# Transmission through graphene of electrons in the 30 - 900 eV range

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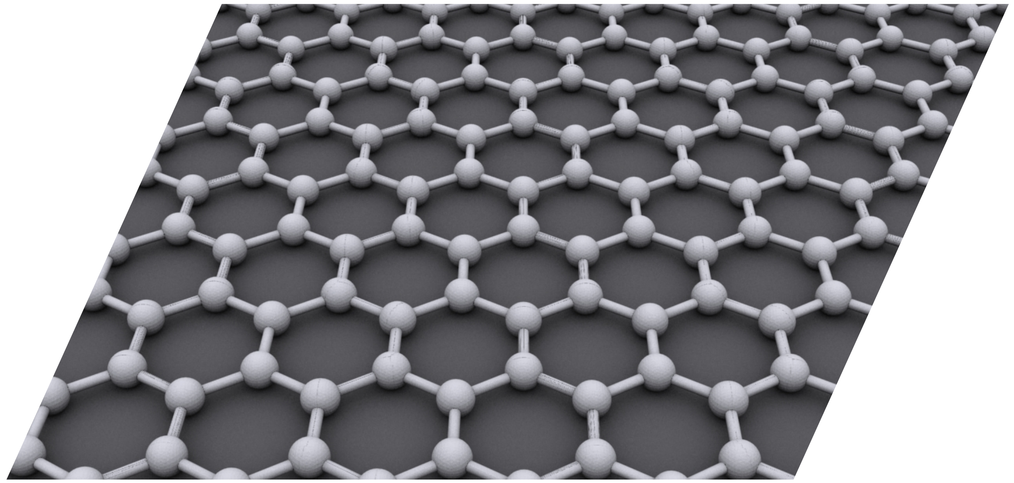
# Graphene transparency: a growing topic of interest

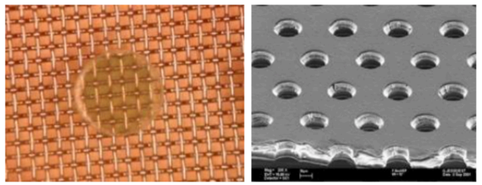
Graphene:

- Single sheet 1 atom thick
- C atoms $sp_2$ hybridised (planar, 120°) arranged in hexagons



Transmission of low-energy electrons through graphene:

- Many experiments several electron energy ranges
- Only a few below 1 keV
- Discussion still open
- Interesting for novel detectors



MicroMegas GEM

Integration of graphene in MPGD
Transparency to electrons
Impermeability to atoms

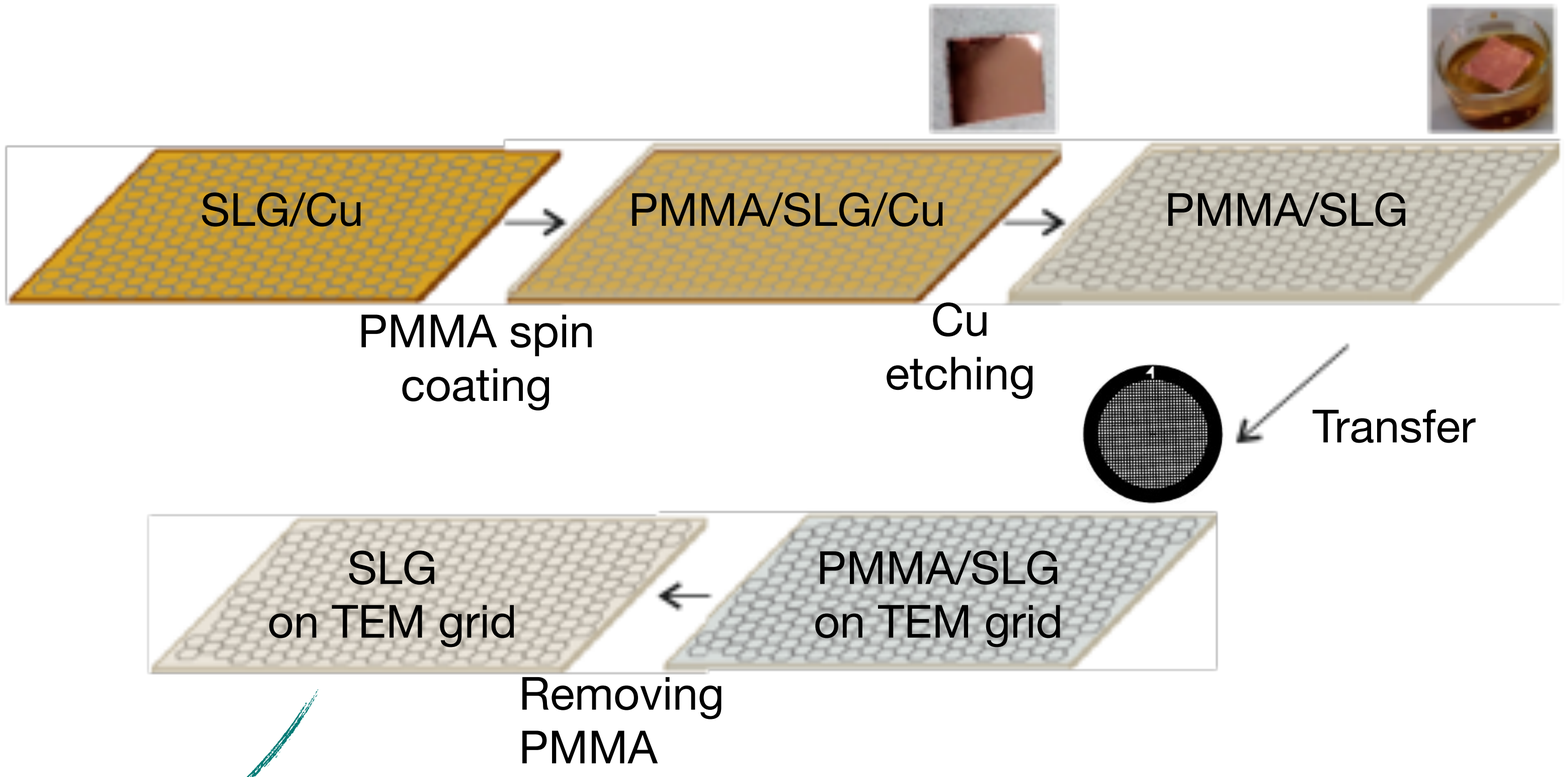
PTOLEMY

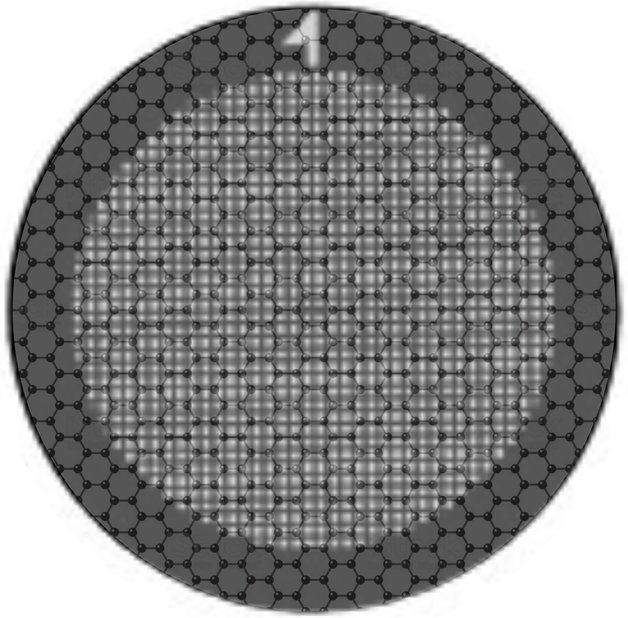
Tritiated graphene target
Measure the $\beta$-electrons

# Sample preparation: graphene growth and transfer on TEM grid

Mono-/tri- layer graphene on nickel TEM grid:

- G2000HAN - Ted Pella Inc.
- 2000 mesh per inch → 12.5 $\mu$m pitch
- Hole width 6.5 $\mu$m
- Nominal geometrical transmission 41%



PMMA = Poly-methyl-methacrylate $(C_5O_2H_8)_n$

# Measurements of graphene on TEM grids

Graphene characterisation with spectroscopy:

- Micro-Raman
- X-rays Photoemission Spectroscopy (XPS)
- Electron Energy Loss Spectroscopy (EELS)

Transmission of low-energy electrons (30-900 eV):

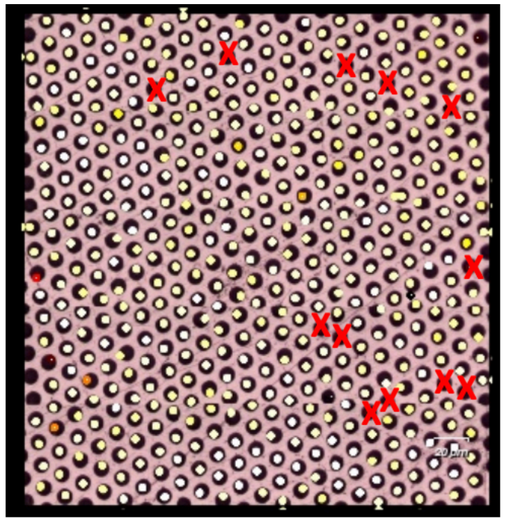
- Fixed point measurement as a function of the energy

# Raman spectra: full coverage good quality graphene

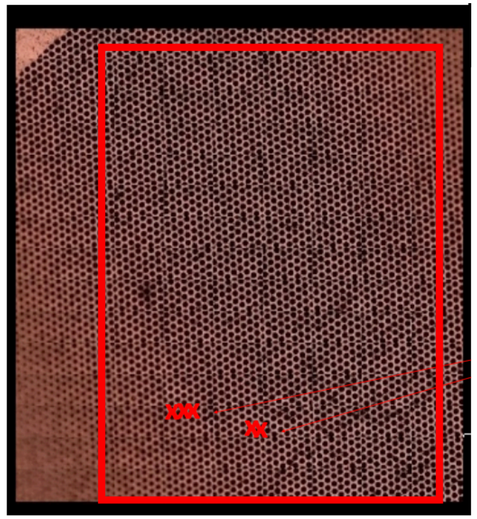
Micro-Raman maps:

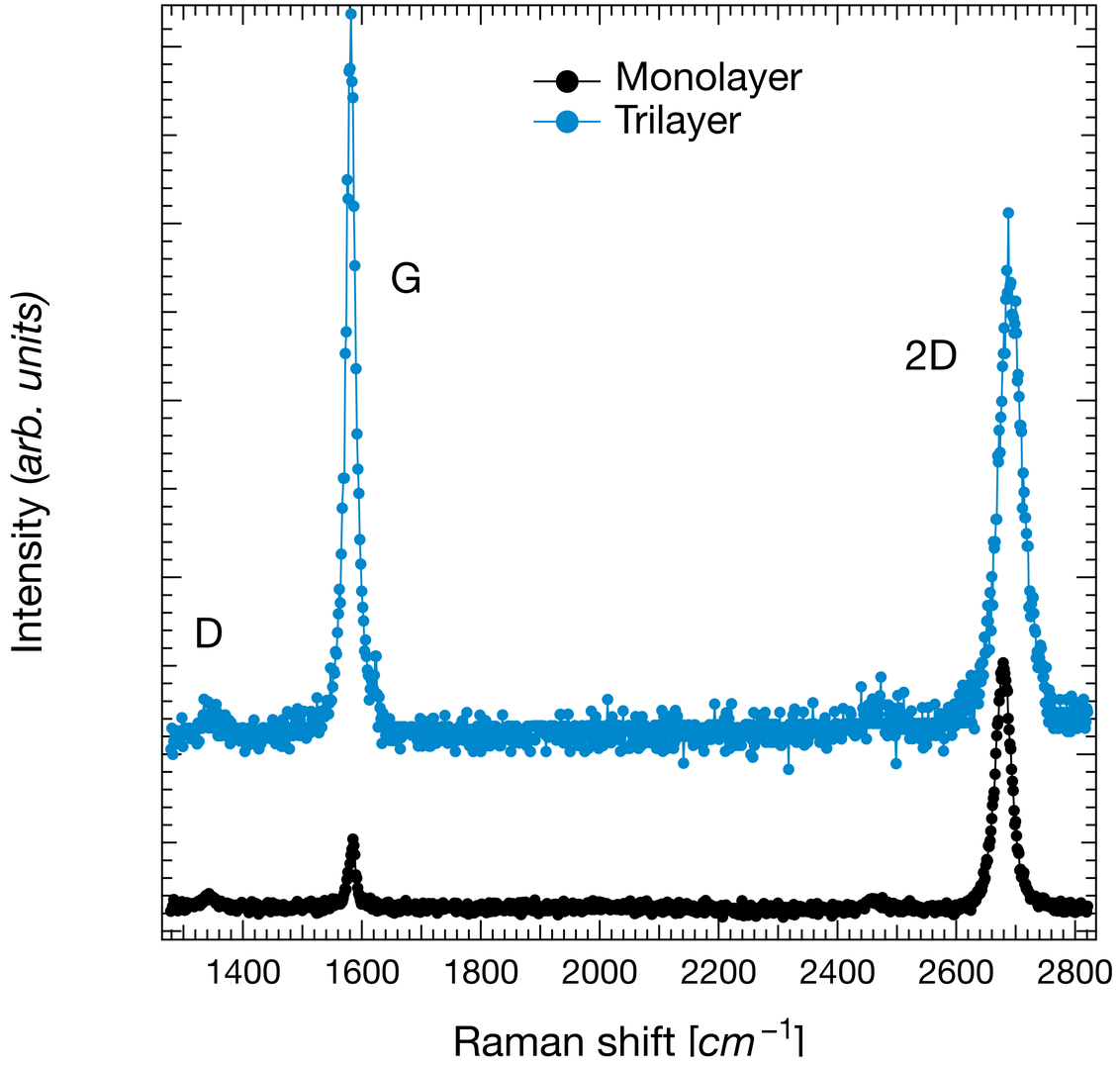
- Full coverage achieved
- Few spots without graphene X

Monolayer

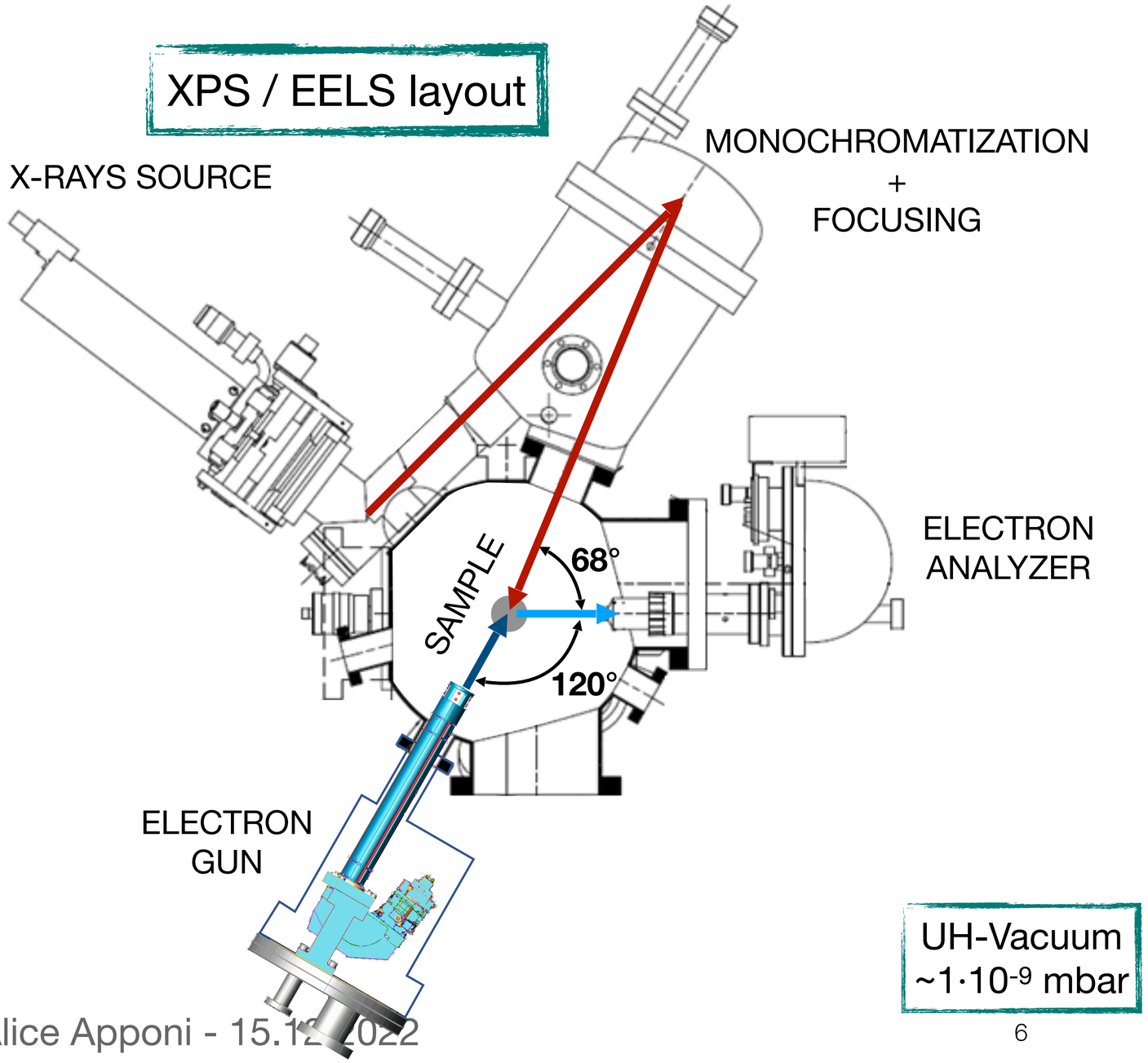


Trilayer





# The LASEC experimental layout



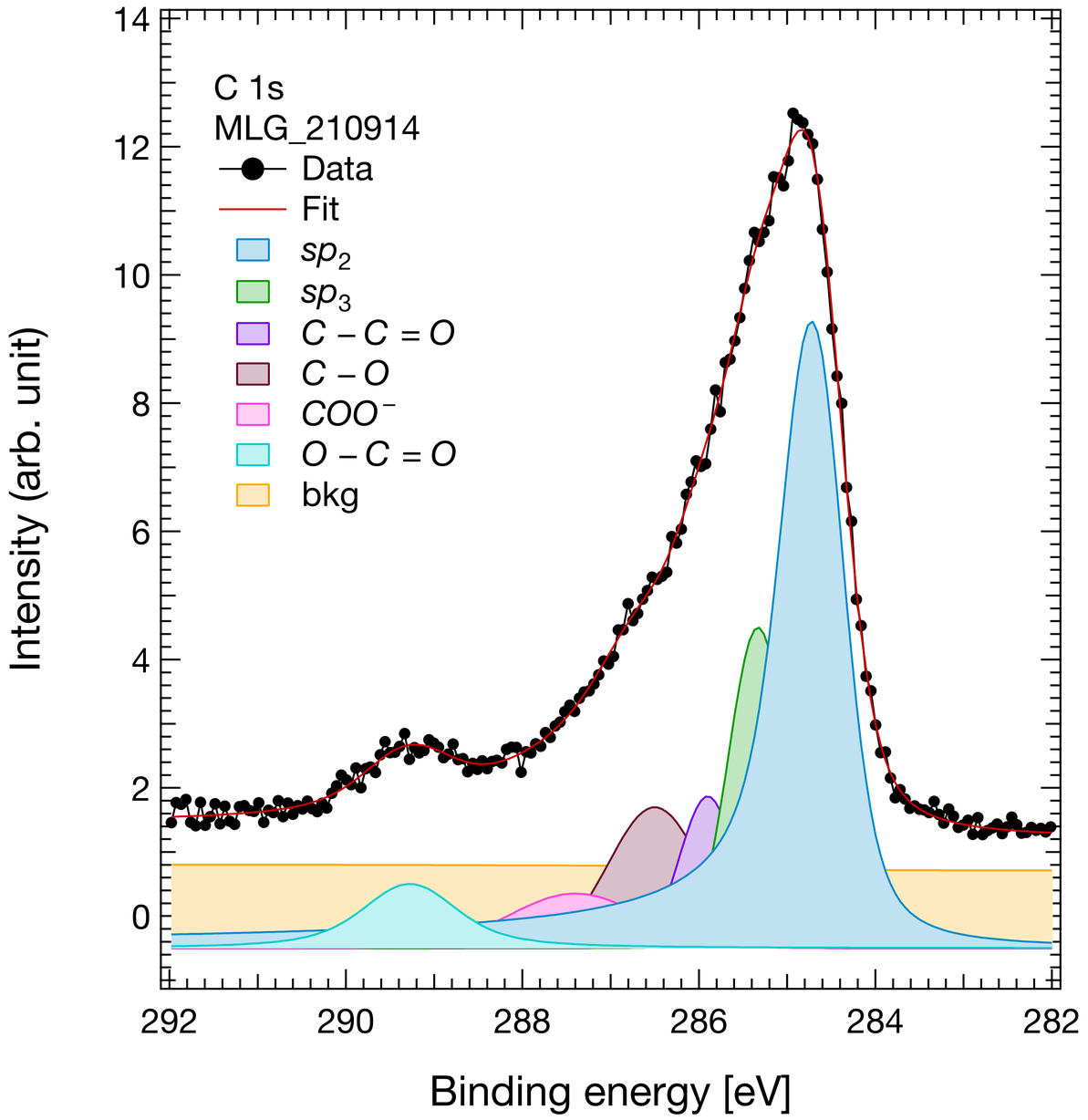

Al K$\alpha$ source:

- hv = 1486.7 eV
- Resolution 0.35 eV
- Analyser wf = 4.3 eV
- Tot resolution = 0.46 eV

Custom-made monochromatic electron gun:

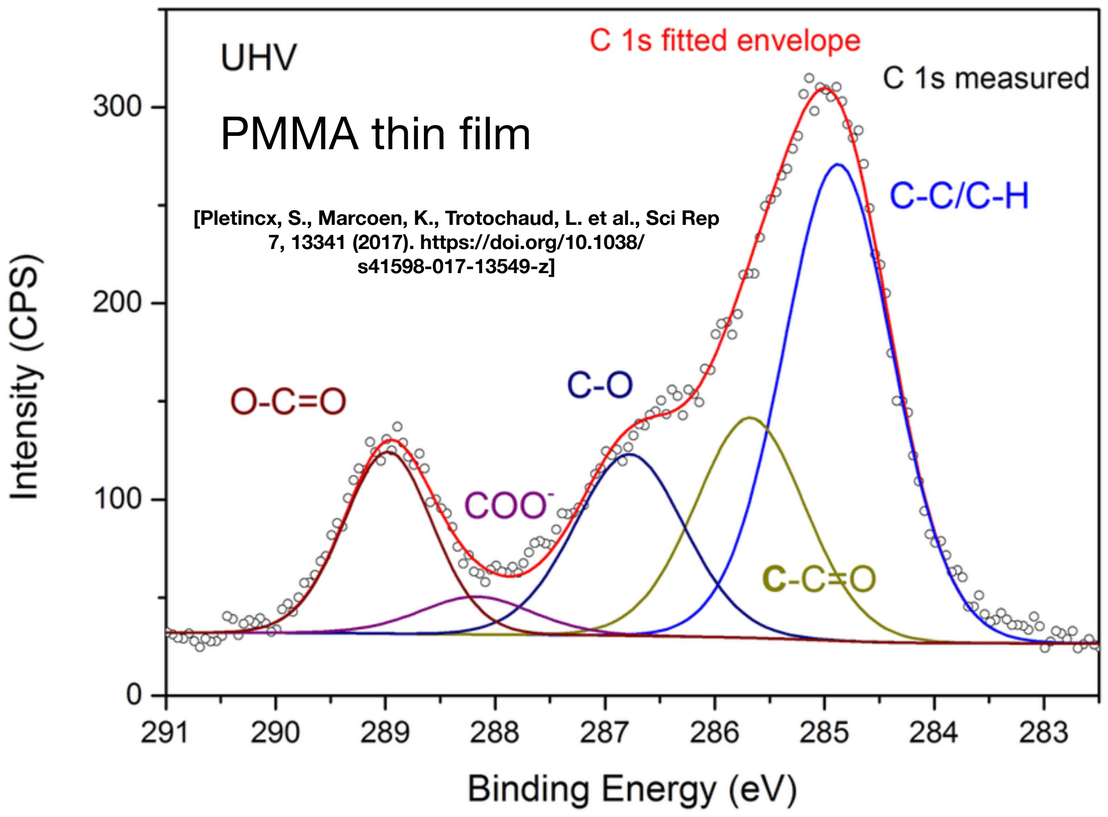
- Continuous electron beam
- Tuneable energy 30 - 900 eV
- Resolution = 45 meV

# Monolayer C 1s: high contamination




Monolayer sample measured before annealing:

- High contamination
- PMMA residues due to graphene transfer
- Clean the sample is necessary

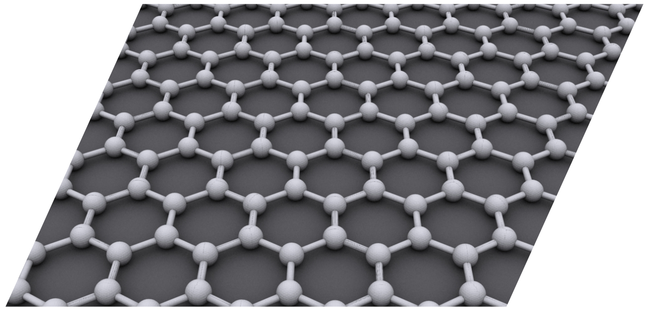


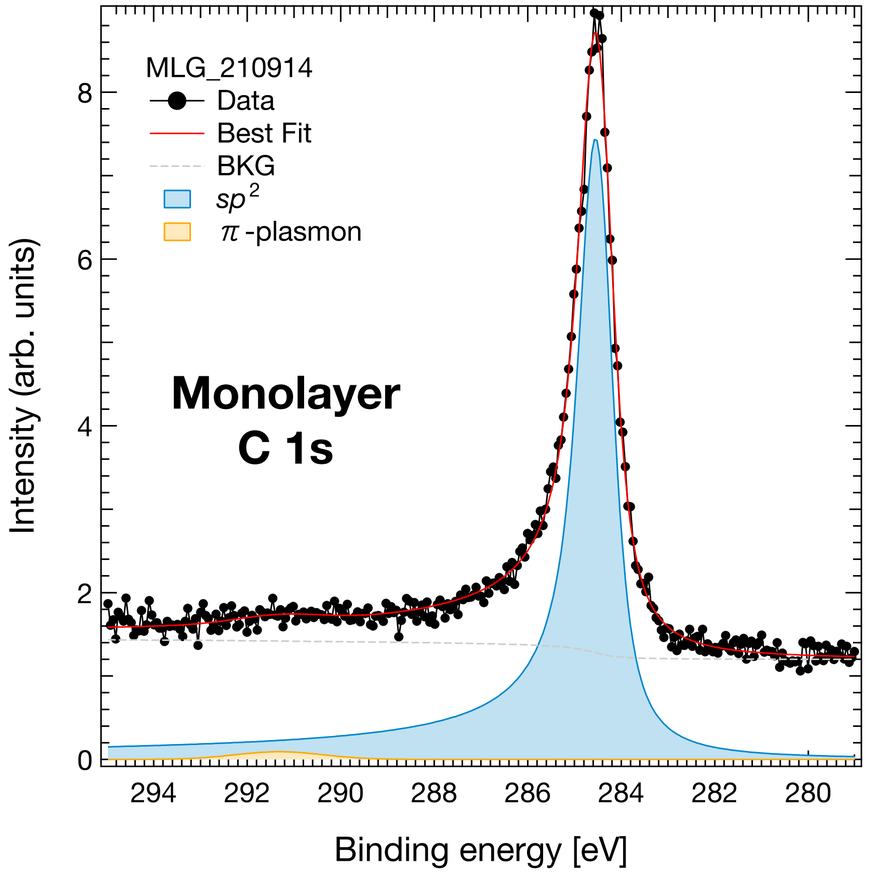
# XPS: good quality graphene

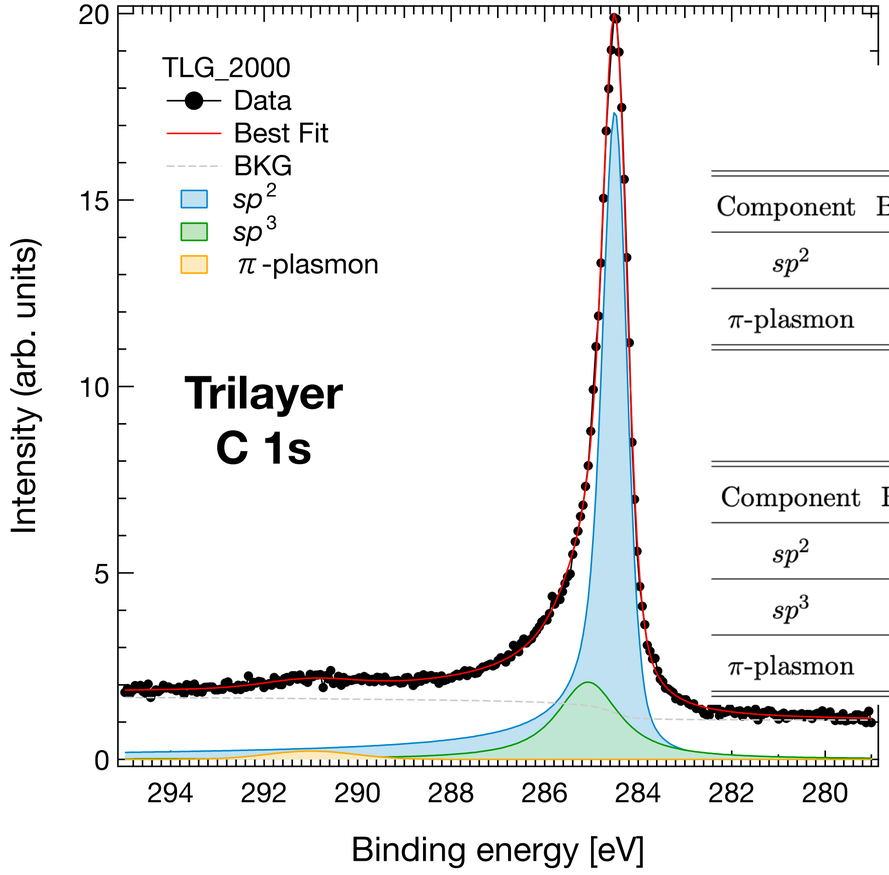
500°C annealing in vacuum

Both C 1s spectra reveal a good quality graphene:

- Main contribution due to $sp_2$
- Slight amount (~20%) of $sp_3$ in the trilayer
- Lorentzian width of $sp_2$ higher in the monolayer





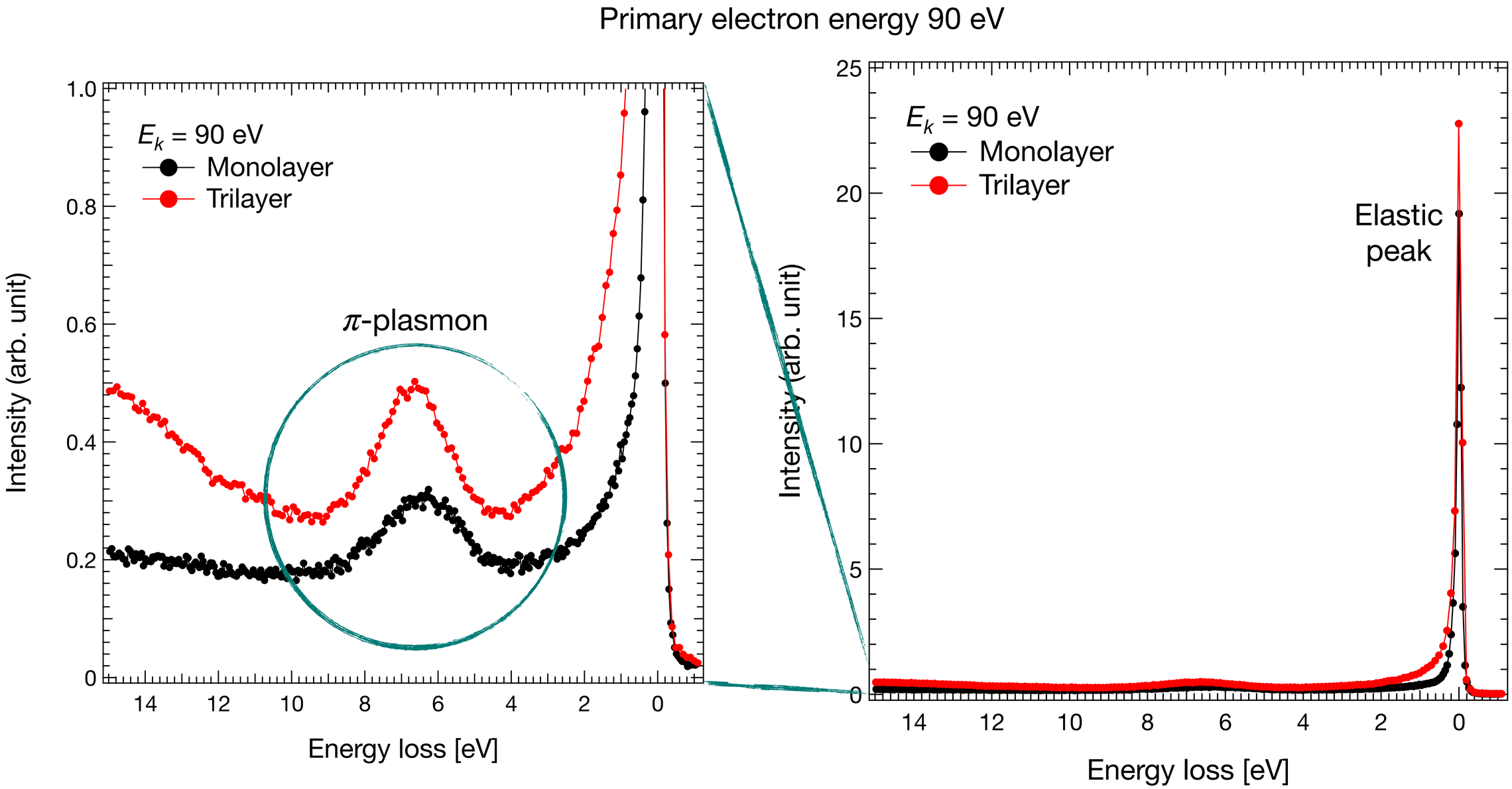

Monolayer graphene

| Component | Binding energy [eV] | Area | GW [eV] | LW [eV] | Asymmetry |
|---|---|---|---|---|---|
| $sp^2$ | 284.45 | 204 | 0.45 | 0.58 | 0.1 |
| $\pi$-plasmon | 290.9 | 4 | 1.9 | 0 | 0 |

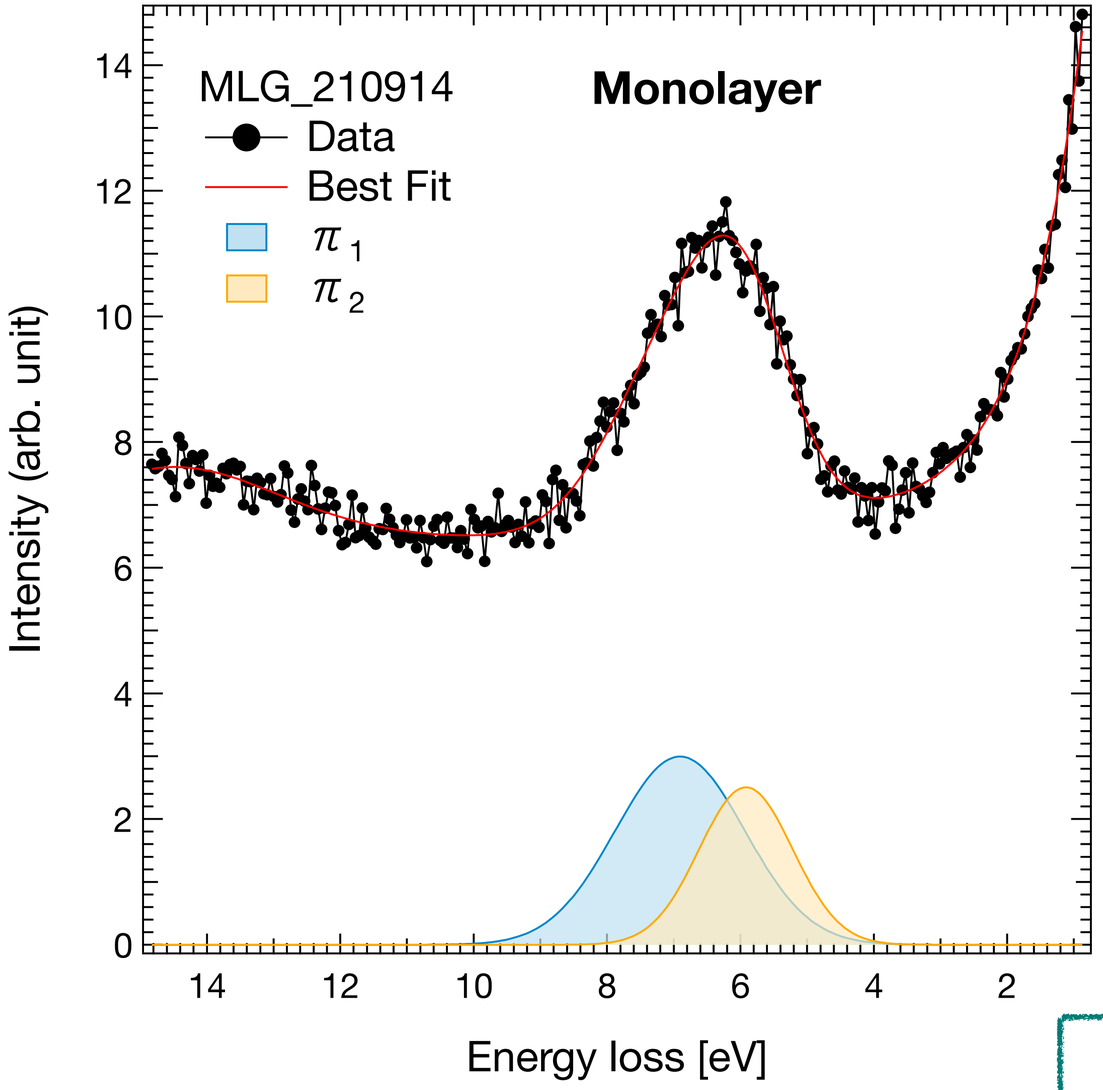
Trilayer graphene

| Component | Binding energy [eV] | Area | GW [eV] | LW [eV] | Asymmetry |
|---|---|---|---|---|---|
| $sp^2$ | 284.47 | 311 | 0.46 | 0.24 | 0.1 |
| $sp^3$ | 285.1 | 84 | 0.5 | 1.5 | 0 |
| $\pi$-plasmon | 291.0 | 10 | 2.2 | 0 | 0 |

# Comparison of the EELS spectra

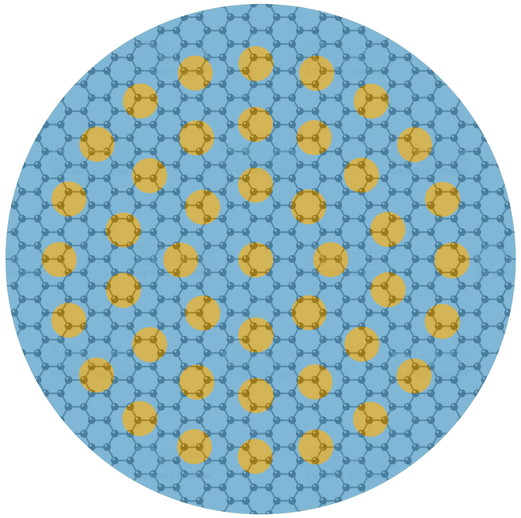


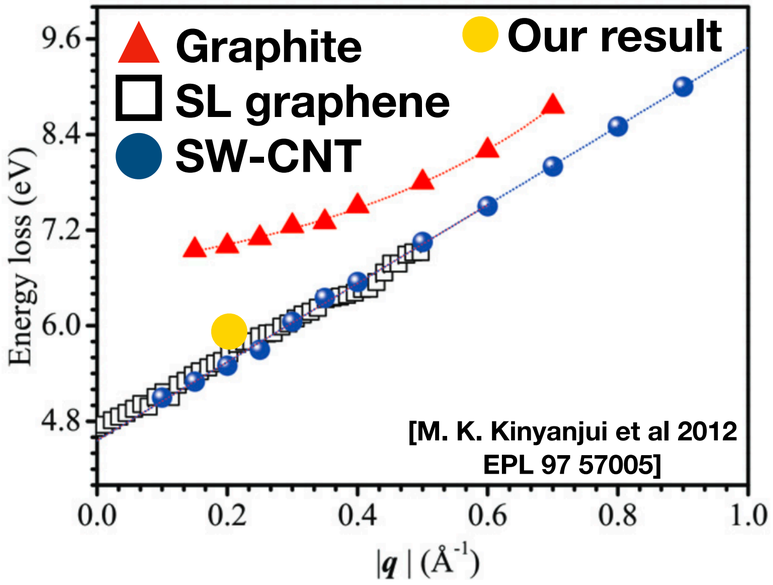
# EELS on monolayer: suspended graphene




Monolayer graphene

| Component | Energy loss [eV] | Area | FWHM [eV] |
|---|---|---|---|
| $\pi_1$-plasmon | 6.9 | 143 | 2.3 |
| $\pi_2$-plasmon | 5.9 | 87 | 1.7 |

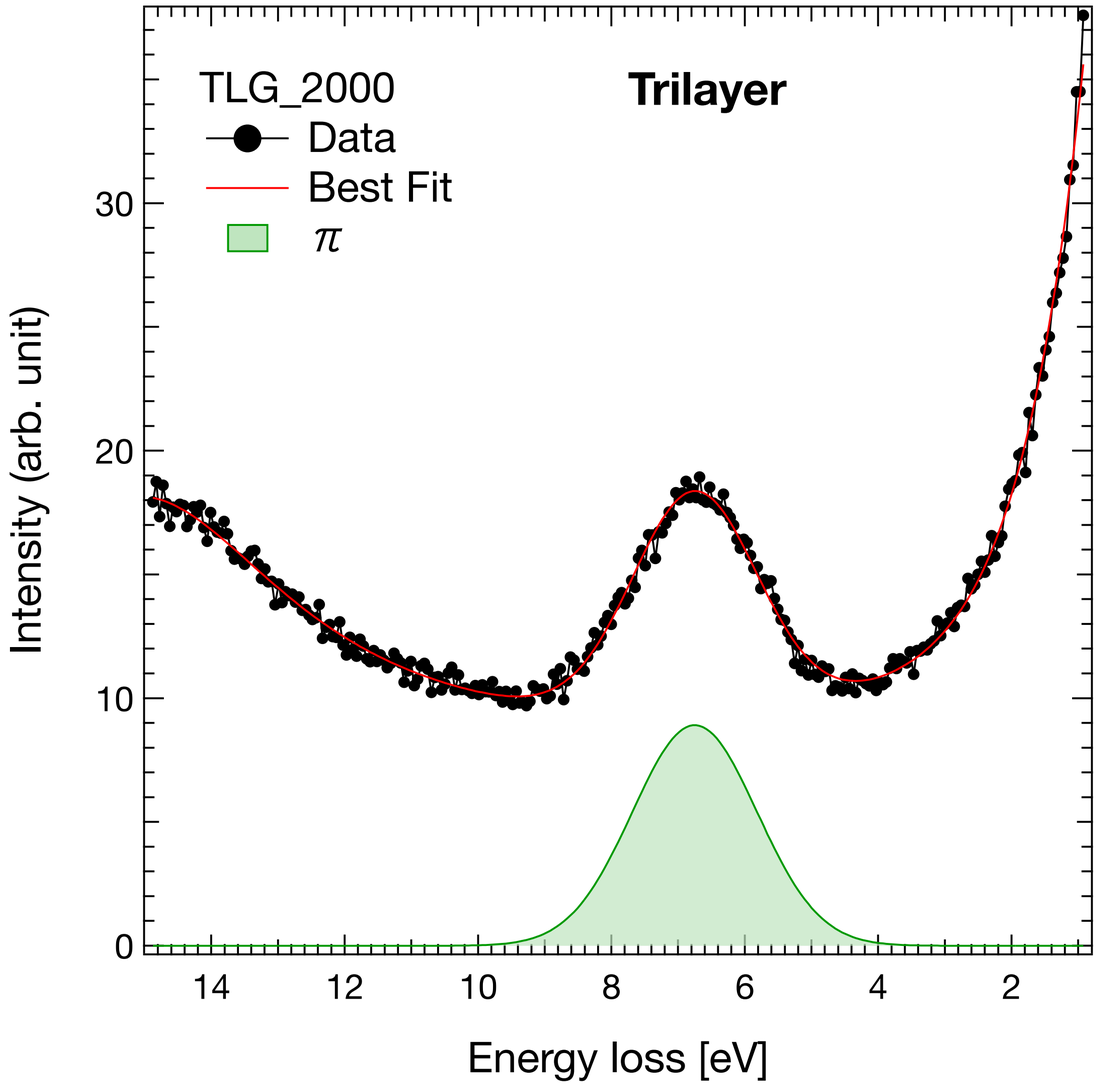





$$\frac{A_{\pi_2}}{A_{\pi_1} + A_{\pi_2}} = 38\,\%$$

Keep in mind this number, we'll see later on!

# EELS on trilayer: $\pi$-plasmon energy shifted




Trilayer graphene

| Component | Energy loss [eV] | Area | FWHM [eV] |
|---|---|---|---|
| $\pi$-plasmon | 6.8 | 410 | 2.2 |

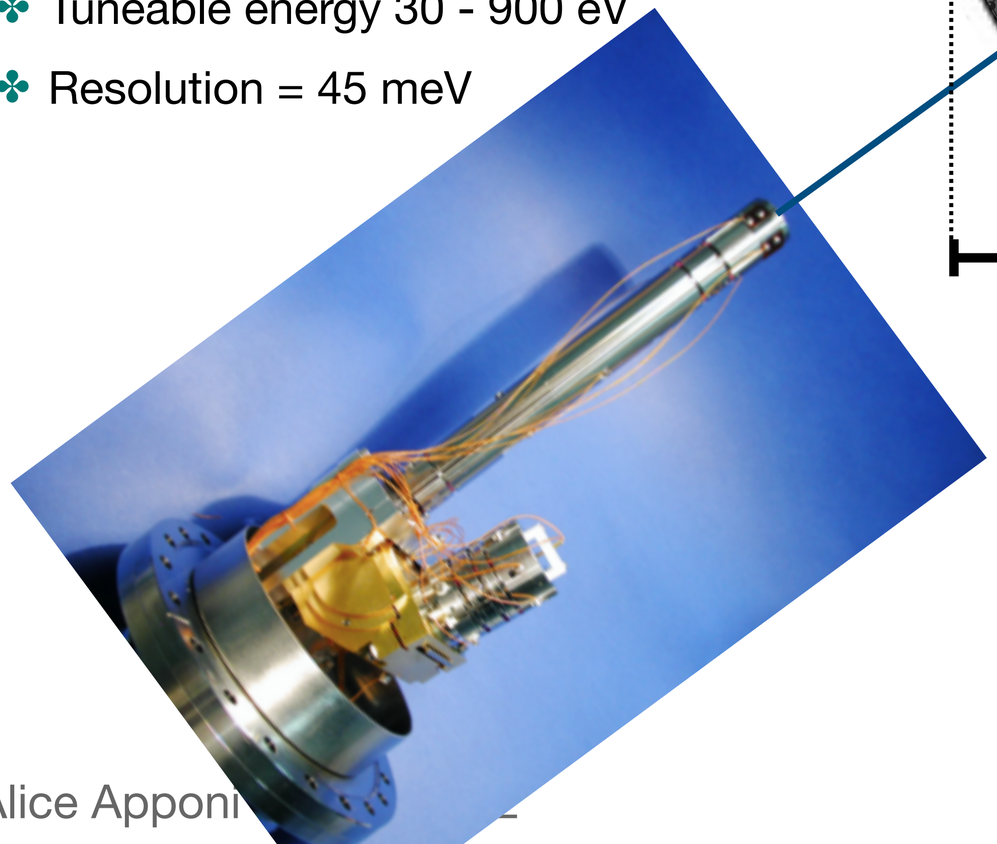
$\pi$-plasmon energy shifted increasing the number of graphene layers

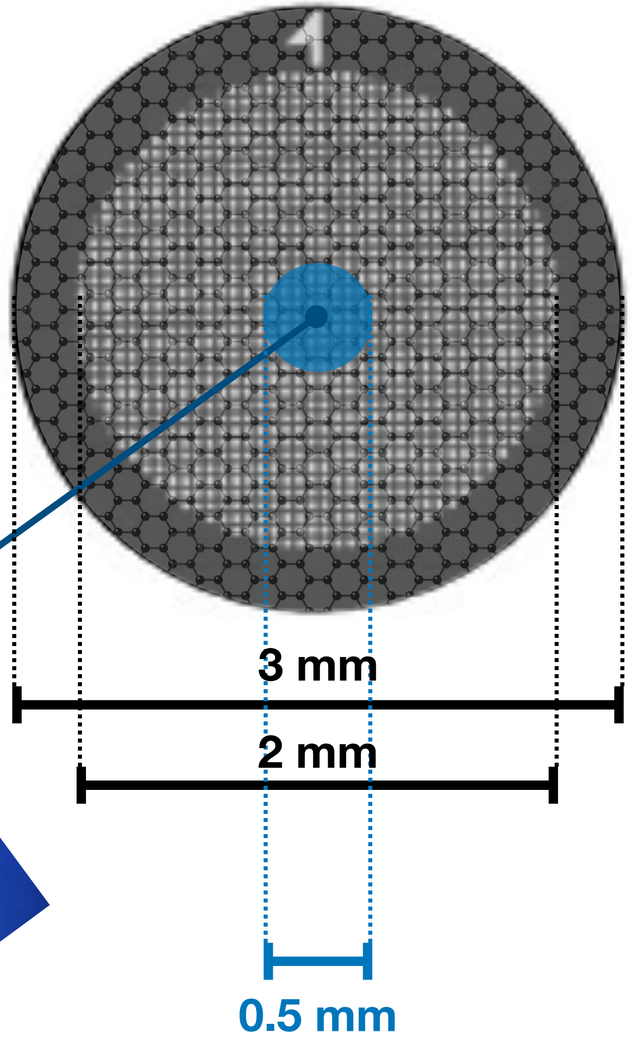
~1 eV wrt monolayer

# Transmission measurement: average on several grid holes

Monochromatic electron gun:

- Continuous electron beam
- Tuneable energy 30 - 900 eV
- Resolution = 45 meV

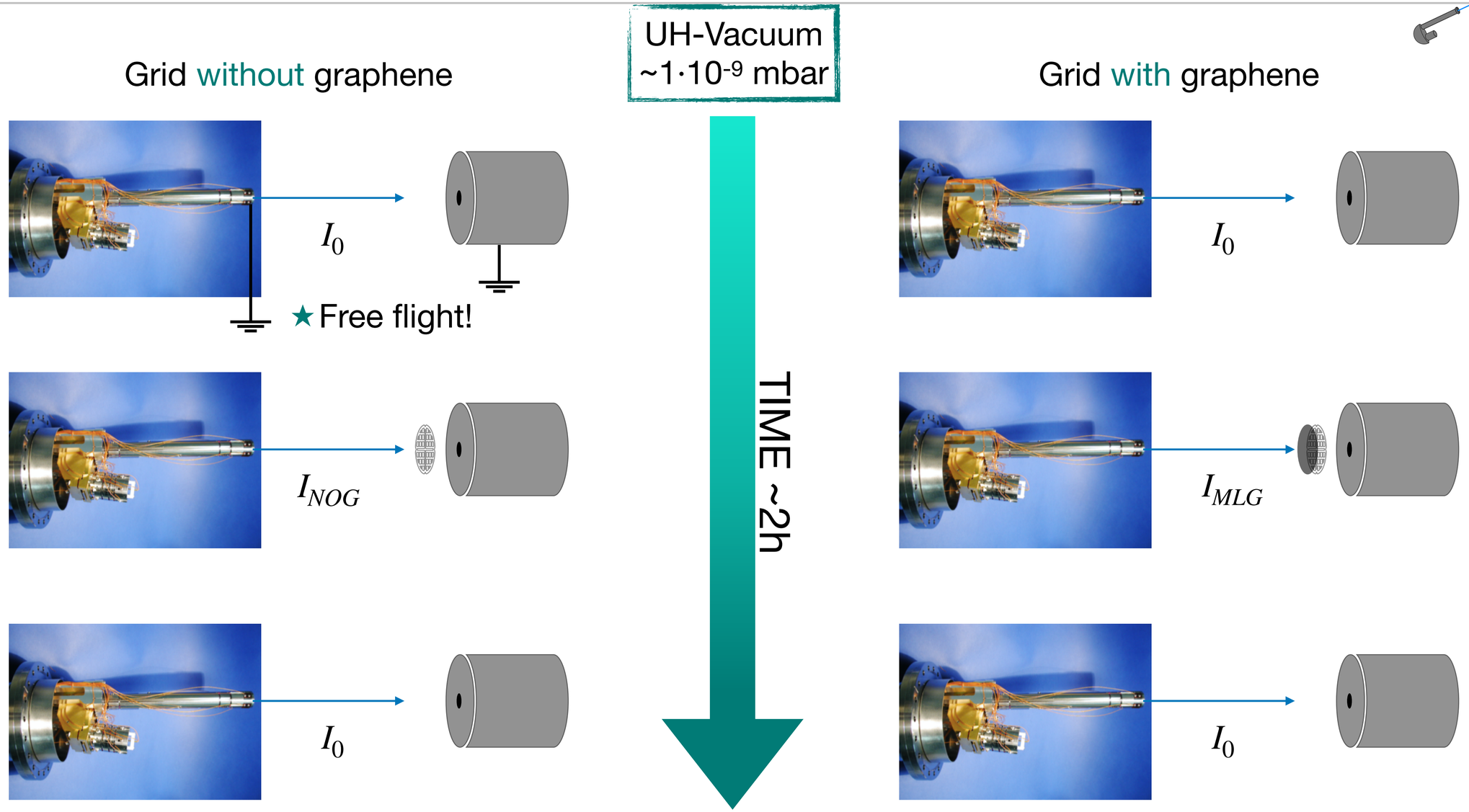





Dimension outline:

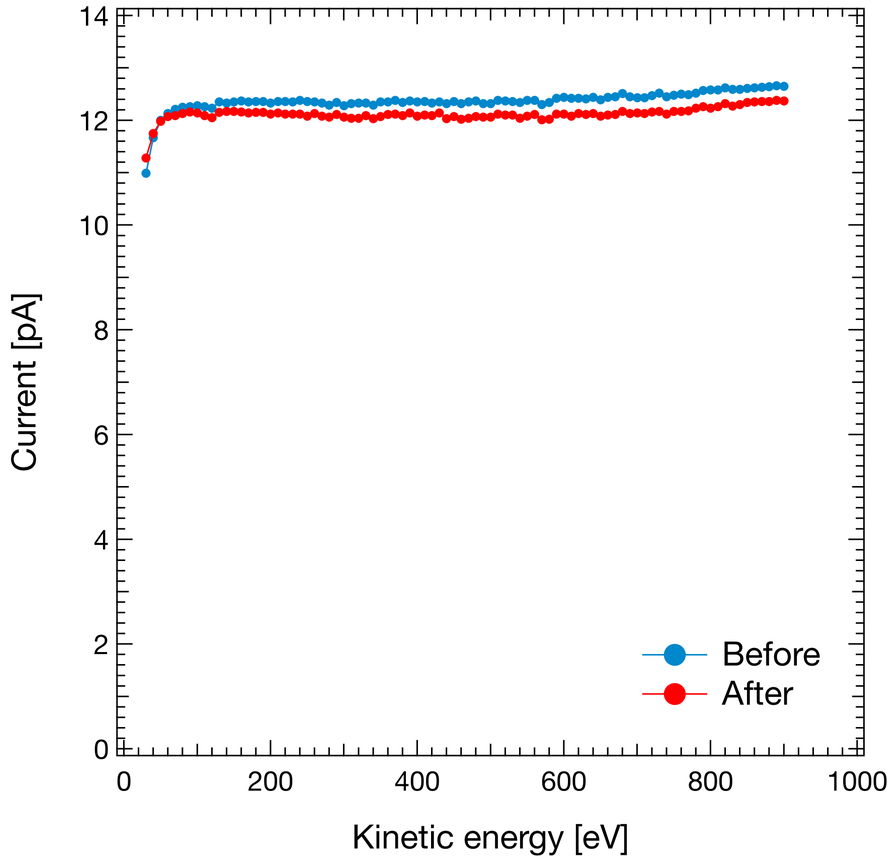
- Diameter 3 mm
- Effective diameter 2 mm
- 2000 mesh per inch → 12.5 $\mu$m pitch
- Hole width 6.5 $\mu$m
- Beam size ~ 0.5 mm

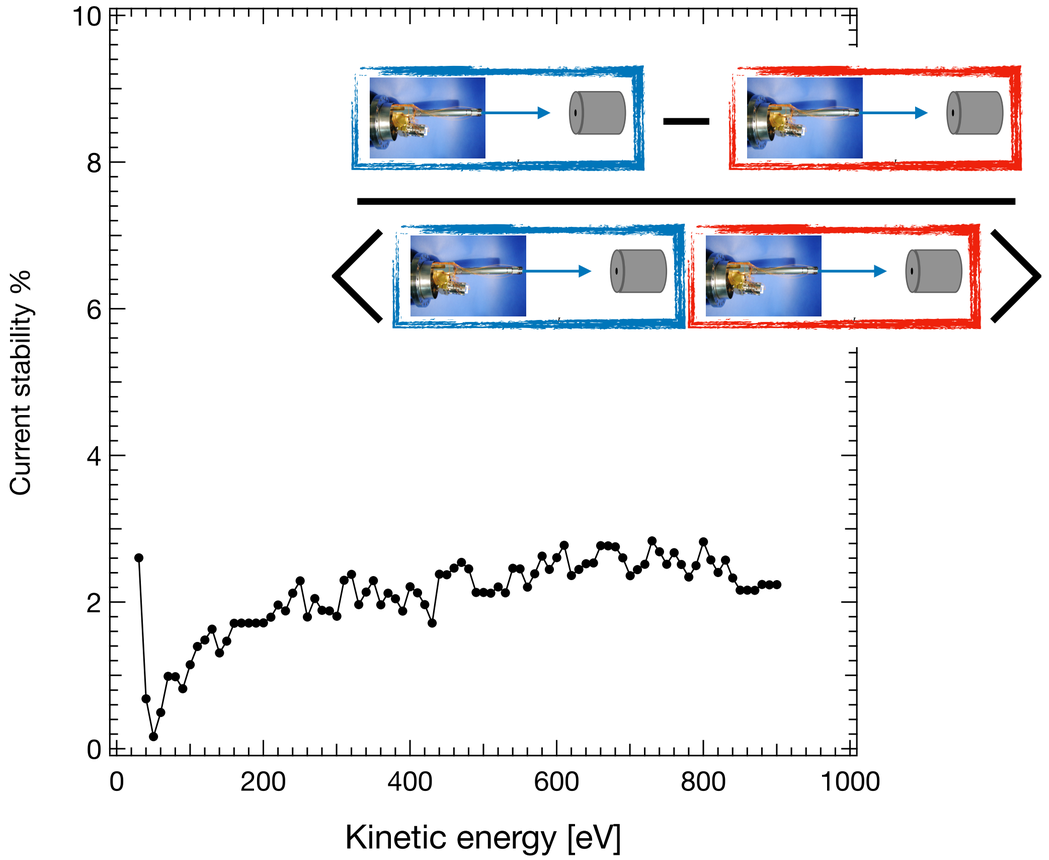
# Transmission measurement: the method




✤Check stability with current measurement before and after

# Current stability < 3%



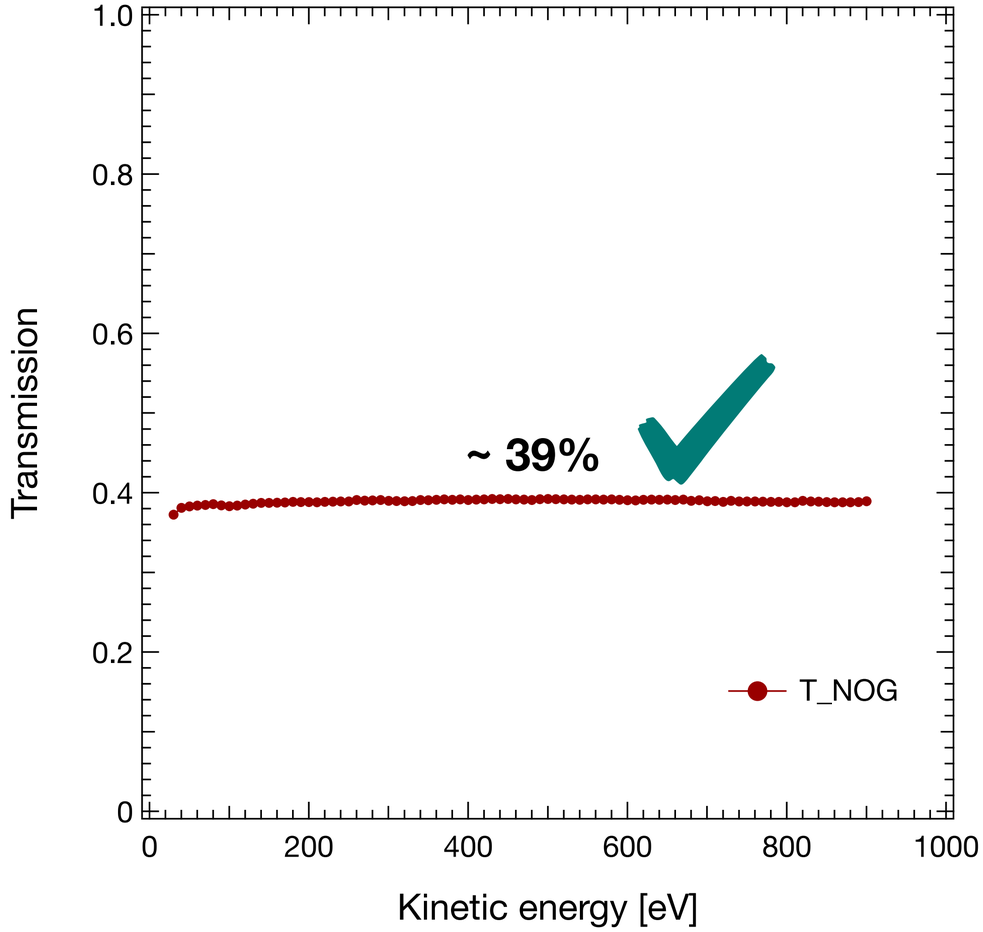




- Current stability → before - after difference / average
- Picoammeter accuracy 0.5%
- Uncertainty essentially due to current stability

# Transmission of grid without graphene ~ 39%

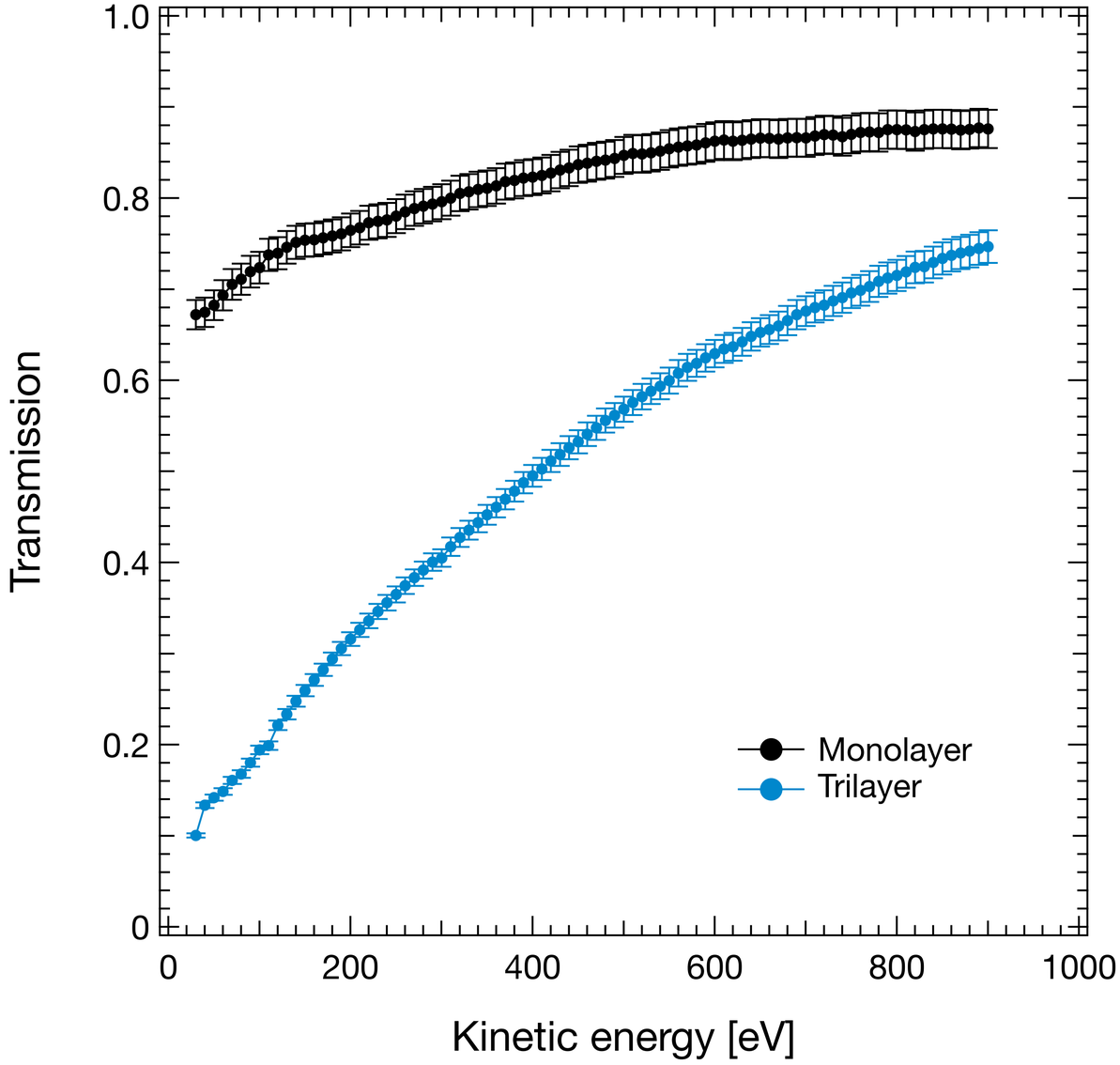
$\frac{I_{NOG}}{I_0}$ ⟶ grid without graphene (i.e. geometrical transmission)

- Nominal geometrical transmission 41%
- Uncertainty 1.7% (not shown ~same size of the dots)

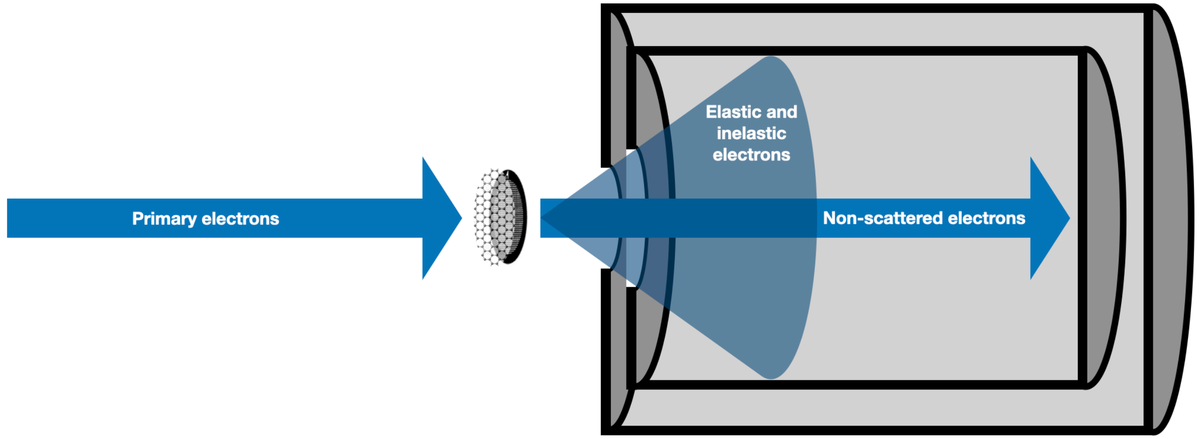


# Transmission through mono- and tri- layer graphene

$$\frac{I_{xLG}}{I_0 \cdot 0.39} \longrightarrow$$ grid with graphene (net of the 39% grid transparency )



# Monolayer: elastically scattered electrons less than 8%




$N_s$ = # elastically scattered electrons

$N_i$ = # incident electrons

$$\frac{N_s}{N_i} = n_a \; f_g \; 2\pi \int_\theta \frac{d\sigma}{d\Omega}(\theta) \sin\theta \; d\theta$$

Carbon atom density

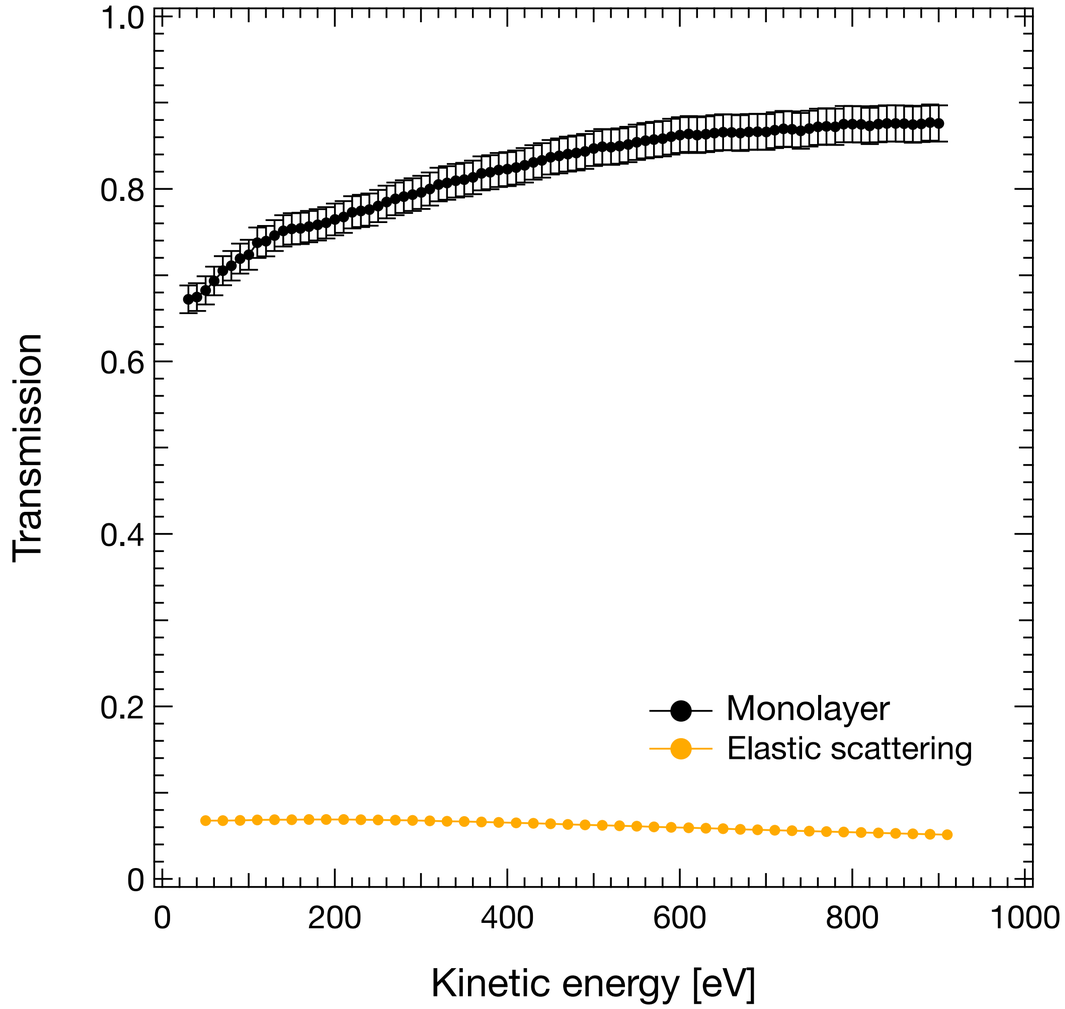
$39 \; nm^{-2} = 0.11 \; a_0^{-2}$

Geometrical factor

39%

Taken from NIST database

[A. Jablonski, F. Salvat, C. J. Powell and A. Y. Lee, NIST Electron Elastic-Scattering Cross-Section Database Version 4.0. NIST Standard Reference Database Number 64, National Institute of Standards and Technology, Gaithersburg, MD, 20899, 2016]



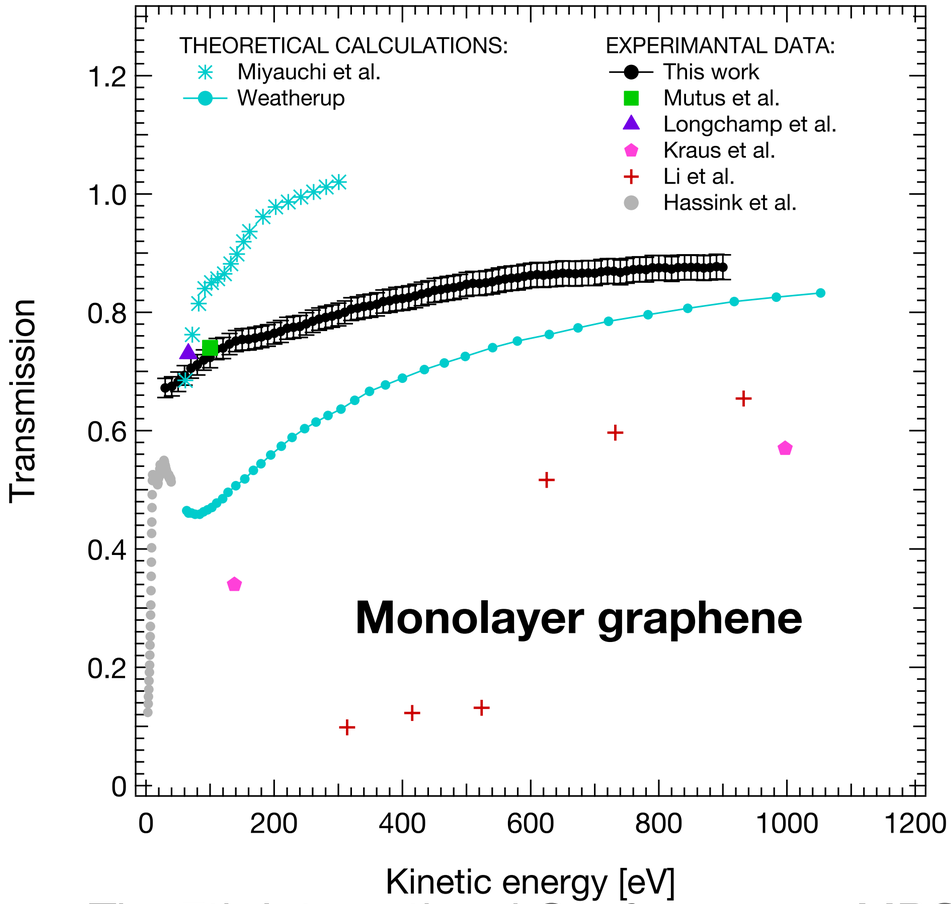
# To conclude

Graphene characterisation with spectroscopy:

- Contaminants removed with 500°C in-vacuum annealing
- High quality graphene, C 1s mainly $sp_2$
- Evidence of suspended monolayer graphene (38% $\pi$-plasmon ratio, 39% measured open area!)
- Energy shifted $\pi$-plasmon for trilayer graphene

Transmission of low-energy electrons (30-900 eV):

- Experimental gap filled
- 70% to 90% transmission through monolayer graphene
- 10% to 80% transmission through trilayer graphene
- Main contribution to the transmitted beam through monolayer due to non-scattered electrons



# Graphene On meSH collaboration - GOSH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