Secondary nuclei and production cross sections in astrophysics of cosmic rays

Yoann Genolini

A work in collaboration with:
David Maurin, Igor Moskalenko and Michael Unger

Based on: **PhysRevC.98.034611**

CERN, November 2019

Outline

I- Motivations and state of the art

II- What are the most important cross-sections?

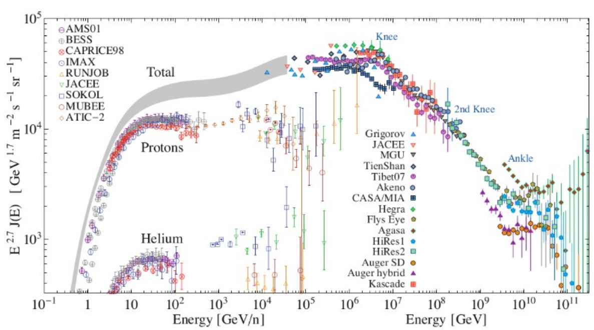
III- Priority order for a beam+fixed target experiment

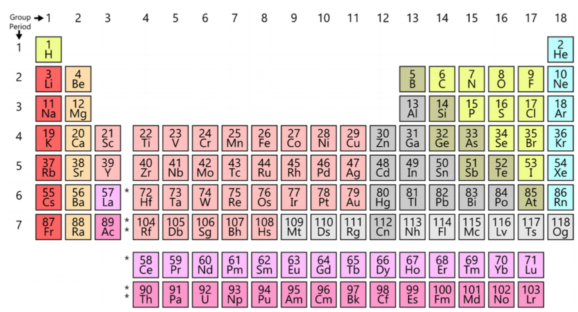
IV- Conclusions and prospects

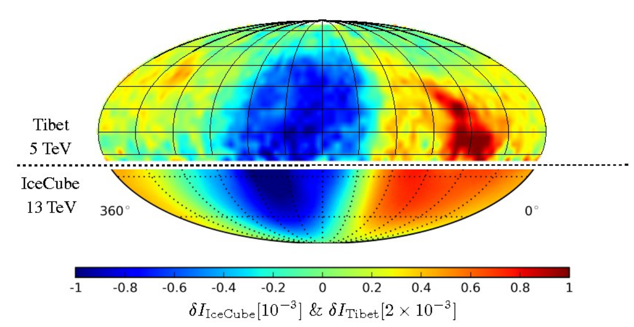
Charged cosmic-ray observables at Earth:

$$\Psi_i = \frac{dN_i}{dE\, dT\, d\Omega\, dS}$$

Energy | **Composition** | **Direction**







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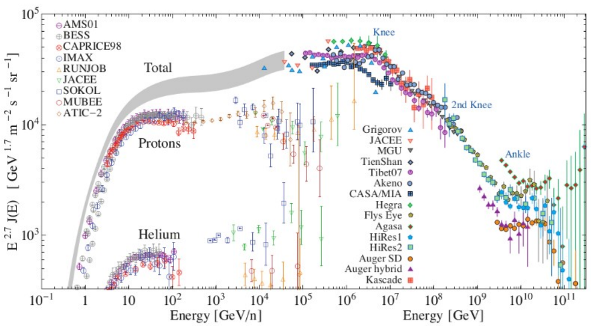
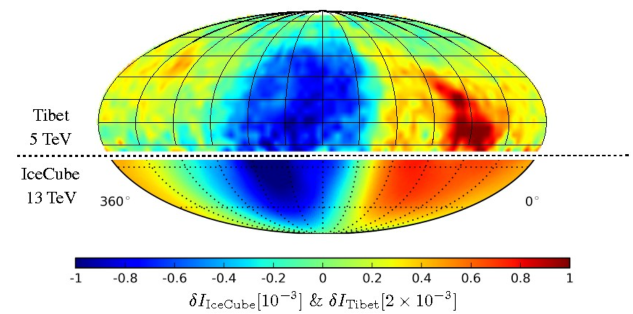


Ultimate information:

Flux for each isotope

Direction



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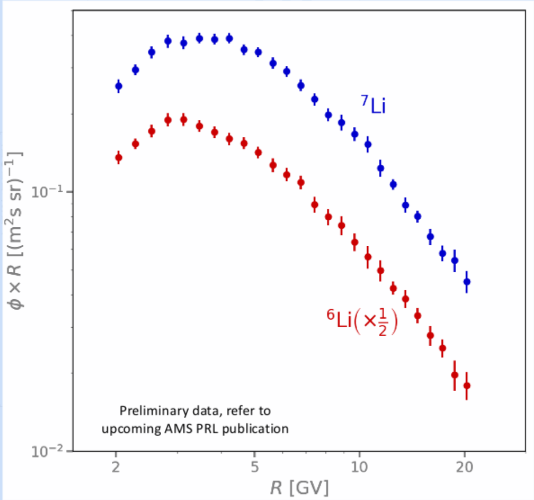
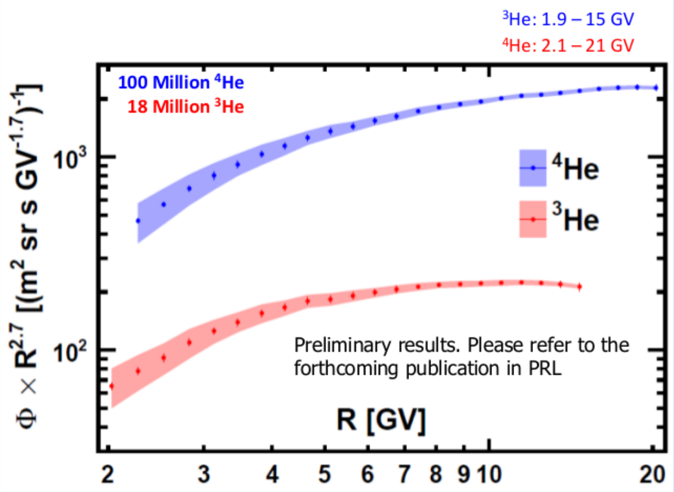
That is no longer a dream since this summer...



ICRC CRD6d L. Derome



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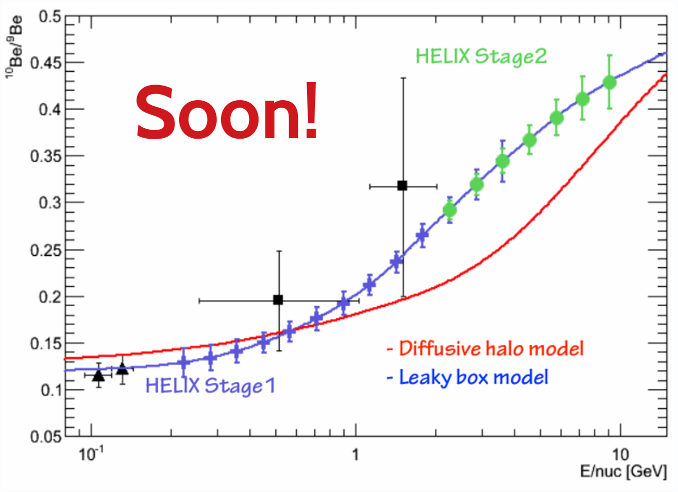

ICRC CRD6h N.Park

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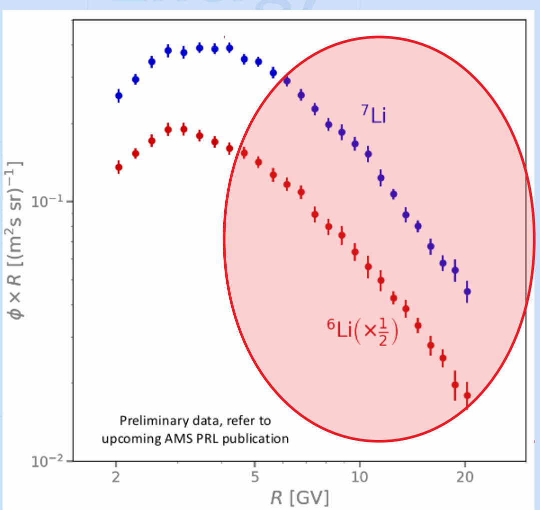

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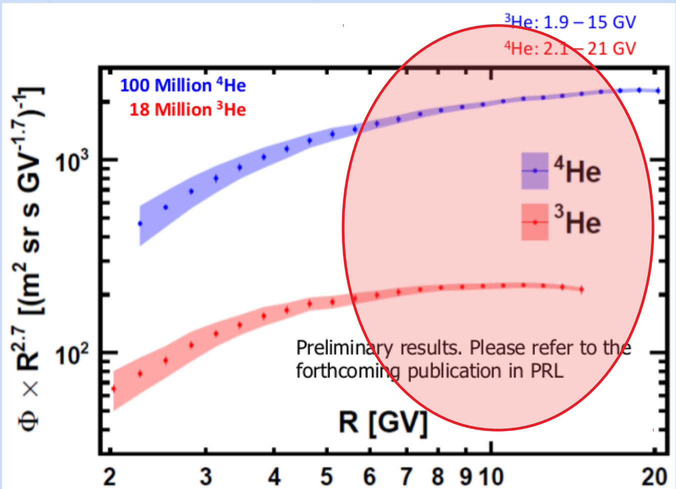

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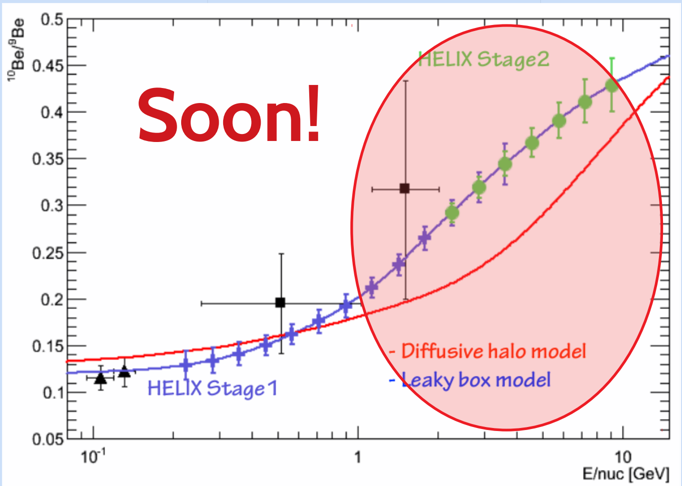

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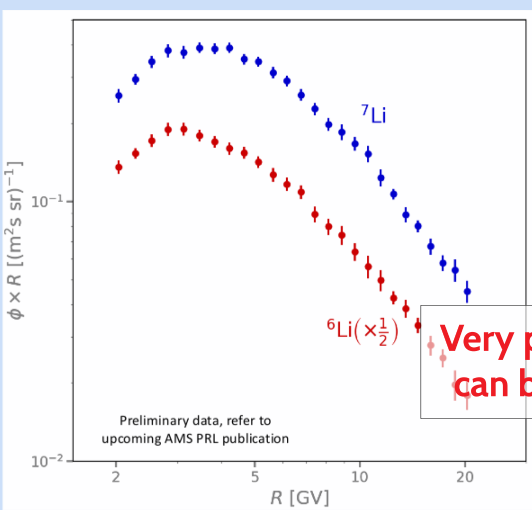

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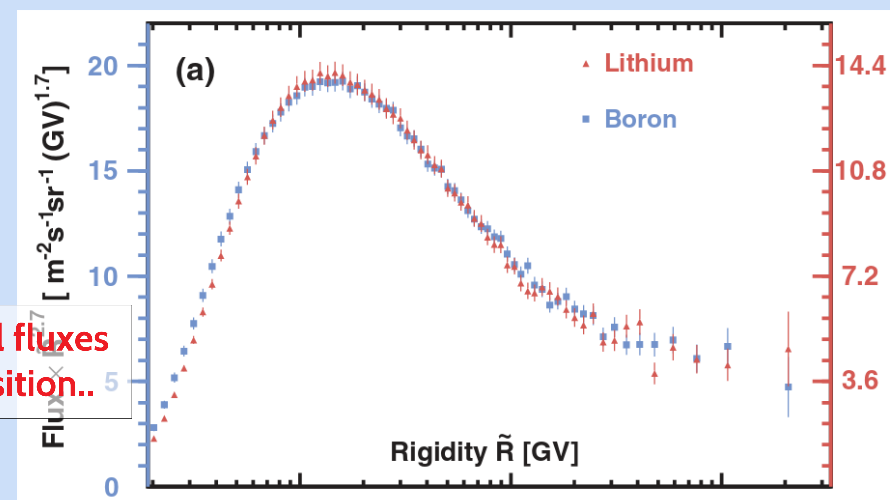
Very precice measurement of elemental fluxes can be sensitive to the isotopic composition..



AMS02 PRL 12021101 (2018)

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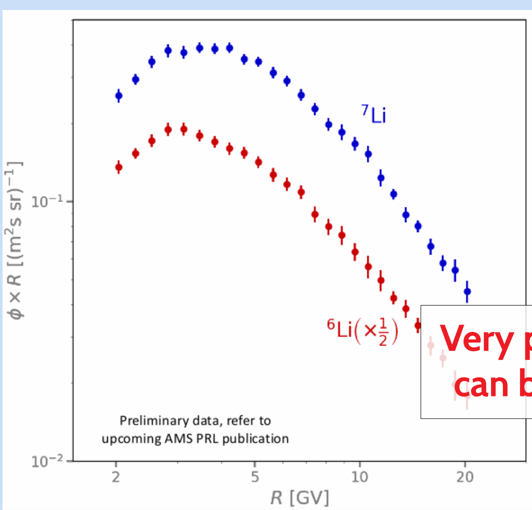

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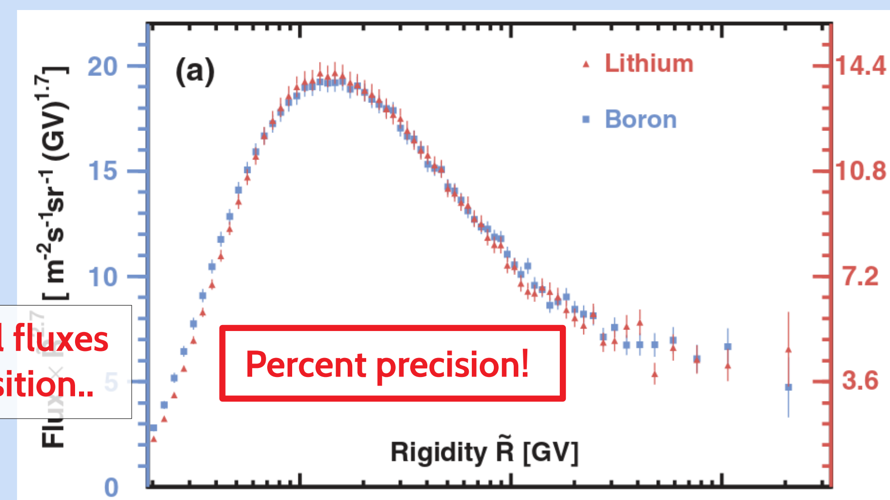

Percent precision!

AMS02 PRL 12021101 (2018)

Digging a little bit deeper:

$$\Psi_i = \frac{dN_i}{dR\,dT\,dS} = \mathcal{F}_i^{prop}\left(\mathcal{Q}_i^{inj}(R)\right) \approx \mathcal{N}_i R^{\gamma_i}$$

Measured!

Propagation:
- Galactic and ISM physics

Injection:
- Physics of sources (acceleration and escape)

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Convoluted information

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Measured!

Studied with:

Propagation:

Secondary CRs

^{2}H, ^{3}He, Li, Be, B..

Injection :

Primary CRs

H, He, C, O..

Digging a little bit deeper:

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Measured!

Propagation:
- Galactic and ISM physics

Injection :
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Assumptions in the following:

Diffusion and spallation

Power law injection

Fragmentation cross section

$$\sigma_{b\to a}$$

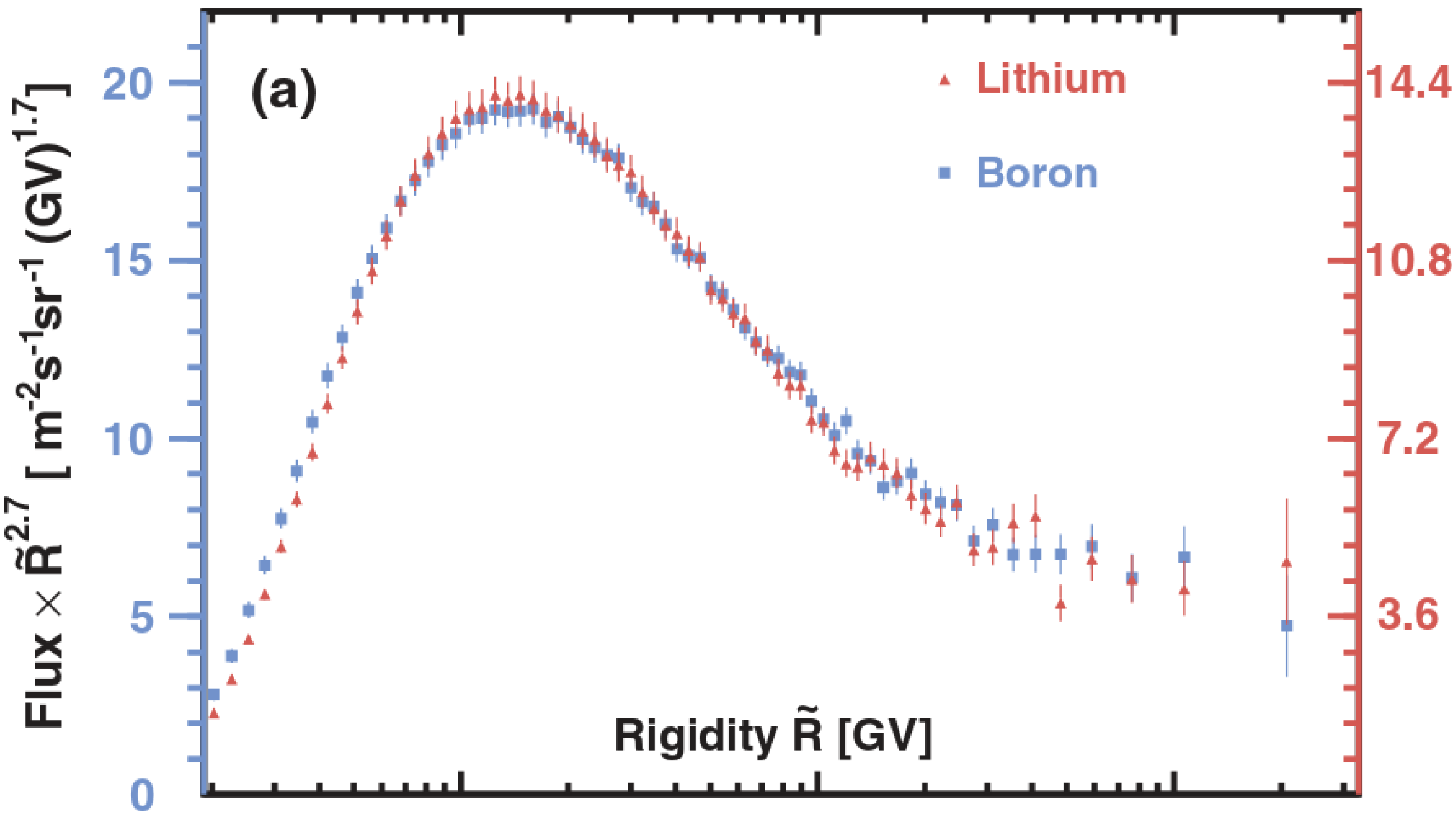
Inelastic cross section

$$\sigma_a$$

$$K(R) = K_0 \beta R^\delta$$

$$\mathcal{Q}_i^{inj}(R) = q_i R^{\alpha_i}$$

Secondary cosmic rays: the boron



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Secondary cosmic rays: the boron

$$B = {}^{10}B \; {}^{11}B$$

30 % + 70 %

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${}^{12}\mathrm{C}$ ${}^{13}\mathrm{C}$

$$\Psi_{\mathrm{B}} = \sum_{a>\mathrm{B}} \left(\frac{\sigma_{a\to{}^{10}\mathrm{B}}}{\mathcal{K}\; R^{\delta} + \sigma_{{}^{10}\mathrm{B}}(R)} + \frac{\sigma_{a\to{}^{11}\mathrm{B}}}{\mathcal{K}\; R^{\delta} + \sigma_{{}^{11}\mathrm{B}}(R)} \right) \Psi_{a}$$

Measured by detectors

Theoretical prediction in slab diffusion geometry

Measured isotopic flux

e.g. ${}^{12}\mathrm{C}$

Secondary cosmic rays: the boron

$$\mathrm{B} = {}^{10}\mathrm{B} \quad {}^{11}\mathrm{B} \qquad {}^{12}\mathrm{C} \quad {}^{13}\mathrm{C}$$

30 % + 70 %

Measured up to few percent!

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Inputs!

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Measured by detectors

Constraints on CR propagation parameters

Measured isotopic flux

e.g. $^{12}\mathrm{C}$

Secondary cosmic rays: the boron

$^{12}\mathrm{C}$ $^{13}\mathrm{C}$

$$\mathrm{B} = {}^{10}\mathrm{B} \; {}^{11}\mathrm{B}$$

30 % + 70 %

Measured up to few percent!

Inputs!.. large uncertainties

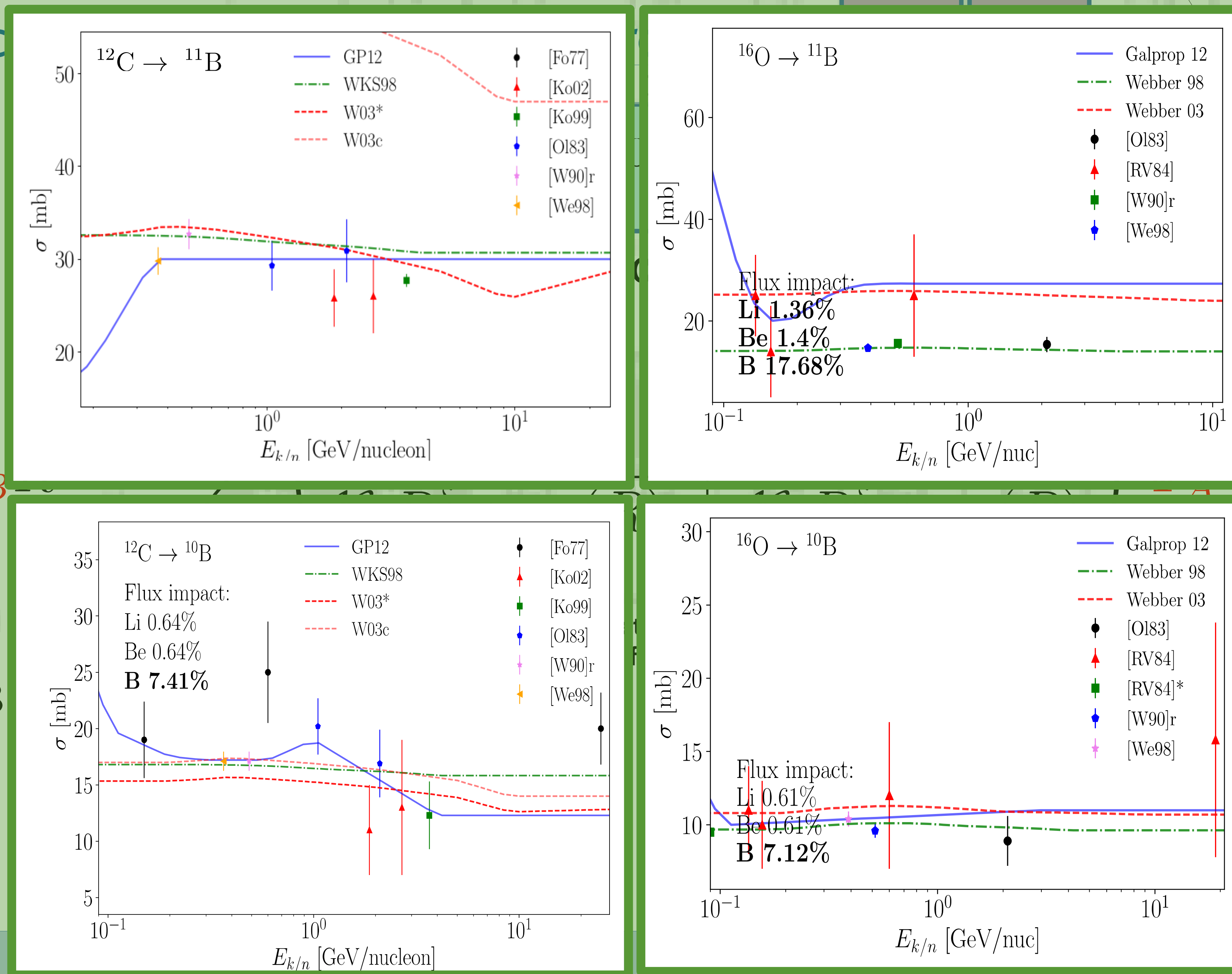
$$\Psi_{\mathrm{B}} = \sum_{a>\mathrm{B}} \left(\frac{\sigma_{a\to{}^{10}\mathrm{B}}}{\mathcal{K}\, R^{\delta} + \sigma_{{}^{10}\mathrm{B}}(R)} + \frac{\sigma_{a\to{}^{11}\mathrm{B}}}{\mathcal{K}\, R^{\delta} + \sigma_{{}^{11}\mathrm{B}}(R)} \right) \Psi_a$$

Measured by detectors

Measured isotopic flux

e.g. $^{12}\mathrm{C}$

Sec

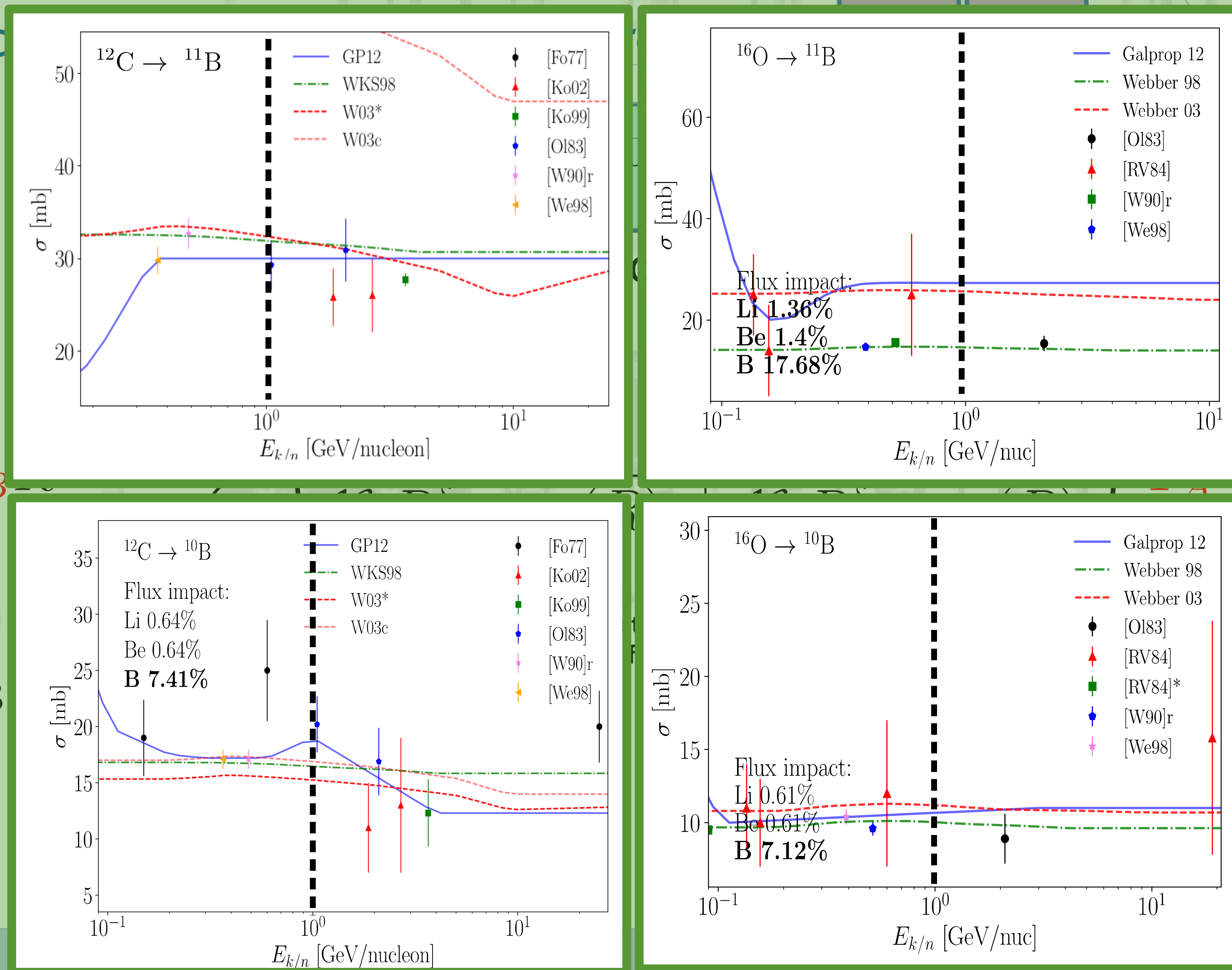


$\mathcal{N}_B$

Ψ_B

opic flux

Sec



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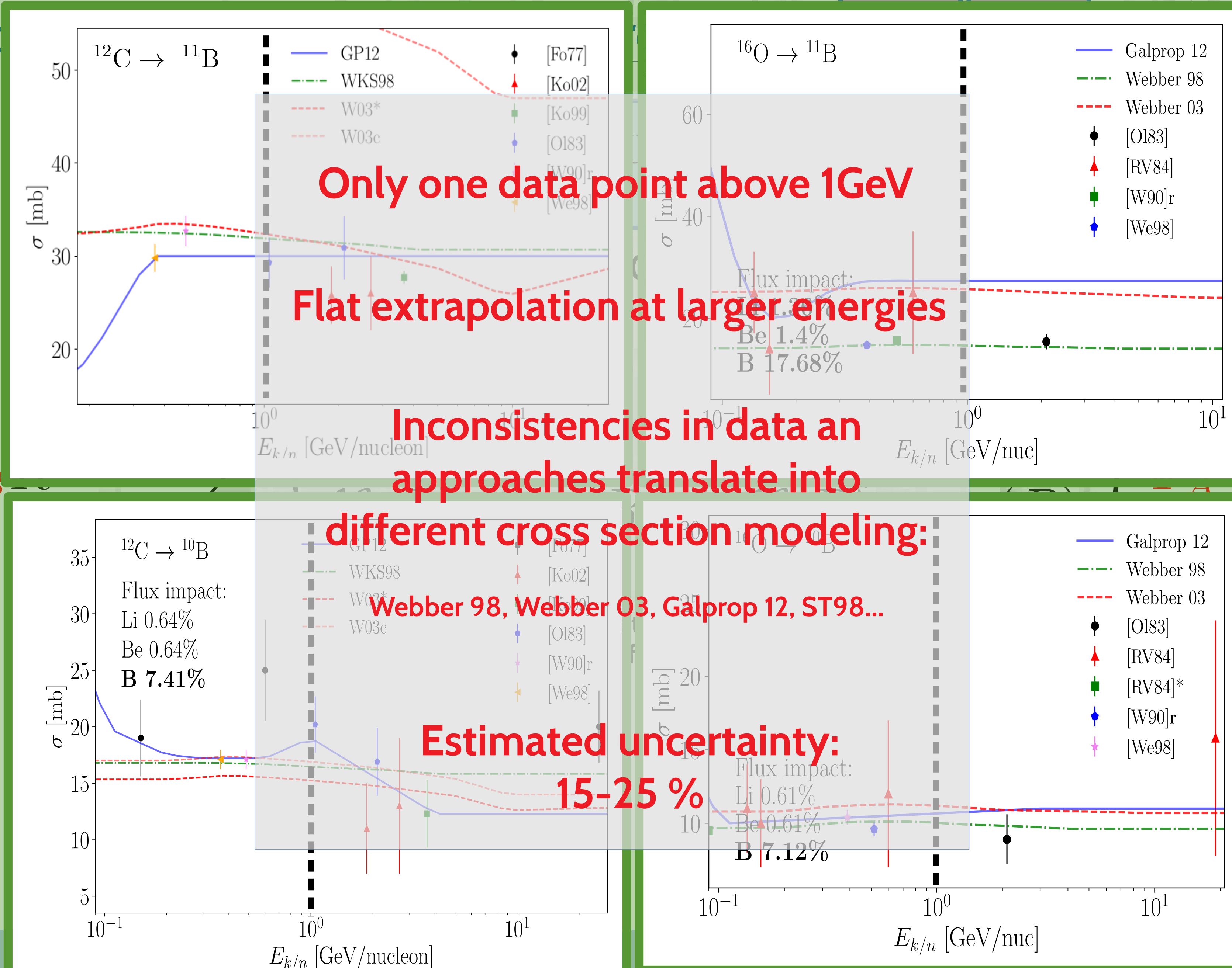


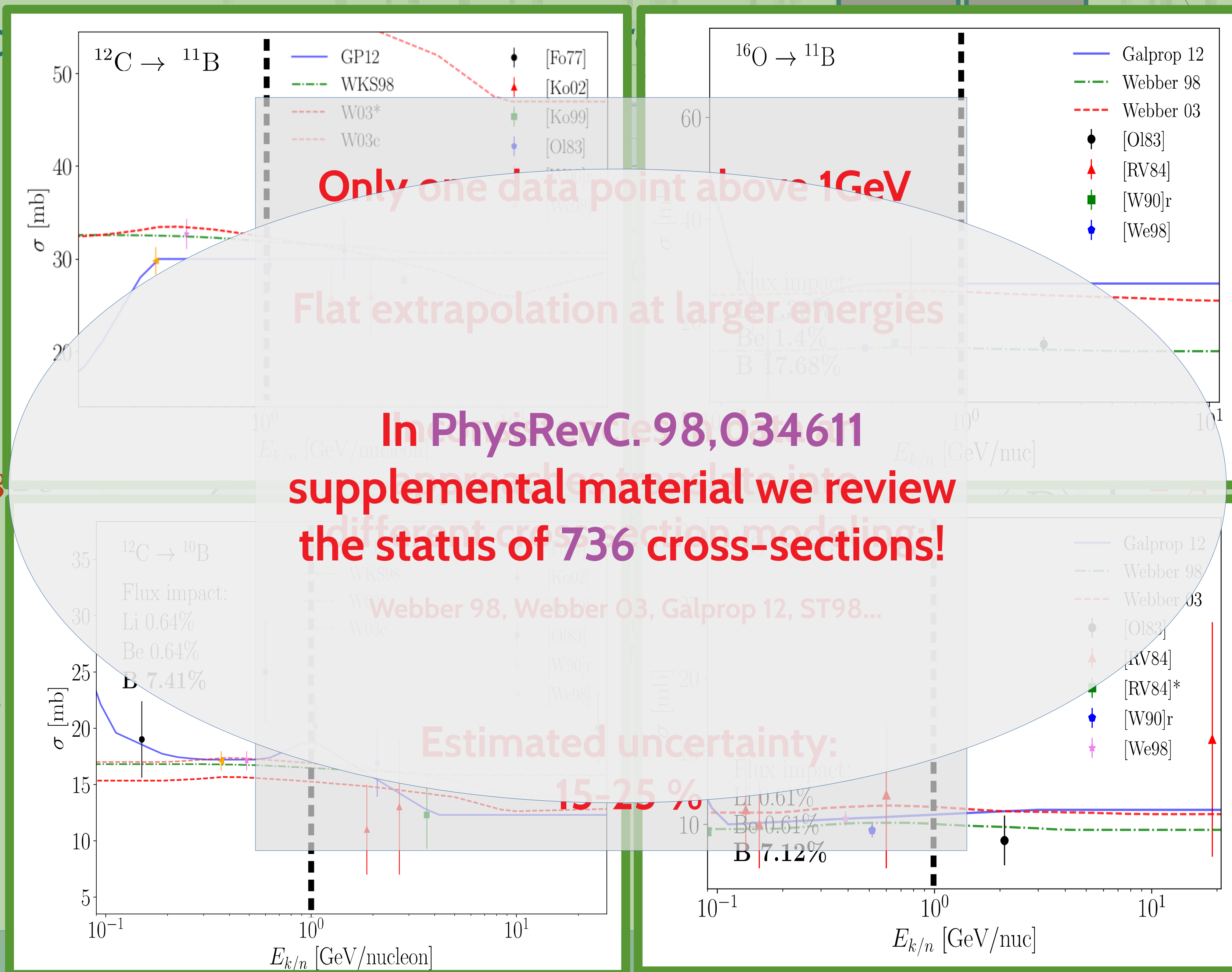
Only one data point above 1GeV

Flat extrapolation at larger energies

Inconsistencies in data an approaches translate into different cross section modeling:

Webber 98, Webber 03, Galprop 12, ST98...

Estimated uncertainty: 15-25 %



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In PhysRevC. 98,034611 supplemental material we review the status of 736 cross-sections!

Secondary cosmic rays: the boron

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$$\Psi_{\mathrm{B}} = \sum_{a>\mathrm{B}} \left(\frac{\sigma_{a\to{}^{10}\mathrm{B}}}{\mathcal{K}\ R^{\delta} + \sigma_{{}^{10}\mathrm{B}}(R)} + \frac{\sigma_{a\to{}^{11}\mathrm{B}}}{\mathcal{K}\ R^{\delta} + \sigma_{{}^{11}\mathrm{B}}(R)} \right) \Psi_a$$

Measured by detectors

Measured by detectors ?

Subtlety!

If only the flux by element is measured :
-> uncertainty on the isotopic contributions propagates!

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Measured by detectors

Measured by detectors ?

Subtlety!

Multisteps reactions matter!

e.g. $\sigma_{b\to a} \times \sigma_{a\to{}^{11}\mathrm{B}}$

Primary cosmic rays: the carbon

$^{12}\mathrm{C}$ $^{13}\mathrm{C}$

For now spectrometers (e.g AMS02) only measure C flux ..

$$\mathcal{N}_{\mathrm{C}} R^{\gamma_{\mathrm{C}}} = \left(\frac{f}{\mathcal{K}\, R^{\delta} + \sigma_1(R)} + \frac{1-f}{\mathcal{K}\, R^{\delta} + \sigma_2(R)} \right) q R^{\alpha}$$

Ψ_{C} Measured by detectors

Theoretical prediction in slab diffusion geometry

Uncertainties on cross-sections and propagation dominate

Carbon is not a pure primary → ~ 20 % of C is secondary!

i.e. : $^{16}\mathrm{O} + \mathrm{H} \rightarrow {}^{12}\mathrm{C}$

Underdetermined system.. required further assumptions:

$$\alpha_1 = \alpha_2 = \alpha \qquad q_1 = f\, q \qquad q_2 = (1-f)\, q$$

Universality hypothesis

Isotopic fraction at injection

Primary cosmic rays: the carbon

^{12}C ^{13}C

For now spectrometers (e.g AMS02) only measure C flux

$\mathcal{N}_C R^{\gamma_C} = \Big(\ldots \Big) qR^{\alpha}$

Ψ_C Measured by detectors

...inties on cross-sections ... propagation dominate

Carbon is not a pu... ...f C is secondary!

CR	% isotope	% of total flux Prim.	Frag.	Rad.	% of multistep secondaries 1	2	>2
Li		0	100	0	66	25	9
	(56%) ^{6}Li	0	100	0	66	25	9
	(44%) ^{7}Li	0	100	0	66	26	8
Be		0	100	0	73	20	7
	(63%) ^{7}Be	0	100	0	78	17	6
	(30%) ^{9}Be	0	100	0	65	26	9
	(6%) ^{10}Be	0	100	0	66	26	7
B		0	95	5	79	17	5
	(33%) ^{10}B	0	85	15	70	24	6
	(67%) ^{11}B	0	100	0	82	14	4
C		79	21	0	77	17	5
	(90%) ^{12}C	88	12	0	72	21	6
	(10%) ^{13}C	7	93	0	83	13	4
	(0.02%) ^{14}C	0	100	0	56	35	9
N		27	72	2	87	9	4
	(54%) ^{14}N	49	48	3	83	13	4
	(46%) ^{15}N	0	100	0	89	7	3

Underdeterm... i.e. ...sumptions:

$\alpha_1 = \alpha \ldots \quad q_2 = (1-f)\, q$

Universality hypothesis — Isotopic fraction at injection

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So far:

- Extracting physics information from CR fluxes requires a carefull treatment of systematics.
- Cross-sections are a major systematic, typical uncertainties of 15-25 % for $\sigma_{b\to a}$ and 5 % for σ_a .
- All CR nuclei break-up and contain a secondary component.
- When we do not measure isotopic fluxes, multistep reactions matter.

II- What are the most important fragmentation cross-sections?

Flux Impact

The flux of a given element *c* can be decomposed in two parts :

$$\Psi_c = \Psi_c^{prim} + \Psi_c^{sec}$$

Contains radioactive decay!

Flux impact f_{abc} of a cross section $\sigma_{a+b\to c}$:
relative variation of the flux when switching off this reaction.

$$f_{abc} = \frac{\Psi_c^{\rm sec}(\rm ref) - \Psi_c^{\rm sec}(\sigma_{a+b\to c} = 0)}{\Psi_c^{\rm sec}(\rm ref)}$$

Example: at 10 GeV/nuc for the boron flux, for $\sigma_{^{12}\mathrm{C+H}\to{}^{11}\mathrm{B}}$ **:**

$$f_{^{12}\mathrm{C,H},^{11}\mathrm{B}} = \mathbf{18.1}\%$$

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Mostly H and He targets in the ISM

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Example : case of boron

Reaction $a + b \to c$	Flux impact f_{abc} [%] min	**mean**	max	σ [mb] range	Data	σ^c/σ
$\sigma(^{12}C + H \to ^{11}B)$	18.0	**18.1**	19.0	30.0	✓	1.8
$\boldsymbol{\sigma(^{12}C + H \to ^{11}C)}$	16.0	**16.2**	17.0	26.9	✓	**n/a**
$\sigma(^{16}O + H \to ^{11}B)$	11.3	**11.8**	12.0	18.2	✓	1.5
$\sigma(^{12}C + H \to ^{10}B)$	7.20	**7.41**	7.60	12.3	✓	1.1
$\sigma(^{16}O + H \to ^{10}B)$	6.82	**7.03**	7.21	10.9	✓	
$\boldsymbol{\sigma(^{16}O + H \to ^{11}C)}$	5.67	**5.89**	6.00	9.1		**n/a**
$\sigma(^{11}B + H \to ^{10}B)$	4.00	**4.07**	4.20	38.9	✓	
$\sigma(^{12}C + He \to ^{11}B)$	2.50	**2.59**	2.70	38.6		1.8
$\boldsymbol{\sigma(^{12}C + He \to ^{11}C)}$	2.10	**2.14**	2.20	32.0		**n/a**
$\sigma(^{15}N + H \to ^{11}B)$	2.00	**2.03**	2.10	26.1	✓	1.2
$\boldsymbol{\sigma(^{12}C + H \to ^{10}C)}$	1.80	**1.87**	1.90	3.1	✓	**n/a**
$\sigma(^{16}O + He \to ^{11}B)$	1.67	**1.75**	1.80	24.4		1.5
$\sigma(^{13}C + H \to ^{11}B)$	1.50	**1.53**	1.60	22.2		1.7
$\sigma(^{12}C + H \to ^{10}Be)$	1.40	**1.48**	1.50	4.0	✓	
$\sigma(^{14}N + H \to ^{11}B)$	1.30	**1.34**	1.36	17.3	✓	1.7
$\sigma(^{12}C + He \to ^{10}B)$	1.00	**1.06**	1.10	15.8		1.1
$\sigma(^{16}O + He \to ^{10}B)$	0.99	**1.05**	1.09	14.6		
$\sigma(^{24}Mg + H \to ^{11}B)$	0.98	**1.01**	1.00	10.4		1.6

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Fluctuations using different cross-section parameterization.

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$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{11}\mathrm{B})$	11.3	**11.8**	12.0	18.2	✓	1.5
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{B})$	7.20	**7.41**	7.60	12.3	✓	1.1
$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{10}\mathrm{B})$	6.82	**7.03**	7.21	10.9	✓	
$\boldsymbol{\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{11}\mathrm{C})}$	5.67	**5.89**	6.00	9.1		**n/a**
$\sigma(^{11}\mathrm{B}+\mathrm{H}\to{}^{10}\mathrm{B})$	4.00	**4.07**	4.20	38.9	✓	
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{11}\mathrm{B})$	2.50	**2.59**	2.70	38.6		1.8
$\boldsymbol{\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{11}\mathrm{C})}$	2.10	**2.14**	2.20	32.0		**n/a**
$\sigma(^{15}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{B})$	2.00	**2.03**	2.10	26.1	✓	1.2
$\boldsymbol{\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{C})}$	1.80	**1.87**	1.90	3.1	✓	**n/a**
$\sigma(^{16}\mathrm{O}+\mathrm{He}\to{}^{11}\mathrm{B})$	1.67	**1.75**	1.80	24.4		1.5
$\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{11}\mathrm{B})$	1.50	**1.53**	1.60	22.2		1.7
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{Be})$	1.40	**1.48**	1.50	4.0	✓	
$\sigma(^{14}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{B})$	1.30	**1.34**	1.36	17.3	✓	1.7
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{10}\mathrm{B})$	1.00	**1.06**	1.10	15.8		1.1
$\sigma(^{16}\mathrm{O}+\mathrm{He}\to{}^{10}\mathrm{B})$	0.99	**1.05**	1.09	14.6		
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.98	**1.01**	1.00	10.4		1.6

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Expected value (from Galprop parameterization).

Example : case of boron

Reaction $a + b \to c$	Flux impact f_{abc} [%] min	**mean**	max	σ [mb] range	Data	σ^c/σ
$\sigma(^{12}C + H \to ^{11}B)$	18.0	**18.1**	19.0	30.0	✓	1.8
$\sigma(\mathbf{^{12}C + H \to ^{11}C})$	16.0	**16.2**	17.0	26.9	✓	n/a
$\sigma(^{16}O + H \to ^{11}B)$	11.3	**11.8**	12.0	18.2	✓	1.5
$\sigma(^{12}C + H \to ^{10}B)$	7.20	**7.41**	7.60	12.3	✓	1.1
$\sigma(^{16}O + H \to ^{10}B)$	6.82	**7.03**	7.21	10.9	✓	
$\sigma(\mathbf{^{16}O + H \to ^{11}C})$	5.67	**5.89**	6.00	9.1		n/a
$\sigma(^{11}B + H \to ^{10}B)$	4.00	**4.07**	4.20	38.9	✓	
$\sigma(^{12}C + He \to ^{11}B)$	2.50	**2.59**	2.70	38.6		1.8
$\sigma(\mathbf{^{12}C + He \to ^{11}C})$	2.10	**2.14**	2.20	32.0		n/a
$\sigma(^{15}N + H \to ^{11}B)$	2.00	**2.03**	2.10	26.1	✓	1.2
$\sigma(\mathbf{^{12}C + H \to ^{10}C})$	1.80	**1.87**	1.90	3.1	✓	n/a
$\sigma(^{16}O + He \to ^{11}B)$	1.67	**1.75**	1.80	24.4		1.5
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$\sigma(^{12}C + H \to ^{10}Be)$	1.40	**1.48**	1.50	4.0	✓	
$\sigma(^{14}N + H \to ^{11}B)$	1.30	**1.34**	1.36	17.3	✓	1.7
$\sigma(^{12}C + He \to ^{10}B)$	1.00	**1.06**	1.10	15.8		1.1
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$\sigma(^{24}Mg + H \to ^{11}B)$	0.98	**1.01**	1.00	10.4		1.6

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Are there any data? -> In the Supplemental Material.

Example : case of boron

Reaction $a+b\rightarrow c$	Flux impact f_{abc} [%] min	mean	max	σ [mb] range	Data	σ^c/σ
$\sigma(^{12}C+H\rightarrow^{11}B)$	18.0	**18.1**	19.0	30.0	✓	1.8
$\sigma(^{\mathbf{12}}\mathbf{C}+\mathbf{H}\rightarrow^{\mathbf{11}}\mathbf{C})$	16.0	**16.2**	17.0	26.9	✓	n/a
$\sigma(^{16}O+H\rightarrow^{11}B)$	11.3	**11.8**	12.0	18.2	✓	1.5
$\sigma(^{12}C+H\rightarrow^{10}B)$	7.20	**7.41**	7.60	12.3	✓	1.1
$\sigma(^{16}O+H\rightarrow^{10}B)$	6.82	**7.03**	7.21	10.9	✓	
$\sigma(^{\mathbf{16}}\mathbf{O}+\mathbf{H}\rightarrow^{\mathbf{11}}\mathbf{C})$	5.67	**5.89**	6.00	9.1		n/a
$\sigma(^{11}B+H\rightarrow^{10}B)$	4.00	**4.07**	4.20	38.9	✓	
$\sigma(^{12}C+He\rightarrow^{11}B)$	2.50	**2.59**	2.70	38.6		1.8
$\sigma(^{\mathbf{12}}\mathbf{C}+\mathbf{He}\rightarrow^{\mathbf{11}}\mathbf{C})$	2.10	**2.14**	2.20	32.0		n/a
$\sigma(^{15}N+H\rightarrow^{11}B)$	2.00	**2.03**	2.10	26.1	✓	1.2
$\sigma(^{\mathbf{12}}\mathbf{C}+\mathbf{H}\rightarrow^{\mathbf{10}}\mathbf{C})$	1.80	**1.87**	1.90	3.1	✓	n/a
$\sigma(^{16}O+He\rightarrow^{11}B)$	1.67	**1.75**	1.80	24.4		1.5
$\sigma(^{13}C+H\rightarrow^{11}B)$	1.50	**1.53**	1.60	22.2		1.7
$\sigma(^{12}C+H\rightarrow^{10}Be)$	1.40	**1.48**	1.50	4.0	✓	
$\sigma(^{14}N+H\rightarrow^{11}B)$	1.30	**1.34**	1.36	17.3	✓	1.7
$\sigma(^{12}C+He\rightarrow^{10}B)$	1.00	**1.06**	1.10	15.8		1.1
$\sigma(^{16}O+He\rightarrow^{10}B)$	0.99	**1.05**	1.09	14.6		
$\sigma(^{24}Mg+H\rightarrow^{11}B)$	0.98	**1.01**	1.00	10.4		1.6

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Including short-lived nuclei

Flux impacts for other elements Li, Be, B, C, N

Li

Reaction $a + b \to c$	Flux impact f_{abc} [%] min	**mean**	max	σ [mb] range	Data	σ^c/σ
$\sigma(^{12}C + H \to {}^{6}Li)$	11.0	**13.6**	16.0	14.0	✓	
$\sigma(^{16}O + H \to {}^{6}Li)$	11.0	**13.5**	16.0	13.0	✓	
$\sigma(^{12}C + H \to {}^{7}Li)$	10.0	**11.9**	14.0	12.6	✓	
$\sigma(^{16}O + H \to {}^{7}Li)$	9.6	**11.3**	13.0	11.2	✓	
$\sigma(^{11}B + H \to {}^{7}Li)$	3.00	**3.53**	4.00	21.5	✓	

Be

Reaction $a + b \to c$	Flux impact f_{abc} [%] min	**mean**	max	σ [mb] range	Data	σ^c/σ
$\sigma(^{16}O + H \to {}^{7}Be)$	17.0	**17.6**	19.0	10.0	✓	
$\sigma(^{12}C + H \to {}^{7}Be)$	15.0	**15.9**	17.0	9.7	✓	
$\sigma(^{12}C + H \to {}^{9}Be)$	8.80	**9.27**	9.80	6.8	✓	
$\sigma(^{16}O + H \to {}^{9}Be)$	5.00	**5.34**	5.60	3.7	✓	
$\sigma(^{16}O + He \to {}^{7}Be)$	2.70	**2.87**	3.00	14.7		

B

Reaction $a + b \to c$	Flux impact f_{abc} [%] min	**mean**	max	σ [mb] range	Data	σ^c/σ
$\sigma(^{12}C + H \to {}^{11}B)$	18.0	**18.1**	19.0	30.0	✓	1.8
$\boldsymbol{\sigma(^{12}C + H \to {}^{11}C)}$	16.0	**16.2**	17.0	26.9	✓	**n/a**
$\sigma(^{16}O + H \to {}^{11}B)$	11.3	**11.8**	12.0	18.2	✓	1.5
$\sigma(^{12}C + H \to {}^{10}B)$	7.20	**7.41**	7.60	12.3	✓	1.1
$\sigma(^{16}O + H \to {}^{10}B)$	6.82	**7.03**	7.21	10.9	✓	
$\boldsymbol{\sigma(^{16}O + H \to {}^{11}C)}$	5.67	**5.89**	6.00	9.1		**n/a**
$\sigma(^{11}B + H \to {}^{10}B)$	4.00	**4.07**	4.20	38.9	✓	

Flux impacts for other elements Li, Be, B, C, N

Li

Reaction $a + b \to c$	Flux impact f_{abc} [%] min	mean	max	σ [mb] range	Data	σ^c/σ
$\sigma(^{12}C + H \to ^{6}Li)$	11.0	**13.6**	16.0	14.0	✓	
$\sigma(^{16}O + H \to ^{6}Li)$	11.0	**13.5**	16.0	13.0	✓	
$\sigma(^{12}C + H \to ^{7}Li)$	10.0	**11.9**	14.0	12.6	✓	
$\sigma(^{16}O + H \to ^{7}Li)$	9.6	**11.3**	13.0	11.2	✓	
$\sigma(^{11}B + H \to ^{7}Li)$	[illegible]	[illegible]	[illegible]	[illegible]	✓	

This ranking have been used to identify relevant nuisance parameters in B/C fits.

Derome et al. A&A 627, A158 (2019)
Genolini et al. PRD 99, 123028 (2019)

Be

Reaction $a + b \to c$	Flux impact f_{abc} [%] min	mean	max	σ [mb] range	Data	σ^c/σ
$\sigma(^{16}O + H \to ^{7}Be)$	17.0	**17.6**	19.0	10.0	✓	
$\sigma(^{12}C + H \to ^{7}Be)$	[illegible]	[illegible]	[illegible]	9.7	✓	
$\sigma(^{12}C + H \to ^{9}Be)$	[illegible]	[illegible]	[illegible]	6.8	✓	
$\sigma(^{16}O + H \to ^{9}Be)$	5.00	**5.34**	5.60	3.7	✓	
$\sigma(^{16}O + He \to ^{7}Be)$	2.70	**2.87**	3.00	14.7		

B

Reaction $a + b \to c$	Flux impact f_{abc} [%] min	mean	max	σ [mb] range	Data	σ^c/σ
$\sigma(^{12}C + H \to ^{11}B)$	18.0	**18.1**	19.0	30.0	✓	1.8
$\boldsymbol{\sigma(^{12}C + H \to ^{11}C)}$	16.0	**16.2**	17.0	26.9	✓	**n/a**
$\sigma(^{16}O + H \to ^{11}B)$	11.3	**11.8**	12.0	18.2	✓	1.5
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$\sigma(^{16}O + H \to ^{10}B)$	6.82	**7.03**	7.21	10.9	✓	
$\boldsymbol{\sigma(^{16}O + H \to ^{11}C)}$	5.67	**5.89**	6.00	9.1		**n/a**
$\sigma(^{11}B + H \to ^{10}B)$	4.00	**4.07**	4.20	38.9	✓	

III - Priority order for a beam+fixed target experiment

III - Priority order for a beam+fixed target experiment

-> At which reaction shall we stop?

Propagating the uncertainty to the flux:

At a given energy, consider the variation of the flux :

$$d\psi_{\mathrm{B}} = \sum_{a,b,c} \frac{\partial \psi_{\mathrm{B}}}{\partial \sigma^{abc}}\, d\sigma^{abc}$$

Introducing the flux impact f_{abc} :

$$\left(\frac{\Delta\psi_{\mathrm{B}}}{\psi_{\mathrm{B}}}\right) \approx \sum_{a,b,c} f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}$$

Example: with f_{abc} = 10% and a relative uncertainty of 10% for the cross section, the uncertainty on the flux is of 1%.

Uncertainties of cross sections : several cases

Correlated case:

$$\left(\frac{\Delta\psi_{\rm B}}{\psi_{\rm B}}\right)^{\rm corr} \approx \sum_{a,b,c} f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}$$

Uncorrelated case:

$$\left(\frac{\Delta\psi_{\rm B}}{\psi_{\rm B}}\right)^{\rm uncorr} \approx \sqrt{\sum_{a,b,c} \left(f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}\right)^2}$$

***Realistic* case:**

$$\left(\frac{\Delta\psi_{\rm B}}{\psi_{\rm B}}\right)^{\rm mix} \approx \sum_{a} \sqrt{\sum_{b,c} \left(f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}\right)^2}$$

→ Correlated projectile & uncorrelated fragments.

Uncertainties of cross sections : several cases

Assumed to be 20 %

Correlated case:

$$\left(\frac{\Delta\psi_{\rm B}}{\psi_{\rm B}}\right)^{\rm corr} \approx \sum_{a,b,c} f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}$$

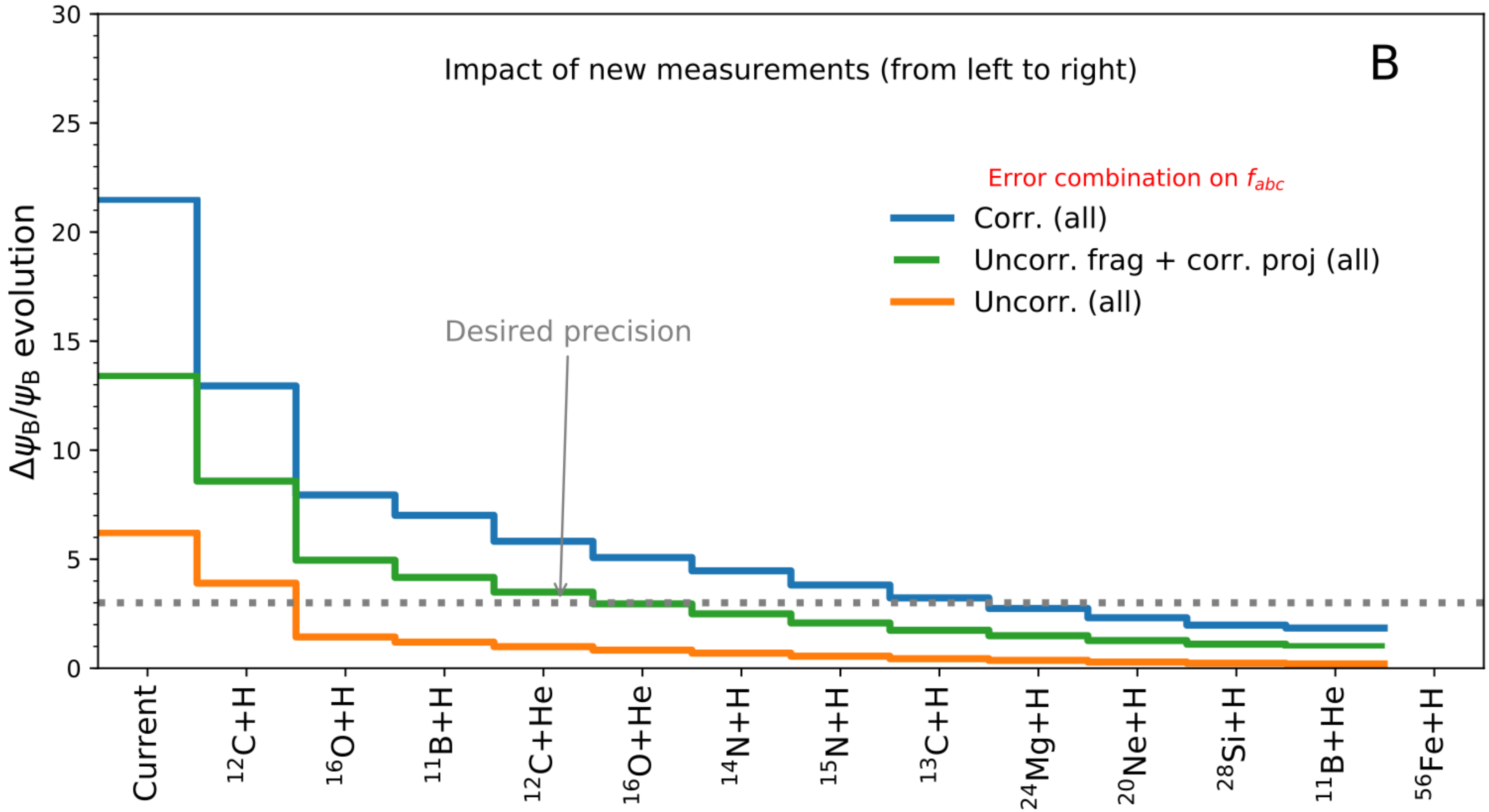
Uncorrelated case:

$$\left(\frac{\Delta\psi_{\rm B}}{\psi_{\rm B}}\right)^{\rm uncorr} \approx \sqrt{\sum_{a,b,c} \left(f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}\right)^2}$$

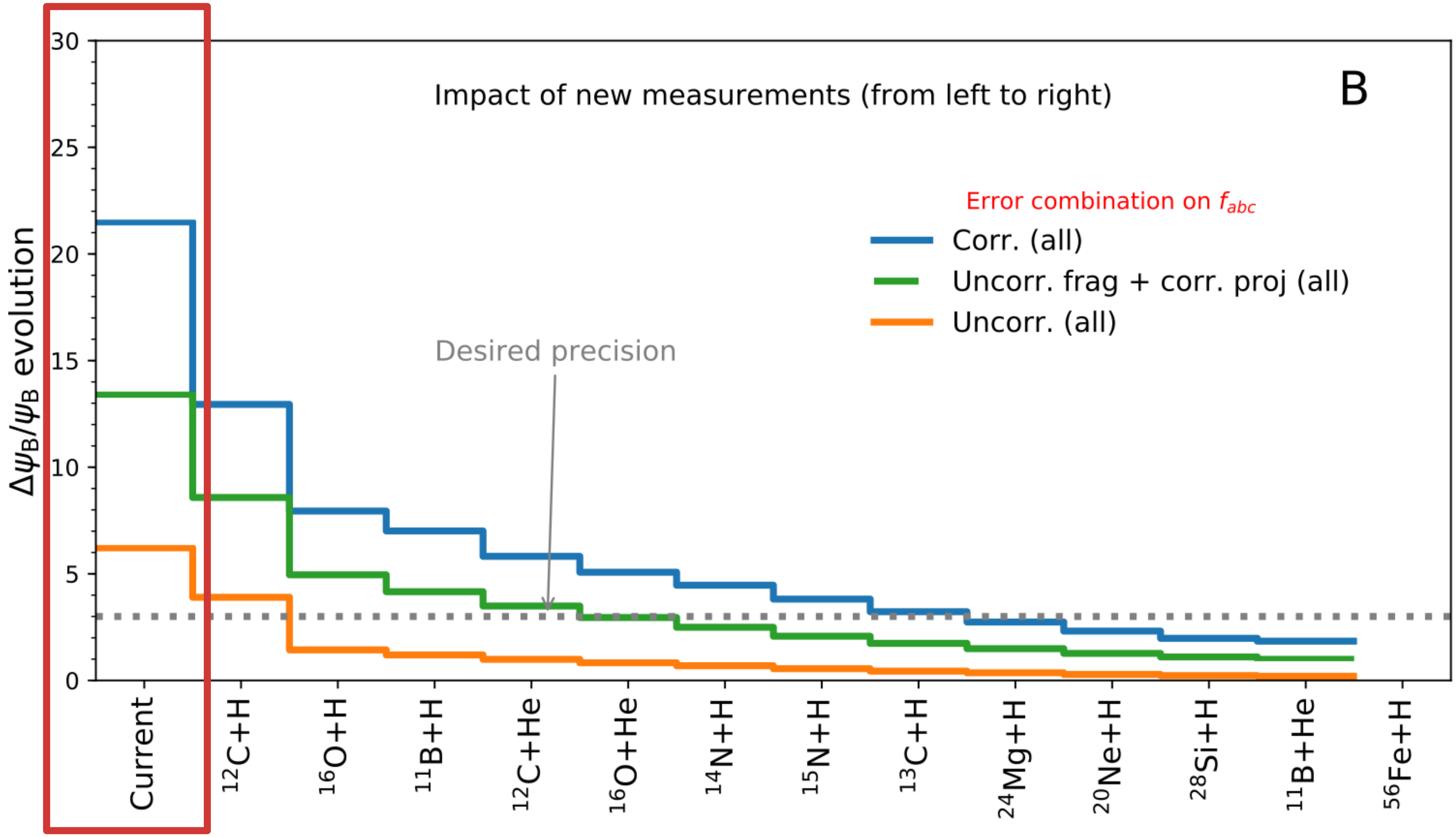
***Realistic* case:**

$$\left(\frac{\Delta\psi_{\rm B}}{\psi_{\rm B}}\right)^{\rm mix} \approx \sum_{a} \sqrt{\sum_{b,c} \left(f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}\right)^2}$$

Beam + fix target experiment

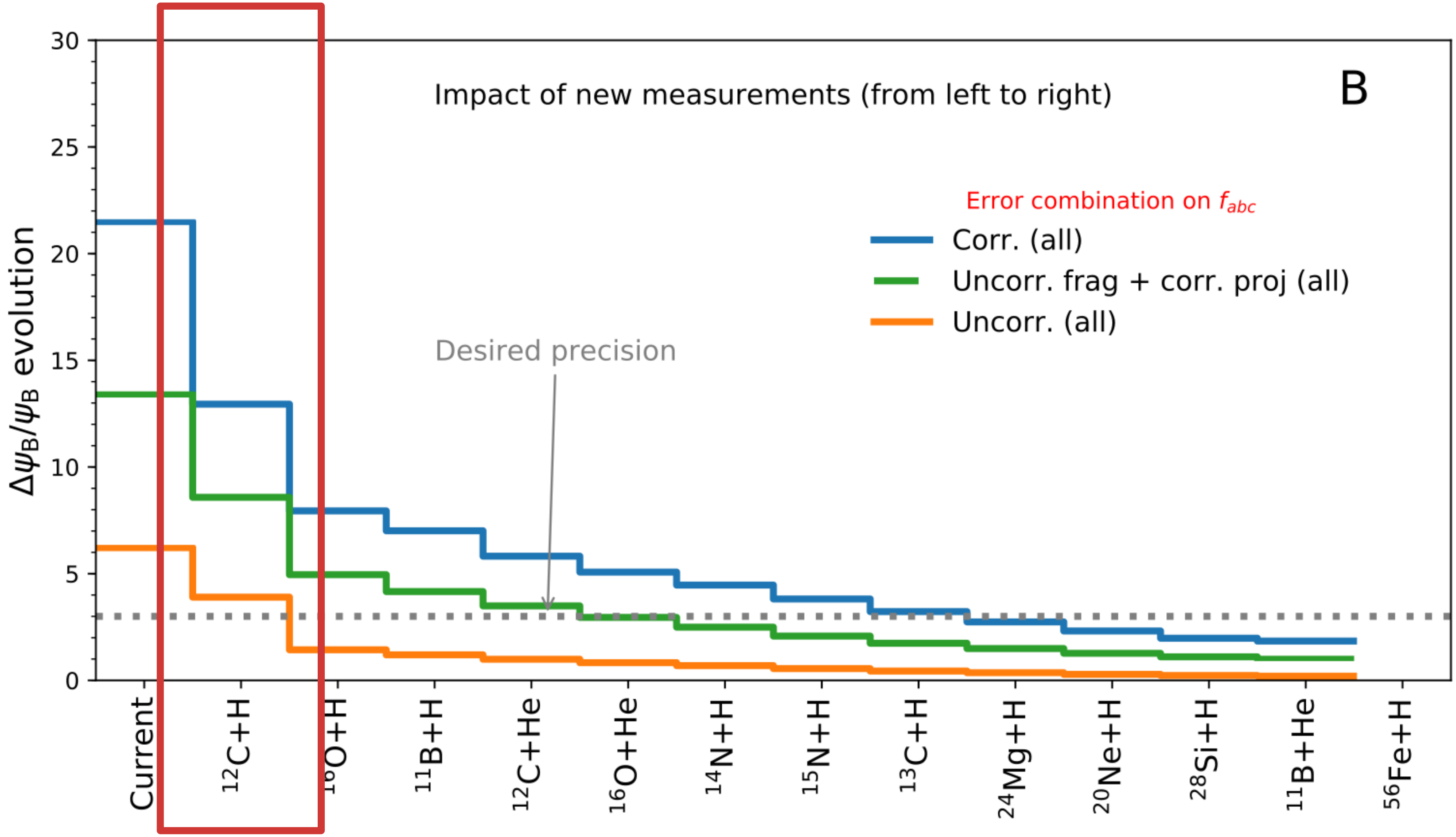


Beam + fix target experiment



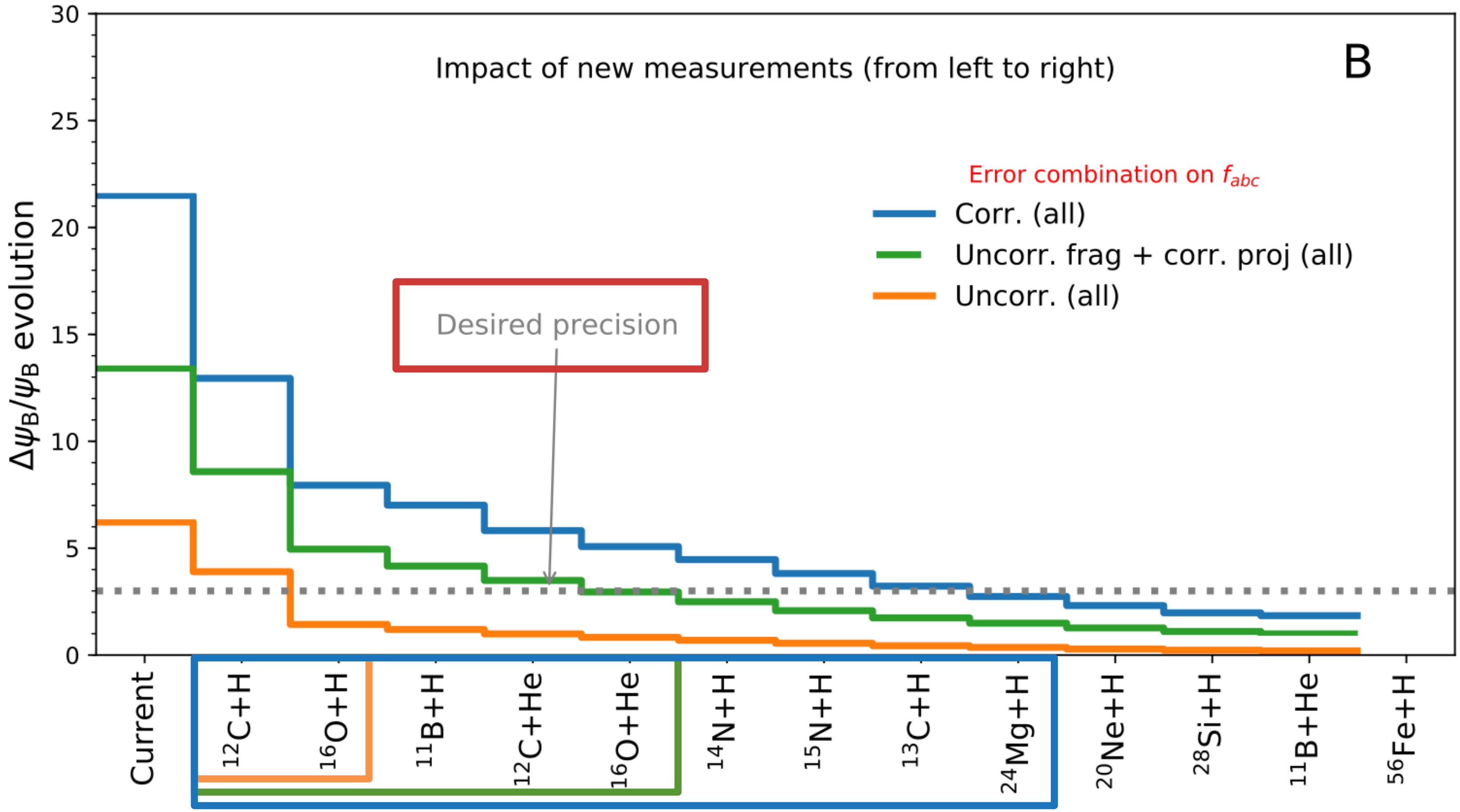
Current status

Beam + fix target experiment

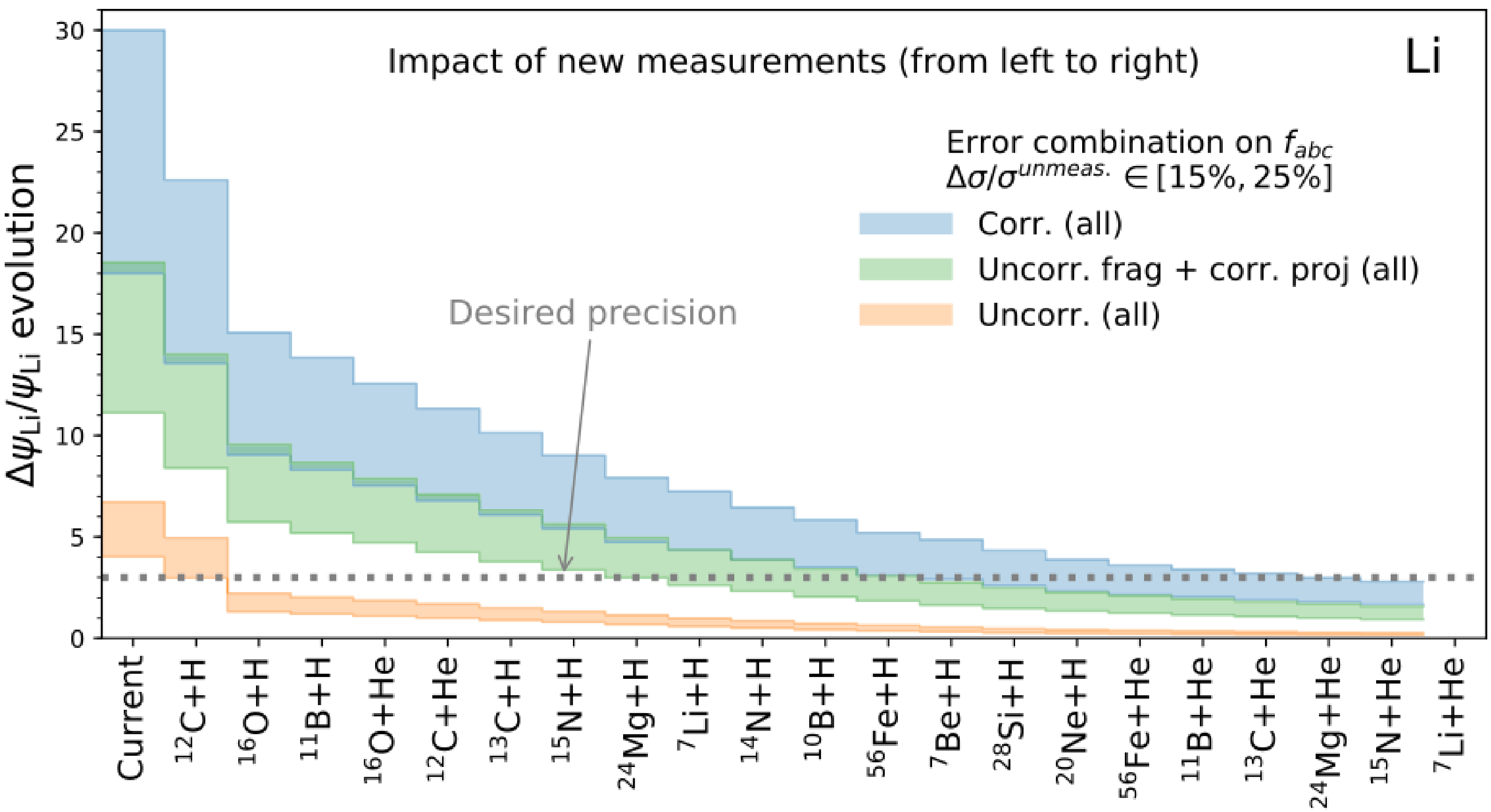


Measured with infinite precision

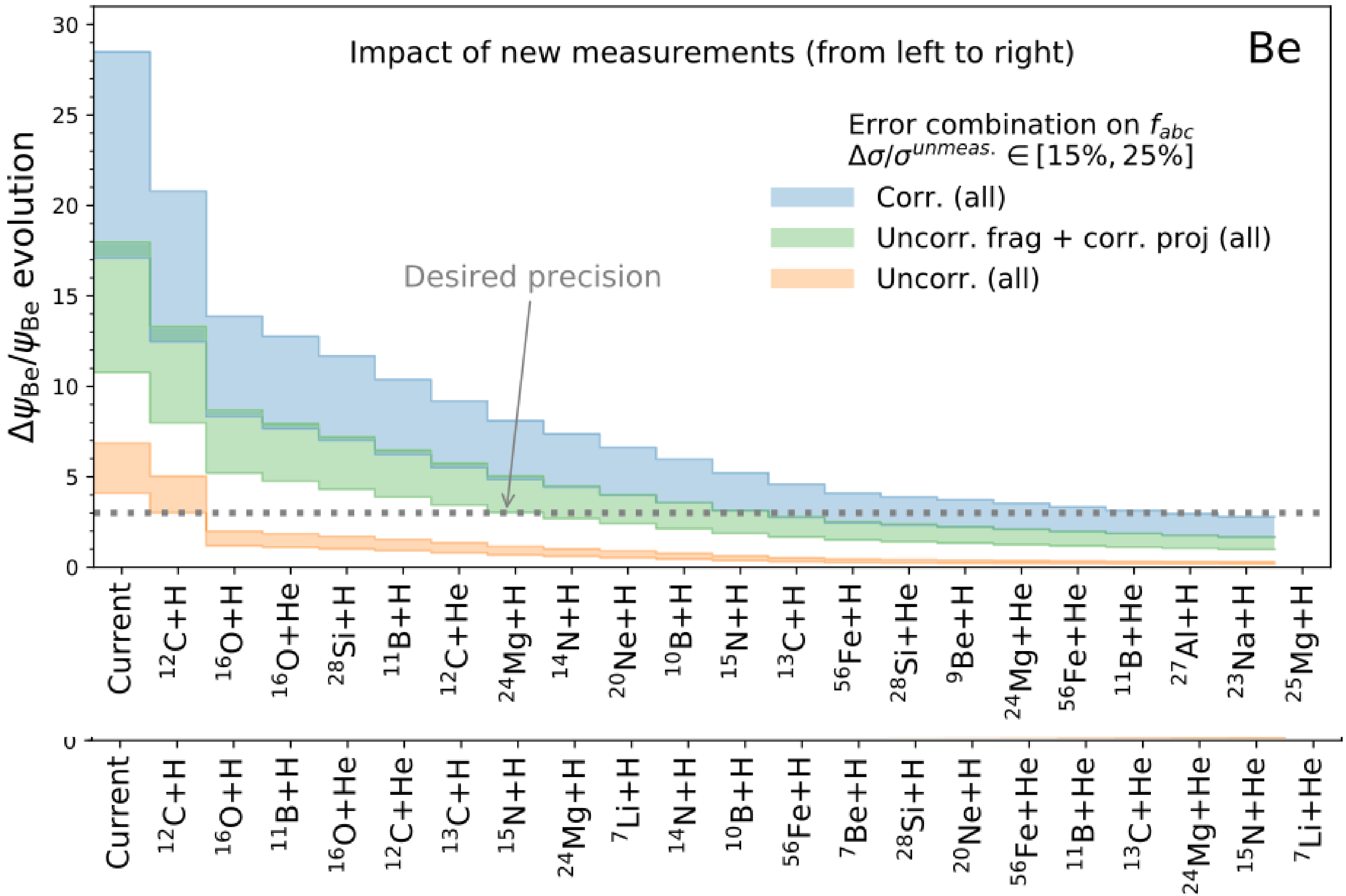
Beam + fix target experiment



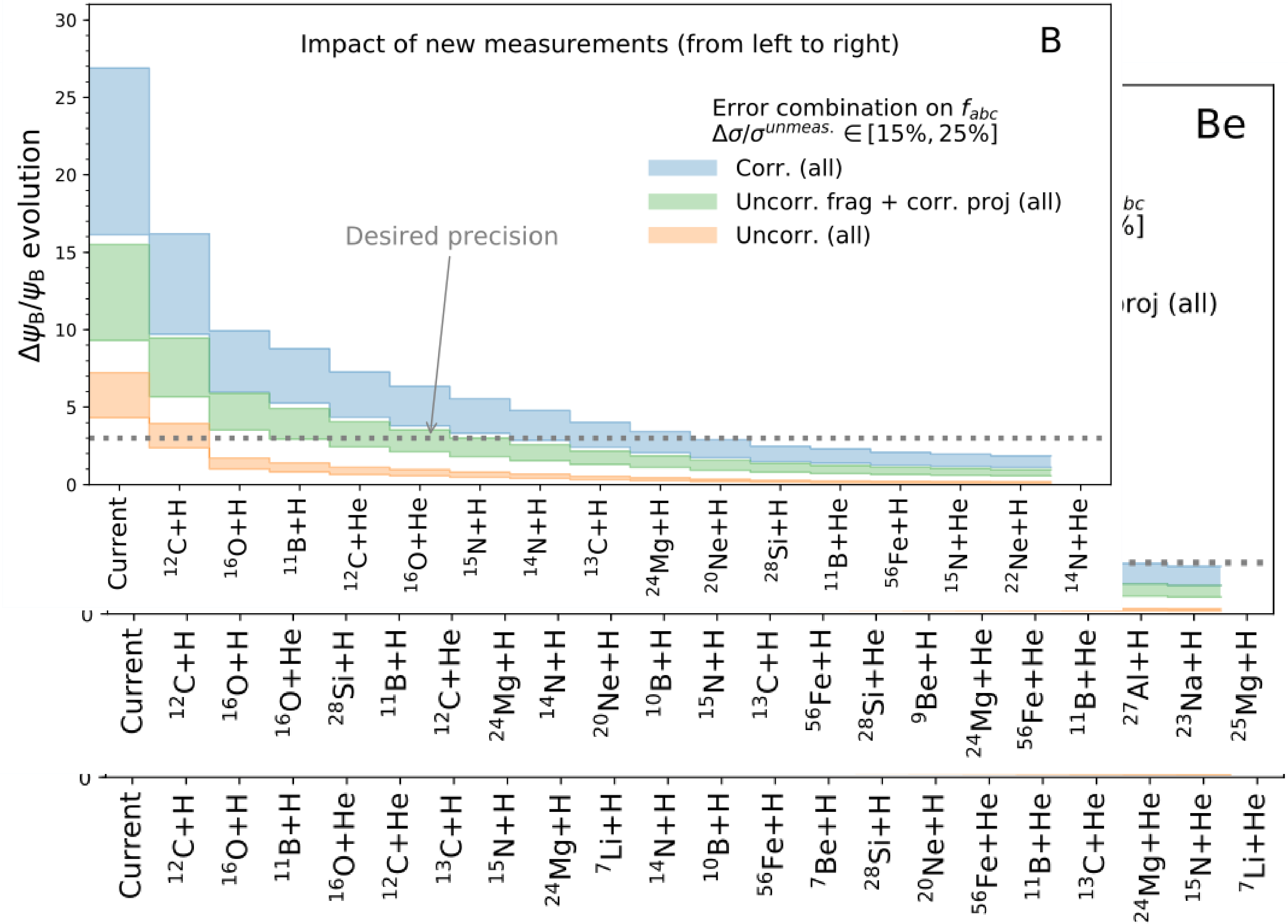
Beam + fix target experiment



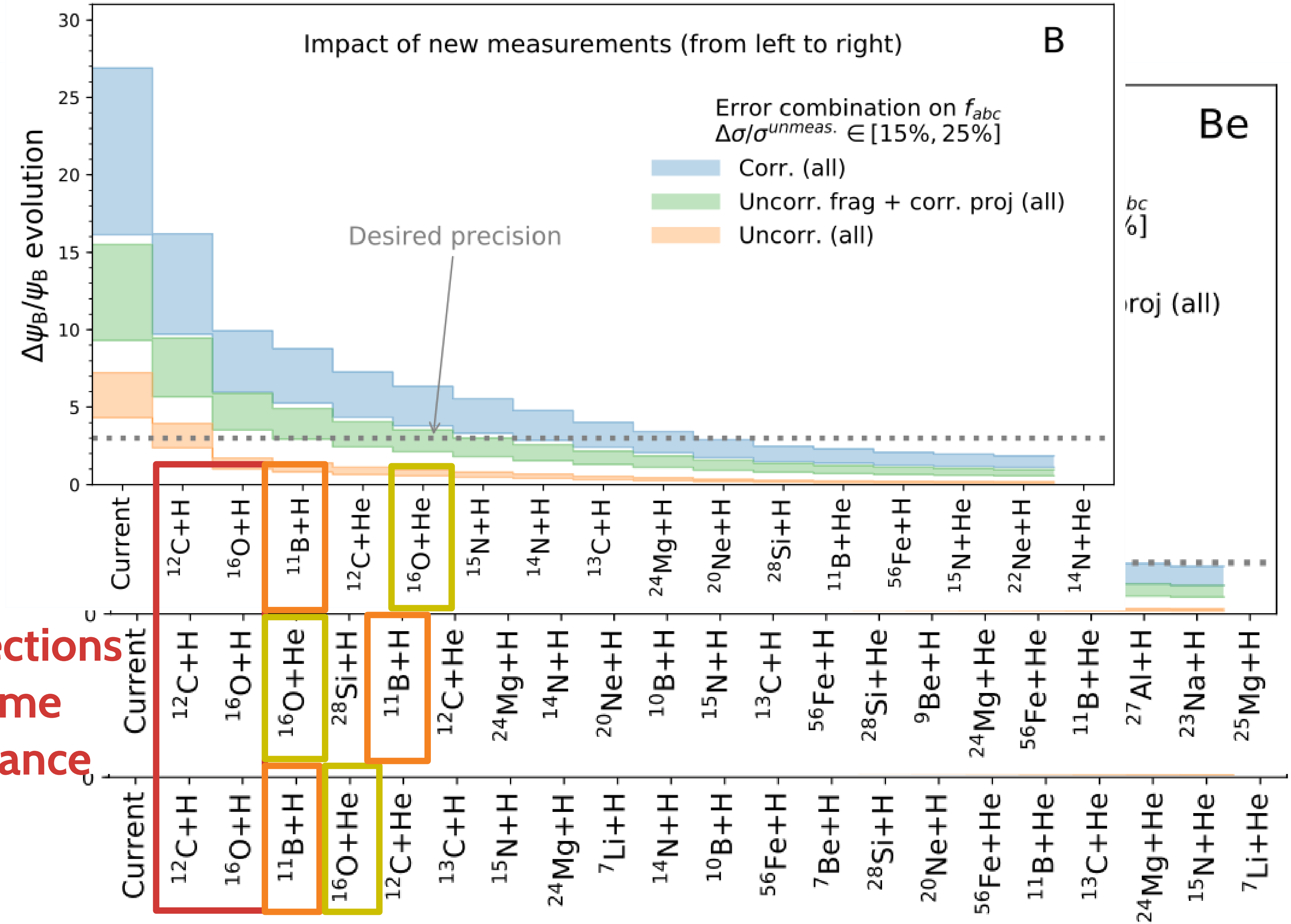
Beam + fix target experiment



Beam + fix target experiment



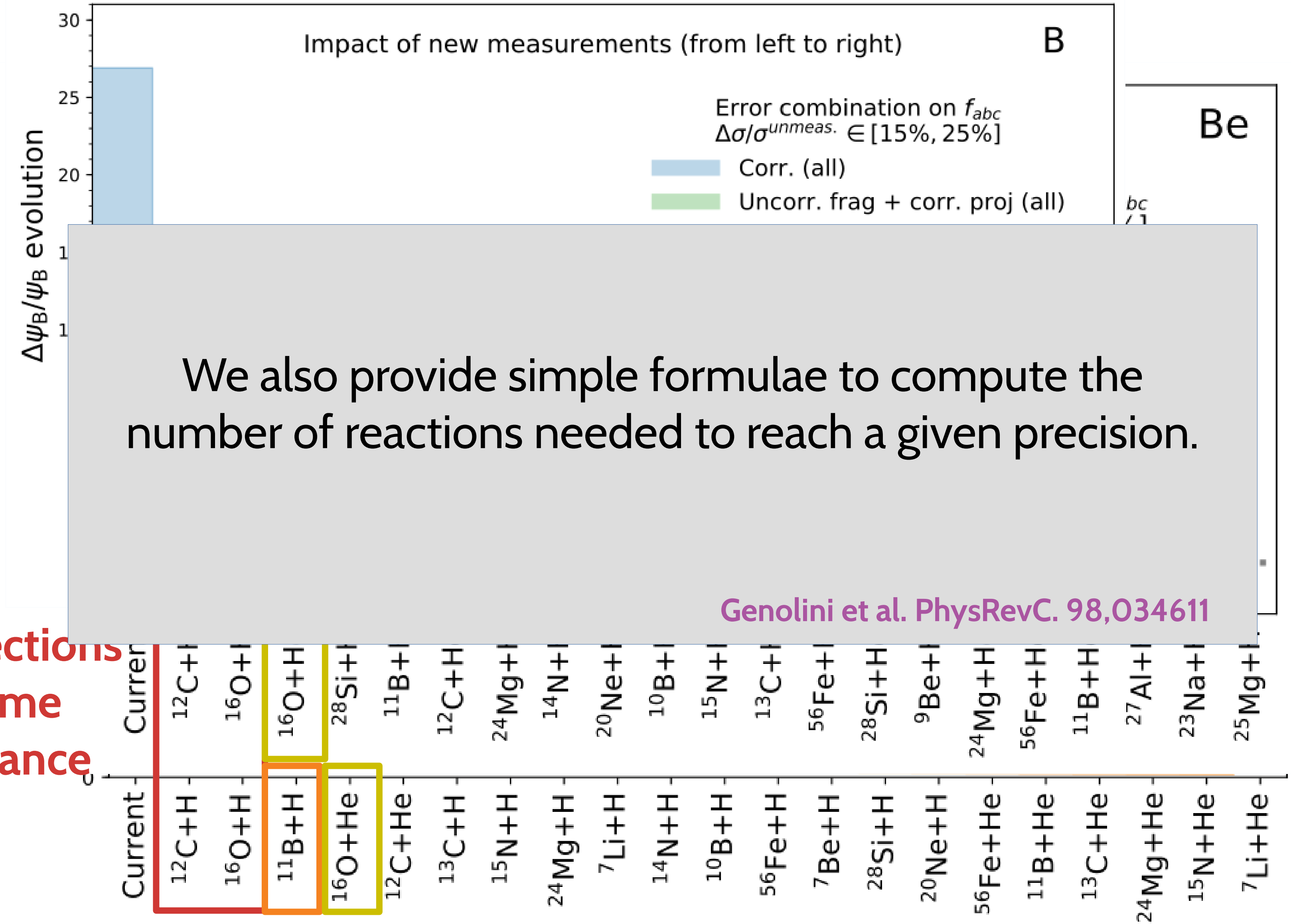
Beam + fix target experiment



Cross-sections of prime importance

Yoann Genolini

Beam + fix target experiment



Cross-sections of prime importance

We also provide simple formulae to compute the number of reactions needed to reach a given precision.

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IV- Conclusion and prospects

IV- Conclusion and prospects

The problem: Fragmentation cross sections are a limiting factor to reach the percent precision in modelling!

The question: What should we do?

The answer: Measuring few key interactions with high accuracy in the range:

[50MeV/nuc – 1 TeV]

$^{12}\mathrm{C} + \mathrm{H}$

$^{16}\mathrm{O} + \mathrm{H}$

Voyageur

AMS-02, CALET, DAMPE,..

Top 2!

Started at NA61
@ 10GeV/nuc!

PoS(ICRC2019)446

Soon: New update for the light elements: $^{1}\mathrm{H}, ^{2}\mathrm{H}, ^{3}\mathrm{He}, ^{4}\mathrm{He}$

TABLE XV: List of ghost nuclei with significant contributions to Li-C fluxes from Tables X to XIV: the half-life, decay channel, and branching ratio are taken from [142].

Nucleus	$T_{1/2}$	Daughter (decay mode)
^{6}He	806.92 ms	^{6}Li (β^-, 100%)
^{9}Li	178.3 ms	^{9}Be (β^-, 49.2%, ^{4}He ($\beta^- n$, 50.8%)
^{10}C	19.3009 s	^{10}B (β^+, 100%)
^{11}C	20.364 m	^{11}B (β^+, 100%)
^{12}B	20.20 ms	^{12}C (β^-, 98.4%), ^{4}He ($\beta^- 3\alpha$, 1.6%)
^{13}N	9.965 m	^{13}C (β^+, 100%)
^{13}O	8.58 ms	^{13}C (β^+, 89.1%), ^{12}C ($\beta^+ p$, 10.9%)
^{14}O	70.620 s	^{14}N (β^+, 100%)
^{15}O	122.24 s	^{15}N (β^+, 100%)

$$N^k + (p, He) \longrightarrow \quad {}^9_3Li \; {\scriptstyle (t_{1/2}=178\ ms)} \xrightarrow{\beta^-} {}^9_4Be \qquad (\mathcal{B}r = 49.2\%)$$

$$N^k + (p, He) \longrightarrow \; {}^{11}_3Li \; {\scriptstyle (t_{1/2}=8.6\ ms)} \xrightarrow{\beta^- + 2n} {}^9_4Be \quad (\mathcal{B}r = 4.1\%)$$

$$\sigma^{effective}_{i \to {}^9_4Be} = \sigma_{i \to {}^9_4Be} + 49.2\% \;\; \sigma_{i \to {}^9_3Li} + 4.1\% \;\; \sigma_{i \to {}^{11}_3Li}$$