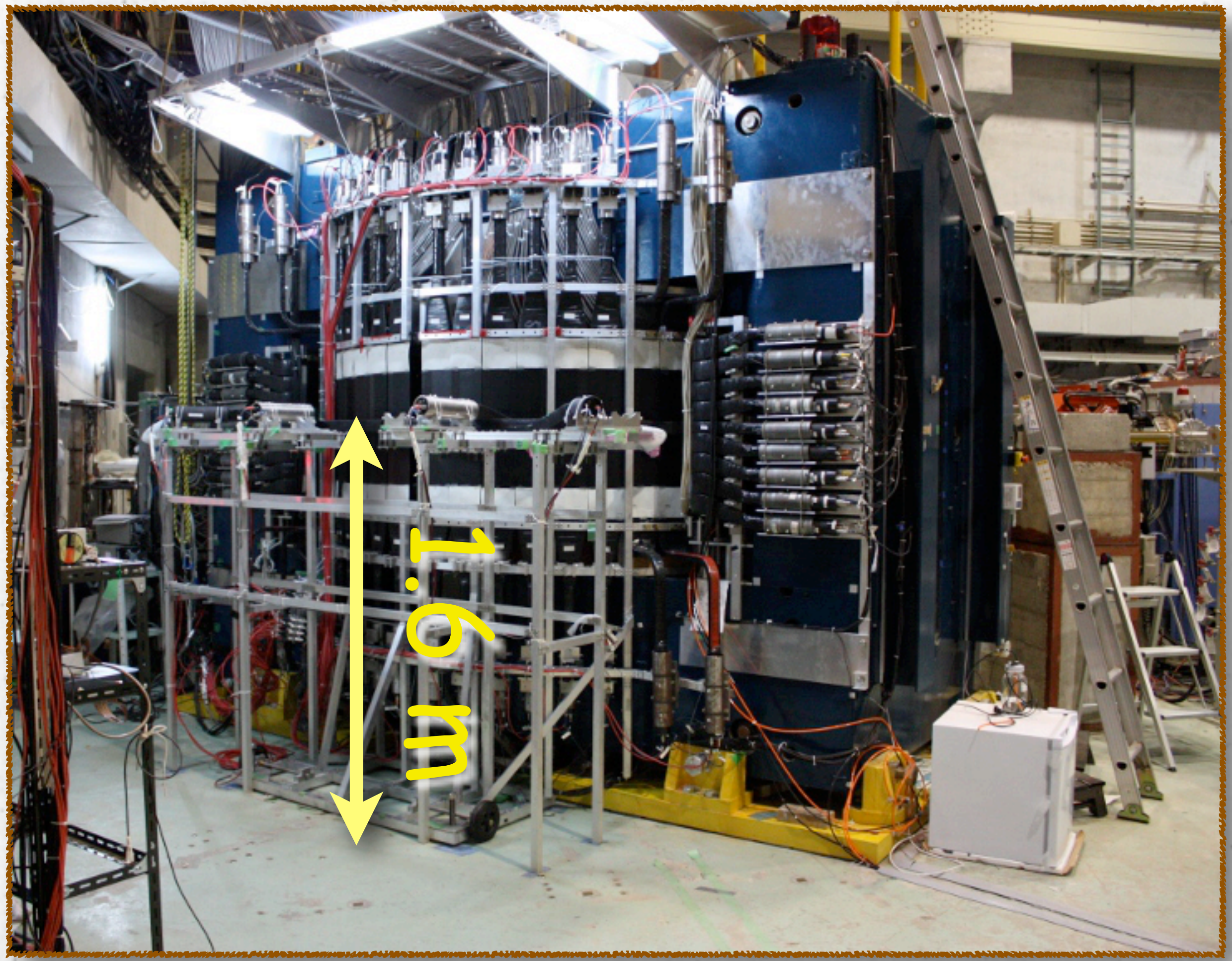
Duty Factor: ~85%

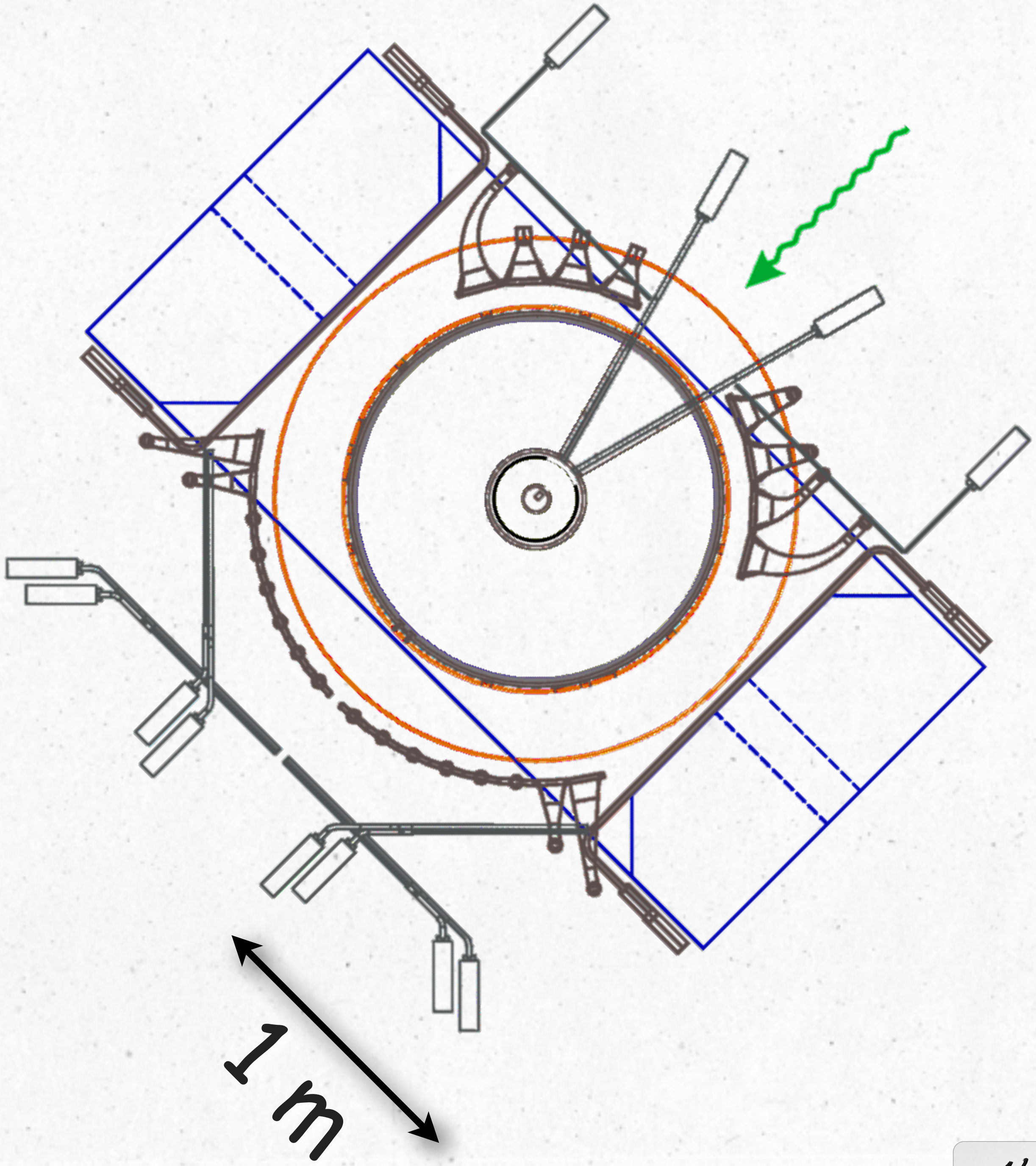




The NKS2 Experiment

- Tagged photon beam
  - E_γ = 0.80-1.08 GeV
- Liquid D_2 or H_2 target
- Magnetic spectrometer
  - Tracker
    - Two drift chambers
    - Charged particle momentum, trajectory, and decay vertex
  - Hodoscopes
    - Plastic scintillator + PMT
    - Time-Of-Flight (TOF)
    - Particle identification combined with momentum
  - Electron Veto
- Acceptance
  - Covering large kinematic region including forward angle





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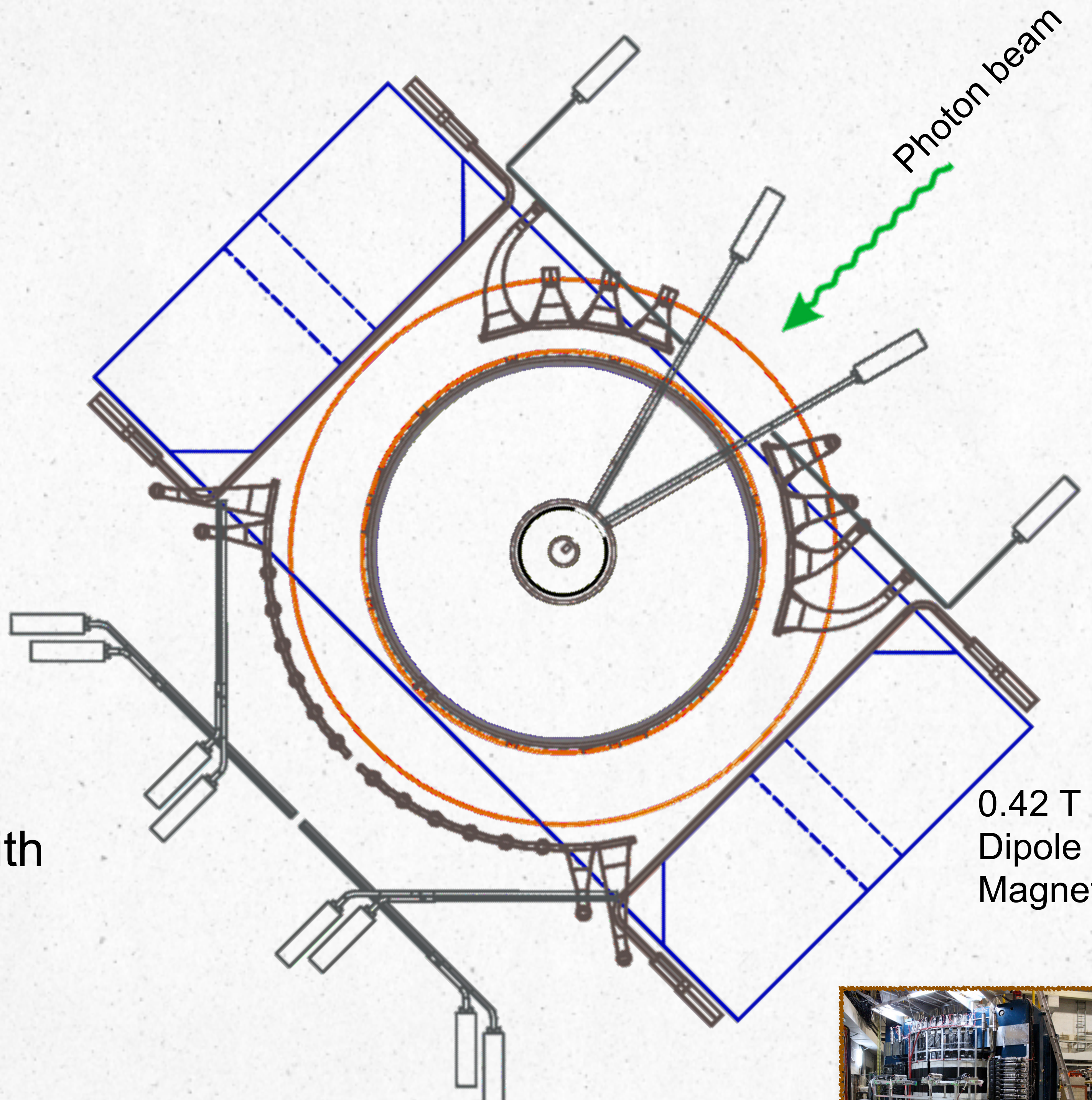

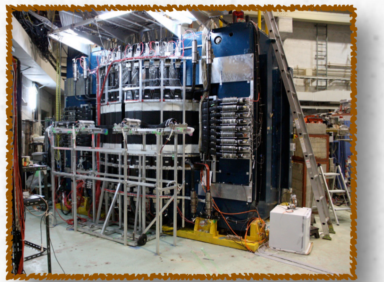

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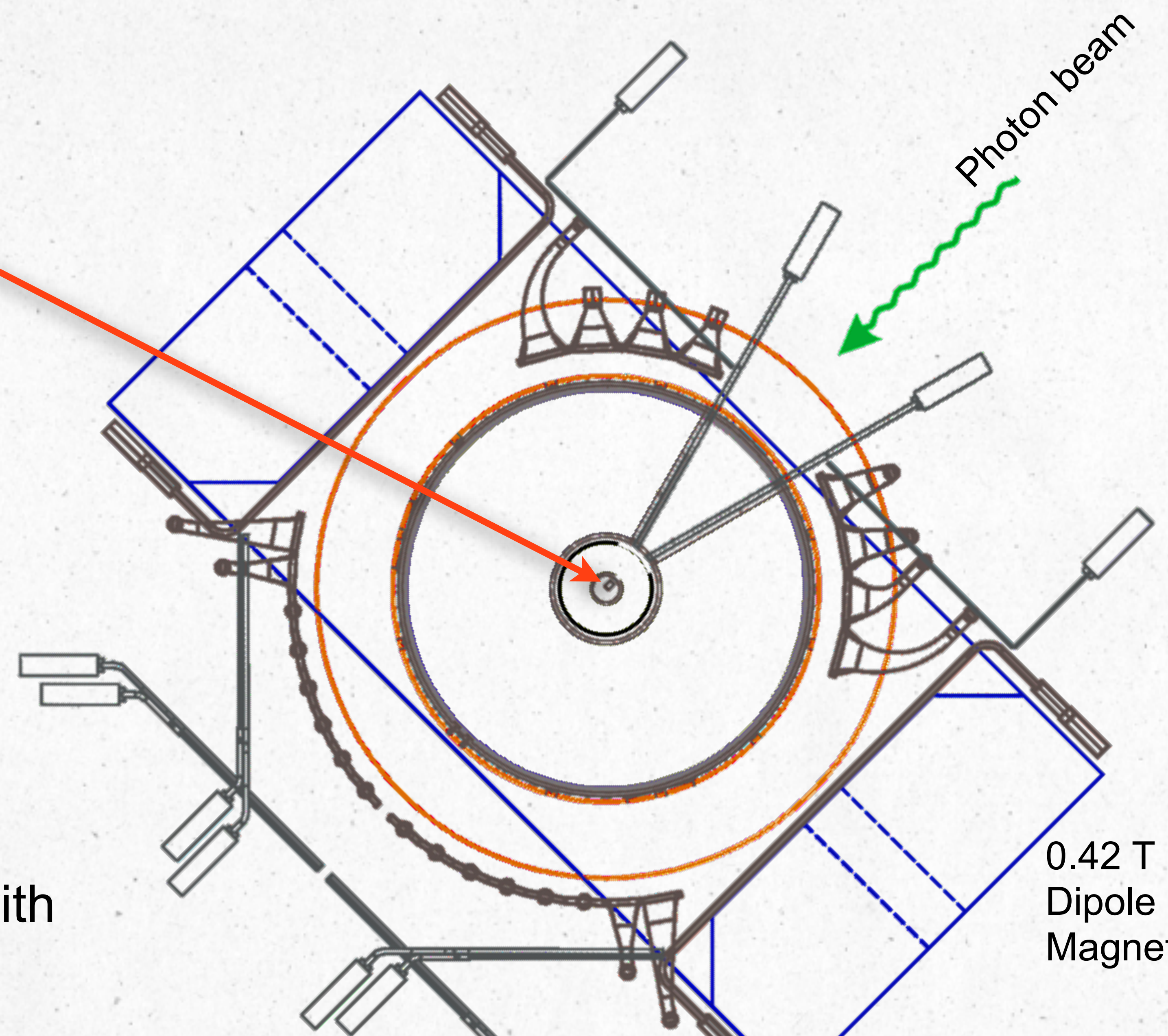

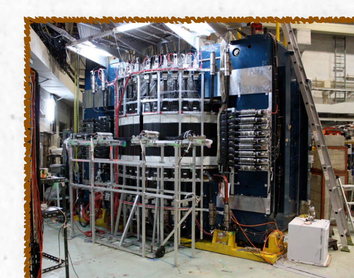

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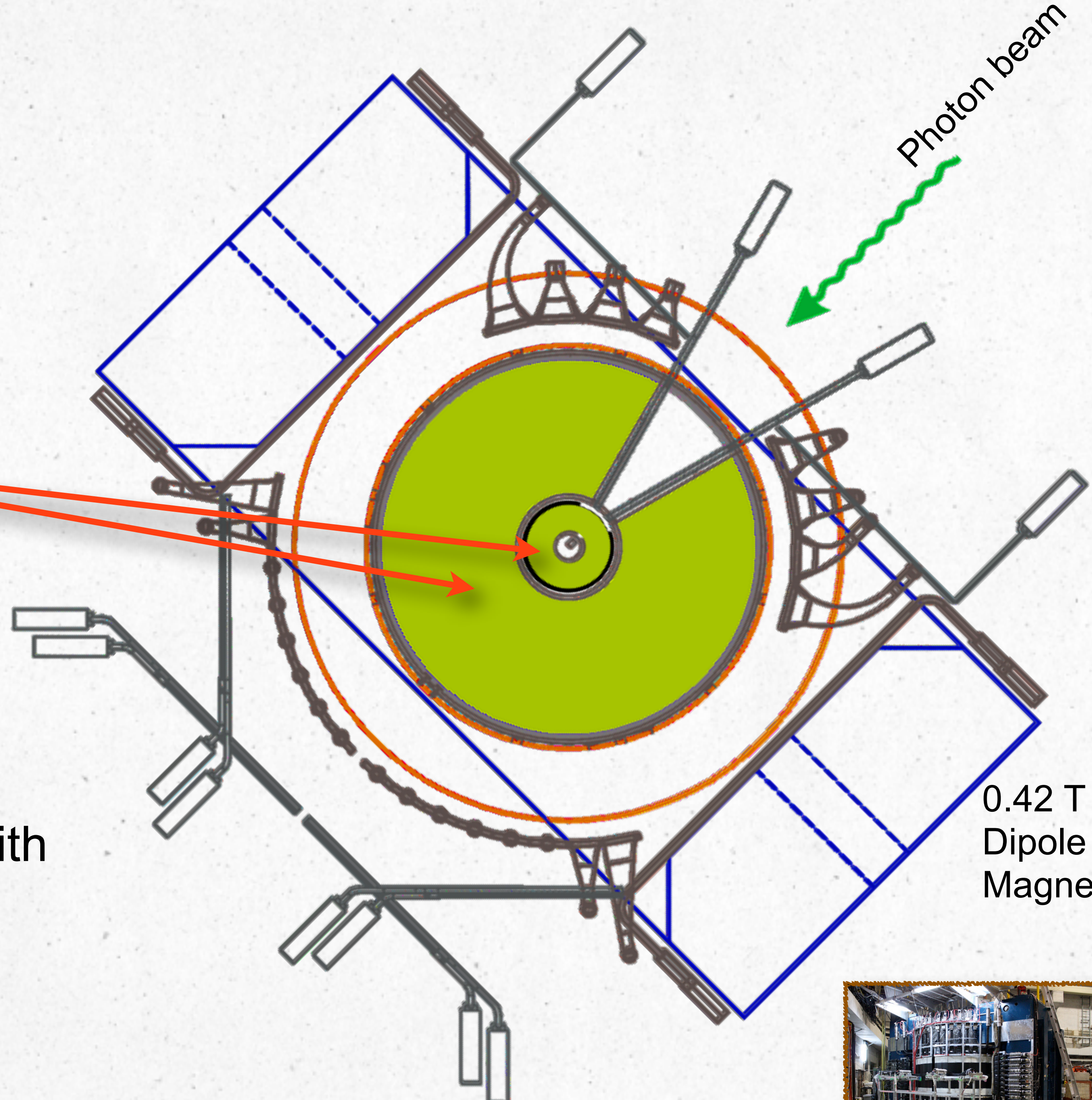

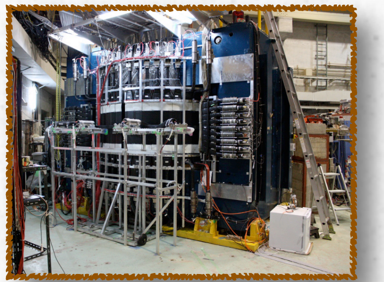

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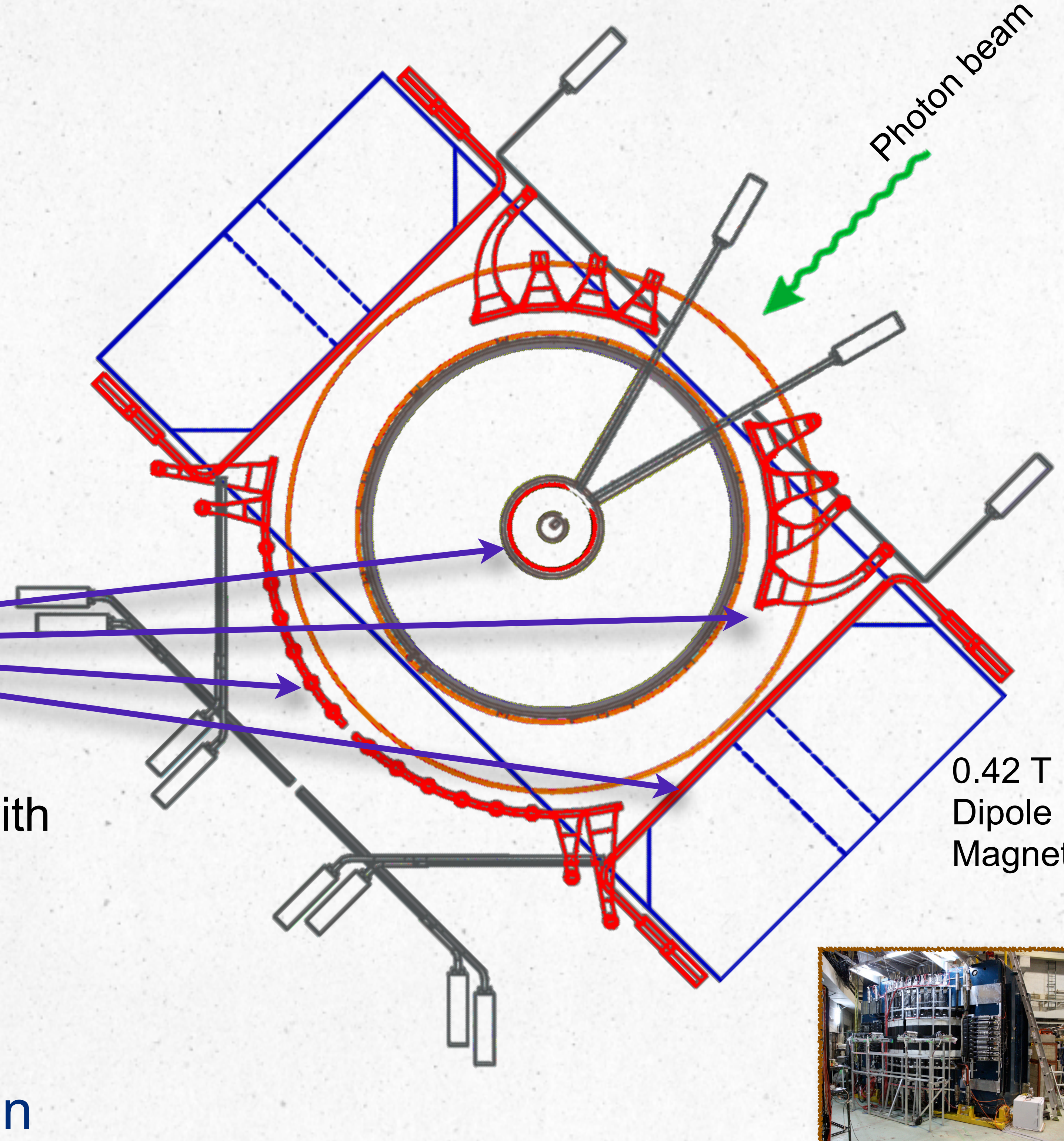

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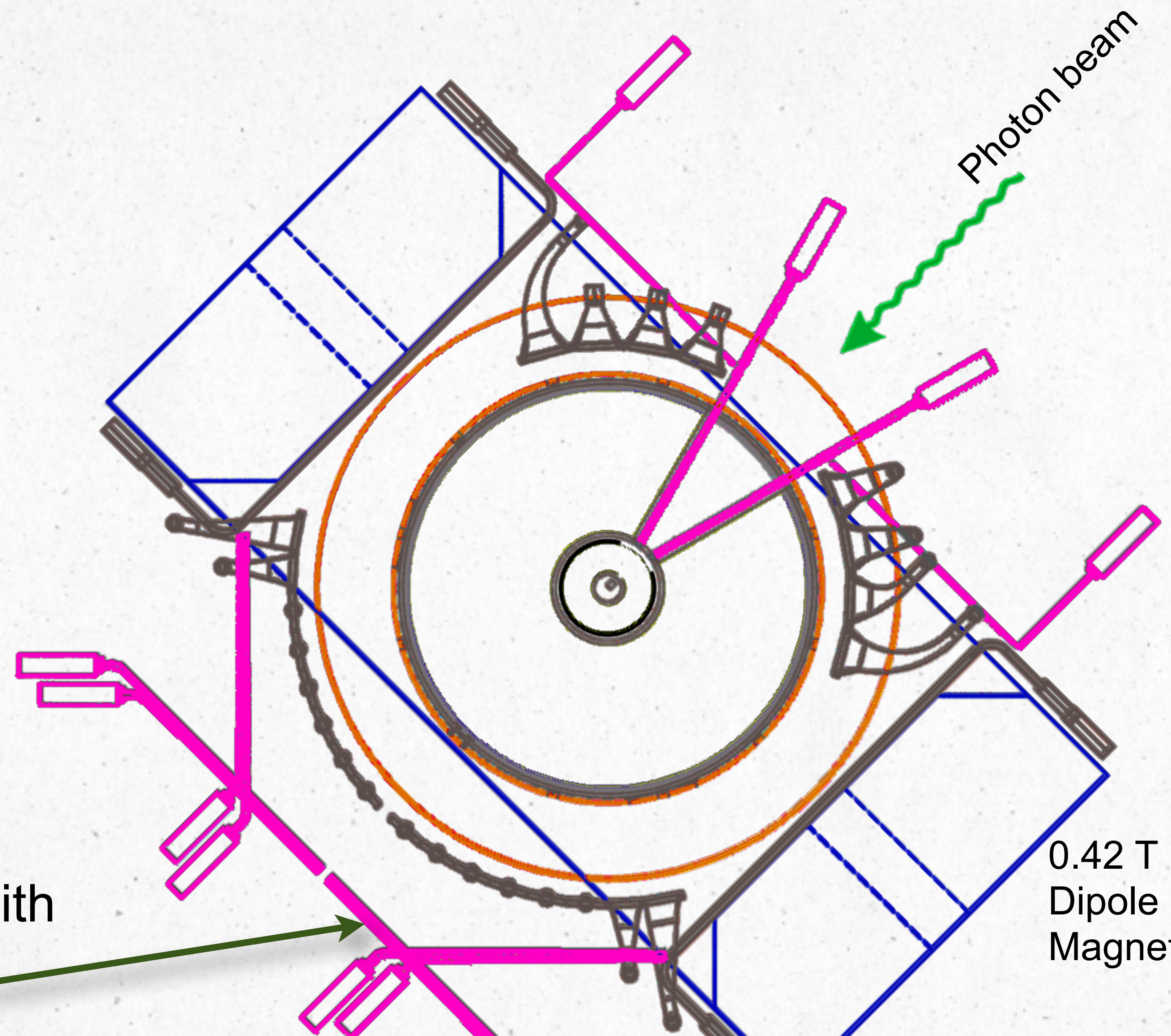

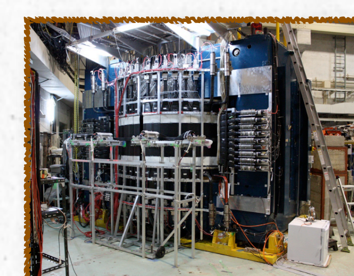

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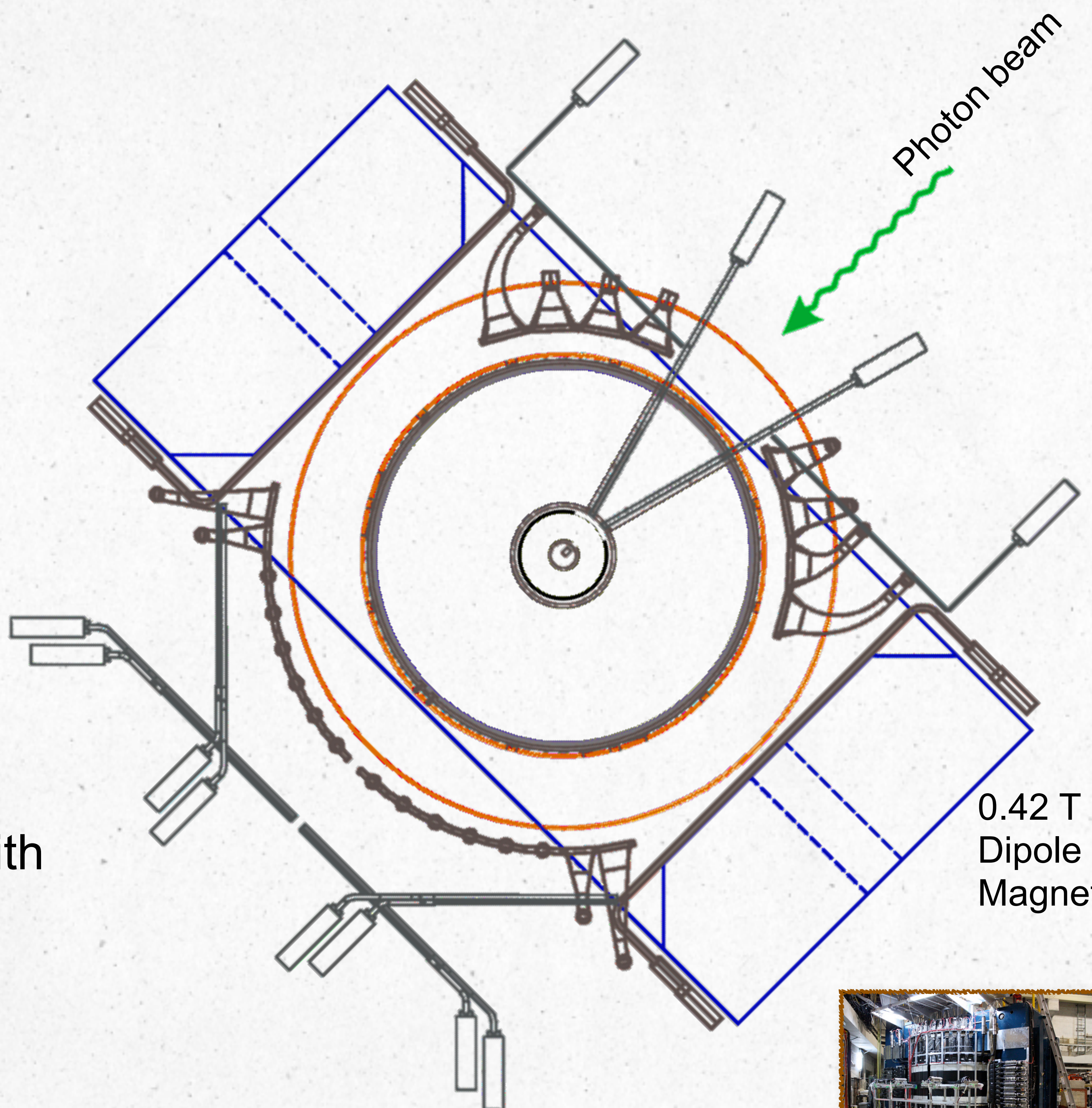
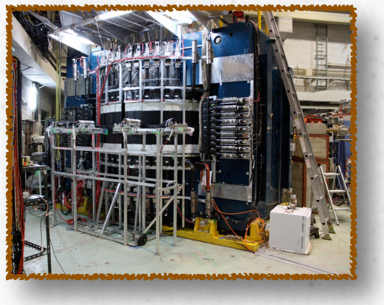
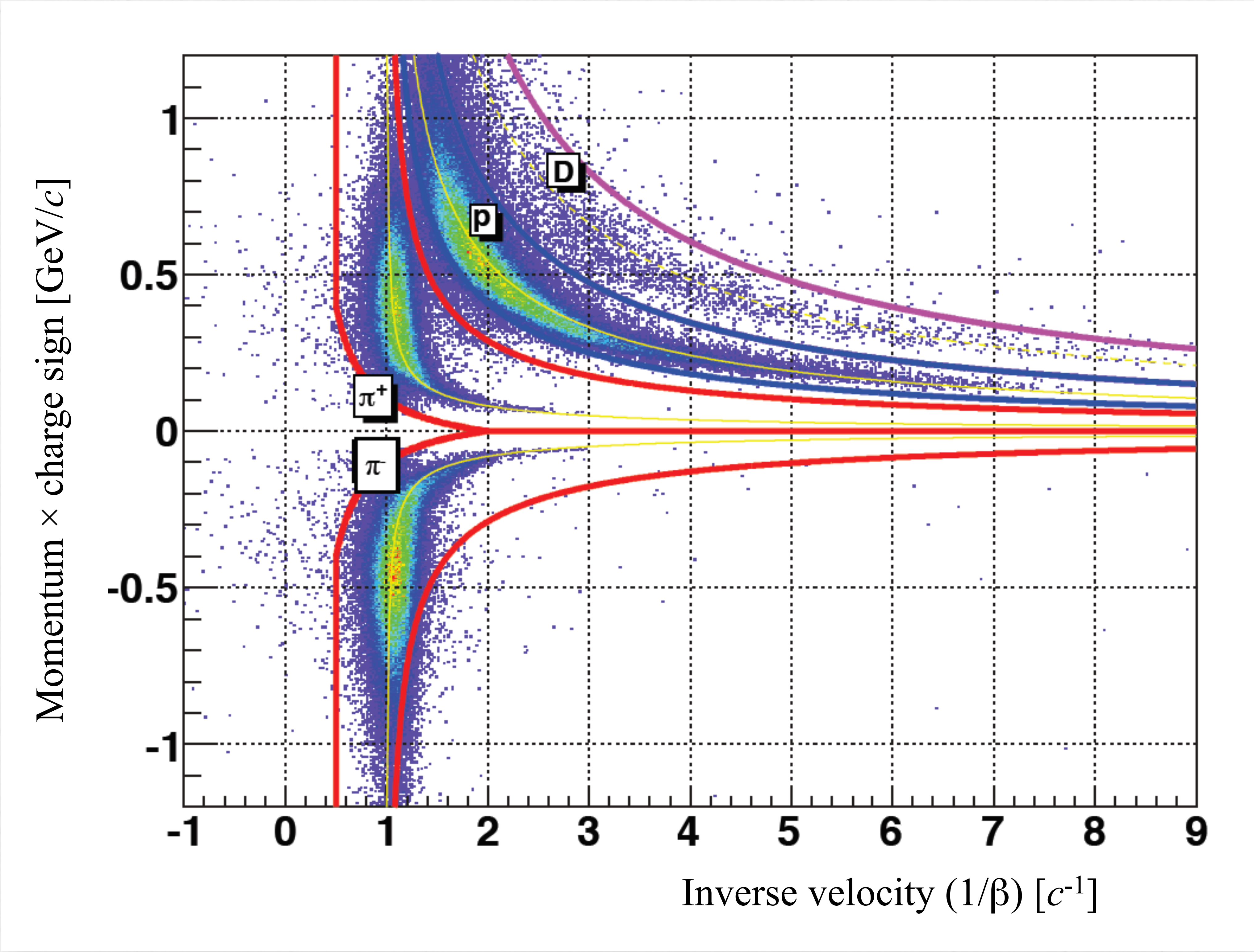




Particle Identification



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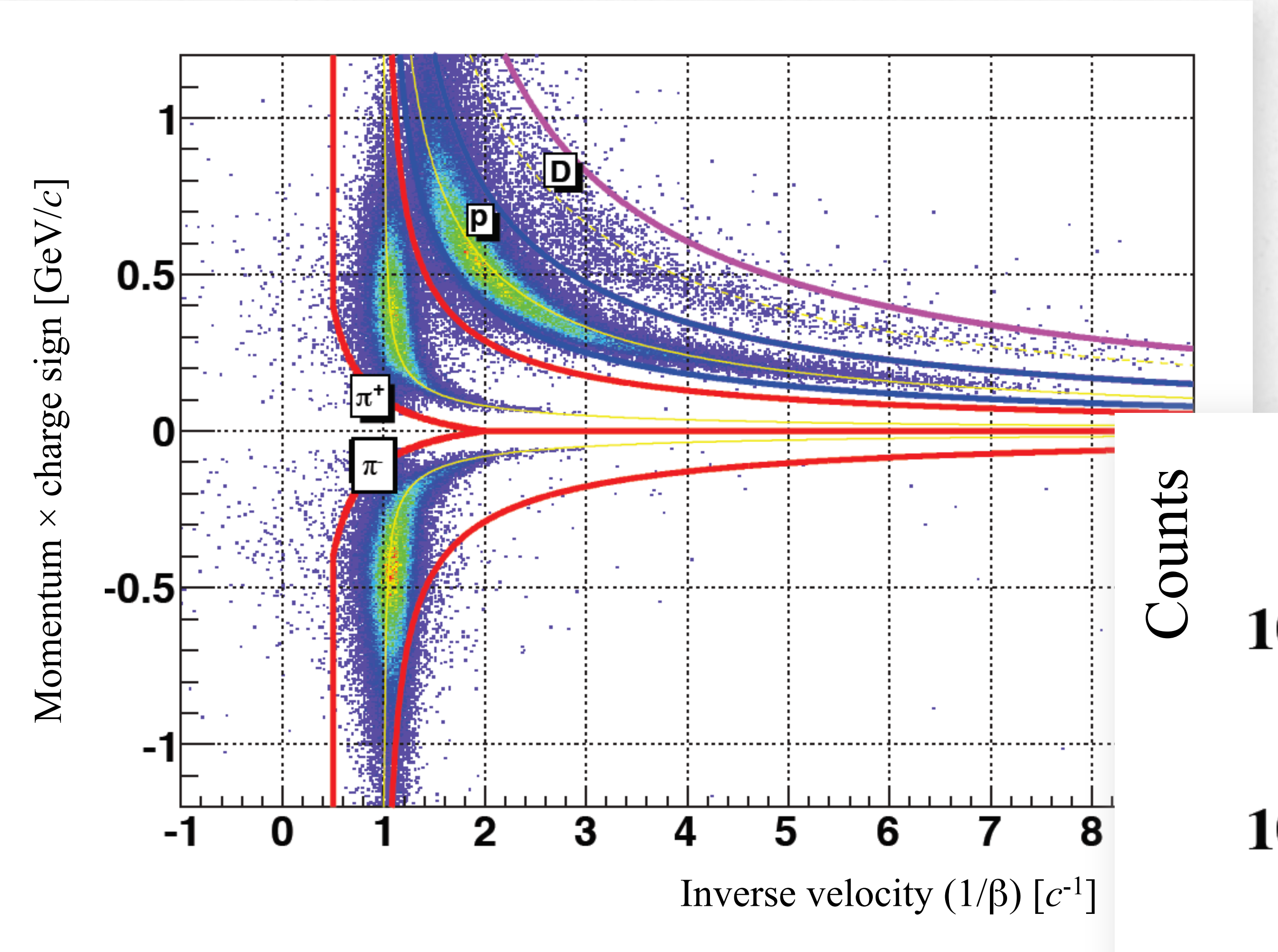
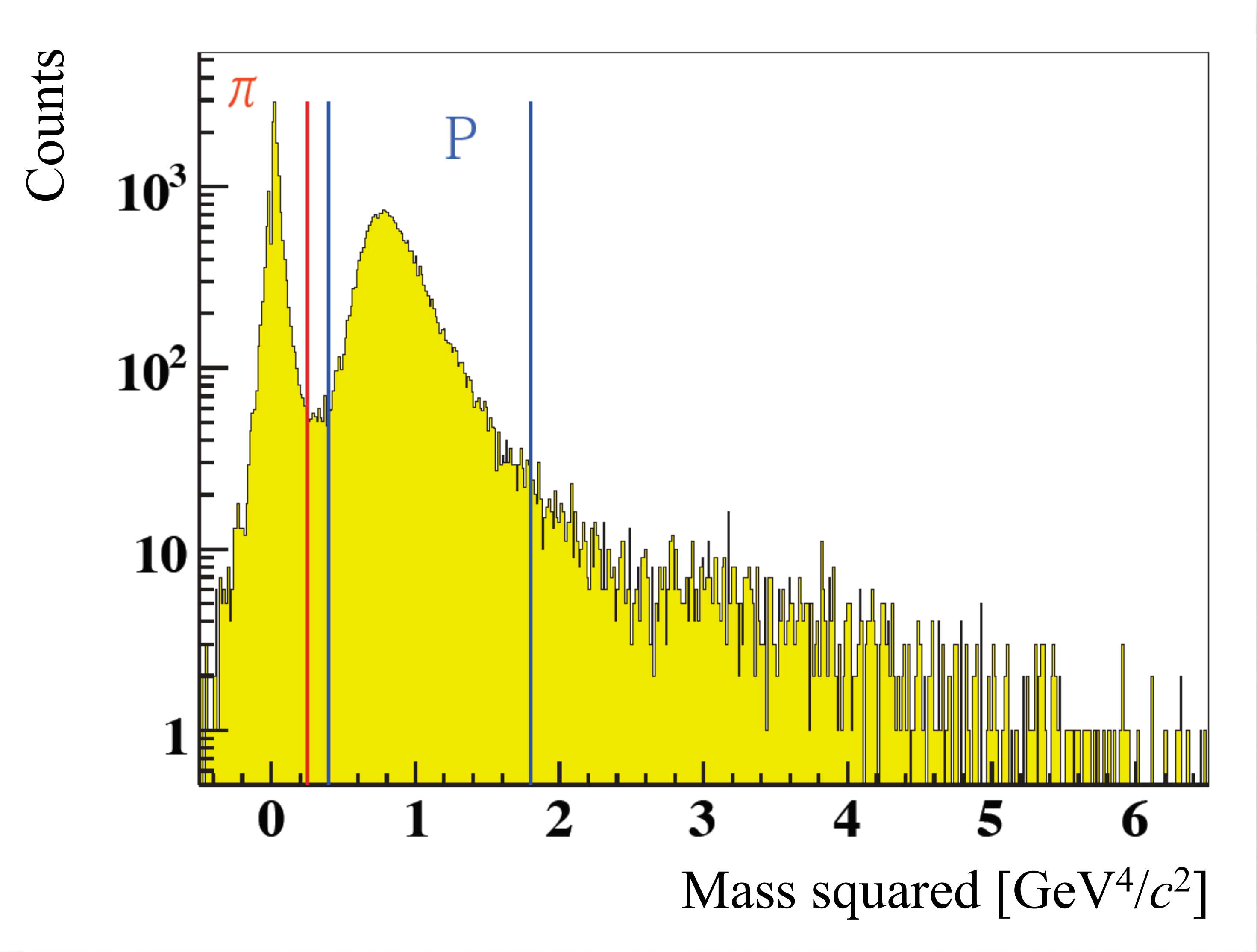


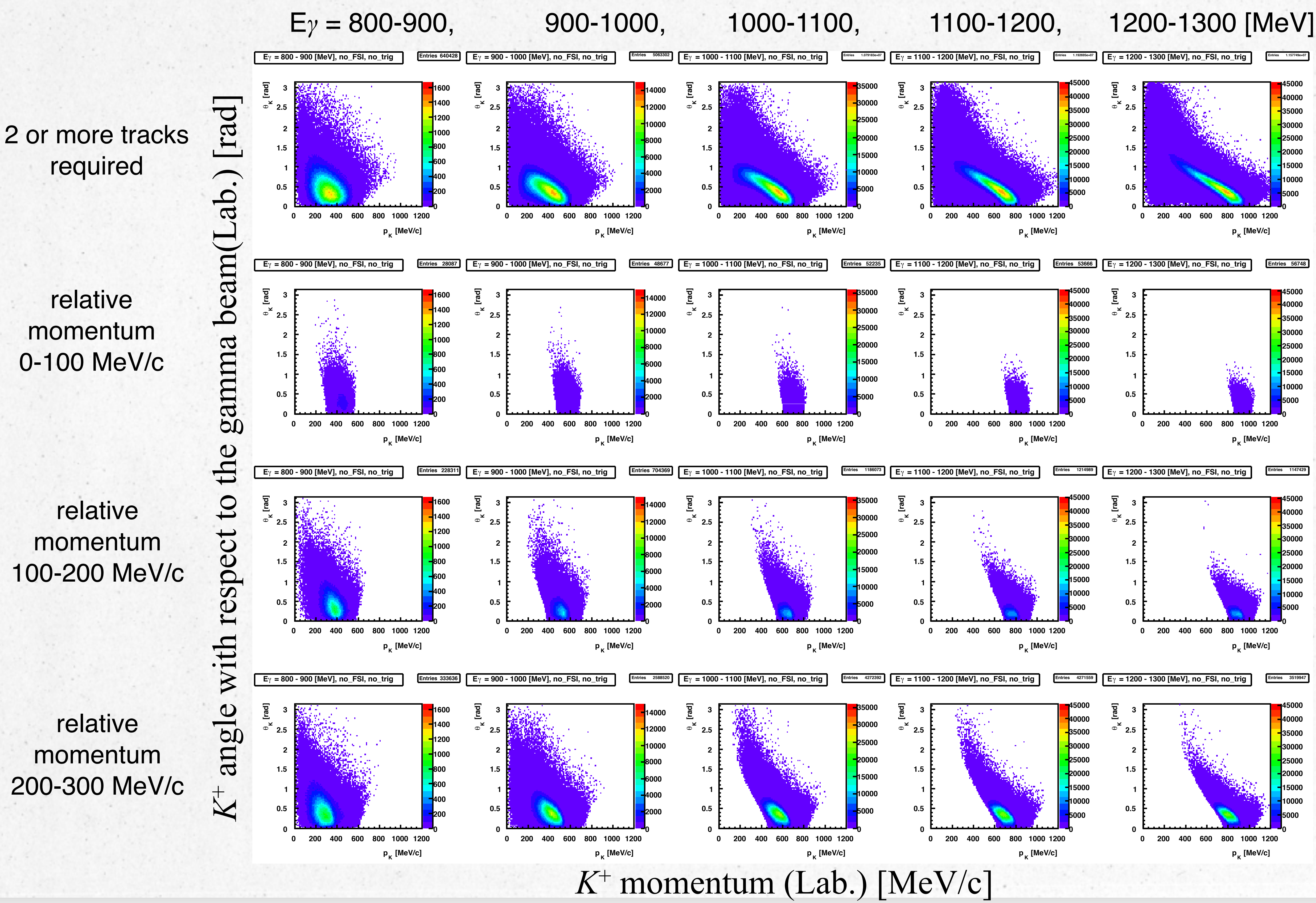


Feasibility in NKS2

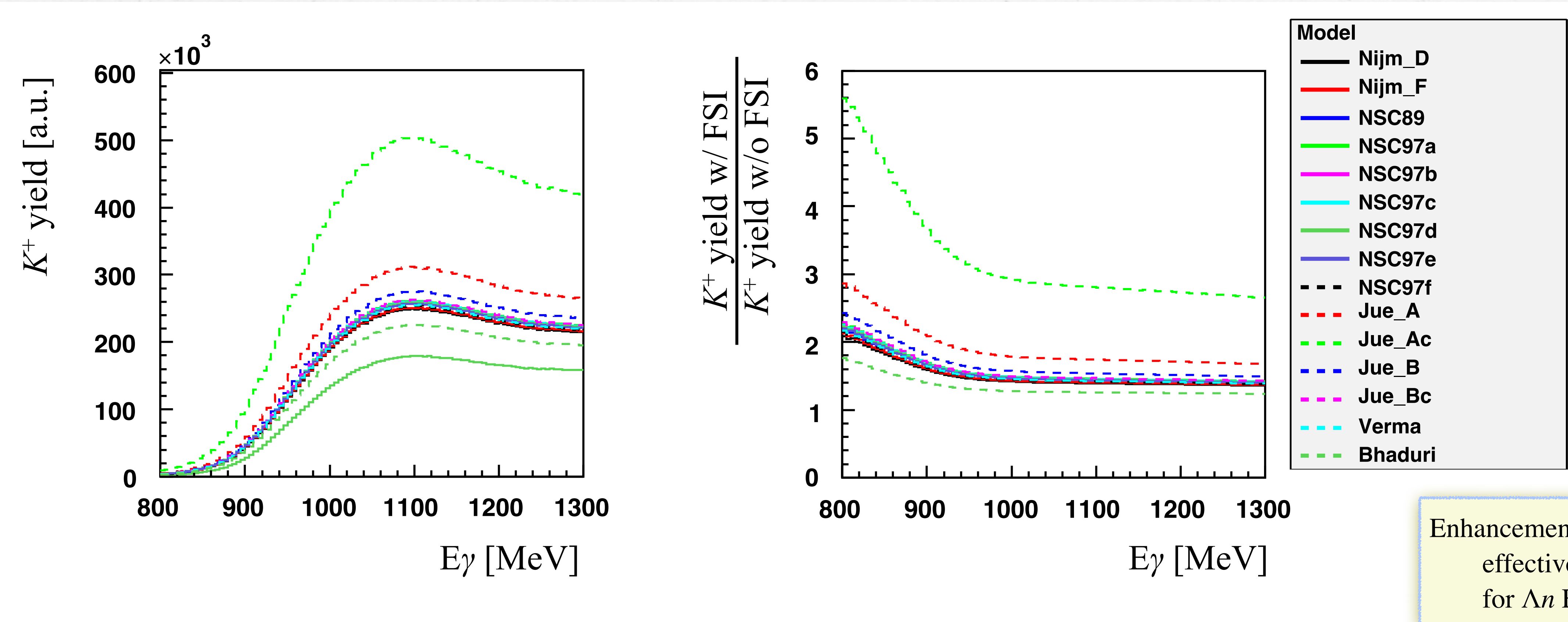
Feasibility Study by a Simulation

- FSI affects to cross section
  - Using effective range approximation
    - Large in low relative momentum region
    - How looks like in K and Λ distribution (*p* and *θ*)?
- Acceptance
  - K^+ single, and $K^+ + \Lambda$ coincidence
- Study by a Monte-Carlo simulation
  - GEANT4 based
  - $\gamma + \mathrm{d} \rightarrow K^+ + \Lambda + n$
    - Kaon-MAID: $\gamma + p \rightarrow K^+ \Lambda$
    - Applying the effect of Fermi motion inside of deuteron
  - New K^+ ID detector
    - same acceptance with current outer hodoscopes

K^+ angle vs. K^+ momentum



K^+ Single Measurement (MC studied)



Enhancement factor:
effective range approximation
for Λn FSI (S-wave, low energy)

- 2 track trigger requested
- Geometrical acceptance for K^+:
  - ~20-30% (varied by relative momentum)
  - note: ~1-2 % for $K^+ + \Lambda$
- If requesting of < 3% error
  - in each 100 MeV step of Eγ bin
  - total number of K^+ event: ~50000

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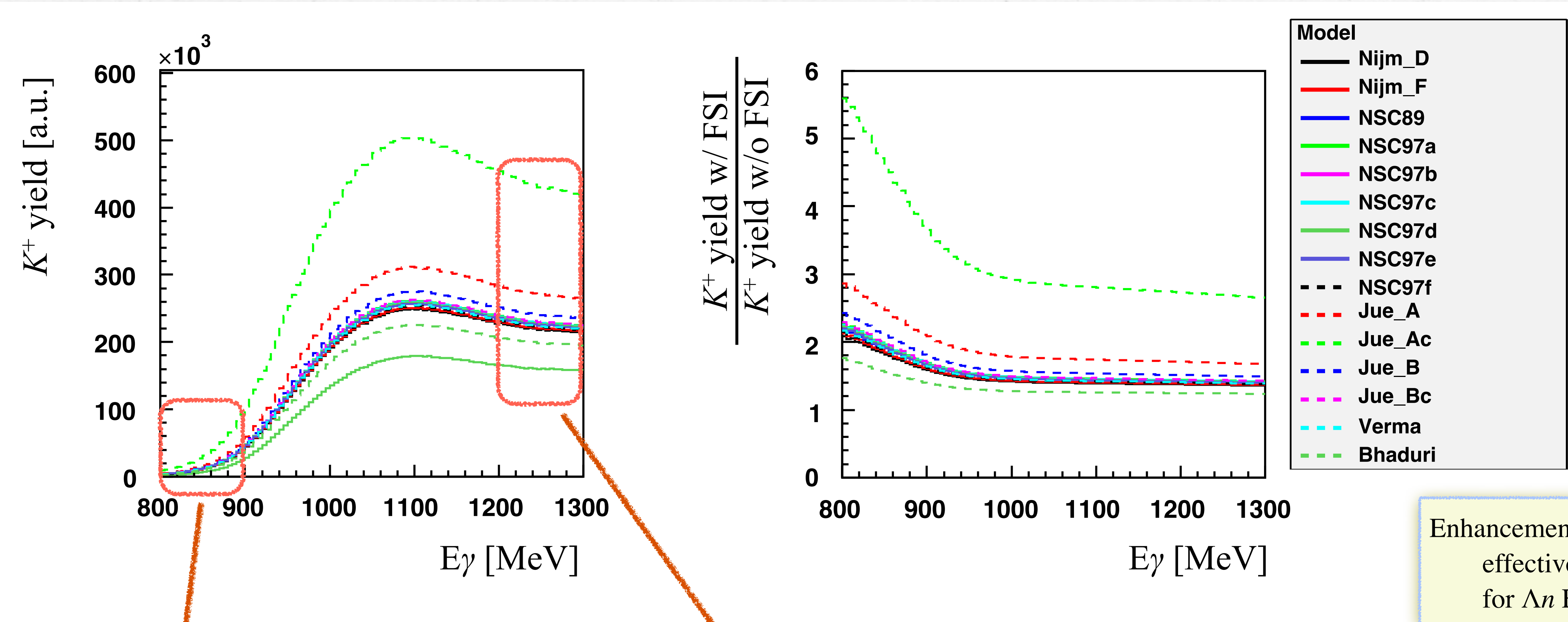

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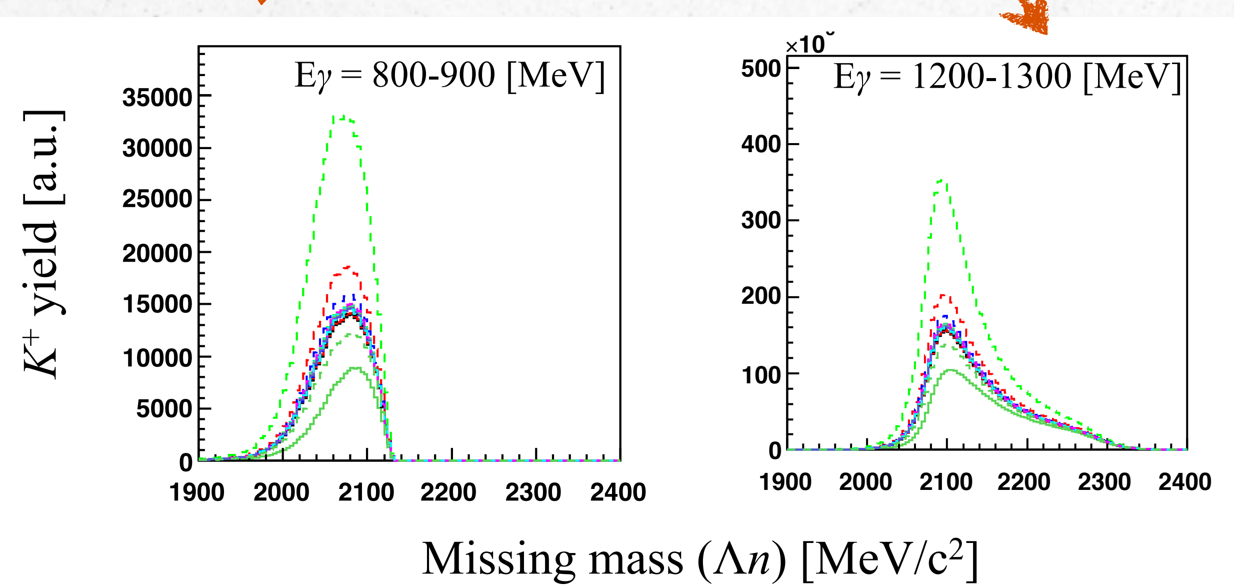

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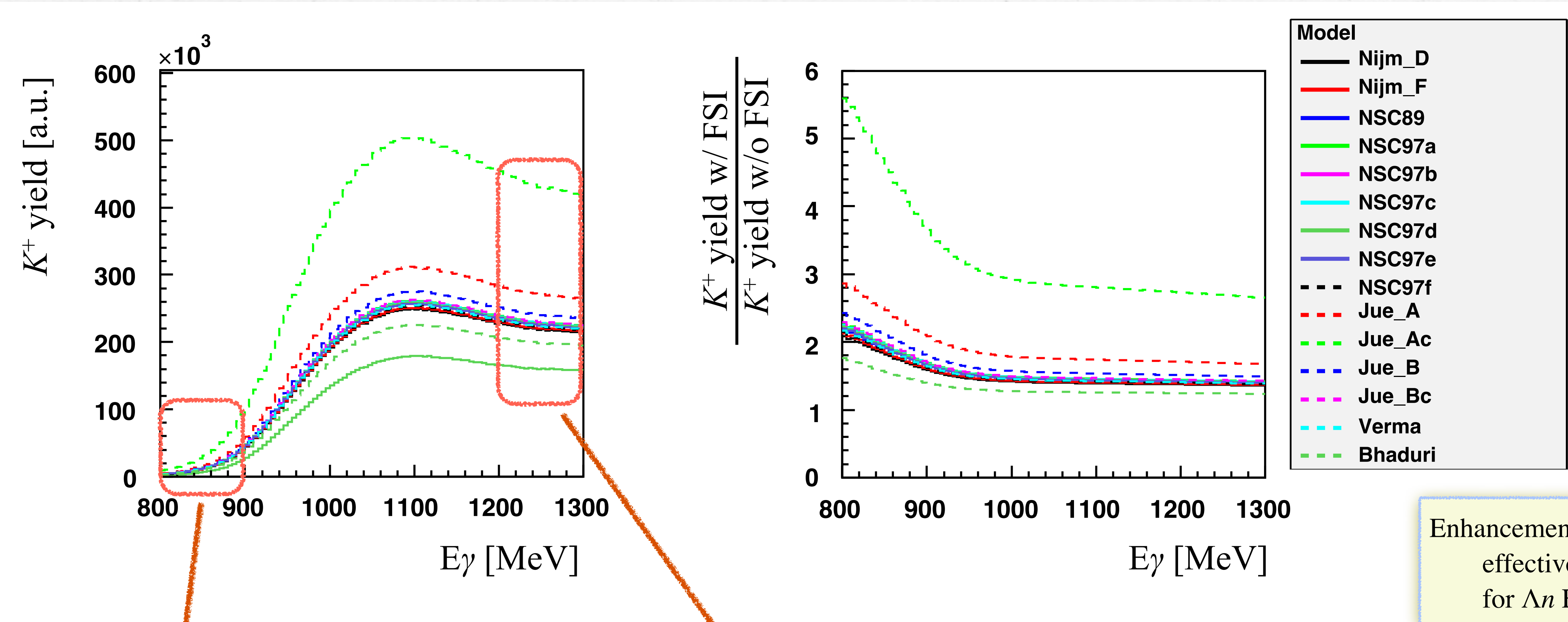

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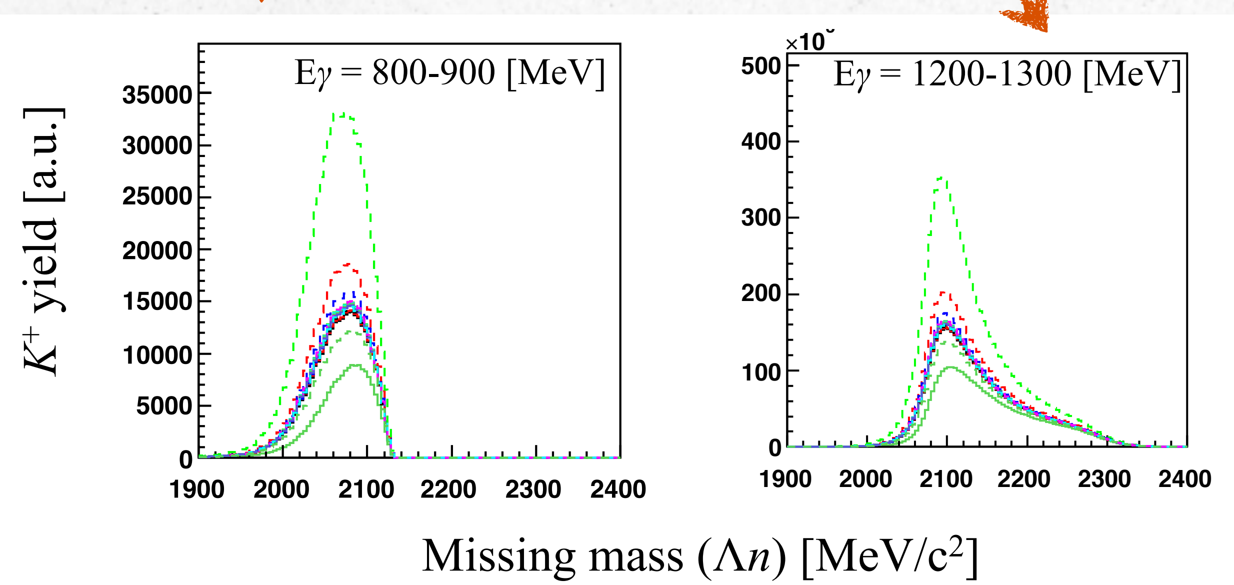

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  - total number of K^+ event: ~50000

Beam time estimated: ~150 days
for each D_2 and H_2 target
It is realistic in ELPH

Summary

- Λn interaction via FSI effect
  - $\gamma + d \rightarrow K^+ + \Lambda + n$ and $\gamma + p \rightarrow K^+ + \Lambda$
- NKS2 experiment
  - NKS2 spectrometer covers forward angle region
  - Liquid Deuterium and Hydrogen target
  - Strangeness photo-production near the threshold
- Feasibility of measurements of the Λn interaction
  - Studied by the MC simulation based on GEANT4
    - K^+ single measurement
      - ~20-30% geometrical acceptance (for Λn relative momentum <300 MeV/c)
      - ~150 days of beam time for 50000 event
    - $K^+ \Lambda$ coincidence measurement
      - ~1-3% geometrical acceptance (for Λn relative momentum <300 MeV/c)
      - Capability of the complete measurement of kinematics
      - Λ recoil polarization may give us more information
        - need helps of theoretical study
        - single/triplet separation?

Backup

Scattering length and Effective range for Λp interaction

Table 2. Test of potential model results performed with two-parameter fit.

Model	a_s (fm)	r_s (fm)	a_t (fm)	r_t (fm)	$\lvert\mathcal{M}_s\rvert^2$ (b/sr)	$\lvert\mathcal{M}_t\rvert^2$ (b/sr)	χ^2	χ^2/n.d.f.
Nijm a	−0.71	5.86	−2.18	2.76	$0. \pm 0.1$	22.8 ± 0.2	47.6	1.22
Nijm b	−0.90	4.92	−2.13	2.84	$0. \pm 0.1$	23.4 ± 0.2	53.9	1.38
Nijm c	−1.20	4.11	−2.08	2.92	$0. \pm 0.1$	23.9 ± 0.2	62.2	1.60
Nijm d	−1.71	3.46	−1.95	3.08	$0. \pm 0.1$	25.0 ± 0.2	83.3	2.14
Nijm e	−2.10	3.19	−1.86	3.19	77.5 ± 0.7	$0. \pm 0.1$	76.6	1.97
Nijm f	−2.51	3.03	−1.75	3.32	74.7 ± 0.7	$0. \pm 0.1$	44.8	1.15
Jül Ã	−2.04	0.64	−1.33	3.91	7.3 ± 0.5	7.8 ± 1.6	55.9	1.43
Jül B̃	−0.40	12.28	−2.12	2.57	$0. \pm 0.1$	21.3 ± 0.2	43.6	1.12
Jül A	−1.56	1.43	−1.59	3.16	33.8 ± 0.3	$0. \pm 0.1$	80.2	2.06
Jül B	−0.56	7.77	−1.91	2.43	$0. \pm 0.1$	20.1 ± 0.2	55.5	1.42
NSC	−2.78	2.88	−1.41	3.11	71.6 ± 0.7	$0. \pm 0.1$	32.8	0.84
Nijm D	−1.90	3.72	−1.96	3.24	$0. \pm 0.2$	26.1 ± 0.2	91.6	2.35
Nijm F	−2.29	3.17	−1.88	3.36	77.4 ± 0.7	$0. \pm 0.1$	62.6	1.61
Jül 03	−1.02	4.49	−1.89	2.57	$0. \pm 0.1$	21.3 ± 0.2	62.4	1.60

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Production matrix elements of Λp Singlet and Triplet state are varied by model

Effective Range and Scattering Length for Λn interaction

	Refs.	a_s [fm]	r_s [fm]	a_t [fm]	r_t [fm]
Nijmegen D	PRD15 (1977) 2547	-2.03	3.66	-1.84	3.32
Nijmegen F	PRD20 (1979) 1633	-2.40	3.15	-1.84	3.37
NSC89	PRC40 (1989) 2226	-2.86	2.91	-1.24	3.33
NSC97a	PRC59 (1999) 3009	-0.77	6.09	-2.15	2.71
NSC97b		-0.97	5.09	-2.09	2.80
NSC97c		-1.28	4.22	-2.07	2.86
NSC97d		-1.82	3.52	-1.94	3.01
NSC97e		-2.24	3.24	-1.83	3.14
NSC97f		-2.68	3.07	-1.67	3.34
Jülich A (Λ*N*)	NPA570 (1994) 543	-1.56	1.43	-1.59	3.16
Jülich A~ (Λ*N*)		-2.04	0.64	-1.33	3.91
Jülich B (Λ*N*)		-0.56	7.77	-1.91	2.43
Jülich B~ (Λ*N*)		-0.40	12.28	-2.12	2.57
Verma	PRC22 (1980) 229	-2.29	3.14	-1.77	3.25
Bhaduri (Set I, Λ*N*)	PR 155 (1967) 1671	-2.46	3.87	-2.07	4.50