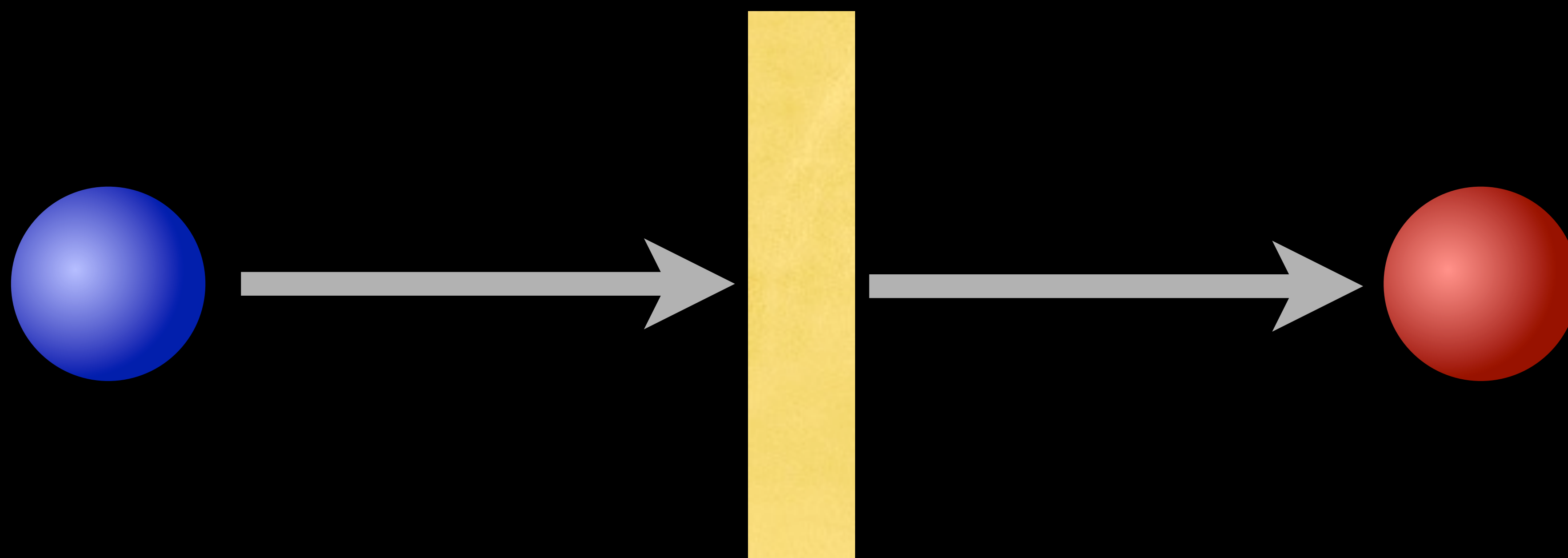
Momentum distribution and production cross section of projectile-like fragments at intermediate energies

Sadao MOMOTA
Kochi University of Technology

Introduction

Fragmentation process

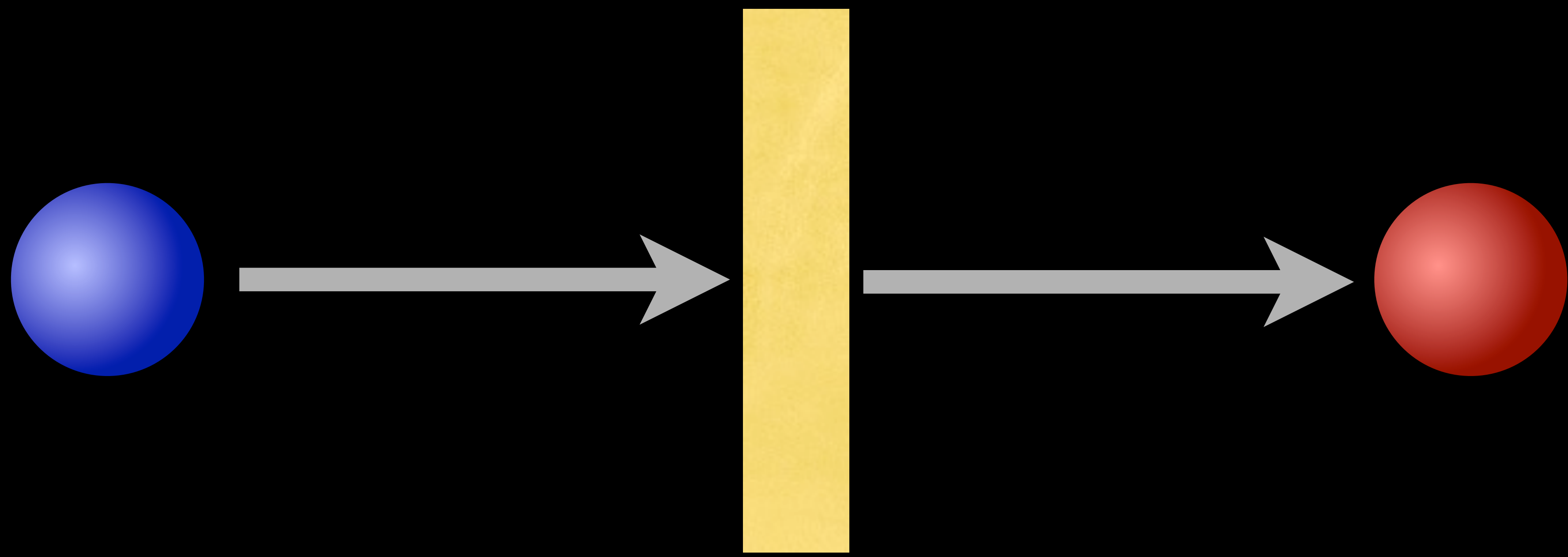
- as a means to produce RI beams



- $\sigma_{\mathrm{Prod.}}$
- $\frac{d\sigma_{\mathrm{Prod.}}}{dP_L}, \frac{d\sigma_{\mathrm{Prod.}}}{dP_T}$

Fragmentation process

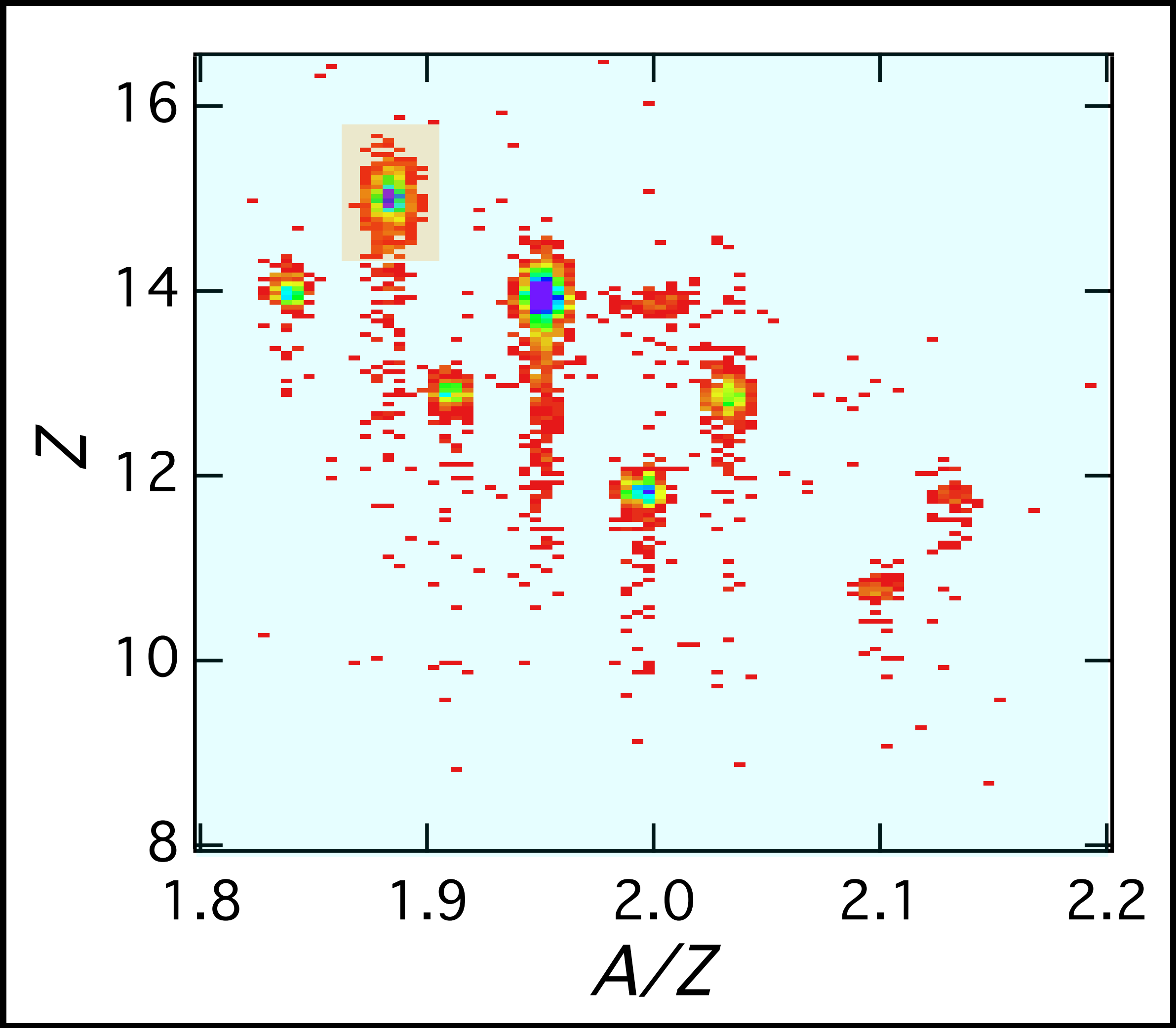
- as a means to produce RI beams



- $\sigma_{\mathrm{Prod.}}$
- $\dfrac{d\sigma_{\mathrm{Prod.}}}{dP_{\mathrm{L}}}, \dfrac{d\sigma_{\mathrm{Prod.}}}{dP_{\mathrm{T}}}$

1. Quality of RI beams
2. Reaction mechanism / nuclear structure
3. Nuclear database

Quality of RI beams



- Intensity/Purity

↑

- Simulation code
  INTENSITY, LISE, MOCADI
- Empirical systematics/ formulation
  EPAX *etc.*

↑

- $\sigma_{Prod.}$
- P_L, P_T distribution

Nuclear database

Transport of heavy ions in materials

- Radiation shield at RIB facility
- Space mission (Irr. effect of galactic cosmic ray)
- HI therapy

Nuclear database

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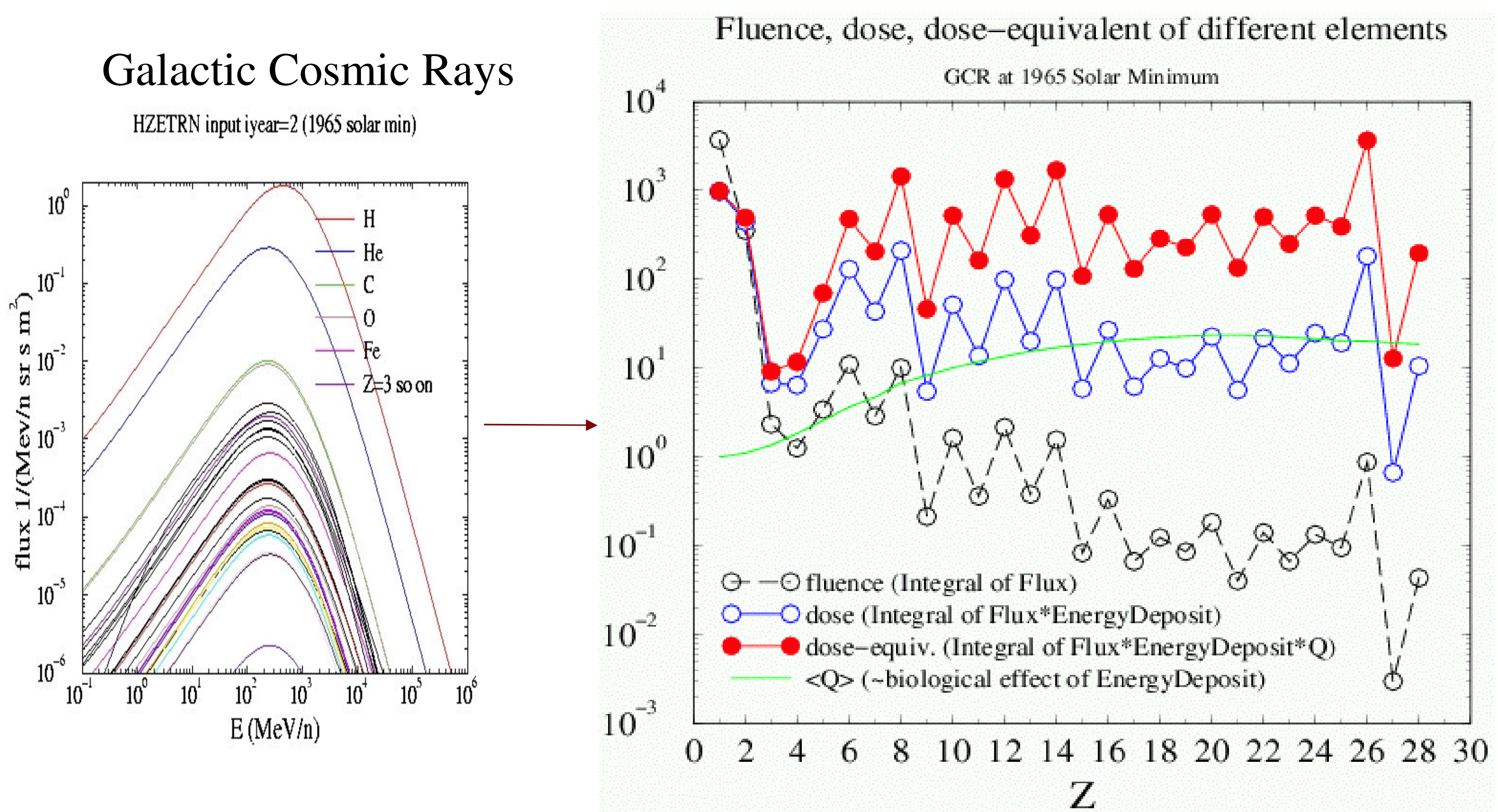
Heavy Ions:
small in number - but important in radiation effects



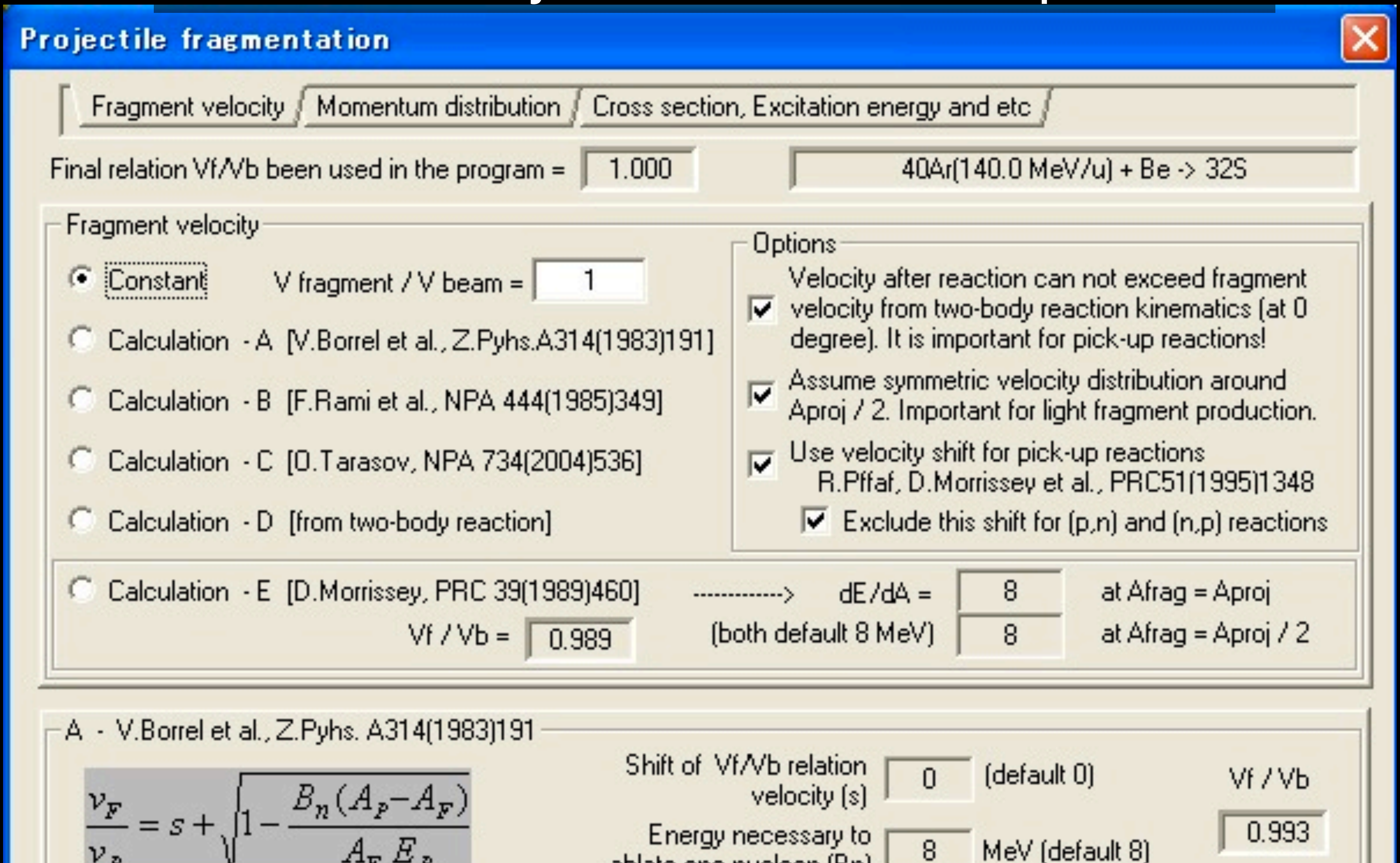
Zi-Wei Lin,
Workshop at Arkansas State Univ.,
April 14, 2005

Momentum dist. and $\sigma_{Prod.}$

Evaluation of prod. rate

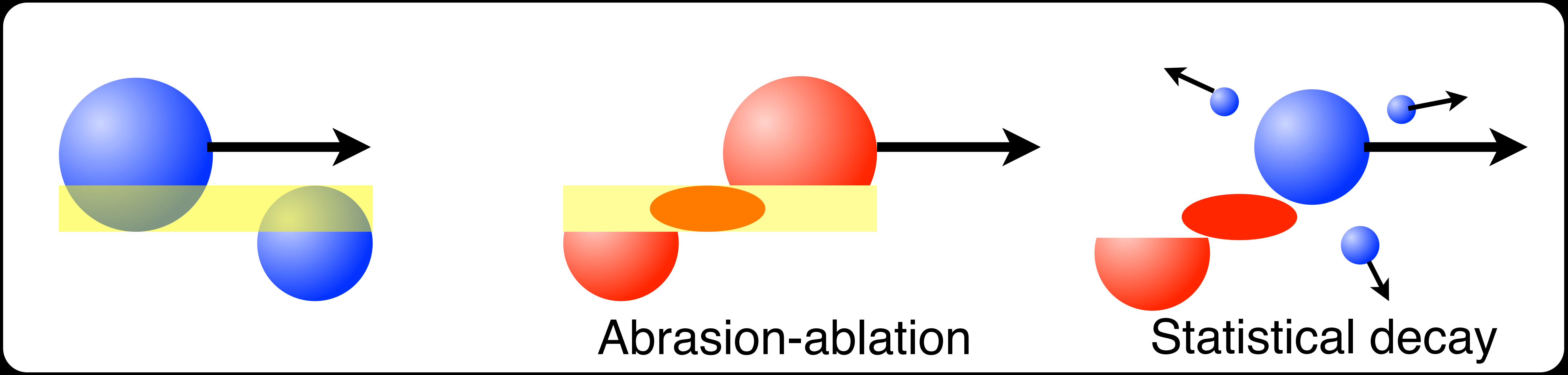
- In case of LISE++

Formulation/Systematics ← Prod. process



Participant-Spectator

- Independent particle model



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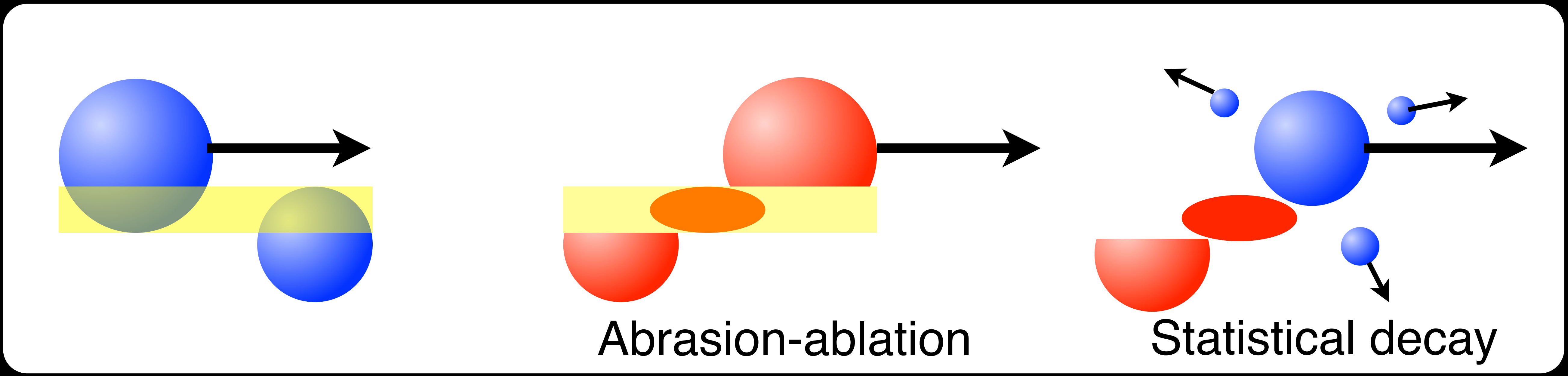


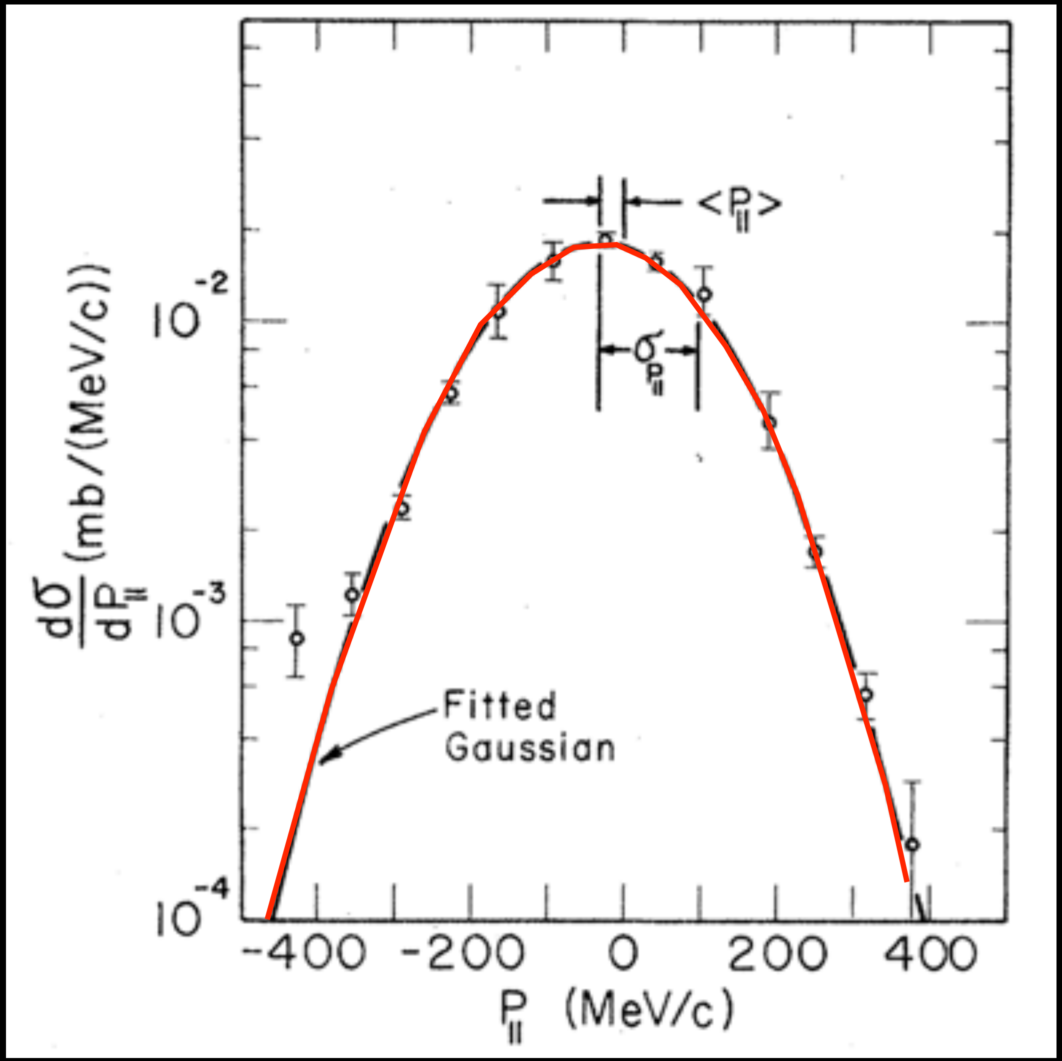
This model provides

1) Velocity shift : small
2) P dist. : P_{Fermi} of removed nucleons

P dist. at $E \geqq 1$ GeV/u

- Isotropic distribution

^{12}C (2.1 GeV/u) + Be → ^{10}Be



D.E. Greiner et al., PRL 35 (1975) 152.

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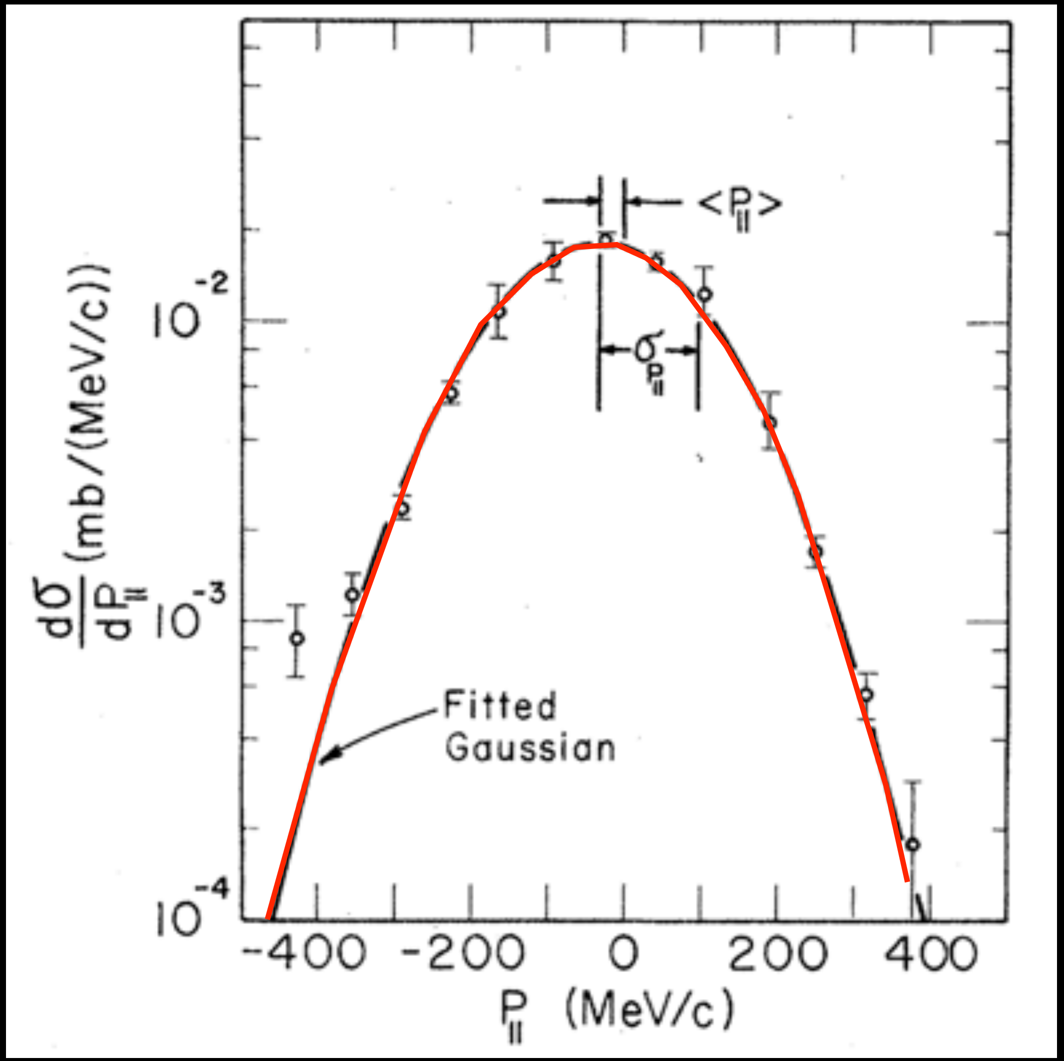

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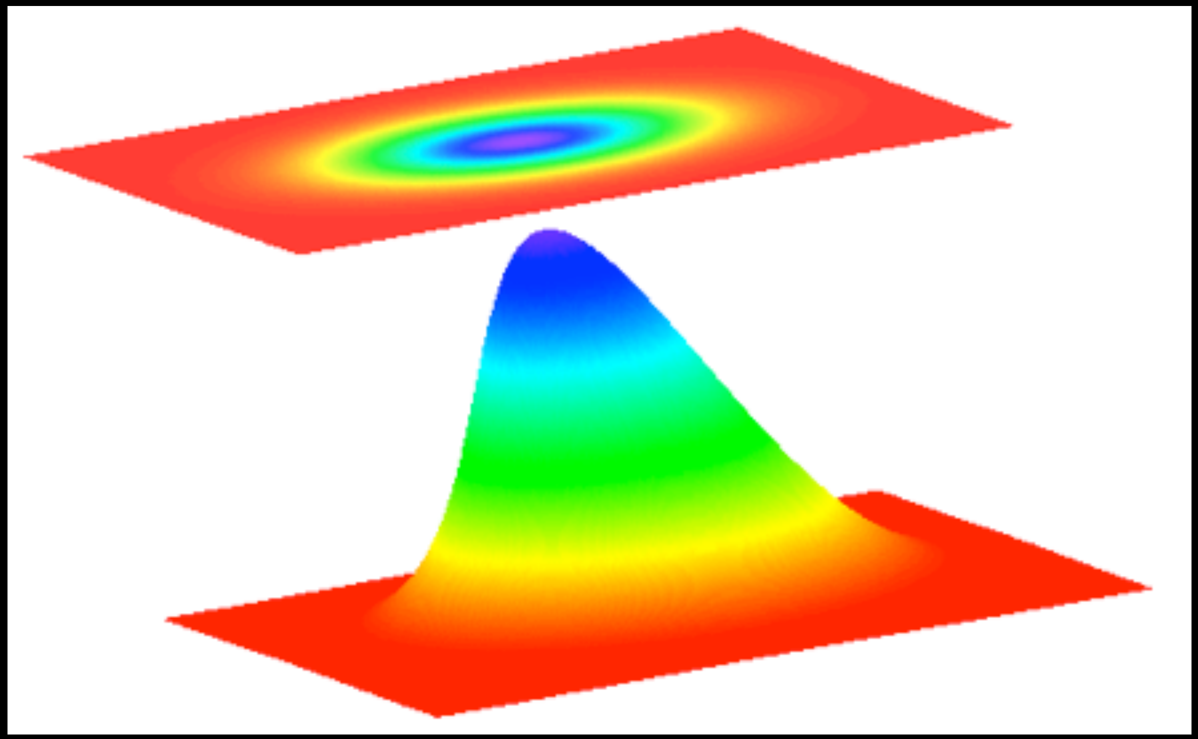


- Isotropic Gaussian dist.

  $\sigma(P_{\mathrm{High}}) \sim \sigma(P_{\mathrm{Low}})$

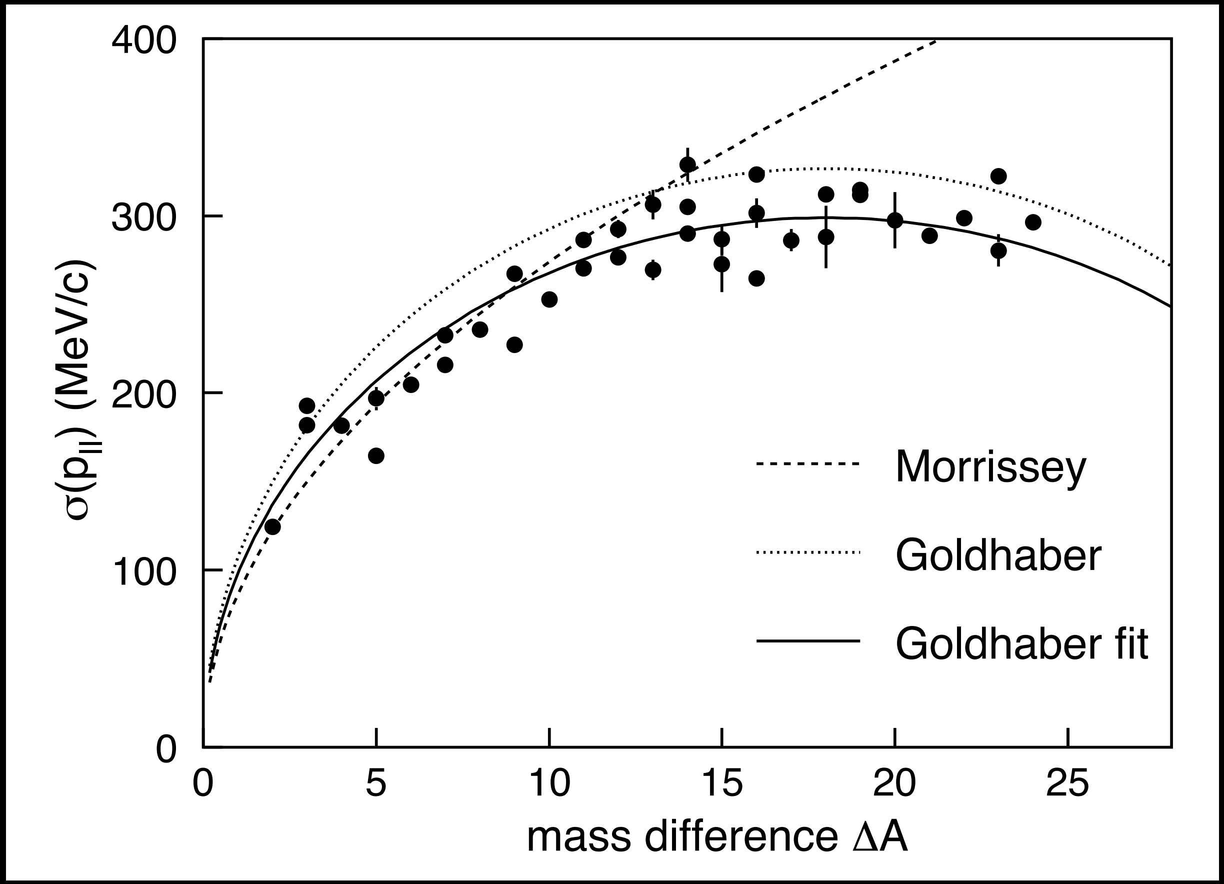
  $\sigma(P_{\mathrm{T}}) \sim \sigma(P_{\mathrm{L}})$

- Small velocity shift

P dist. at $E \geqq 1$ GeV/u

- Dispersion of distribution

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



M. Caamano et al, Nucl. Phys. A 733 (2004) 187.

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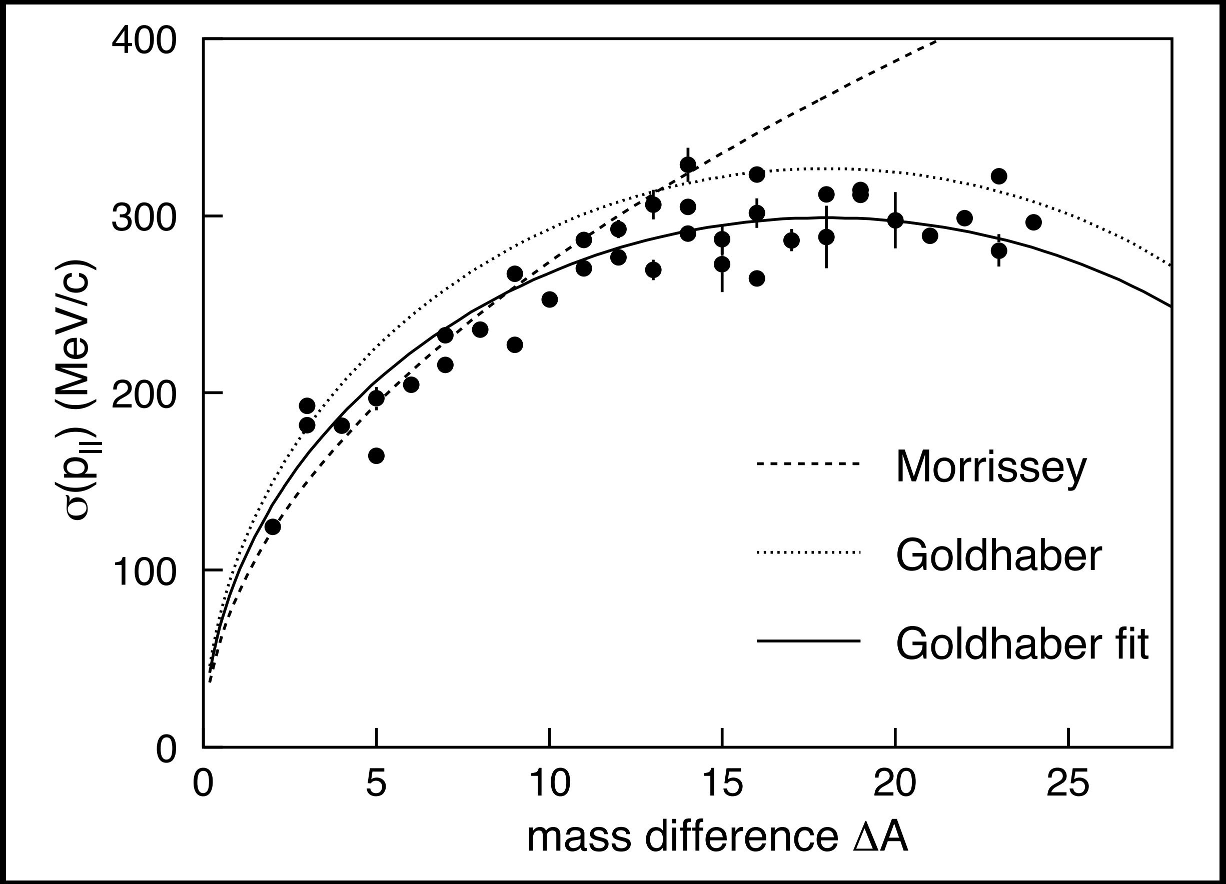

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$\sigma(P_L) \leftarrow P_{Fermi}$ of removed nucleons

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

$$\sigma_{GH} = \sigma_0 \sqrt{\frac{A_F(A_P - A_F)}{A_P - 1}}$$

$$\sigma_0 \sim 100\,(\mathrm{MeV/c})$$

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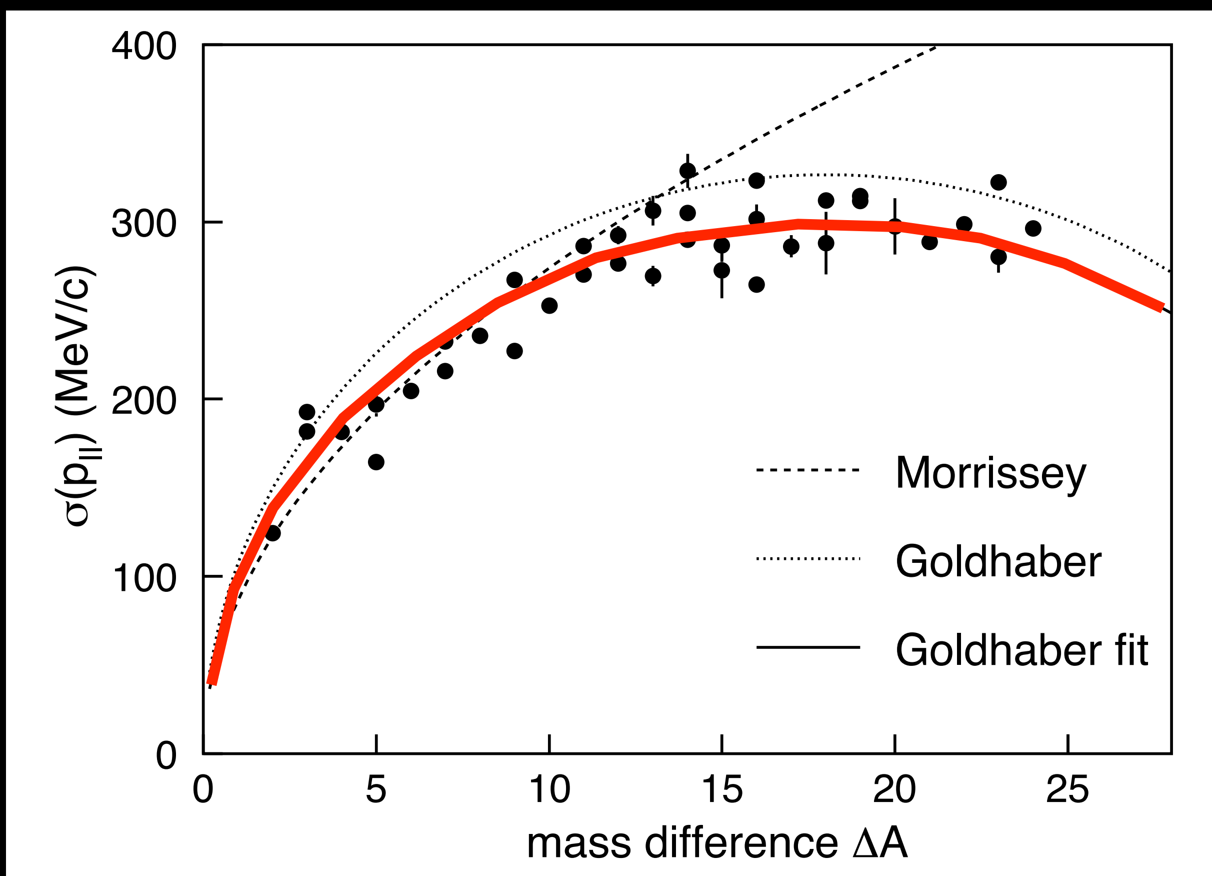

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$\sigma_0 = 98.2 \pm 0.2$ MeV/c

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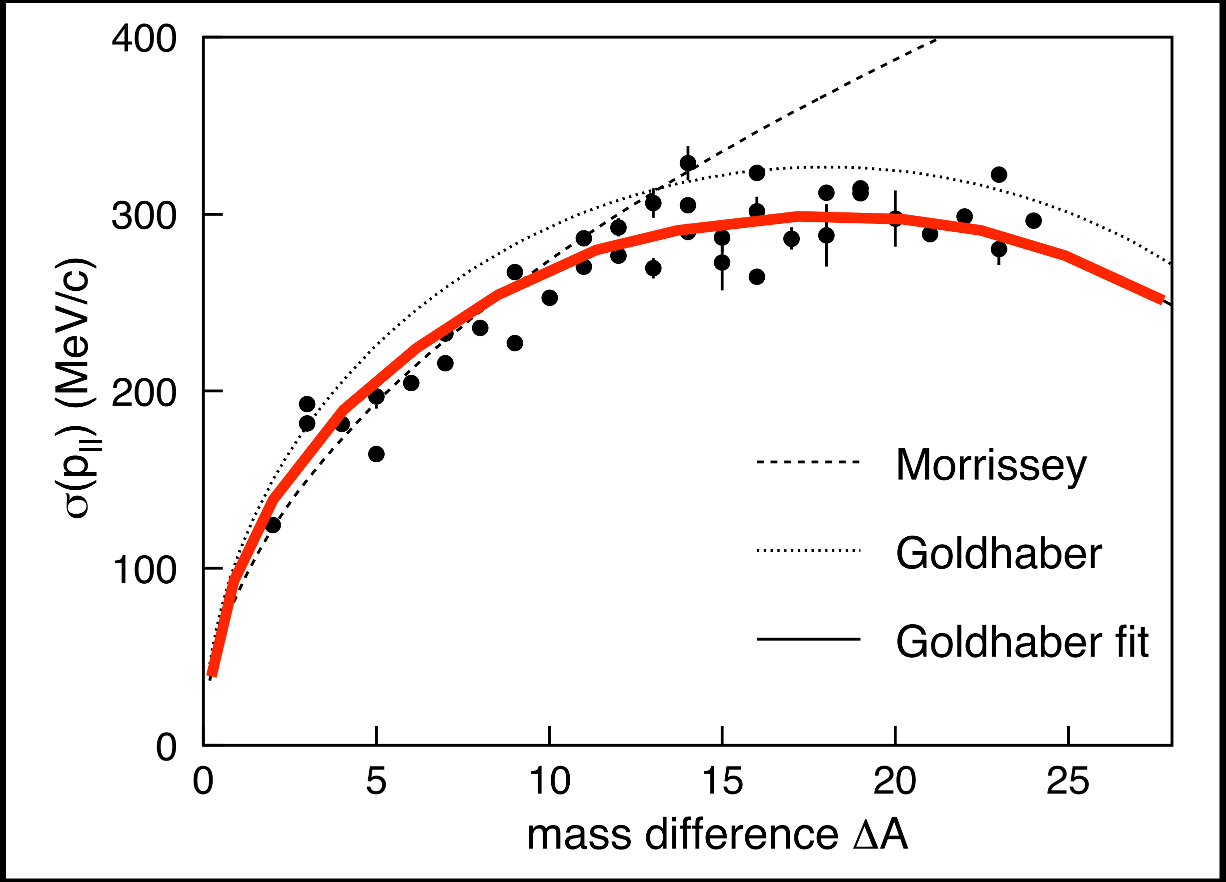

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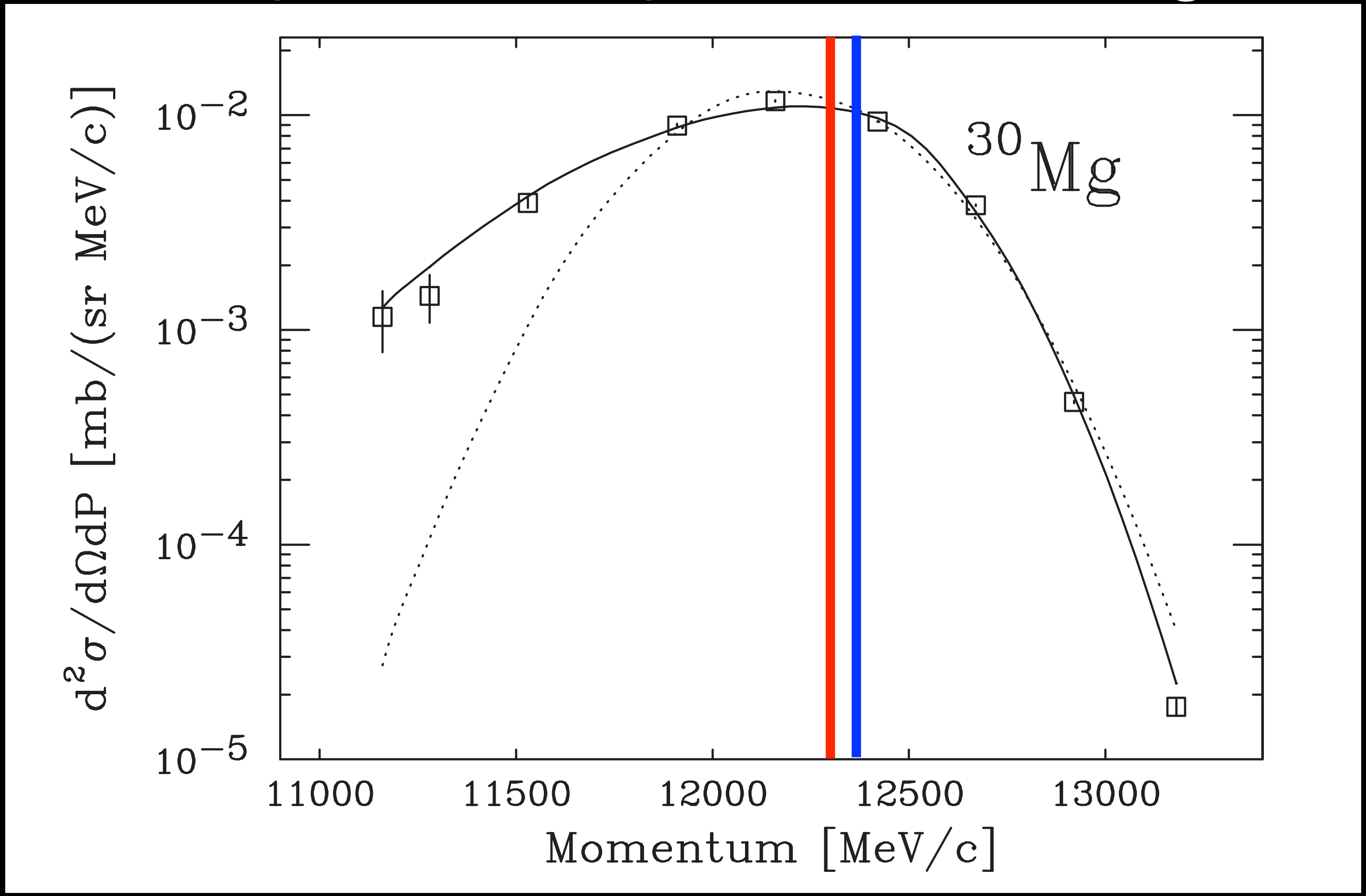
$\sigma(P_L) \sim \sigma(P_T)$

P_L dist. at E ~ 100 MeV/u

- Asymmetric longitudinal distribution

^{40}Ar (90 MeV/u) + ^{9}Be → ^{30}Mg



M. Notani et al., PRC 76 (2007) 044605.

$\sigma(P_{High}) < \sigma(P_{Low})$

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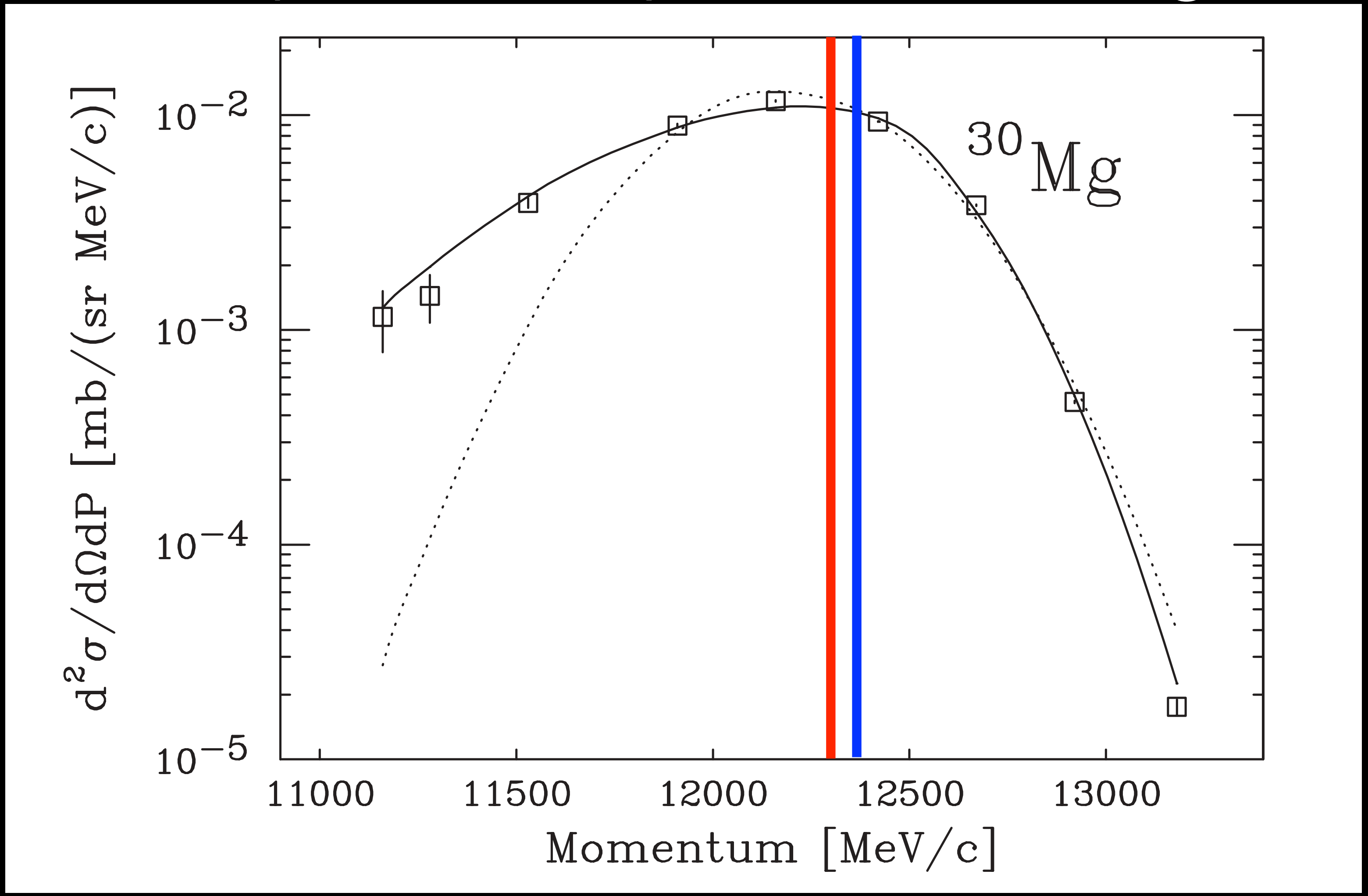

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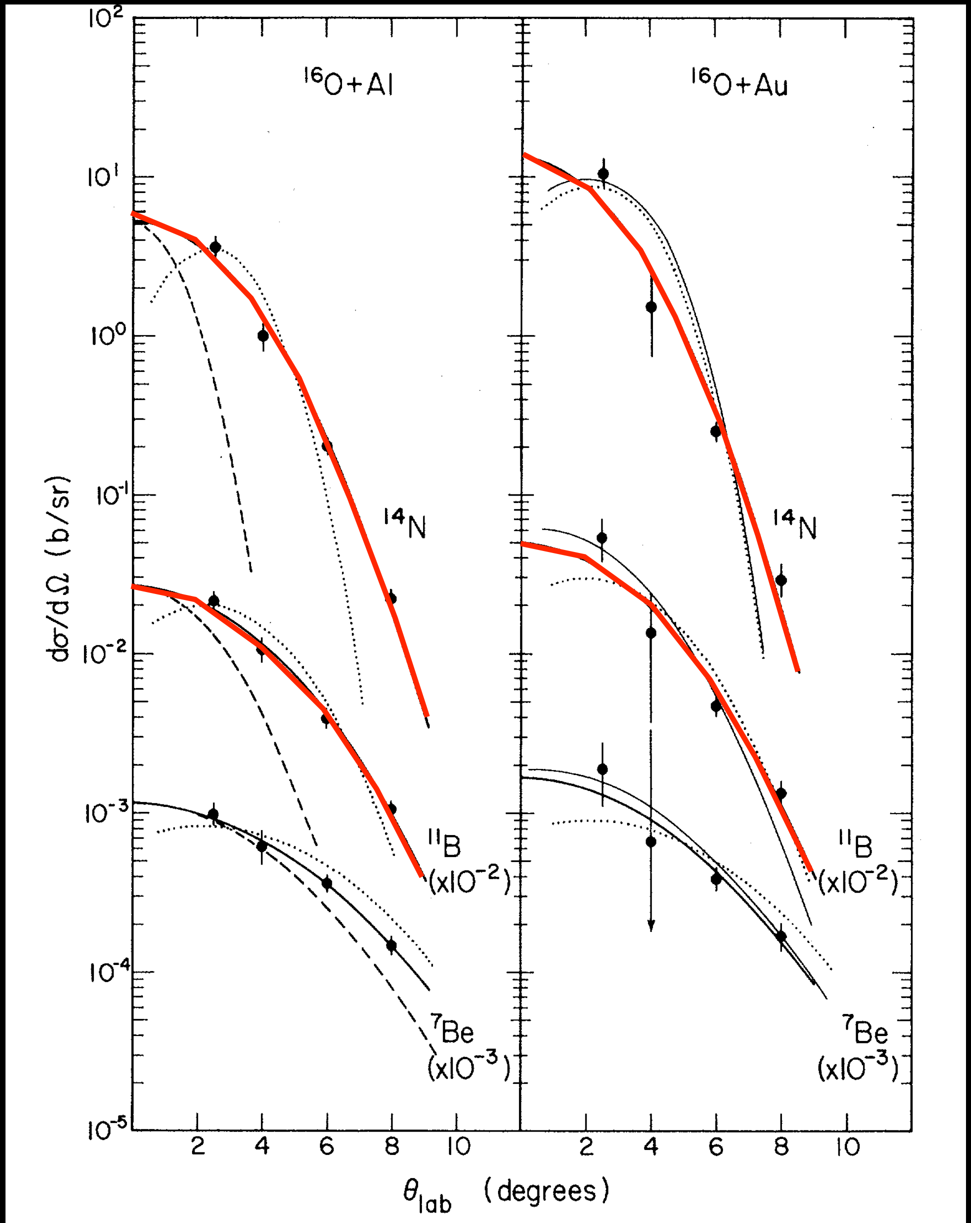
$\sigma(P_{High}) < \sigma(P_{Low})$

How about at *E* ~ 300 MeV/u?

P_T dist. at E ~ 100 MeV/u

- Additional dispersion found in P_T

^{16}O (92.5 MeV/u) + ^{27}Al, ^{197}Au



K. Van Bibber *et al.*, PRL 43 (1979) 840.

Anisotropy induced by orbital dispersion

$\sigma(P_L) < \sigma(P_T)$

Empirical formulation

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

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

$$\sigma_0 = 195\,(\text{MeV/c})$$

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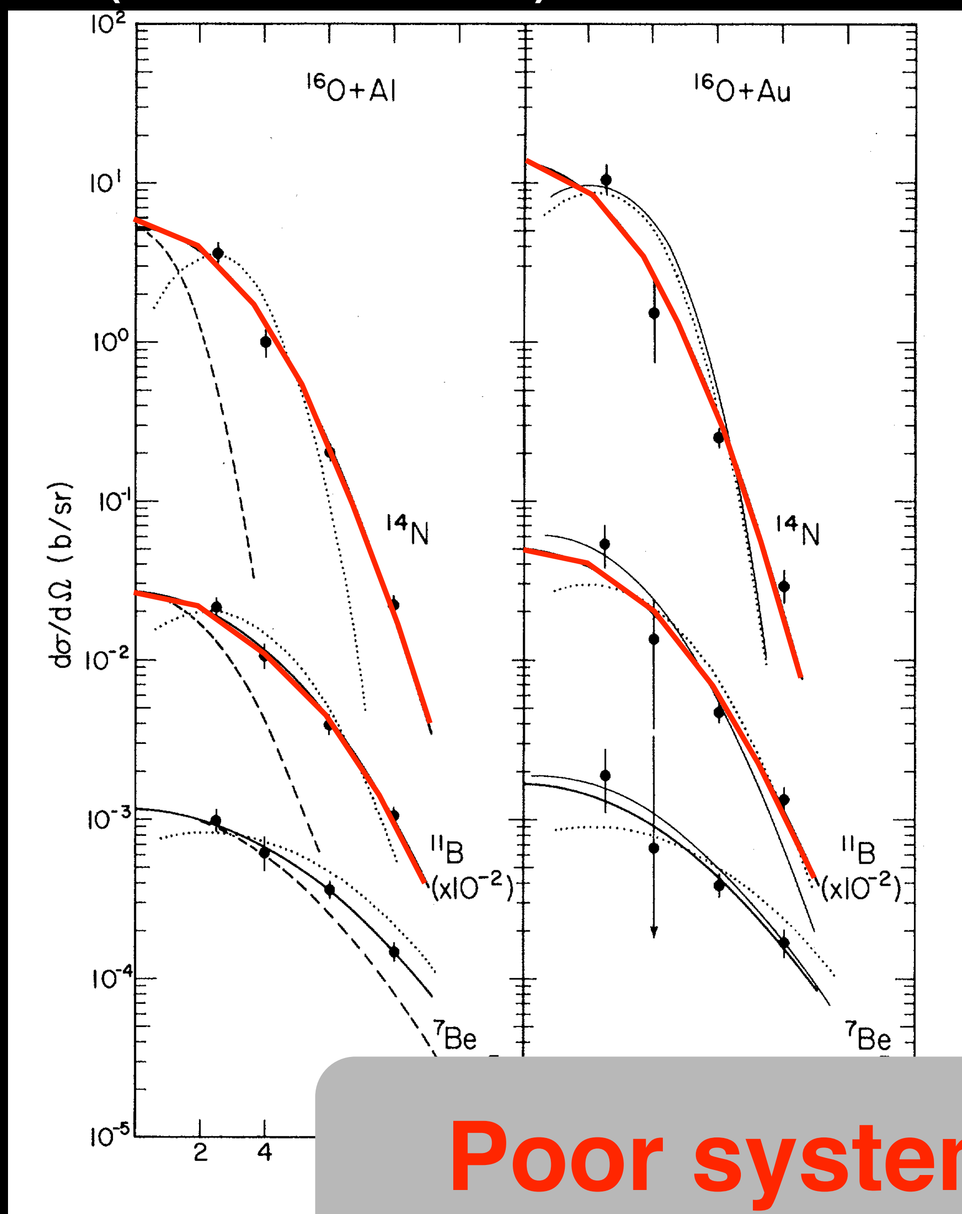

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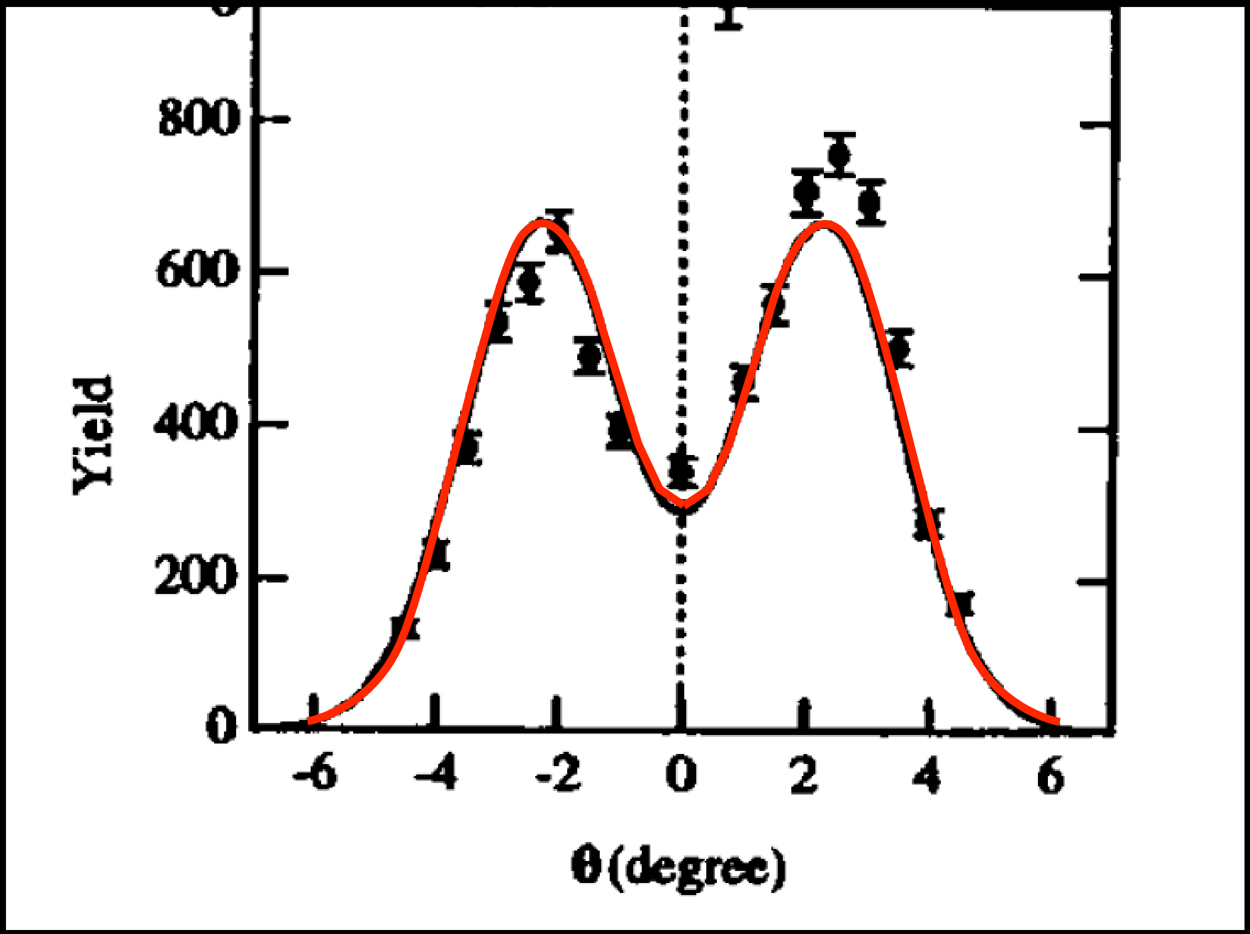
Poor systematic measurements

P_T dist. at E ~ 100 MeV/u

- Orbital deflection in case of heavy target

^{36}Ar (100 MeV/u) + ^{197}Au → ^{35}Ar



K. Matsuta et al., NP A701 (2002) 383c.

Off-centered distribution

↑

Orbital deflection caused by Coulomb repulsion

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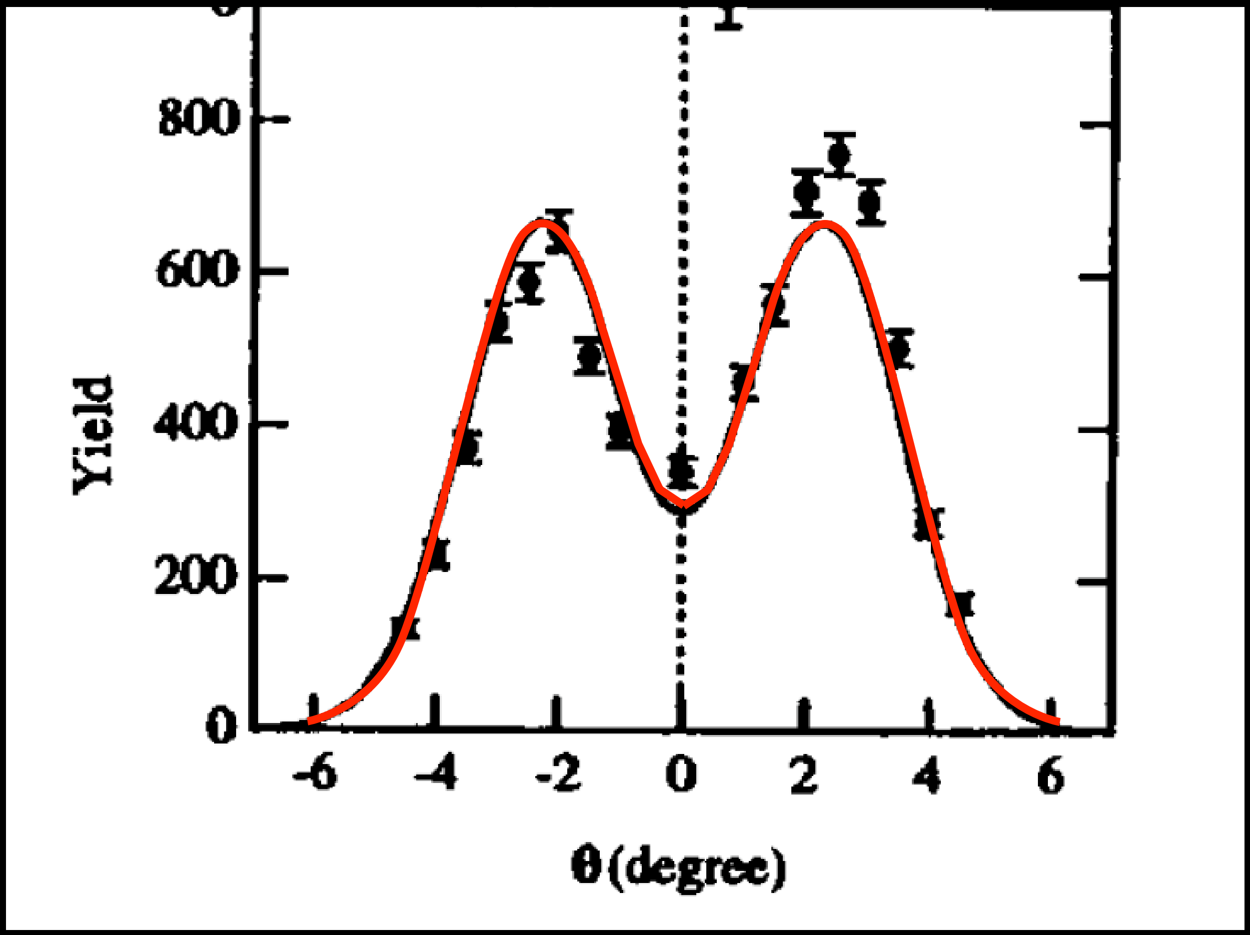

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Orbital deflection caused by Coulomb repulsion

Target, *E* dependence

Evaluation of $\sigma_{Prod.}$

- Theoretical calculation

ex. A) ABRABLA : abrasion-ablation model

J.J. Gaimard et al., Nucl. Phys. A 53 I (1991) 709.

B) QMD, AMD .....

Time consuming, ambiguity of model

- Empirical formulation

ex. EPAX : Based on high-E spallation

K. Sümmerer et al., Phys. Rev. C 61 (2000) 034607.

Simple and good for rough estimation

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***E*, target dependence**

Contribution of nucl. structure

Experimental setup

- **HIMAC@NIRS 290 MeV/u**
- RRC@RIKEN 90, 95 MeV/u

Experiments
- RIKEN & NIRS

- RRC+RIPS

  S. Momota et al., Nucl. Phys. A746, 407c (2004).
  M. Notani et al., Phys. Rev. C 76, 044605 (2007).

  P_L dist.(Machine study)

  Beam : ^{40}Ar @90 MeV/u
  Target : ^{9}Be

  P_T dist. (r280n)

  Beam : ^{40}Ar @95 MeV/u
  Target : ^{9}Be

- HIMAC+SB2

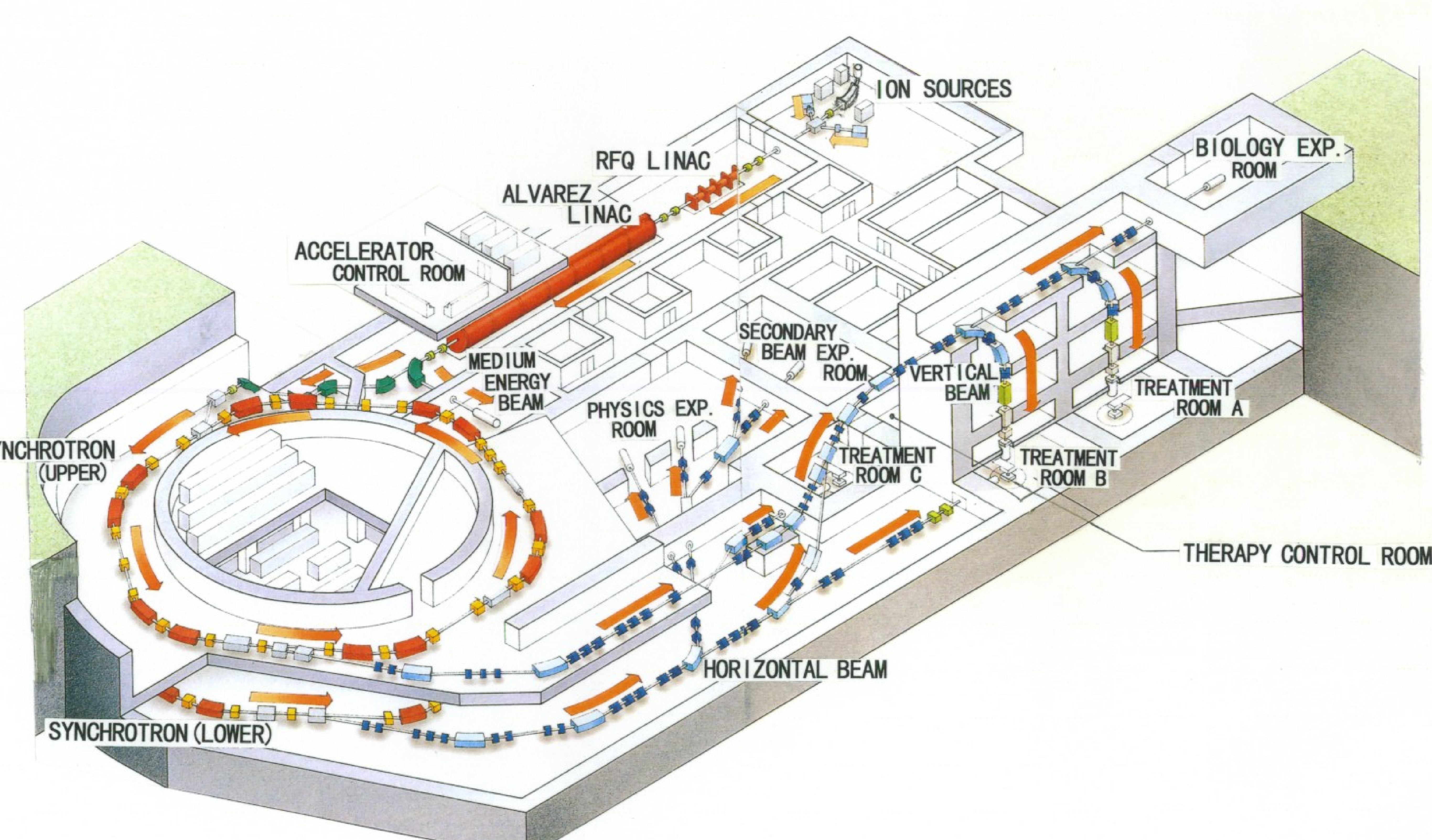
  S. Momota et al., Eur. Phys. J. Special Topics 150, 315–316 (2007).
  S. Momota et al., to be published in J. of Korean Phys. Soc.

  P_L dist., P_L dist. (P078, P178)

  Beam : ^{40}Ar, ^{84}Kr@290 MeV/u
  Target : ^{12}C, ^{27}Al, ^{93}Nb, ^{159}Tb, ^{197}Au

HIMAC facility at NIRS

- dedicated for cancer therapy



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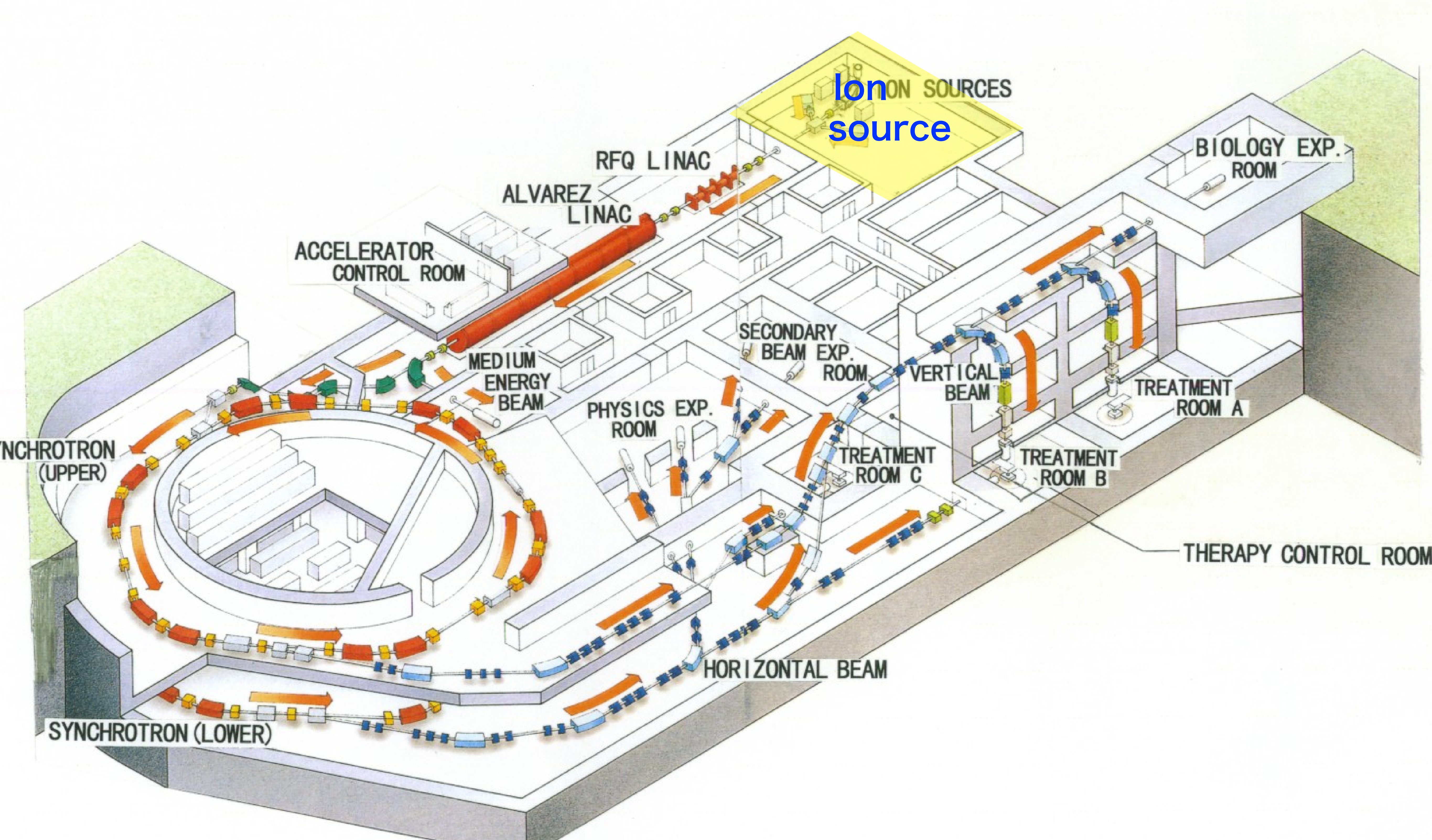

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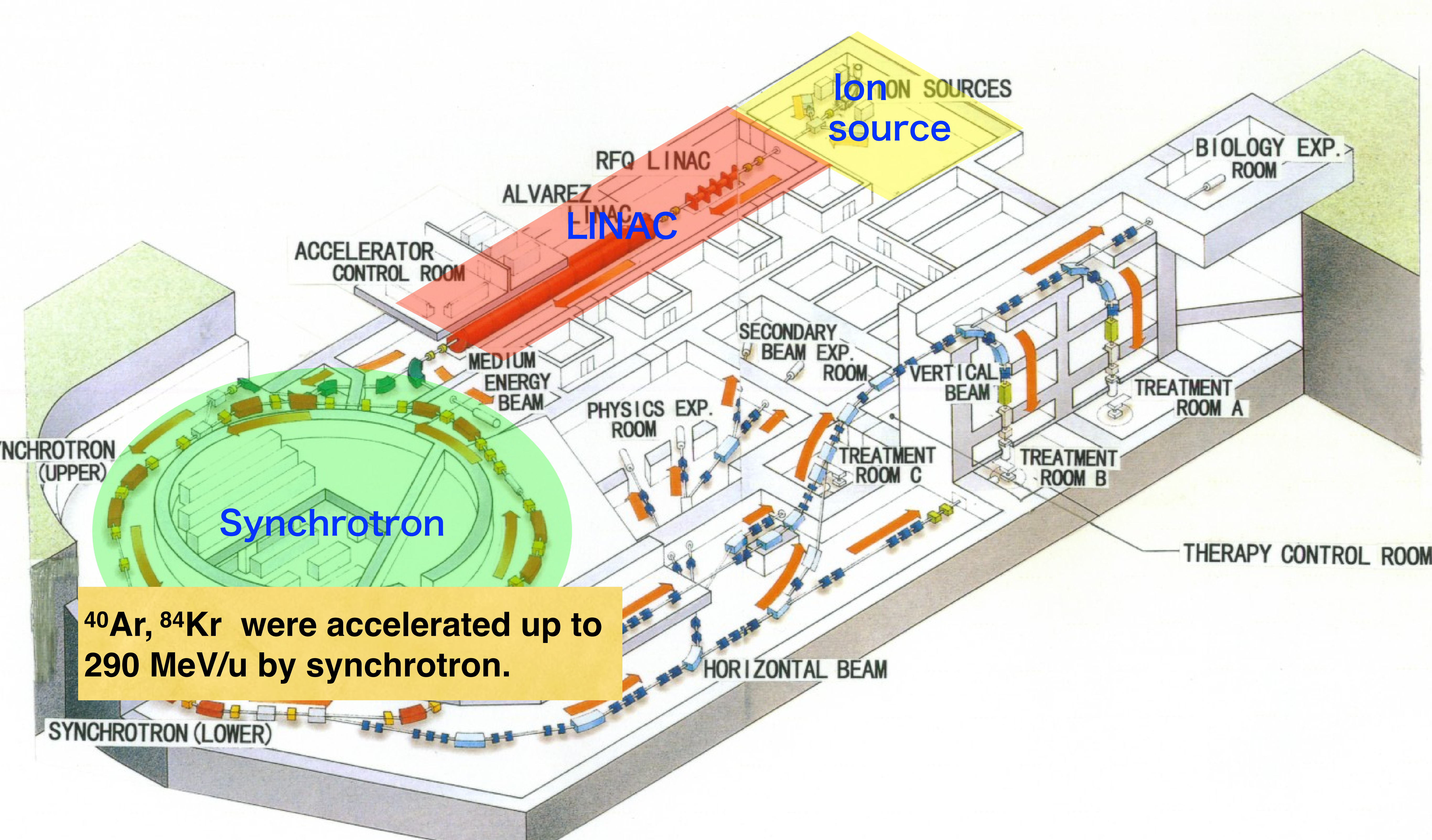

^{40}Ar, ^{84}Kr were accelerated up to 290 MeV/u by synchrotron.

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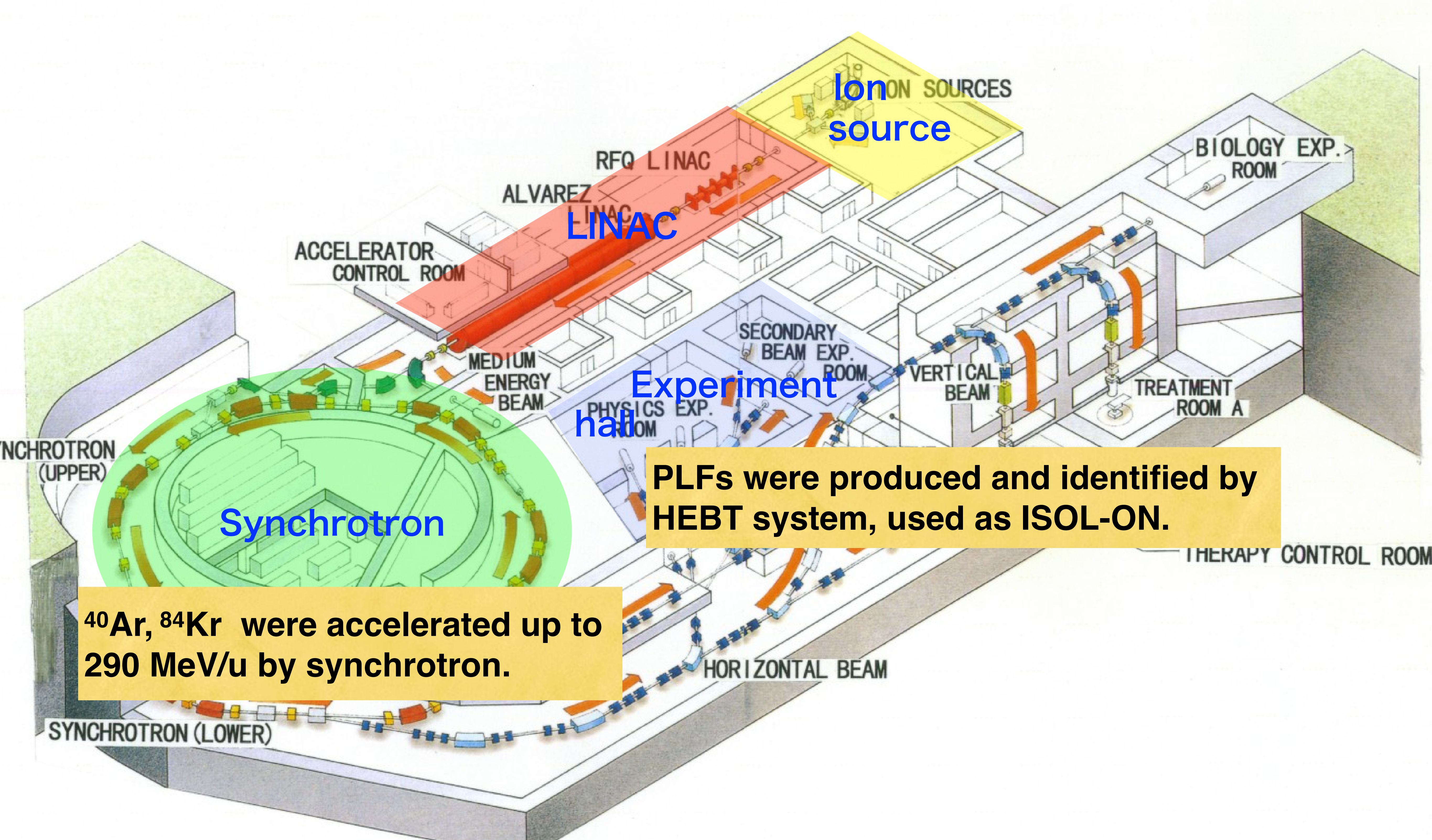
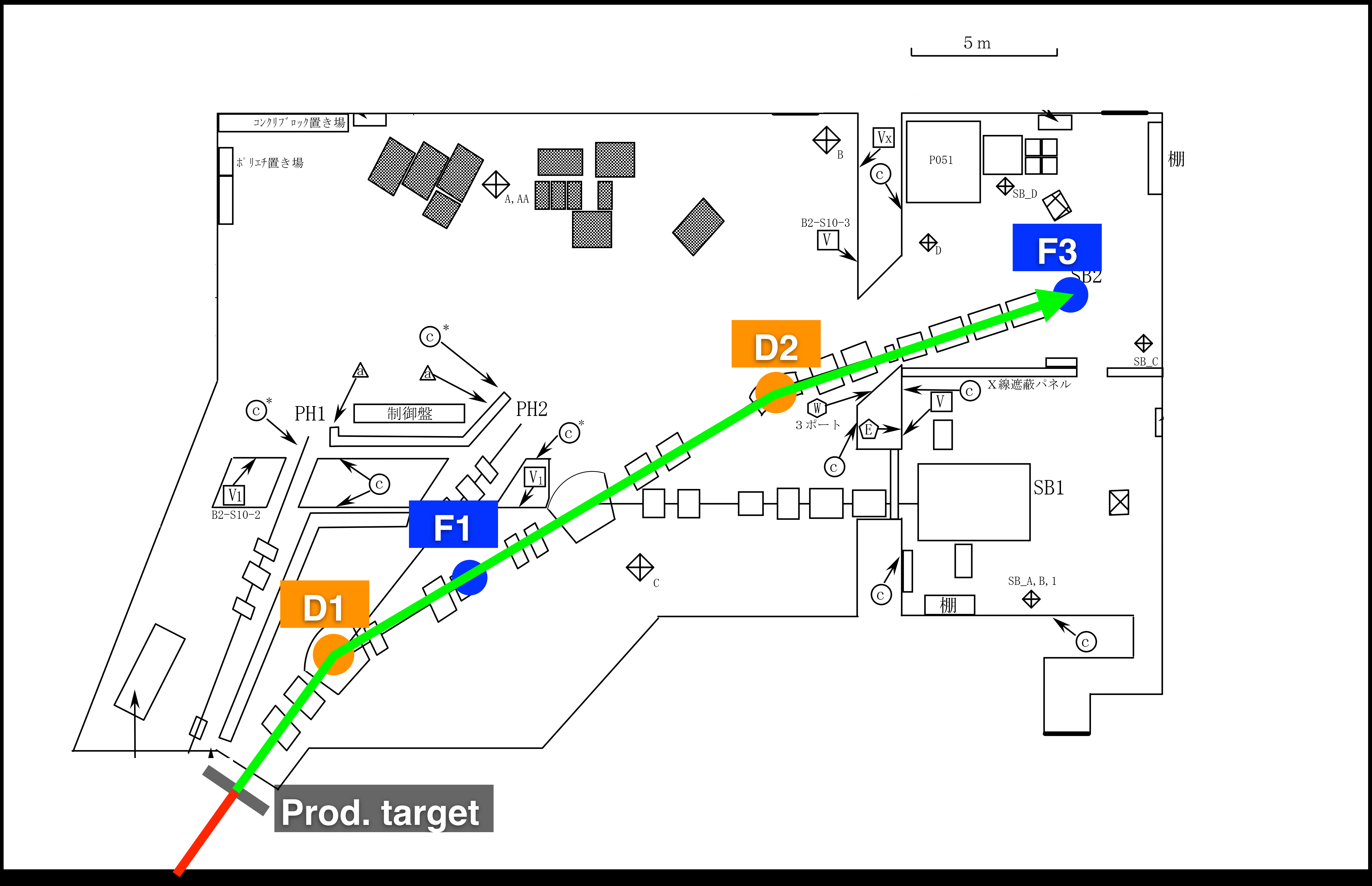


PLFs were produced and identified by HEBT system, used as ISOL-ON.

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

Fragment separator



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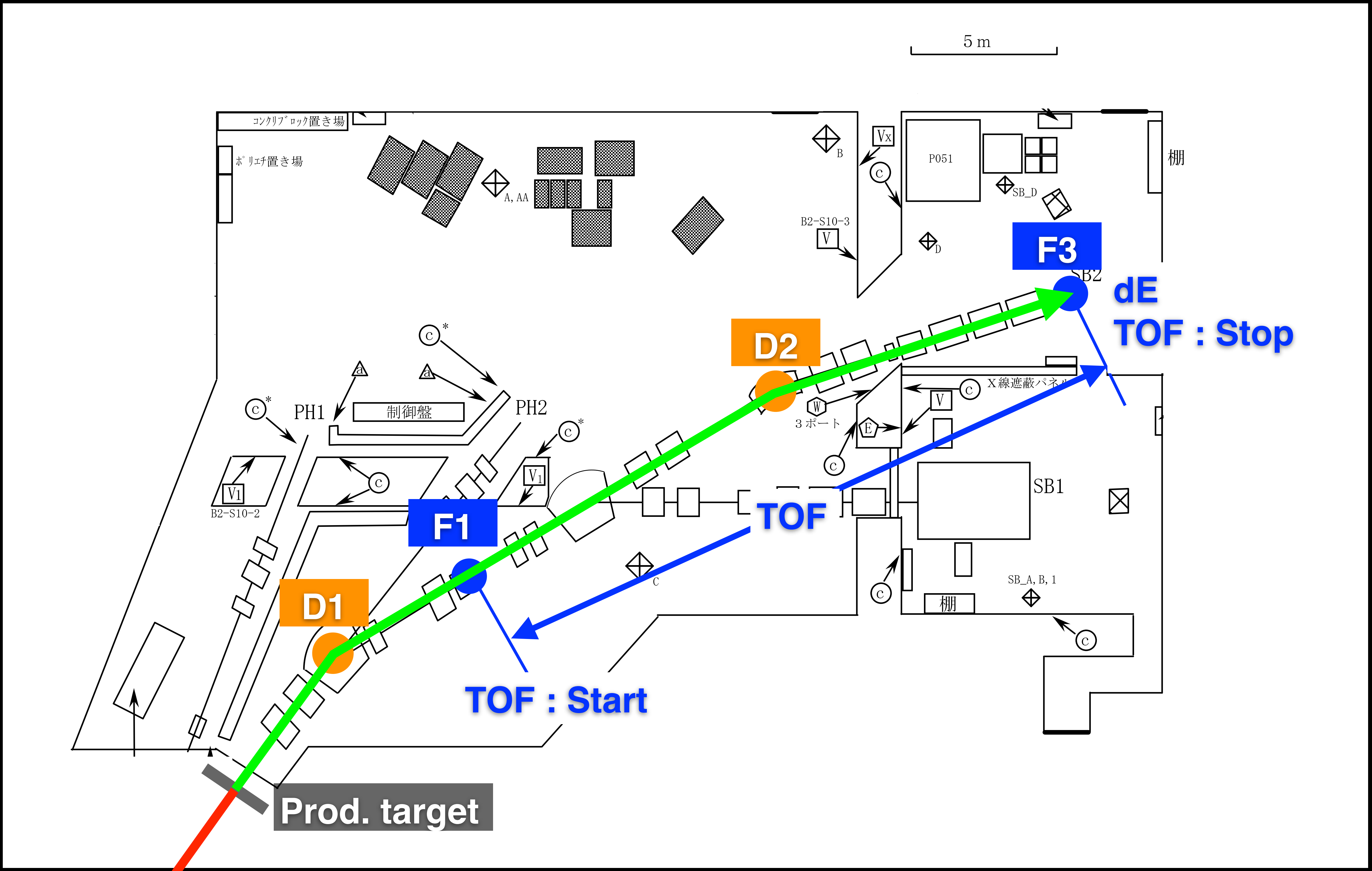

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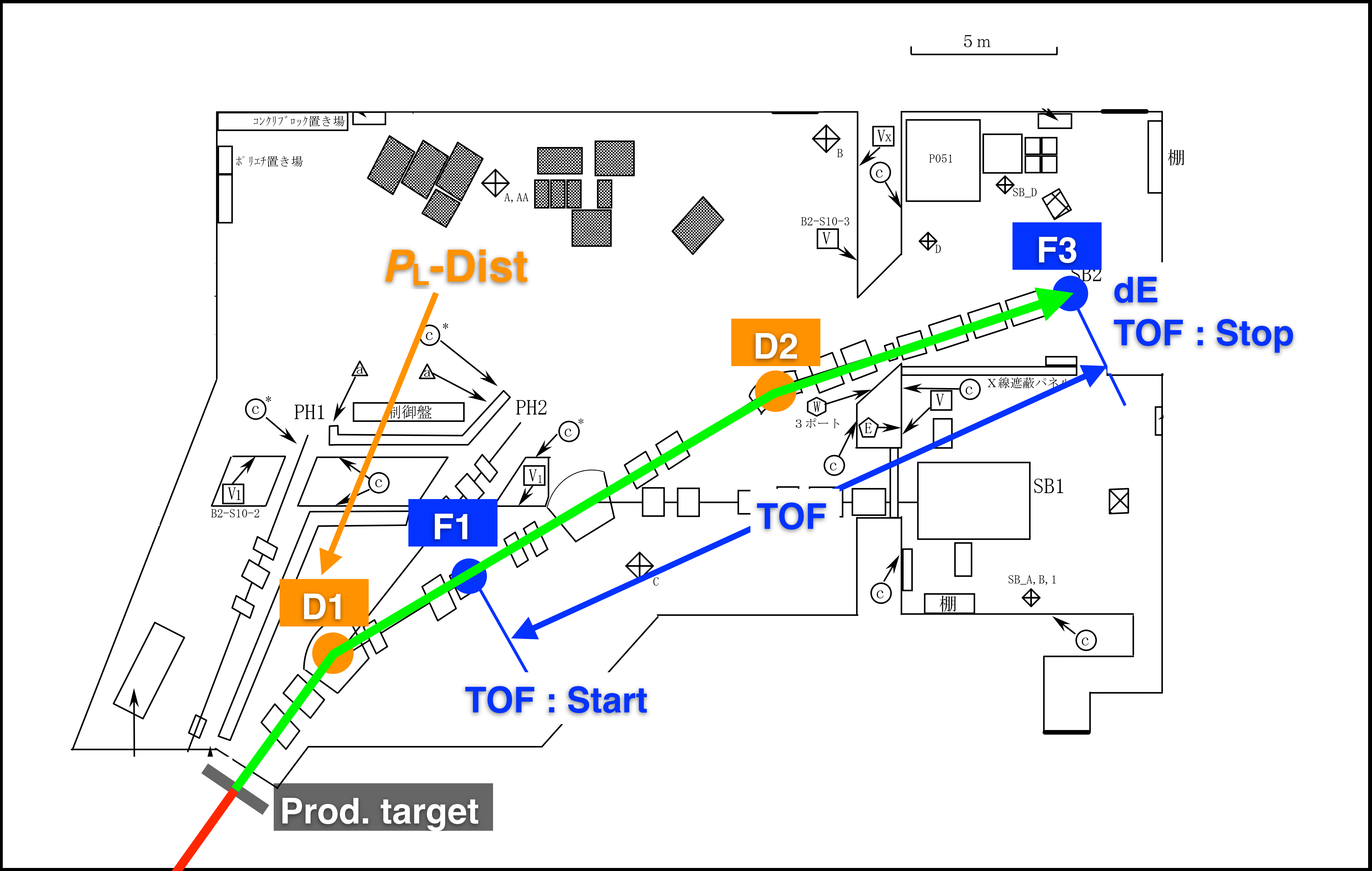

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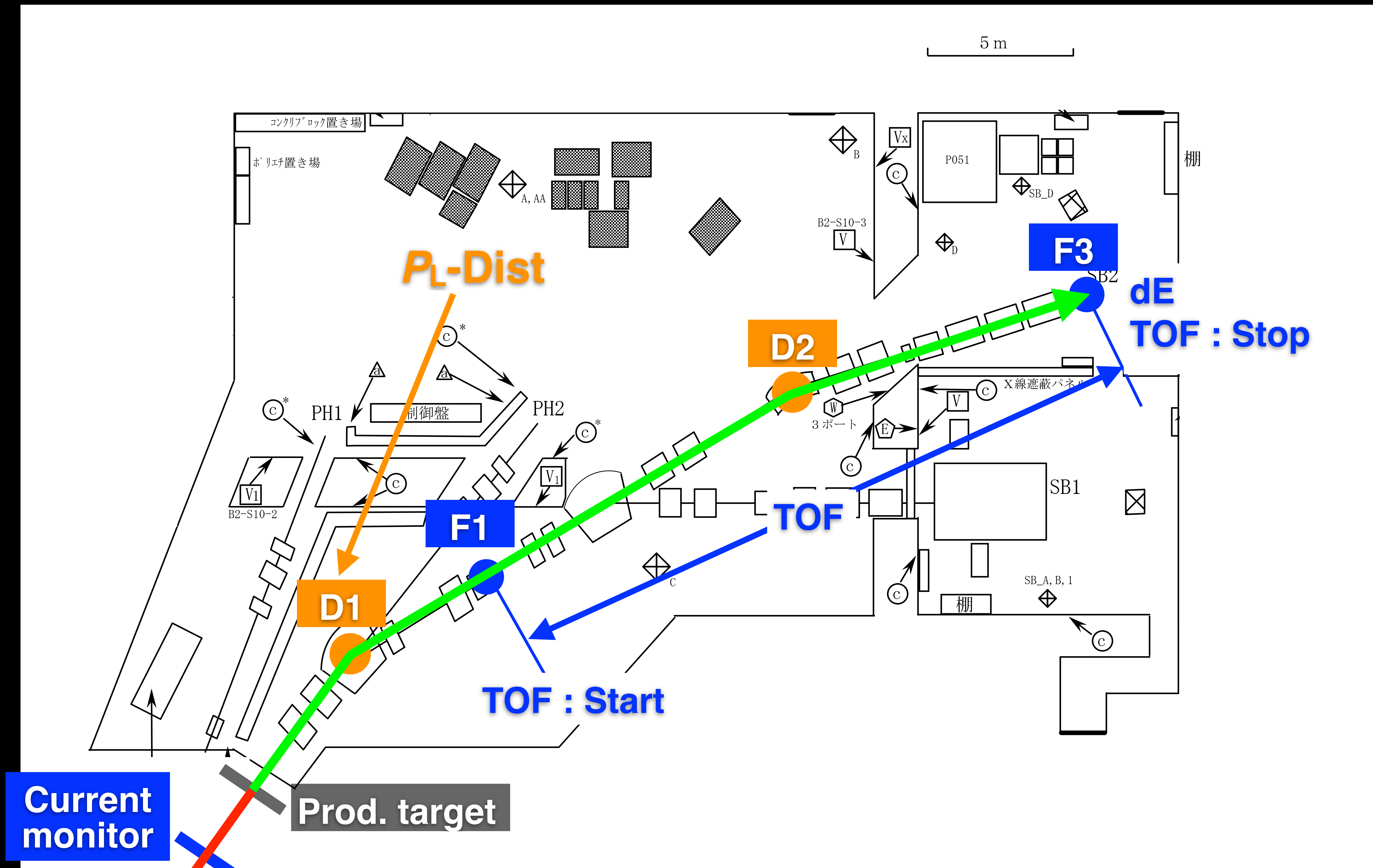
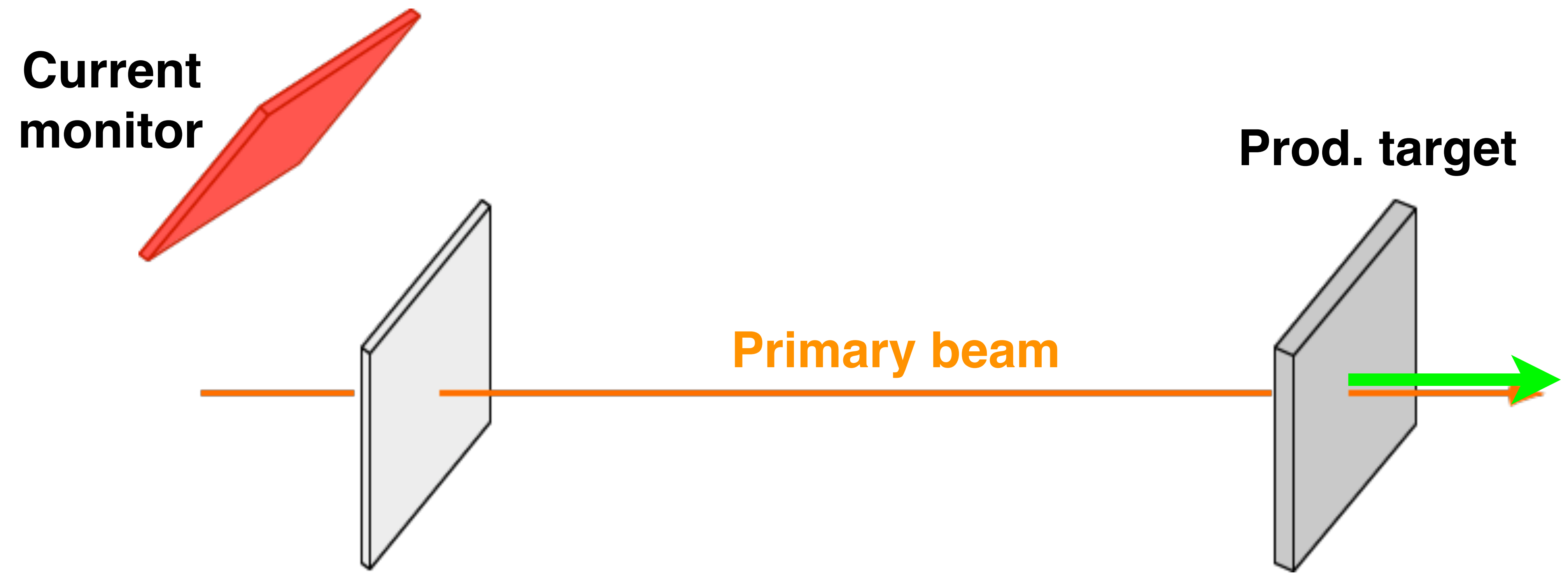


Angular (P_T) distribution



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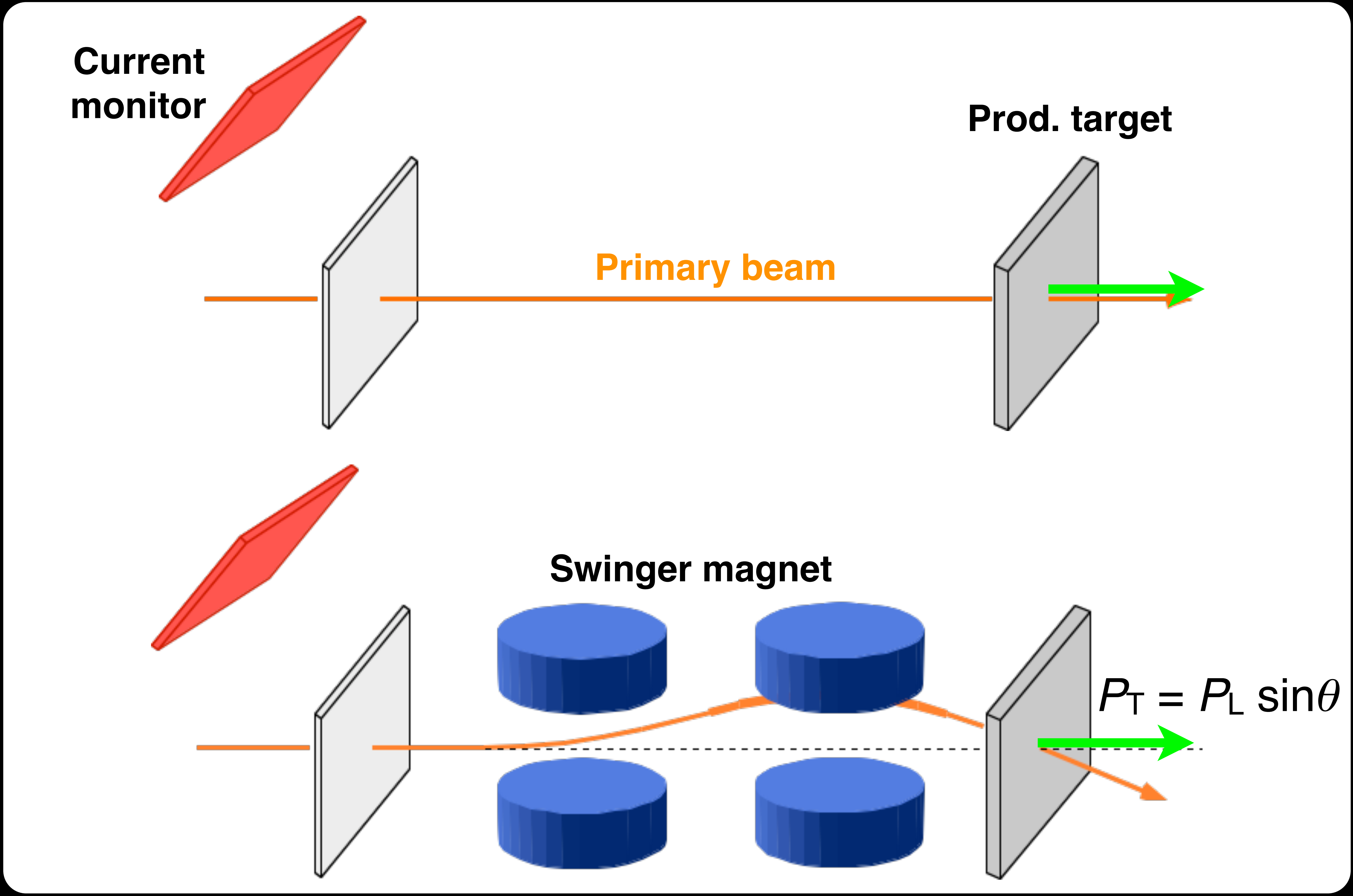
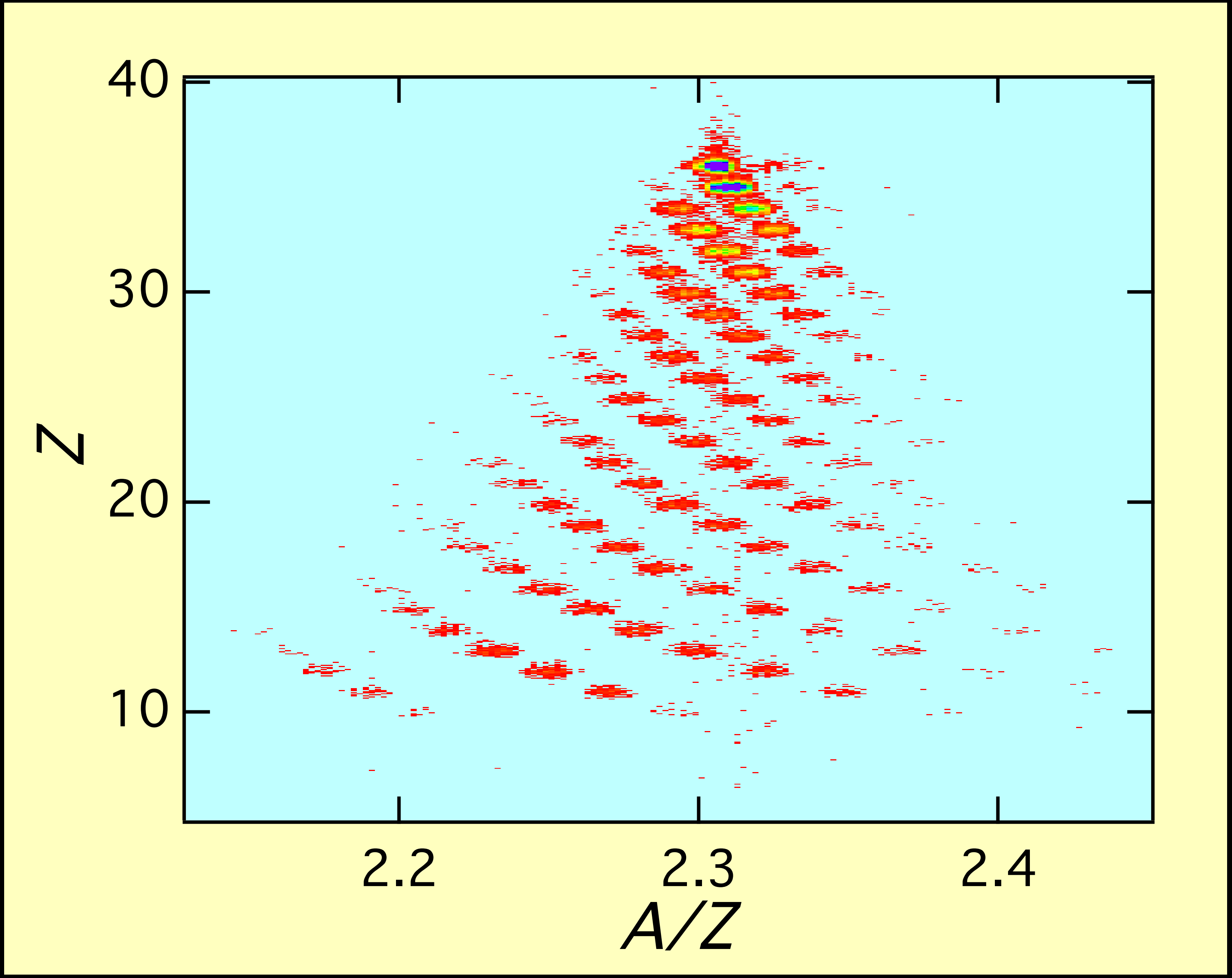


Particle identification

- $^{84}Kr + ^{159}Tb \rightarrow {}^{A}Z + X$

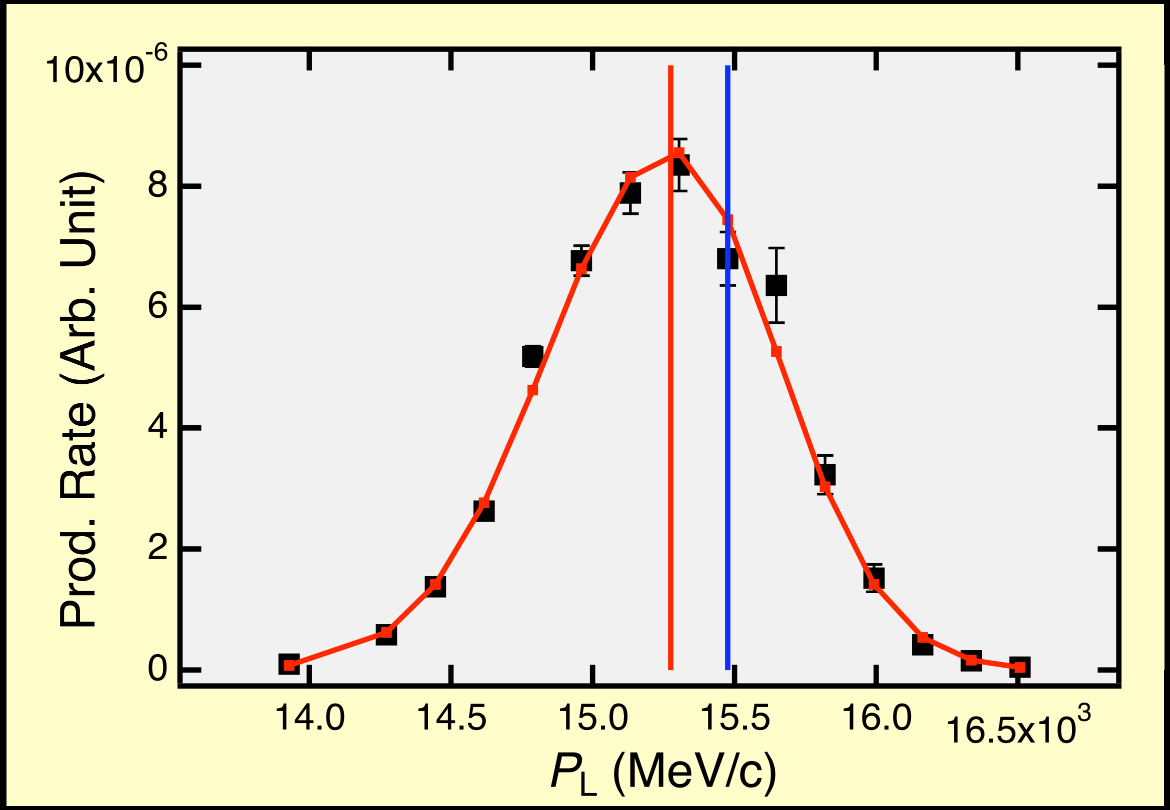


$B\rho$=99.0 ± 0.25%, θ = 16 ± 4 mrad

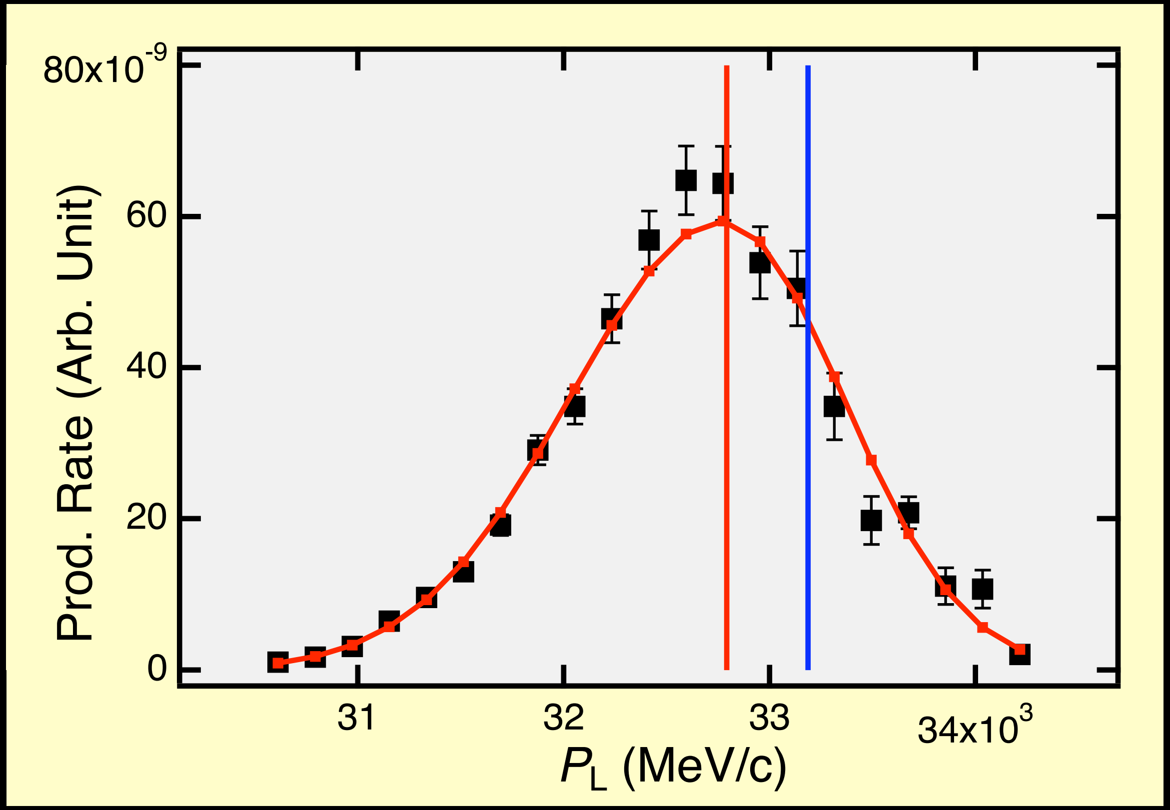
P_L distribution

Analysis of P_L distributions

- $^{40}Ar+^{93}Nb \rightarrow ^{20}Ne$



- $^{84}Kr+^{12}C \rightarrow ^{43}Ca$



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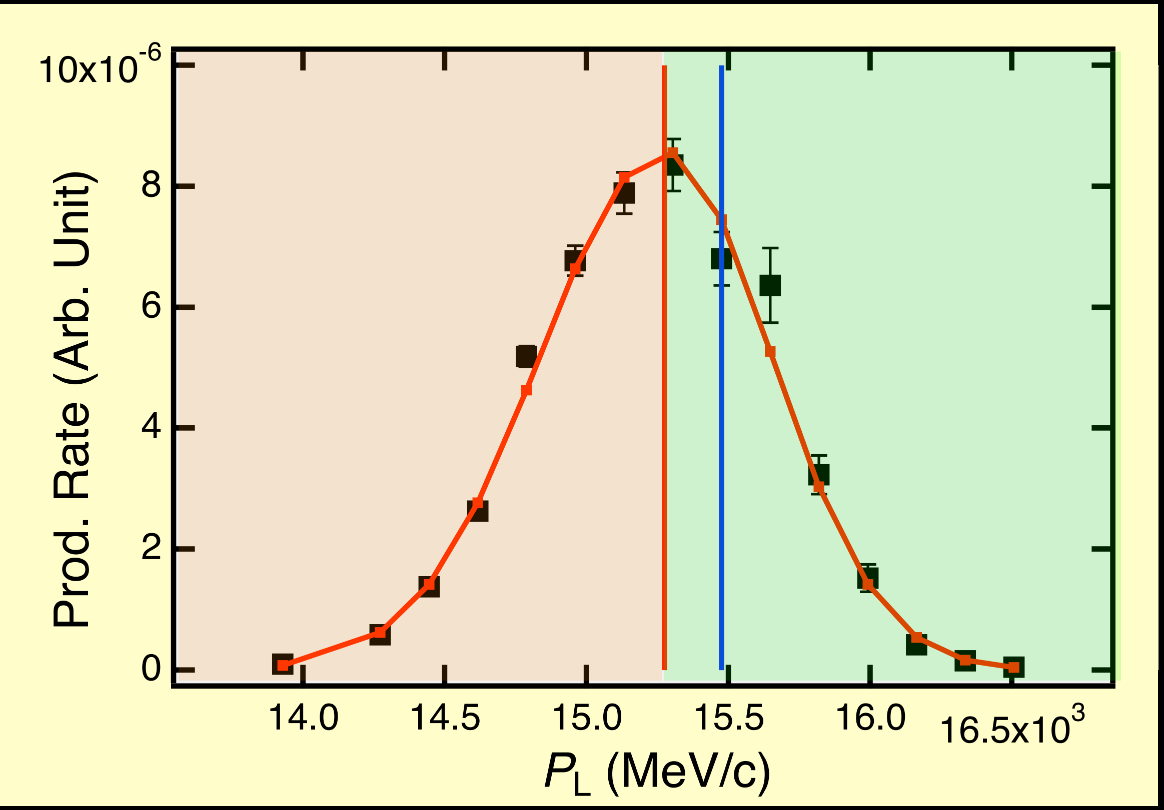

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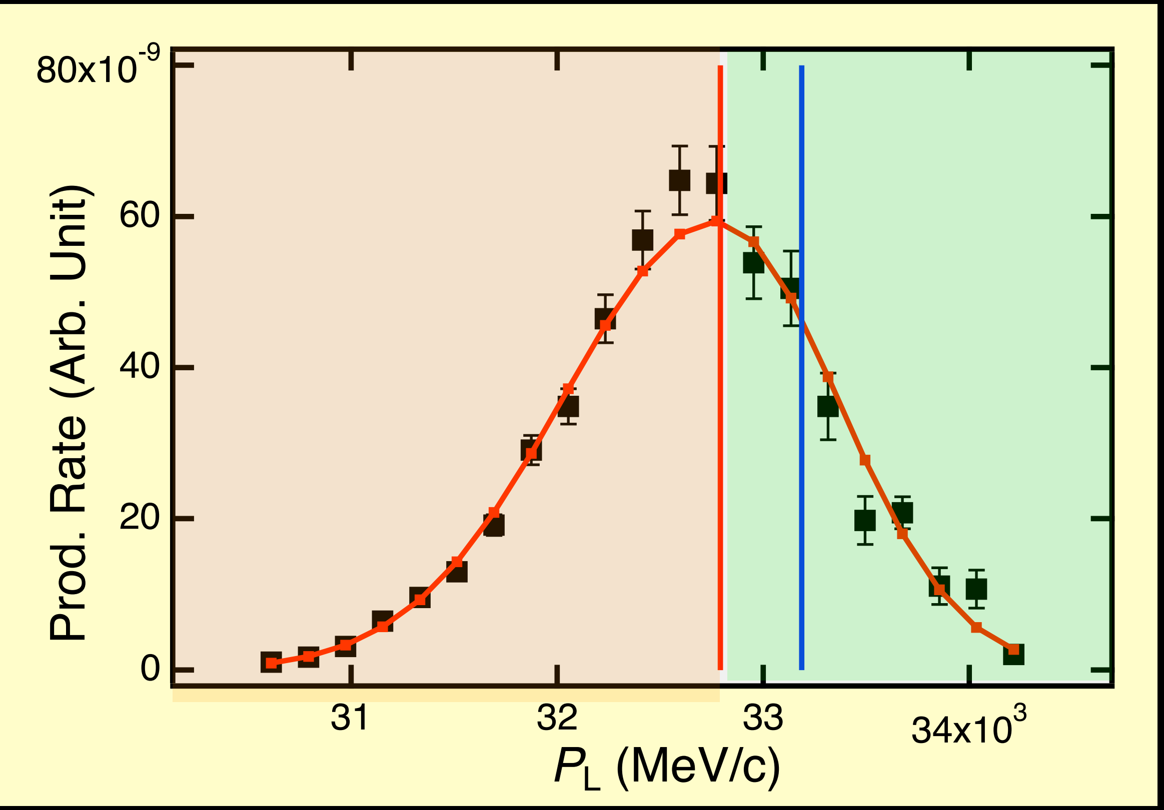

$$Y(P_L) = A \exp\left(-\frac{(P_L - P_0)^2}{2\sigma(P_L)^2}\right) \quad \begin{cases} \sigma(P_L) = \sigma_{Low} & \text{if } P_L < P_0 \\ \sigma(P_L) = \sigma_{High} & \text{if } P_L > P_0 \end{cases}$$

Analysis of P_L distributions

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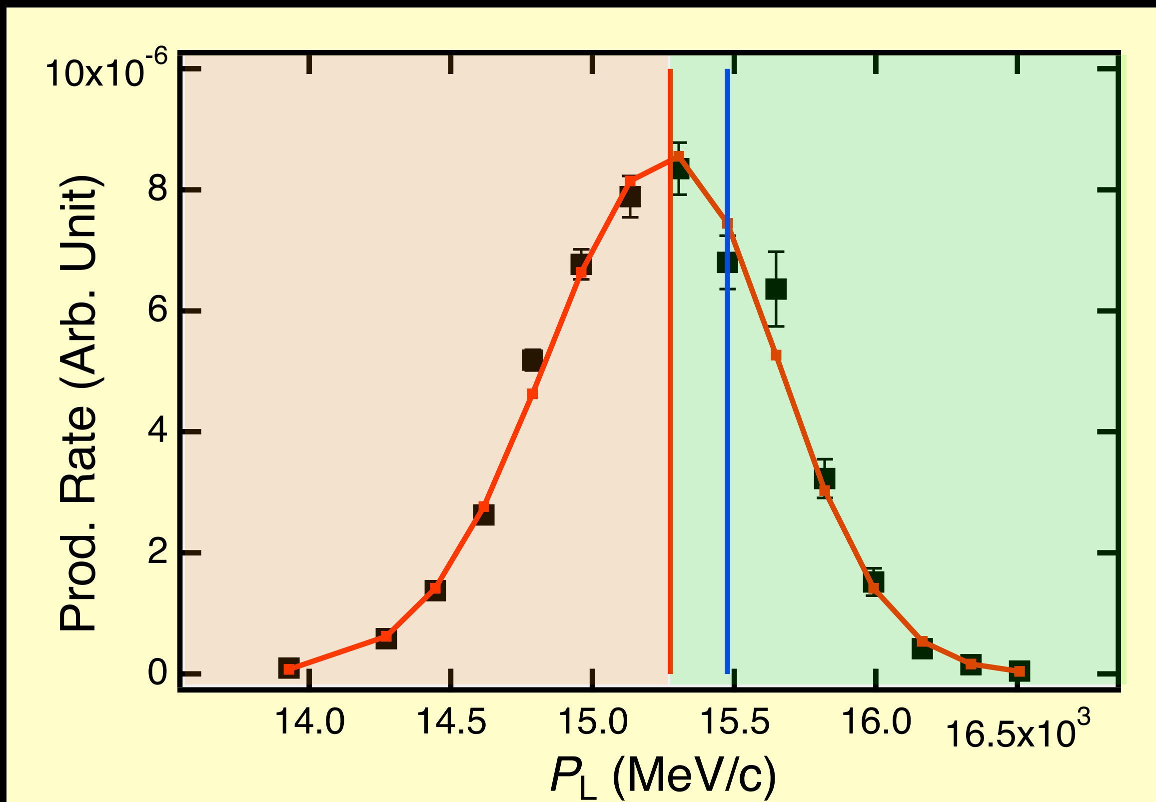

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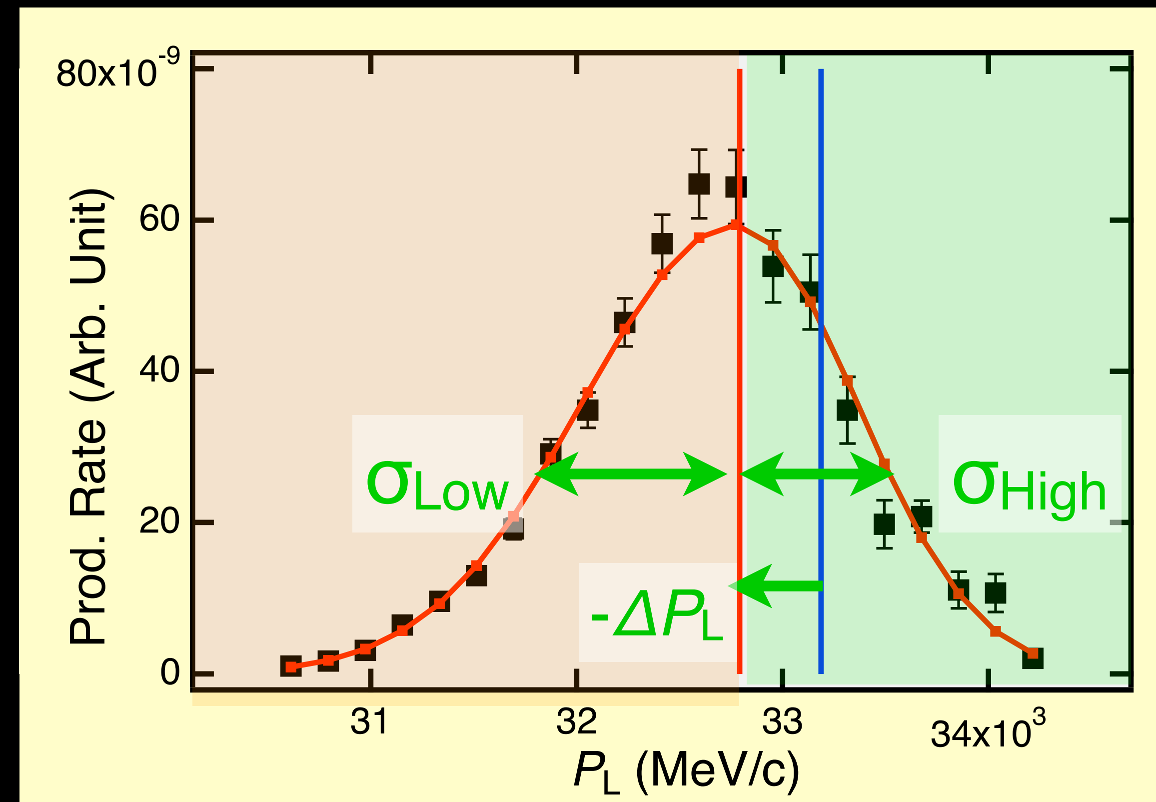

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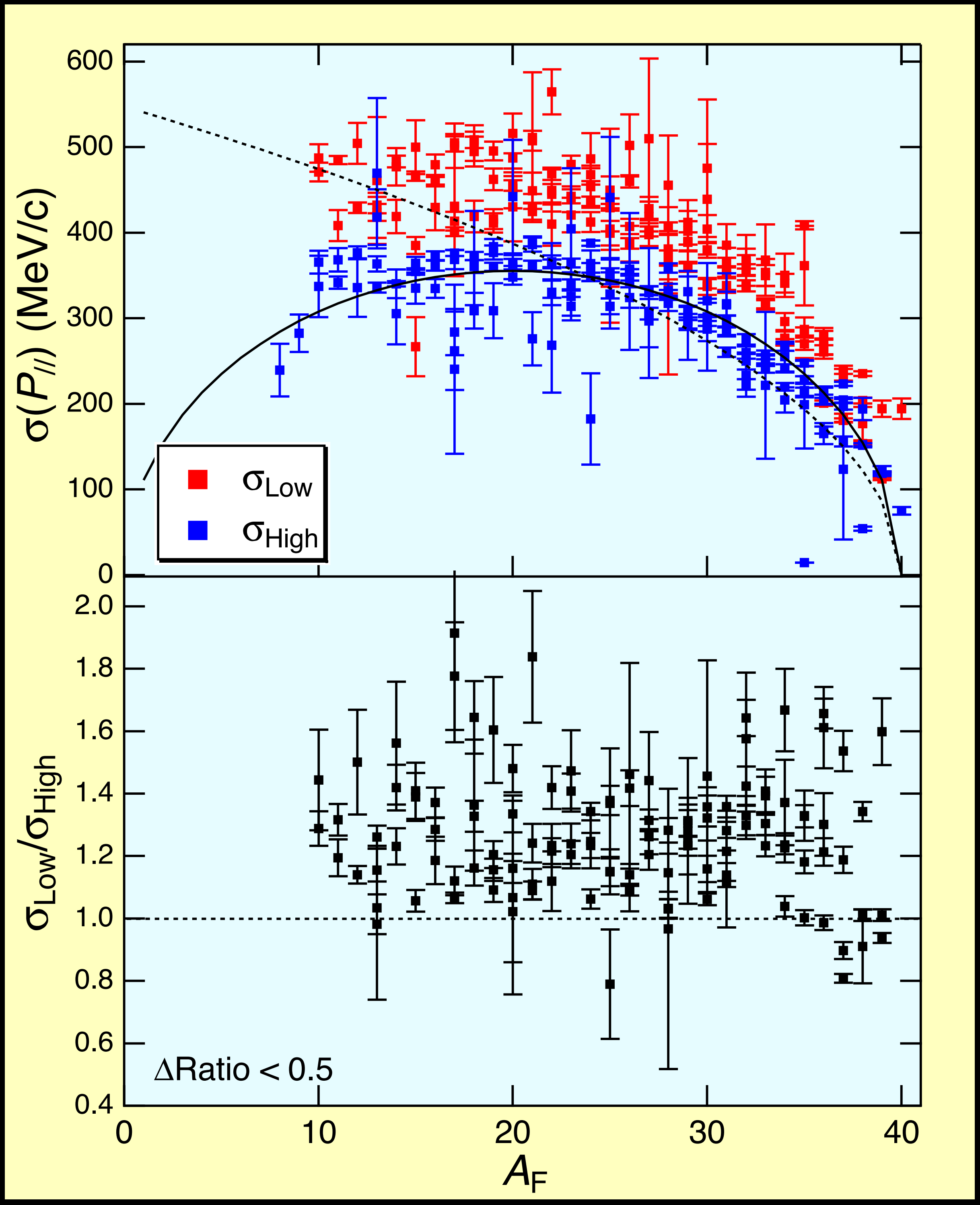
Fitting results → width and velocity shift

σ_{Low} , σ_{High} $-\Delta P_L$

Asymmetry in P_L distributions

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



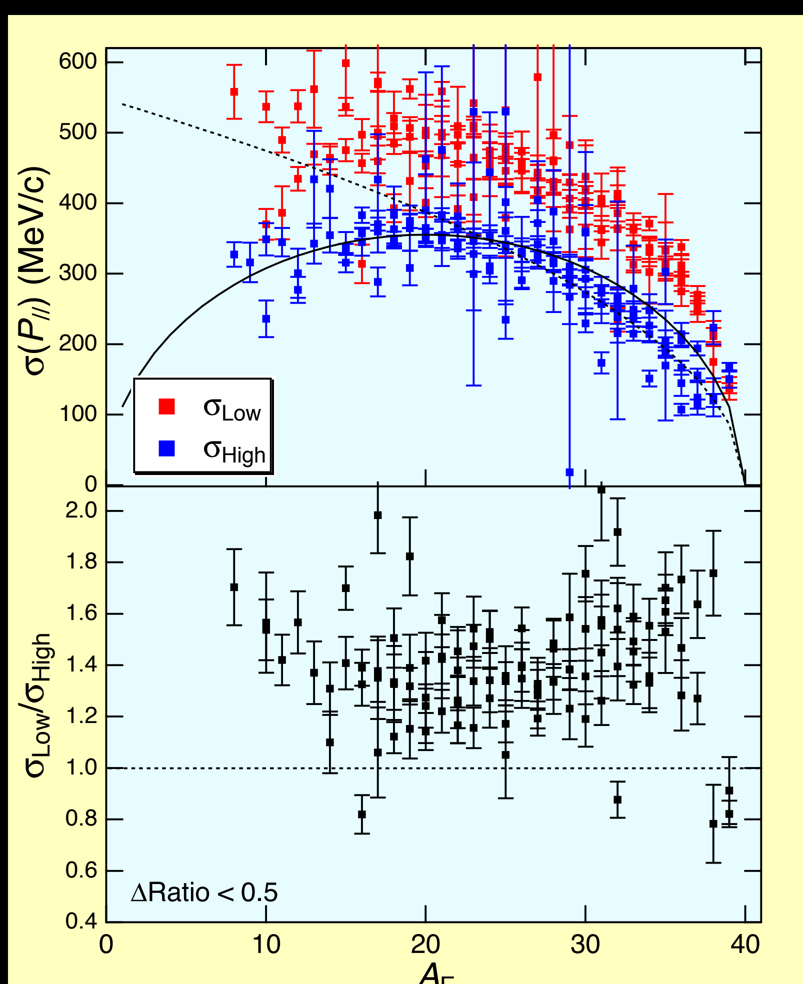
- GH model is valid for σ_{High}.
- $\sigma_{Low} / \sigma_{High}$ = 120~130 %.

Asymmetric P_L distributions

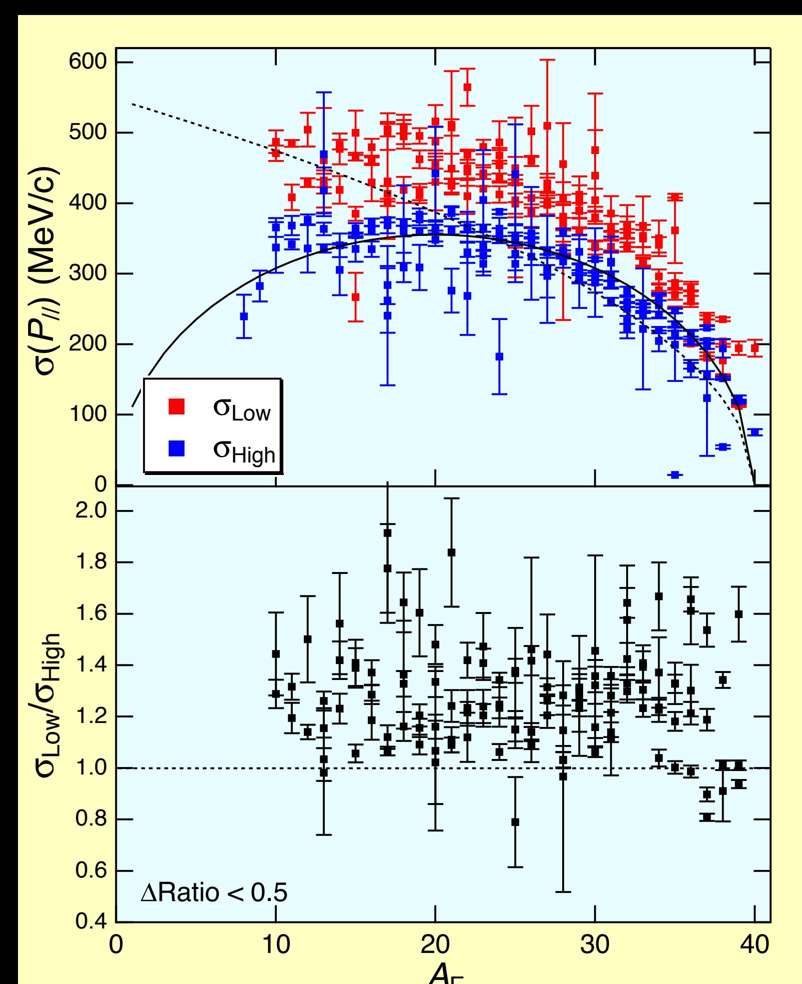
- Target dependence

^{40}Ar +

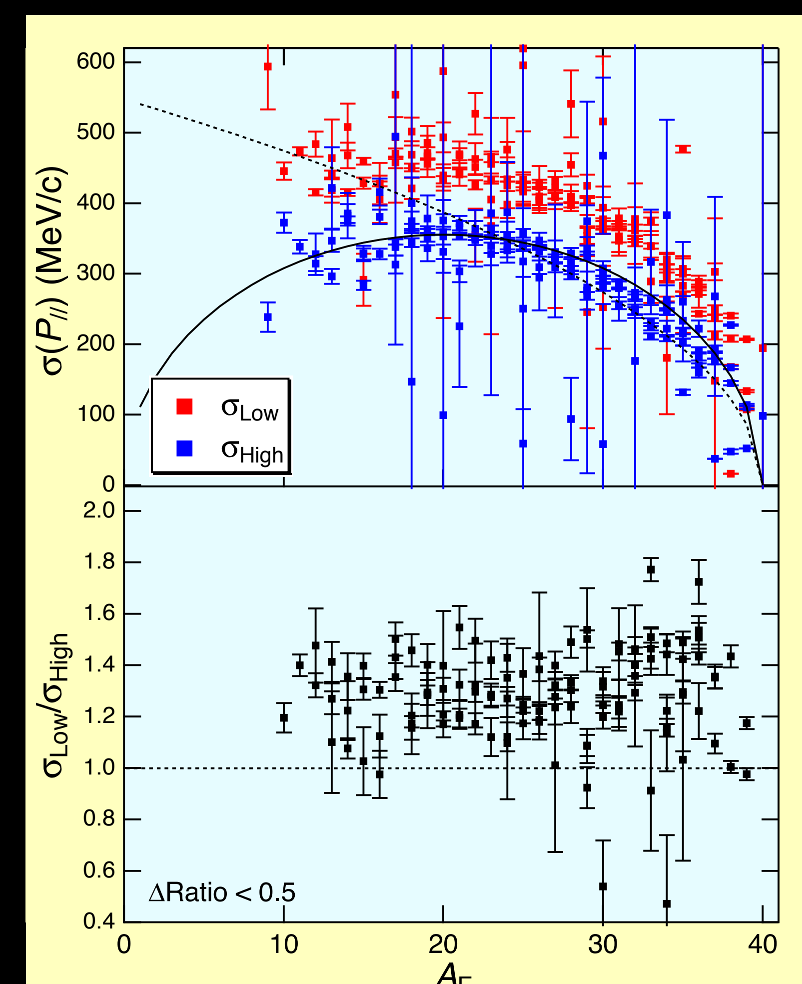
- ^{12}C



- ^{93}Nb

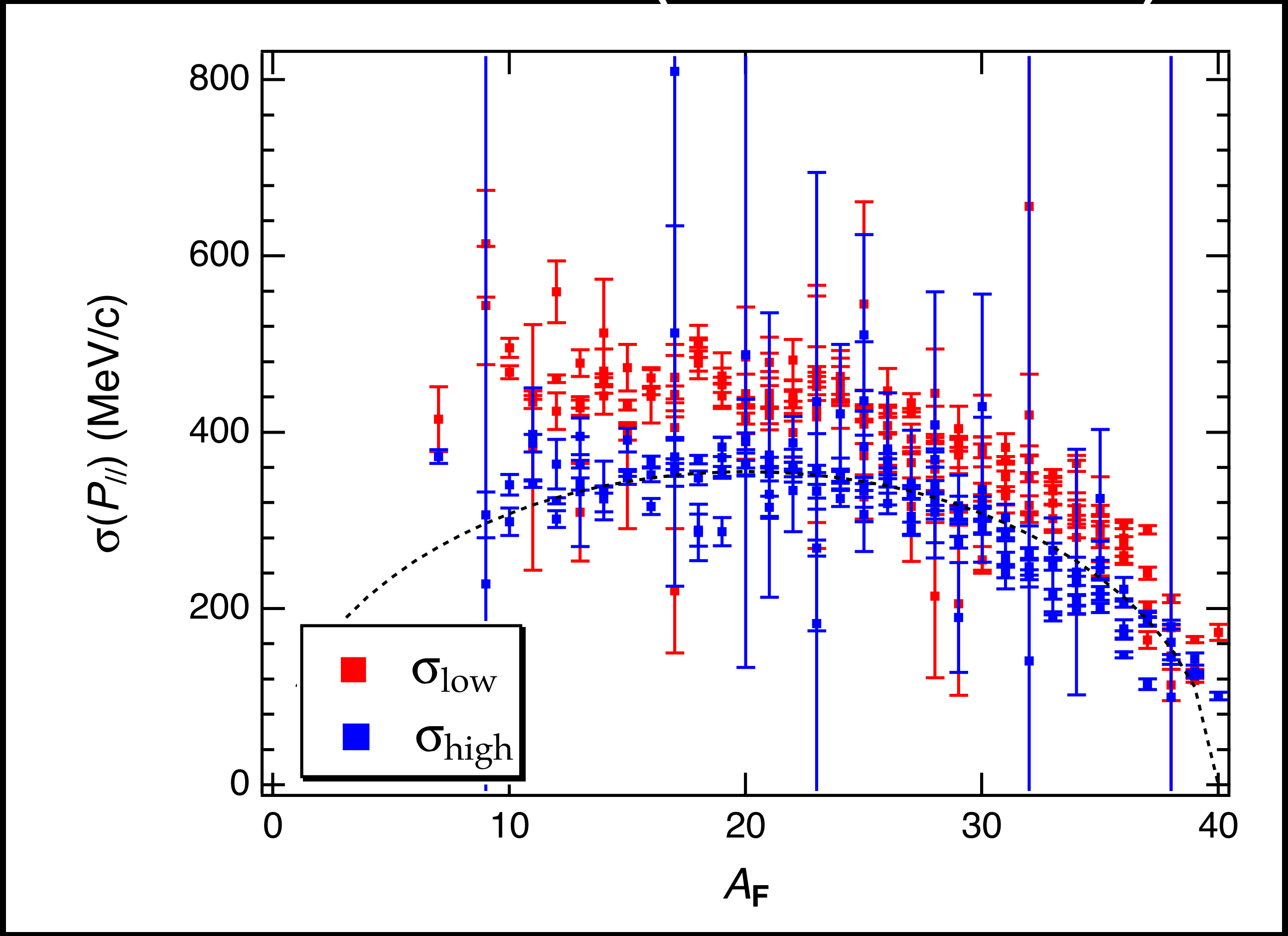


- ^{197}Au

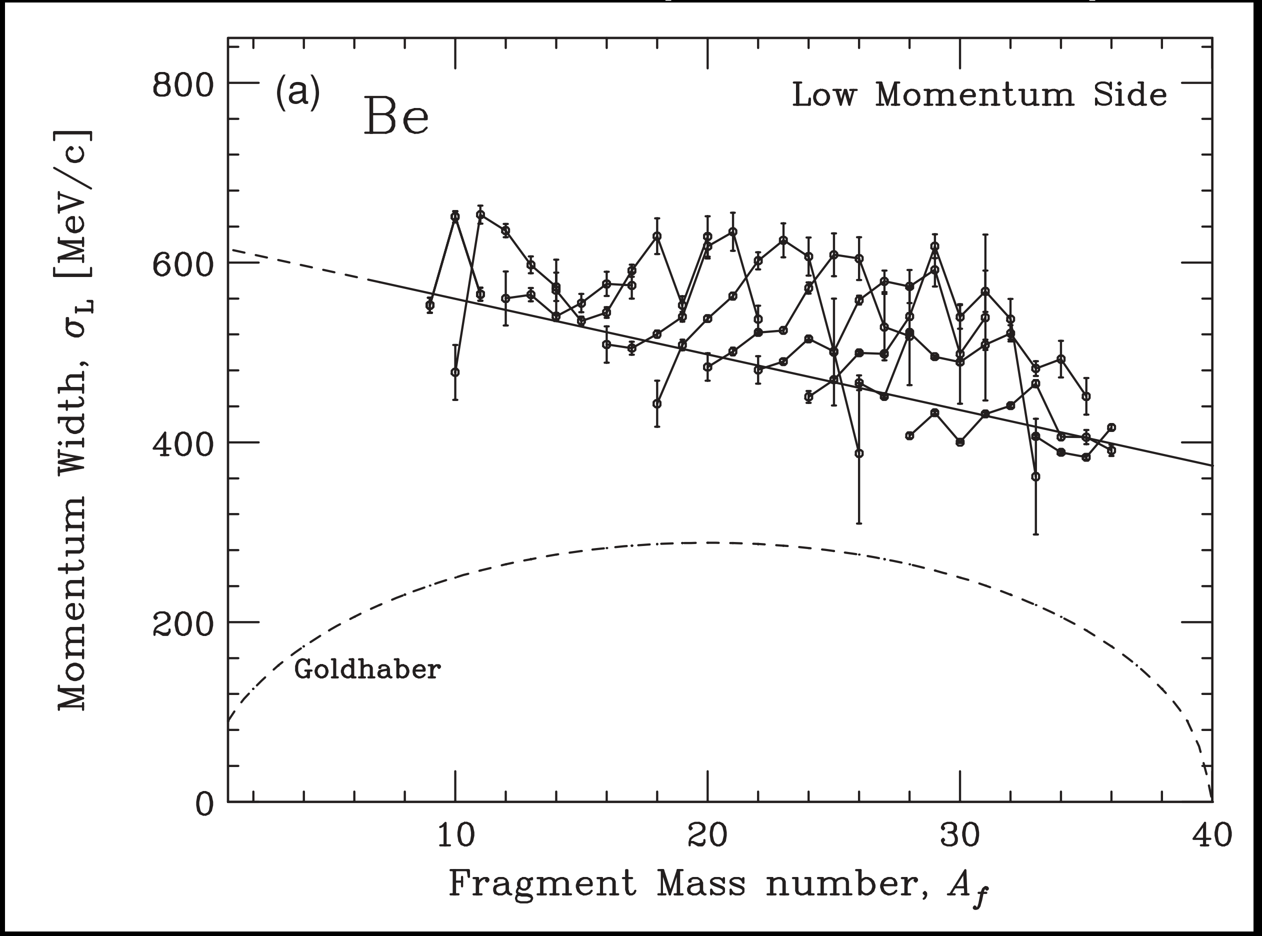


Asymmetric P_L distributions
- *E* dependence

- $^{40}Ar+^{12}C$ (290 MeV/u)



- $^{40}Ar+^{9}Be$ (90 MeV/u)



- Broadening effect is suppressed compared with lower energy reaction.

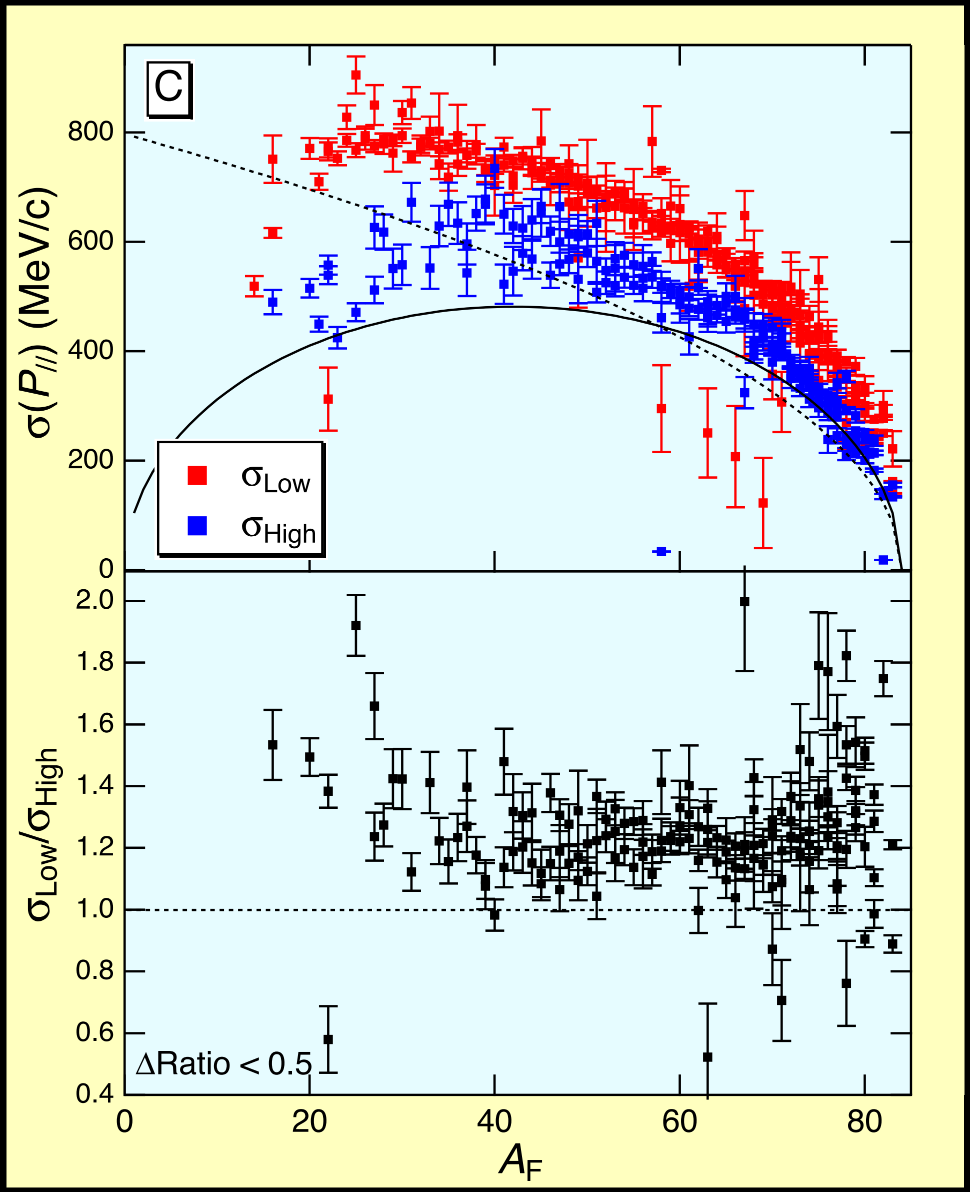
- $^{40}Ar+^{9}Be$@95 MeV/u Notani et al.
  M. Notani et al., PRC 76 (2007) 044605.

Asymmetric P_L distributions

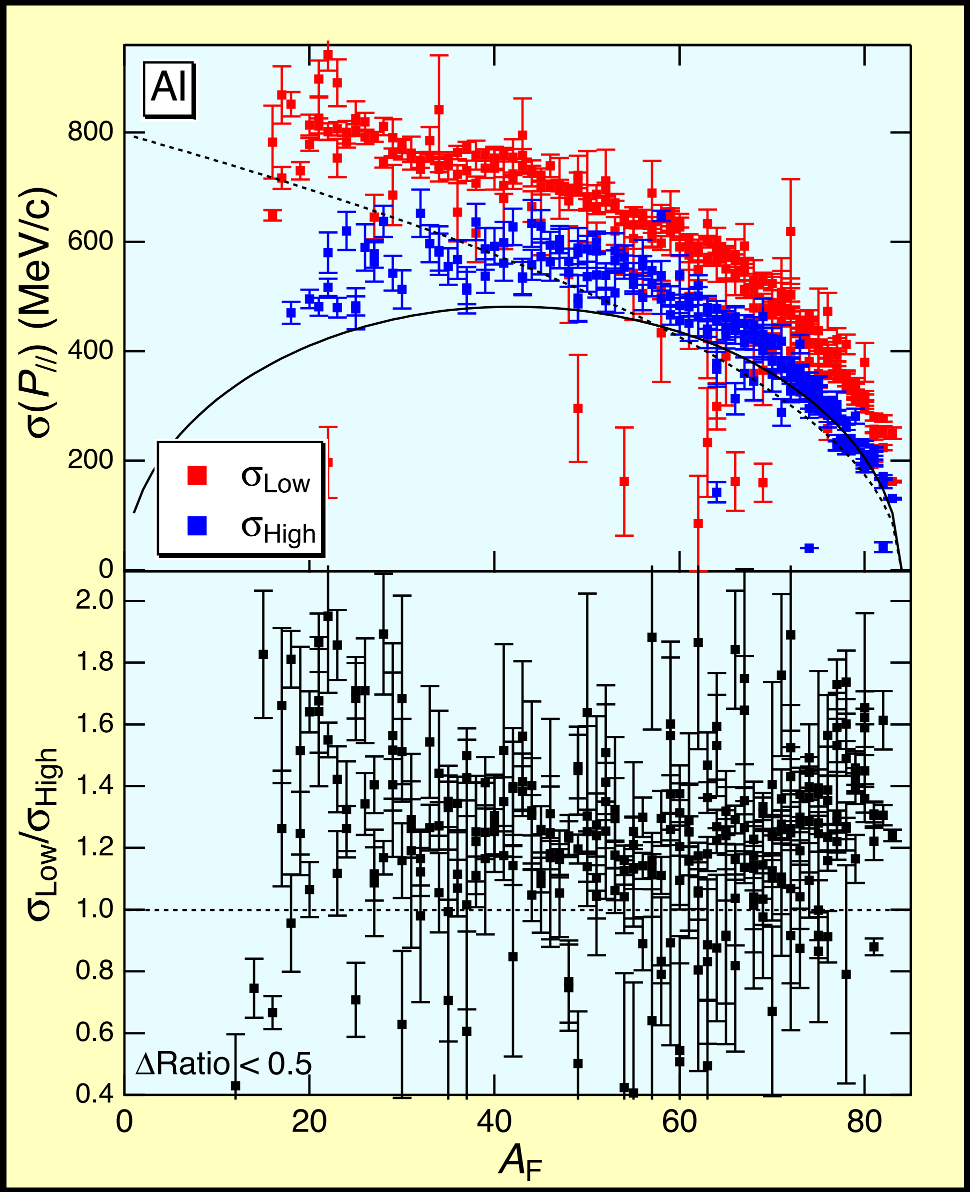
- Target dependence

^{84}Kr +

- ^{12}C



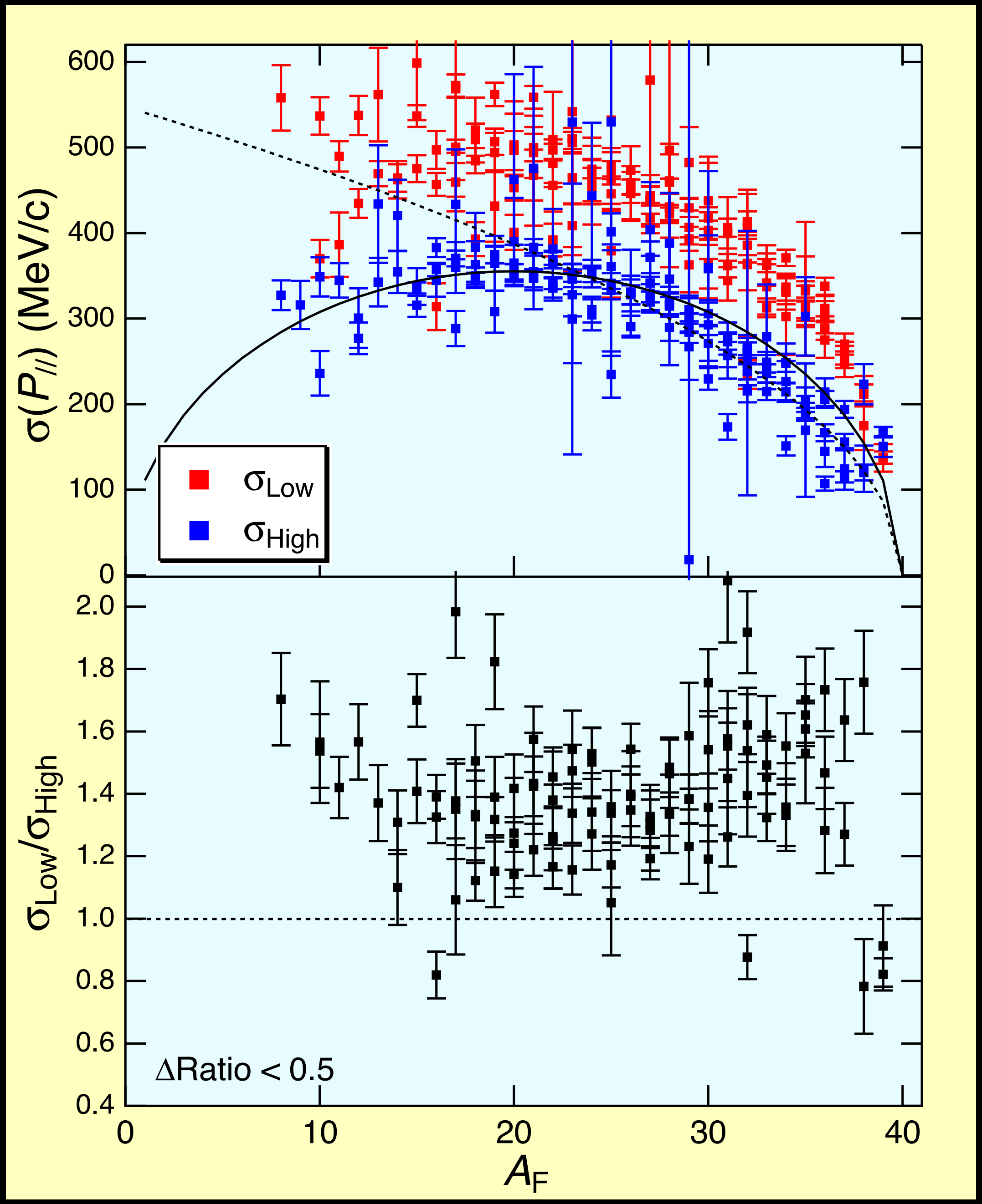
- ^{27}Al



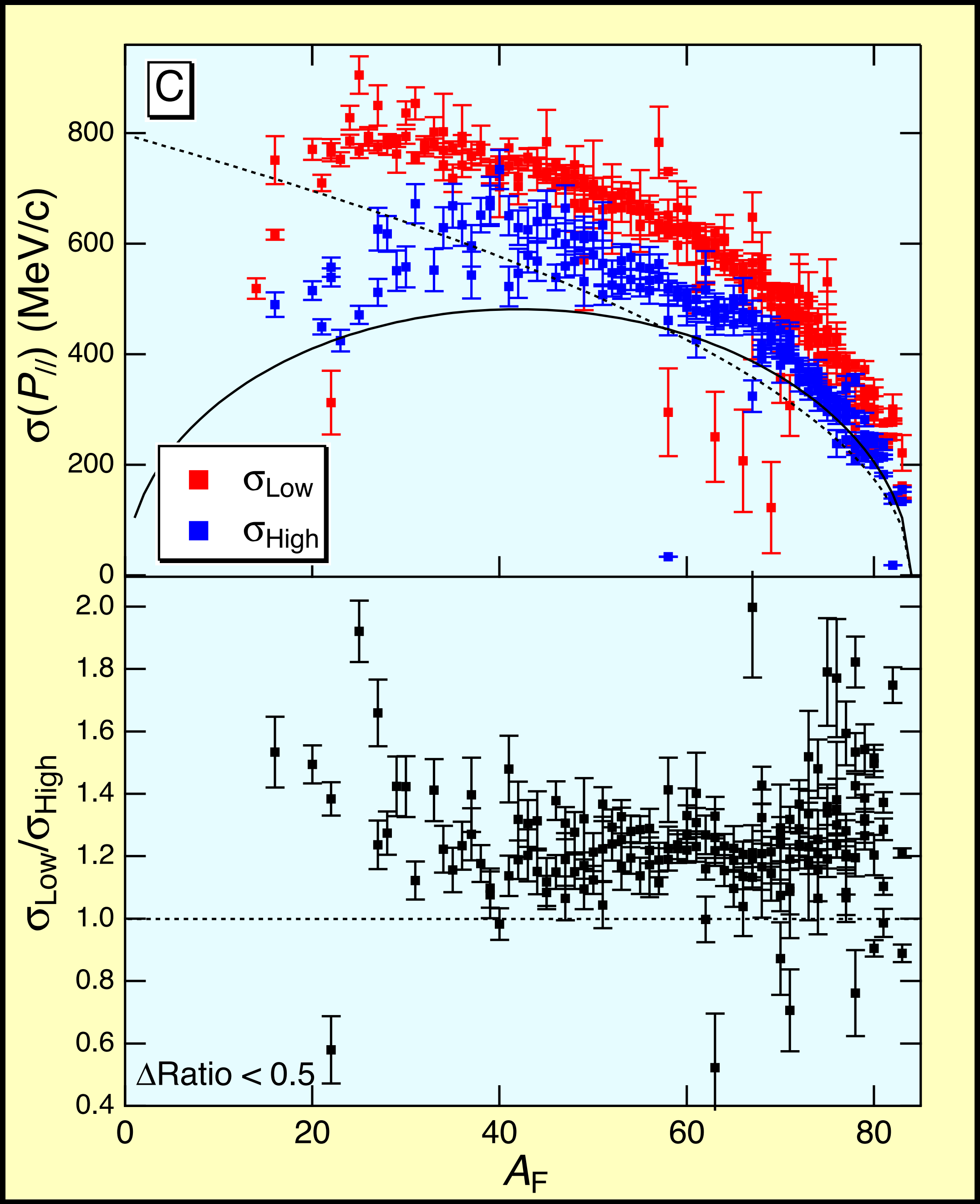
Asymmetry in P_L distributions

- Ar and Kr beam

- $^{40}Ar+^{12}C$

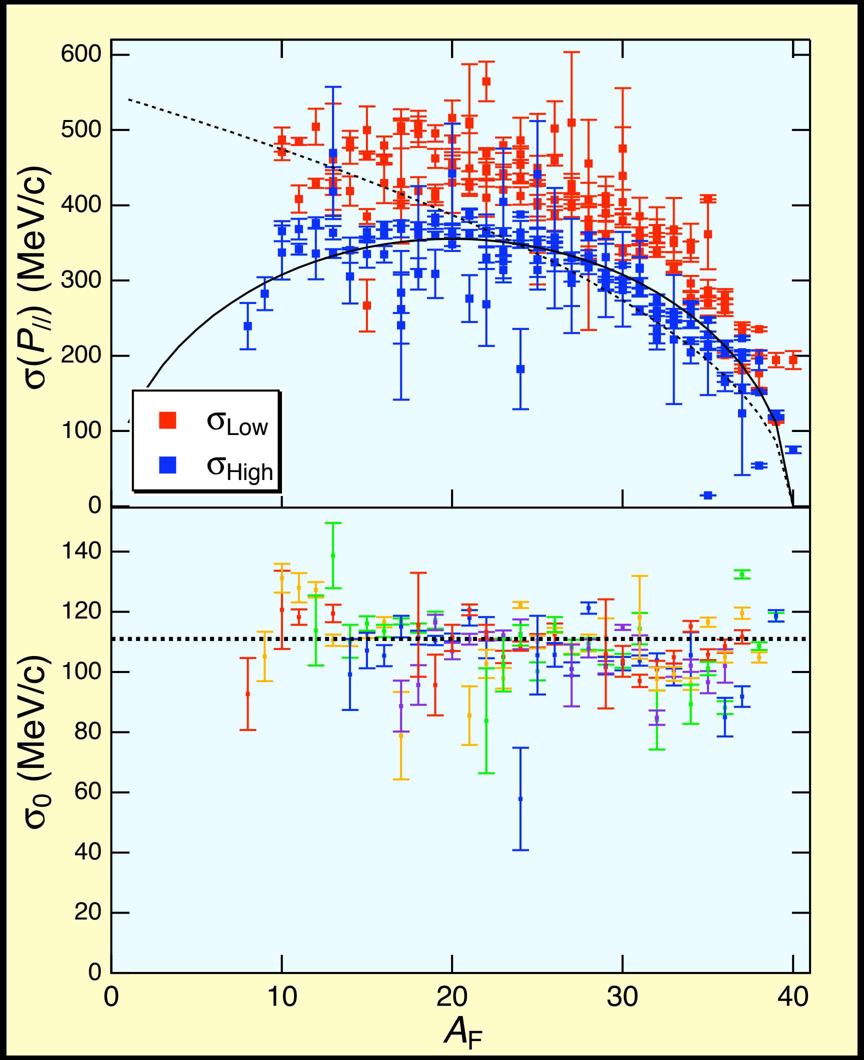


- $^{84}Kr+^{12}C$



Reduced width : σ_0

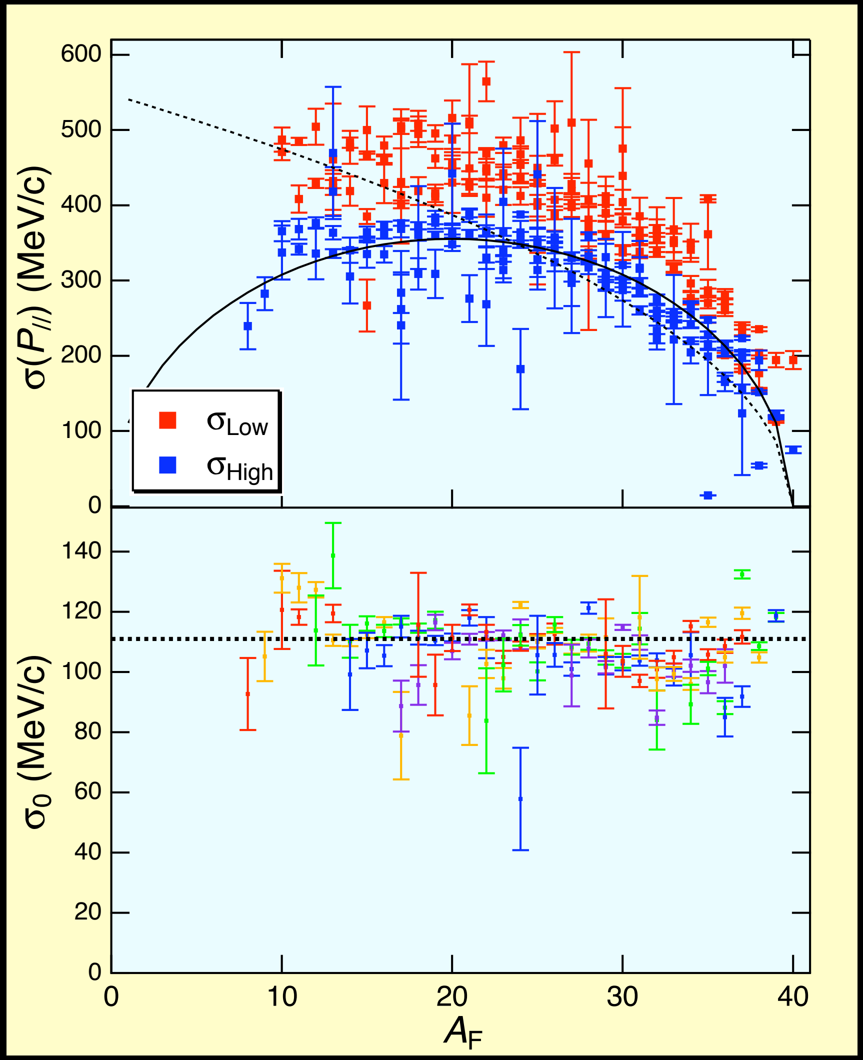
- $^{40}Ar + ^{93}Nb \rightarrow {}^{A}Z$



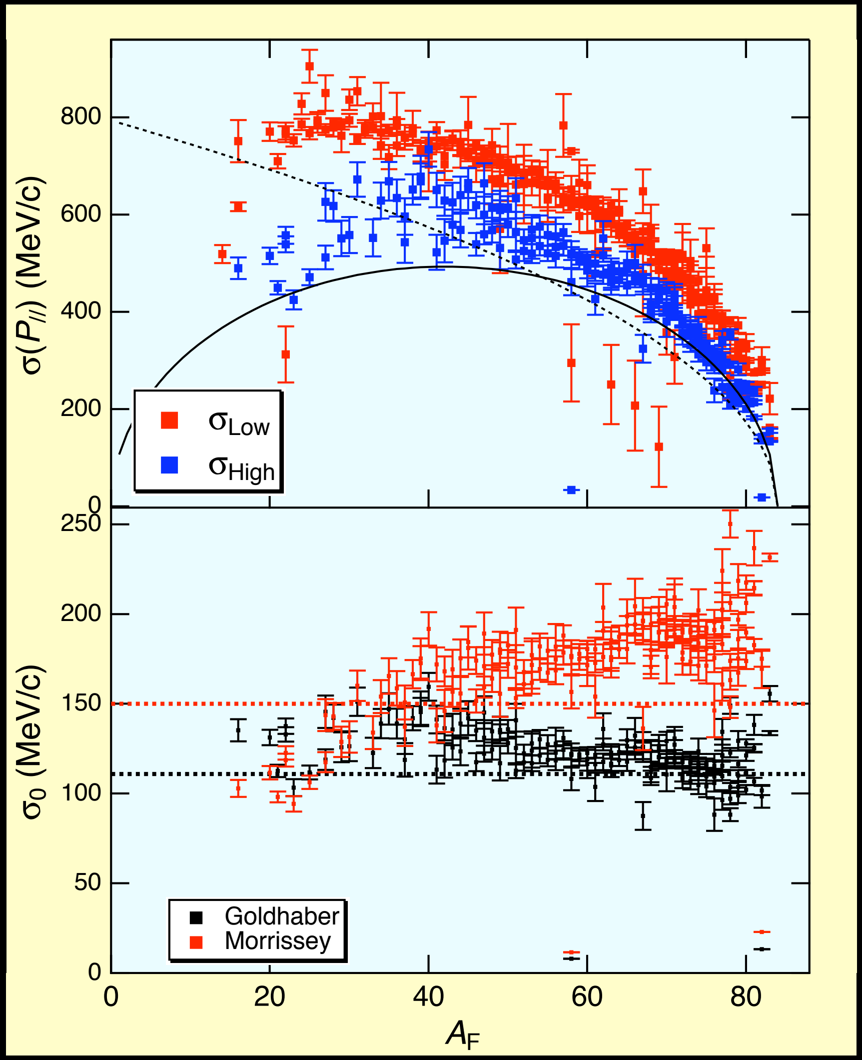
- GH formulation is valid for σ_{High}.
- σ_o obtained from σ_{High} is ~ 110 MeV/c.

Reduced width : σ_0

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



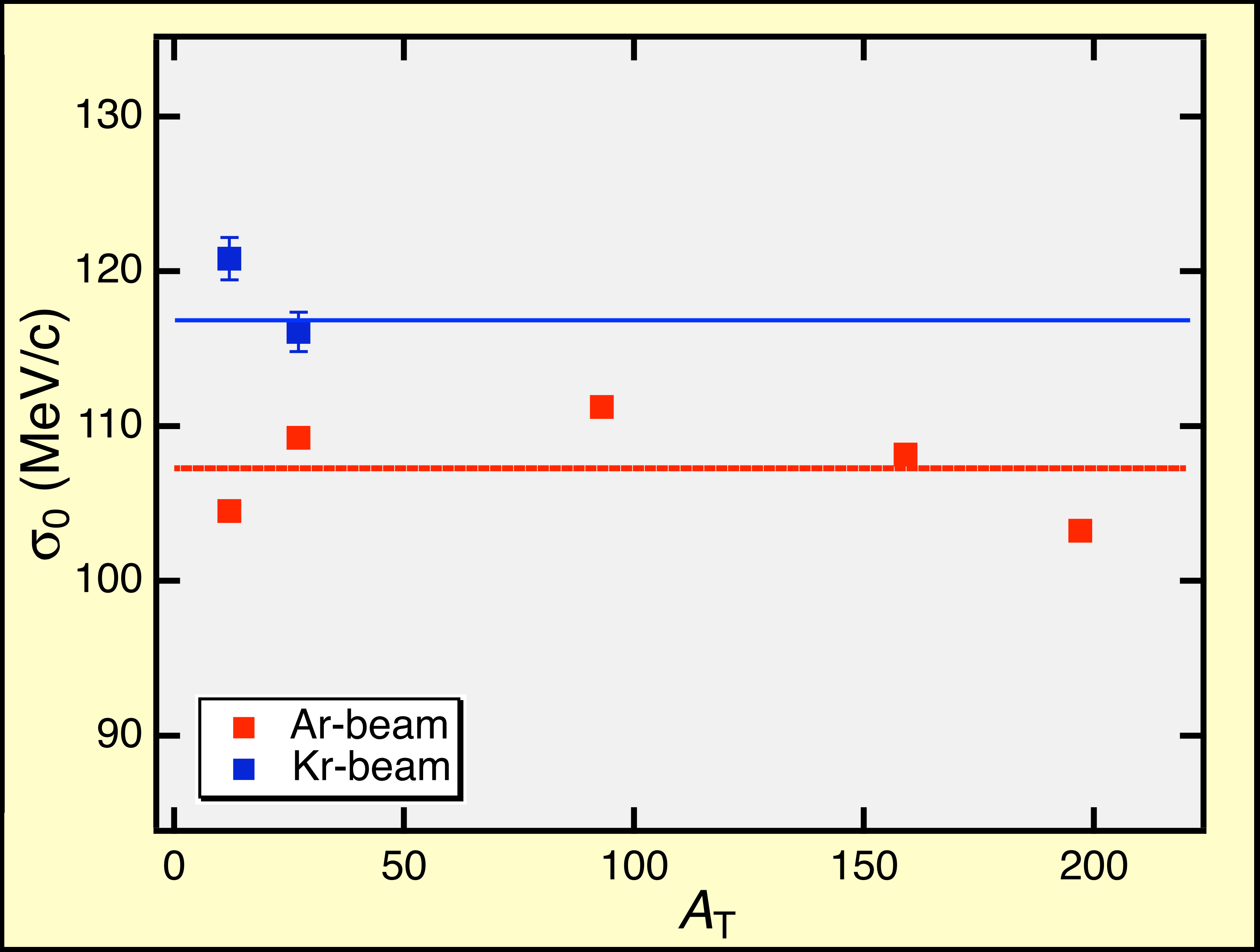
- $^{84}Kr+^{12}C \rightarrow {}^{43}Ca$



- GH formulation is valid for σ_{High}.
- σ_o obtained from σ_{High} is ~ 110 MeV/c.
- GH formulation is valid only for heavy PLFs.
- σ_o is slightly larger than that for Ar-beam.

Reduced width : σ_0

- Target dependence

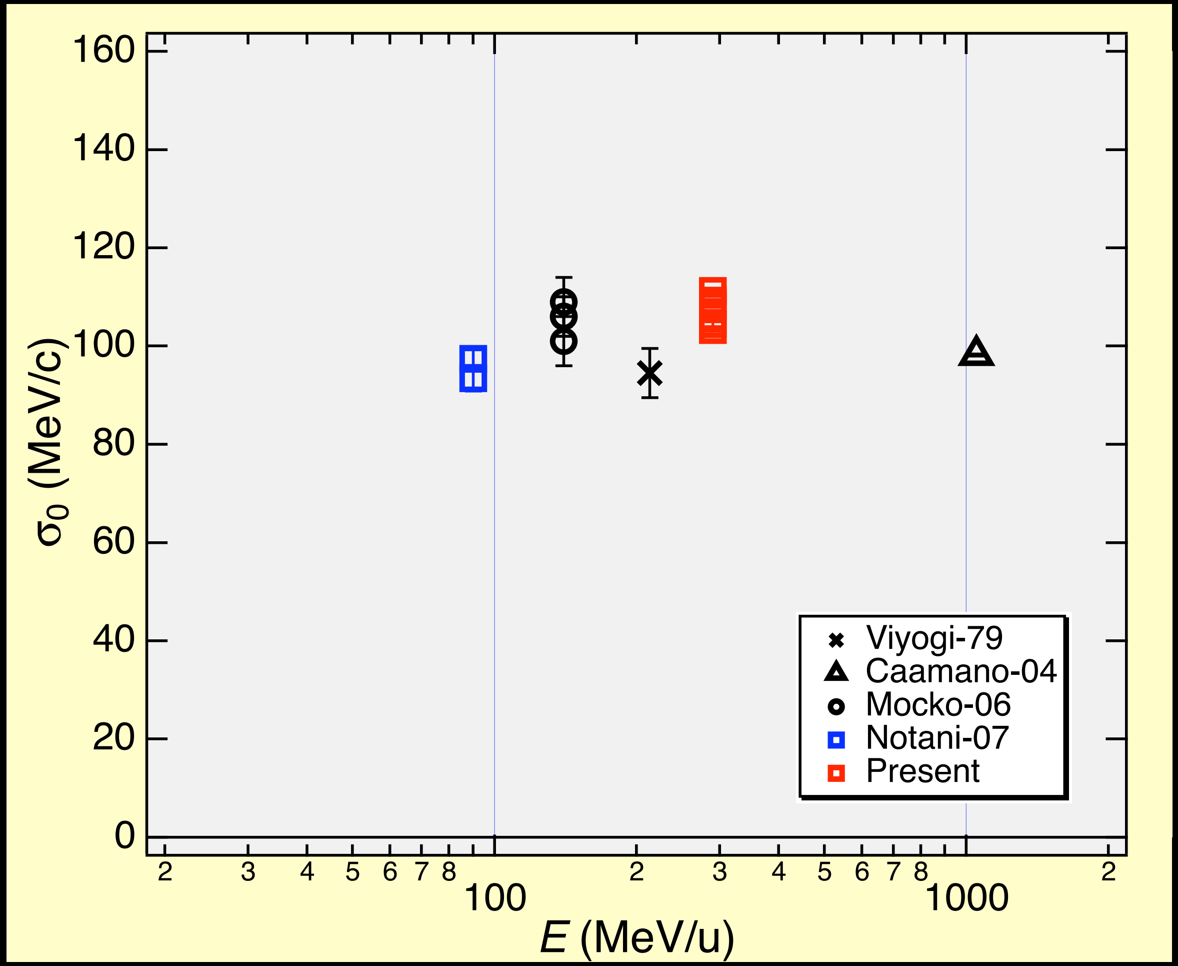


- Small target dependence
- σ_0(Kr) is larger than σ_0(Ar).

Reduced width : σ_0

- *E* dependence

Ar-beam

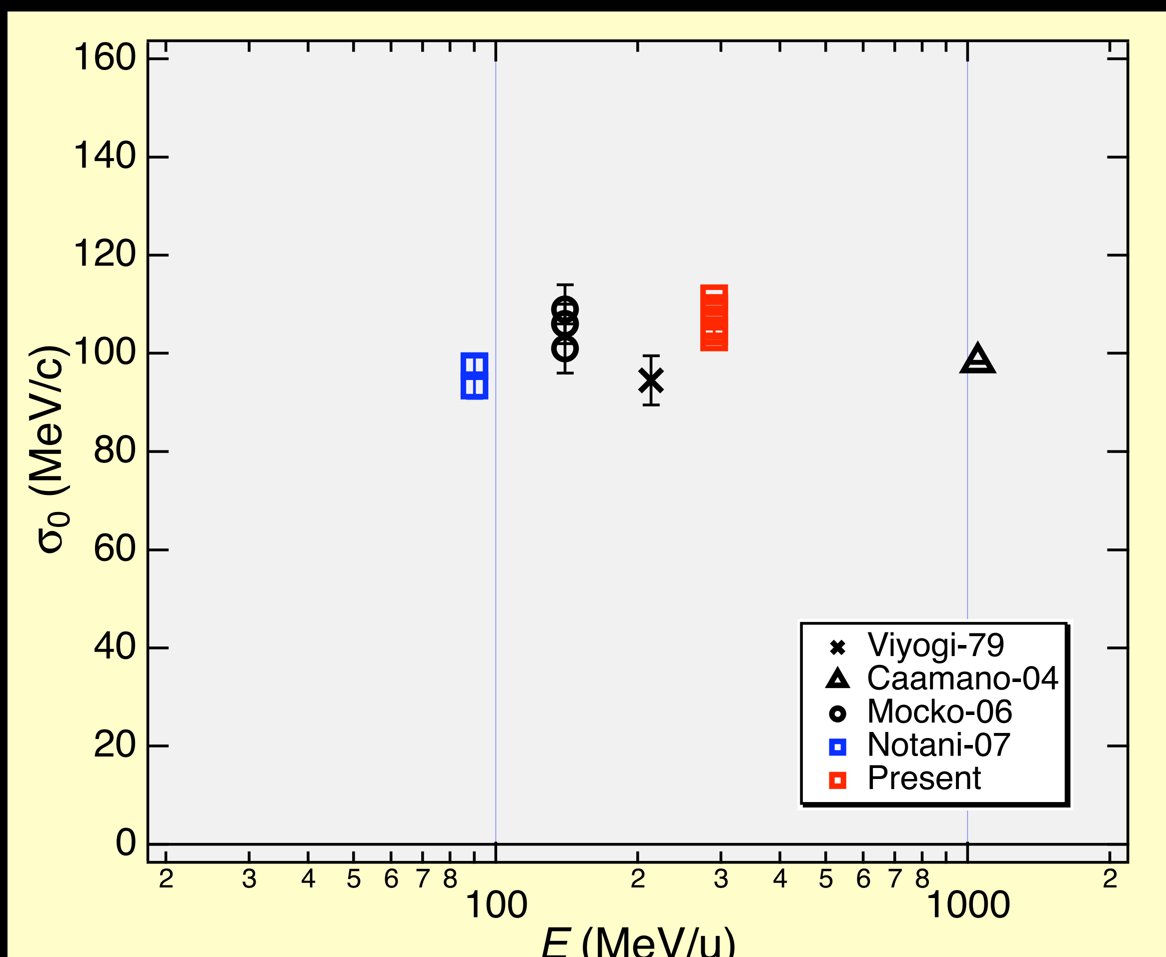


- σ_0 is constant at $E = 90$~1000 MeV/u.

Reduced width : σ_0

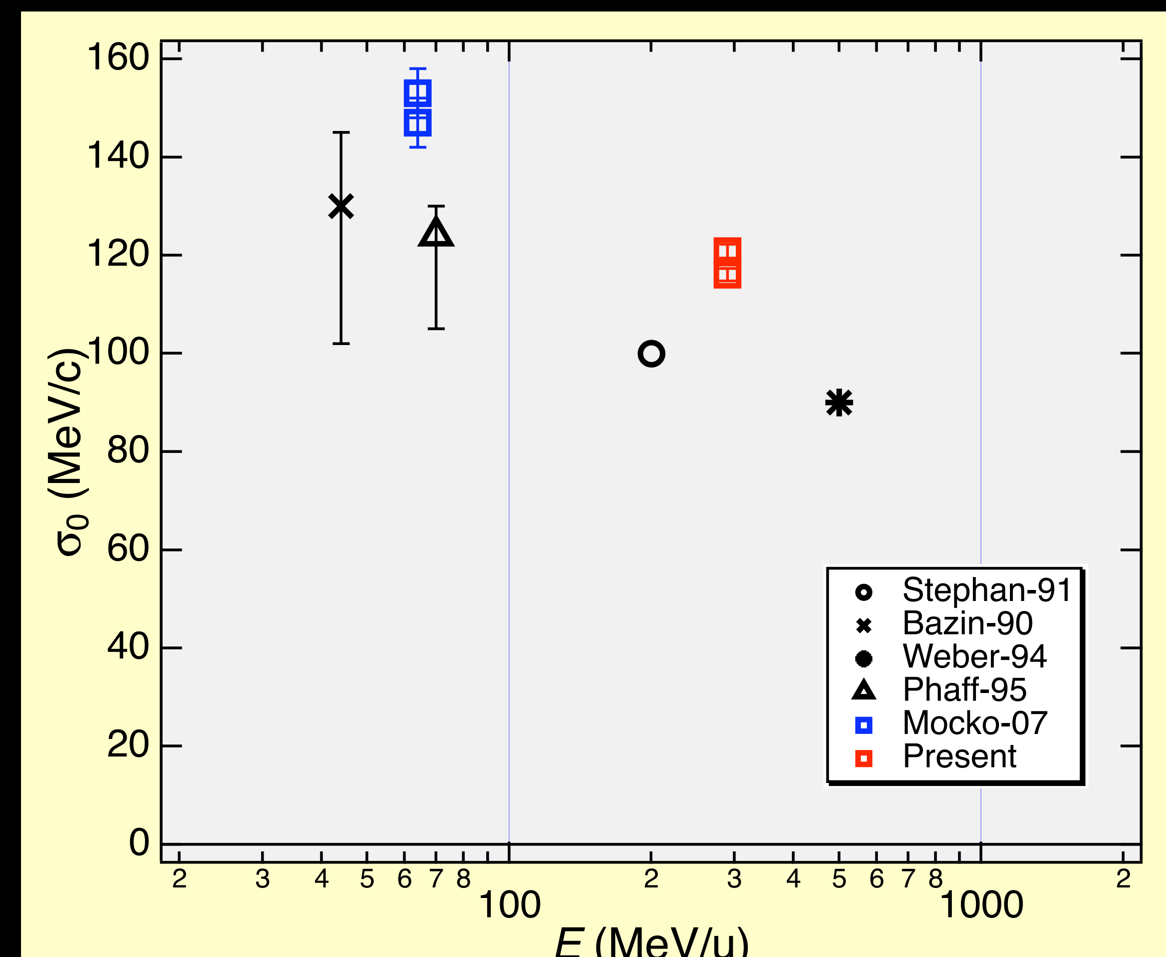
- *E* dependence

Ar-beam



- σ_0 is constant at $E = 90 \sim 1000$ MeV/u.

Kr-beam

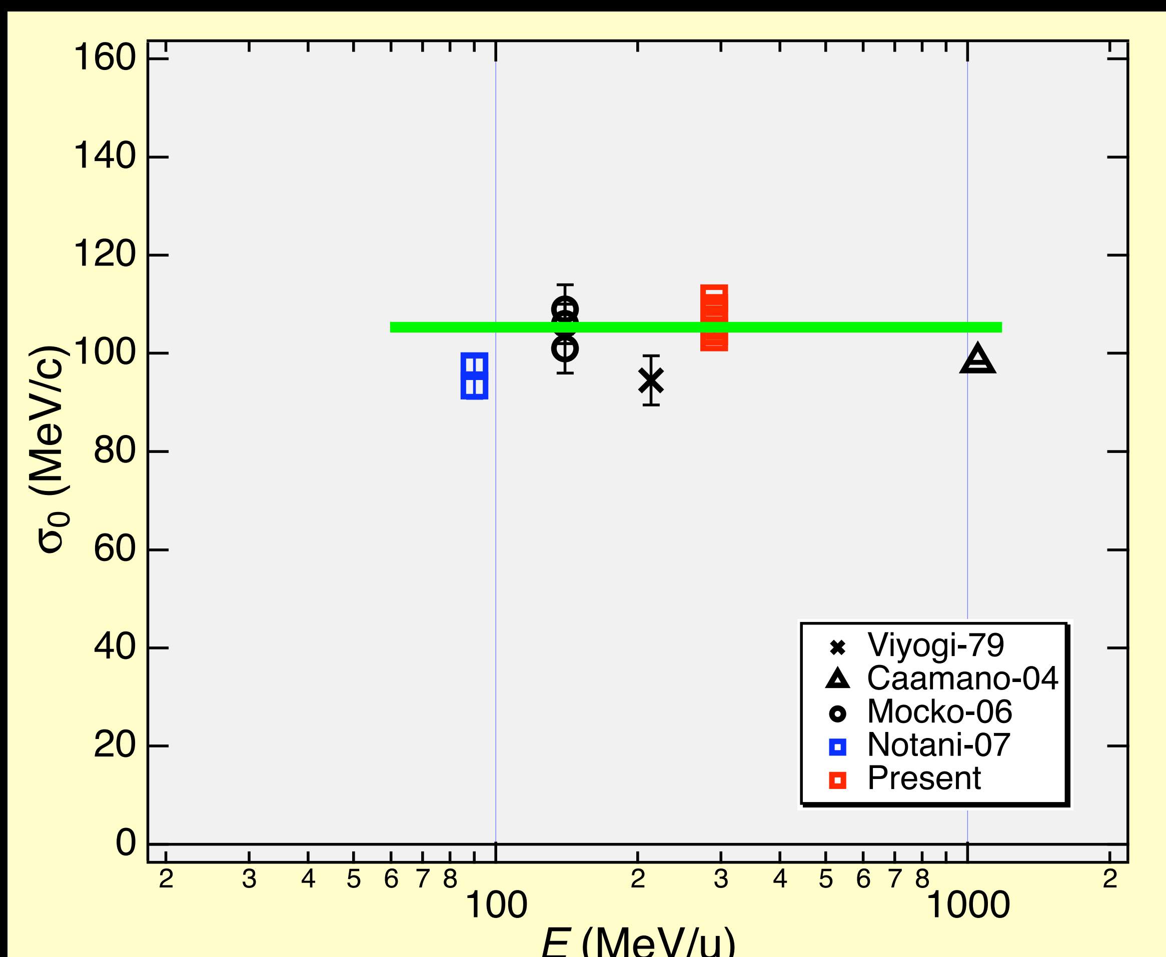


- σ_0 decreases at $E = 40 \sim 500$ MeV/u.
- Recent results are larger than previous ones.

Reduced width : σ_0

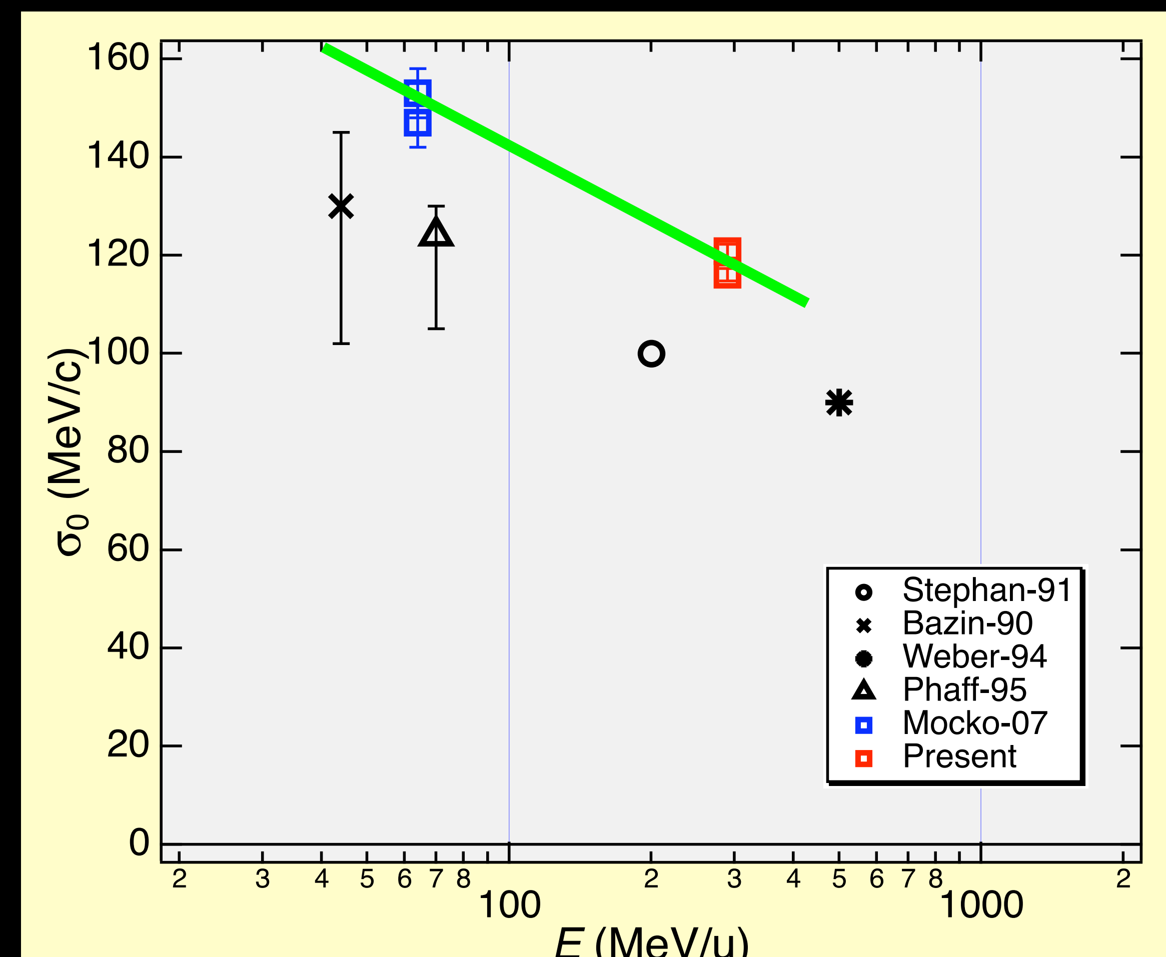
- *E* dependence

Ar-beam



- σ_0 is constant at E = 90~1000 MeV/u.

Kr-beam



- σ_0 decreases at E = 40 ~ 500 MeV/u.
- Recent results are larger than previous ones.

Parametrization of σ_0

- Based on observed systematics

Formulation proposed by Tripathi

$$\sigma_{0,\mathrm{exp.}} = \left(1 + \frac{E_\mathrm{C}}{4T_\mathrm{lab.}}\right)\left(70 + \frac{2}{3}A_\mathrm{P}\right) \quad \mathrm{MeV/c}$$

$$E_\mathrm{C} = \frac{1.44 Z_\mathrm{P} Z_\mathrm{T}}{r_\mathrm{P} + r_\mathrm{T}}, \; r_\mathrm{i} = \sqrt{\frac{5}{3}}(r_\mathrm{i})_\mathrm{rms}$$

$T_\mathrm{lab.}$: Beam E in MeV/u

Tripathi et al., Phys. Rev. C 49 (1994) 2237.

^{12}C, ^{16}O	(1, 2 GeV/u)	: Greiner	@1975
^{139}La	(1.2 GeV/u)	: Brady	@1988
^{40}Ar	(213 MeV/u)	: Viyogi	@1979
^{197}Au	(1 GeV/u)	: Dreute	@1991

Parametrization of σ_0

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Formulation proposed by Tripathi

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$$E_C = \frac{1.44 Z_P Z_T}{r_P + r_T}, \quad r_1 = \sqrt{\frac{5}{3}}(r_1)_{\mathrm{rms}}$$

$T_{\mathrm{lab.}}$: Beam E in MeV/u

Tripathi et al., Phys. Rev. C 49 (1994) 2237.

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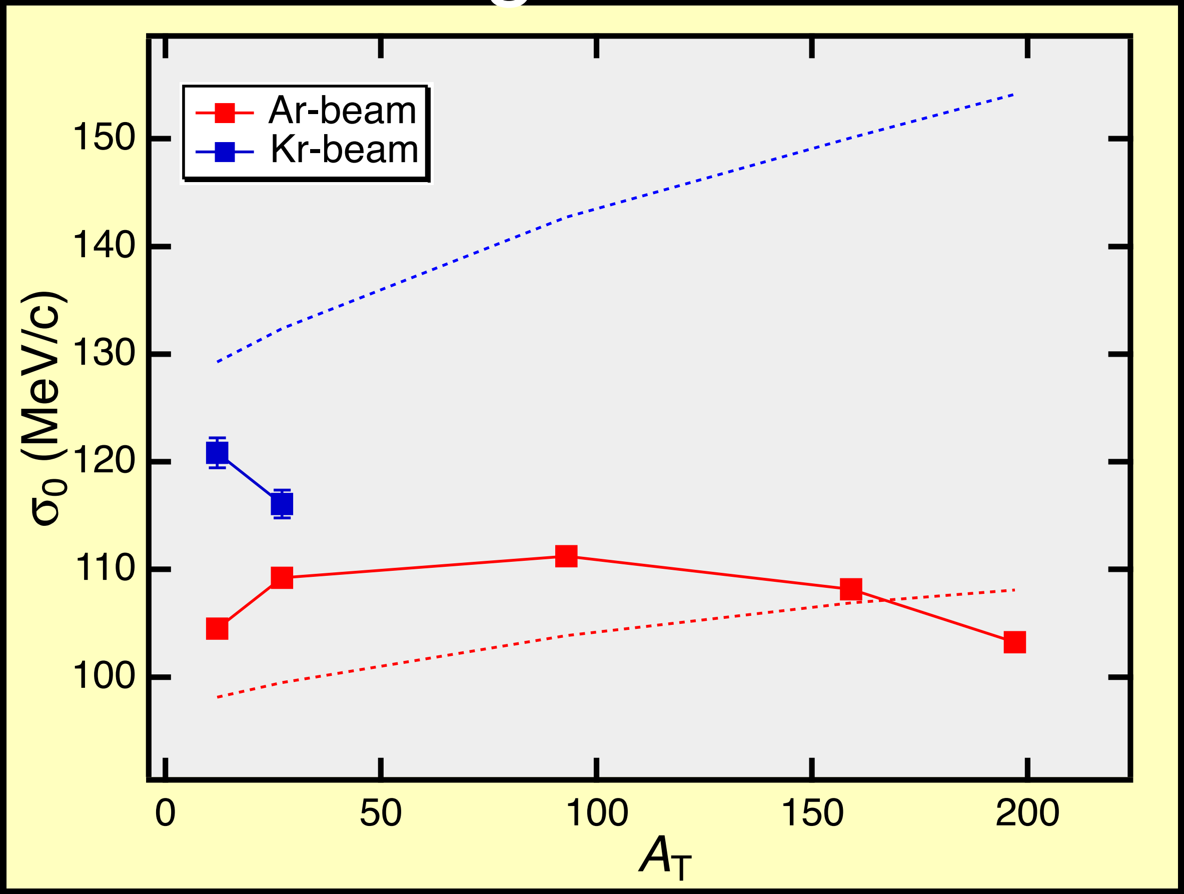
^{40}Ar	(213 MeV/u)	: Viyogi	@1979
^{197}Au	(1 GeV/u)	: Dreute	@1991

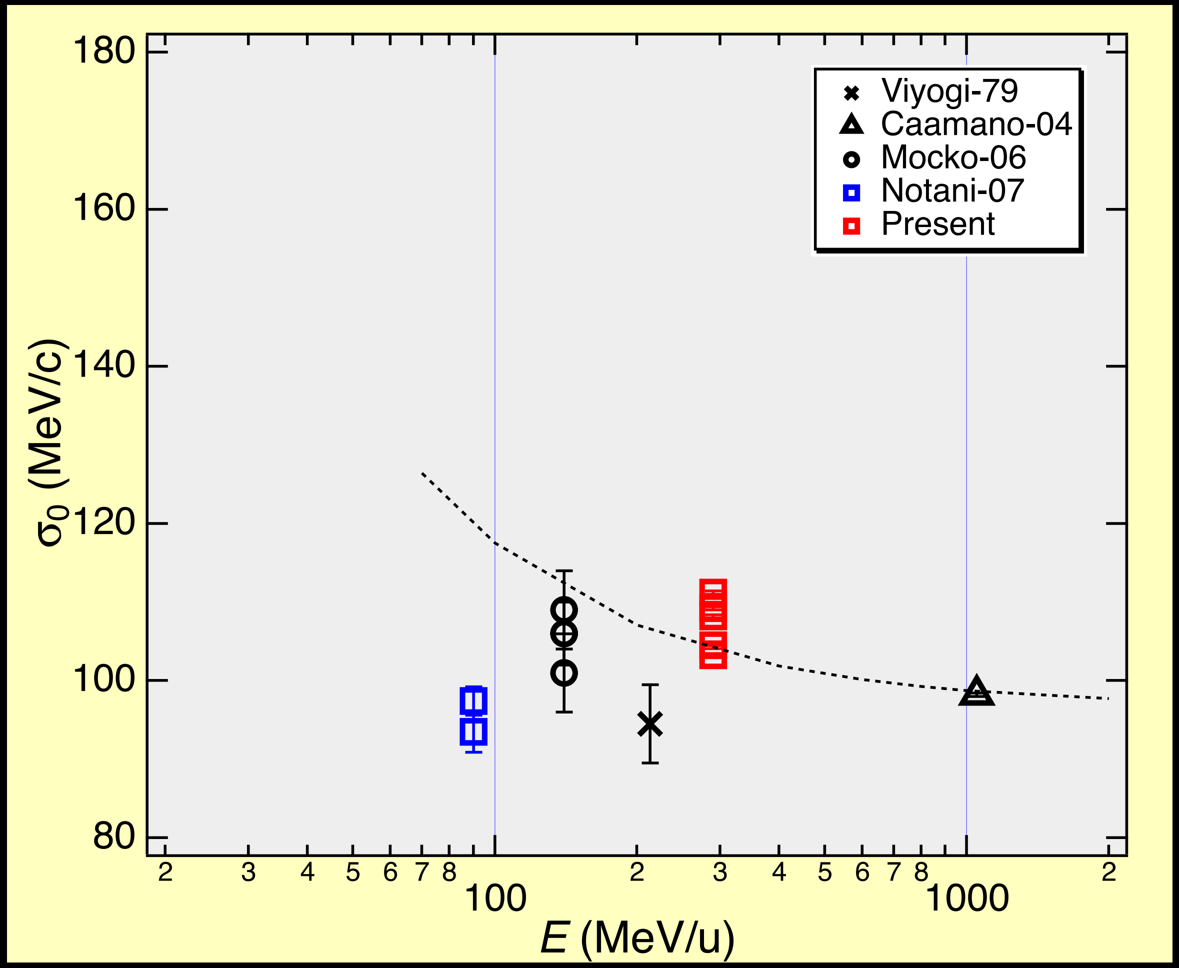
• Target mass



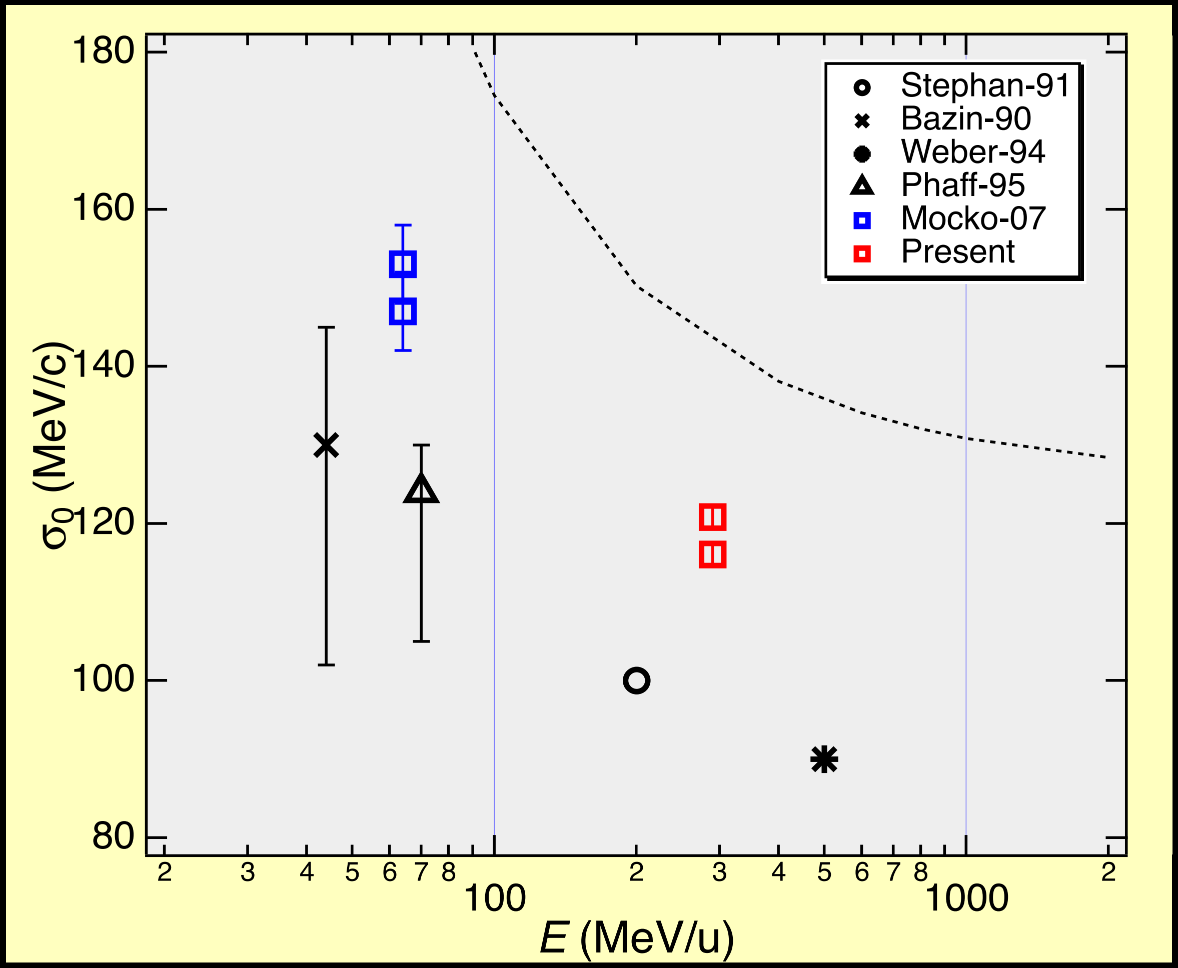
Parametrization of σ_0

- Energy dependence

•Ar

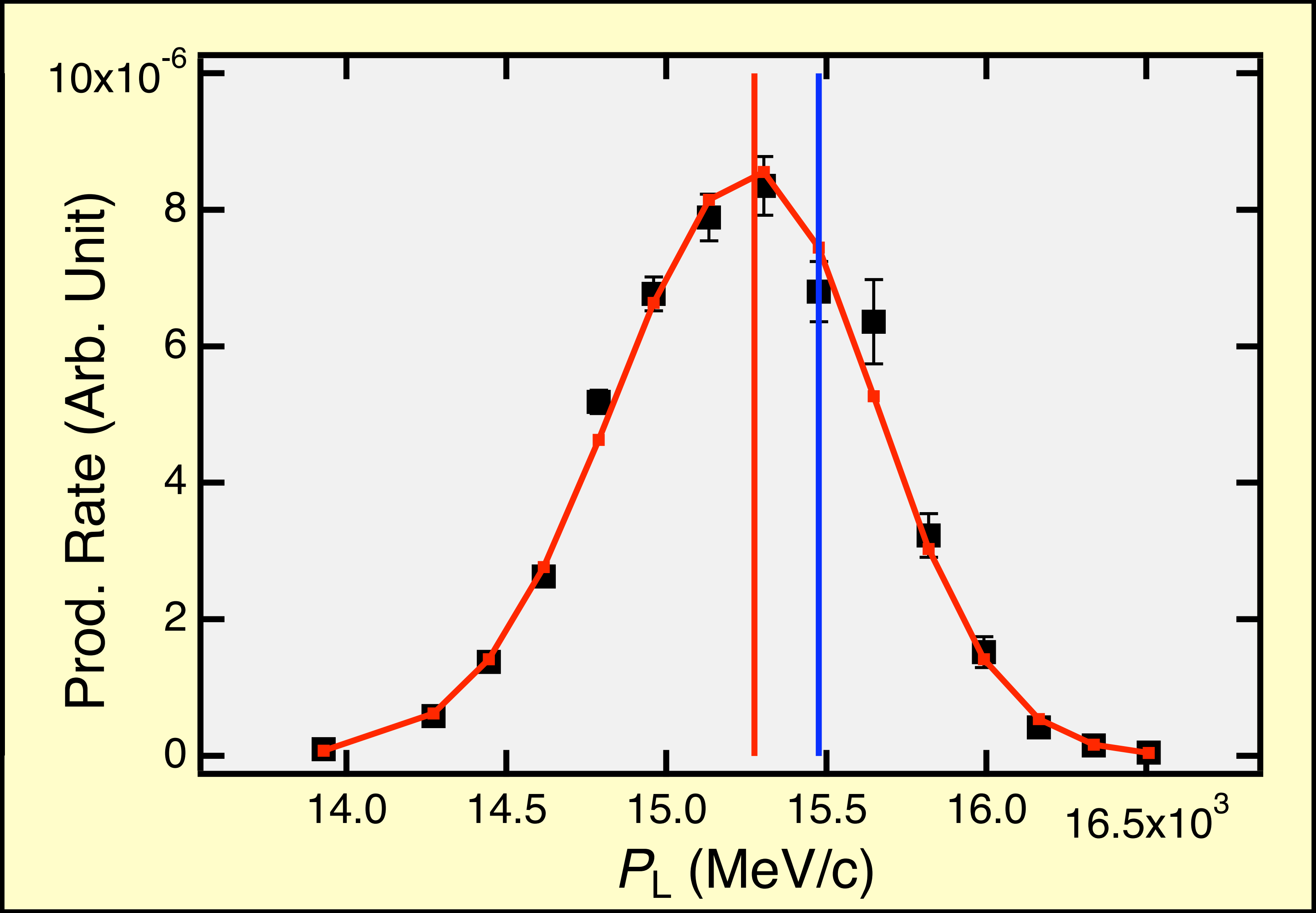


•Kr



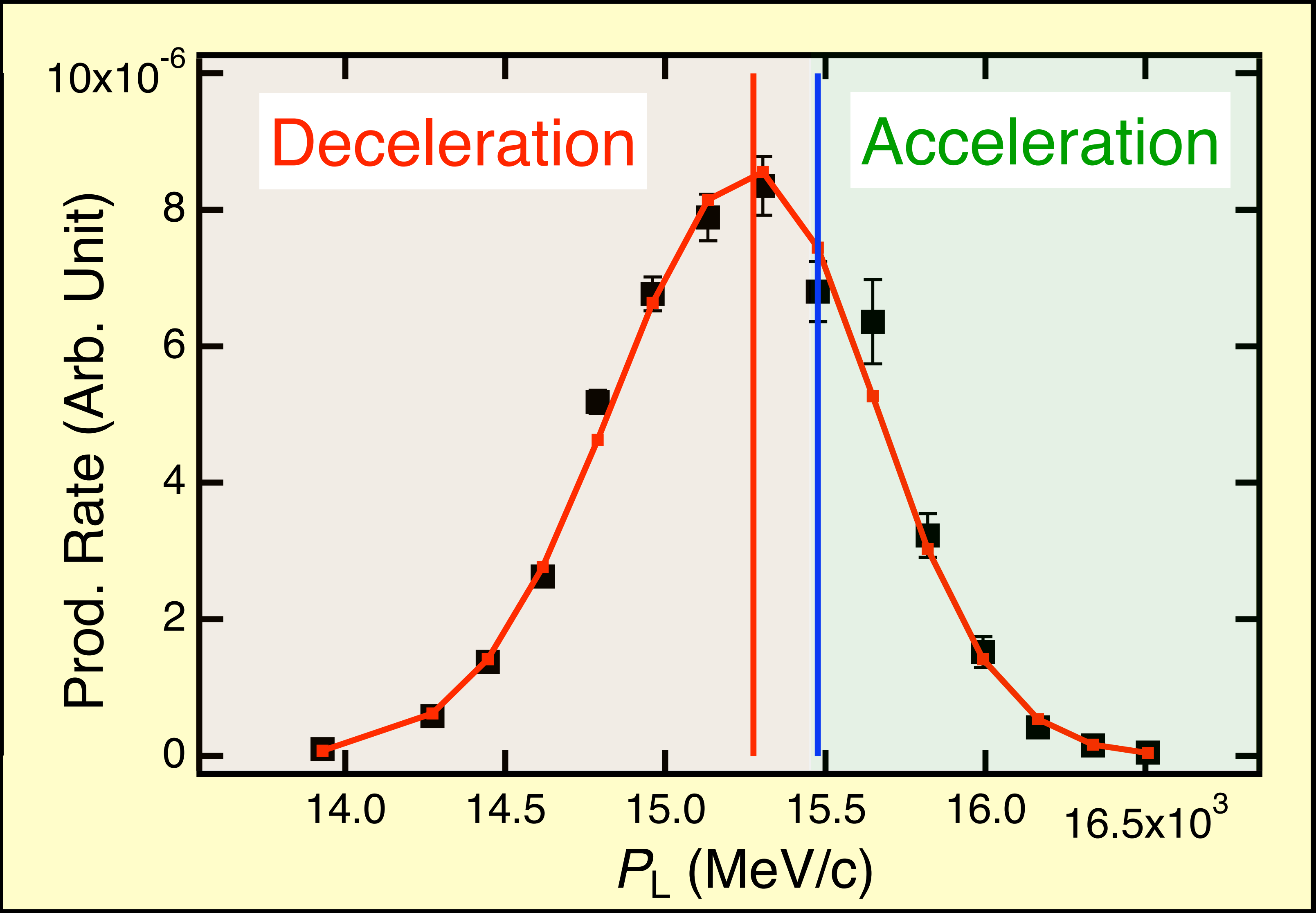
Velocity shift

- $^{40}Ar + ^{93}Nb \rightarrow ^{20}Ne$



Velocity shift

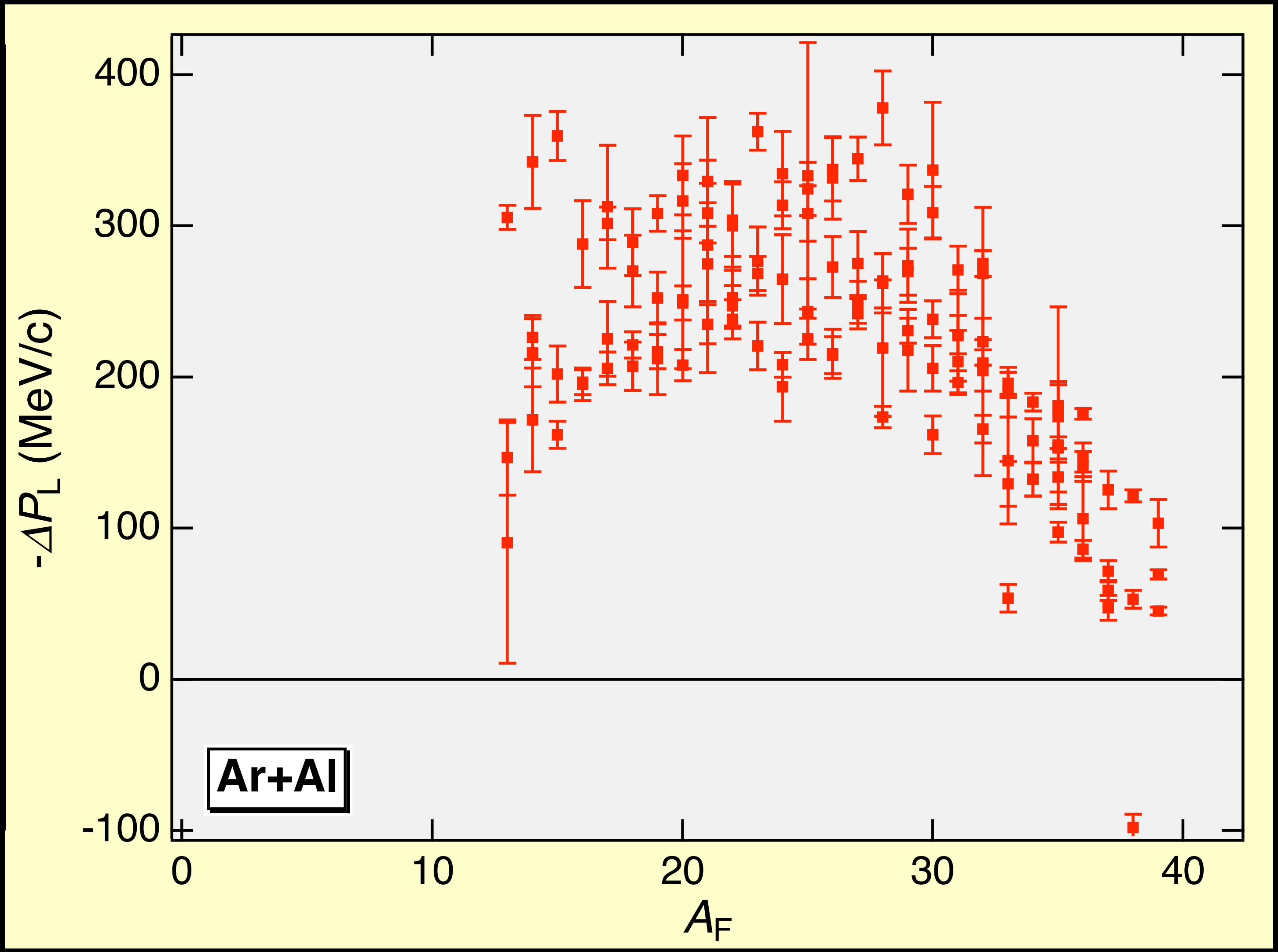
- $^{40}Ar + ^{93}Nb \rightarrow ^{20}Ne$



Velocity shift

- In case of Ar-beam

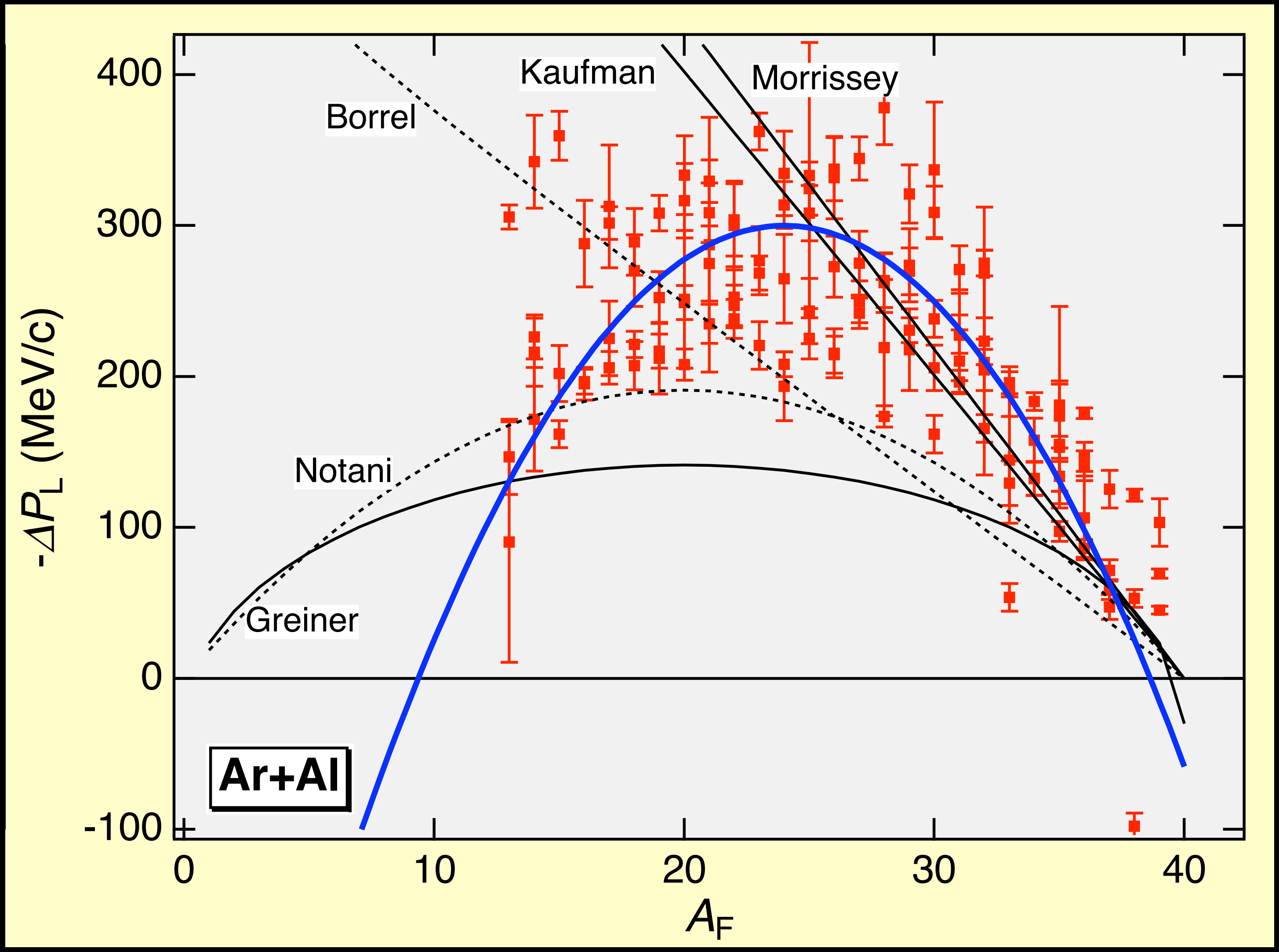
- $^{40}Ar + ^{27}Al \rightarrow {}^{A}Z$



Velocity shift

- In case of Ar-beam

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

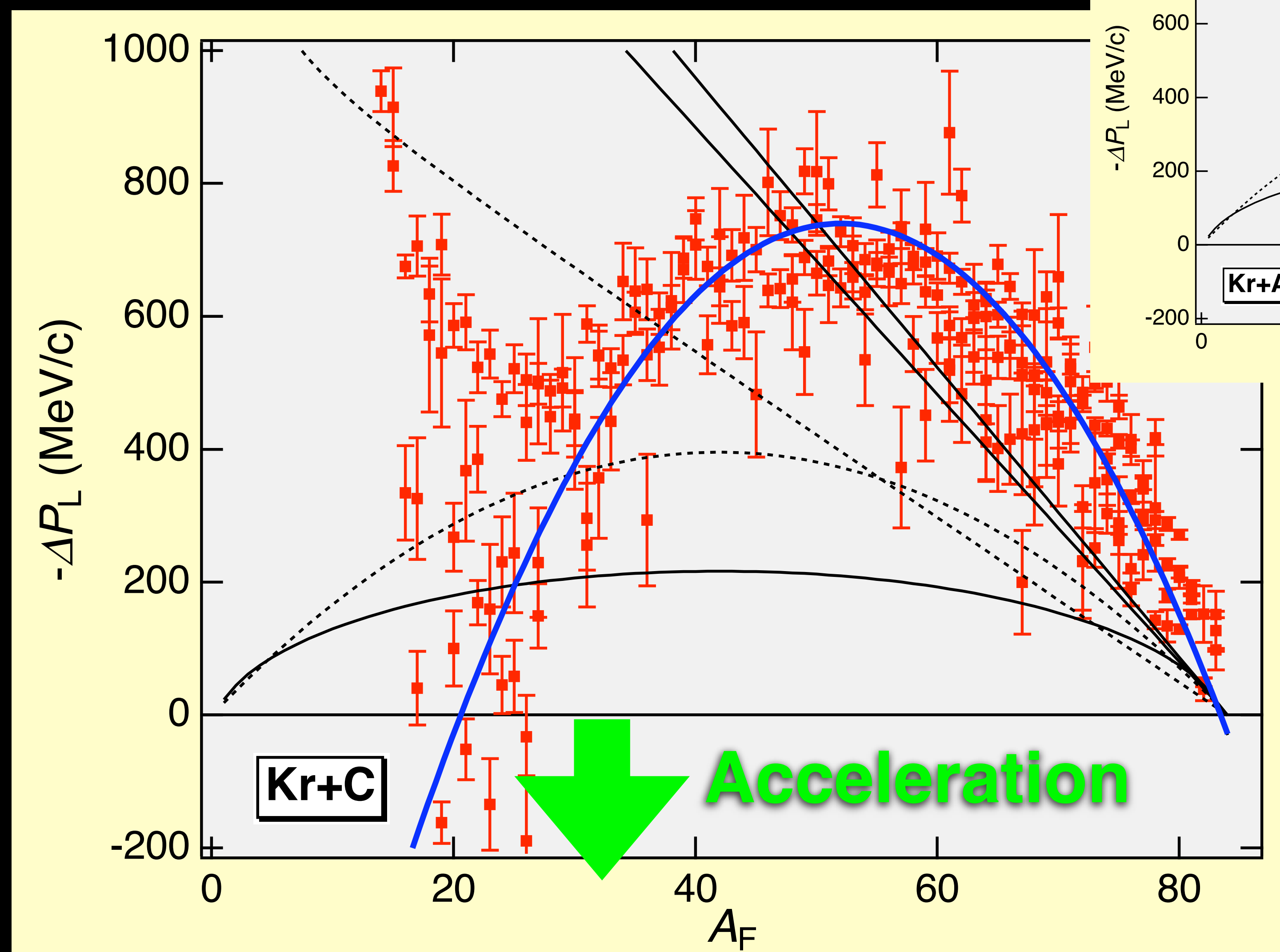


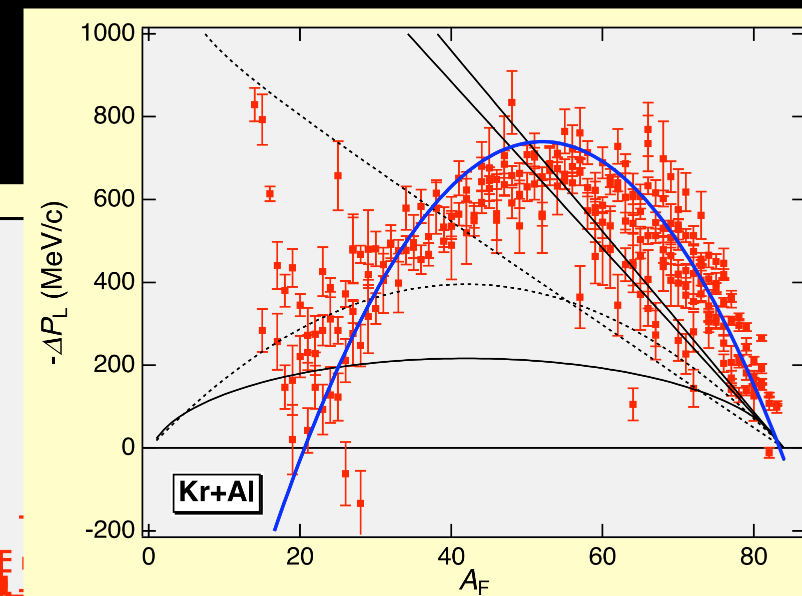
- $-\Delta P_L$ distribution shows parabolic shape and become its maximum 300 MeV/c at $A_F \sim 25$.
- Morrissey/Kaufman formulation is probable for heavier PLFs.

Velocity shift

- Kr-beam

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



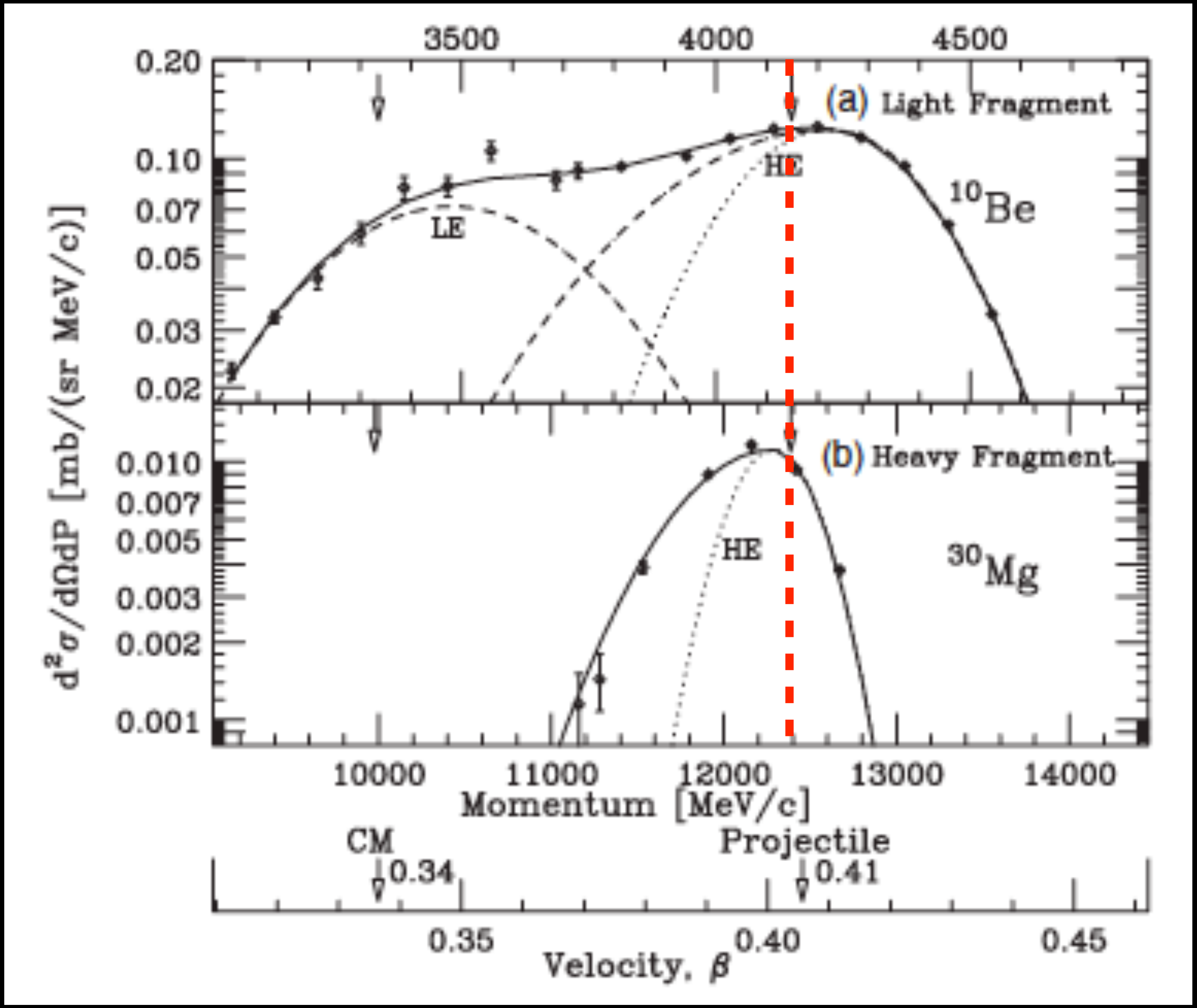


- $-\Delta P_L$ distribution shows parabolic shape and become its maximum 700 MeV/c at $A_F \sim 50$.
- Morrissey/Kaufman formulation is probable for heavier PLFs.

Acceleration effect

- at E = 90 MeV/u

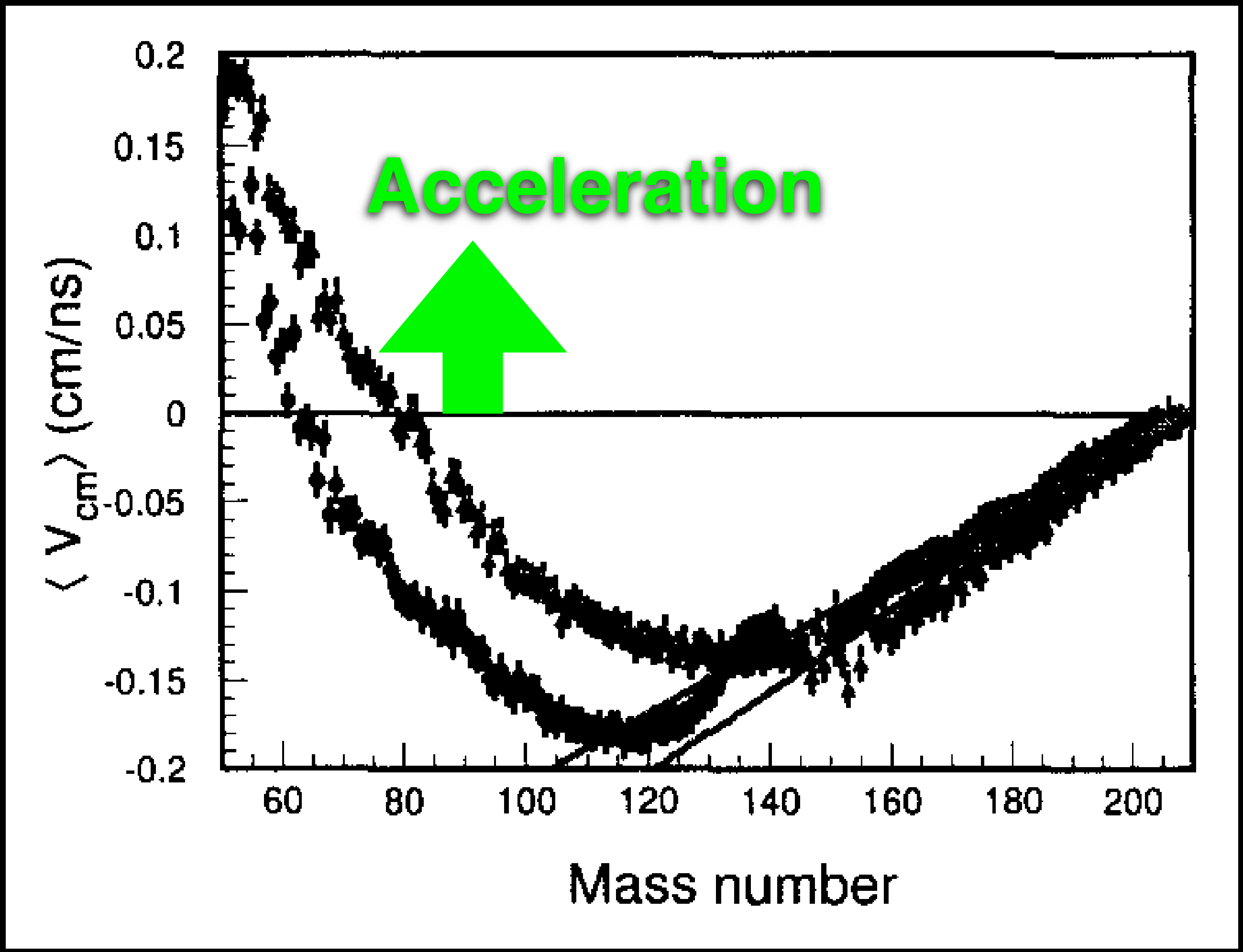
- $^{40}Ar + ^{9}Be \rightarrow ^{9}Be$



Acceleration effect

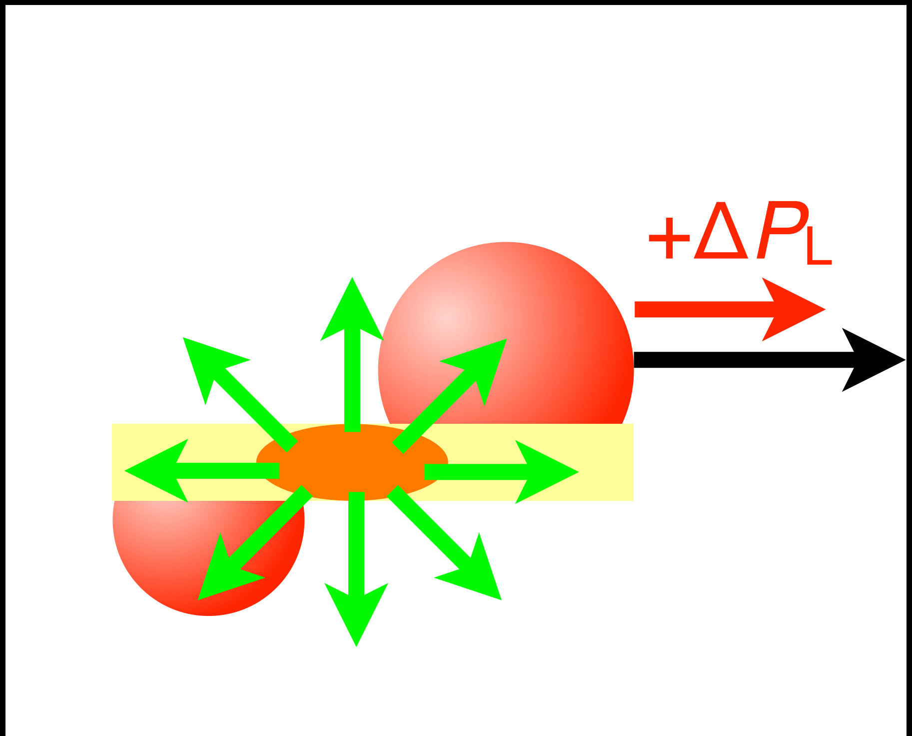
- Tool to investigate EOS

^{208}Pb (0.5, 1.0 GeV/u) + Ti



J. Benlliure et al., NP A 734 (2004) 609.

Participant blast pushes spectator.

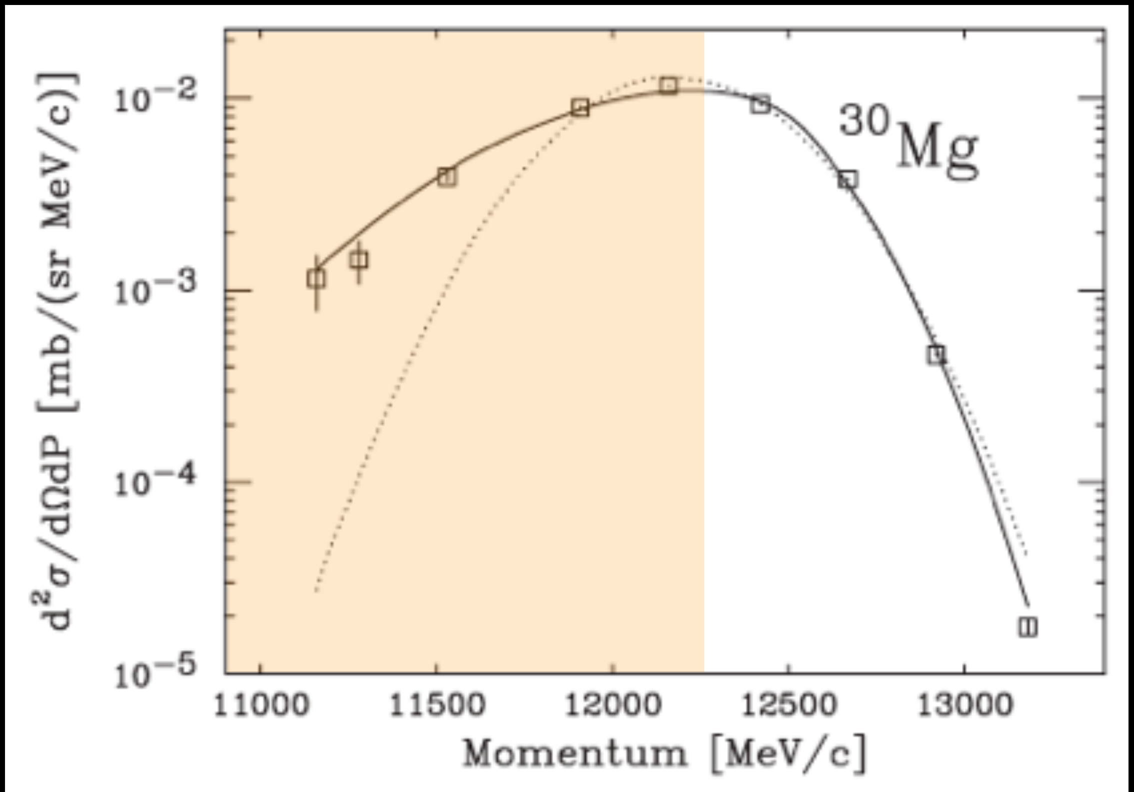


L. Shi et al., PR C 64 (2001) 034601.

P_T distribution

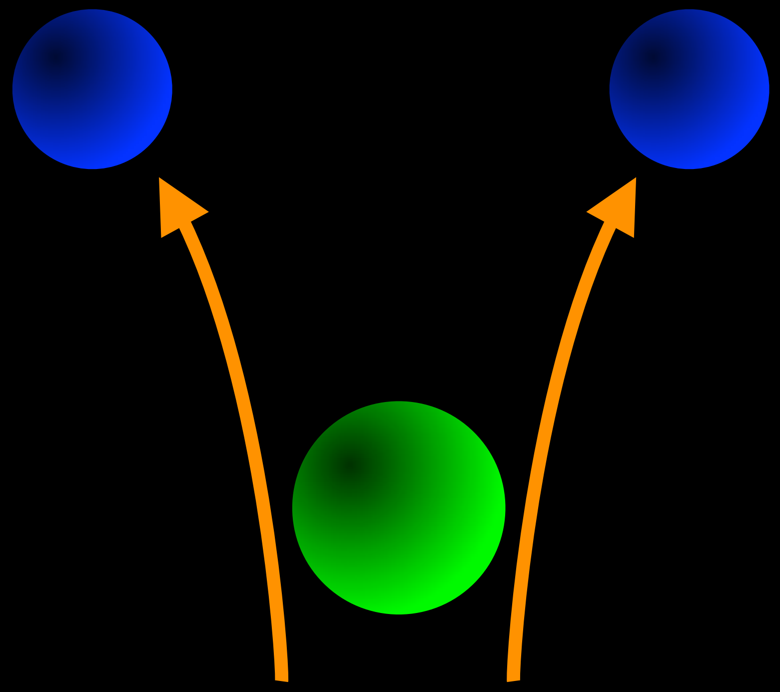
P_T distribution

1) Contamination of another process



Dispersion would depend on P_L.

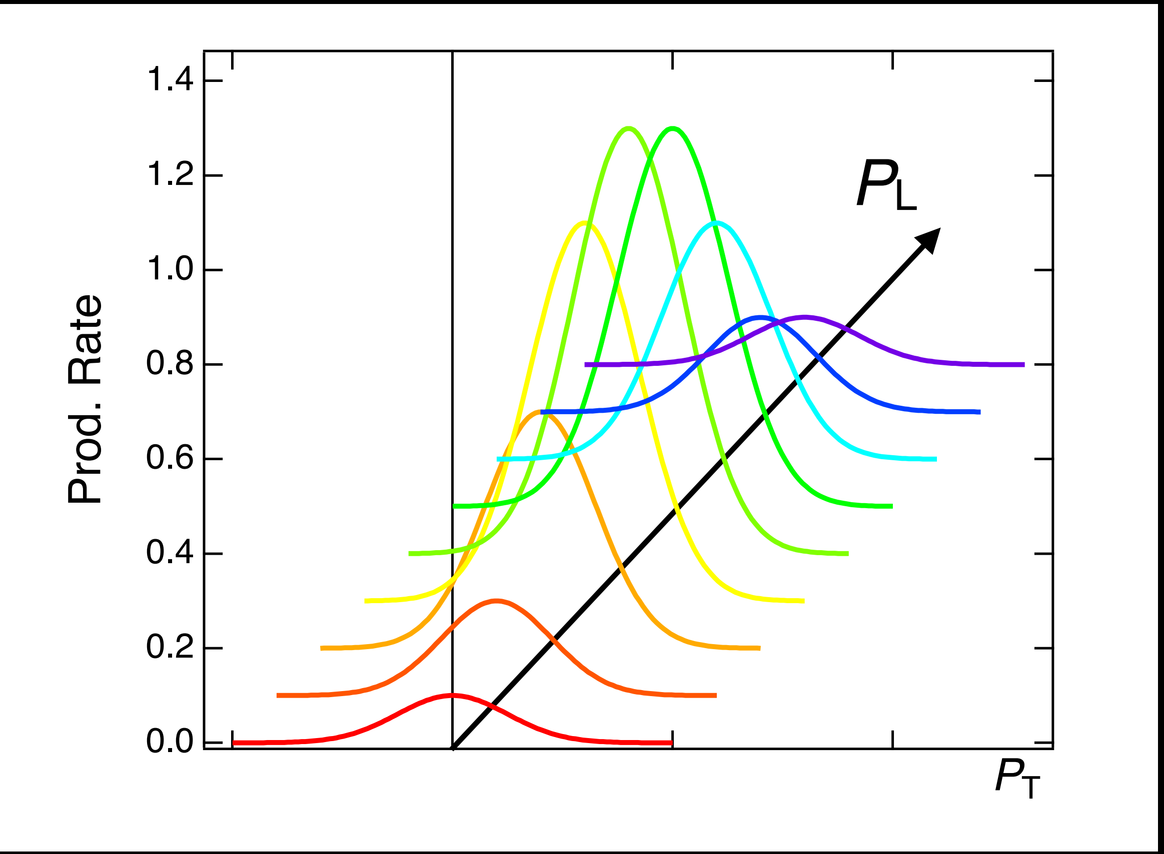
2) Orbital deflection with heavy target

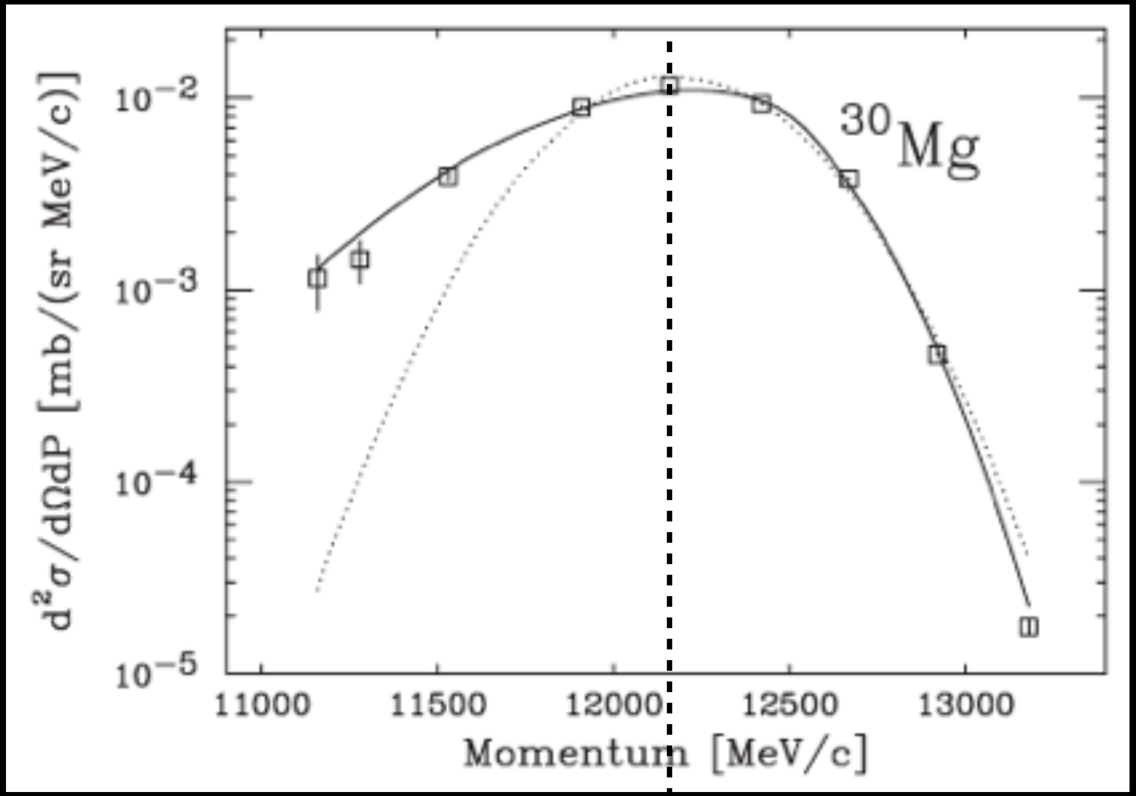


Off-centered P_T dist.

Meas. of P_T distribution

- as a function of P_L

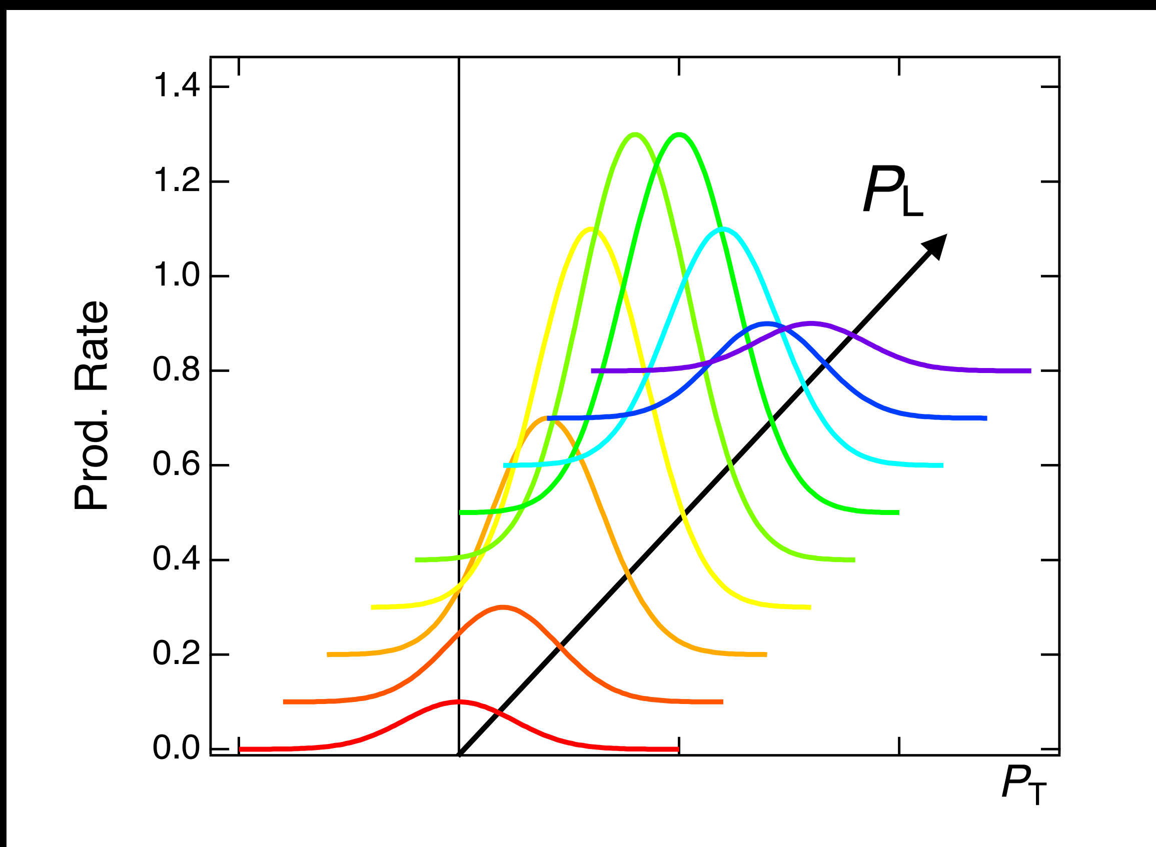




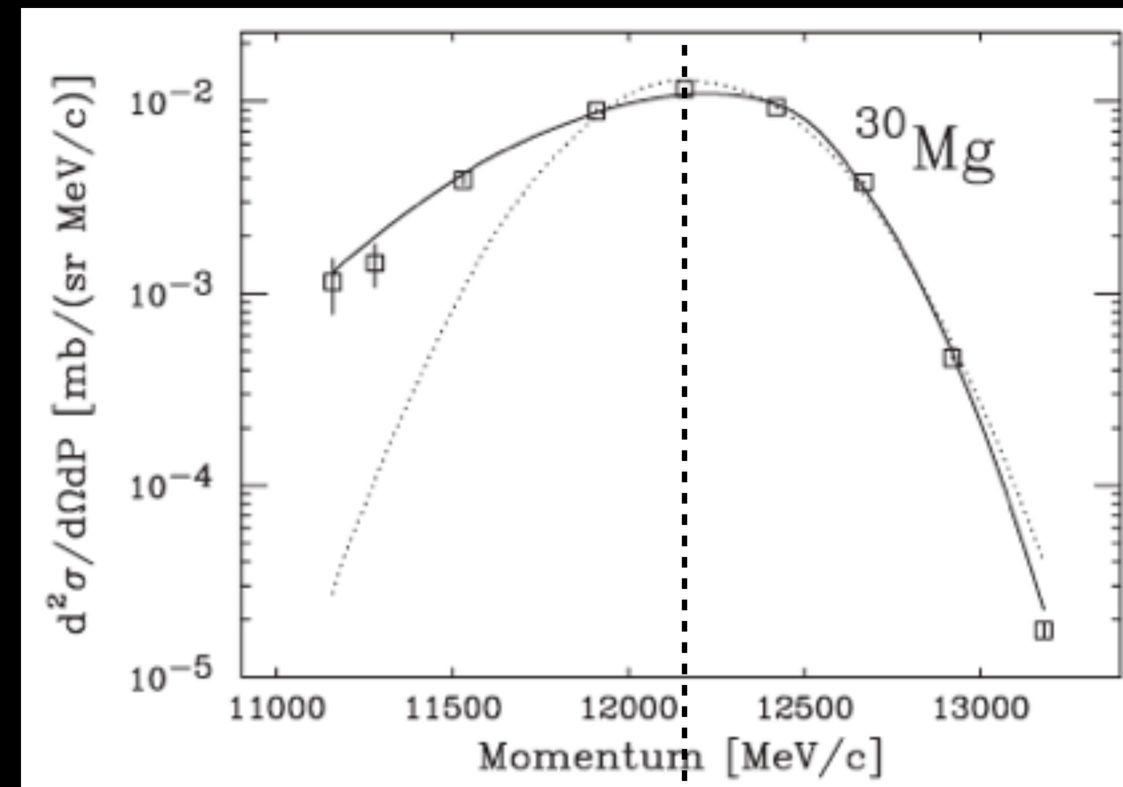
Dispersion (σ_T) observed at each P_L.

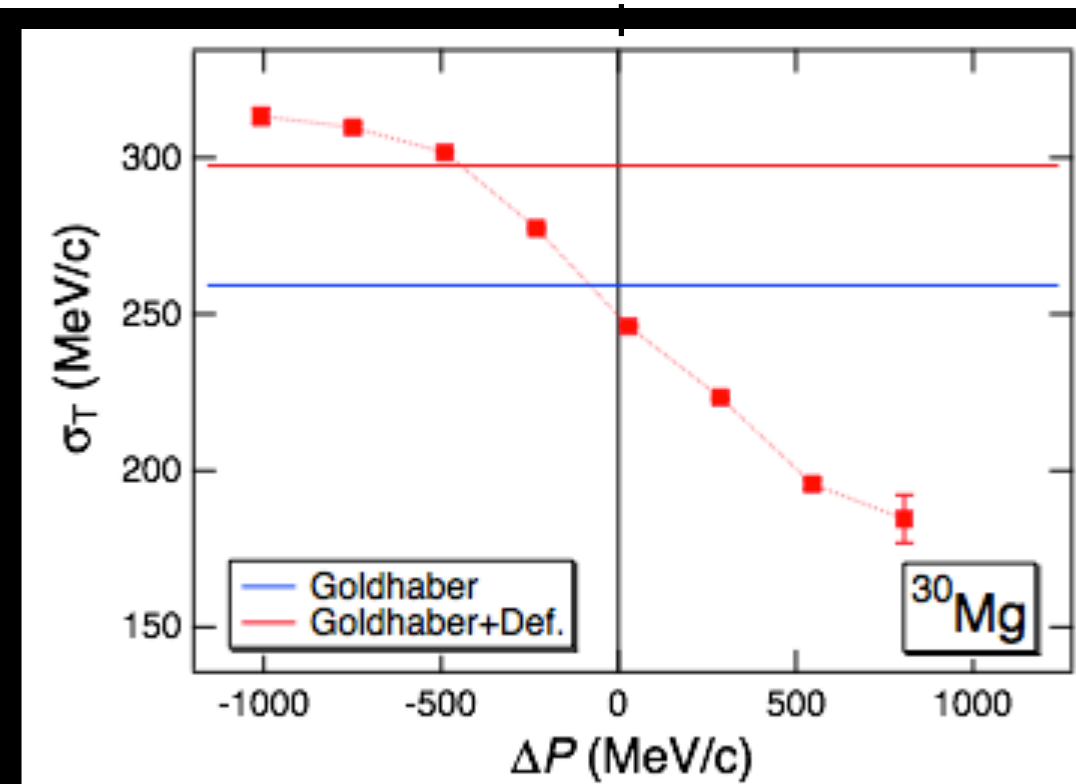
Meas. of P_T distribution

- as a function of P_L



Dispersion (σ_T) observed at each P_L.

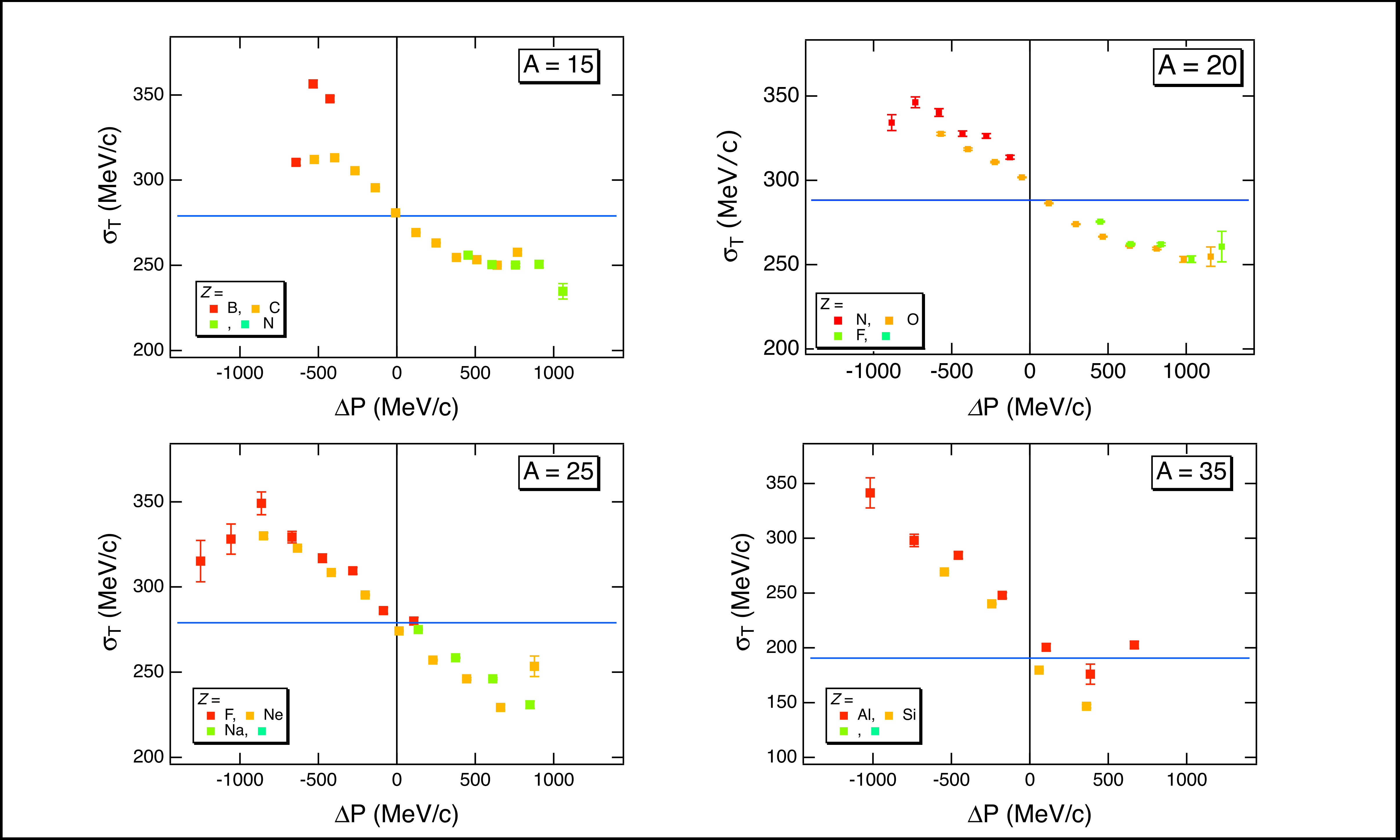




Correlation between σ_T and P_L

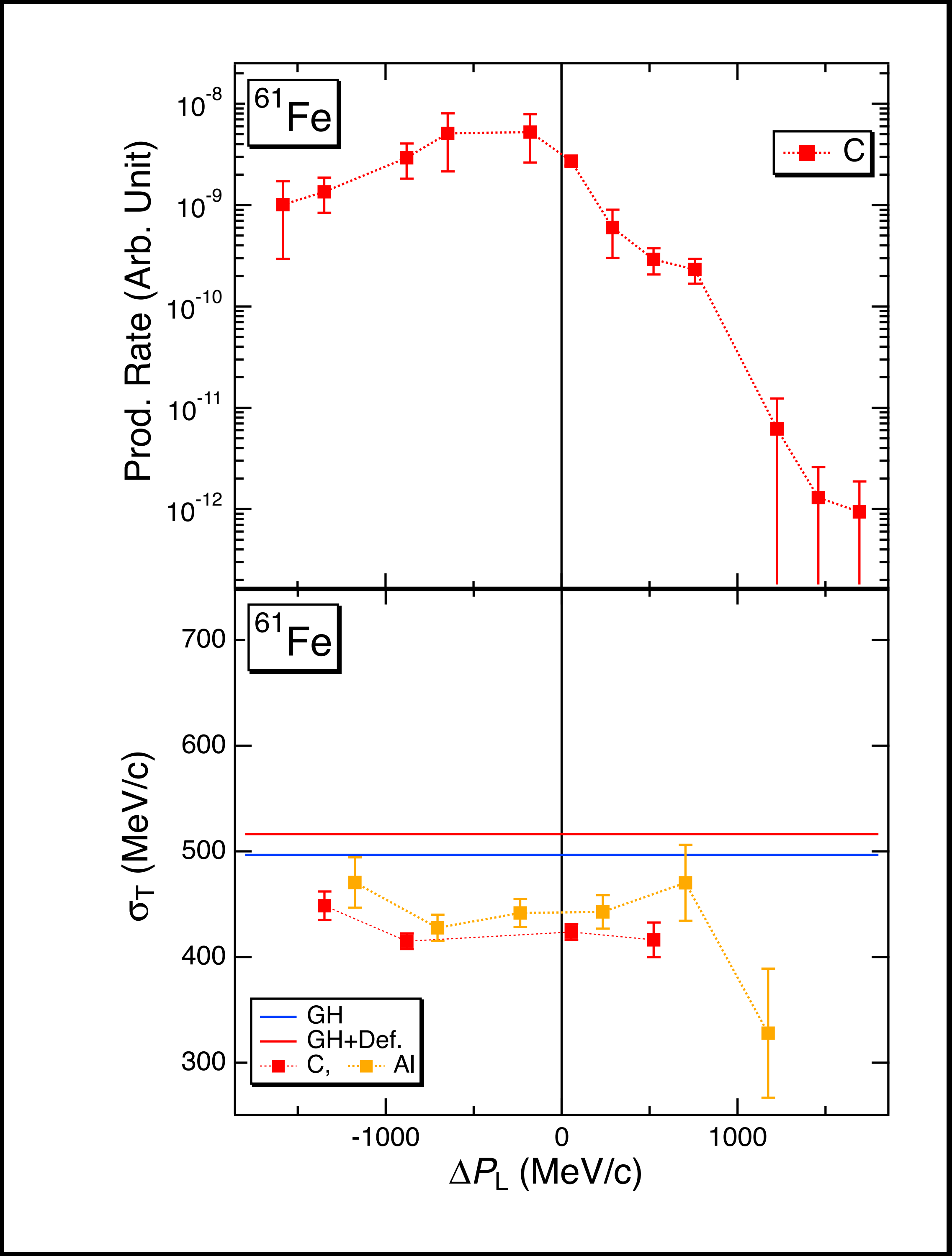
- $^{40}Ar+^{9}Be$@95 MeV/u

σ_T decrease monotonously.



Correlation between σ_T and P_L

- $^{84}Kr+^{12}C$@290 MeV/u

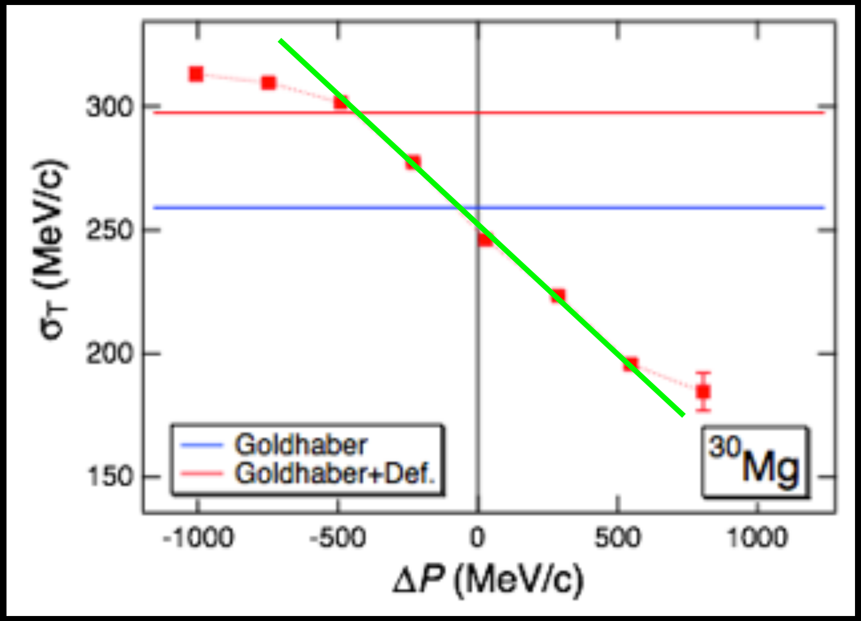


1. σ_T ~ const.

2. $\sigma_T < \sigma_L$

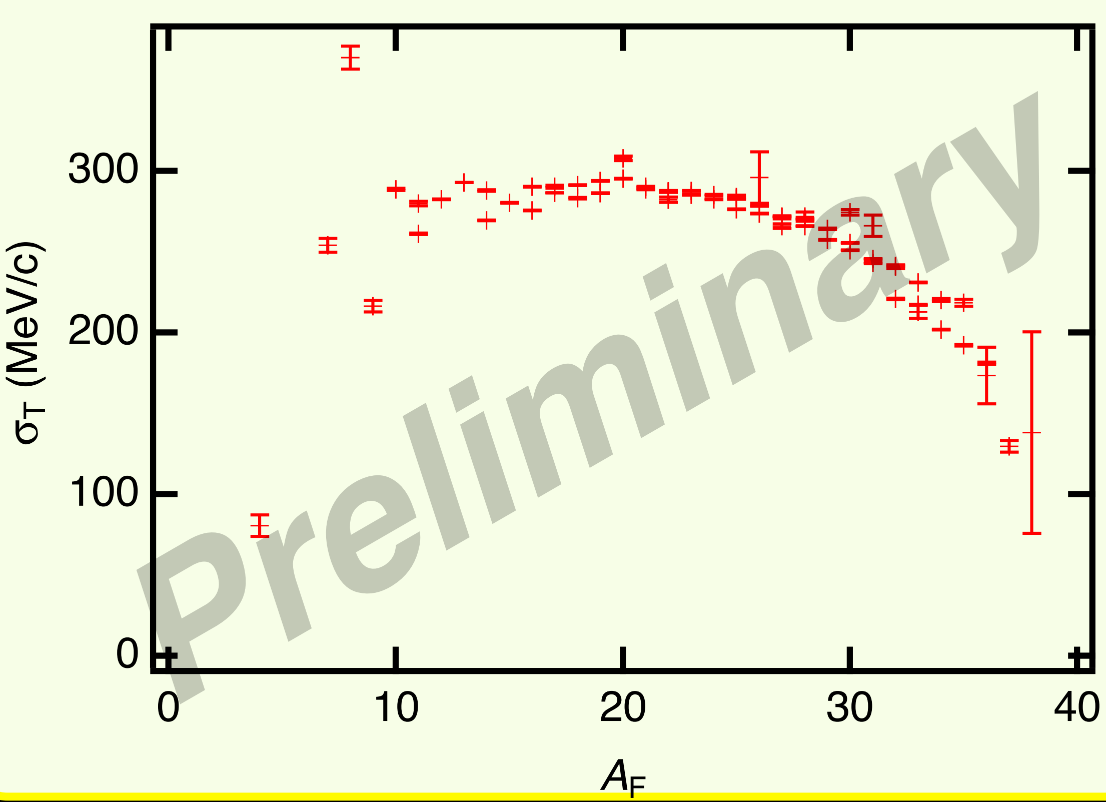
Correlation between σ_T and P_L

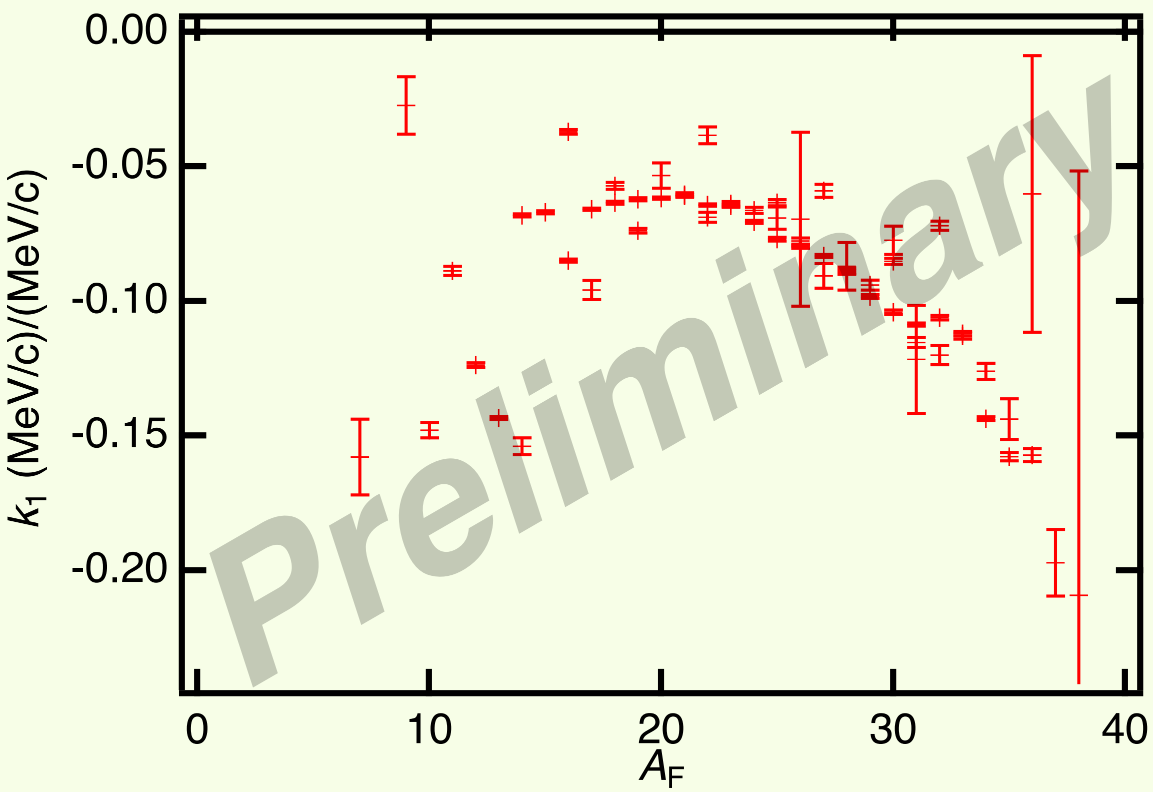
- Analysis by linear function



σ_T decrease monotonously.

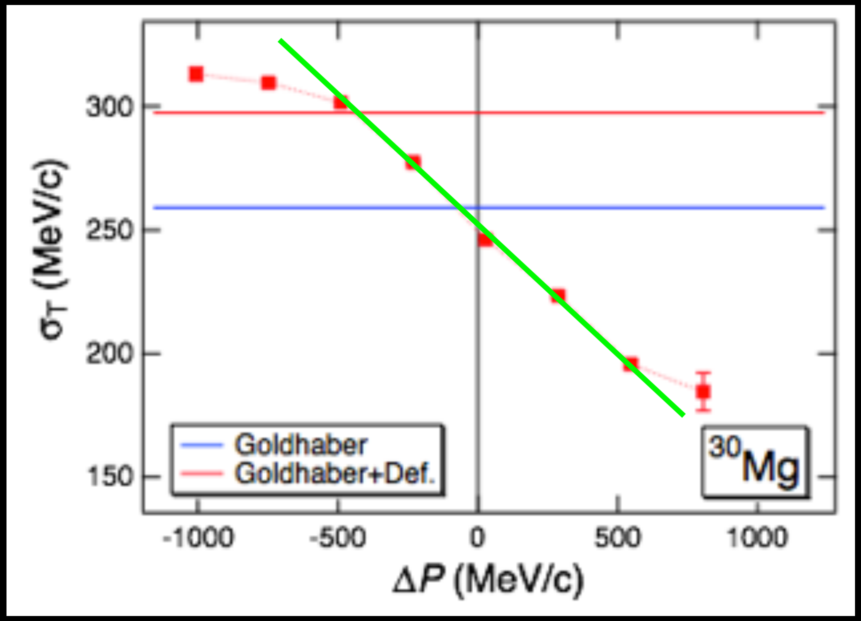
Fitting function :
$\sigma_T = k_0 + k_1 \Delta P$





Correlation between σ_T and P_L

- Analysis by linear function



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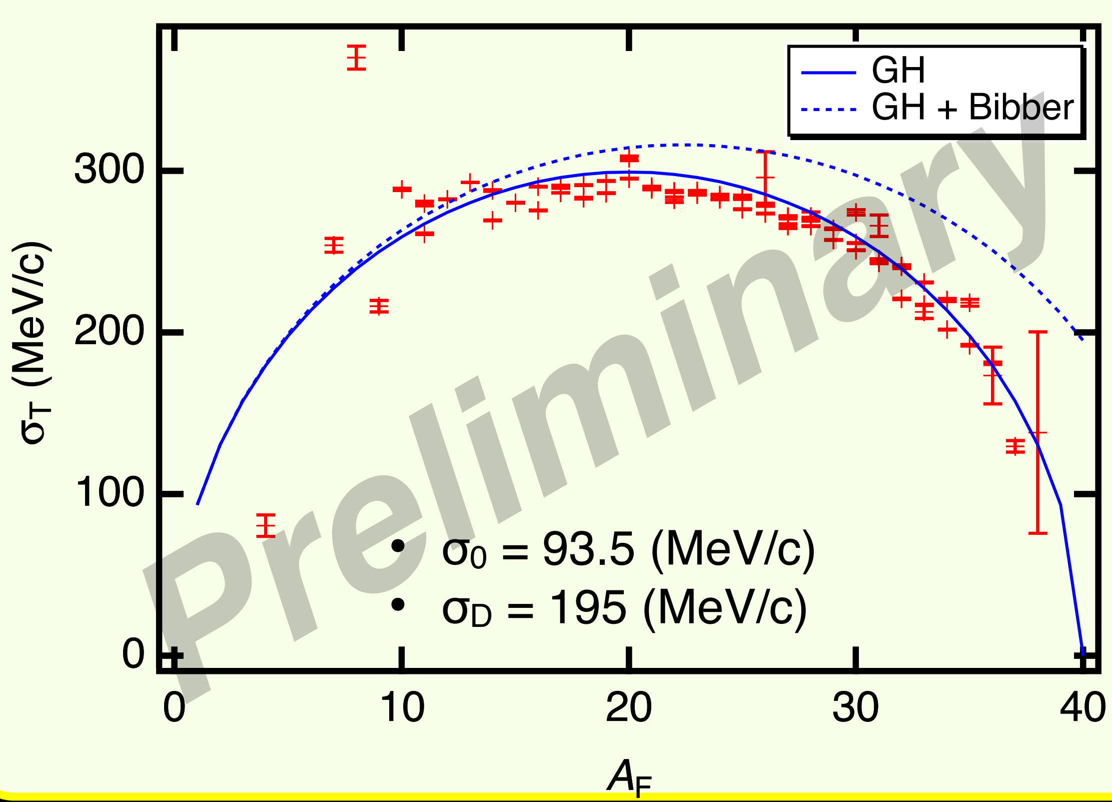
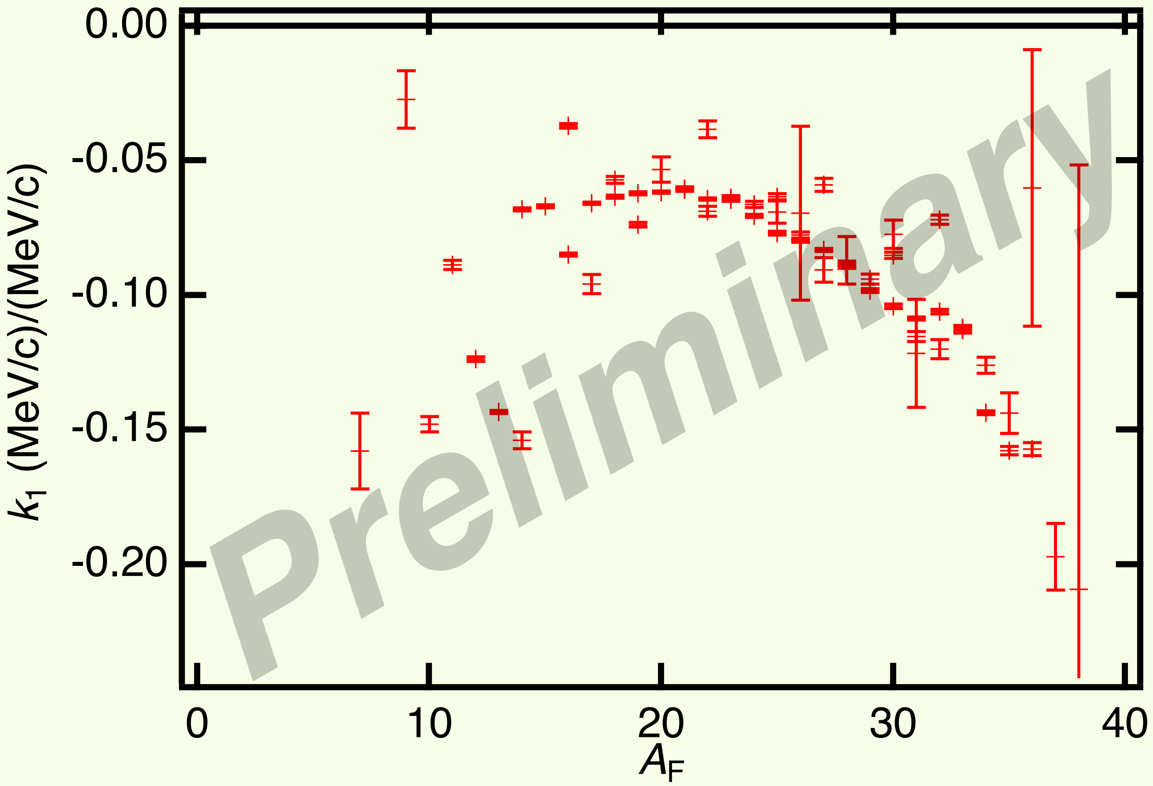
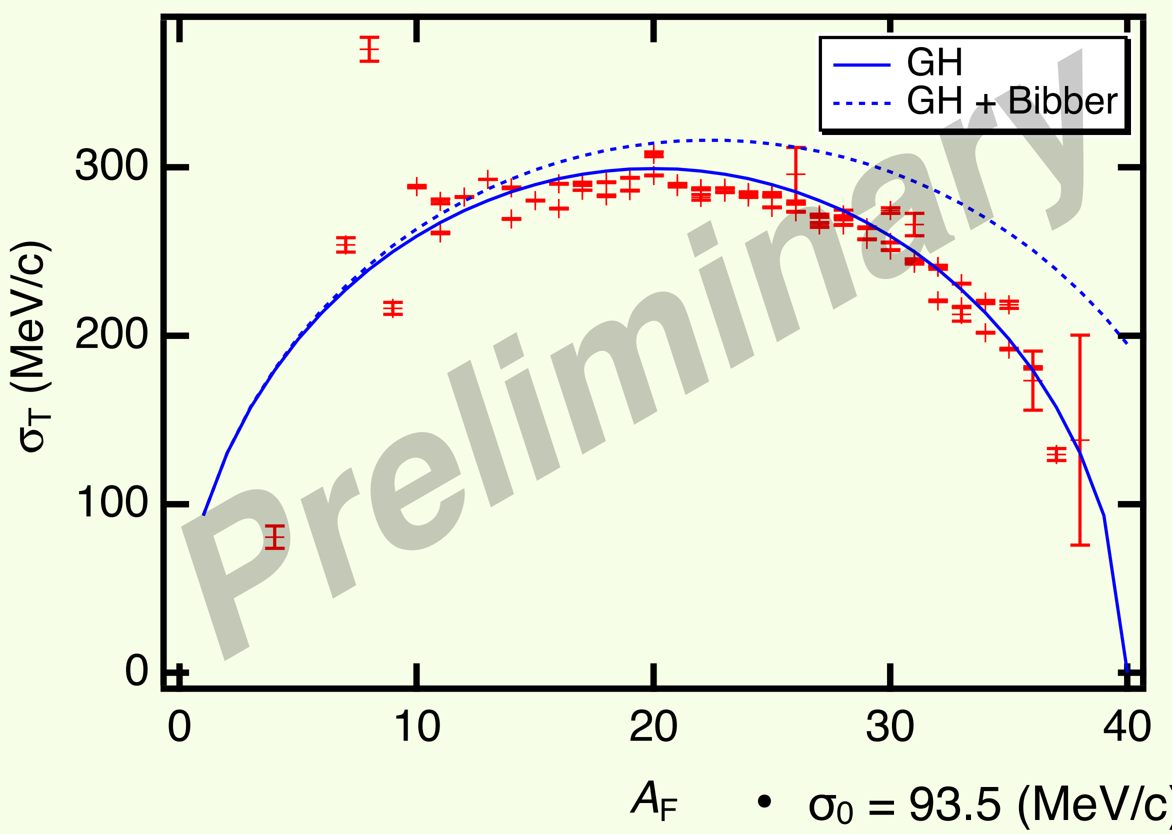




Dispersion of P_T at P_0

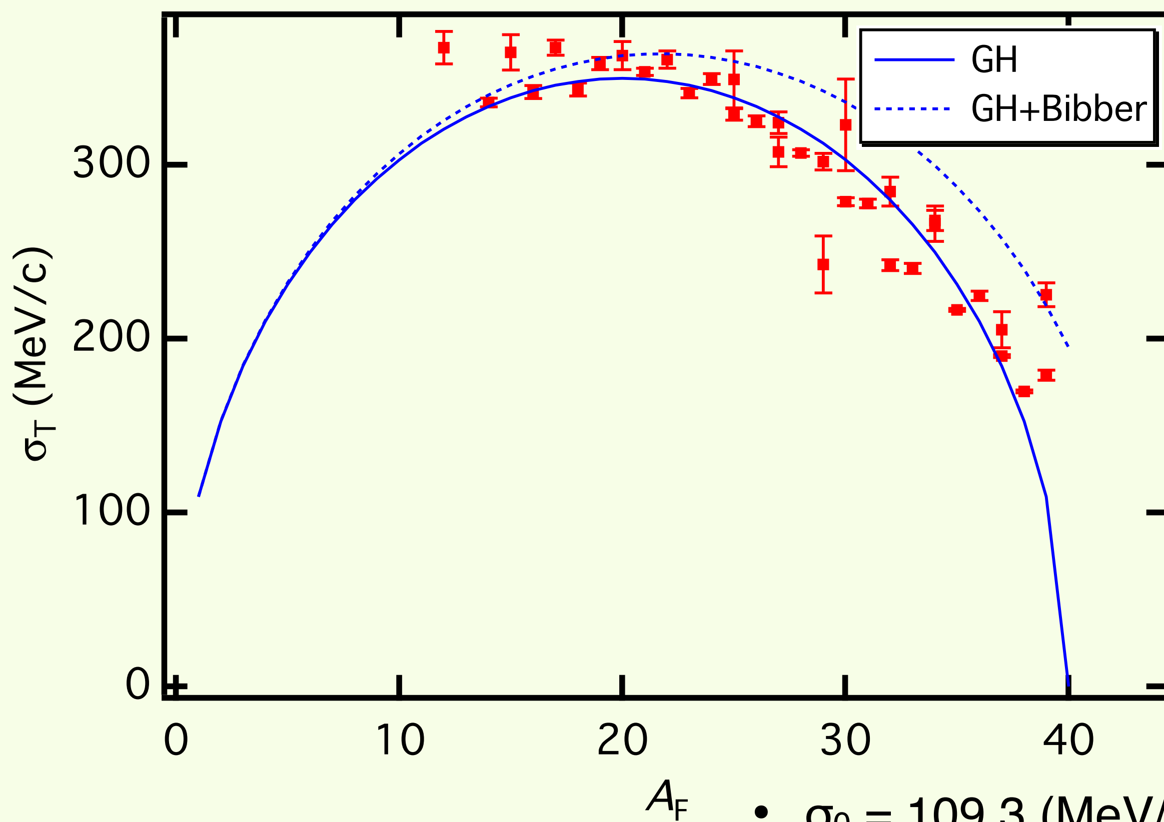
- ^{40}Ar beam

- $^{40}Ar+^{9}Be$@95 MeV/u



- σ_0 = 93.5 (MeV/c)
- σ_D = 195 (MeV/c)

- $^{40}Ar+^{27}Al$@290 MeV/u



- σ_0 = 109.3 (MeV/c)
- σ_D = 195 (MeV/c)

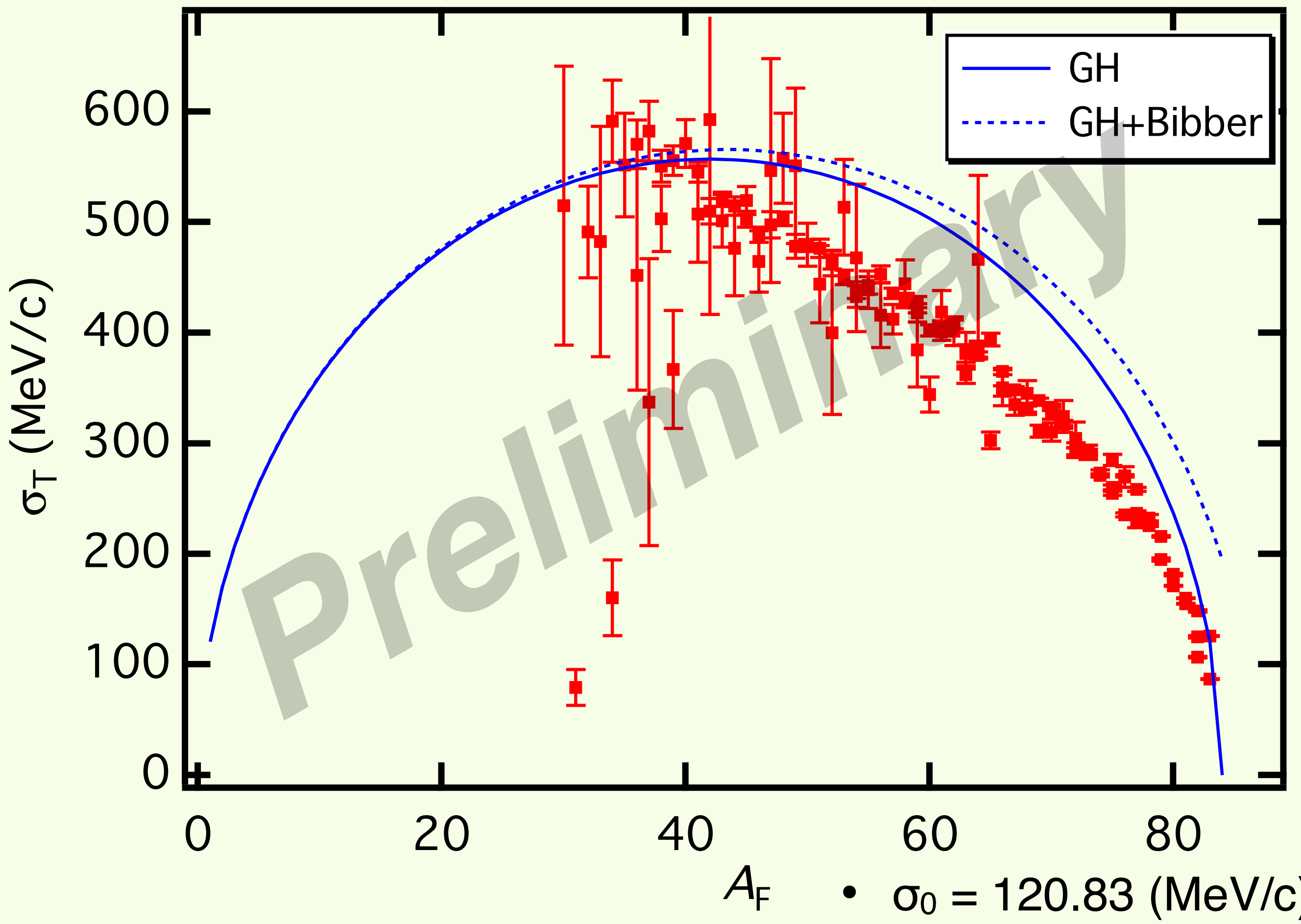
In case of Ar beam with light targets,

1) P_T distribution is well reproduced only by GH formulation.
2) $\sigma_T \sim \sigma_{High}$

Dispersion of P_T at P_0

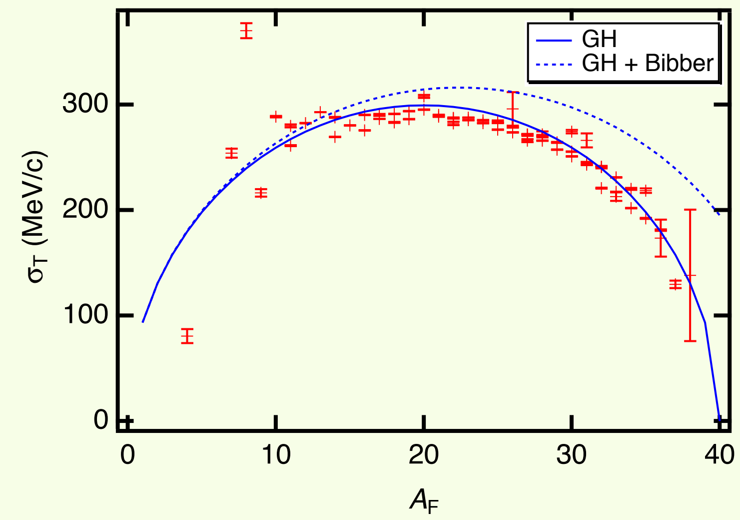
- ^{84}Kr beam

- $^{84}Kr+^{12}C$@290 MeV/u



- σ_0 = 120.83 (MeV/c)
- σ_D = 195 (MeV/c)

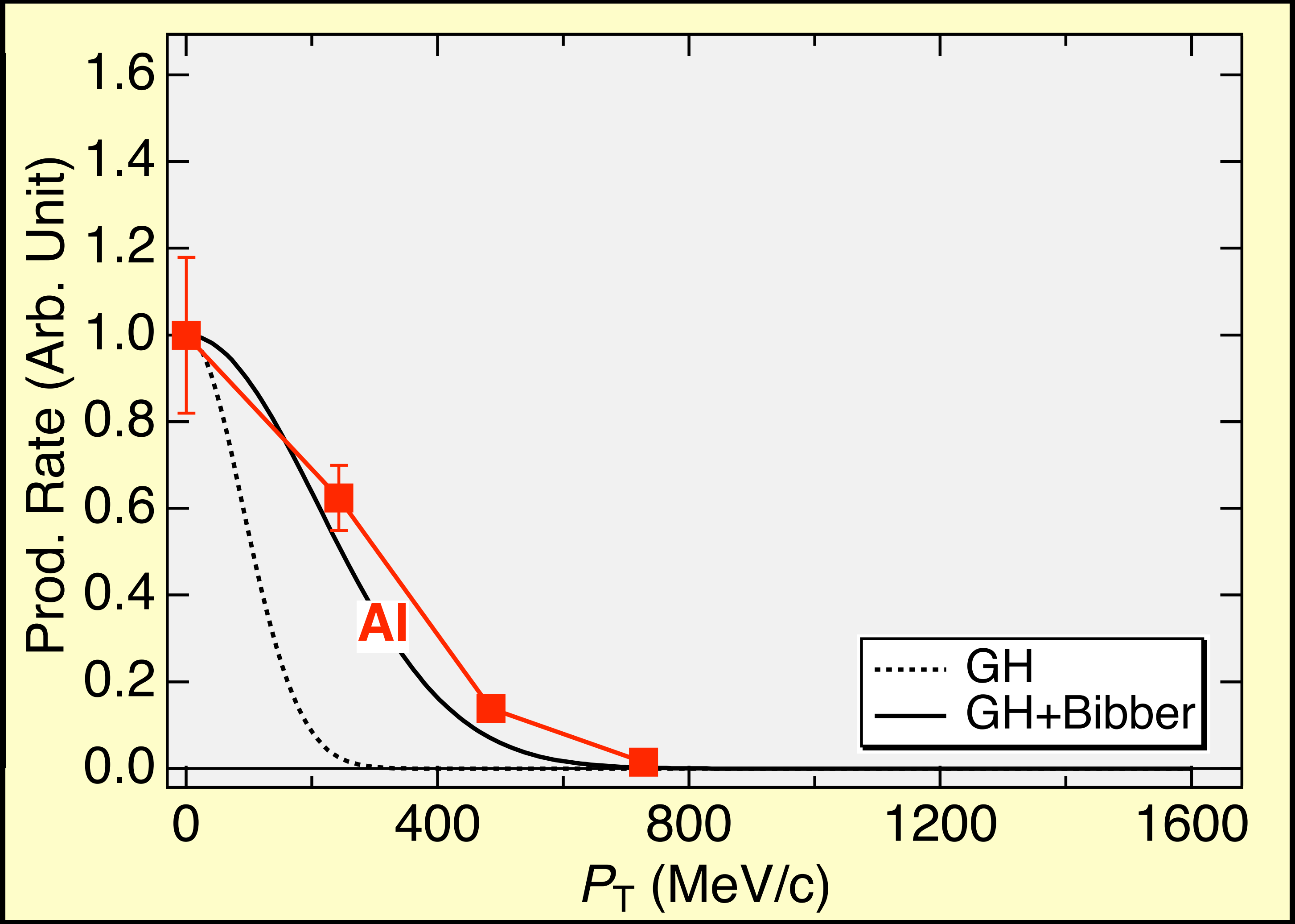
- $^{40}Ar+^{27}Al$@290 MeV/u



In case of Kr beam with light targets,
P_T distribution is narrower than P_L distribution.

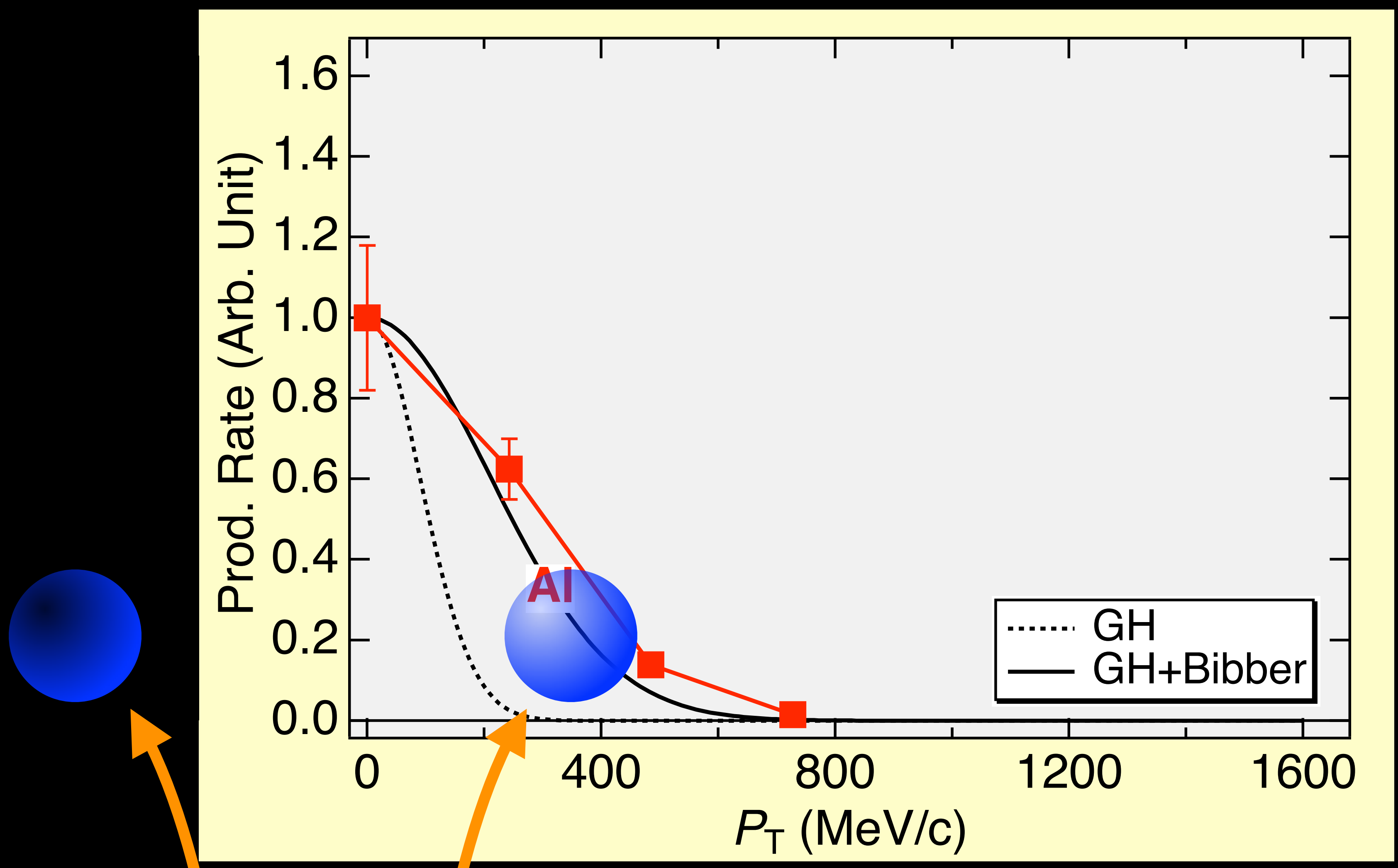
In case of heavier target

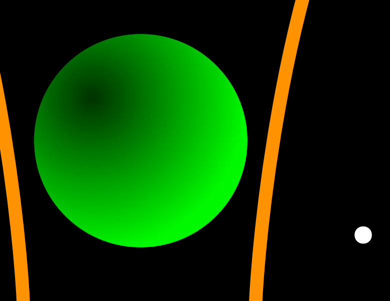
- ^{40}Ar+Al, Nb, Tb, Au →^{39}Cl



In case of heavier target

- ^{40}Ar+Al, Nb, Tb, Au $\rightarrow$ ^{39}Cl

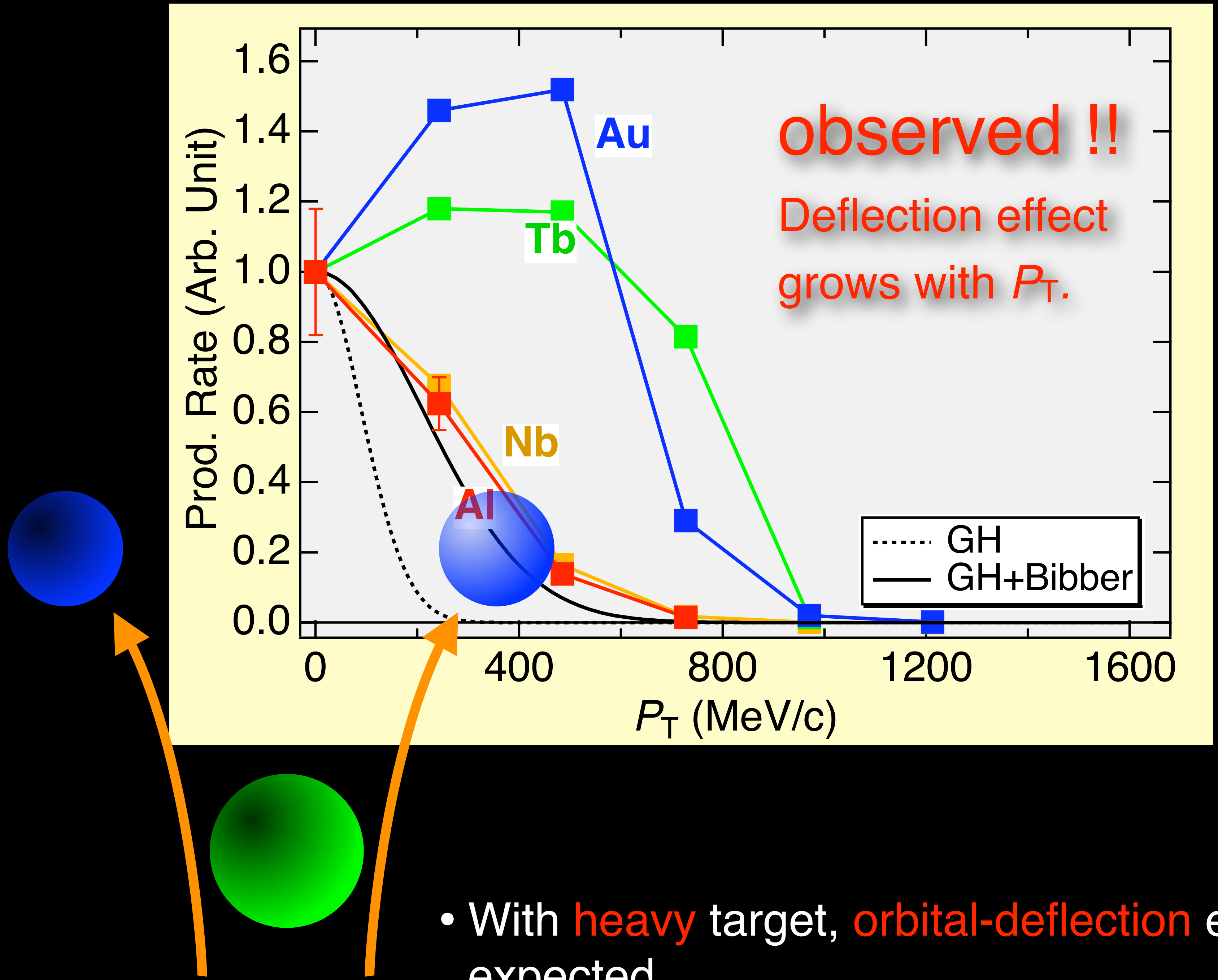




- With heavy target, orbital-deflection effect is expected.

In case of heavier target

- ^{40}Ar+Al, Nb, Tb, Au $\rightarrow$ ^{39}Cl

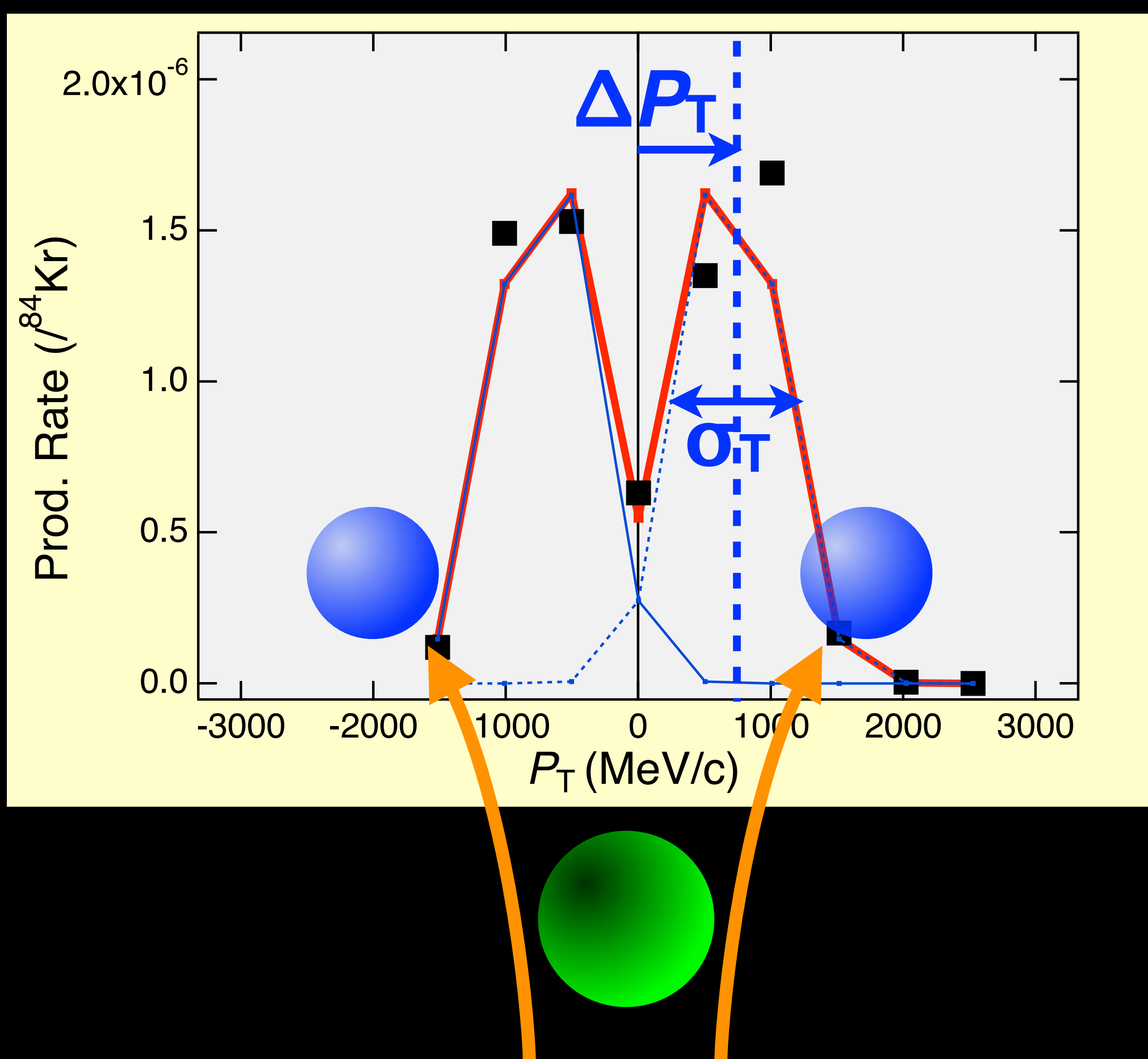


- With heavy target, orbital-deflection effect is expected.

Analysis of P_T distribution

- Evaluation of deflection effect

- ^{84}Kr+Au $\rightarrow$ ^{83}Br



Off-centered Gaussian functions

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

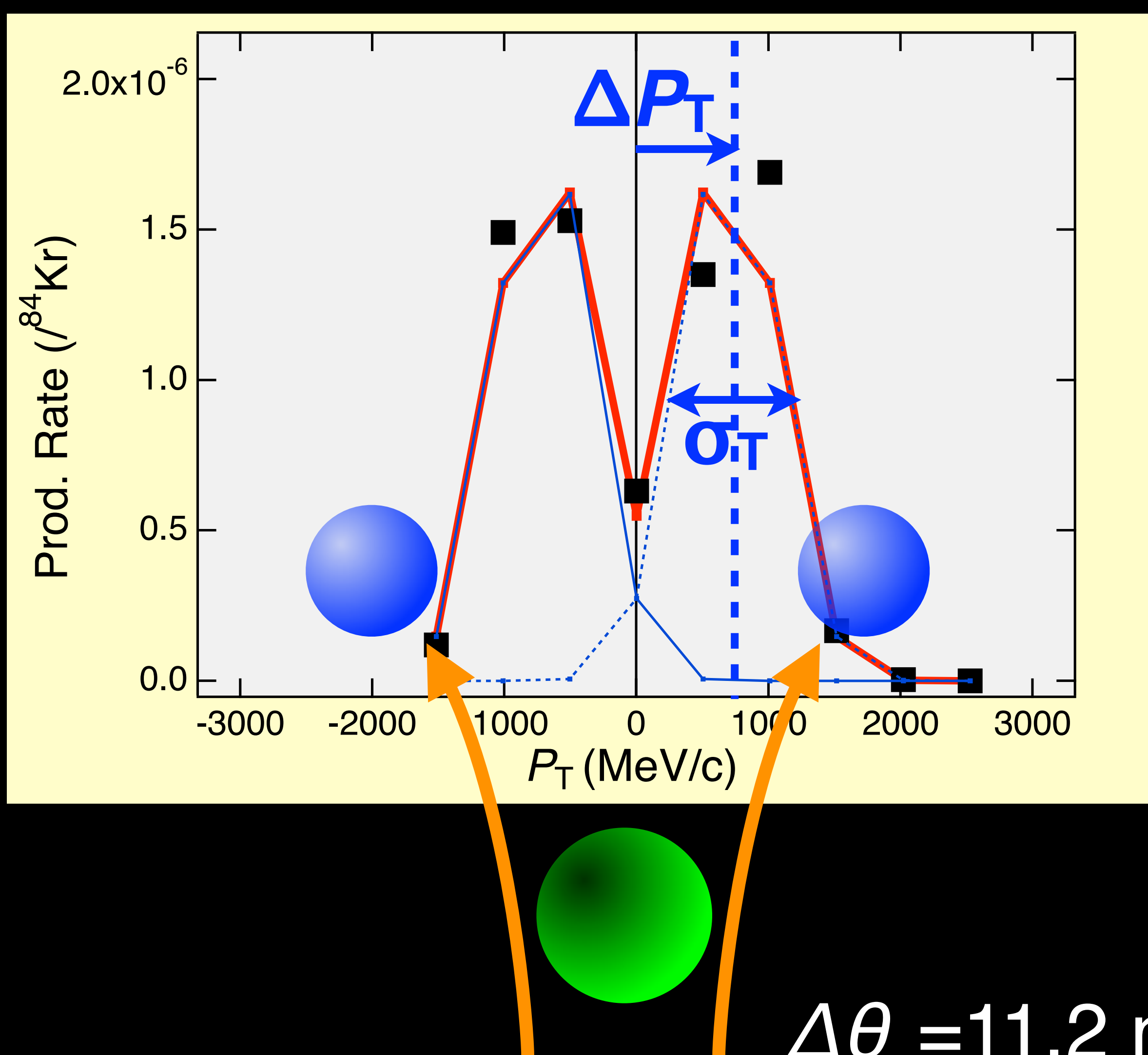
Let $\sigma(P_T) = \sigma_{GH}$, then

fitting to provide A, $\Delta(P_T)$.

Analysis of P_T distribution

- Evaluation of deflection effect

- ^{84}Kr+Au $\rightarrow$ ^{83}Br



Off-centered Gaussian functions

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

Let $\sigma(P_T) = \sigma_{GH}$, then fitting to provide A, $\Delta(P_T)$.

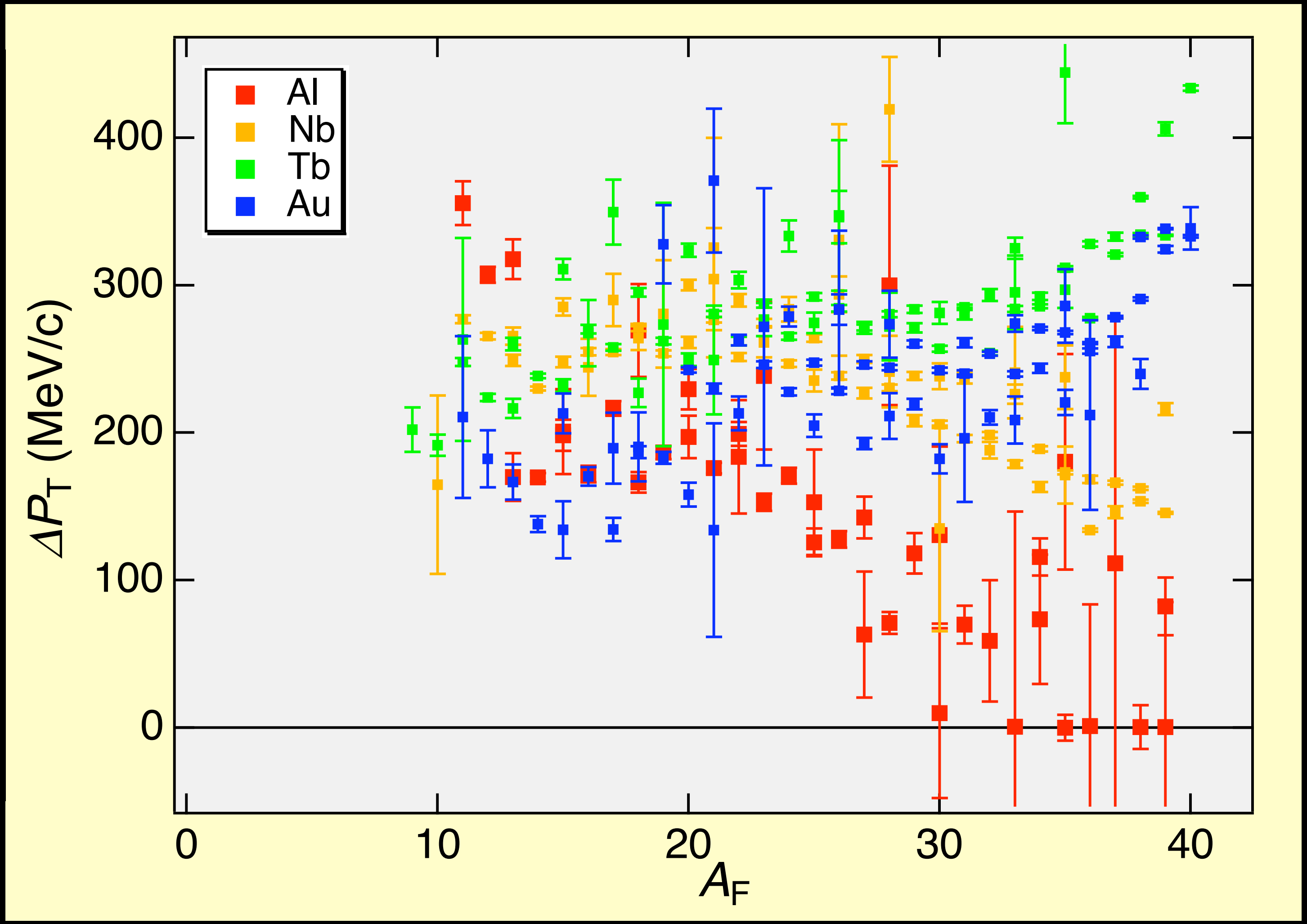
$\Delta\theta$ =11.2 mrad

Grazing angle :14 mrad

Orbital-deflection effect

- Target dependence with Ar-beam

- $^{40}Ar+^{A}Z$

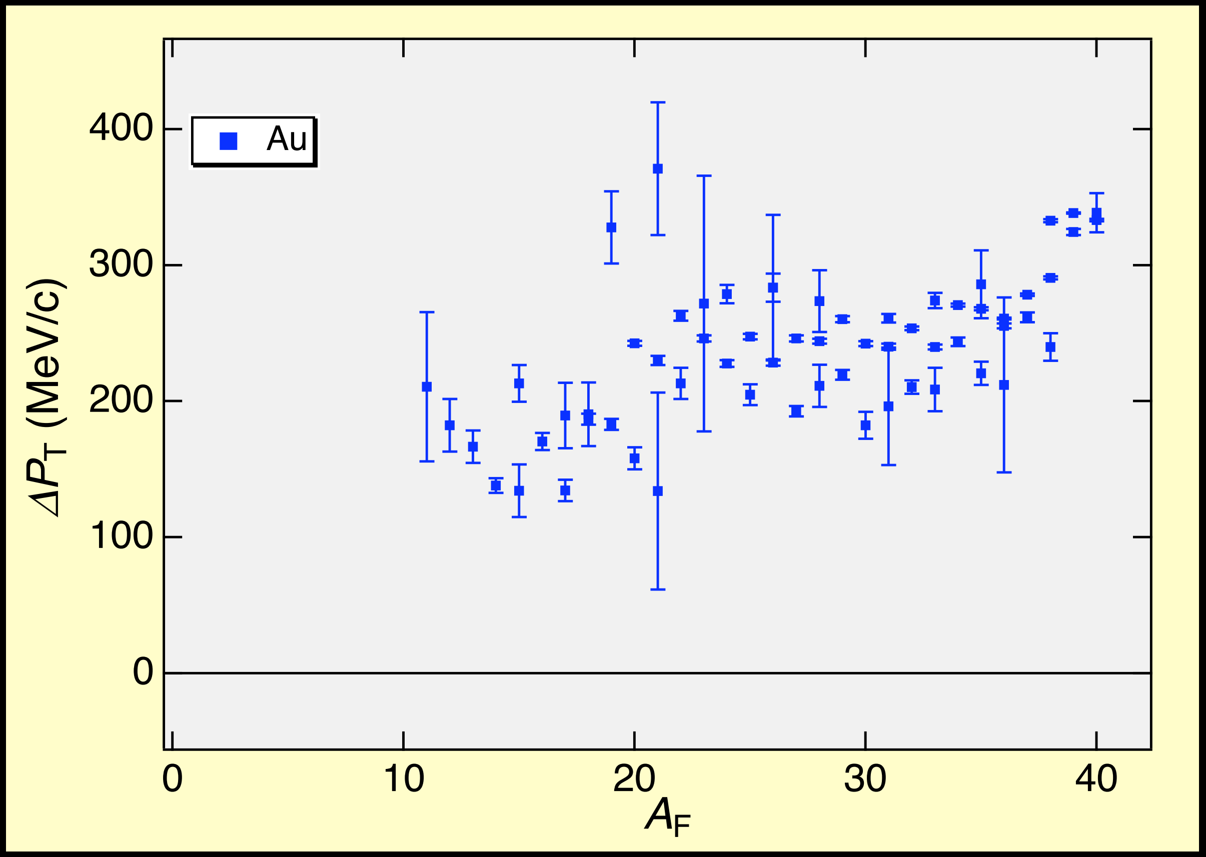


- The orbital-deflection effect grows with target mass.
- The target effect is remarkable for PLFs with $A_T > 20$.

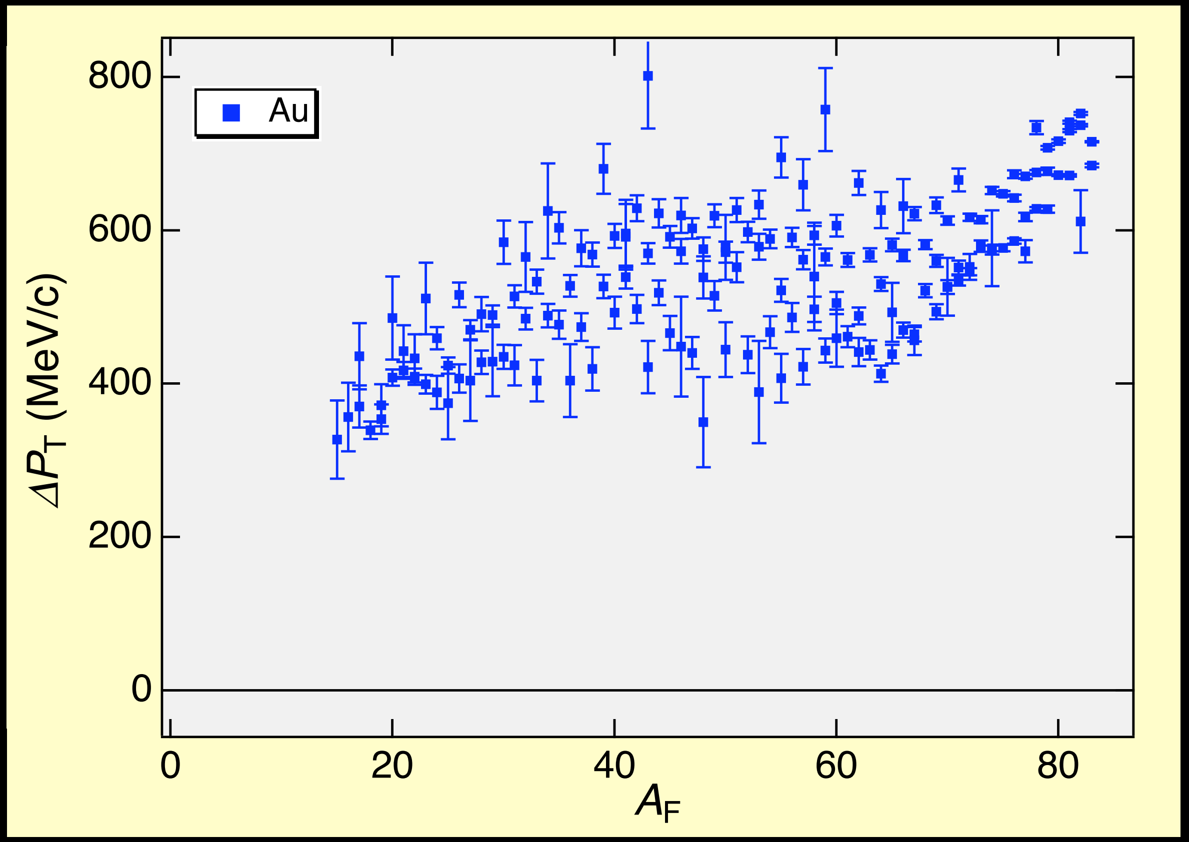
Orbital-deflection effect

- Ar, Kr + Au

- $^{40}Ar+^{197}Au$



- $^{84}Kr+^{197}Au$

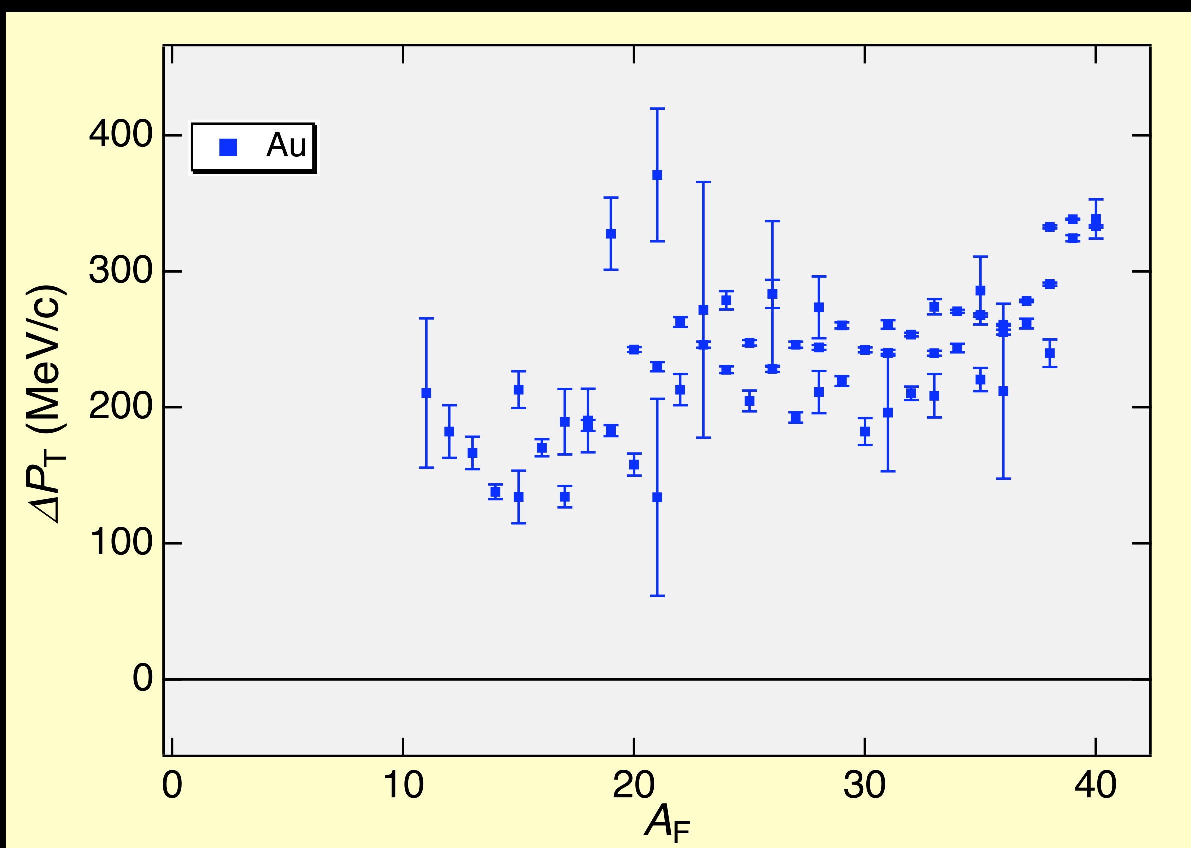


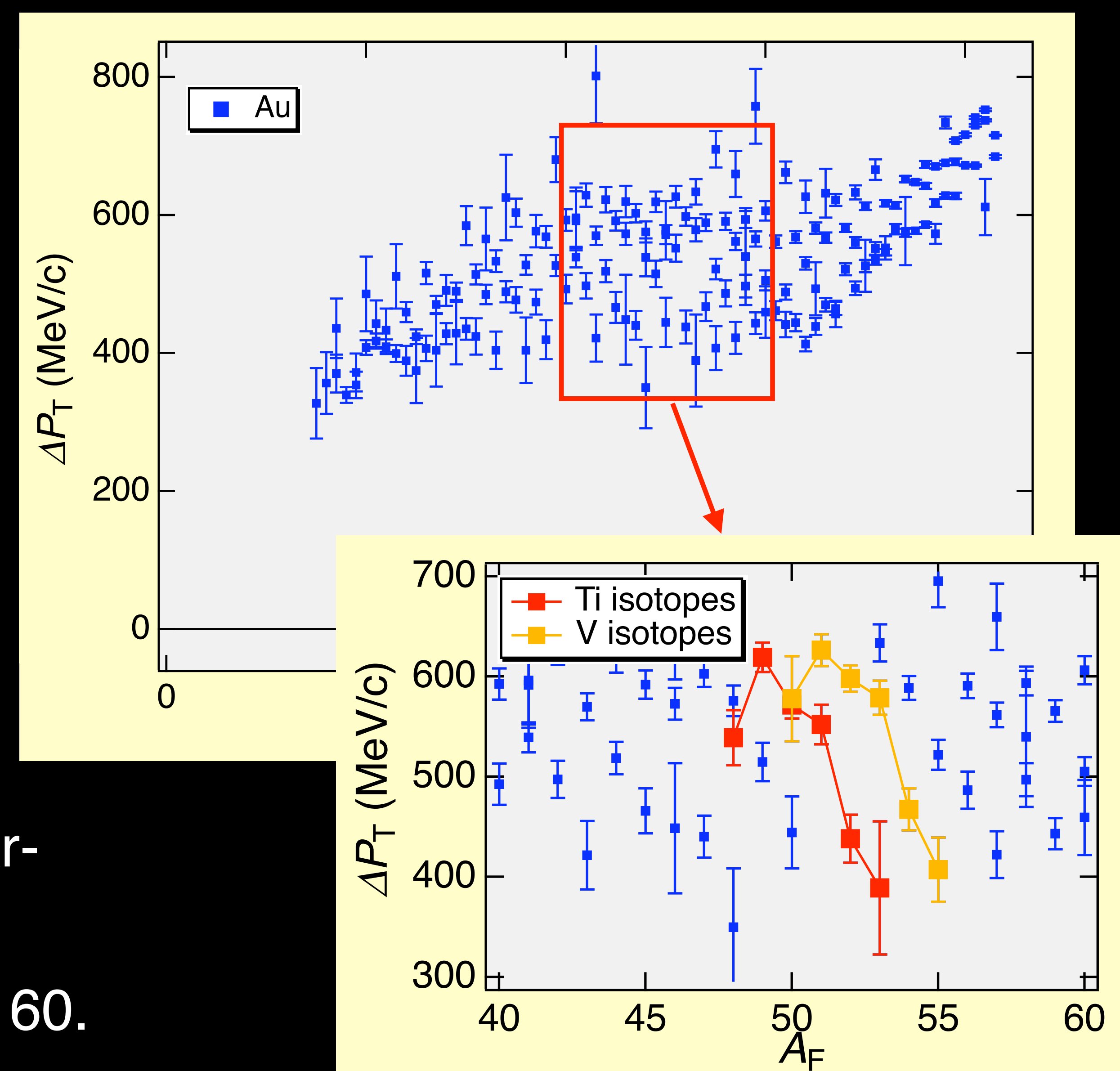
- The orbital-deflection effect is similar for Ar- and Kr-beam.
- The large fluctuation is found at $A_T = 30 \sim 60$.

Orbital-deflection effect

- Ar, Kr + Au

- $^{40}Ar+^{197}Au$
- $^{84}Kr+^{197}Au$

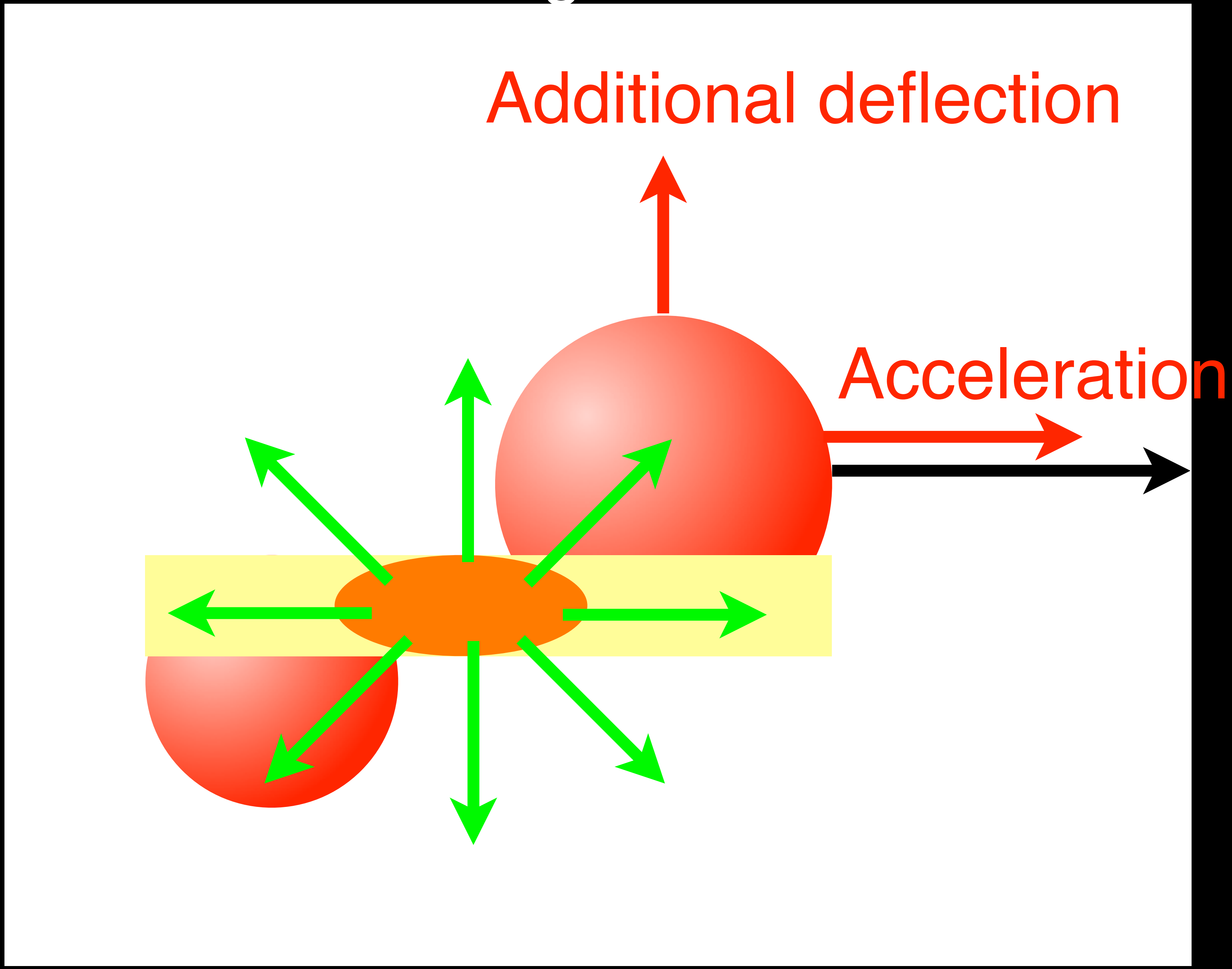




- The orbital-deflection effect is similar for Ar- and Kr-beam.
- The large fluctuation is found at A_T = 30 ~ 60.
- The fluctuation comes from isotopic drift.

Participant blast effect in P_T dist.?

For light/intermediate fragments



$\sigma_{Prod.}$ of fragment

How to obtain σ_{Prod}

- Consideration of ang. acpt.

Prod. rate at 0 deg. in limited ang. acpt.

→ Integration assuming reliable P_T distributions

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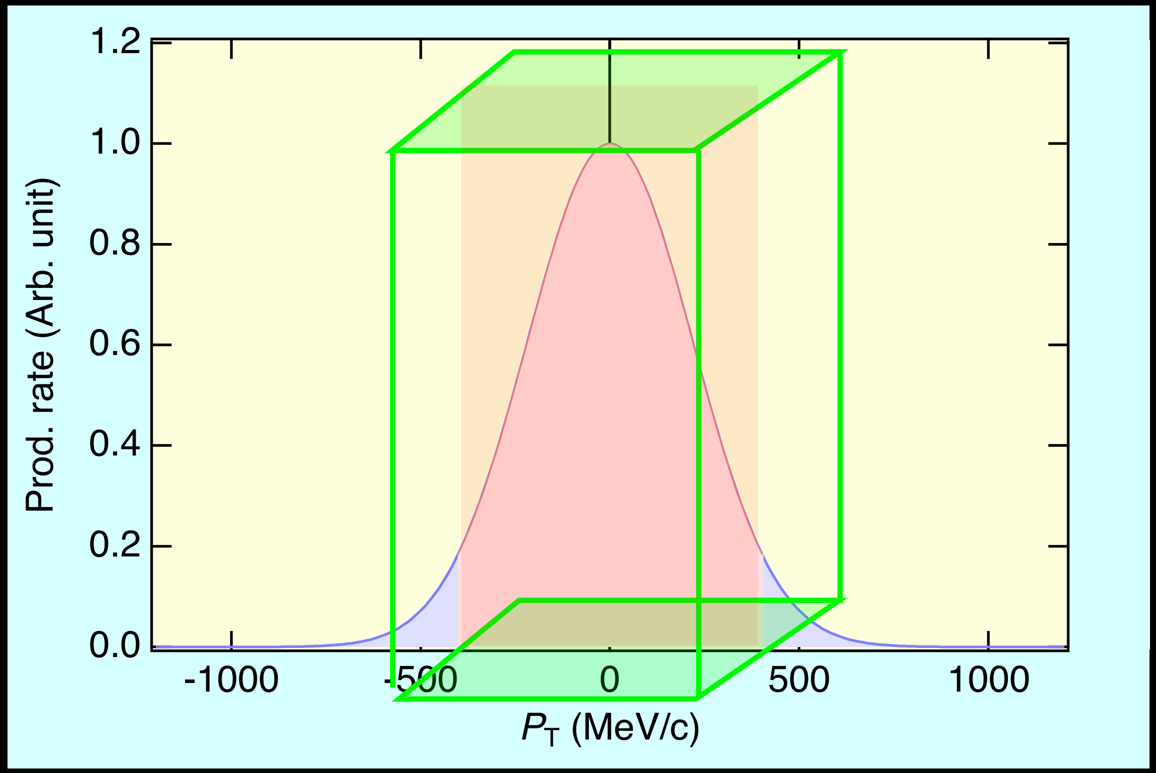
Prod. rate at 0 deg. in limited ang. acpt.

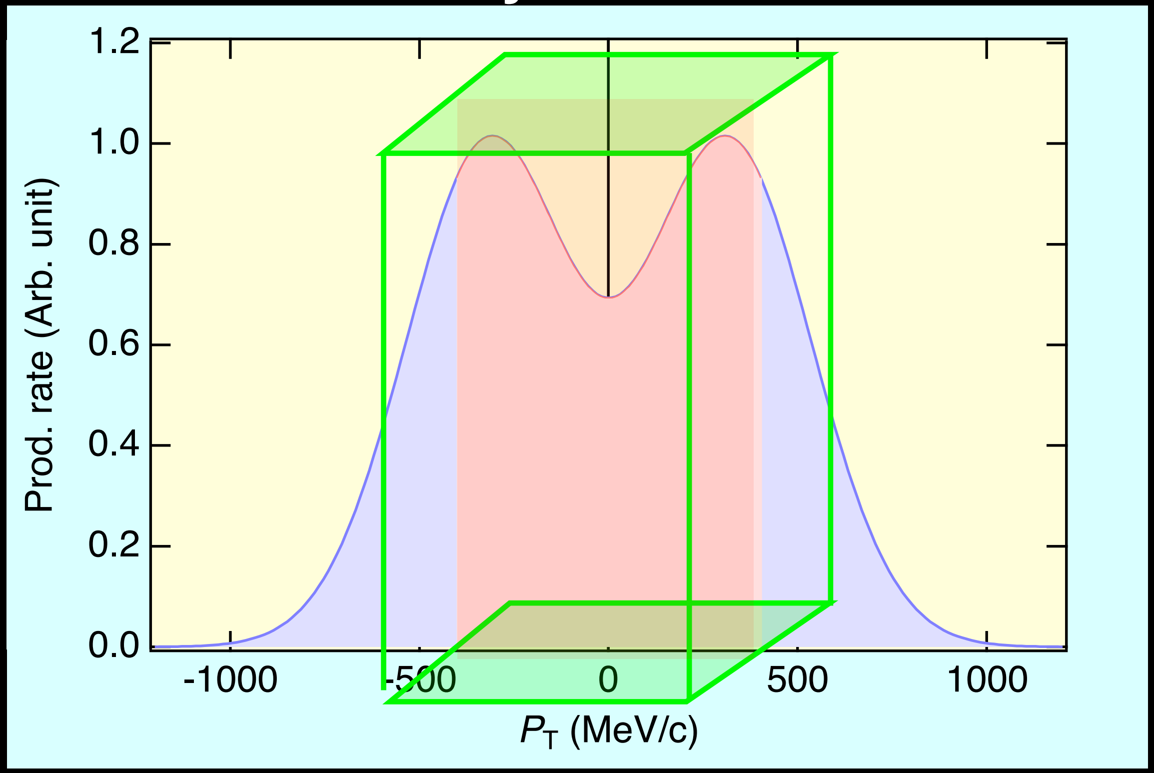
→ Integration assuming reliable P_T distributions

Ex. ^{40}Ar + ^{197}Au → ^{39}Cl

If GH + Bibber is assumed,



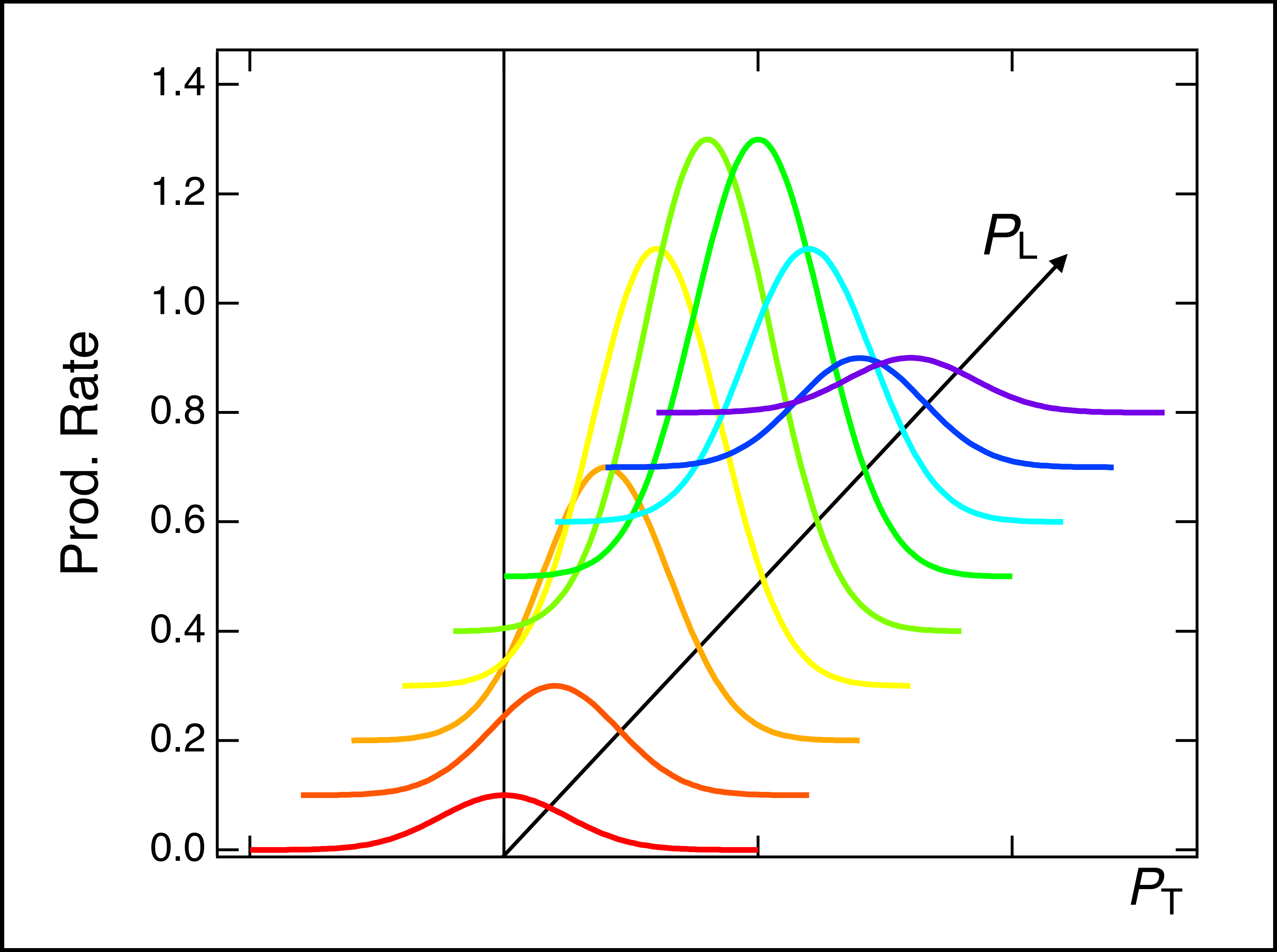
Actually...



Spuriously underestimated σ_{Prod} would be provided.

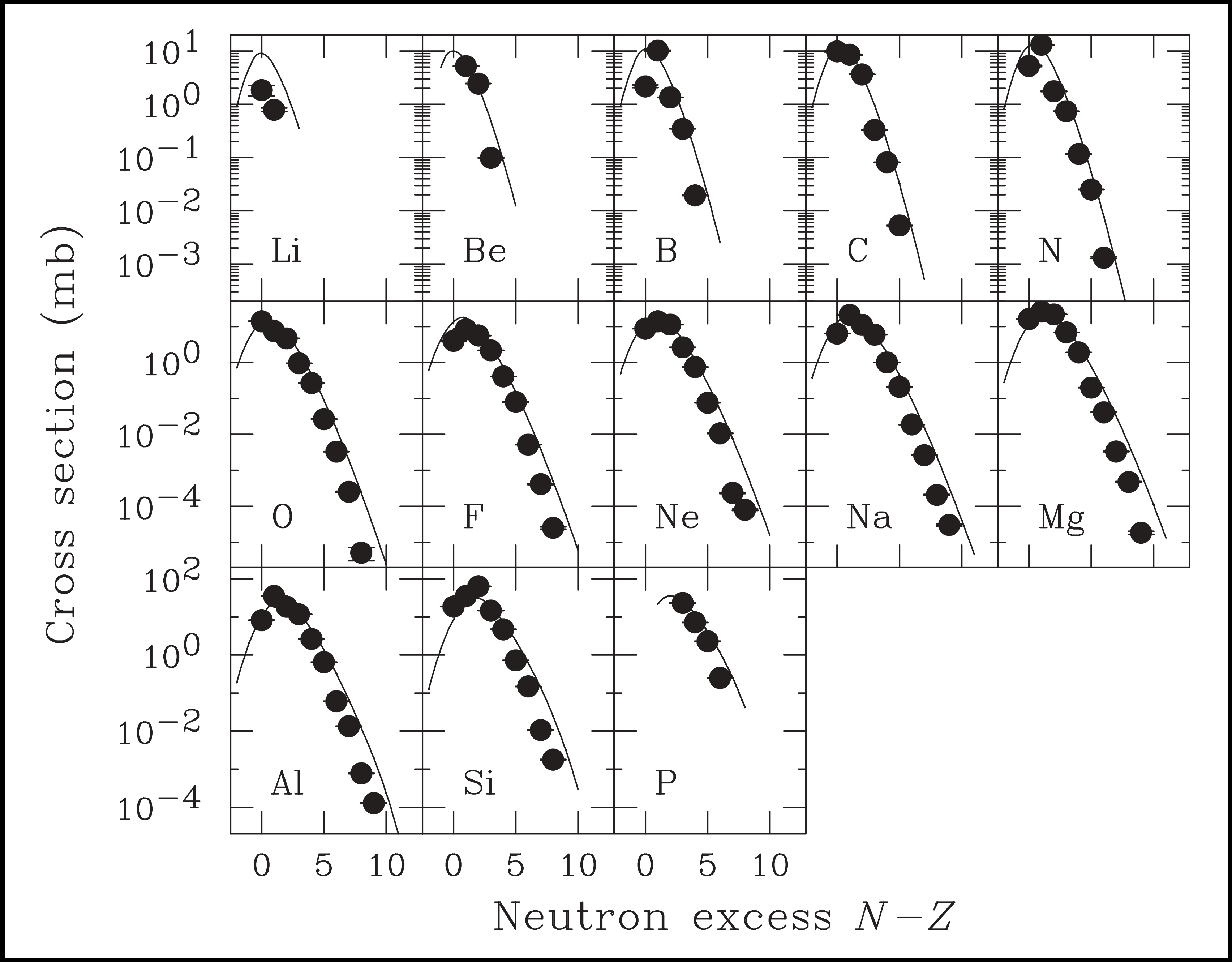
How to obtain σ_{Prod}

- Integration along P_L



$\sigma_{Prod.}$ at E = 90 MeV/u

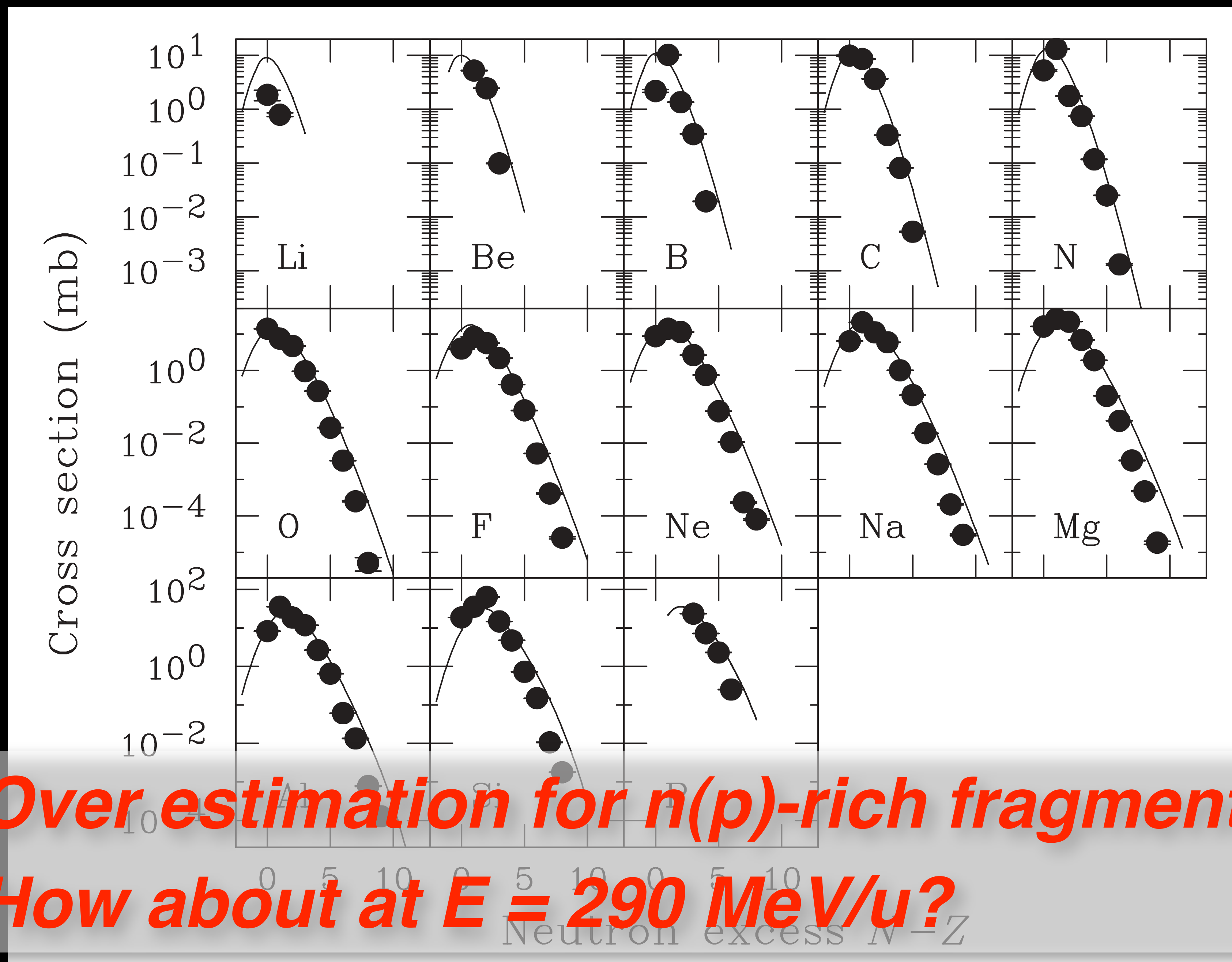
- $^{40}Ar + {}^{9}Be$



M. Notani et al., PRC 76 (2007) 044605.

$\sigma_{Prod.}$ at E = 90 MeV/u

- ^{40}Ar + ^{9}Be



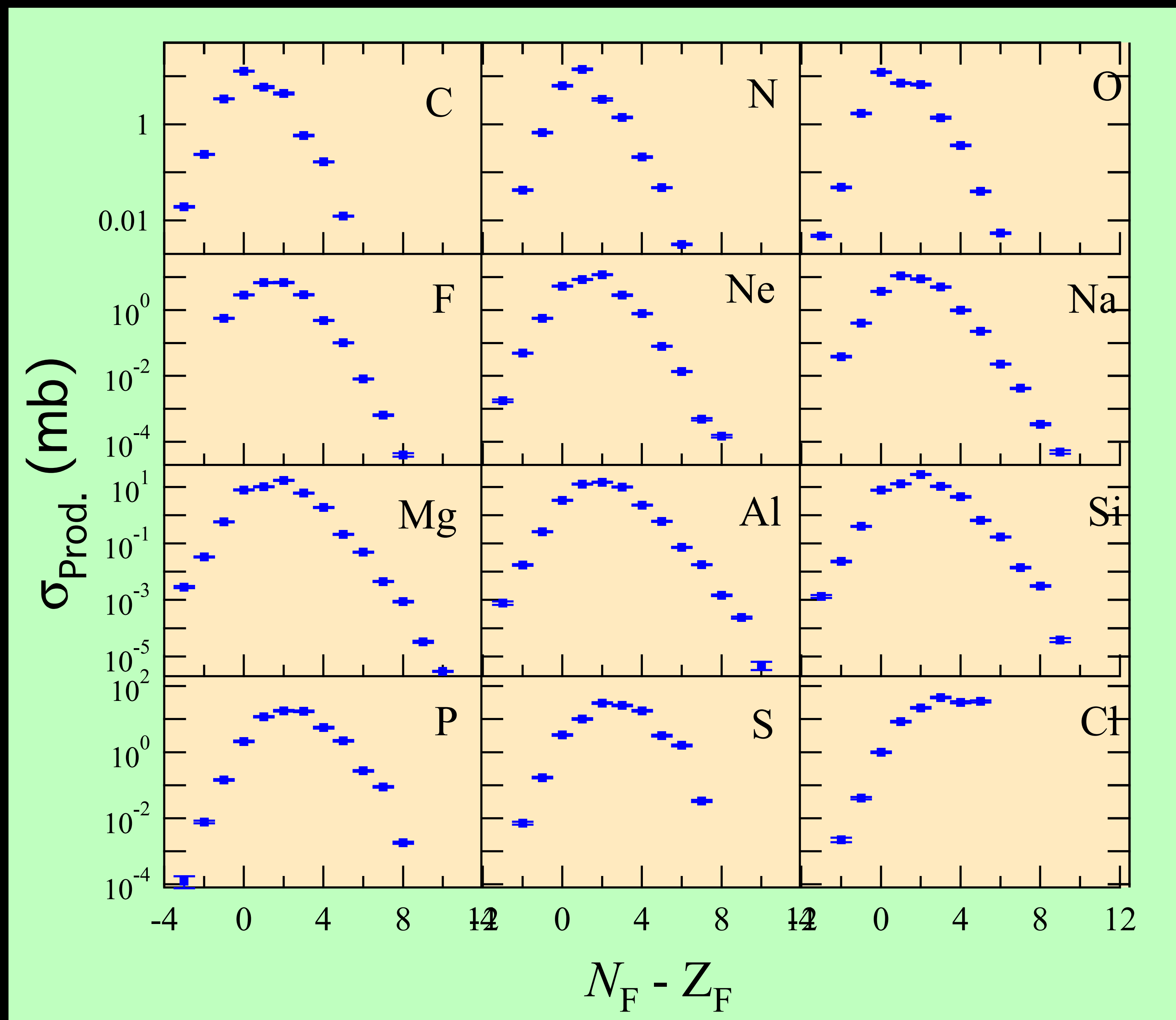
Over estimation for n(p)-rich fragments

How about at E = 290 MeV/u?

M. Notani et al., PRC 76 (2007) 044605.

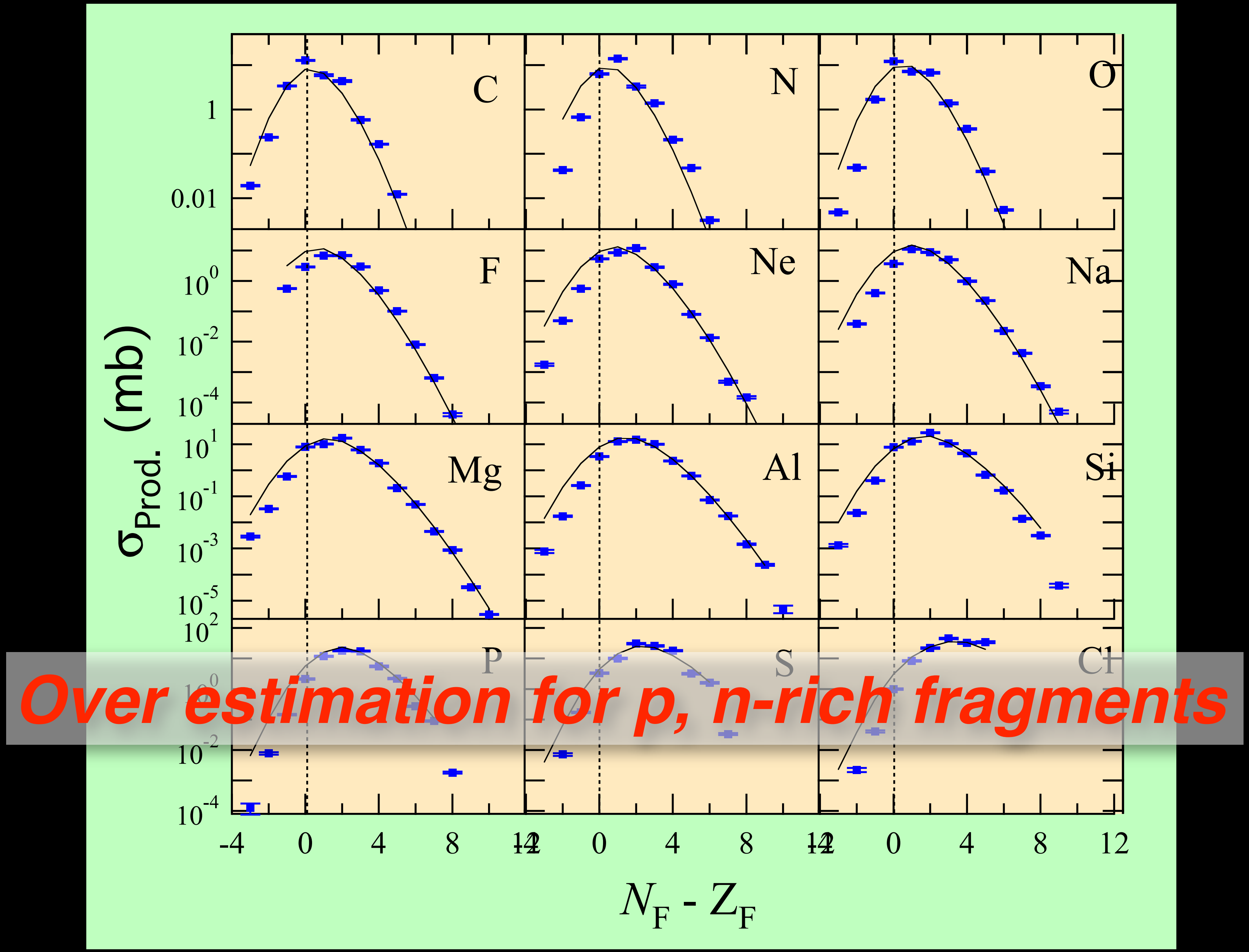
$\sigma_{Prod.}$ at E = 290 MeV/u

- ^{40}Ar (290 MeV/u) + ^{12}C



$\sigma_{Prod.}$ at E = 290 MeV/u

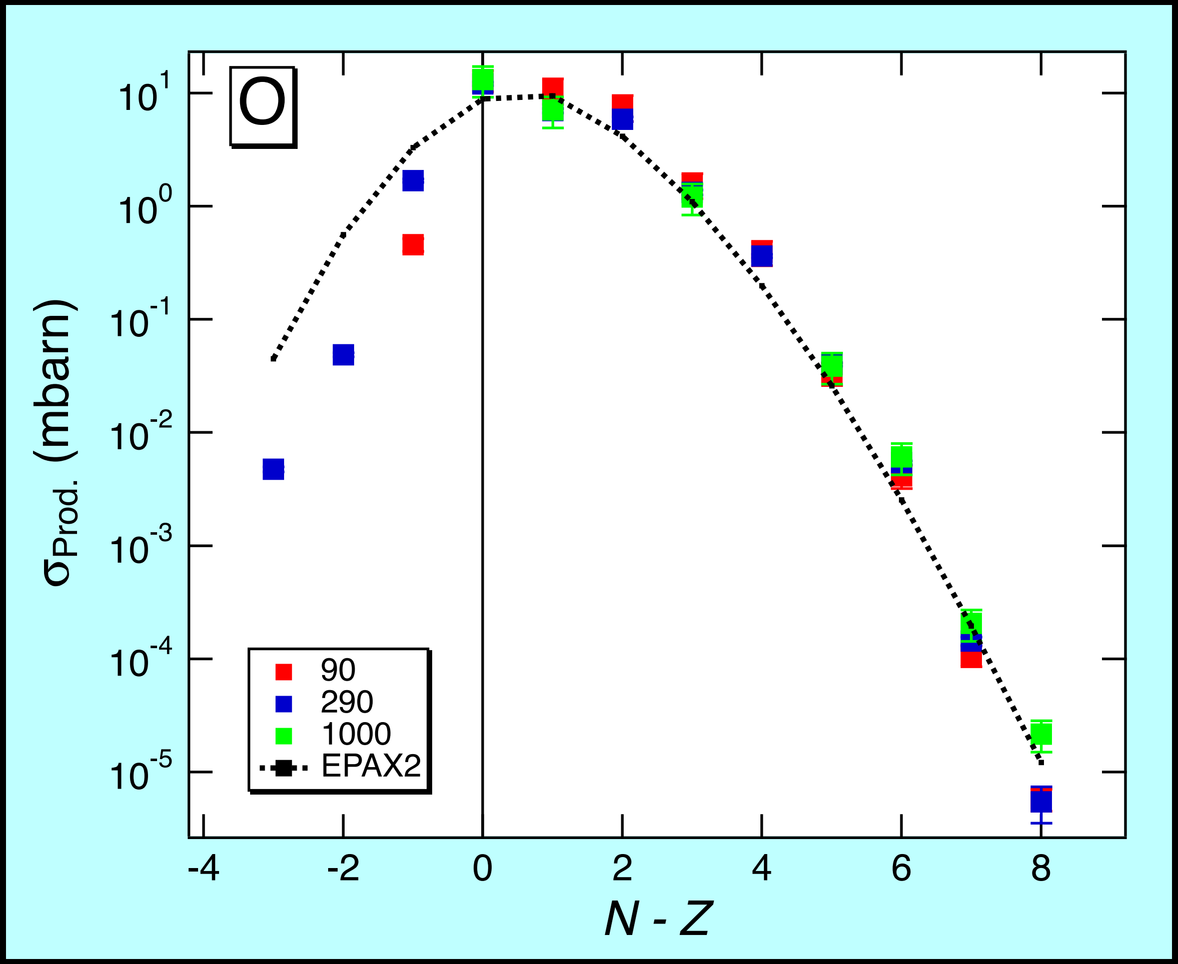
- ^{40}Ar (290 MeV/u) + ^{12}C



Energy dependence

- ^{40}Ar (290 MeV/u) + ^{9}Be, ^{12}C

Normalized by EPAX2



90 MeV/u : *M. Notani et al.*, PRC 76 (2007) 044605.
290 MeV/u : Our results
1000 MeV/u : *A. Ozawa et al.*, NP A 673 (2000) 375.

Energy dependence

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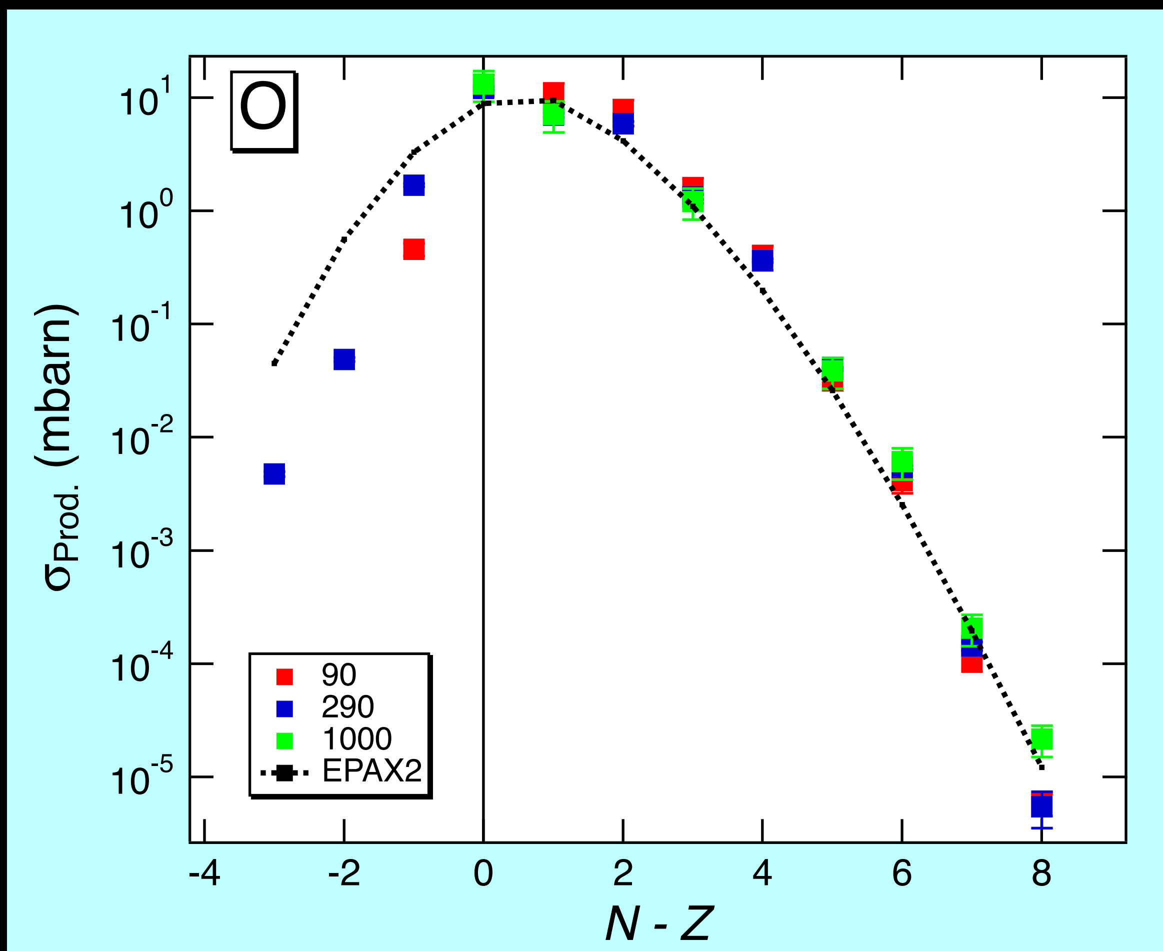
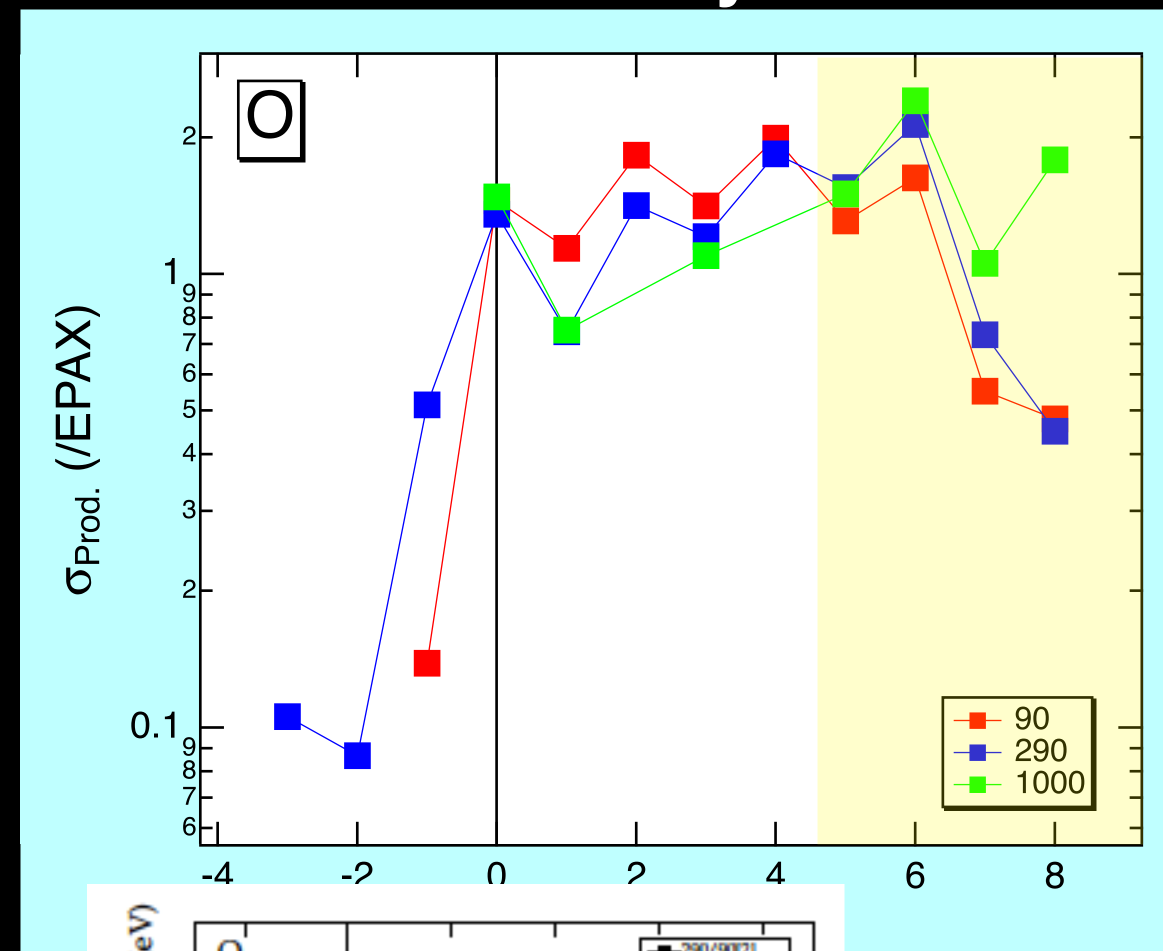
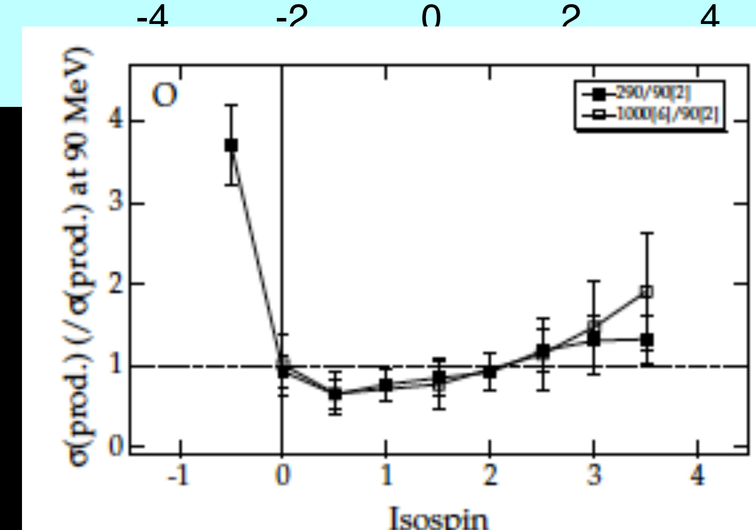


Normalized by EPAX2





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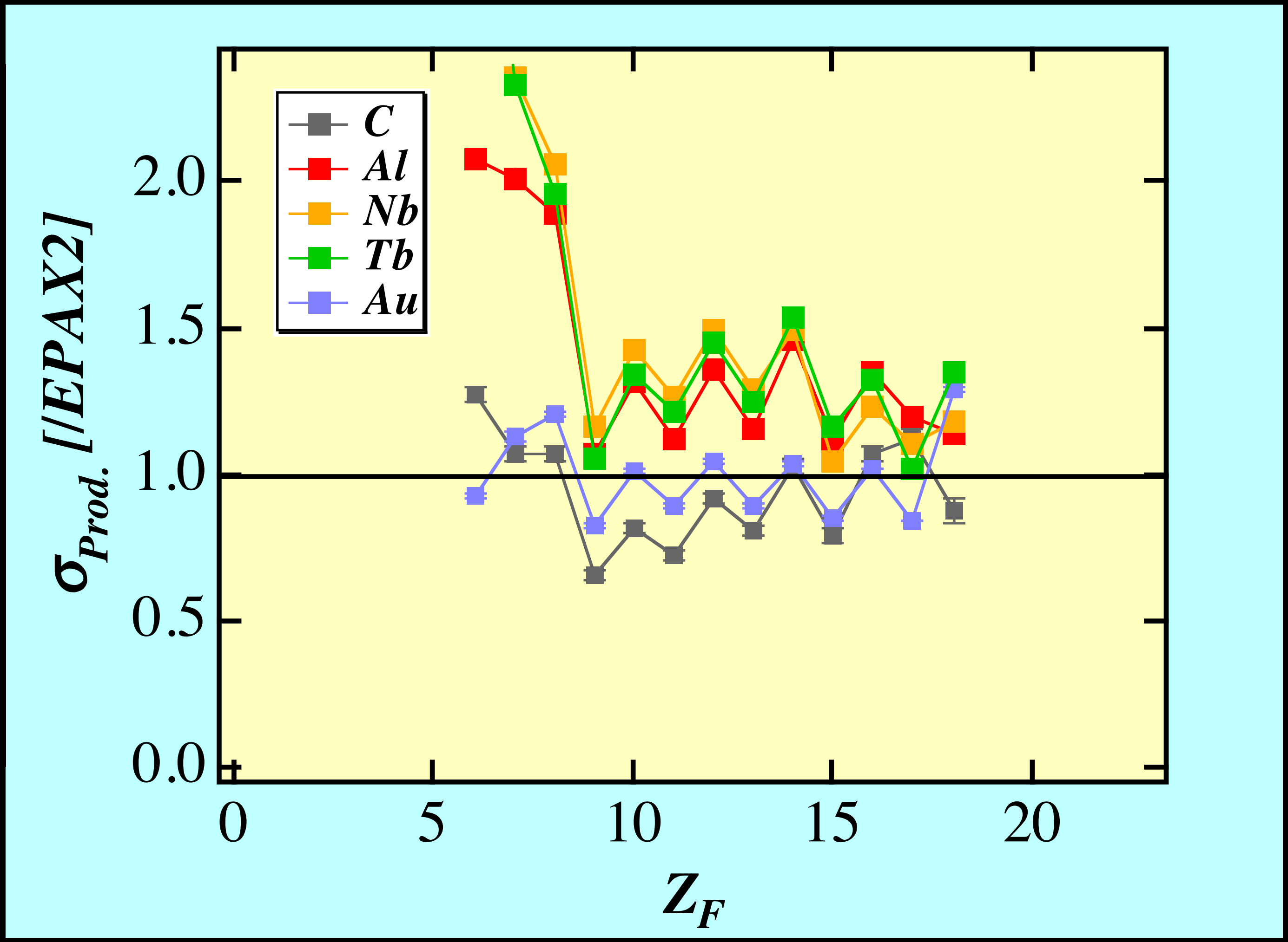
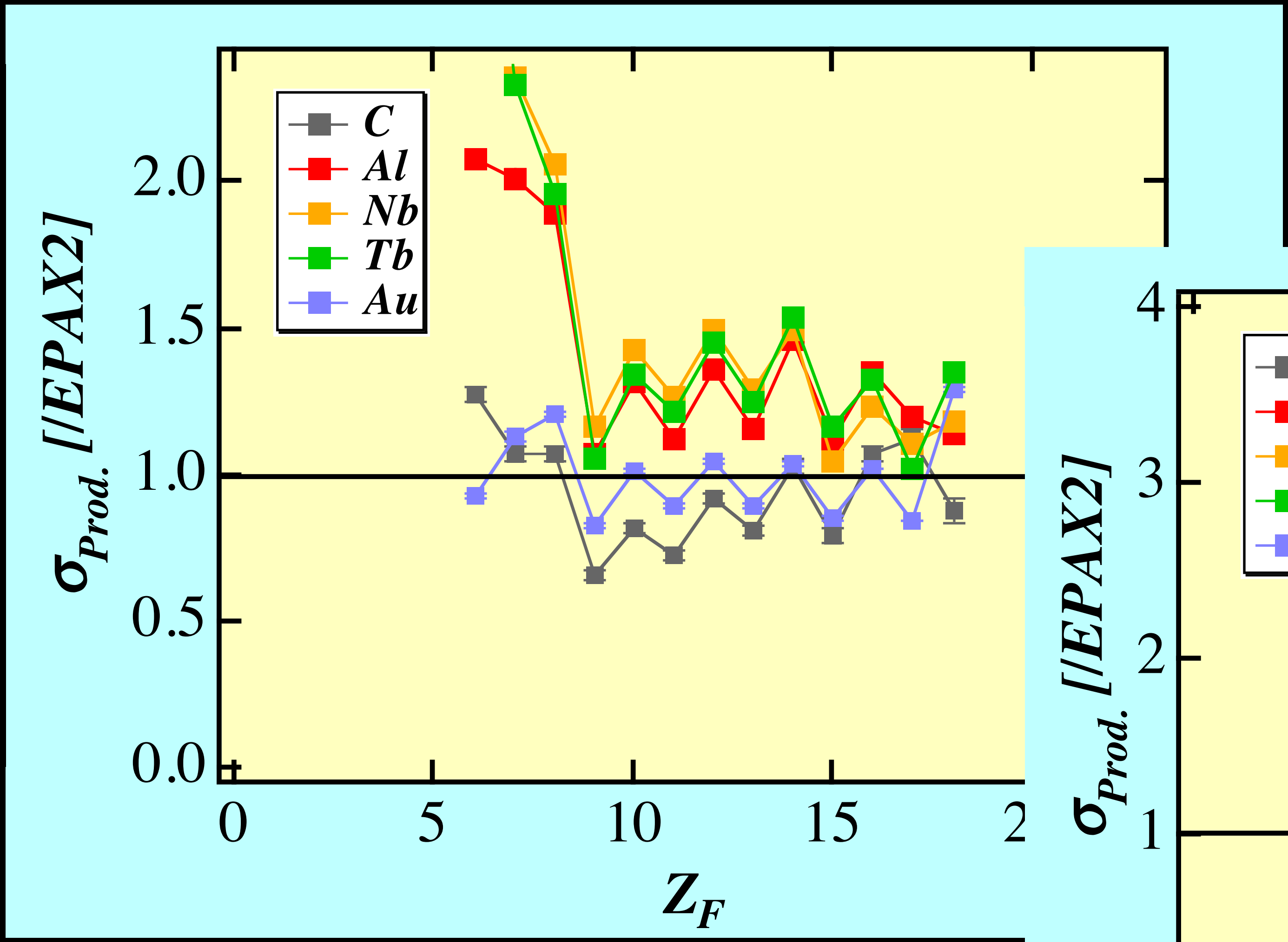
Contribution of nucl. structure

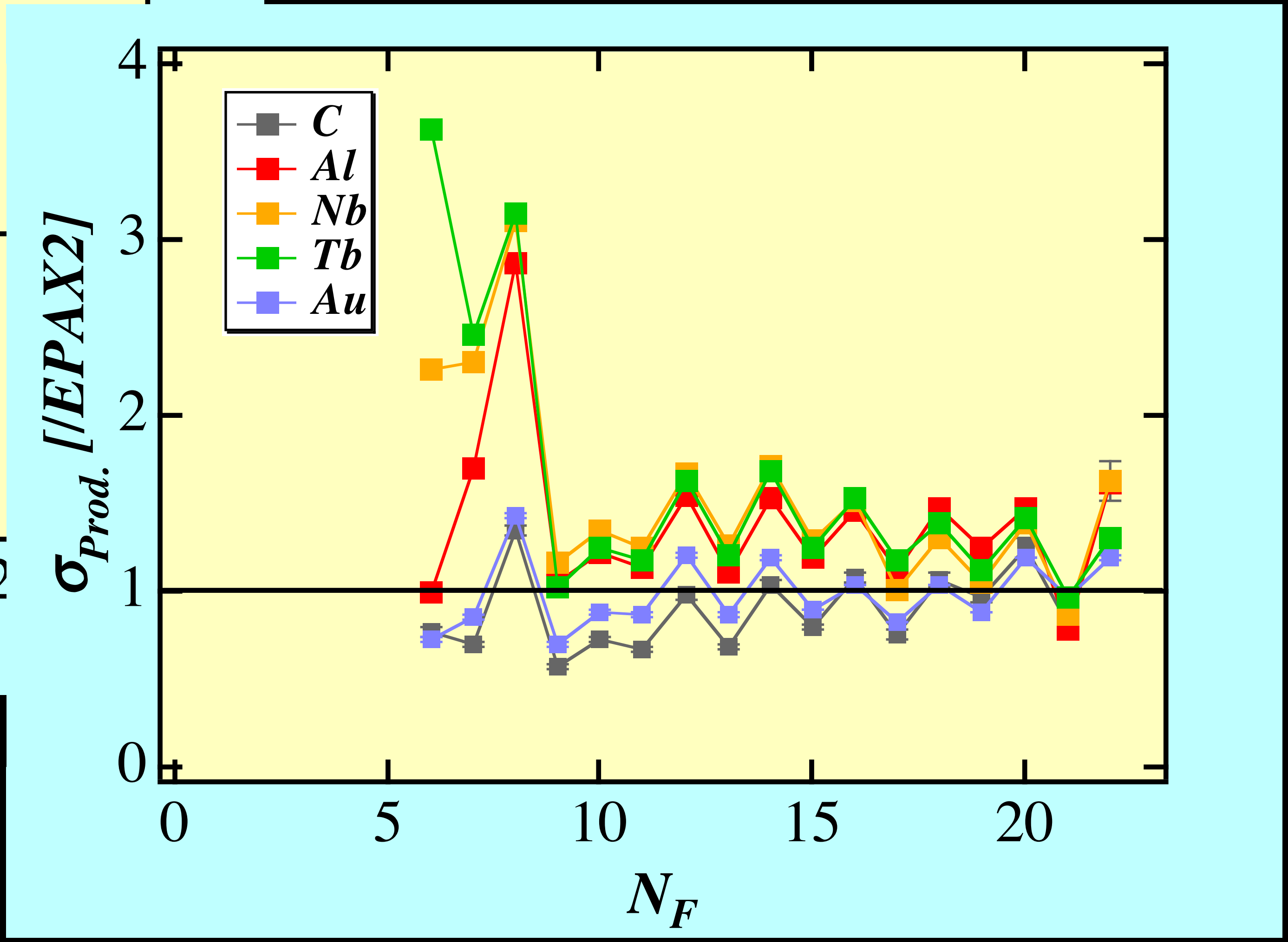
- Paring, Shell effect



Contribution of nucl. structure

- Paring, Shell effect





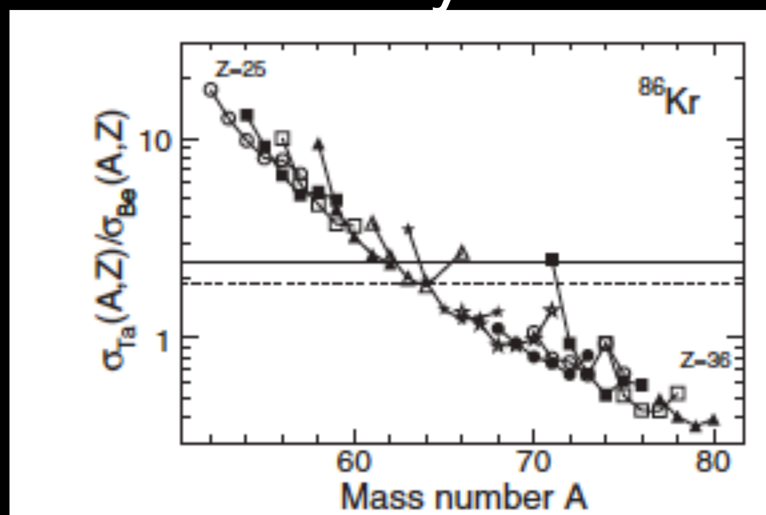
$\sigma_{Prod.}$ with Kr-beam

Measured and analysis in progress

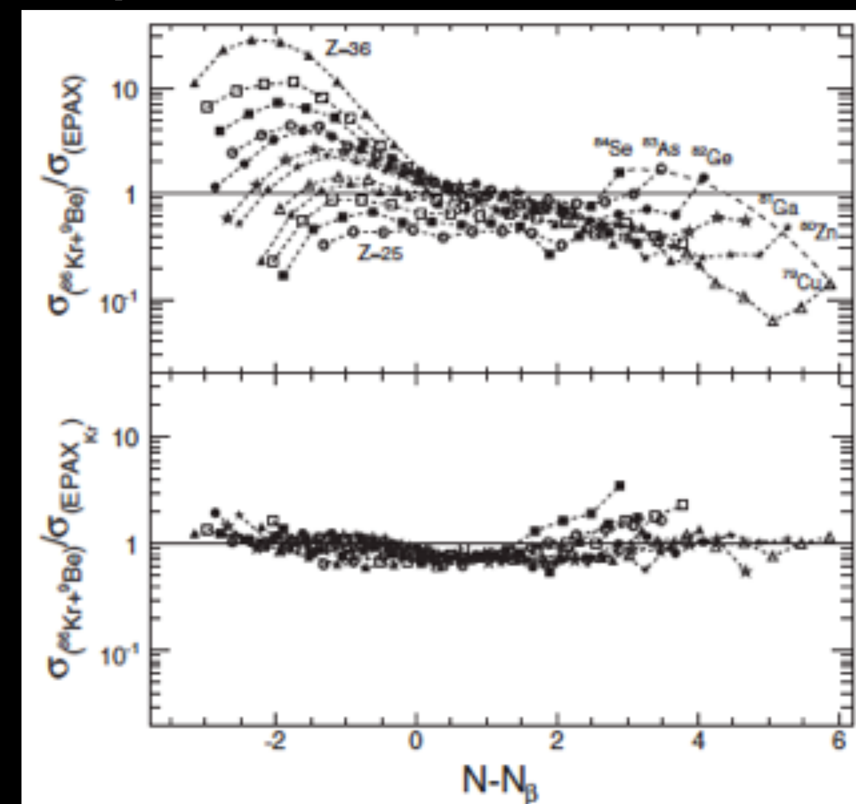
Modification of EPAX

- ^{86}Kr (64 MeV/u) + ^{9}Be, ^{181}Ta *M. Mocho et al.*, PRC 76 (2007) 014609.

Mass yield



Optimization of EPAX



Modification of EPAX

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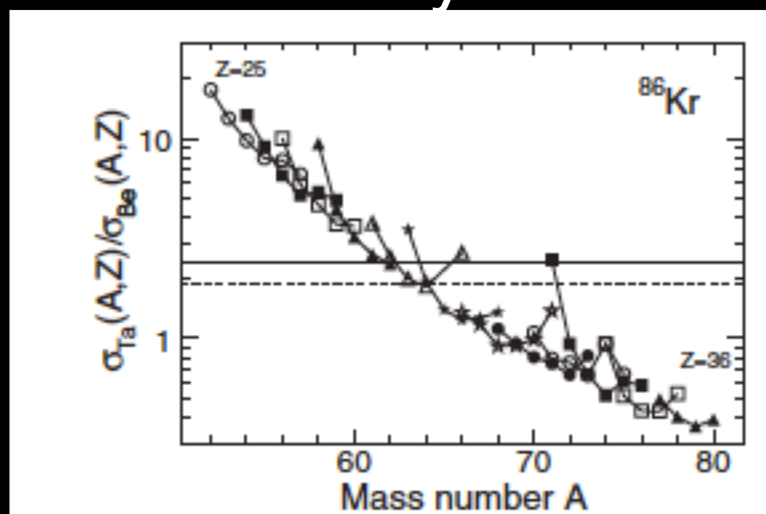
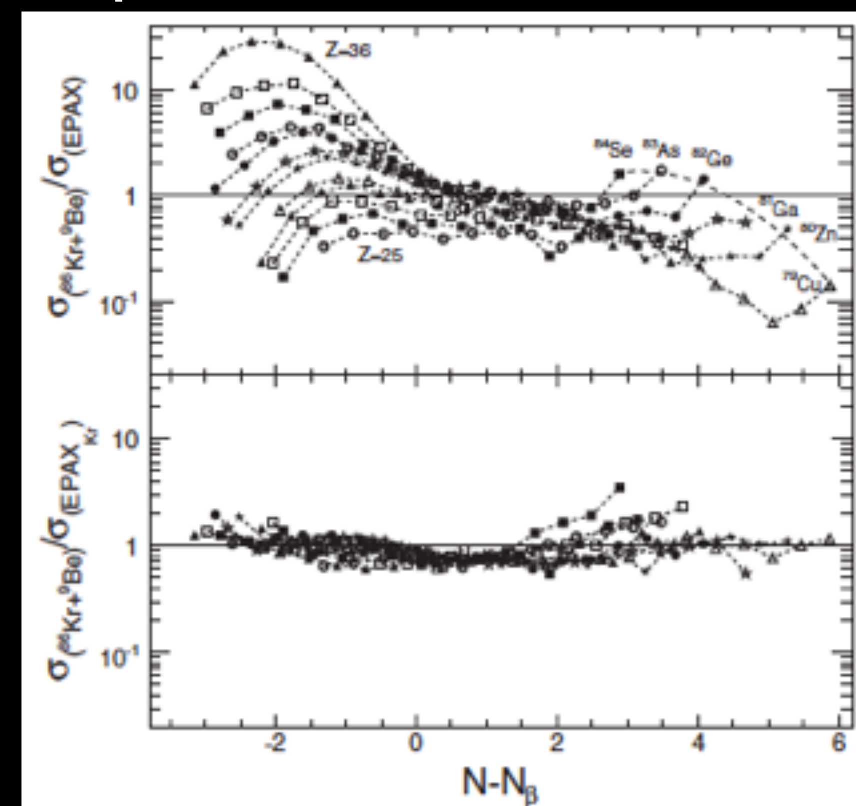


Optimization of EPAX



P_T distribution is assumed to be a simple Gaussian.

$$\sigma_\perp^2 = \sigma_0^2 \frac{A(A_P - A)}{A_P - 1} + \sigma_D^2 \frac{A(A-1)}{A_P(A_P-1)}$$

If the orbital deflection is considered, ...

Conclusions

At E = 90, 290 MeV/u

- P_L distribution
  - Lower side : contribution of other reaction processes
  - Higher side: well reproduced by Goldhaber formulation.
- P_T distribution
  - @95 MeV/u : contribution of other reaction processes
  - @290 MeV/u
    - Light targets : No additional dispersion
    - Heavy targets: Orbital deflection effect
- Production cross sections
  - Contribution of nuclear structure
  - Careful consideration to P_T distribution
  - Development of formulation/HI transport code

Thanks to

RIKEN: r280n collaboration

I. Tanihata, A. Ozawa, M. Notani, K. Yoshida,
K. Morimoto, T. Onishi, T. Yamaguchi, A. Yoshida,
Y.X. Watanabe, L. Zhong, and Y. Nojiri

NIRS: P078, P178 Collaboration

M. Kanazawa, A. Kitagawa, S. Sato, and M. Suda