Comparison of available data of the absolute air-fluorescence yield: an average value?

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Outline

1. Introduction
2. Normalization procedure
3. Monte Carlo analysis
    - The algorithm
    - Some results
4. Comparison of FY data. Average value

1. Introduction

The fluorescence yield FY (P, T, h) is a key ingredient for an accurate reconstruction of UHECR showers.

Available measurements of:

1. Fluorescence spectrum at given air conditions
2. FY dependence on atmospheric conditions P, T, h (quenching)
3. Absolute FY value at given conditions

Laboratory measurements provide us with a set of parameters which allows evaluation of absolute FY (P, T, h)

Physics of the fluorescence emission

$$Y = \text{fluorescence yield}\left[\text{ph/MeV}\right]$$

$$Y_\lambda = \frac{Y_\lambda^0}{1 + P / P'_\lambda}\ ; \quad Y = \sum_\lambda Y_\lambda$$

$$P'_\lambda(T) = P'_\lambda(T_0)\left(\frac{T}{T_0}\right)^{1/2-\alpha}$$

$$\frac{1}{P'_{\text{hum}}(\lambda, T)} = \frac{1}{P'_{\text{dry}}(\lambda, T)}\left(1 - \frac{P_w}{P}\right) + \frac{P_w}{P}\frac{1}{P'_w(\lambda, T)}$$

FY selection

$Y_{337}\ (P_0, T_0)$ **Absolute value**

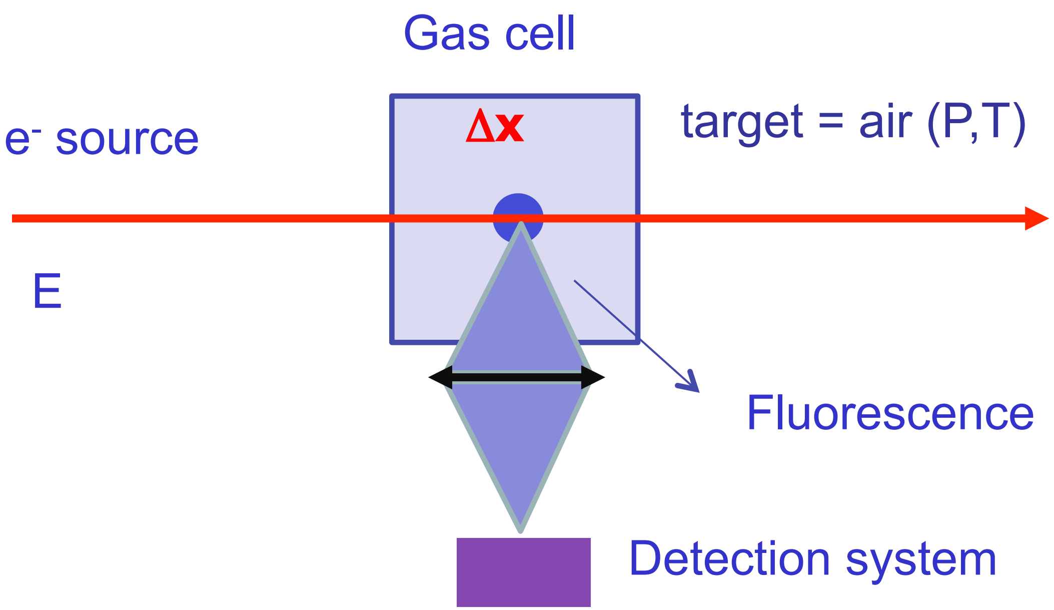
$\lambda_i\ ,\quad I(\lambda_i),\ \ldots$ Spectrum

$P'_\lambda(T_0),\ \ldots$ P dependence

α_λ T dependence

$P'_w(T_0)$ h dependence

The measurement of the absolute air-fluorescence yield



Absolute number of λ fluorescence photons per unit of electron path length (or deposited energy) at given P, T conditions

Problems for the comparison of absolute FY

- ✓ Single bands vs. wide spectral range
- ✓ Different units (ph/m or ph/MeV).
- ✓ Discrepancies in the P' parameters

Summary of available FY data[1]

Experiment	$\Delta\lambda$ (nm)	P (hPa)	T (K)	E (MeV)	Experimental result	Error (%)
Kakimoto (1996)	337	800	288	1.4	5.7 ph/MeV	10
	300 – 400	1013	288	1.4 300 650 1000	3.3 ph/m 4.9 ph/m 4.4 ph/m 5.0 ph/m	10
Nagano (2004)	337	1013	293	0.85	1.021 ph/m	13
Lefeuvre (2007)	300 – 430	1005	296	1.1 1.5	3.95 ph/m 4.34 ph/m	5
MACFLY (2007)	290 – 440	1013	296	1.5 $20 \cdot 10^3$ $50 \cdot 10^3$	17.0 ph/MeV 17.4 ph/MeV 18.2 ph/MeV	13
FLASH (2008)	300 – 420	1013	304	$28.5 \cdot 10^3$	20.8 ph/MeV	7.5
AirLight (2008)	337	-	-	0.2 – 2	$Y^0 = 384$ ph/MeV	16
AIRFLY[a] (2010)	337	1013	~ 300	$120 \cdot 10^3$	5.60 ph/MeV	≤ 5

[a]Preliminary result using 120 GeV protons.

[1]More details of this compilation in:
J. Rosado *et al.*, *Astropart. Phys.* 34 (2010) 164

2. Normalization procedure

Normalization procedure[1]

- Wavelength interval: **337 nm**
  Relative intensities from AIRFLY[2] consistent with theoretical predictions.

- Pressure (**1013 hPa**) and temperature (**293 K**).
  Standard formulation.

- Units: **ph/MeV**
  MC simulation of the experiment[1].
  Some corrections to the reported FY results are proposed[1].

[1] J. Rosado *et al.*, *Astropart. Phys.* 34 (2010) 164
[2] M. Ave *et al.*, *Astropart. Phys.*, 28 (2007) 41

➔ Measurements performed for a wide spectral range $\Delta\lambda$ are normalize to 337 nm using relative intensities of AIRFLY[1] within 290 – 430 nm

$$\mathrm{FY}_{337} = \mathrm{FY}_{\Delta\lambda} \frac{I_{337}}{I_{\Delta\lambda}}, \quad I_{\Delta\lambda} = \sum_{\Delta\lambda} I_{\lambda}$$

➔ Fluorescence spectrum can be extended beyond the 290 – 430 nm spectral range using[2].

$P >> P'$

$$\frac{I_{vv'}}{I_{00}} = \frac{q_{X\to v} A_{vv'}}{q_{X\to 0} A_{00}} \frac{1 + P/P'_0}{1 + P/P'_v} \approx \frac{q_{X\to v} A_{vv'}}{q_{X\to 0} A_{00}} \frac{P'_v}{P'_0}$$

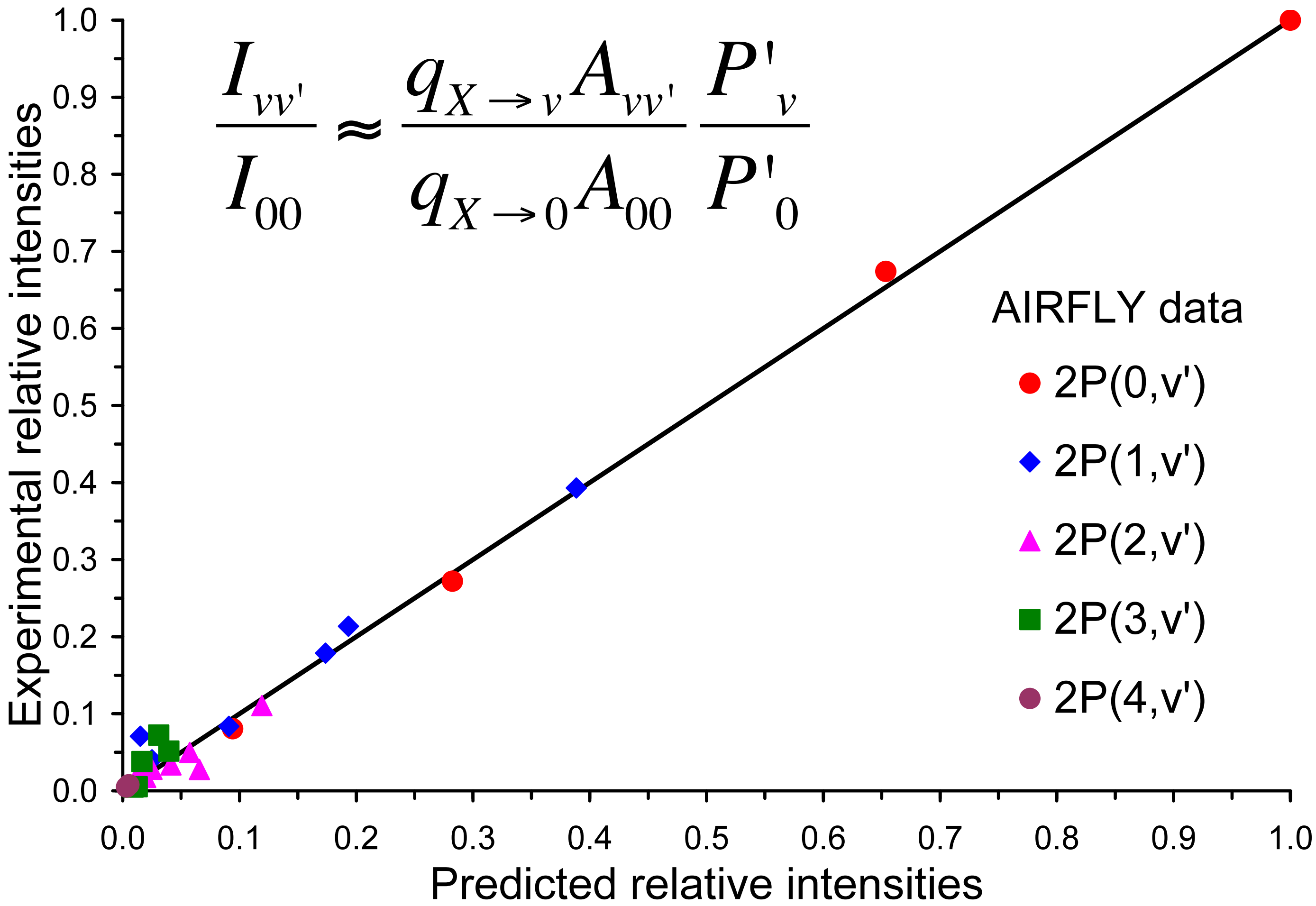
independent of P

[1]M. Ave *et al.*, *Astropart. Phys.*, 28 (2007) 41

[2]F. Arqueros *et al.*, *New J. Phys.* 11 (2009) 065011

Comparison between experimental and predicted relative intensities

$$\frac{I_{vv'}}{I_{00}} \approx \frac{q_{X\rightarrow v} A_{vv'}}{q_{X\rightarrow 0} A_{00}} \frac{P'_v}{P'_0}$$



Normalization to common P and T

➔ Pressure dependence:

$$Y = \frac{Y^0}{1 + P/P'} \overset{P>>P'}{\approx} Y^0 \frac{P'}{P}$$

➔Temperature dependence:

$$P' \sim T^{1/2}$$

Scaling law nearly independent of *P'*

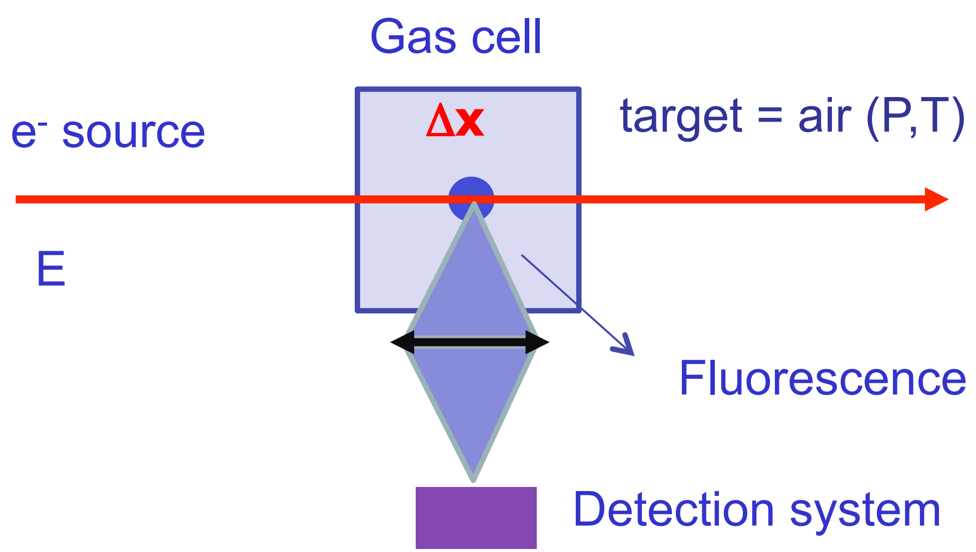
$$Y(1013\,\mathrm{hPa}, 293\,\mathrm{K}) \approx Y(P, T) \frac{P(\mathrm{hPa})}{1013} \sqrt{\frac{293}{T(\mathrm{K})}}$$

Conversion of ε (ph/m) to Y (ph/MeV)

$$Y = \frac{\varepsilon}{(\mathrm{d}E/\mathrm{d}x)_{\mathrm{dep}}}$$

In general $(\mathrm{d}E/\mathrm{d}x)_{\mathrm{dep}} \leq (\mathrm{d}E/\mathrm{d}x)_{\mathrm{loss}}$

A non-negligible fraction of the energy lost by the electron is deposited outside the field of view of the optical system



Both fluorescence and deposited energy must be measured/computed in the same volume

Conversion of ε (ph/m) to Y (ph/MeV)

- A MC simulation including the microscopic molecular processes was carried out for each experiment:

  a) Energy deposition

$$\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle_{\mathrm{dep}} = \frac{\int_{\mathrm{vol}} E_{\mathrm{dep}}}{\int_{\mathrm{track}} x}$$

Primary electrons lose energy in collisions and have fluctuating trajectories

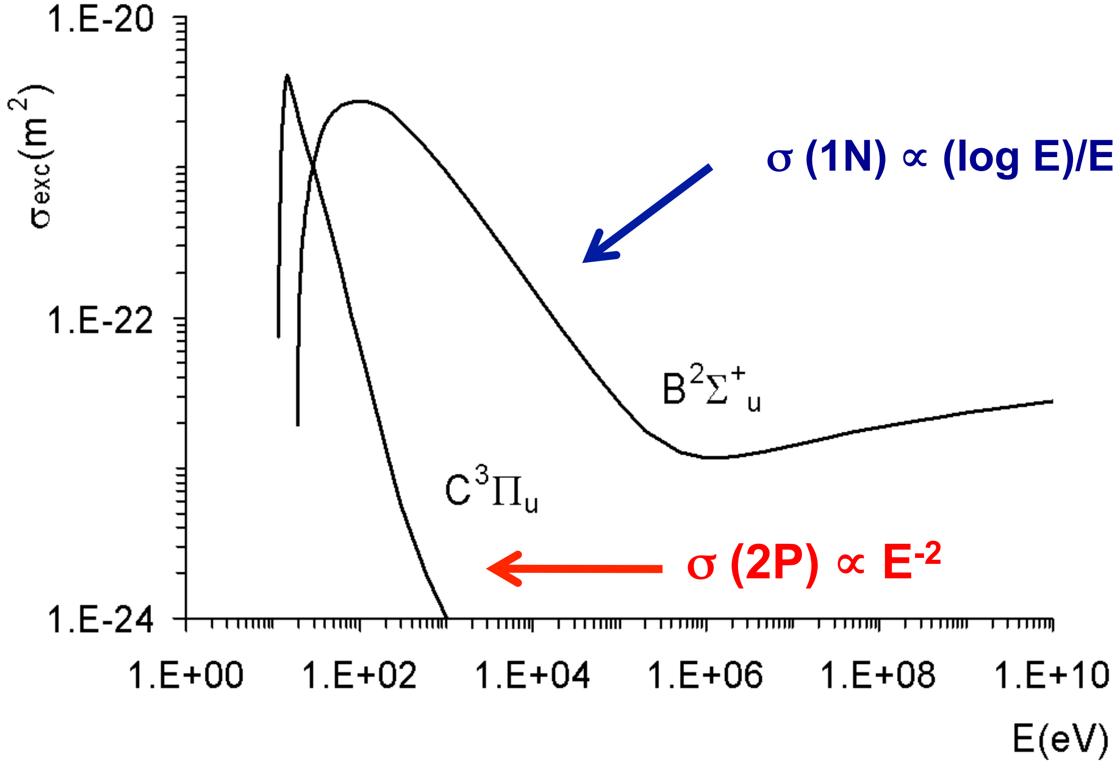
  b) Geometrical factors

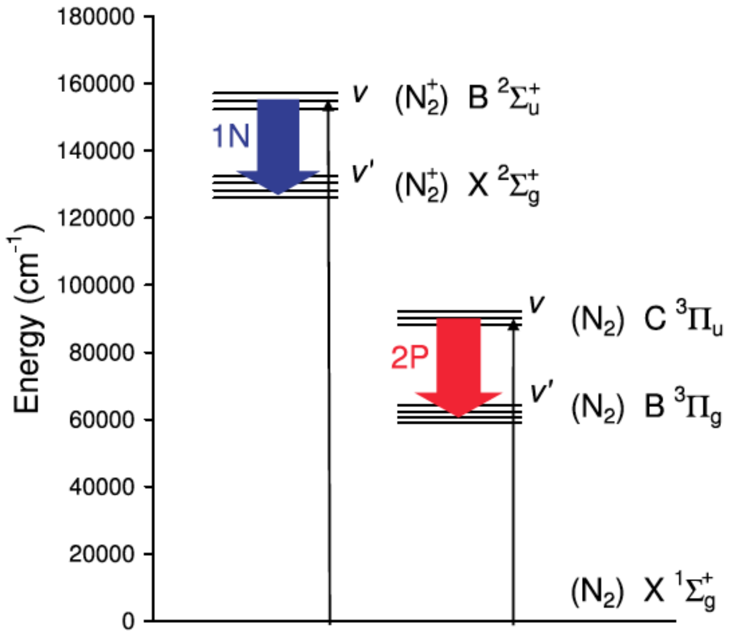
$$\langle \Omega \rangle = \int_{\mathrm{vol}} \phi_{\mathrm{light}} \Omega$$

- Comparison with results reported by the authors

3. MC analysis: the algorithm

The generation of air-fluorescence by electron (charged particle) collisions





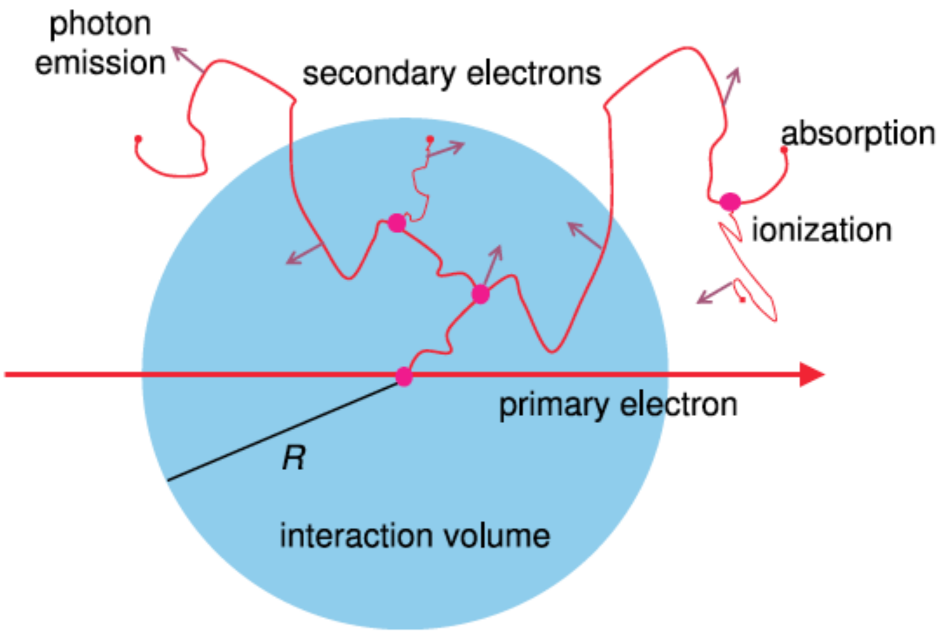
Excitation of 2P system is negligible at E > keV. However (at high pressure) 2P dominates over 1N even a very high electron E

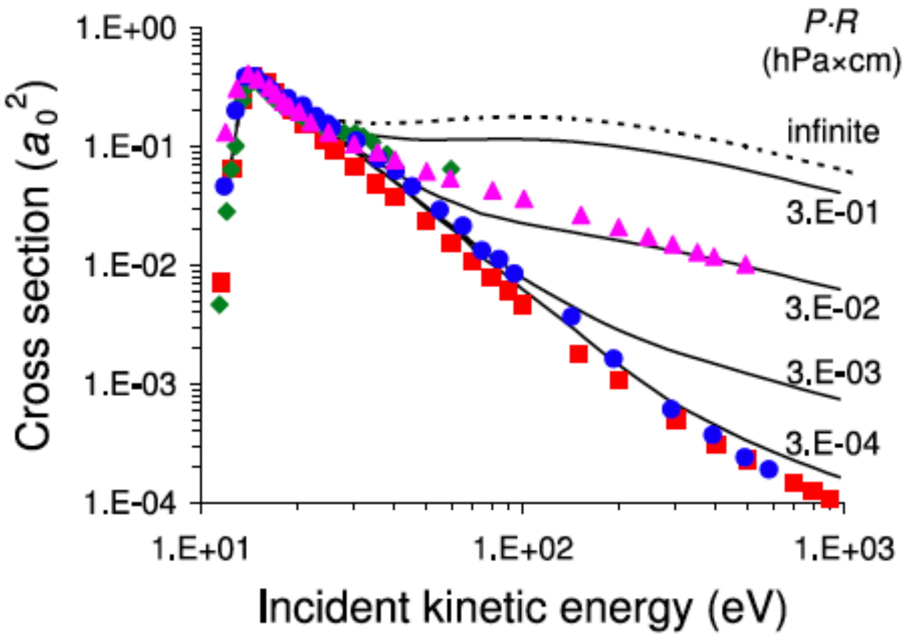
More details in F. Arqueros *et al.*, *New J. Phys.* 11 (2009) 065011

Air-fluorescence is mainly generated by low energy secondary electrons produced in ionization processes

- First suggested by Bunner (1967) PhD thesis

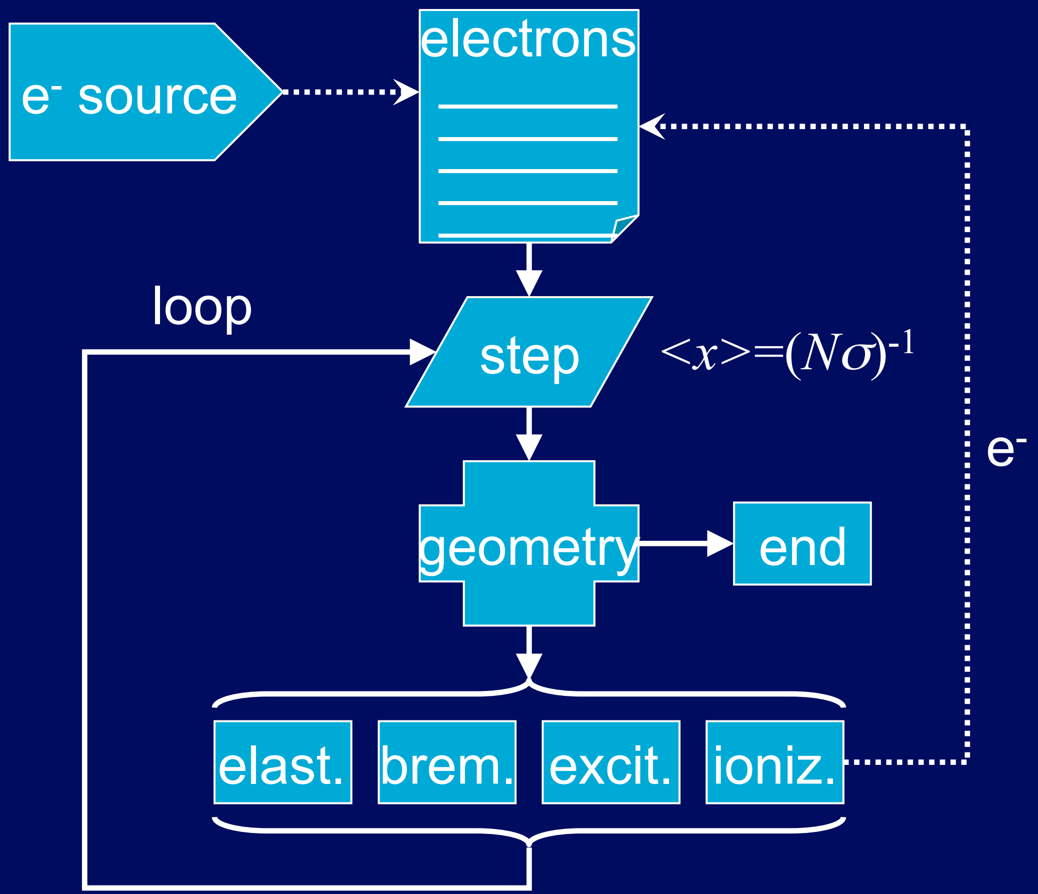
- Demonstrated quantitavely very recently
  F. Blanco and F. Arqueros, Phys. Lett. A 345 (2006) 355.





See also F. Arqueros *et al.*, *New J. Phys.* 11 (2009) 065011

Layout of the simulation algorithm



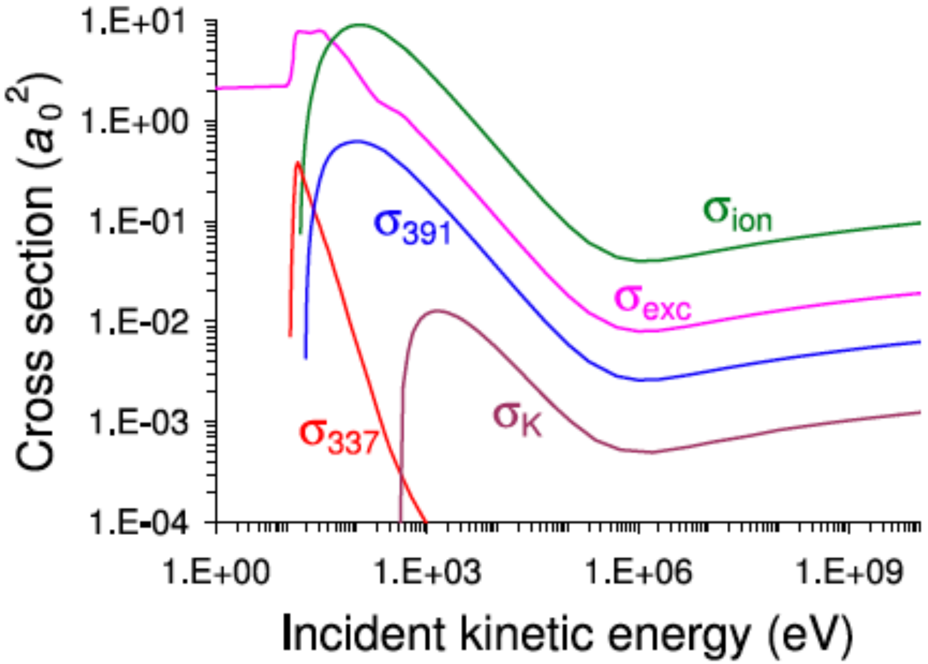
- Cutoff energy of 11 eV
- X-rays also included
- Predictions on
  - Deposited energy
  - Fluorescence

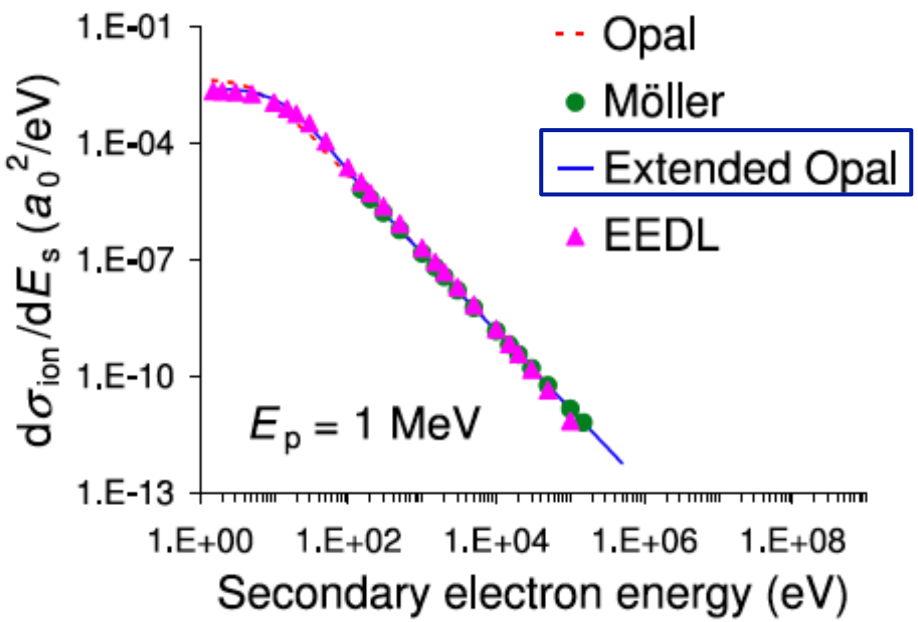
Ingredients of our simulation:

➡ <u>Cross sections</u> of the various processes: elastic, inelastic, ionization, bremstrahlung

➡ Energy spectrum of <u>secondary electrons</u>: analytical aproximation consistent with experimental data both at low and high primary energy.

➡ Average values of <u>excitation (ionization) energy</u>



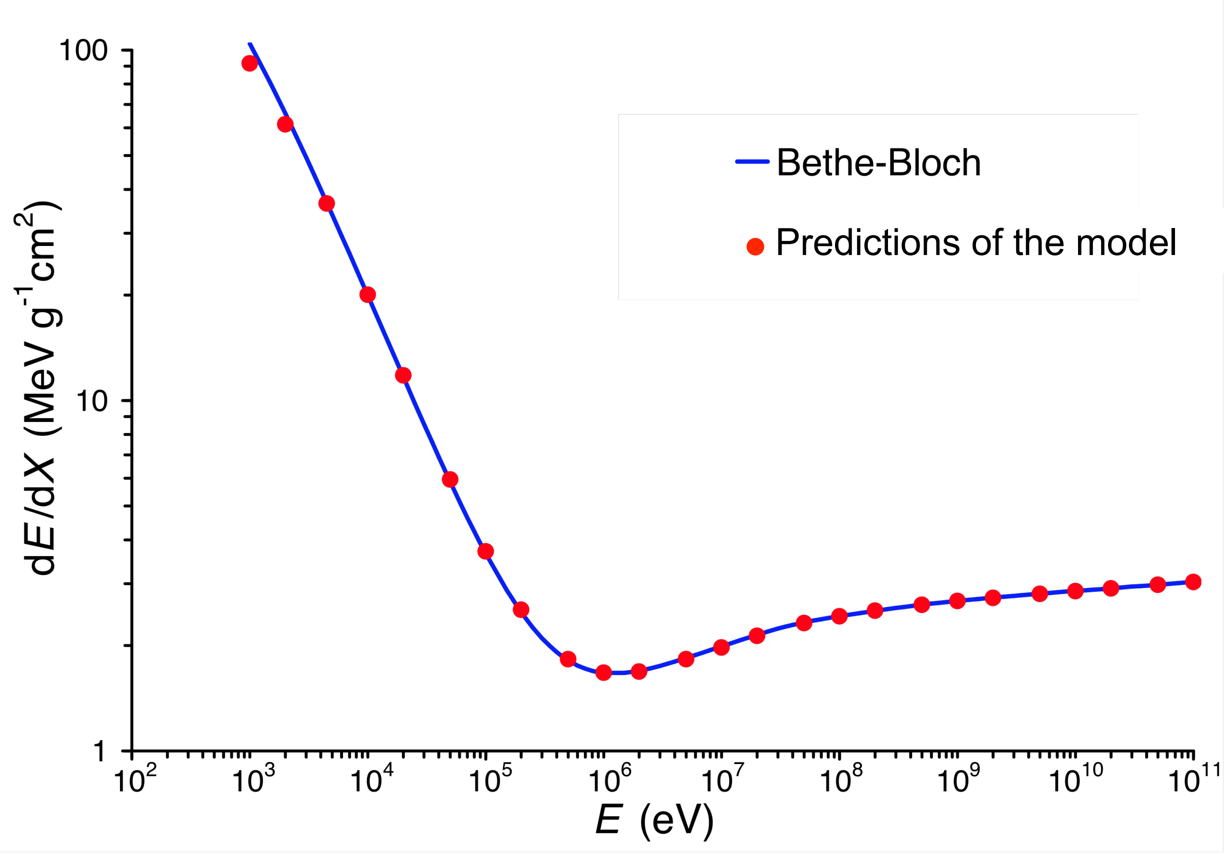


Details in F. Arqueros *et al.*, *New J. Phys.* 11 (2009) 065011

Predictions on energy losses

➡ Our ingredients accounts accurately for the energy loss of electrons (Bethe-Bloch)

➡ Density correction at the corresponding pressure included in all ionization cross sections (also for K shell)



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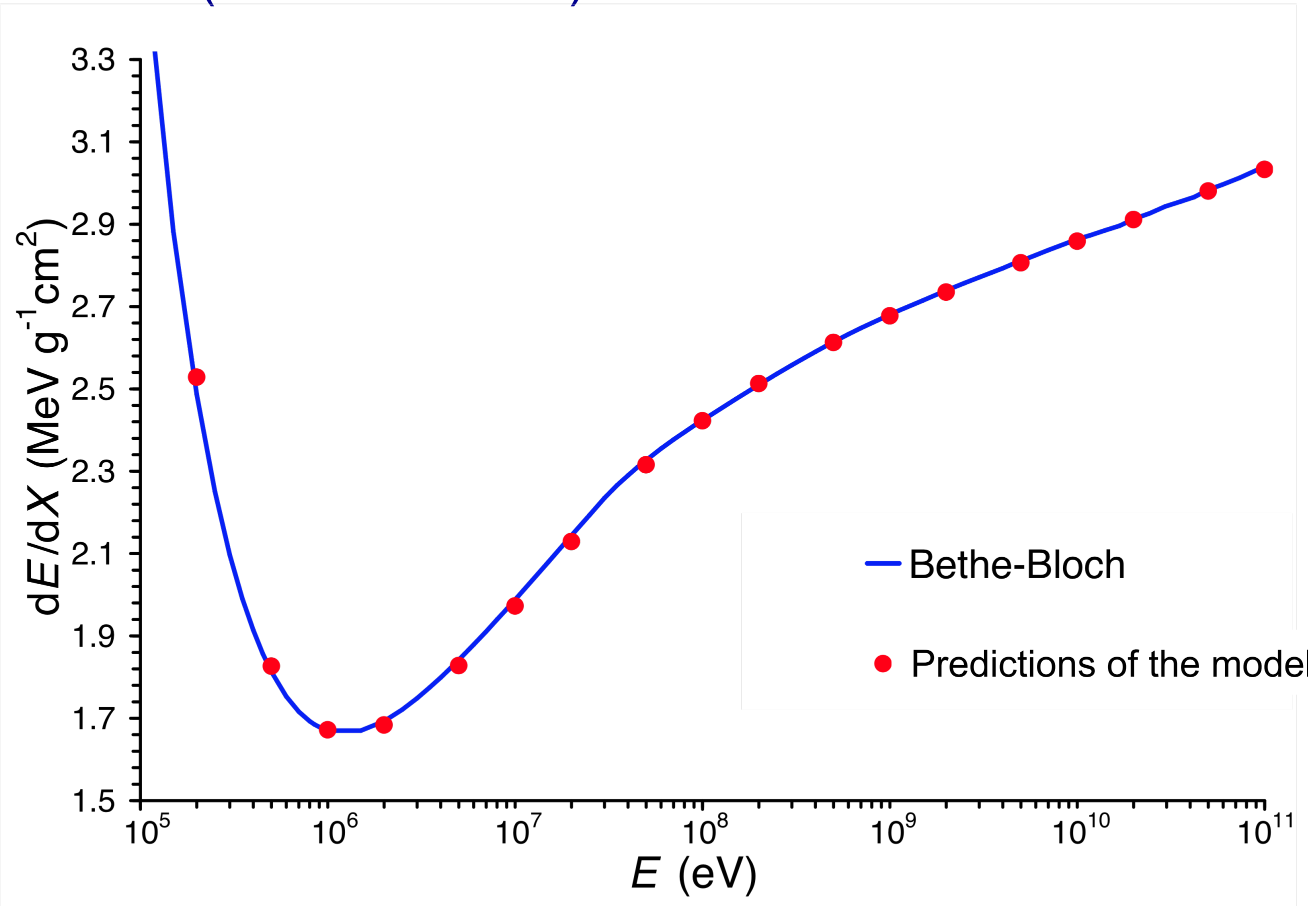
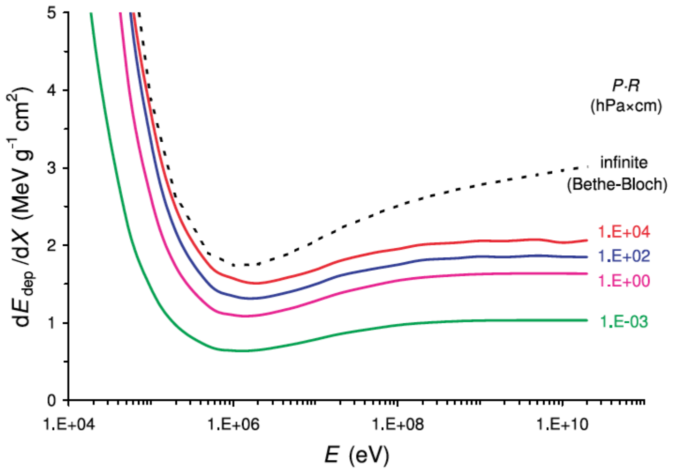
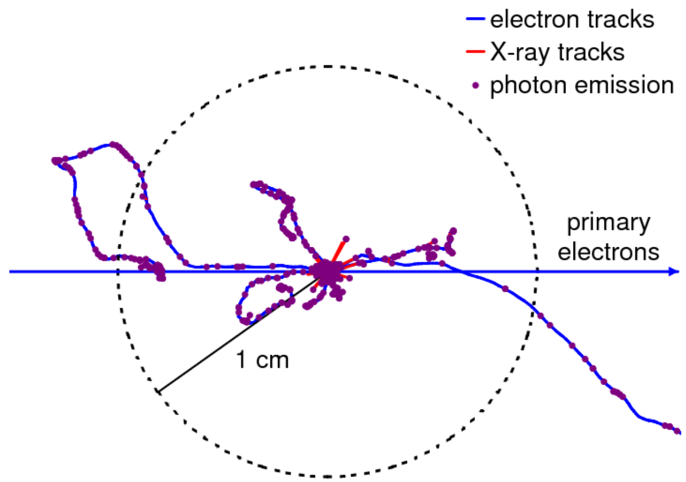


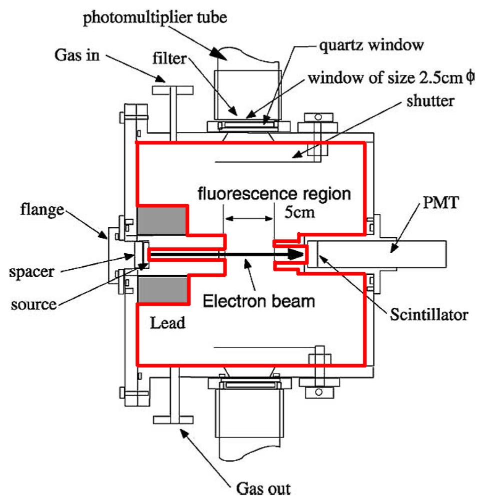
Geometry

1. **Generic simulation:** Primary electrons collide at the center of a sphere of radius R.
   - Deposited energy weakly dependent on R. Results on Edep in very good agreement with those obtained using a detailed geometry
   - Fluorescence yield can be computed.





2. **Detailed geometry:**
   - Deposited energy
   - Geometrical factors
   - Fluorescence yield



Expected accuracy of the simulation

➡ Energy deposition in the collision chamber. High accuracy at the level of 2% as far as the total energy loss is well reproduced

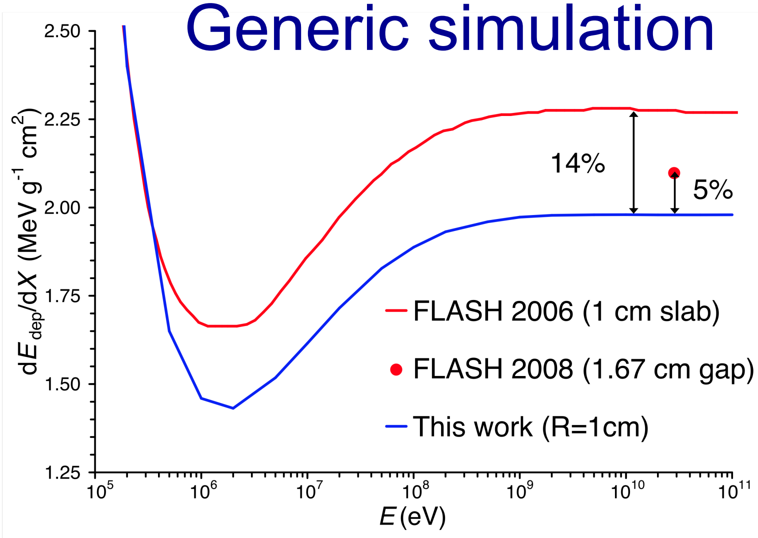
➡ Fluorescence emission. Depends on many molecular parameters not accurately known. We expect uncertainties at the level of 25%.

➡ Fluorescence yield also at the level of 25%

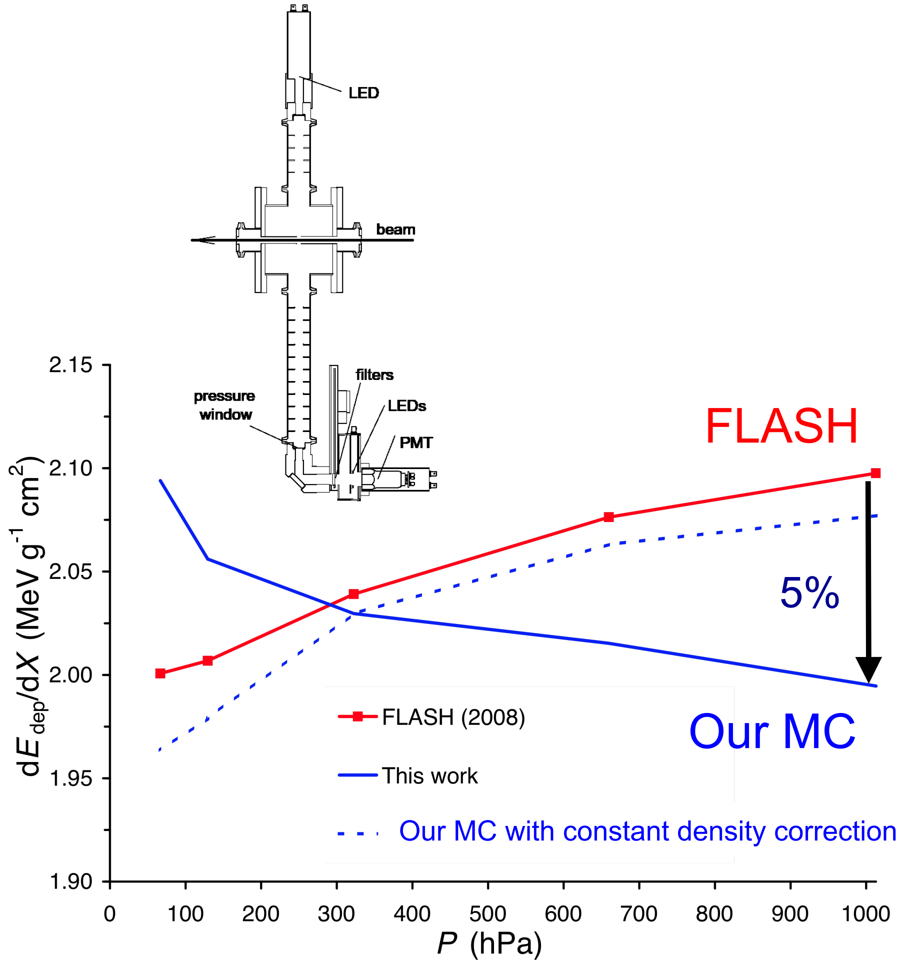
Energy deposition: Comparison with other simulations

FLASH

Generic simulation



Detailed simulation

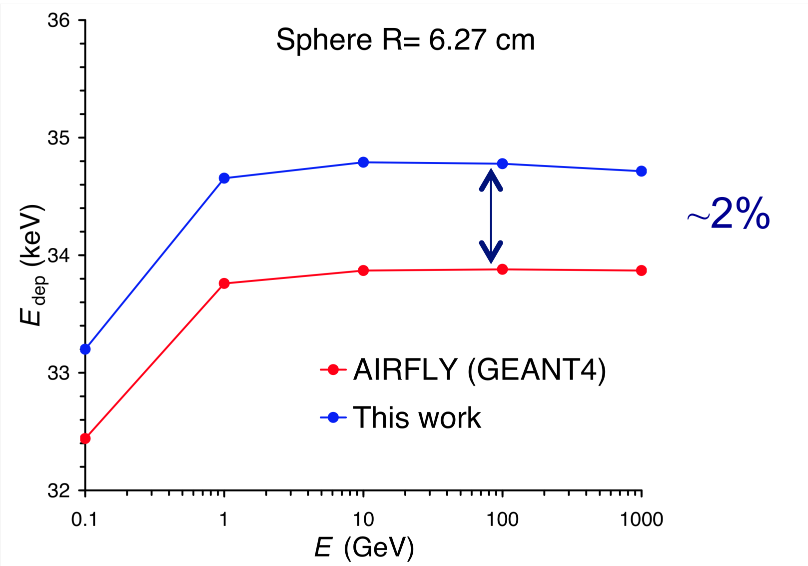


Disagreement in the P dependence of E_{dep}

Energy deposition: Comparison with other simulations

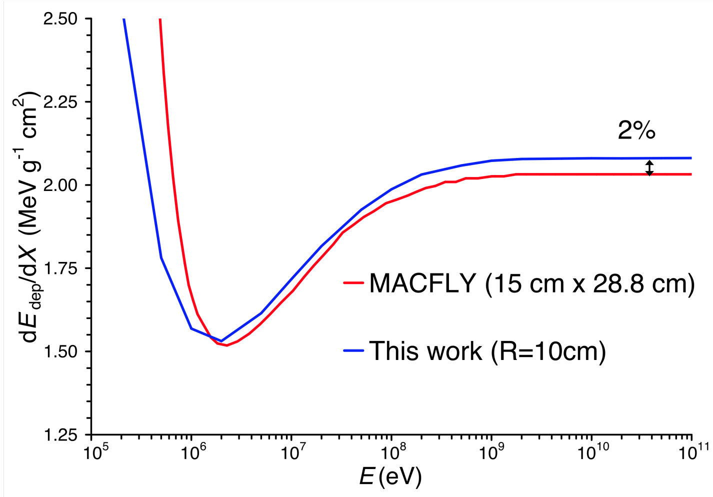
AIRFLY (GEANT4)

Detailed simulation



MACFLY (GEANT4)

Generic simulation



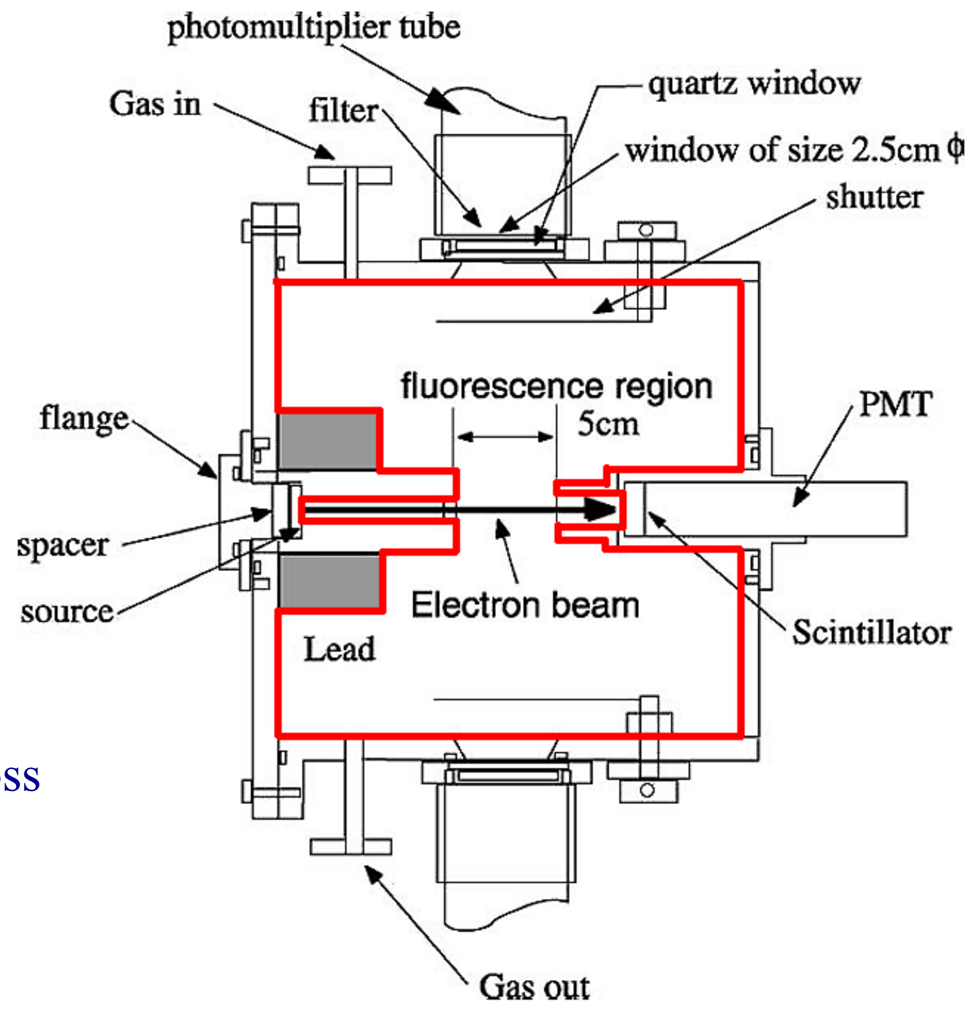
At high energy (GeVs) GEANT4 gives a deposited energy around 2% smaller than our MC

3. MC analysis: Some results

Nagano's experiment

Nagano *et al.*[*] made three assumptions:

1. $\Delta x = \Delta x_{gap}$
2. $<\Omega> = <\Omega>_{beam}$
3. $(dE/dx)_{dep} = (dE/dx)_{loss}$



[*]M. Nagano *et al.*, *Astropart. Phys.* 20 (2003) 293; *Astropart. Phys.* 22 (2004) 235

Nagano's experiment

- Three corrections have been applied:

$$Y = Y_{\mathrm{Nag}} \frac{\langle \Omega \rangle_{\mathrm{beam}}}{\langle \Omega \rangle} \frac{\Delta x_{\mathrm{gap}}}{\Delta x} \frac{\left(\mathrm{d}E/\mathrm{d}x\right)_{\mathrm{loss}}}{\langle \mathrm{d}E/\mathrm{d}x \rangle_{\mathrm{dep}}}$$

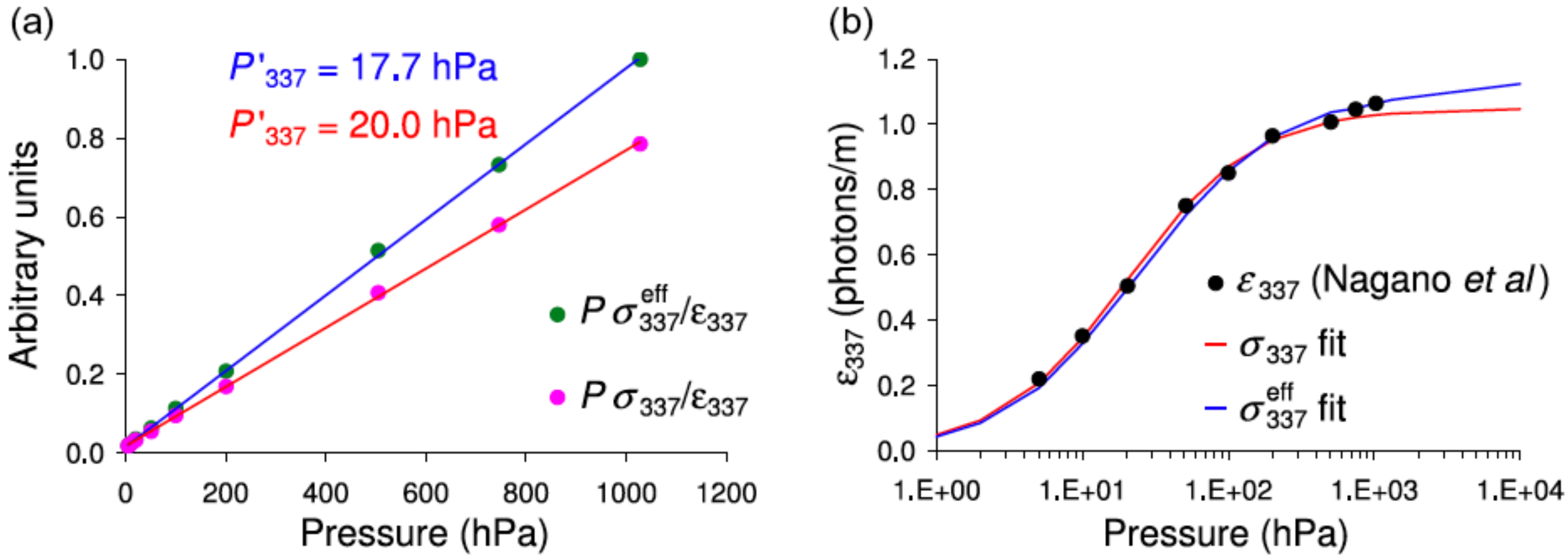
~1% increase

~1% decrease

6% increase

- FY of Nagano should be increased by 6%

Nagano's experiment



➡ Secondary electrons escaping the field of view can also induce systematic errors in the determination of quenching parameters from the measurement of FY(P).

➡ P' values of Nagano get closer to those of AIRFLY when the effetc of secondary electrons are taken into account

More details in F. Arqueros *et al.*, *New J. Phys.* 11 (2009) 065011

4. Comparison of FY values

Normalized FY values (337 nm, 1013 hPa, 293 K)

uncorrected | **corrected**

Experiment	E (MeV)	Quoted error	Y_{337} (ph/MeV)	Correction
Kakimoto (1996)	1.4	10%	4.5 / **4.8**	+6%
	300		4.4 / **5.5**	+25%
	650		3.8 / **4.8**	+27%
	1000		4.3 / **5.5**	+29%
Nagano (2004)	0.85	13%	5.0 / **5.4**	+6%
Lefeuvre (2007)	1.1	5%	5.1 / **5.5**	+7%
	1.5		5.6 / **6.1**	+8%
MACFLY (2007)	1.5	13%	4.3 / **4.4**	+1%
	$20 \cdot 10^3$		4.4 / **4.3**	-2%
	$50 \cdot 10^3$		4.6 / **4.5**	-2%
FLASH (2008)	$28.5 \cdot 10^3$	7.5%	5.5 / **5.6**	+2%
AirLight (2008)	$0.2 - 2$	16%	5.8 / **5.4**	-7%
AIRFLY (2010)	$120 \cdot 10^3$	$\leq$ 5%	5.6 / **-**	-

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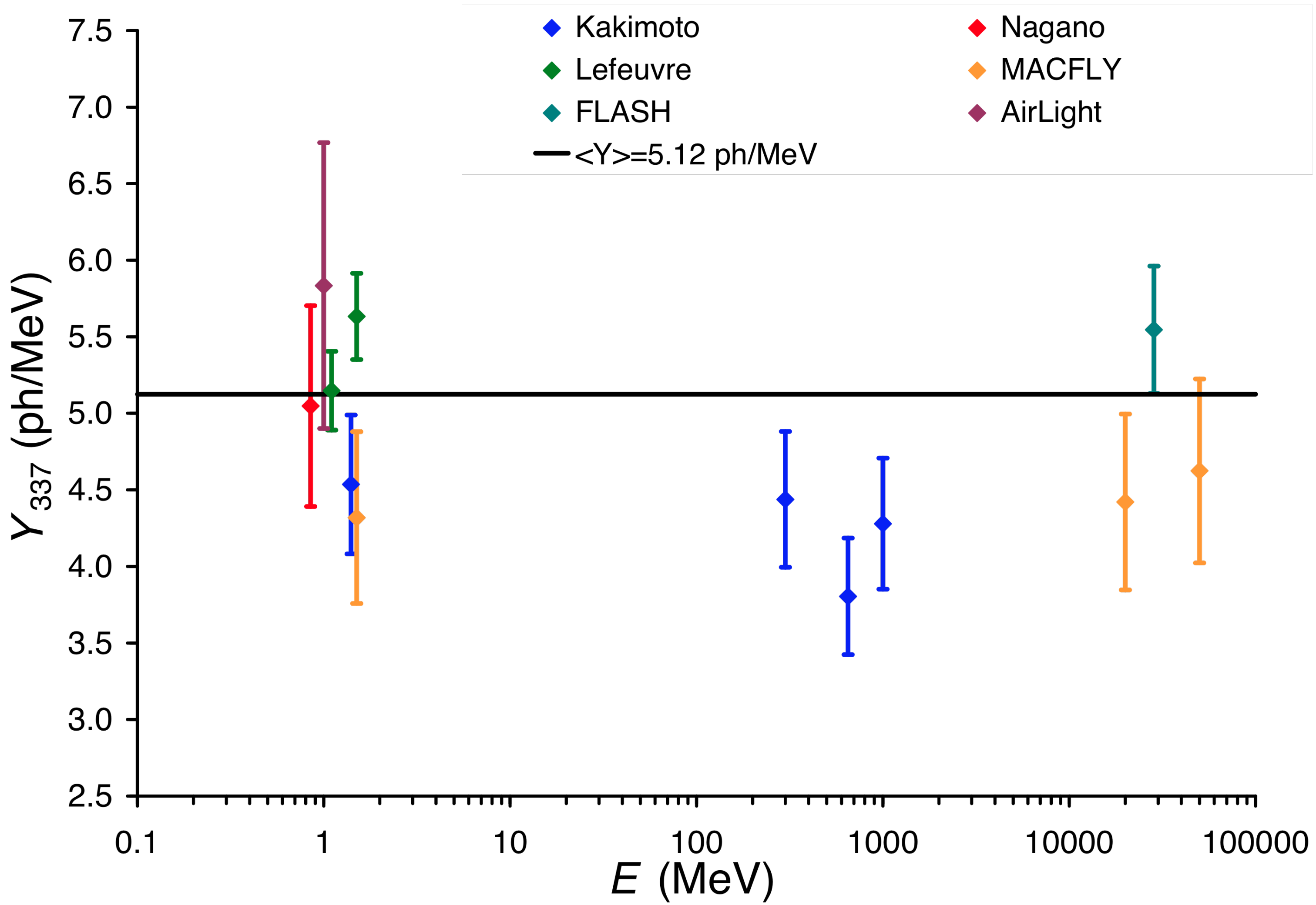
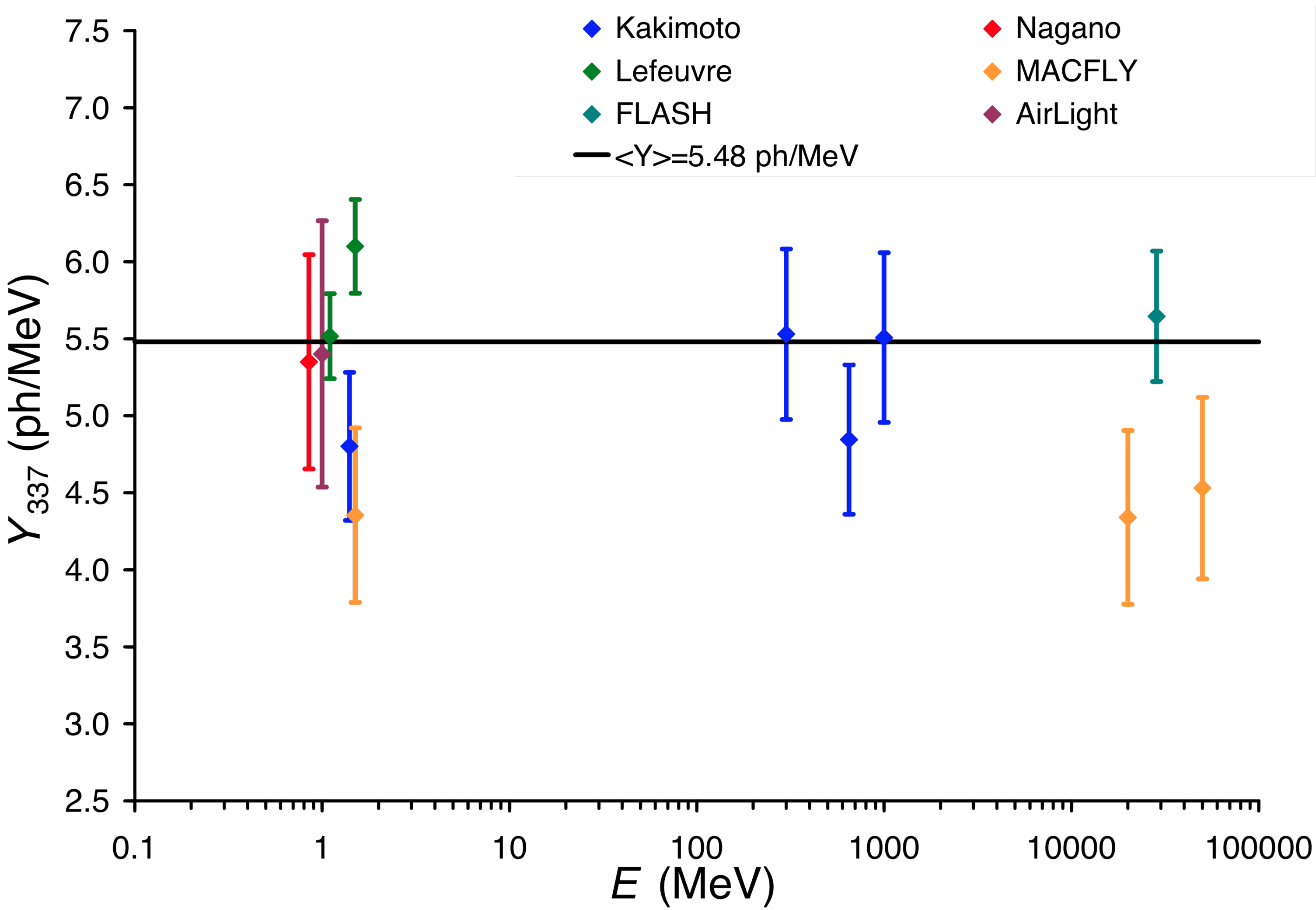
Our correction is sometimes larger than the error reported by the authors

Uncorrected FY versus primary electron energy



Corrected FY versus primary electron energy



Our correction supports the expected E independence of the fluorescence yield

FY results (337 nm, 1013 hPa, 293 K)

	uncorrected	corrected	
Experiment	$Y_{337}^{\mathrm{uncorr}}$ (ph/MeV)	Y_{337}^{corr} (ph/MeV)	Quoted error
Kakimoto (1996)	4.3	5.2	10%
Nagano (2004)	5.0	5.4	13%
Lefeuvre (2007)	5.4	5.8	5%
MACFLY (2007)	4.5	4.4	13%
FLASH (2008)	5.5	5.6	7.5%
AirLight (2008)	5.8	5.4	16%
AIRFLY (2010)	5.6	-	$\leq$ 5%

Averaged FY for each experiment

Weighted average and error

$w_i = 1/\sigma_i^2$ Weight = reciprocal of the sq. uncertainty quoted by the authors

$$\langle Y \rangle = \frac{\sum_i w_i Y_i}{\sum_i w_i},$$ Weighted mean

$$\sigma^2 = \frac{\sum_i w_i \left(Y_i - \langle Y \rangle\right)^2}{\sum_i w_i}.$$ Weighted variance

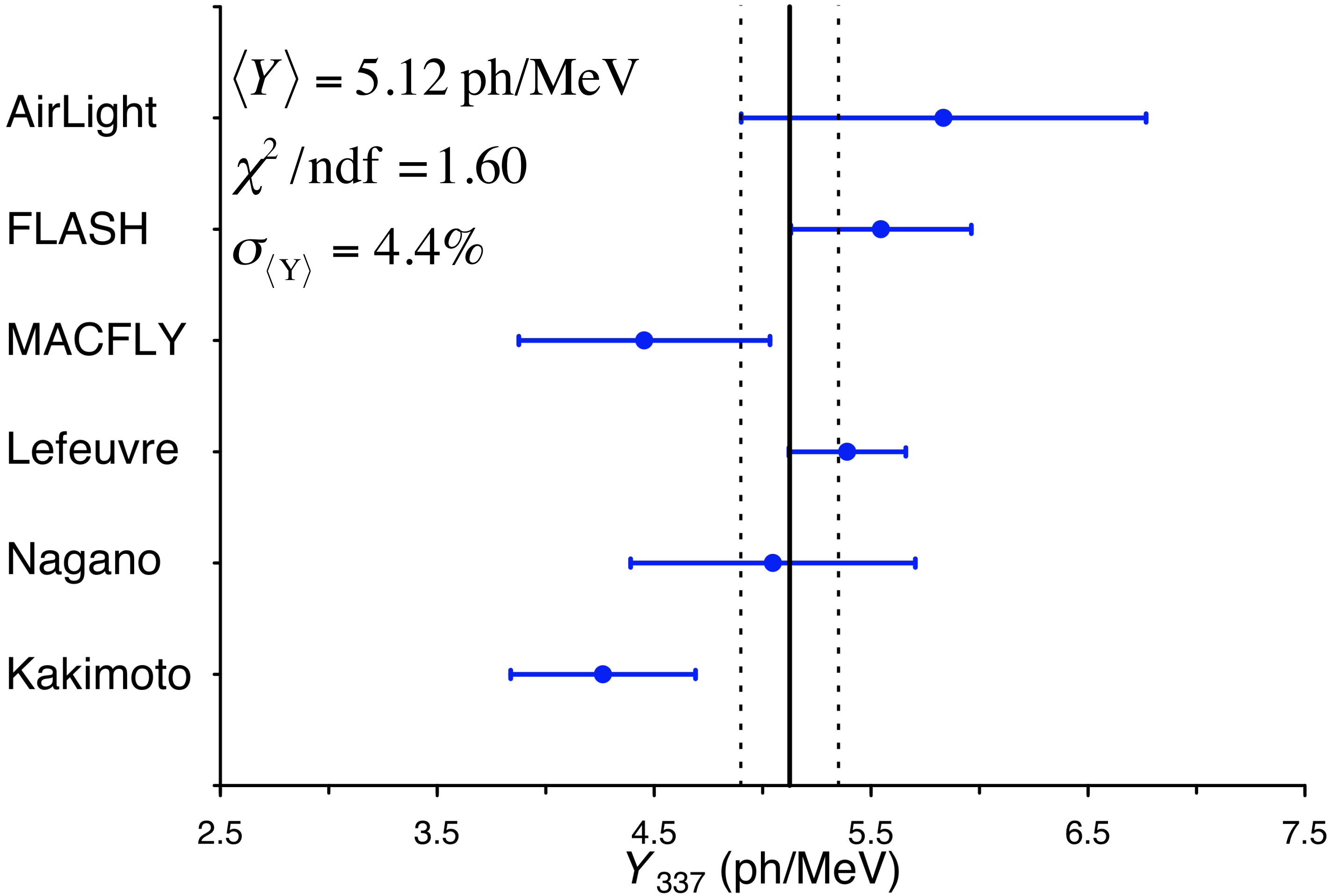
If squared uncertainties actually represented the variance of the corresponding normal distribution, the uncertainty of the mean would be:

$$\left(\sum_i \frac{1}{\sigma_i^2}\right)^{-1/2}$$ and

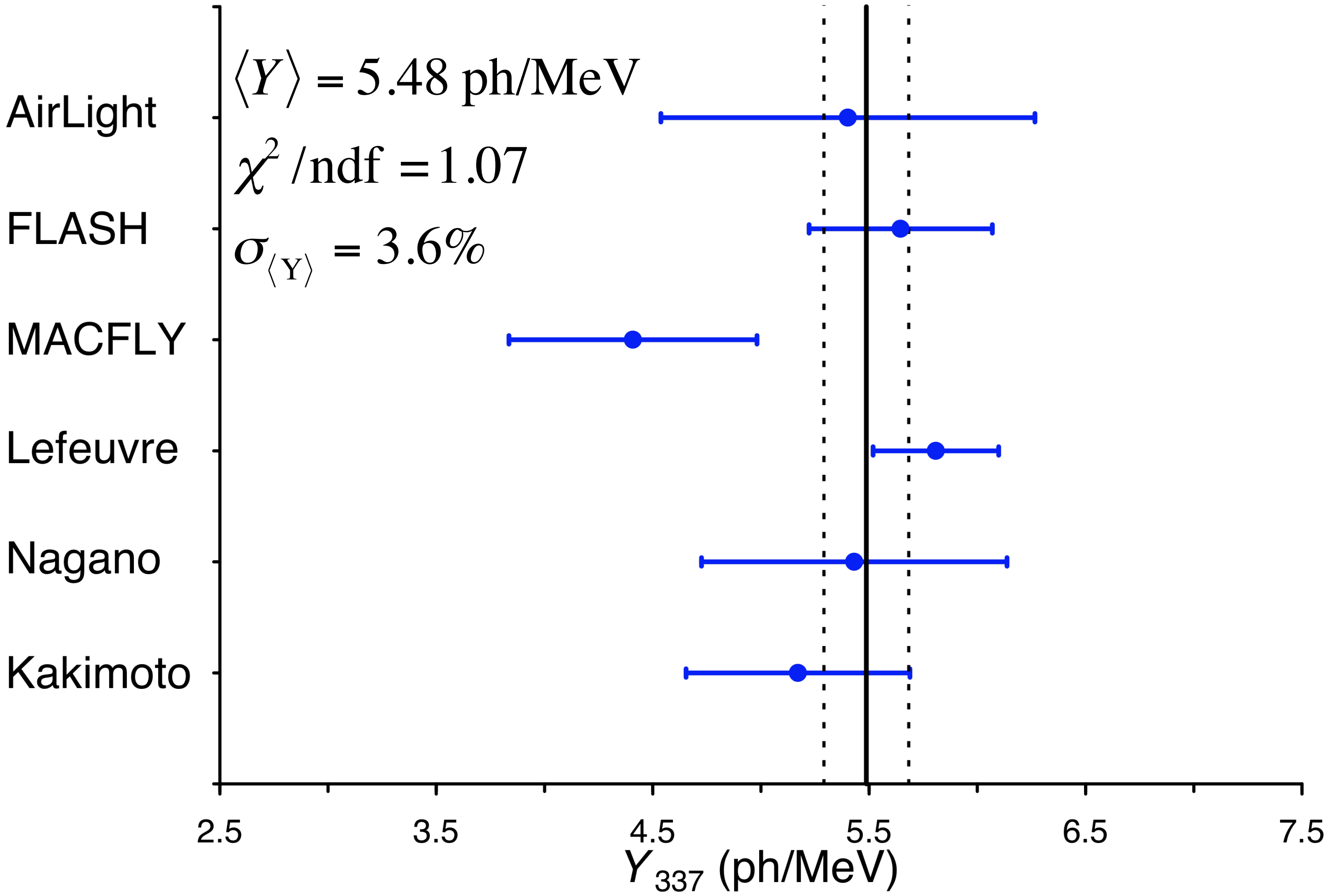
$$\chi^2/\mathrm{ndf} = \frac{1}{n-1} \sum_i \frac{\left(Y_i - \langle Y \rangle\right)^2}{\sigma_i^2},$$ is an indicator of data compatibility

Our final error bar could be given by $\sigma_{\langle Y \rangle} = \left(\sum_i \frac{1}{\sigma_i^2}\right)^{-1/2} \times \sqrt{\chi^2/\mathrm{ndf}}$

Uncorrected Y_{337} (1013hPa, 293K)

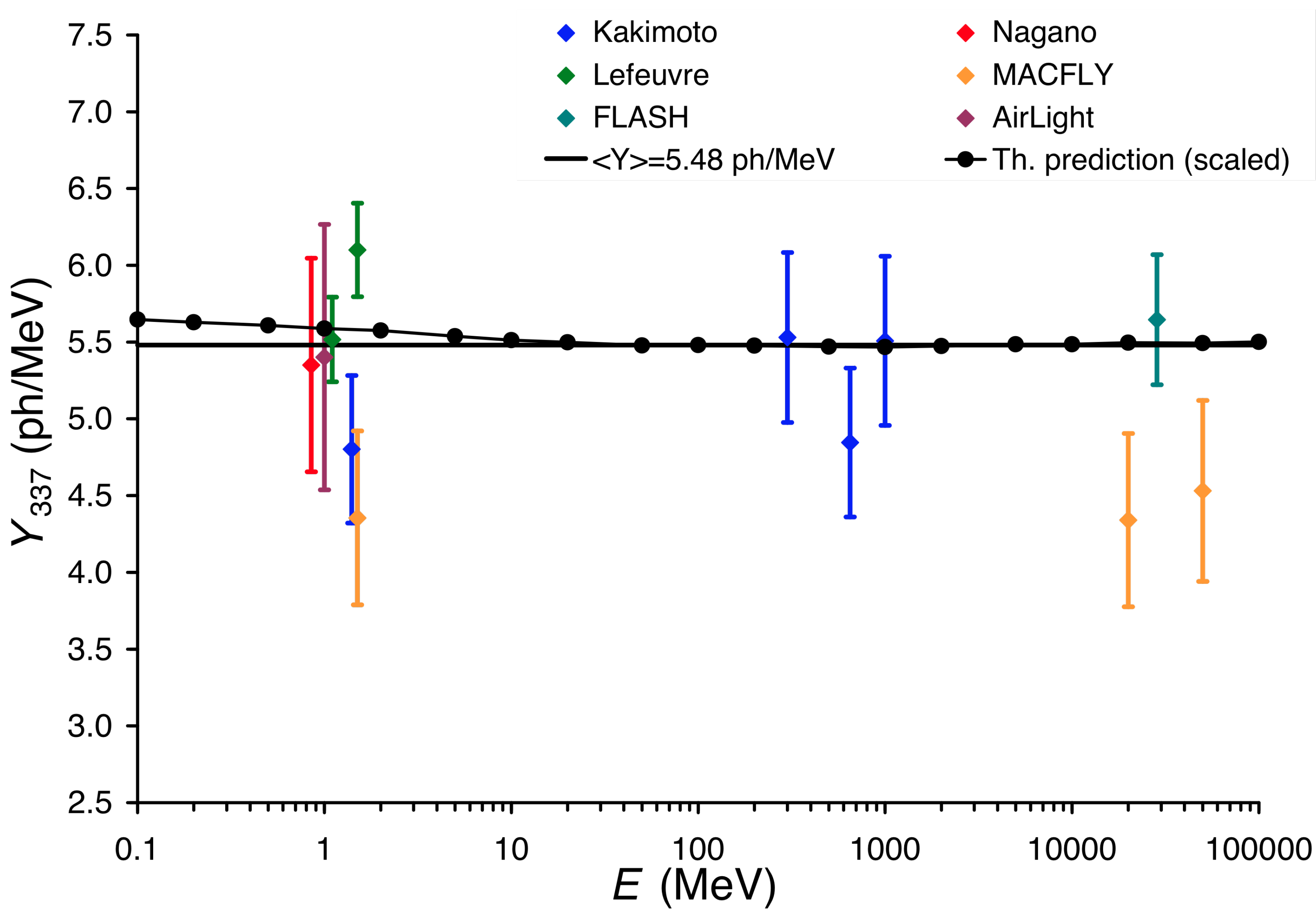


Corrected Y_{337} (1013hPa, 293K)



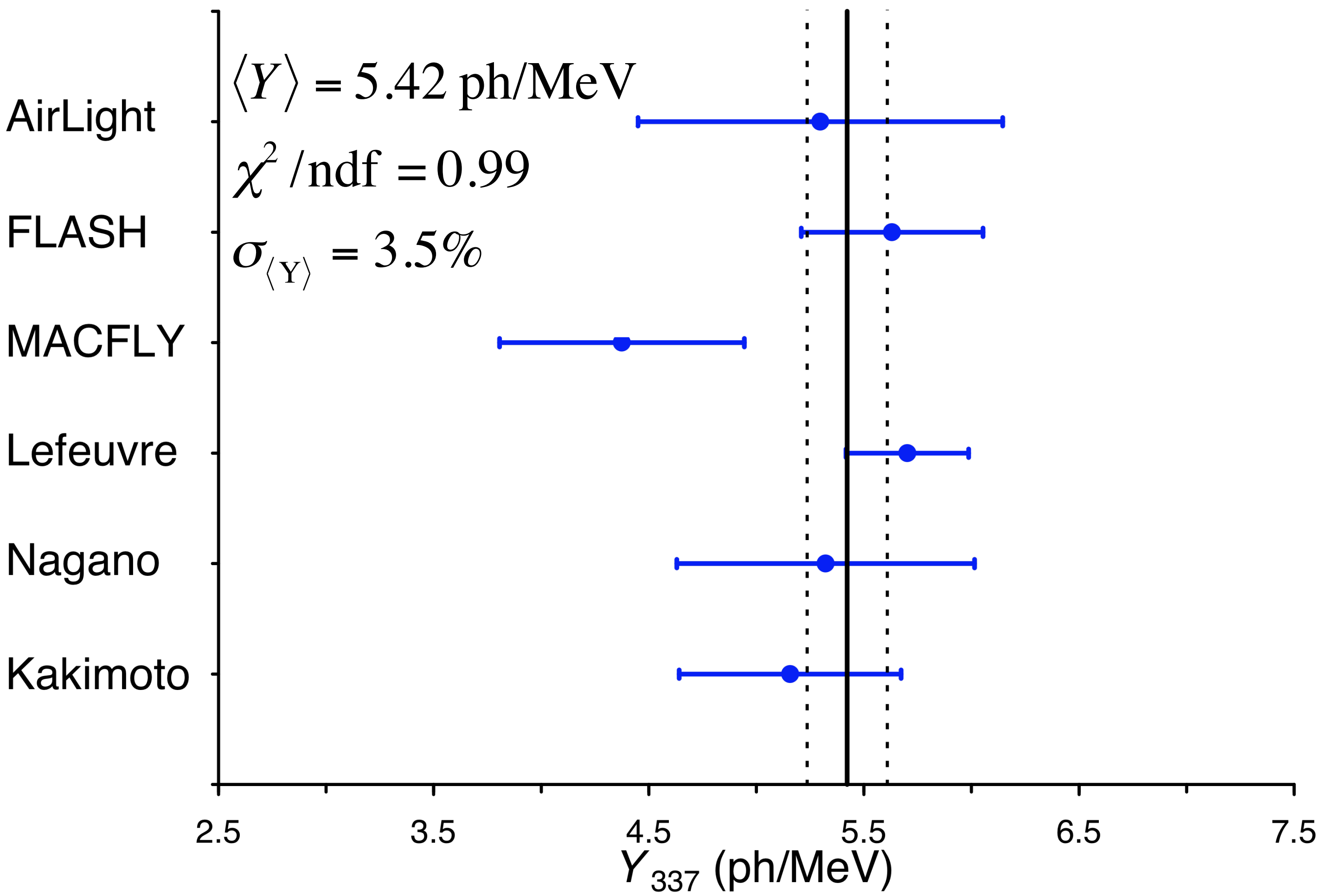
The correction increases compatibility of measurements

Corrected FY versus primary electron energy



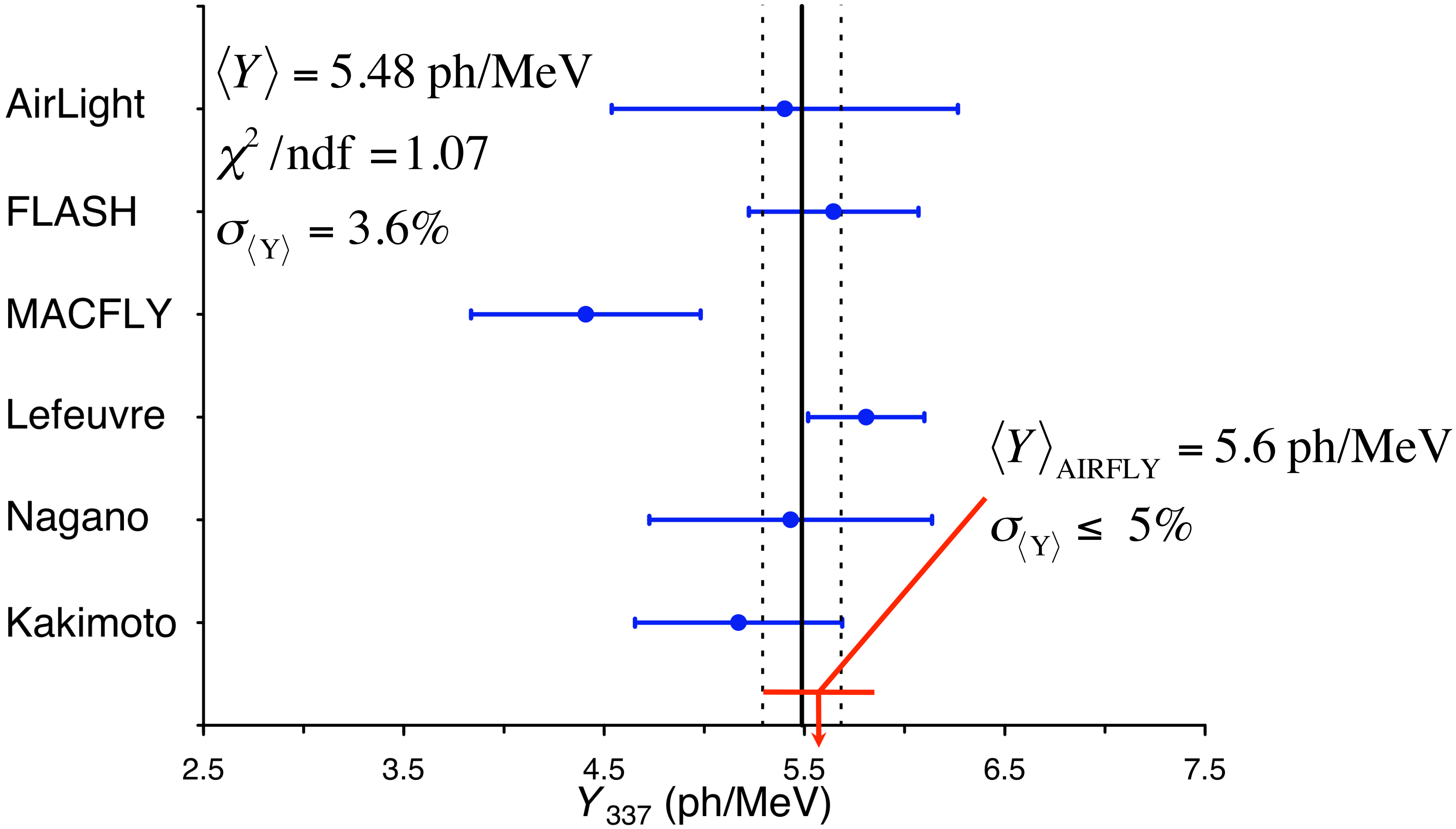
Our simulation predicts a weak E dependence of the FY

Y_{337} corrected by weak E dependence



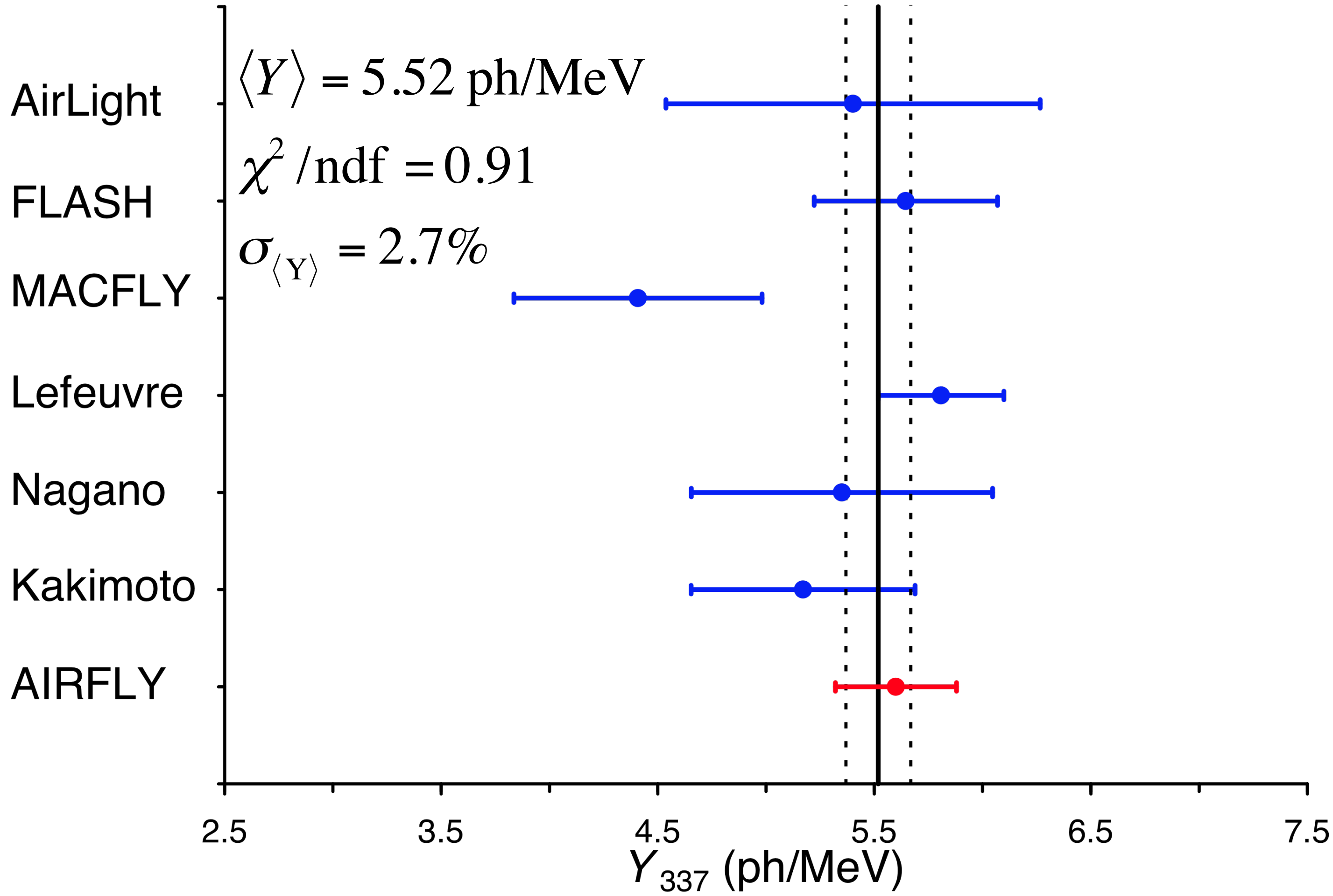
This weak energy dependence <u>increases slightly</u> the <u>compatibility</u> of measurements

Corrected Y_{337} (1013hPa, 293K)



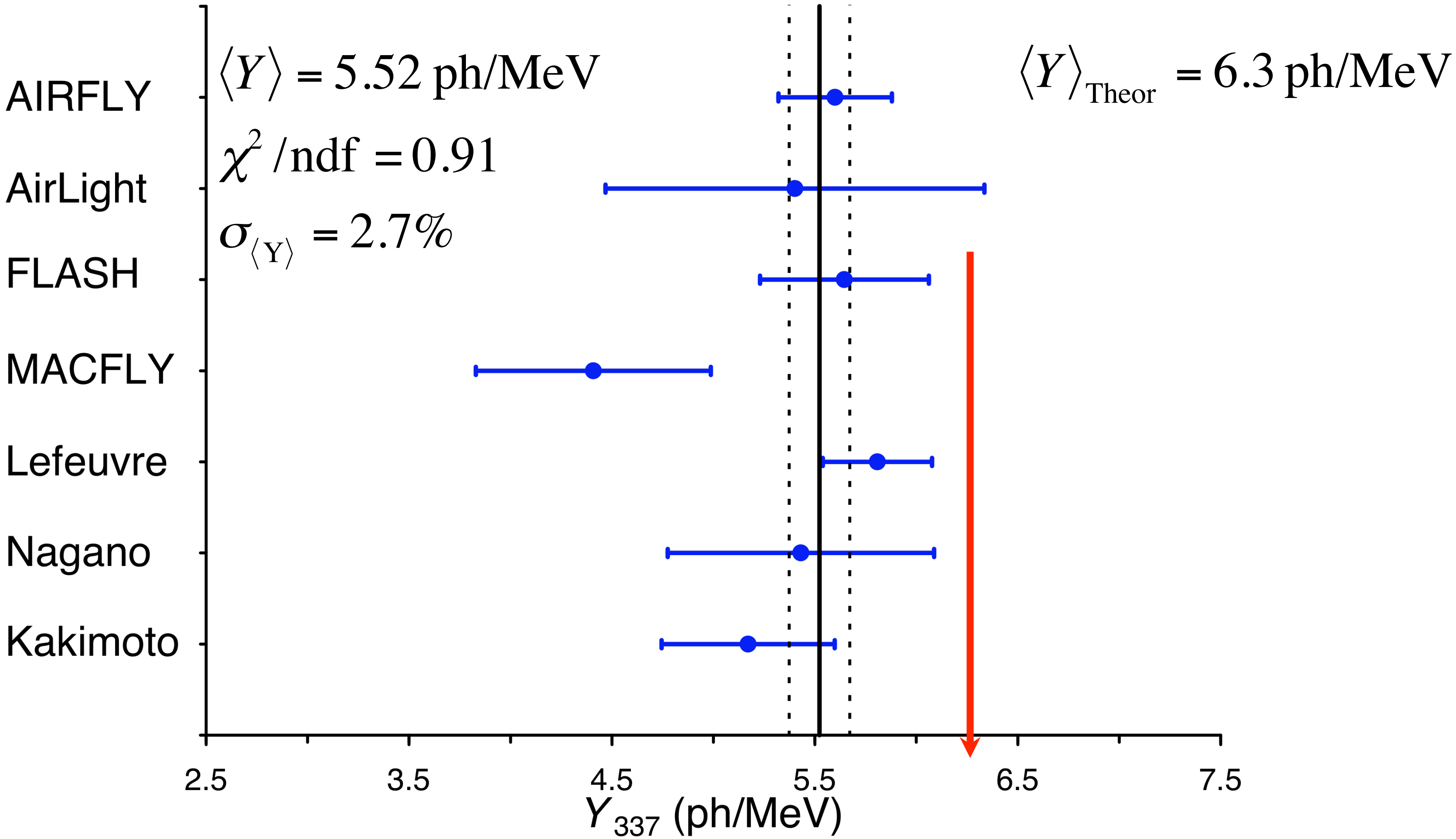
The preliminary result of AIRFLY is fully compatible with this average value

Average value of Y_{337} (1013hPa, 293K) including the preliminary AIRFLY result



The AIRFLY result lowers further the uncertainty of the average value

Comparison with the theoretical value



Our theoretical FY value is in VERY GOOD agreement with the experimental one taking into account the uncertainties in the molecular parameters

Conclusions

1. Our corrections increase significantly the compatibility of available measurements of the absolute FY (χ^2 = 1.60 ➔ 1.07) as well as its expected E independence.

2. Assuming the experimental errors are properly calculated, a simple statistical analysis leads to an average value (1013hPa, 239K) of **Y_{337} = 5.48 ph./MeV** with an uncertainty of 3.6%. This average value is weakly dependent on the weighting procedure or from excluding outsiders.

3. Taking into account the E_{dep} uncertainty from our simulations and the likely underestimated error of some experiments, a more realistic uncertainty for this average would be around a **5%**.

Conclusions

4. The preliminary result of AIRFLY is fully compatible with this average value.

5. Including the AIRFLY result in the data set, an average value of **Y_{337} = 5.52 ph./MeV** with a (theoretical) uncertainty of 2.7% is found.

6. A realistic uncertainty for such average value would be **below** the **5%** level.

Thanks !