Underground measurement of the $D(p,\gamma)^3He$ reaction: nuclear and cosmological implications

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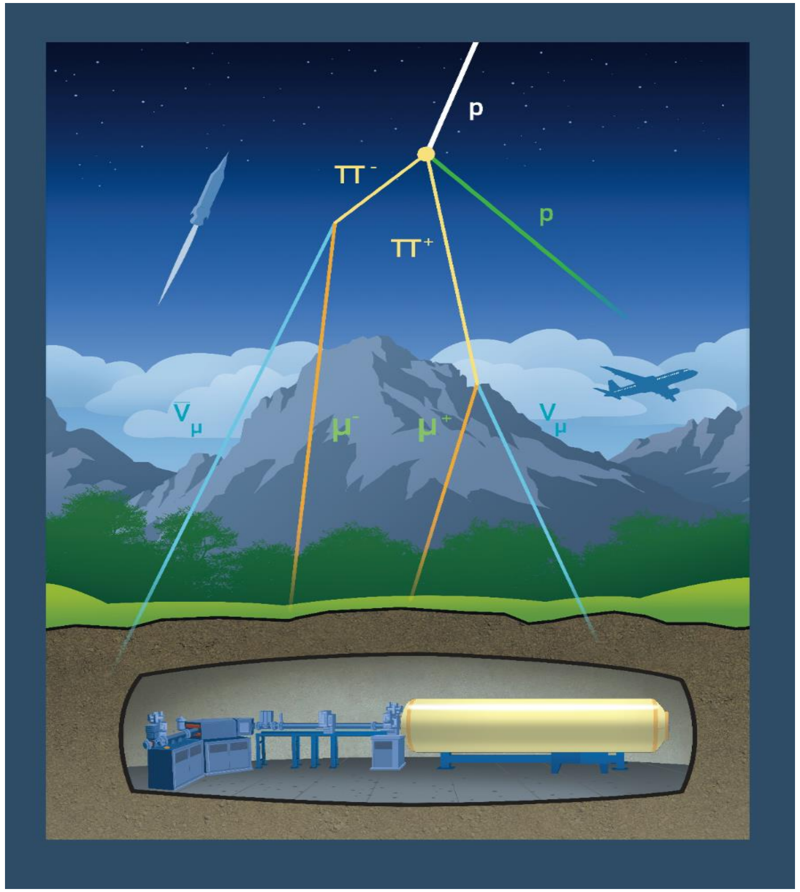
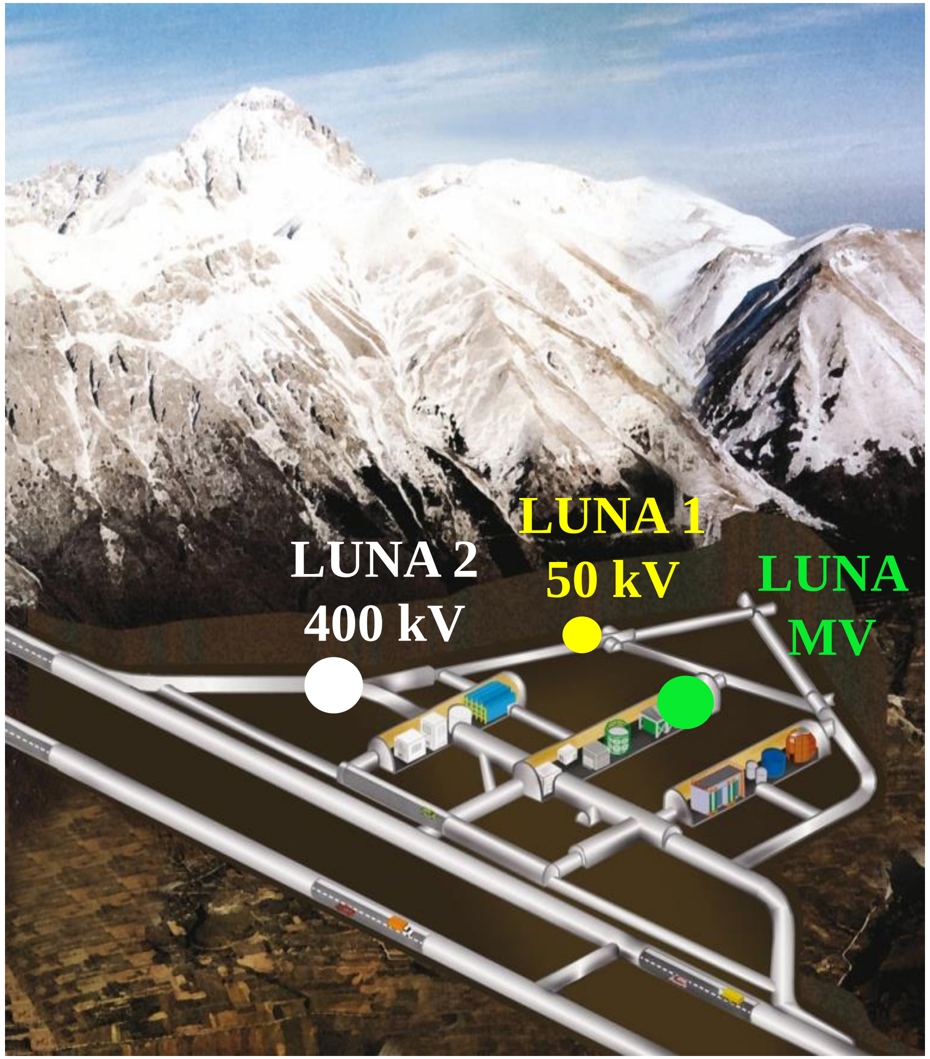
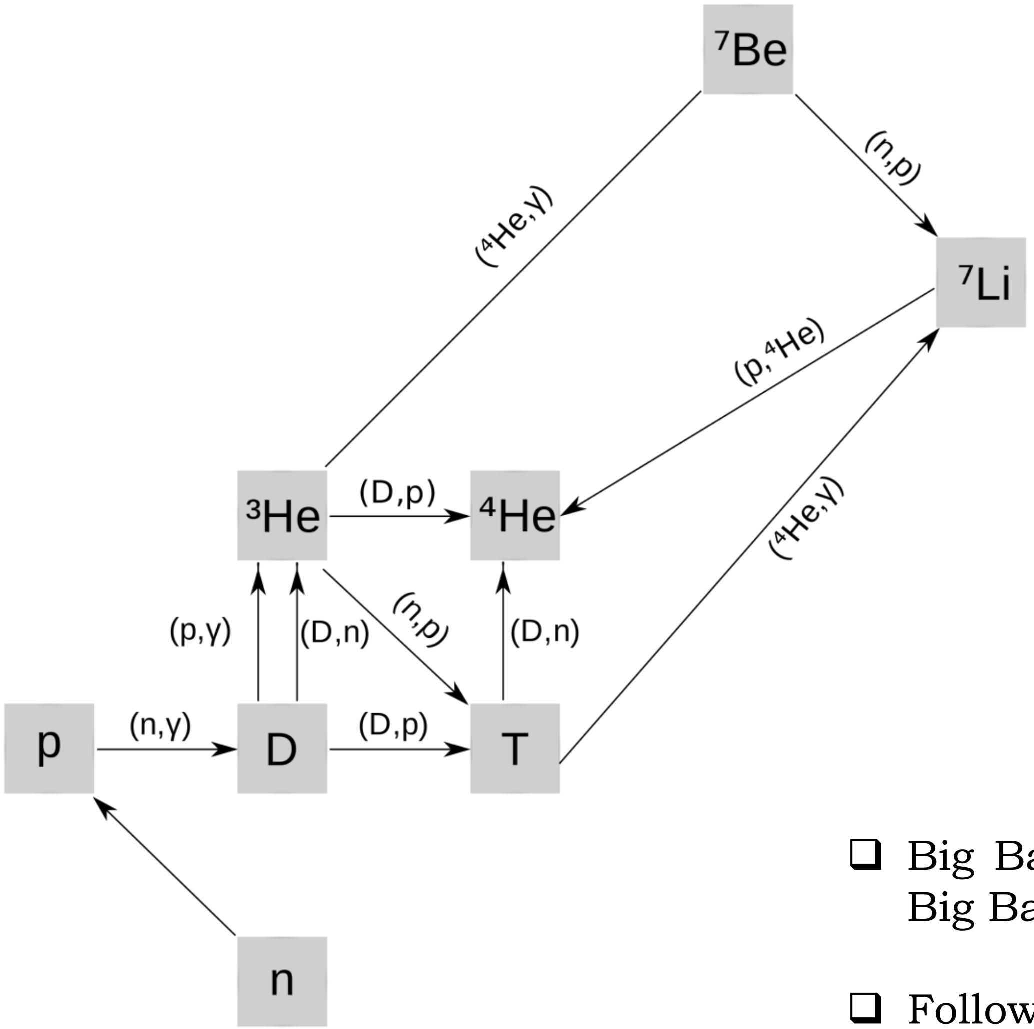


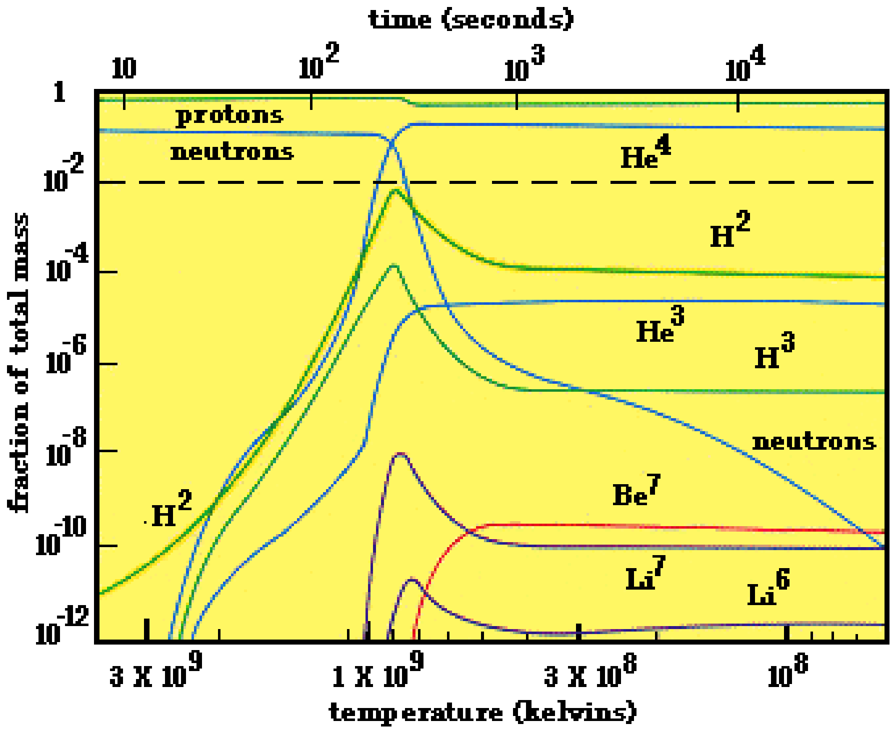
Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}



LNGS (1400 m rock shielding ≡ 4000 m w.e.)

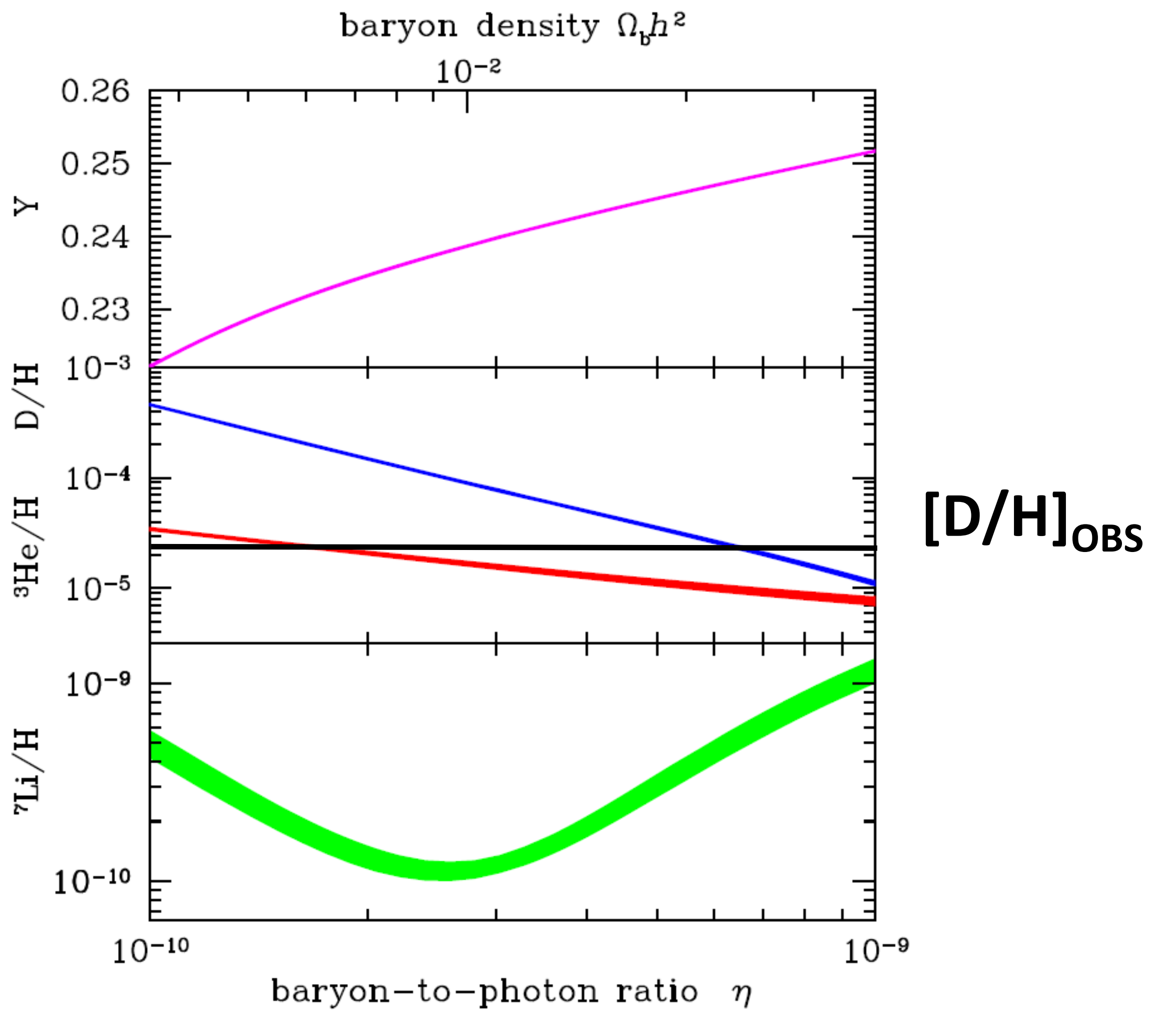
Big Bang Nucleosynthesis





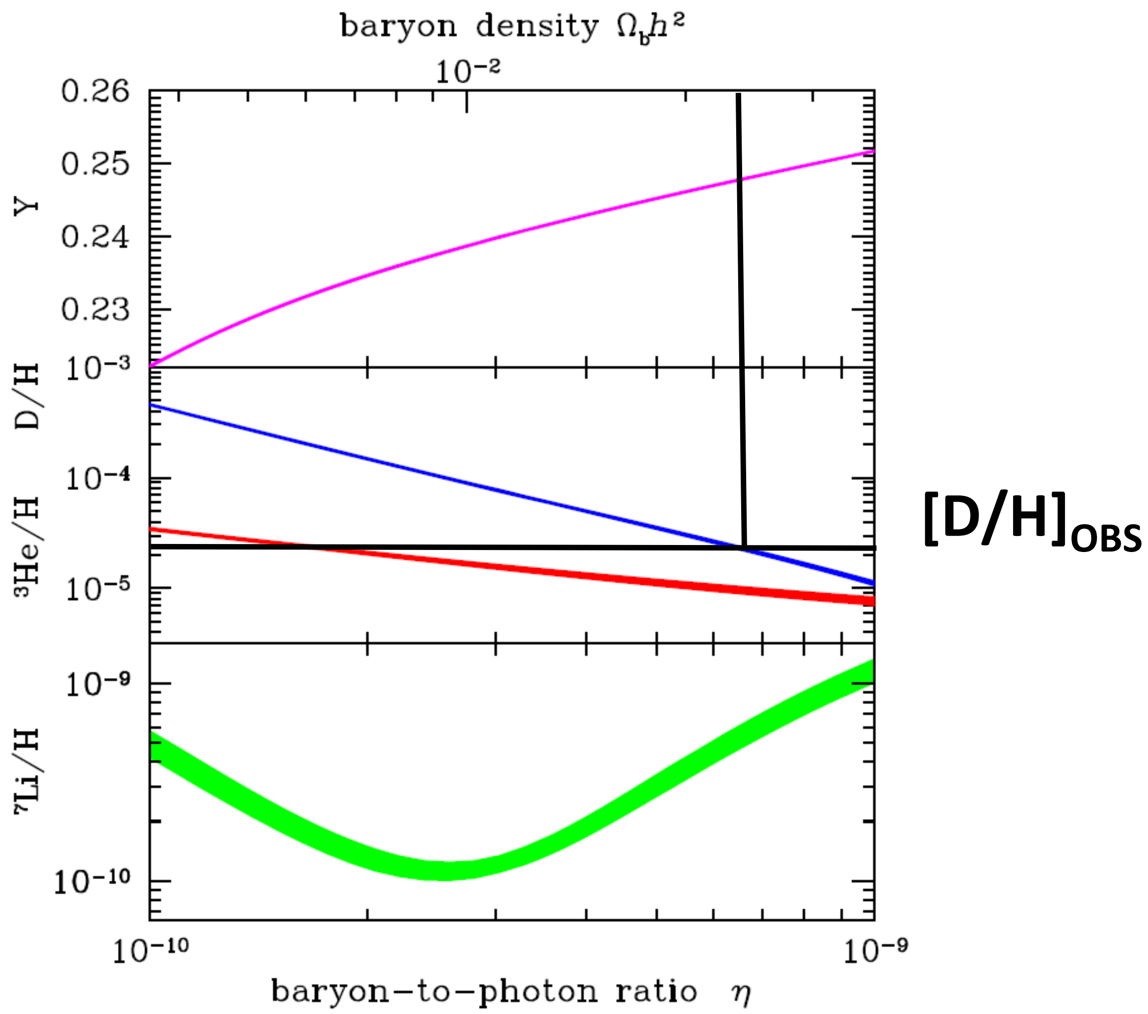
- ❑ Big Bang Nucleosynthesis (BBN) takes place 3 minutes after Big Bang
- ❑ Following BBN we have mostly H and ^{4}He with trace amounts of ^{3}H, ^{3}He, ^{6}Li, ^{7}Li and ^{7}Be

The primordial deuterium abundance



In the standard cosmological Model BBN predicts the baryon density parameter to be sensitive to the Primordial Deuterium abundance

The primordial deuterium abundance



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The primordial deuterium abundance

The Primordial Deuterium abundance is estimated from

- **Direct Astronomical observation** ~1% accuracy

$$[D/H]_{OBS} = (2.527 \pm 0.030) \times 10^{-5}$$

Cooke et al, APJ 855 (2018) 102

- **From theoretical Big Bang Nucleosynthesis (BBN) calculations**

$$[D/H]_{BBN} = (2.587 \pm 0.055) \times 10^{-5}$$

$$[D/H]_{BBN} = (2.439 \pm 0.052) \times 10^{-5}$$

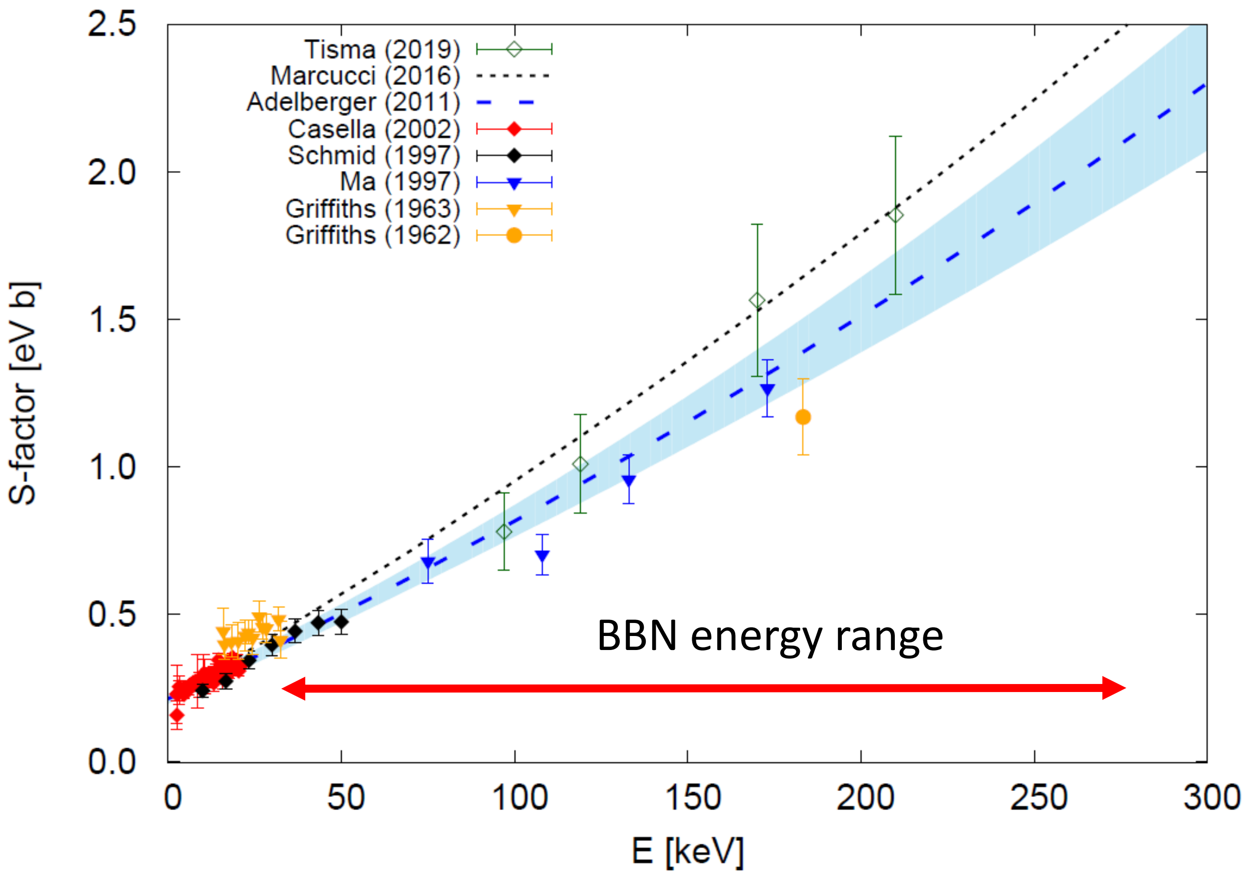
Planck, A&A 641 (2018) A6

Discrepancy of 6% depending on which cross section is taken

$D(p,\gamma)^3He$ reaction : State of the art (Before LUNA results)

Reaction	$\sigma_D\ 10^5$
$p(n,\gamma)D$	0.002
$D(p,\gamma)^3He$	0.062
$D(d,n)^3He$	0.020
$D(d,p)^3H$	0.013

- The **$D(p,\gamma)^3He$** process has the largest uncertainty.
- Previously measured experimental S-Factor suffer from systematic uncertainties of ~9%.
- Theoretical ab-intio calculations of the S-factor show disagreement with experimental values

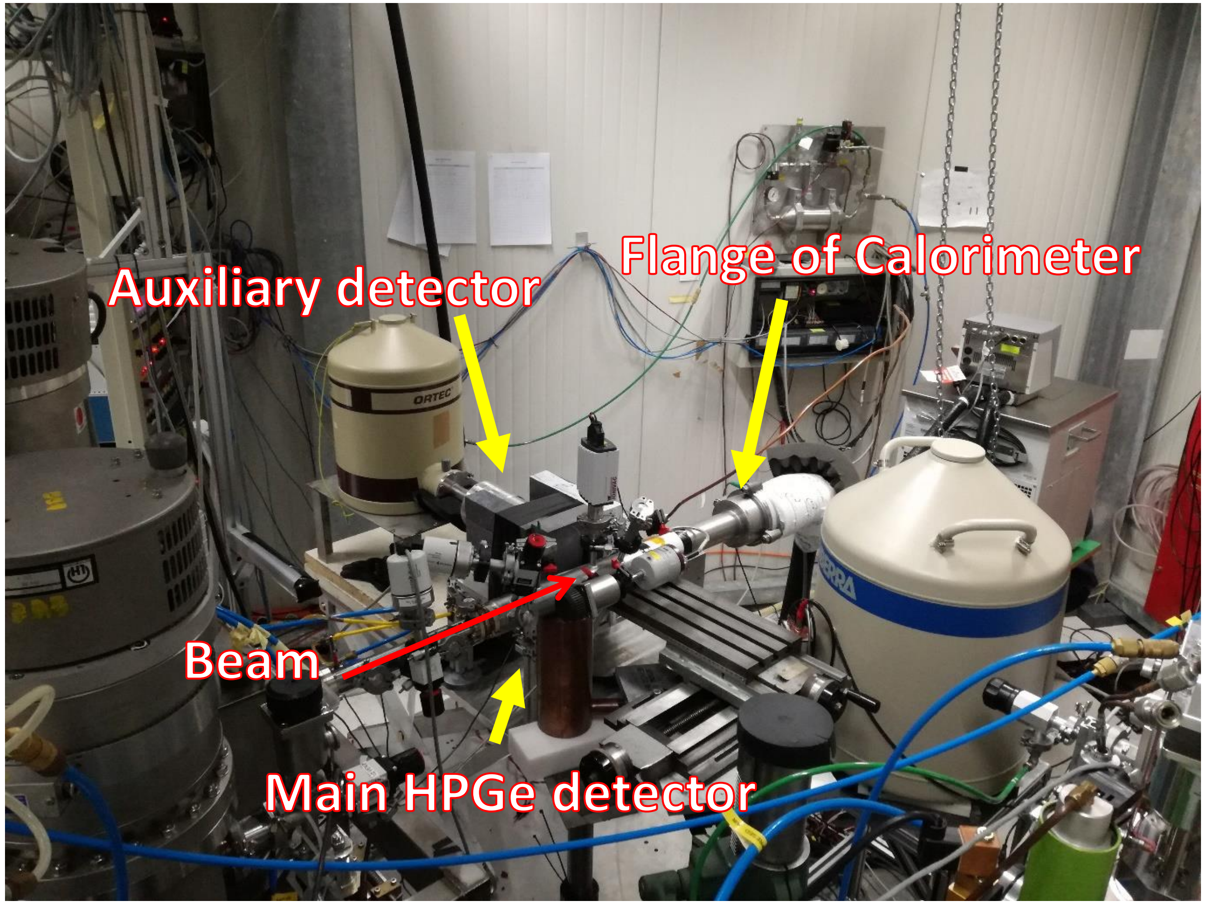


D(p,γ)^{3}He Experiment @ LUNA

- Experiment commissioned at LUNA for measuring the D(p,γ)^{3}He cross section at E_{cm}=30-260keV
- High precision (<0.3 keV) proton beam from LUNA400 accelerator with average current of ~ 250μA
- Extended D_2 windowless gas target at 0.3 mbar
- High resolution HPGe detector for γ-rays

Cross section values reported with <3% systematic error

V. Mossa *et al.*, EPJ A, vol.56, p.144, May 2020

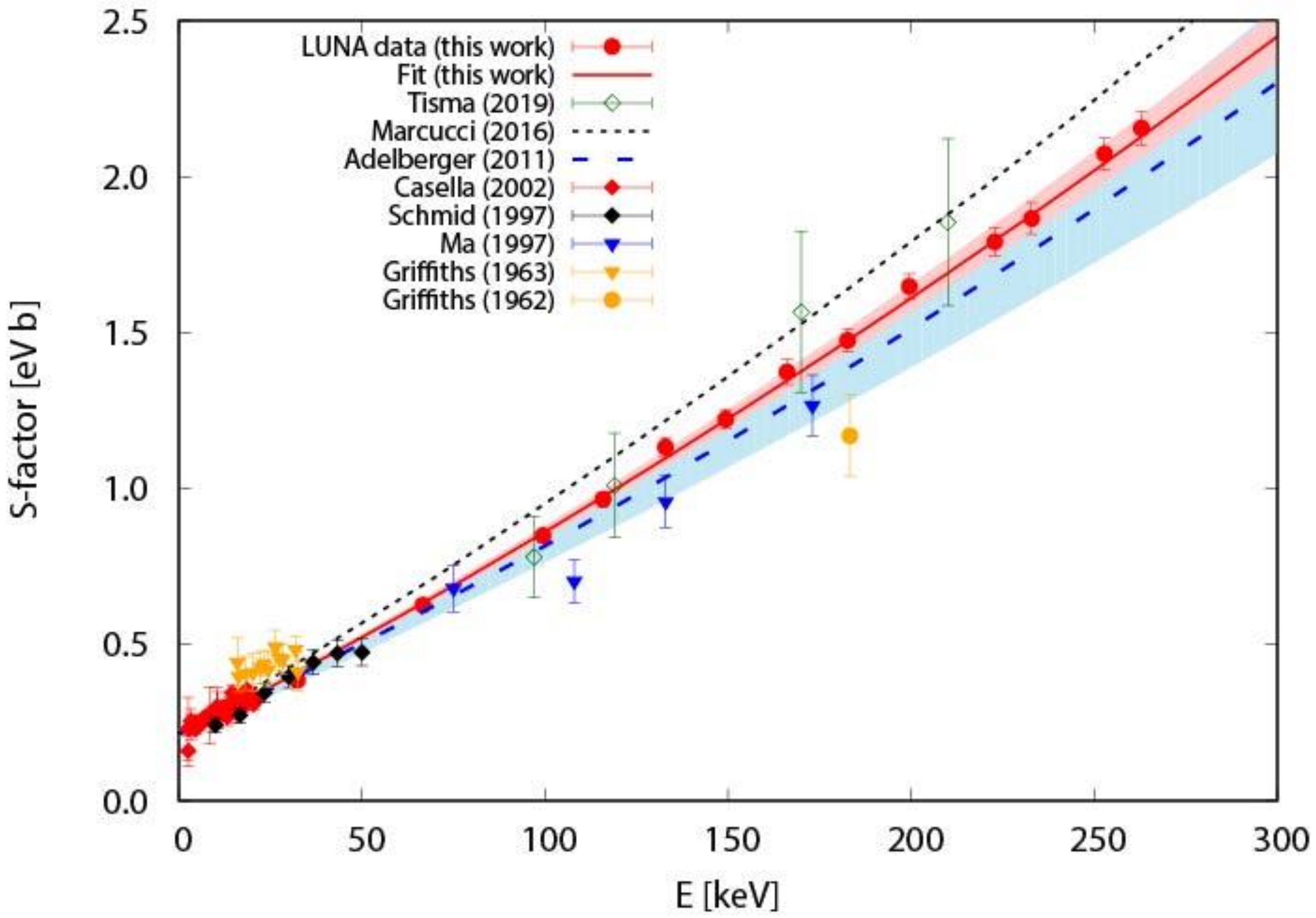


Gas target experimental setup

$D(p,\gamma)^3He$ Experiment @ LUNA : S-Factor

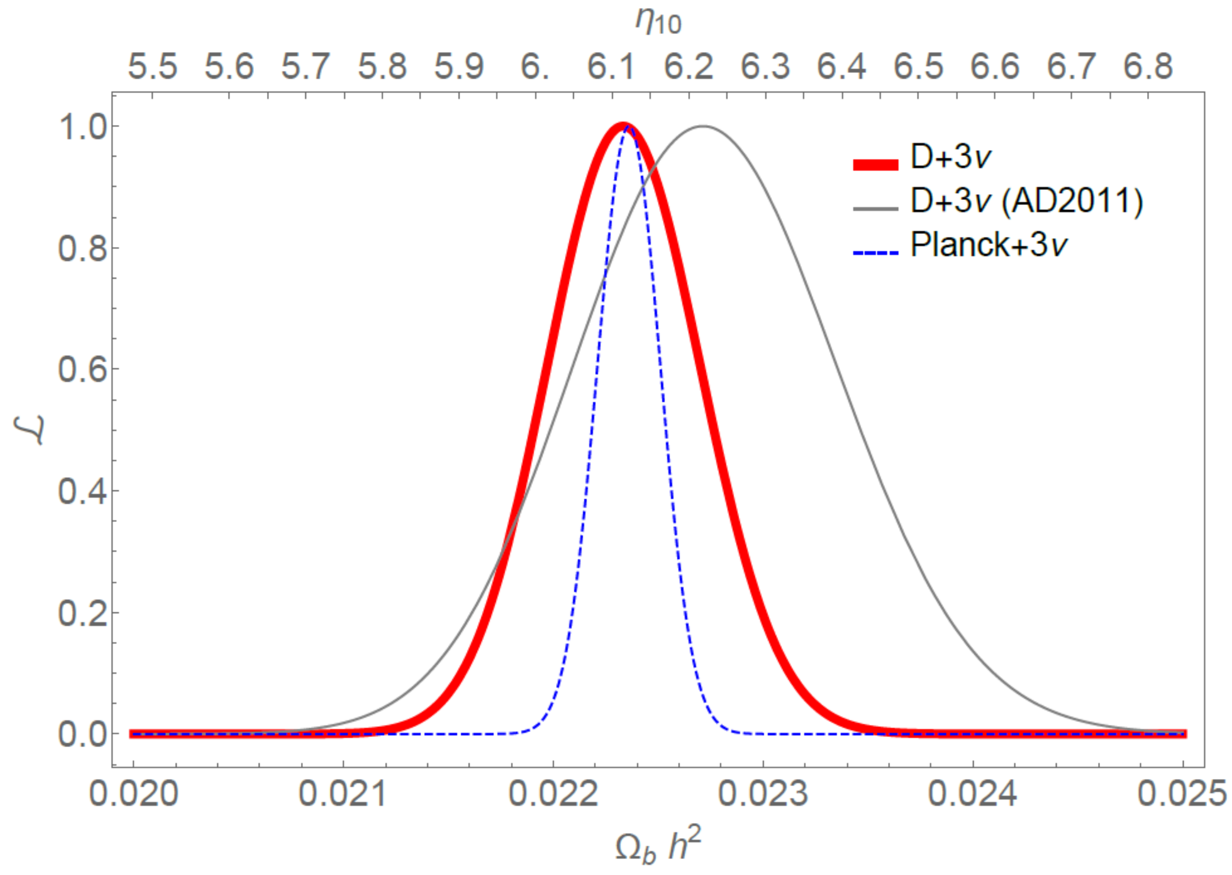
- ❑ Complete range of energies relevant to BBN covered with highly precise data

- ❑ New cross section higher than that reported previously



Mossa *et al*. The baryon density of the Universe from an improved rate of deuterium burning. *Nature* **587,** 210–213 (2020)

D(p,γ)^{3}He Experiment @ LUNA : Baryon density parameter



Obtained baryon density in excellent agreement with that obtained from direct observations !!

Mossa *et al*. The baryon density of the Universe from an improved rate of deuterium burning. *Nature* **587,** 210–213 (2020)

$D(p,\gamma)^3He$ angular distribution

- First time measurement of the $D(p,\gamma)^3He$ angular distribution in the BBN energy range, for which there is no reliable data reported.

- Novel technique introduced for the measurement involving a single detector and an extended gas target.

- Angular distributions are strong observables to compare with theoretical methods such as ab initio calculations which provide exact solution for such few body systems.

L. E. Marcucci, et al. Phys. Rev. Lett. 116, 102501 (2016) + private communications

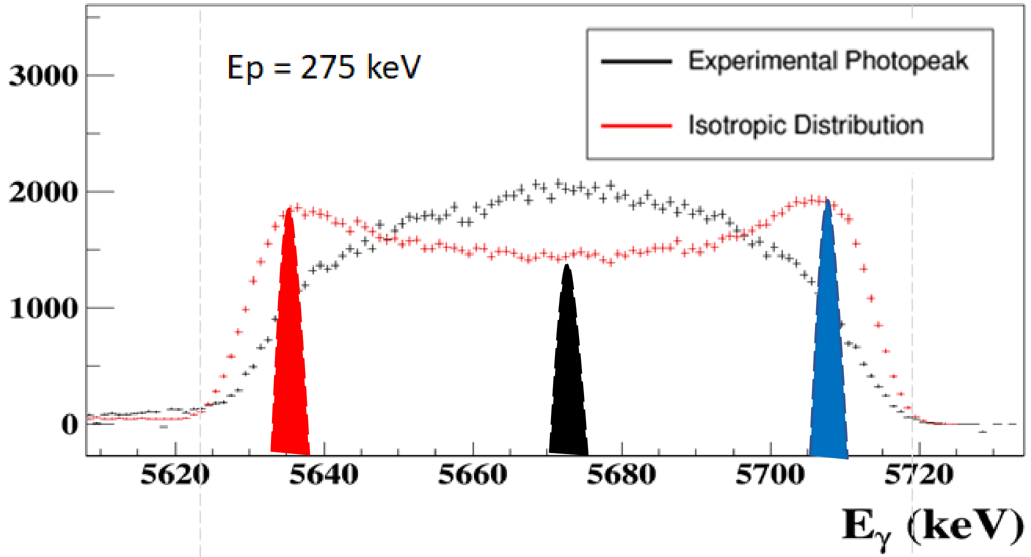
D(p,γ)^{3}He angular distribution systematics

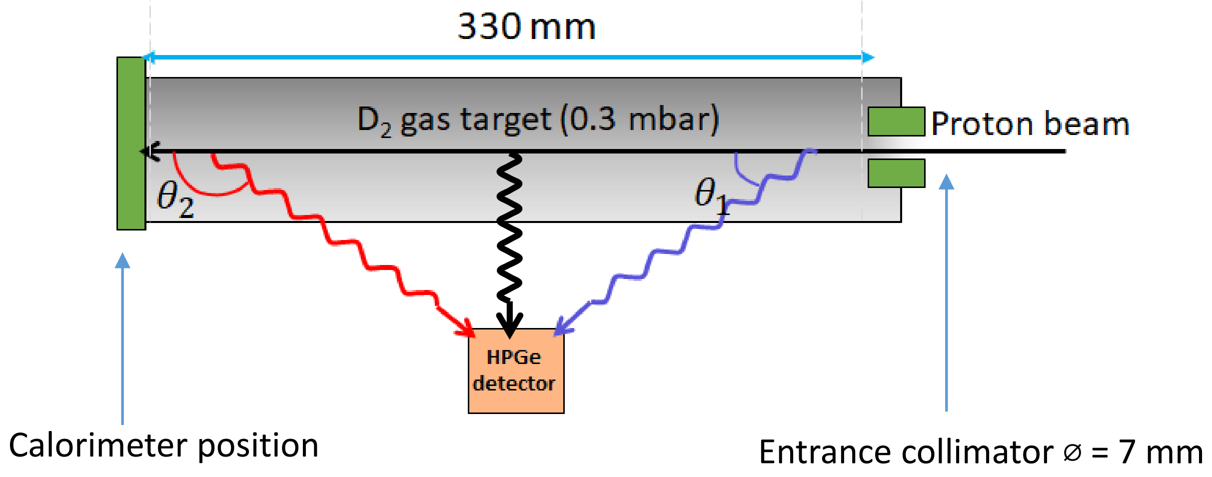
- Use of extended target leads to broadening of the peak due to kinematics

- Final shape of the peak depends on the photon angular distribution

- With P = 0.3 mbar cross section variation due to energy loss in the target is negligible

$$E_\gamma = \frac{m_p^2 + m_d^2 - m_{He}^2 + 2E_p^{tot} m_d}{2(E_p^{tot} + m_d - p_p \cos\theta)}$$





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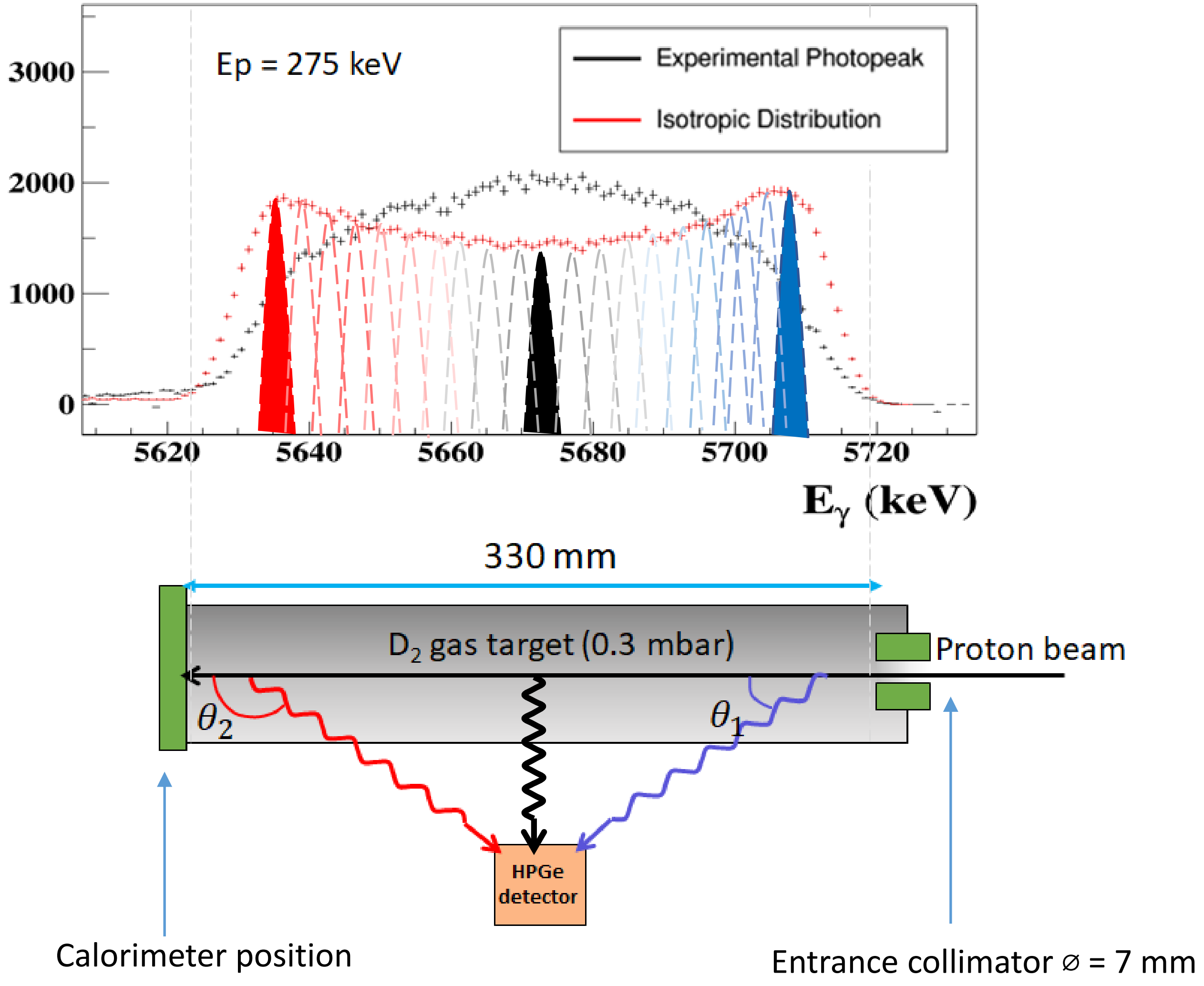

Method 1 : Analytical fit function

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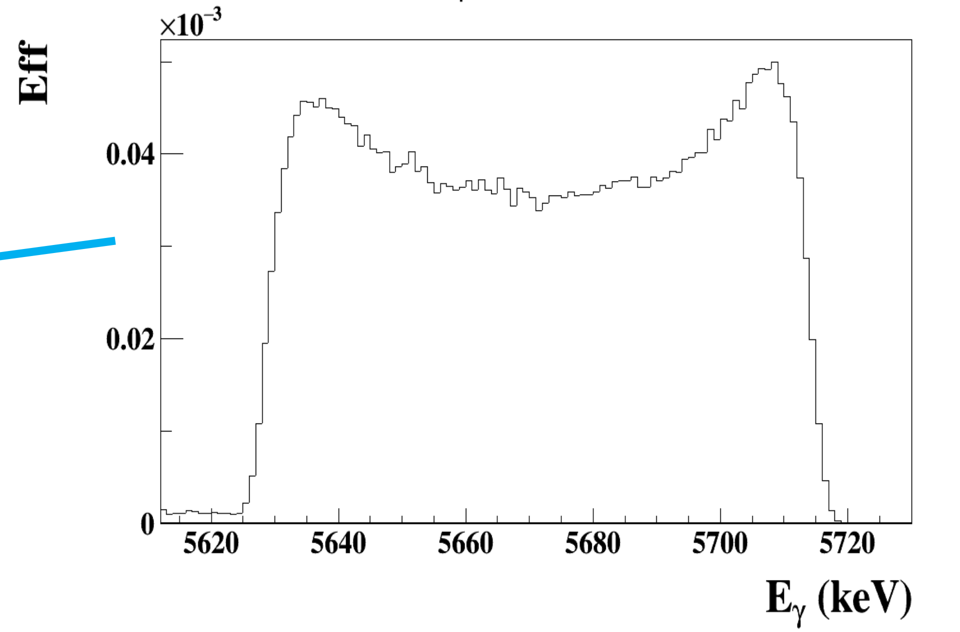
$$f(E_\gamma) = A_0\left(1 + \sum_{l=1}^{l_{max}} a_l\, P_l\left(x(E_\gamma)\right)\right).\boxed{\varepsilon(E_\gamma)}$$



Efficiency distribution for isotropic source taken into account in fit, generated from the Monte Carlo simulations

Where,

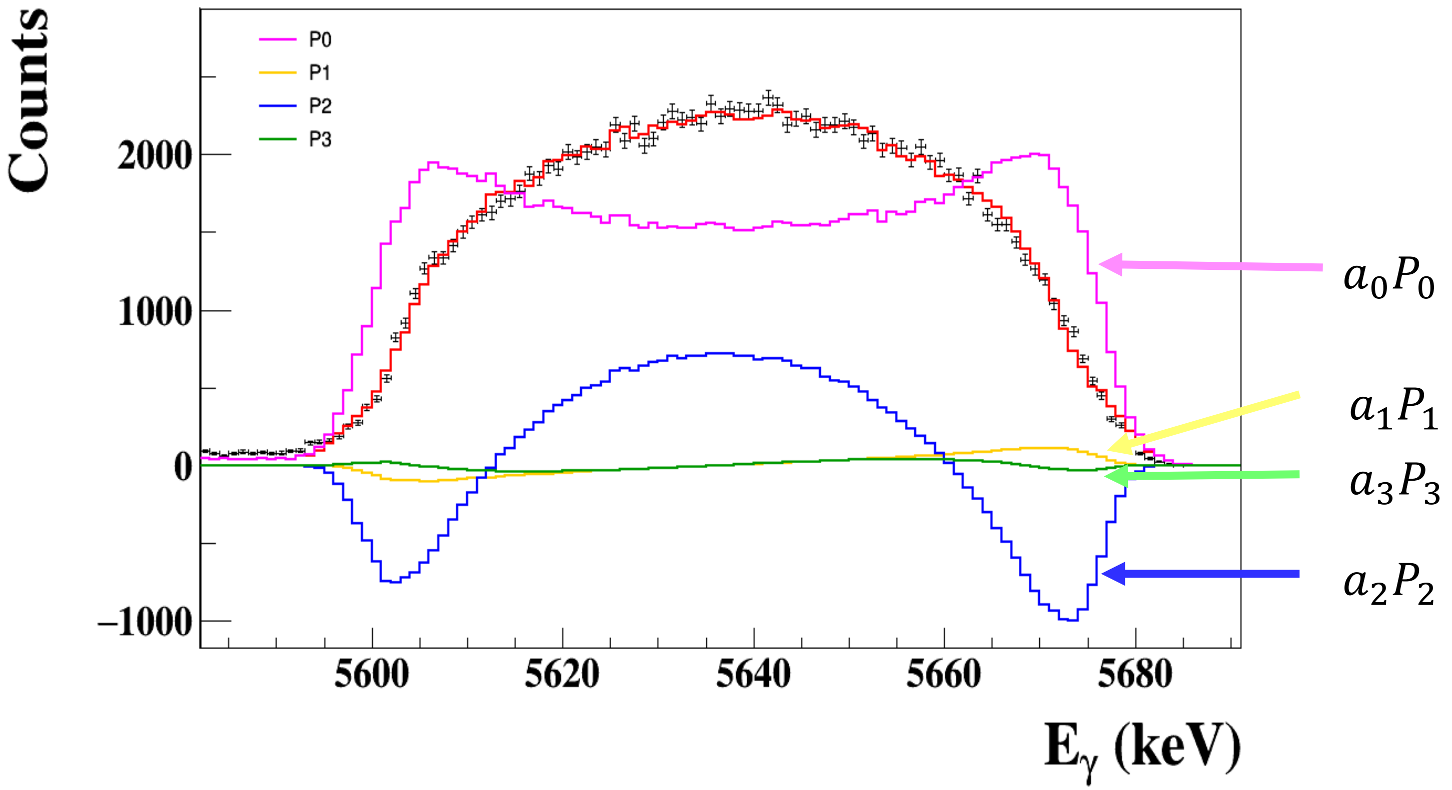
$$x(E_\gamma) = \frac{m_d + E_p^{tot}}{p_p} - \frac{m_p^2 + m_d^2 - m_{He}^2 + 2m_d E_p^{tot}}{2p_p E_\gamma}$$

Fit with reduction of the minimization function for the fit parameters A_0, a_l where l=1,2,3

$$\chi^2 = \sum_{j=1}^{N} \frac{\left(N(E_j) - A_0\left(1 + \sum_{l=1}^{l_{max}} a_l P_l^{mod}(E_\gamma)\right).\varepsilon(E_\gamma)\right)}{err\left(N(E_j)\right)}$$

Considering few orders of Legendre polynomials from $P_0 - P_3$

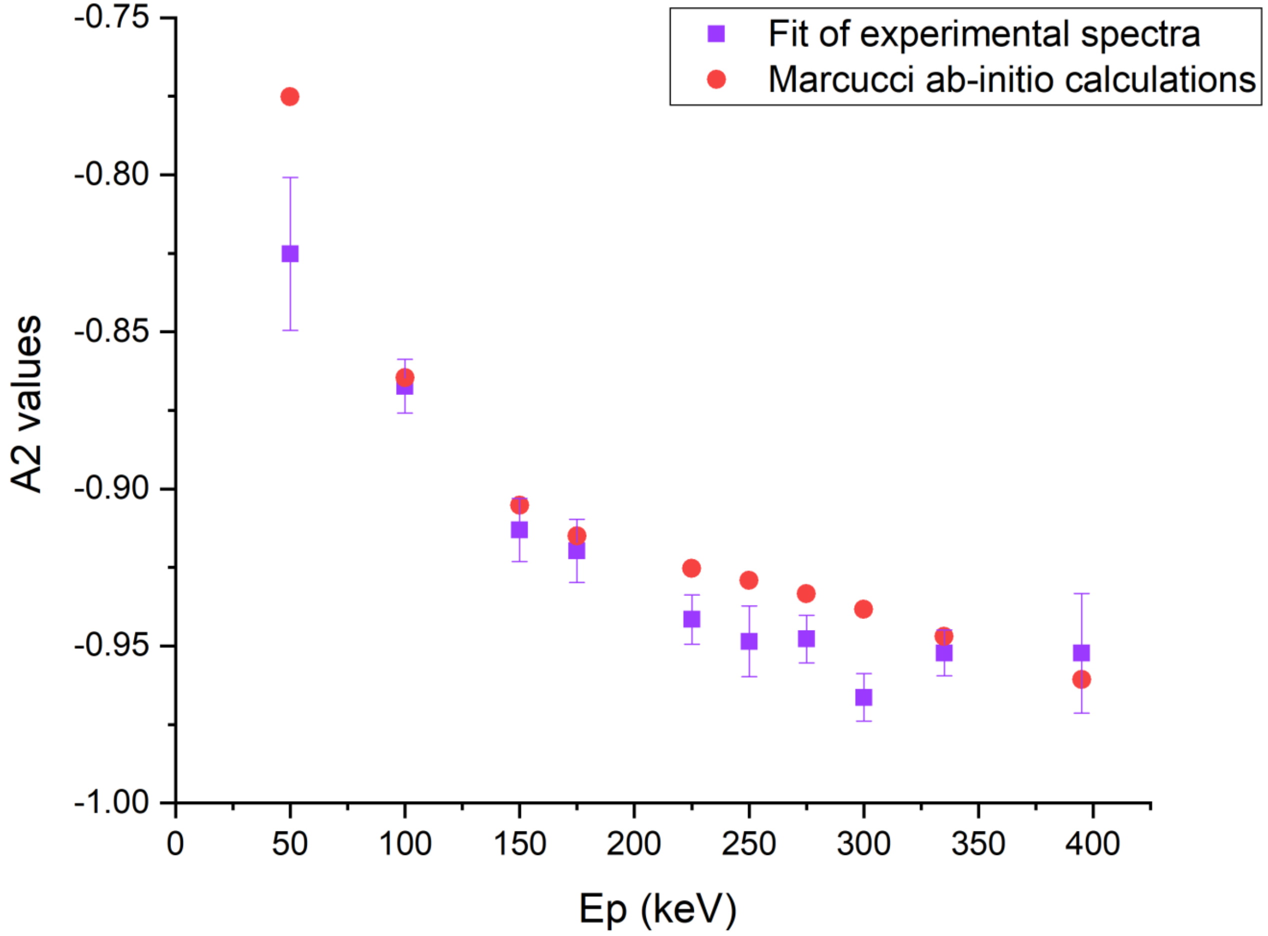
Method 1 : Analytical fit function



- The fit reproduces the peak shape very well.
- P_2 has the dominant contribution while P_1 and P_3 are an order of magnitude smaller.
- To check our results we shall focus only on the coefficient of P_2 which is the parameter a_2

Method 1 : Analytical fit function

a_2 parameter values from fit of Experimental Spectra



Variation of a_2 parameter values from fit of **experimental** spectra as a function of the incoming proton energies. Errors shown are those obtained from the minimization procedure

Method 2 : Fitting with Simulated spectra

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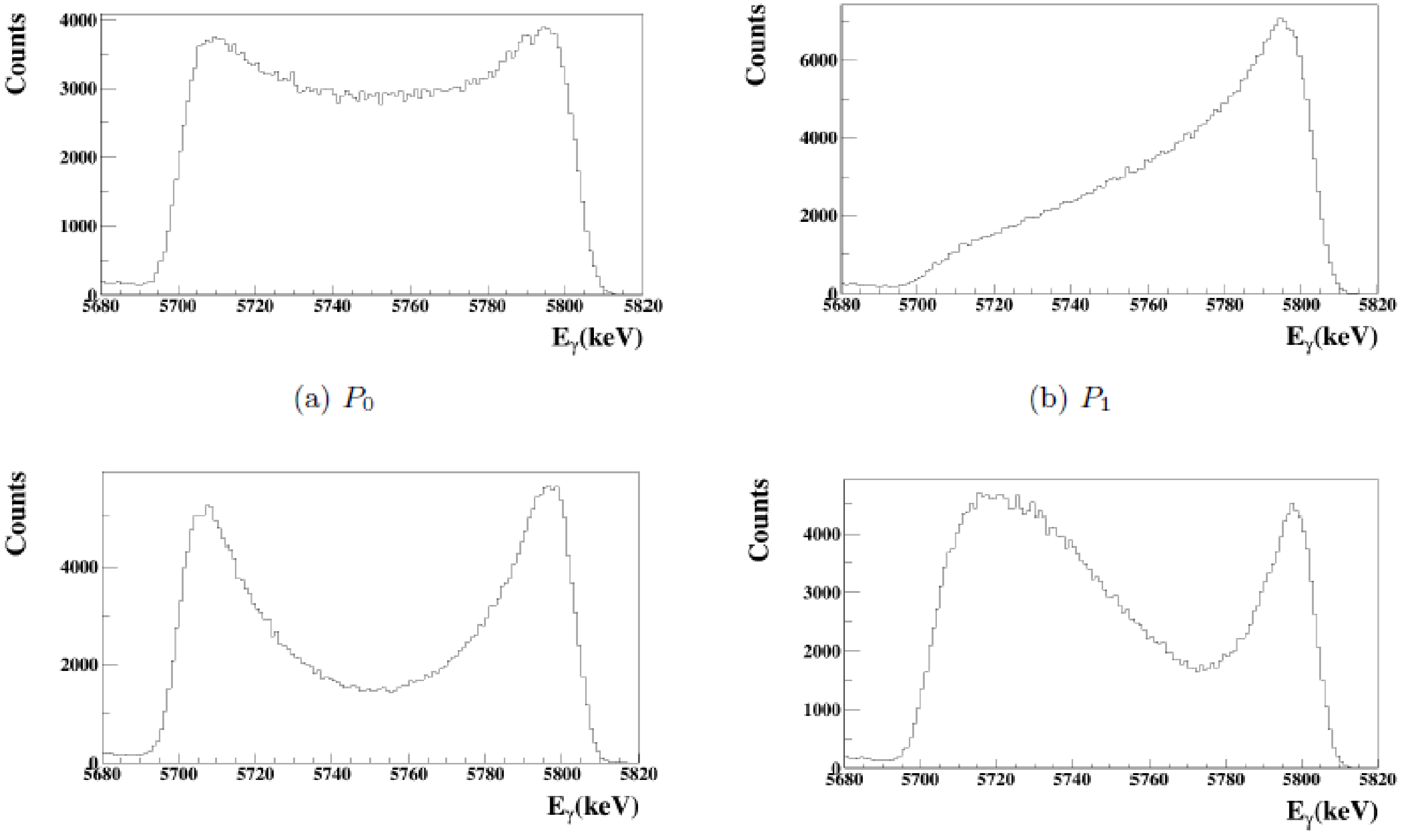
- Monte Carlo simulations are used to create spectra having a specific angular distribution for a fixed Legendre polynomial $P_k(x)$ where k=0,1,2,3…

- Combination of these generated templates used to fit the experimental distribution



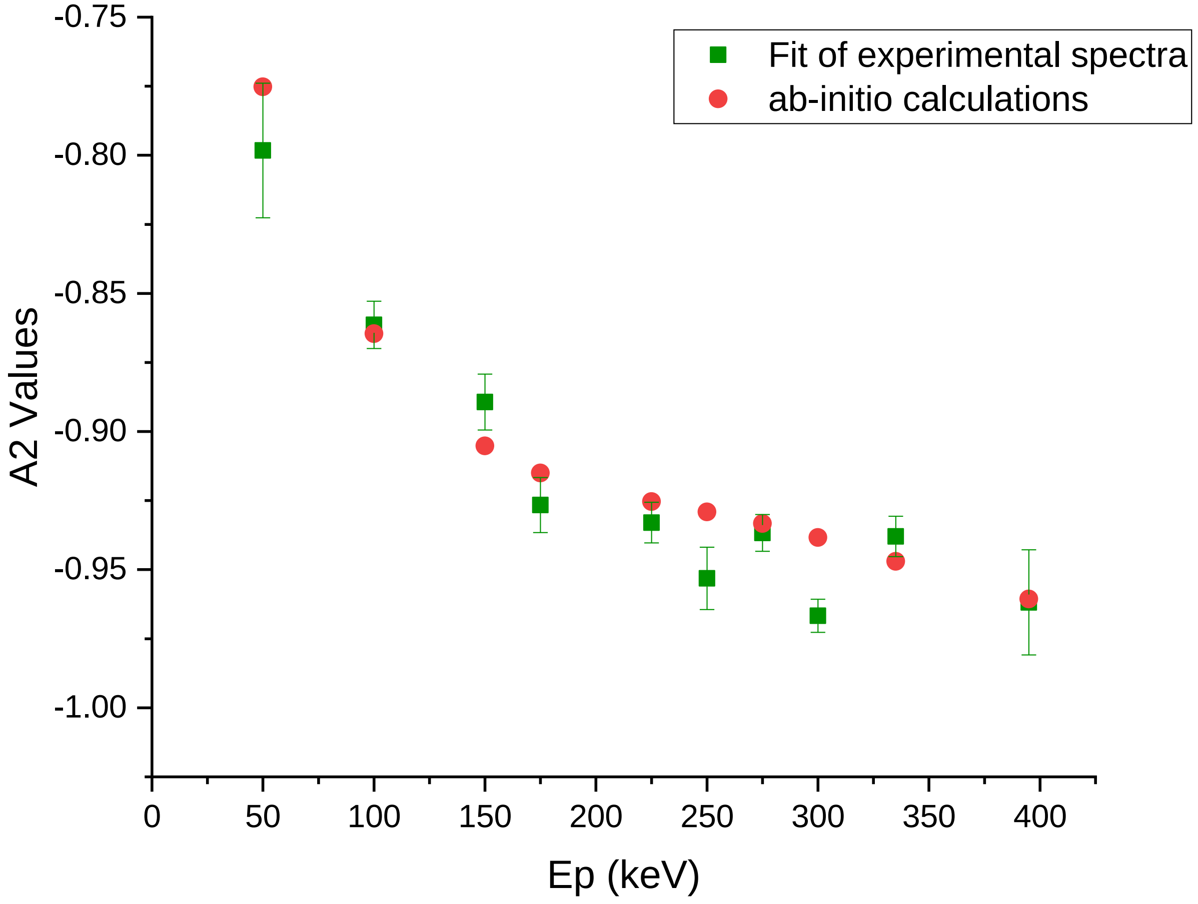
(a) P_0 (b) P_1 (c) P_2 (d) P_3

$$N(E_\gamma) = a_0 \times P_0(E_\gamma) + \sum_{l=1}^{l=l_{max}} a_l * P_l(E_\gamma)$$

Where a_0, a_l for l=1,2,3.. are the coefficients of each template of the angular distribution at a given l

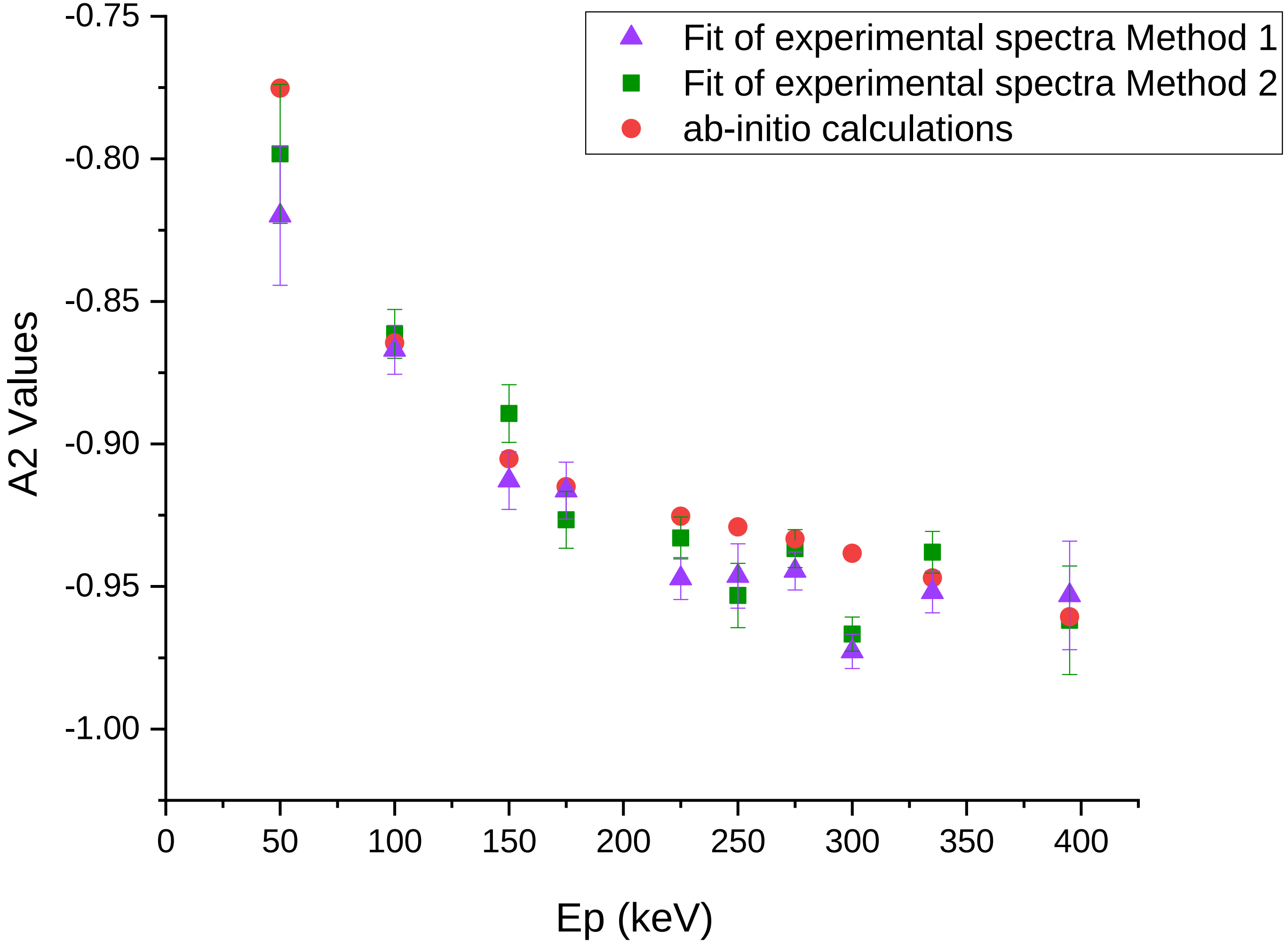
Method 2 : Fitting with Simulated spectra

a_2 parameter values from fit of Experimental Spectra



Variation of a_2 parameter values from fit of **experimental** spectra as a function of the incoming proton energies. Errors shown are those obtained from the minimization procedure

Comparison of Method 1 and Method 2



Variation of a_2 parameter values from fit of **experimental** spectra for both methods. Errors shown are those obtained from the minimization procedure

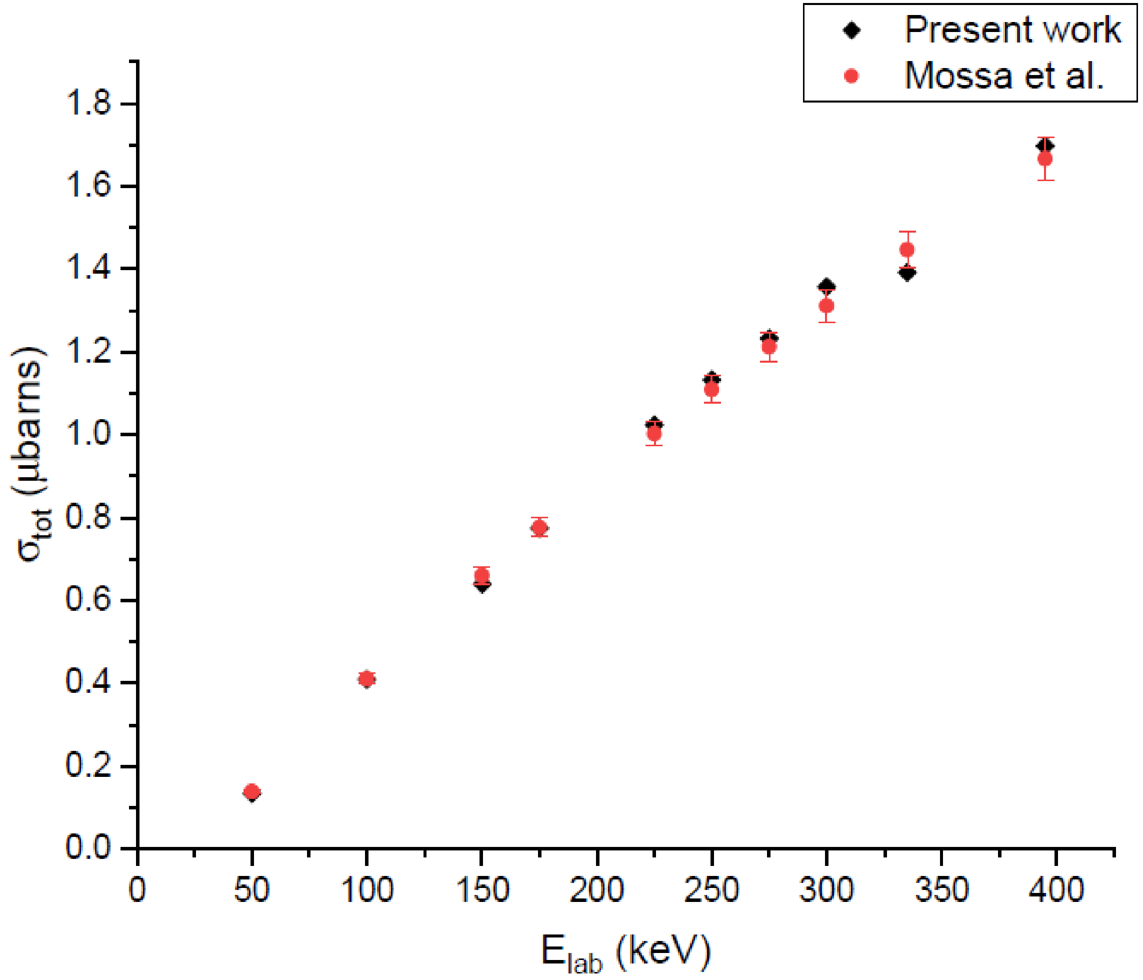
- Good agreement of both methods with each other and with the theoretical values obtained from the ab-initio calculations.

D(p,γ)^{3}He Cross Sections revisited

$$\sigma(E) = \sum_{\ell=0}^{3} \left(\frac{a_\ell N_\ell(E)}{N_p \int_0^L \rho(z)\epsilon_\ell(z, E_\gamma)} \right)$$

- Cross sections calculated by explicitly taking into account the angular distribution

- Good agreement with those published by Mossa et al. with maximum discrepancy of $\sim 4\%$



CONCLUSION

- The LUNA results settled the most uncertain nuclear physics input to BBN calculations and improved the reliability of using primordial abundances as probes of the physics of the early Universe

- We also report the preliminary results of the angular distribution of the **D(p,γ)^{3}He** reaction. Very good agreement is observed in the a_2 values for both methods. Agreement is also seen with the theoretical ab-initio calculations.

- Sensitivity to the other parameters are being investigated as well as some improvement in the analysis