Systematic investigation on momentum distributions of projectile-like fragments at E/A = 290 MeV

S. Momota (Kochi Univ. of Tech.)
M. Kanazawa, A. Kitagawa, S. Sato (NIRS)

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Motivation

- **Systematic measurements of momentum distribution of projectile-like fragments (PLFs)**

↓ Analysis

provide physical quantities

- Center/width of distribution
- Prod. cross-section

↓ Contribute

Nuclear physics

- Reaction mechanism
- Nuclear structure effect
  ex. pairing/shell effect

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- **Systematic measurements of momentum distribution of projectile-like fragments (PLFs)**

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provide physical quantities
- Center/width of distribution
- Prod. cross-section

Compile

extract
- Systematics
- Formulation

Contribute

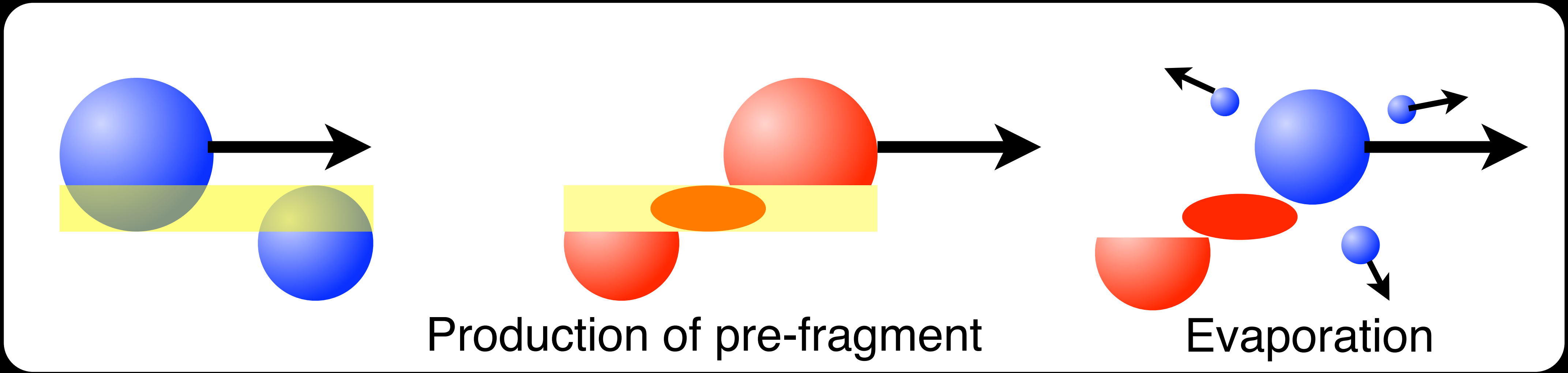
Nuclear physics
- Reaction mechanism
- Nuclear structure effect
  ex. pairing/shell effect

Contribute

Application
- RIB facility
- Space mission
(Heavy ion transport simulation)

Projectile fragmentation process

- $E \geqq 100$ MeV/u



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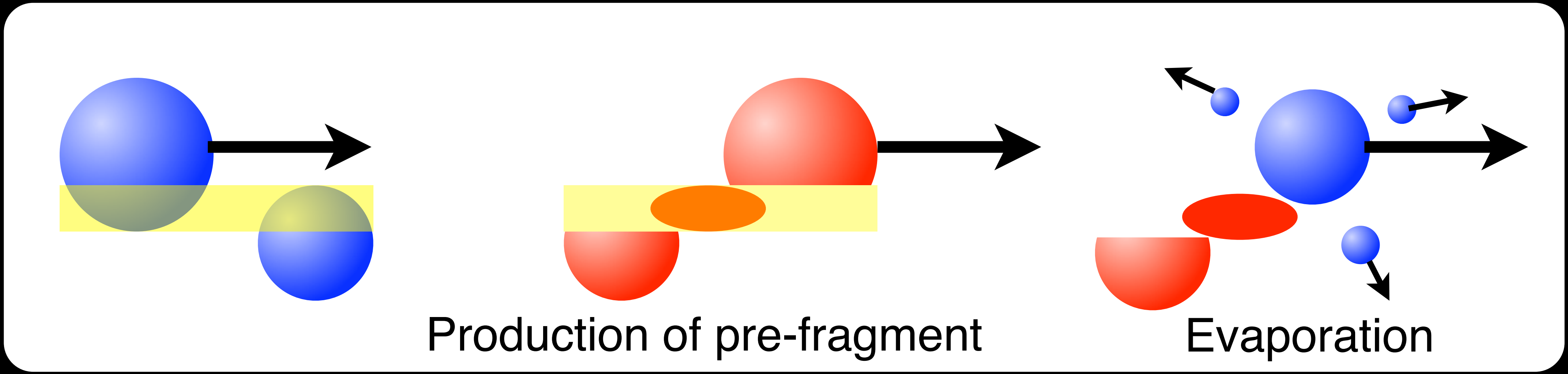
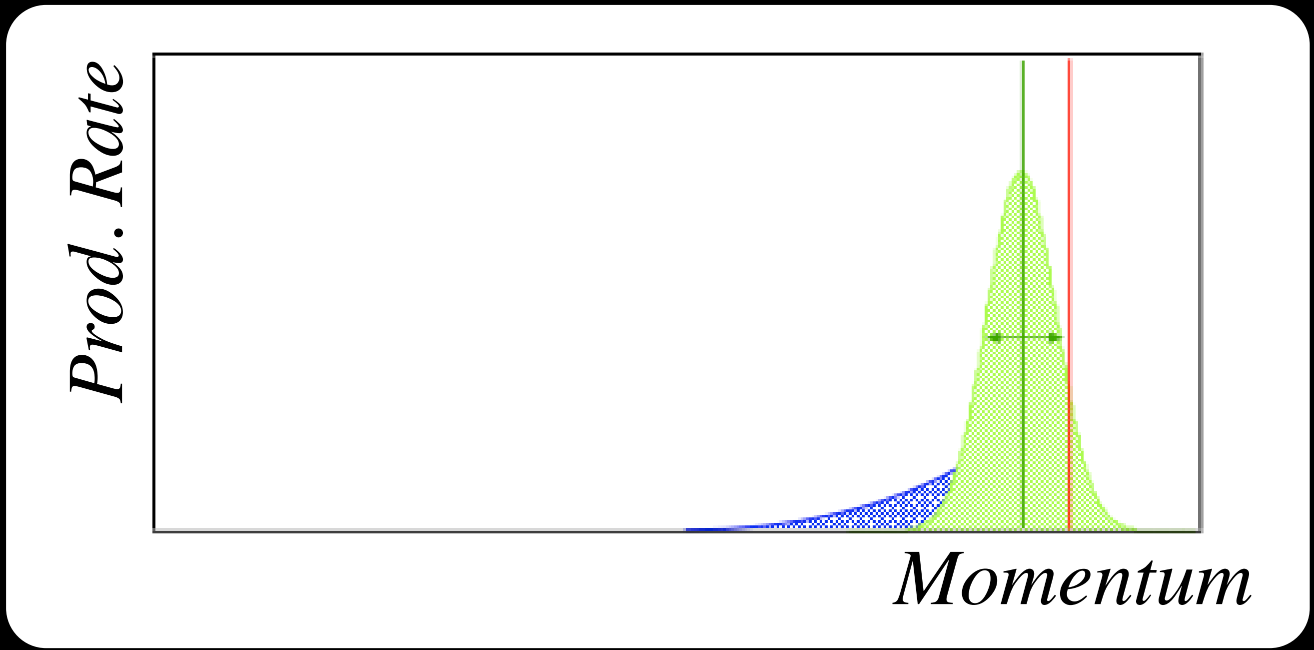




- The shift and width of momentum distribution are small.
- Well defined velocity -> can be used as secondary beam.

P_L distributions

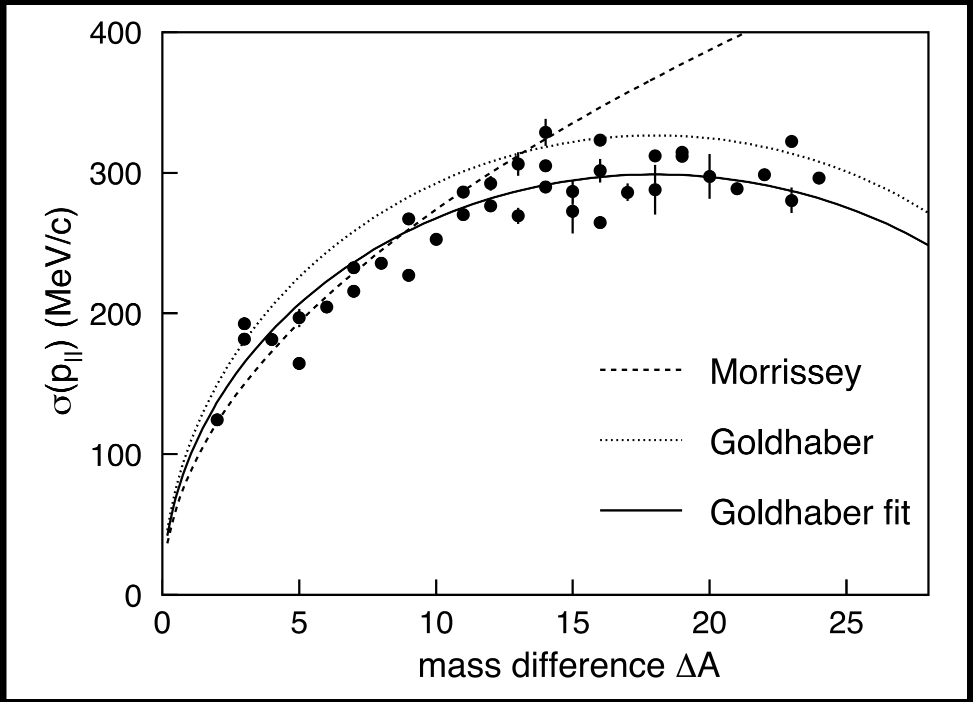
- Width : $\sigma(P_{//})$

  Fermi momentum of removed nucleons

  A.S. Goldhaber, Phys. Lett. B 53 (1974) 244.

$$\sigma_{GH} = \sigma_0 \sqrt{\frac{A_F(A_P - A_F)}{A_P - 1}}, \quad \sigma_0 \sim 100\,[\mathrm{MeV/c}]$$

^{36}Ar(1.05 GeV/u) + Be



σ_0 = 98.2 ± 0.2 MeV/c

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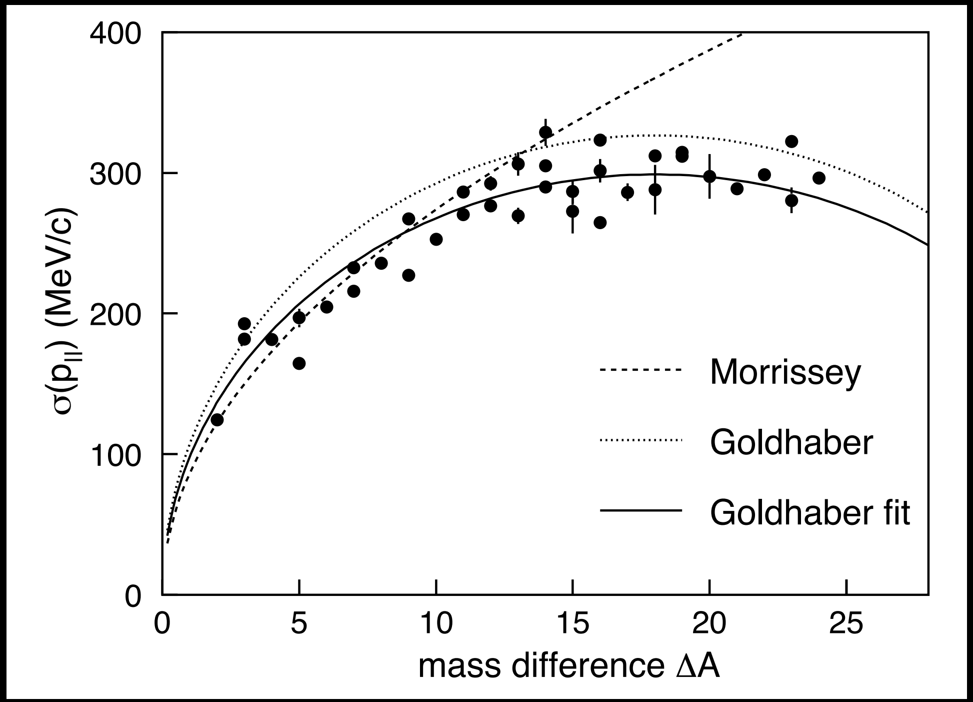

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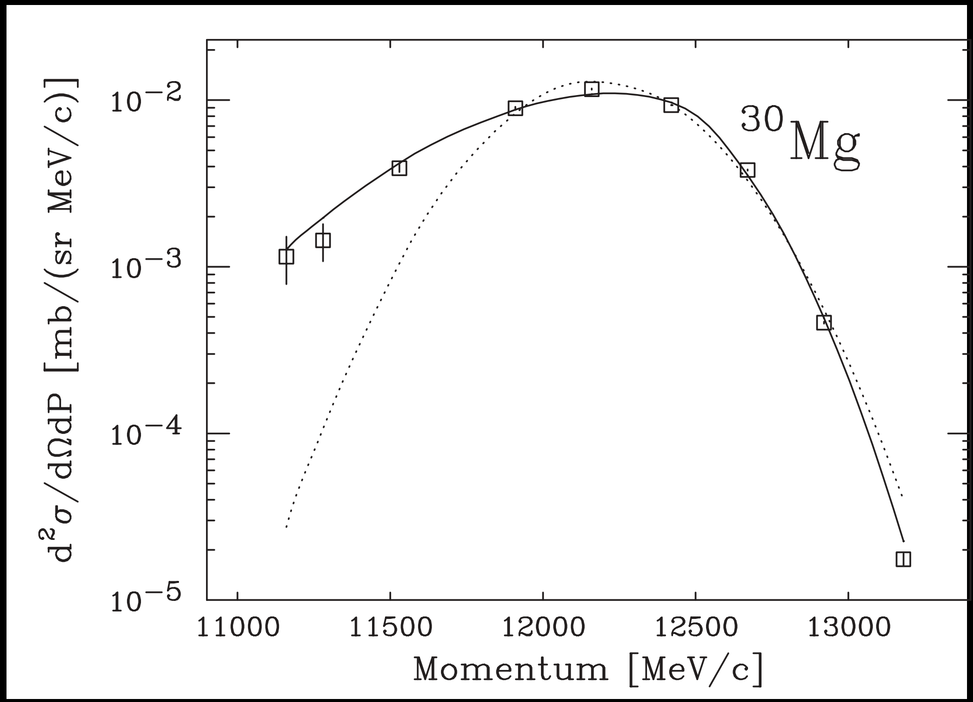
^{40}Ar(90MeV/u) + Ar



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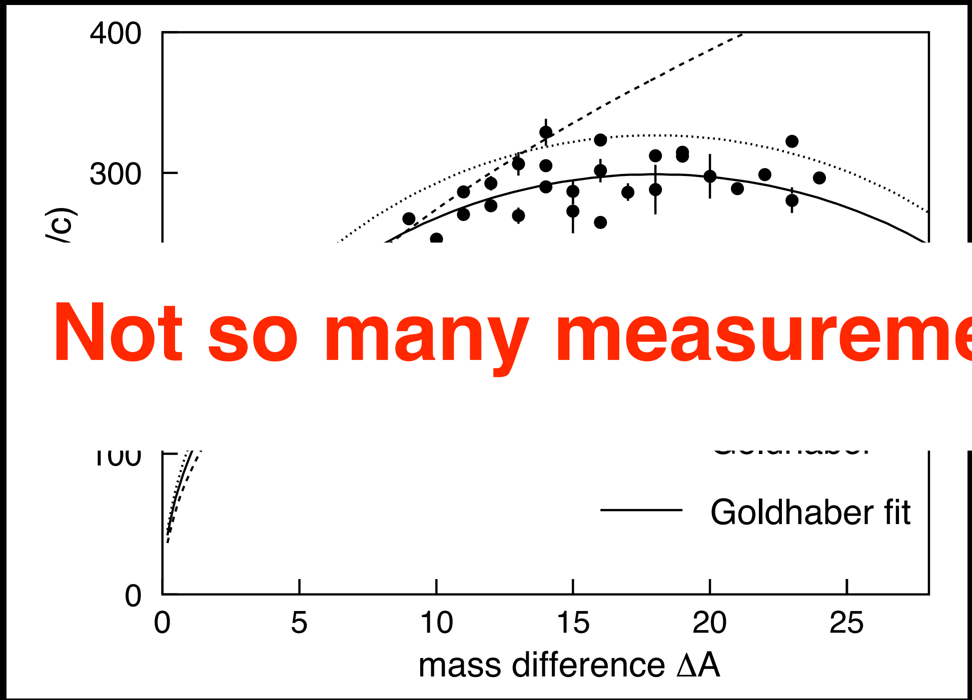

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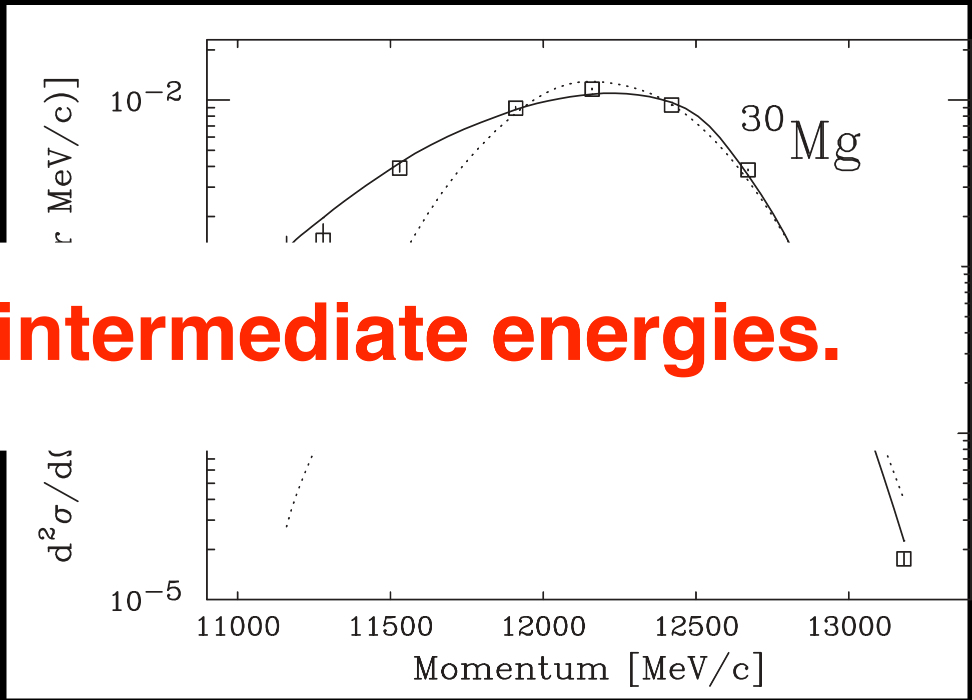

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Not so many measurements at intermediate energies.

P_T distributions

- Width : $\sigma(P_\perp)$

- At high energy : $E > 1$ GeV/u

  Isotropic, $\sigma(P_\perp) \sim \sigma(P_{//})$

- At lower energy : $E < 100$ MeV/u

  anisotropic, $\sigma(P_\perp) > \sigma(P_{//})$

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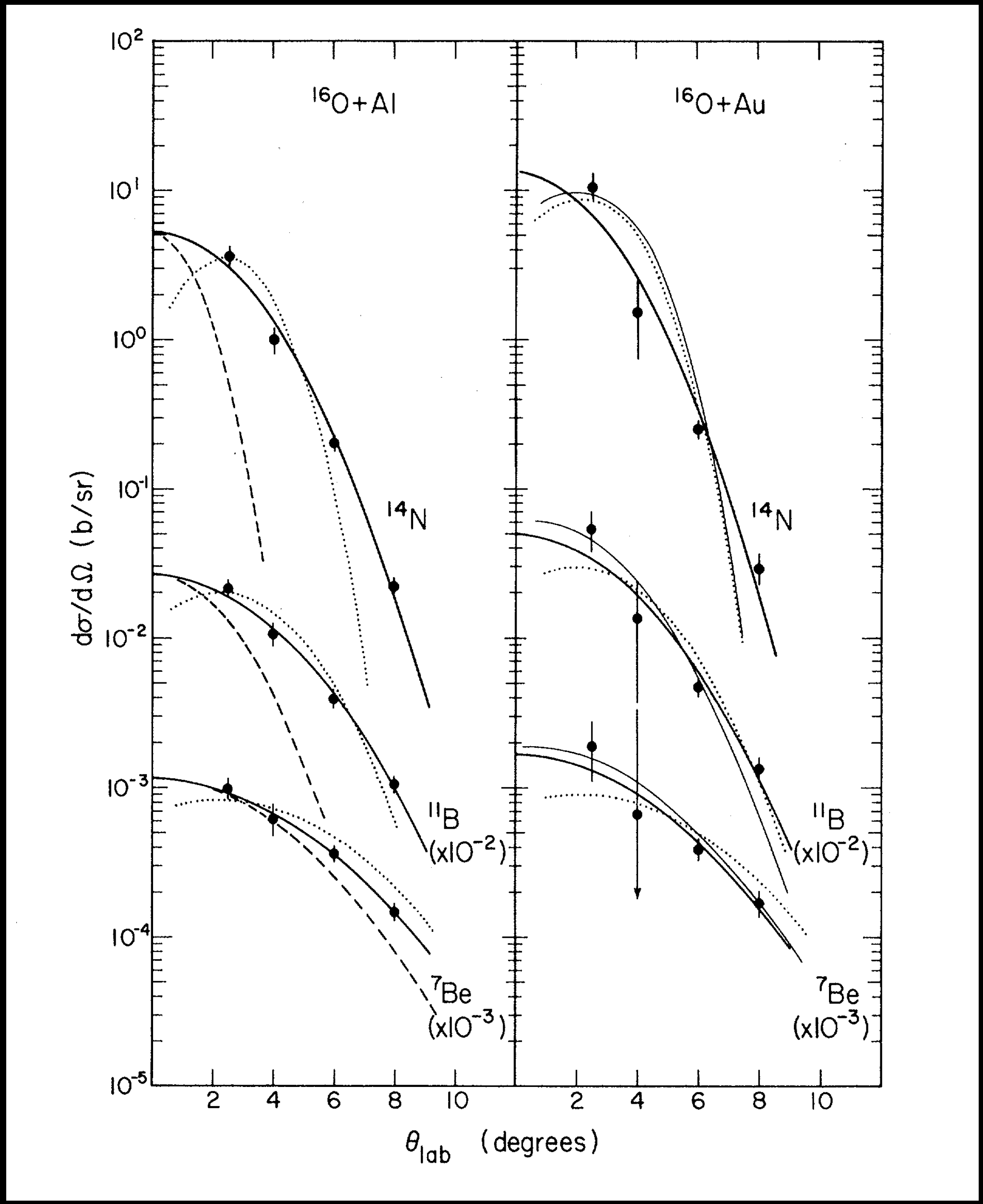
Orbital dispersion

K. Van Bibber et al., Phys. Rev. Lett. 43 (1979) 840.

$$\sigma(P_\perp) = \sqrt{\sigma(P_{//})^2 + \frac{A_F(A_F-1)}{A_P(A_P-1)}\sigma_{D0}^2}$$

$$\sigma_0 = 195\,[\mathrm{MeV/c}]$$

^{16}O(~100 MeV/u) + Al, Au



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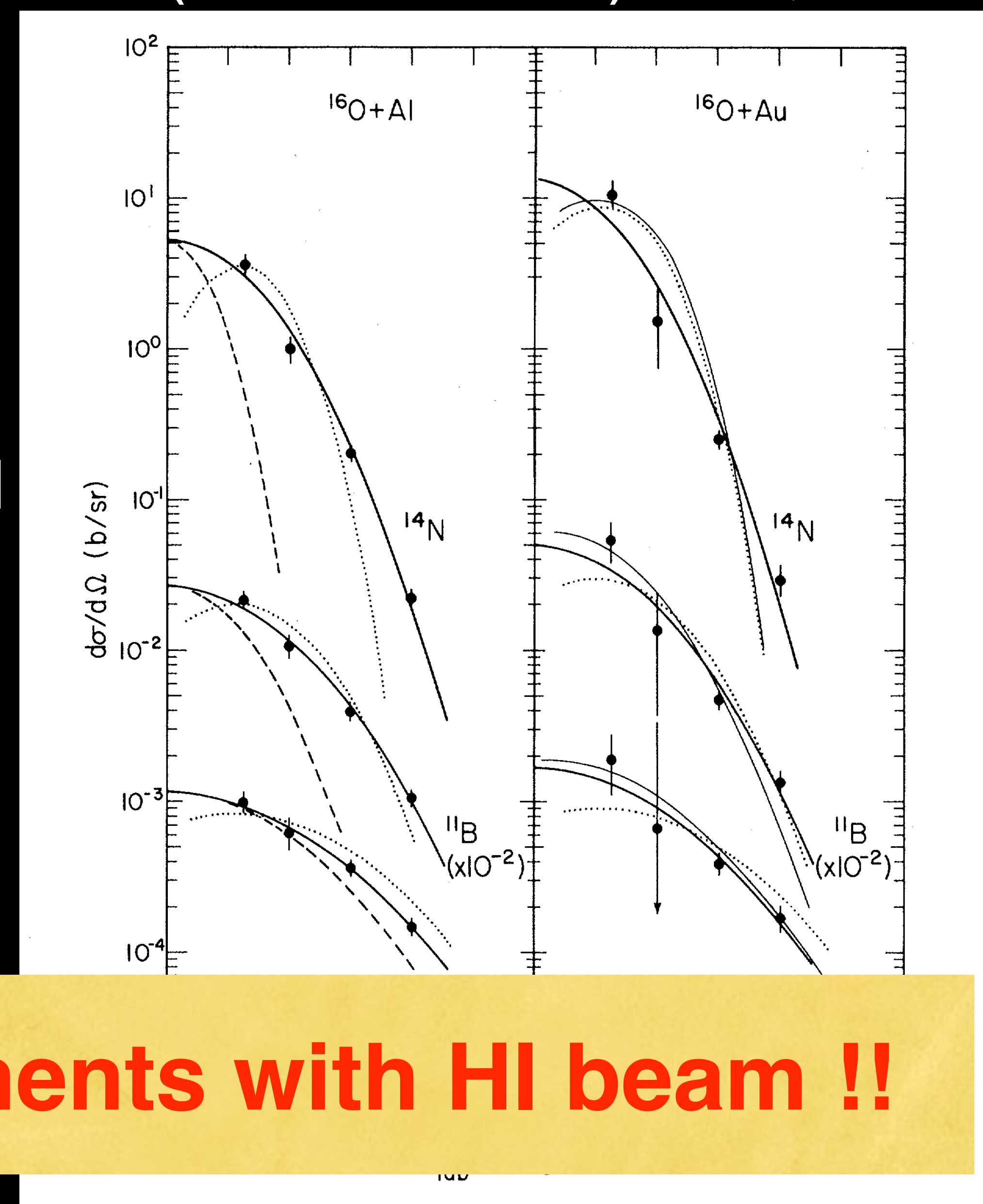

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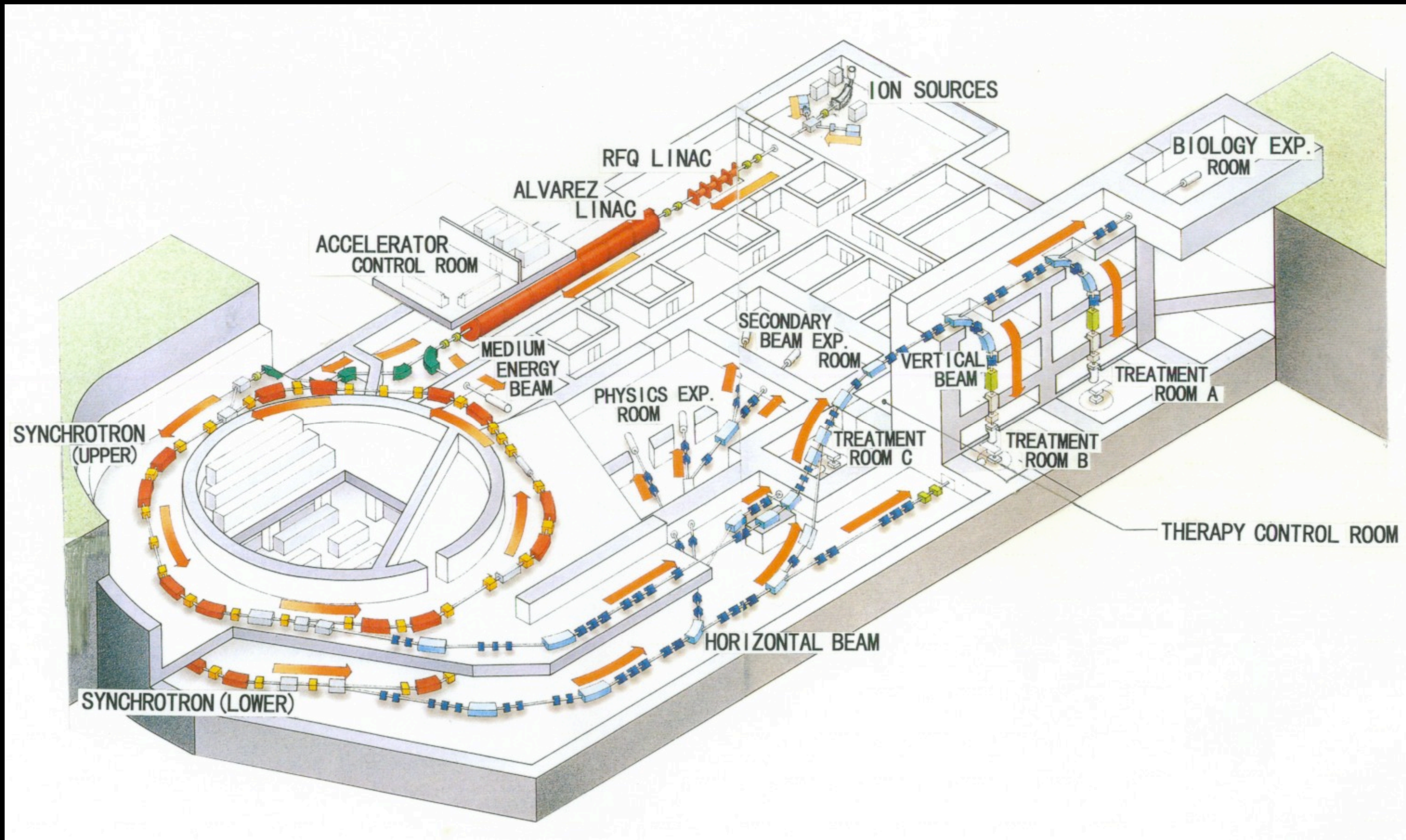
Few systematic measurements with HI beam !!

HIMAC facility at NIRS

- Synchrotron dedicated to cancer therapy



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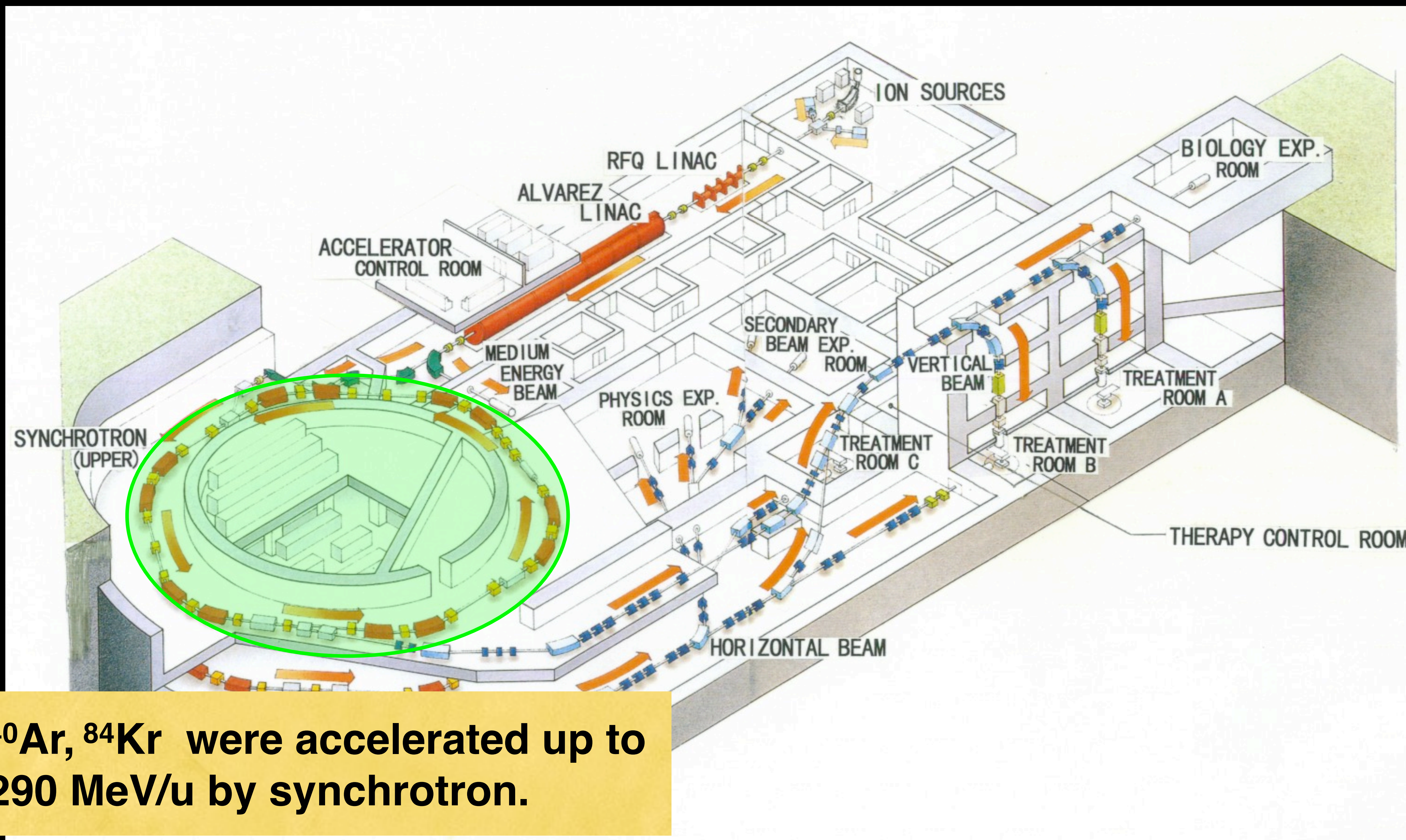

^{40}Ar, ^{84}Kr were accelerated up to 290 MeV/u by synchrotron.

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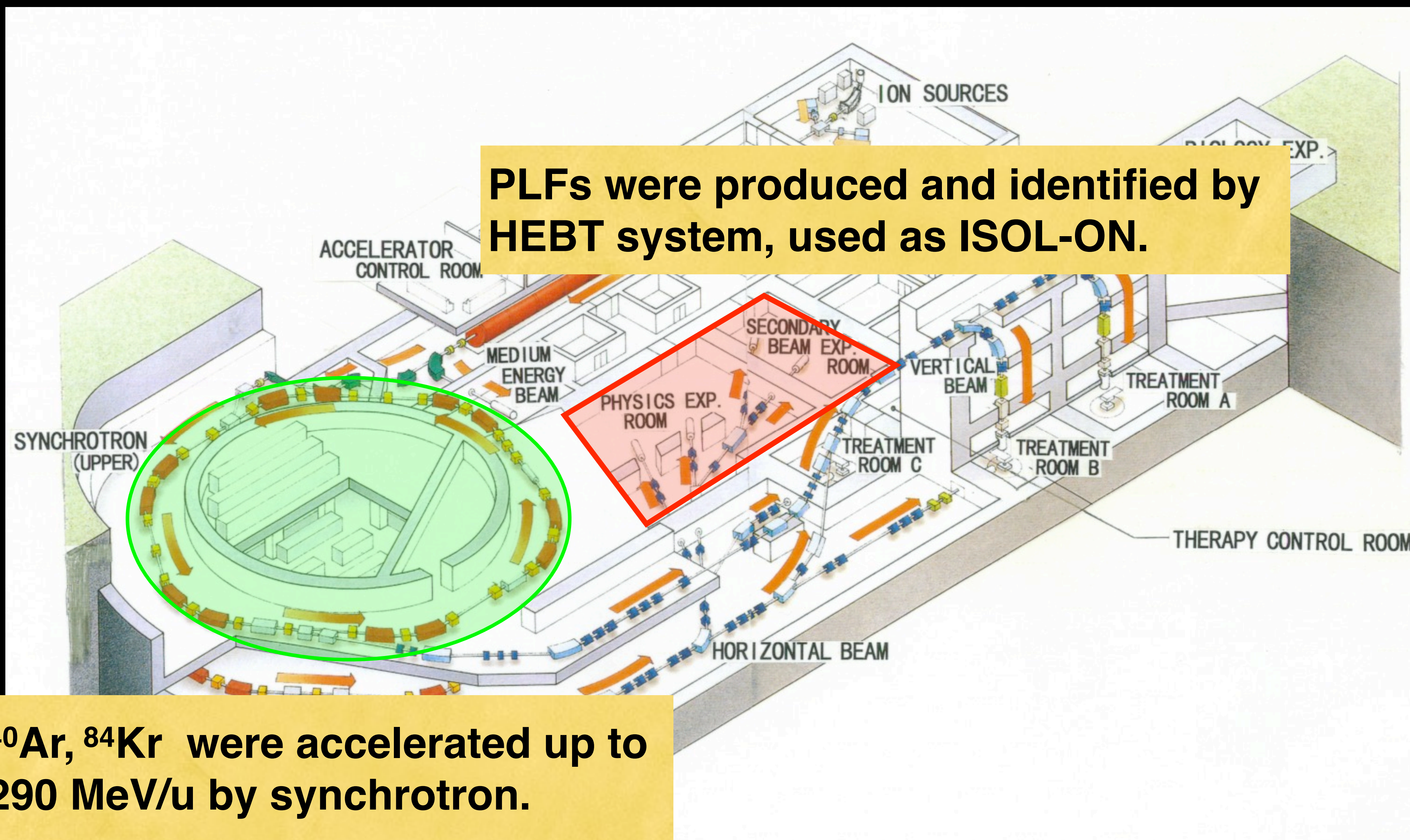

PLFs were produced and identified by HEBT system, used as ISOL-ON.

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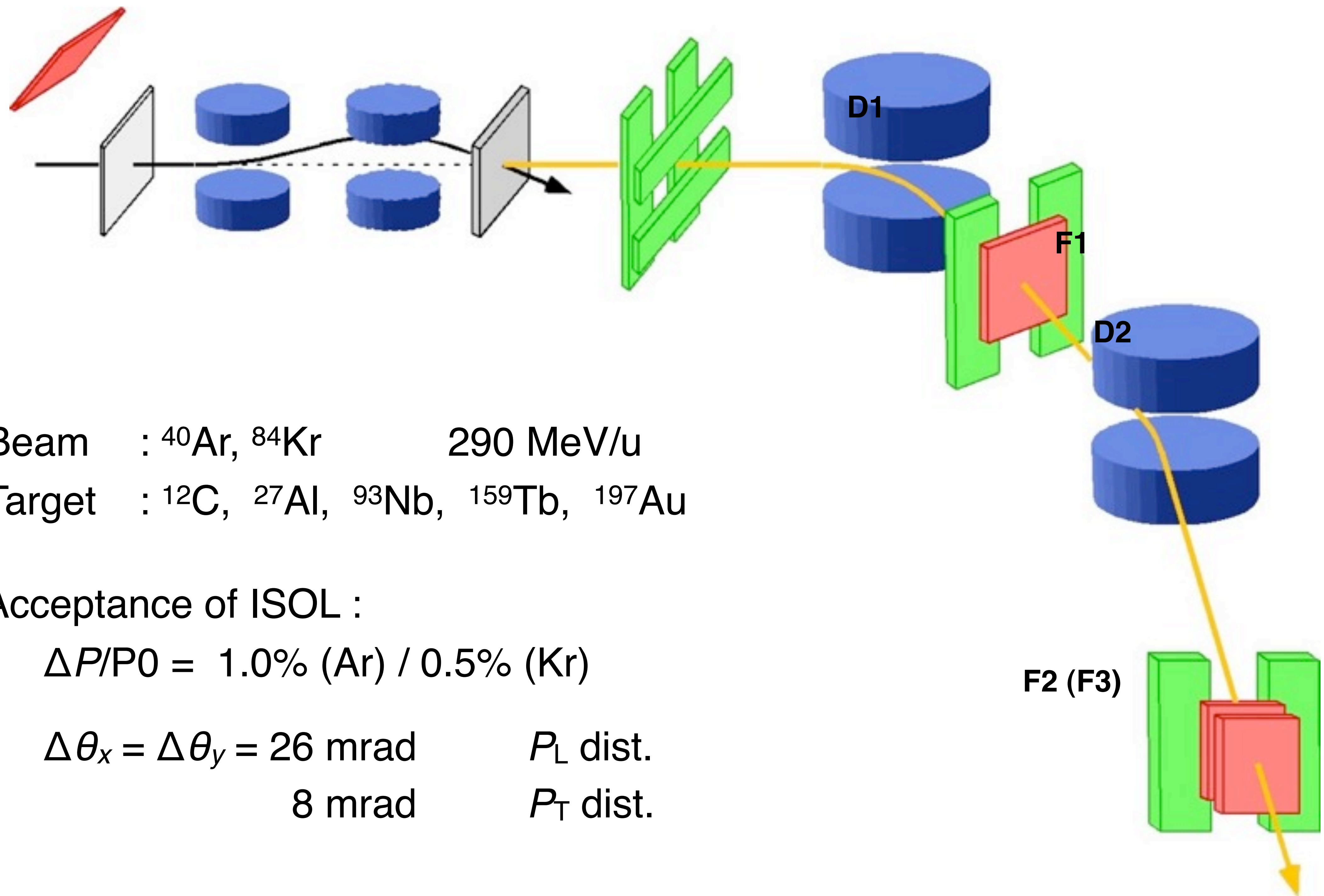
Production and identification



Beam : ^{40}Ar, ^{84}Kr 290 MeV/u

Target : ^{12}C, ^{27}Al, ^{93}Nb, ^{159}Tb, ^{197}Au

Acceptance of ISOL :

$\Delta P/P0$ = 1.0% (Ar) / 0.5% (Kr)

$\Delta\theta_x = \Delta\theta_y$ = 26 mrad P_L dist.

8 mrad P_T dist.

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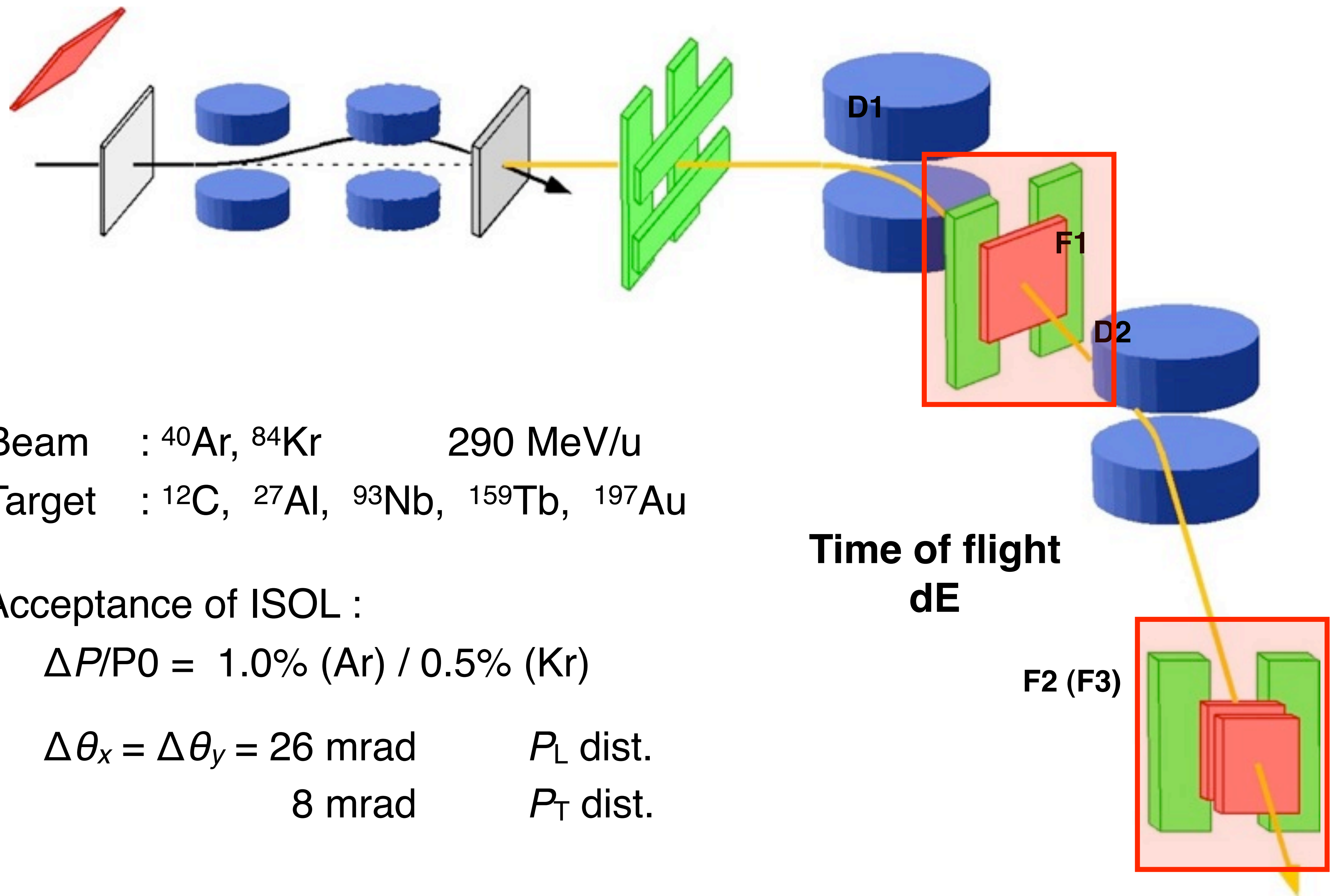

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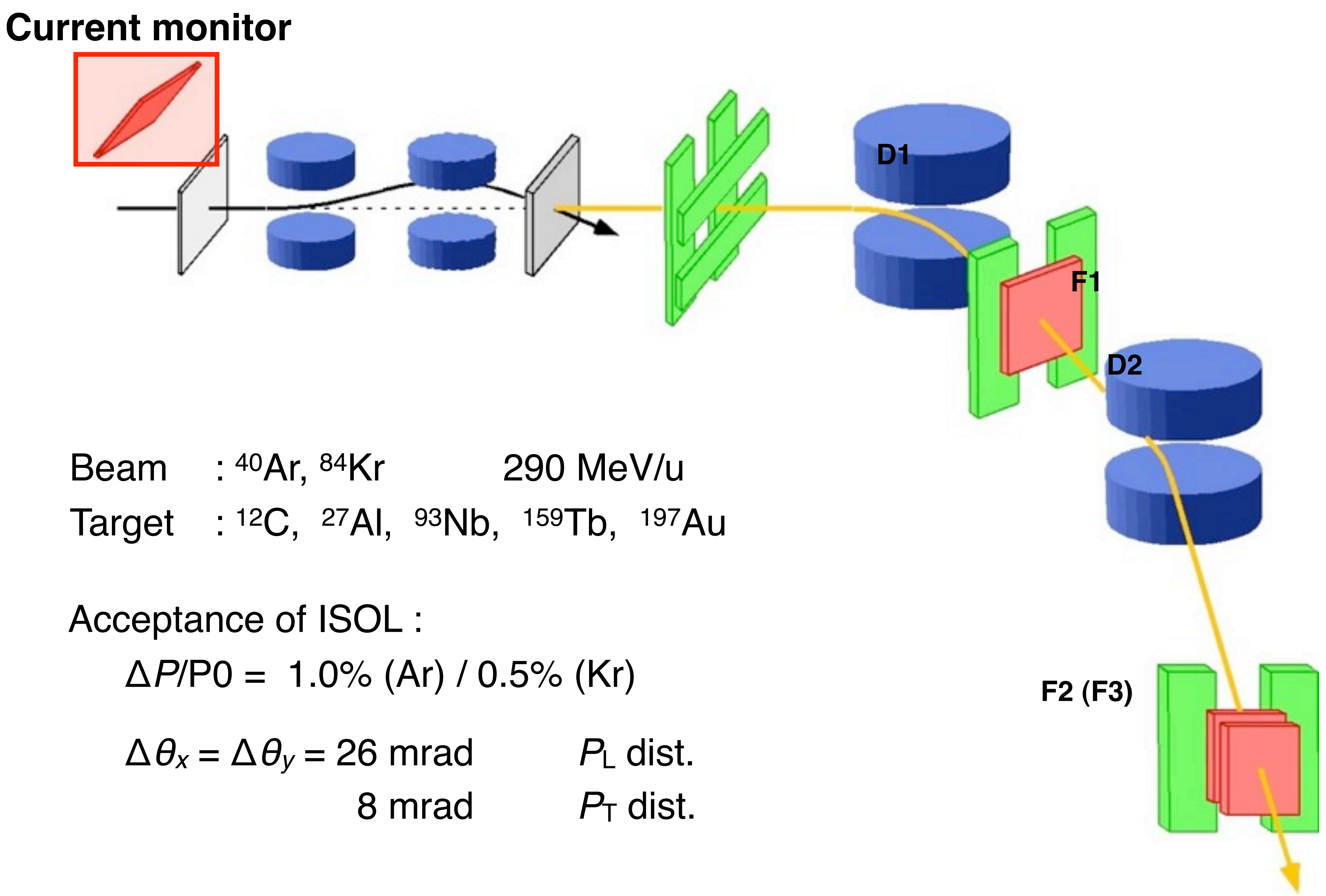

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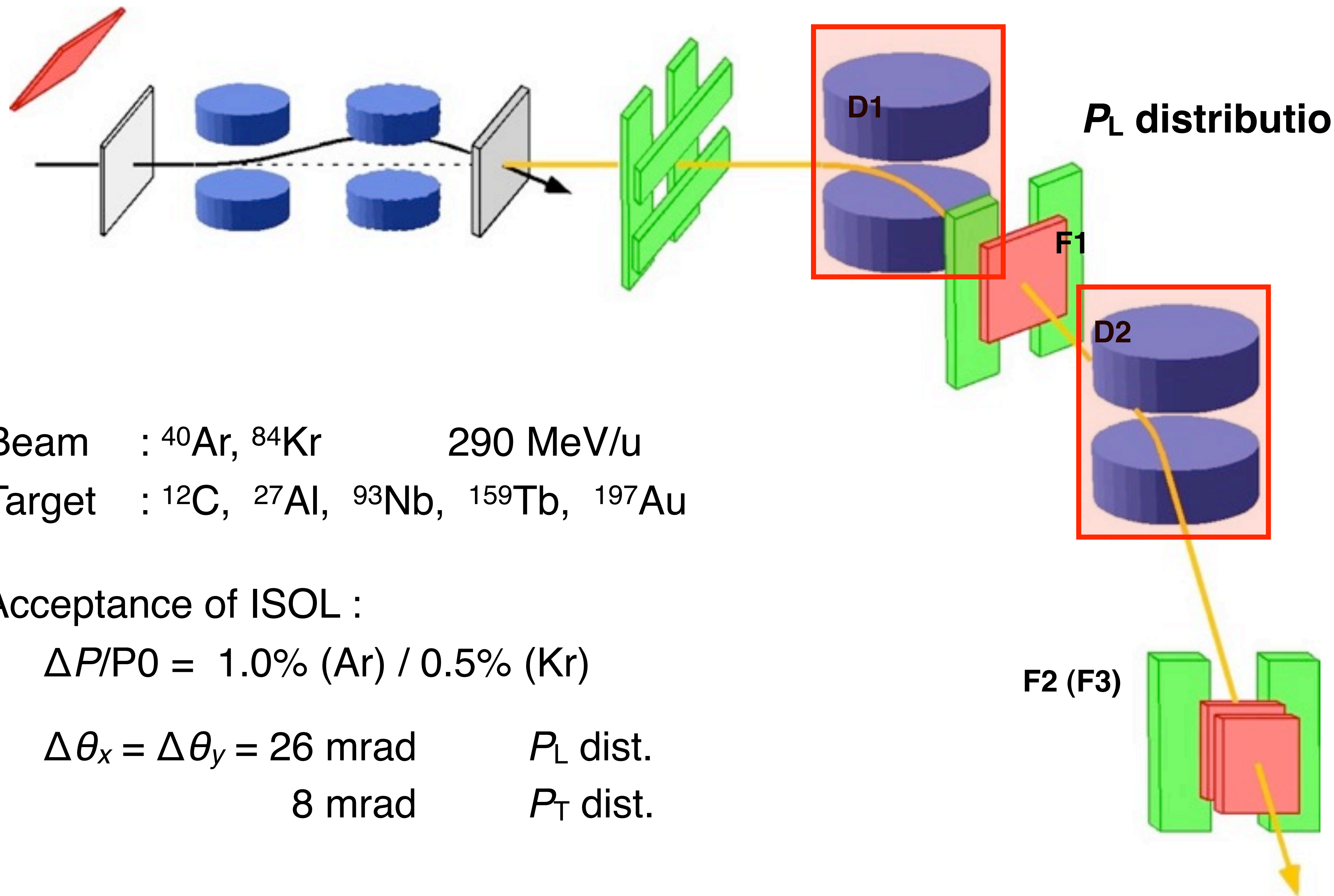

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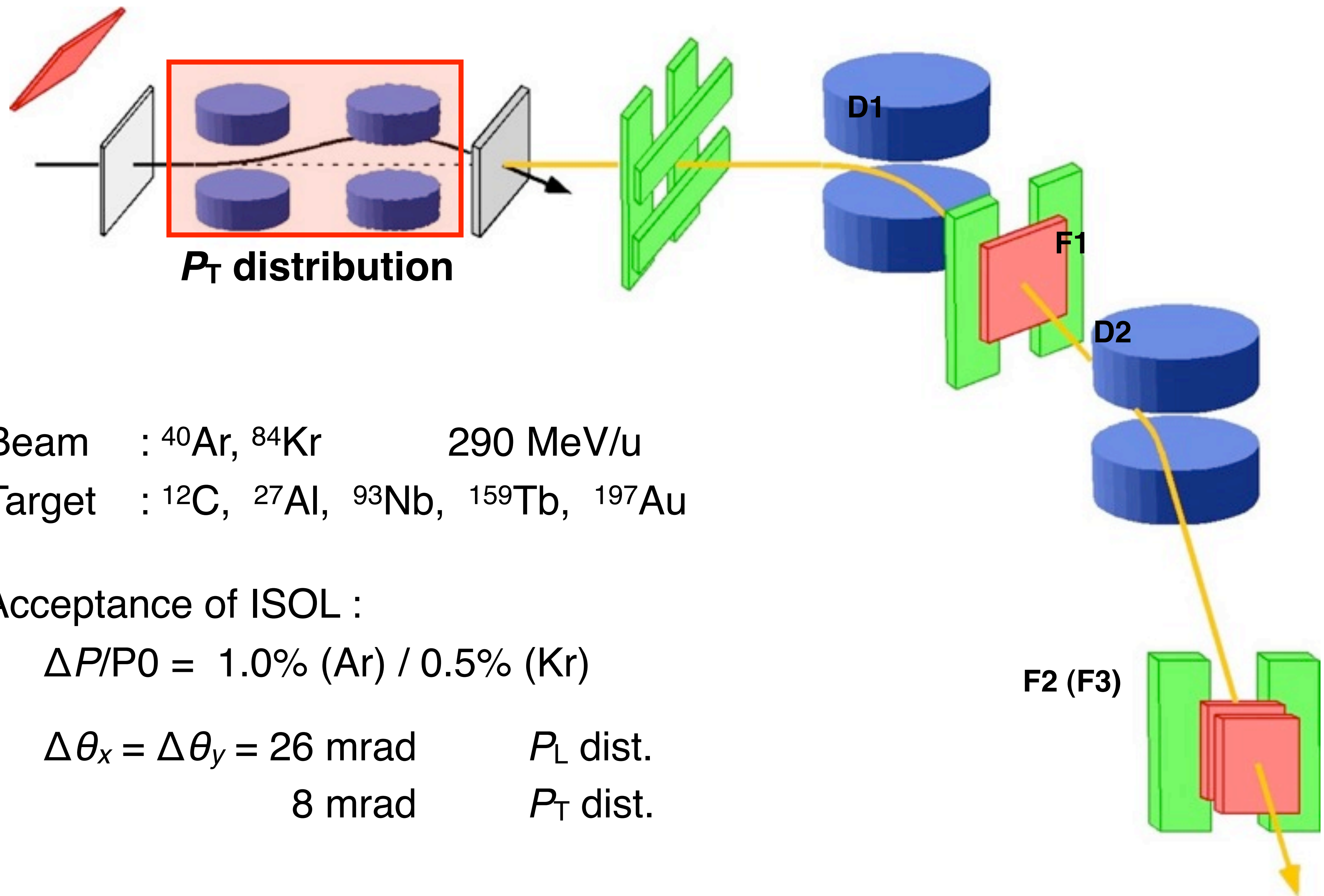

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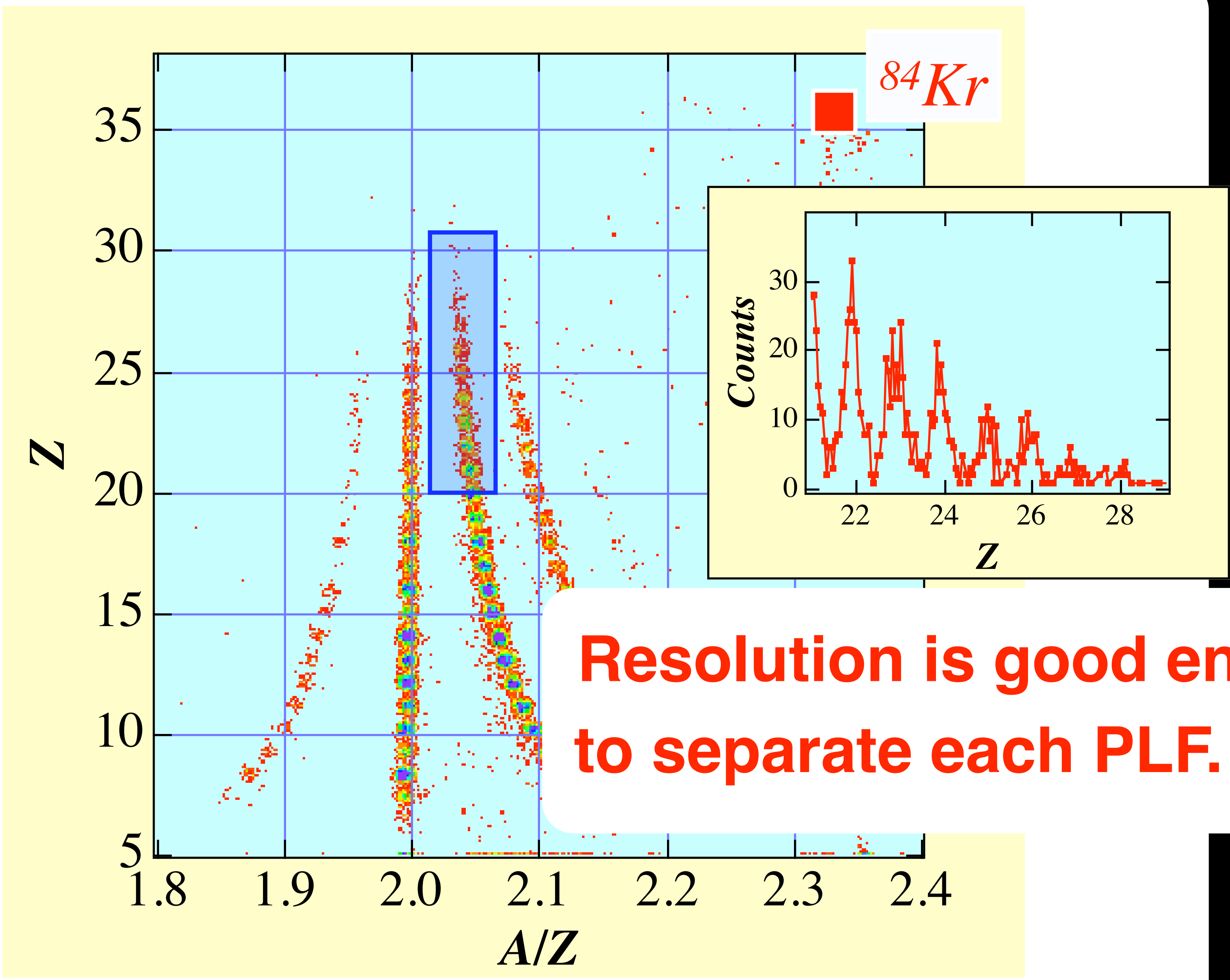
Identification of PLFs

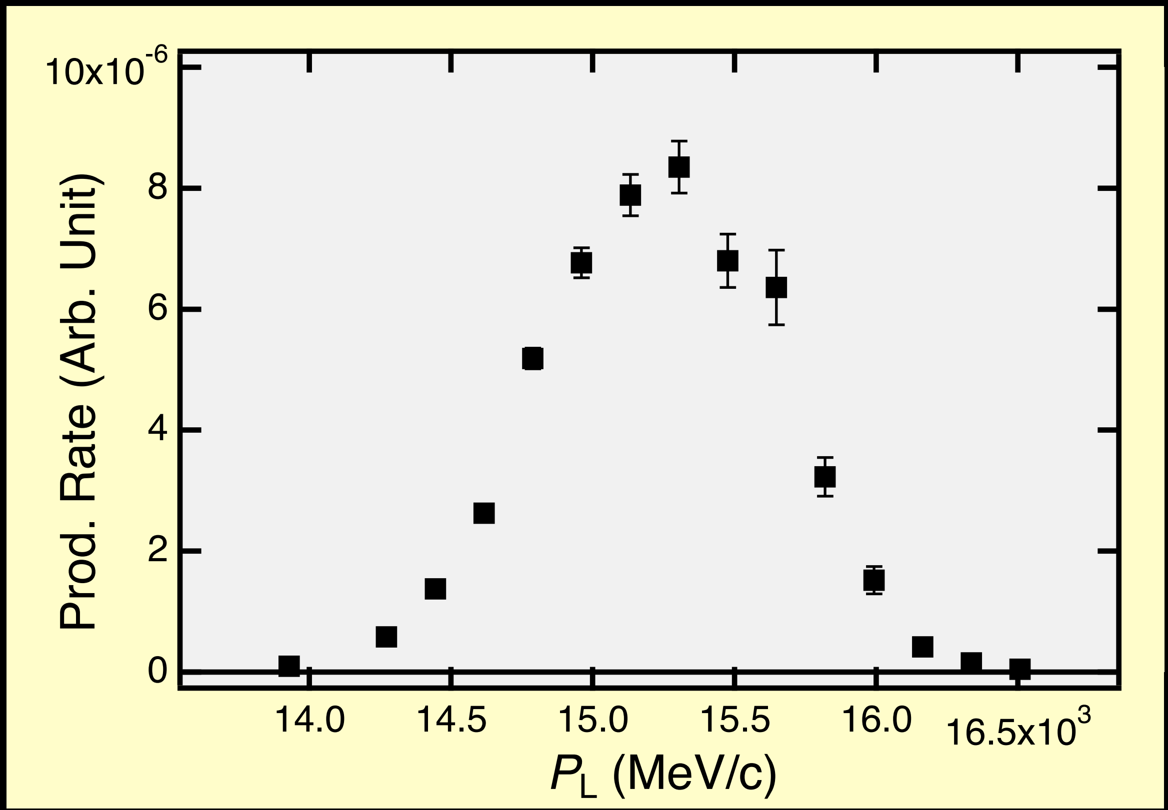
- ^{84}Kr + ^{12}C → ^{A}Z + X : $B\rho$=82.5%



Resolution is good enough to separate each PLF.

Analysis of P_L distributions

- $^{40}Ar+^{93}Nb \rightarrow ^{20}Ne$
- $^{84}Kr+^{12}C \rightarrow ^{43}Ca$



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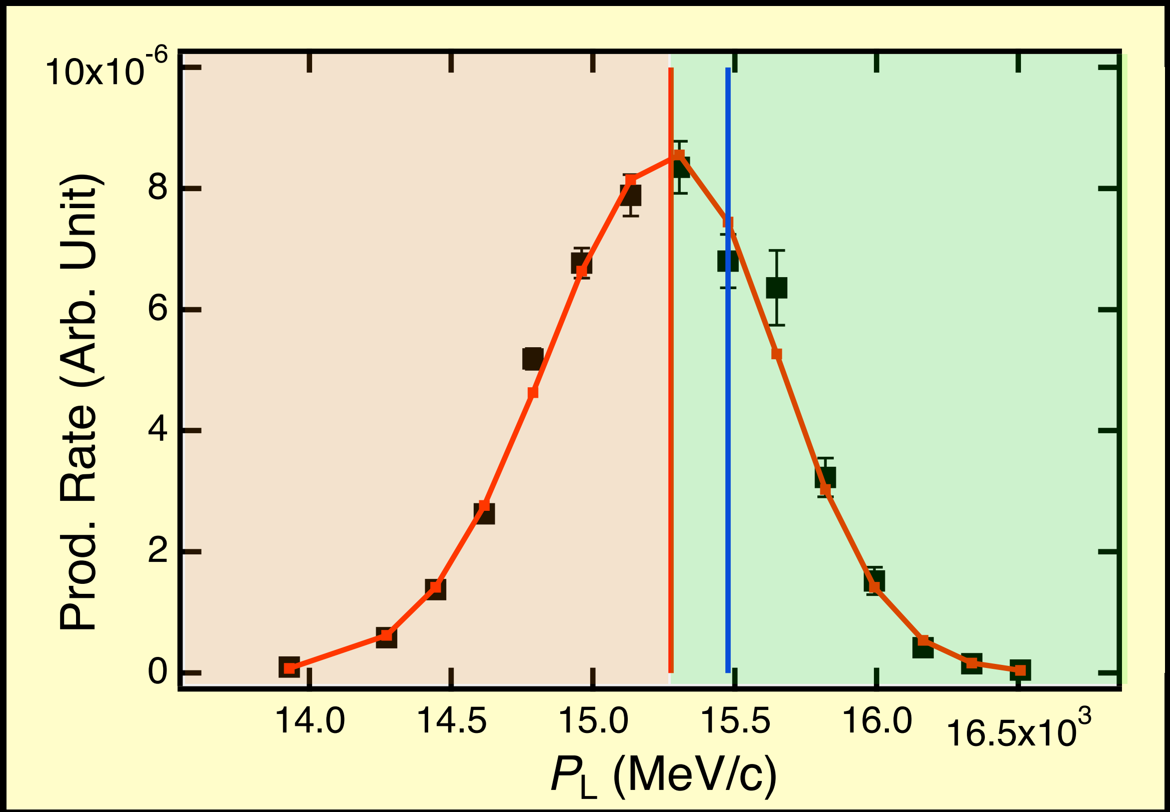

$$Y(P_L) = A\exp\left(-\frac{(P_L - P_0)^2}{2\sigma(P_L)^2}\right) \quad \begin{cases} \sigma(P_L) = \sigma_{Low} & \text{if } P_L < P_0 \\ \sigma(P_L) = \sigma_{High} & \text{if } P_L > P_0 \end{cases}$$

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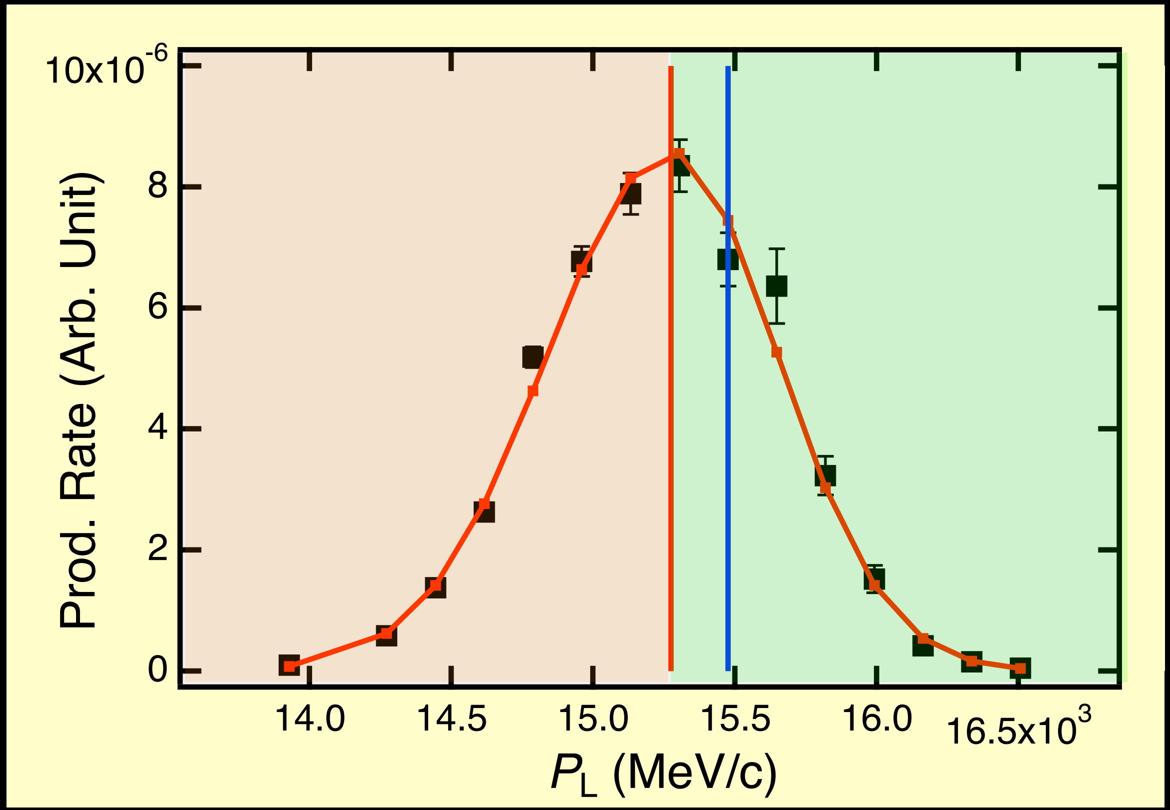

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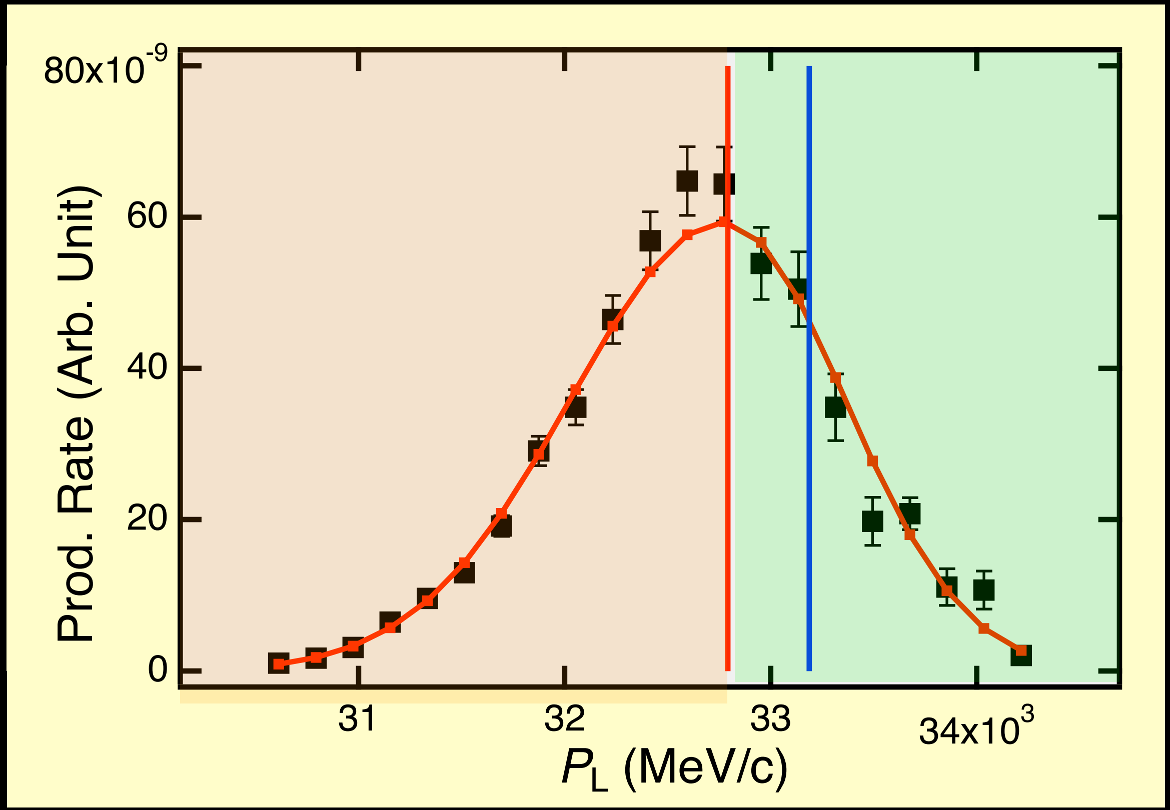

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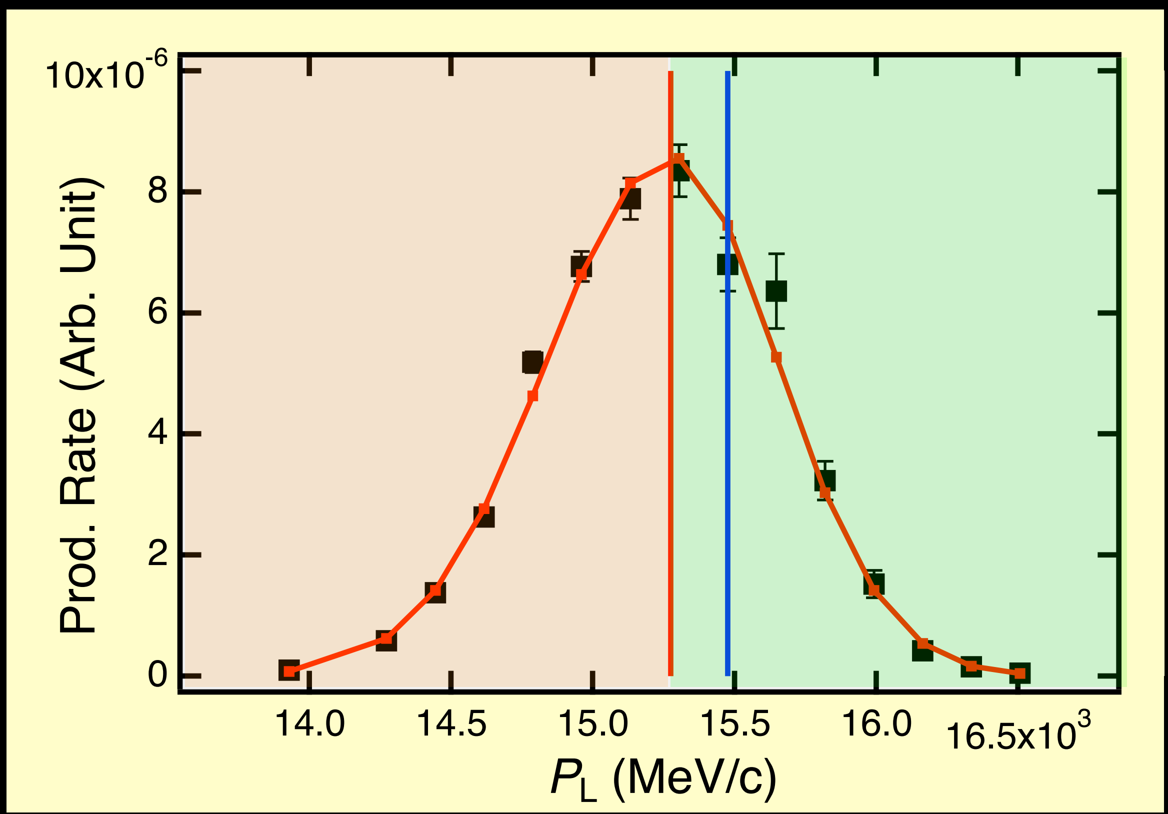

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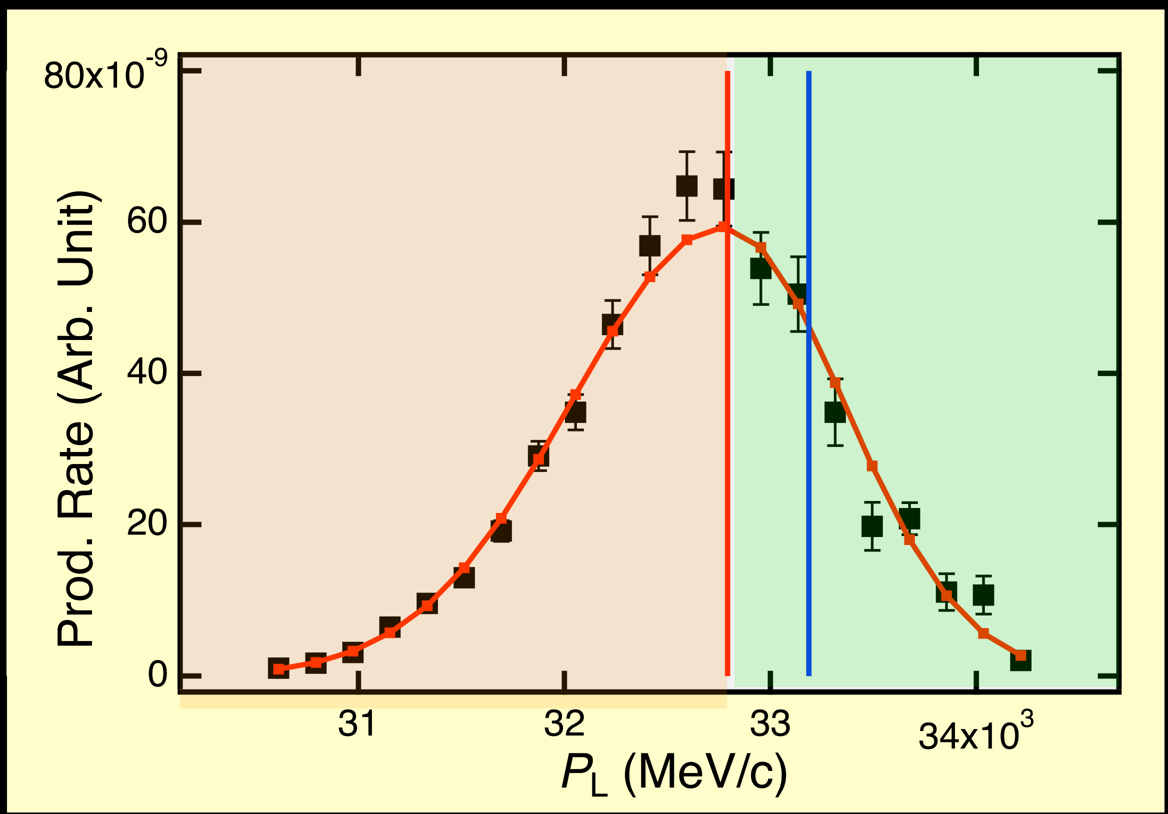

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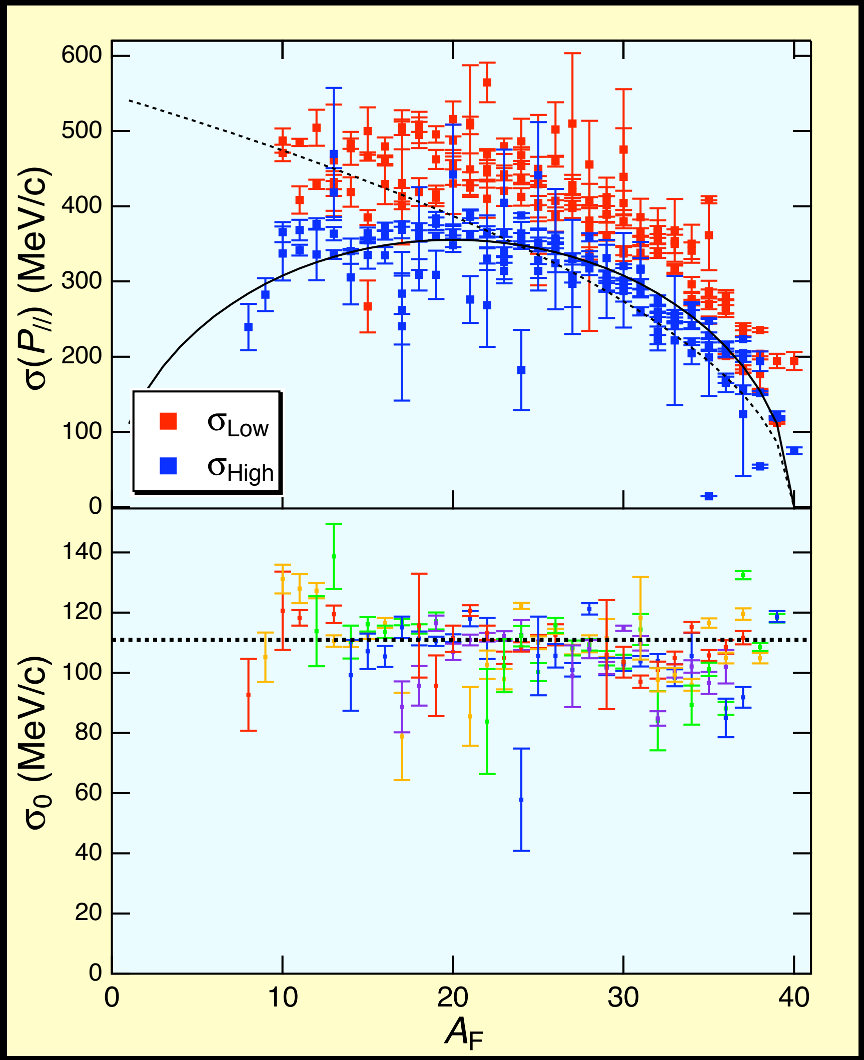
The analysis provides the width and the deceleration effect.

σ_{Low} , σ_{High} $-\Delta P_L$

Width of P_L distributions

- $^{40}Ar+^{93}Nb \rightarrow {}^{A}Z$



- $\sigma_{Low}/\sigma_{High}$ is about 20 %.
- GH formulation is valid for σ_{High}.
- σ_o obtained from σ_{High} is ~ 110 MeV/c.

Width of P_L distributions

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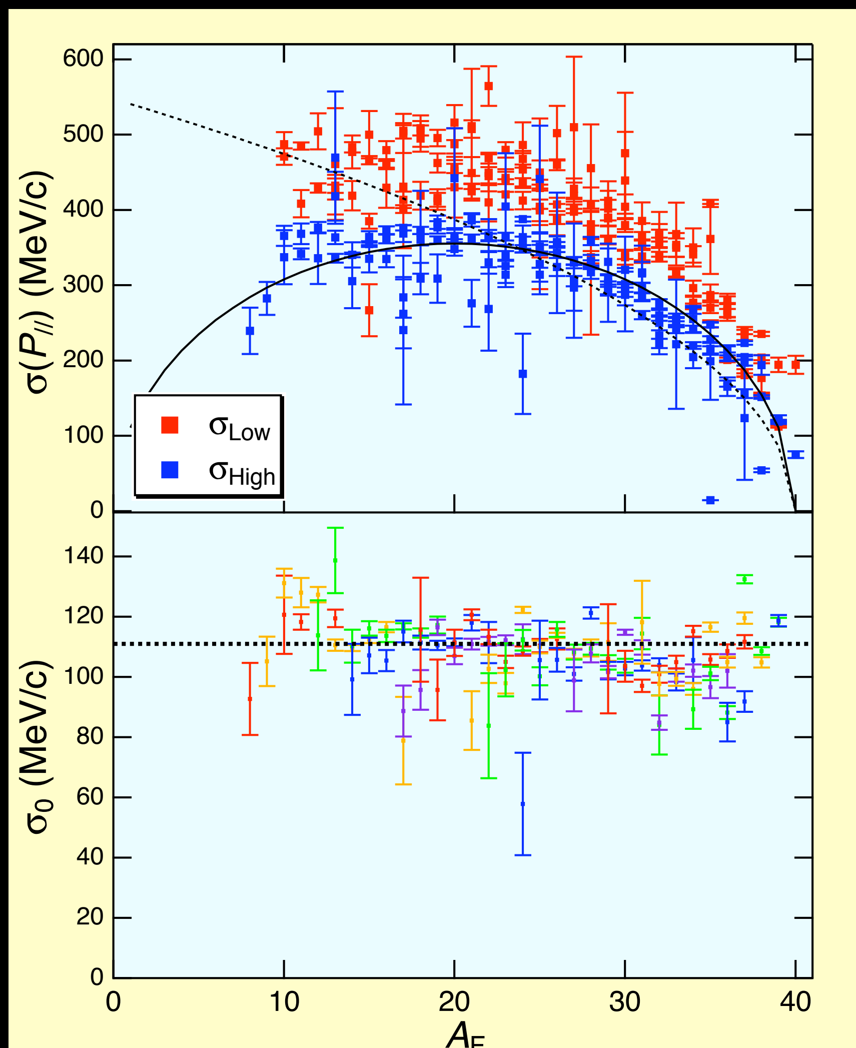

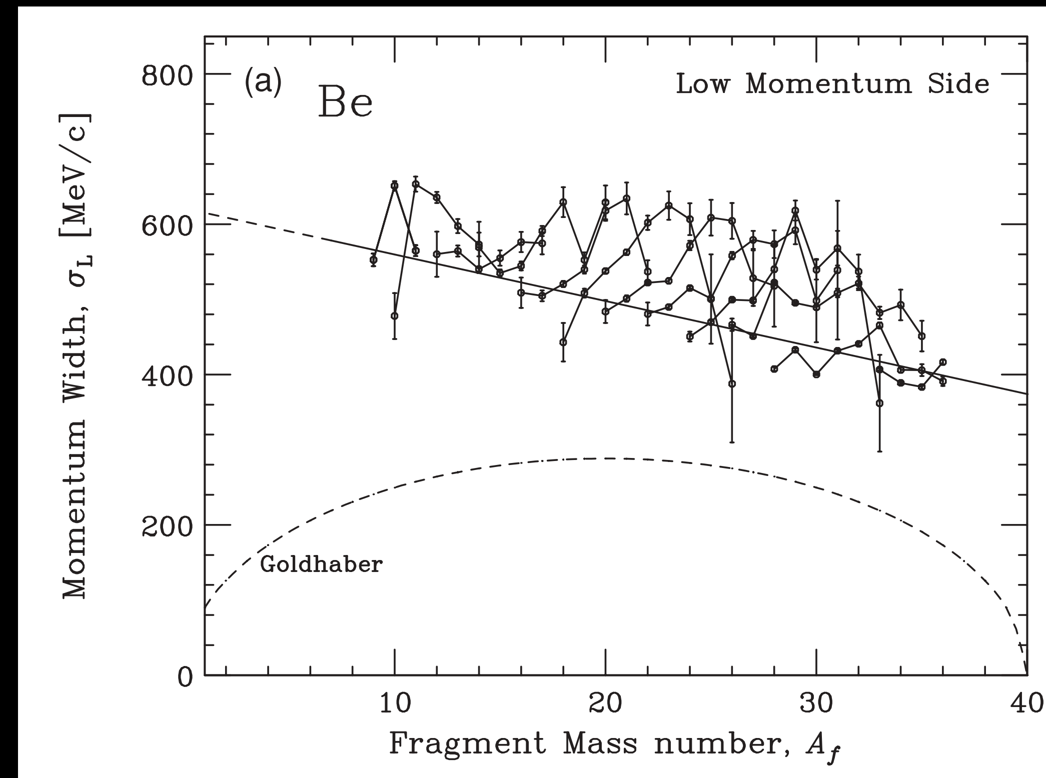

- $^{40}Ar+^{9}Be$@95 MeV/u Notani et al.
- Broadening effect is suppressed compared with lower energy reaction.

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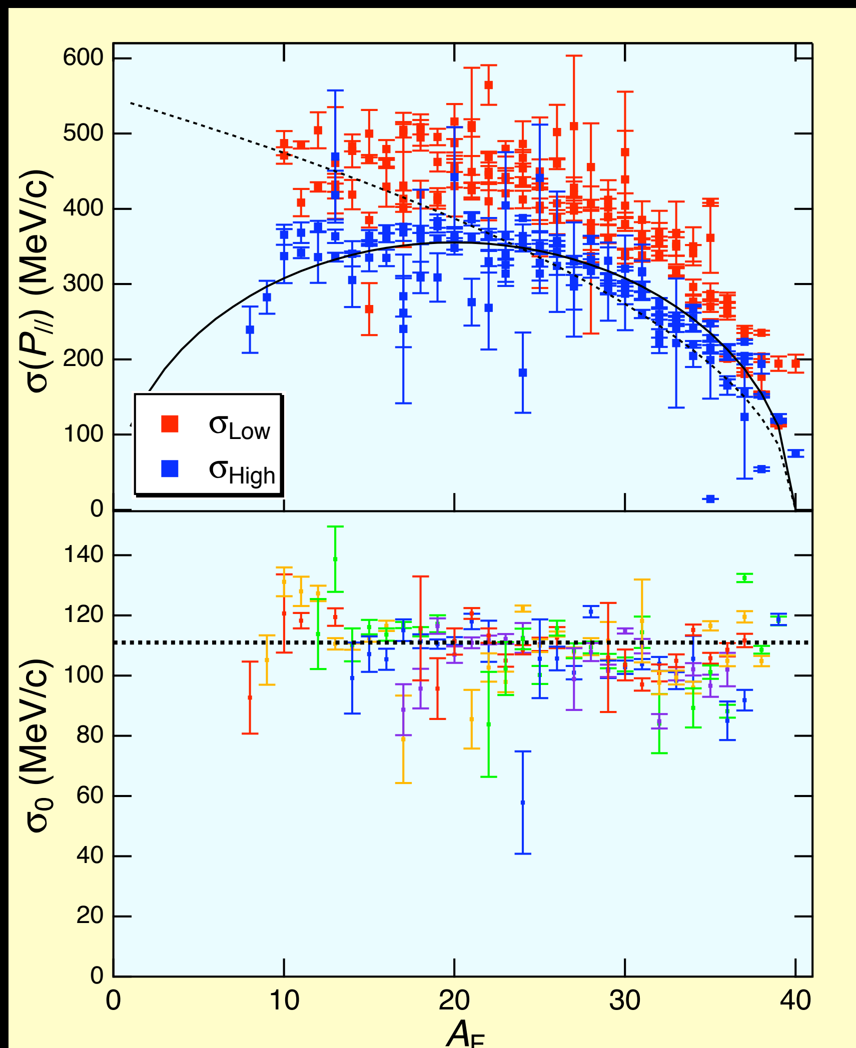

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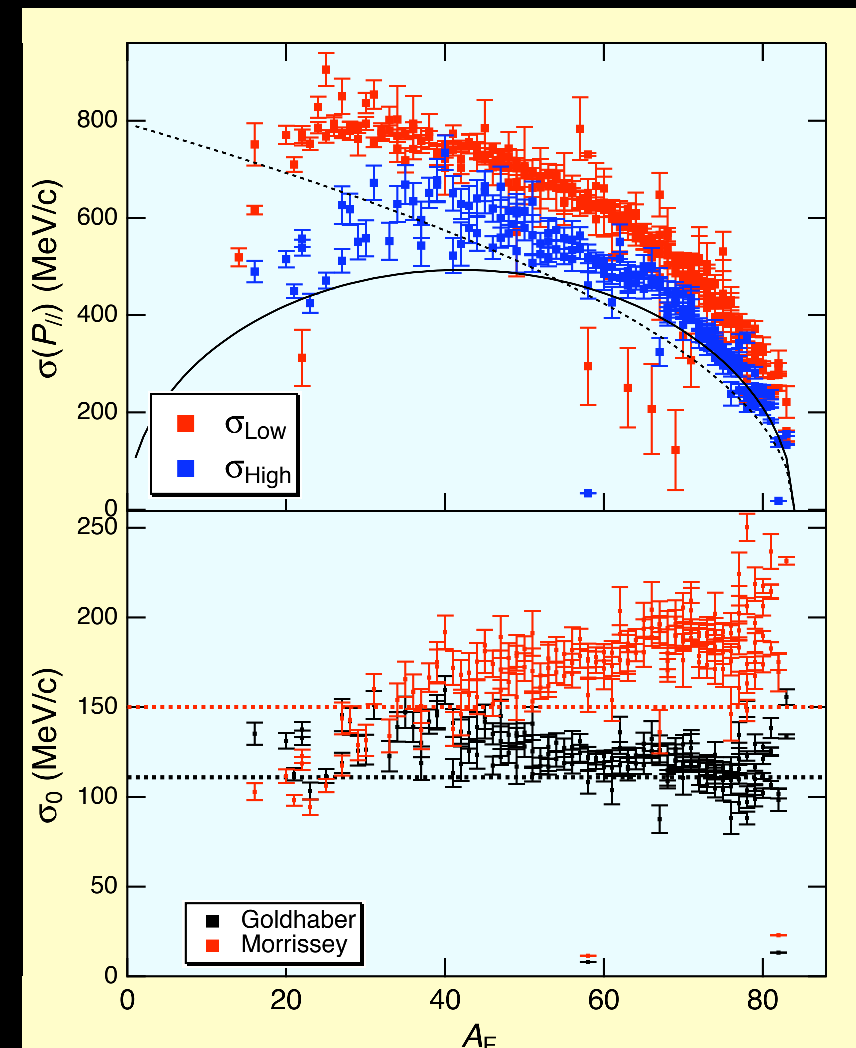
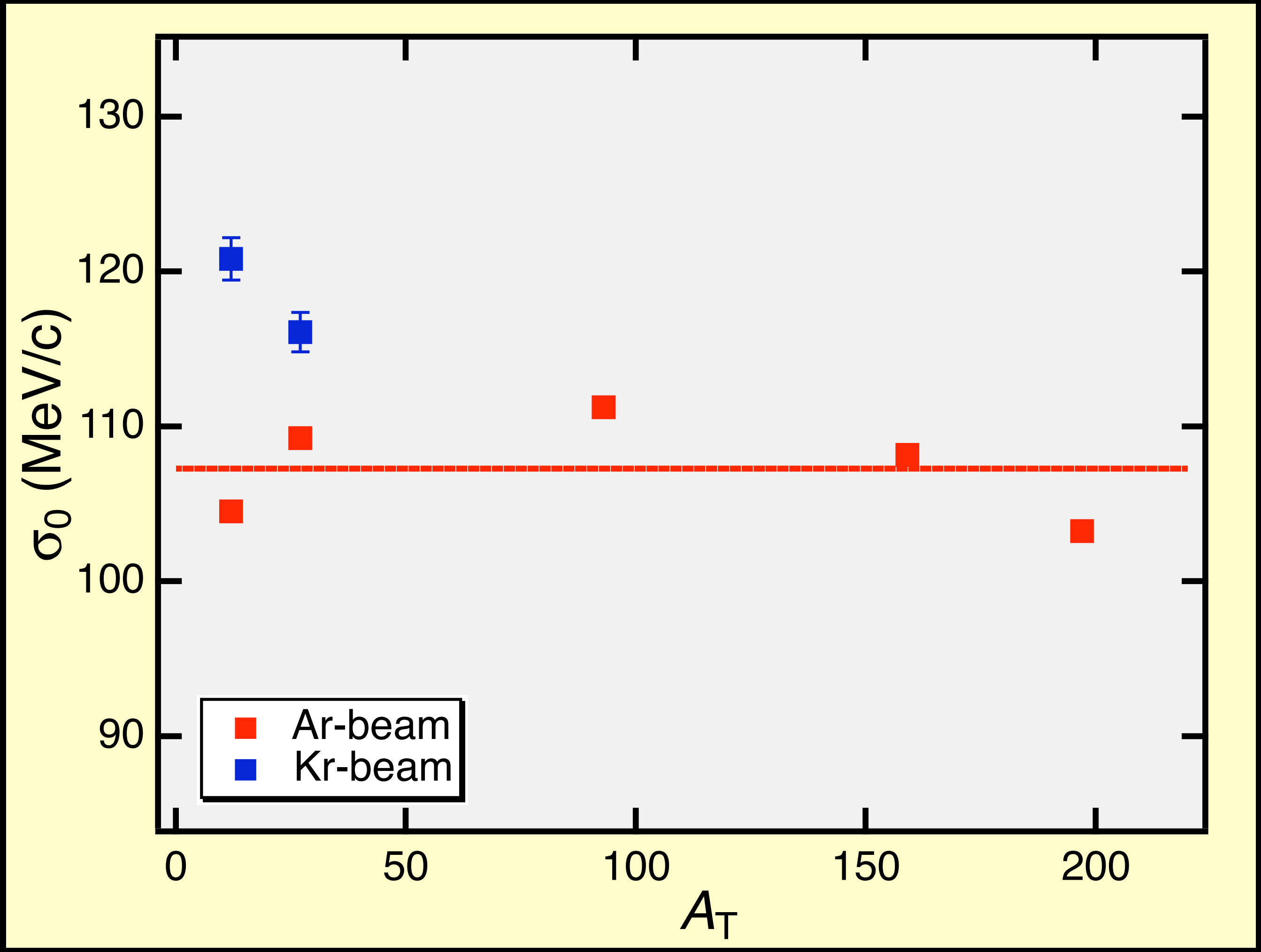


- $\sigma_{Low}/\sigma_{High}$ is about 20 %.
- GH formulation is valid only for heavy PLFs.
- σ_o is slightly larger than that for Ar-beam.

Reduced width : σ_0

- Target dependence

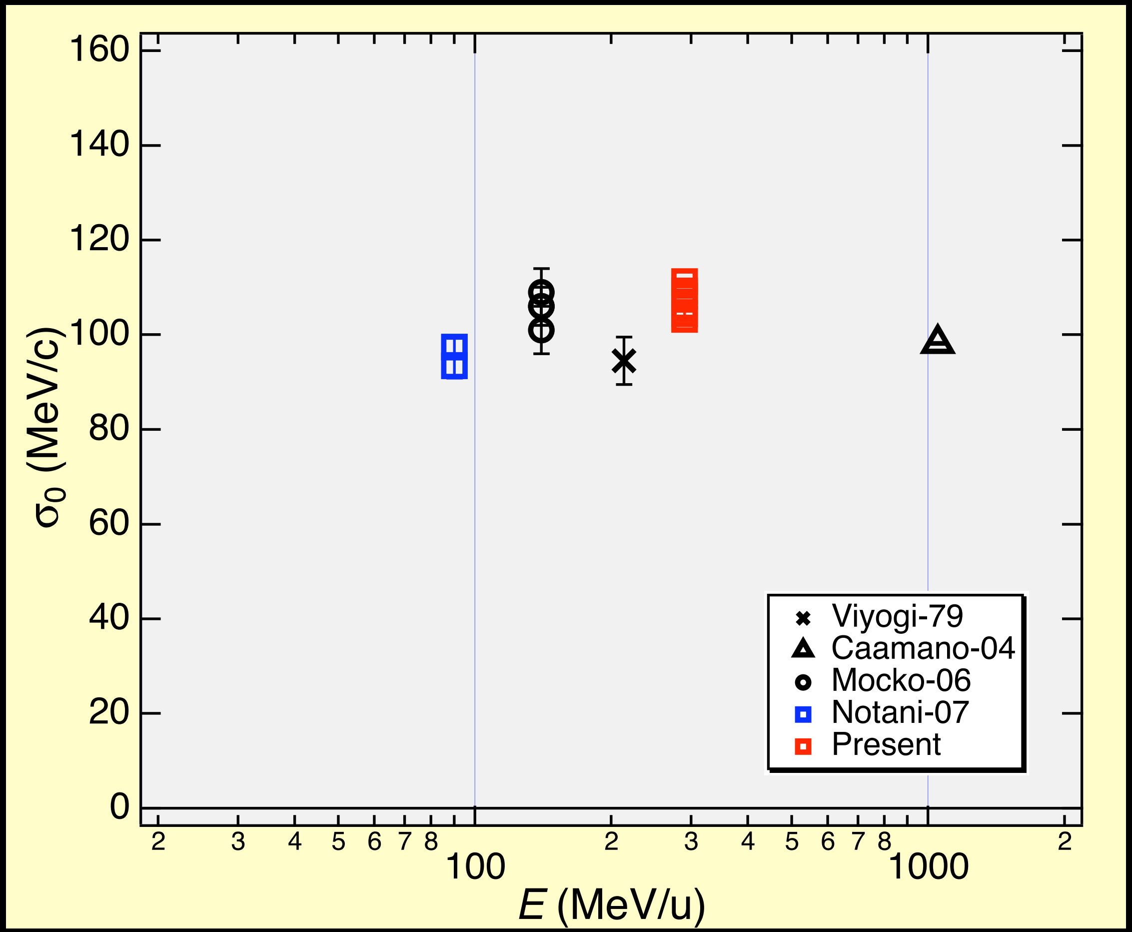


- σ_0 is independent on target nuclei.
- σ_0(Kr) is larger than σ_0(Ar).

Reduced width : σ_0

- Energy dependence

Ar-beam

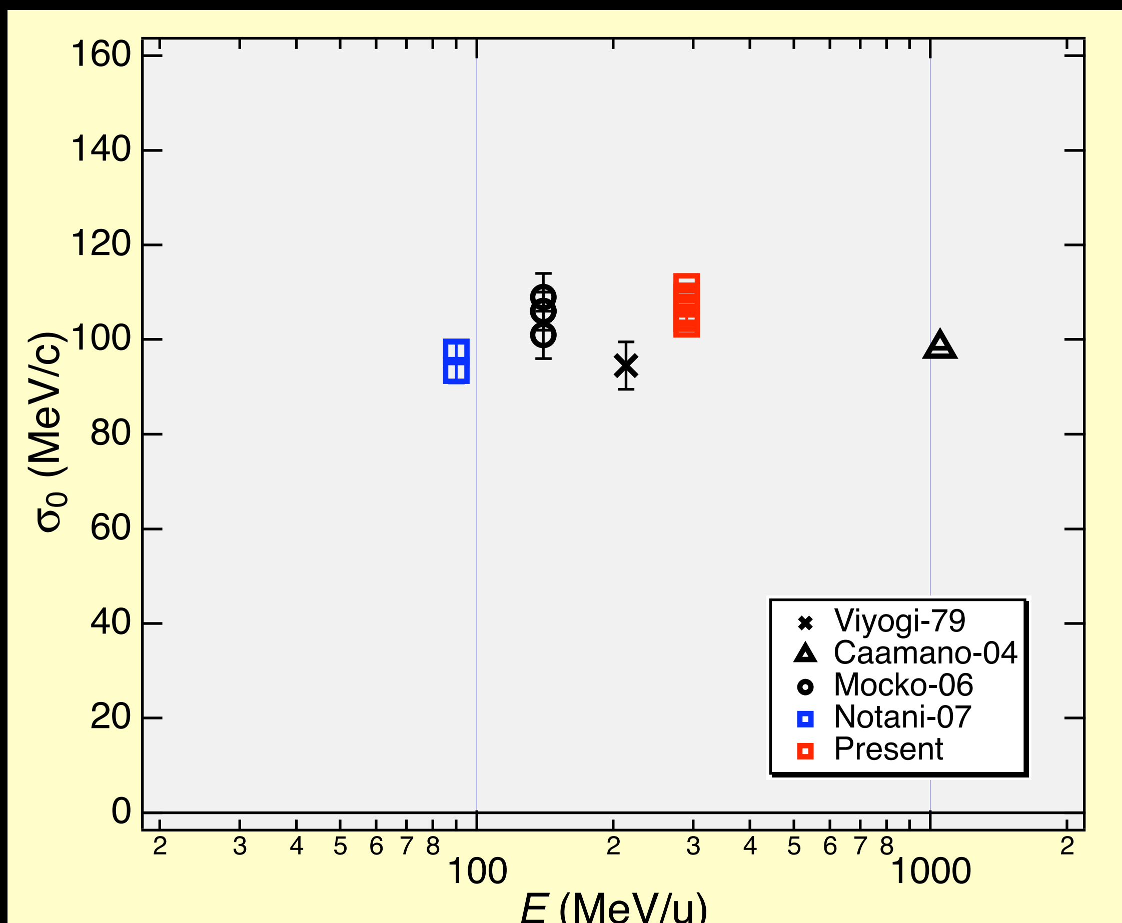


- σ_0 is constant at E = 100 ~ 1000 MeV/u.

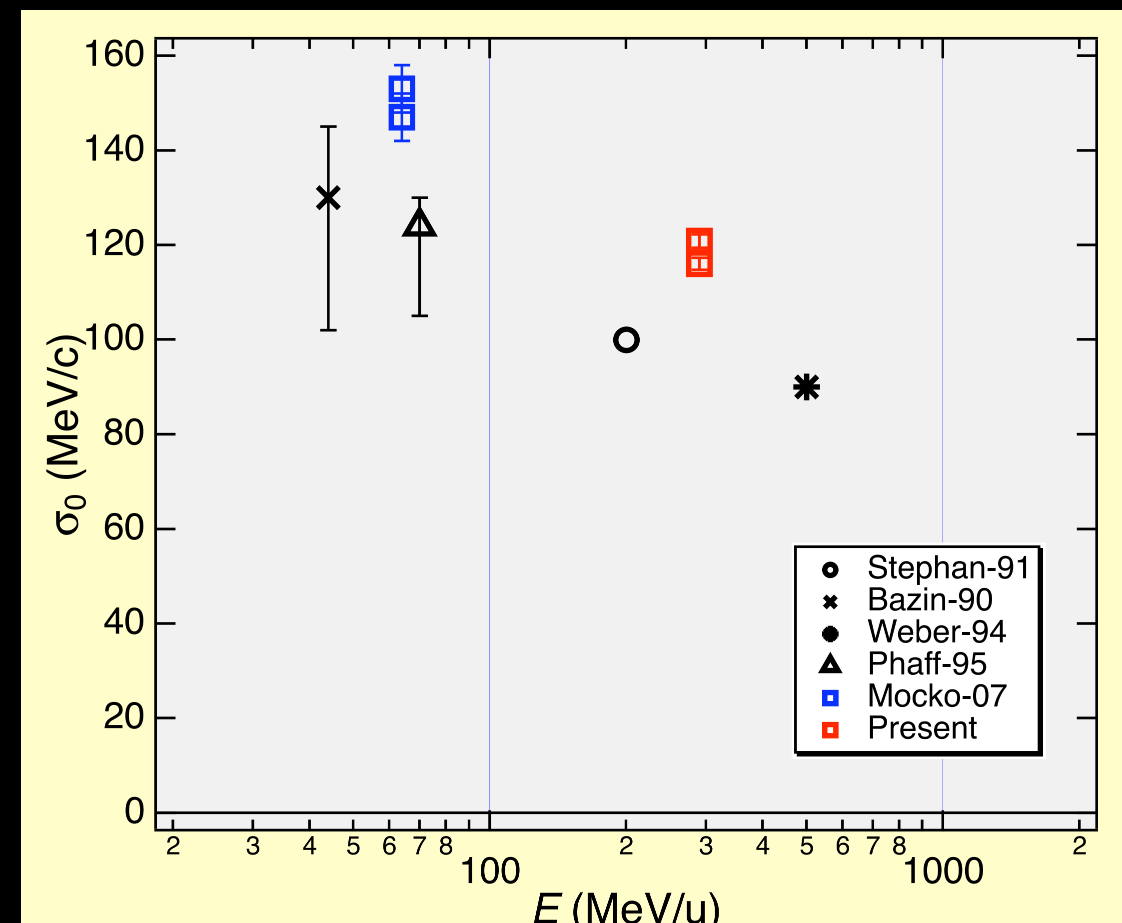
Reduced width : σ_0

- Energy dependence

Ar-beam



Kr-beam

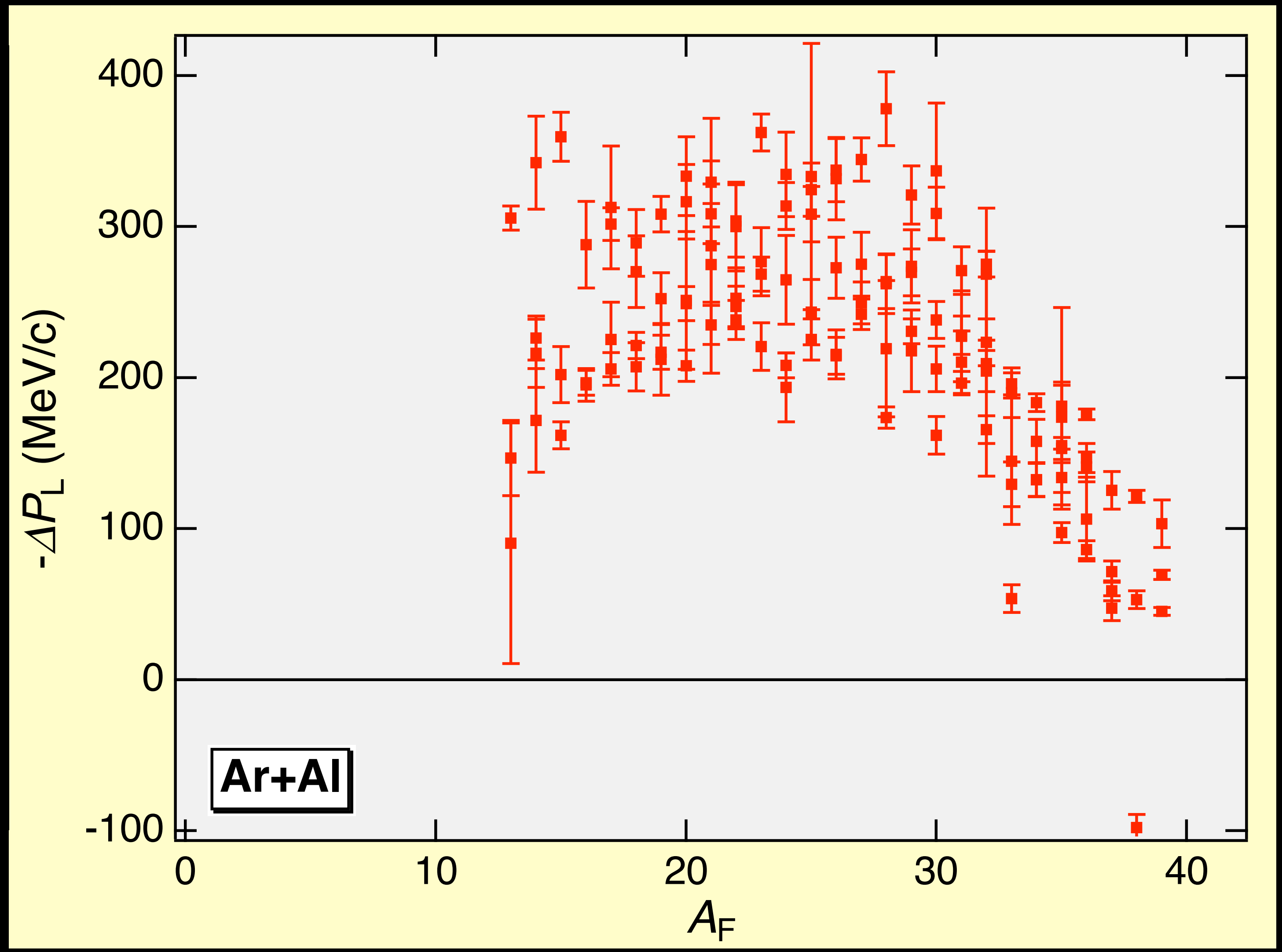


- σ_0 is constant at E = 100 ~ 1000 MeV/u.

- σ_0 is energy dependent for at E = 40 ~ 500 MeV/u.

Deceleration effect : Ar-beam

- $^{40}Ar + ^{27}Al \rightarrow {}^{A}Z$



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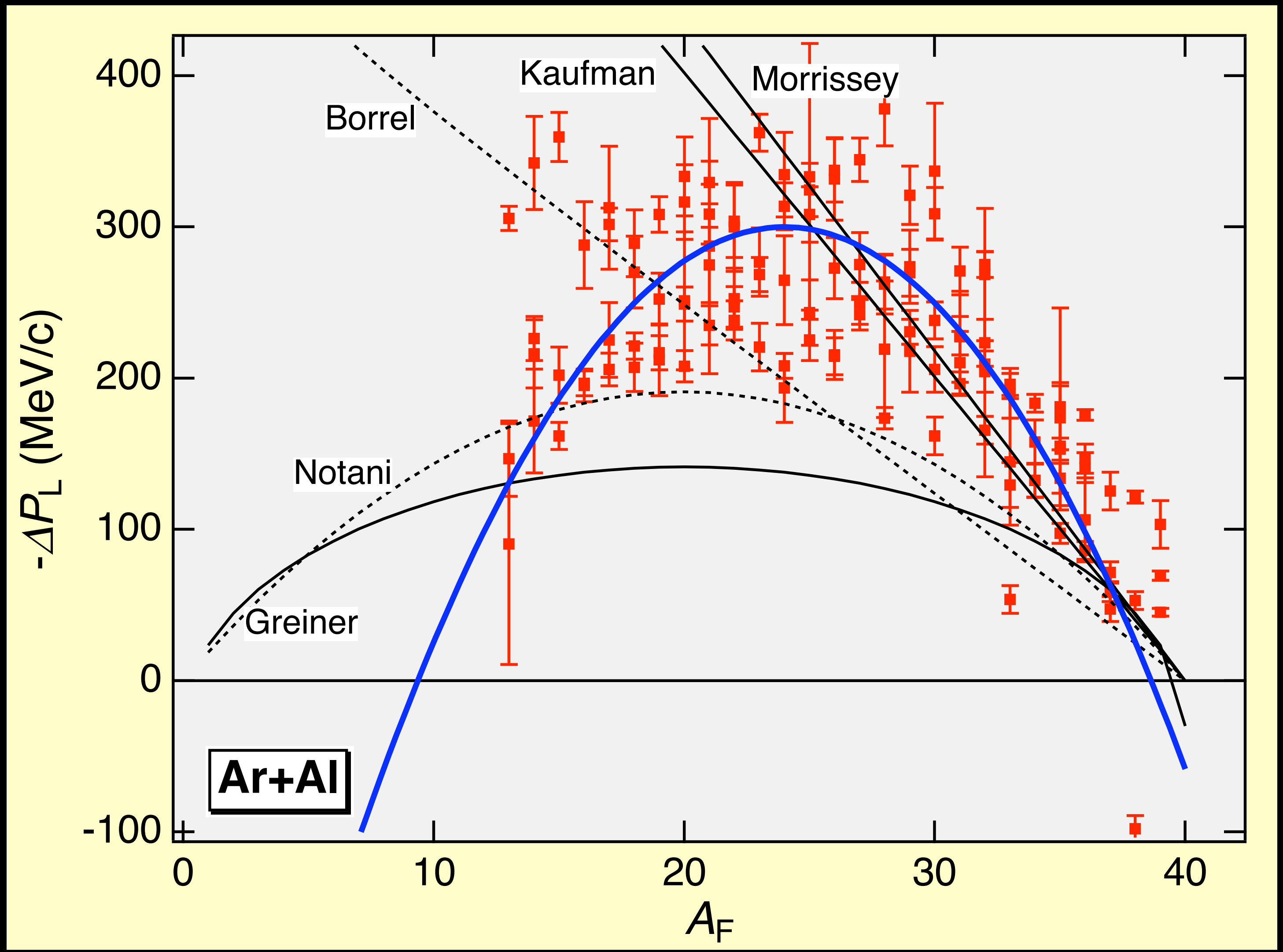
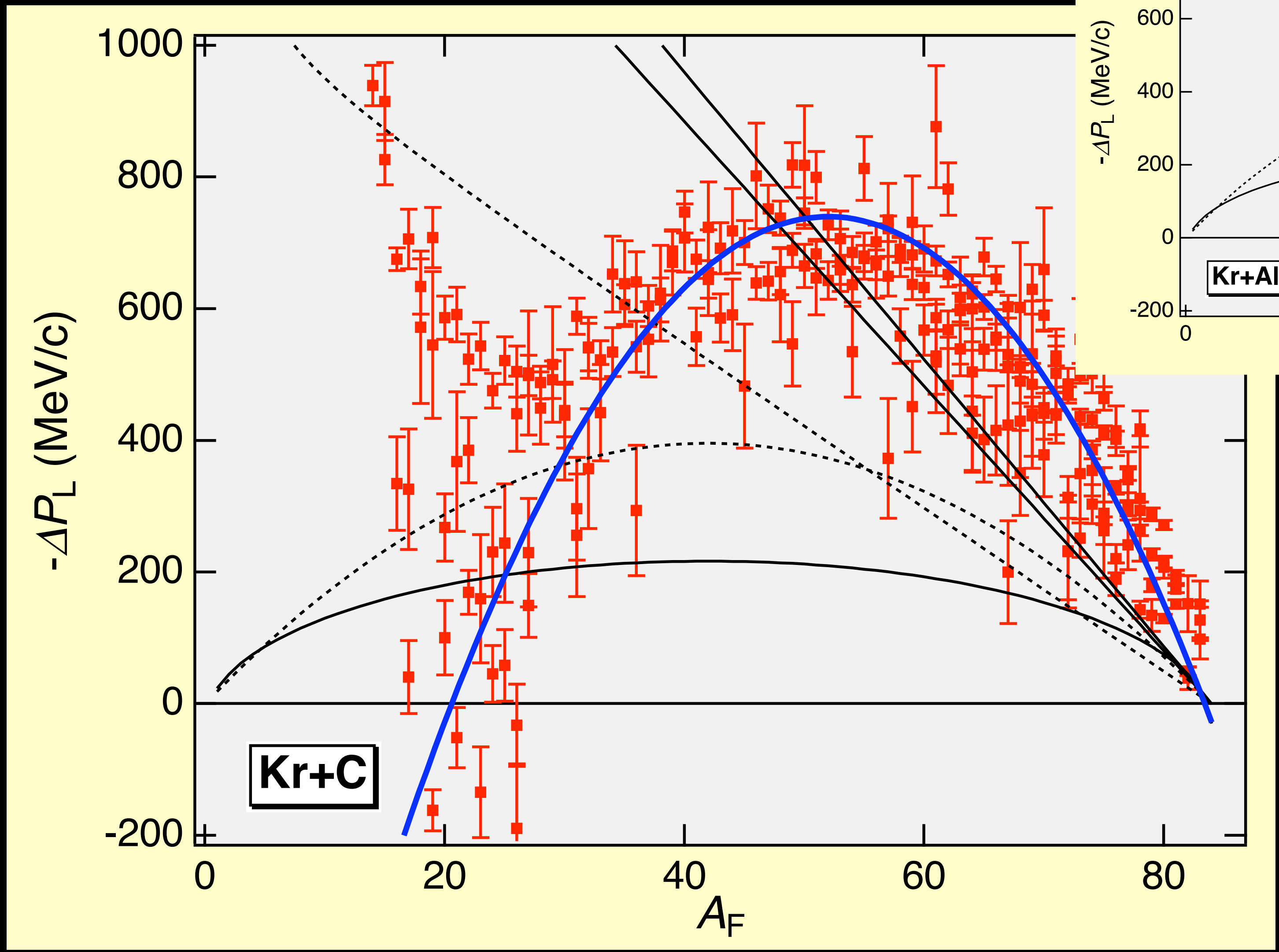
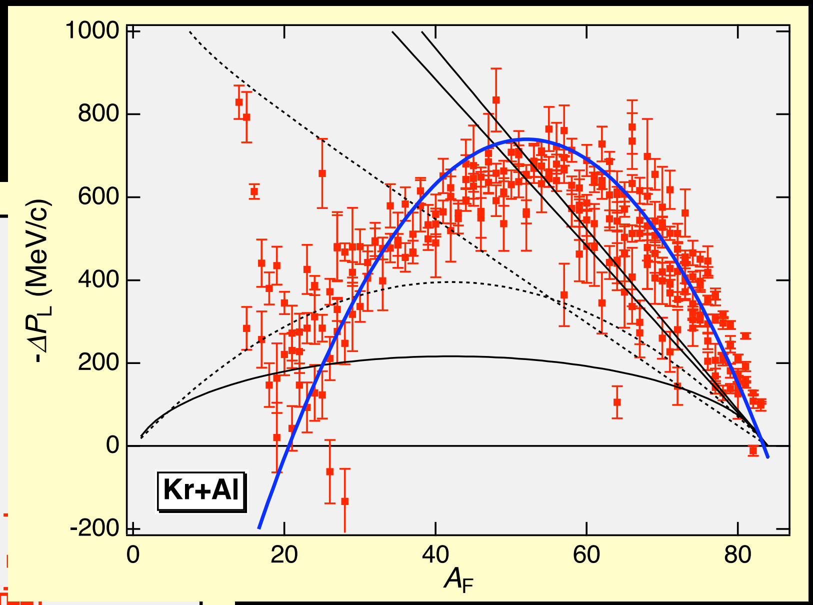


- $-\Delta P_L$ distribution shows parabolic shape and become its maximum 300 MeV/c at $A_F \sim 25$.
- Morrissey/Kaufman formulation is probable for heavier PLFs.

Deceleration effect : Kr-beam

- $^{84}Kr+^{12}C \rightarrow {}^{A}Z$

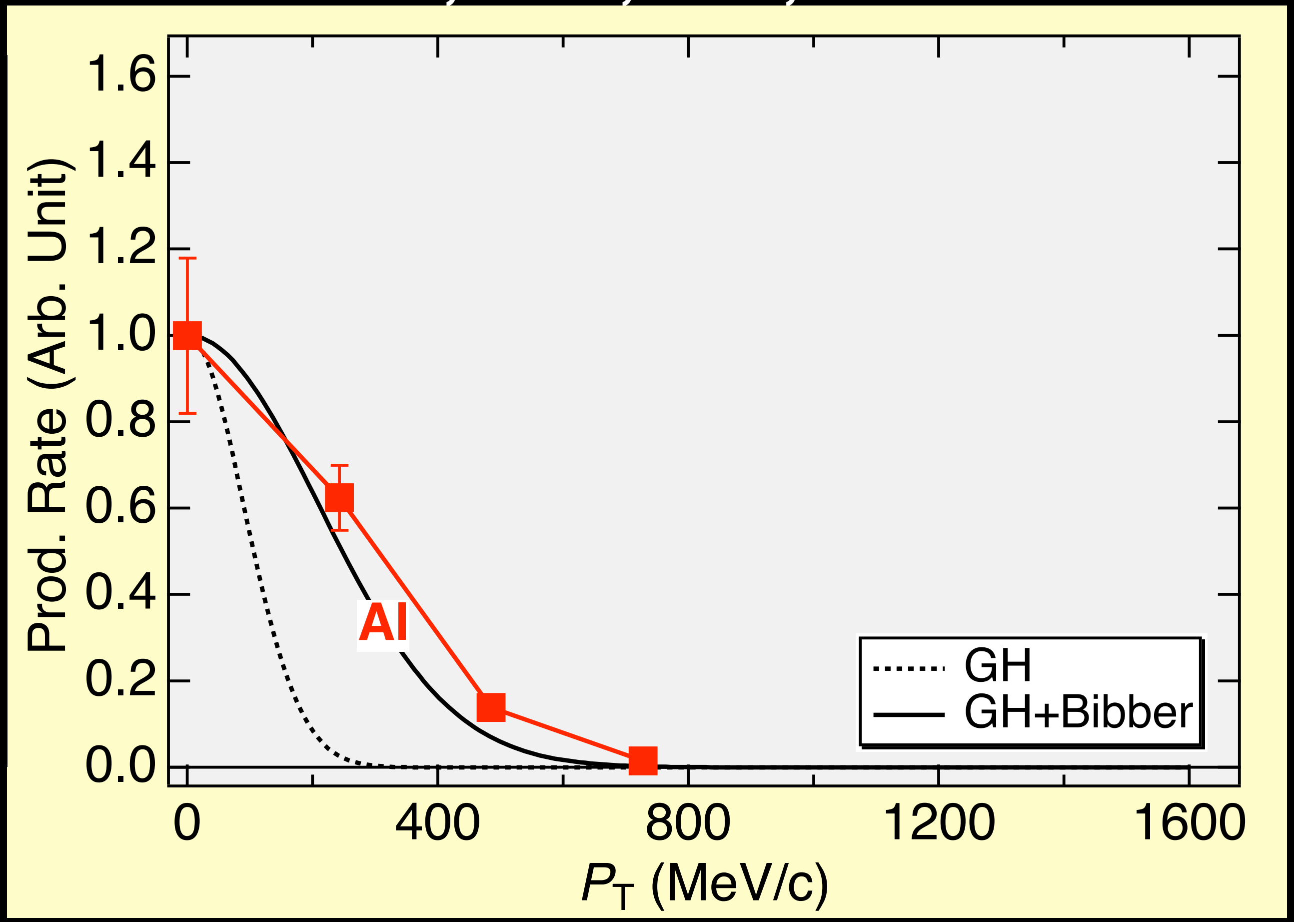




- $-\Delta P_L$ distribution shows parabolic shape and become its maximum 700 MeV/c at $A_F \sim 50$.
- Morrissey/Kaufman formulation is probable for heavier PLFs.

Observed P_T distribution

- ^{40}Ar+Al, Nb, Tb, Au →^{39}Cl



- In case of light target, P_T distribution is well reproduced by previously proposed formulation.

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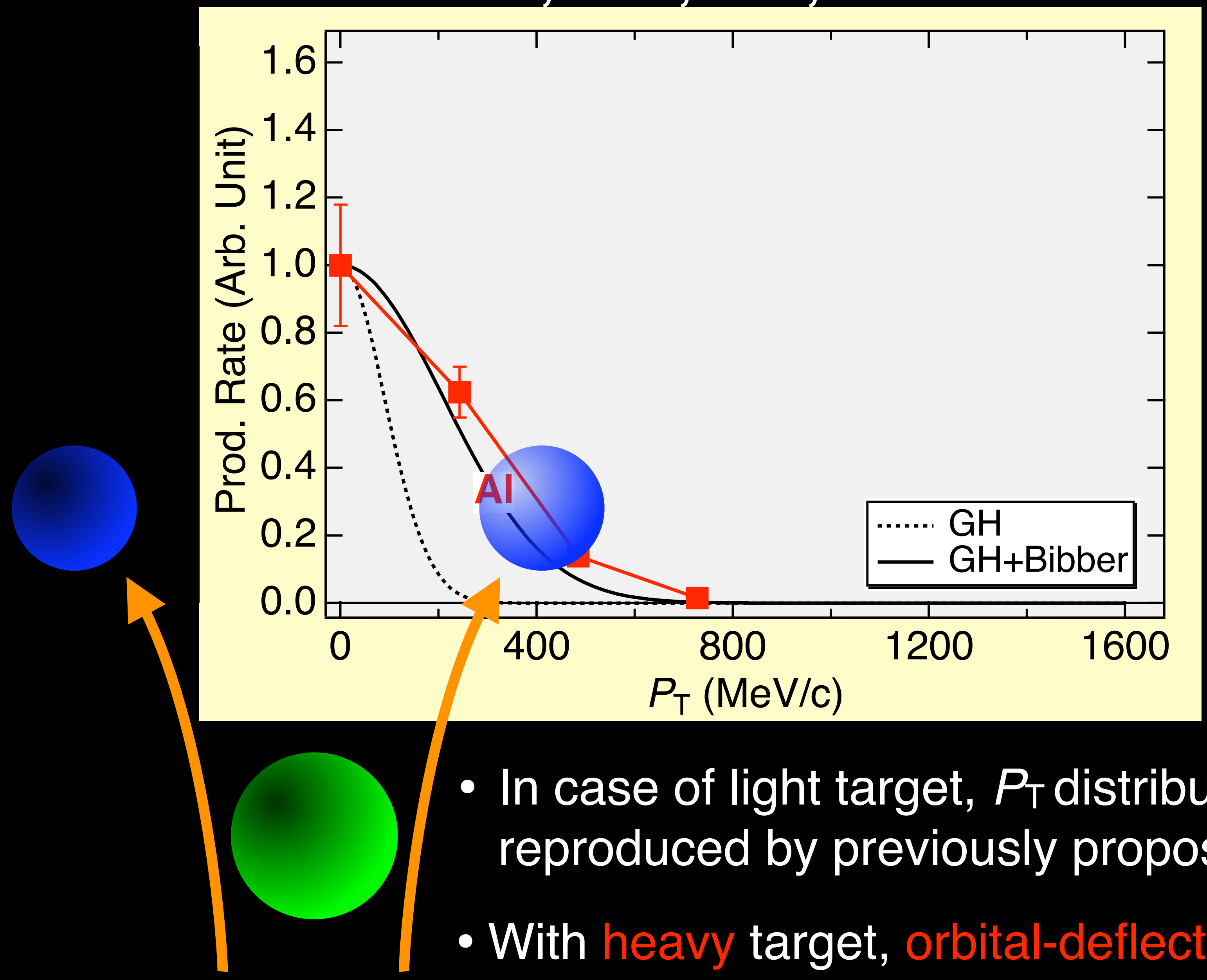

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- With heavy target, orbital-deflection effect is expected.

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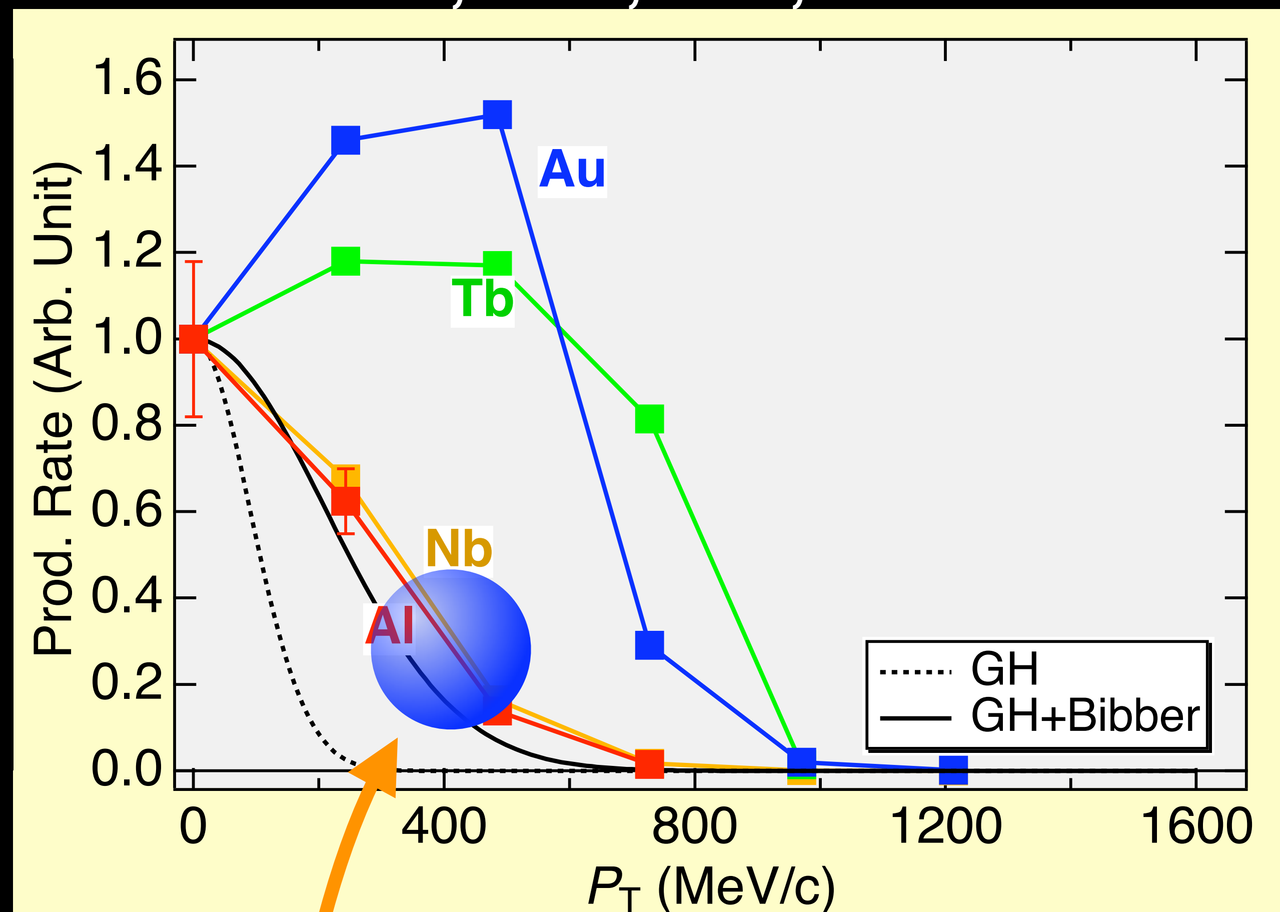
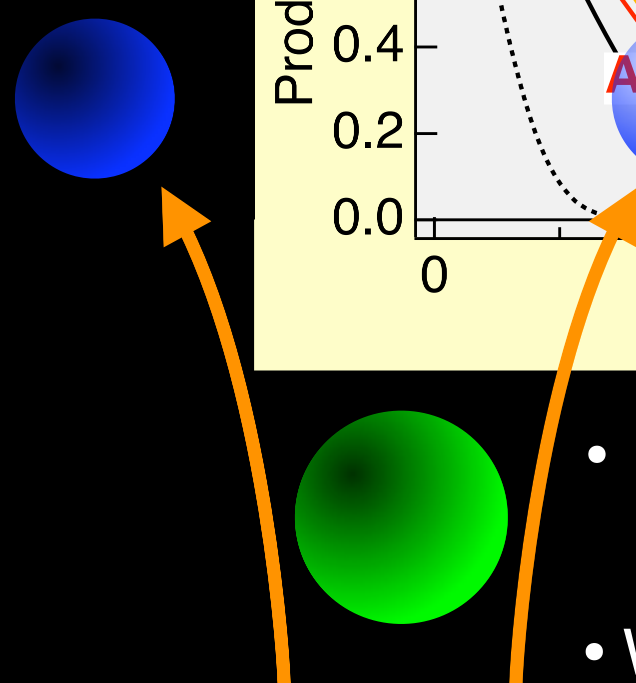


observed !!

Deflection effect grows with P_T.



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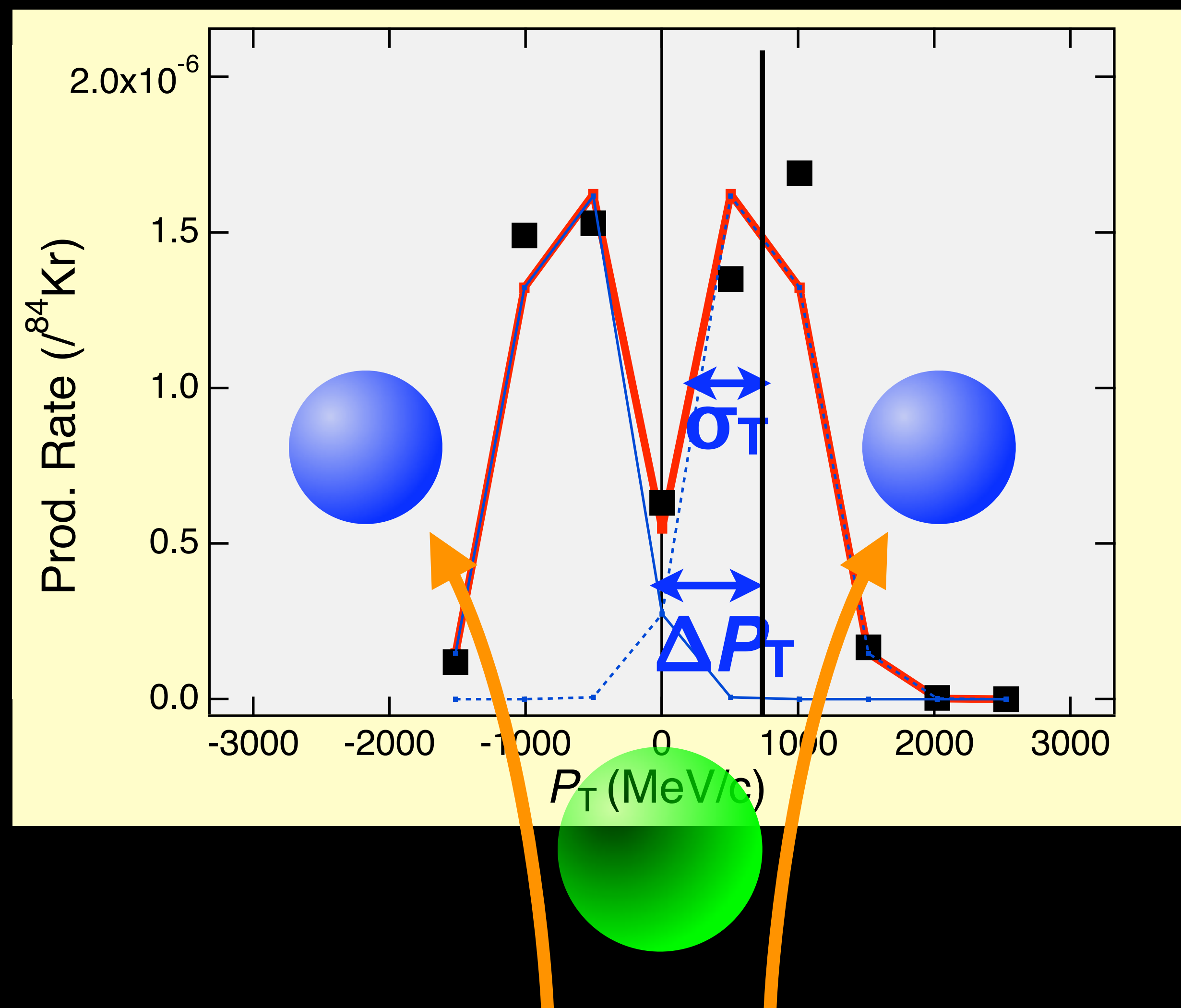
Analysis of P_T distribution

- ^{84}Kr+Au → ^{83}Br



Analysis of P_T distribution

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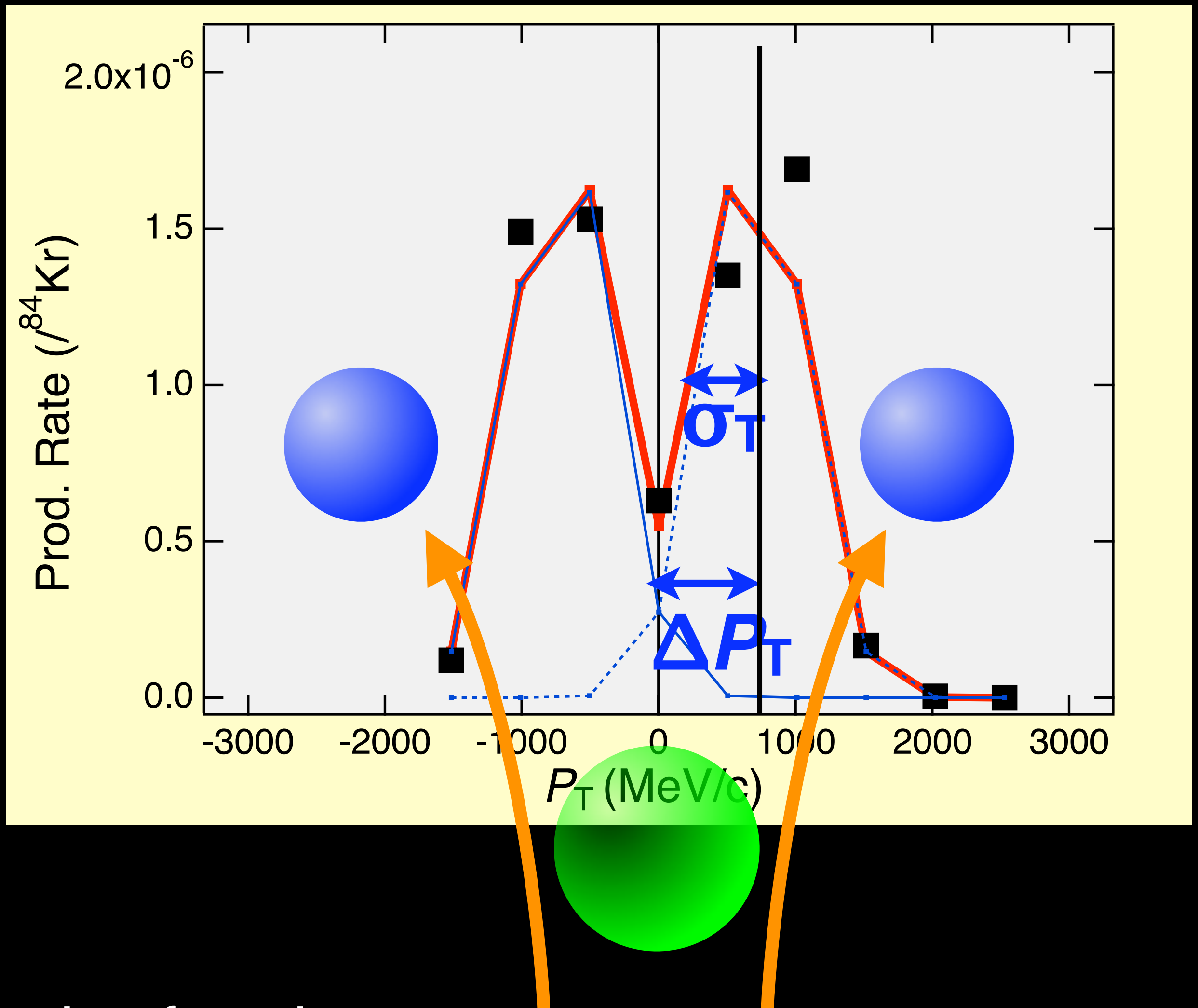

Off-centered Gaussian functions

$$Y(P_T) = A\left\{\exp\left(-\frac{(P_T - \Delta P_T)^2}{2\sigma(P_T)^2}\right) + \exp\left(-\frac{(P_T + \Delta P_T)^2}{2\sigma(P_T)^2}\right)\right\}$$

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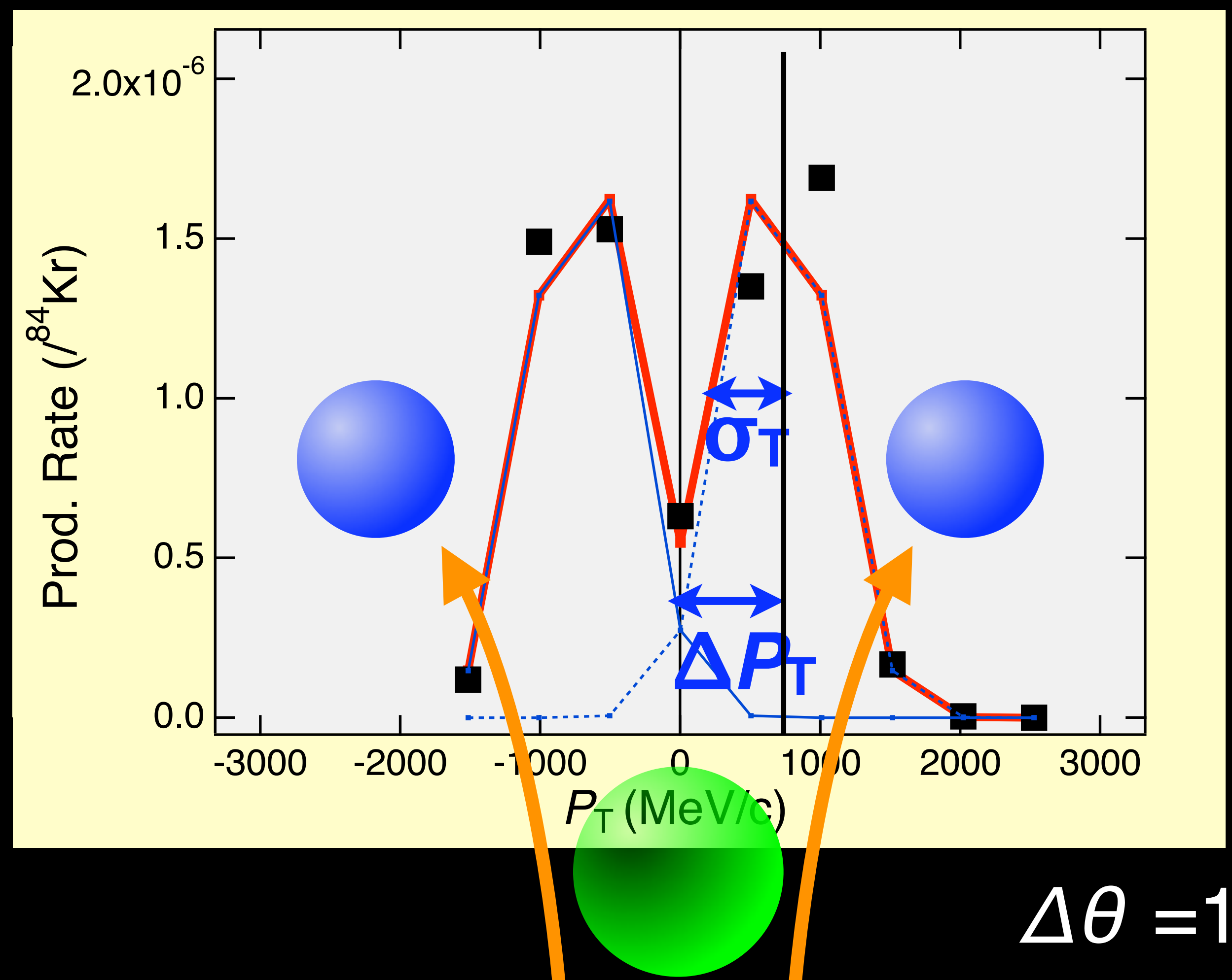


$\Delta\theta$ =11.2 mrad

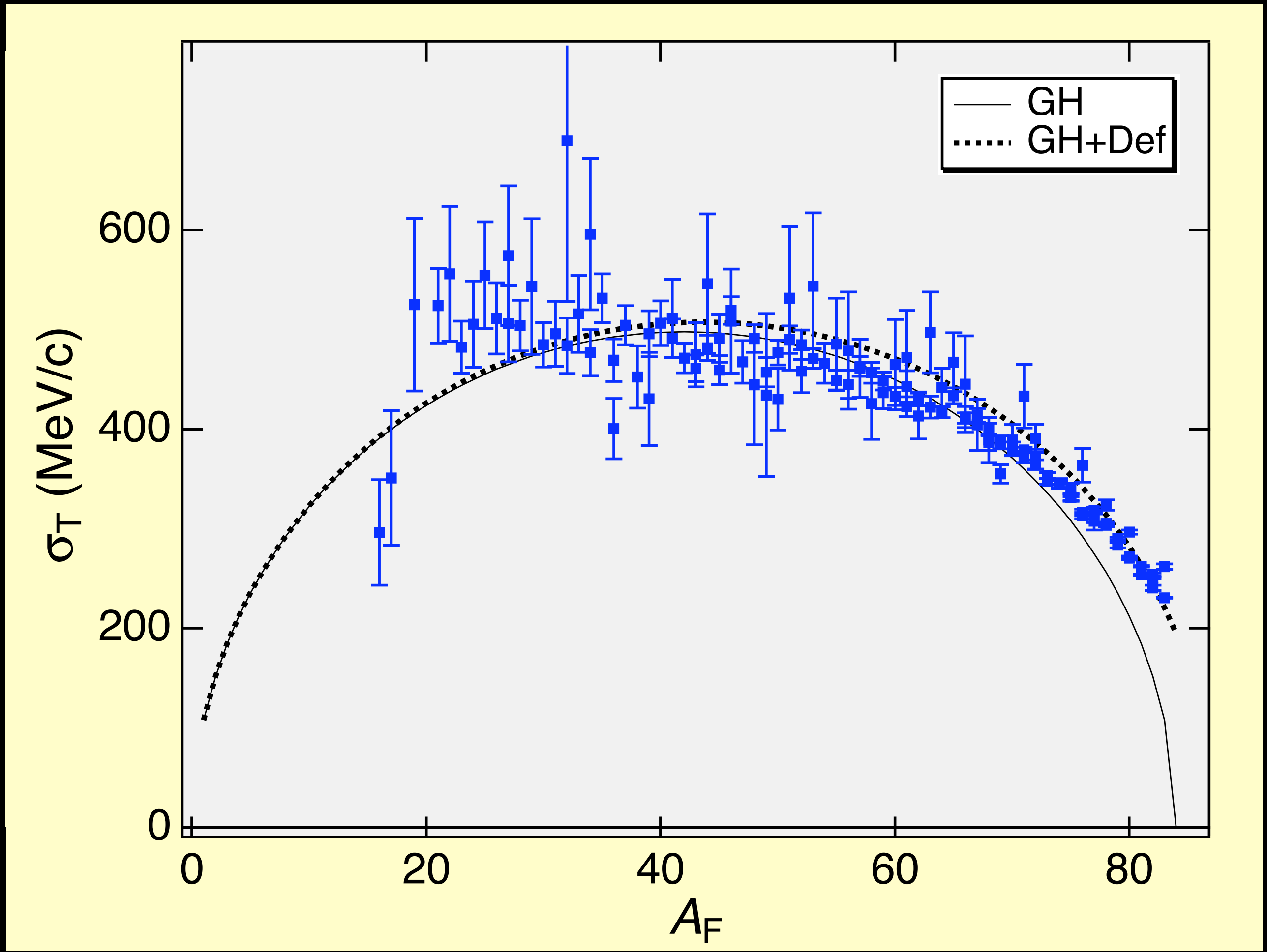
Grazing angle :14 mrad

Off-centered Gaussian functions

$$Y(P_T) = A\left\{\exp\left(-\frac{(P_T - \Delta P_T)^2}{2\sigma(P_T)^2}\right) + \exp\left(-\frac{(P_T + \Delta P_T)^2}{2\sigma(P_T)^2}\right)\right\}$$

Width of P_T distributions

- PFLs produced from ^{84}Kr + Al



- P_T distribution is successfully analyzed with $\Delta P_T = 0$.
- For light target, σ_T can be reproduced by $\sigma_T^2 = \sigma_{GH}^2 + \sigma_{Bibber}^2$.

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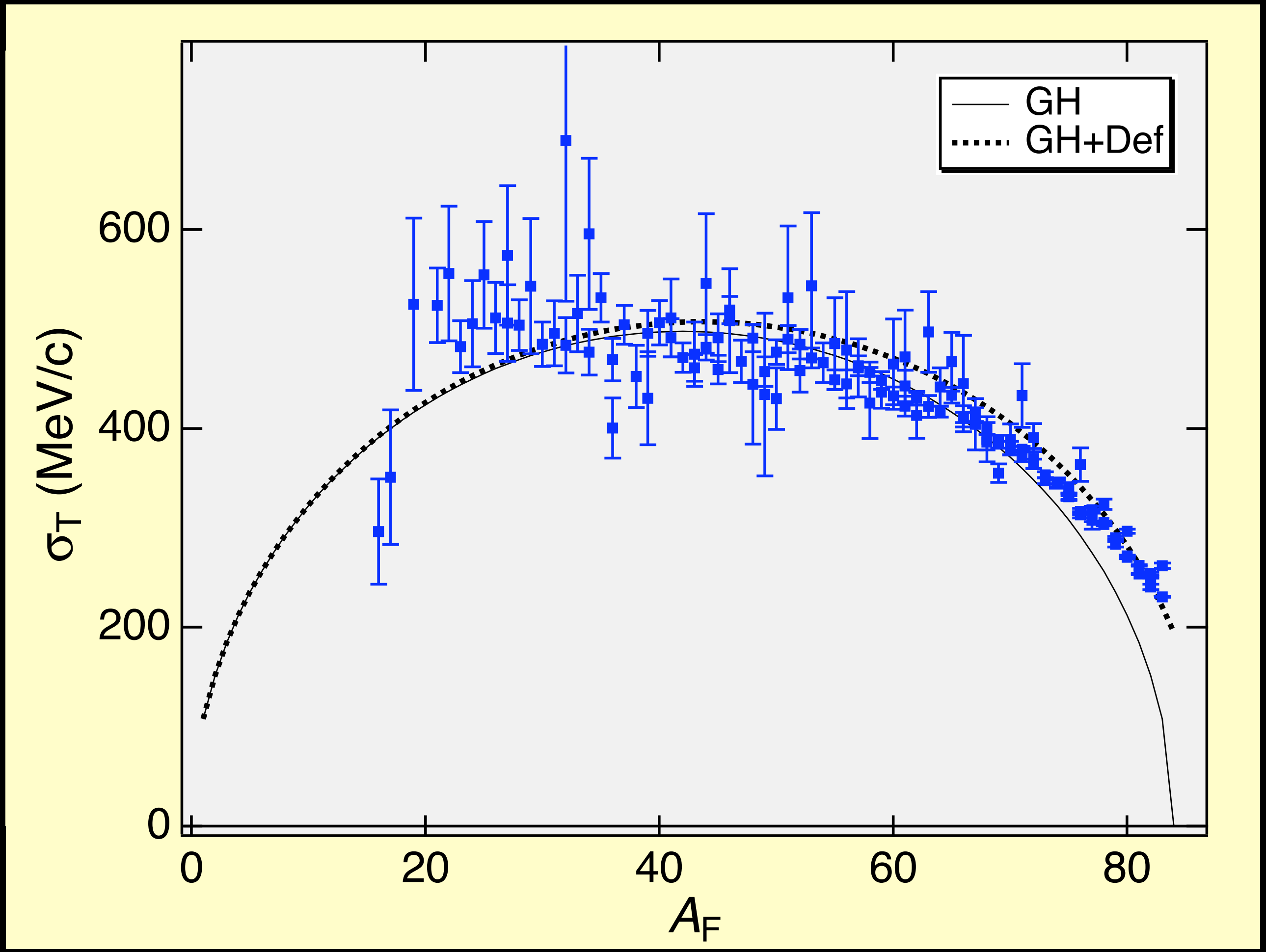
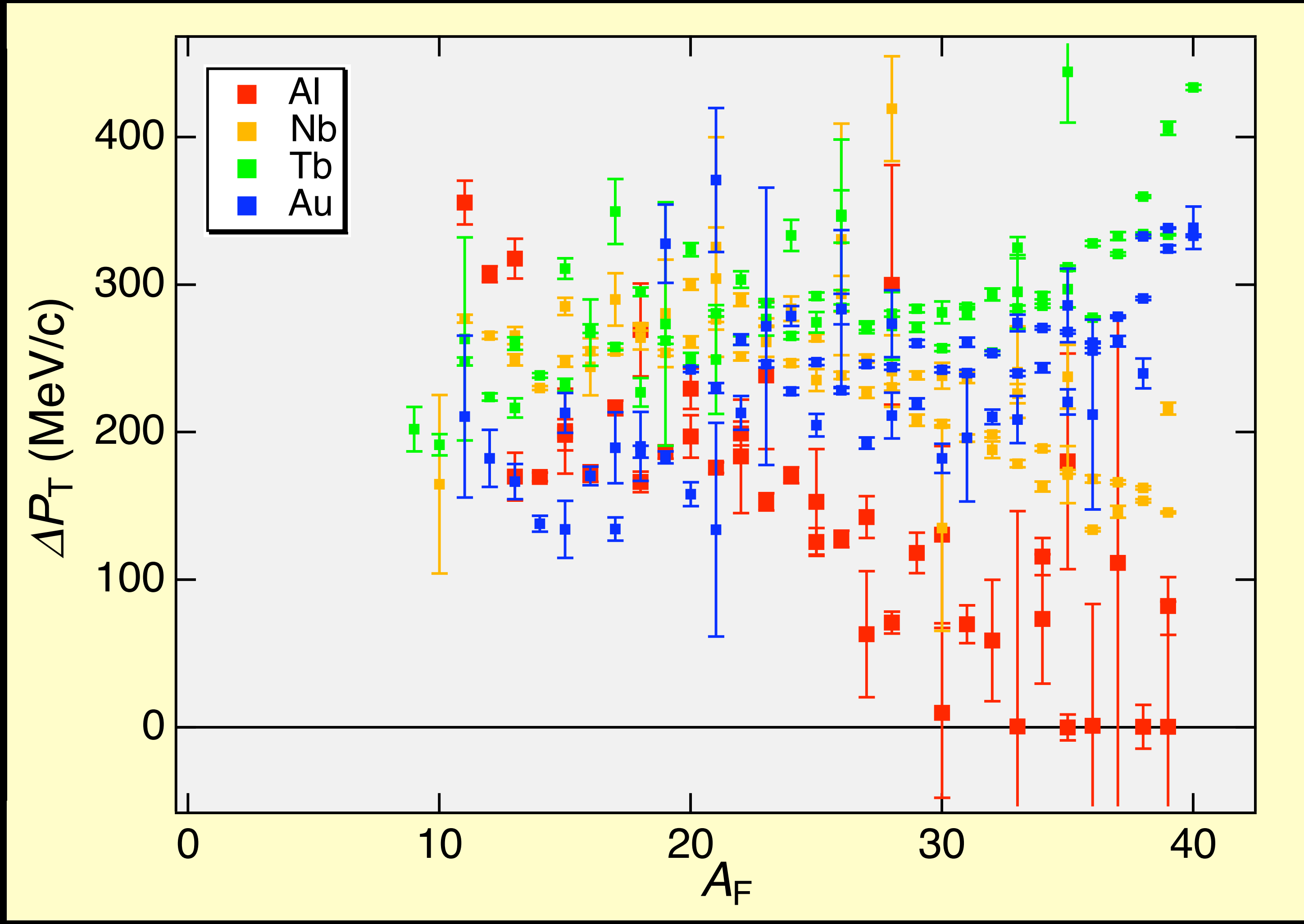


- P_T distribution is successfully analyzed with $\Delta P_T = 0$.
- For light target, σ_T can be reproduced by $\sigma_T^2 = \sigma_{GH}^2 + \sigma_{Bibber}^2$.
- $\sigma_T^2 = \sigma_{GH}^2 + \sigma_{Bibber}^2$ is assumed to be valid for heavier target.

Orbital-deflection effect

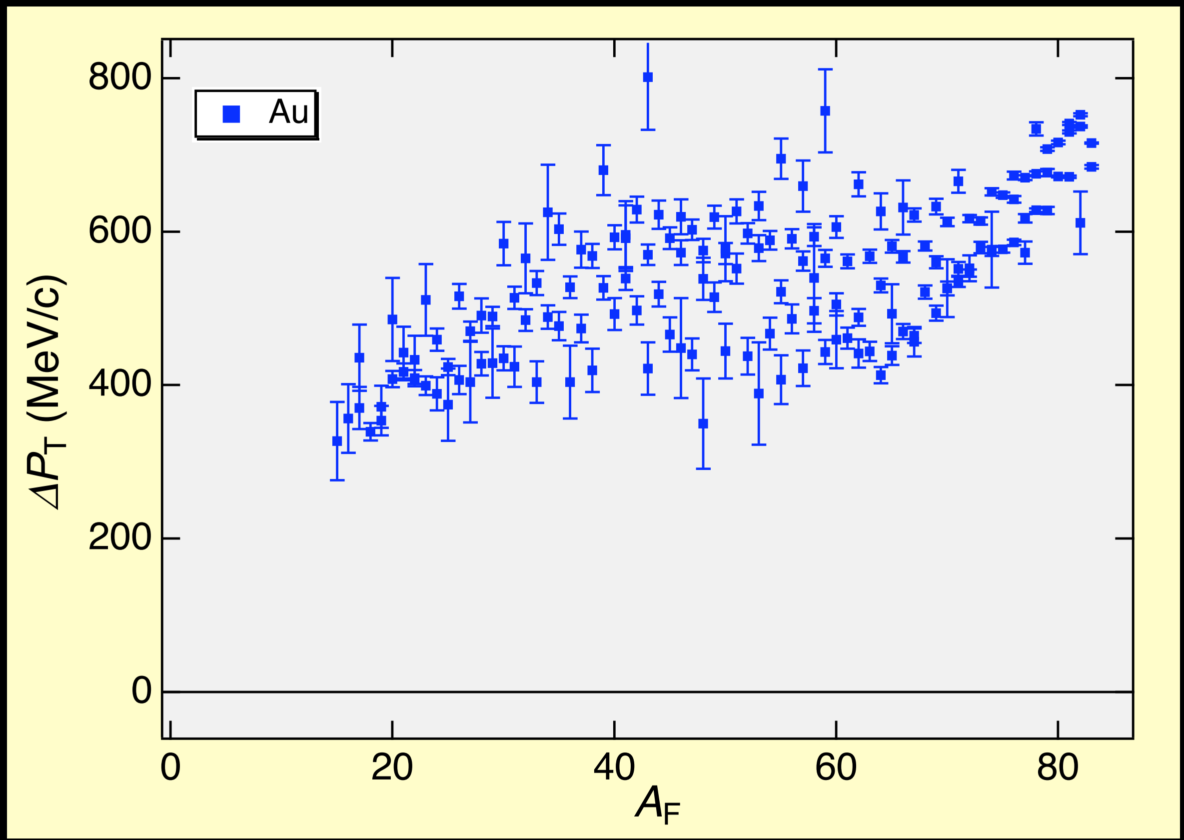
- PFLs produced from ^{40}Ar-beam



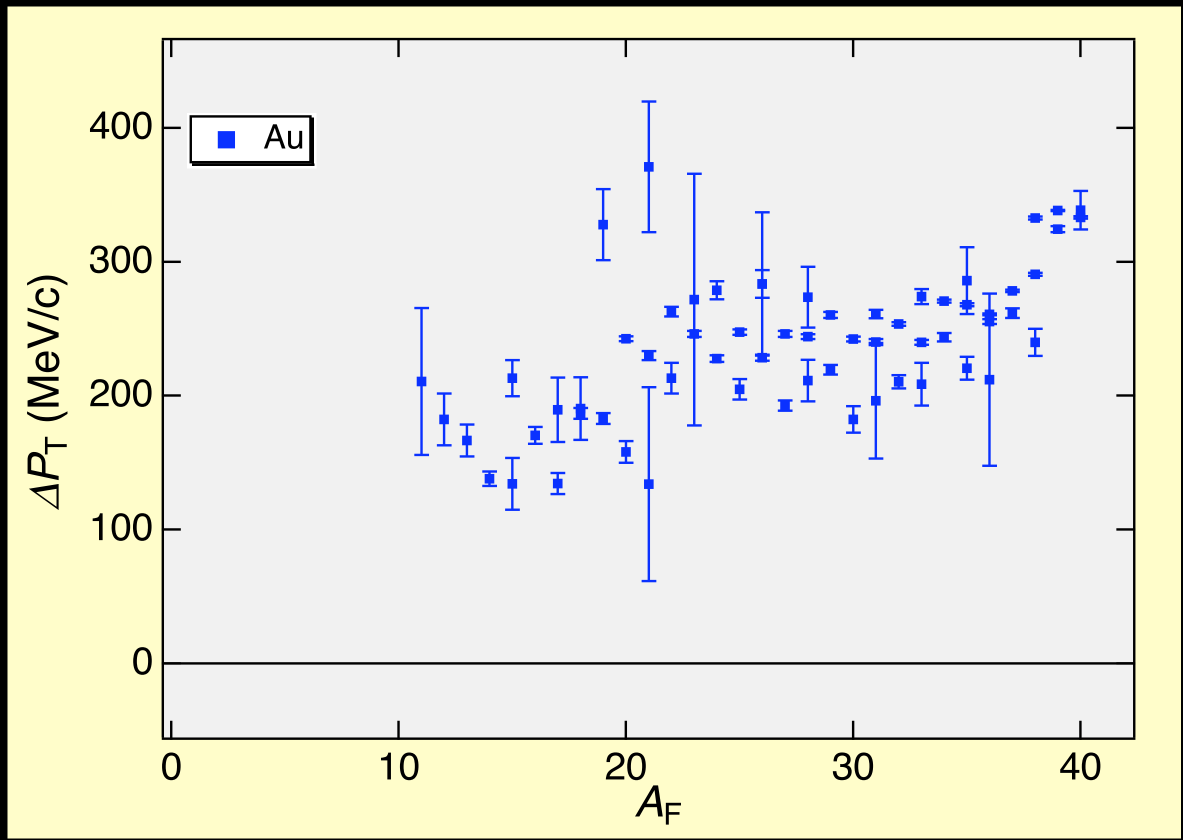
- The orbital-deflection effect grows with target mass.
- The target effect is remarkable for PLFs with $A_T > 20$.

Orbital-deflection effect

- PFLs from Kr+Au



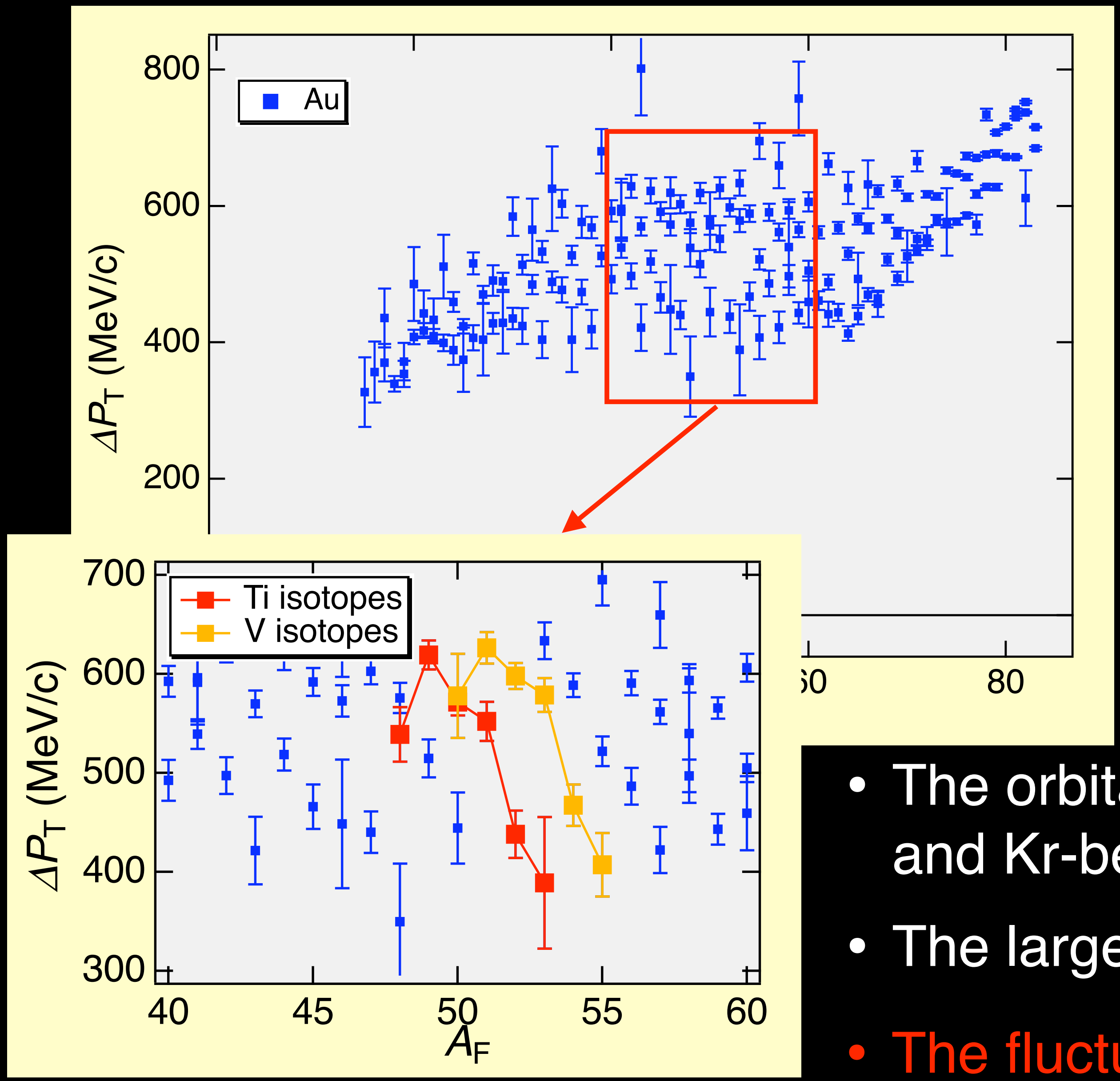
- PFLs from Ar+Au



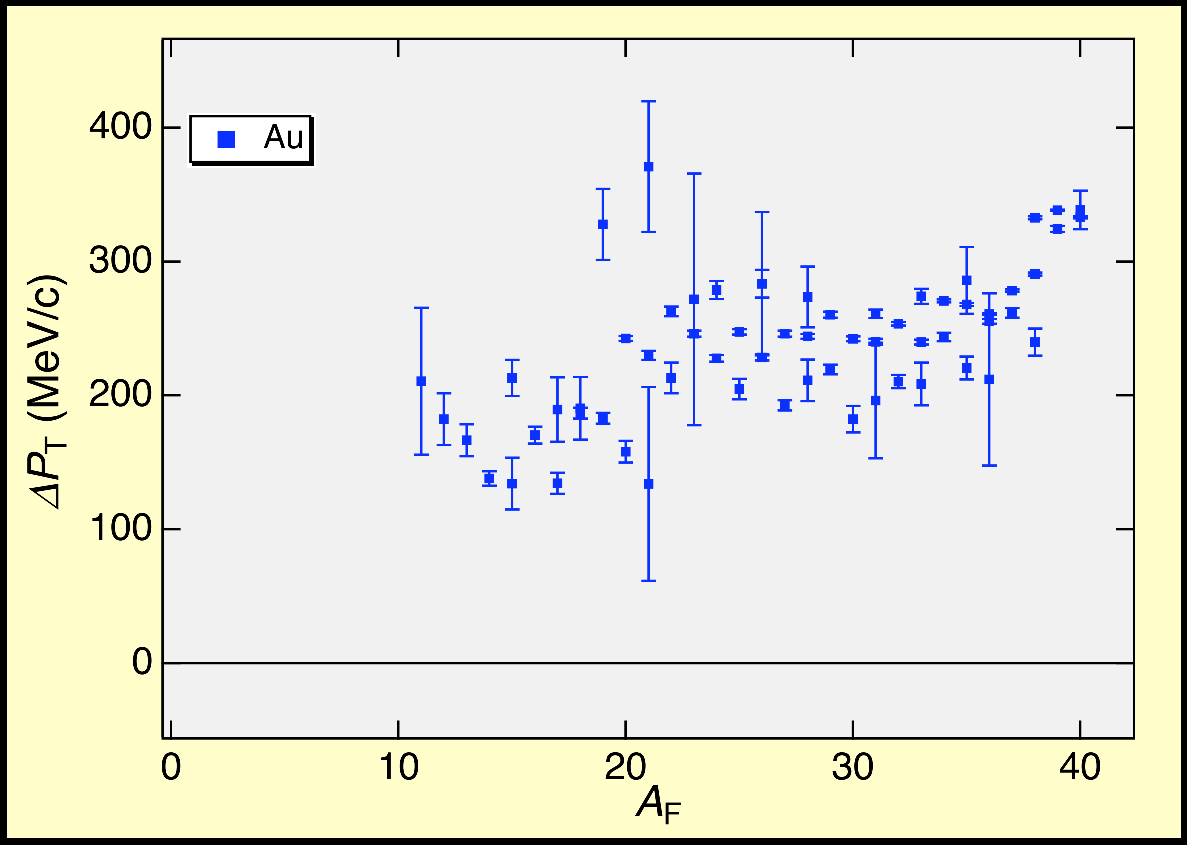
- The orbital-deflection effect is similar for Ar- and Kr-beam.
- The large fluctuation is found at A_T = 30 ~ 60.

Orbital-deflection effect

- PFLs from Kr+Au



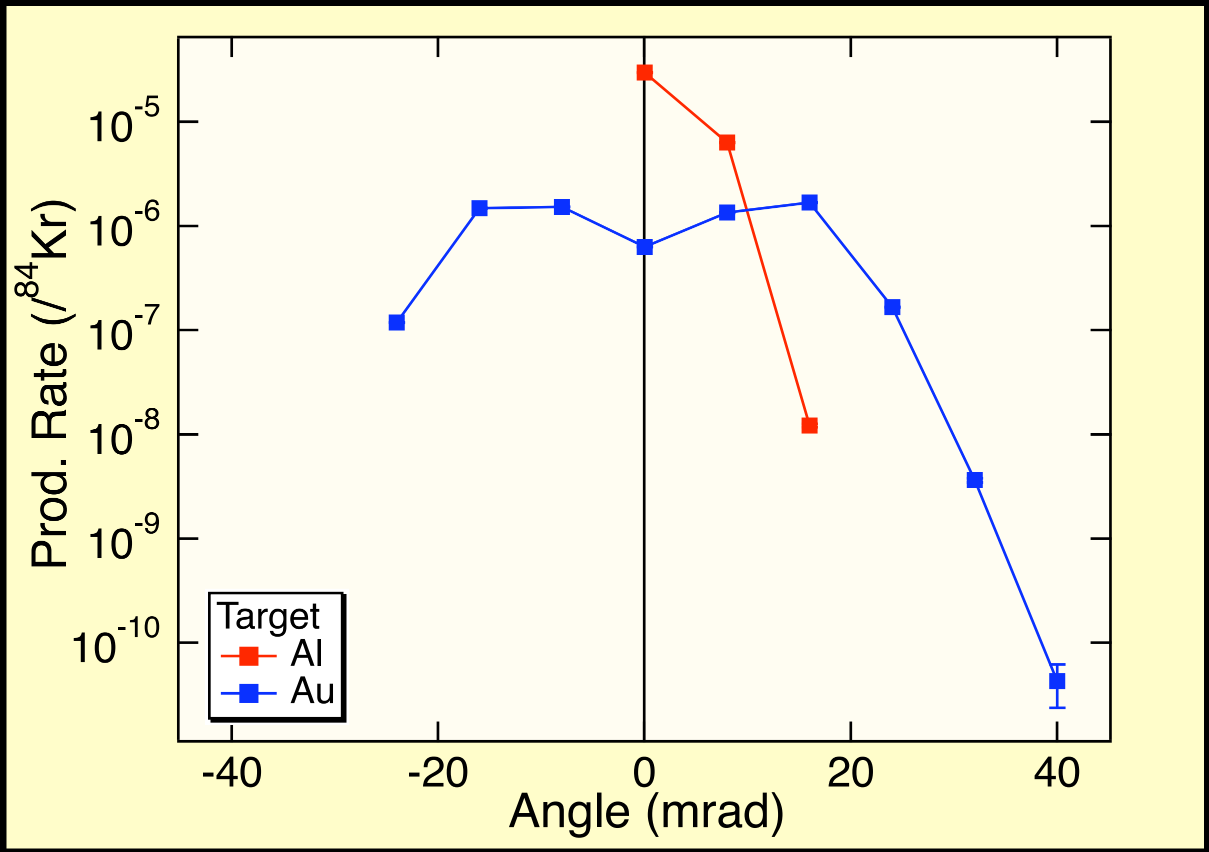
- PFLs from Ar+Au



- The orbital-deflection effect is similar for Ar- and Kr-beam.
- The large fluctuation is found at A_T = 30 ~ 60.
- The fluctuation comes from isotopic drift.

Be careful, when you use PLF

- produced from heavy target
- in small angle acceptance at forward angle



you might use the minor part in distribution.

Conclusions

- P_L distribution
  - The broadening effect at lower momentum side was observed.
  - Target/Energy dependence of reduced momentum width σ_0 was observed.
  - The systematics of the deceleration effect was observed.
- P_T distribution
  - The orbital-deflection effect (ΔP_T) was extracted.
  - ΔP_T grows with target mass for heavy PLFs.
  - The isotopic drift causes the large fluctuation found in ΔP_T -systematics.
    More consideration is needed.

- Based on the present results, production cross section should be calculated.

Motivation

- **Systematic measurements of momentum distribution of projectile-like fragments (PLFs)**

↓ Analysis

provide physical quantities
- Center/width of distribution
- Prod. cross-section

↓ Contribute

Nuclear physics
- Reaction mechanism
- Nuclear structure effect
  ex. pairing/shell effect

Isotonic distribution of $\sigma_{Prod.}$ of PFLs produced from Ar-beam