

Motivations

- Describe **entanglement** in **quantum conductors** with **electronic coherences** [1]
- Access **two-electron states** physics with **photo-assisted quantum tomography**
- Detect **energy-entangled electrons** with **current correlations** measurements

Second-order electronic coherence

- Quantum **mesoscopic conductor** ($\nu = 2$ regime): two **Hall edge channels** (A/B)
- $\tilde{\mathcal{G}}^{(2e)} \Leftrightarrow$ overlap between two **two-electron quantum paths** (+/-) [2]

$$\tilde{\mathcal{G}}_{AB}^{(2e)}(\omega_A^+, \omega_B^+ | \omega_A^-, \omega_B^-) = \langle \hat{\psi}_A^\dagger(\omega_A^-) \hat{\psi}_B^\dagger(\omega_B^-) \hat{\psi}_B(\omega_B^+) \hat{\psi}_A(\omega_A^+) \rangle_{\hat{\rho}}$$

- Decomposition into a **"Wick"** and a **"deviation"** contributions

$$\tilde{\mathcal{G}}_{AB}^{(2e)} = \underbrace{\tilde{\mathcal{G}}_A^{(e)} \tilde{\mathcal{G}}_B^{(e)} - \tilde{\mathcal{G}}_{AB}^{(e)} \tilde{\mathcal{G}}_{BA}^{(e)}}_{\text{Wick}} + \underbrace{\Delta_W \tilde{\mathcal{G}}_{AB}^{(2e)}}_{\text{deviation}}$$

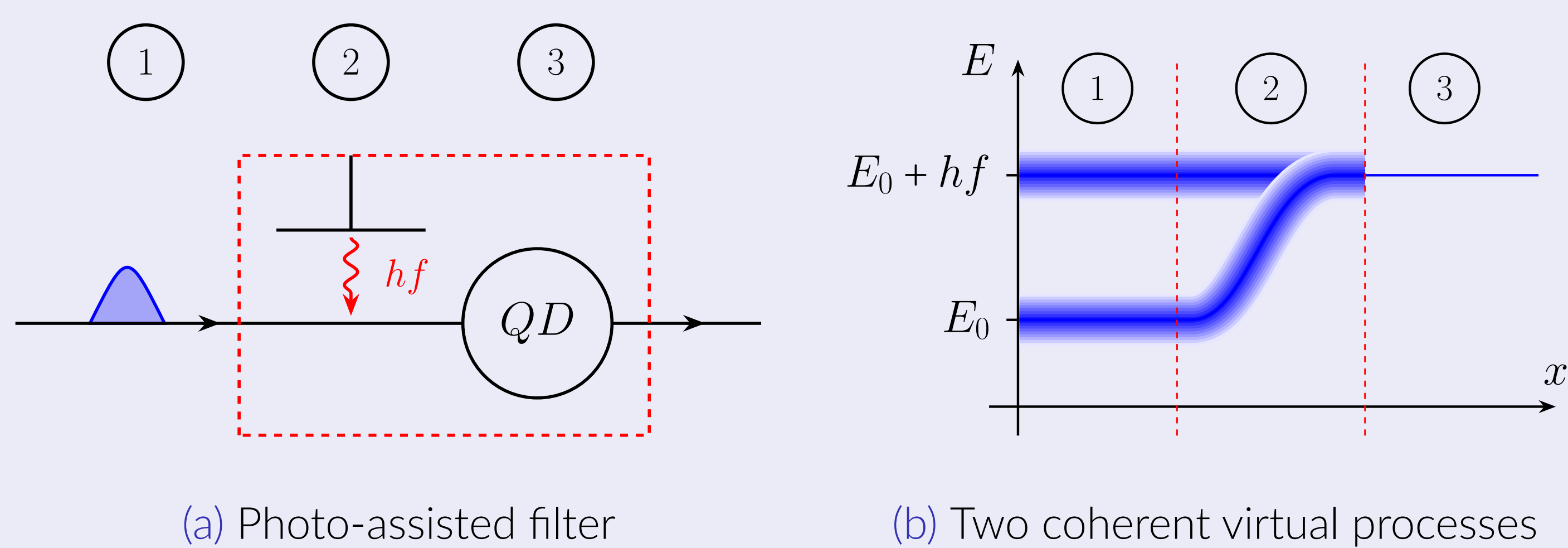
- Wick term**: coherence due to **single-electron** processes (expressed in terms of $\tilde{\mathcal{G}}^{(e)}$ functions)
- deviation term**: irreducible **two-electron** contribution
- Cauchy-Schwarz entanglement witness** on the $\tilde{\mathcal{G}}^{(2e)}$ function [3]

$$|\tilde{\mathcal{G}}_{AB}^{(2e)}(\omega_A^+, \omega_B^+ | \omega_A^-, \omega_B^-)|^2 \leq \tilde{\mathcal{G}}_{AB}^{(2e)}(\omega_A^+, \omega_B^- | \omega_A^+, \omega_B^-) \tilde{\mathcal{G}}_{AB}^{(2e)}(\omega_A^-, \omega_B^+ | \omega_A^-, \omega_B^+)$$

- Connected coherence** (order-two cumulant): $\Delta_C \tilde{\mathcal{G}}_{AB}^{(2e)} = \Delta_W \tilde{\mathcal{G}}_{AB}^{(2e)} - \tilde{\mathcal{G}}_{AB}^{(e)} \tilde{\mathcal{G}}_{BA}^{(e)}$

Photo-assisted tomography protocol

- Photo-assisted filter**: electron's energy changes with **photo-assisted processes**
- radiation coupler** (classical radiation): recombines **virtual processes** with different energies
- quantum dot** acts as an **energy filter** to select the electron's output energy



- Off-diagonal coherence** is notoriously difficult to access experimentally
- Photo-assisted filtering**: changes **off-diagonal** into **diagonal** coherence [4]

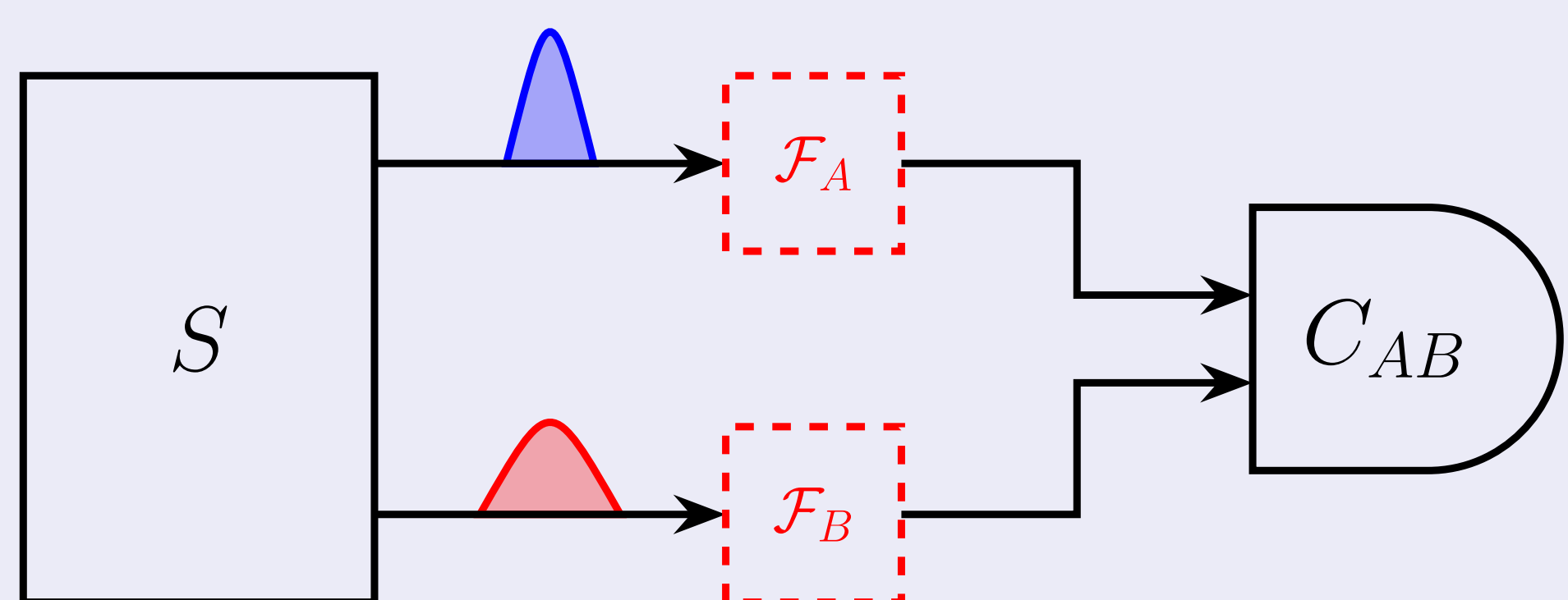


Figure 2. Photo-assisted two-electron tomography setup.

- Tomographic determination** of $\Delta_C \tilde{\mathcal{G}}_{AB}^{(2e)}$ with **current correlations** measurements
 - $\tilde{\mathcal{G}}_{AB}^{(e)} \tilde{\mathcal{G}}_{BA}^{(e)} = 0$: direct reconstruction of $\tilde{\mathcal{G}}^{(2e)}$ through $\Delta_W \tilde{\mathcal{G}}_{AB}^{(2e)}$
 - $\tilde{\mathcal{G}}_{AB}^{(e)} \tilde{\mathcal{G}}_{BA}^{(e)} \neq 0$: necessary to reconstruct $\tilde{\mathcal{G}}^{(e)}$ first to isolate $\Delta_W \tilde{\mathcal{G}}_{AB}^{(2e)} \Rightarrow$ **nested tomography**
- Entanglement comes from **single-particle delocalization**: $\tilde{\mathcal{G}}_{AB}^{(e)} \tilde{\mathcal{G}}_{BA}^{(e)}$ or $\Delta_W \tilde{\mathcal{G}}_{AB}^{(2e)}$
- Geometry where $\tilde{\mathcal{G}}_{AB}^{(e)} \tilde{\mathcal{G}}_{BA}^{(e)} = 0$: entanglement due to $\Delta_W \tilde{\mathcal{G}}_{AB}^{(2e)}$ (see next section)

Two-electron coherent collision

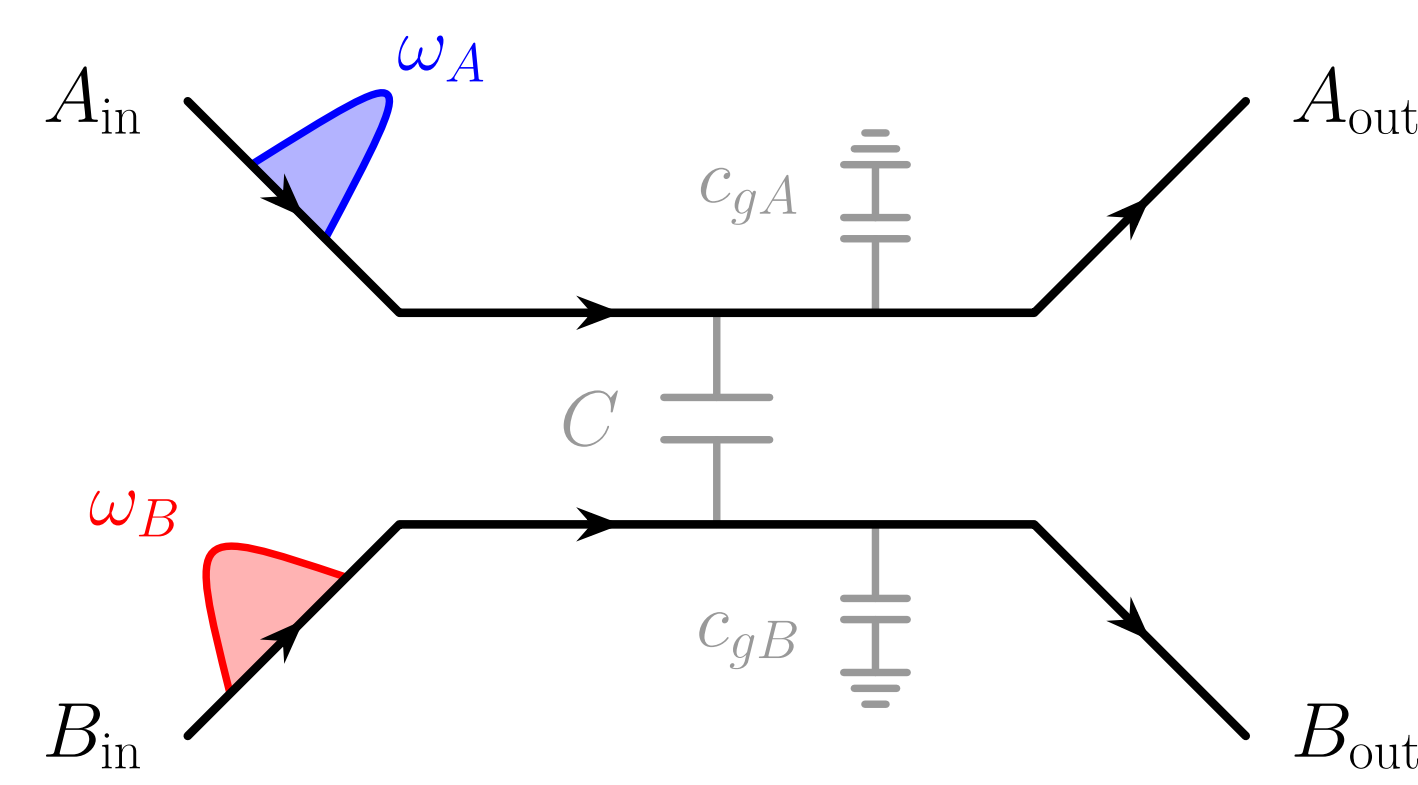
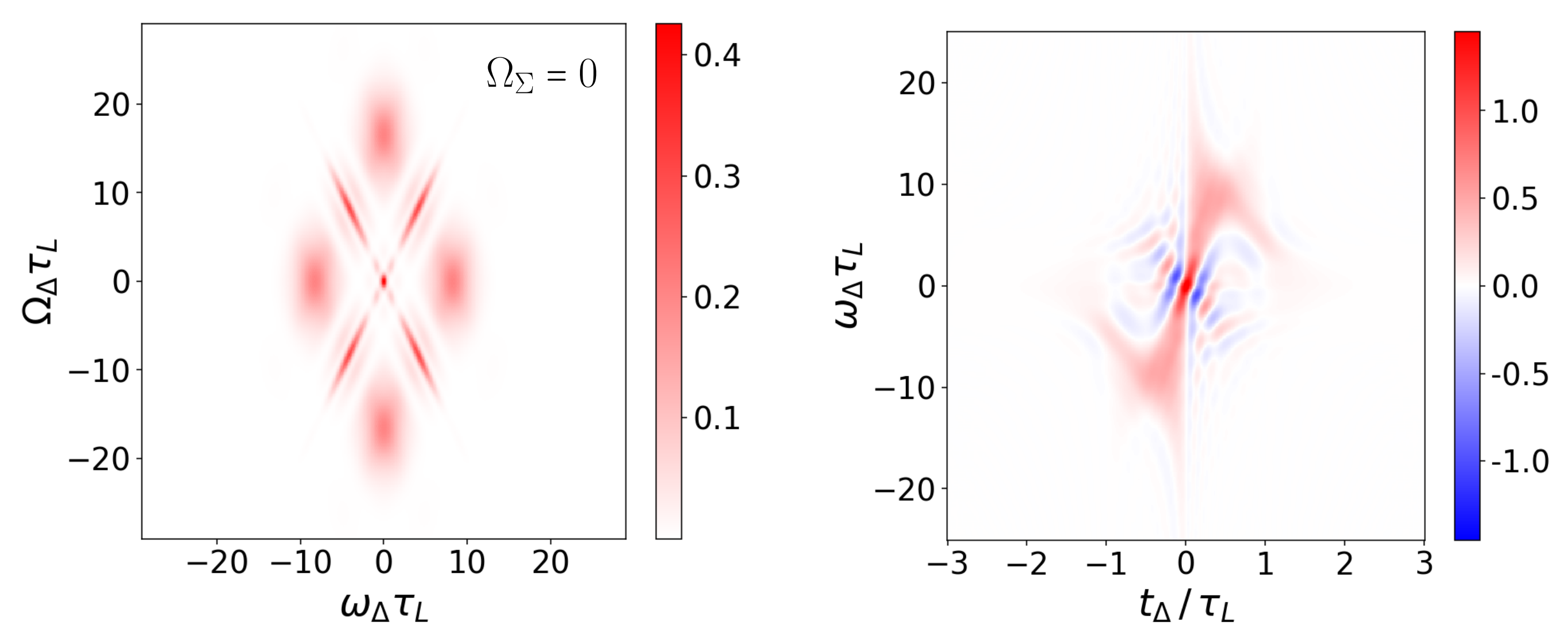


Figure 3. Electronic coherent collision model.

- Two **capacitively-coupled** channels
- Collision of **Landau wavepackets** [5]
- Conservation of $E_{tot} = \hbar(\omega_A + \omega_B)$
- Energy transfer** between A and B
- $\tilde{\mathcal{G}}_{AB}^{(e)} \tilde{\mathcal{G}}_{AB}^{(e)} = 0$ because **no tunneling**

- Center-of-mass and relative particles** description: focus on the **relative particle**

- $(\omega_\Delta, \Omega_\Delta) \Leftrightarrow$ **classical energy and quantum fluctuations** of the relative particle

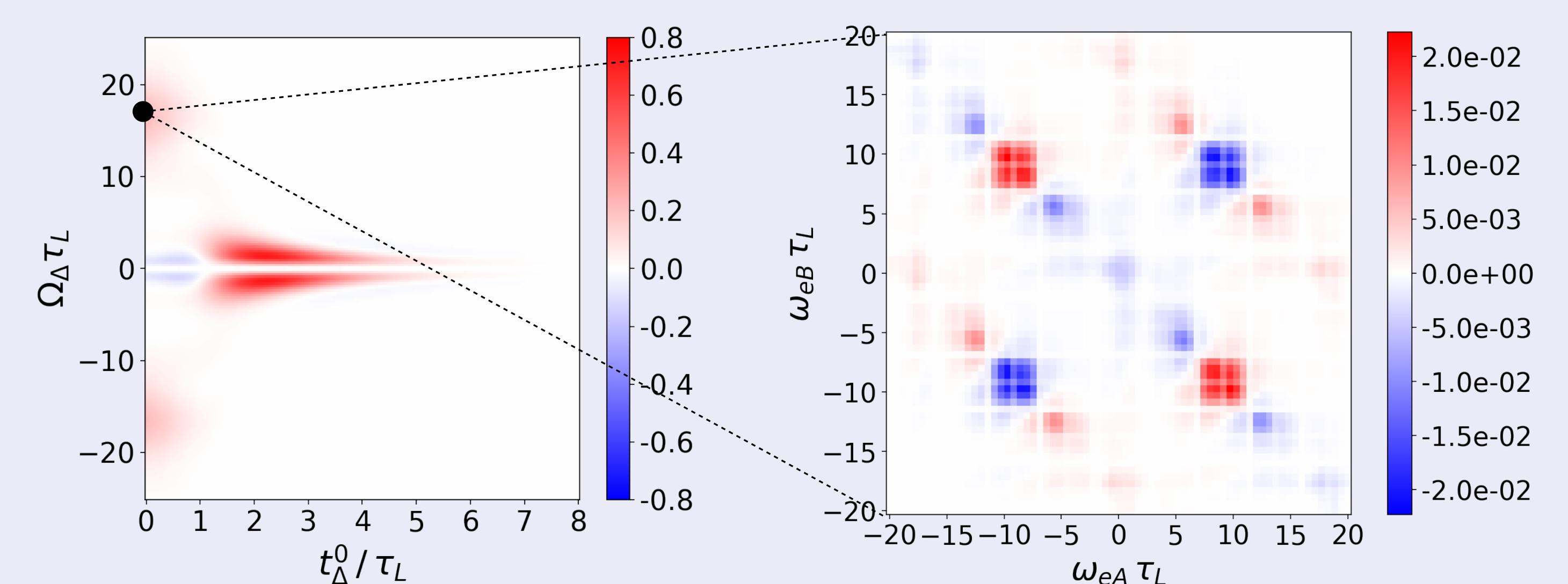


(a) Output coherence ($\omega_\Sigma = \omega_A^0 + \omega_B^0$)

(b) Relative particle's Wigner transform

- Diagonal lobes** in post-collision coherence ($\Omega_\Delta = 0$) $\Leftrightarrow$ **energy transfers**
- Off-diagonal lobes** $\Leftrightarrow$ coherent superposition of **energy transfer** processes
- Negativities** in the Wigner function [6] $\Leftrightarrow$ signature of **entanglement**

Tomographic detection of entanglement



- Witness violation** sensible to the **time delay** between wavepackets
 - off-diagonal areas** ($\Omega_\Delta \sim 18$) for **simultaneous injection** ($t_\Delta^0 \sim 0$) $\Rightarrow$ **large** energy exchange
 - near-diagonal areas** ($\Omega_\Delta \sim 3$) for **delayed injection** ($t_\Delta^0 \in [1, 6]$) $\Rightarrow$ **small** energy exchange
- One point** in the $(t_\Delta^0, \Omega_\Delta)$ plane $\Leftrightarrow$ **one plane** (ω_{eA}, ω_{eB}) of tomographic signal
 - compare **one off-diagonal** coherence to **two diagonal** coherences (Cauchy-Schwarz witness)
 - off-diagonal**: current correlations ($e^2 f$ units) after lorentzian filtering (**inversion problem**)

References

- [1] E. Bocquillon *et al.*, Ann. Phys. (Berlin) **526**, 1 (2014).
- [2] E. Thibierge *et al.*, Phys. Rev. B **93**, 081302 (2016).
- [3] S. Wölk *et al.*, Phys. Rev. A **90**, 022315 (2014).
- [4] M. Paulet *et al.* (in preparation)
- [5] G. Fève *et al.*, Science **316**, 1169 (2007).
- [6] D. Ferraro *et al.*, Phys. Rev. B **120**, 205303 (2013).

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